Cosmology

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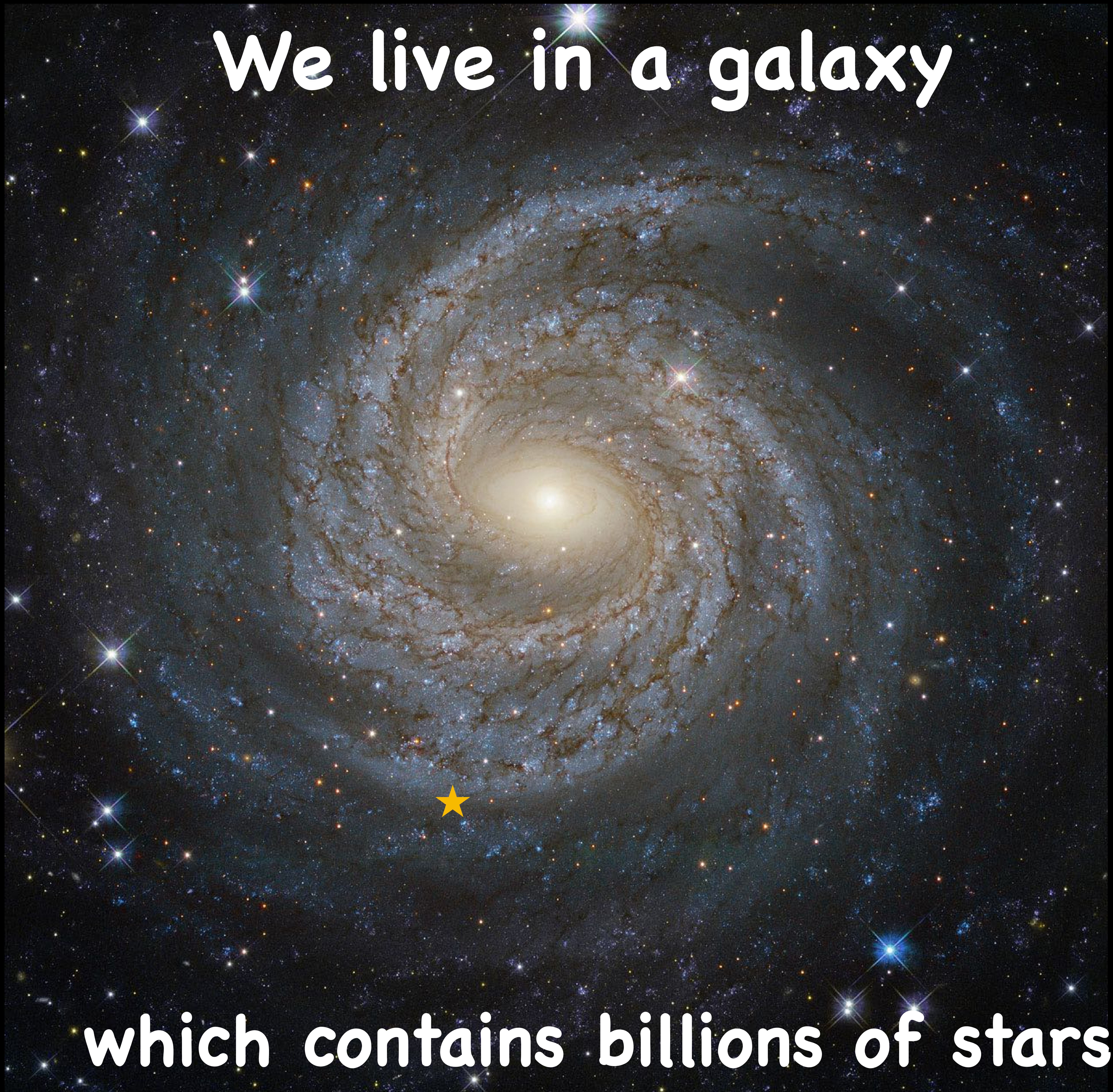
THE UNIVERSITY OF SYDNEY

CLASHEP2023

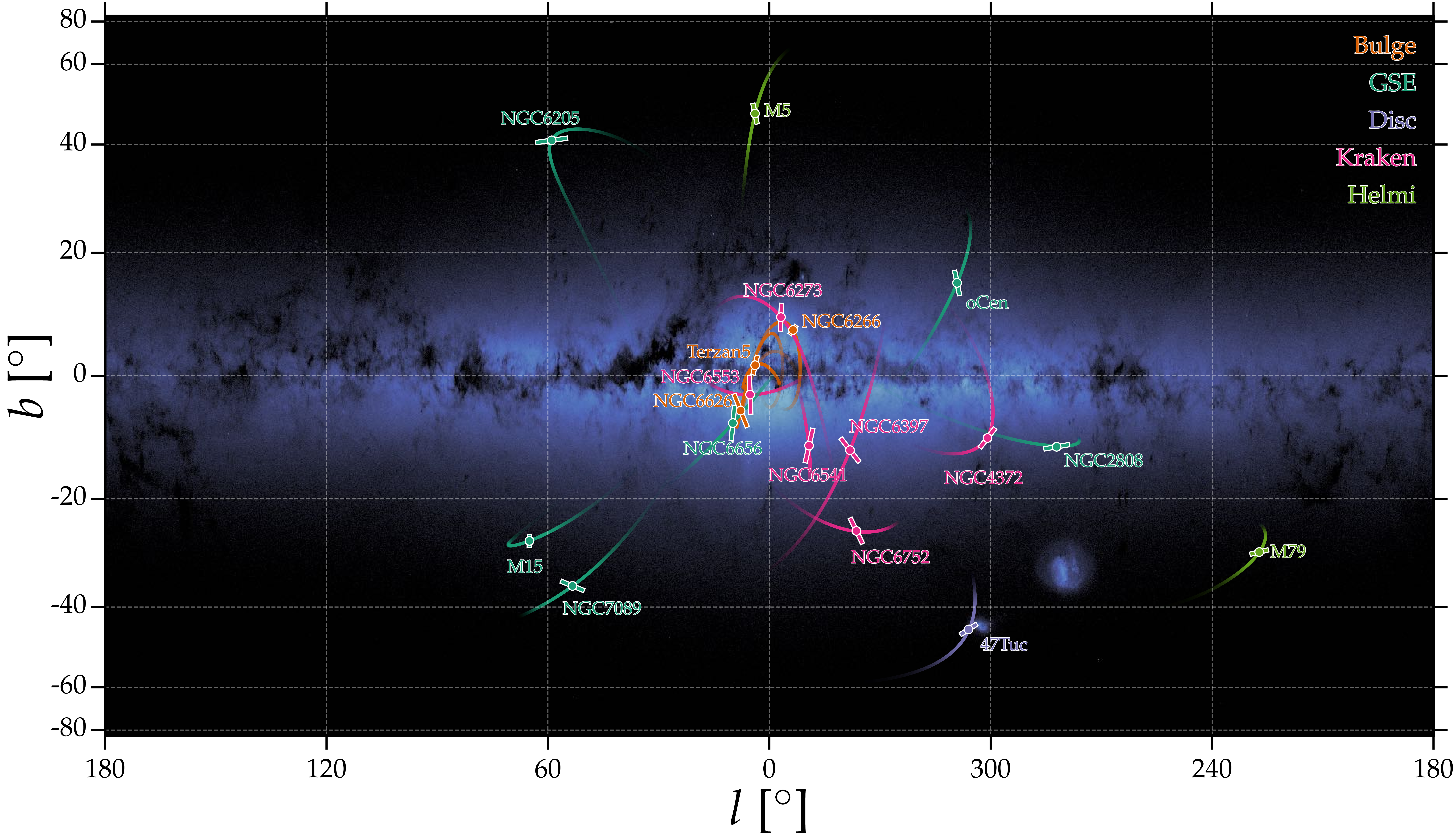
Norris-2016-Dawes-Review-Aboriginal-Astronomy.pdf



We live in a galaxy

which contains billions of stars

Courtesy Ciaran O’Hare



Our place in the Universe

Galaxies within galaxies

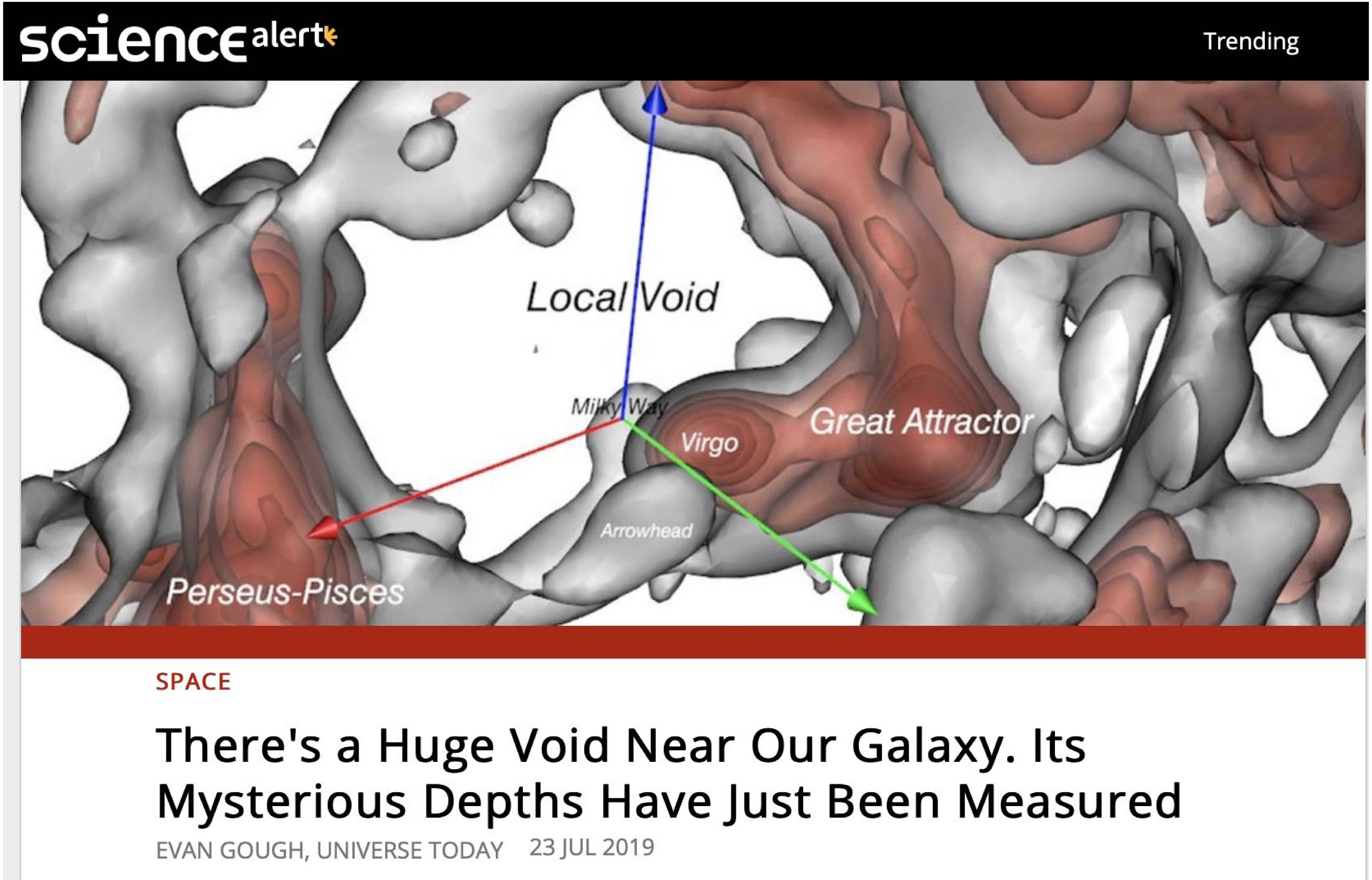
LMC and SMC are galaxies within the Milky Way and many more

Clusters of galaxies

Abell 370, credit Nasa

Our Local Group belongs to an even larger structure, a supercluster with the rich **Virgo cluster** of galaxies at its centre, about 70 million light years (about 21 **Mpc**) away. (Courtesy Astronomy @ Swinburn uni)

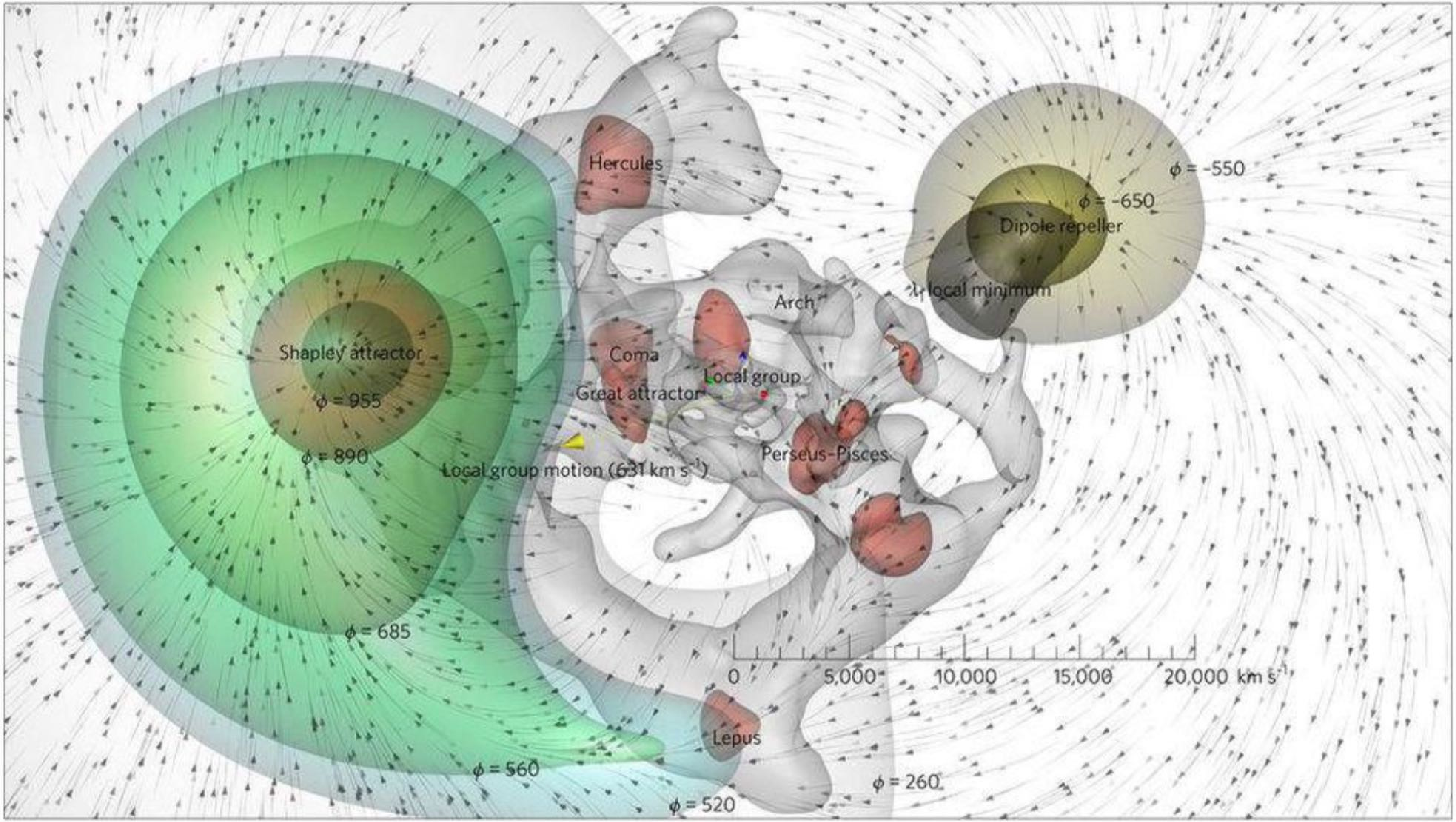
Laniakea, our super cluster



SPACE

There's a Huge Void Near Our Galaxy. Its Mysterious Depths Have Just Been Measured

EVAN GOUGH, UNIVERSE TODAY 23 JUL 2019



The relative attractive and repulsive effects of overdense and underdense regions on the Milky Way...

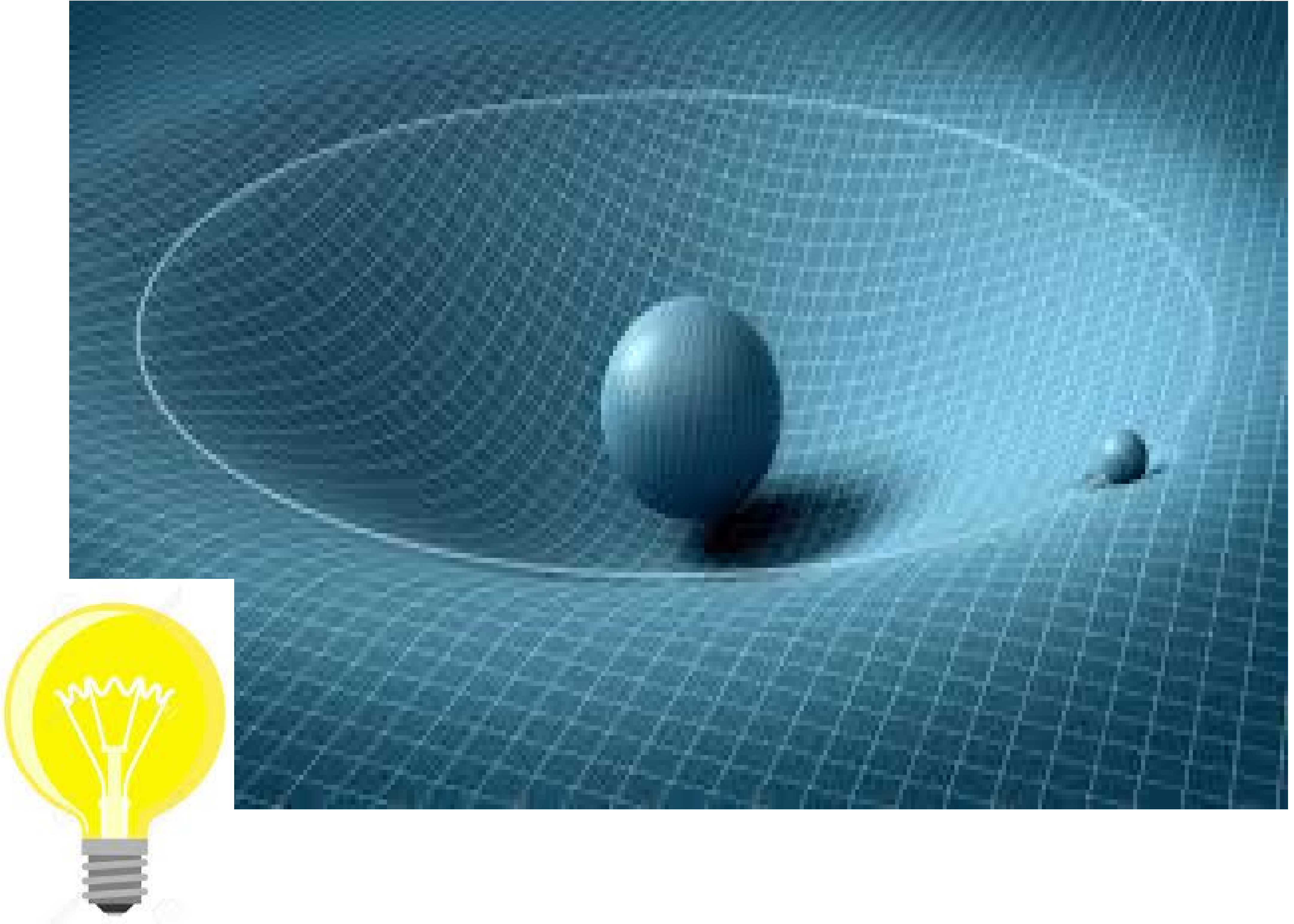
[+] YEHUDA HOFFMAN, DANIEL POMARÈDE, R. BRENT TULLY, AND HÉLÈNE COURTOIS, NATURE ASTRONOMY 1, 0036 (2017)

The cosmic web

How did we get this particular Universe?

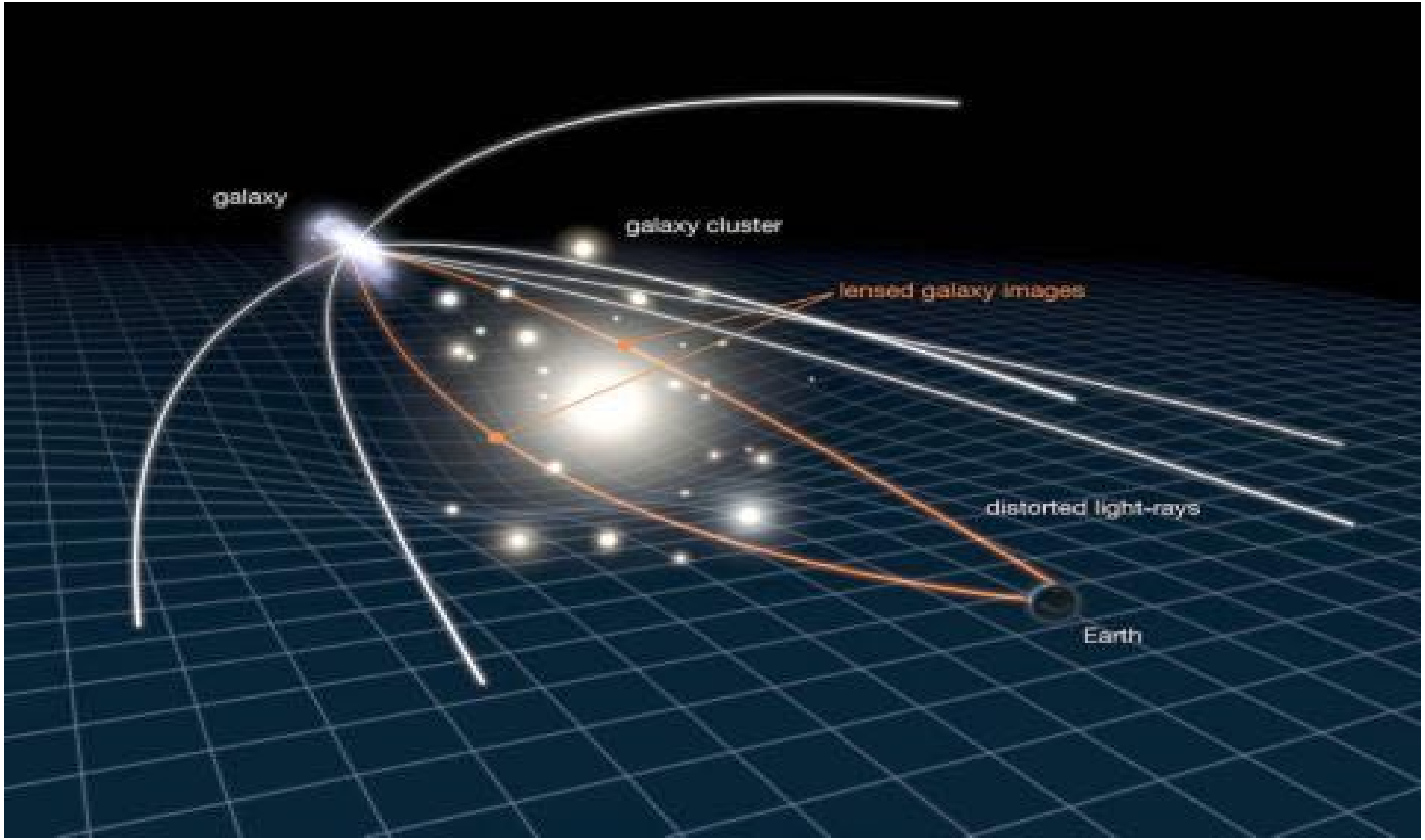
This is first and foremost a story about photons making their way to us

Do photons travel straight?

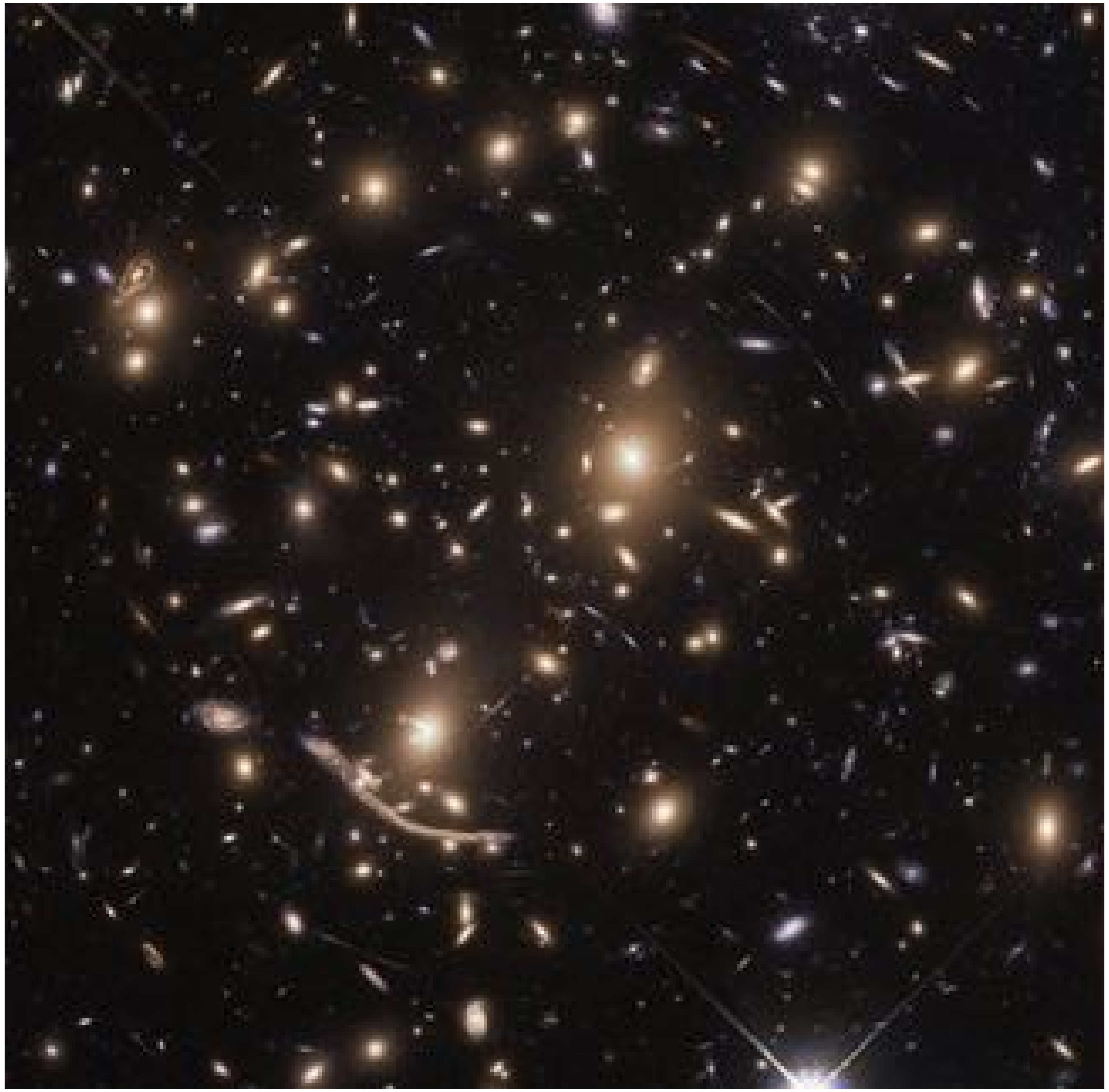


Light follows space-time but its path will be distorted and therefore its path is curved.

We know that matter curves space-time

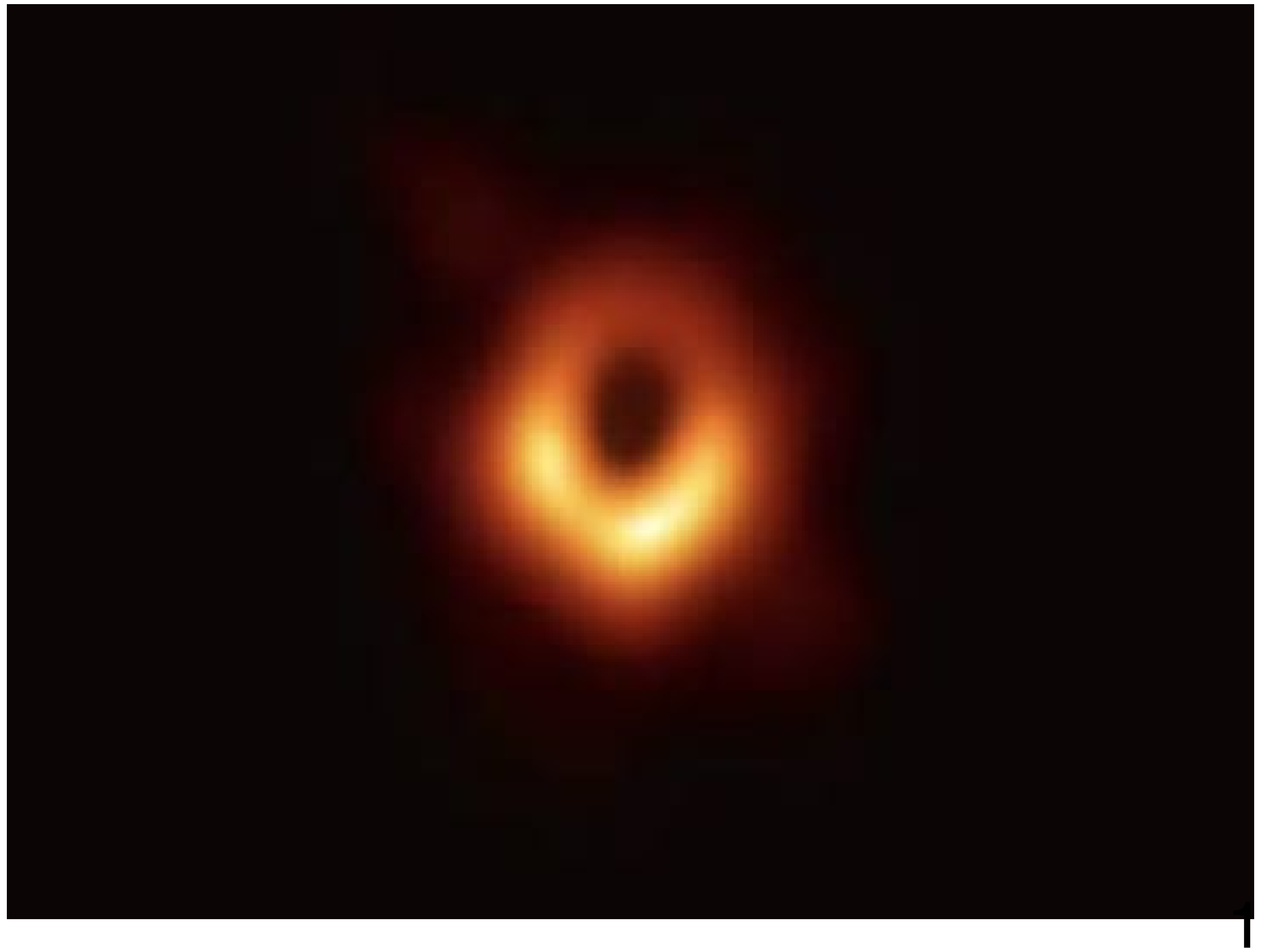


We know that matter curves space-time



The matter inside is curving space
So all objects appear distorted
One can use these distortions to reconstruct the invisible mass

Event horizon is the same phenomena
EHT collaboration 2019



My take on cosmology

Geometry of the Universe

Content of the Universe

CMB & structure formation

The invisible (challenges)

Part I. Geometry

The fact that the photons travel means we need to define a metric

Minkowski metric $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

Metric associated with a flat space-time

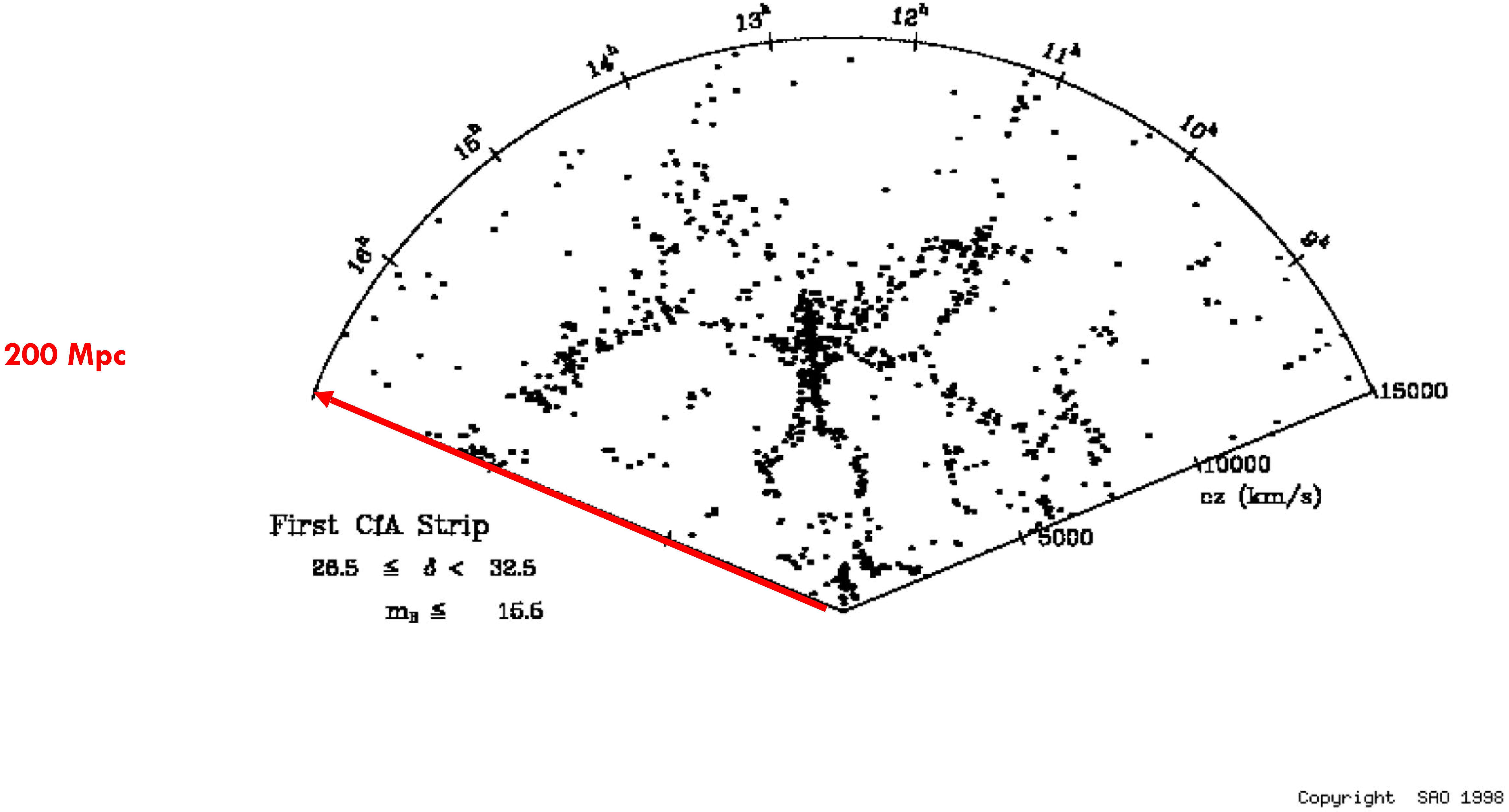
But this is not taking into account the key principles from GR and the fact that matter can curve space.

How do we generalise? $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

with $g_{\mu\nu} = ...$

Part I. Geometry

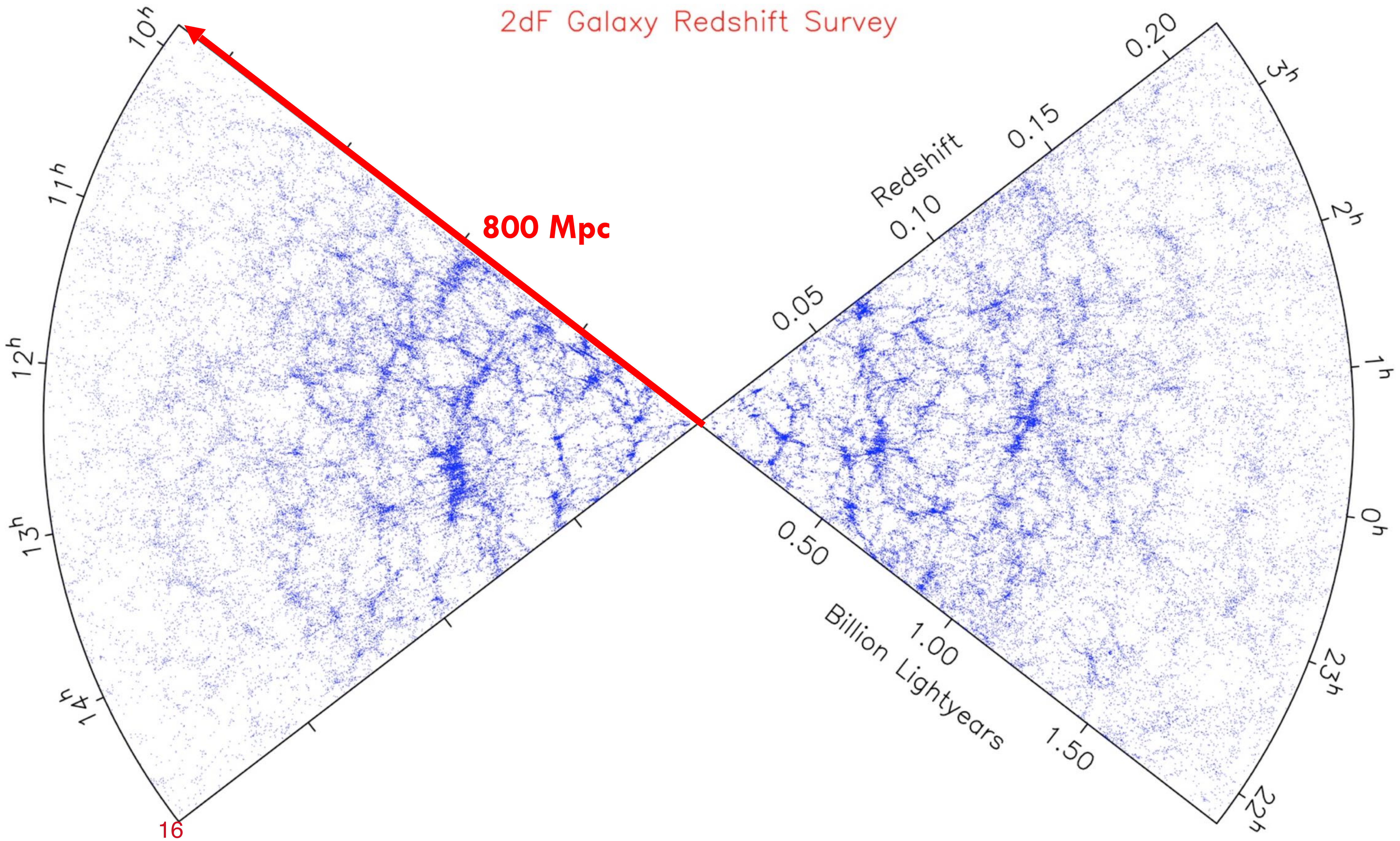
The Universe is mostly homogeneous and isotropic



Center for Astrophysics (CfA) Survey: Geller & Huchra 1989

Part I. Geometry

The Universe is mostly homogeneous and isotropic



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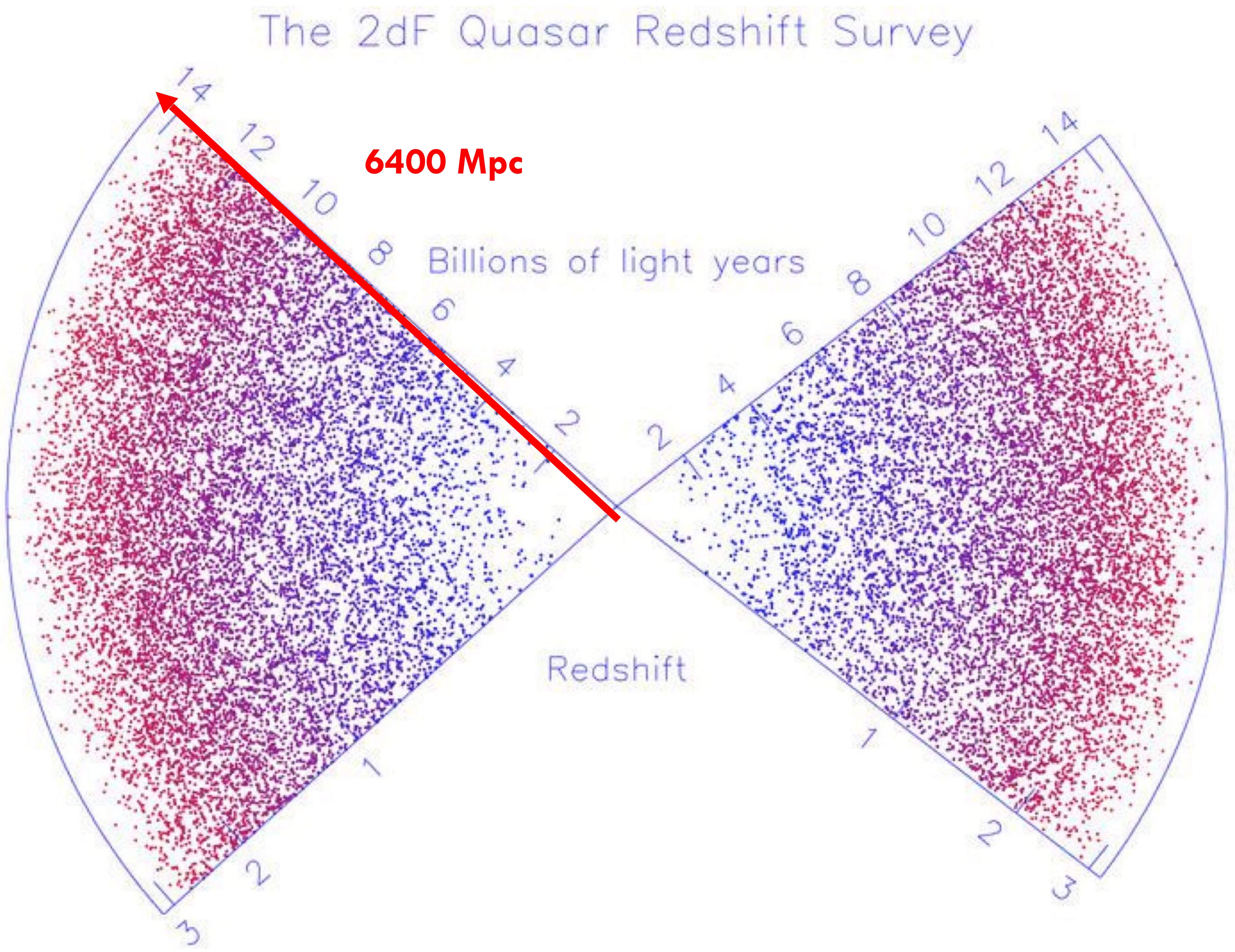
2dF Galaxy&Redshift Survey (2dFGRS): Colless et al 2001

Part I. Geometry

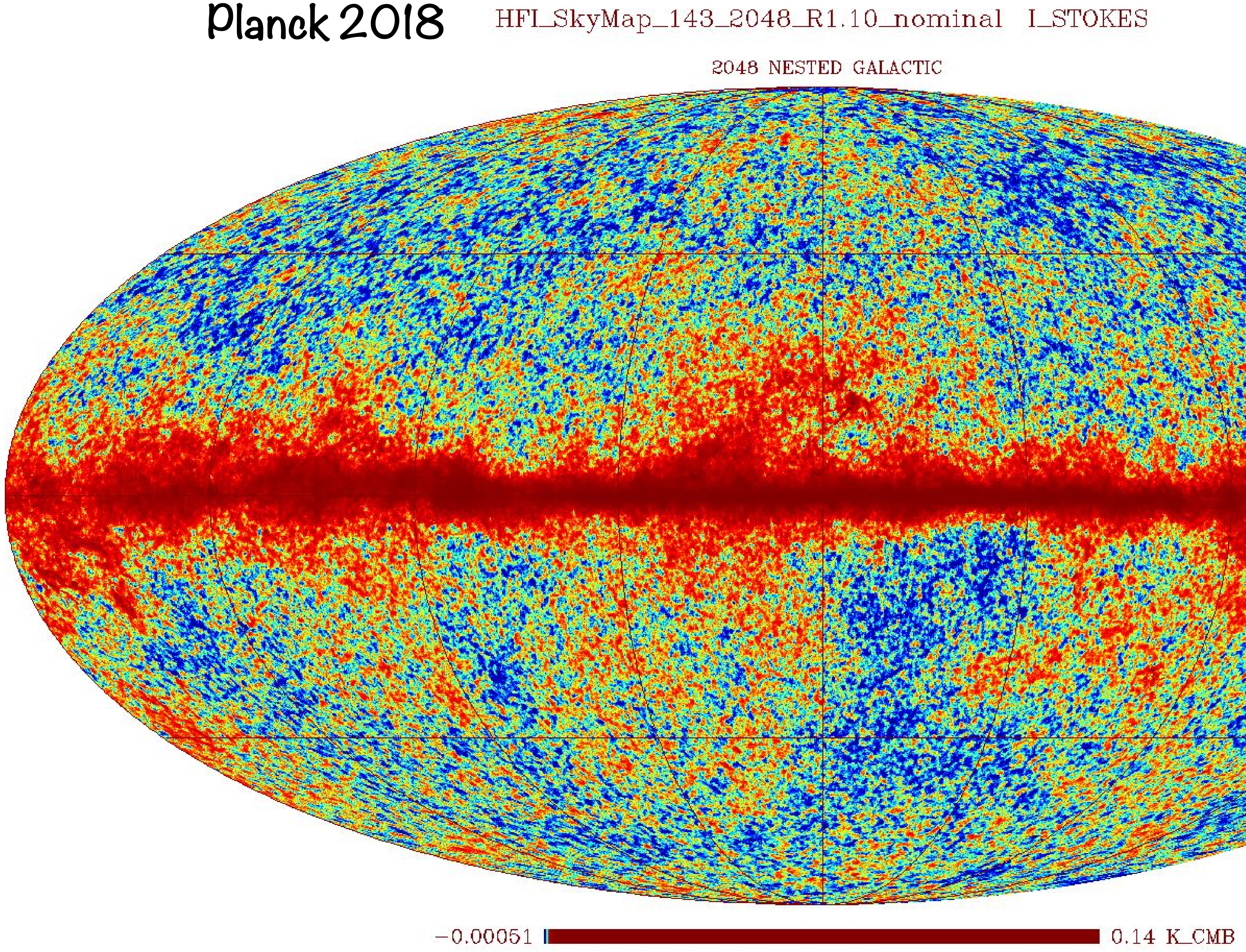
The Universe is mostly homogeneous and isotropic



Part I. Geometry

The Universe is mostly homogeneous and isotropic even at very large redshift

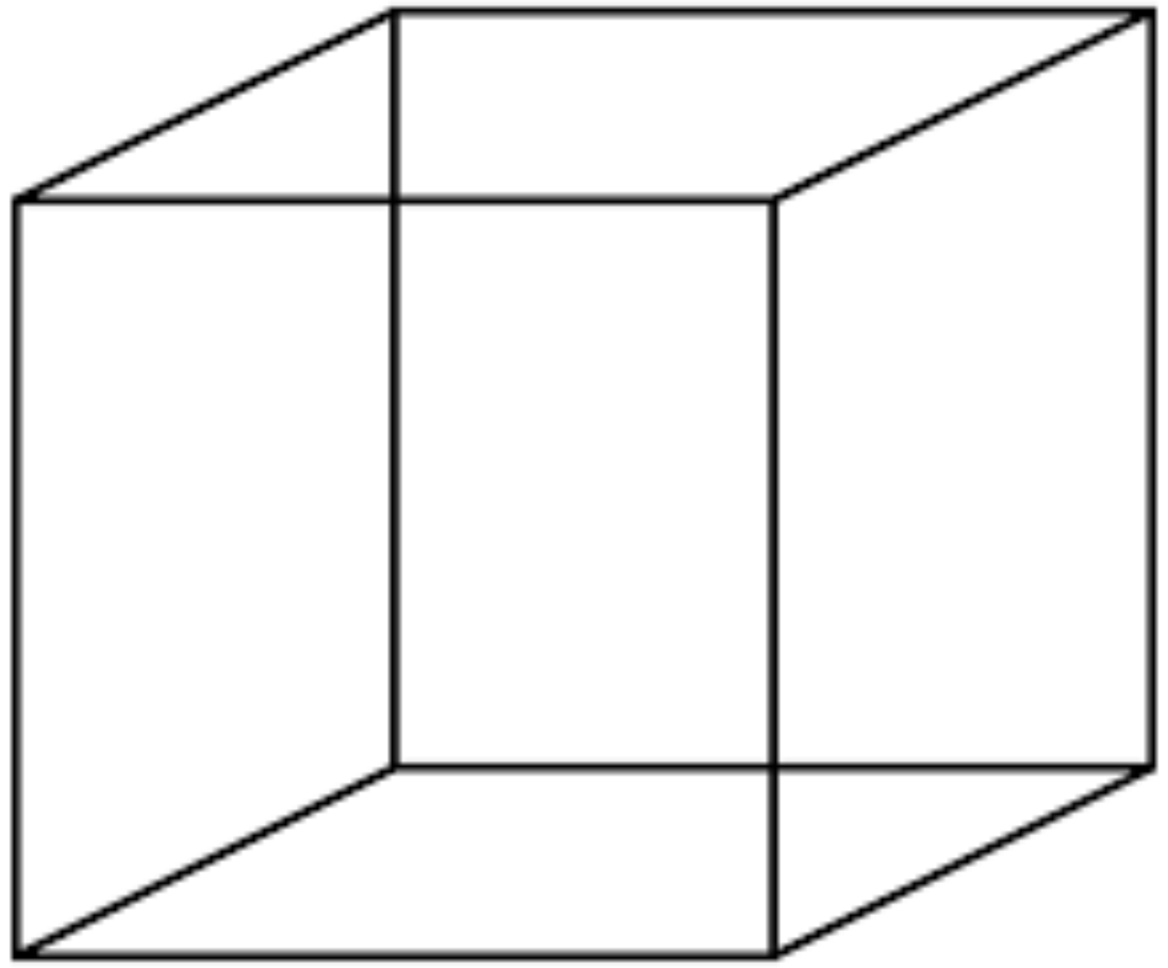
Planck 2018

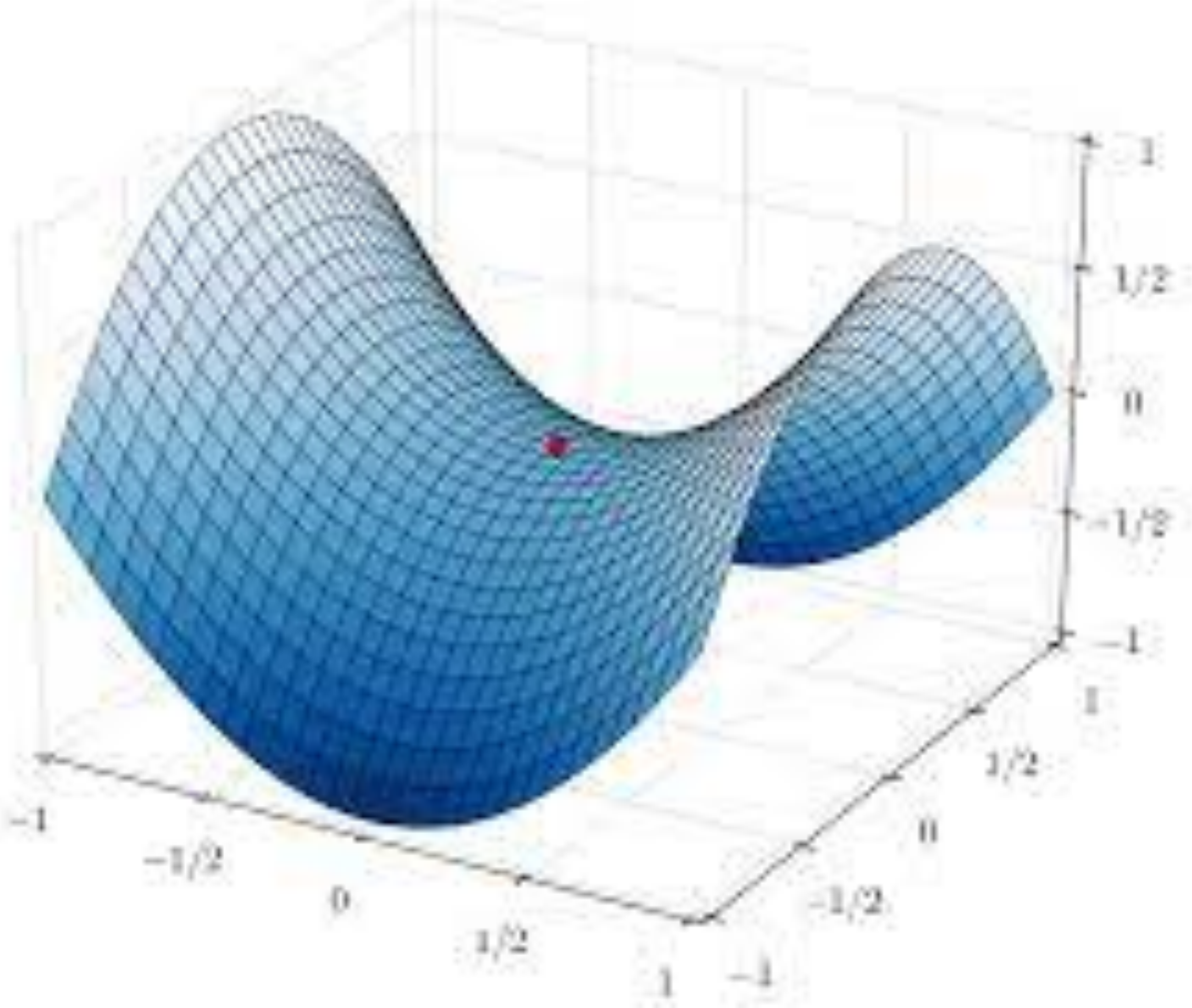


$$\frac{\delta T}{T} \simeq 10^{-5}$$

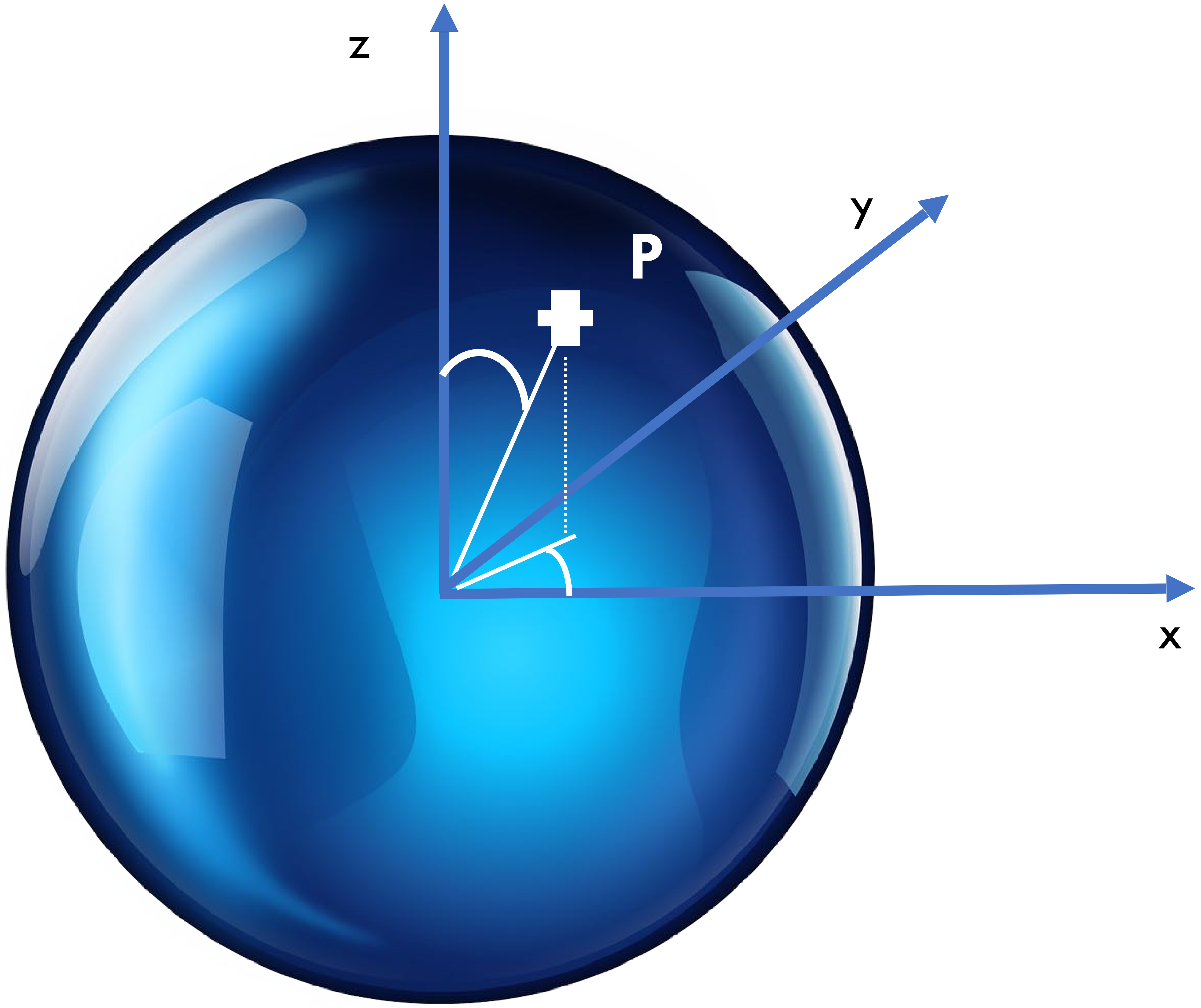
Part I. Geometry

The Universe is mostly homogeneous and isotropic means





Part I. Geometry



P is located on a sphere of radius R

$$ds^2 = x_p^2 + y_p^2 + z_p^2$$

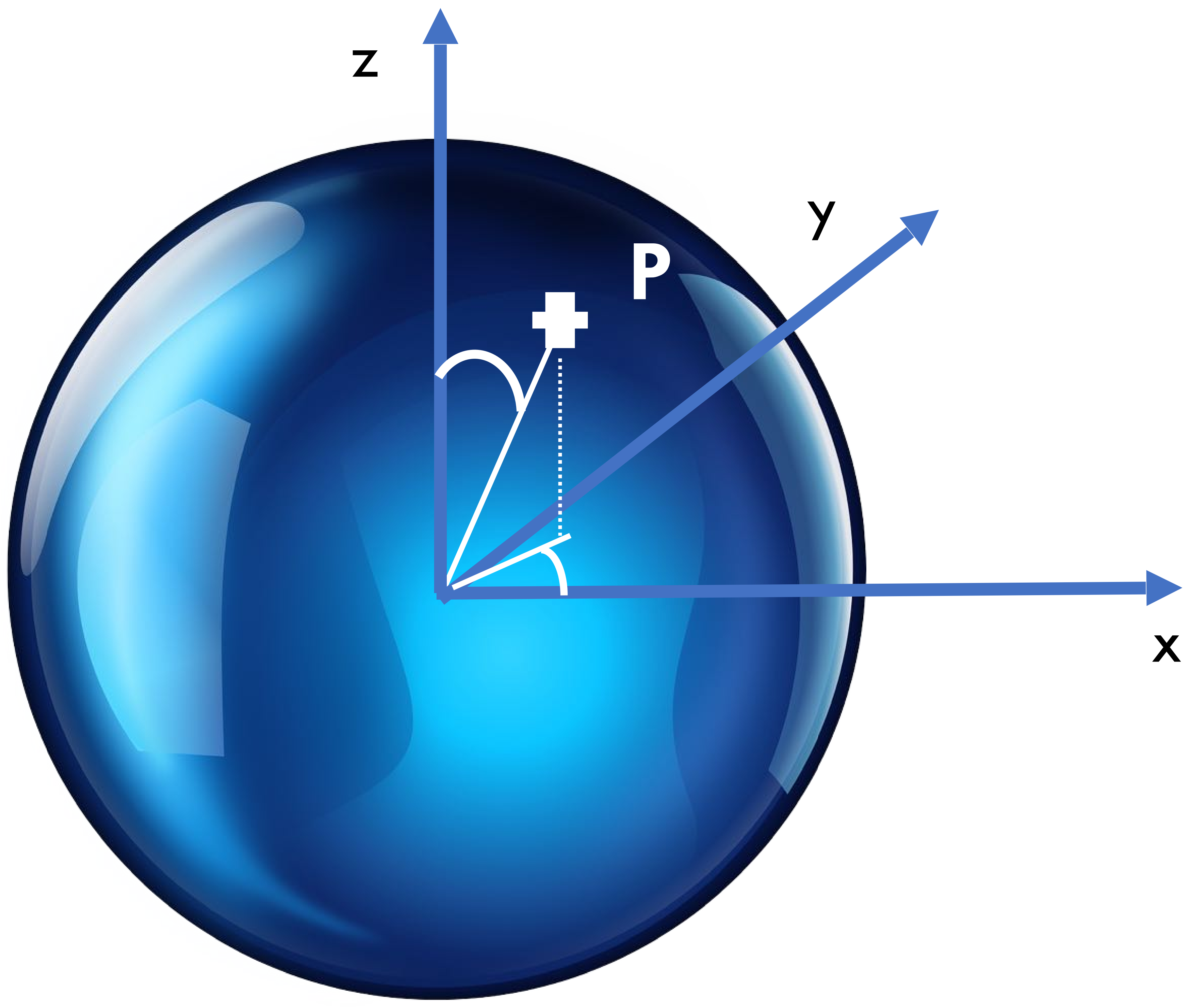
Can be reinterpreted by defining the coordinated on the sphere

$$\begin{aligned} x_p &= R\ \sin\theta\cos\phi \\ y_p &= R\ \sin\theta\sin\phi \\ z_p &= R\ \cos\theta \end{aligned}$$

$$ds^2 = \underbrace{(x_p - x_0)^2}_{\text{(dx)^2}} + \underbrace{(y_p - y_0)^2}_{\text{(dy)^2}} + \underbrace{(z_p - z_0)^2}_{\text{(dz)^2}} \Longrightarrow ds^2 = dx^2 + dy^2 + dz^2$$

Part I. Geometry

$$ds^2 = dx^2 + dy^2 + dz^2$$



$$\begin{aligned} x_p &= R\ \sin\theta\cos\phi \\ y_p &= R\ \sin\theta\sin\phi \\ z_p &= R\ \cos\theta \end{aligned}$$

derivative

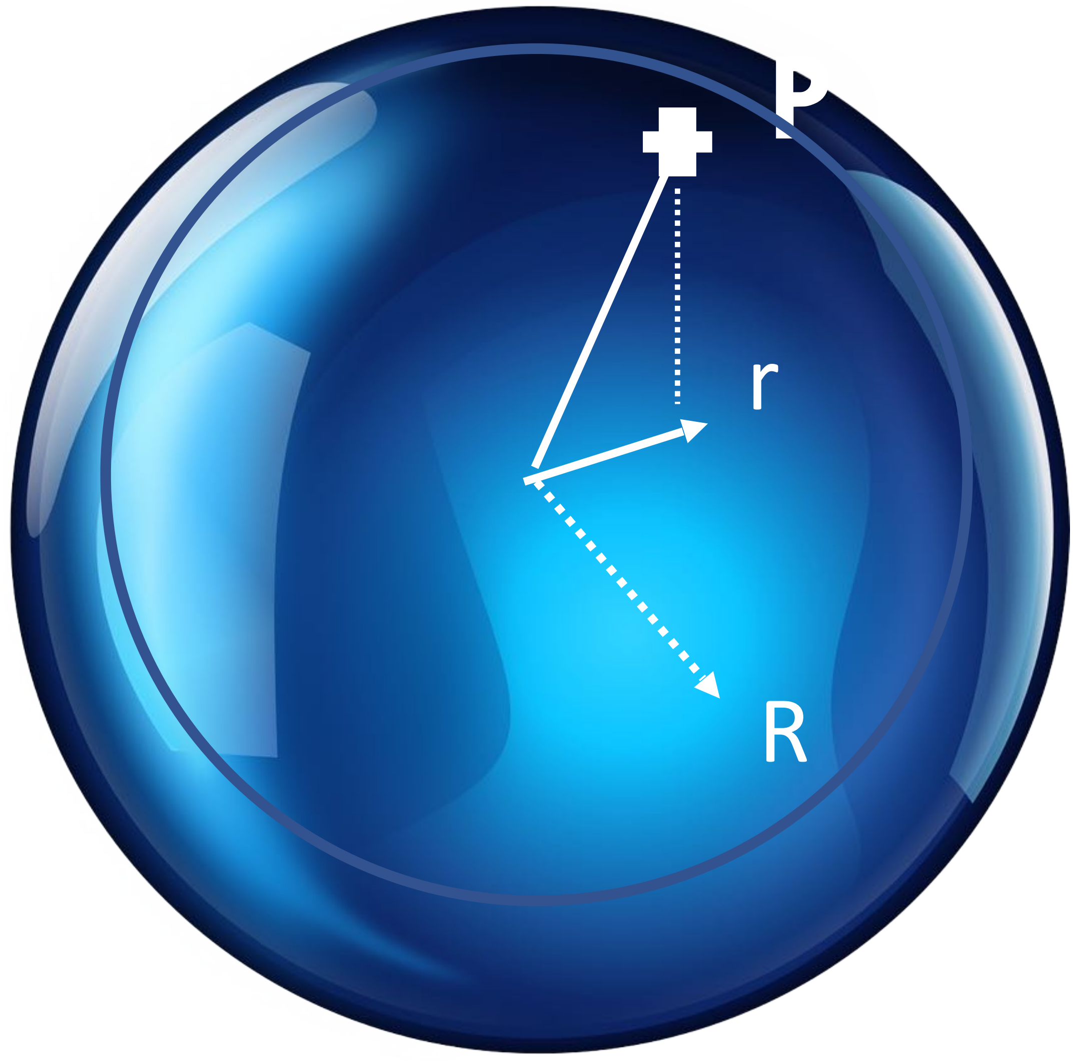
$$\boxed{\begin{aligned} &dx = \underbrace{dR\sin\theta\cos\phi}_{=0} + R\ \cos\theta d\theta\cos\phi - R\sin\theta\sin\phi d\phi \\ &dy = \underbrace{dR\sin\theta\cos\phi}_{=0} + R\ \cos\theta d\theta\sin\phi + R\sin\theta\cos\phi d\phi \\ &dz = -R\sin\theta\, d\theta \end{aligned}}$$

$$ds^2 = R^2\left(\underbrace{d\theta^2 + \sin^2\theta\ d\phi^2}_{\text{Only geometrical information}}\right)$$

Size of the sphere

Part I. Geometry

Projection from 3d to 2d



$$z = \sqrt{R^2 - x^2 - y^2}$$

$$dz = -\frac{(xdx + ydy)}{\sqrt{R^2 - x^2 - y^2}}$$

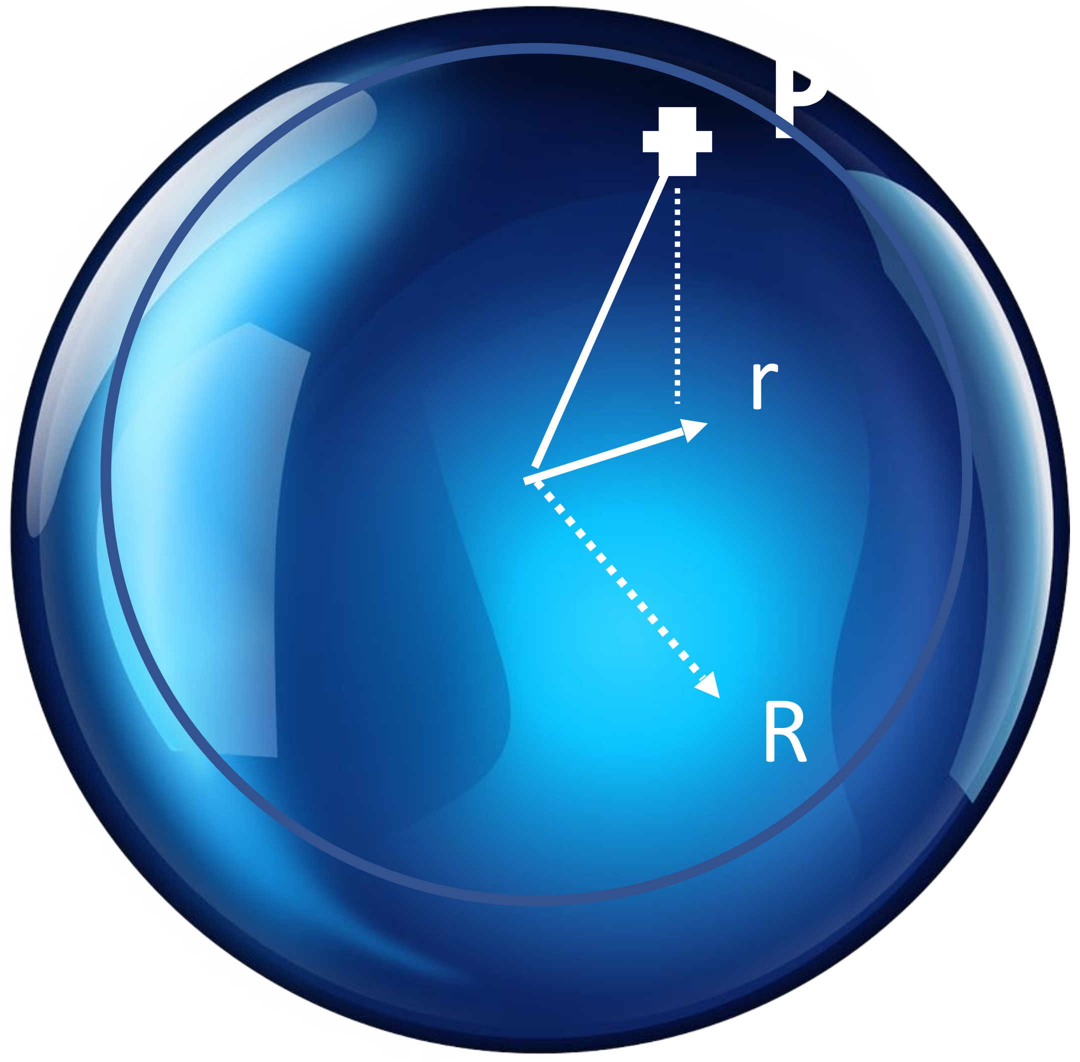
$$ds^2 = dx^2 + dy^2 + \frac{(xdx + ydy)^2}{(R^2 - x^2 - y^2)}$$

$$x = r\ \cos\theta$$
$$y = r\ \sin\theta$$
$$dx^2 + dy^2 = dr^2 + r^2 d\theta^2$$

$$\boxed{dz^2 = \frac{r^2 dr^2}{(R^2 - r^2)} \Longrightarrow ds^2 = dr^2 + r^2 d\theta^2 + \frac{r^2\ dr^2}{R^2 - r^2}}$$

Part I. Geometry

Projection from 3d to 2d



$$ds^2 = \underbrace{dr^2 + r^2 d\theta^2 + \frac{r^2 \; dr^2}{R^2 - r^2}}$$

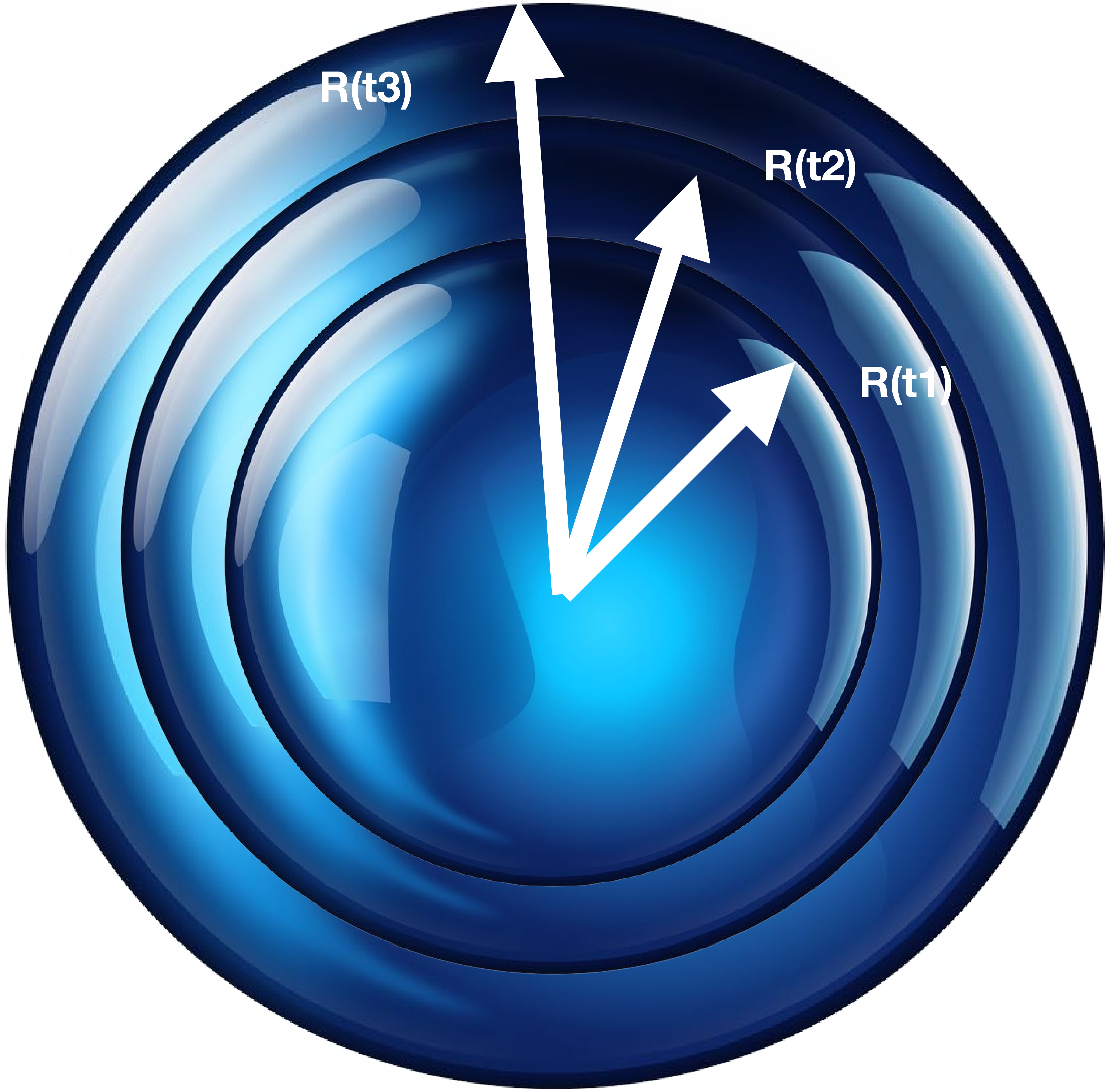
Let us define r’= r/R

$$ds^2 = R^2 \left(\underbrace{\frac{dr^{‘2}}{1 - r'^2}}_{\text{Singularity}} + r'^2 d\theta^2 \right)$$

with $r' = \dfrac{r}{R}$

What if we live in 4d but do not see the 4th dimension?

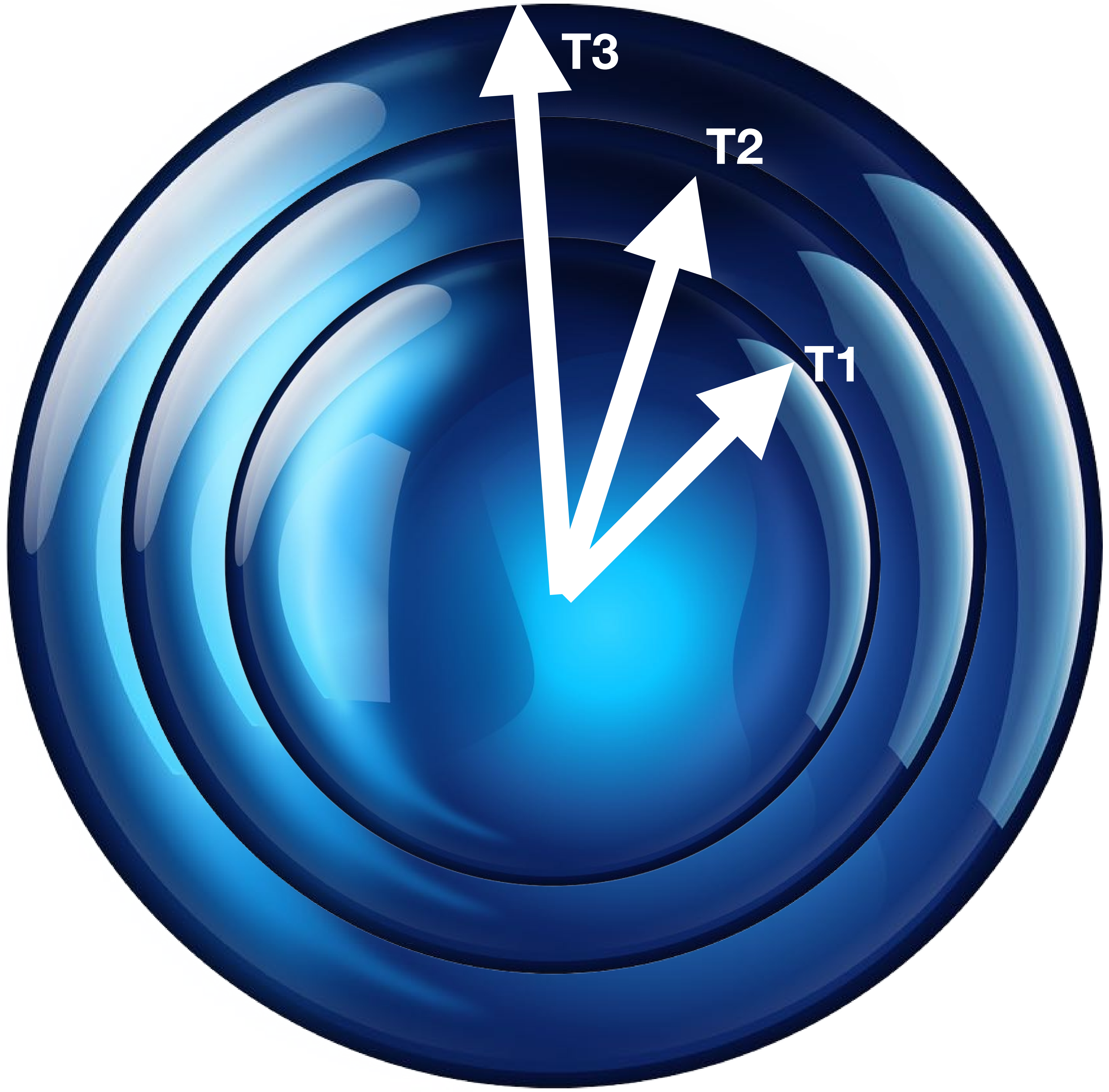
Nested spheres



Typical situation if the Universe evolved with time

Part I. Geometry

Projection from 4d to 3d



4th dimension of time added
Spheres can grow

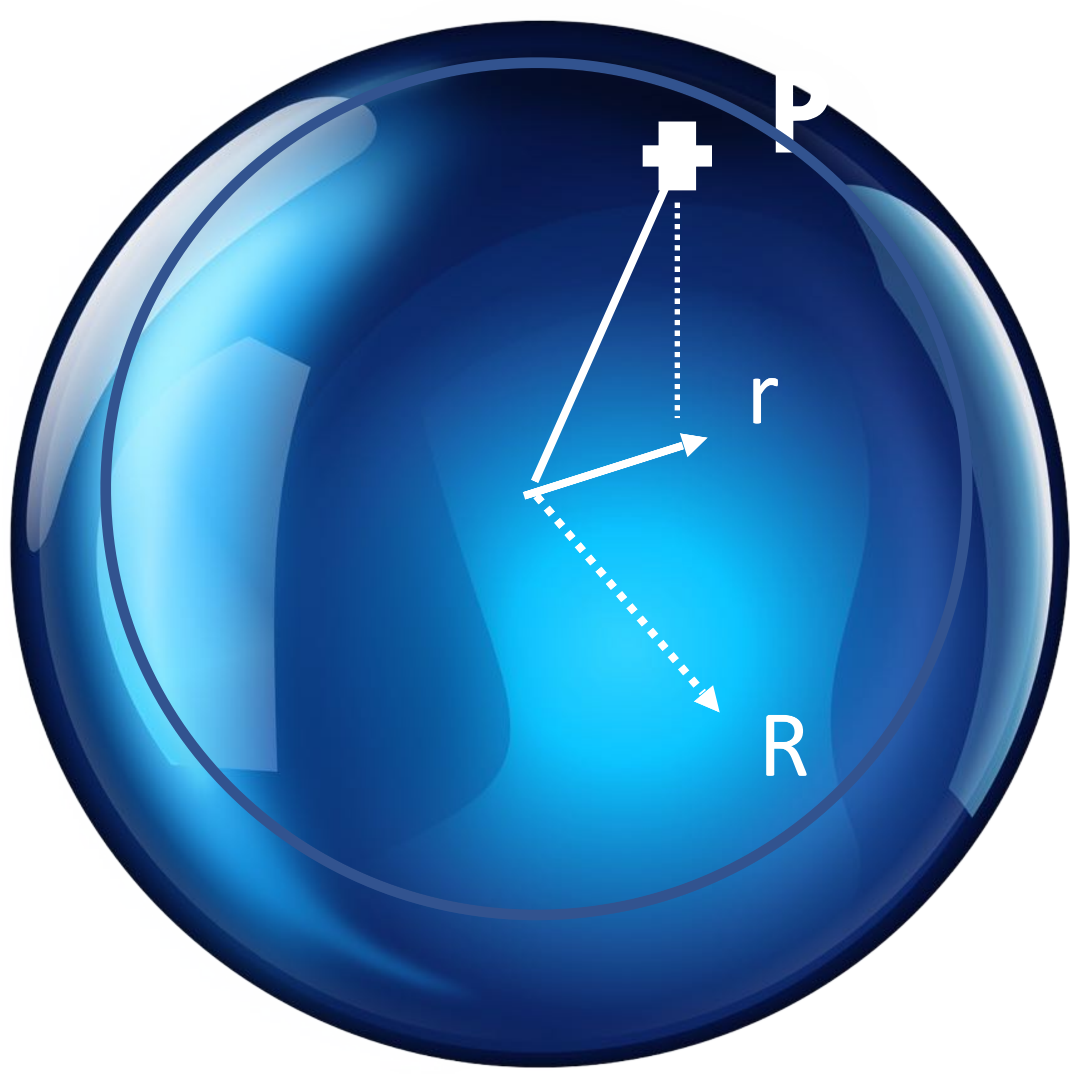
$$x^2 + y^2 + z^2 + w^2 = R^2$$

$$w = \sqrt{R^2 - (x^2 + y^2 + z^2)}$$

$$\begin{aligned} x &= R\sin\theta\sin\phi\sin\chi \\ y &= R\sin\theta\cos\phi\sin\chi \\ z &= R\cos\theta\sin\chi \\ w &= R\cos\chi \end{aligned}$$

Part I. Geometry

Projection from 4d to 3d



Step 1: Getting rid off the 4th dimensions

$$x^2 + y^2 + z^2 + w^2 = R^2$$

$$w = \sqrt{R^2 - (x^2 + y^2 + z^2)}$$

$$r^2 = (x^2 + y^2 + z^2)$$

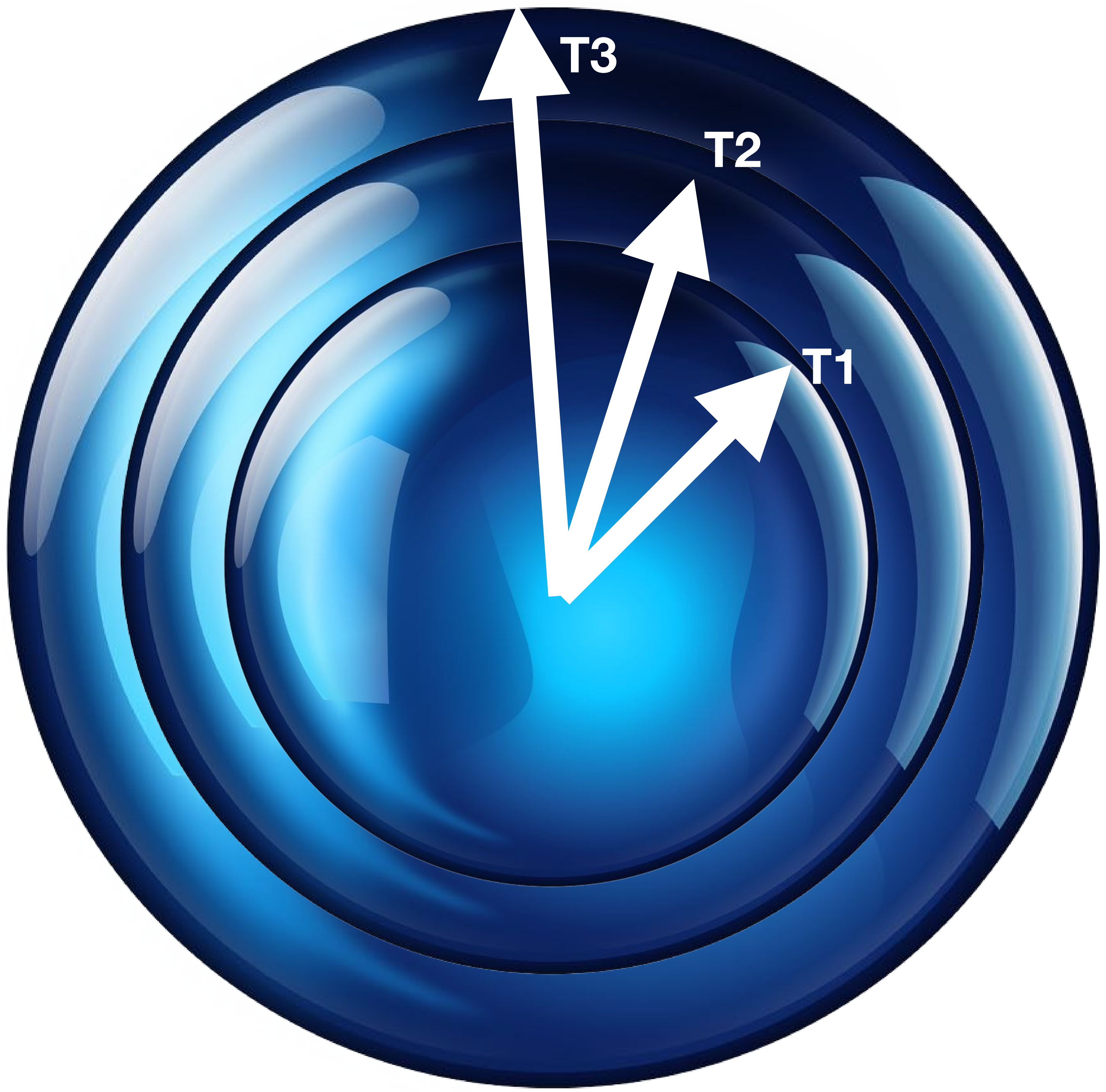
$$w = \sqrt{R^2 - r^2}$$

$$r^2 = (x^2 + y^2 + z^2) \Rightarrow r^2 = \sum_i x_i^2 \Rightarrow r^2 = r^2 \sum_i {x'}_i^2$$

R fixed
x' = x/r

Part I. Geometry

Projection from 4d to 3d



Step 2: taking derivatives

$$ds^2 = dx^2 + dy^2 + dz^2 + dw^2$$
$$w = \sqrt{R^2 - (x^2 + y^2 + z^2)}$$

R fixed
x' = x/r

$$ds^2 = \frac{r^2 dr^2}{R^2 - r^2} + dr^2 \sum_i {x'}_i^2 + r^2 \underbrace{\sum_i {dx'}_i^2}_{\text{3d-sphere}}$$

Part I. Geometry

Projection from 4d to 3d

Step 3: use spherical coordinates

$$ds^2 = \frac{r^2 dr^2}{R^2 - r^2} + dr^2 \sum_i {x'}_i^2 + r^2 \underbrace{\sum_i d{x'}_i^2}_{\text{3d-sphere}}$$

with

$$\sum_i d{x'}_i^2 = (d\theta^2 + \sin^2\theta \, d\phi^2)$$

$$\sum_i {x'}_i^2 = 1$$

$$dr^2 \sum_i {x'}_i^2 = dr^2$$

$$r^2 \sum_i d{x'}_i^2 = r^2 \; (d\theta^2 + sin^2\theta d\phi^2)$$

Part I. Geometry

Projection from 4d to 3d

$$ds^2 = \underbrace{\frac{r^2 dr^2}{R^2 - r^2} + dr^2 \sum_i {x'}_i^2} + r^2 \underbrace{\sum_i d{x'}_i^2}_{\text{3d-sphere}}$$

with

$$\sum_i d{x'}_i^2 = (d\theta^2 + \sin^2\theta\, d\phi^2)$$

$$\sum_i {x'}_i^2 = 1$$

$$ds^2 = \frac{R^2 dr^2}{R^2 - r^2} + r^2 \underbrace{\sum_i d{x'}_i^2}_{\text{3d-sphere}} \Longrightarrow ds^2 = \frac{R^2 dr^2}{R^2 - r^2} + r^2 (d\theta^2 + \sin^2\theta d\phi^2)$$

$$ds^2 = R^2 \left[\frac{dr'^2}{1 - r'^2} + r'^2 (d\theta^2 + \sin^2\theta d\phi^2) \right]$$

r'=r/R

Interpretation of the metric (from 4d to 3d)

Part I. Geometry

Projection from 4d to 3d

$$ds^2 = R^2 \left[\frac{dr'^2}{1 - r'^2} + r'^2 (d\theta^2 + \sin^2 \theta d\phi^2) \right]$$

$$w = \sqrt{R^2 - (x^2 + y^2 + z^2)}$$

and

$$\begin{aligned} x &= R \sin\theta \sin\phi \sin\chi \\ y &= R \sin\theta \cos\phi \sin\chi \\ z &= R \cos\theta \sin\chi \\ w &= R \cos\chi \end{aligned}$$

$$w = R\cos\chi = \sqrt{R^2 - r^2} \Longrightarrow r = R\sin\chi \Longrightarrow r' = \frac{r}{R} = \sin\chi$$

$$\frac{dr'^2}{1 - r'^2} = \frac{(\cos\chi \; d\chi)^2}{\cos^2\chi}$$

Part I. Geometry

Projection from 4d to 3d

$$ds^2 = R^2 \left[\frac{dr'^2}{1 - r'^2} + r'^2 (d\theta^2 + \sin^2\theta d\phi^2) \right]$$

with $\frac{dr'^2}{1 - r'^2} = \frac{(\cos\chi\ d\chi)^2}{\cos^2\chi} = d\chi^2$ and $r' = \frac{r}{R} = \sin\chi$

$$ds^2 = R^2 \left[d\chi^2 + r'^2 (d\theta^2 + \sin^2\theta d\phi^2) \right]$$

$$ds^2 = R^2 \left[d\chi^2 + sin^2\chi\ (d\theta^2 + \sin^2\theta d\phi^2) \right]$$

Part I. Geometry

Projection from 4d to 3d

Projection from 3d to 2d

$$ds^2 = R^2\left(\frac{dr^2}{\underbrace{1-r'^2}_{\text{Singularity}}} + r'^2 d\theta^2\right) \quad \text{with} \quad r' = \frac{r}{R}$$

Projection from 4d to 3d

$$ds^2 = R^2\left[\underbrace{d\chi^2}_{\text{Singularity}} + r'^2(d\theta^2 + \sin^2\theta d\phi^2)\right] \quad \text{with} \quad d\chi^2 = \frac{dr'^2}{1-r'^2}$$

Part I. Geometry

Projection from 4d to 3d

$$ds^2 = R^2 \left[\frac{dr'^2}{1 - r'^2} + r'^2 (d\theta^2 + \sin^2\theta d\phi^2) \right]$$

$$ds^2 = R^2 \left[d\chi^2 + sin^2\chi \; d\Omega^2 \right]$$

(“chi”) is the angle associated with 4th dimension; R = R(t) and R(t) representing spherical Universe from the past

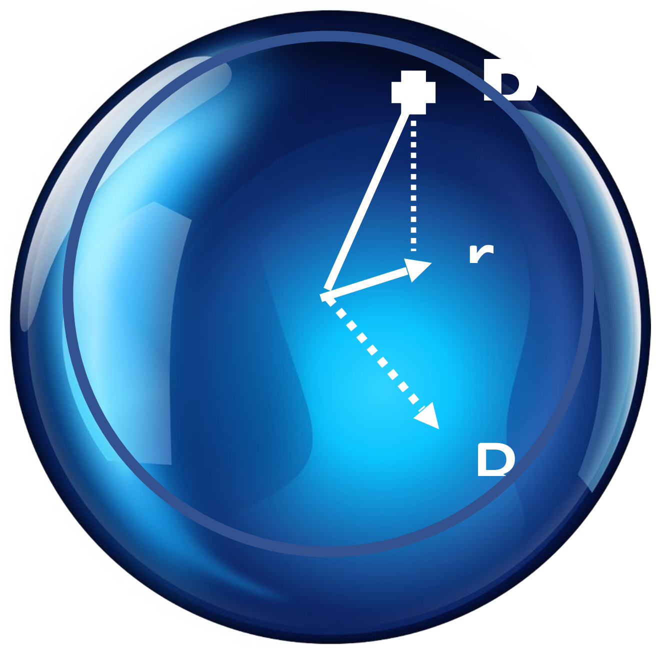
Adding time

$$ds^2 = -c^2 dt^2 + R^2 \left[d\chi^2 + \sin^2\chi \; d\Omega^2 \right]$$

$$ds^2 \overset{c=1}{=} -dt^2 + R^2 \left[d\chi^2 + sin^2\chi \; d\Omega^2 \right]$$

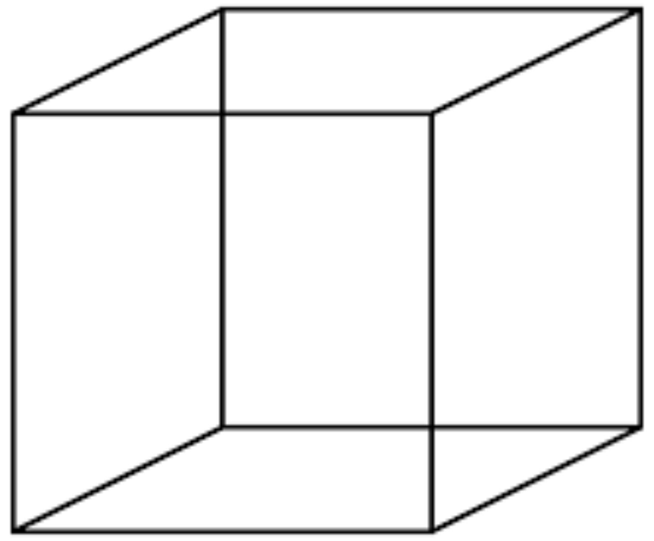
Part I. Geometry

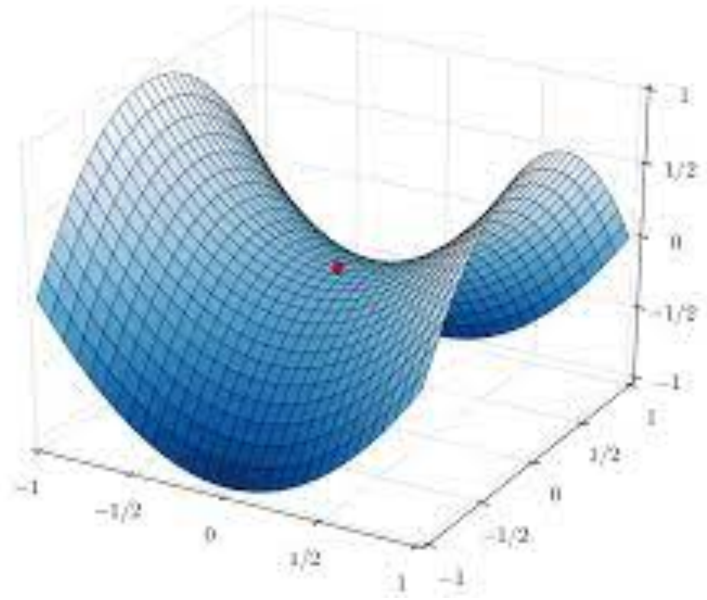
Friedman-LeMaitre-Robertson-Walker



$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2 + dw^2$$

$$ds^2 = -dt^2 + R^2 \left[d\chi^2 + \boxed{\sin^2\chi}\, d\Omega^2\right]$$





Generalising

$$ds^2 = -c^2 dt^2 + R^2 \left[d\chi^2 + f_k(\chi)\ d\Omega^2\right]$$

Part I. Geometry

Projection from 4d to 3d

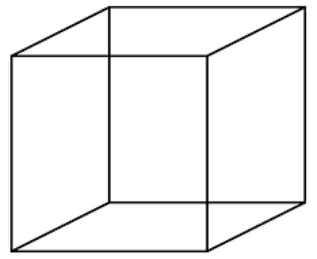
$$ds^2 = -dt^2 + R^2\left[d\chi^2 + sin^2\chi\ d\Omega^2\right]$$

Spherical metric in 4d

$$d\chi^2 = \frac{dr'^2}{1-r'^2}$$

$$ds^2 = -dt^2 + R^2\left[d\chi^2 +\ d\Omega^2\right]$$

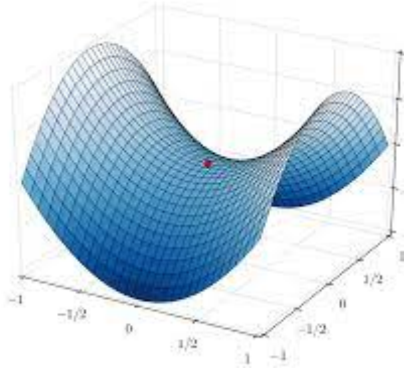
Flat metric in 4d



$$d\chi^2 = dr'^2$$

$$ds^2 = -dt^2 + R^2\left[d\chi^2 + \sinh^2\chi\ d\Omega^2\right]$$

Open metric in 4d



$$d\chi^2 = \frac{dr'^2}{1+r'^2}$$

Generalisation to FRLW metric

$$ds^2 = -dt^2 + \boxed{R^2}\,\underbrace{\left[d\chi^2 + f_k(\chi)d\Omega^2\right]}$$

Grows with time

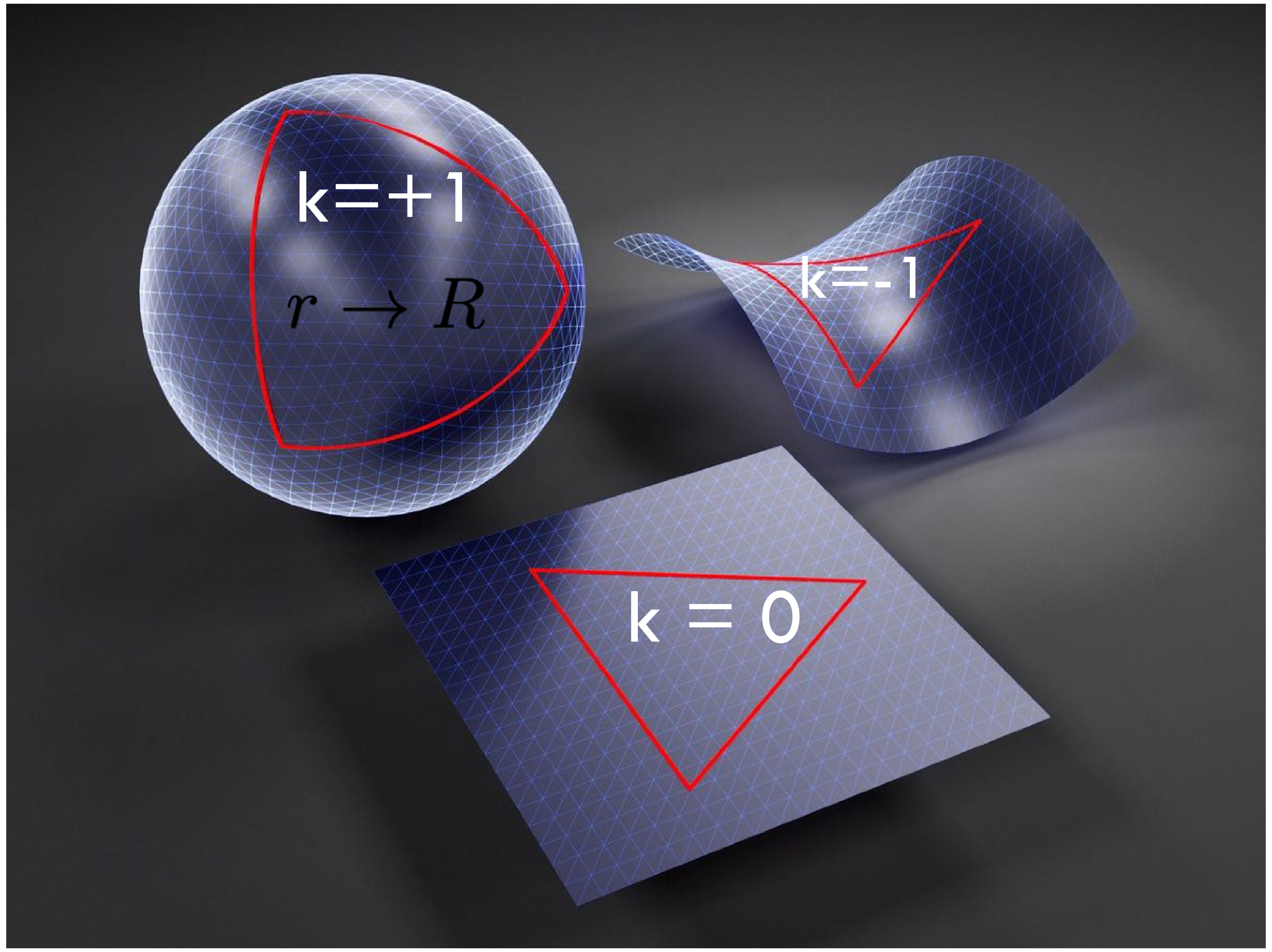
Independent of time evolution “comoving”

$$d\chi^2 = \frac{dr'^2}{1 - k\ r'^2}$$

$k = 1; f_k(\chi) = \sin^2\chi$ Spherical

$k = 0; f_k(\chi) = \chi^2$ Flat

$k = -1; f_k(\chi) = \sinh^2\chi$ Hyperbolic



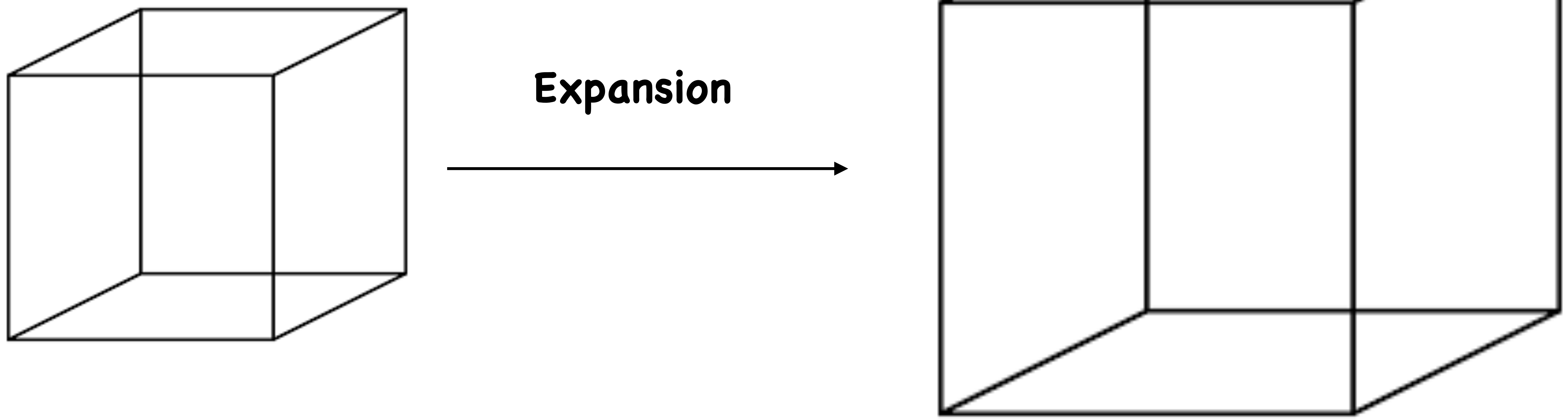
Generalisation to FRLW metric

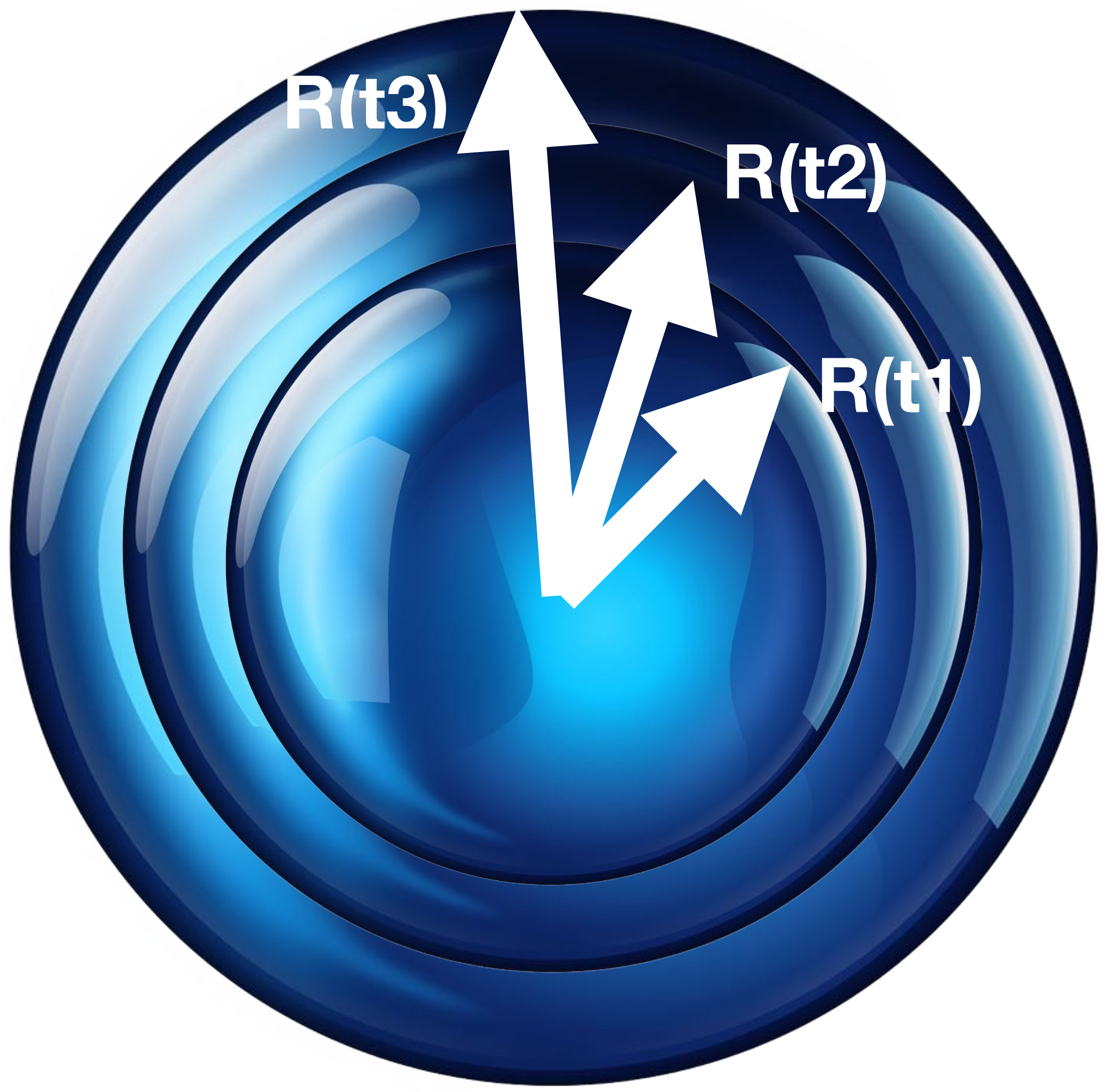
$$d\chi^2 = \frac{dr'^2}{1 - k\ r'^2}$$

Singularity in 4d but now the 4th dimension represents the time evolution projected onto the Universe at a given time.

$$ds^2 = -dt^2 + \boxed{R^2}\left[d\chi^2 + f_k(\chi)d\Omega^2\right]$$

with R(t) the scale factor





Part I. Geometry

Meaning of FRLW Metric

$$ds^2 = -c^2dt^2 + \boxed{R^2}\,[\underbrace{d\chi^2 + f_k(\chi)\ d\Omega^2}_{\text{Independent of time evolution “comoving”}}]$$

Scale factor; expansion

$$ds = 0$$

$$\underbrace{c^2dt^2 = R^2\ [d\chi^2}_{\text{The term which matters}} + \underbrace{f_k(\chi)\ d\Omega^2}_{\substack{\text{Geometric factor} \\ \text{Isotropic so it doesn't change the distance}}}]$$

Part I. Geometry

Consequences of FRLW Metric

$$c^2dt^2 = R^2\left[d\chi^2 + f_k(\chi)\ d\Omega^2\right]$$

⇒

$$c^2dt^2 = R^2d\chi^2$$

with $d\chi^2 = \dfrac{dr'^2}{1 - k\ r'^2}$

⇒

$$|\chi| = c\int\frac{dt}{R} + cst$$

Measure the expansion

and

$$|\chi| = \int\frac{dr'}{1 - kr'} + cst$$

Measure the curvature …

Consequences of FRLW Metric

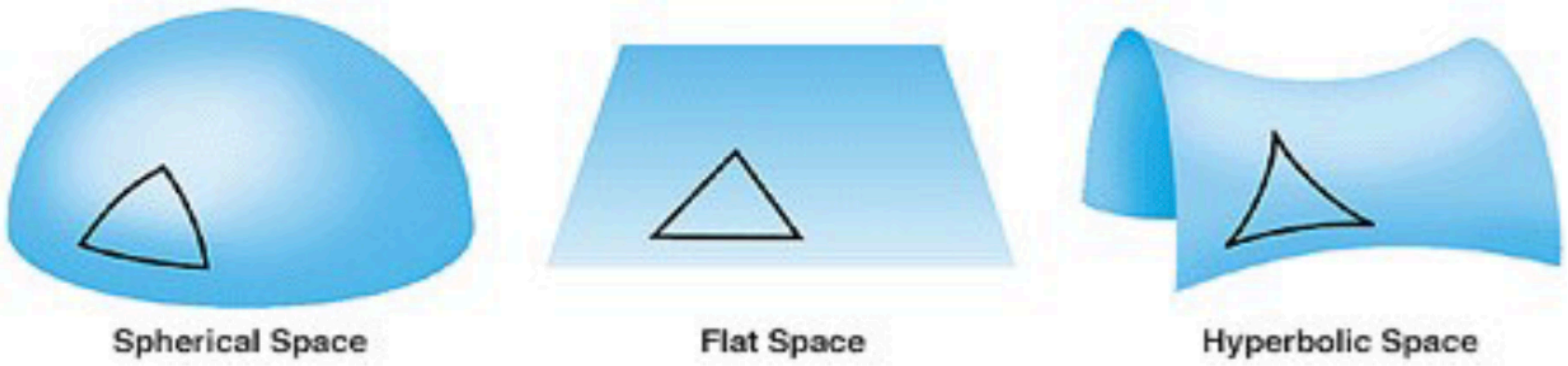
$$ds^2 = -c^2 dt^2 + R^2 \left[d\chi^2 + f_k(\chi)\; d\Omega^2 \right]$$

- Possible singularity which occur when r tends to R (closed Universe)
- This singularity does not exist in a flat (Euclidian/Minkowski) or hyperbolic metric
- Current paradigm: current curvature = 0 but R = R(t) and R(t=0) ~ 0.
- Analogy of a balloon that keeps growing.
- The photon (i.e. light) defines **OUR** space-time!
- All coordinates are defined with respect to the light in the Universe!

Metric = contains an information about the size of the Universe today

Part I. Geometry

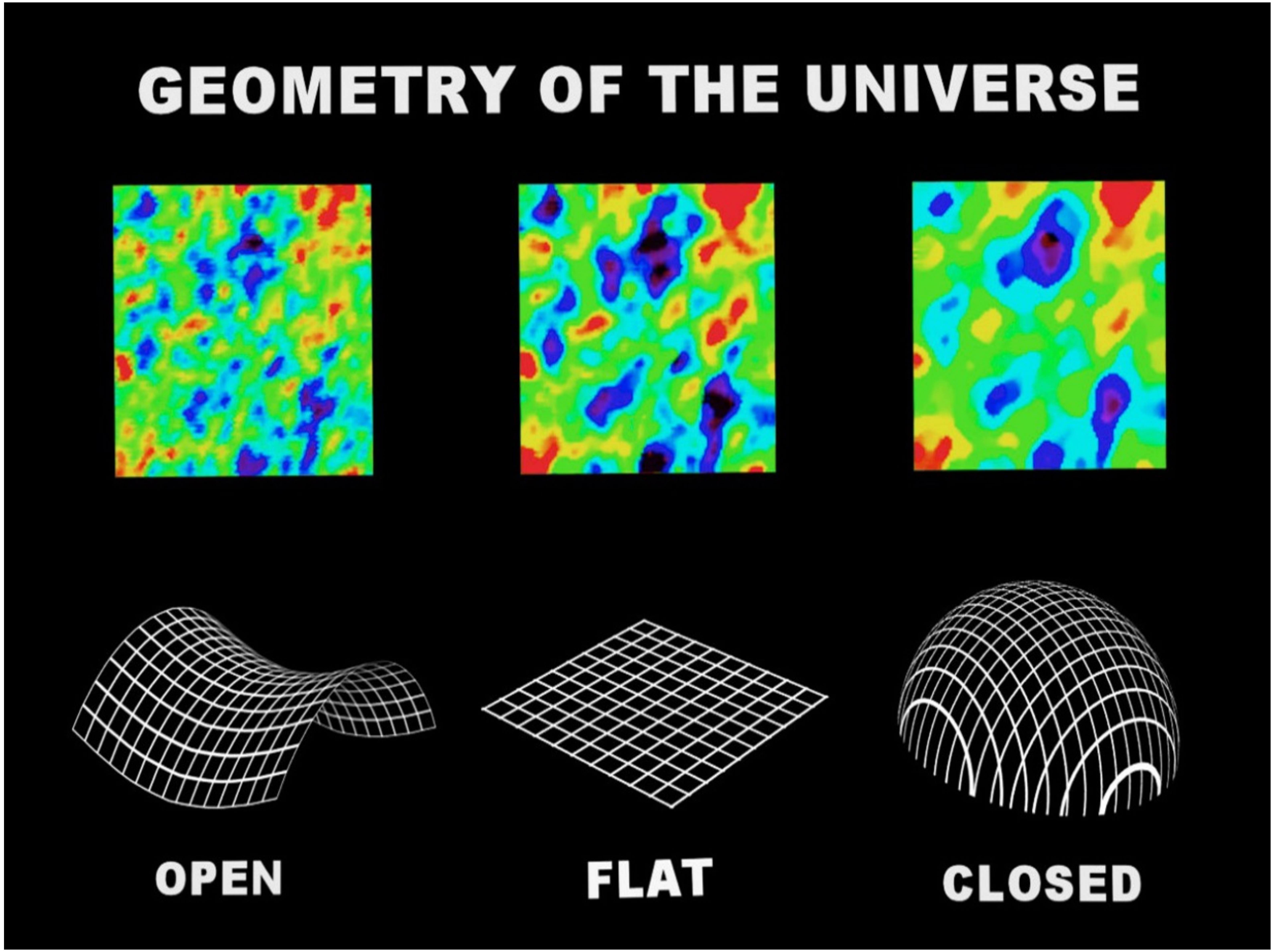
How to measure the curvature?



	Closed	Flat	Open
Curvature:	+	0	--
Sum of angles of triangle:	> 180°	= 180°	< 180°
Circumference of circle:	$< 2\pi r$	$= 2\pi r$	$> 2\pi r$
Parallel lines:	converge	remain parallel	diverge
Size:	finite	infinite	infinite
Edge:	no	no	no

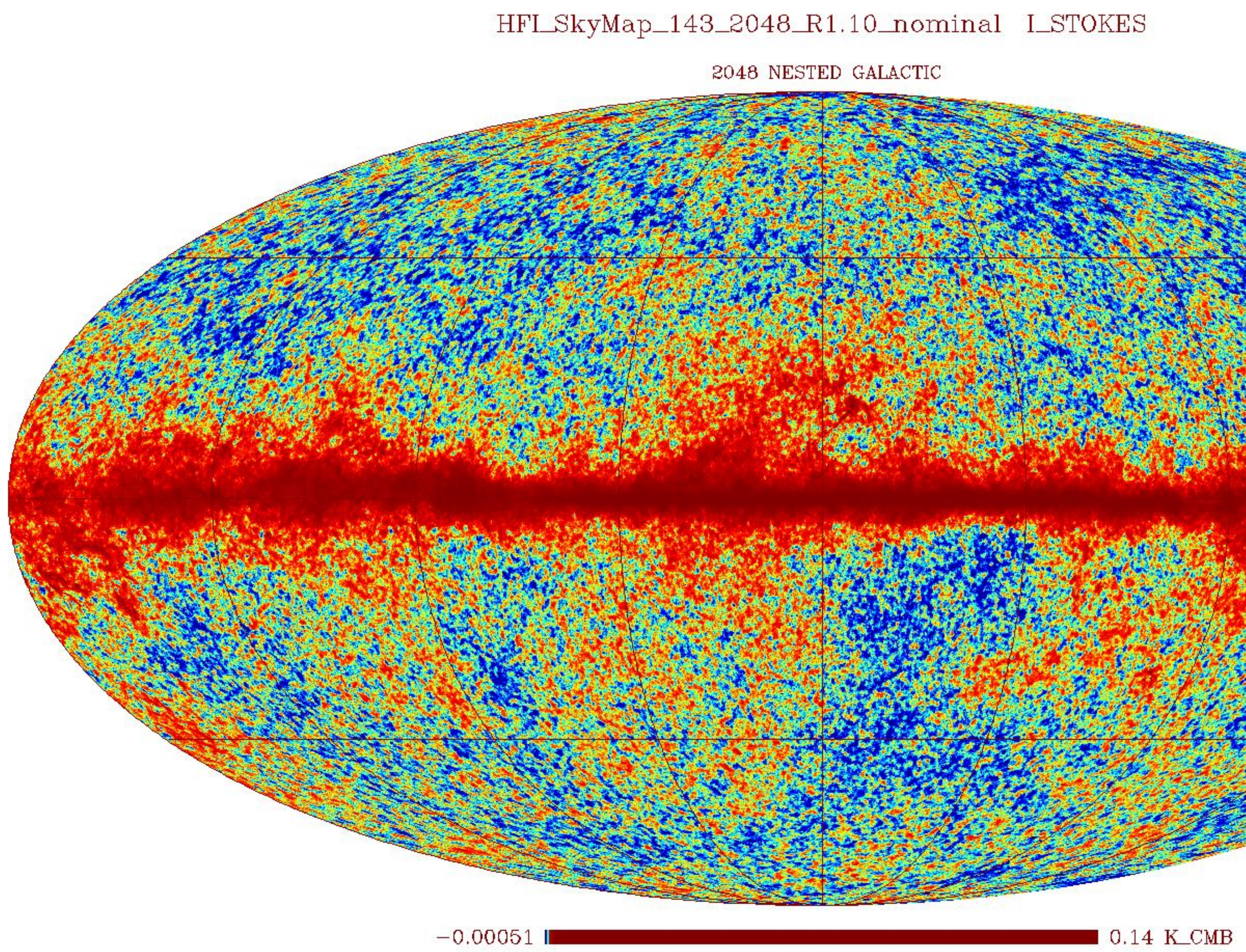
Part I. Geometry

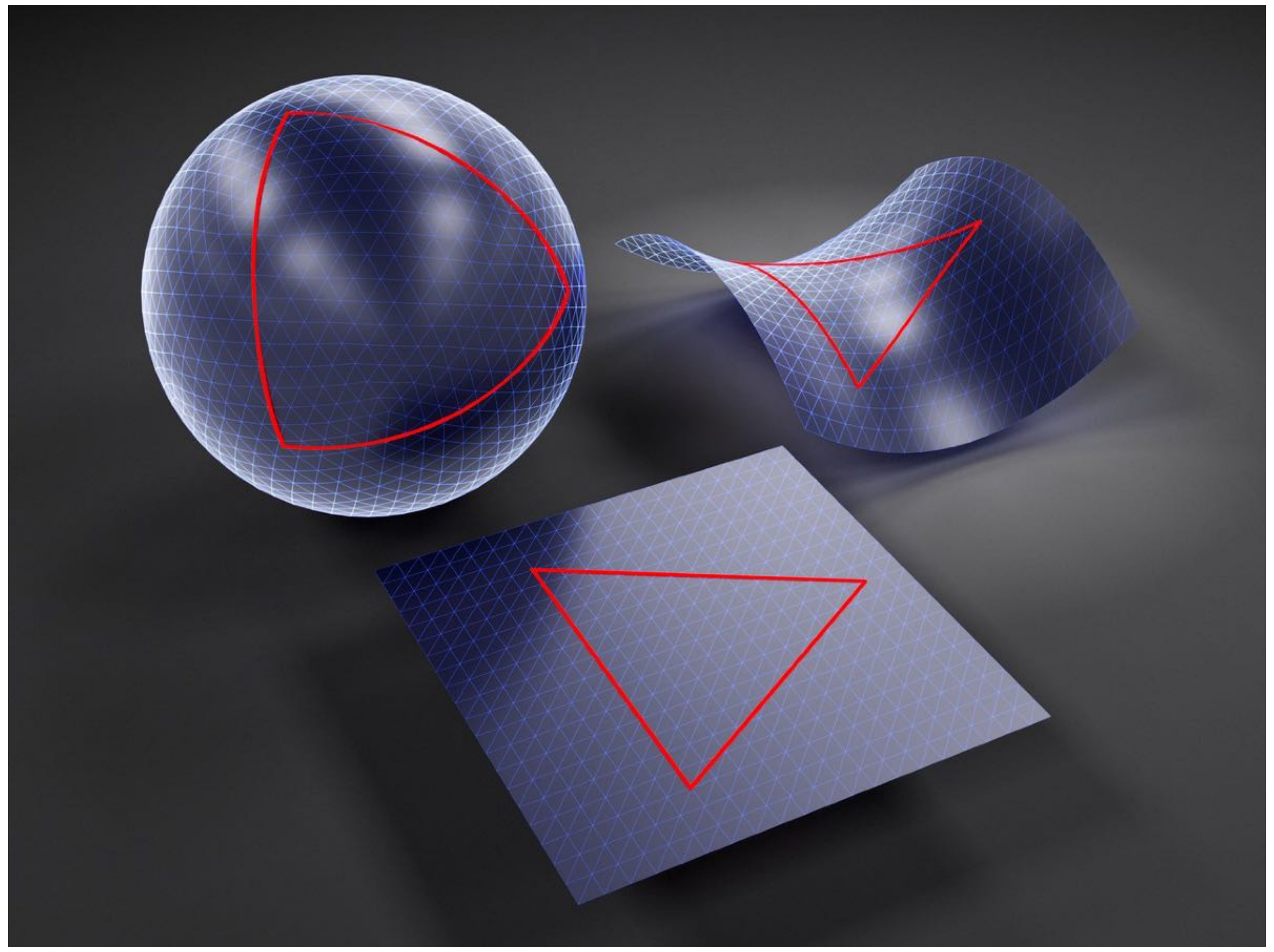
How to measure the curvature?



Part I. Geometry

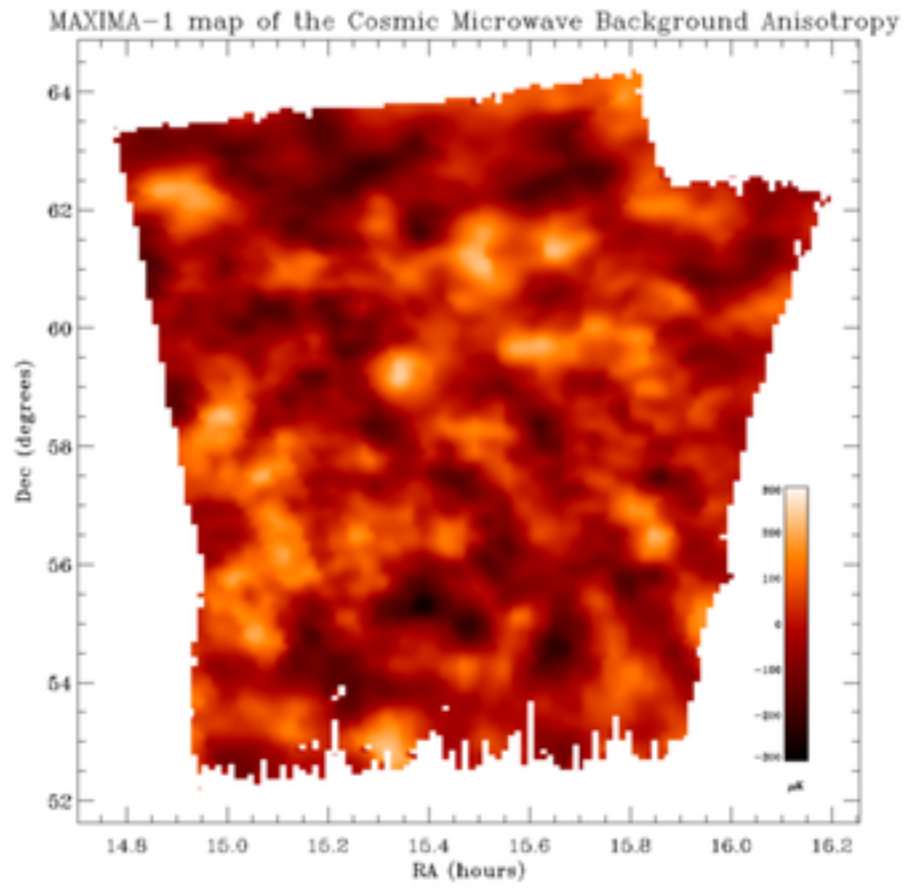
How to measure the curvature?





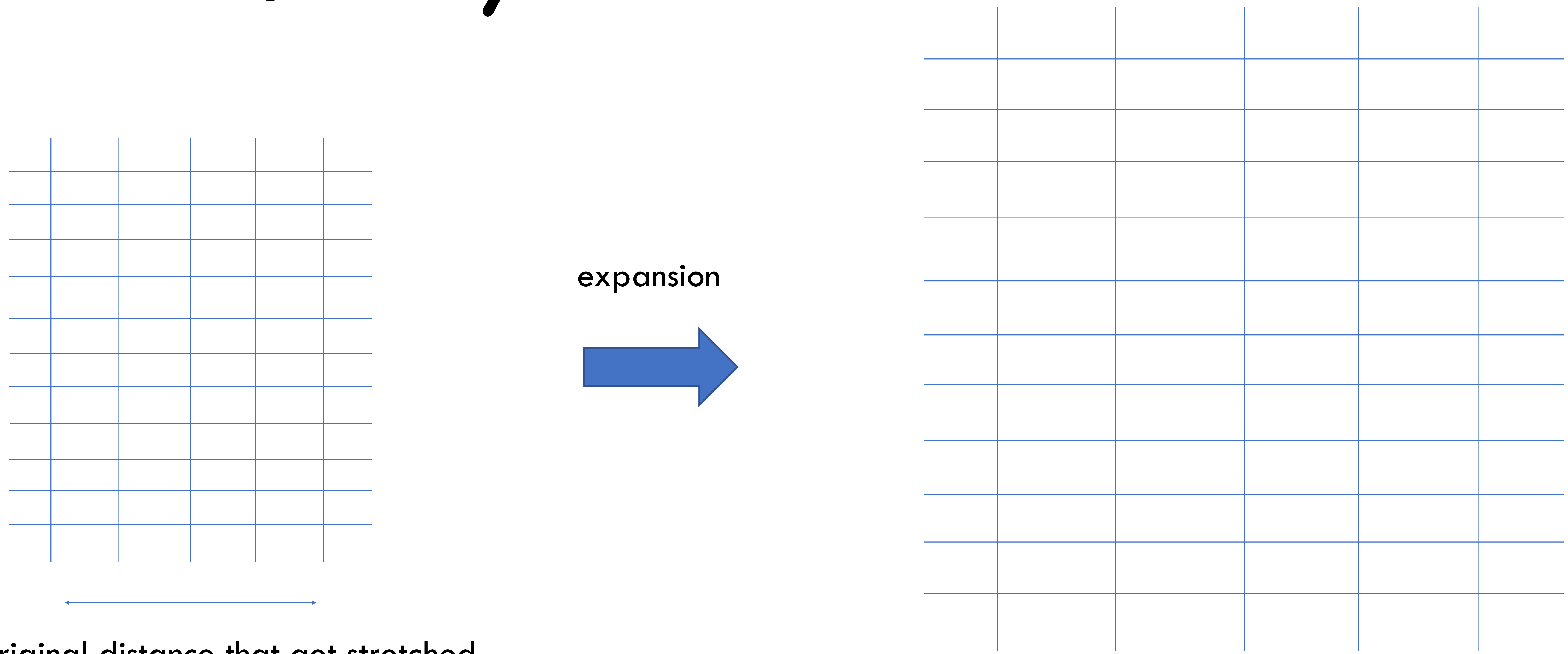
$$ds^2 = -c^2dt^2 + R^2\left[d\chi^2 + f_k(\chi)\ d\Omega^2\right]$$

BOOMERang, MAXIMA, ARCHEOPS



$k = 1;\ f_k(\chi) = \sin^2\chi$	Spherical
$k = 0;\ f_k(\chi) = \chi^2$	Flat
$k = -1;\ f_k(\chi) = \sinh^2\chi$	Hyperbolic

Part I. Geometry



R times original distances

expansion

Original distance that get stretched

$$l = l_{\text{comoving}}$$

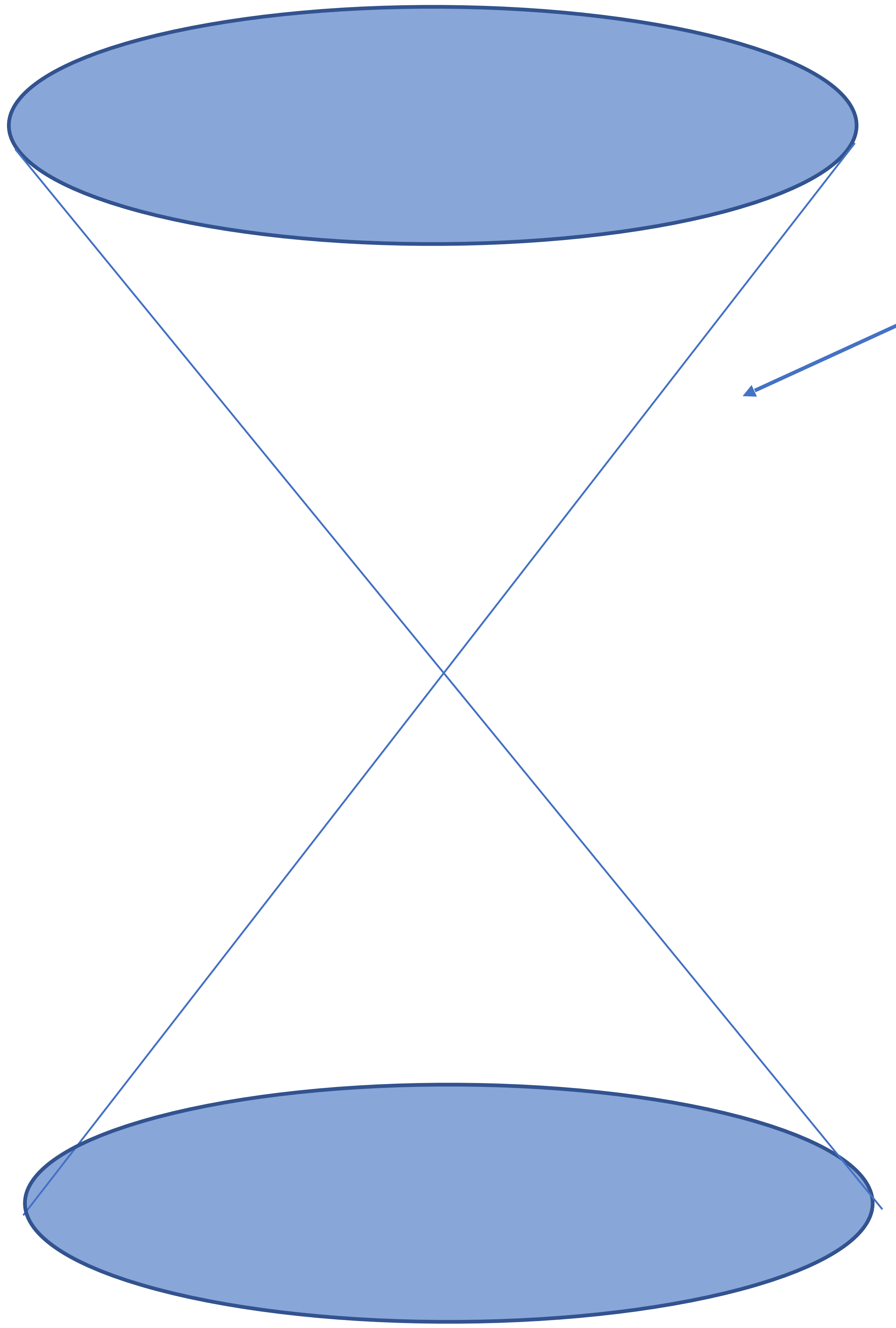
$$r = R\, l_{comoving}$$

$$ds^2 = -dt^2 + \boxed{R^2}\left[\underbrace{d\chi^2 + f_k(\chi)d\Omega^2}_{l_{\text{comoving}}}\right]$$

Part I. Geometry

Horizon

$$ds^2 = -c^2 dt^2 + R^2 \left[d\chi^2 + f_k(\chi)\ d\Omega^2 \right]$$



Light cone, ds= 0 $\quad d = c\ t$

Inside cone, particles (v<c) $\quad ds^2 > 0$

Outside cone, tachyons (v>c) $\quad ds^2 < 0$

Tachyons are not physical
(we have never seen v>c)

Part II. Content of the Universe

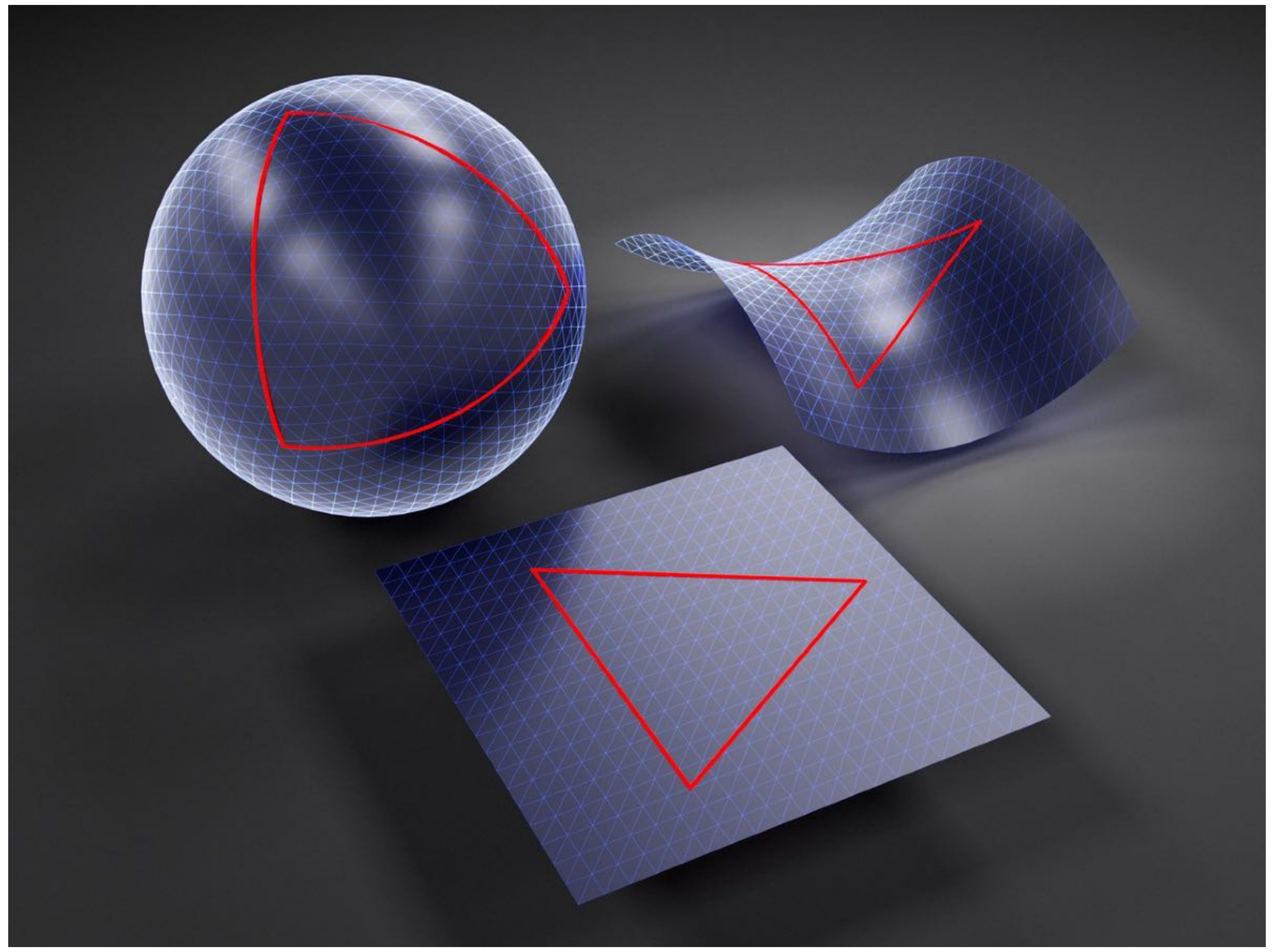
Part II. Content of the Universe

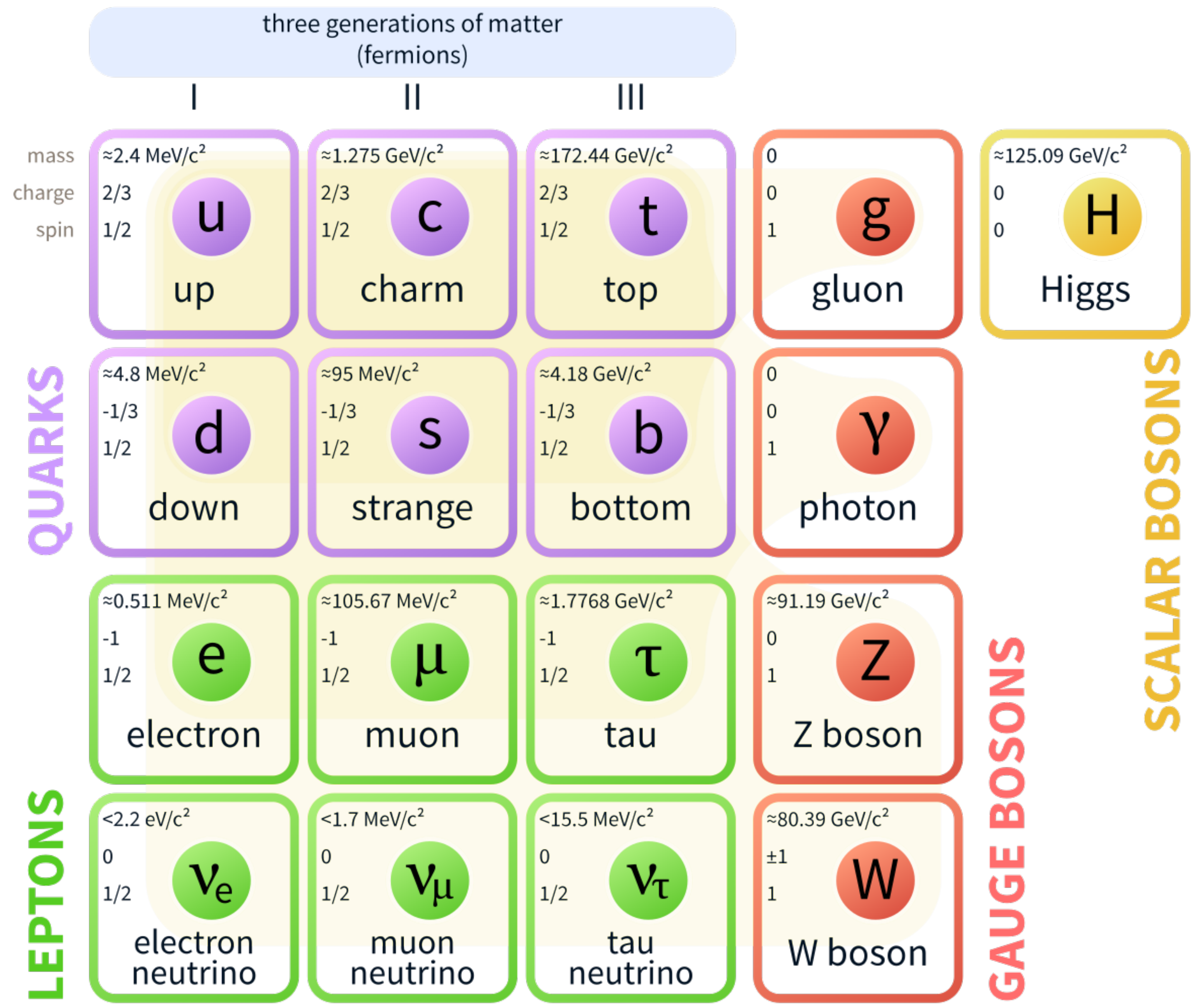
Metric
+curvature

matter

Constant
Because why not?

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu} + \Lambda\, g_{\mu\nu}$$





three generations of matter (fermions)

	I	II	III		
mass charge spin	≈2.4 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈172.44 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c^2 0 0 H Higgs
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
	≈0.511 MeV/c^2 -1 1/2 e electron	≈105.67 MeV/c^2 -1 1/2 μ muon	≈1.7768 GeV/c^2 -1 1/2 τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	
				GAUGE BOSONS	

$$\Lambda$$

Part II. Content of the Universe & metric

Intuitively:

- Energy should increase distances -> expansion
- Matter feels gravity so it should slow expansion
- Curvature ?

The mixture of all components must be constrained by the observed expansion or lack of...

Part II. Content

Expansion rate (or Hubble rate)

$$ds^2 = -dt^2 + \boxed{R^2}\left[\underbrace{d\chi^2 + f_k(\chi)d\Omega^2}_{l^2_{\text{comoving}}}\right]$$

$$r = R\, l_{comoving}$$

$$ds^2 = -dt^2 + R^2\ l^2_{\text{comoving}} = -dt^2 + dr^2$$

$$v = \frac{dr}{dt} = \frac{d(R\ l)}{dt} \Rightarrow v = \frac{dr}{dt} = l\ \frac{dR}{dt} \Rightarrow v = \frac{dr}{dt} = \frac{r}{R}\ \frac{dR}{dt}$$

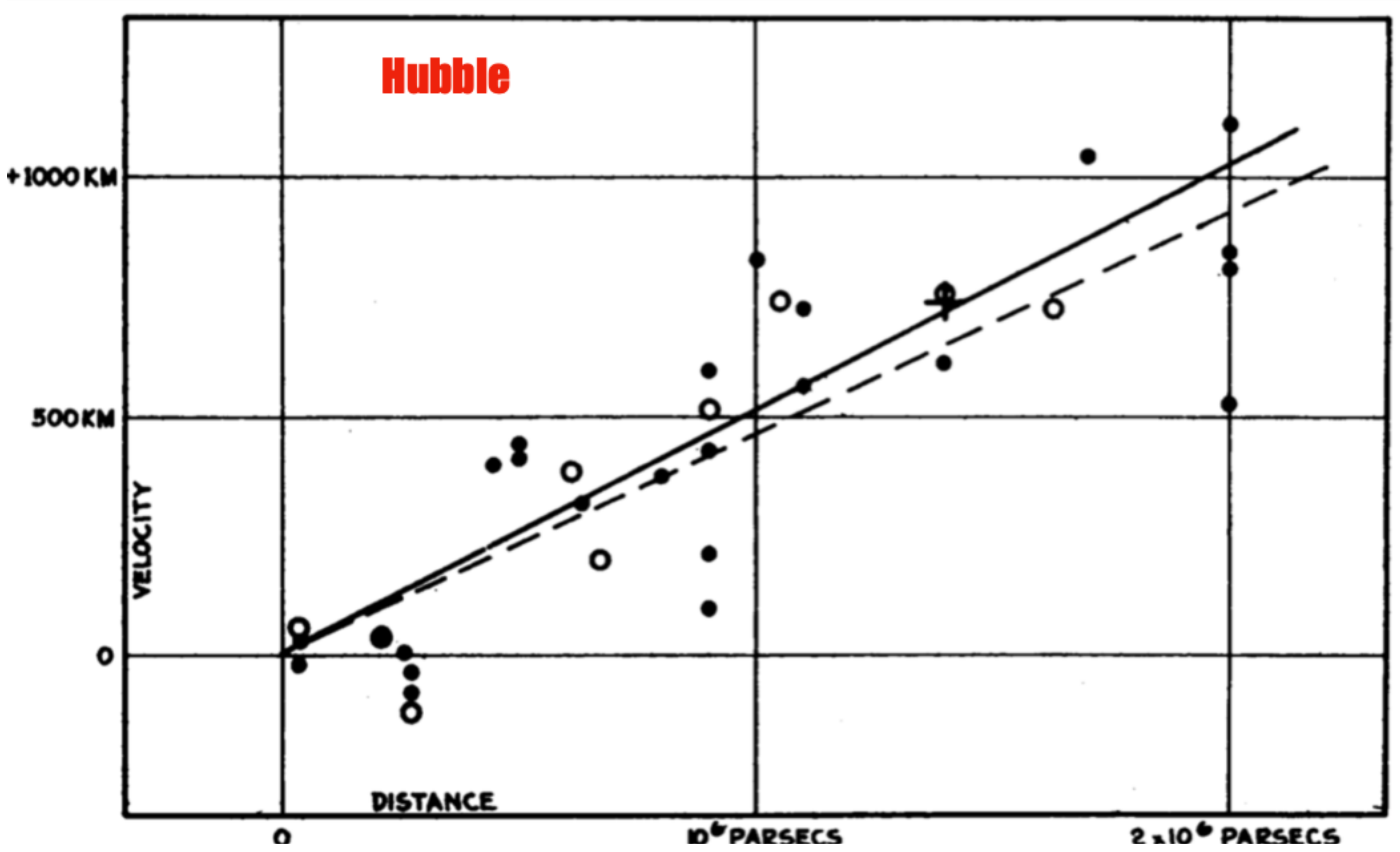
$$v = \frac{dr}{dt} = H\ r$$

Part II. Content

Expansion rate (or Hubble rate)

$$v = \frac{\dot{a}}{a} r = H \; r \quad \Longrightarrow \quad H = \frac{\dot{R}(t)}{R(t)} = \frac{\dot{a}(t)}{a(t)}$$

($R(t) \equiv a(t)$ **Modern writing convention**)



For light emitted in the past at time t_e from a galaxy moving with the cosmic flow, and received today at time t_0, also in a galaxy moving with the cosmic flow,

$$1 + z = \frac{a(t_0)}{a(t_e)} = \frac{1}{a(t_e)}$$

leading to the generic relation

$$a(t) = \frac{1}{(1+z)}. \qquad \textbf{with} \;\; a(t_0) = 1$$

Part II. Content

Expansion rate (or Hubble rate)

$$H = \frac{\dot{a}}{a}$$

Hubble rate defines the rate of expansion of the Universe

$$H = \frac{\dot{a}}{a} = \frac{d}{dt}\left(\frac{a(t_0)}{(1+z)}\right)\frac{1}{a} = -\frac{1}{(1+z)}\frac{dz}{dt}$$

and

$$H = -\frac{1}{(1+z)}\frac{dz}{dt} \Rightarrow dt = -\frac{1}{(1+z)}\frac{dz}{H}.$$

Today $H_0 \simeq 70\ \mathrm{km/s/Mpc}$

$$H_0 \equiv [s^{-1}] \quad \Longrightarrow \quad 1/H_0 \sim \text{age of the Universe}$$

$$t_0 \simeq 1.4 \times 10^{10}\ yr$$

Part II. Content

Expansion rate (or Hubble rate)

$$H(t) = \frac{\dot{a}}{a} \equiv \frac{\dot{a}(t)}{a(t)}$$ Hubble

$$1 + z_{emitted} = \frac{a(t_0)}{a(t_{emitted})} \qquad a(t_0) = a_0 = 1$$ Convention as we can't measure a0

- If we can access the redshift of an object in the past, we have access to the size of the Universe at that time, i.e. $a(t_1)$
- If we have access to the redshift of many objects in the past we can reconstruct a(t) and its evolution.
- If we have a(t), we can compute the derivative and therefore find H(t) and thus have access to the Universe History, its evolution and a chance to understand what drove the recent expansion.

Part II. Content

Expansion rate (or Hubble rate)

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 10 Jul 2019 (v1), last revised 6 Nov 2019 (this version, v2)]

H0LiCOW XIII. A 2.4% measurement of H_0 from lensed quasars: 5.3σ tension between early and late-Universe probes

Kenneth C. Wong, Sherry H. Suyu, Geoff C.-F. Chen, Cristian E. Rusu, Martin Millon, Dominique Sluse, Vivien Bonvin, Christopher D. Fassnacht, Stefan Taubenberger, Matthew W. Auger, Simon Birrer, James H. H. Chan, Frederic Courbin, Stefan Hilbert, Olga Tihhonova, Tommaso Treu, Adriano Agnello, Xuheng Ding, Inh Jee, Eiichiro Komatsu, Anowar J. Shajib, Alessandro Sonnenfeld, Roger D. Blandford, Leon V. E. Koopmans, Philip J. Marshall, Georges Meylan

We present a measurement of the Hubble constant (H_0) and other cosmological parameters from a joint analysis of six gravitationally lensed quasars with measured time delays. All lenses except the first are analyzed blindly with respect to the cosmological parameters. In a flat ΛCDM cosmology, we find $H_0 = 73.3^{+1.7}_{-1.8}$, a 2.4% precision measurement, in agreement with local measurements of H_0 from type Ia supernovae calibrated by the distance ladder, but in 3.1σ tension with *Planck* observations of the cosmic microwave background (CMB). This method is completely independent of both the supernovae and CMB analyses. A combination of time-delay cosmography and the distance ladder results is in 5.3σ tension with *Planck* CMB determinations of H_0 in flat ΛCDM. We compute Bayes factors to verify that all lenses give statistically consistent results, showing that we are not underestimating our uncertainties and are able to control our systematics. We explore extensions to flat ΛCDM using constraints from time-delay cosmography alone, as well as combinations with other cosmological probes, including CMB observations from *Planck*, baryon acoustic oscillations, and type Ia supernovae. Time-delay cosmography improves the precision of the other probes, demonstrating the strong complementarity. Allowing for spatial curvature does not resolve the tension with *Planck*. Using the distance constraints from time-delay cosmography to anchor the type Ia supernova distance scale, we reduce the sensitivity of our H_0 inference to cosmological model assumptions. For six different cosmological models, our combined inference on H_0 ranges from $\sim$ 73–78 $\mathrm{km\ s^{-1}\ Mpc^{-1}}$, which is consistent with the local distance ladder constraints.

Part II. Content

Expansion rate (or Hubble rate)

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A Comprehensive Measurement of the Local Value of the Hubble Constant with $1\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ Uncertainty from the Hubble Space Telescope and the SH0ES Team

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Abstract

We report observations from the Hubble Space Telescope (HST) of Cepheid variables in the host galaxies of 42 Type Ia supernovae (SNe Ia) used to calibrate the Hubble constant (H_0). These include the complete sample of all suitable SNe Ia discovered in the last four decades at redshift $z \leqslant 0.01$, collected and calibrated from $\geqslant$1000 HST orbits, more than doubling the sample whose size limits the precision of the direct determination of H_0. The Cepheids are calibrated geometrically from Gaia EDR3 parallaxes, masers in NGC 4258 (here tripling that sample of Cepheids), and detached eclipsing binaries in the Large Magellanic Cloud. All Cepheids in these anchors and SN Ia hosts were measured with the same instrument (WFC3) and filters (*F555W*, *F814W*, *F160W*) to negate zero-point errors. We present multiple verifications of Cepheid photometry and six tests of background determinations that show Cepheid measurements are accurate in the presence of crowded backgrounds. The SNe Ia in these hosts calibrate the magnitude–redshift relation from the revised Pantheon+ compilation, accounting here for covariance between all SN data and with host properties and SN surveys matched throughout to negate systematics. We decrease the uncertainty in the local determination of H_0 to $1\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ including systematics. We present results for a comprehensive set of nearly 70 analysis variants to explore the sensitivity of H_0 to selections of anchors, SN surveys, redshift ranges, the treatment of Cepheid dust, metallicity, form of the period–luminosity relation, SN color, peculiar-velocity corrections, sample bifurcations, and simultaneous measurement of the expansion history. Our baseline result from the Cepheid–SN Ia sample is $H_0 = 73.04 \pm 1.04\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, which includes systematic uncertainties and lies near the median of all analysis variants. We demonstrate consistency with measures from HST of the TRGB between SN Ia hosts and NGC 4258, and include them simultaneously to yield $72.53 \pm 0.99\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The inclusion of high-redshift SNe Ia yields $H_0 = 73.30 \pm 1.04\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = -0.51 \pm 0.024$. We find a 5σ difference with the prediction of H_0 from Planck cosmic microwave background observations under ΛCDM, with no indication that the discrepancy arises from measurement uncertainties or analysis variations considered to date. The source of this now long-standing discrepancy between direct and cosmological routes to determining H_0 remains unknown.

Part II. Content

Relation between H and content

To all observers we can associate a potential energy and a kinetic energy

$$U = T + V$$

$$\left.\begin{aligned} &T = \frac{1}{2} m v^2 \qquad T = \frac{1}{2} m \left(H r\right)^2 \\ &V = - \frac{G\, m\, M}{r} = \frac{4\pi\, G \rho\, r^2\, m}{3} \end{aligned}\right\} \Rightarrow \begin{aligned} \frac{1}{2} m\, H^2\, r^2 - \frac{4\pi\, G \rho\, r^2\, m}{3} = U \\ H^2 - \frac{8\pi G \rho}{3} = \frac{2U}{m\, r^2} \end{aligned}$$

$$\boxed{H^2 = \frac{8\pi G \rho}{3} + \frac{2U}{m\, r^2}}$$

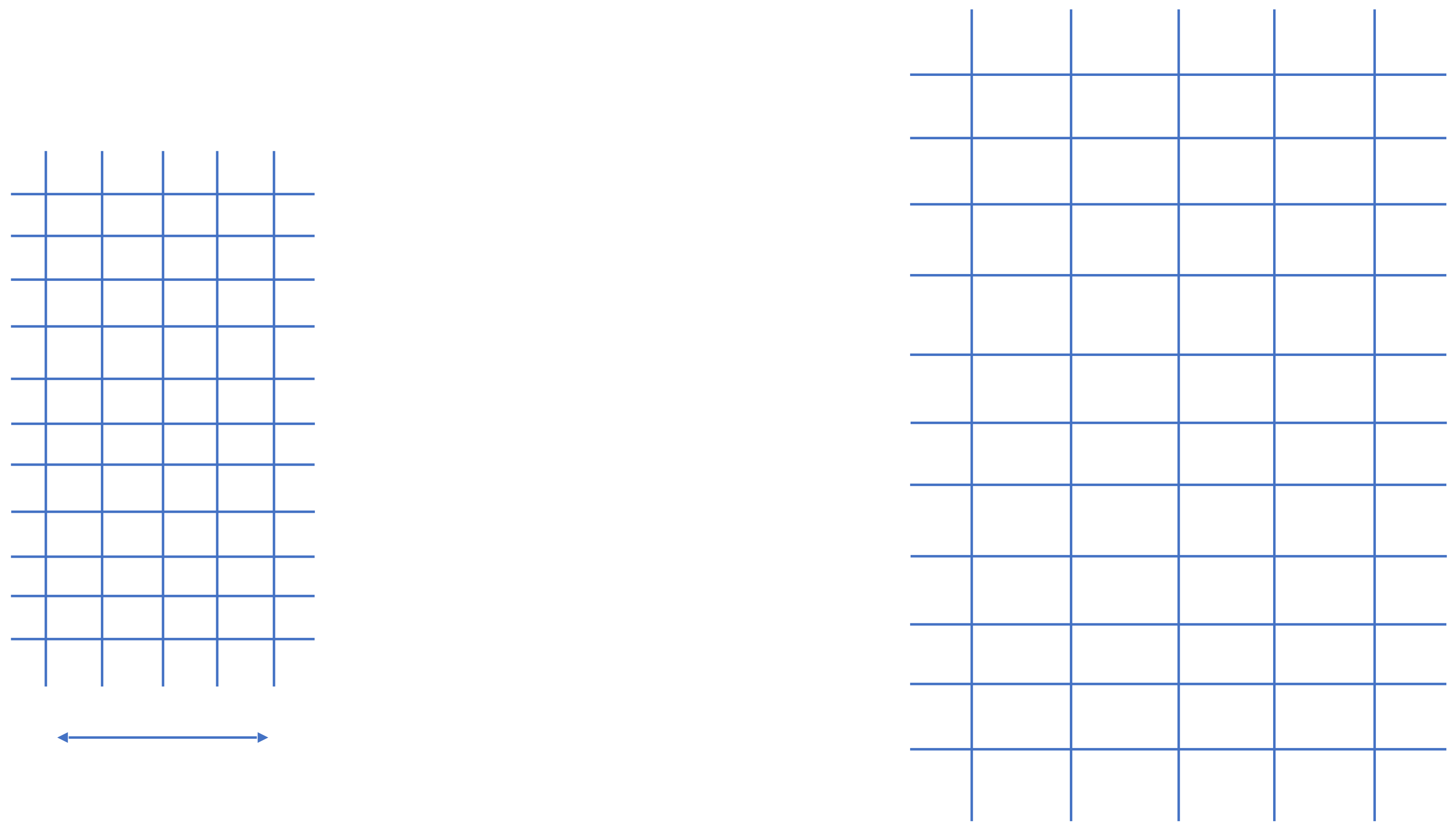
Part II. Content

Relation between H and content

$$H^2 = \frac{8\pi G\rho}{3} + \frac{2U}{m\,r^2}$$

The expansion depends on the density and therefore the Universe's content

$$R \rightarrow \frac{\dot{R}}{R} \equiv \left(\frac{\dot{a}}{a}\right)$$



Part II. Content

Relation between H and content

Version using General Relativity

$$\boxed{G_{\mu\nu} = 8\pi\, G\, T_{\mu\nu} + \Lambda\, g_{\mu\nu}}$$

GEOMETRY=CONTENTS

$g_{\mu\nu}$ = spacetime metric ($ds^2 = g_{\mu\nu}\, dx^\mu\, dx^\nu$)

$G_{\mu\nu}$ = Einstein tensor (spacetime curvature)

G = Newton's gravitational constant

$T_{\mu\nu}$ = energy - momentum tensor

Λ = cosmological constant

Part II. Content

Relation between H and content

$$H^2 = \boxed{\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} \underbrace{- \frac{kc^2}{a^2} + \frac{\Lambda}{3}}}$$

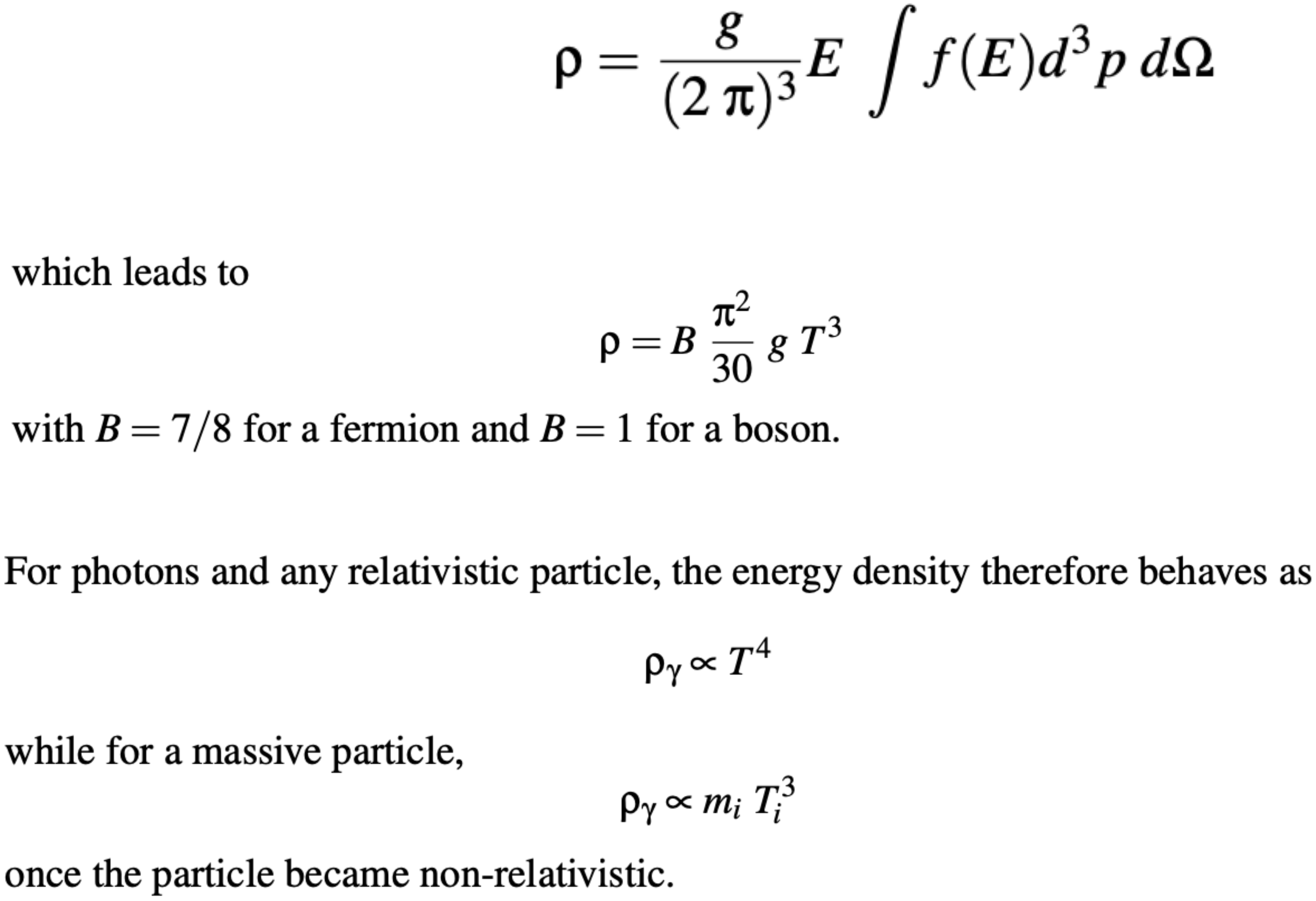
$$H^2 = \frac{8\pi G\rho}{3} + \frac{2U}{m\,r^2}$$

$$\boxed{G_{\mu\nu} = 8\pi\, G\, T_{\mu\nu} + \Lambda\, g_{\mu\nu}}$$

Expansion is driven by the energy associated with particles, curvature & a cosmological constant

Part II. Content

Energy densities



$$\rho = \frac{g}{(2\,\pi)^3} E \int f(E) d^3p\, d\Omega$$

which leads to

$$\rho = B\,\frac{\pi^2}{30}\, g\, T^3$$

with $B = 7/8$ for a fermion and $B = 1$ for a boson.

For photons and any relativistic particle, the energy density therefore behaves as

$$\rho_\gamma \propto T^4$$

while for a massive particle,

$$\rho_\gamma \propto m_i\, T_i^3$$

once the particle became non-relativistic.

Part II. Content

Energy densities

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2} + \frac{\Lambda}{3}$$

For photons and any relativistic particle, the energy density therefore behaves as

$$\rho_\gamma \propto T^4$$

while for a massive particle,

$$\rho_\gamma \propto m_i\, T_i^3$$

once the particle became non-relativistic.

We are missing

- the relation between time and temperature
- the time evolution of the density

- **Generic time evolution of an energy density**

Part II. Content

Time evolution of densities

$$dE = -p\,dV$$

P = pression; V = volume

$$E = m\,c^2$$ with $$m = \rho\,V$$ → $$E = \rho\,V\,c^2$$

$$dE = d\rho\,V\,c^2 + \rho\,dV\,c^2$$

Using $V = a^3 l^3_{coming}$ → $$\frac{dV}{dt} = 3\frac{\dot{a}}{a}V$$

$$\boxed{\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + \frac{p}{c^2}) = 0}$$

Background equation

- time evolution of massive particles energy density

Part II. Content

Time evolution of matter densities

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + \frac{p}{c^2}\right) = 0$$

Particles ~ dust, p=0

$$\dot{\rho} + 3\frac{\dot{a}}{a}\rho = 0 \quad \Rightarrow \quad \frac{\dot{\rho}}{\rho} = -3\frac{\dot{a}}{a}$$

$$\ln \rho(t) = -3\ \ln a(t) + cst$$

$$\rho(t) = cst \times a(t)^{-3}$$

- time evolution of massless particle energy density

Part II. Content

Time evolution of radiation density

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + \frac{p}{c^2}\right) = 0$$

with

$$\rho = \frac{1}{3}\frac{p}{c^2}$$

$$\dot{\rho} + 4\frac{\dot{a}}{a}\rho = 0$$

→

$$\ln \rho(t) = -4 \;\ln a(t) + cst$$

$$\rho(t) = cst \times a(t)^{-4}$$

- **Hubble evolution**

Part II. Content

Time evolution of Hubble rate

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2} + \frac{\Lambda}{3}$$

$$H^2 = \frac{8\pi G\rho}{3} - k\frac{c^2}{a^2} + \frac{\Lambda}{3}$$

$$k = 0 \ \& \ \Lambda = 0 \Rightarrow \qquad H^2 = \frac{8\pi G\rho_{crit}}{3} \Rightarrow \rho_{crit} = \frac{3\,H^2}{8\,\pi\,G}$$

$$1 = \underbrace{\frac{\rho}{\rho_{crit}}}_{\Omega} - k\underbrace{\frac{3\,c^2}{8\,a^2\,\pi G\,\rho_{crit}}}_{\Omega_k} + \underbrace{\frac{\Lambda}{8\pi G\,\rho_{crit}}}_{\Omega_\lambda}$$

Cosmological parameters

$$\rho = \rho_r + \rho_m$$

radiation matter

$$1 = \Omega_{r,m} + \Omega_k + \Omega_\Lambda$$

Part II. Content

Time evolution of Hubble rate

$$\rho_{crit} = \frac{3\,H_0^2}{8\,\pi\,G} \simeq 0.92 \times 10^{-26}\ \mathrm{kg/m^3}$$

Today

Converted to Solar Masses / Mega parsec

$$\rho_{crit} \simeq 1.36 \times 10^{11}\ \mathrm{M_\odot/Mpc^3}$$

Given that the typical size of galaxies is around 10^11 solar masses and the typical separation between galaxies is 1 Mpc, the Universe must be near the critical density and therefore ~ flat.

Time evolution of Hubble rate

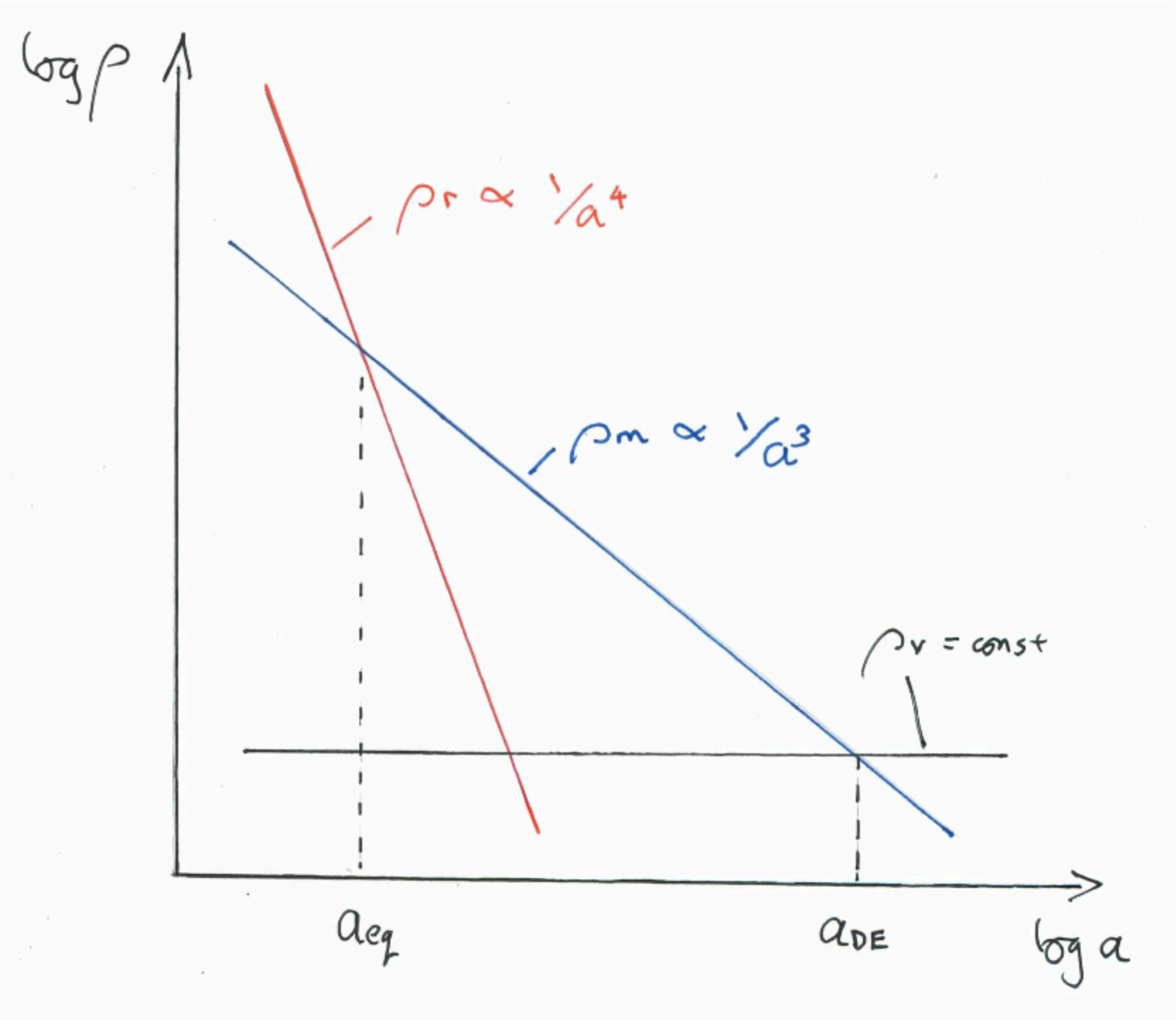
$$1 = \underbrace{\frac{\rho}{\rho_{crit}}}_{\Omega} - k\,\underbrace{\frac{3\,c^2}{8\,a^2\,\pi G\,\rho_{crit}}}_{\Omega_k} + \underbrace{\frac{\Lambda}{8\pi G\,\rho_{crit}}}_{\Omega_\lambda}$$

→

$$1 = \Omega_{r,m} + \Omega_k + \Omega_\Lambda$$

=

$$\frac{\rho}{\rho_{crit}}$$



matter $\rho(t) = cst \times a(t)^{-4}$

radiation $\rho(t) = cst \times a(t)^{-3}$

Past dominated by radiation
Then matter and today Universe
dominated by Lambda

- **Expansion vs content & geometry**

Part II. Content of the Universe

$$H^2 = \frac{8\,\pi\,G\,\rho}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}$$

$$H(z) = H_0\,\sqrt{\Omega_r + \Omega_m + \Omega_\Lambda + \Omega_k(1+z)^2}$$

a^{-4} a^{-3}

- **Energy (lambda and radiation) fuels expansion when they dominate**
- **Matter too but also slows expansion due to gravity**
- **Curvature does too for k = -1 (otherwise contraction)**

Part II. Content

Role of lambda in expansion

$$1 = \frac{\rho}{\rho_{crit}} - k\frac{3\,c^2}{8\,a^2\,\pi G\,\rho_{crit}} + \frac{\Lambda}{8\pi G\,\rho_{crit}}$$

Universe with no cosmological constant “Lambda” $1 - \frac{\rho}{\rho_{crit}} = -(... > 0)$

$\rho > \rho_{crit}$: Universe is over dense — Positive curvature (k=1); Sphere; closed Universe

$\rho = \rho_{crit}$ — Zero curvature (k=-0); Flat Universe

$\rho < \rho_{crit}$: Universe is under dense — Negative curvature (k=-1); Hypolic; Open Universe

Part II. Content

Role of lambda in expansion

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2} + \frac{\Lambda}{3}$$

$$\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + \frac{p}{c^2}) = 0$$

Sub for ρ from fluid equation :

$$2\frac{\dot{a}}{a}[\frac{a\ddot{a} - \dot{a}^2}{a^2}] = -\frac{8\pi G}{3}3\frac{\dot{a}}{a}\left(\rho + \frac{p}{c^2}\right) + \frac{2kc^2\dot{a}}{a^3}$$

$$\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2} = -4\pi G\left(\rho + \frac{p}{c^2}\right) + \frac{kc^2}{a^2}$$

Sub for $(\dot{a}/a)^2$ and rearrange to get :

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + \frac{3p}{c^2}) + \frac{\Lambda}{3}$$

← **Deceleration equation**
(or acceleration eq!)

Role of lambda in expansion

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + \frac{3p}{c^2}) + \frac{\Lambda}{3}$$

If Lambda dominates on the right hand side $\frac{\ddot{a}}{a} = \frac{\Lambda}{3}$

$$\Lambda > 0, \quad \frac{\ddot{a}}{a} > 0$$

Expansion is accelerating

$$\Lambda < 0, \quad \frac{\ddot{a}}{a} < 0$$

Expansion is decclerating

Otherwise $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right)$

Part II. Content

Role of lambda in expansion

What is Lambda?

$$\Omega_\Lambda = \frac{\Lambda}{3H^2}$$

$$\boxed{\dot{\rho} + 3\frac{\dot{a}}{a}(\rho + \frac{p}{c^2}) = 0}$$

$$\rho = -\frac{p}{c^2}$$

(Positive) Lambda exerts (negative) pressure!

forces the Universe to expand faster

$$\frac{\ddot{a}}{a} = \frac{\Lambda}{3}$$

- **Time dependence of the scale-factor**

Part II. Content

Time evolution of scale-factor

(flat, matter dominated)

$$H^2 = \frac{8\pi G\rho}{3} - k\frac{c^2}{a^2} + \frac{\Lambda}{3} \quad\Longrightarrow\quad H^2 = \frac{8\pi G\rho_m}{3}$$

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho_m}{3} \quad\Longrightarrow\quad \left(\frac{\dot{a}}{a}\right)^2 = cst\ \rho_{m,0}\ a^{-3}$$

$$\dot{a}^2 = cst\ \rho_{m,0}\ a^{-1}$$

$$\frac{da}{dt} = cst\ \sqrt{\rho_{m,0}}\ a^{-1/2}$$

$$a^{1/2}\ da = cst\ \sqrt{\rho_{m,0}}\ dt$$

$$a = [cst\ \sqrt{\rho_{m,0}}]^{3/2}\ t^{2/3}$$

Part II. Content

Time evolution of scale-factor

$$H^2 = \frac{8\pi G\rho}{3} - k\frac{c^2}{a^2} + \frac{\Lambda}{3}$$

$$a = [cst\ \sqrt{\rho_{m,0}}]^{3/2}\ t^{2/3}$$

$$a \propto t^{2/3}$$

$$\dot{a} = [cst\ \sqrt{\rho_{m,0}}]^{3/2}\ \frac{2}{3}\ t^{2/3-1}$$

$$\frac{\dot{a}}{a} = \frac{t_m}{t} \quad \text{with } \mathrm{t_m} \text{ normalisation}$$

Part II. Content

Time evolution of scale-factor

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho_r}{3} \quad \Longrightarrow \quad \begin{aligned} \dot{a}^2 &= cst\ \rho_{r,0}\ a^{-2} \\ \dot{a} &= cst\ \rho_{r,0}^{1/2}\ a^{-1} \\ a^2 &= cst\ \rho_{r,0}^{1/2} t \end{aligned}$$

$$a \propto t^{1/2} \quad \Longrightarrow \quad \begin{aligned} H &\propto \frac{1}{t} \\ H &\propto a^{-2} \end{aligned}$$

Part II. Content

Time evolution of scale-factor

No number density if lambda is a real constant

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + \frac{p}{c^2}\right) = 0 \qquad \text{wit} \qquad \rho = -\frac{p}{c^2} \qquad \text{an} \qquad \rho_\Lambda \propto \frac{\Lambda}{8\,\pi\,G}$$

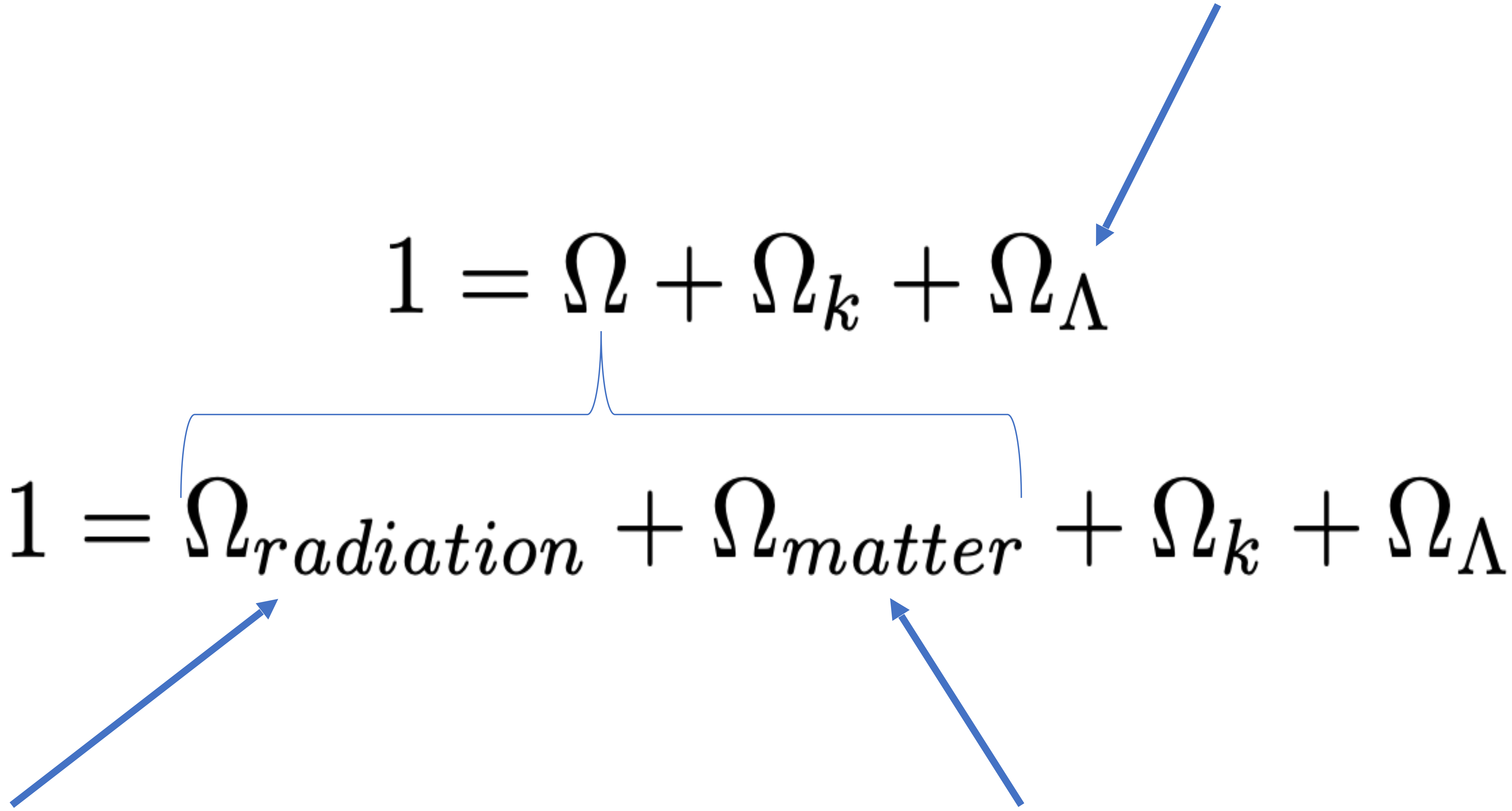
$$\boxed{\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} - \frac{kc^2}{a^2} + \frac{\Lambda}{3}} \Longrightarrow \left(\frac{\dot{a}}{a}\right) = \left(\frac{\Lambda}{3}\right)^{1/2} \Longrightarrow \left(\frac{da}{a}\right) = \left(\frac{\Lambda}{3}\right)^{1/2} dt$$

$$a \propto e^{\sqrt{\Lambda}t}$$

Accelerated expansion!

- **Putting it all together**

Part II. Content



If dominates, Universe expands
Accelerating expansion

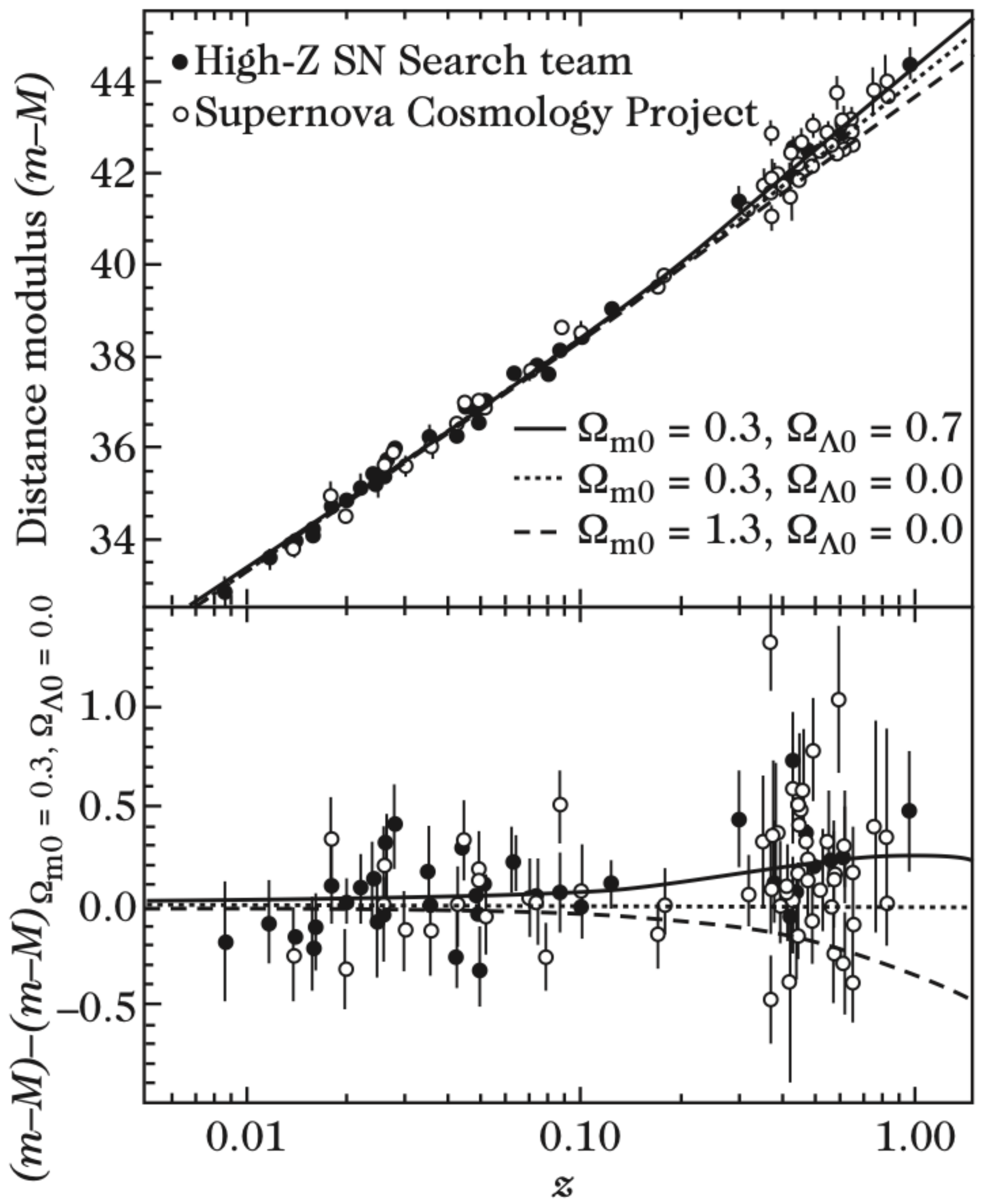
$$1 = \Omega + \Omega_k + \Omega_\Lambda$$

$$1 = \overbrace{\Omega_{radiation} + \Omega_{matter}}^{\Omega} + \Omega_k + \Omega_\Lambda$$

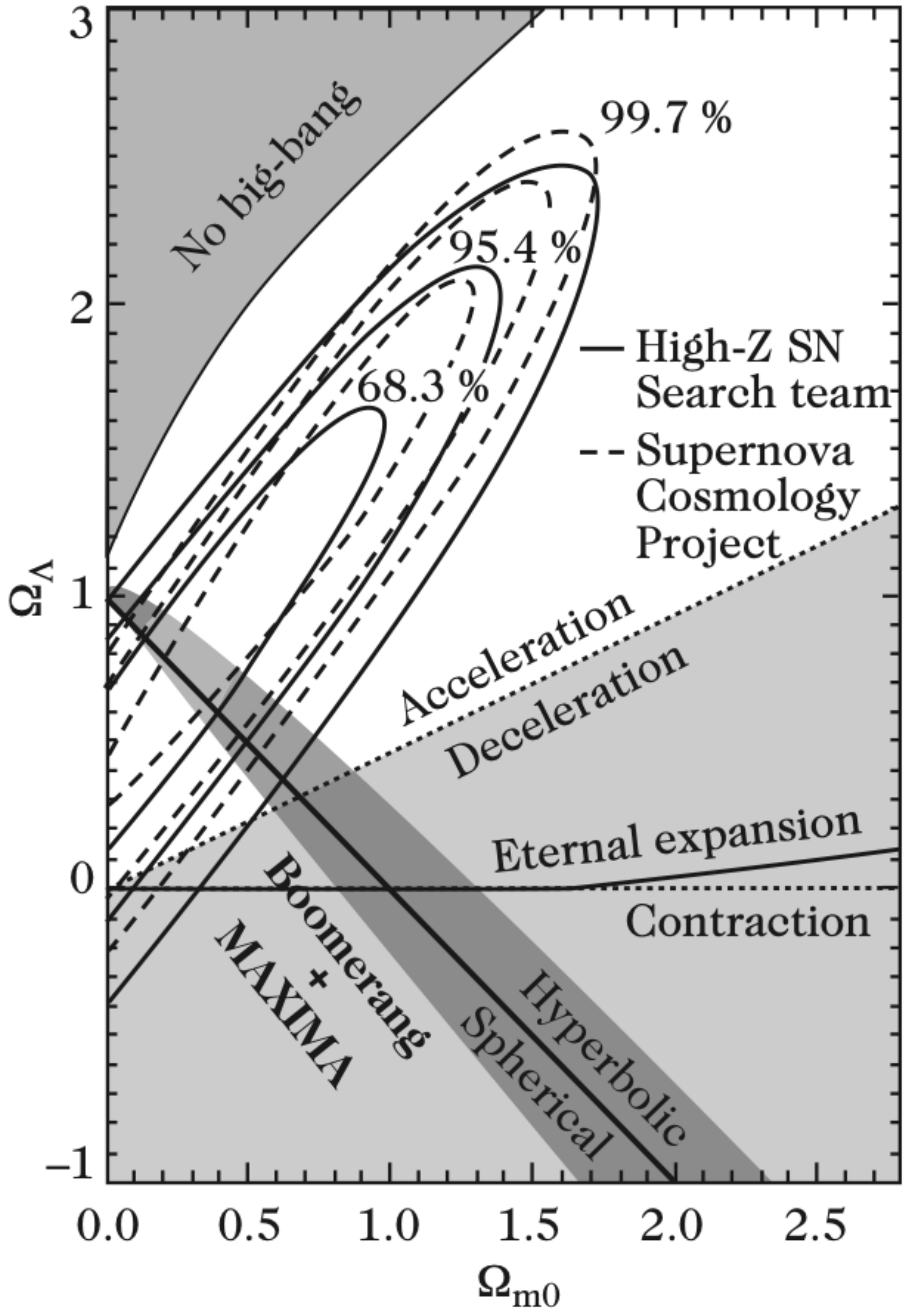
If dominates, Universe expands
Accelerating expansion

If dominates, Universe collapses
Decelerating expansion

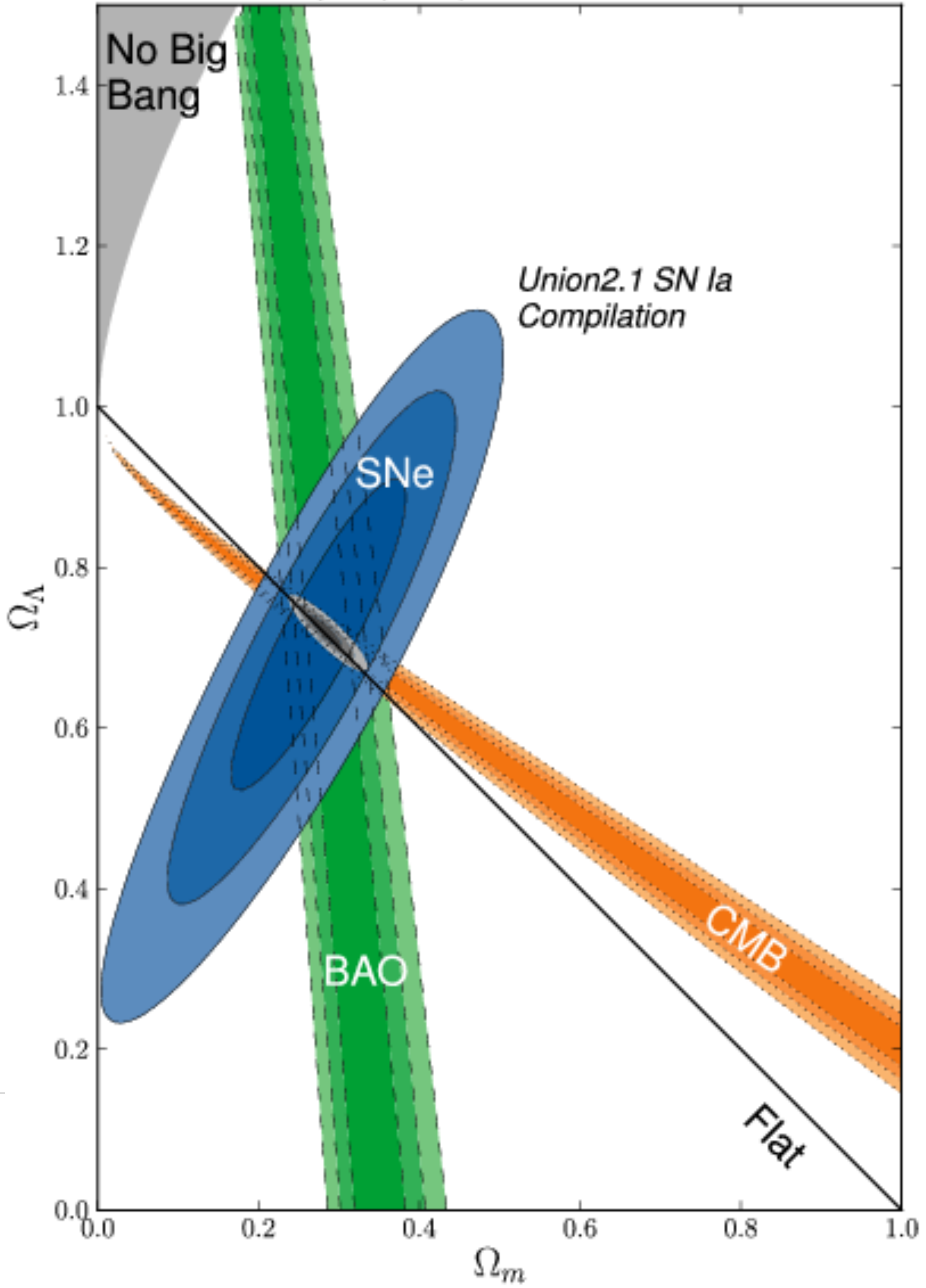
Part II. Content

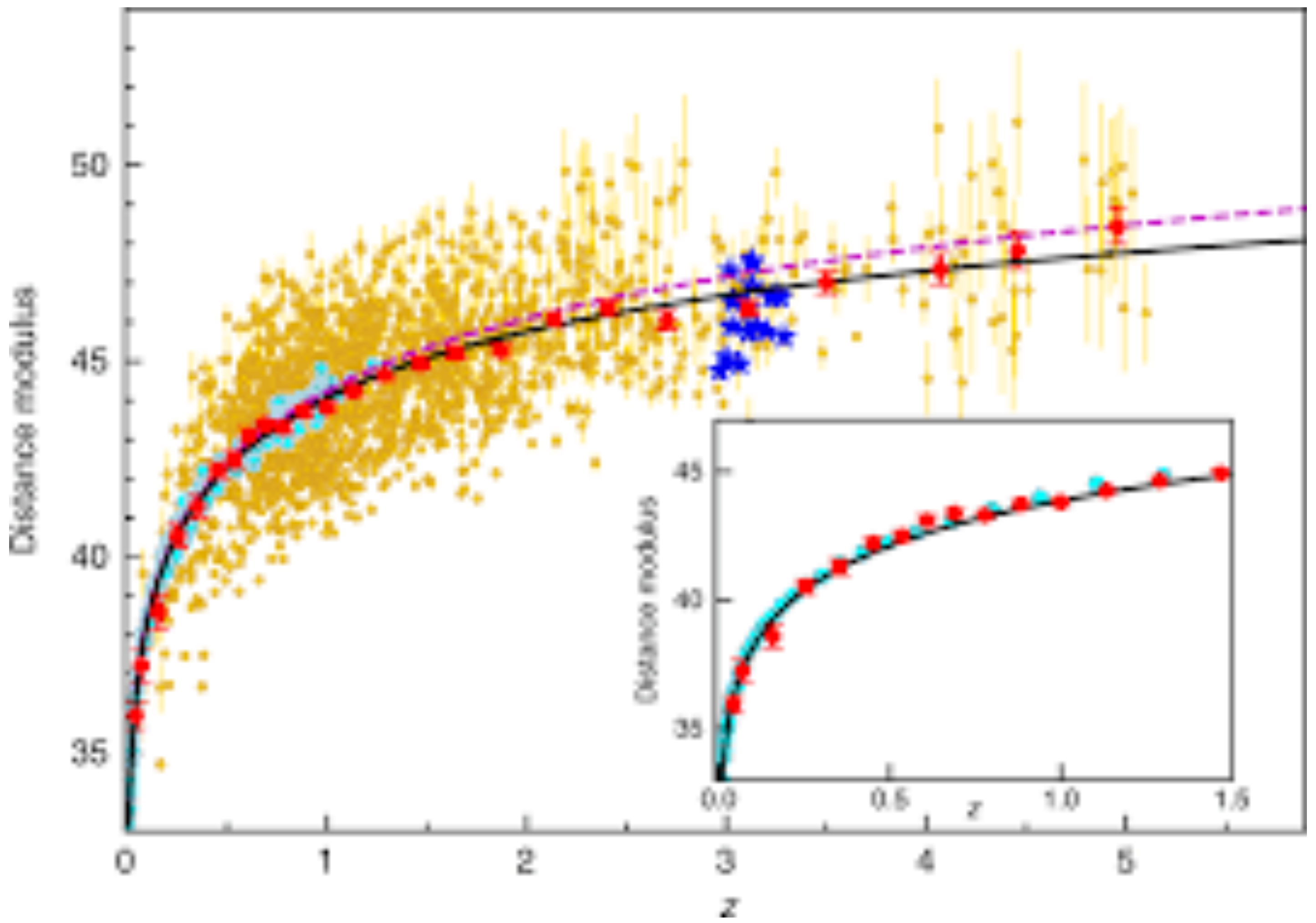


Courtesy Peter&Uzan textbook



Supernova Cosmology Project
Suzuki, et al., *Ap.J.* (2011)

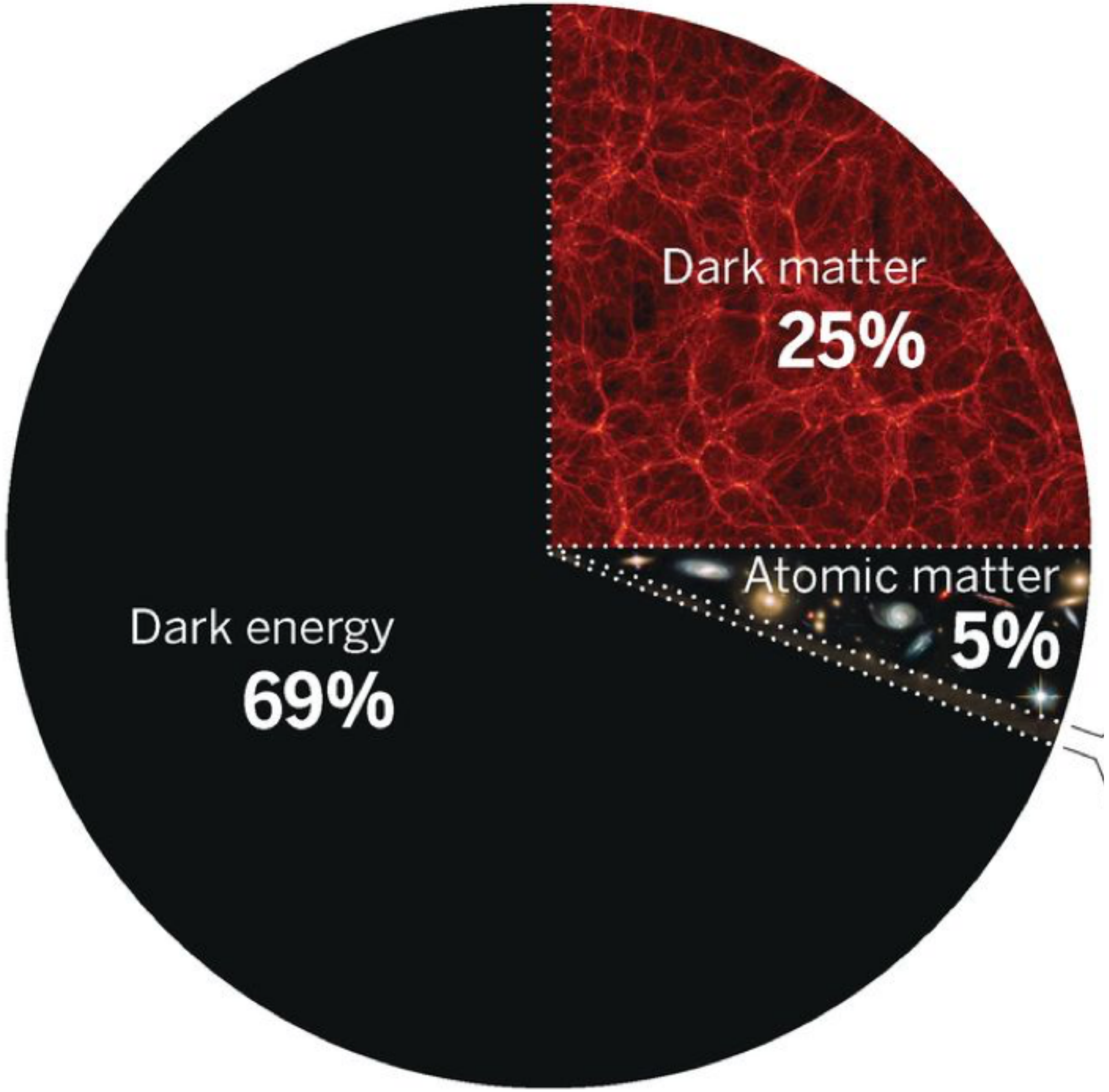




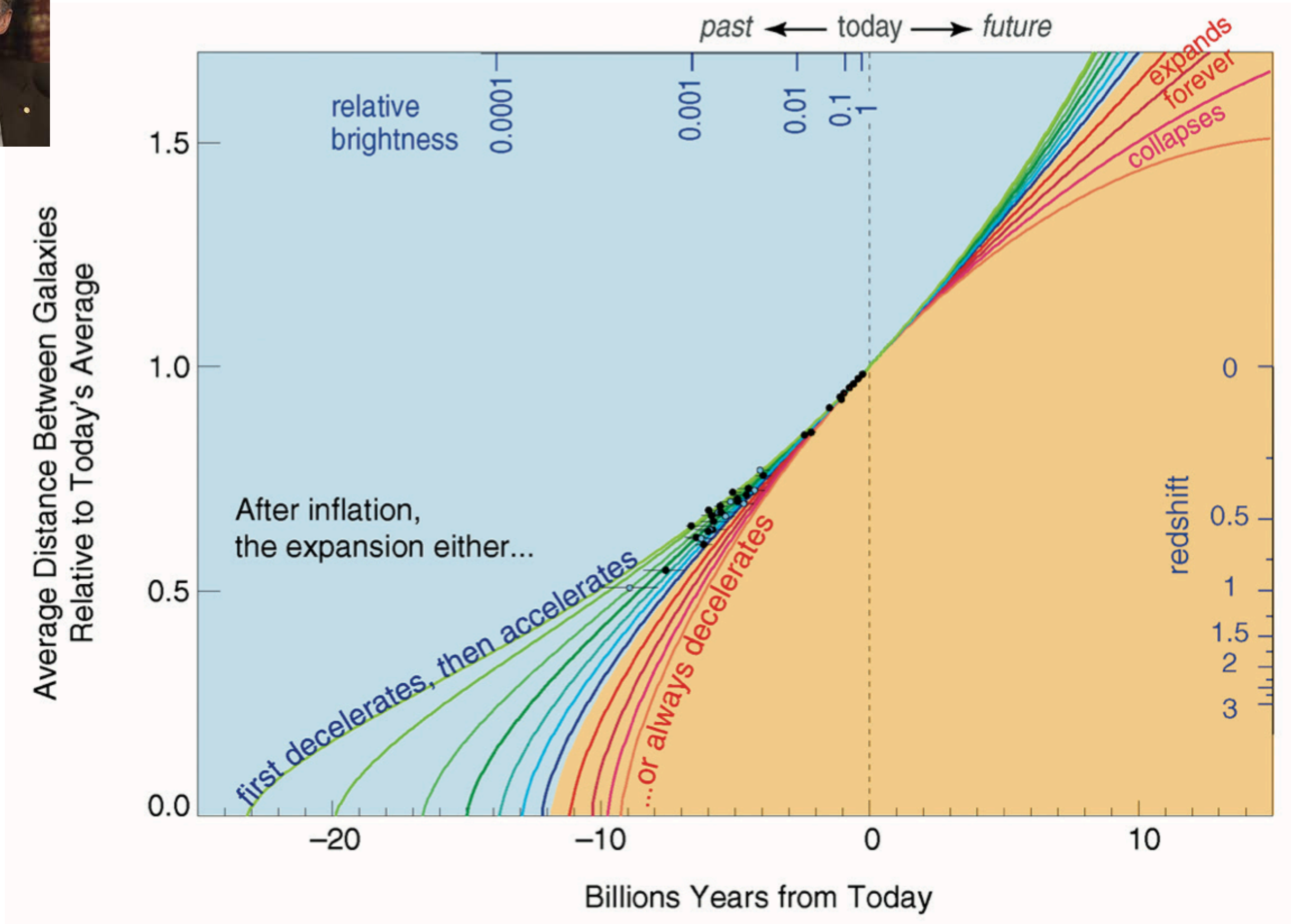
We live in a flat Universe; No curvature

$$1 = \underbrace{\frac{\rho}{\rho_{crit}}}_{\Omega} - k\underbrace{\frac{3\,c^2}{8\,a^2\,\pi G\,\rho_{crit}}}_{\Omega_k} + \underbrace{\frac{\Lambda}{8\pi G\,\rho_{crit}}}_{\Omega_\lambda}$$

Part II. Content

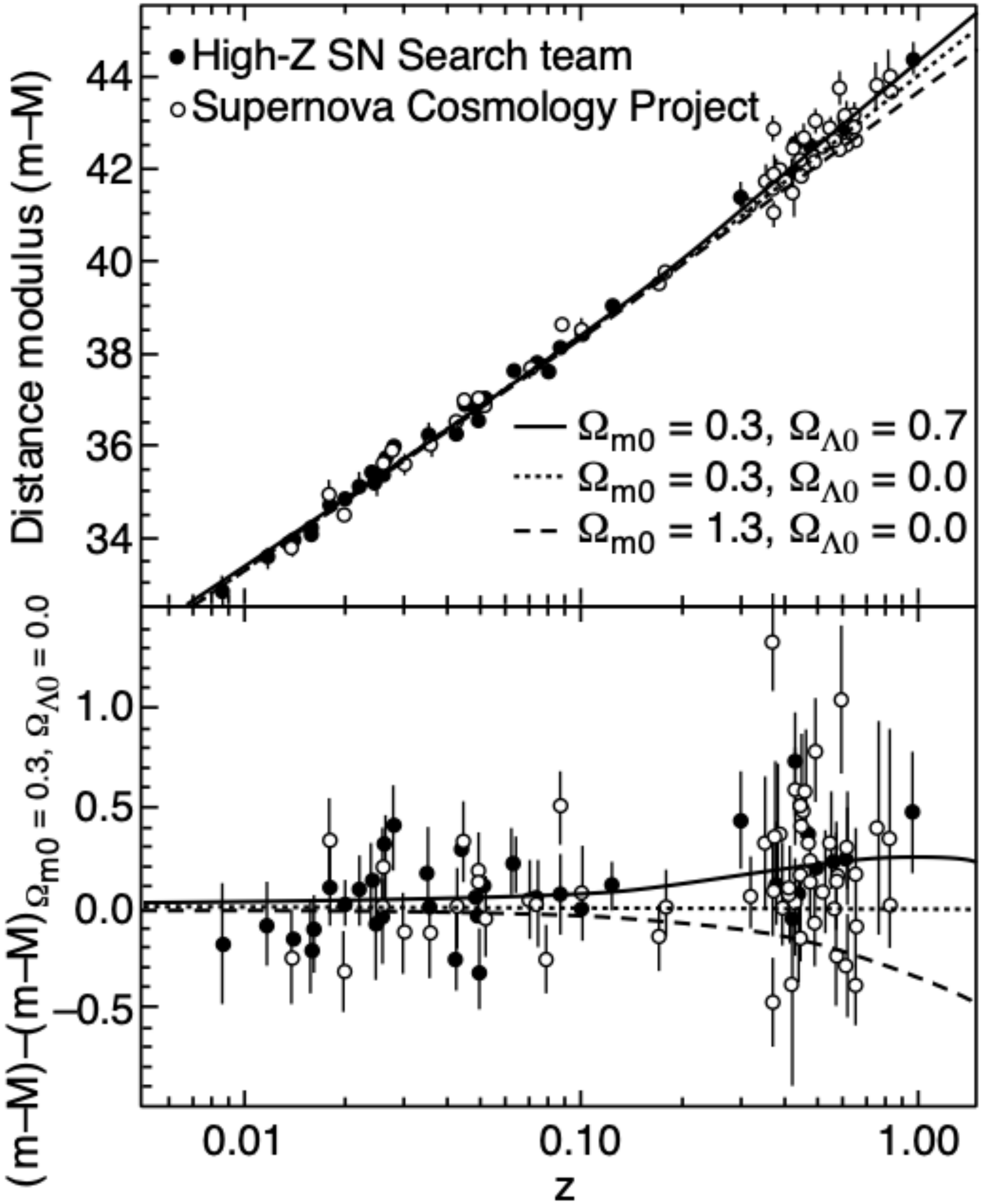


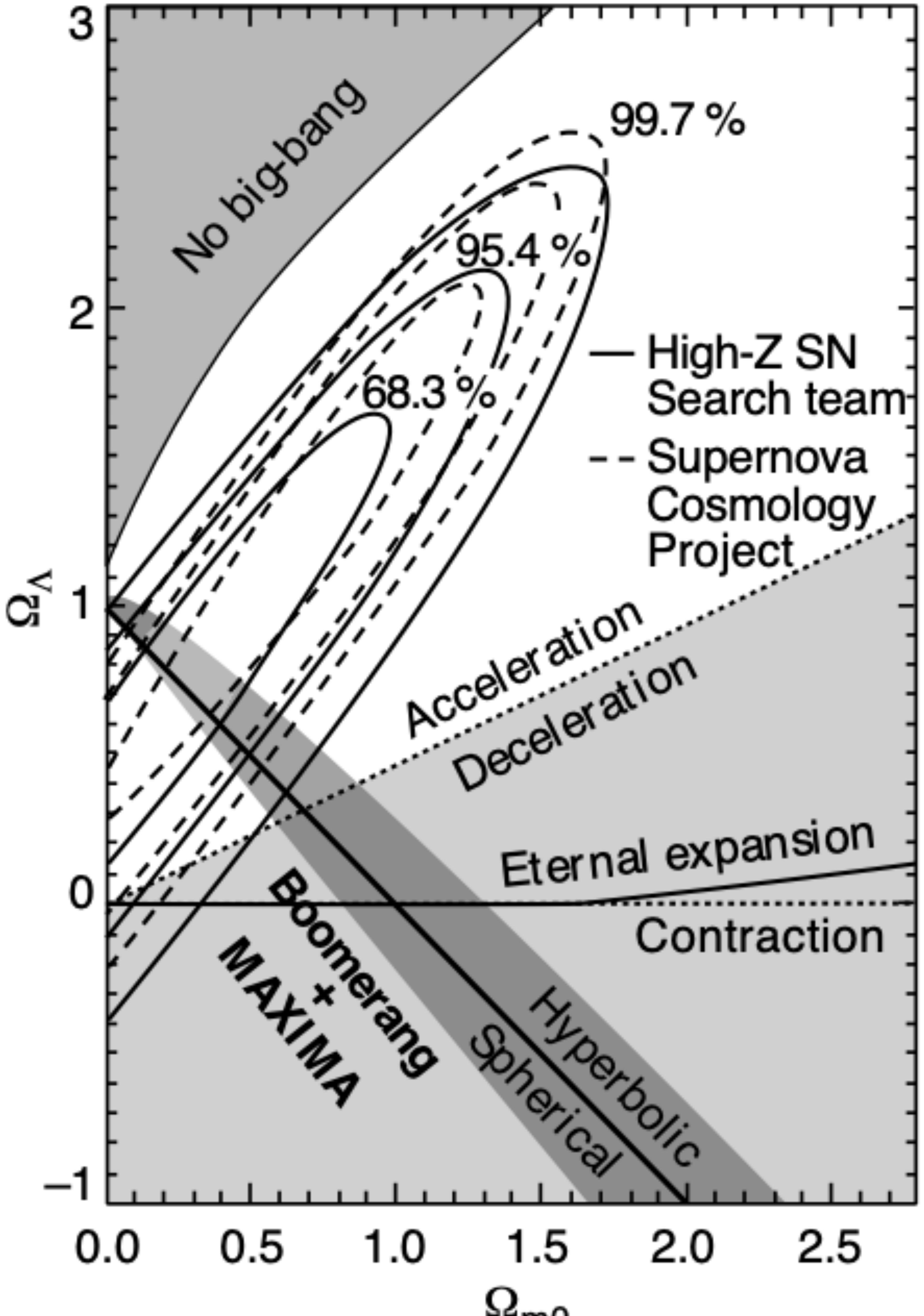
Part II. Content



Part II. Content

Courtesy Peter&Uzan textbook





$$m - M = -2.5 \log [\phi(z) / \phi(10\,\mathrm{pc})]$$

$$m - M = 25 + 5 \log \left[3000 \frac{D_L}{D_{H_0}} \right] - 5\ \mathrm{bg}\, h$$

Part II. Content

$$H \propto \frac{1}{t}$$

matter $\rho(t) = cst \times a(t)^{-4}$ $a \propto t^{1/2}$ $H \propto a^{-2}$

$\Rightarrow$

radiation $\rho(t) = cst \times a(t)^{-3}$ $a \propto t^{2/3}$ $H \propto a^{-3/2}$

Lambda $\rho(t) = constant$ $a \propto e^{\sqrt{\Lambda}t}$

Part III. CMB & structure formation

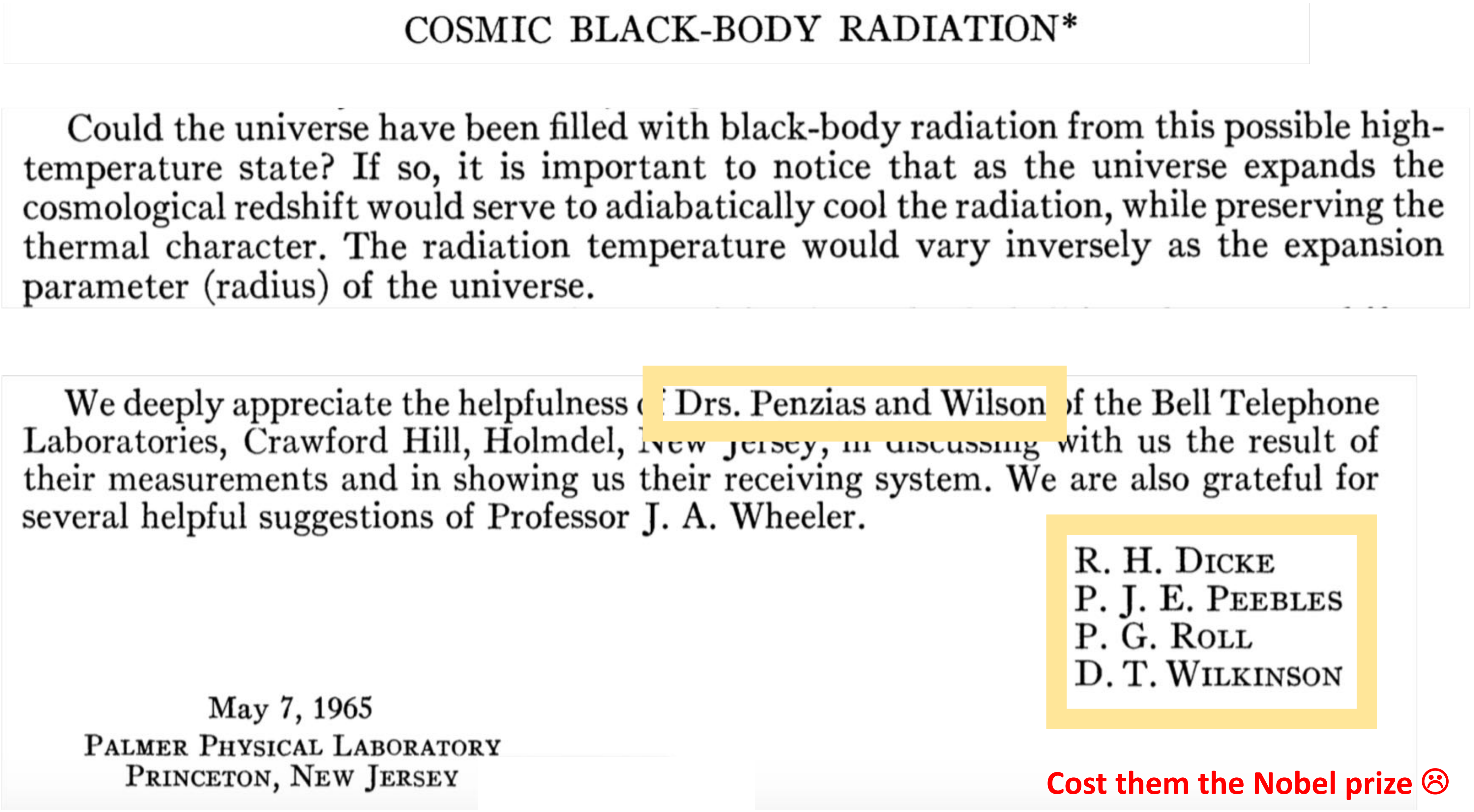
Part III. CMB & structure formation

We saw how the content of the Universe relates to its expansion & geometry

We saw that the Universe was first dominated by radiation, matter and then Lambda

Now we need to understand how structures got to form

Part III. CMB & structure formation



COSMIC BLACK-BODY RADIATION*

Could the universe have been filled with black-body radiation from this possible high-temperature state? If so, it is important to notice that as the universe expands the cosmological redshift would serve to adiabatically cool the radiation, while preserving the thermal character. The radiation temperature would vary inversely as the expansion parameter (radius) of the universe.

We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

Cost them the Nobel prize ☹

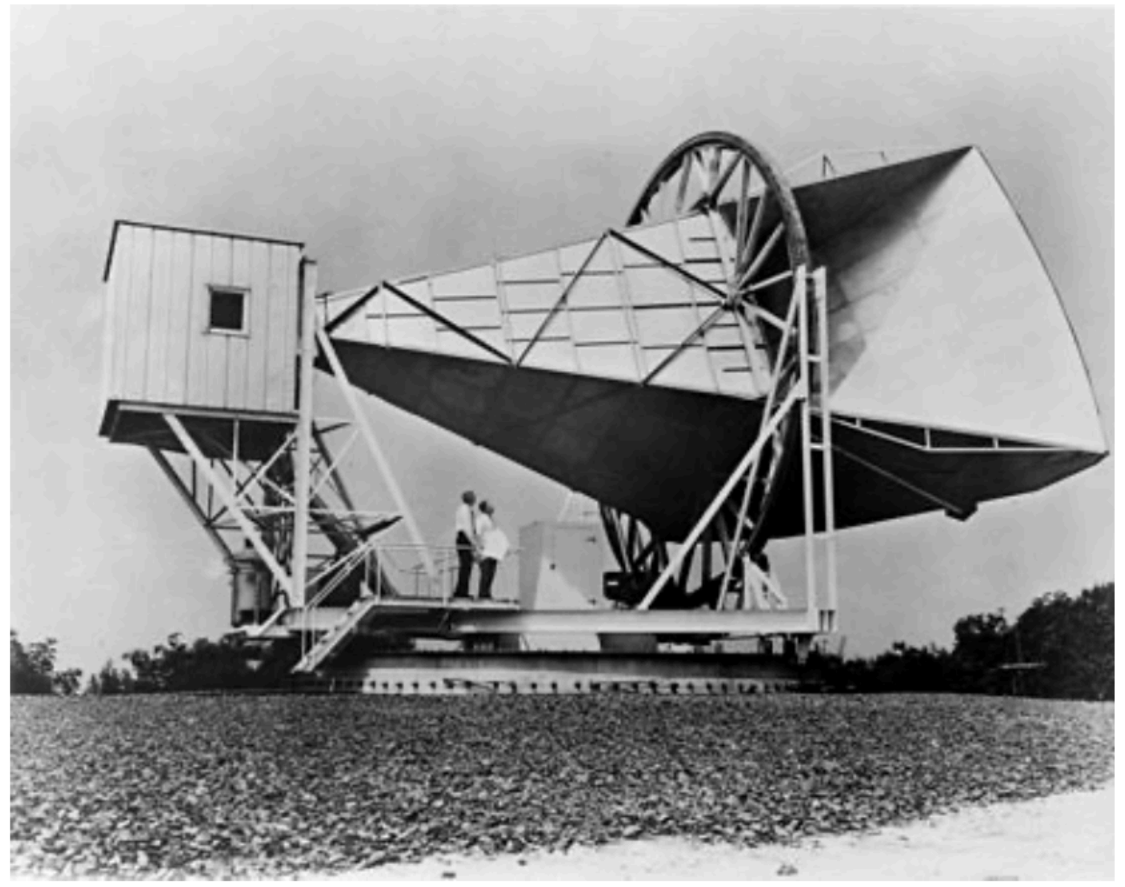


Figure 30: The Holmdel radio antenna at Bell Telephone Laboratories.

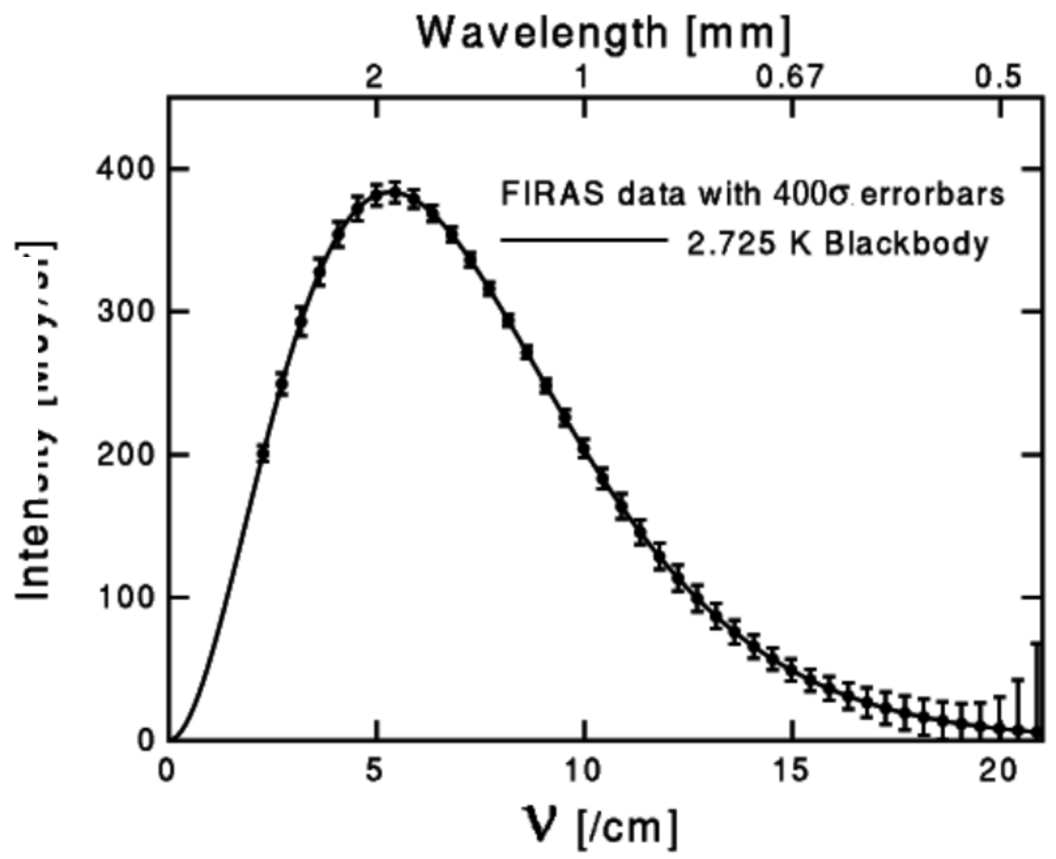


Figure 29: The blackbody spectrum of the CMB, measured in 1990 by the FIRAS detector on the COBE satellite. The error bars have been enlarged by a factor of 400 just to help you see them.

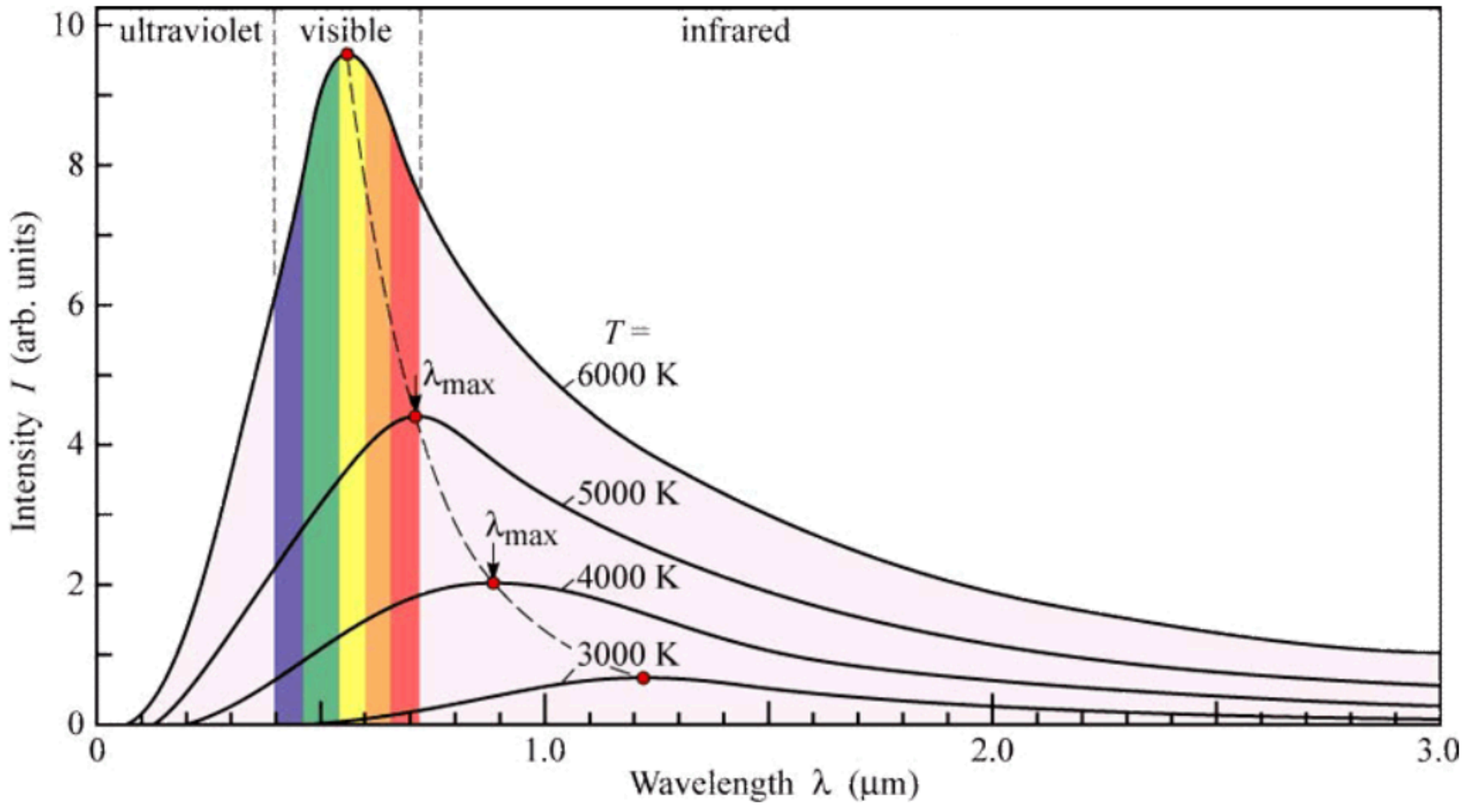
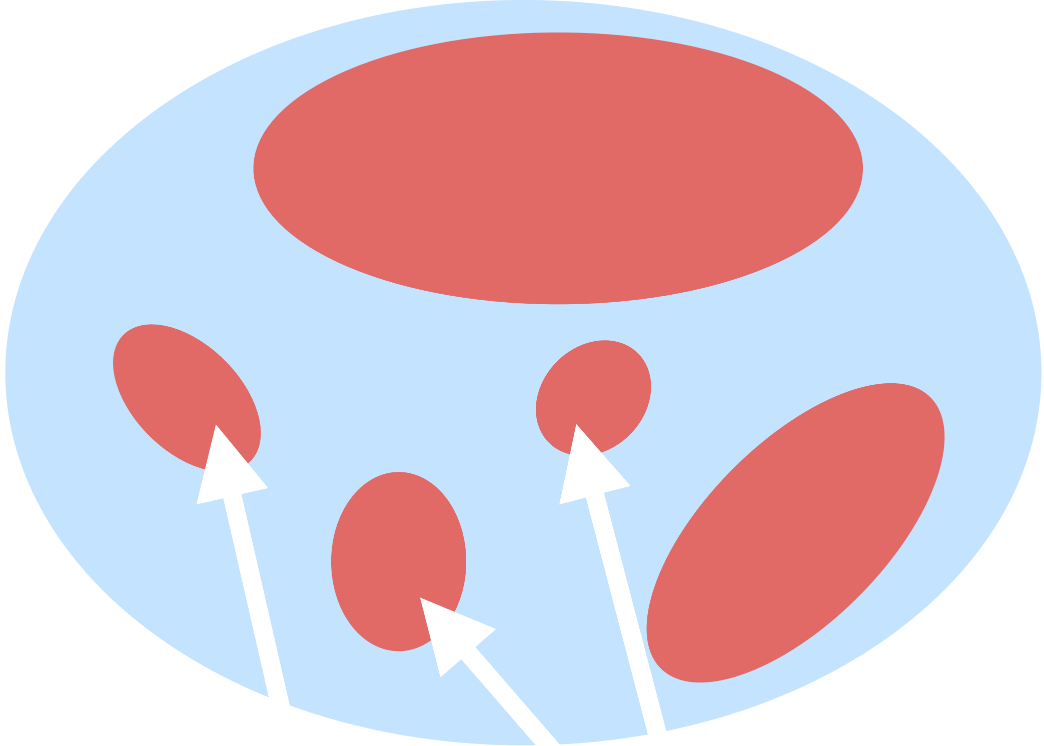
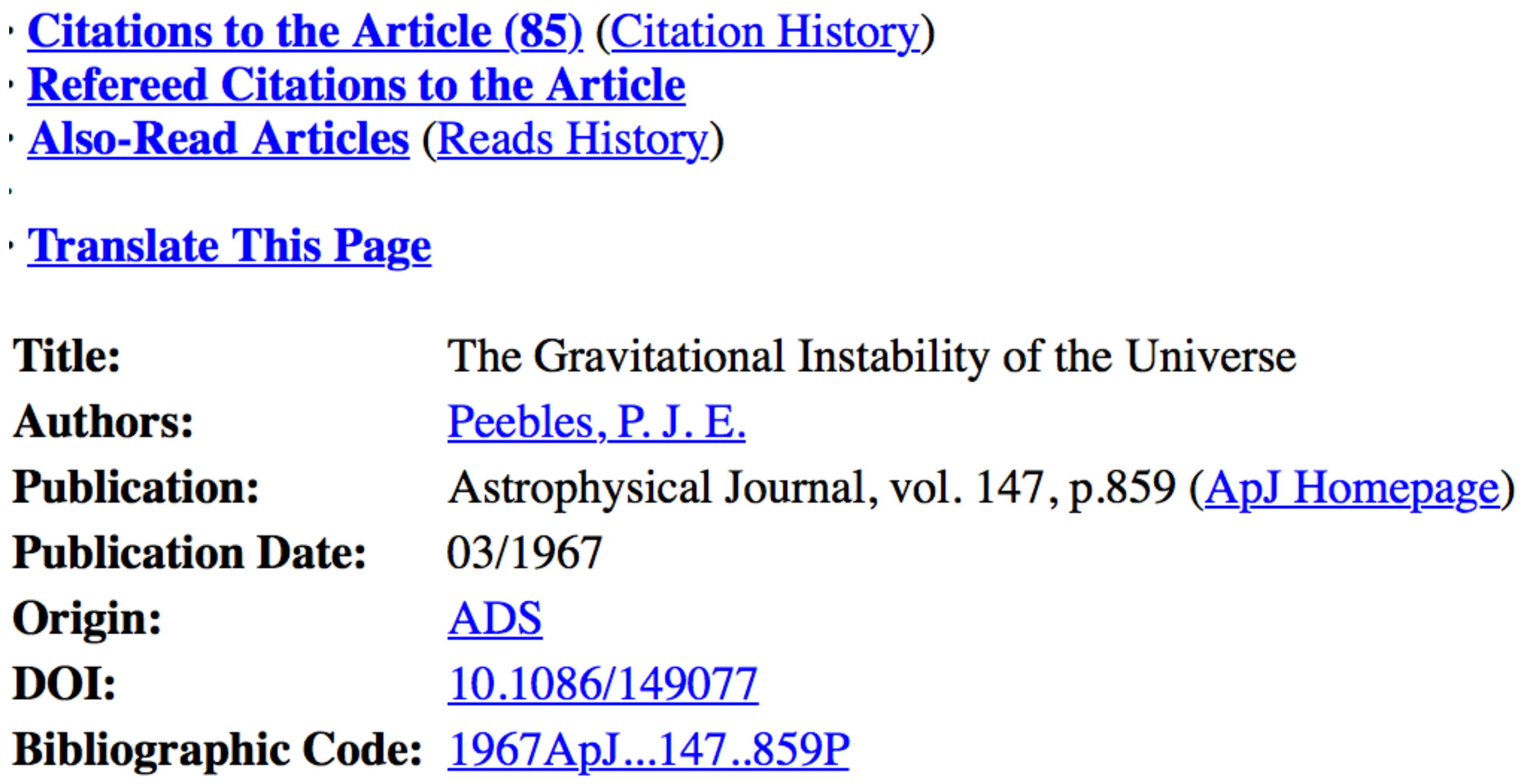


Figure 28: The distribution of colours at various temperatures.

Part III. CMB & structure formation





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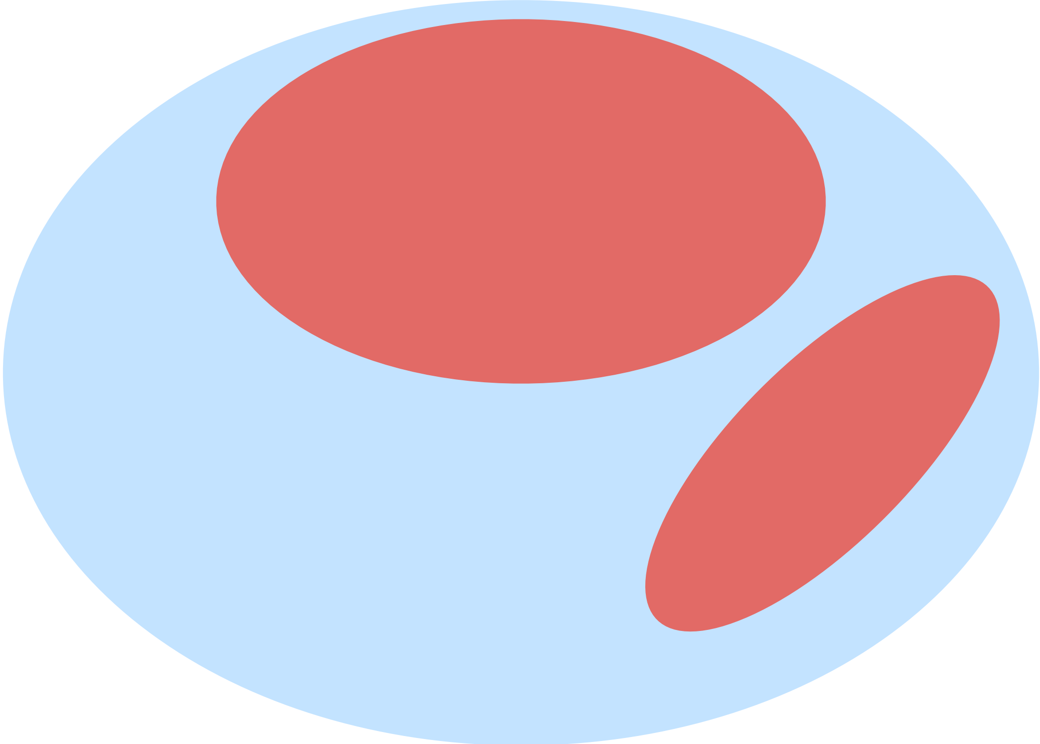
Authors:	Peebles, P. J. E.
Publication:	Astrophysical Journal, vol. 147, p.859 (ApJ Homepage)
Publication Date:	03/1967
Origin:	ADS
DOI:	10.1086/149077
Bibliographic Code:	1967ApJ...147..859P



letters to nature

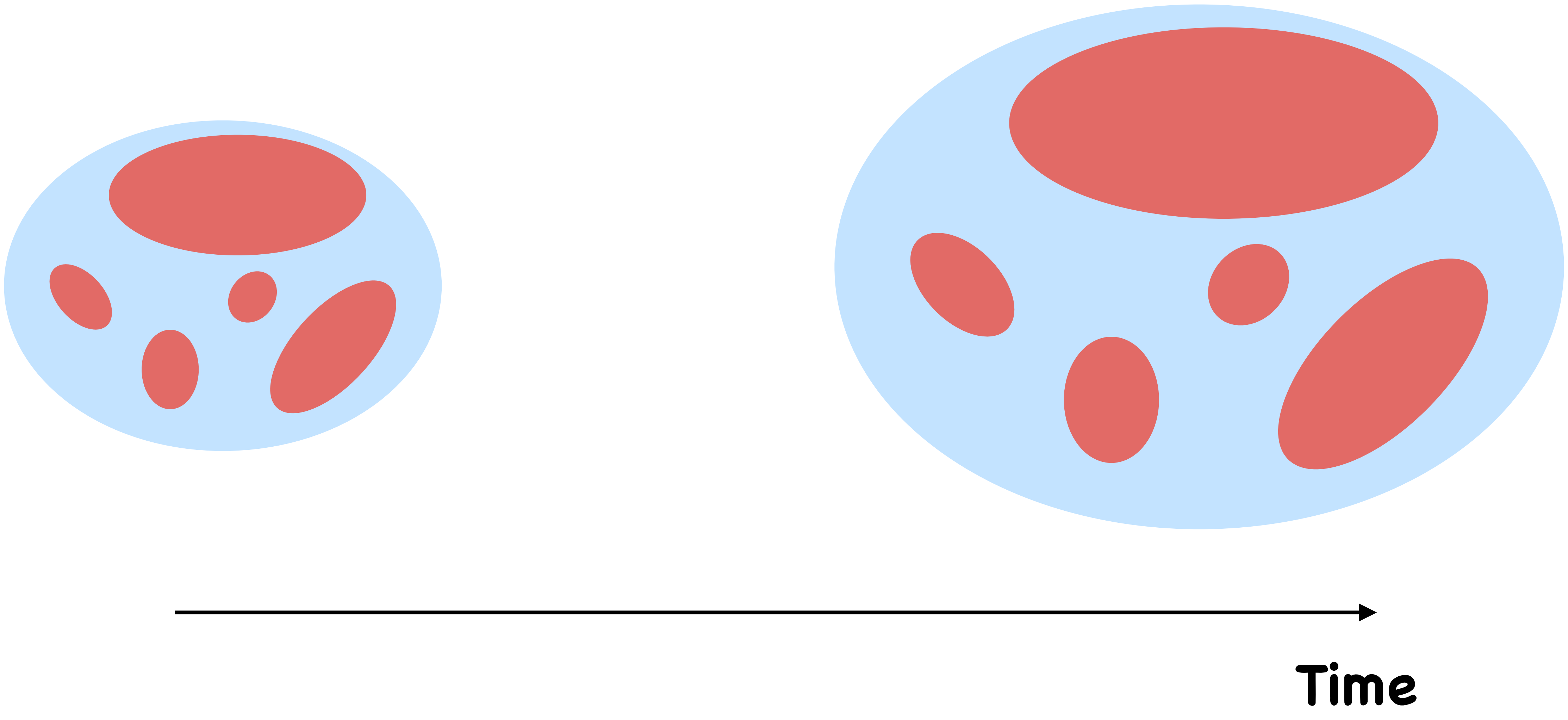
Nature **215**, 1155 - 1156 (09 September 1967); doi:10.1038/2151155a0

Fluctuations in the Primordial Fireball

JOSEPH SILK

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's gravitational theory to explain the process of galaxy formation[1–6]. A means of evading this problem has been to postulate an initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature T_D of the order of 4,000° K. The question may then be posed: would fluctuations in the primordial fireball survive to an epoch when galaxy formation is possible ?

Part III. CMB & structure formation



$$\phi = \frac{L}{4\pi d^2}$$

$$ds^2 = -dt^2 + \enclose{circle}{R^2}\left[d\chi^2 + f_k(\chi)d\Omega^2\right]$$

$$E_0 = \hbar\nu_0 = \frac{E_1}{1+z}$$

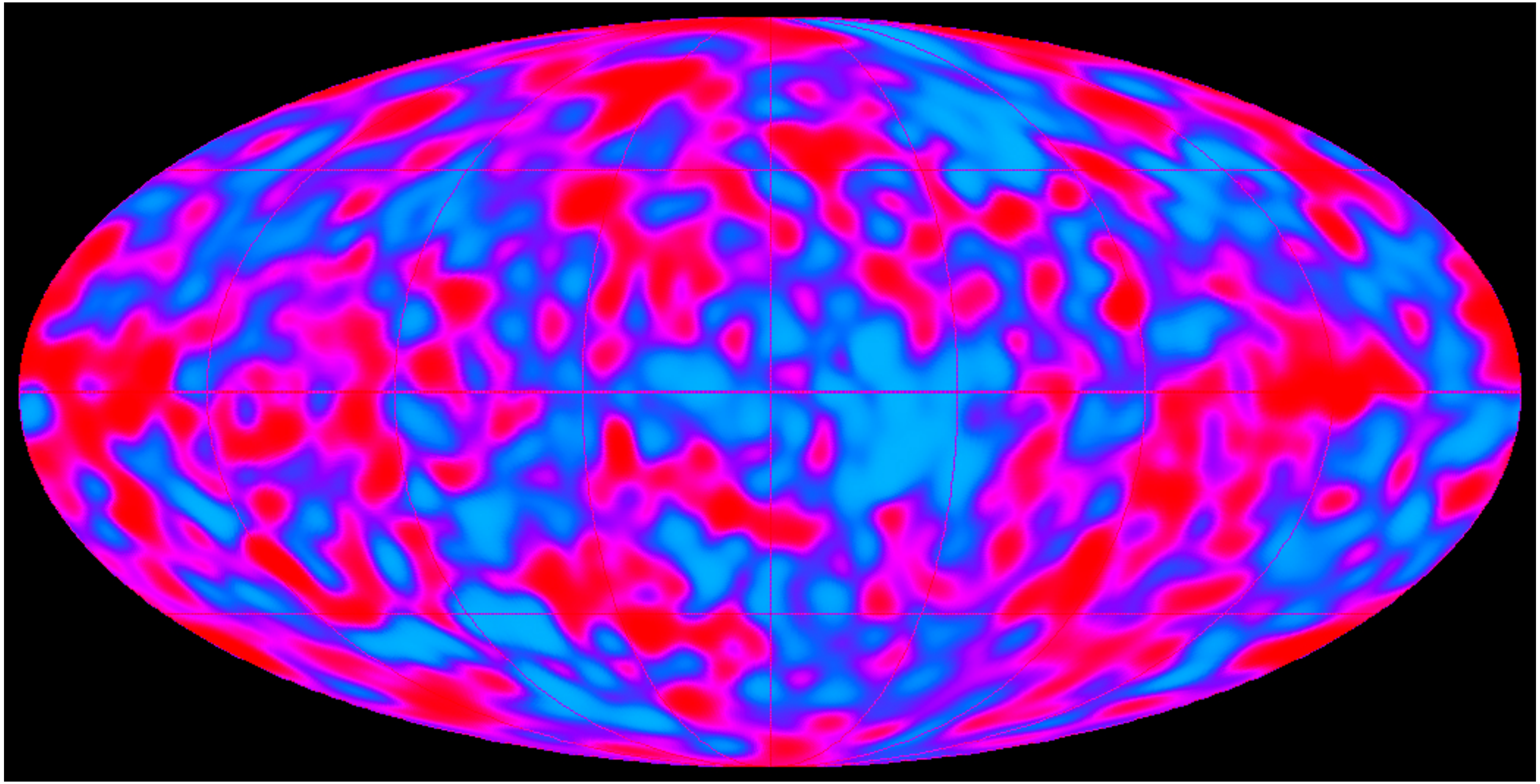
$$\phi = \frac{L}{4\pi a^2 f_k(\chi)^2(1+z)^2}$$

$$d_L(\chi) = RS_k(\chi)(1+z)$$

$$d_A(\chi) = \frac{d_L(\chi)}{(1+z)^2}$$

Part III. CMB & structure formation

$$\bar{T} = 2.7K \qquad \frac{\delta T}{T} \simeq 10^{-5}$$

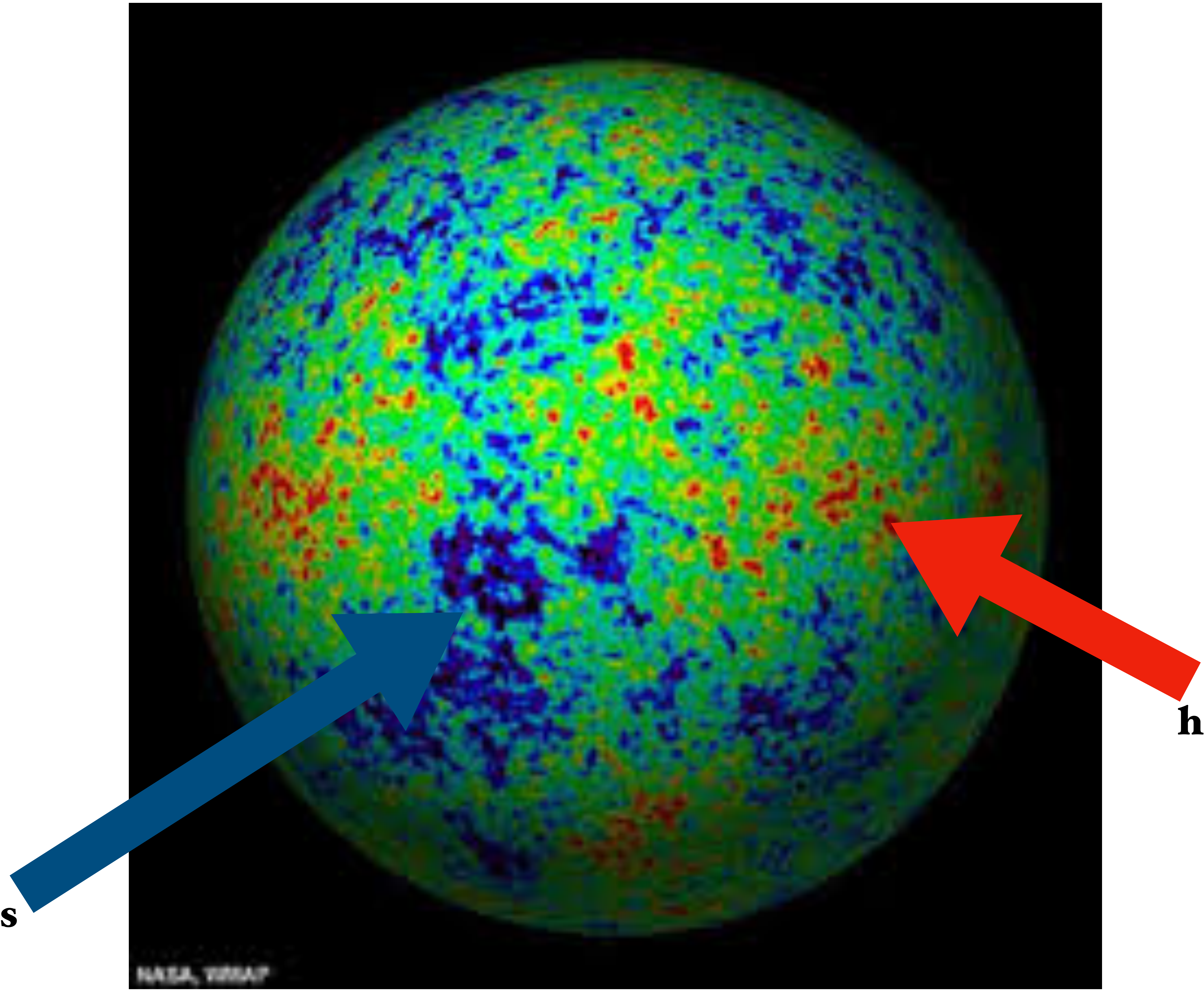


Credit: COBE (1992)

Part III. CMB & structure formation

$$\bar{T} = 2.7K$$

2003, WMAP



NASA, WMAP

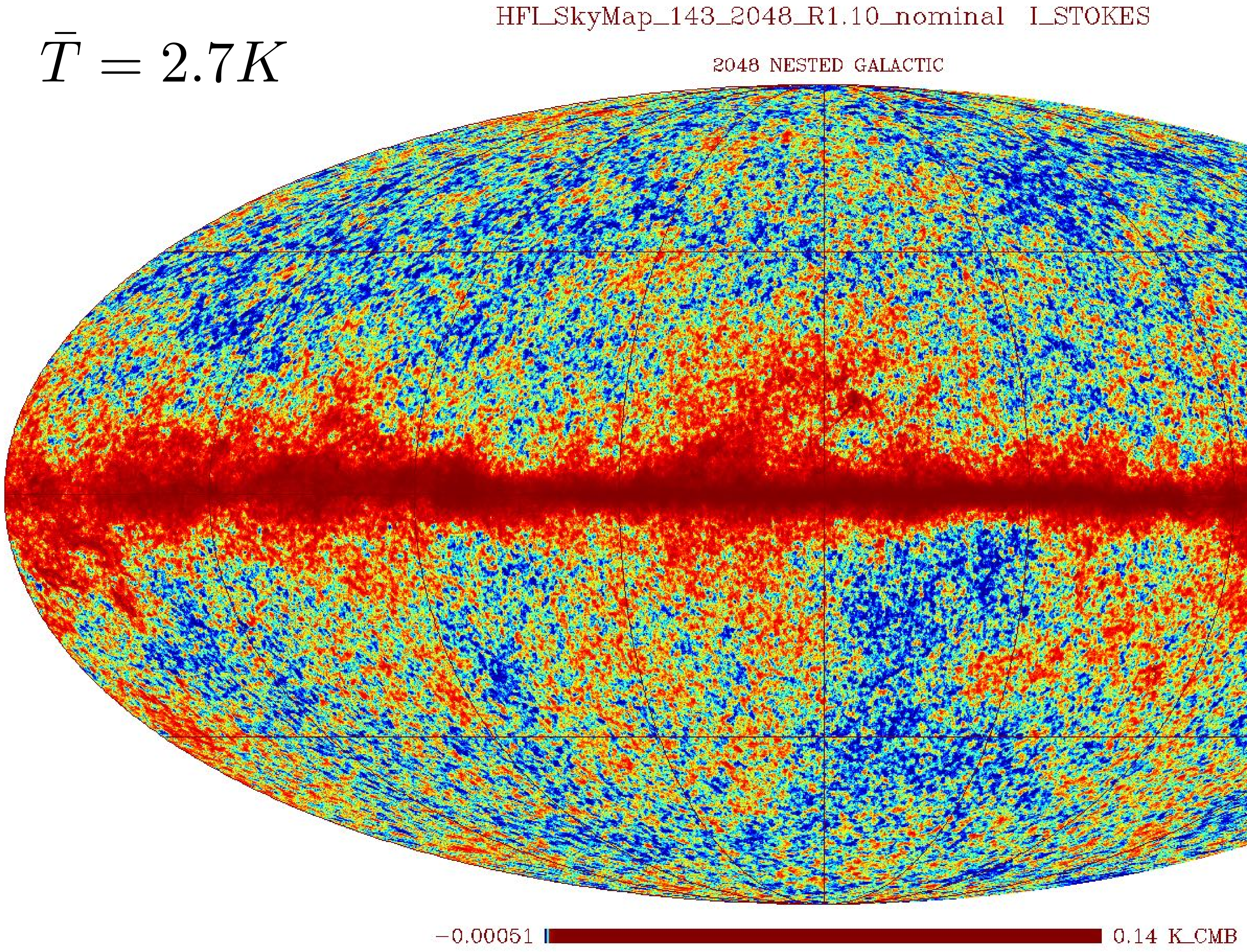
hotter regions

colder regions

$$\frac{\delta T}{T} \simeq 10^{-5}$$

Part III. CMB & structure formation

$\bar{T} = 2.7K$

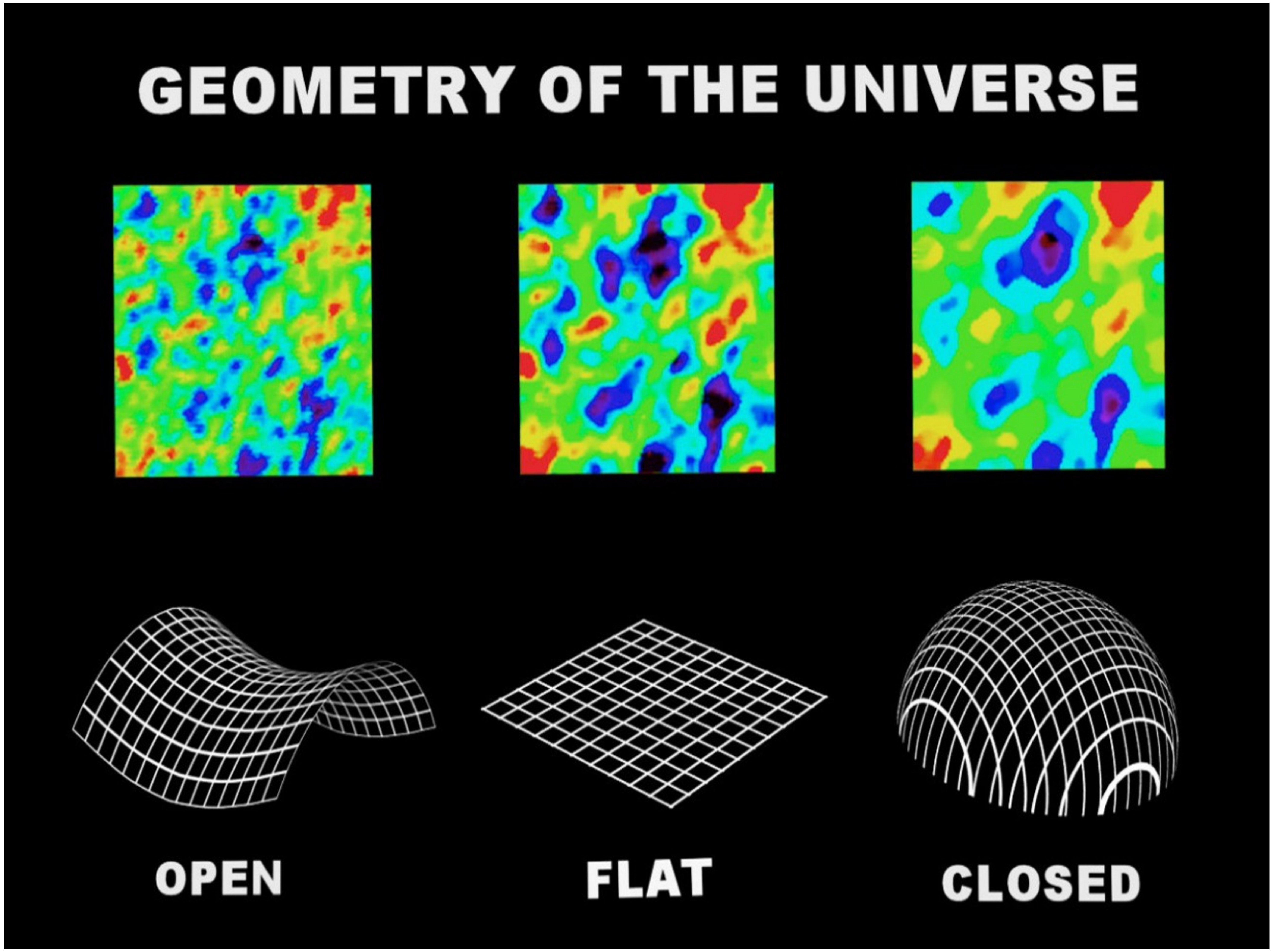


$$\frac{\delta T}{T} \simeq 10^{-5}$$

Planck 2018

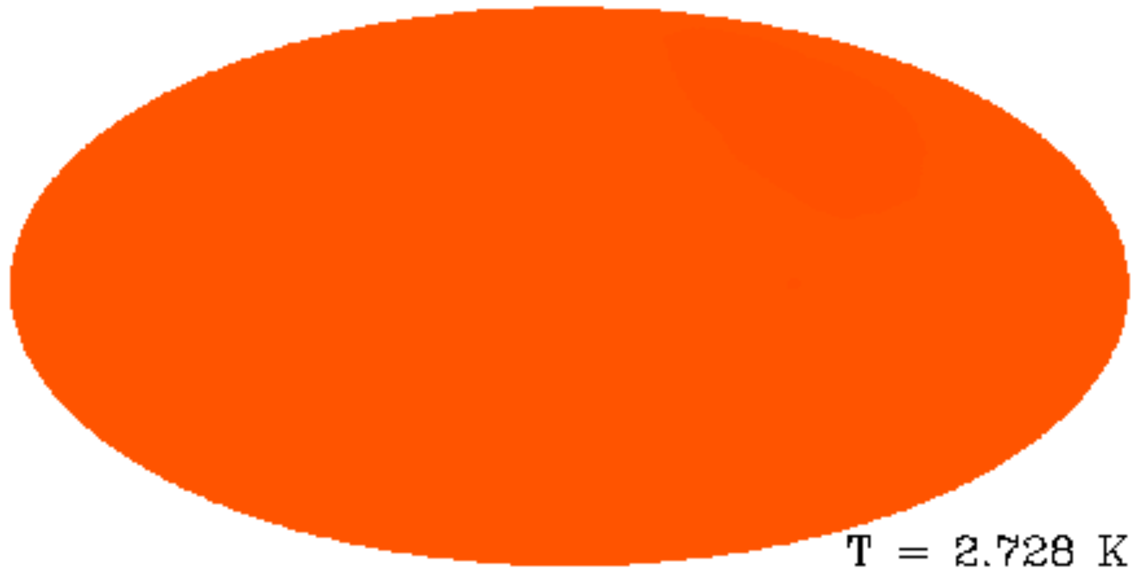
Part III. CMB & structure formation

$$ds^2 = c^2dt^2 - R(t)^2 \left(d\chi^2 + f_k(\chi)\ d\Omega^2\right)$$

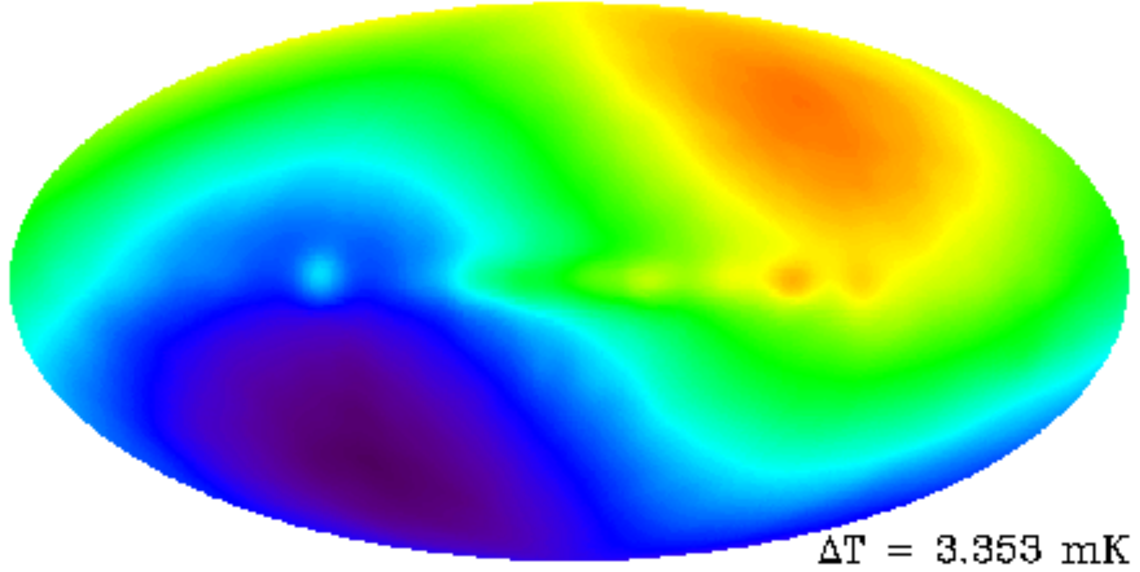


Part III. CMB & structure formation

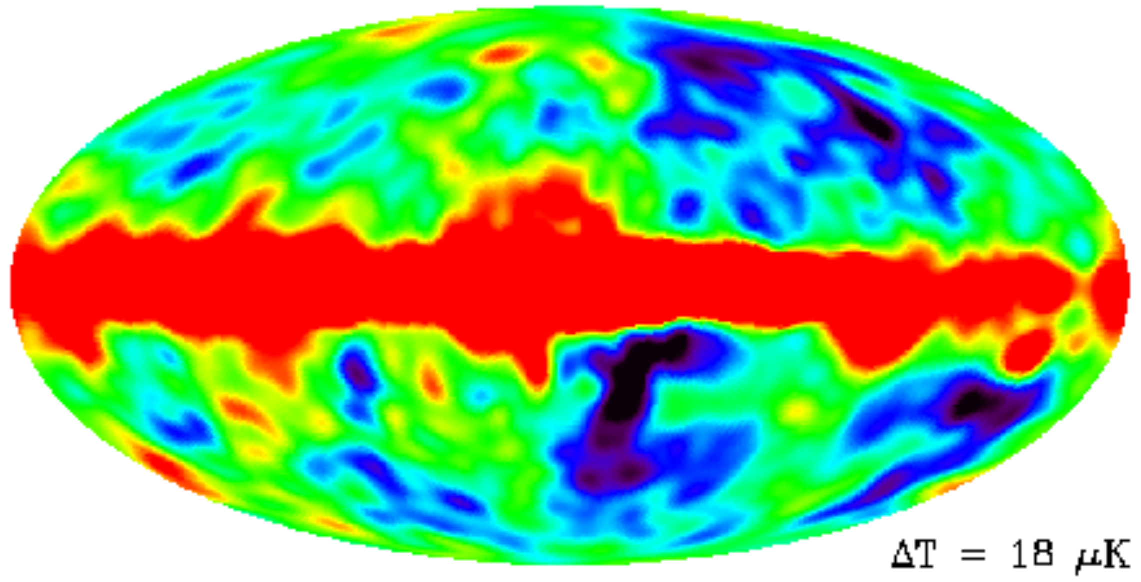
$$Y_0^0 = cst$$

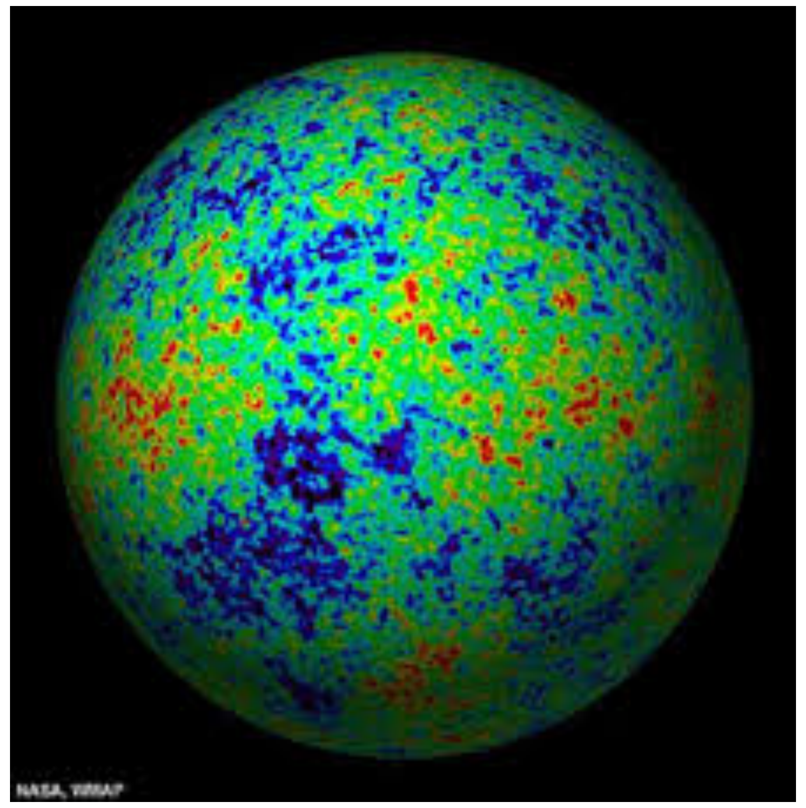


$$Y_1^0 = \cos\theta$$



$$Y_l^m$$

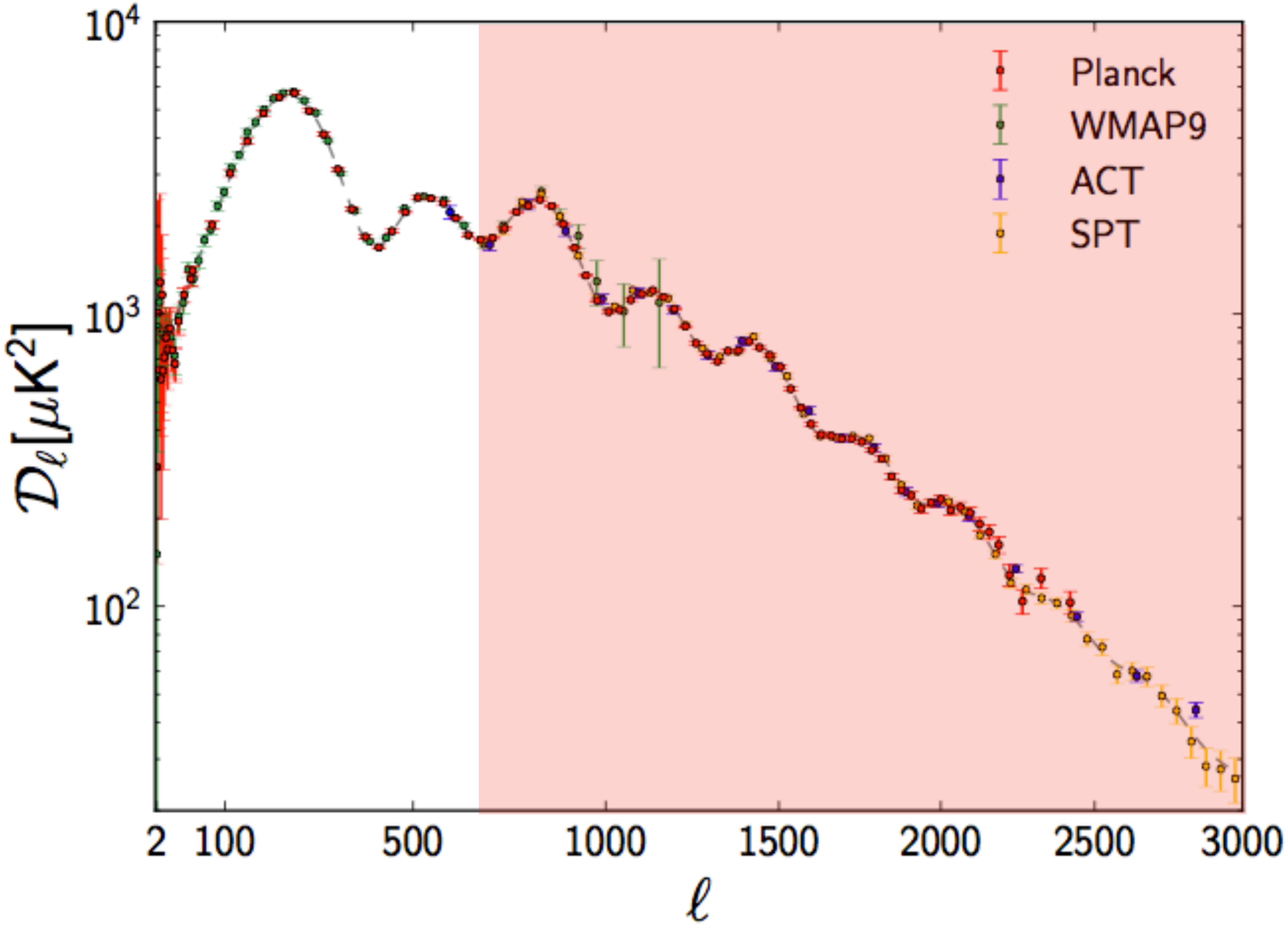




l > 2000

The higher l, the smaller the structures

Part III. CMB & structure formation



To describe the temperature variations, we can define a temperature field as a function of direction

$$T(\vec{n}) = \bar{T}\ \left(1+\Theta(\vec{n})\right)$$

where $\bar{T}$ stands for the average temperature. From this definition, we obtain that

$$\Theta(\vec{n}) = \frac{(T(\vec{n})-\bar{T})}{\bar{T}} \equiv \frac{\Delta T}{\bar{T}}$$

which can be decomposed using Fourier as

$$\Theta(\vec{x}) = \int \frac{d^3k}{(2\pi)^3}\, e^{i\,\vec{k}\vec{x}}\, \Theta(\vec{k})$$

Hence at last scattering, and in the direction $\vec{n}$, the contrast of temperature can be expressed as

$$\Theta(D_{a\star}\,\vec{n}) = \int \frac{d^3k}{(2\pi)^3}\, e^{i\,\vec{k}.\vec{n}D_{a\star}}\, \Theta(\vec{k})$$

So for each direction of the last scattering surface, we can define $\Theta(D_{a\star}\,\vec{n})$. Since the last scattering surface is the surface of a sphere of radius $l_\star$, we can use spherical harmonics to describe the angular variations of the temperature field.
Spherical harmonics are the basis functions of the decomposition over the sphere so any function f defined on the sphere can be decomposed as

$$f(\vec{w}) = \sum_l \sum_m y_{lm}\, f_{lm}$$

with

$$f_{lm} = \int y_{lm}\, f(\vec{w})\, d\vec{w}$$

After some maths…

$$\Theta_{lm} = \sum_{p=-\infty}^{\infty} i^n \int d\vec{n}\, y_{lm} \left[\int \frac{d^3k}{(2\pi)^3}\quad j_p(kD_{a\star})\, Y_{lm}(k)^\star\Theta(\vec{k})\right] Y_{lm}(n)$$

Extracting the Hubble rate

From David Tong's lectures

Extracting H_0

Finally, we can use this machinery to determine the Hubble constant H_0. We first Taylor expand the scale factor $a(t)$ about the present day. Setting $a_0 = 1$, we have

$$a(t) = 1 + H_0(t - t_0) - \frac{1}{2}q_0 H_0^2(t - t_0)^2 + \ldots \qquad (1.29)$$

Here we've introduced the second order term, with dimensionless parameter q_0. This is known as the *deceleration parameter*, and should be thought of as the present day value of the function

$$q(t) = -\frac{\ddot{a}a}{\dot{a}^2} = -\frac{\ddot{a}}{aH^2}$$

The name is rather unfortunate because, as we will learn in Section 1.4, the expansion of our universe is actually accelerating, with $\ddot{a} > 0$! In our universe, the deceleration parameter is negative: $q_0 \approx -0.5$.

First, we integrate the path of a light-ray (1.18) to get an expression for the co-moving distance χ in terms of the "look-back time" $(t_0 - t_1)$

$$\begin{aligned} R\chi = c\int_{t_1}^{t_0} \frac{dt}{a(t)} &= c\int_{t_1}^{t_0} \Big[1 - H_0(t_0 - t) + \ldots\Big]dt \\ &= c(t - t_0)\left[1 + \frac{1}{2}H_0(t - t_0) + \ldots\right] \end{aligned} \qquad (1.30)$$

Next, we get an expression for the look-back time $t_0 - t_1$ in terms of the redshift z. From (1.21), light emitted at some time t_1 suffers a redshift $1 + z = 1/a(t)$. Inverting the Taylor expansion (1.29), we have

$$z = \frac{1}{a(t_1)} - 1 \approx H_0(t_0 - t_1) + \frac{1}{2}(2 + q_0)H_0^2(t_0 - t_1)^2 + \ldots$$

We now invert this to give the "look-back time" $t_0 - t_1$ as a Taylor expansion in the redshift z. (As an aside: you could do the inversion by solving the quadratic formula, and subsequently Taylor expanding the square-root. But when inverting a power series, it's more straightforward to write an ansatz $H_0(t_0 - t_1) = A_1 z + A_2 z^2 + \ldots$, which we substitute this into the right-hand side and match terms.) We find

$$H_0(t_0 - t_1) = z - \frac{1}{2}(2 + q_0)z^2 + \ldots \qquad (1.31)$$

Combining (1.30) and (1.31) gives

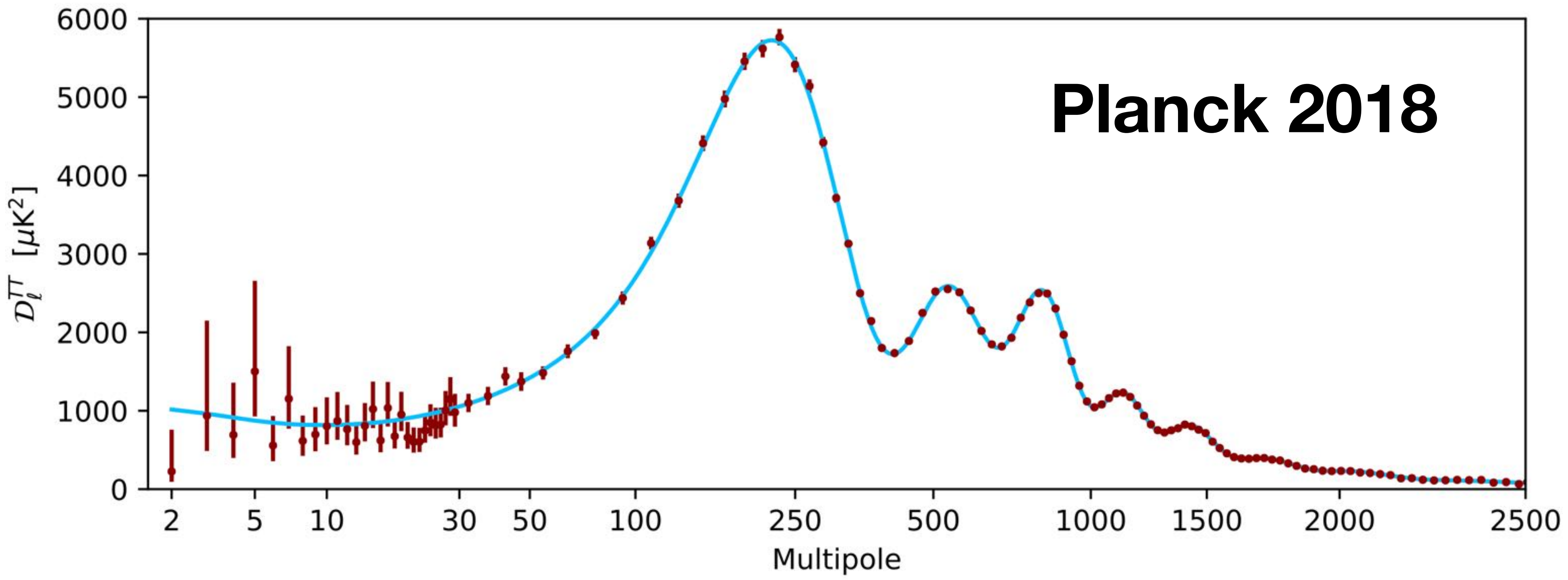
$$\frac{H_0 R\chi}{c} = z - \frac{1}{2}(1 + q_0)z^2 + \ldots$$

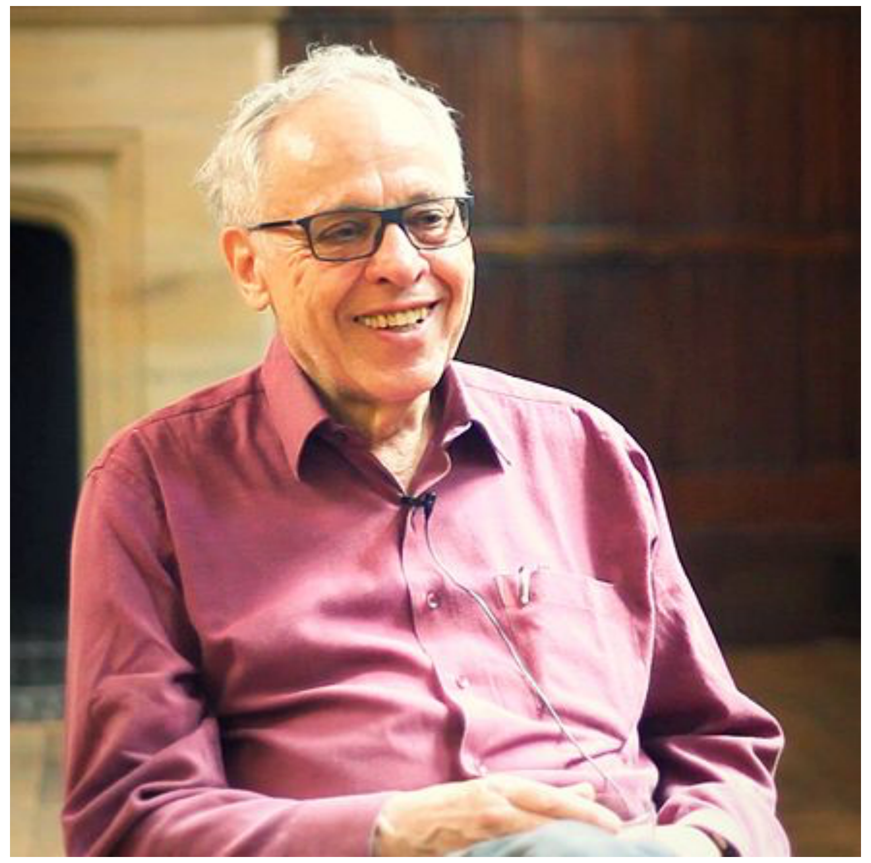
We can now substitute this into our expression for the luminosity distance (1.28). Life is easiest in flat space, where $RS_k(\chi) = R\chi$ and we find

$$d_L = \frac{c}{H_0}\left(z + \frac{1}{2}(1 - q_0)z^2 + \ldots\right)$$

This expression is valid only for $z \ll 1$. By plotting the observed d_L vs z, and fitting to this functional form, we can extract H_0 and q_0.

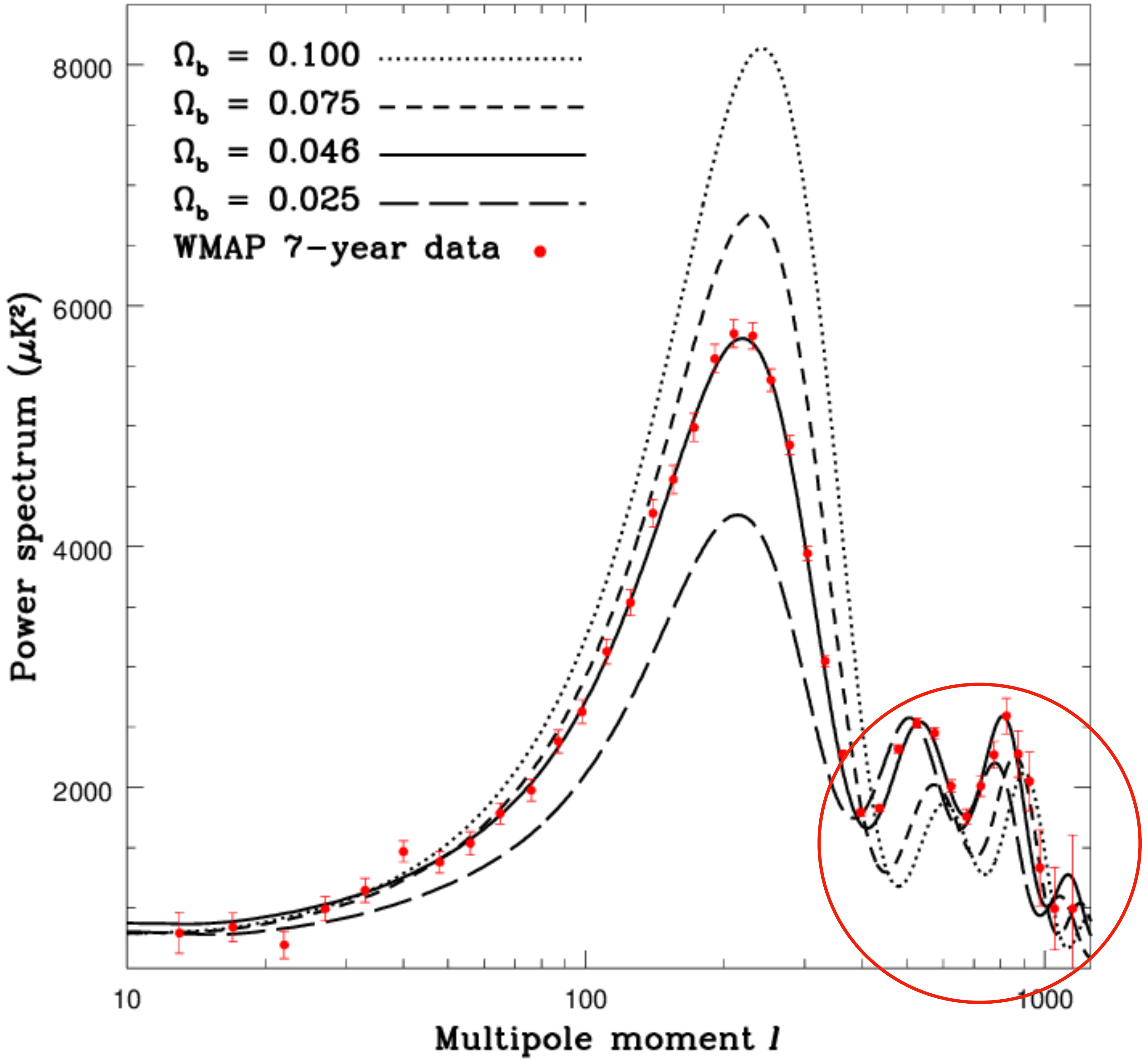
Extracting the parameters





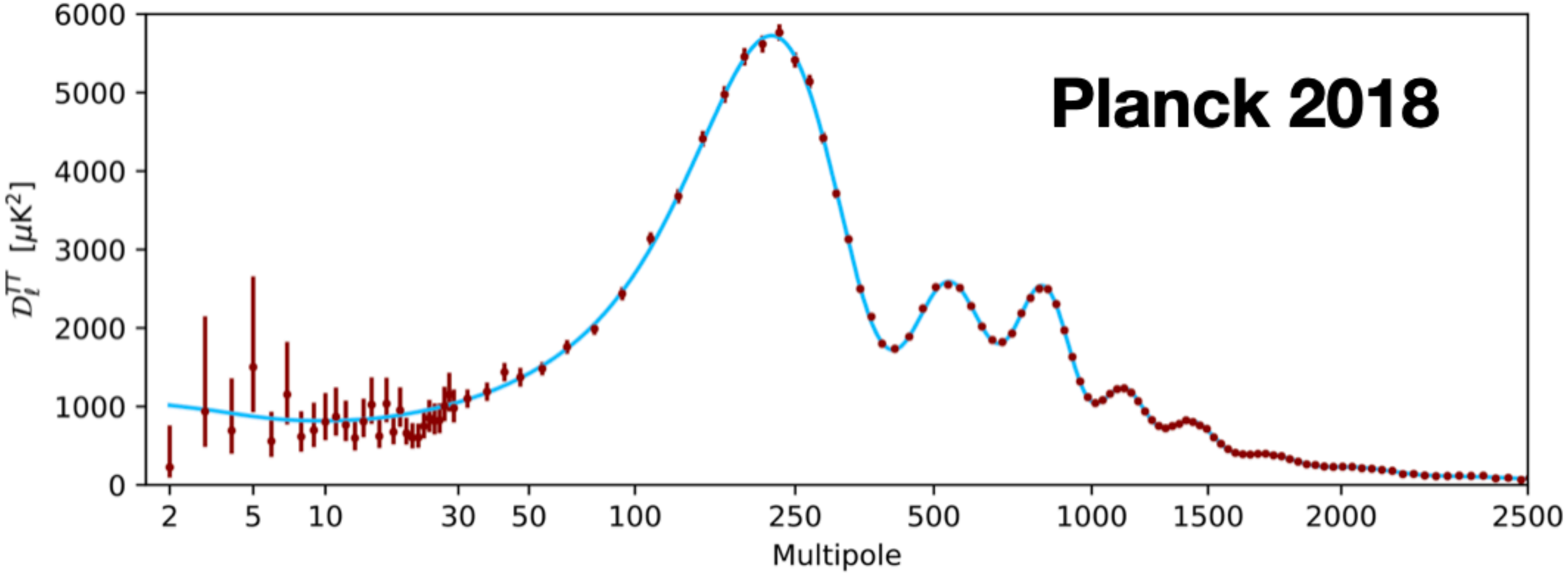
Too many baryons lead to a deficit of small structures: *Silk damping* (more later)

Follow the dotted line vs hard line!



Part III. CMB

Extracting the parameters



Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_{MC}$	1.040909
τ	0.0543
$\ln(10^{10}A_s)$	3.0448
n_s	0.96605
$\Omega_m h^2$	0.14314
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32
Ω_m	0.3158
Age [Gyr]	13.7971
σ_8	0.8120
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331
z_{re}	7.68
$100\theta_*$	1.041085
r_{drag} [Mpc]	147.049

Part III. CMB & structure formation

$$\delta(\mathbf{x},t) = \frac{\delta\rho(\mathbf{x},t)}{\bar{\rho}(t)}$$

$$\ddot{\delta} + 2H\dot{\delta} - c_s^2\left(\frac{1}{a^2}\nabla^2 + k_J^2\right)\delta = 0 \qquad \delta(\mathbf{k},t) = \int d^3x\ e^{i\mathbf{k}\cdot\mathbf{x}}\,\delta(\mathbf{x},t) \qquad \ddot{\delta}(\mathbf{k},t) + 2H\dot{\delta}(\mathbf{k},t) + c_s^2\left(\frac{k^2}{a^2} - k_J^2\right)\delta(\mathbf{k},t) = 0$$

$$\lambda_J = c_s\sqrt{\frac{\pi}{Gm\bar{n}}} = c_s c\sqrt{\frac{\pi}{G\bar{\rho}}} \qquad d_H \approx cH^{-1} = c^2\sqrt{\frac{3}{8\pi G\bar{\rho}}}$$

Matter perturbations in matter dominated

$$\ddot{\delta}(\mathbf{k}) + 2H\dot{\delta}(\mathbf{k}) - \frac{4\pi G\bar{\rho}}{c^2}\delta(\mathbf{k}) = 0 \qquad \ddot{\delta}(\mathbf{k}) + \frac{4}{3t}\dot{\delta}(\mathbf{k}) - \frac{2}{3t^2}\delta(\mathbf{k}) = 0 \qquad \delta(\mathbf{k},t) \sim \begin{cases} t^{2/3} & \sim a \\ t^{-1} & \sim a^{-3/2} \end{cases}$$

Radiation perturbations in radiation dominated

$$\ddot{\delta}(\mathbf{k}) + 2H\dot{\delta}(\mathbf{k}) + c_s^2(1+w)\left(\frac{k^2}{a^2} - (1+3w)k_J^2\right)\delta(\mathbf{k}) = 0 \qquad \ddot{\delta}_r(\mathbf{k}) + \frac{1}{t}\dot{\delta}_r(\mathbf{k}) - \frac{1}{t^2}\delta_r(\mathbf{k}) = 0 \qquad \delta_r(\mathbf{k},t) \sim \begin{cases} t & \sim a^2 \\ t^{-1} & \sim a^{-2} \end{cases}$$

Part III. CMB & structure formation

$$\delta(\mathbf{k},t) = \int d^3x\; e^{i\mathbf{k}\cdot\mathbf{x}}\,\delta(\mathbf{x},t)$$

$$\begin{aligned}\langle\delta(\mathbf{k},t)\,\delta(\mathbf{k}',t)\rangle &= \int d^3x\,d^3y\; e^{i\mathbf{k}\cdot\mathbf{x}+i\mathbf{k}'\cdot\mathbf{y}}\,\langle\delta(\mathbf{x},t)\,\delta(\mathbf{y},t)\rangle \\ &= \int d^3x\,d^3y\; e^{i\mathbf{k}\cdot\mathbf{x}+i\mathbf{k}'\cdot\mathbf{y}}\,\xi(r,t) \\ &= \int d^3r\,d^3y\; e^{i\mathbf{k}\cdot\mathbf{r}+i(\mathbf{k}+\mathbf{k}')\cdot\mathbf{y}}\,\xi(r,t) \\ &= (2\pi)^3\,\delta_D^3(\mathbf{k}+\mathbf{k}')\int d^3r\; e^{i\mathbf{k}\cdot\mathbf{r}}\,\xi(r,t)\end{aligned}$$

$$P(k,t) = \int d^3r\; e^{i\mathbf{k}\cdot\mathbf{r}}\,\xi(r,t)$$

$$\begin{aligned}P(k,t) &= \int_0^{2\pi} d\phi \int_{-1}^{+1} d(\cos\theta)\int_0^\infty dr\; r^2 e^{ikr\cos\theta}\xi(r,t) \\ &= 2\pi\int_0^\infty \frac{r^2}{ikr}\left[e^{ikr}-e^{-ikr}\right]\,\xi(r,t) \\ &= \frac{4\pi}{k}\int_0^\infty dr\; r\sin(kr)\,\xi(r,t)\end{aligned}$$

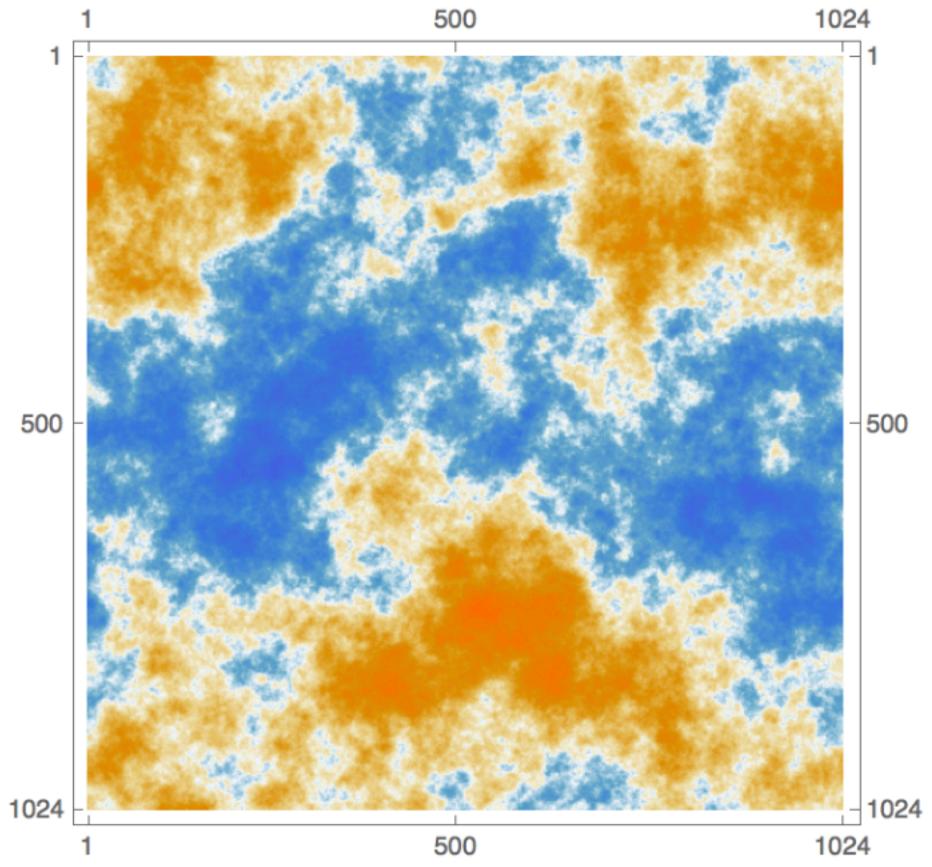
$$\langle\delta(\mathbf{k},t_i)\,\delta(\mathbf{k}',t_i)\rangle = (2\pi)^3\,\delta_D^3(\mathbf{k}+\mathbf{k}')\,P(k)$$

$$P(k) = Ak^n$$

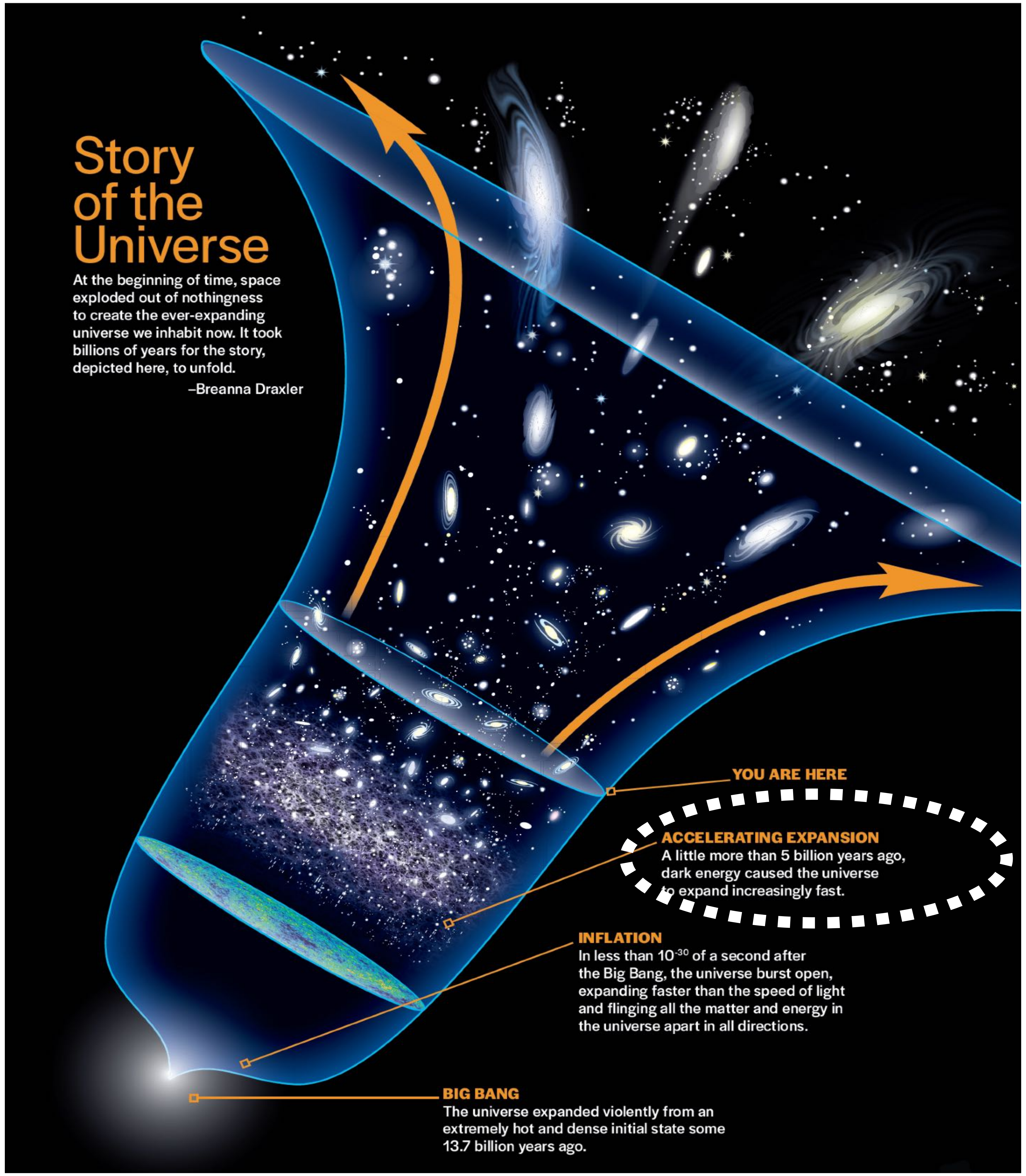
$$\Delta(k) = \frac{4\pi k^3\,P(k)}{(2\pi)^3}$$

Harrison-Zel'dovich Spectrum

$n = 1$



Part III. CMB & structure formation



Story of the Universe

At the beginning of time, space exploded out of nothingness to create the ever-expanding universe we inhabit now. It took billions of years for the story, depicted here, to unfold.

–Breanna Draxler

YOU ARE HERE

ACCELERATING EXPANSION
A little more than 5 billion years ago, dark energy caused the universe to expand increasingly fast.

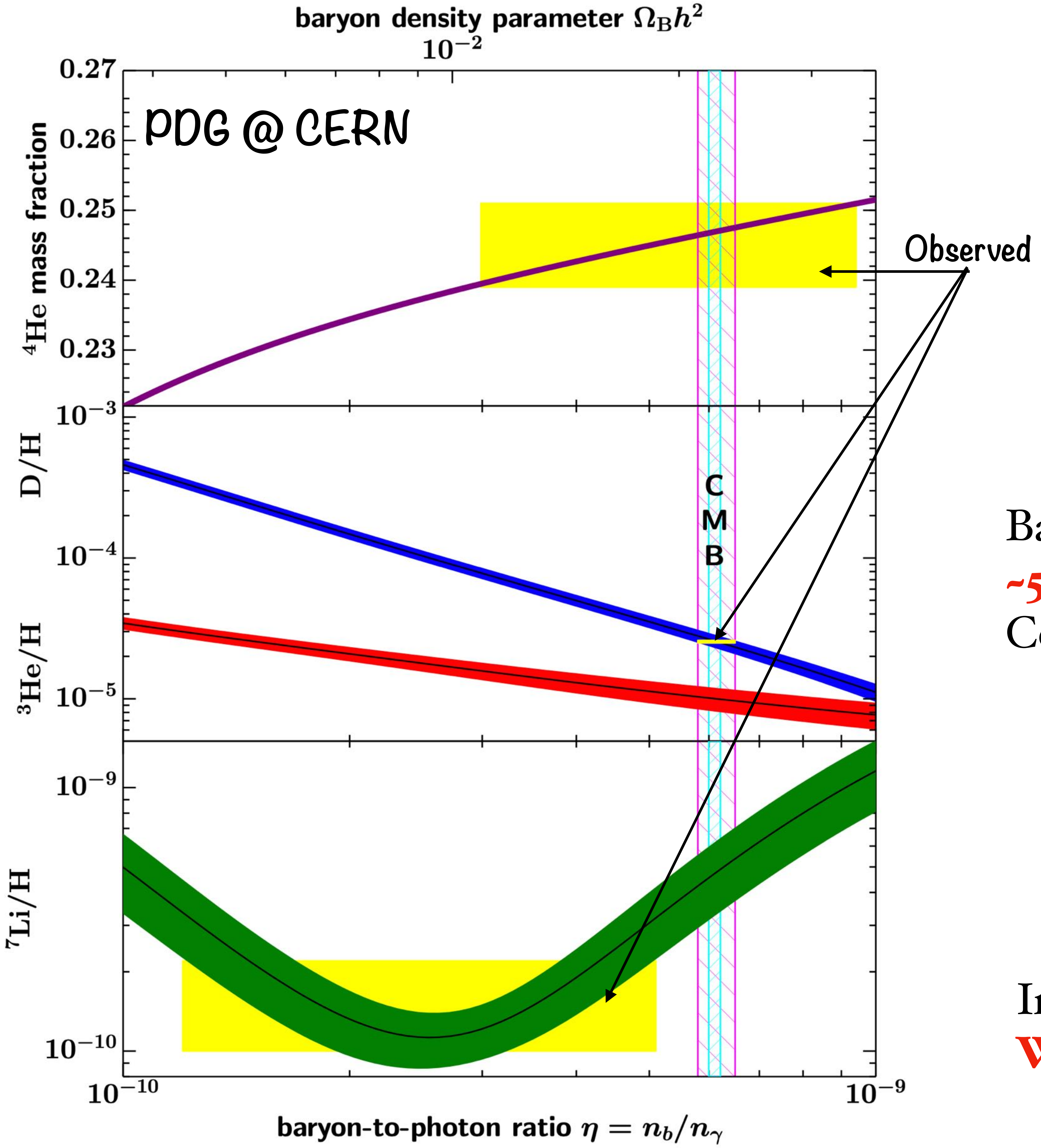
INFLATION
In less than 10^{-30} of a second after the Big Bang, the universe burst open, expanding faster than the speed of light and flinging all the matter and energy in the universe apart in all directions.

BIG BANG
The universe expanded violently from an extremely hot and dense initial state some 13.7 billion years ago.

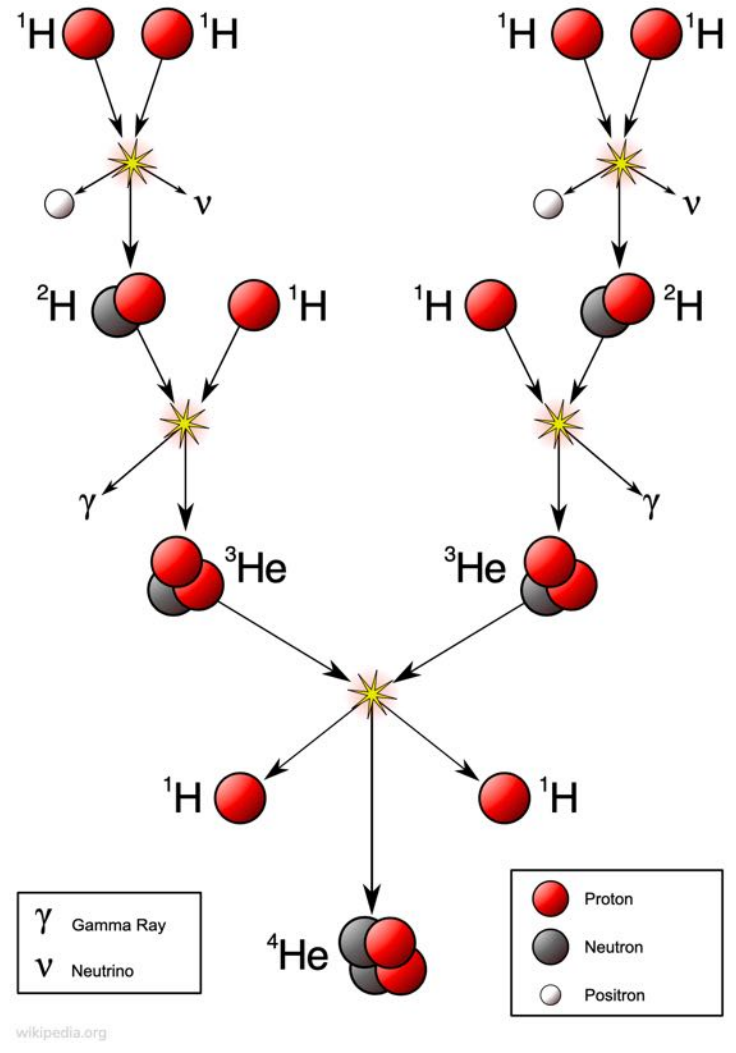
Big Bang (relic photons)

Inflation (flat Universe today)

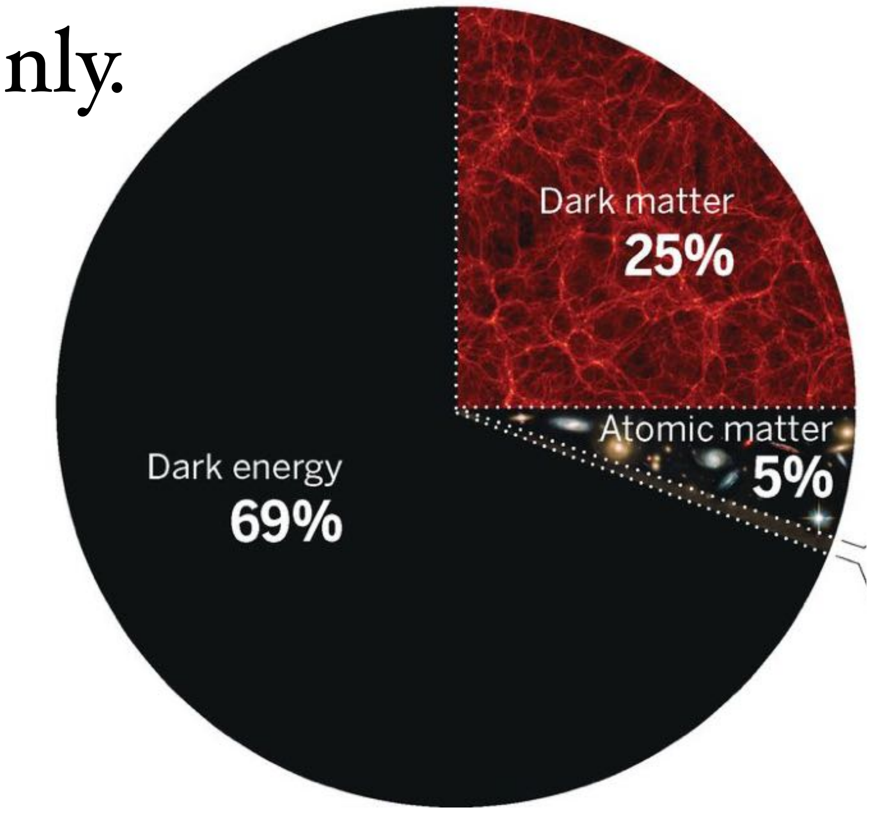
Nucleosynthesis



https://www.nature.com/articles/s41586-020-2878-4.pdf

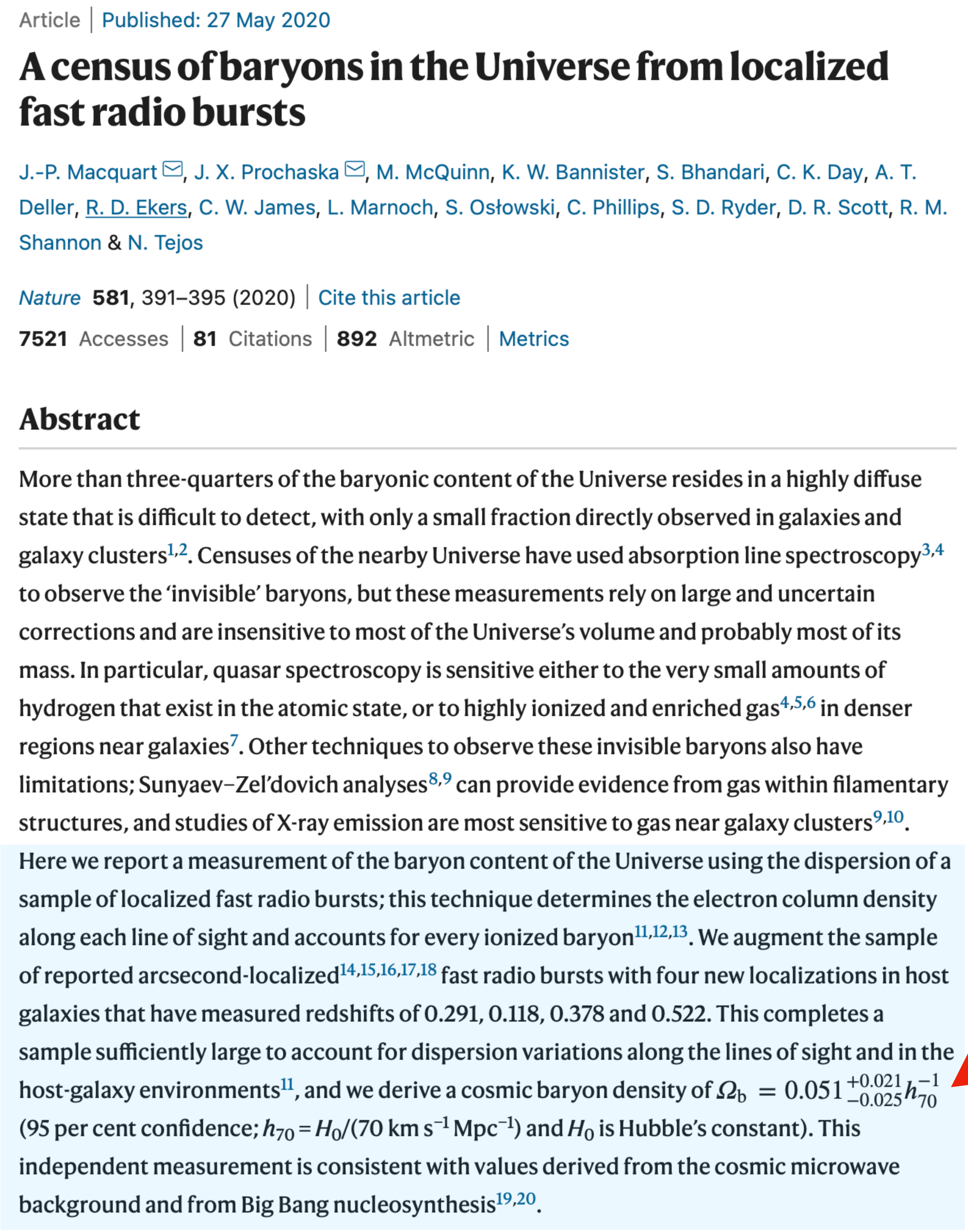


Baryons cannot be (all) the dark matter.
~5% max of baryons only.
Consistent with CMB!



In fact we don't even see this much.
Where are the baryons?

Finding the baryons



Article | Published: 27 May 2020

A census of baryons in the Universe from localized fast radio bursts

J.-P. Macquart, J. X. Prochaska, M. McQuinn, K. W. Bannister, S. Bhandari, C. K. Day, A. T. Deller, R. D. Ekers, C. W. James, L. Marnoch, S. Osłowski, C. Phillips, S. D. Ryder, D. R. Scott, R. M. Shannon & N. Tejos

Nature **581**, 391–395 (2020) | Cite this article

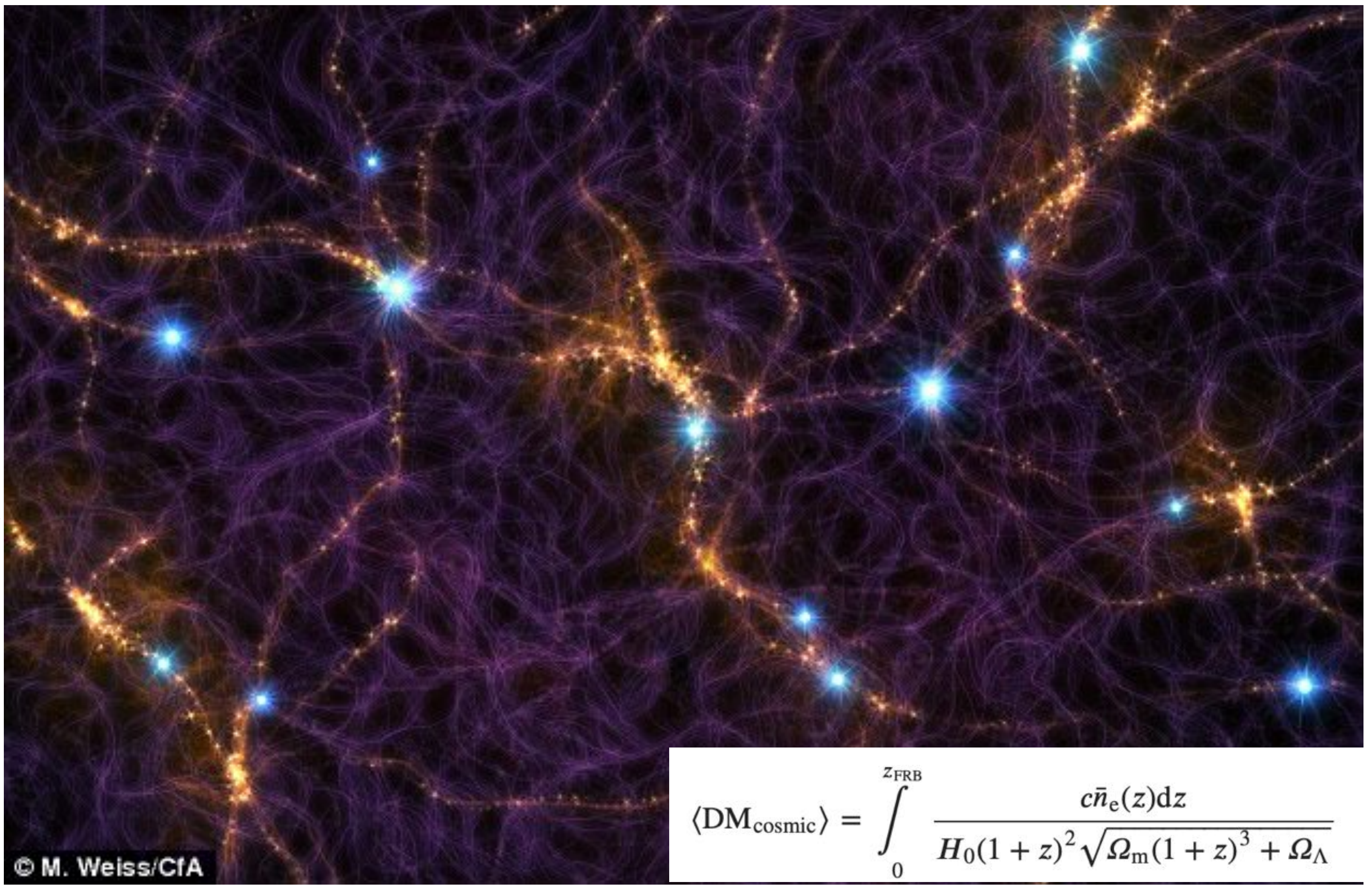
7521 Accesses | **81** Citations | **892** Altmetric | Metrics

Abstract

More than three-quarters of the baryonic content of the Universe resides in a highly diffuse state that is difficult to detect, with only a small fraction directly observed in galaxies and galaxy clusters[1,2]. Censuses of the nearby Universe have used absorption line spectroscopy[3,4] to observe the 'invisible' baryons, but these measurements rely on large and uncertain corrections and are insensitive to most of the Universe's volume and probably most of its mass. In particular, quasar spectroscopy is sensitive either to the very small amounts of hydrogen that exist in the atomic state, or to highly ionized and enriched gas[4,5,6] in denser regions near galaxies[7]. Other techniques to observe these invisible baryons also have limitations; Sunyaev–Zel'dovich analyses[8,9] can provide evidence from gas within filamentary structures, and studies of X-ray emission are most sensitive to gas near galaxy clusters[9,10]. Here we report a measurement of the baryon content of the Universe using the dispersion of a sample of localized fast radio bursts; this technique determines the electron column density along each line of sight and accounts for every ionized baryon[11,12,13]. We augment the sample of reported arcsecond-localized[14,15,16,17,18] fast radio bursts with four new localizations in host galaxies that have measured redshifts of 0.291, 0.118, 0.378 and 0.522. This completes a sample sufficiently large to account for dispersion variations along the lines of sight and in the host-galaxy environments[11], and we derive a cosmic baryon density of $\Omega_b = 0.051^{+0.021}_{-0.025} h_{70}^{-1}$ (95 per cent confidence; $h_{70} = H_0/(70\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$ and H_0 is Hubble's constant). This independent measurement is consistent with values derived from the cosmic microwave background and from Big Bang nucleosynthesis[19,20].

In radio astronomy, a **fast radio burst** (**FRB**) is a transient radio pulse of length ranging from a fraction of a millisecond to a few milliseconds, caused by some high-energy astrophysical process not yet understood.
(Wikipedia)

Artist's impression The bright blue, point sources shown here are the signals from Fast Radio Bursts (FRBs) that may accumulate in a radio exposure lasting for a few minutes. The radio signal from an FRB lasts for only a few thousandths of a second, but they should occur at high rates

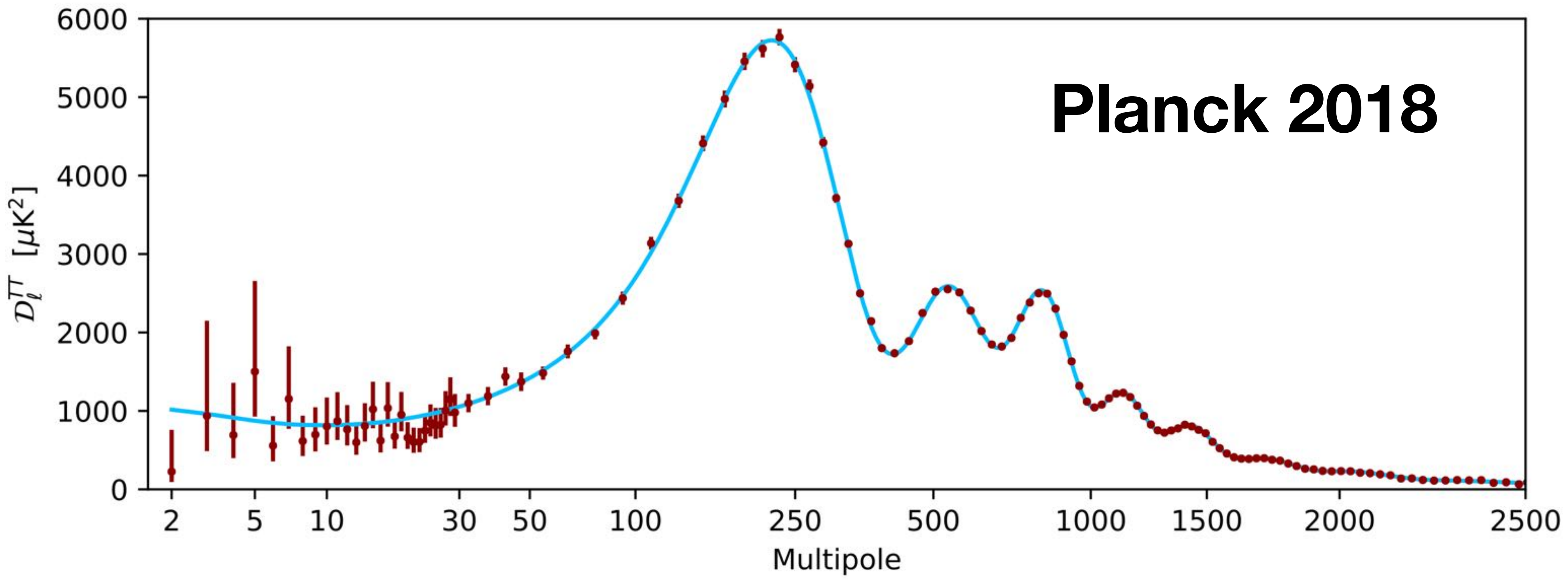


© M. Weiss/CfA

$$\langle \mathrm{DM_{cosmic}} \rangle = \int_0^{z_{\mathrm{FRB}}} \frac{c\bar{n}_e(z)\mathrm{d}z}{H_0(1+z)^2\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

Part IV. Invisible Universe

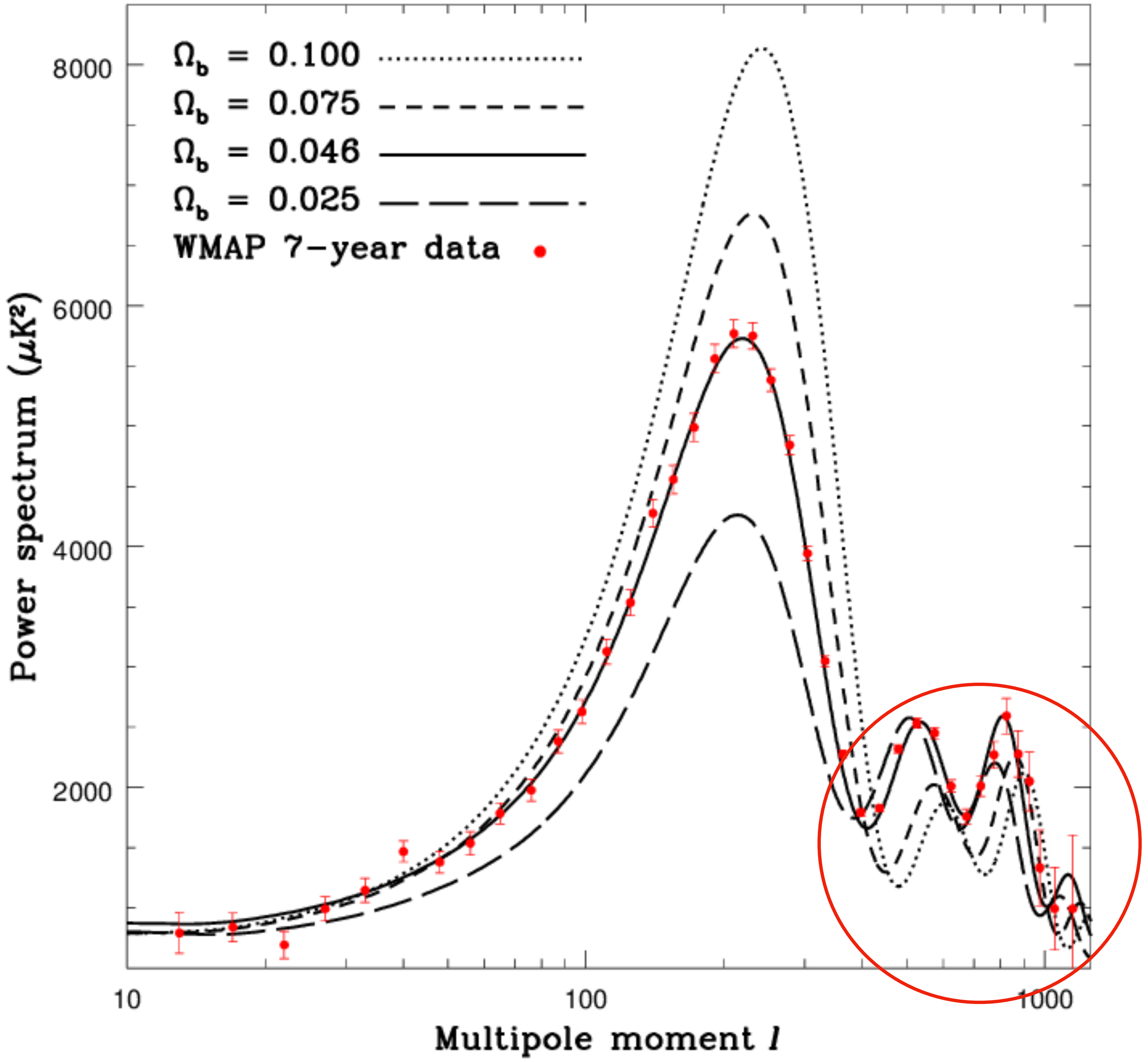
Part IV. Invisible Universe



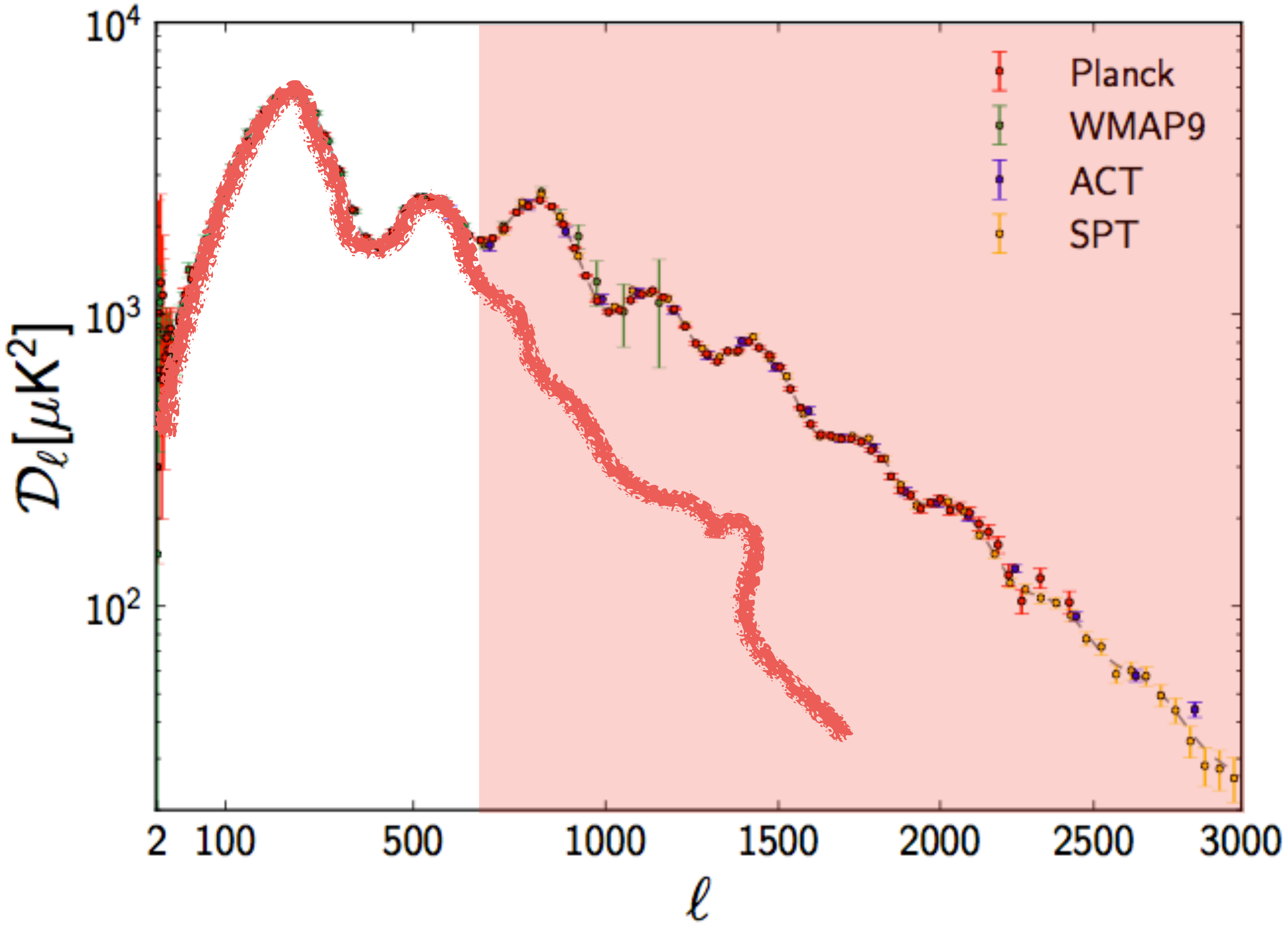
Too many baryons lead to a deficit of small structures: *Silk damping* (more later)

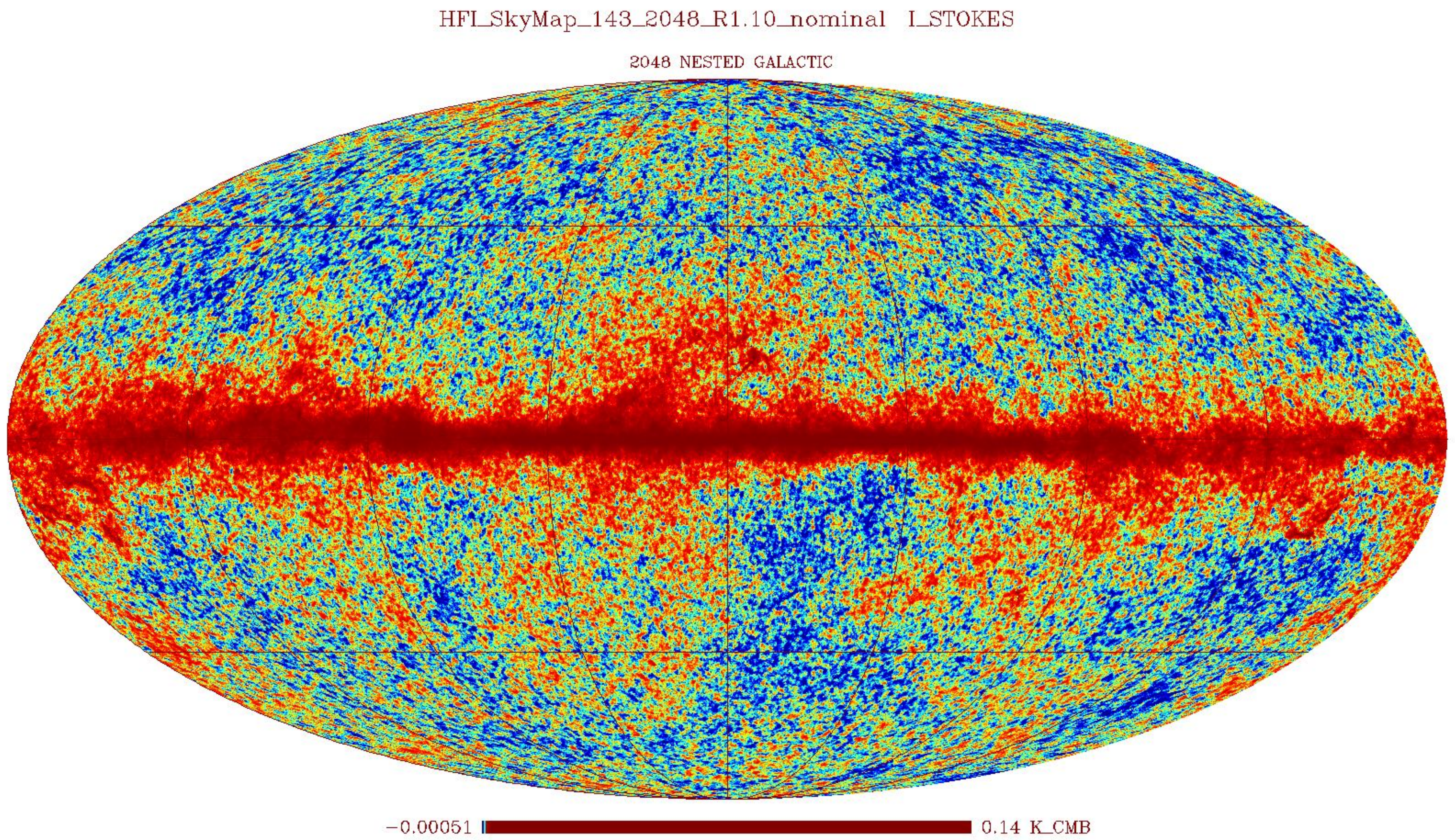
There must be a substance that doesn't interact with photons and therefore doesn't dissipate

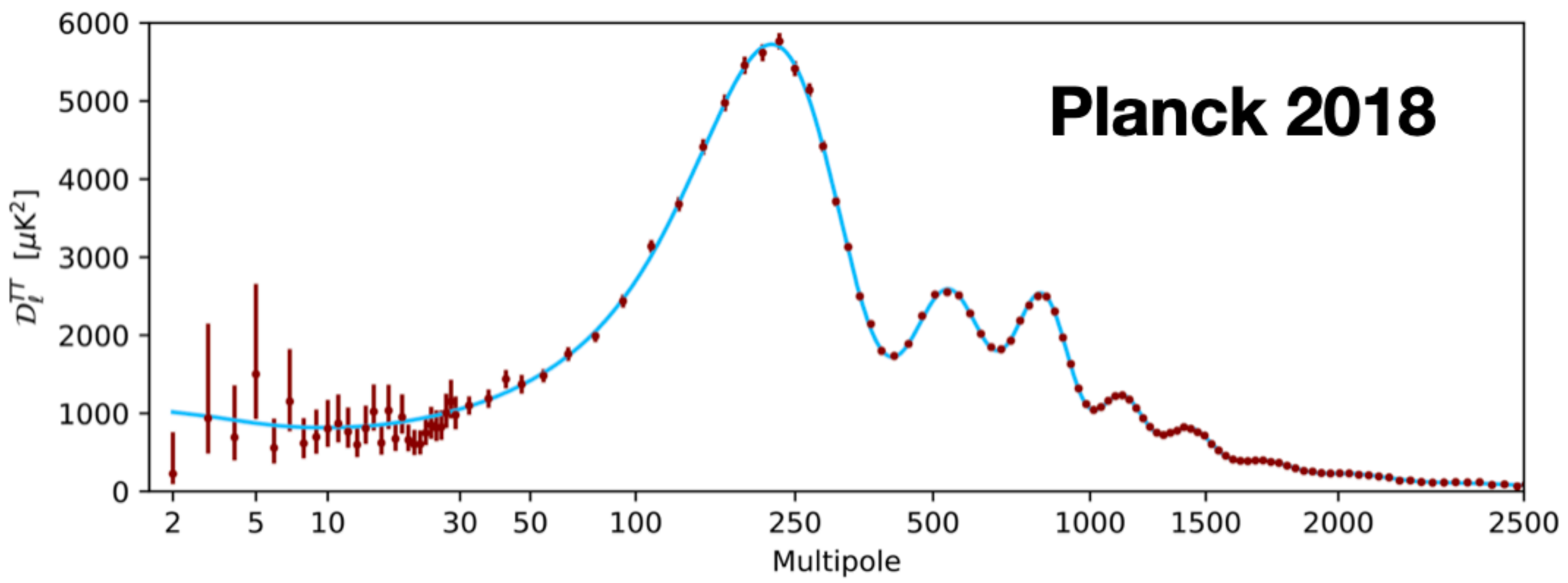
Dark Matter!



Part IV. Invisible Universe

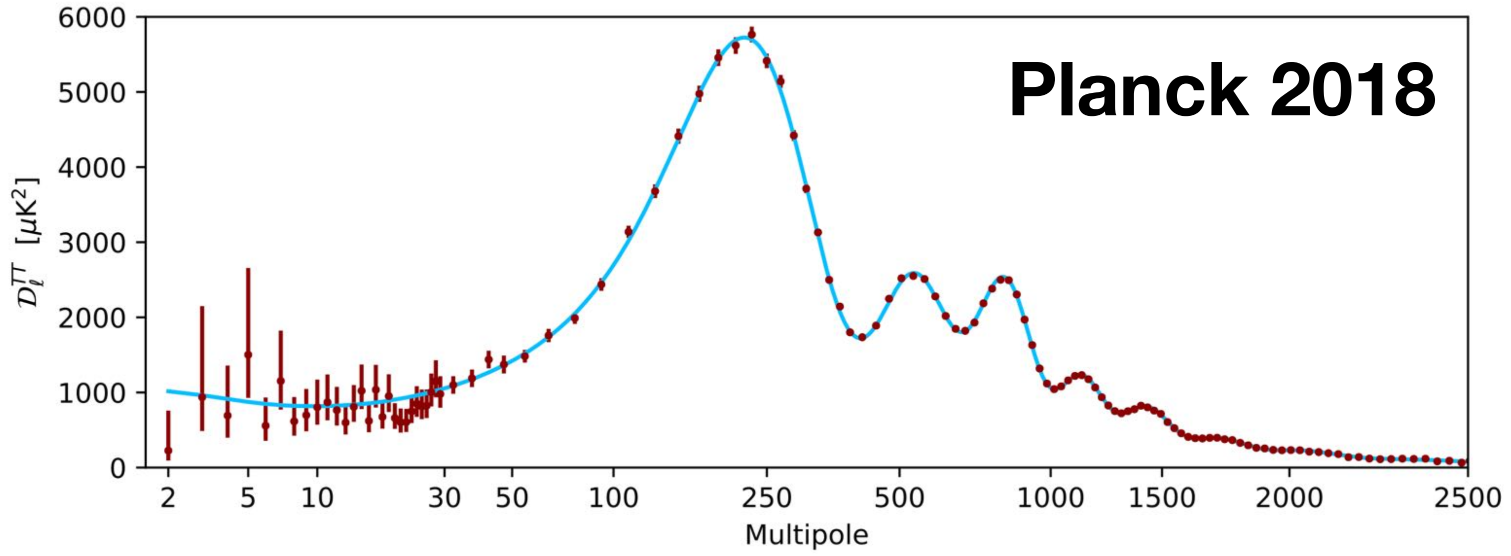






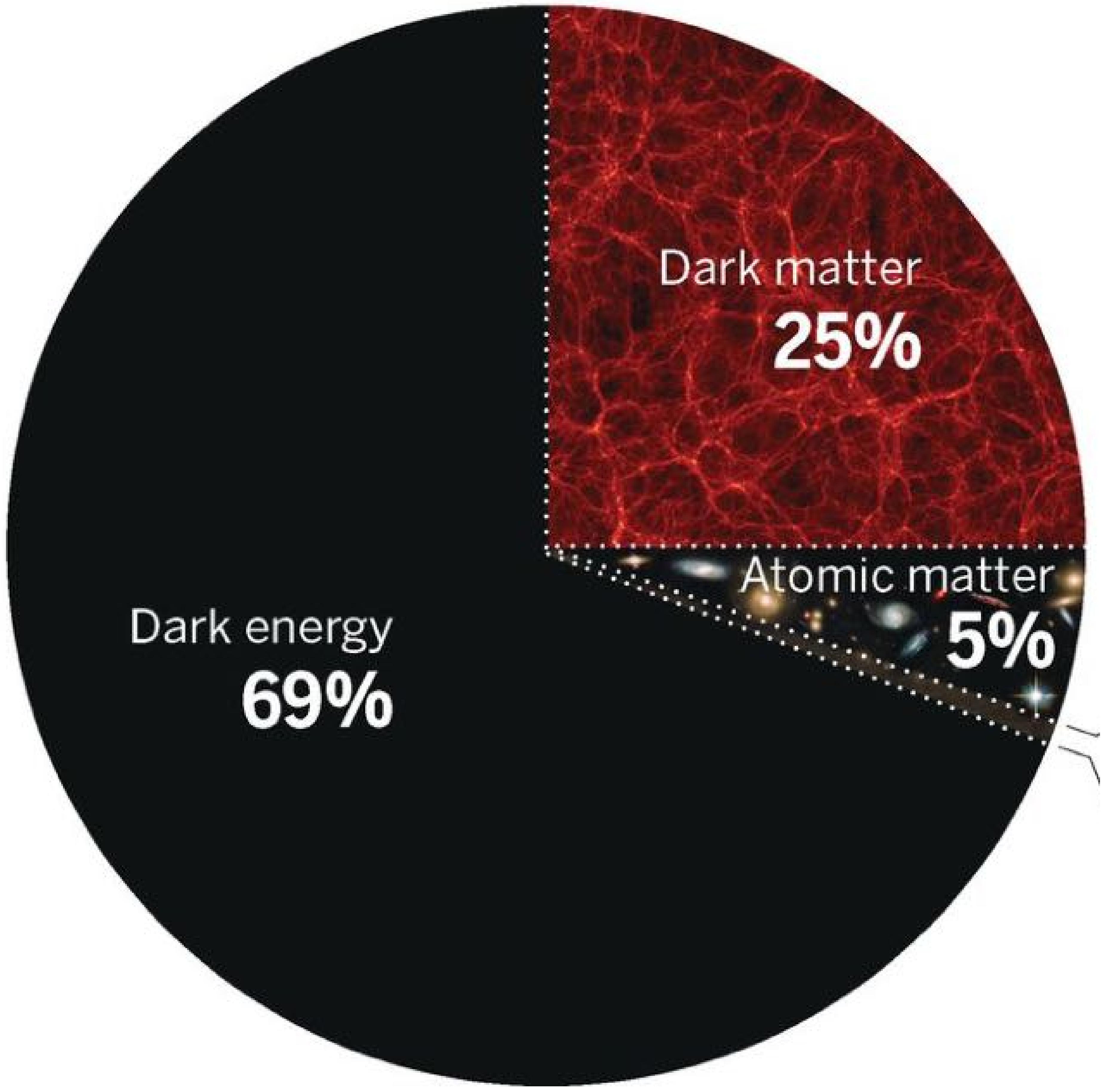
$$
\begin{aligned}
\dot{\theta}_{\mathrm{b}} &= k^2\psi - \mathcal{H}\theta_{\mathrm{b}} + c_s^2 k^2 \delta_{\mathrm{b}} - R^{-1}\dot{\kappa}(\theta_{\mathrm{b}} - \theta_\gamma) \\
\dot{\theta}_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot{\kappa}(\theta_\gamma - \theta_{\mathrm{b}}) \,, \\
\dot{\theta}_{\mathrm{DM}} &= k^2\psi - \mathcal{H}\theta_{\mathrm{DM}} \,,
\end{aligned}
$$

Part IV. Invisible Universe



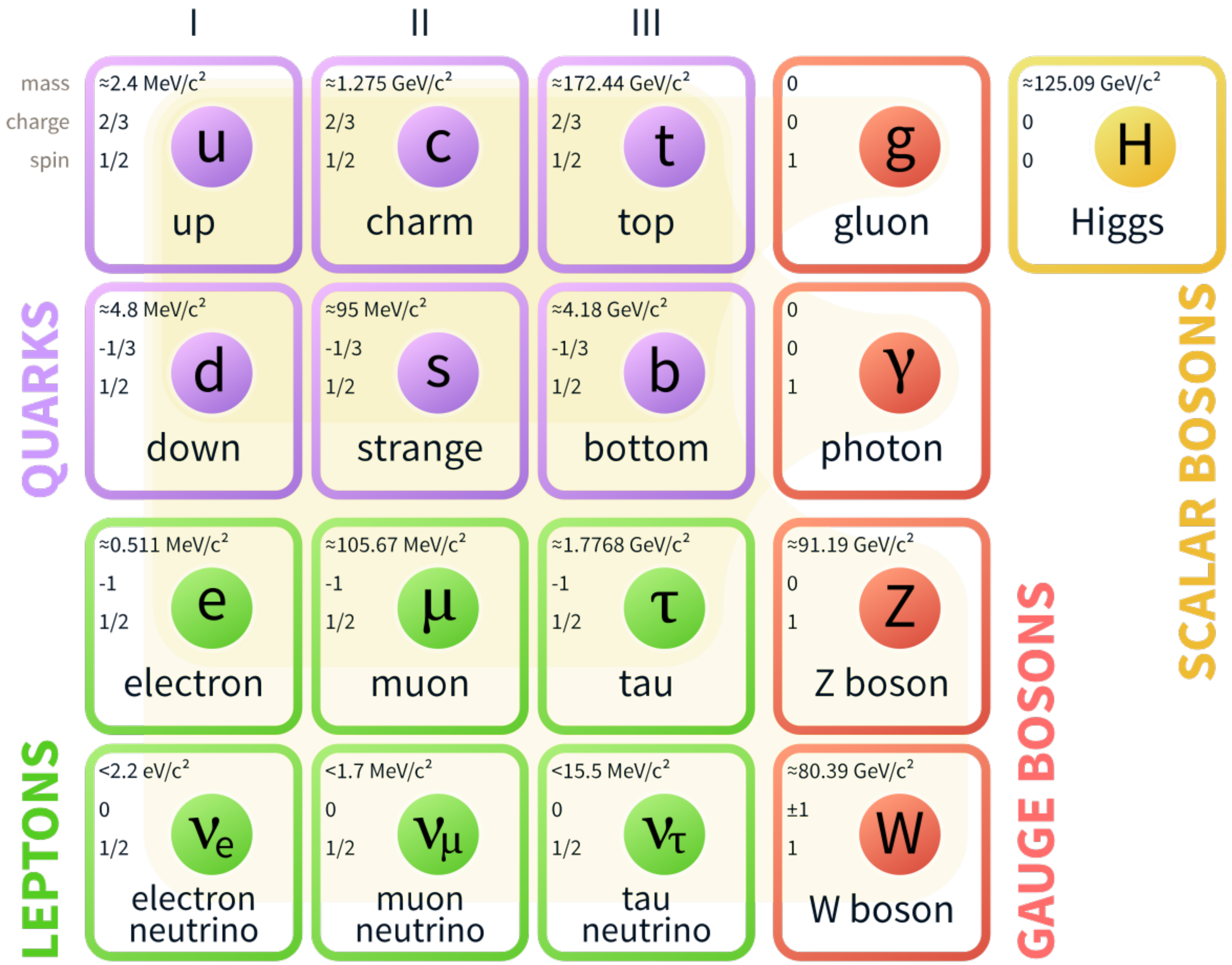
Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_{MC}$	1.040909
τ	0.0543
$\ln(10^{10}A_s)$	3.0448
n_s	0.96605
$\Omega_m h^2$	0.14314
H_0 [km s^{-1}Mpc^{-1}]	67.32
Ω_m	0.3158
Age [Gyr]	13.7971
σ_8	0.8120
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331
z_{re}	7.68
$100\theta_*$	1.041085
r_{drag} [Mpc]	147.049

1807.06209



The SM framework seems valid

All the matter that Particle Physicists know on Earth



	I	II	III		
mass charge spin	≈2.4 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈172.44 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈125.09 GeV/c^2 0 0 H Higgs
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	SCALAR BOSONS
	≈0.511 MeV/c^2 -1 1/2 e electron	≈105.67 MeV/c^2 -1 1/2 μ muon	≈1.7768 GeV/c^2 -1 1/2 τ tau	≈91.19 GeV/c^2 0 1 Z Z boson	
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<1.7 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	≈80.39 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS

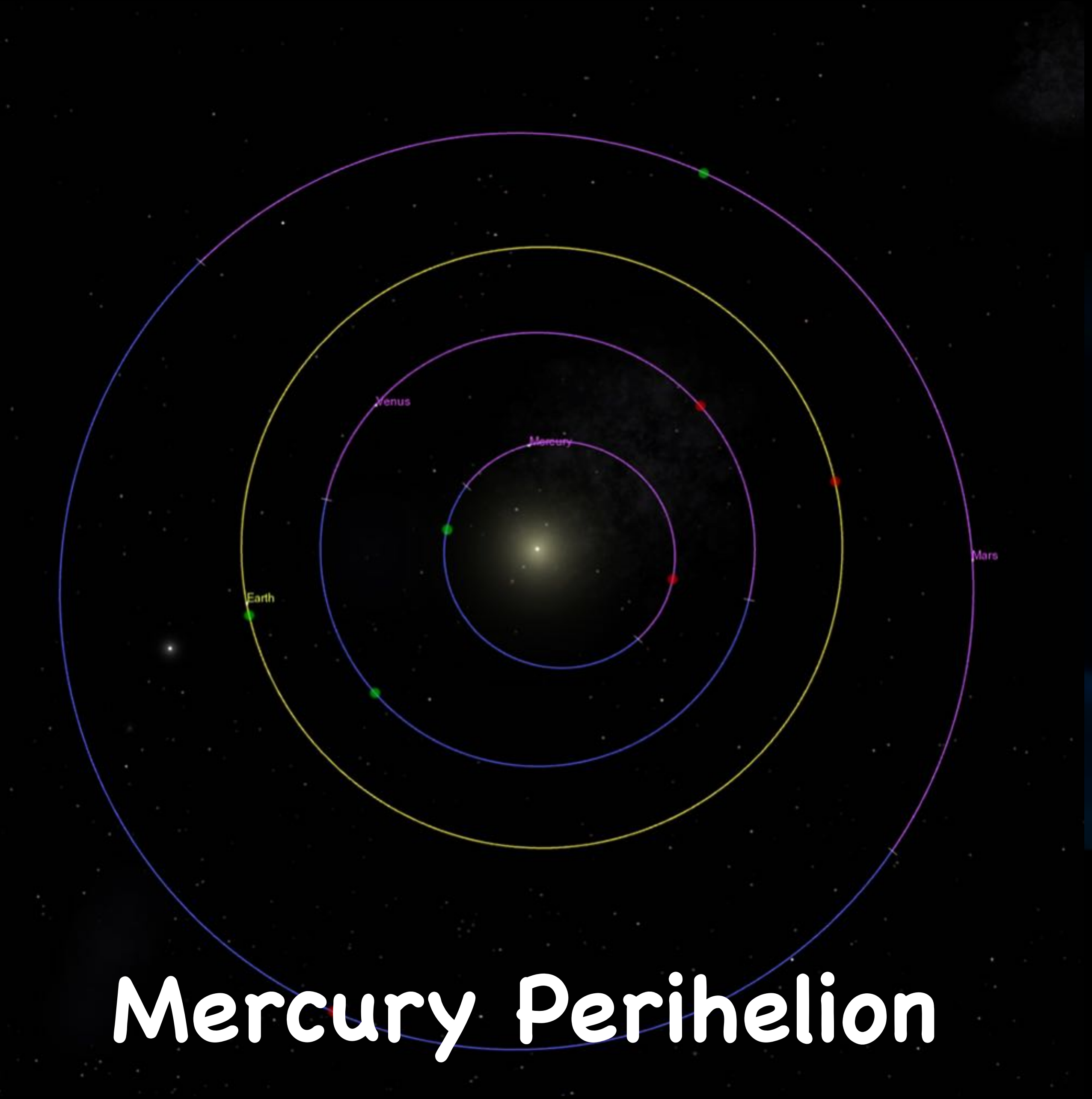
Interactions

Strong force **Weak force** **Electromagnetism**

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

This model perfectly describes everything we see on Earth

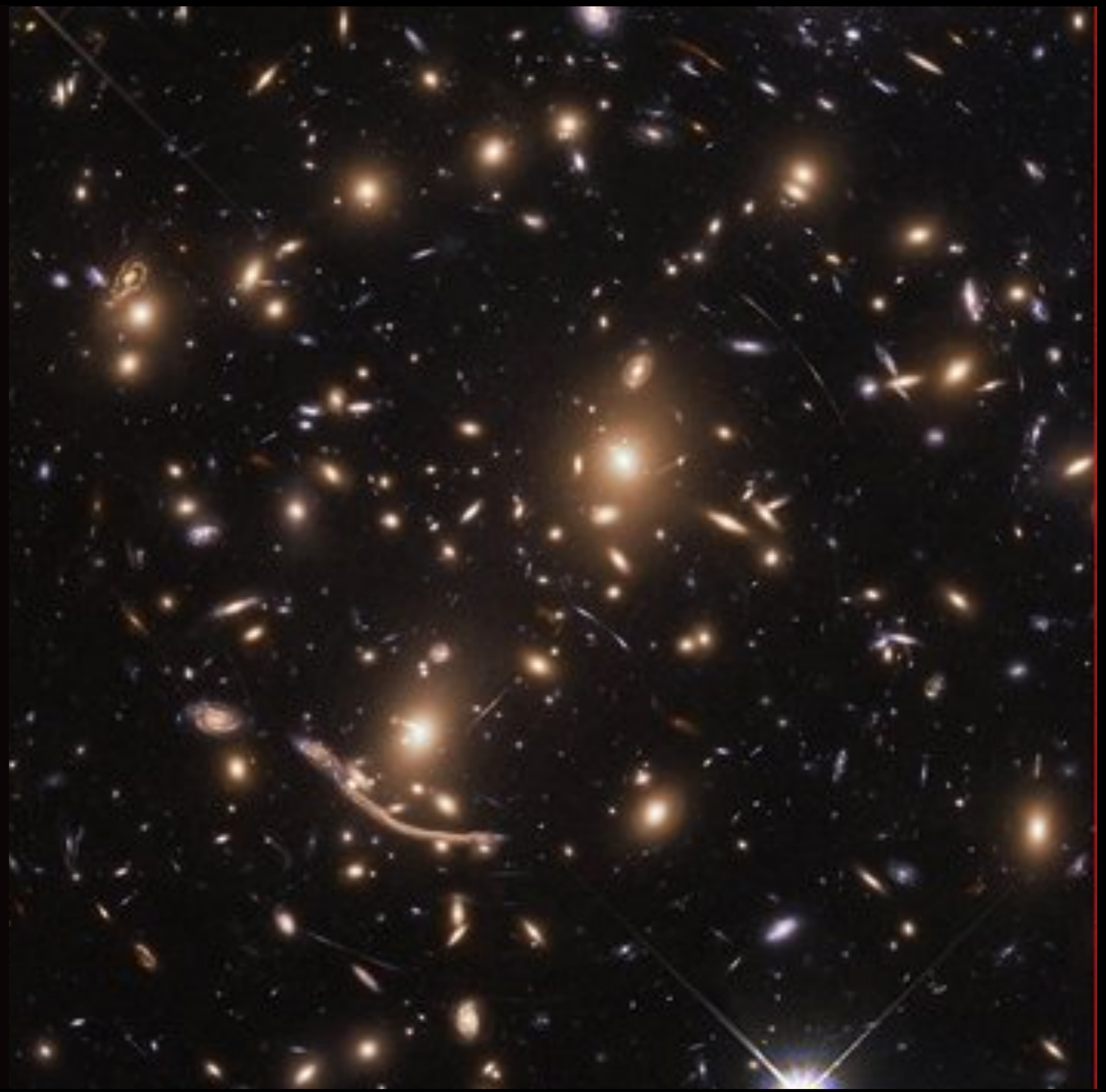
General Relativity seems valid so far



Mercury Perihelion

Gravitational waves

BH horizon



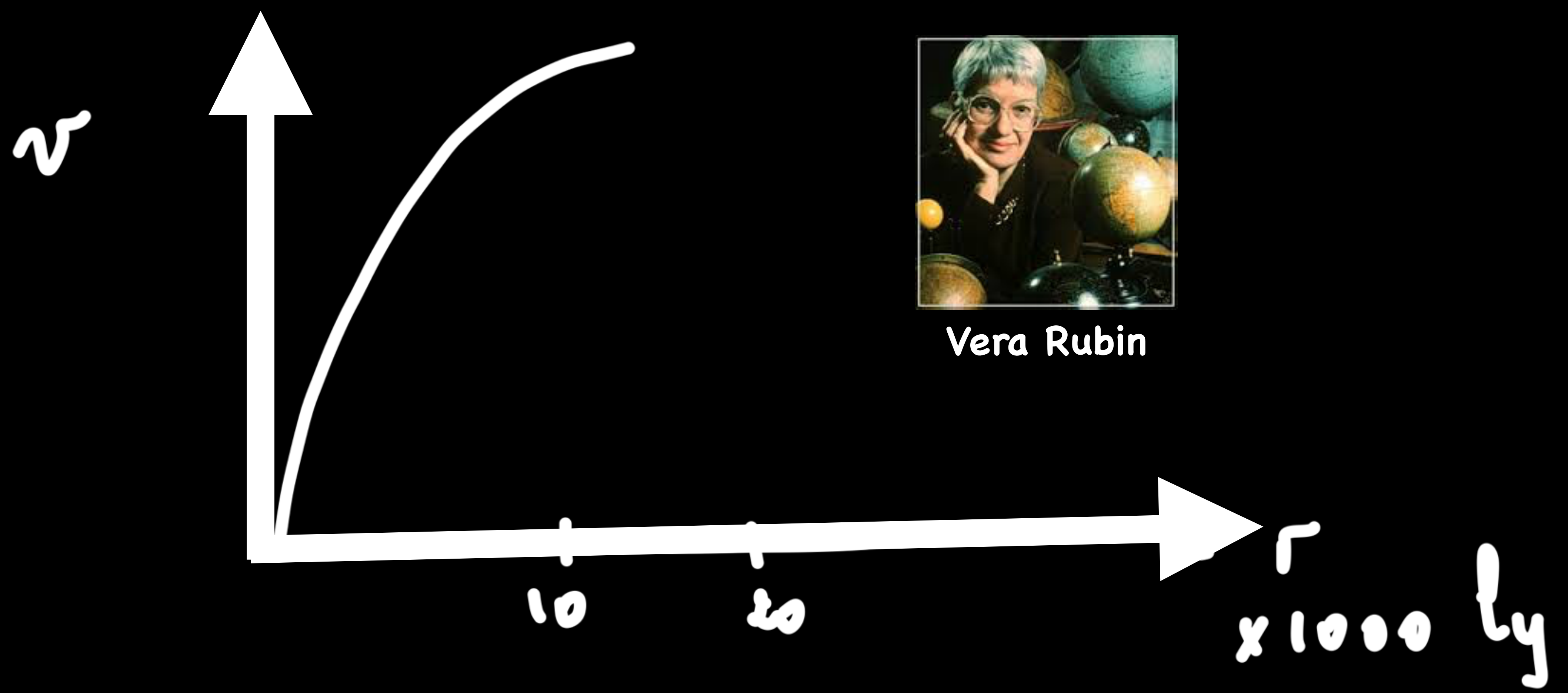
Einstein rings

But there are severe issues

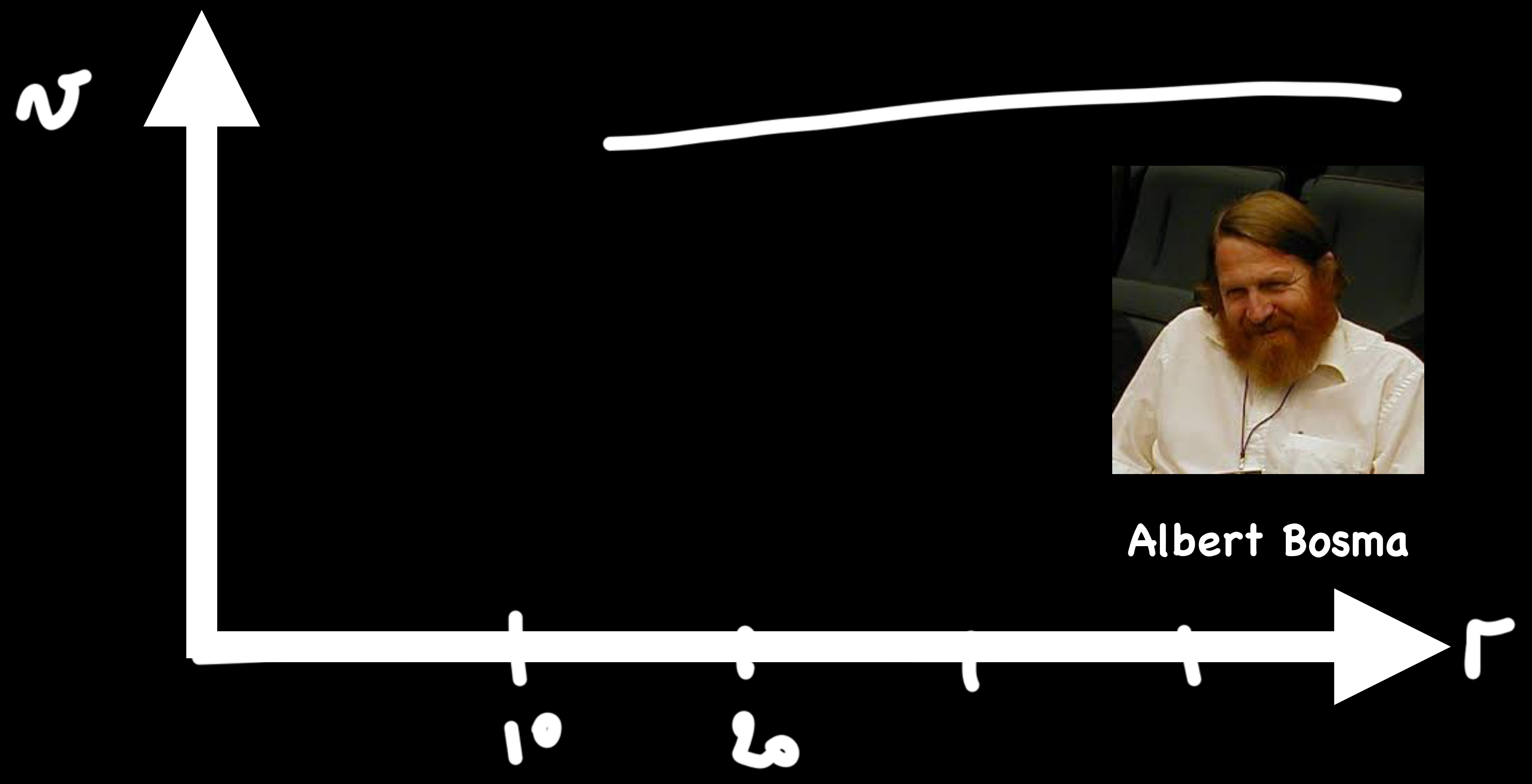
Issue #1

Image credits:
VLA THINGS: Walter et al.
Spitzer SINGS: Kennicutt et al.
Galex NGS: Gil de Paz et al.

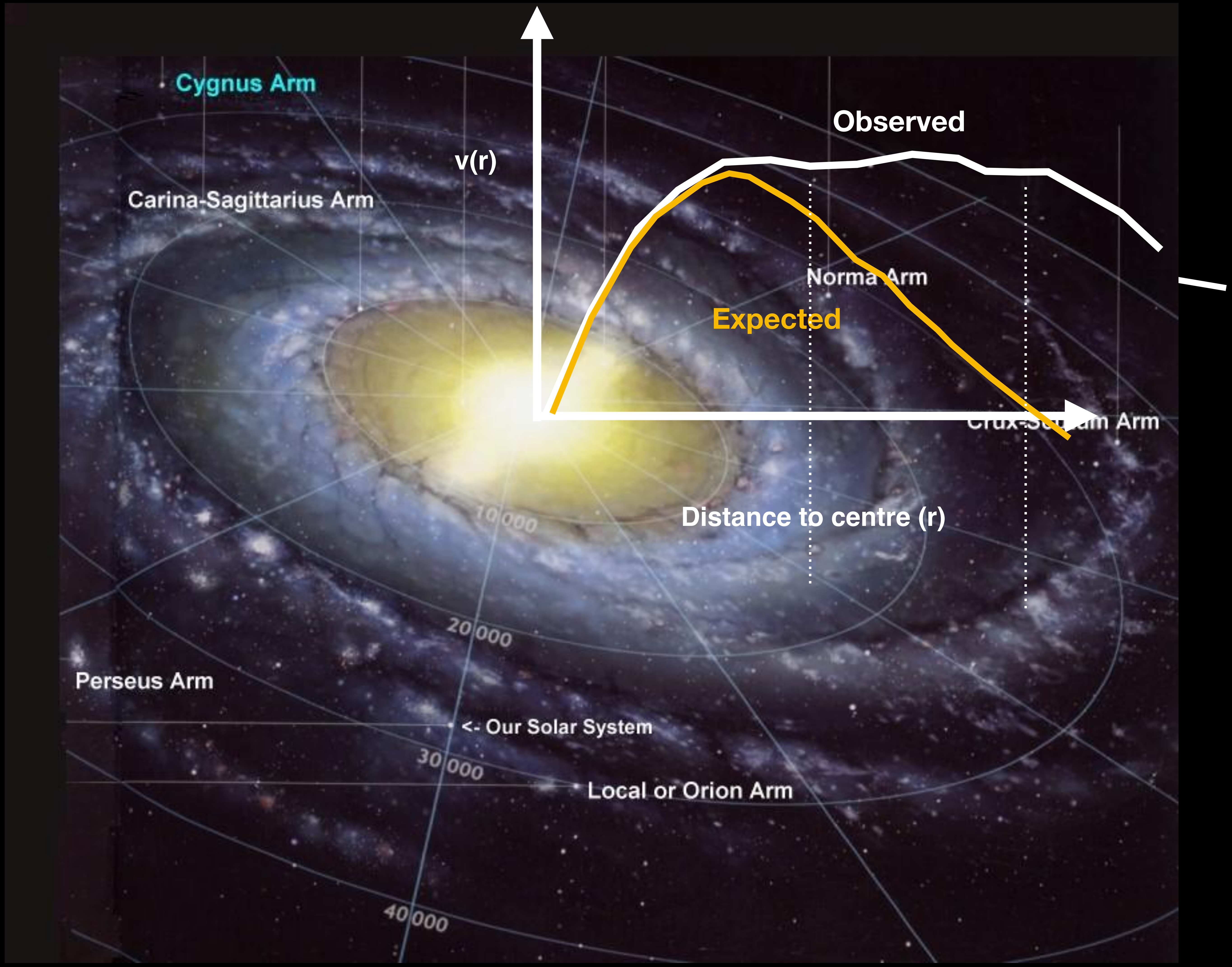
Stars rotate in galaxies



Neutral Hydrogen gas too



Rotation curves of galaxies



No dissipation but ordinary matter does dissipate

Issue #2

Strong lensing in galaxy clusters

Missing mass

Issue #3

Evolution of the Universe

Story of the Universe

At the beginning of time, space exploded out of nothingness to create the ever-expanding universe we inhabit now. It took billions of years for the story, depicted here, to unfold.

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BIG BANG
The universe expanded violently from an extremely hot and dense initial state some 13.7 billion years ago.

How to form cosmological structures from rapid expansion?

Ordinary matter is bound by BBN to be < 5% of the content of the Universe but we need more mass to start the genesis of galaxies

Our place in the Universe

Issue #4

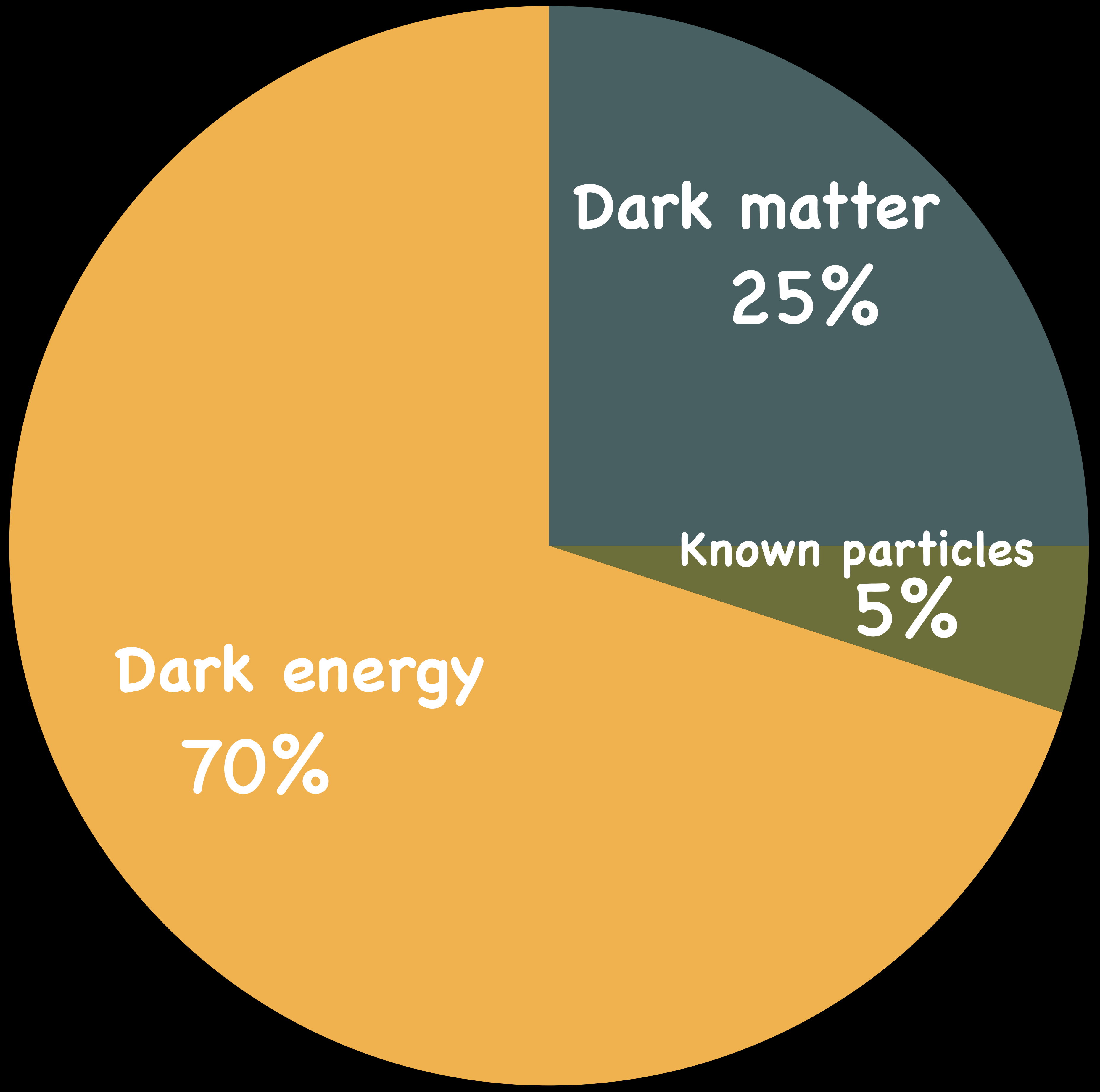
Galaxies within galaxies

LMC and SMC are galaxies within the Milky Way and many more

The physics that we know cannot explain the formation of the objects that we know

We are on for a major paradigm shift

But adding some invisible mass solves all



Solutions?

	Deeper gravitational potential	Fighting Dissipation
Modifying gravity	✓ (Acceleration)	Hard :(
Adding mass/particles	✓	✓

Others… It is all about the initial conditions, i.e. the CMB!!!

The modified gravity route

Modifying Gravity

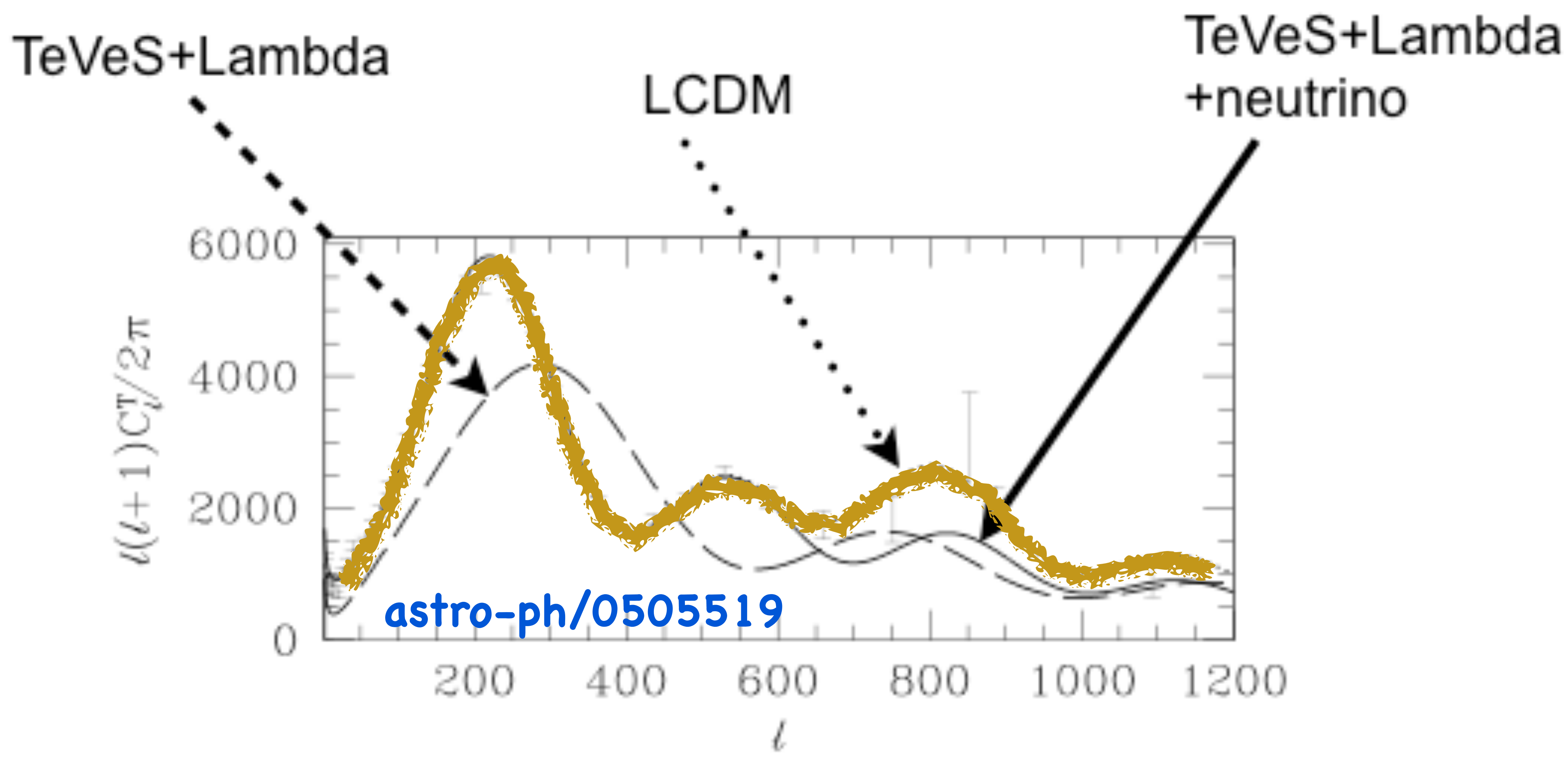
GR′ + SU(3)XSU(2)XU(1)

$$\mu\left(\frac{|\vec{a}|}{a_0}\right)\vec{a} = -\nabla\Phi$$

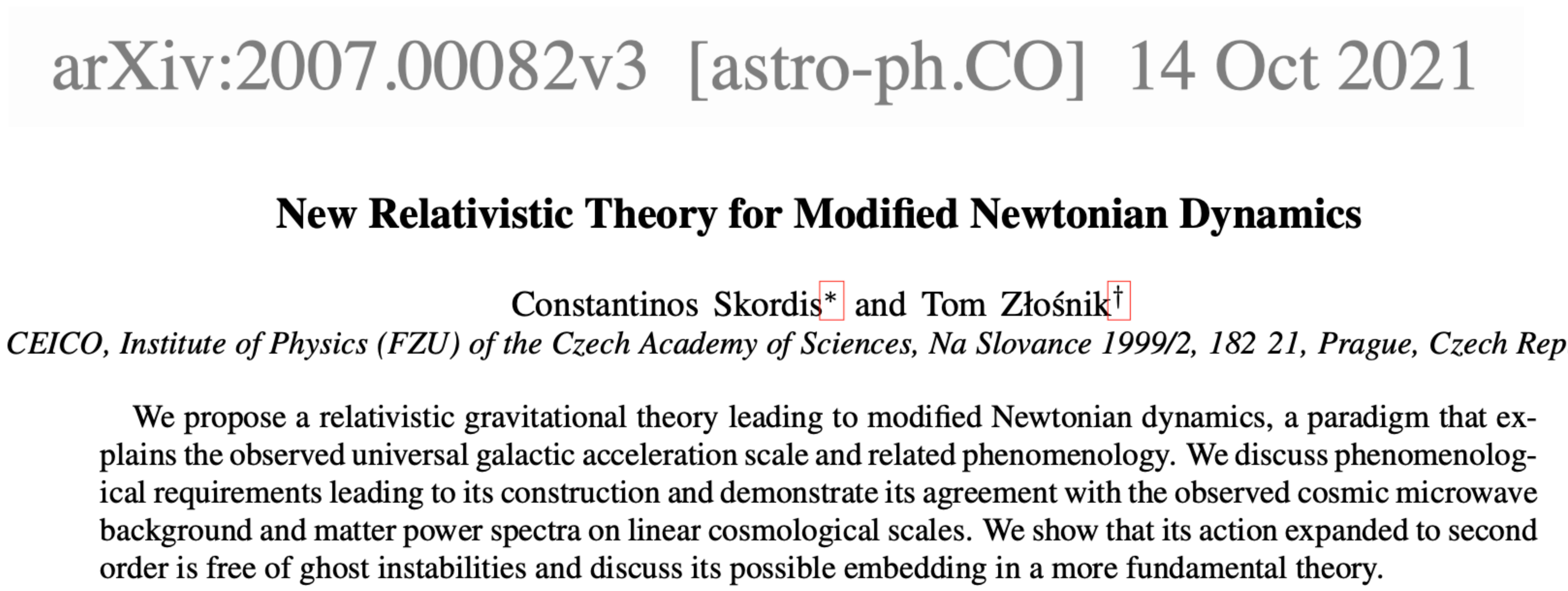
empirical

$\mu(x) = 1$ if x > 1 $\qquad \mu(x) \simeq x$ if x < 1

TEVES: astro-ph/0403694



astro-ph/0505519

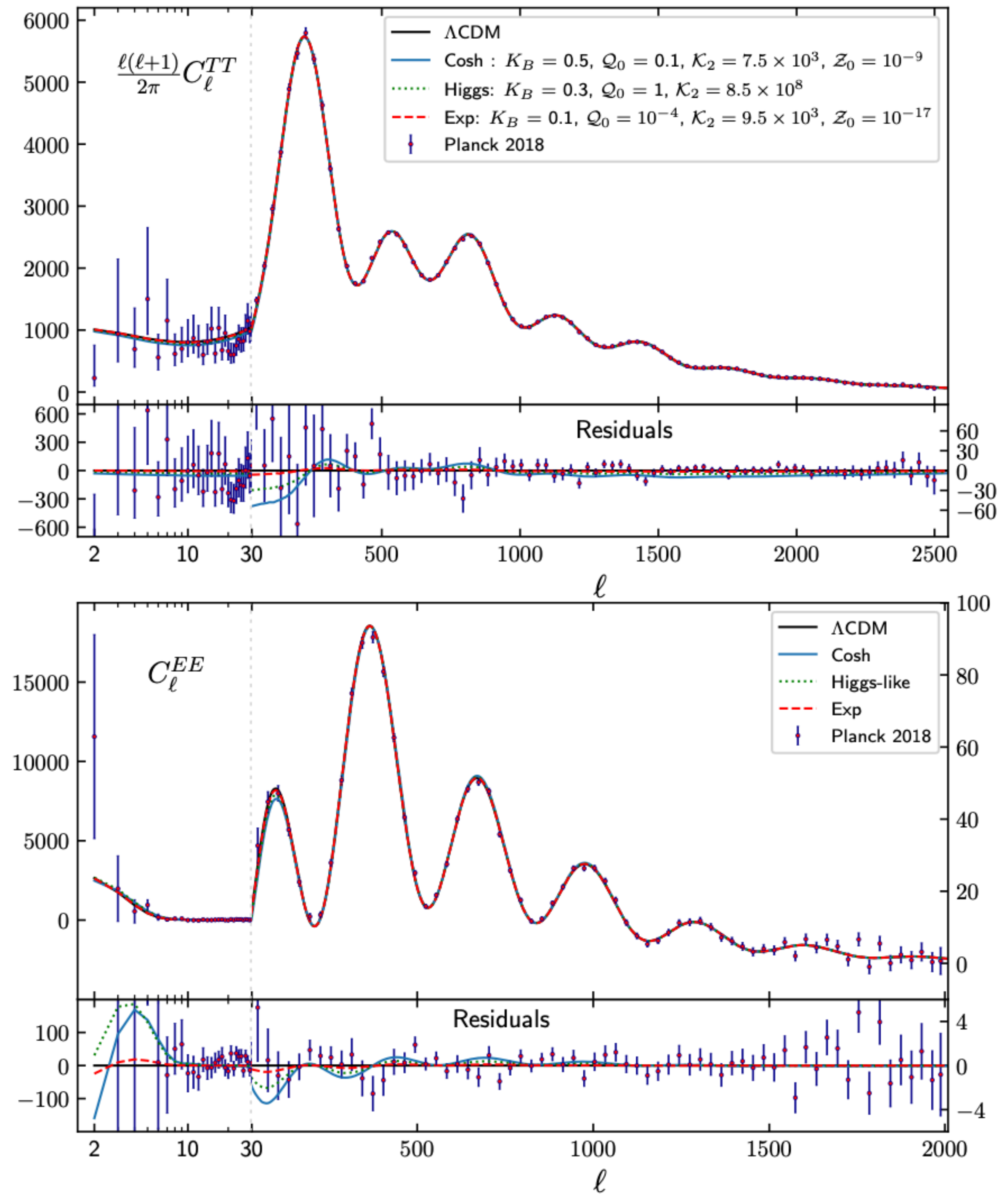


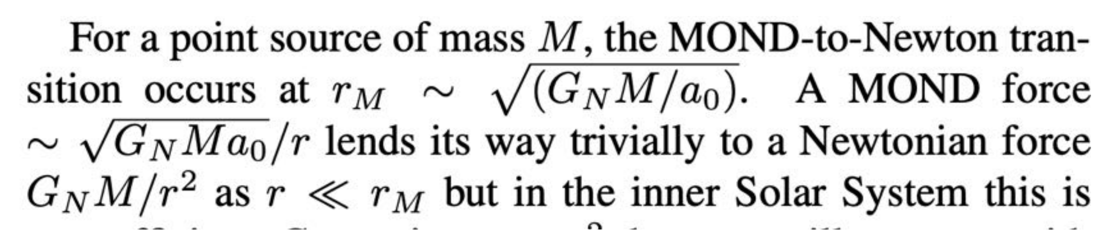
arXiv:2007.00082v3 [astro-ph.CO] 14 Oct 2021

New Relativistic Theory for Modified Newtonian Dynamics

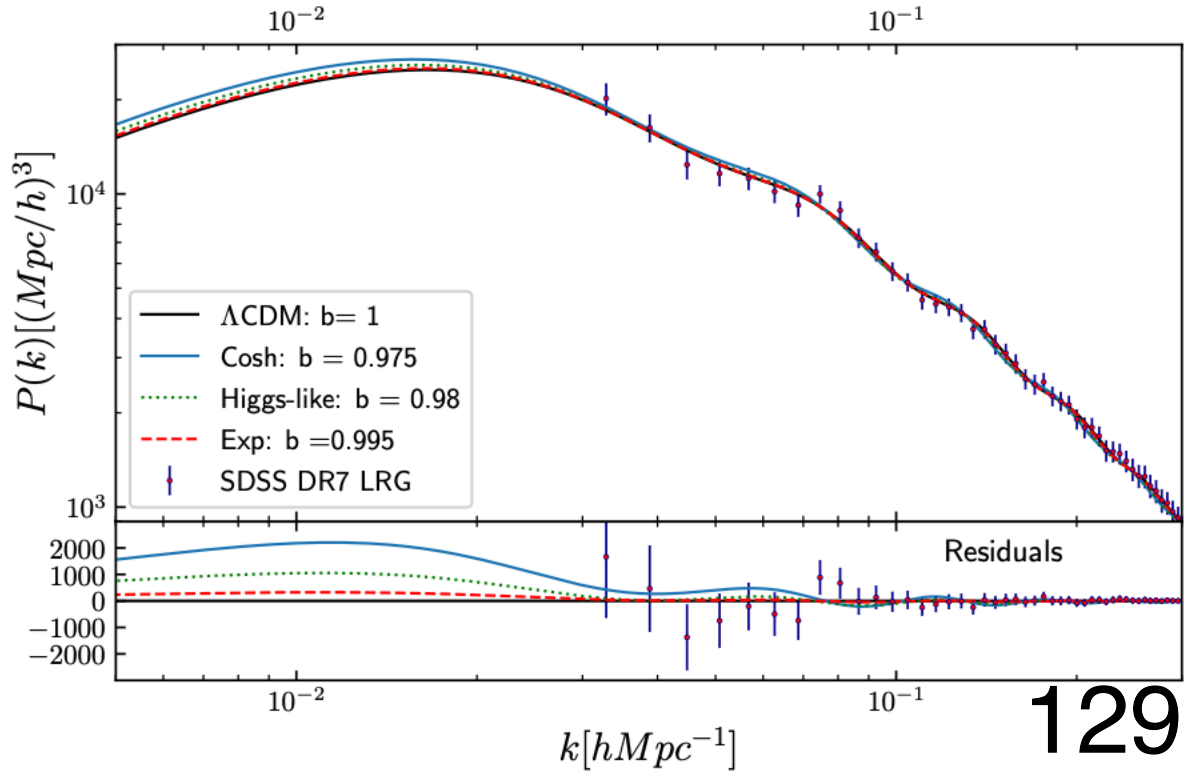
Constantinos Skordis[*] and Tom Złośnik[†]
CEICO, Institute of Physics (FZU) of the Czech Academy of Sciences, Na Slovance 1999/2, 182 21, Prague, Czech Republic

We propose a relativistic gravitational theory leading to modified Newtonian dynamics, a paradigm that explains the observed universal galactic acceleration scale and related phenomenology. We discuss phenomenological requirements leading to its construction and demonstrate its agreement with the observed cosmic microwave background and matter power spectra on linear cosmological scales. We show that its action expanded to second order is free of ghost instabilities and discuss its possible embedding in a more fundamental theory.





For a point source of mass M, the MOND-to-Newton transition occurs at $r_M \sim \sqrt{(G_N M/a_0)}$. A MOND force $\sim \sqrt{G_N M a_0}/r$ lends its way trivially to a Newtonian force $G_N M/r^2$ as $r \ll r_M$ but in the inner Solar System this is



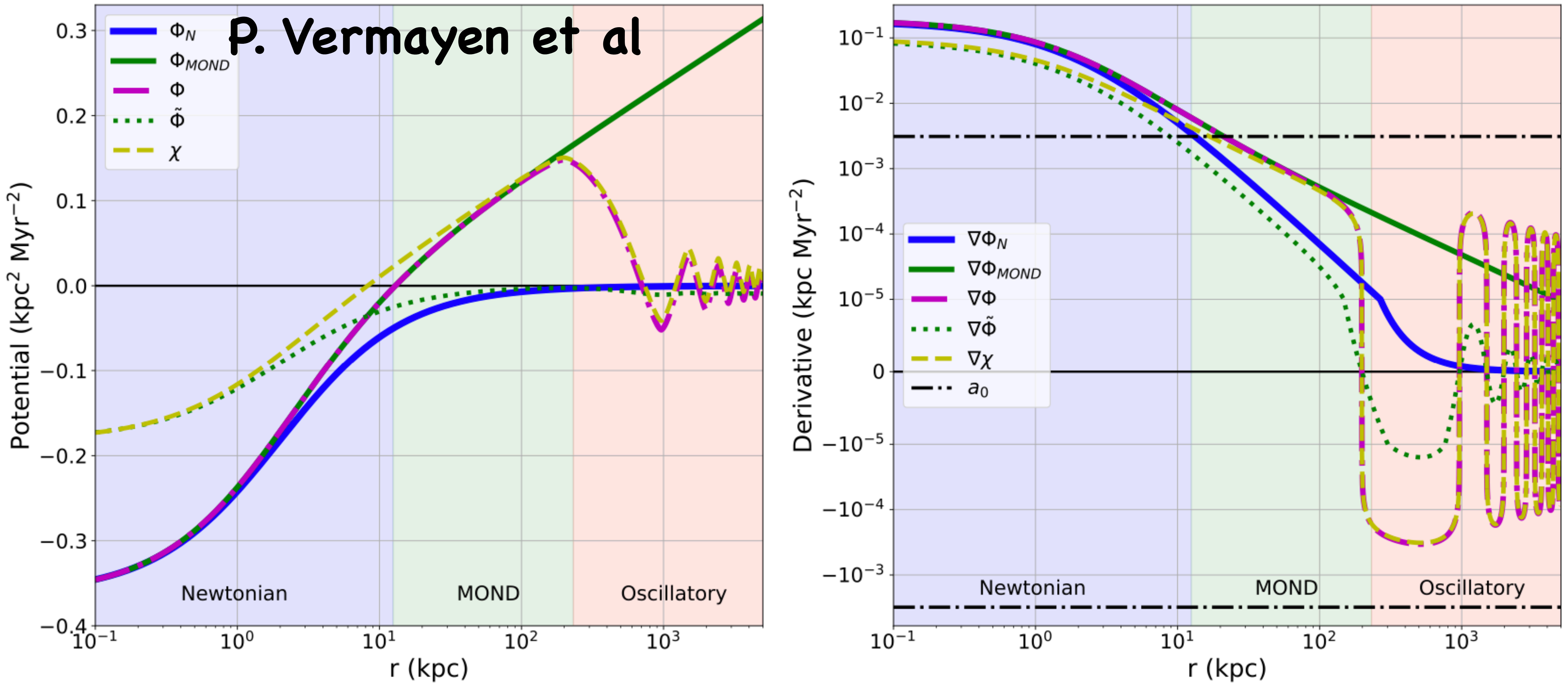
Modifying Gravity

https://arxiv.org/pdf/2007.00082.pdf

$$S = \int d^4x \Big\{ -\frac{1}{2}\bar{\nabla}_\mu h \bar{\nabla}_\nu h^{\mu\nu} + \frac{1}{4}\bar{\nabla}_\rho h \bar{\nabla}^\rho h + \frac{1}{2}\bar{\nabla}_\mu h^{\mu\rho}\bar{\nabla}_\nu h^{\nu}{}_{\rho} - \frac{1}{4}\bar{\nabla}^\rho h^{\mu\nu}\bar{\nabla}_\rho h_{\mu\nu} K_B|\dot{\vec{A}} - \frac{1}{2}\vec{\nabla}h^{00}|^2 - 2K_B\vec{\nabla}_{[i}A_{j]}\vec{\nabla}^{[i}A^{j]}$$

$$+ (2-K_B)\Big[2(\dot{\vec{A}} - \frac{1}{2}\vec{\nabla}h^{00})\cdot(\vec{\nabla}\varphi + \mathcal{Q}_0\vec{A}) - (1+\lambda_s)|\vec{\nabla}\varphi + \mathcal{Q}_0\vec{A}|^2\Big] + 2\mathcal{K}_2\Big|\dot{\varphi} + \frac{1}{2}\mathcal{Q}_0 h^{00}\Big|^2 + \frac{1}{\tilde{M}_p^2}T_{\mu\nu}h^{\mu\nu}\Big\} \quad (13)$$

In preparation

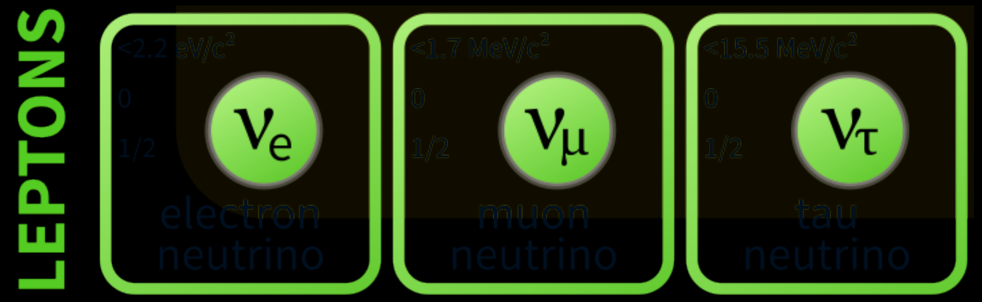


P. Vermayen et al

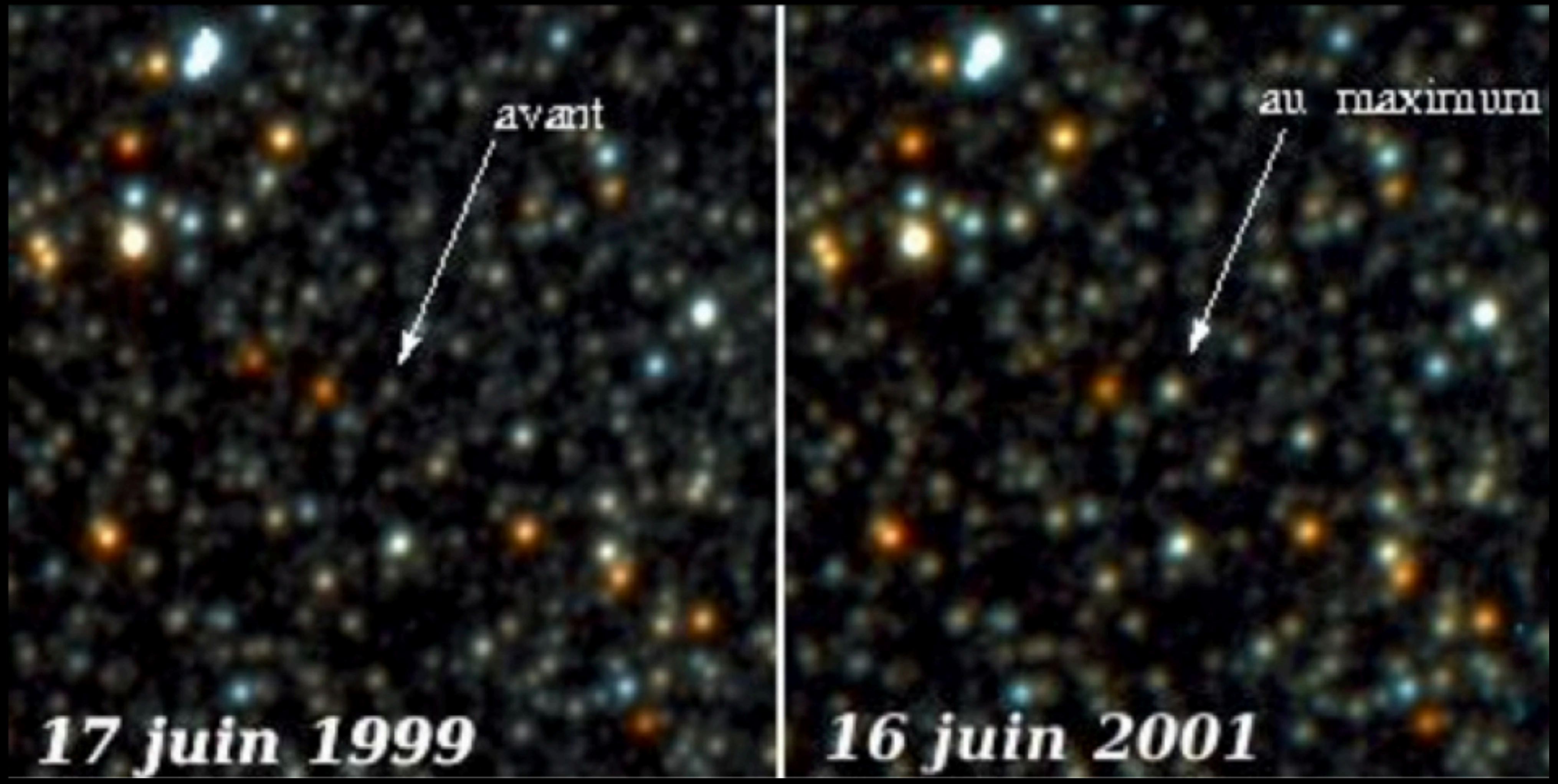
Figure 2. Solution of the field equations (left) and their gradients (right) for the Hernquist density profile and the fiducial model parameters with $(\lambda_s, \mu) = (1, 1\ \mathrm{Mpc}^{-1})$. The blue, green and red regions delineate the Newtonian, MOND and Oscillatory regions respectively. The yellow and green dashed lines are the auxiliary fields $\tilde{\Phi}$ and χ and the pink dotted-dashed line is the metric perturbation which is responsible for defining the trajectories of free falling particles. We have included the Newtonian (blue) and classical MOND (green) solutions for comparison. The break in the blue curve at $\nabla\Phi = 10^{-5}$ is not physical, but related to the symlog scaling that we use for the vertical axis of the right panel.

The “missing mass” route

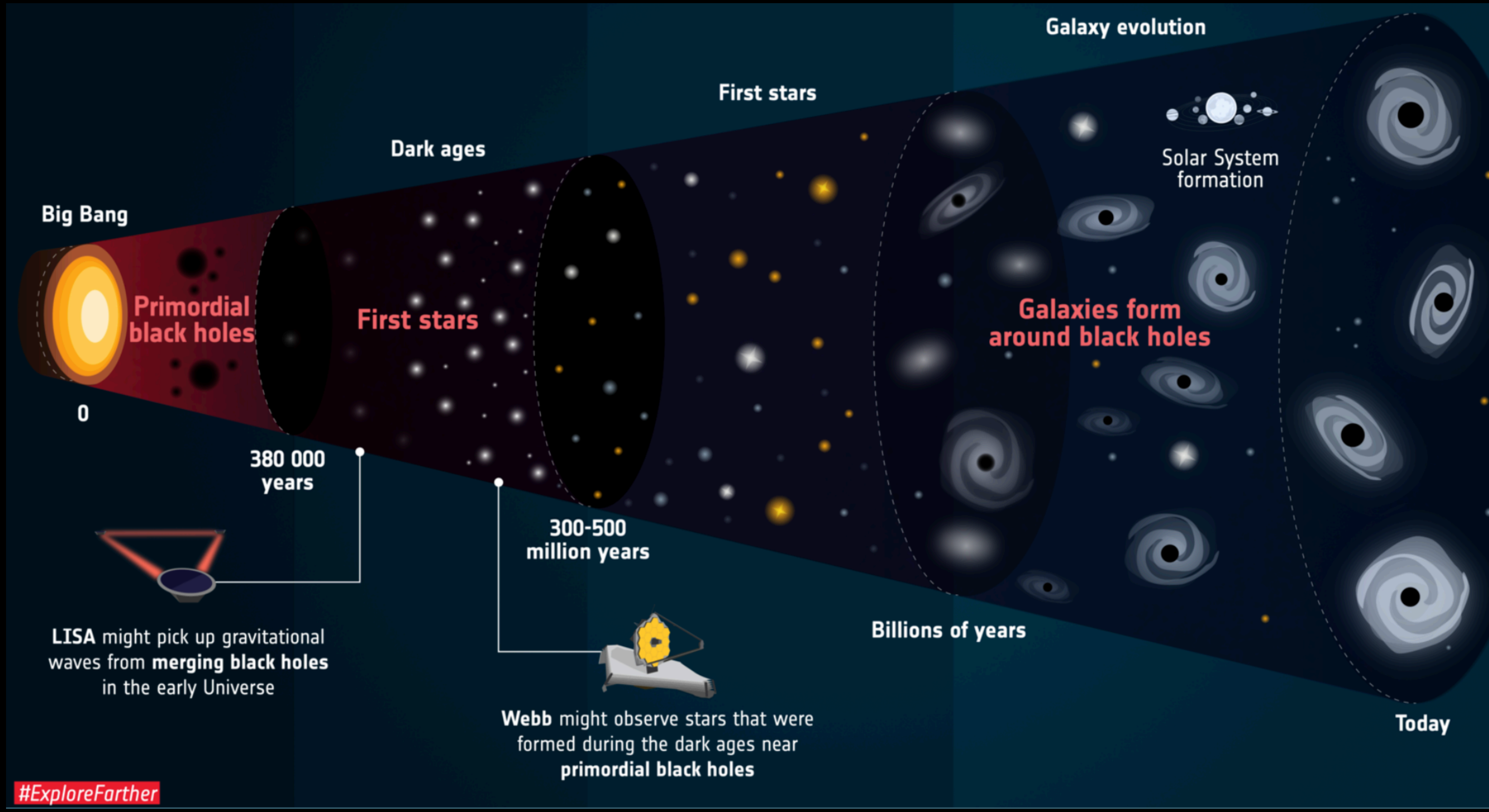
“Standard Model” solutions



MACHOs



PBHs

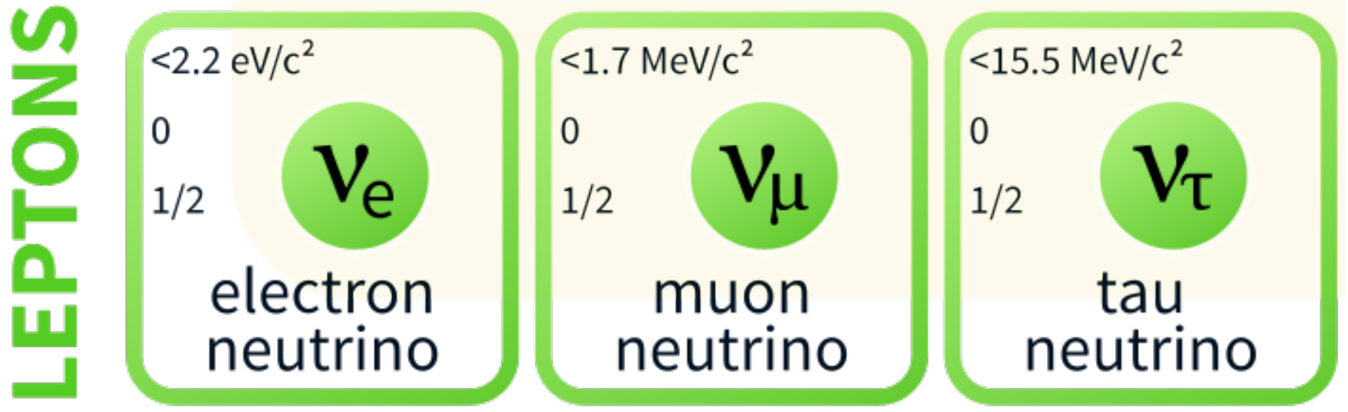


LISA might pick up gravitational waves from **merging black holes** in the early Universe

Webb might observe stars that were formed during the dark ages near **primordial black holes**

Or ?

Neutrinos



Our place in the Universe

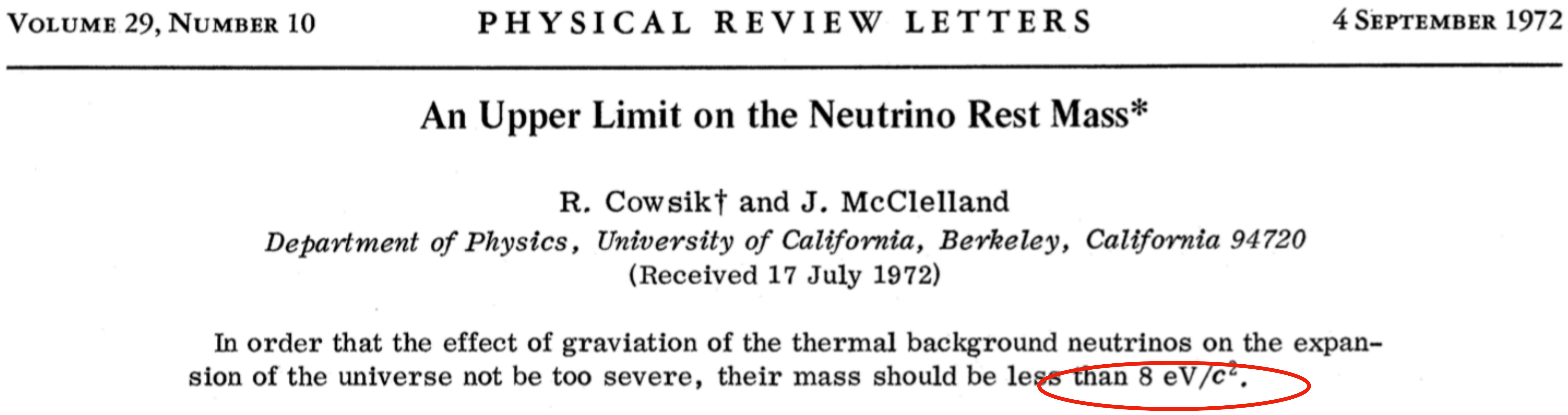
Galaxies within galaxies

LMC and SMC are galaxies within the Milky Way and many more

They would need to have a mass > keV to form as many galaxies as we have observed

Dark Matter as ordinary matter

Is it a neutrino?



VOLUME 29, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 1972

An Upper Limit on the Neutrino Rest Mass*

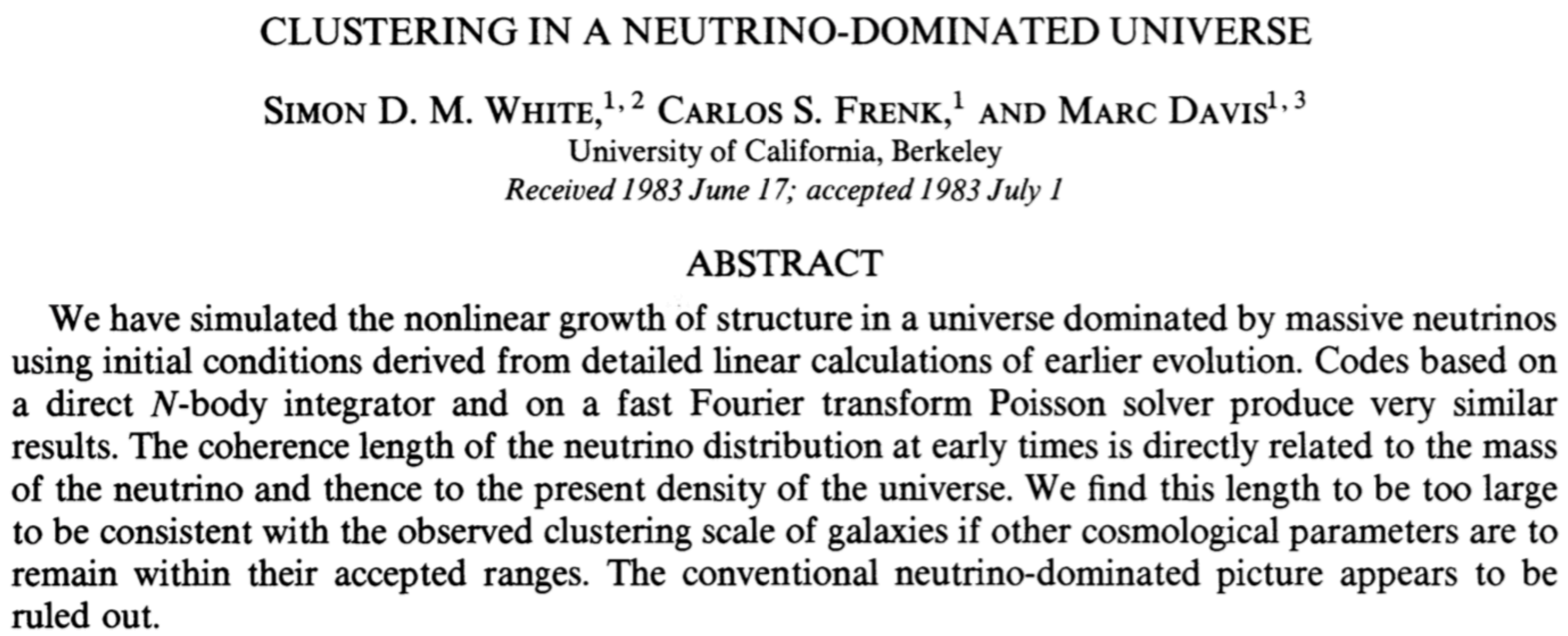
R. Cowsik† and J. McClelland
Department of Physics, University of California, Berkeley, California 94720

(Received 17 July 1972)

In order that the effect of graviation of the thermal background neutrinos on the expansion of the universe not be too severe, their mass should be less than 8 eV/c^2.

1980 - Zel'dovich et al develop Hot Dark Matter (HDM) theory

1983



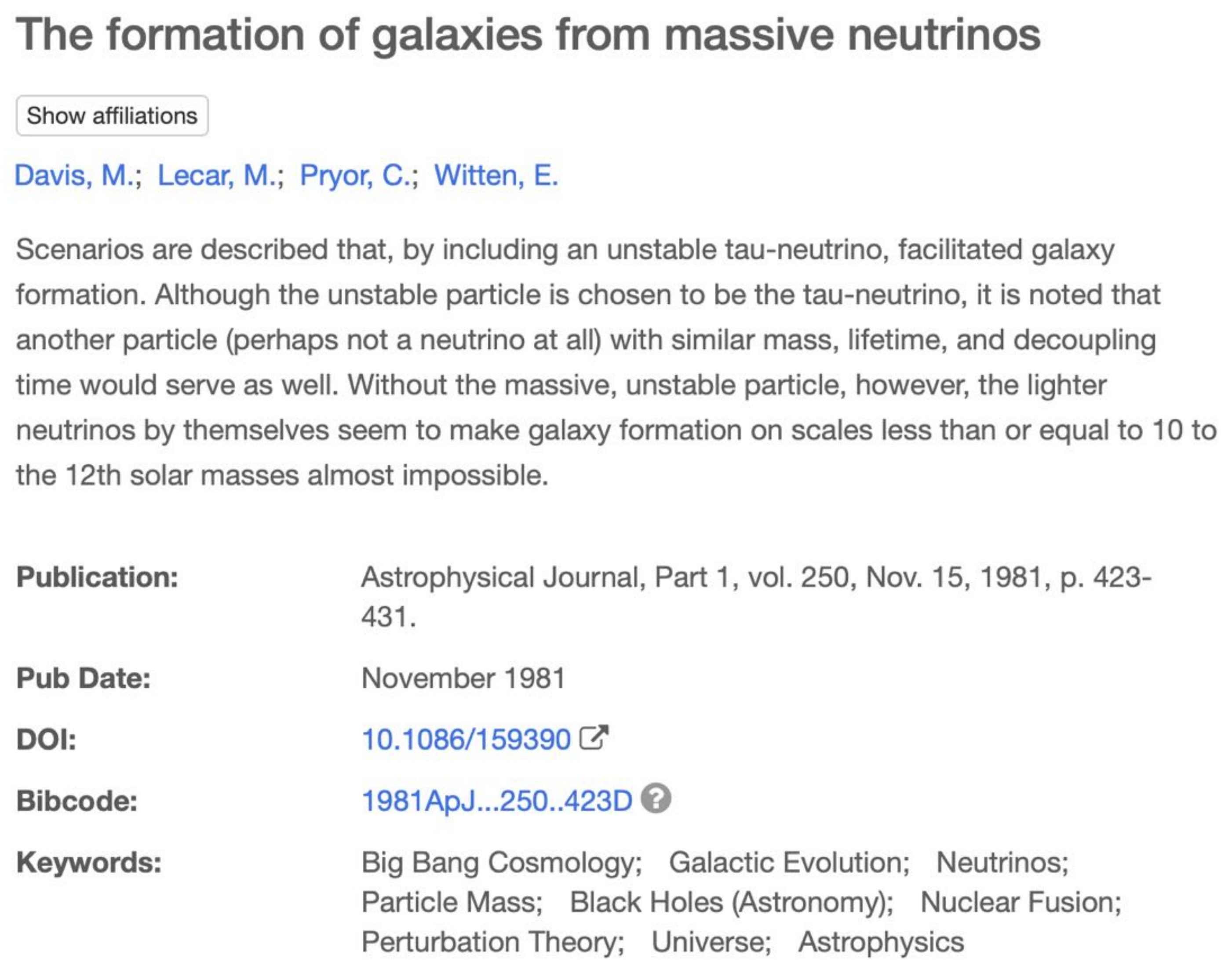
CLUSTERING IN A NEUTRINO-DOMINATED UNIVERSE

SIMON D. M. WHITE,[1,2] CARLOS S. FRENK,[1] AND MARC DAVIS[1,3]
University of California, Berkeley

Received 1983 June 17; accepted 1983 July 1

ABSTRACT

We have simulated the nonlinear growth of structure in a universe dominated by massive neutrinos using initial conditions derived from detailed linear calculations of earlier evolution. Codes based on a direct *N*-body integrator and on a fast Fourier transform Poisson solver produce very similar results. The coherence length of the neutrino distribution at early times is directly related to the mass of the neutrino and thence to the present density of the universe. We find this length to be too large to be consistent with the observed clustering scale of galaxies if other cosmological parameters are to remain within their accepted ranges. The conventional neutrino-dominated picture appears to be ruled out.



The formation of galaxies from massive neutrinos

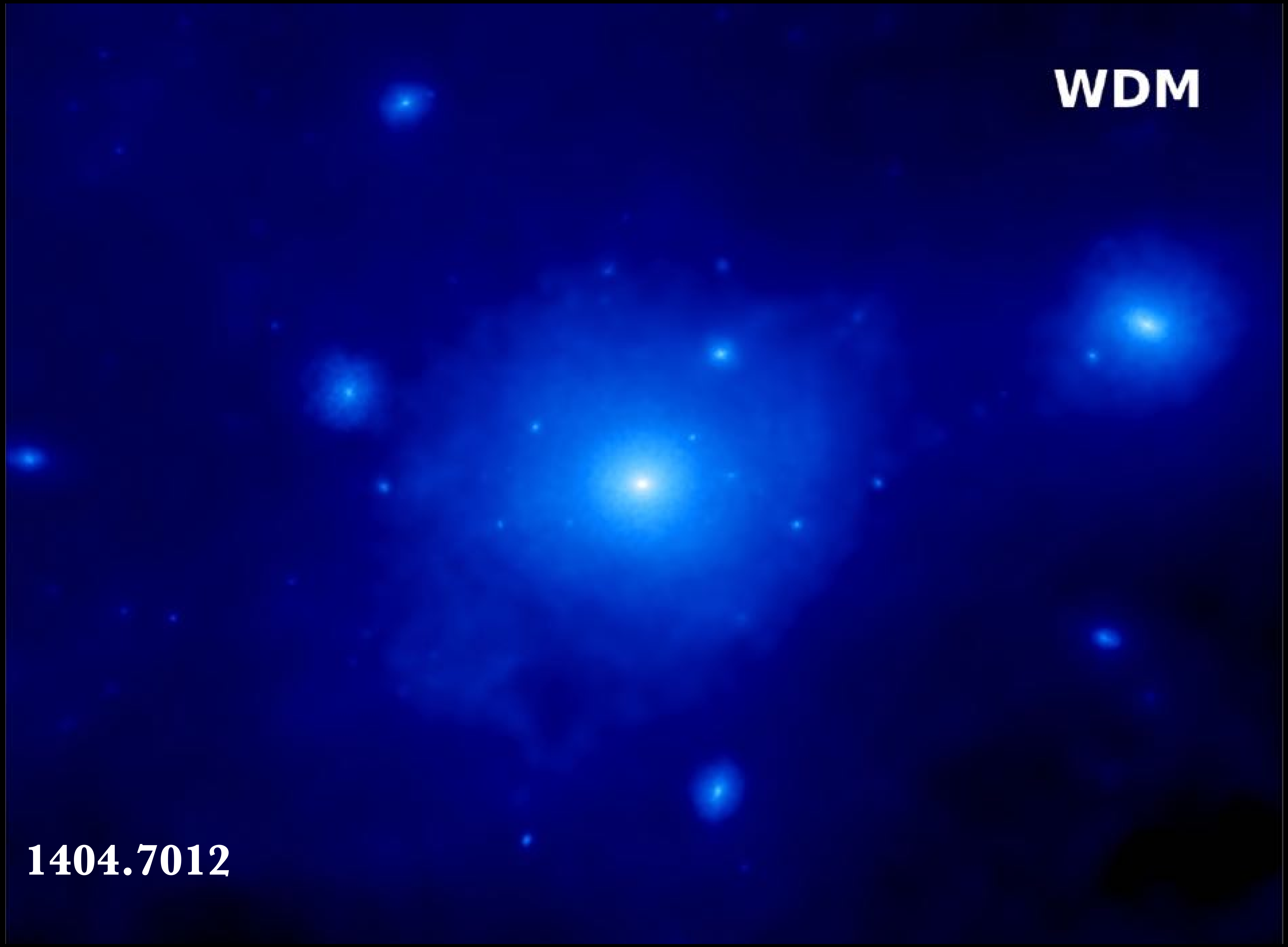
Show affiliations

Davis, M.; Lecar, M.; Pryor, C.; Witten, E.

Scenarios are described that, by including an unstable tau-neutrino, facilitated galaxy formation. Although the unstable particle is chosen to be the tau-neutrino, it is noted that another particle (perhaps not a neutrino at all) with similar mass, lifetime, and decoupling time would serve as well. Without the massive, unstable particle, however, the lighter neutrinos by themselves seem to make galaxy formation on scales less than or equal to 10 to the 12th solar masses almost impossible.

Publication: Astrophysical Journal, Part 1, vol. 250, Nov. 15, 1981, p. 423-431.
Pub Date: November 1981
DOI: 10.1086/159390
Bibcode: 1981ApJ...250..423D
Keywords: Big Bang Cosmology; Galactic Evolution; Neutrinos; Particle Mass; Black Holes (Astronomy); Nuclear Fusion; Perturbation Theory; Universe; Astrophysics

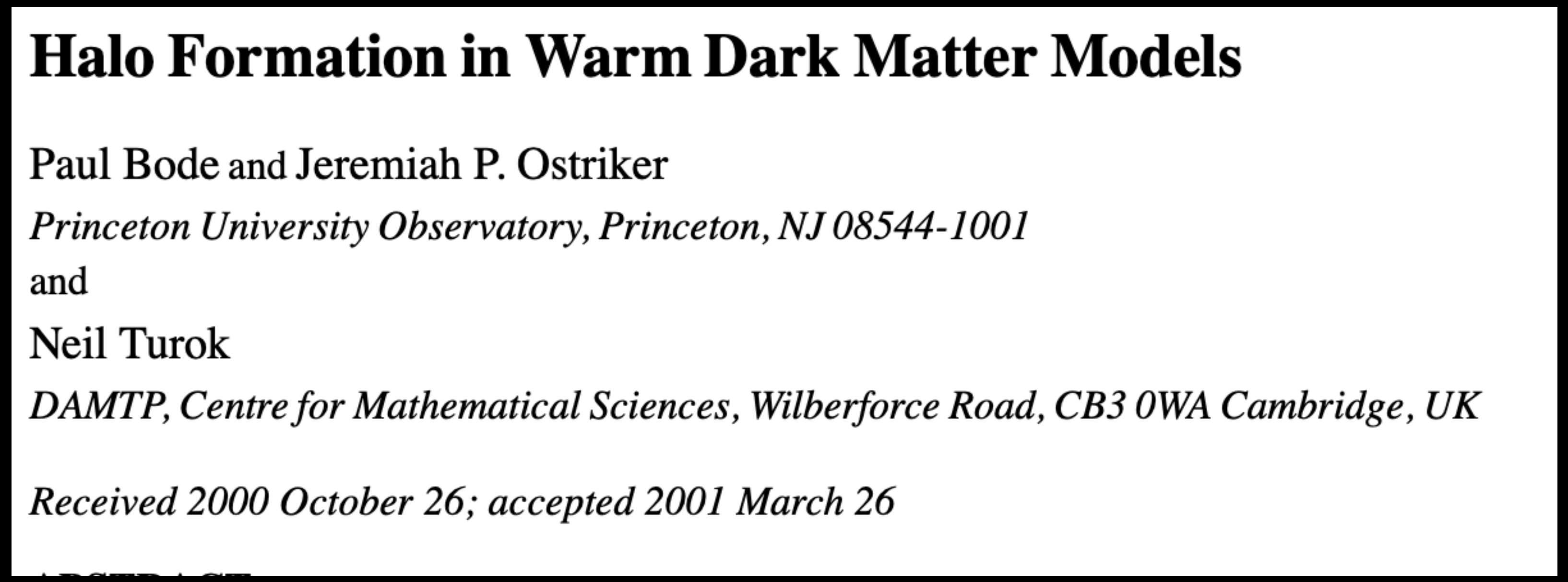
keV neutrinos = Warm dark matter



1404.7012

1988ApJ...332....1S

[Bond & Szalay 1983](#) [Bardeen et al. 1986](#)



Halo Formation in Warm Dark Matter Models

Paul Bode and Jeremiah P. Ostriker

Princeton University Observatory, Princeton, NJ 08544-1001

and

Neil Turok

DAMTP, Centre for Mathematical Sciences, Wilberforce Road, CB3 0WA Cambridge, UK

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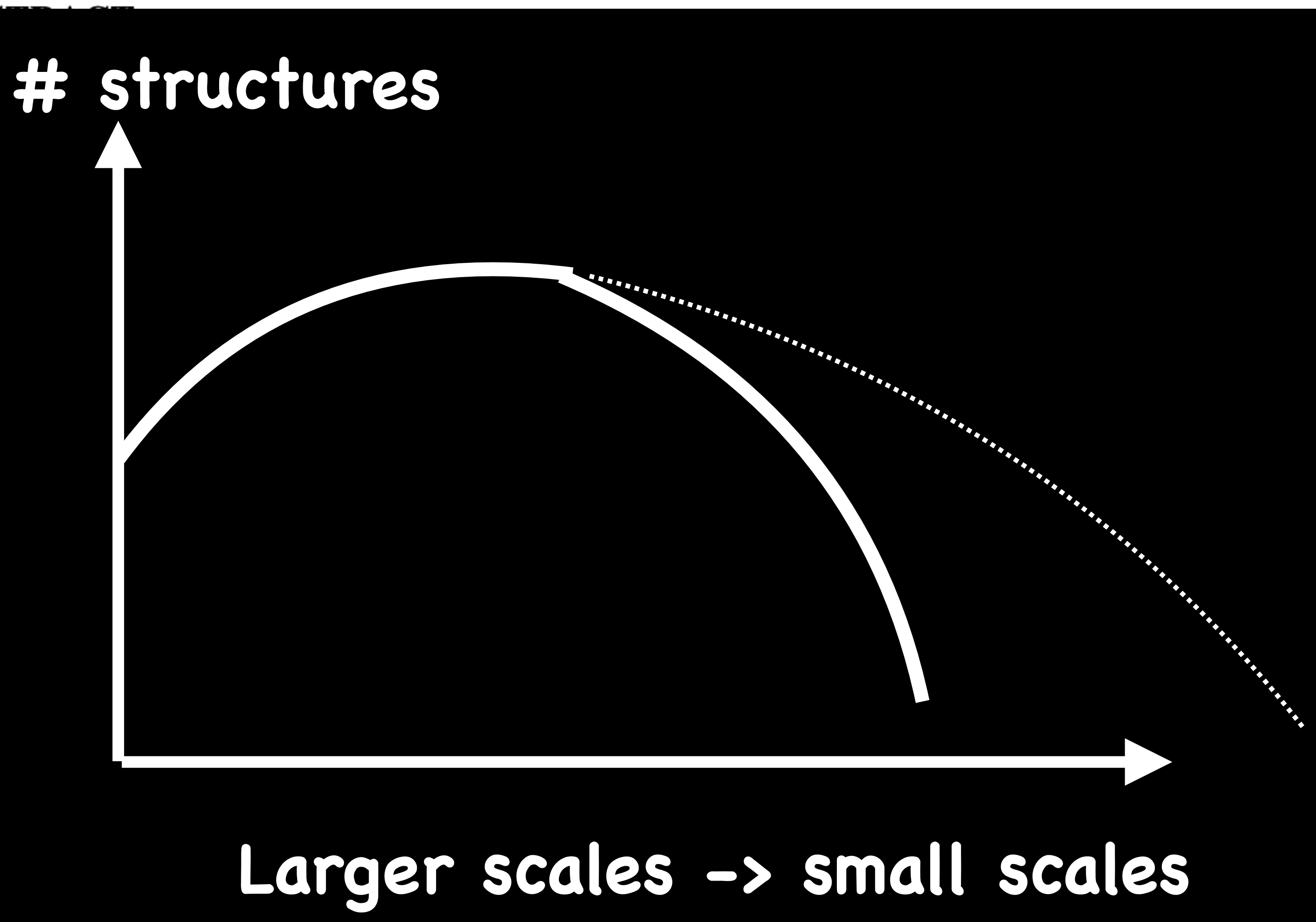
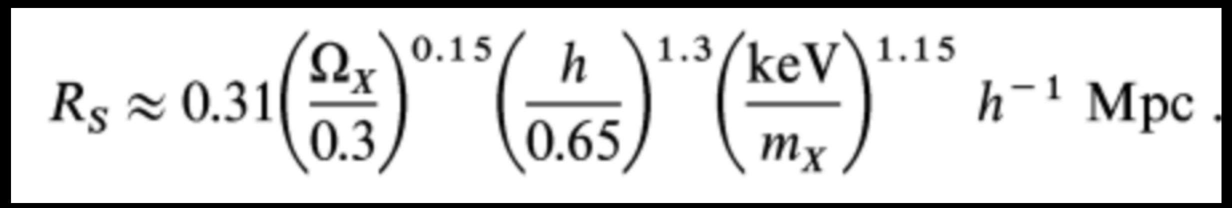
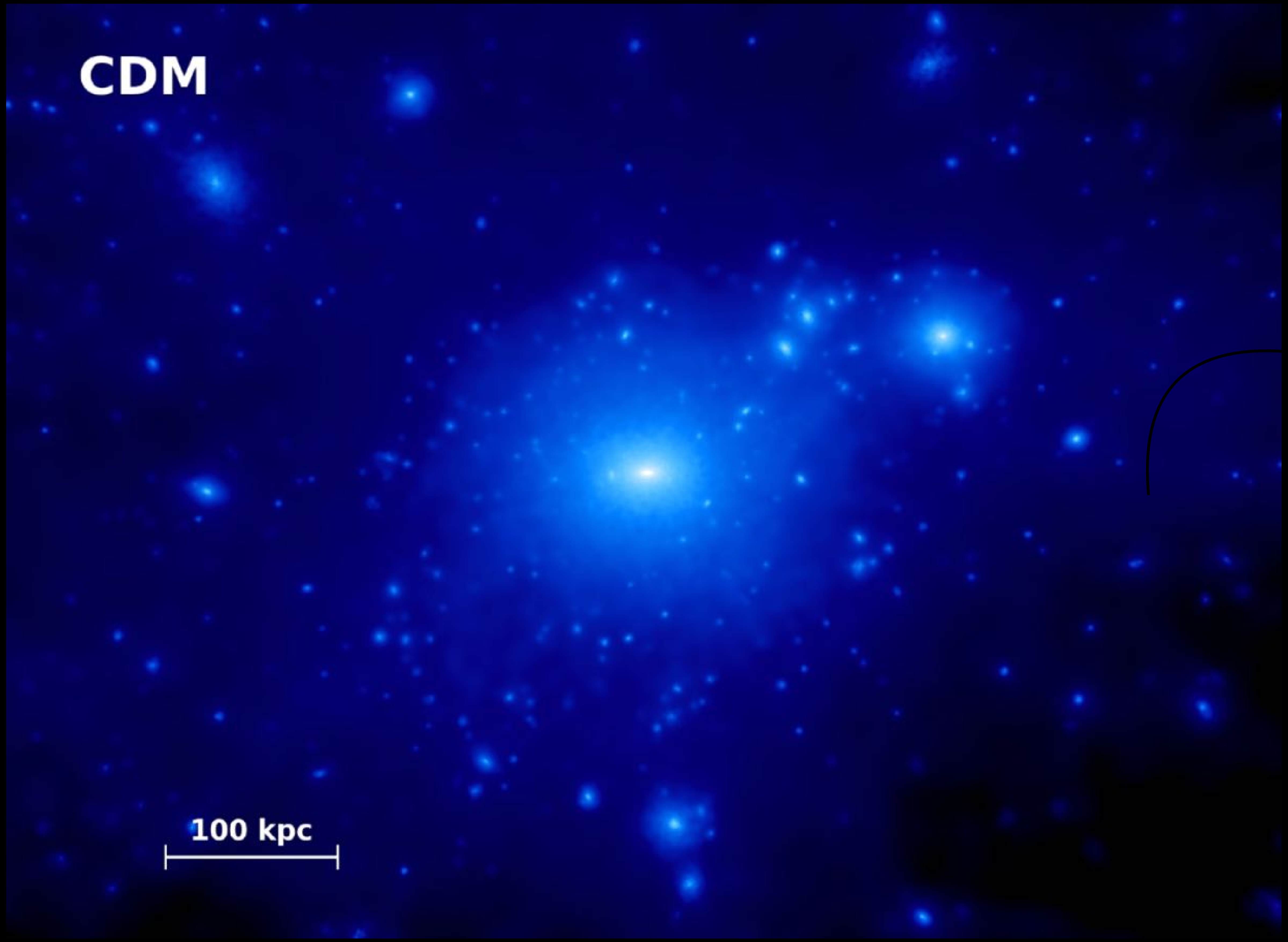
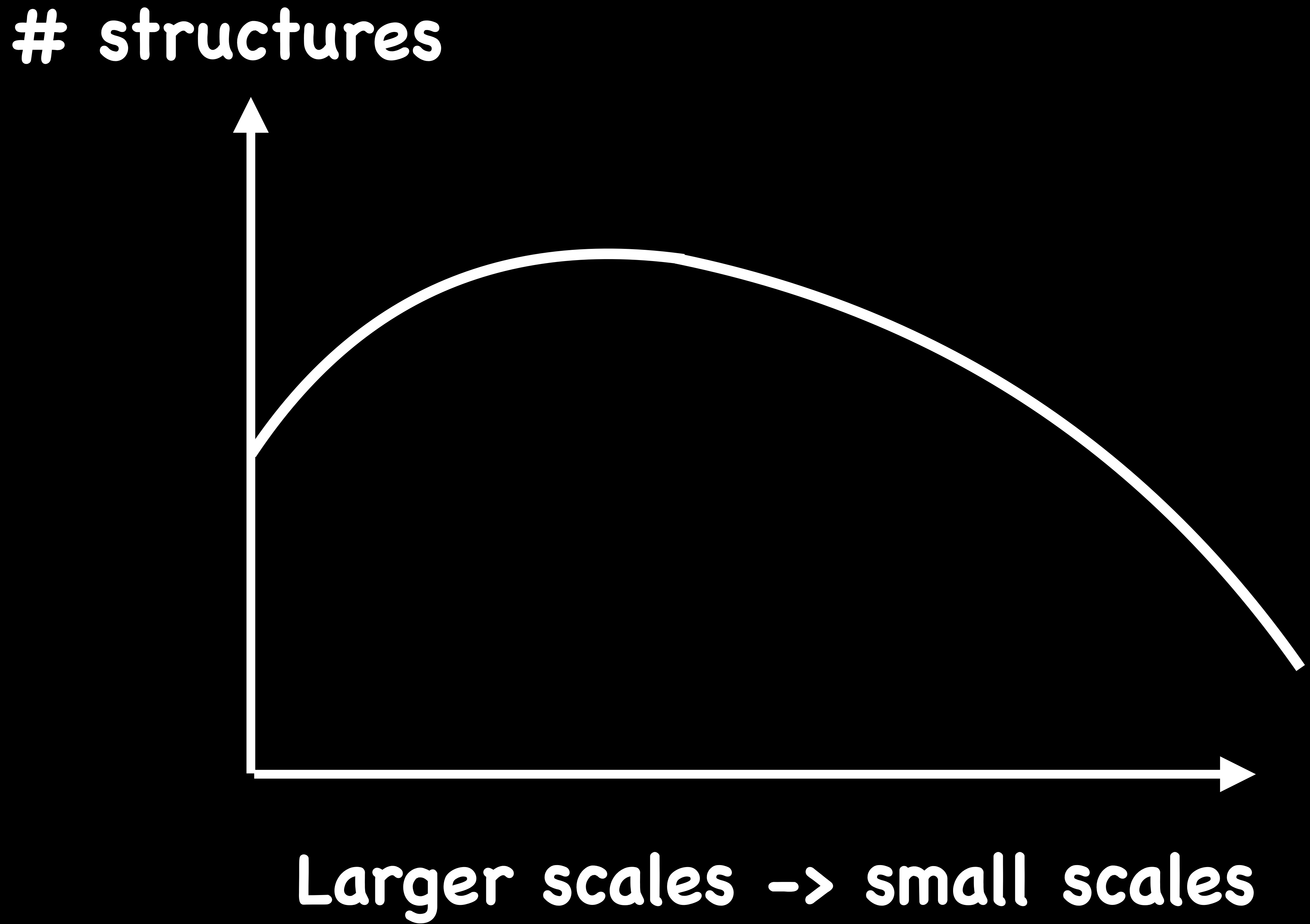




$$R_S \approx 0.31\left(\frac{\Omega_X}{0.3}\right)^{0.15}\left(\frac{h}{0.65}\right)^{1.3}\left(\frac{\mathrm{keV}}{m_X}\right)^{1.15} h^{-1}\ \mathrm{Mpc}\ .$$

Cold Collisionless Dark Matter





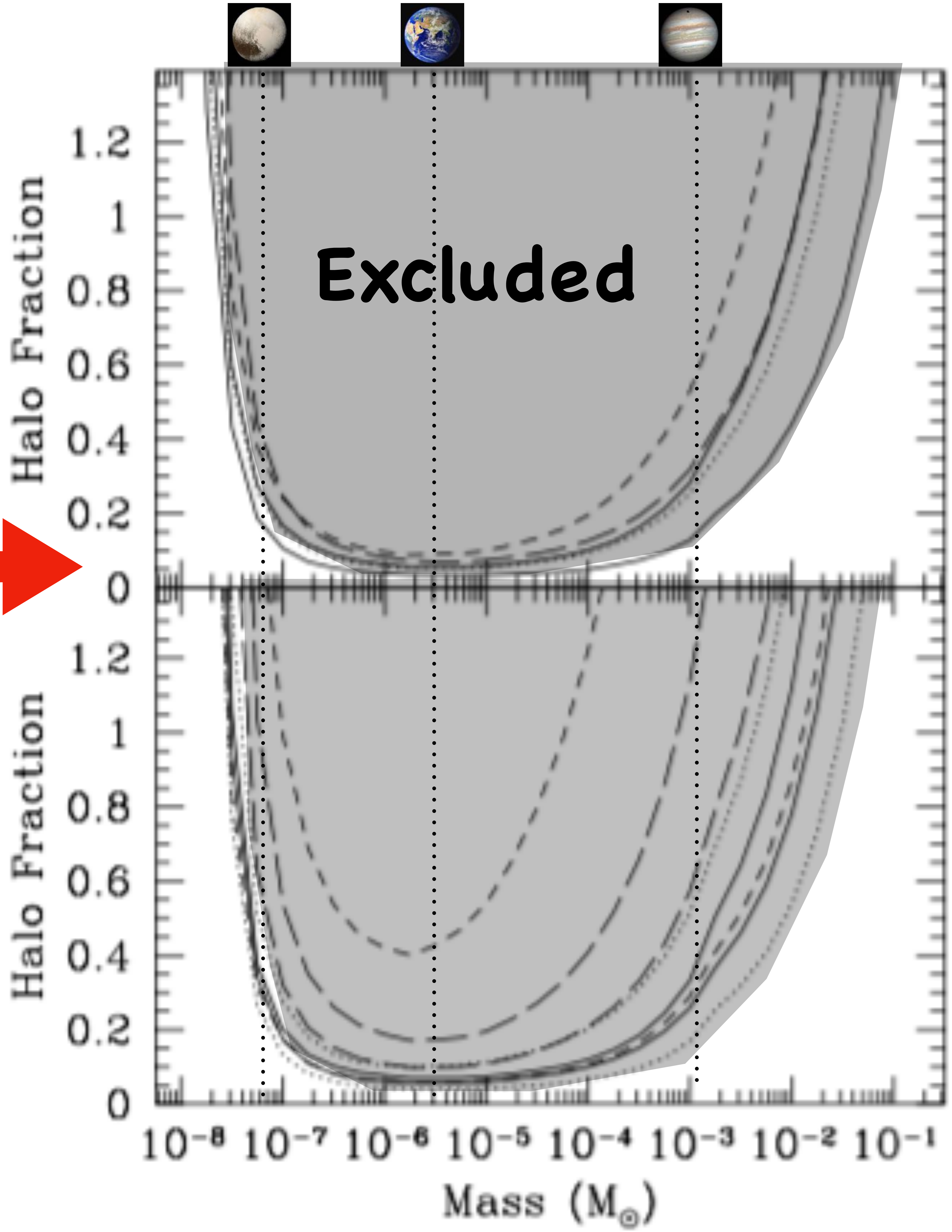
1404.7012

Assuming NO interaction

MACHOs

EROS & MACHO experiments

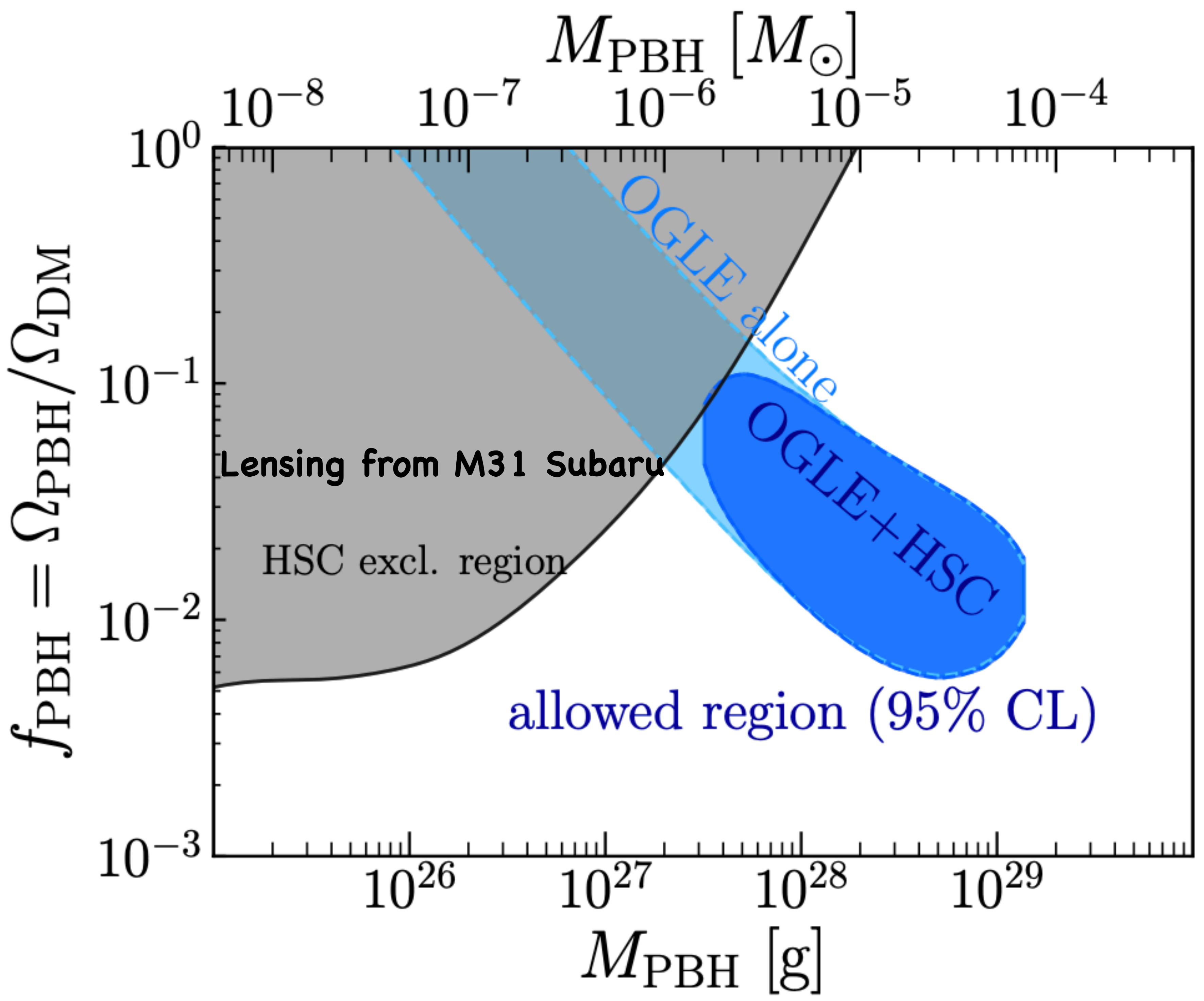
Tiny fraction of our
MW halo allowed but …



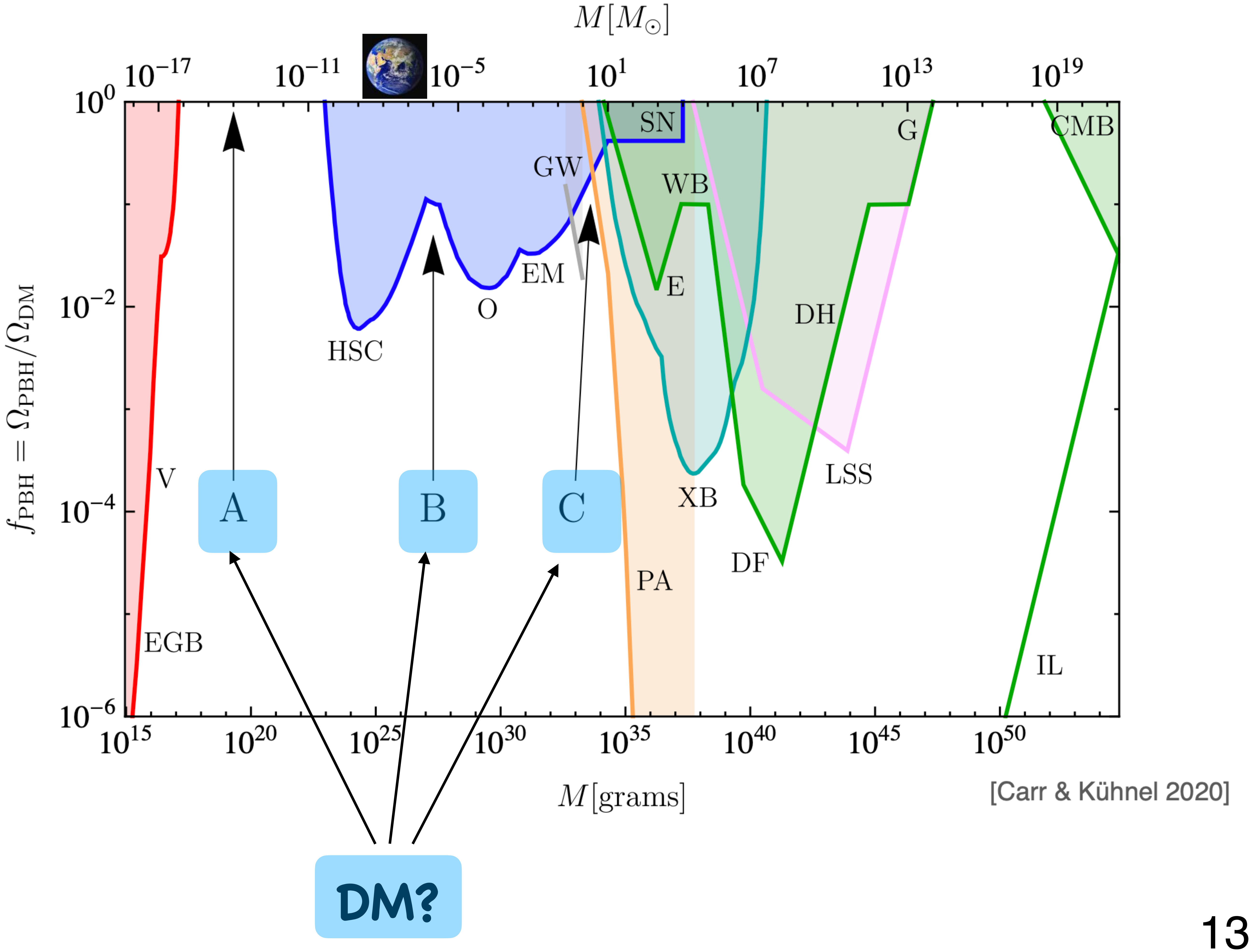
Primordial Black Holes

(See Kuhnel's talk at DSU2022 + papers)

OGLE detected events (0.1-0.3 days light curve timescale)
18/58 events consistent with 2-5 Msol PBH



[Niikura *et al.* 2019]

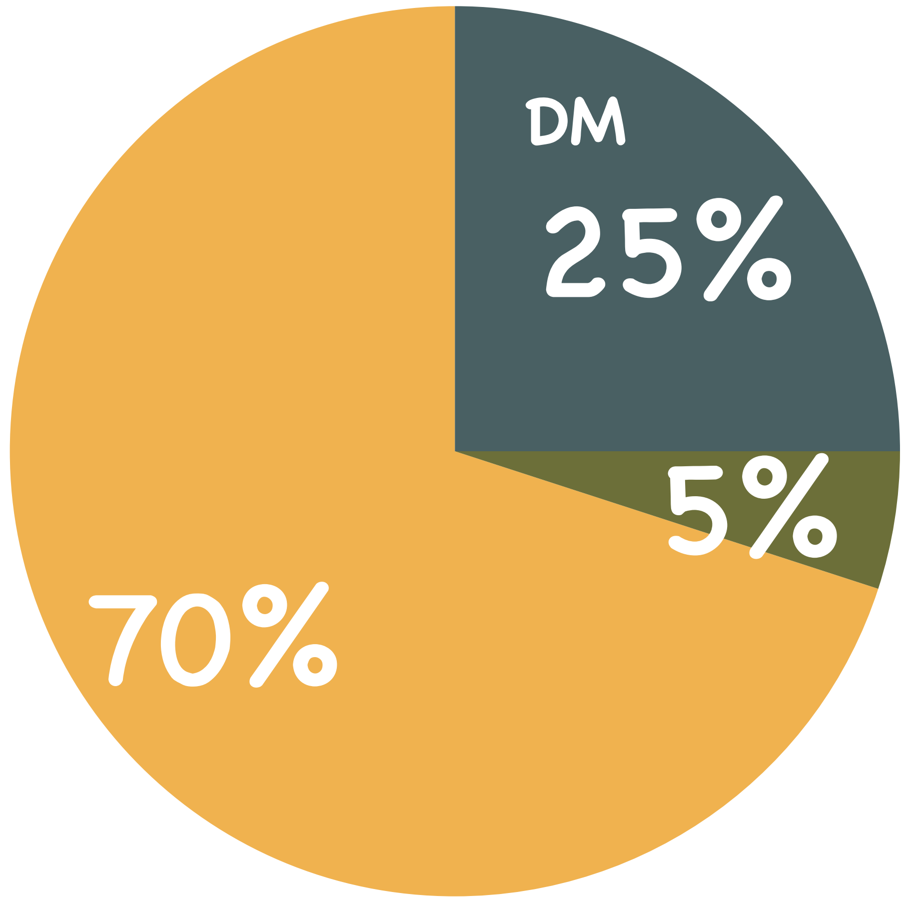


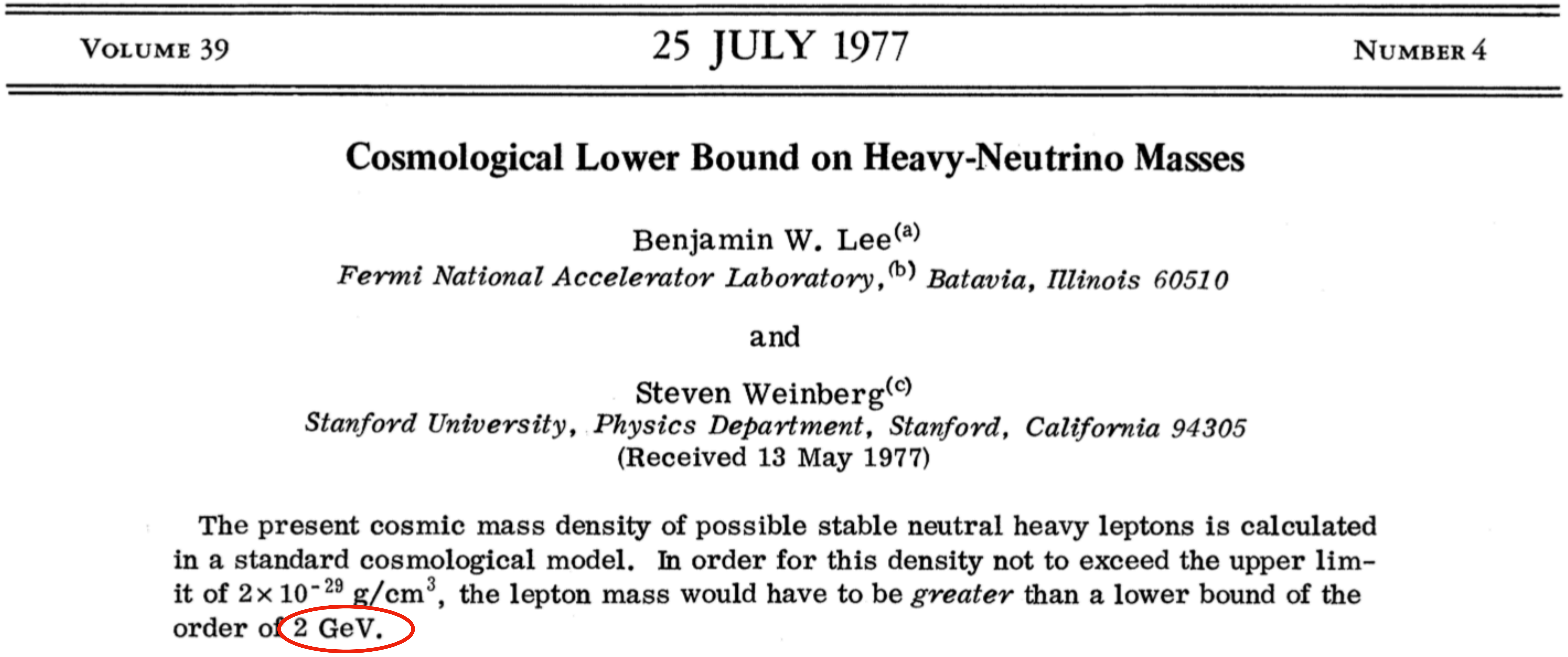
[Carr & Kühnel 2020]

The “missing mass” beyond Standard Physics

“Dark Matter”

Also Hut 1977




Volume 39 25 July 1977 Number 4

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

and

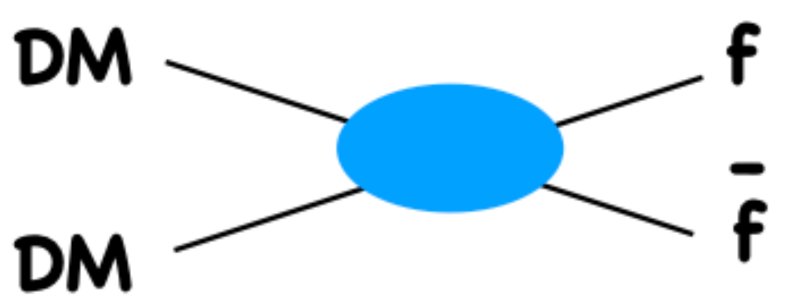
Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305

(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

$$m_\nu < 2\text{eV} \;\; or \;\; \text{m}_\nu > 2\text{GeV}$$

Massive weakly interacting particles



Collisionless (to avoid dissipation) but annihilation

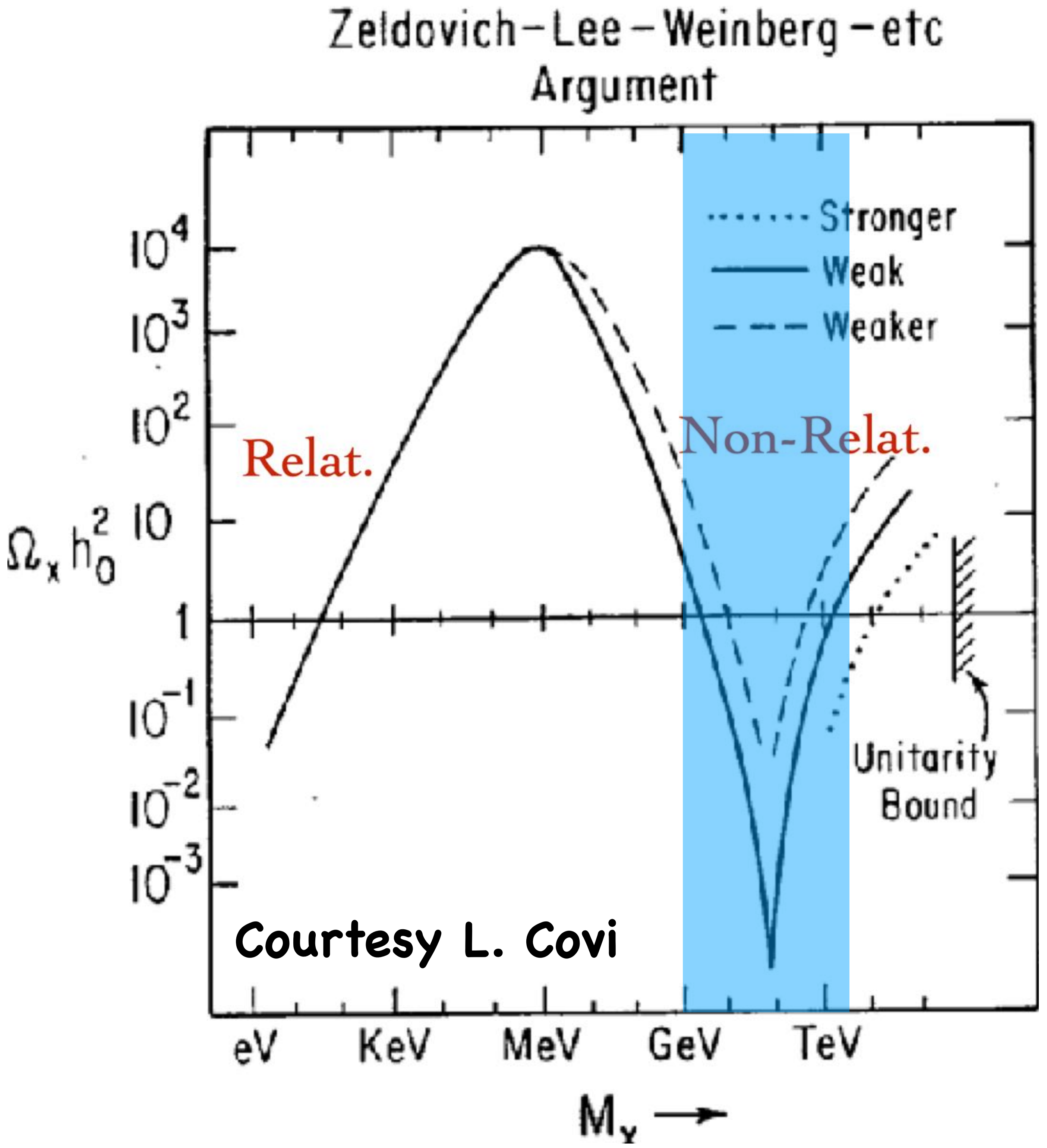
Thermal DM

$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2) \rightarrow \Omega h^2 \simeq \frac{3\times 10^{-27} cm^3/s}{\langle \sigma v\rangle}$$

Planck 2018

Hut, Lee&Weinberg 77

Zeldovich–Lee–Weinberg–etc Argument



Courtesy L. Covi

Add some hypothesis about the DM nature (heavy neutrino)

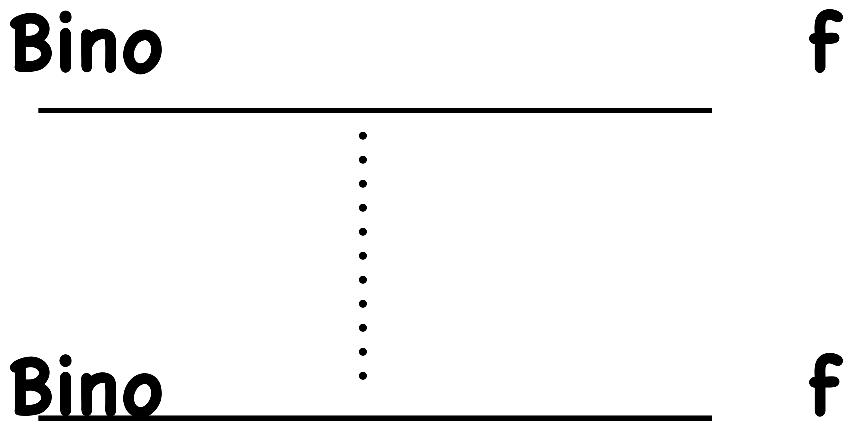
$$\sigma v \propto \frac{m_{DM}^2}{m_W^4}$$

Impose that this cross section explains the relic density

$$\sigma v \propto \frac{m_{DM}^2}{m_W^4} \simeq 3 - 10 \times 10^{-26}\ cm^3/s$$

Supersymmetric WIMPS

https://arxiv.org/pdf/hep-ph/9810360.pdf



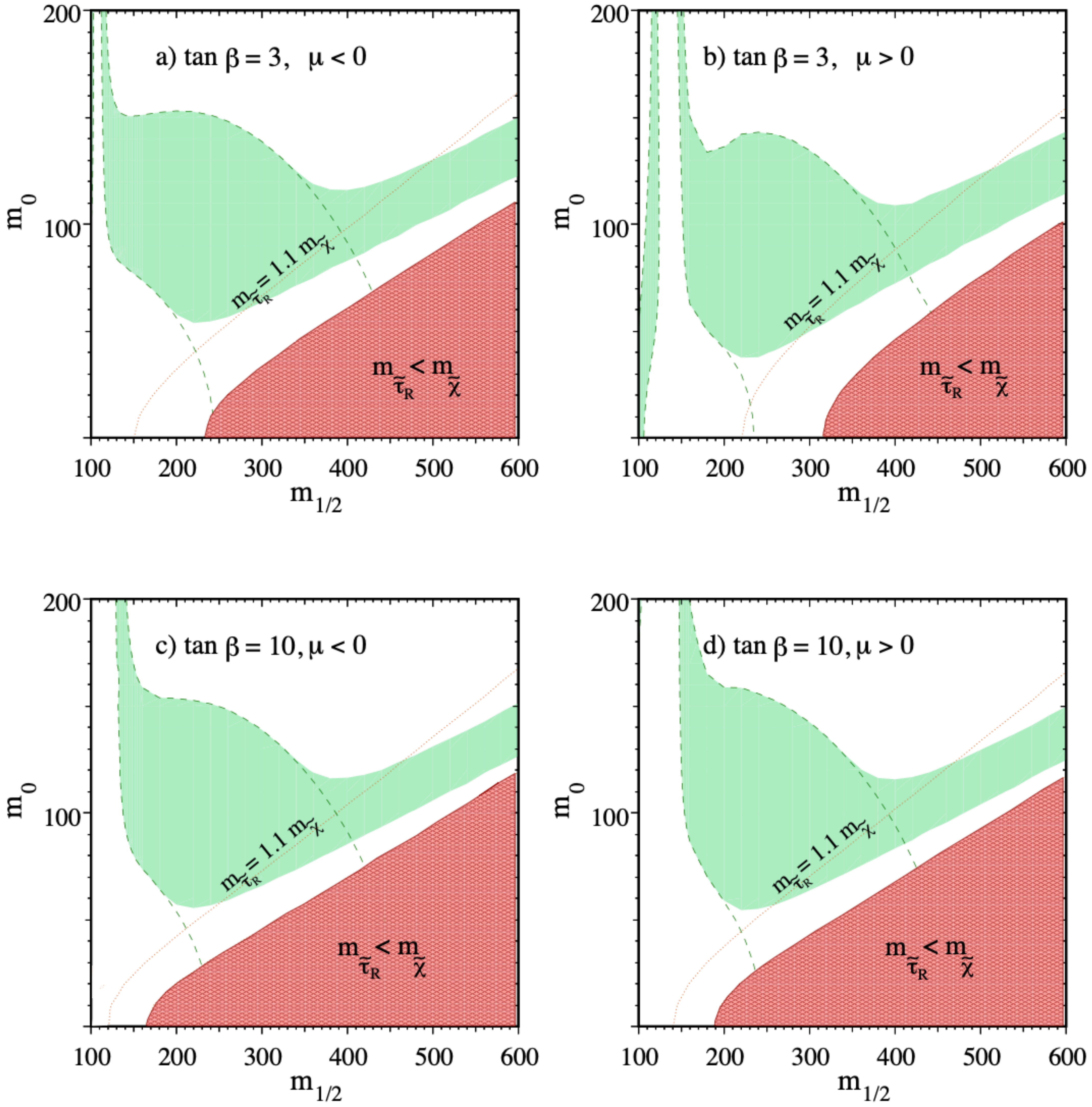
$$\langle \sigma v \rangle = (1 - \frac{m_f^2}{m_{\widetilde{B}}^2})^{1/2} \frac{g_1^4}{128\pi} \left[(Y_L^2 + Y_R^2)^2 (\frac{m_f^2}{\Delta_f^2}) + (Y_L^4 + Y_R^4)(\frac{4m_{\widetilde{B}}^2}{\Delta_f^2})(1 + \ldots)\, x \right]$$

Table 1: Initial and Final States for Coannihilation: $\{i, j = \tau, e, \mu\}$

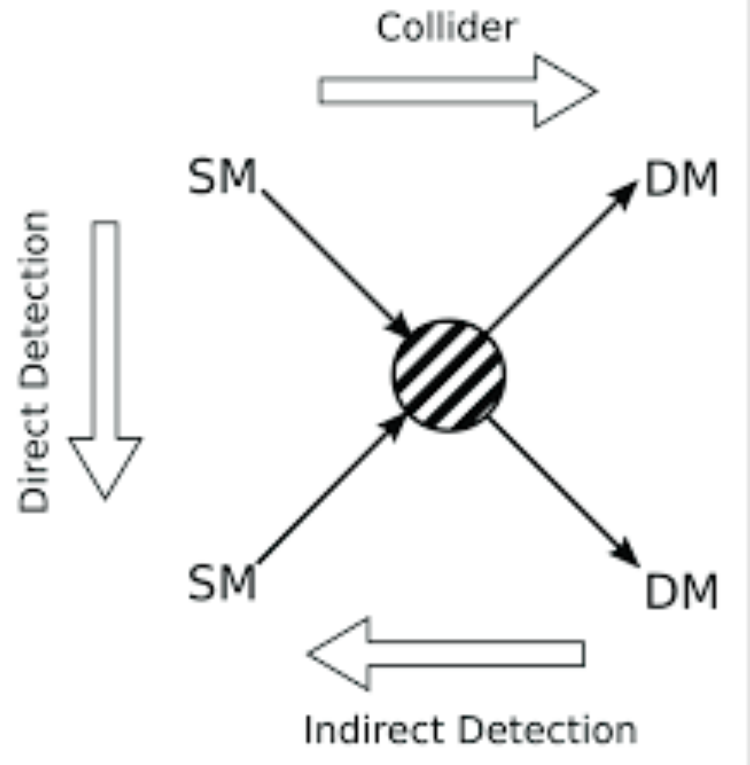
Initial State	Final States
$\widetilde{\ell}^i_R \widetilde{\ell}^{i*}_R$	$\gamma\gamma,\ ZZ\,,\ \gamma Z,\ W^+W^-,\ hh,\ \ell^i\bar{\ell}^i$
$\widetilde{\ell}^i_R \widetilde{\ell}^j_R$	$\ell^i\ell^j$
$\widetilde{\ell}^i_R \widetilde{\ell}^{j*}_R,\ i \neq j$	$\ell^i\bar{\ell}^j$
$\widetilde{\ell}^i_R \widetilde{\chi}$	$\ell^i\gamma, \ell^i Z, \ell^i h$

Neutralino mass >> GeV and
within the reach of LHC (or just at the limit)

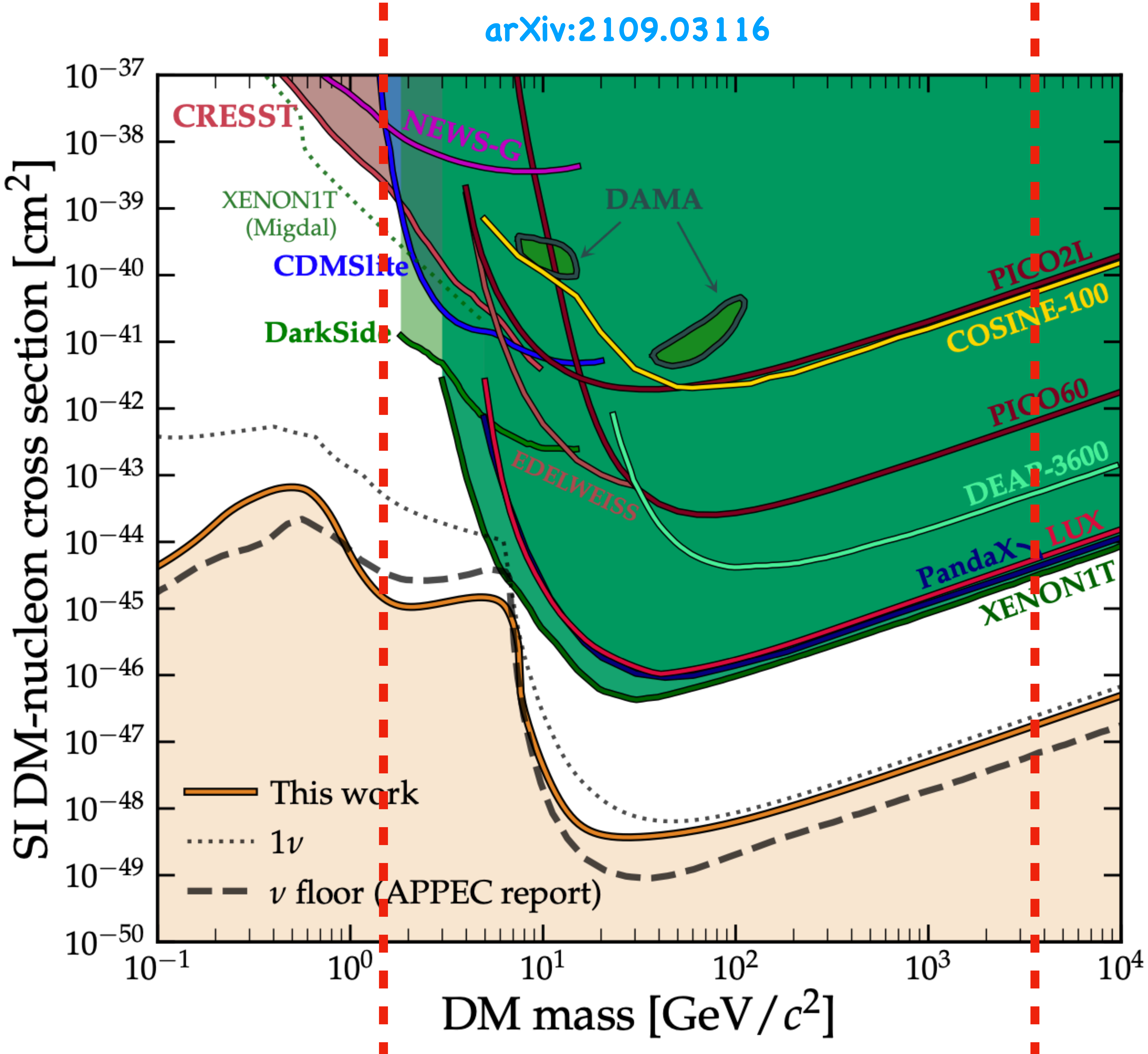
Neutralino-stau co-annihilation



Direct detection constraints

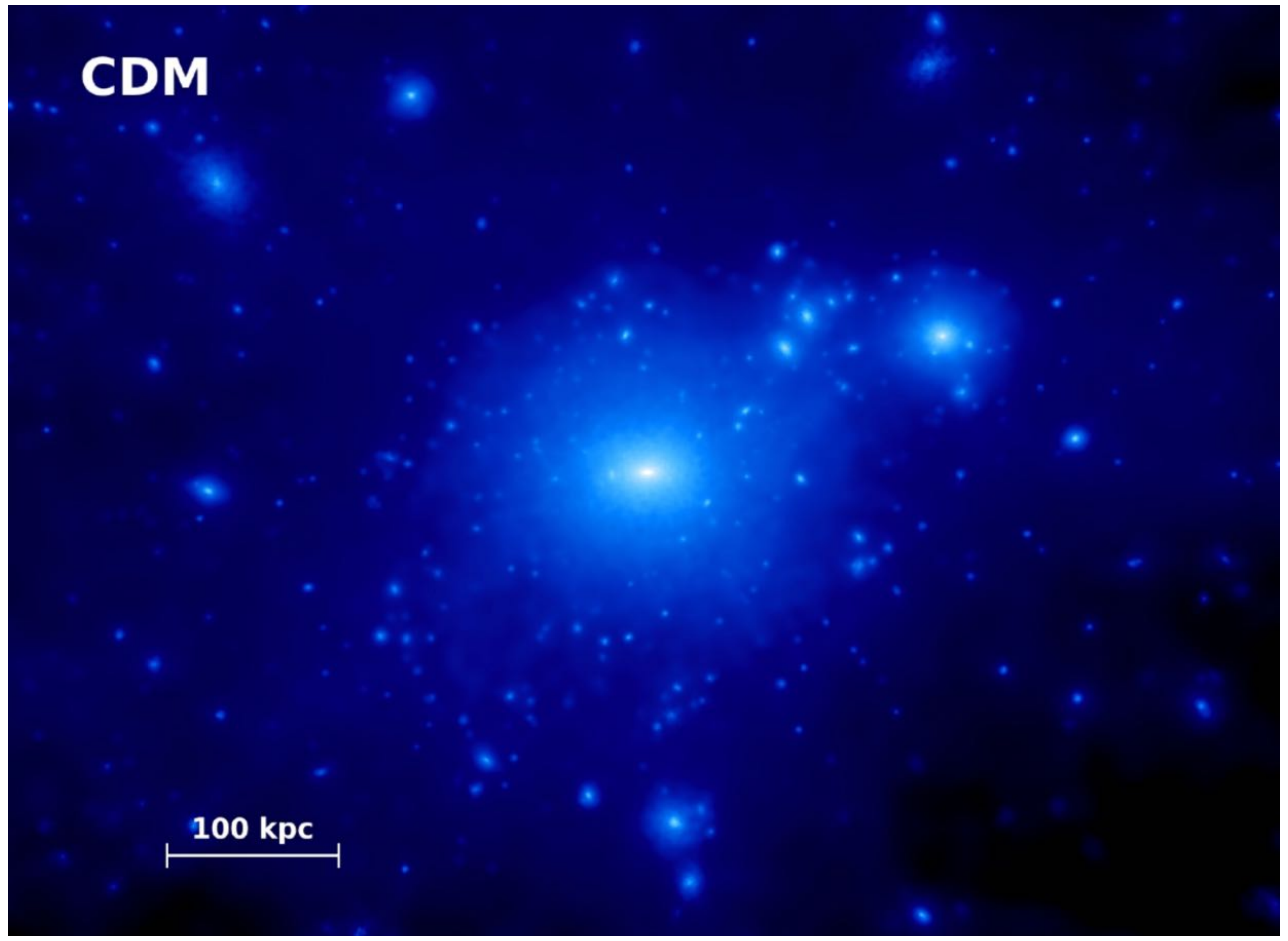


Annihilations



But here is a contradiction

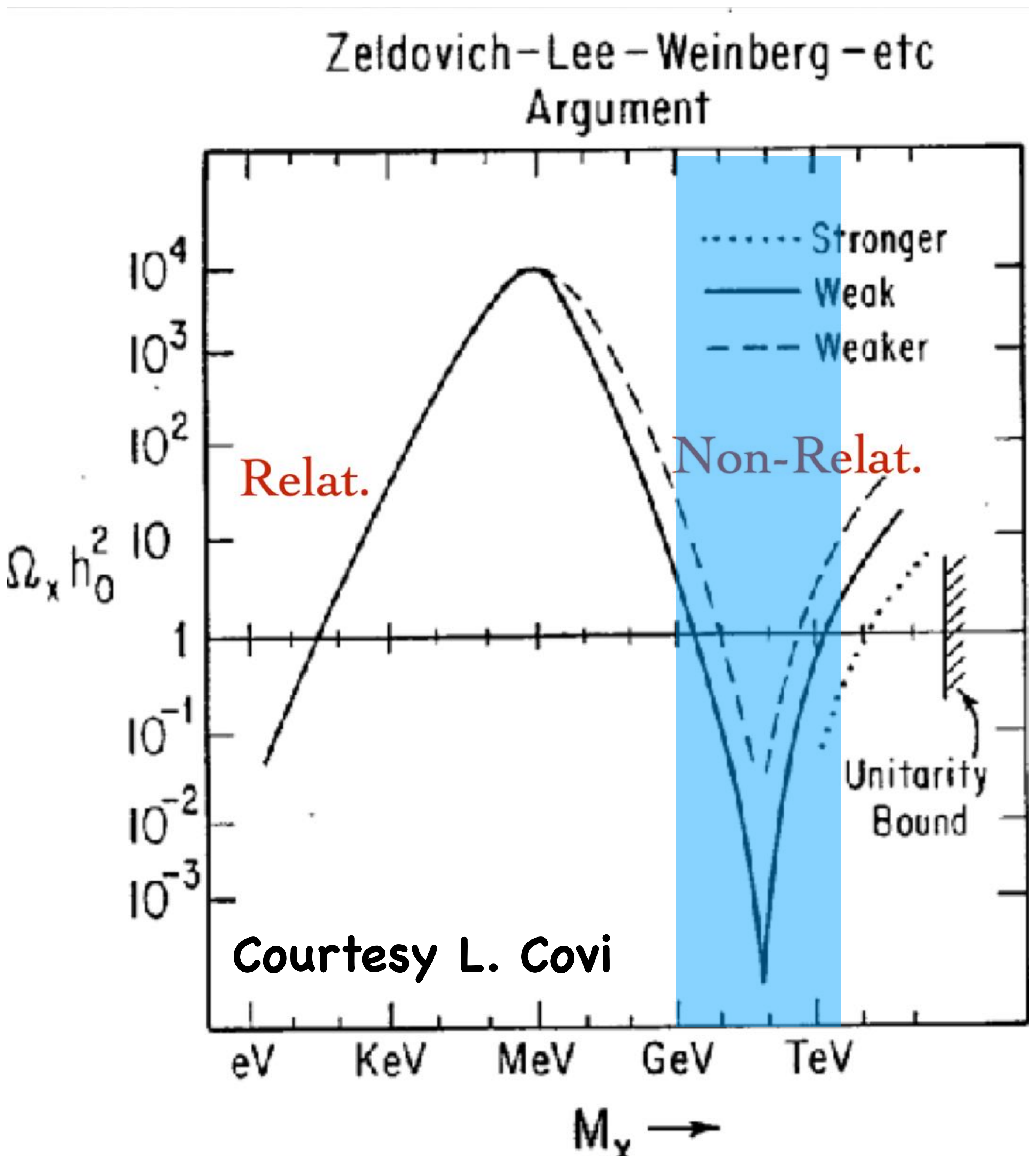
Dark matter is supposedly collisionless but it does annihilate and therefore must be heavier than a proton



Cosmology	Particle Physics	Cosmology
$\sigma = 0$	$\sigma_{ann} \sim \sigma_{weak}$	$\sigma_{SIDM} \sim \sigma_T$

Hold on...

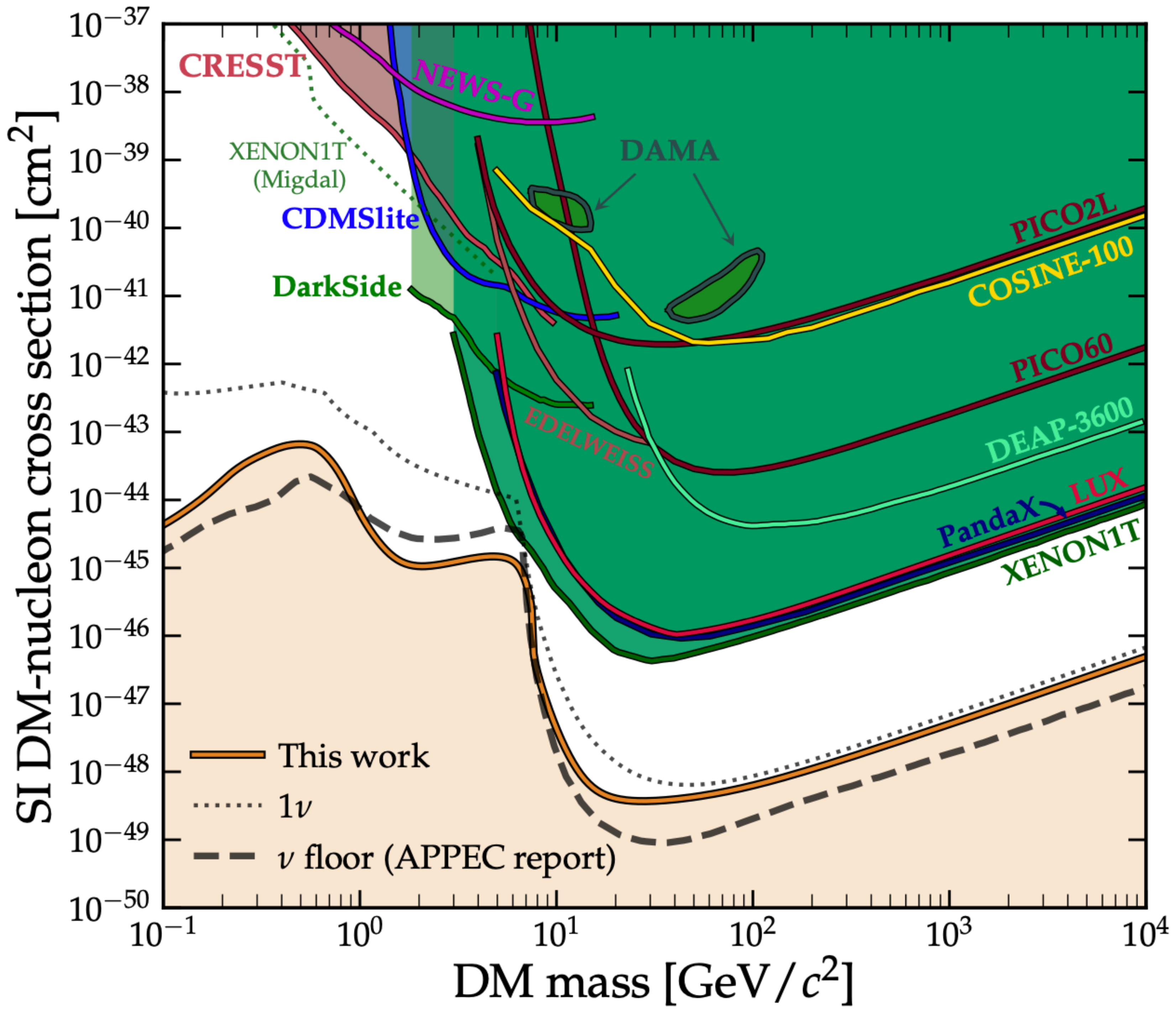
Collisionless but annihilations



Courtesy L. Covi

DM is heavy

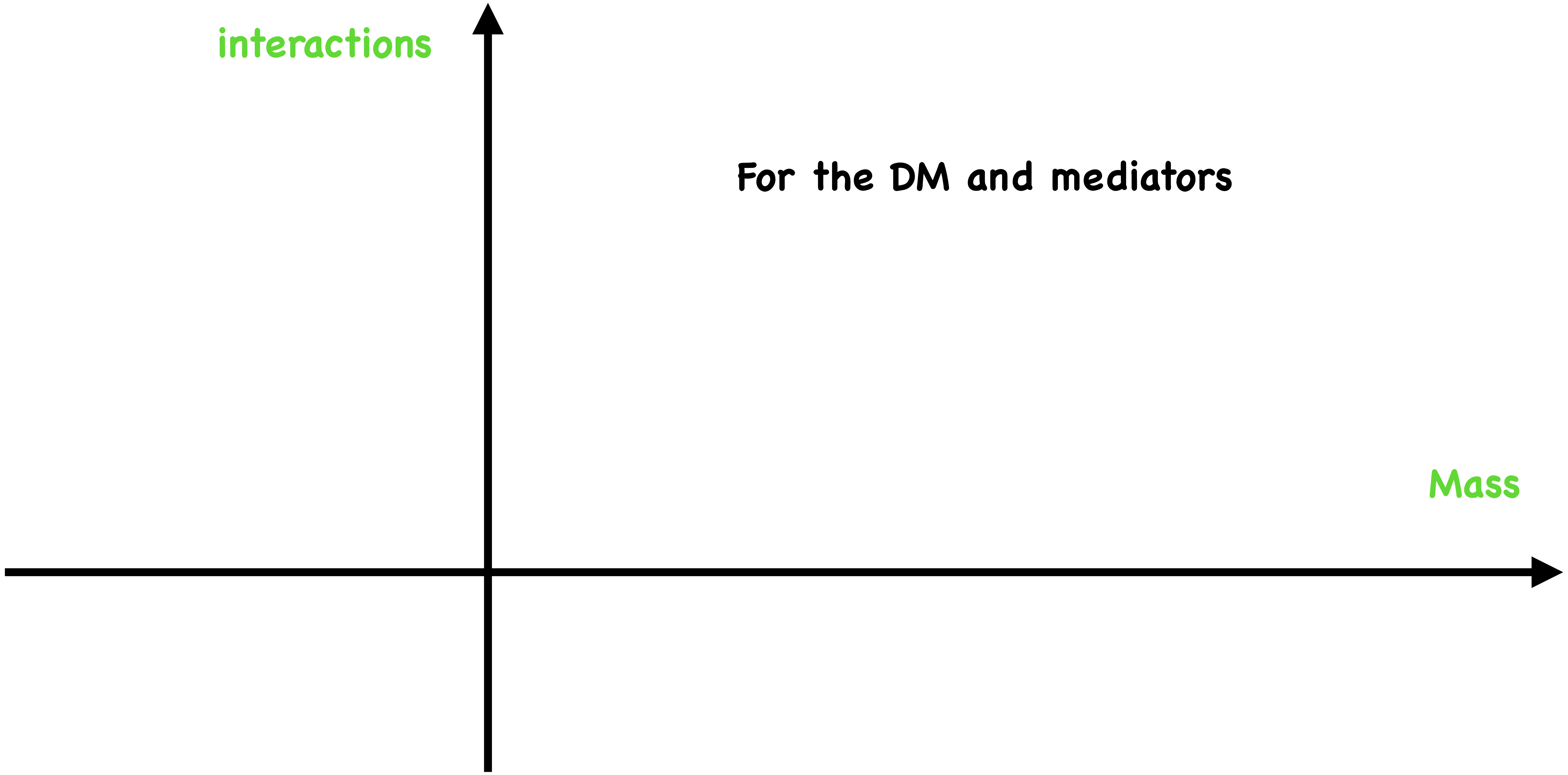
Scattering with nuclei



So DM can scatter off SM particles???

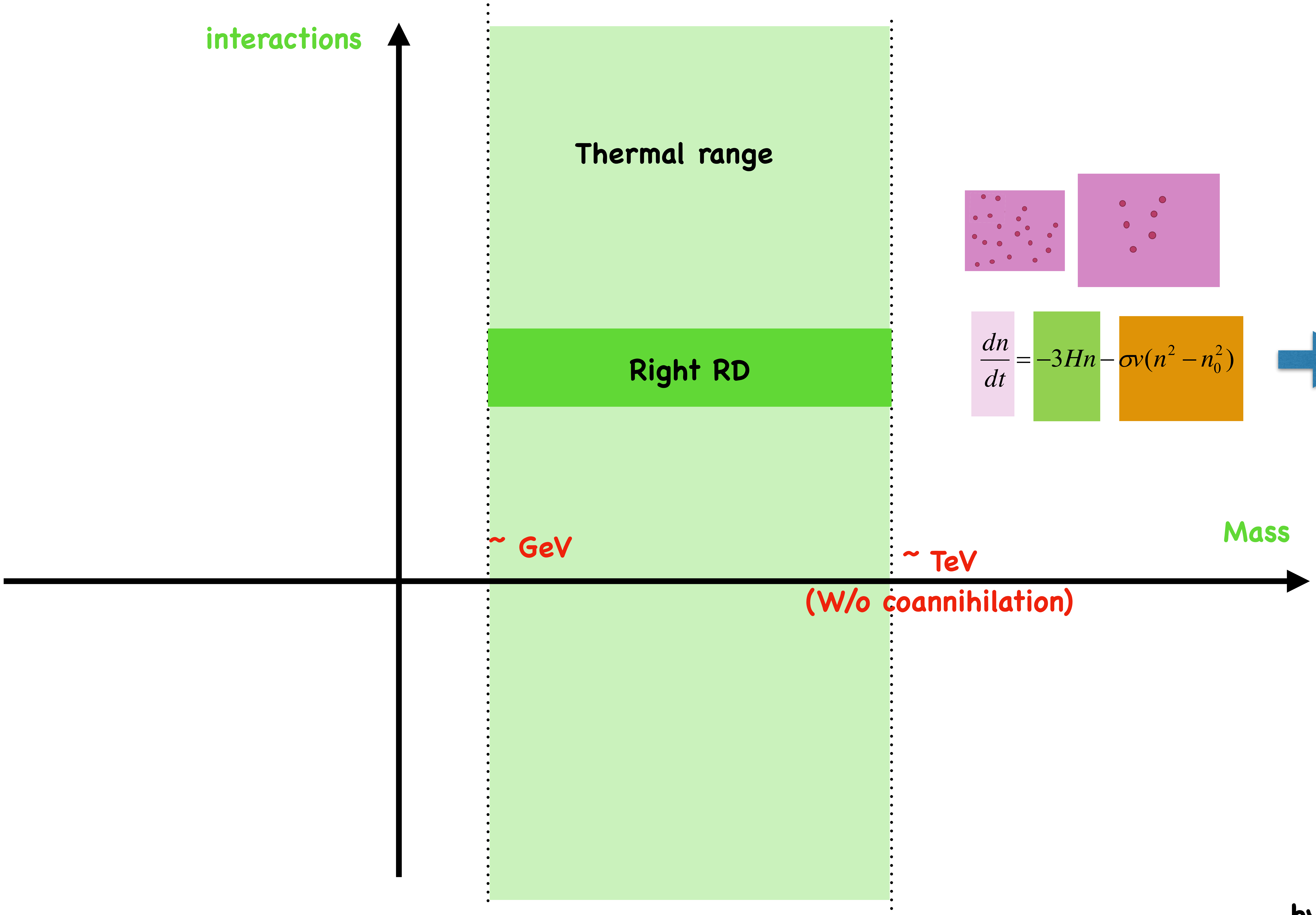
How to characterise Dark Matter?

GR + SU(3)XSU(2)XU(1) X ??



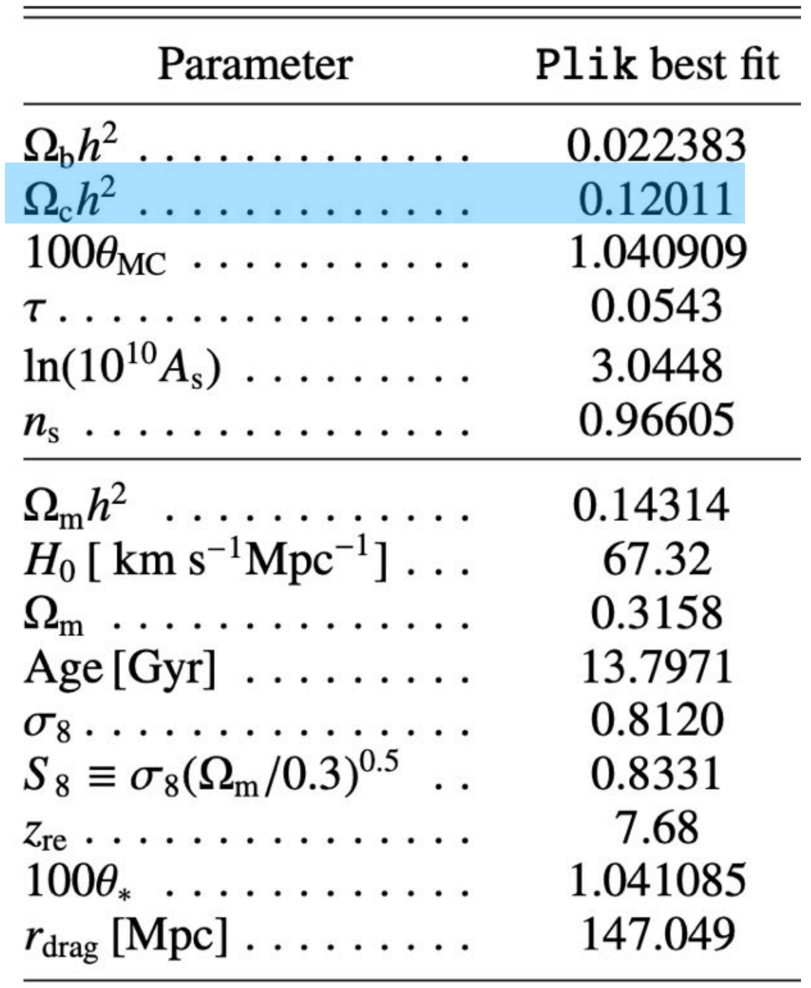
Mass, spin, Quantum numbers, interactions…

Dark Matter mass range (historically)



$$\frac{dn}{dt} = -3Hn - \sigma v(n^2 - n_0^2)$$

$$\Omega h^2 \simeq \frac{3\times 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle}$$



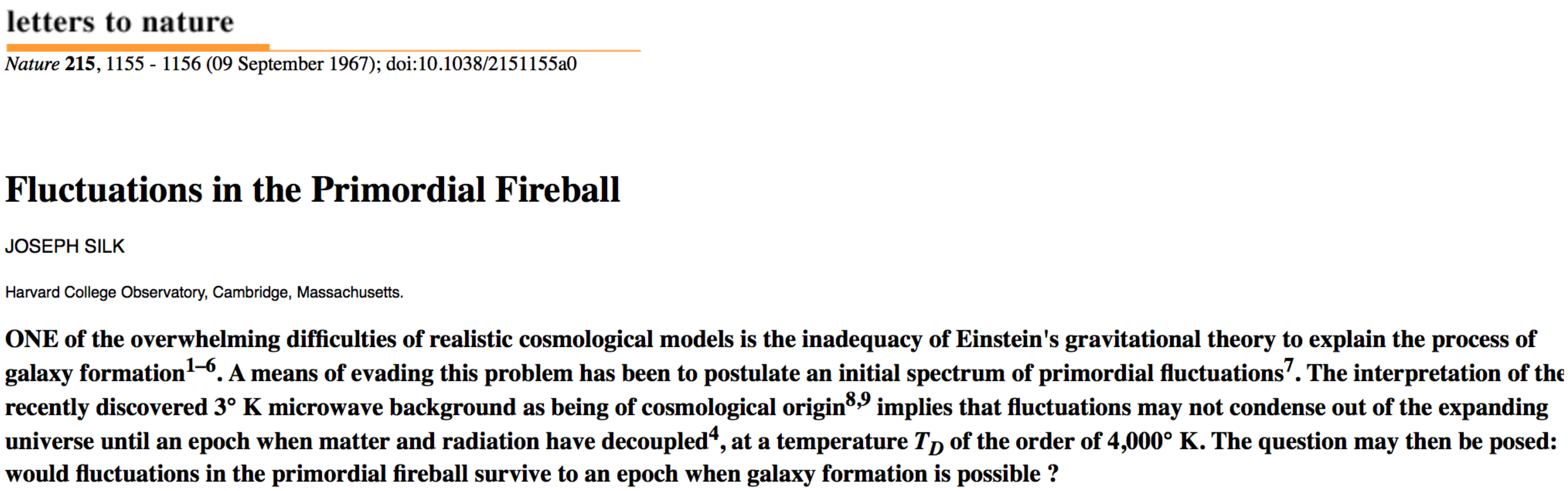
Parameter	Plik best fit
$\Omega_b h^2$	0.022383
$\Omega_c h^2$	0.12011
$100\theta_{MC}$	1.040909
τ	0.0543
$\ln(10^{10}A_s)$	3.0448
n_s	0.96605
$\Omega_m h^2$	0.14314
H_0 [km s^{-1}Mpc^{-1}]	67.32
Ω_m	0.3158
Age [Gyr]	13.7971
σ_8	0.8120
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.8331
z_{re}	7.68
$100\theta_*$	1.041085
r_{drag} [Mpc]	147.049

$$\boxed{\sigma v \sim 3\ 10^{-26}\ \mathrm{cm}^3/\mathrm{s}}$$

Range of interactions is given by experimental value & error bars

How can we constrain the elastic scattering other than by using detectors?

Effect of collisions in cosmology



letters to nature

Nature **215**, 1155 - 1156 (09 September 1967); doi:10.1038/2151155a0

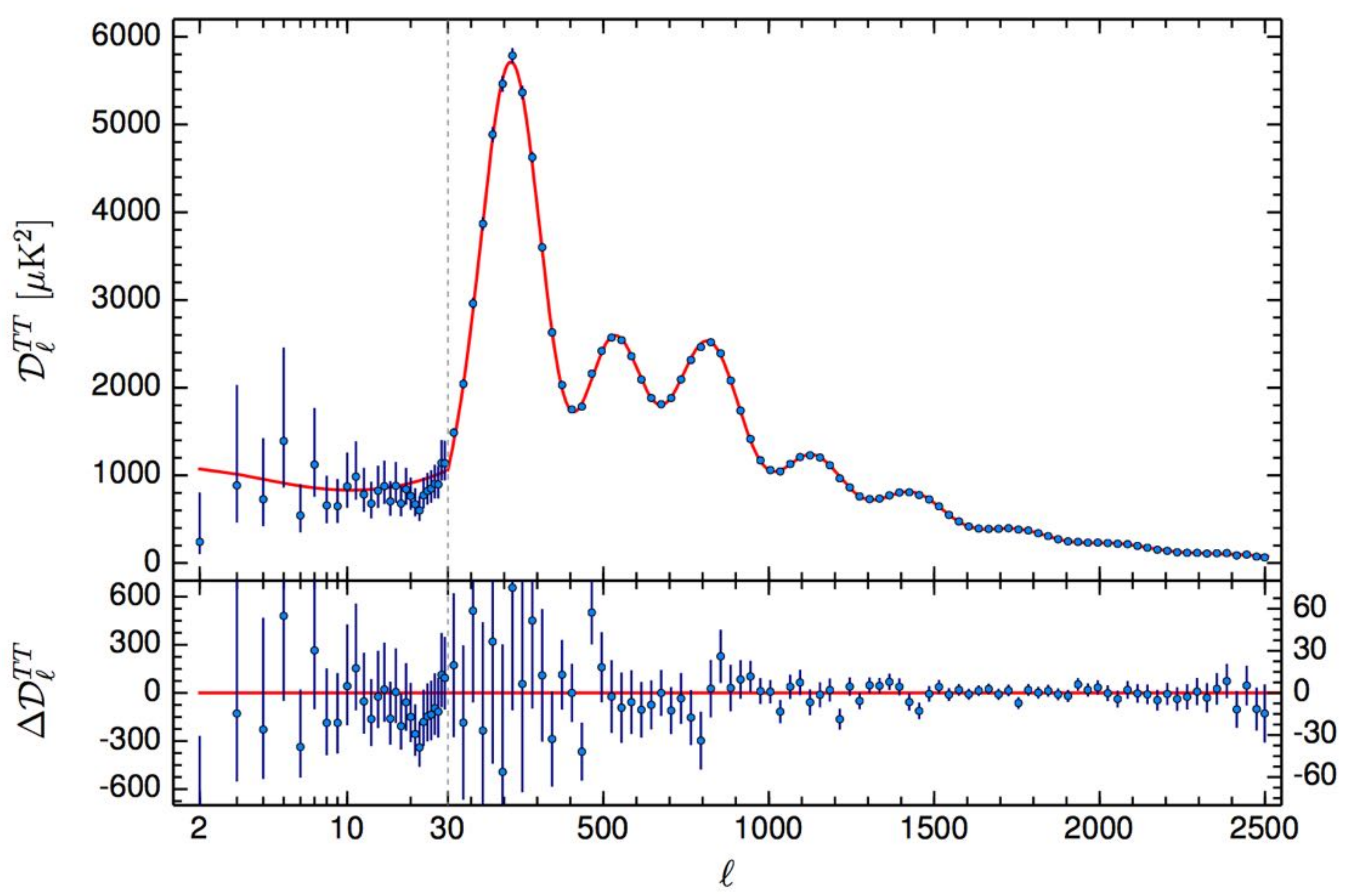
Fluctuations in the Primordial Fireball

JOSEPH SILK

Harvard College Observatory, Cambridge, Massachusetts.

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's gravitational theory to explain the process of galaxy formation[1–6]. A means of evading this problem has been to postulate an initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature T_D of the order of 4,000° K. The question may then be posed: would fluctuations in the primordial fireball survive to an epoch when galaxy formation is possible ?

Planck Collaboration: The *Planck* mission



Silk damping

The photon fluctuations are erased

but so are baryonic fluctuations!

And the rest can also be erased due to free-streaming

Effect of collisions in cosmology

Silk damping revisited

$$l_{Silk}^2 \simeq \frac{2\pi^2}{3} \int^{t_{dec(b-\gamma)}} \frac{c^2\,\rho_\gamma}{\rho_{tot}\ a^2\ \Gamma_\gamma}\ \left(1+\Theta_\gamma\right)\ dt$$

Boehm-Schaeffer 2000, 2004 using Weinberg 1971 & Chapman, Cowling 1970

Generalising the Silk damping

$$l_{cd}^2 \simeq \frac{2\pi^2}{3} \sum_i \int^{t_{dec(DM-i)}} \frac{v_i^2\,\rho_i}{\rho_{tot}\ a^2\ \Gamma_i}\ \left(1+\Theta_i\right)\ dt$$

And the free-streaming

$$l_{fs}^2 \propto \int_{t_{dec(DM)}}^{t_0} \frac{v}{a(t)}\,dt$$

Maximising the collisional damping

$$l^2_{DM-\gamma} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-\gamma)}} \frac{c^2\, \rho_\gamma}{\rho_{tot}\; a^2\; \Gamma_\gamma}\, dt$$

~ **Silk damping**

$$l^2_{DM-\nu} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-\nu)}} \frac{c^2\, \rho_\nu}{\rho_{tot}\; a^2\; \Gamma_\nu}\, dt$$

New and new regime **(Like b-nu interactions by Misner 1966)**

$$l^2_{DM-b} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-b)}} \frac{v^2\, \rho_b}{\rho_{tot}\; a^2\; \Gamma_b}\, dt$$

Inefficient unless dark Coulomb interactions

$$l^2_{DM-DM} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-DM)}} \frac{v^2\, \rho_{DM}}{\rho_{tot}\; a^2\; \Gamma_{DM}}\, dt$$

Self-Interacting

DM-neutrino collisional damping

$$l^2_{DM-\nu} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-\nu)}} \frac{c^2 \rho_\nu}{\rho_{tot}\ a^2\ \Gamma_\nu}\, dt \quad \text{with} \quad \Gamma_\nu \equiv \sum_i \Gamma_{dec(\nu-i)}$$

	SM	**BSM**
Collisional damping	$\Gamma_{\nu-e} > \Gamma_{\nu-DM}$ $\Gamma_\nu > \Gamma_{DM-\nu}$	$\Gamma_{\nu-DM} > \Gamma_{\nu-e}$ $\Gamma_\nu > \Gamma_{DM-\nu}$
Mixed damping	$\Gamma_{\nu-e} > \Gamma_{\nu-DM}$ $\Gamma_{DM-\nu} > \Gamma_\nu$	$\Gamma_{\nu-DM} > \Gamma_{\nu-e}$ $\Gamma_{DM-\nu} > \Gamma_\nu$

$$l^2_{DM-\nu} \simeq \frac{2\pi^2}{3} \int^{t_{dec(DM-\nu)}} \frac{c^2 \rho_\nu}{\rho_{tot}\ a^2\ H}\, dt$$

DM stays coupled to free-streaming neutrinos (i.e. < MeV): the lighter the DM, the more efficient

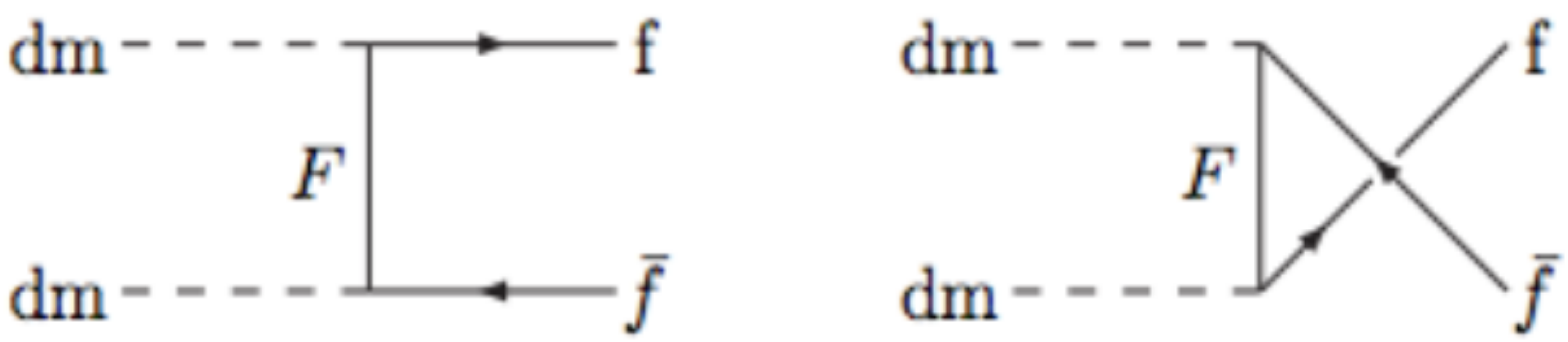
Can the annihilation cross section be independent of the dark matter mass?

Can dark matter be lighter than a proton?

hep-ph/0305261

$$\Omega h^2 \simeq \frac{3\times 10^{-27} cm^3/s}{\langle \sigma v \rangle} \quad \oplus \quad \sigma v \propto \frac{m_{DM}^2}{m_W^4} \quad \Rightarrow$$ **GeV DM**

Take a scalar instead of a fermion and assume new interactions



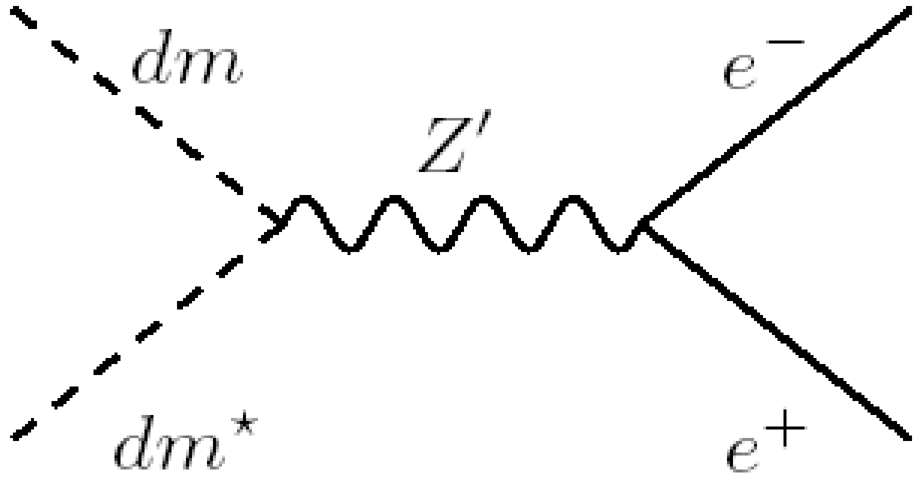
$$\sigma v \propto \frac{1}{m_F^4} \left((C_l^2 + C_r^2) \; m_f + 2 C_l \; C_r \; m_F \right)^2 \quad \Rightarrow \quad \sigma v \propto \frac{C_l^2 C_r^2}{m_F^2}$$

Imposing a specific value for sigma doesn't constrain mdm so DM can be light and it is ok!

Also found by Feng&kumar (0803.4196)

Evading the Lee-Weinberg limit

Boehm & Fayet hep-ph/0305261



$$\sigma v \propto v^2 \, \frac{m_{\rm DM}^2}{m_{Z'}^4} \, g_{\rm DM}^2 \, g_e^2$$

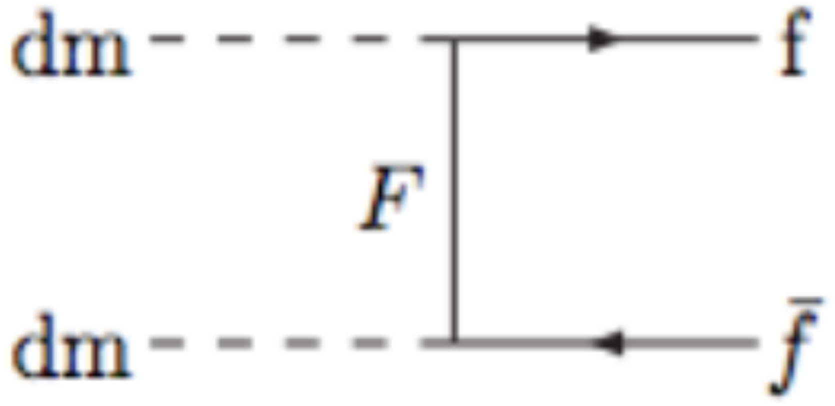
P-wave (but D-wave can be important too)

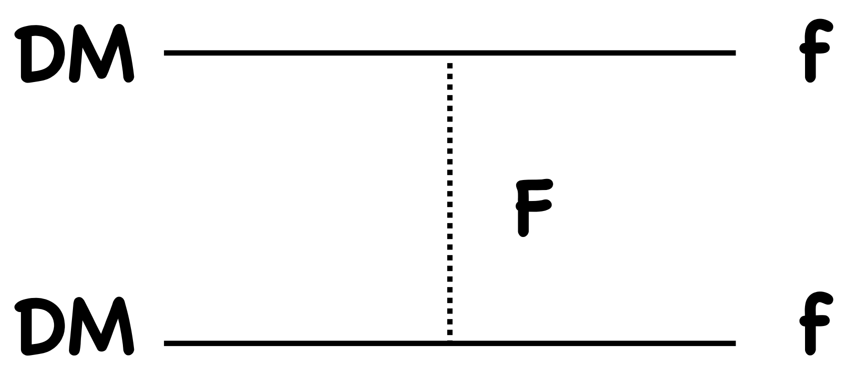
Depends on the DM mass but the cross section can have the right value if mdm = mZ'

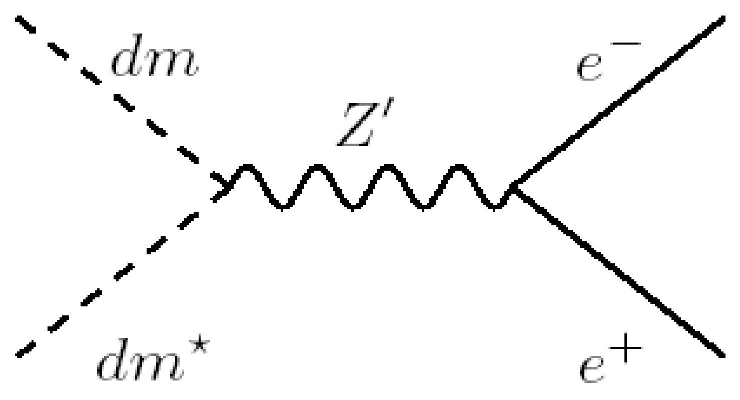
==> viable solution for light DM provided that the dark mediator/dark photon is light

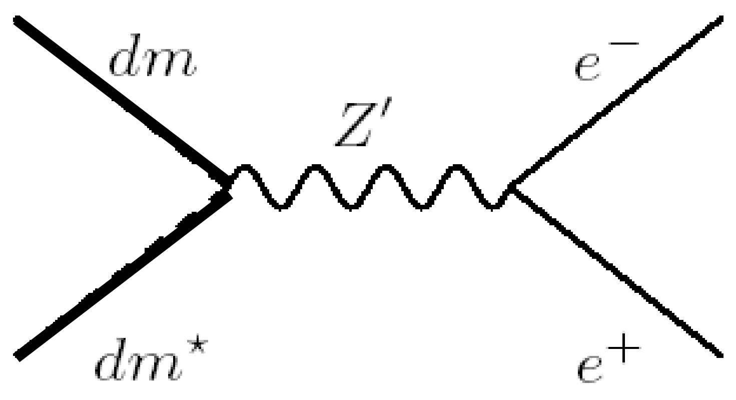
Dark Photons/Z' were used afterwards in a different context: Pamela anomaly, DAMA, Ultra Light DM etc

MeV-GeV range DM : which mediators?









NMSSM-like: light scalar and pseudo scalar (Higgs-like) mediators

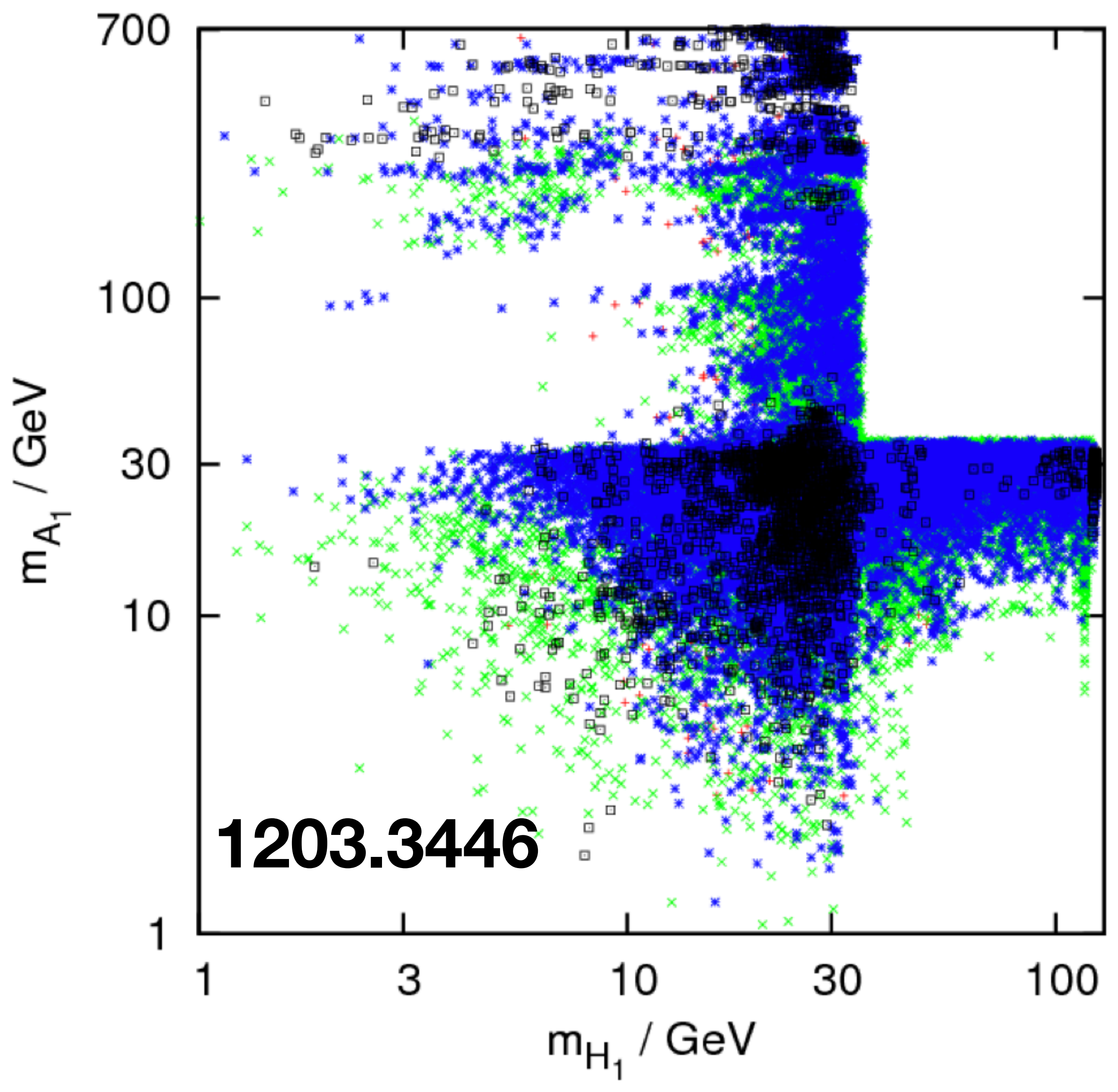


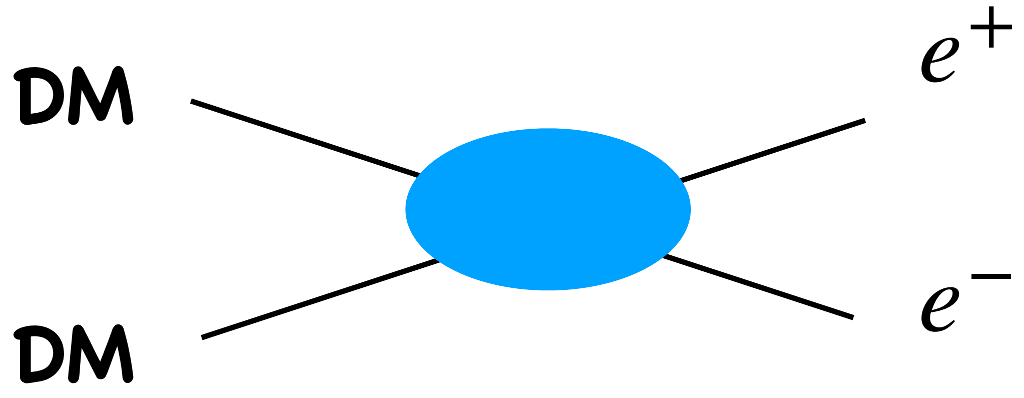
FIG. 2: Masses of the Higgs scalars H_1, H_2 and pseudoscalar A_1. Red points are ruled out either by `HiggsBounds` constraints or the ATLAS 1fb^{-1} jets and missing E_T SUSY search. Green points have no Higgs with a mass in $122-128$ GeV, blue points have a Higgs (H_1 and/or H_2) within this mass range, and black points have such a Higgs with $R_{gg\gamma\gamma} > 0.4$.

Axions?

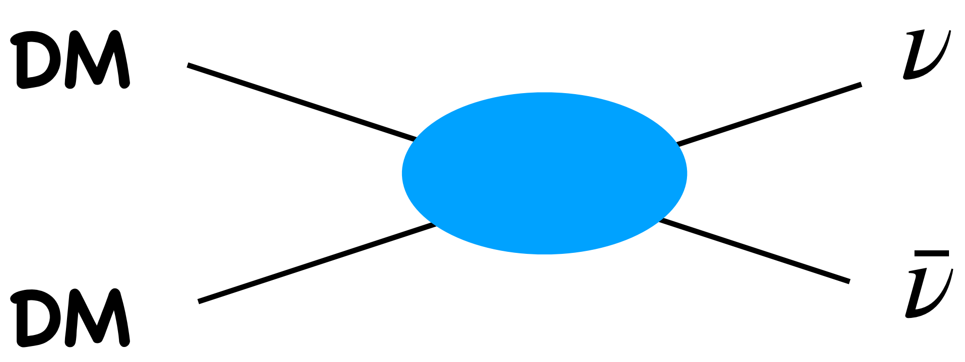
Spin 3/2?

Burst of alternative models/thinking

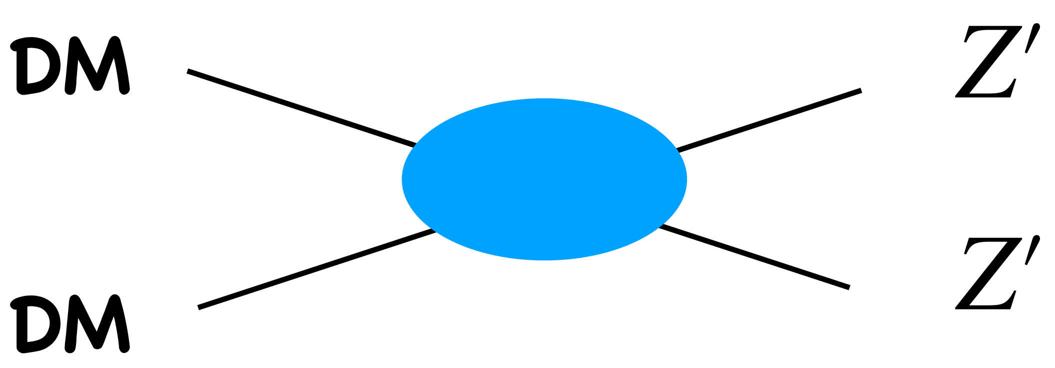
DM can be lighter than a proton but how low can it be?



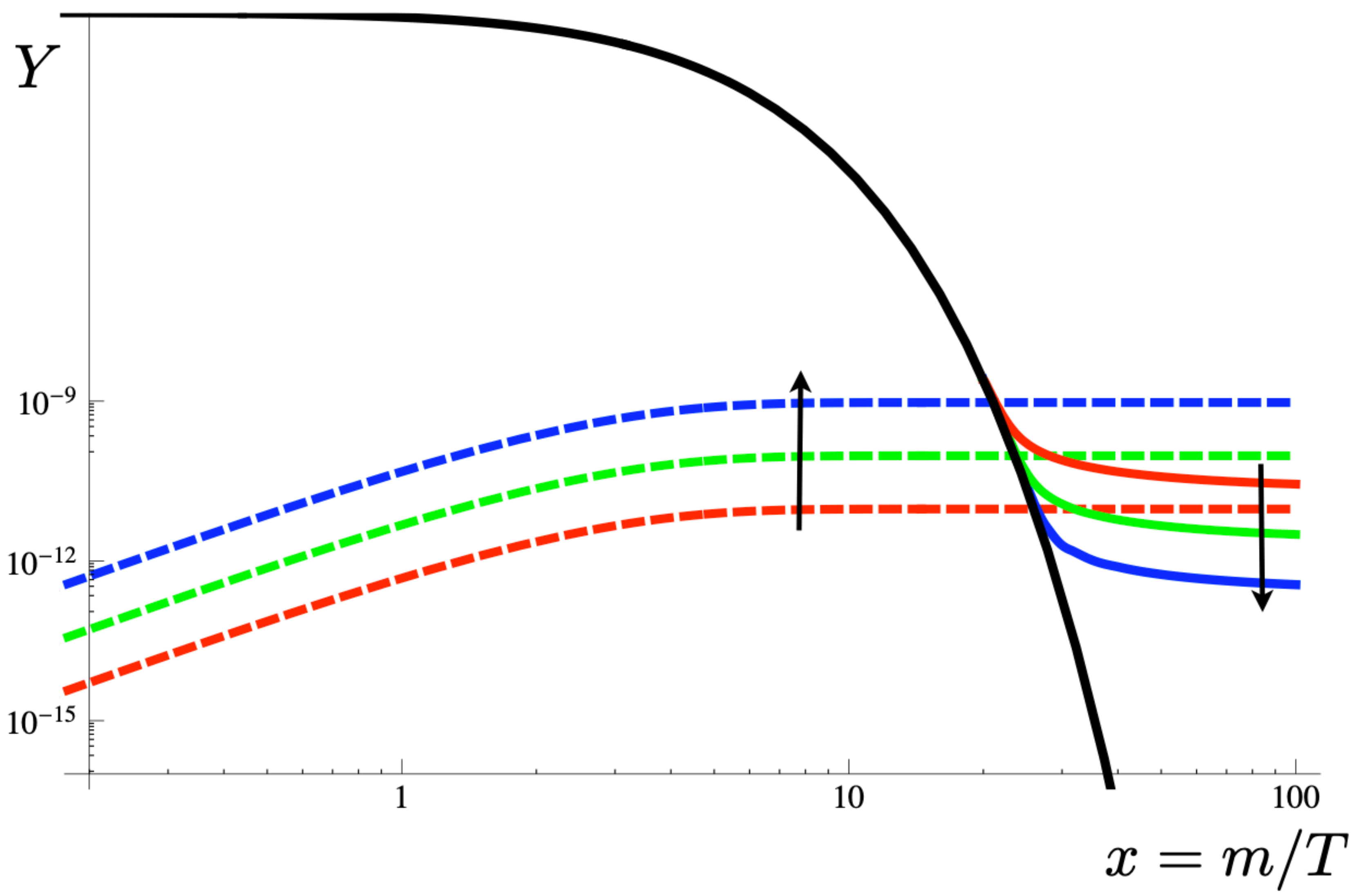
MeV



Sub eV?

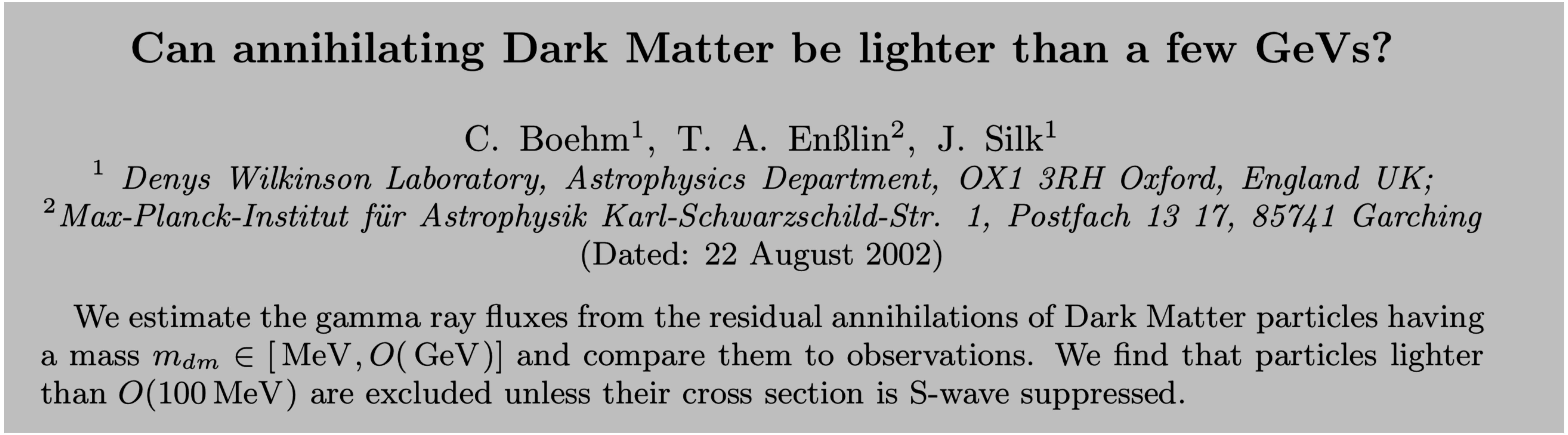


Depends on the dark sector



Should there be annihilations at all?

Asymmetric DM, Freeze-in, non thermal DM

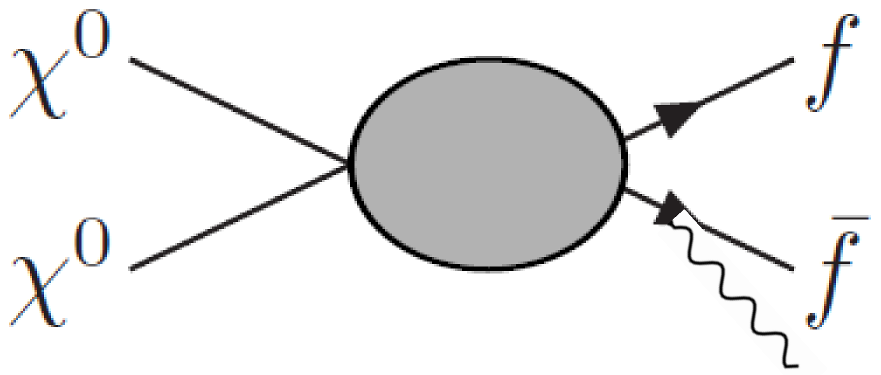


Can annihilating Dark Matter be lighter than a few GeVs?

C. Boehm[1], T. A. Enßlin[2], J. Silk[1]
[1] *Denys Wilkinson Laboratory, Astrophysics Department, OX1 3RH Oxford, England UK;*
[2] *Max-Planck-Institut für Astrophysik Karl-Schwarzschild-Str. 1, Postfach 13 17, 85741 Garching*
(Dated: 22 August 2002)

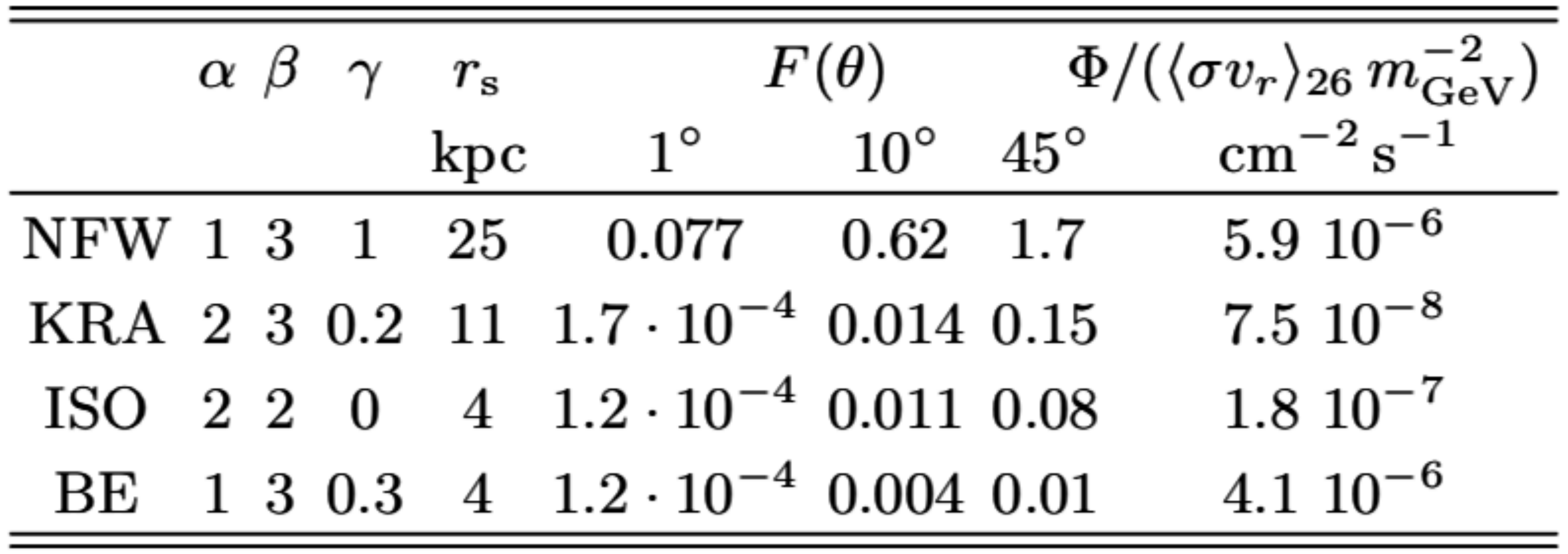
We estimate the gamma ray fluxes from the residual annihilations of Dark Matter particles having a mass $m_{dm} \in [\mathrm{MeV}, O(\mathrm{GeV})]$ and compare them to observations. We find that particles lighter than $O(100\,\mathrm{MeV})$ are excluded unless their cross section is S-wave suppressed.

astro-ph/0208458



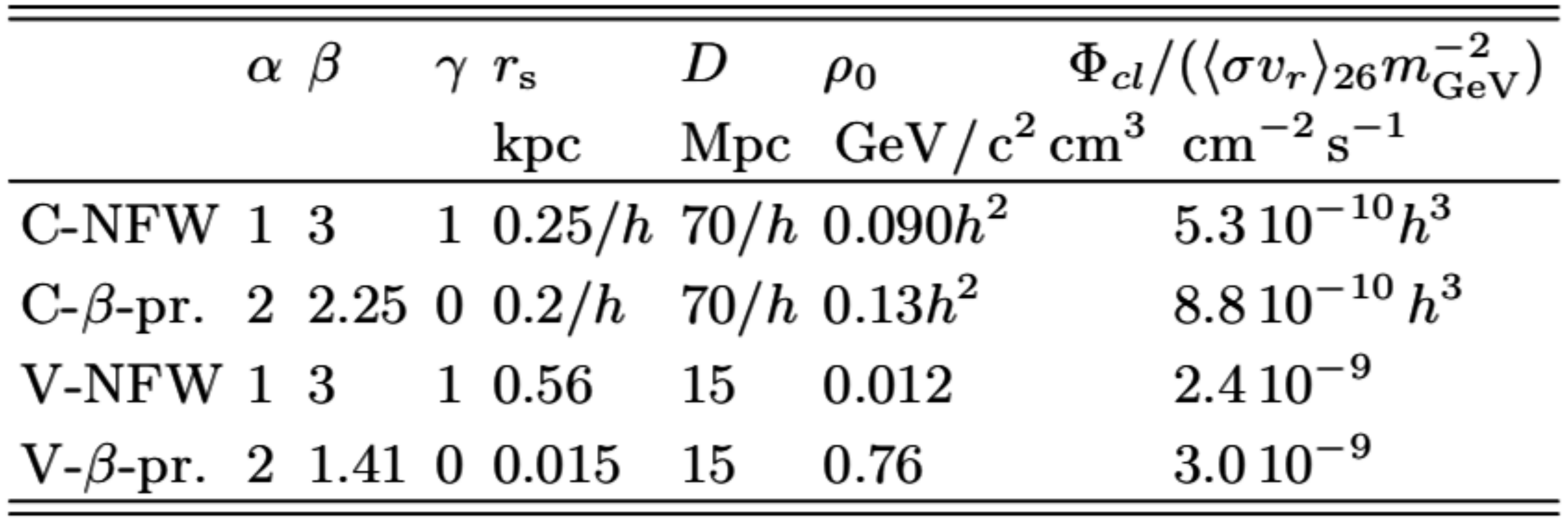
Annihilation for RD needs to be p-wave!

Dark Matter haloes



	α	β	γ	r_s kpc	$F(\theta)$ 1°	10°	45°	$\Phi/(\langle\sigma v_r\rangle_{26}\, m_{\mathrm{GeV}}^{-2})$ cm^{-2} s^{-1}
NFW	1	3	1	25	0.077	0.62	1.7	$5.9\ 10^{-6}$
KRA	2	3	0.2	11	$1.7 \cdot 10^{-4}$	0.014	0.15	$7.5\ 10^{-8}$
ISO	2	2	0	4	$1.2 \cdot 10^{-4}$	0.011	0.08	$1.8\ 10^{-7}$
BE	1	3	0.3	4	$1.2 \cdot 10^{-4}$	0.004	0.01	$4.1\ 10^{-6}$

TABLE I: Angular function $F(\theta)$ and central γ-ray flux $\Phi(< 1.5°)$ for different galactic DM profiles, $R_{\mathrm{sol}} = 8.5\,\mathrm{kpc}$ and ρ_0 chosen so that $\rho(R_{\mathrm{sol}}) = 0.3\,\mathrm{GeV/c^2\,cm^{-3}}$ [23].



	α	β	γ	r_s kpc	D Mpc	ρ_0 GeV/c^2 cm^3	$\Phi_{cl}/(\langle\sigma v_r\rangle_{26} m_{\mathrm{GeV}}^{-2})$ cm^{-2} s^{-1}
C-NFW	1	3	1	$0.25/h$	$70/h$	$0.090h^2$	$5.3\,10^{-10}h^3$
C-β-pr.	2	2.25	0	$0.2/h$	$70/h$	$0.13h^2$	$8.8\,10^{-10}\,h^3$
V-NFW	1	3	1	0.56	15	0.012	$2.4\,10^{-9}$
V-β-pr.	2	1.41	0	0.015	15	0.76	$3.0\,10^{-9}$

TABLE II: Expected fluxes from the Coma (C) and Virgo (V) cluster for different DM profiles [24]. For the β-profile of Virgo, only the flux within 1 Mpc is given. $h = 0.7$.

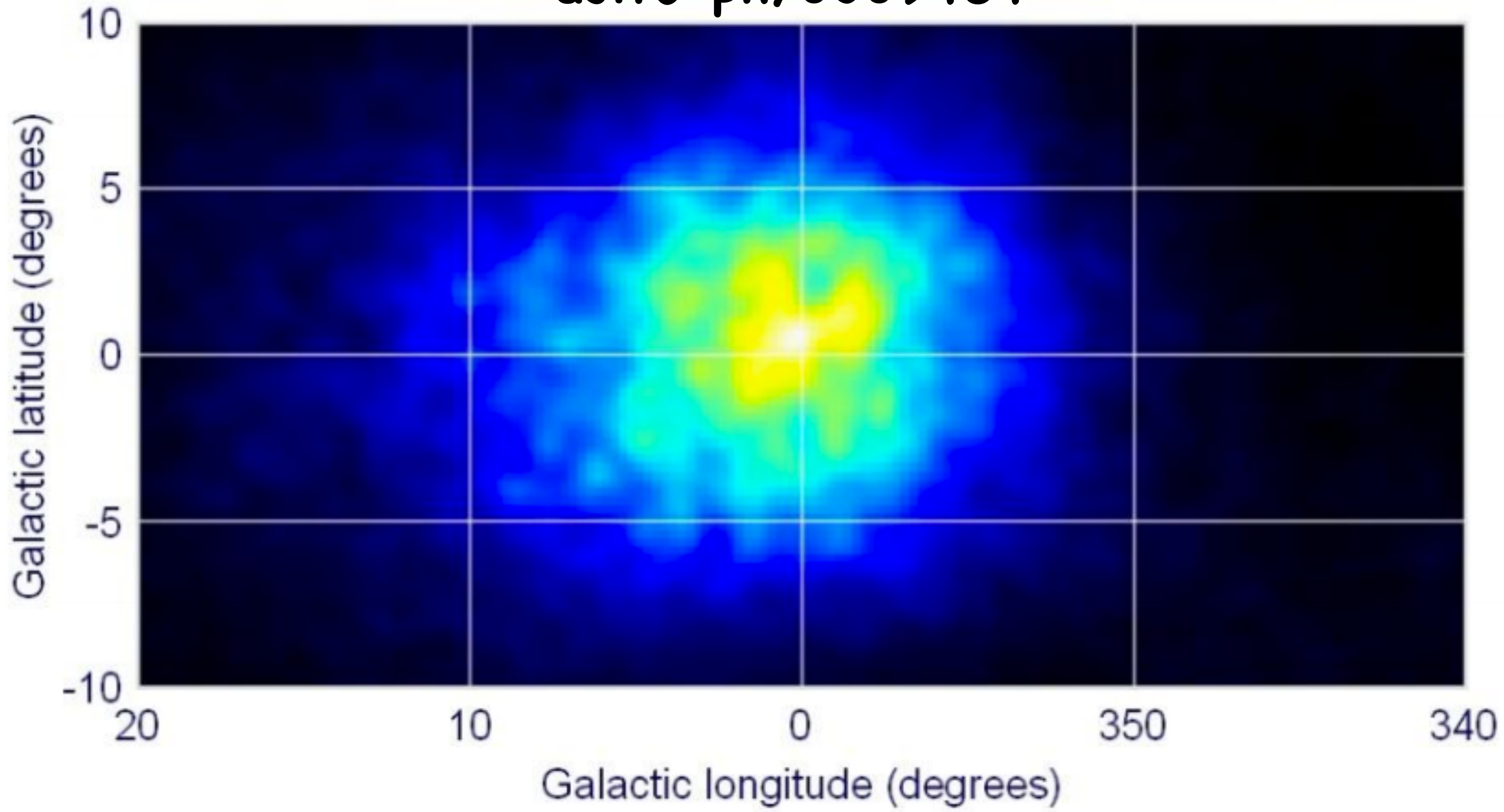
Astrophysical implications of light dark matter

$\mathrm{DM\ DM} \rightarrow \mathrm{e^+ e^-}$ Positronium formation $\rightarrow \gamma\gamma$ 511 keV (para)

$\gamma\gamma\gamma$ continuum (ortho)

511 keV line

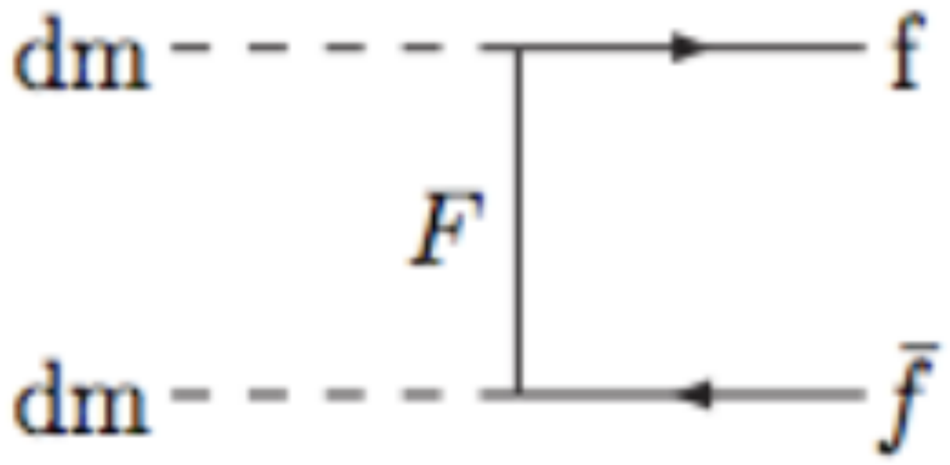
astro-ph/0309484

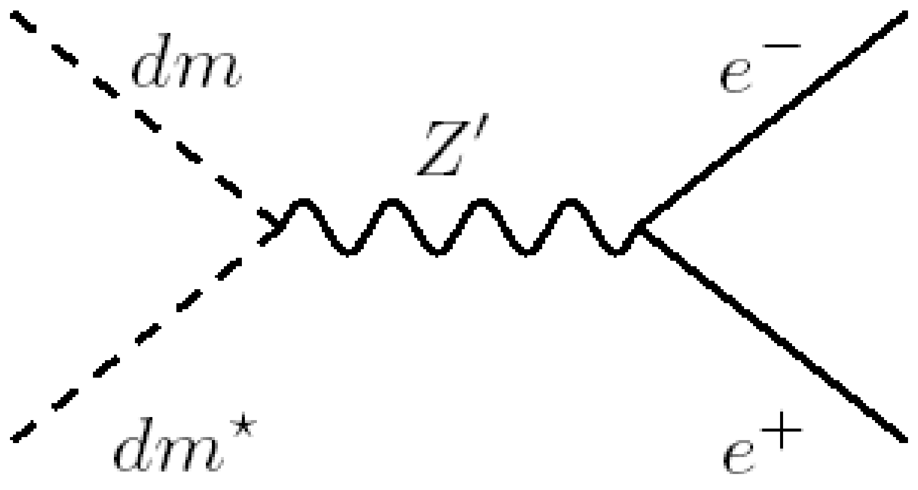


Morphology of 511 keV line in agreement with DM distribution astro-ph/0309686

Astrophysical implications of light dark matter

astro-ph/0507142





Can explain the observed 511 keV morphology
But cannot explain the relic abundance

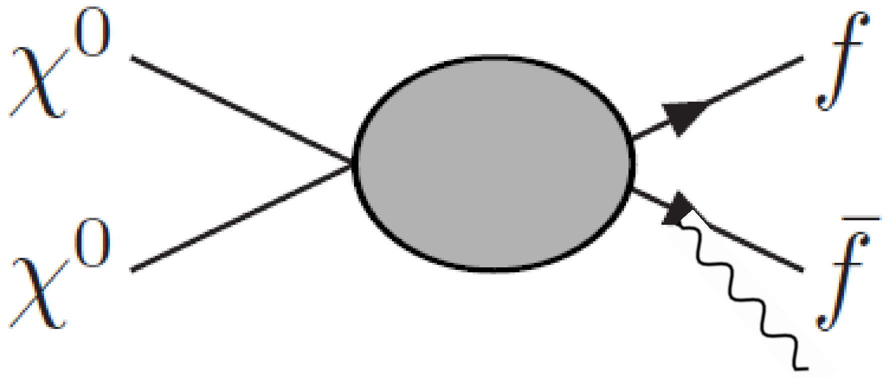
Cannot explain the 511 keV morphology
But can explain the relic abundance

Could explain the observed flux (with scalar dark matter)

$$\frac{m_F}{100\ \text{GeV}} \simeq 6 \times 10^3\ \frac{c_l\, c_r}{m_{\text{MeV}}}$$

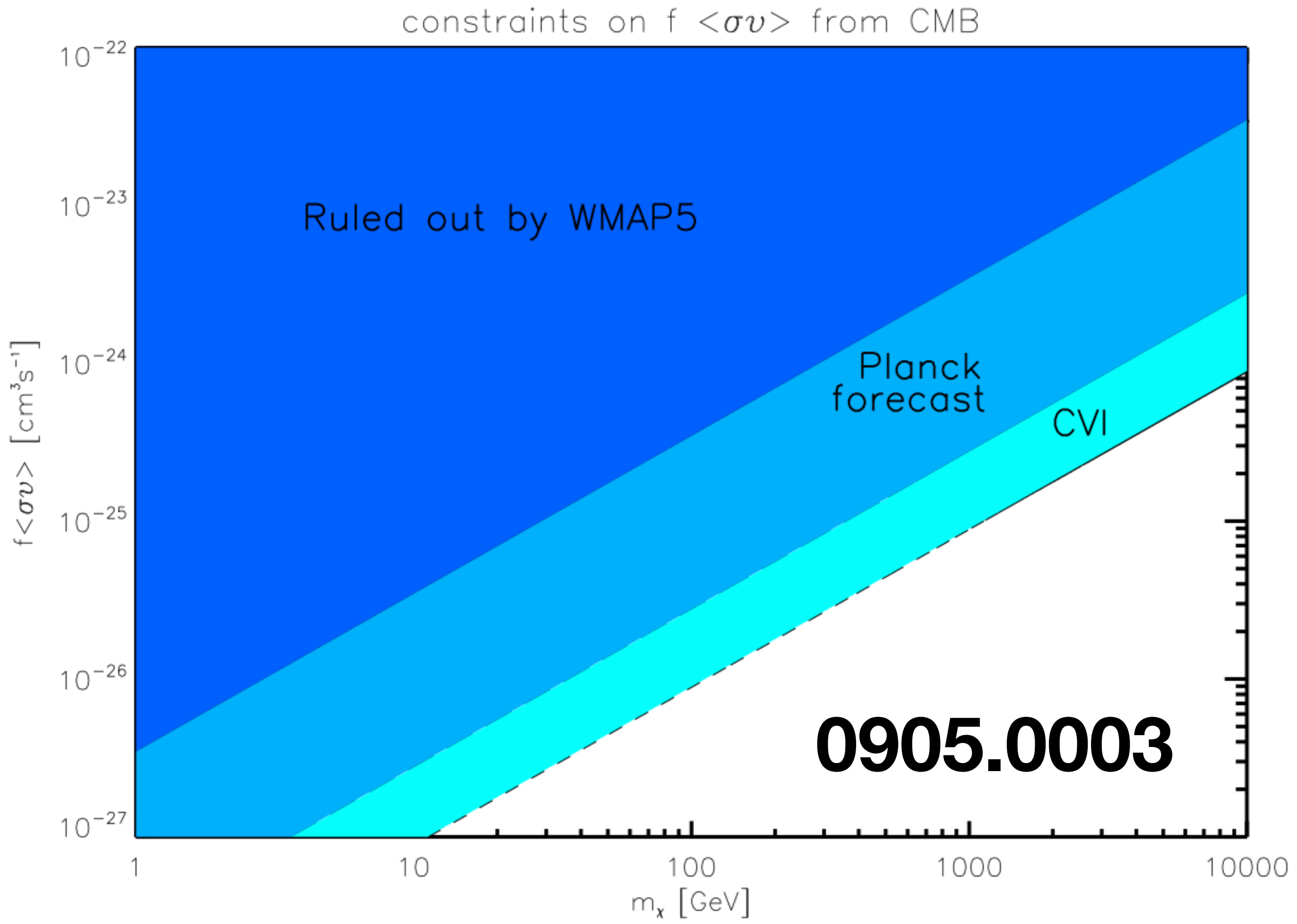
Not the right channel

Astrophysical implications of light dark matter



Gamma-ray emission

S-wave must be suppressed
P-wave ok



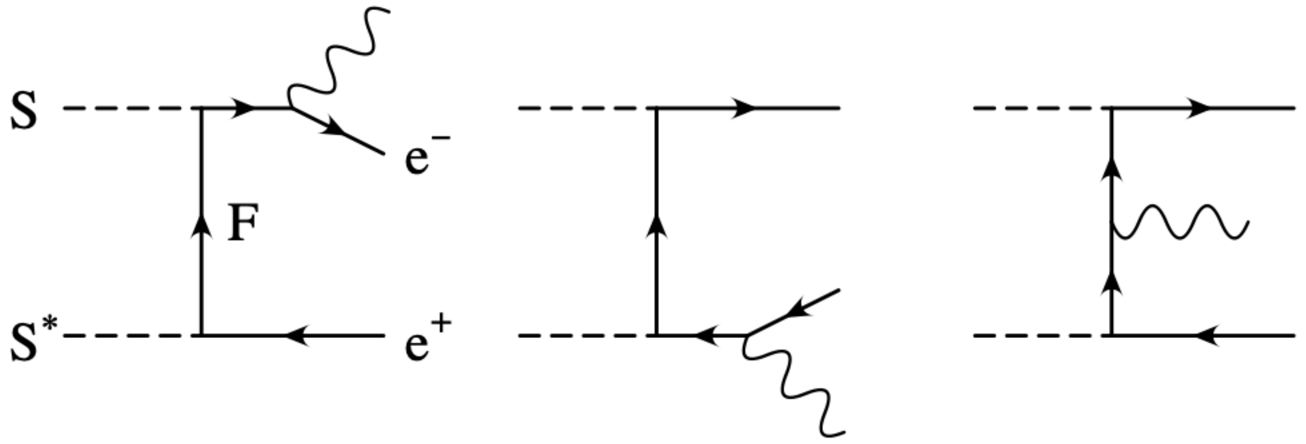
See also by Boudaud et al (1810.01680)
+ X-ray: 2007.11493 (Cirelli et al) — strong constraints m > 20 MeV
+ CMB study in the context of the 511 keV line in 1301.0819

Beacom, Bell & Bertone (0409403)
Using e+e- ann into muons

$$\frac{d\sigma_{\rm Br}}{dE} = \sigma_{\rm tot} \times \frac{\alpha}{\pi}\frac{1}{E}\left[\ln\left(\frac{s'}{m_e^2}\right) - 1\right]\left[1 + \left(\frac{s'}{s}\right)^2\right],$$

mdm < 20 MeV

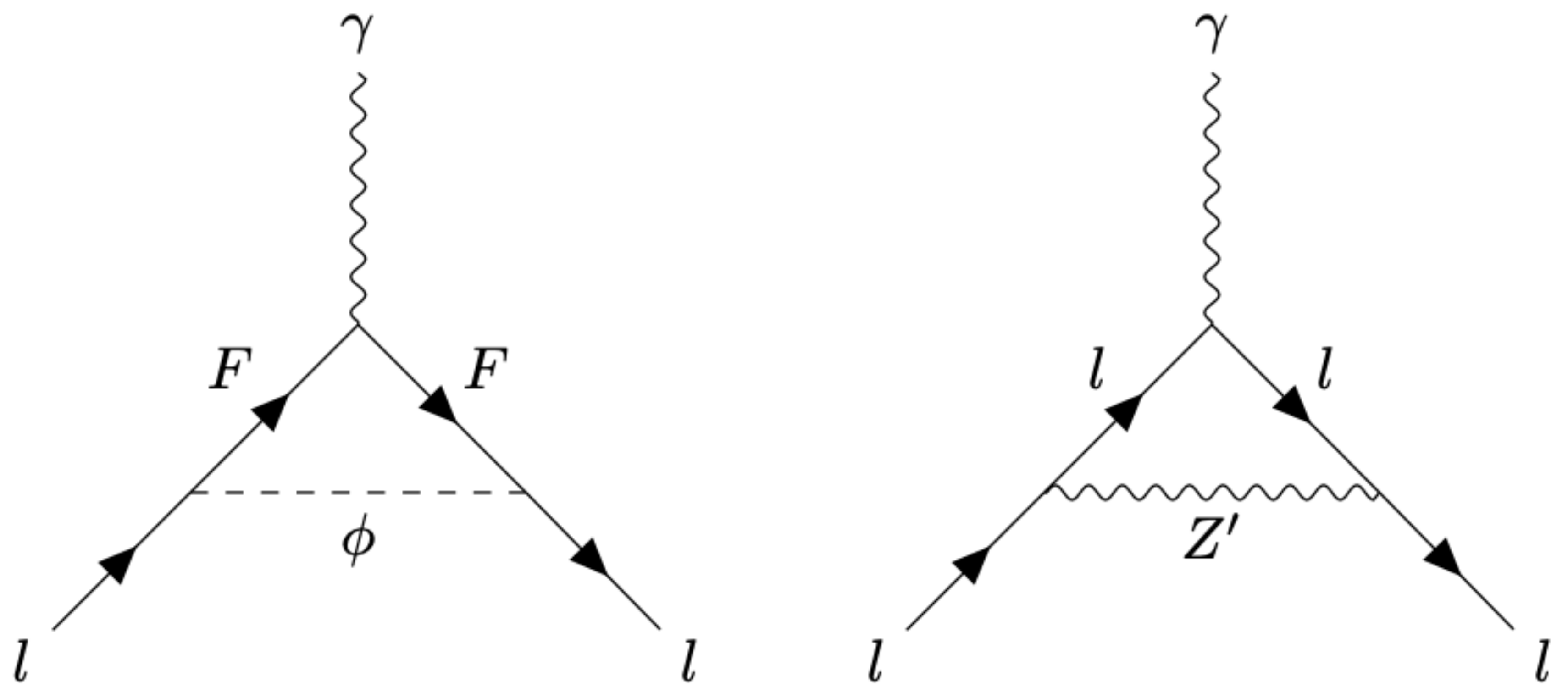
Boehm&Uwer (0606058)



$$\frac{d\sigma_\gamma}{dx_\gamma} \approx \sigma_0 \frac{\alpha}{\pi}\frac{1}{x_\gamma}\left\{\left(1 + \frac{s'^2}{s^2}\right)\ln\left(\frac{s'}{m_e{}^2}\right) - 2\frac{s'}{s}\right\},$$

mdm < 30 MeV

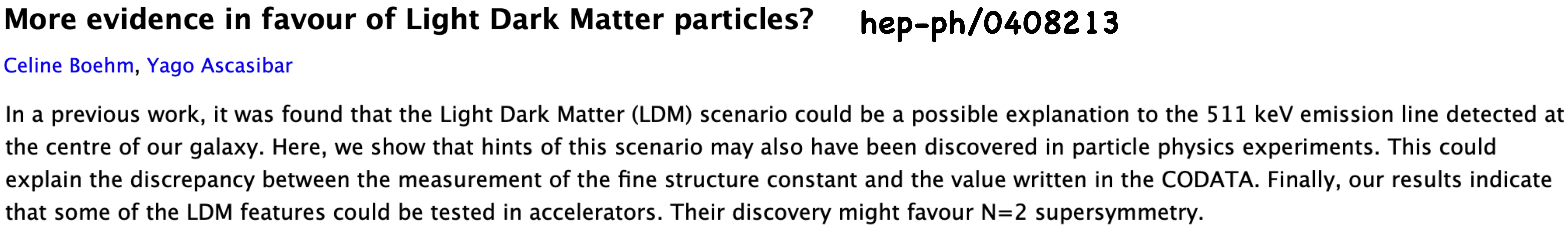
g-2 constraints of light dark matter



hep-ph/0305261 :

electron g-2 sets more severe constraints on this model

hep-ph/0405240 hep-ph/0408213 arXiv:0708.2768

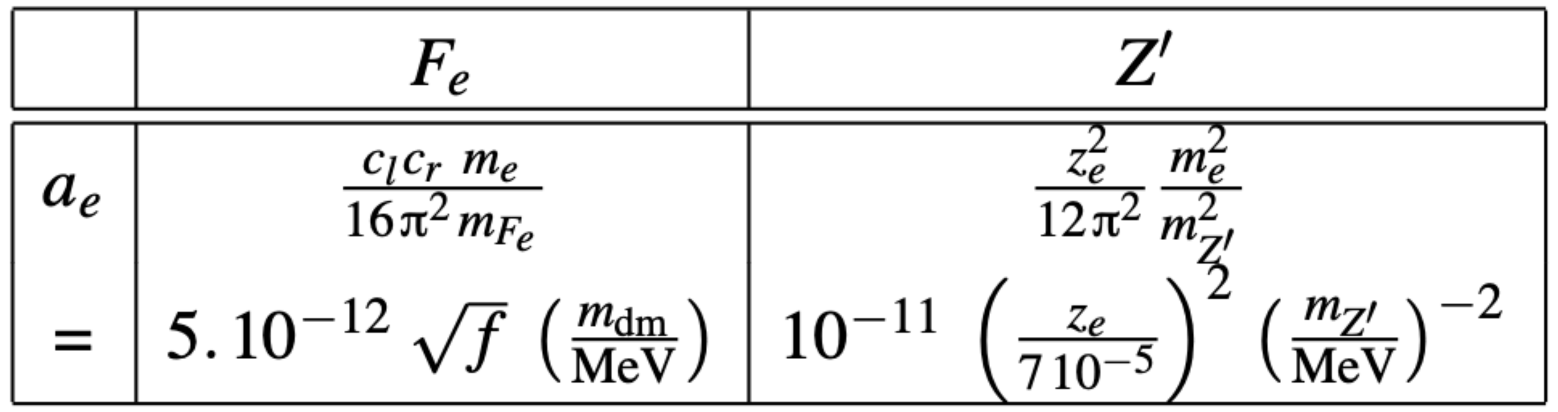


More evidence in favour of Light Dark Matter particles?

hep-ph/0408213

Celine Boehm, Yago Ascasibar

In a previous work, it was found that the Light Dark Matter (LDM) scenario could be a possible explanation to the 511 keV emission line detected at the centre of our galaxy. Here, we show that hints of this scenario may also have been discovered in particle physics experiments. This could explain the discrepancy between the measurement of the fine structure constant and the value written in the CODATA. Finally, our results indicate that some of the LDM features could be tested in accelerators. Their discovery might favour N=2 supersymmetry.



	F_e	Z'
a_e	$\frac{c_l c_r}{16\pi^2}\frac{m_e}{m_{F_e}}$	$\frac{z_e^2}{12\pi^2}\frac{m_e^2}{m_{Z'}^2}$
=	$5.10^{-12}\sqrt{f}\left(\frac{m_{\rm dm}}{\rm MeV}\right)$	$10^{-11}\left(\frac{z_e}{7 10^{-5}}\right)^2\left(\frac{m_{Z'}}{\rm MeV}\right)^{-2}$

To be compared with ae ~10^-13

DM unlikely to explain the 511 keV line

Constraints on vector-like fermions

arXiv:2010.02954

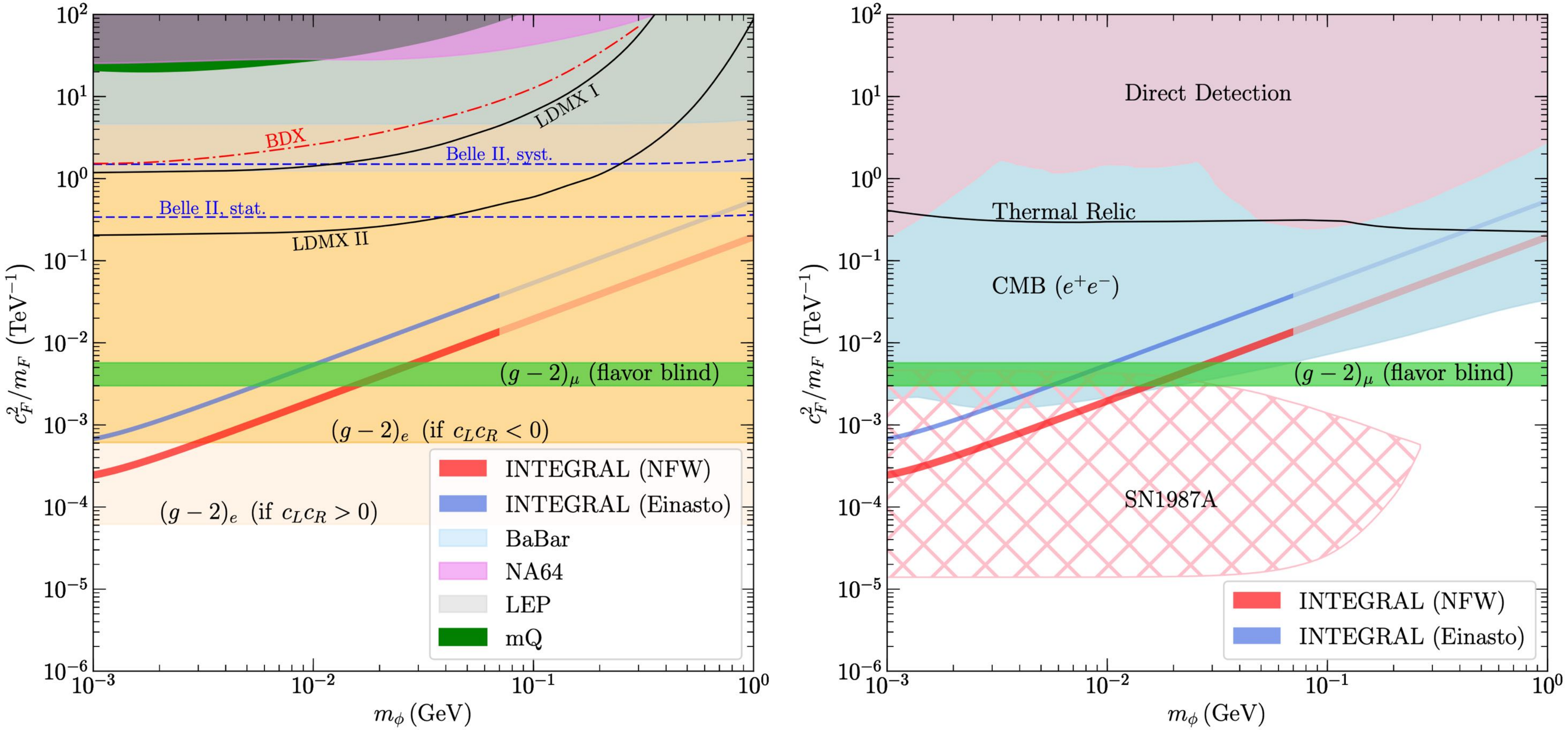


FIG. 6. Bounds on the inverse of effective UV-scale $\Lambda_F^{-1} = c_F^2/m_F$ in the F-mediated model from laboratory experiments (left panel) and from astrophysical observations including direct detection (right panel). The parameter regions of interest for the INTEGRAL excess are shown as thin blue and red bands; for $m_\phi \geq 70\,\text{MeV}$ the DM interpretation is disfavored as indicated by a lighter shading. The green horizontal band where $(g-2)_\mu$ is explained carries the assumption $c_F^\mu = c_F^e$.

Constraints on dark gauge bosons

arXiv:2010.02954

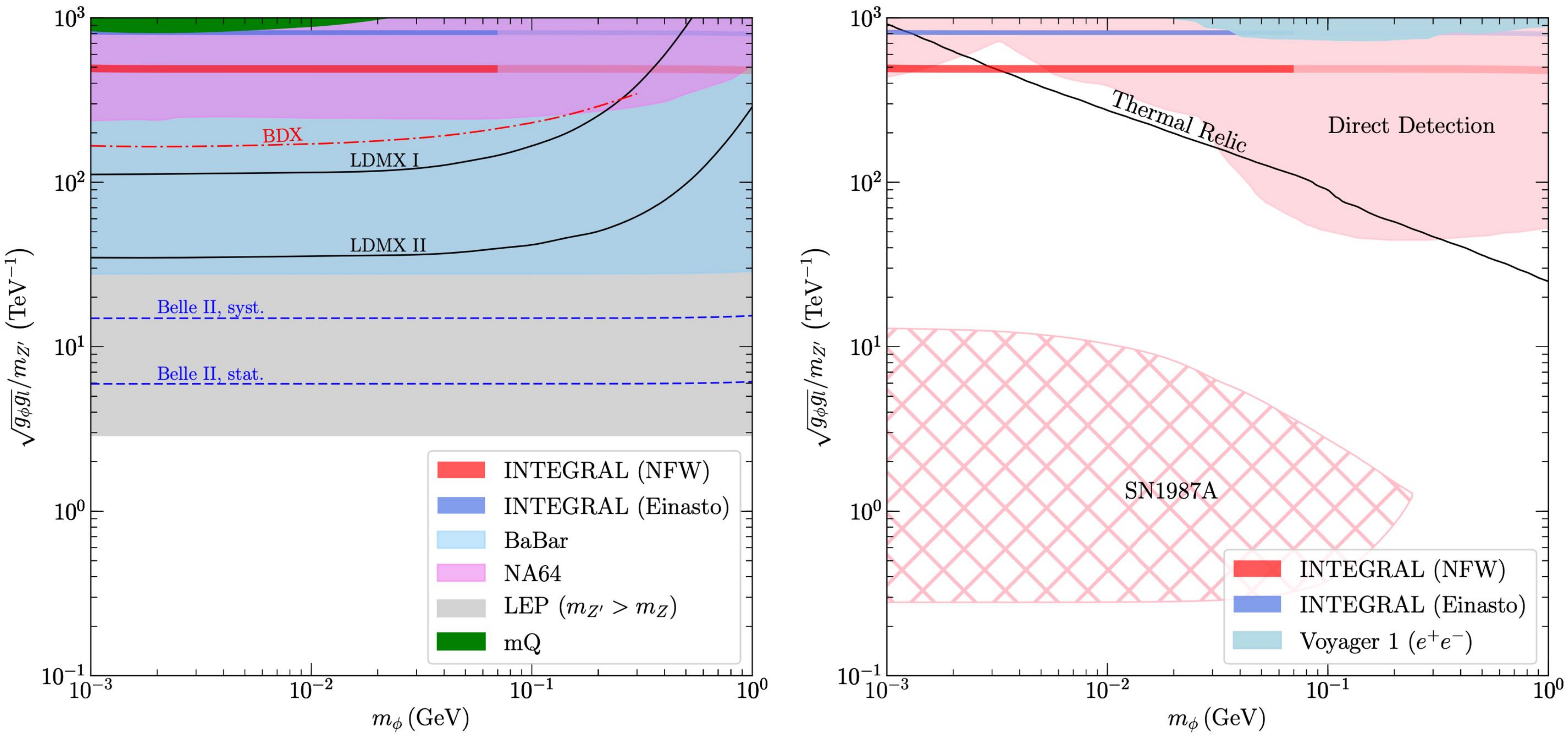
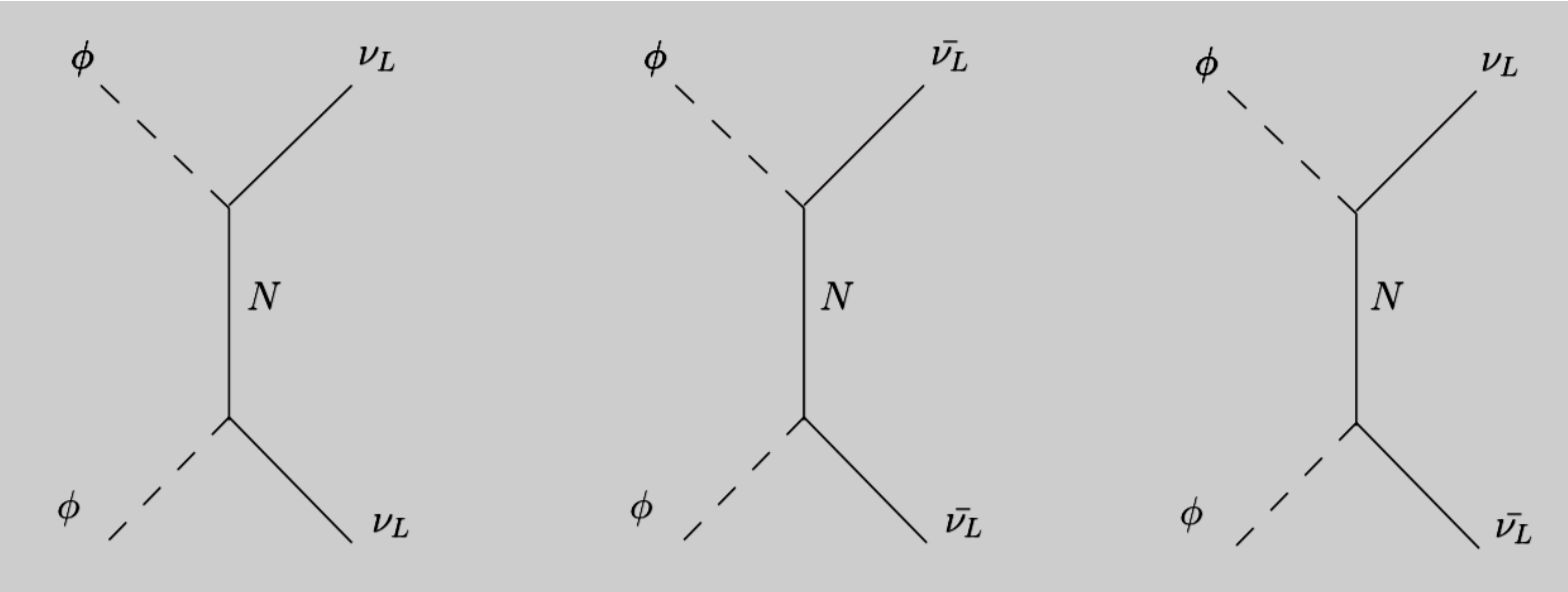


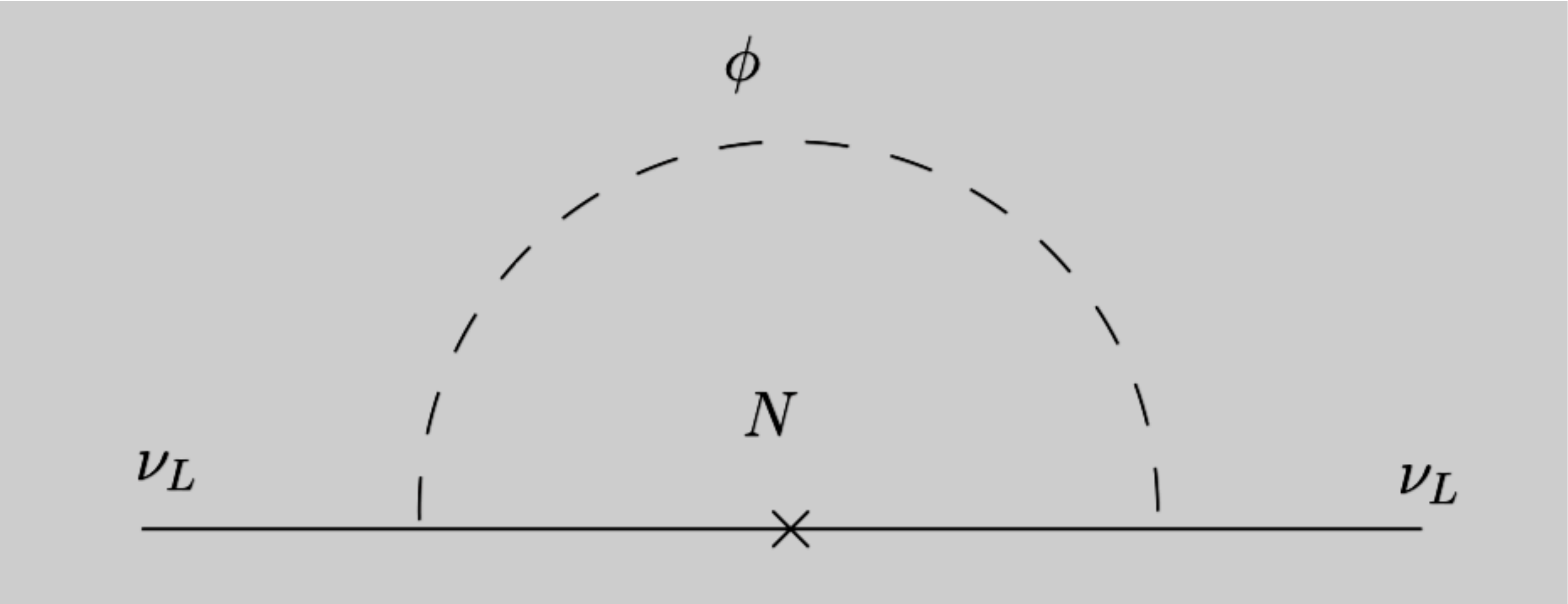
FIG. 7. Bounds on the inverse of effective UV scale $\Lambda_{Z'}^{-1} = \sqrt{g_\phi g_l}/m_{Z'}$ for the Z' model from laboratory tests (left panel) and from cosmological and astrophysical probes including direct detection (right panel). The parameter regions of interest for the INTEGRAL excess are shown as thin blue and red bands; for $m_\phi \geq 70\,\text{MeV}$ the DM interpretation is disfavored as indicated by a lighter shading. LEP bound only applies for $m_{Z'}$ above the EW scale, below which (18) applies instead. We do not show a band for $(g-2)_\mu$, which would need an assumption on g_ϕ/g_l, since it is already excluded elsewhere (see main text and Fig. 2).

Astrophysical implications of light dark matter

hep-ph/0612228

Annihilations into neutrinos





$$m_{\nu_L} \simeq \sqrt{\frac{\langle \sigma v_r \rangle}{128\,\pi^3}}\, m_N^2 (1 + m_\phi^2/m_N^2)\, \ln\left(\frac{\Lambda^2}{m_N^2}\right).$$

Basic model can give rise to neutrino masses in the eV range but UV completion is hard!

See e.g. work by Yasaman Farzan (e.g. 1009.0829 and 1208.2732) + Arhrib et al (1512.08796)

Cosmological implications of light dark matter

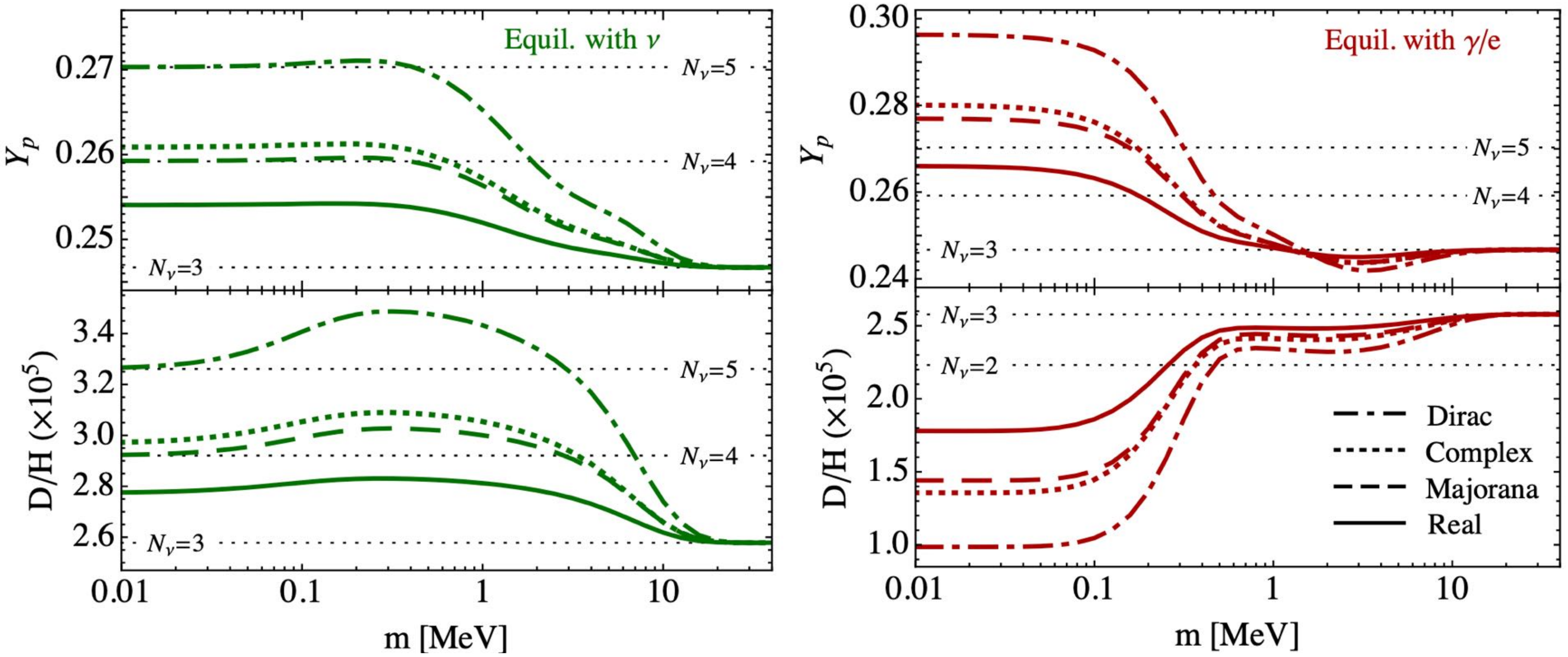
1207.0497 1303.6270

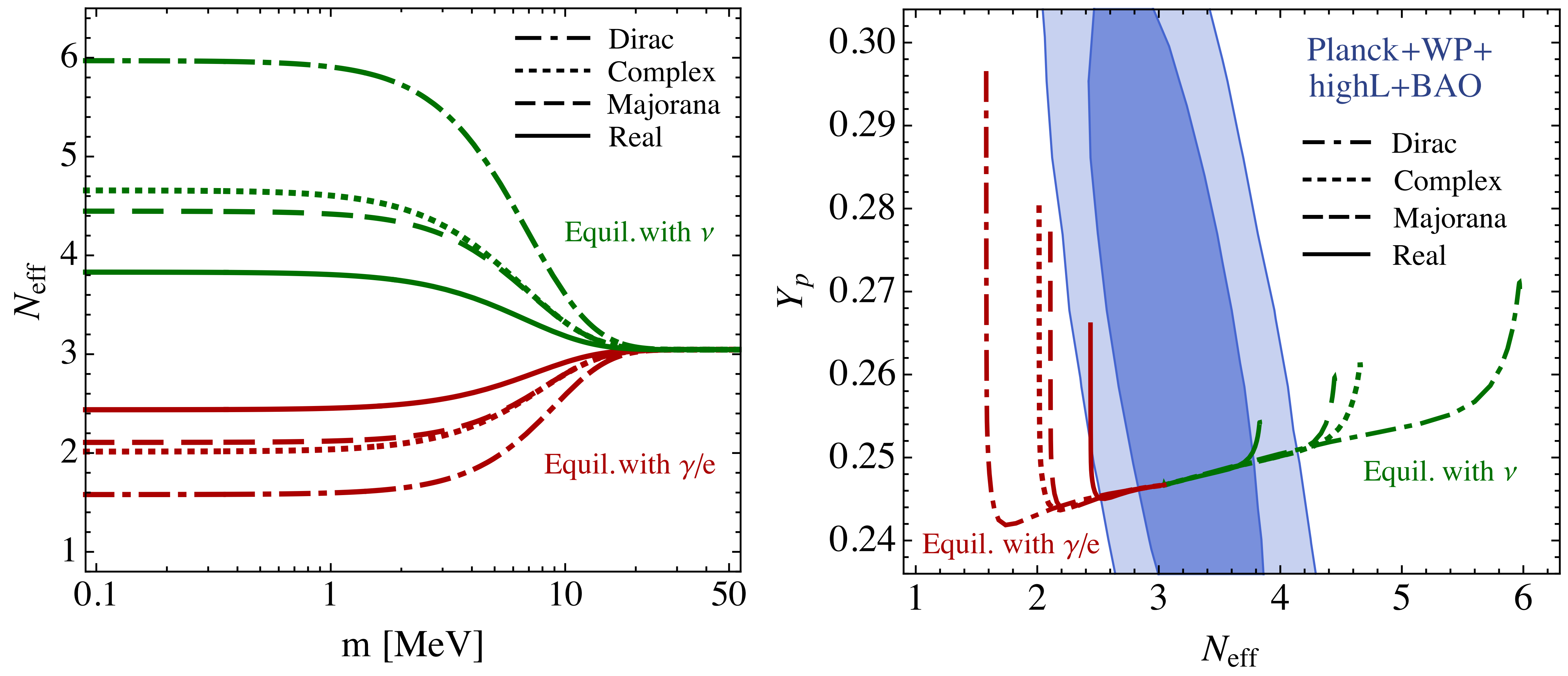
Raffelt & Serpico astro-ph/0403417

M < 10 MeV but [4,10] MeV exciting for 511 keV

Helium/D abundance

Neff





M < 10-20 MeV

Overly simplified summary of (Astro) constraints

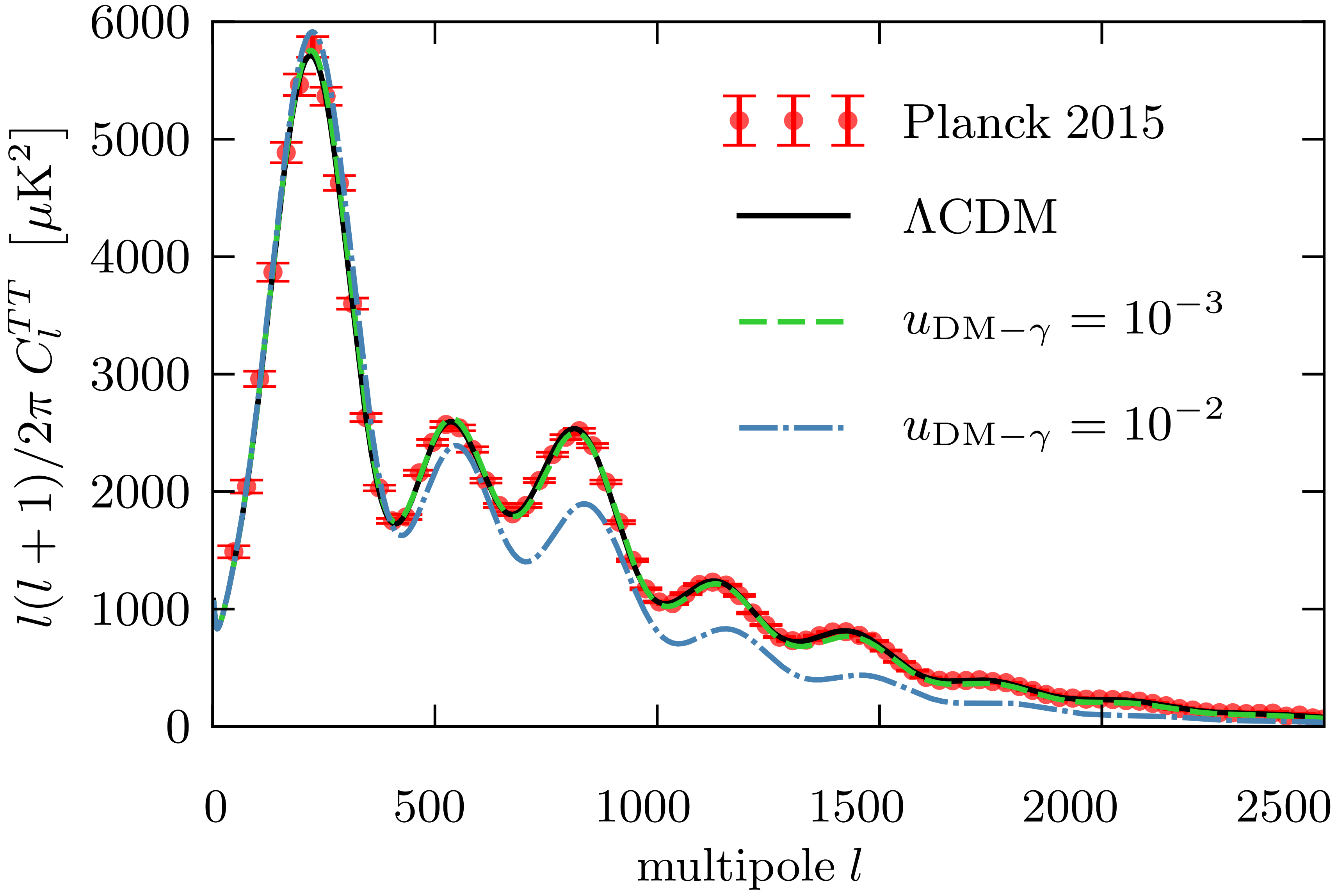
Indirect detection:	mdm < 30 MeV (for the 511 keV line) P-wave annihilations or s-wave suppressed But see talk by Francesca!
CMB / Primordial abundance:	mdm < 10 MeV

Also

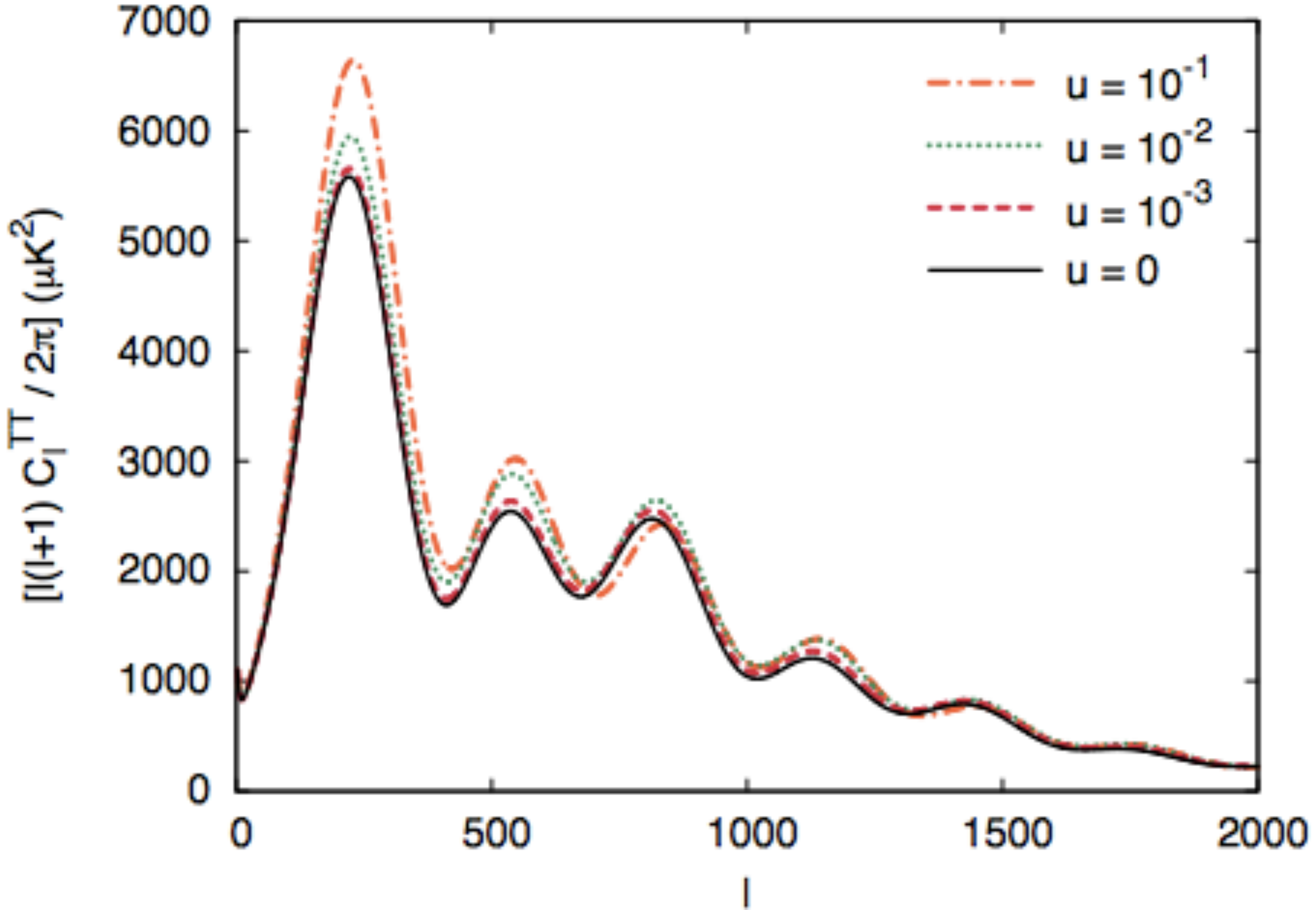
Electron g-2 (muon less stringent)	mdm < 30 MeV and in fact likely kills many "Astro" models

Cosmological implications of light dark matter

DM-photon interactions



DM-neutrino interactions



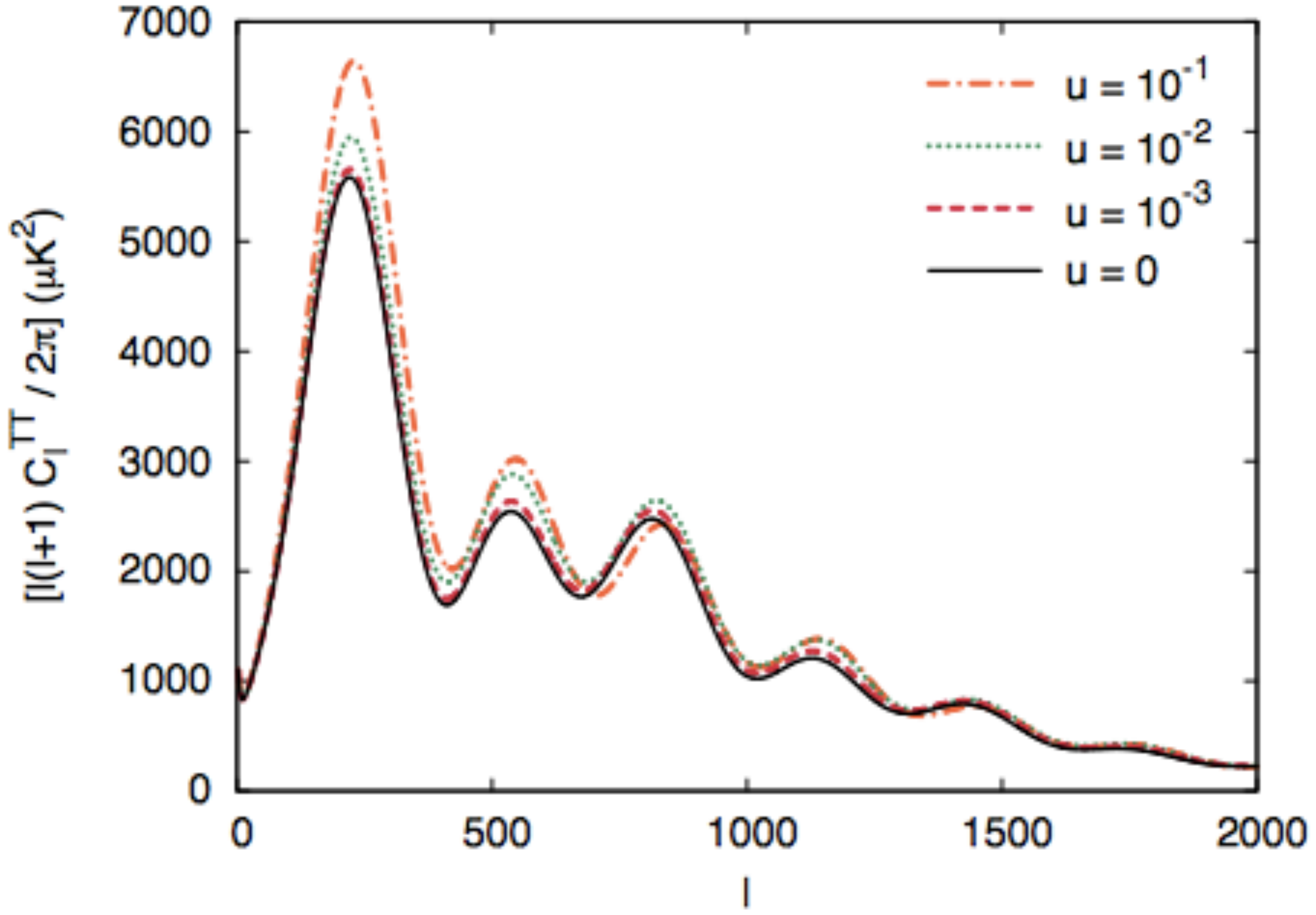
1401.7597

DM-b interactions

SIDM

Impact on cosmological parameters

DM-neutrino interactions

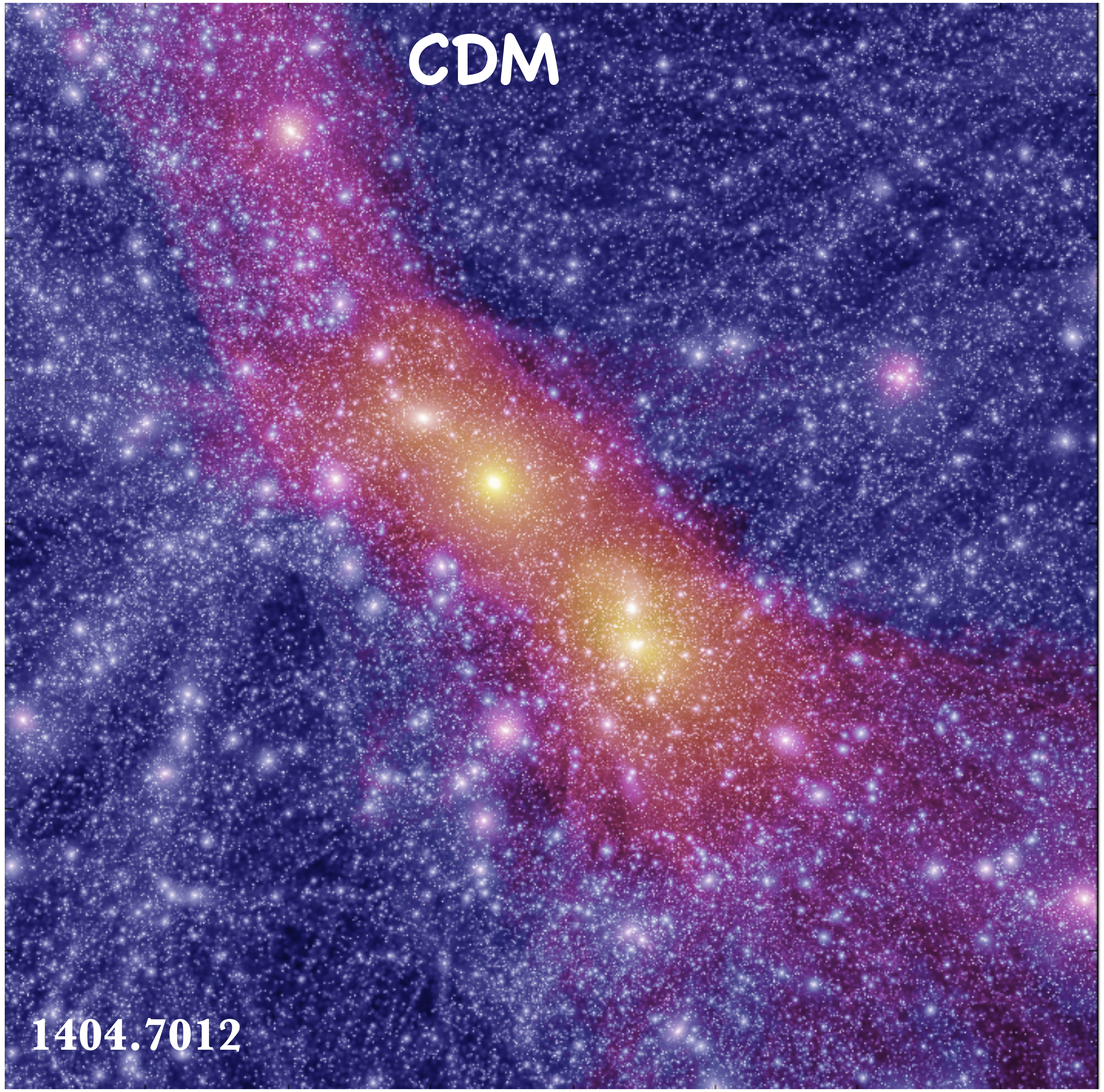


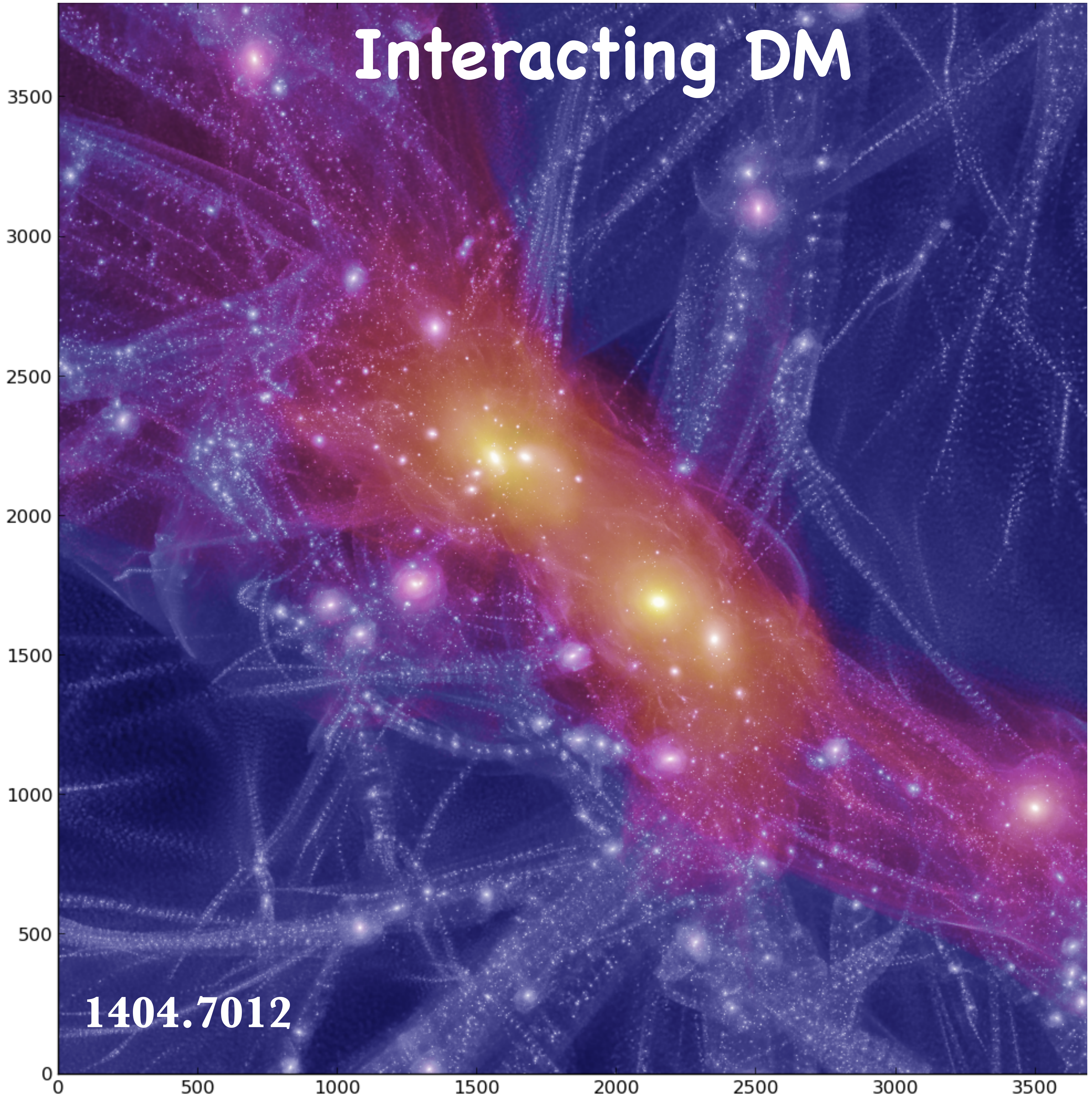
1401.7597

$\Lambda\mathrm{CDM} + u$ Parameter	$+ N_{\rm eff}$ Planck TT $+$ lowTEB $+$ R16	$+ N_{\rm eff} + \Sigma m_\nu$ Planck TT $+$ lowTEB $+$ R16
$\Omega_b h^2$	$0.02278\,^{+0.00026}_{-0.00025}$	$0.02278\,\pm 0.00027$
$\Omega_c h^2$	$0.1238\,^{+0.0037}_{-0.0038}$	$0.1240\,^{+0.0035}_{-0.0045}$
τ	$0.099\,^{+0.019}_{-0.021}$	$0.100\,^{+0.023}_{-0.021}$
n_s	$0.9898\,^{+0.0088}_{-0.0094}$	$0.990\,^{+0.009}_{-0.010}$
$ln(10^{10} A_s)$	$3.143\,^{+0.041}_{-0.039}$	$3.145\,^{+0.054}_{-0.037}$
$H_0[\mathrm{Km\,s^{-1}\,Mpc^{-1}}]$	$72.1\,^{+1.5}_{-1.7}$	$71.9\,^{+1.6}_{-1.8}$
σ_8	$0.850\,^{+0.024}_{-0.018}$	$0.846\,^{+0.030}_{-0.025}$
u	< -4.0	< -4.0
$N_{\rm eff}$	$3.54\,\pm 0.20$	$3.56\,^{+0.19}_{-0.26}$
$\Sigma m_\nu[eV]$	0.06	< 0.87

1710.02559

DM -SM interactions & large scales



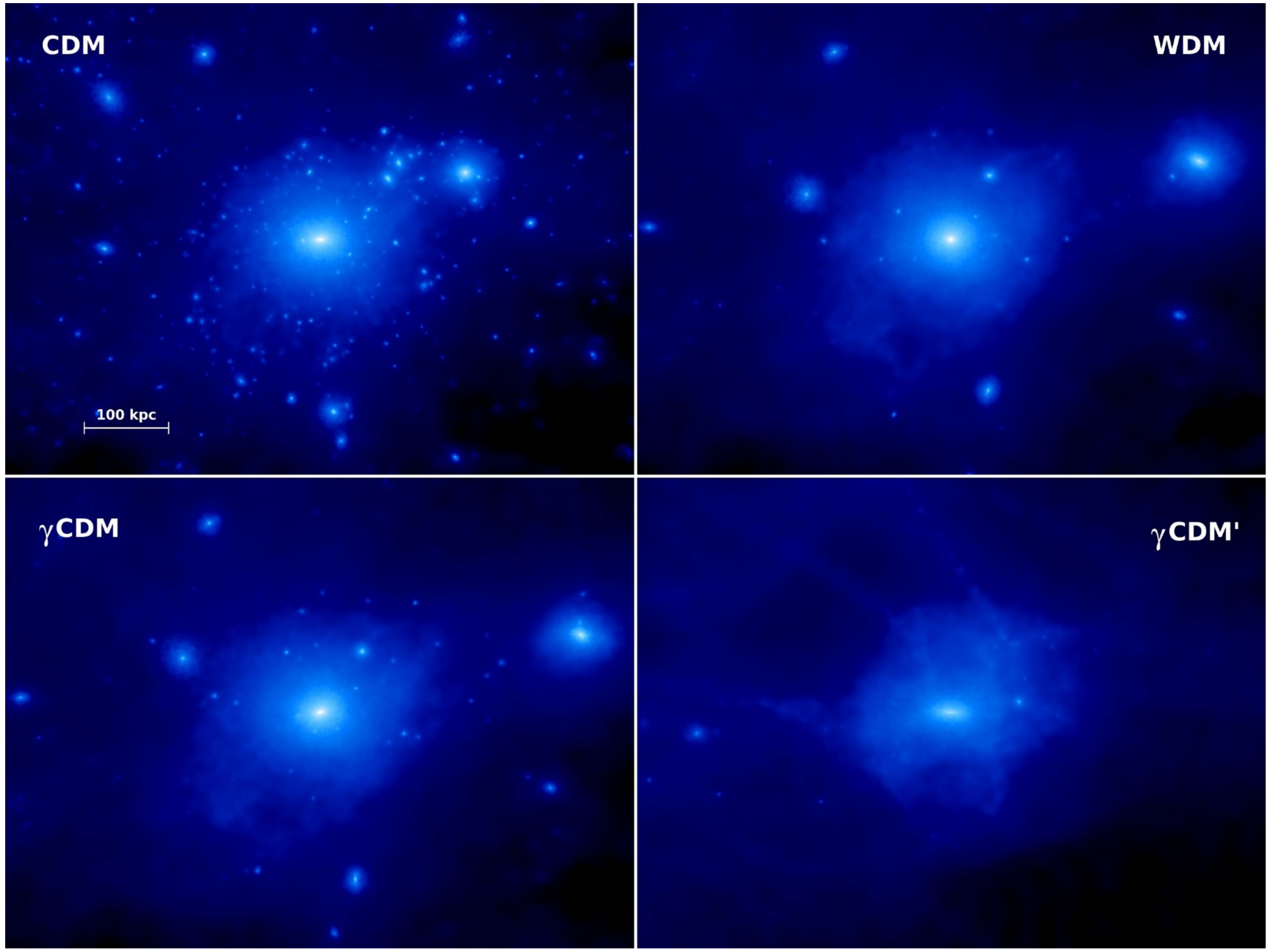


DM-SM 1404.7012

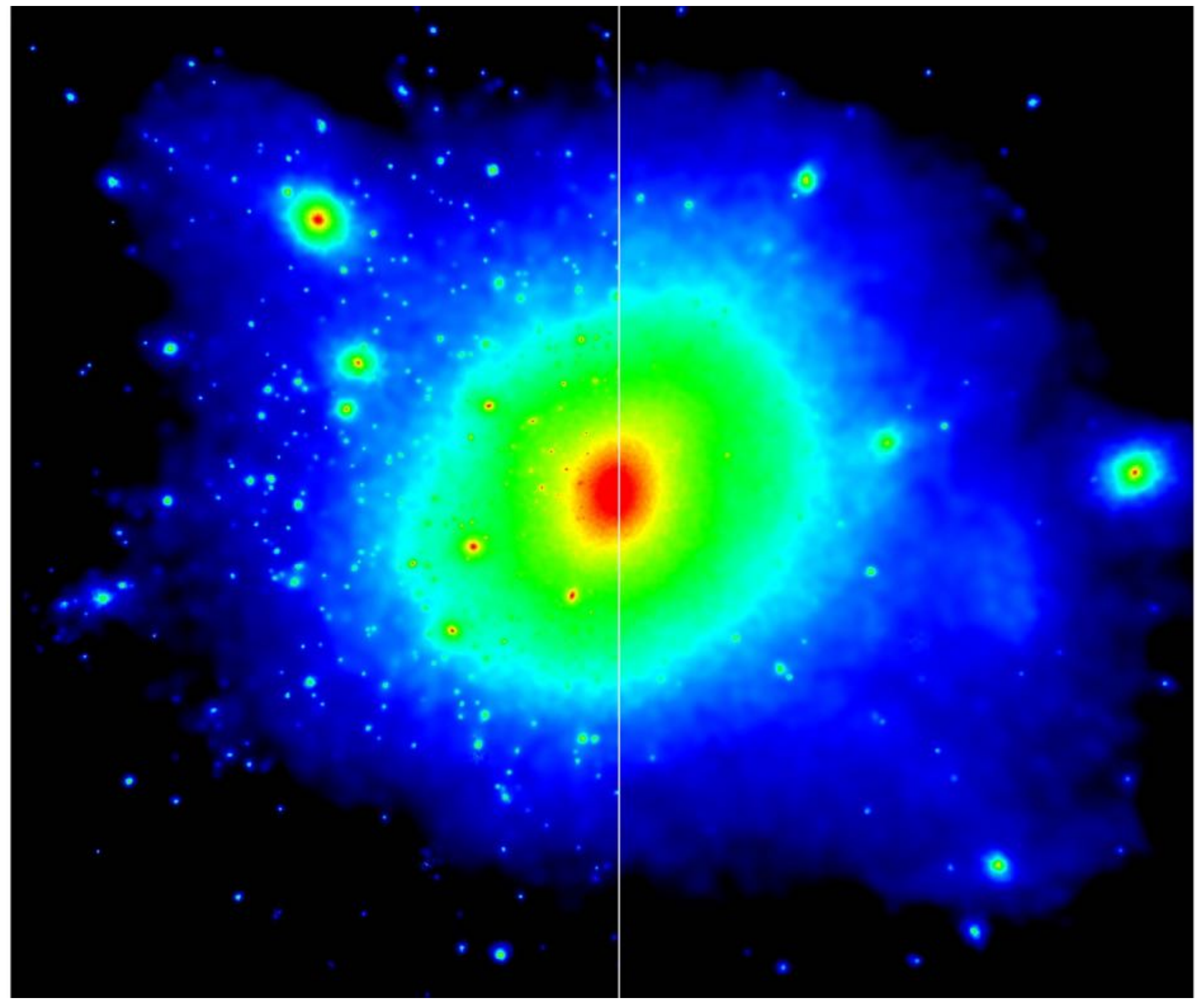
LSST, EUCLID will be essential!

The Milky Way in IDM scenarios

Less satellites

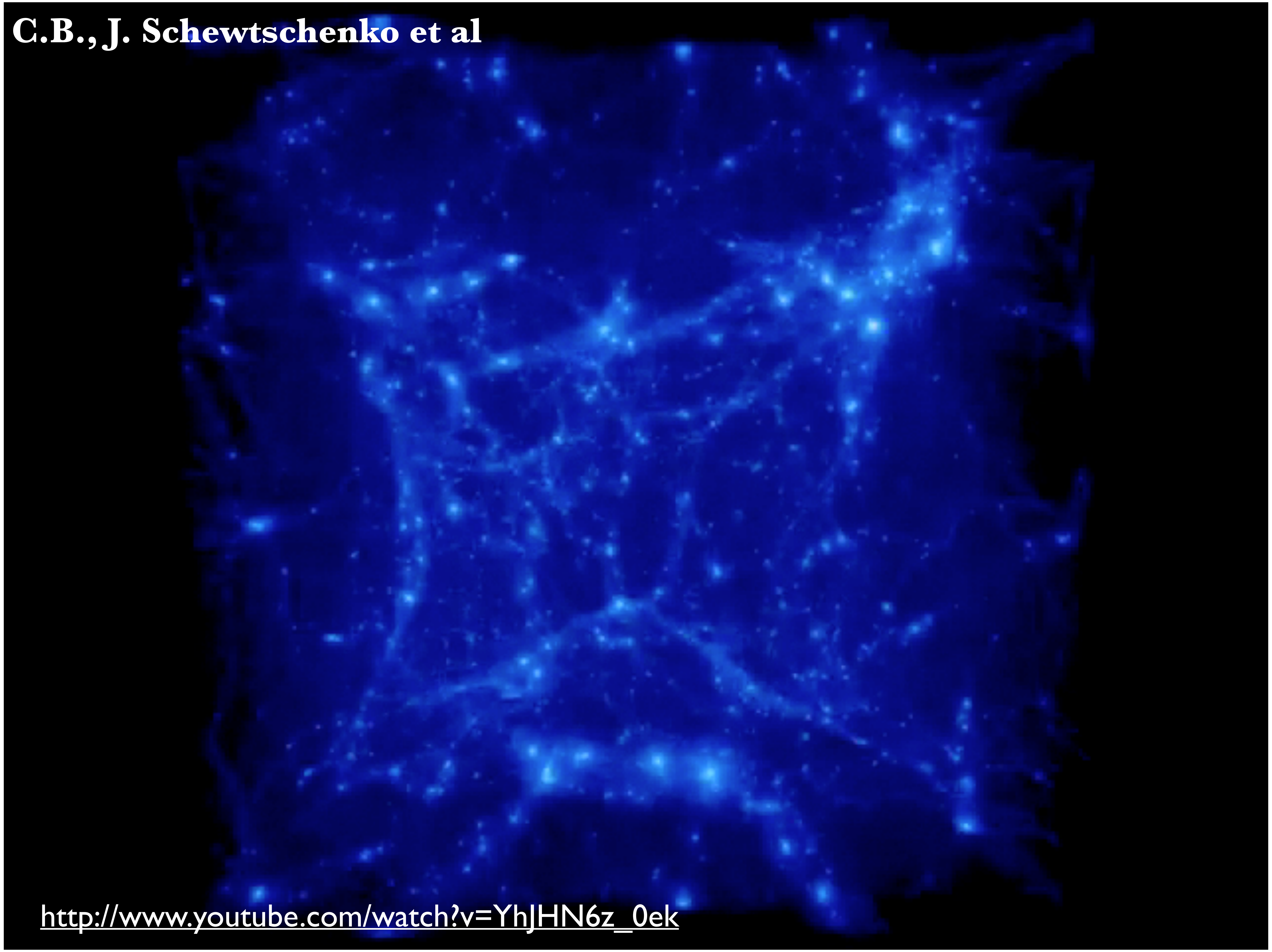


$$u_i = \frac{\sigma_{DM-i}}{\sigma_T}\left(\frac{m_{\rm DM}}{100{\rm GeV}}\right)^{-1}.$$



$$\sigma v \lesssim 10^{-36}\ {\rm cm}^2\ \left(\frac{\rm m_{DM}}{\rm MeV}\right)$$

The Milky Way for interacting DM

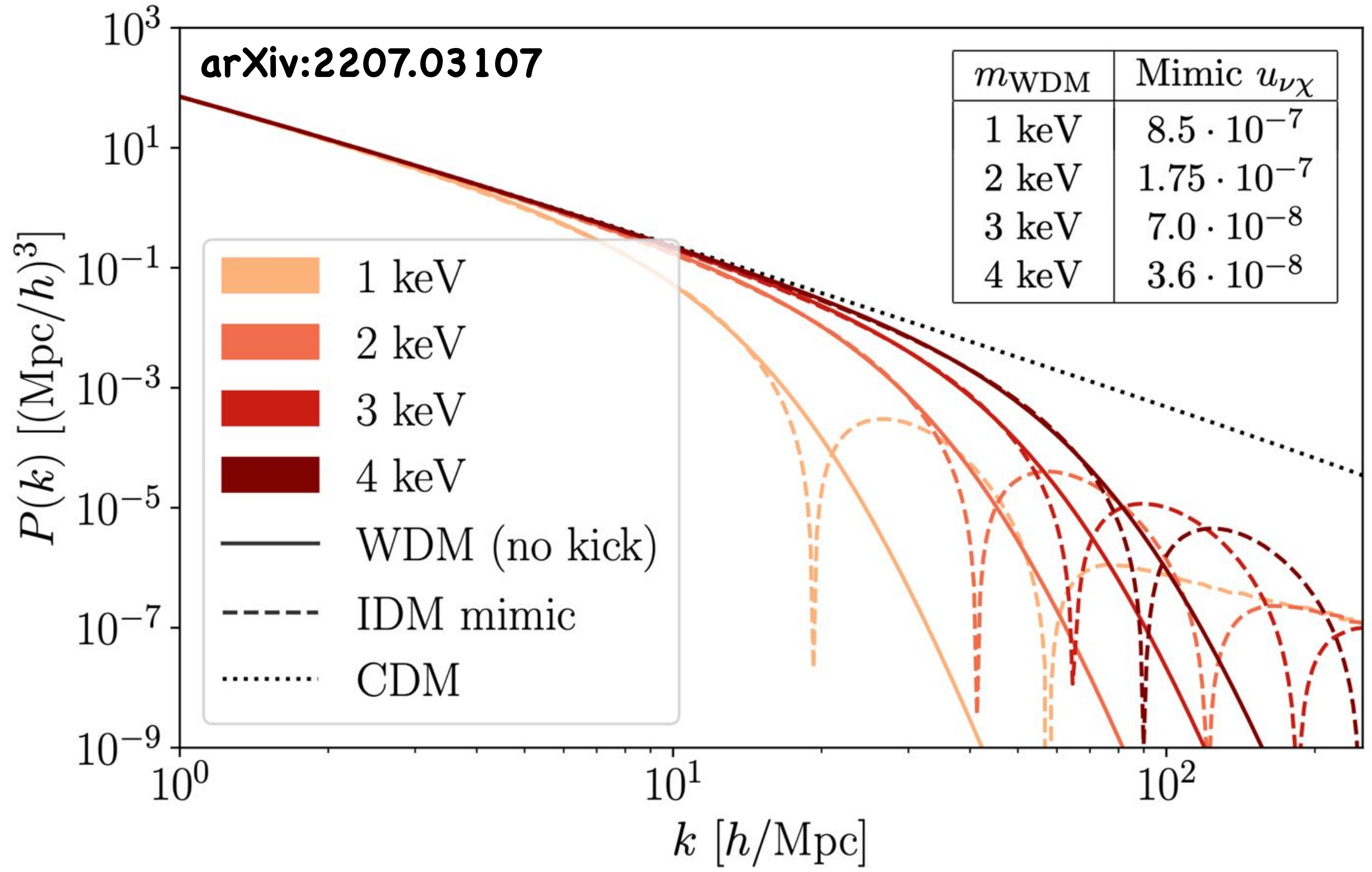


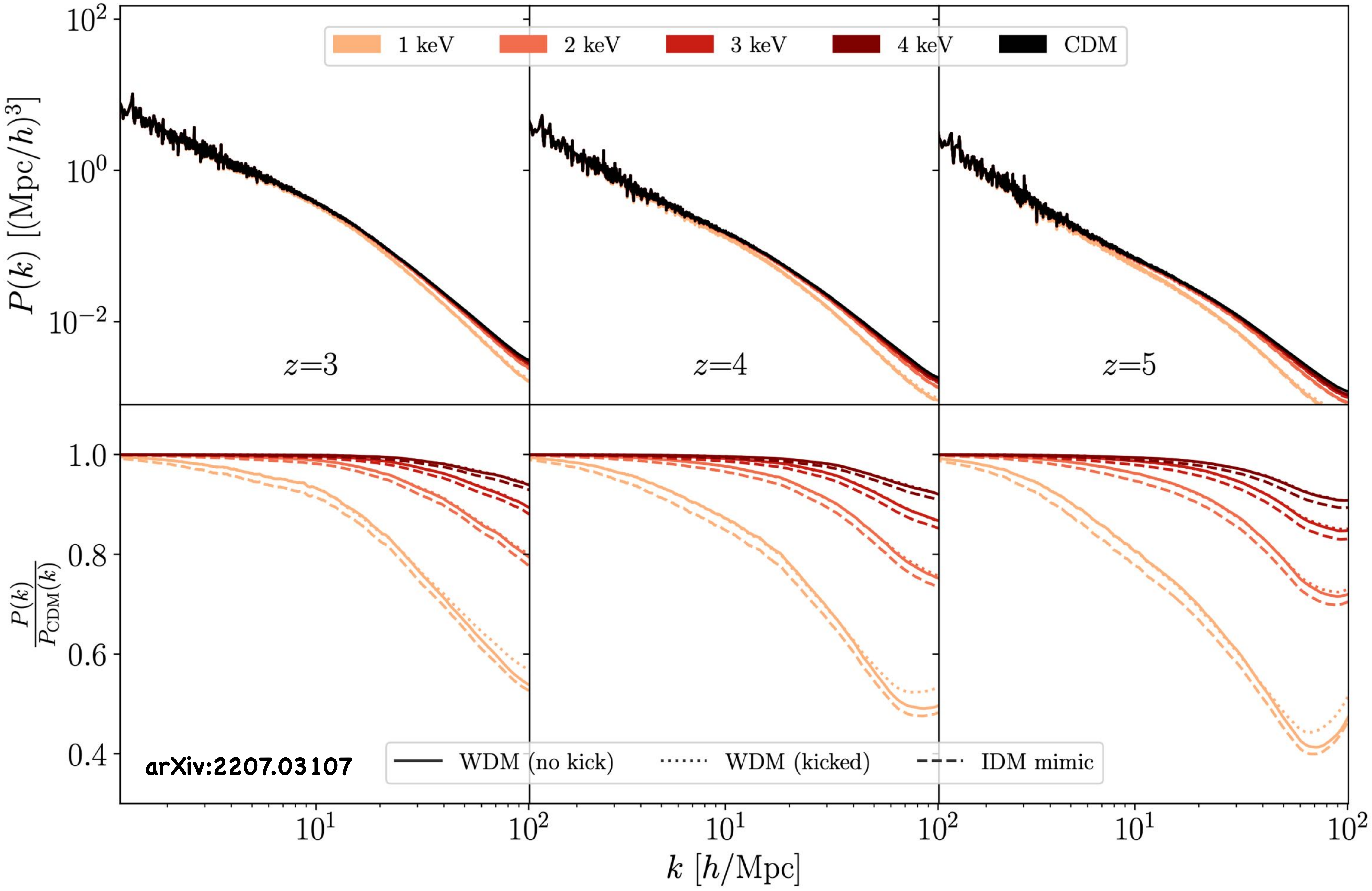
C.B., J. Schewtschenko et al

http://www.youtube.com/watch?v=YhJHN6z_0ek

How to probe Dark Matter interactions?

arXiv:2207.03107 in agreement with astro-ph/0309652





How to probe Dark Matter interactions?

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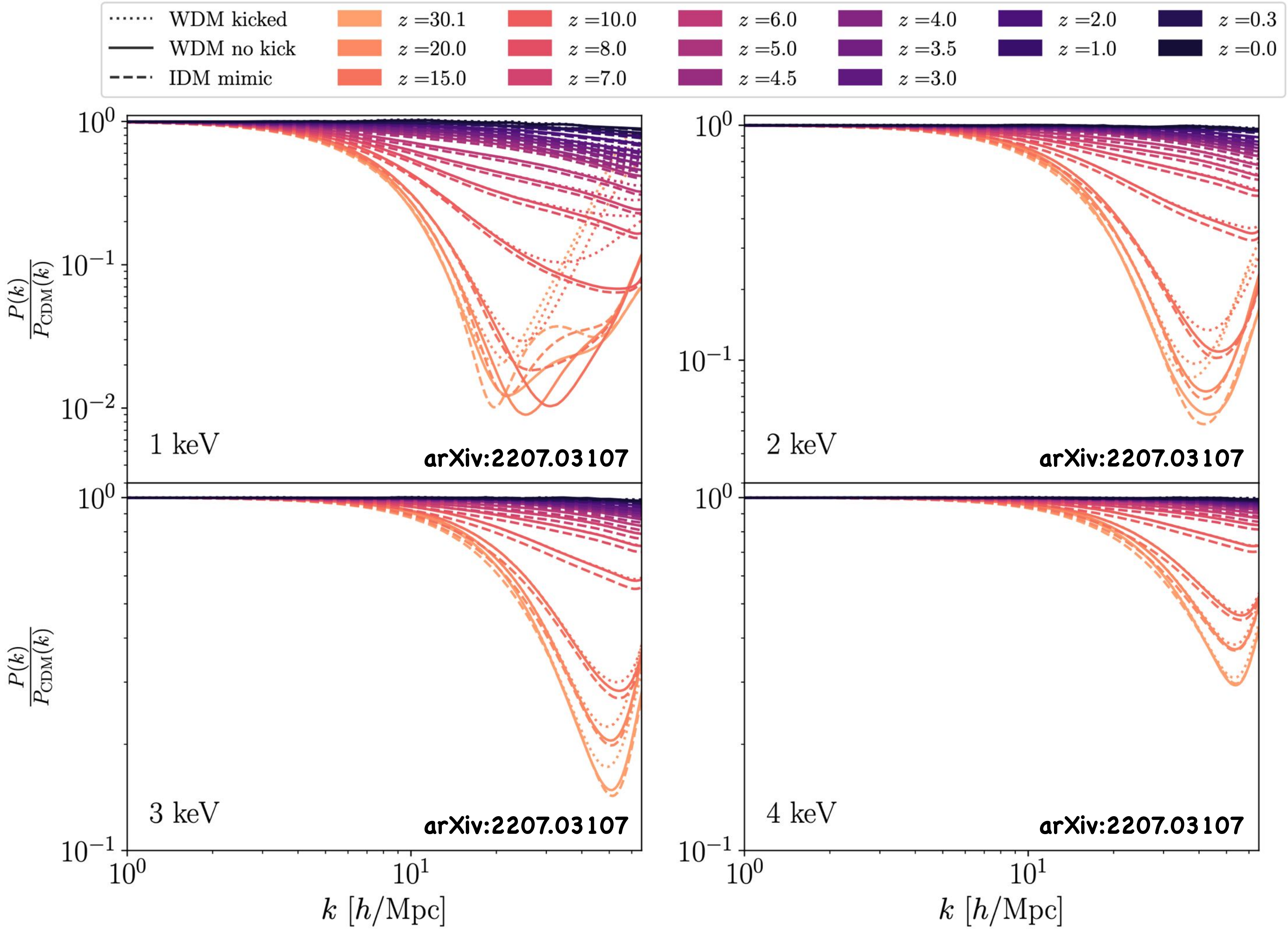
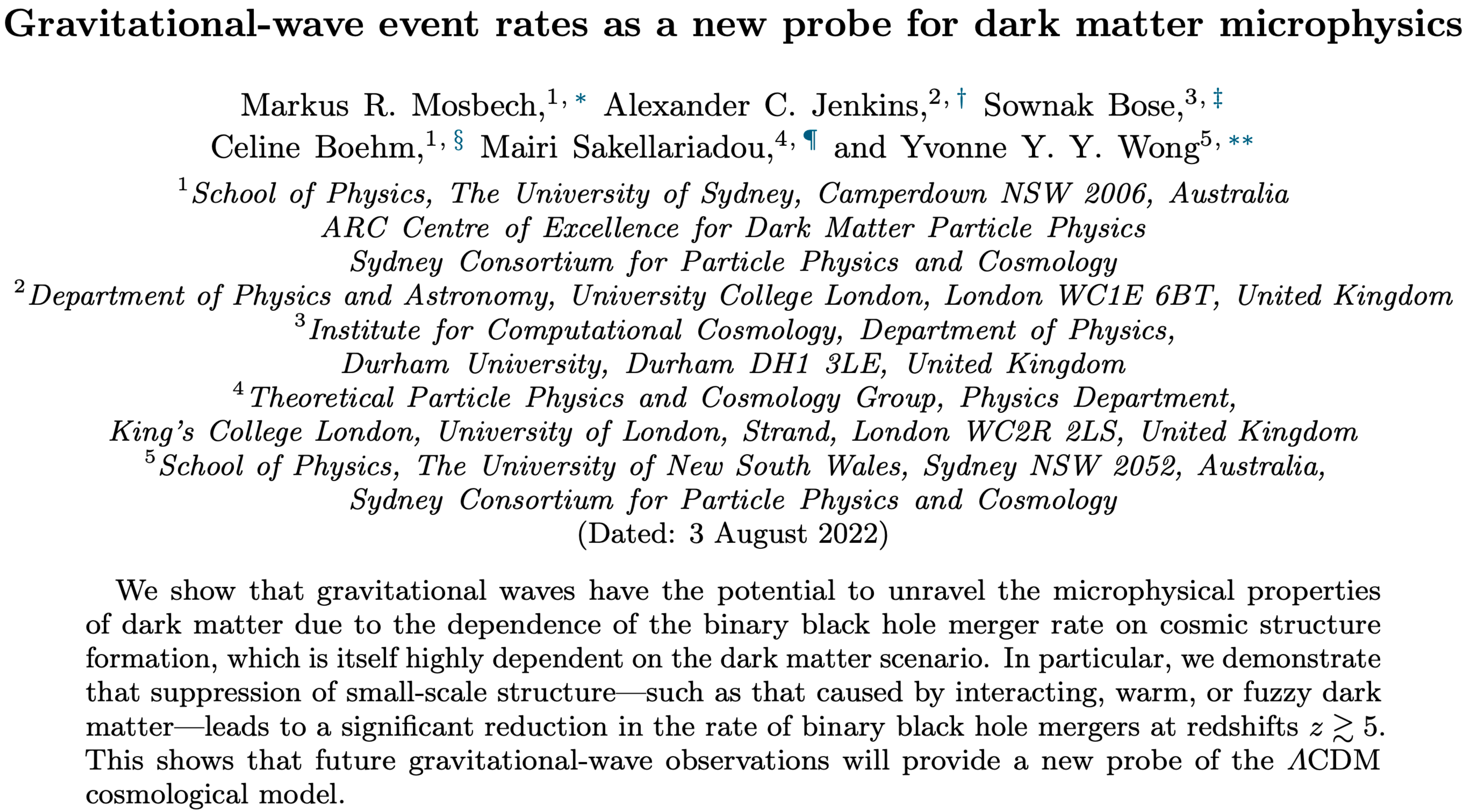


How to probe Dark Matter interactions?

arXiv:2207.14126



Gravitational-wave event rates as a new probe for dark matter microphysics

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Celine Boehm,[1,§] Mairi Sakellariadou,[4,¶] and Yvonne Y. Y. Wong[5,**]
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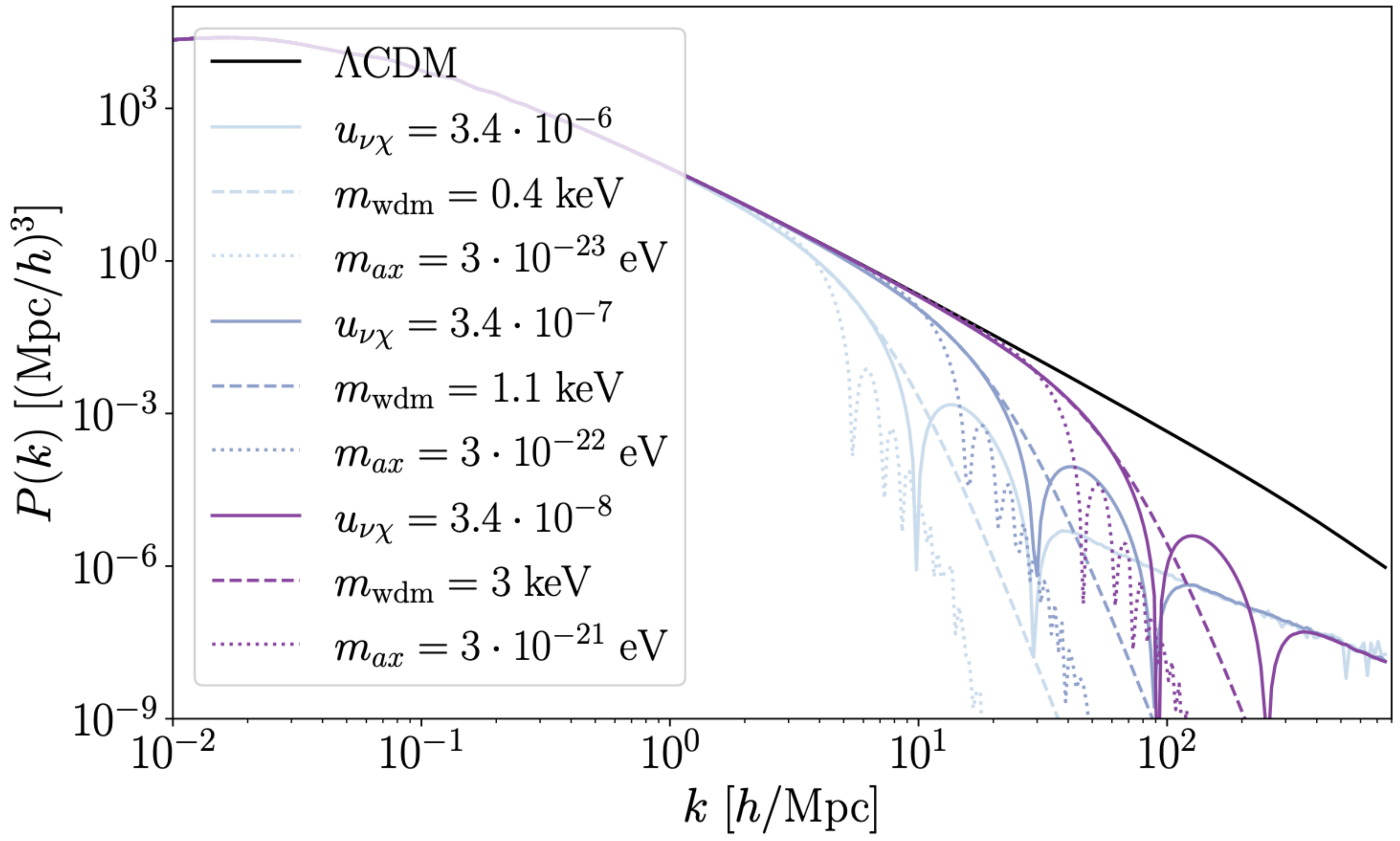
Sydney Consortium for Particle Physics and Cosmology

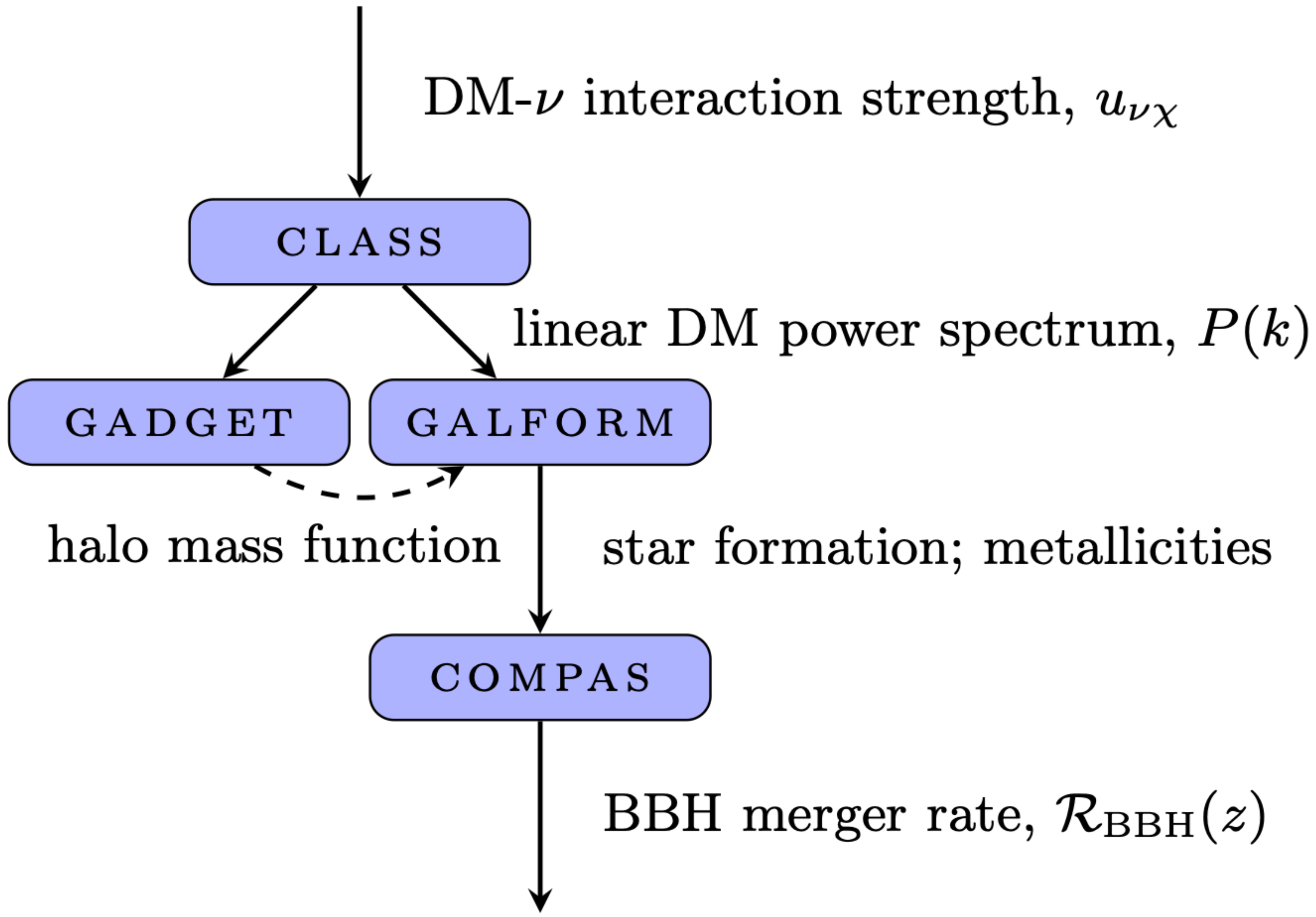
(Dated: 3 August 2022)

We show that gravitational waves have the potential to unravel the microphysical properties of dark matter due to the dependence of the binary black hole merger rate on cosmic structure formation, which is itself highly dependent on the dark matter scenario. In particular, we demonstrate that suppression of small-scale structure—such as that caused by interacting, warm, or fuzzy dark matter—leads to a significant reduction in the rate of binary black hole mergers at redshifts $z \gtrsim 5$. This shows that future gravitational-wave observations will provide a new probe of the ΛCDM cosmological model.

How to probe Dark Matter interactions?

arXiv:2207.14126




DM-ν interaction strength, $u_{\nu\chi}$

CLASS

linear DM power spectrum, $P(k)$

GADGET

GALFORM

halo mass function

star formation; metallicities

COMPAS

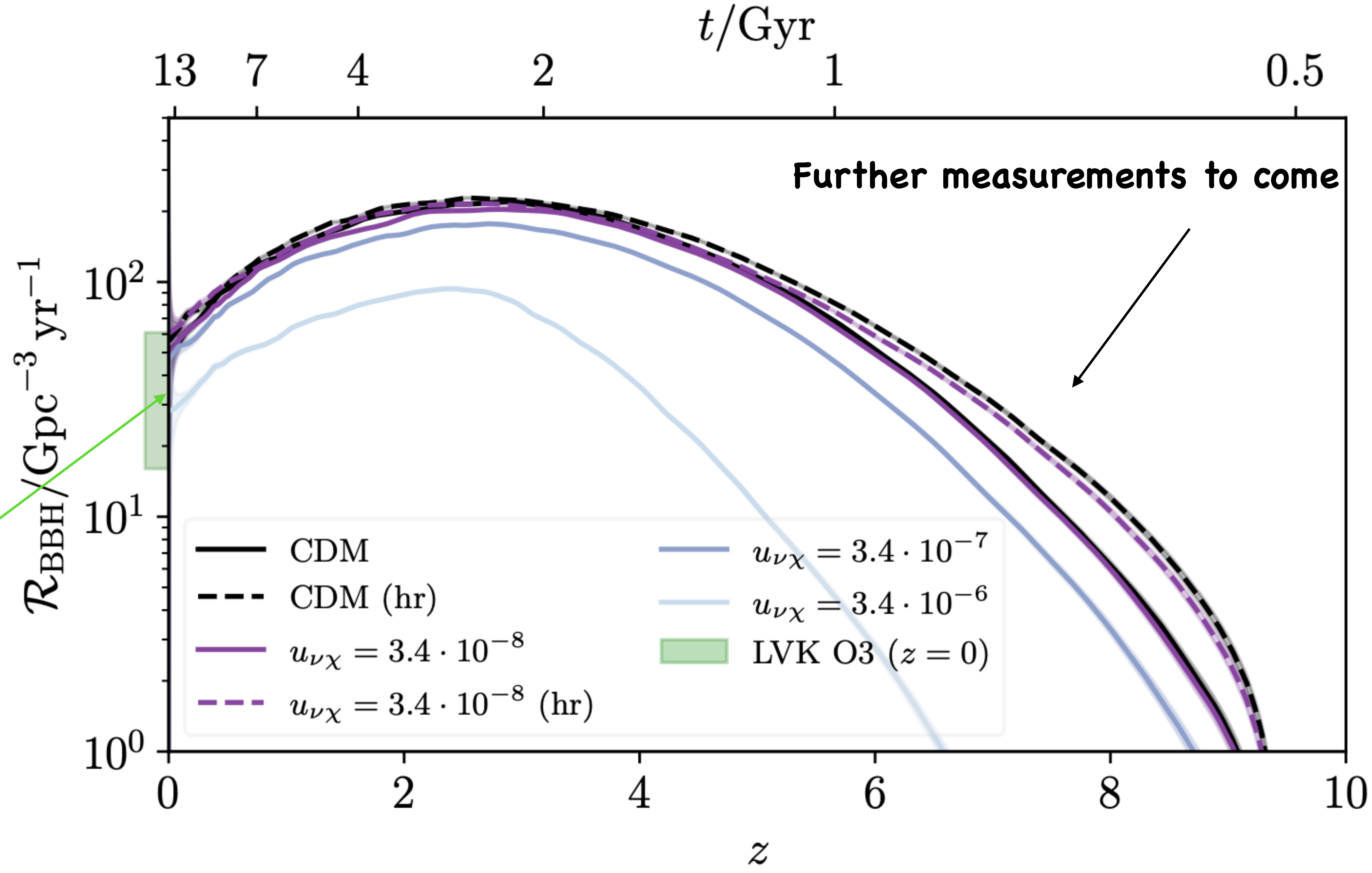
BBH merger rate, $\mathcal{R}_{\rm BBH}(z)$

The BBH merger rate is thus essentially a delayed tracer of star formation, whose normalisation depends on the efficiency with which massive binary stars are converted into BBHs. This efficiency is mostly determined by the stellar metallicity.

We use a compas dataset of 20 million evolved binaries (resulting in ≈ 0.7 million BBHs) presented in [104], which is publicly available at [105]. This gives us the BBH formation efficiency as a function of initial mass and metallicity, as well as the delay time between star formation and BBH merger. By combining this with a model for the star formation rate density and metallicity distribution as functions of redshift, we can use the compas "cosmic integration" module [106] to average over the synthetic population and obtain the cosmic BBH merger rate
(i.e., the fraction of the stellar mass that is in elements heavier than helium).

How to probe Dark Matter interactions?

arXiv:2207.14126



Further measurements to come

Current measurement

LCDM almost excluded (!!!) so next measurements will be critical!