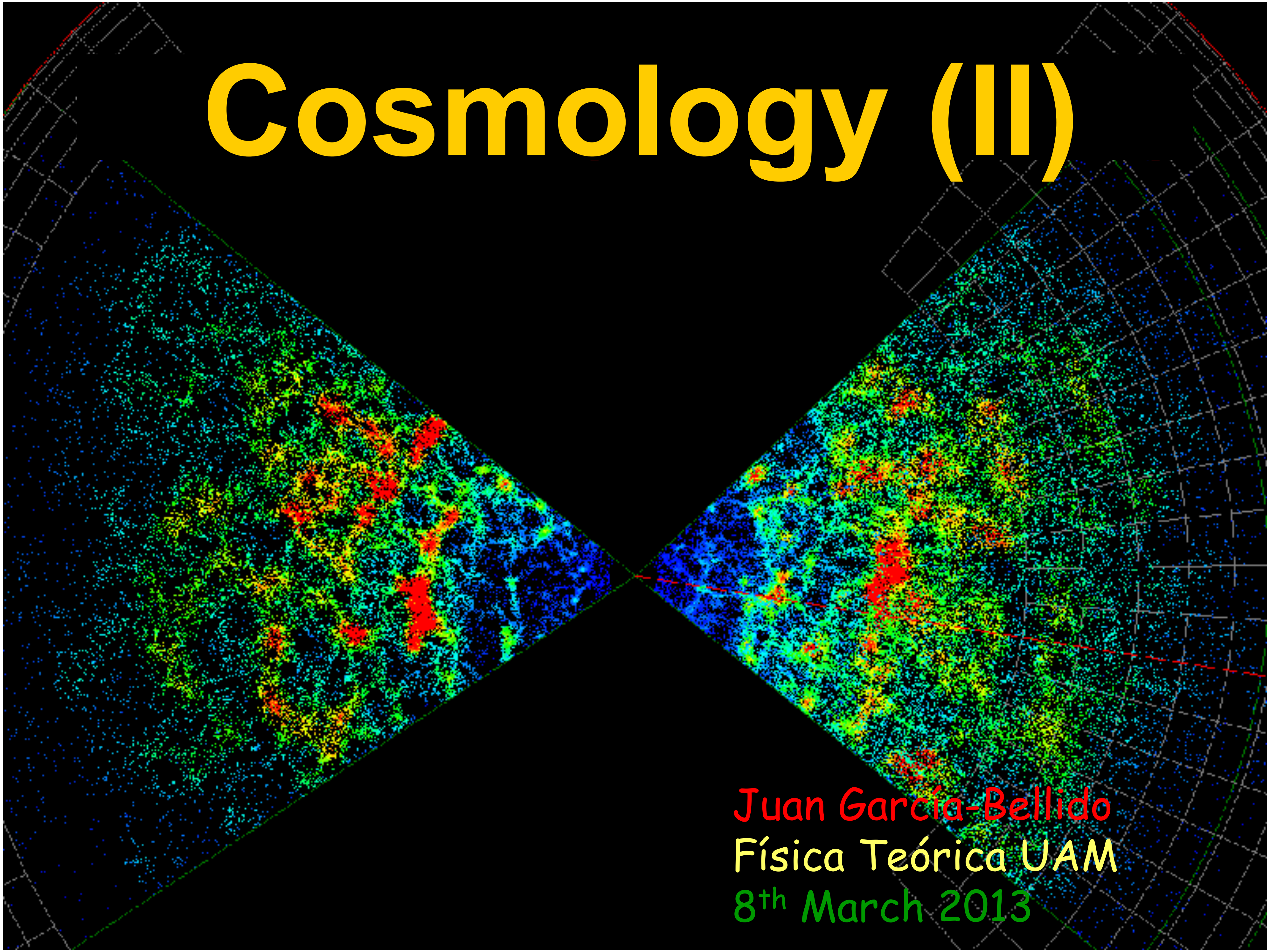
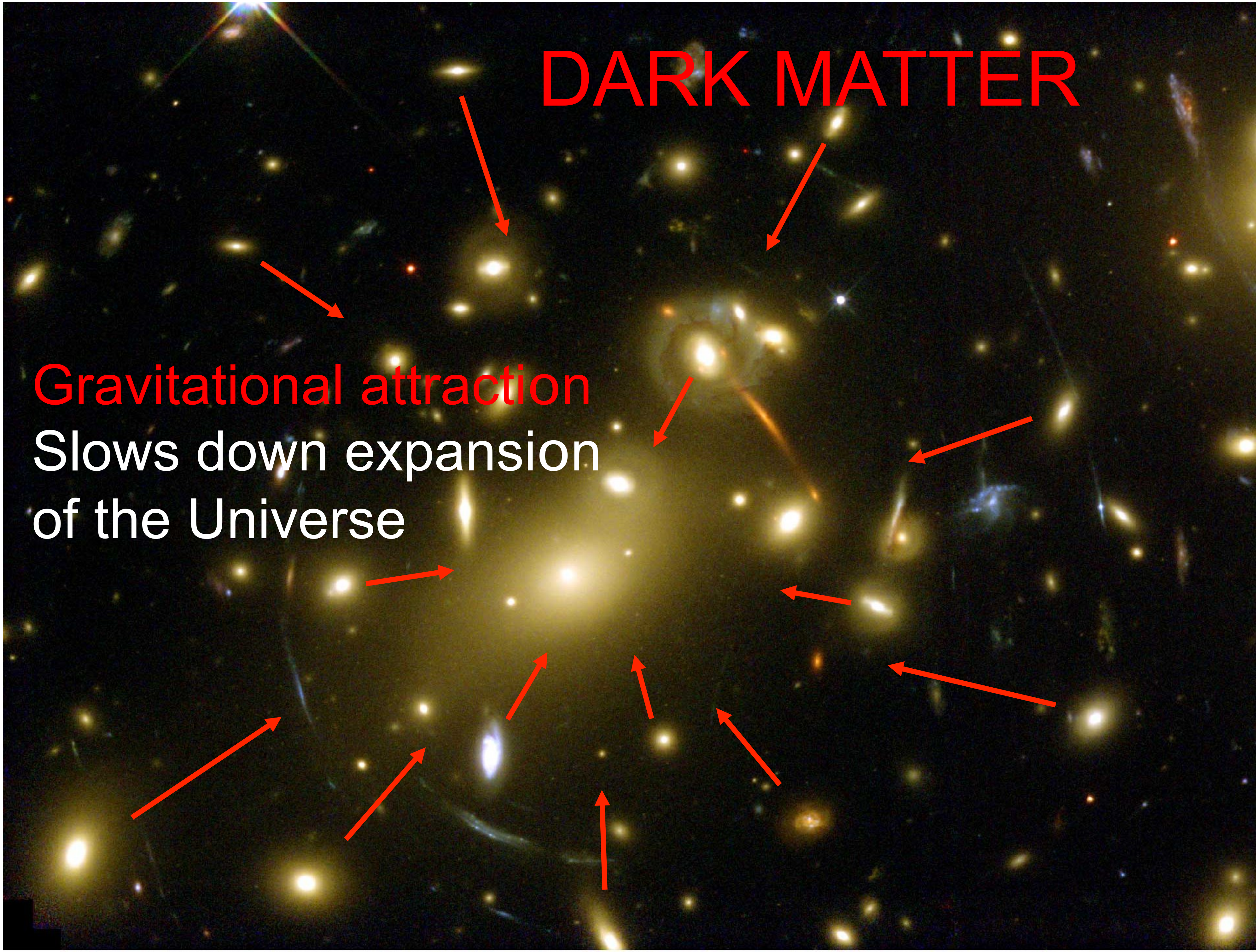
Cosmology (II)



Juan García-Bellido
Física Teórica UAM
8th March 2013



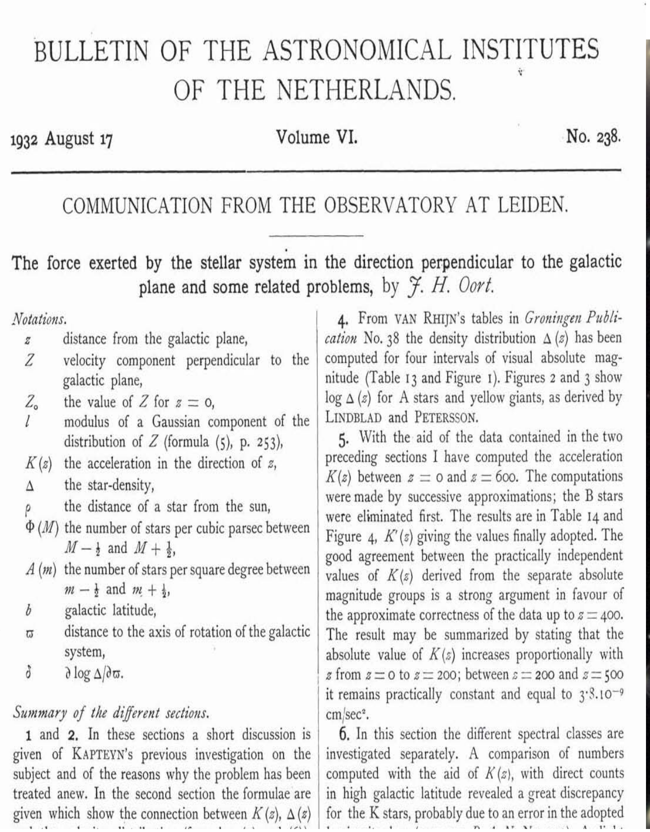
DARK MATTER

Gravitational attraction

Slows down expansion of the Universe

Dark Matter

Jan Oort 1932



BULLETIN OF THE ASTRONOMICAL INSTITUTES
OF THE NETHERLANDS.

1932 August 17 Volume VI. No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

Notations.

z	distance from the galactic plane,
Z	velocity component perpendicular to the galactic plane,
Z_0	the value of Z for $z = 0$,
l	modulus of a Gaussian component of the distribution of Z (formula (5), p. 253),
$K(z)$	the acceleration in the direction of z,
Δ	the star-density,
ρ	the distance of a star from the sun,
$\Phi(M)$	the number of stars per cubic parsec between $M - \frac{1}{2}$ and $M + \frac{1}{2}$,
$A(m)$	the number of stars per square degree between $m - \frac{1}{2}$ and $m + \frac{1}{2}$,
b	galactic latitude,
ϖ	distance to the axis of rotation of the galactic system,
δ	$\partial \log \Delta / \partial \varpi$.

Summary of the different sections.

1 and **2.** In these sections a short discussion is given of KAPTEYN's previous investigation on the subject and of the reasons why the problem has been treated anew. In the second section the formulae are given which show the connection between $K(z)$, $\Delta(z)$

4. From VAN RHIJN's tables in *Groningen Publication* No. 38 the density distribution $\Delta(z)$ has been computed for four intervals of visual absolute magnitude (Table 13 and Figure 1). Figures 2 and 3 show $\log \Delta(z)$ for A stars and yellow giants, as derived by LINDBLAD and PETERSSON.

5. With the aid of the data contained in the two preceding sections I have computed the acceleration $K(z)$ between $z = 0$ and $z = 600$. The computations were made by successive approximations; the B stars were eliminated first. The results are in Table 14 and Figure 4, $K'(z)$ giving the values finally adopted. The good agreement between the practically independent values of $K(z)$ derived from the separate absolute magnitude groups is a strong argument in favour of the approximate correctness of the data up to $z = 400$. The result may be summarized by stating that the absolute value of $K(z)$ increases proportionally with z from $z = 0$ to $z = 200$; between $z = 200$ and $z = 500$ it remains practically constant and equal to $3{\cdot}8 . 10^{-9}$ cm/sec².

6. In this section the different spectral classes are investigated separately. A comparison of numbers computed with the aid of $K(z)$, with direct counts in high galactic latitude revealed a great discrepancy for the K stars, probably due to an error in the adopted

1. Coin “Dark Matter”

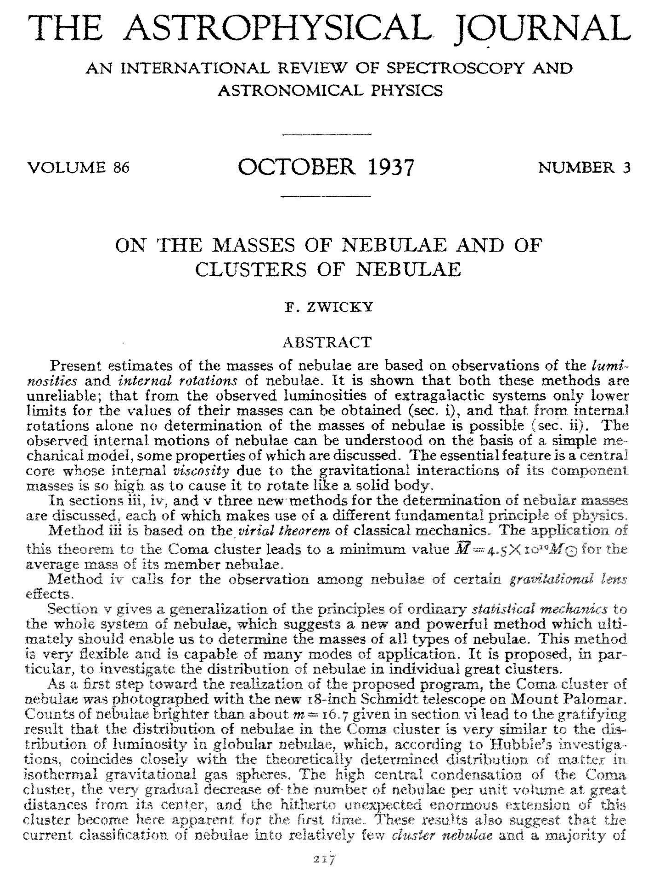
3. Virial mass of Coma

3. M/L in Coma is 500 compared to 3 locally

4. Gravitational lensing could be used with larger telescopes

Coma Cluster HST

Fritz Zwicky 1933



THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND
ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_\odot$ for the average mass of its member nebulae.

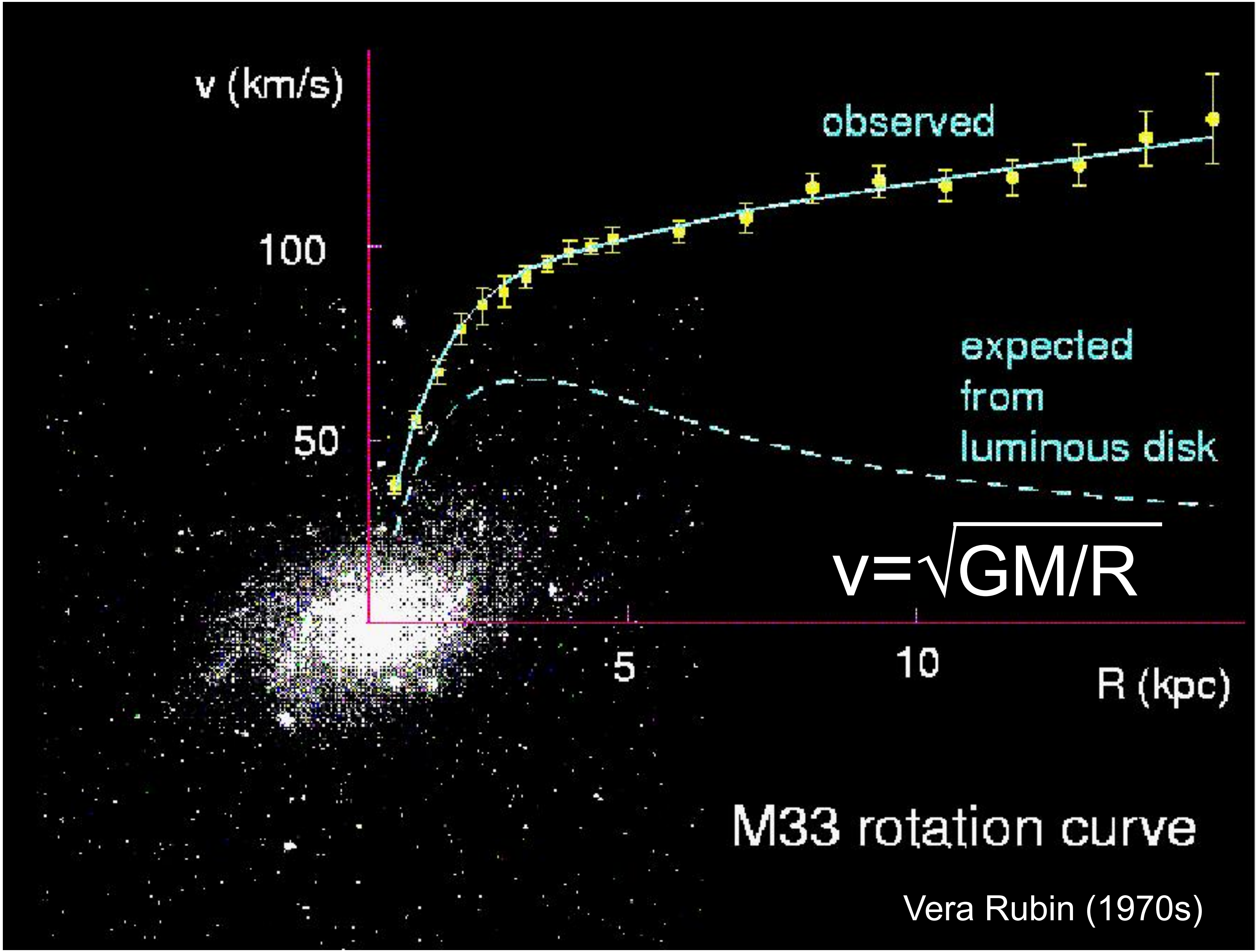
Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar. Counts of nebulae brighter than about $m = 16.7$ given in section vi lead to the gratifying result that the distribution of nebulae in the Coma cluster is very similar to the distribution of luminosity in globular nebulae, which, according to Hubble's investigations, coincides closely with the theoretically determined distribution of matter in isothermal gravitational gas spheres. The high central condensation of the Coma cluster, the very gradual decrease of the number of nebulae per unit volume at great distances from its center, and the hitherto unexpected enormous extension of this cluster become here apparent for the first time. These results also suggest that the current classification of nebulae into relatively few *cluster nebulae* and a majority of

DM in galaxies

Galaxies have **dark halos**



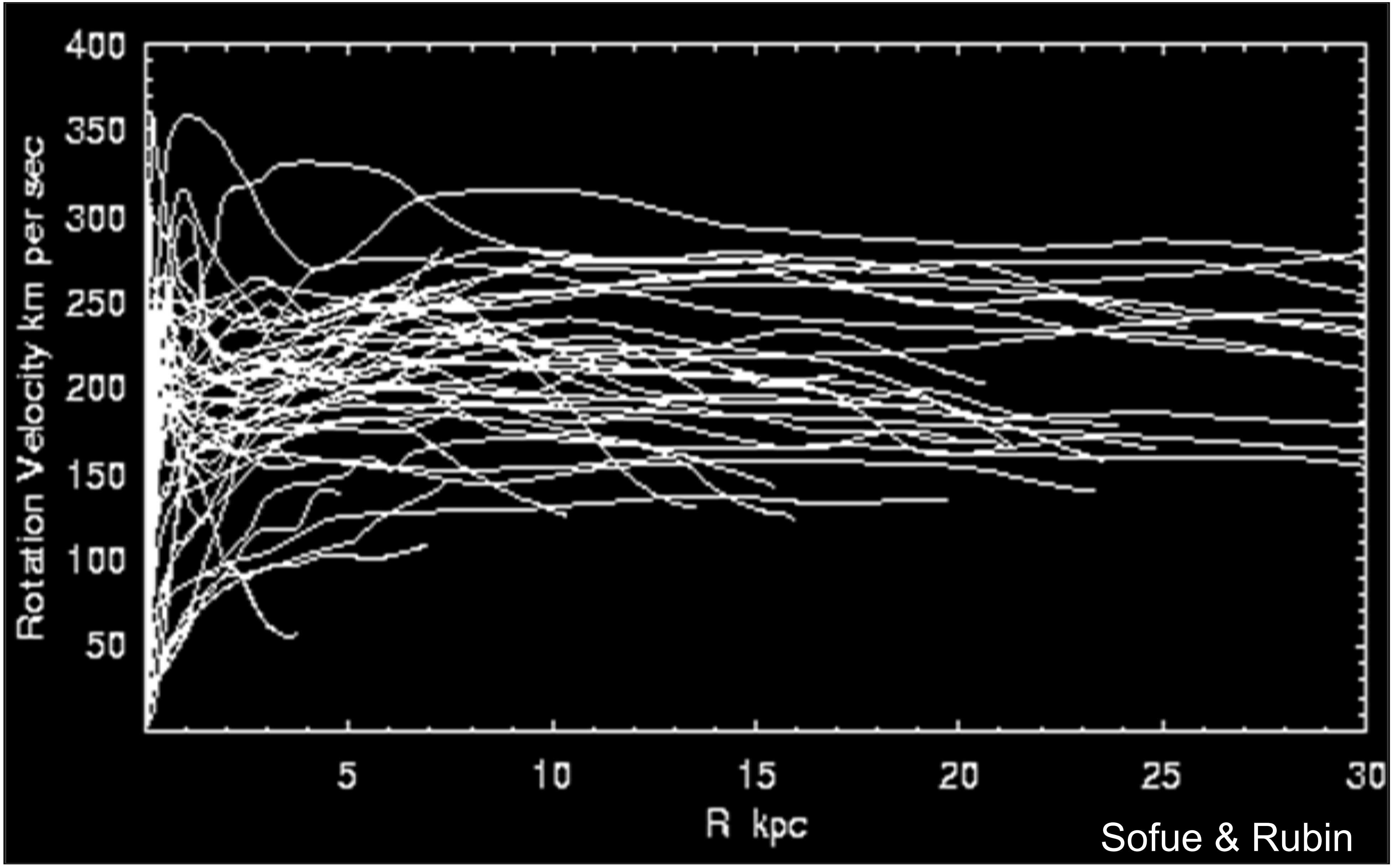
M33 rotation curve

$$v=\sqrt{GM/R}$$

Vera Rubin (1970s)

Dark Matter

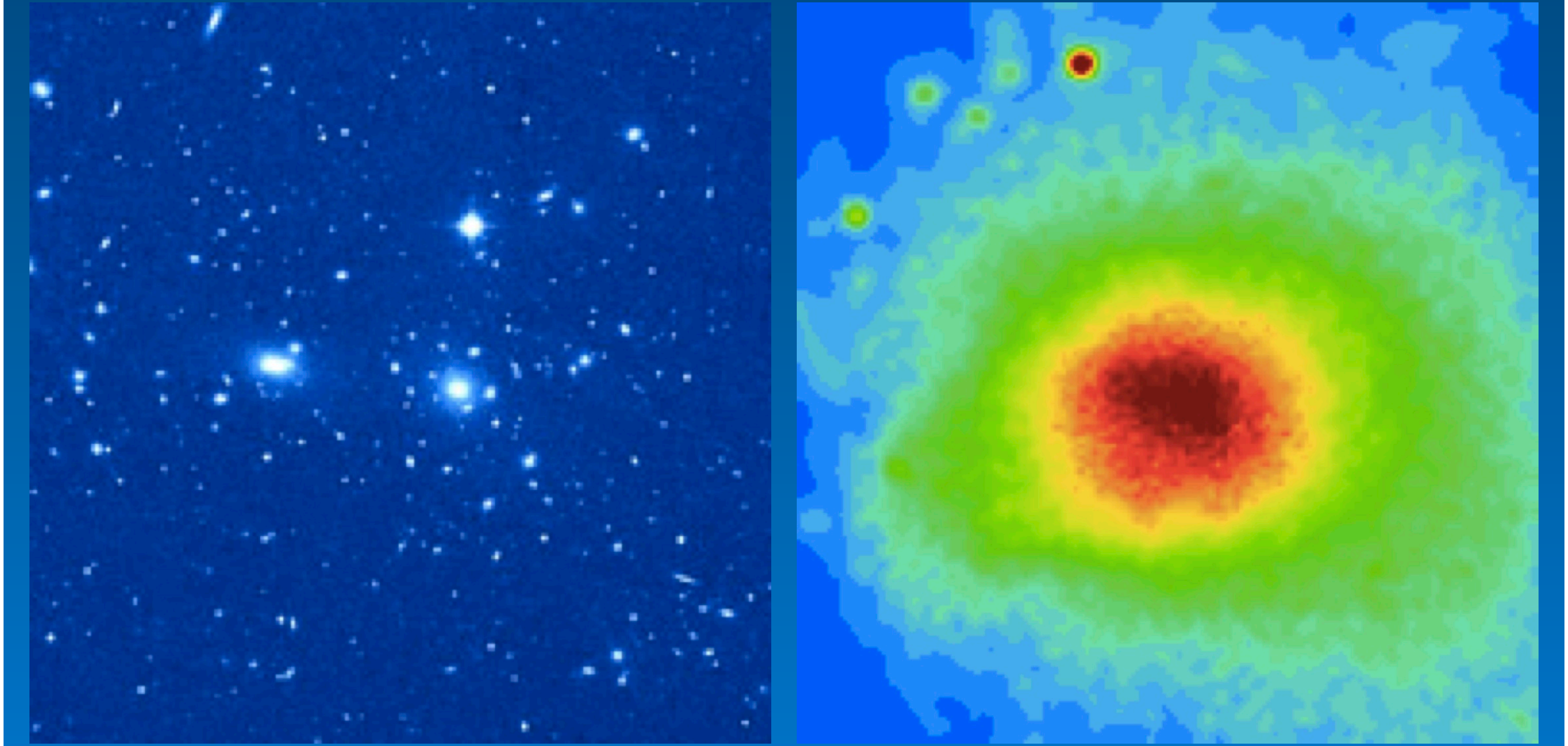
CO – central regions Optical – disks HI – outer disk & halo



Sofue & Rubin

DM in clusters

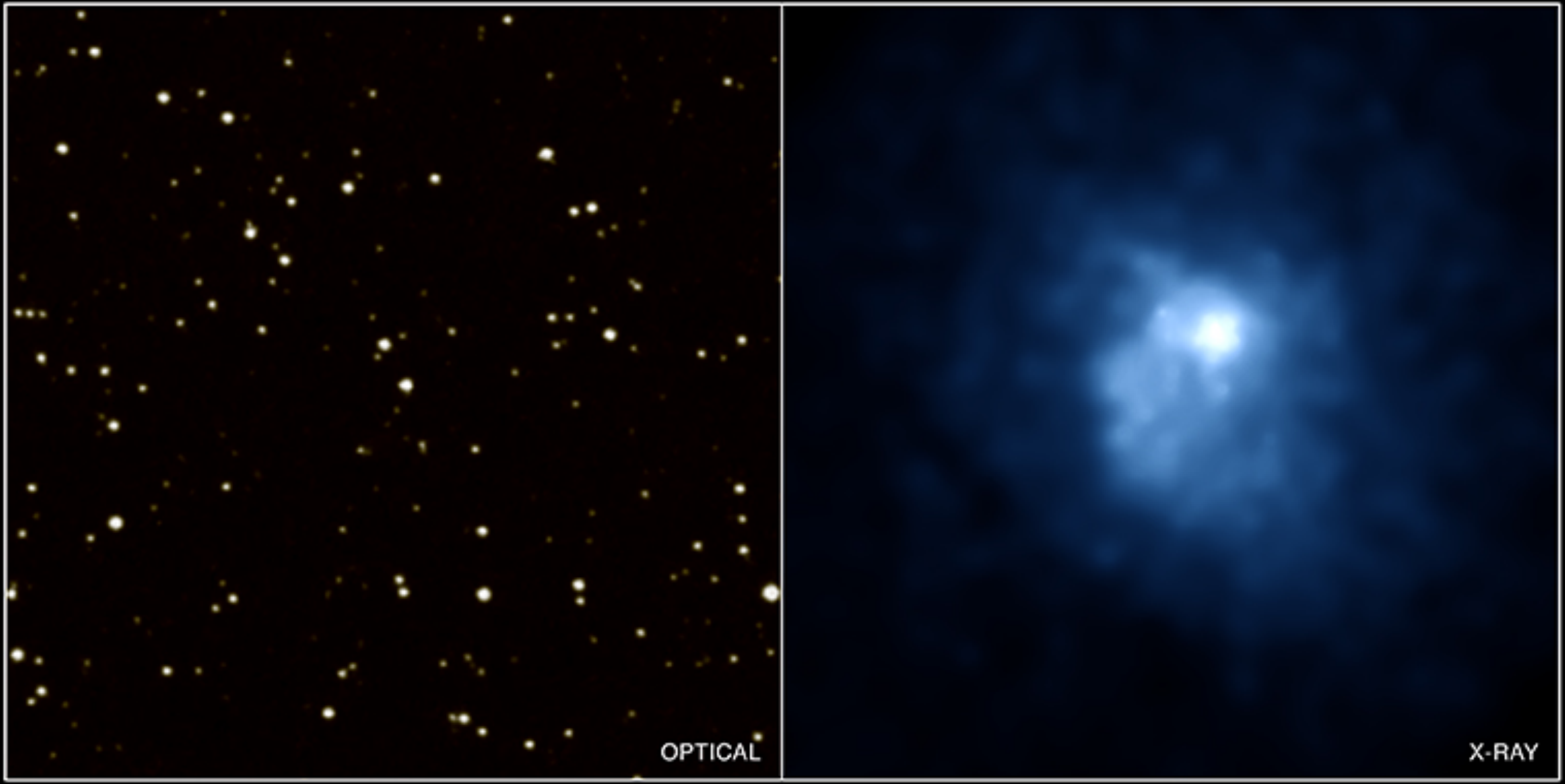
Clusters radiate in X rays



Coma cluster

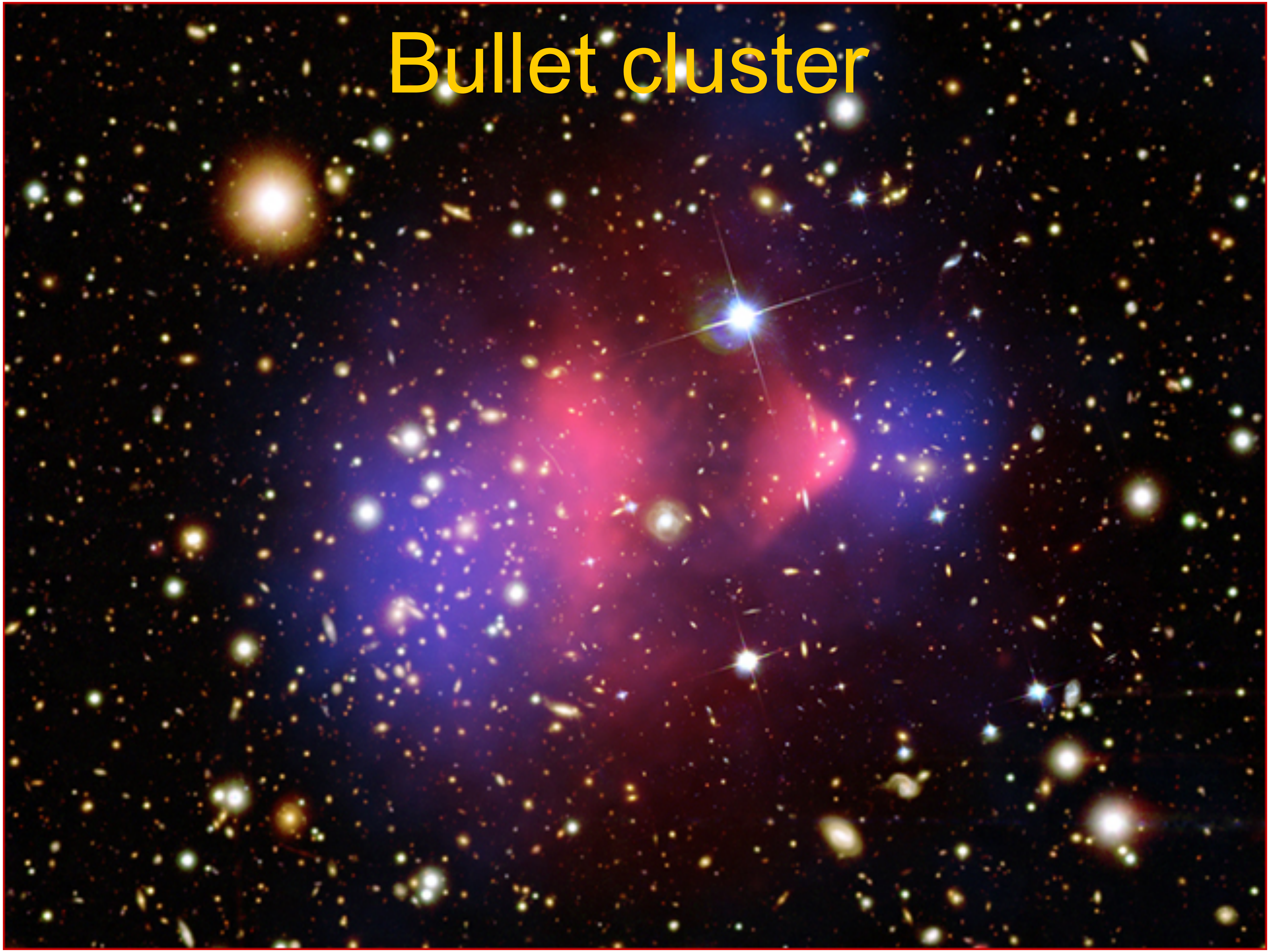
Clusters radiate in X rays

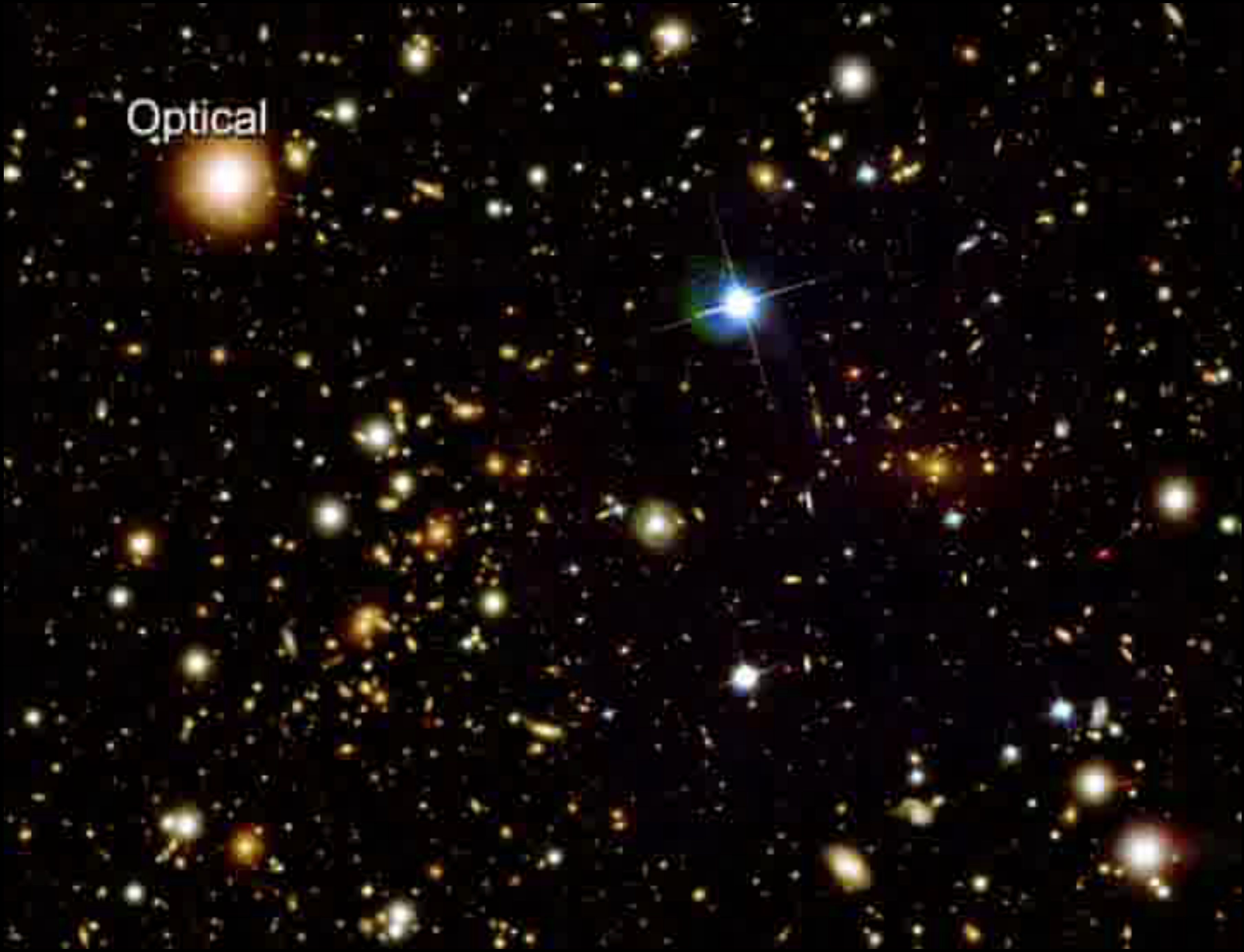
Chandra 2009

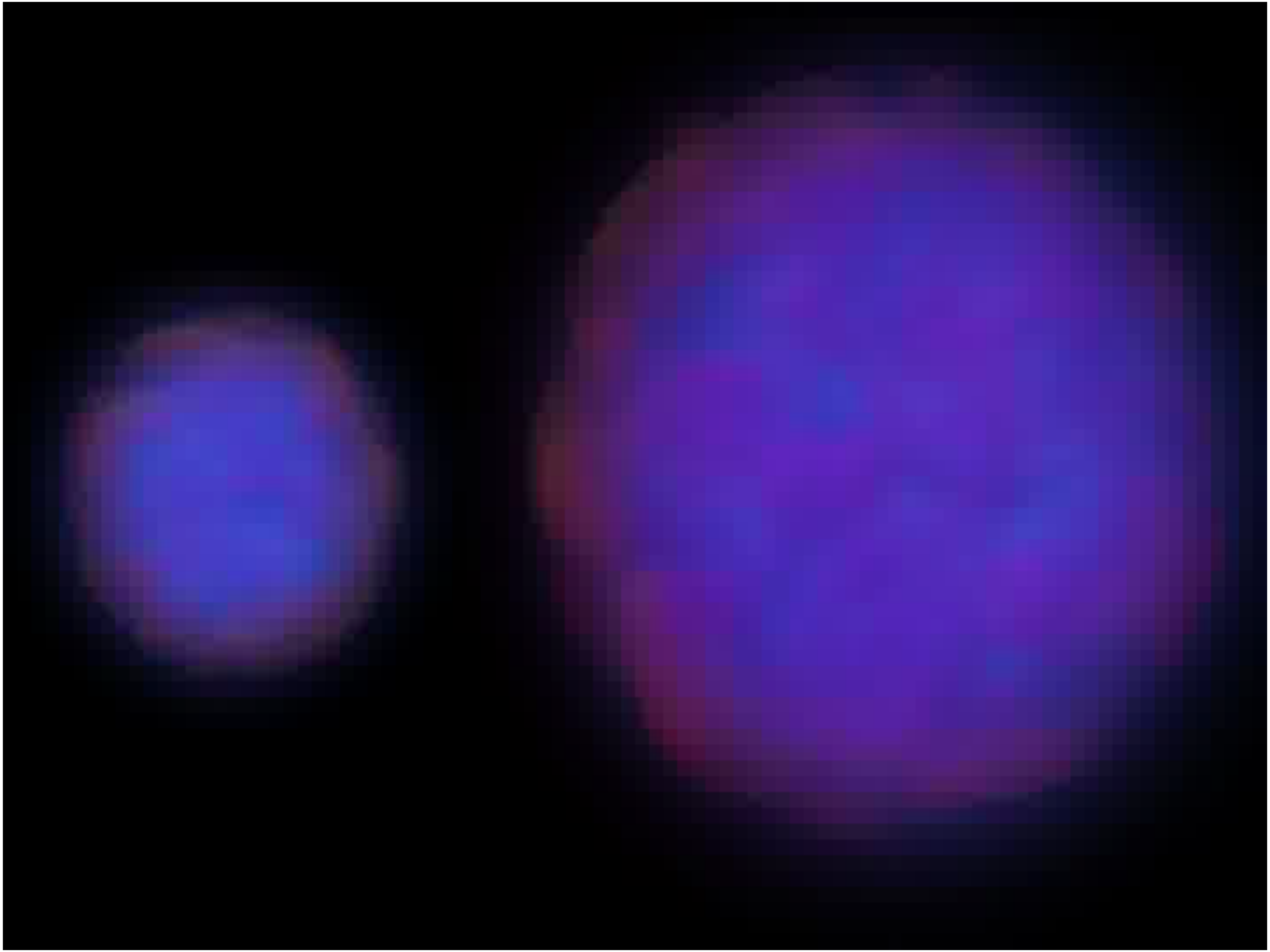


3C438 cluster

Bullet cluster

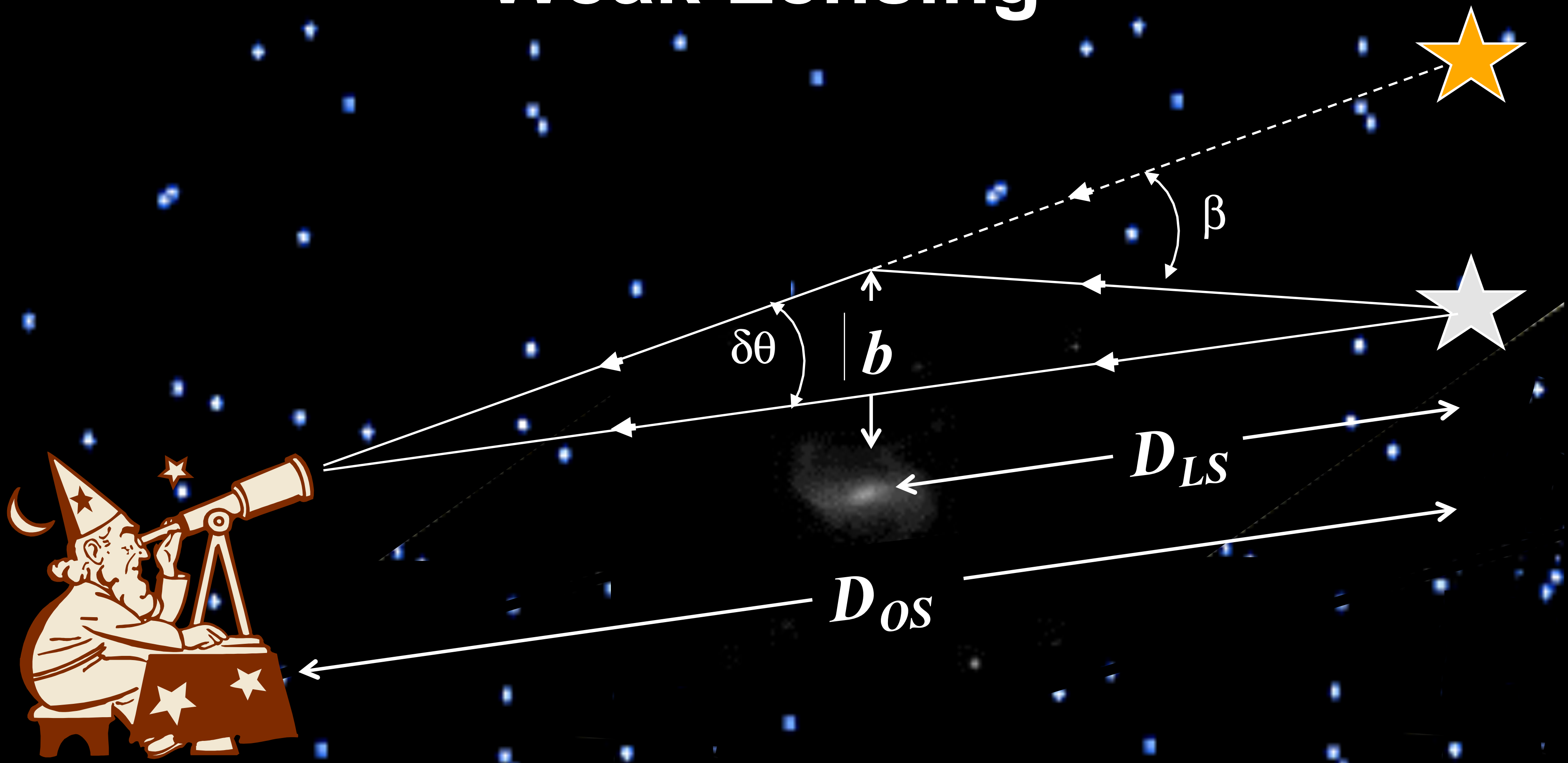



Optical



weak & strong lensing

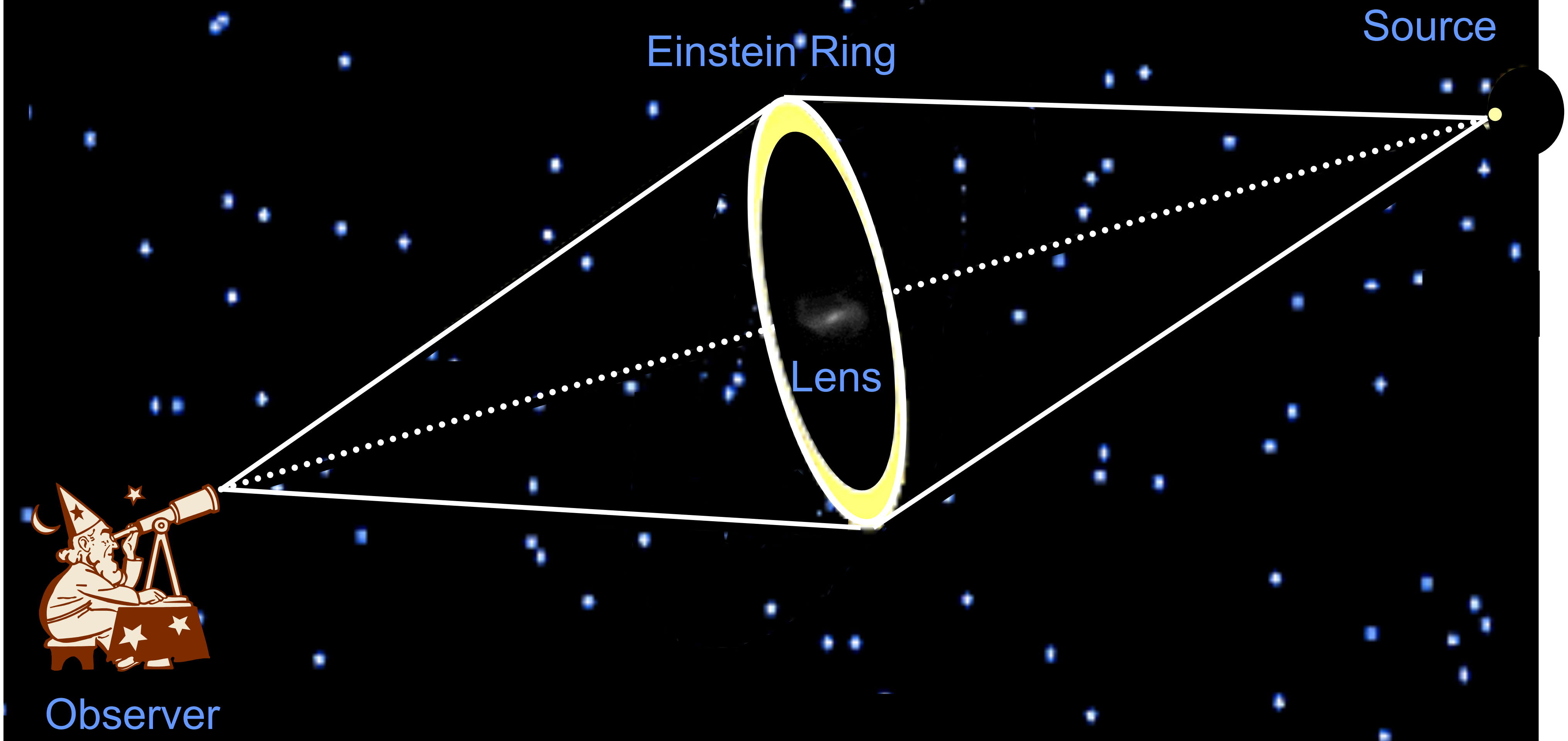
Weak Lensing



observe
deflection
angle

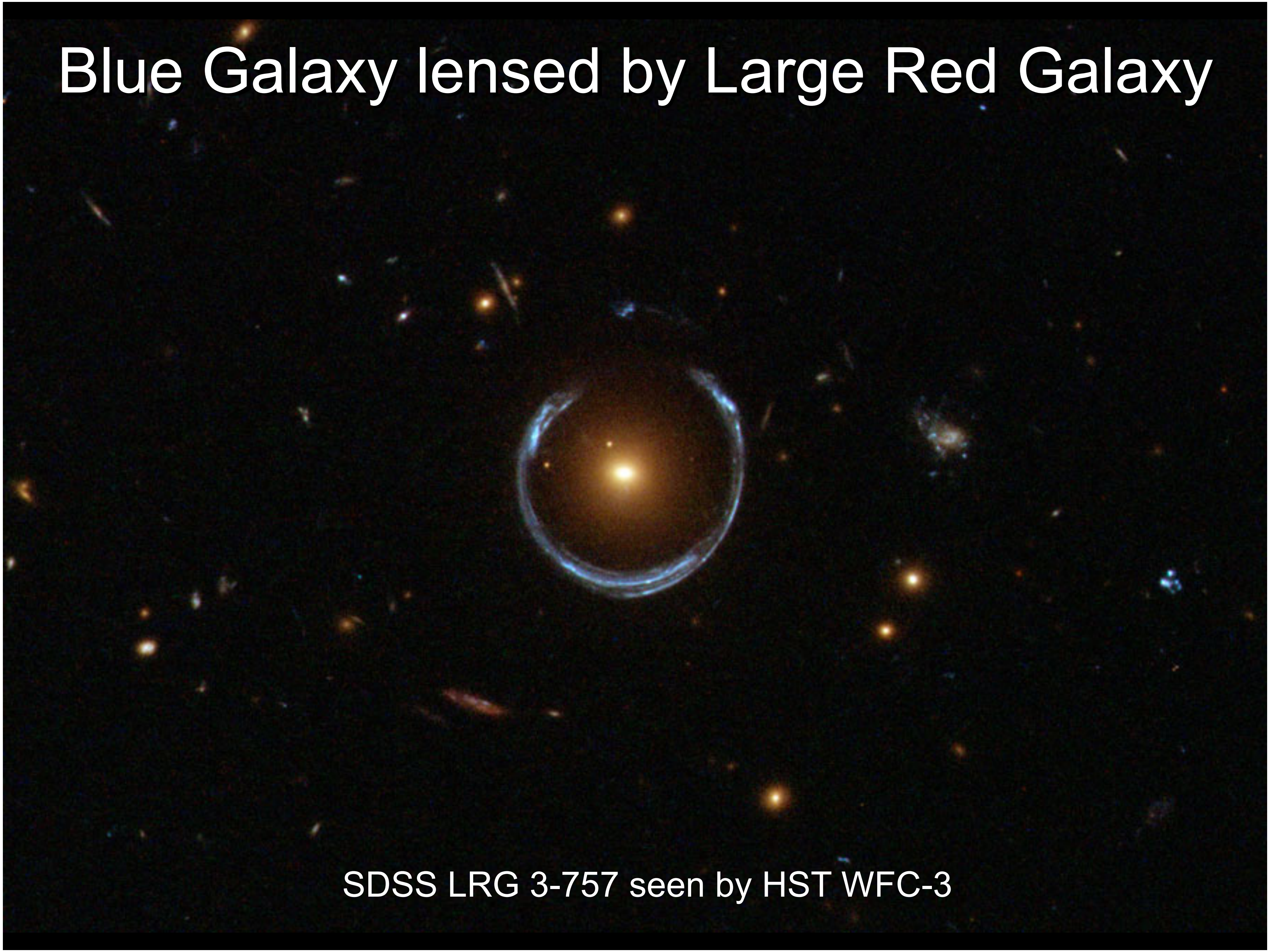
$$\beta o = \frac{4GM}{bD}\frac{D_{LS}}{_{OS}}$$

Einstein Ring



Mass of lens determines angular size of ring

Blue Galaxy lensed by Large Red Galaxy



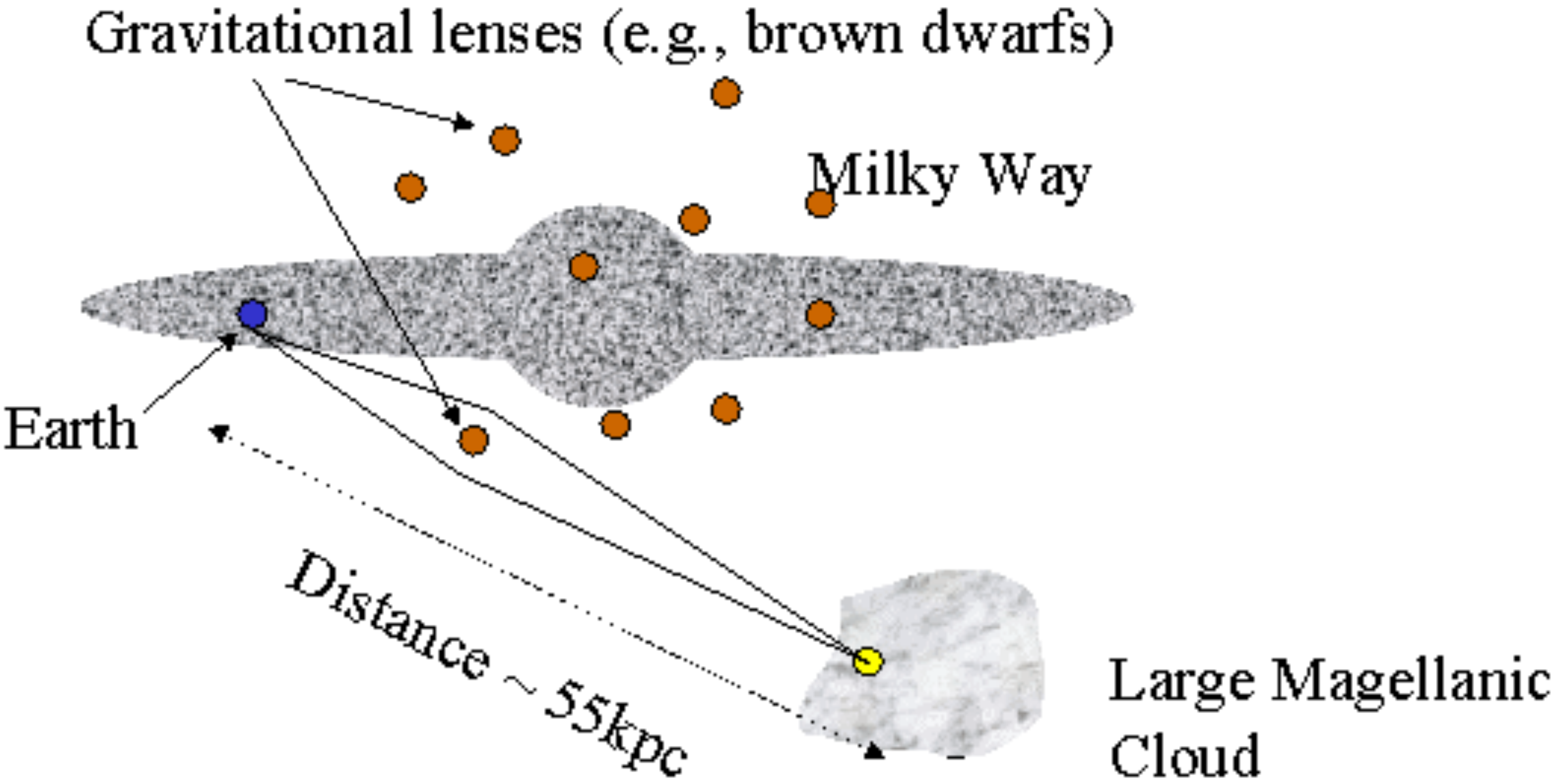
SDSS LRG 3-757 seen by HST WFC-3

Dark Matter in Abell 2218 (HST)

Lensing Mass = Virial Mass

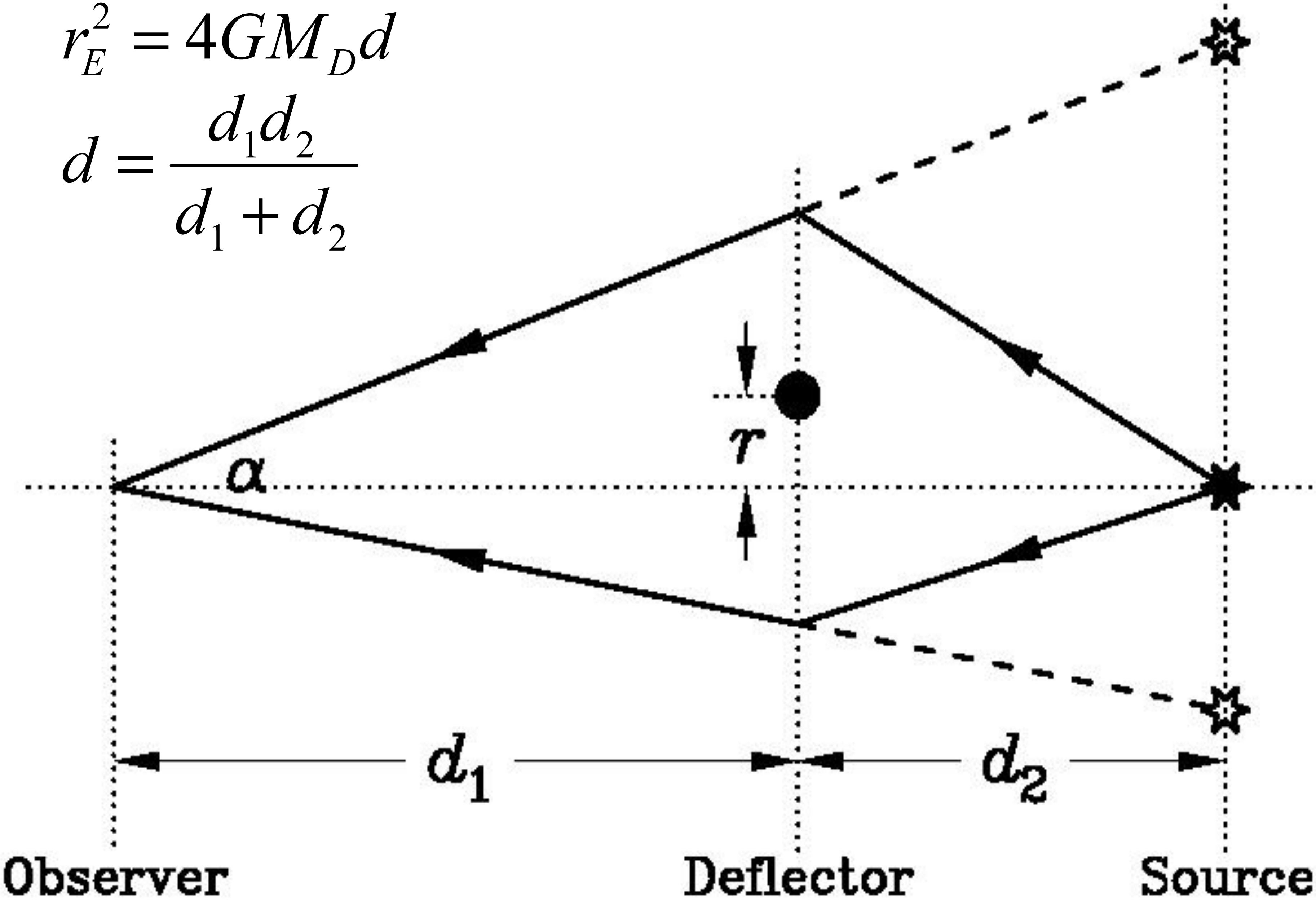
Microlensing

Microlensing



$$r_E^2 = 4GM_D d$$

$$d = \frac{d_1 d_2}{d_1 + d_2}$$



$$A = \frac{2+u^2}{u\sqrt{4+u^2}} \qquad u = \frac{r}{r_E}$$ amplification

$$\overline{\Delta t} = \frac{r_E}{\upsilon} = \frac{\sqrt{4GM_D d}}{\upsilon}$$ average duration

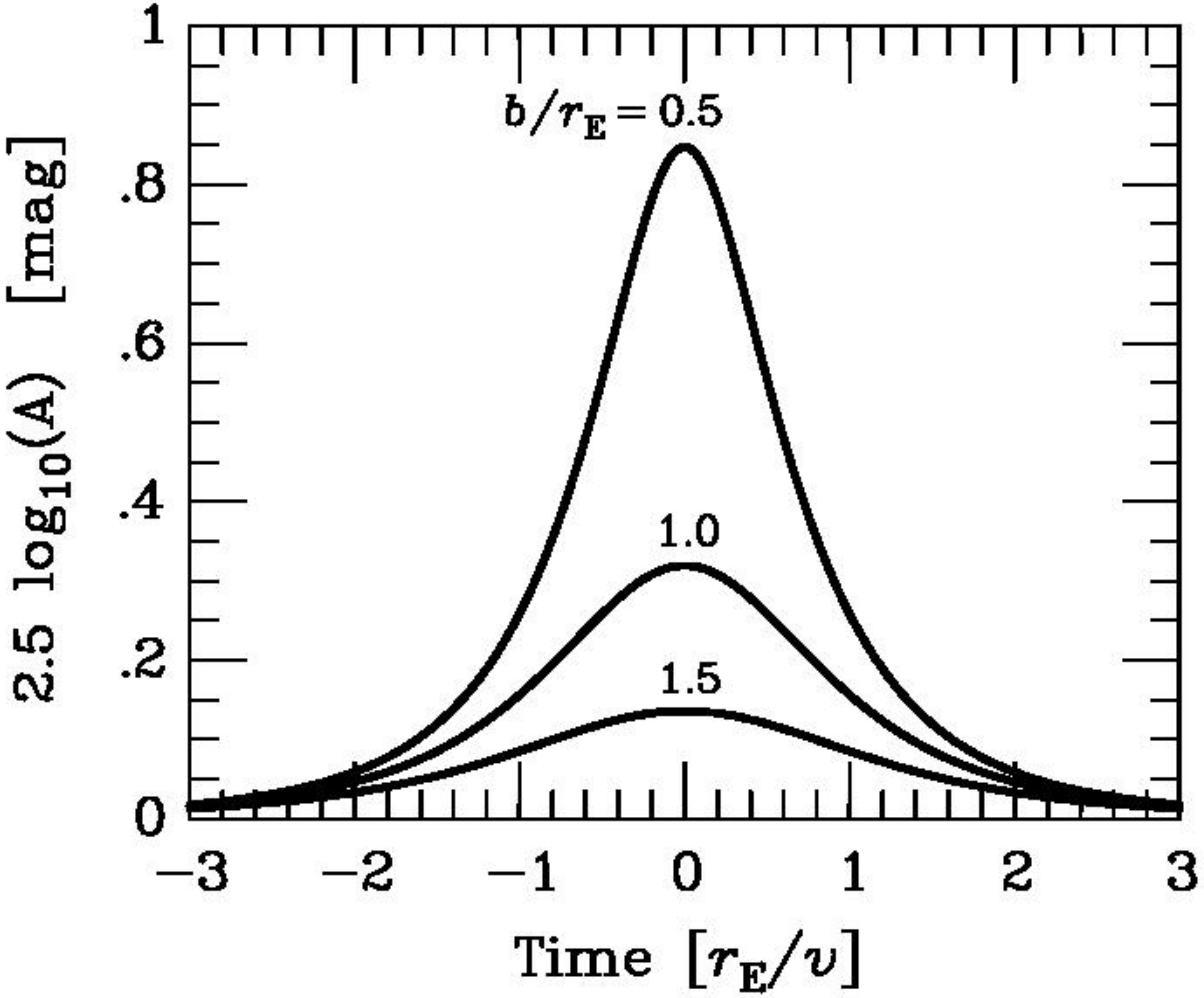
$M_D = 1\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 3$ months

$M_D = 0.1\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 1$ month

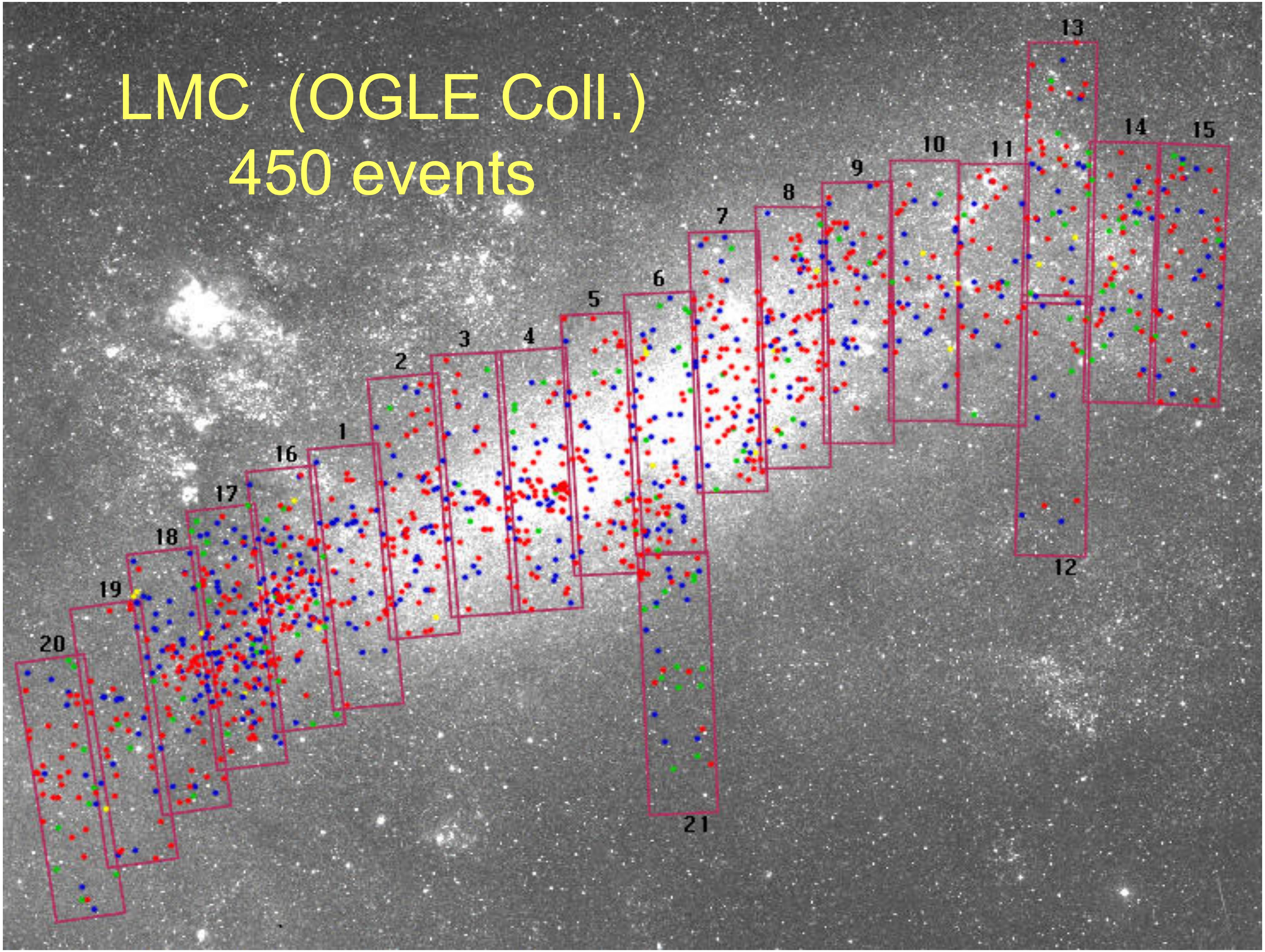
$M_D = 10^{-2}\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 9$ days

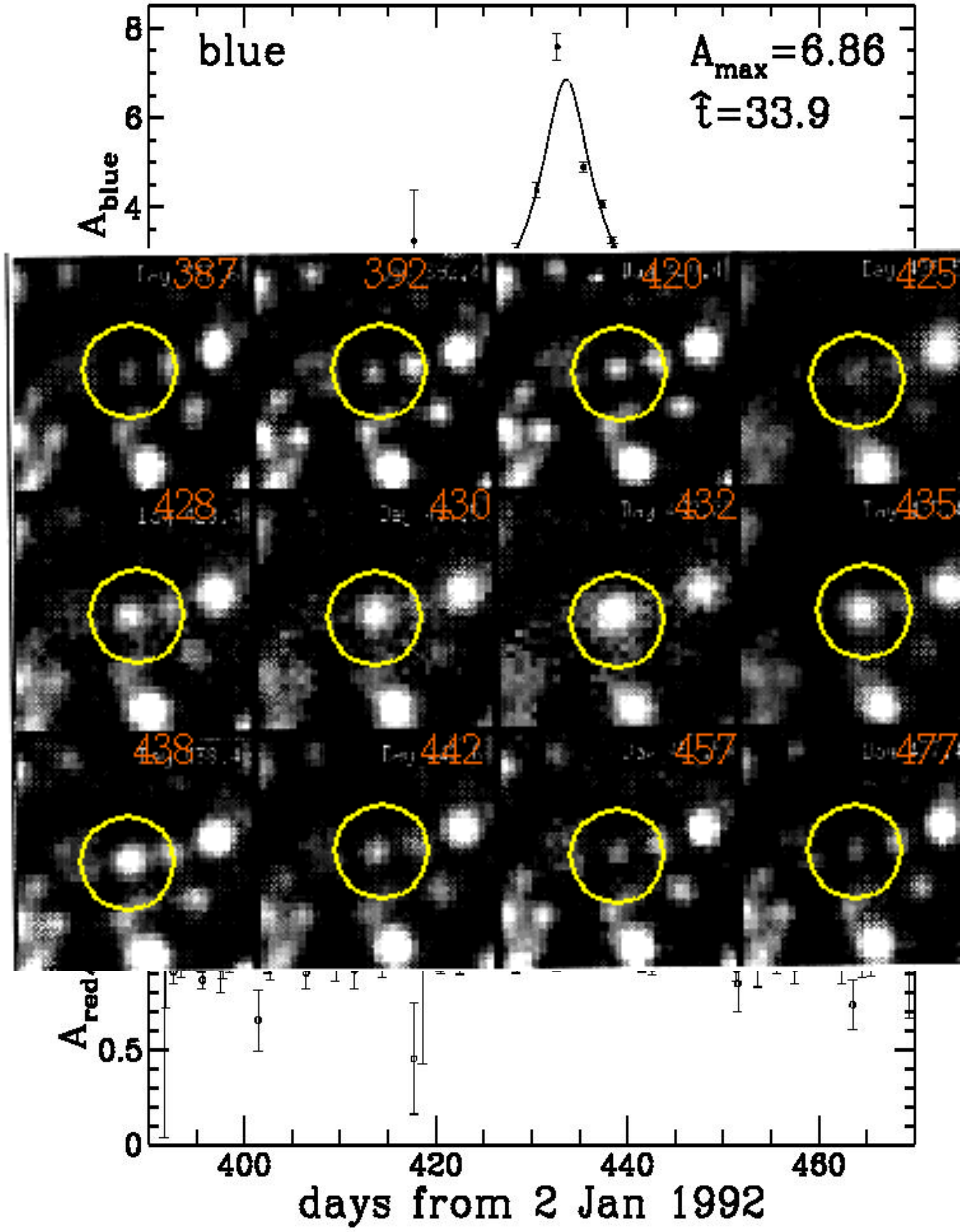
$M_D = 10^{-4}\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 1$ day

$M_D = 10^{-6}\ M_\Theta \quad \Rightarrow \quad \overline{\Delta t} = 2$ hours


$b/r_E = 0.5$
1.0
1.5
1
.8
.6
.4
.2
0
$2.5\ \log_{10}(A)$ [mag]
−3
−2
−1
0
1
2
3
Time $[r_E/v]$

LMC (OGLE Coll.)
450 events





symmetric

$$A_{\mathbf{max}} = 7.20 \pm 0.09$$

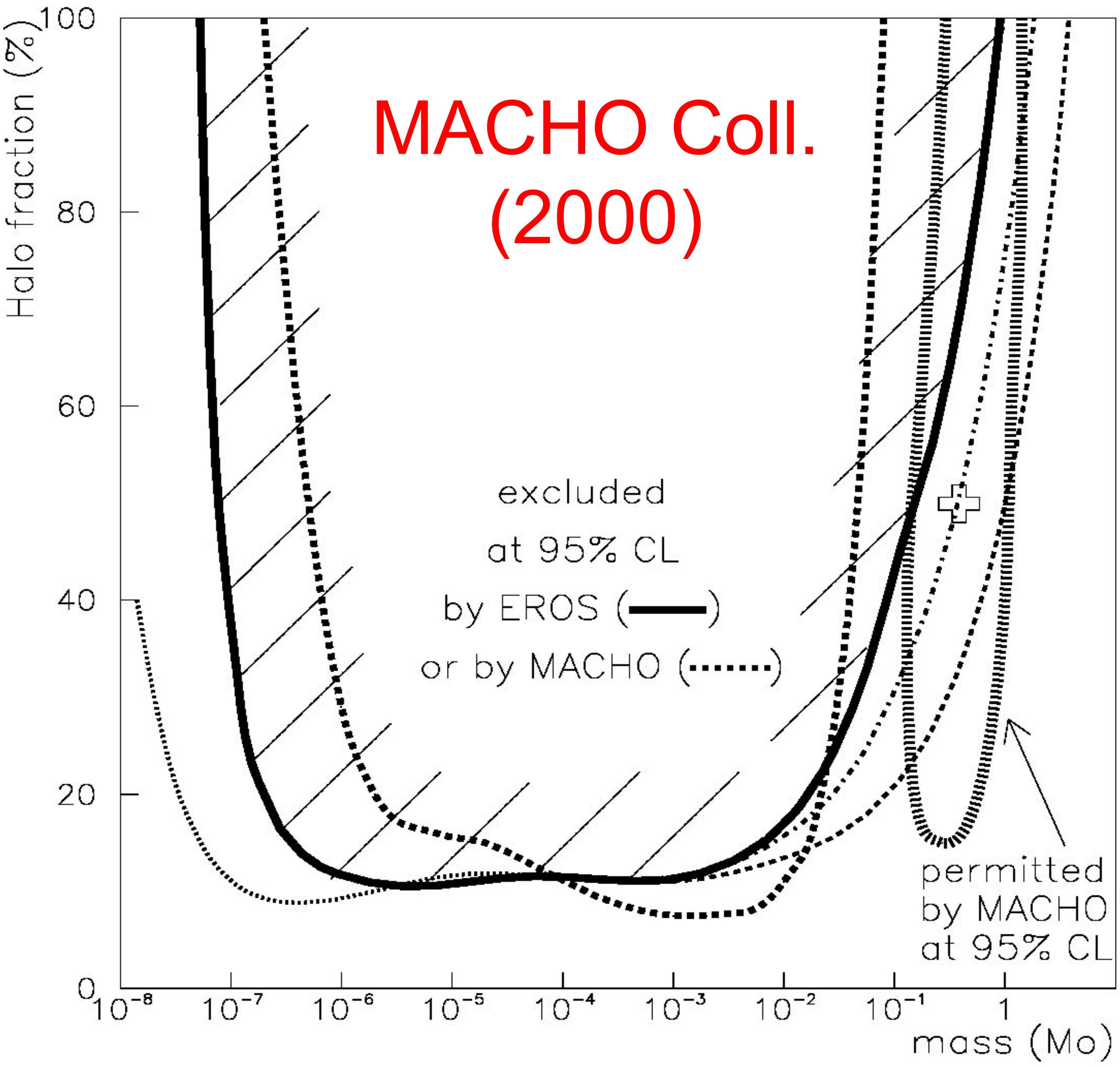
achromatic

$$\frac{A_{red}}{A_{blue}} = 1.00 \pm 0.05$$

unique

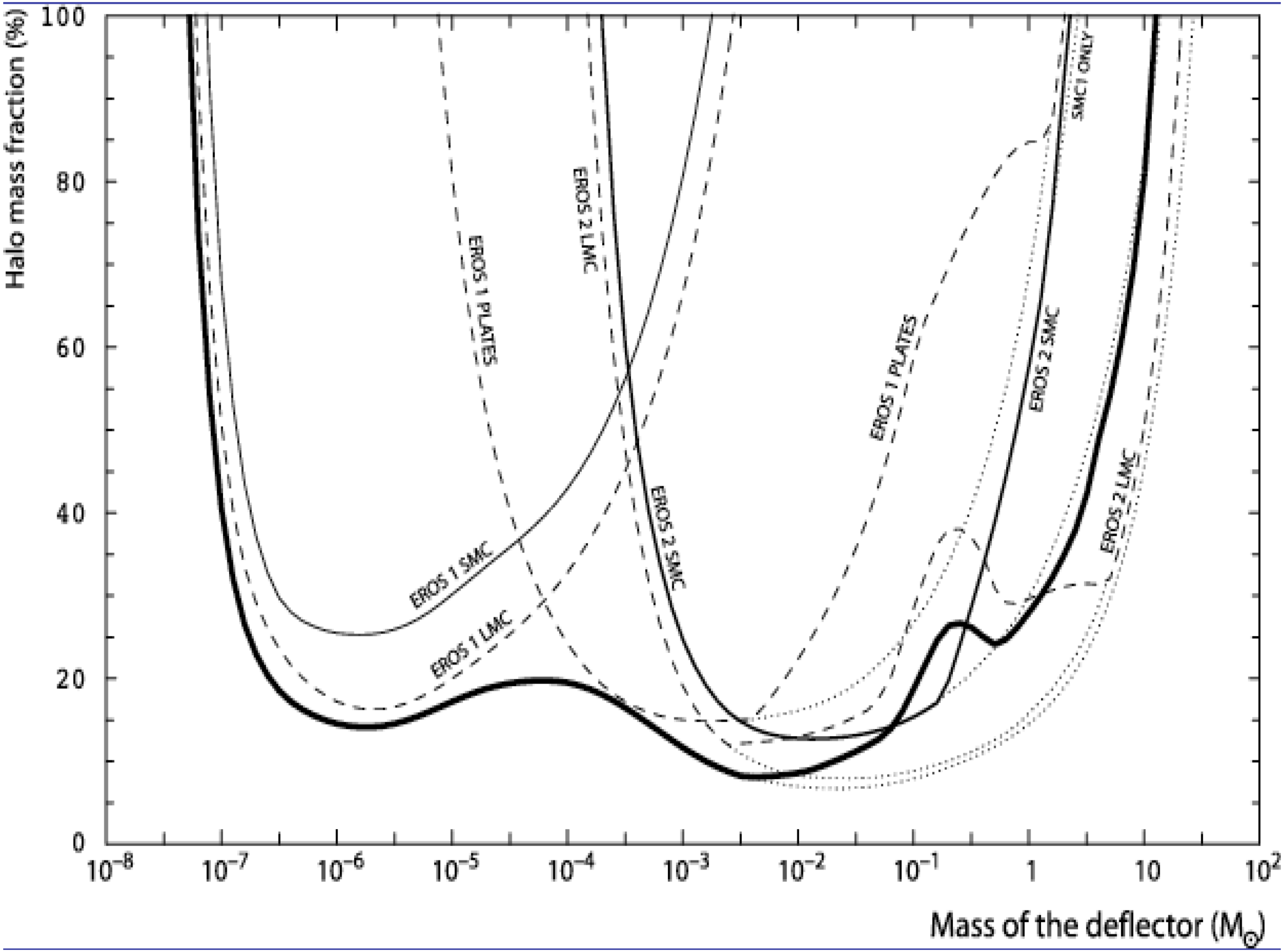
$$t = 34.8 \pm 0.2 \text{ days}$$

$$\Rightarrow \quad M_D \approx 0.1 M_{\Theta}$$

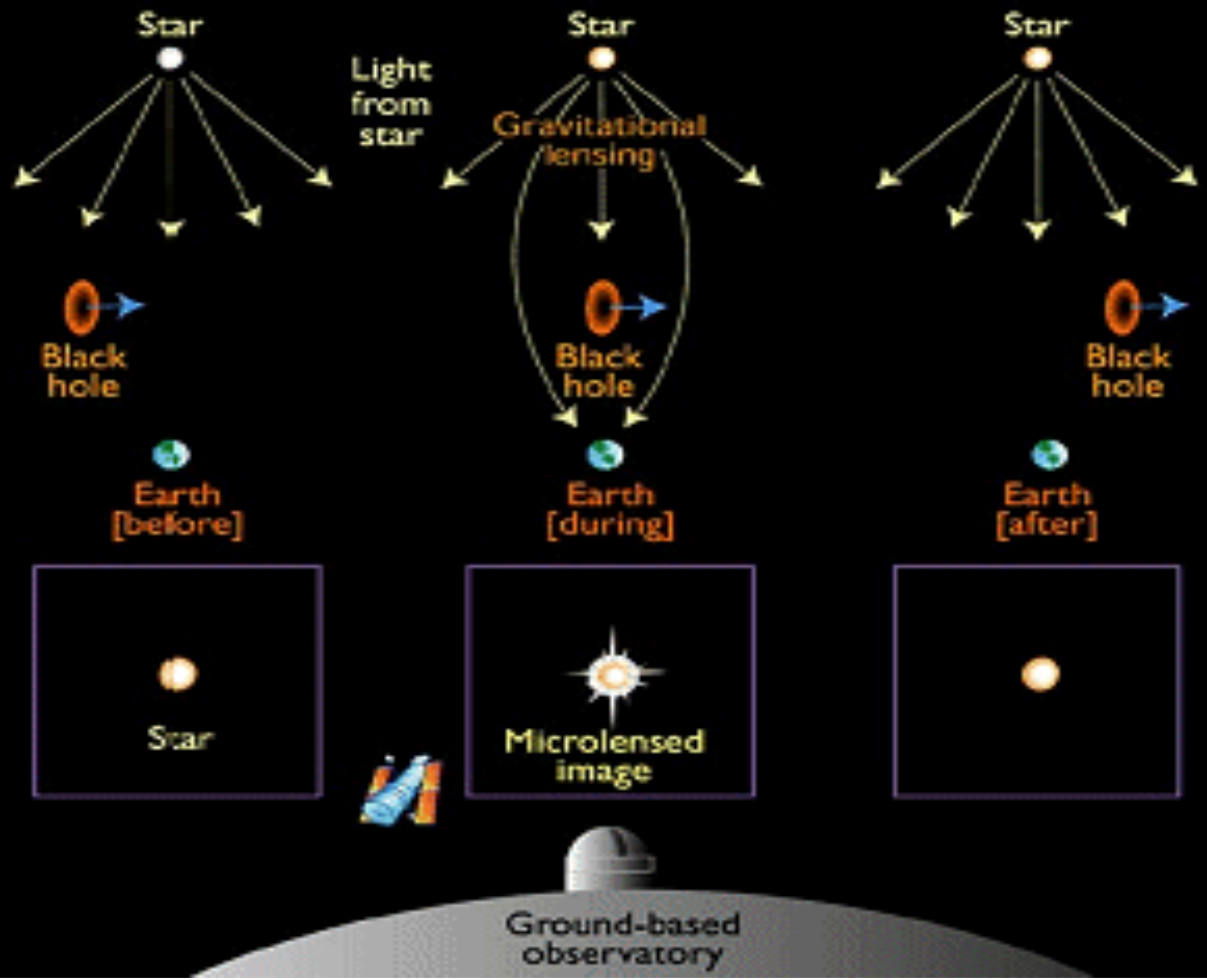


MACHO Coll.
(2000)

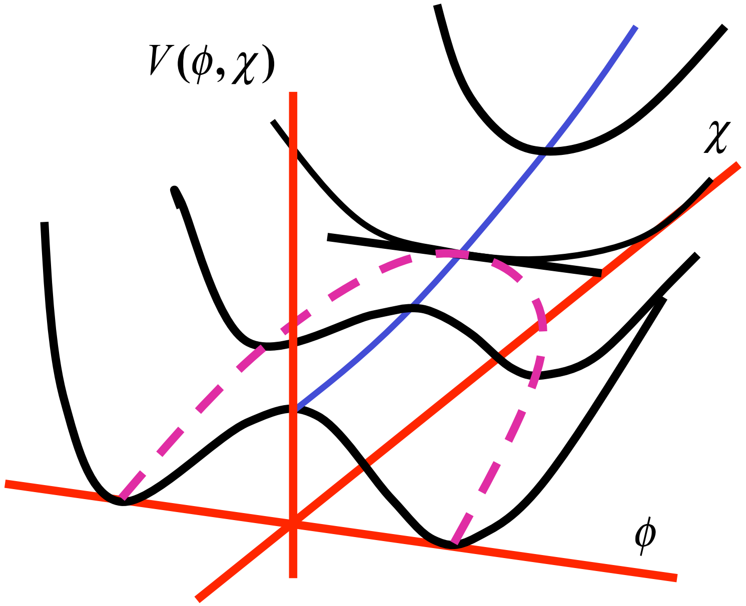
K. Griest (2005)



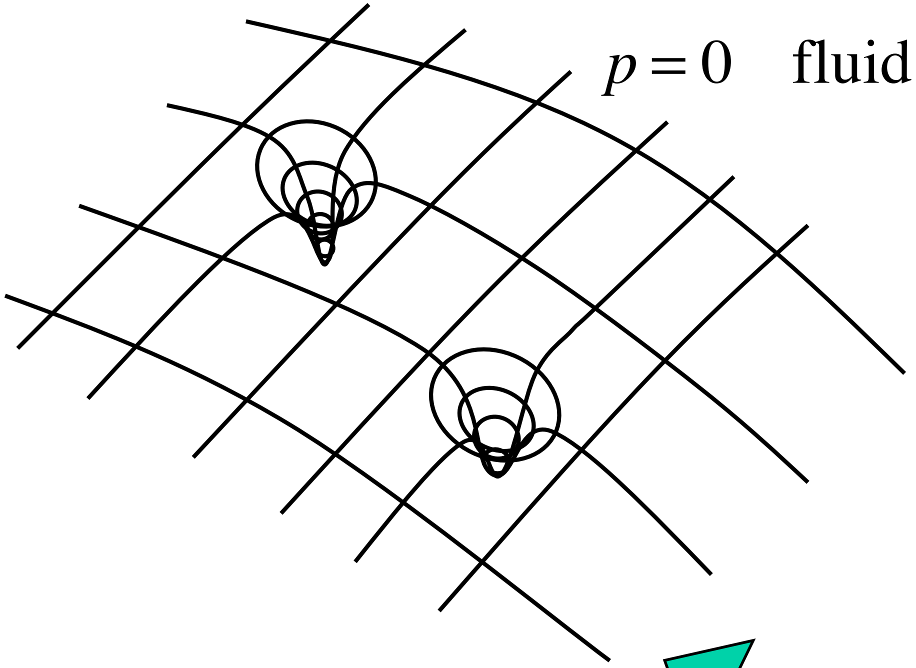
Gravitational Microlensing by Black Hole



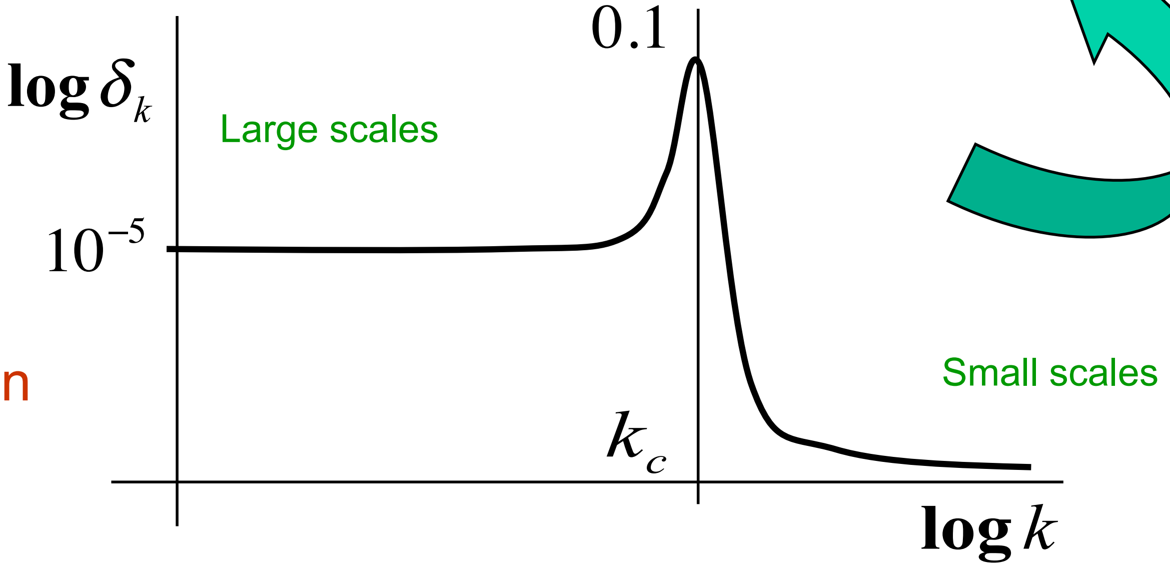
Hybrid Inflation Model



Black Hole Production @ end inflation



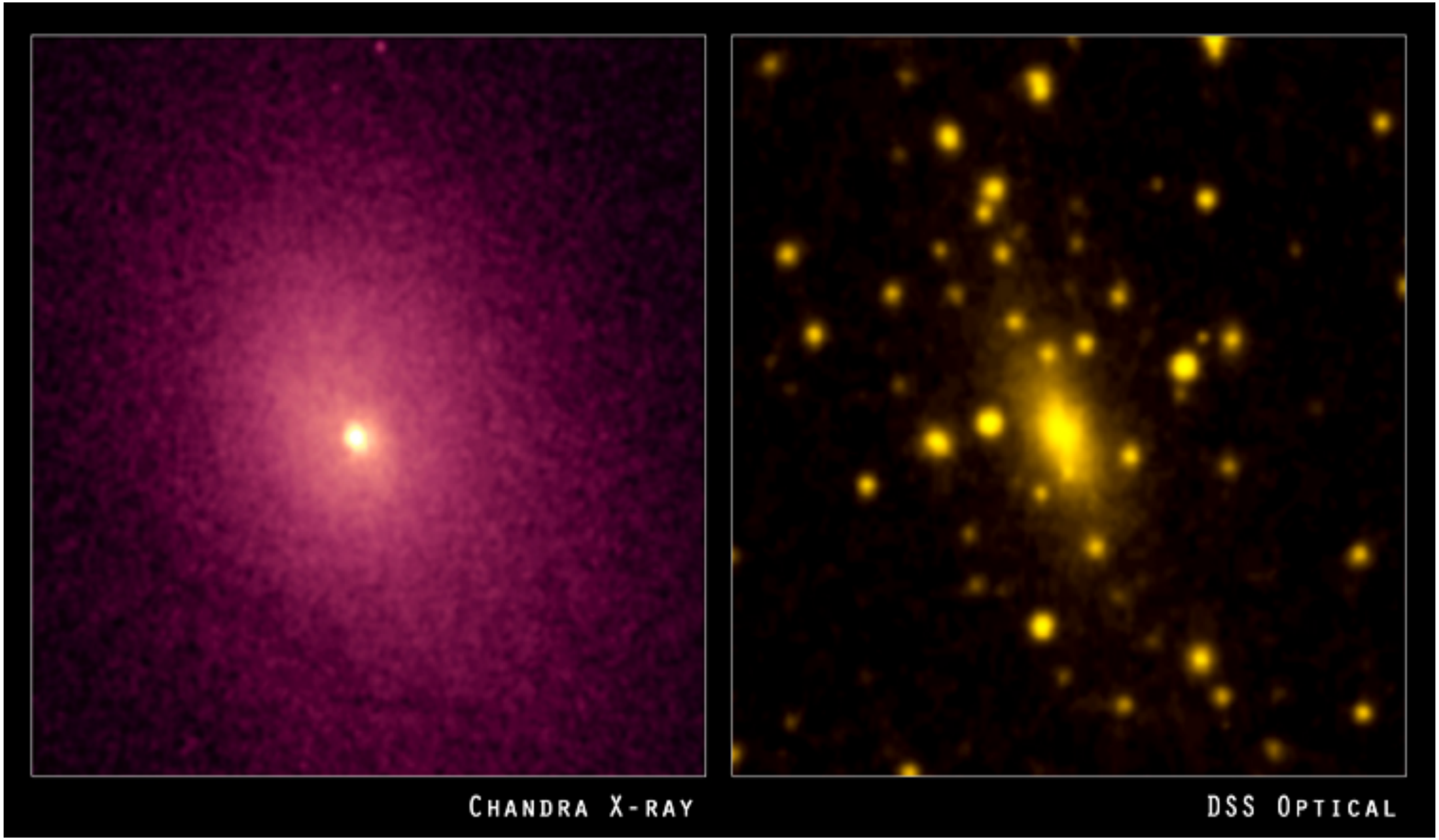
Density Perturbation Spectrum



JGB, A. Linde, D. Wands (1996)

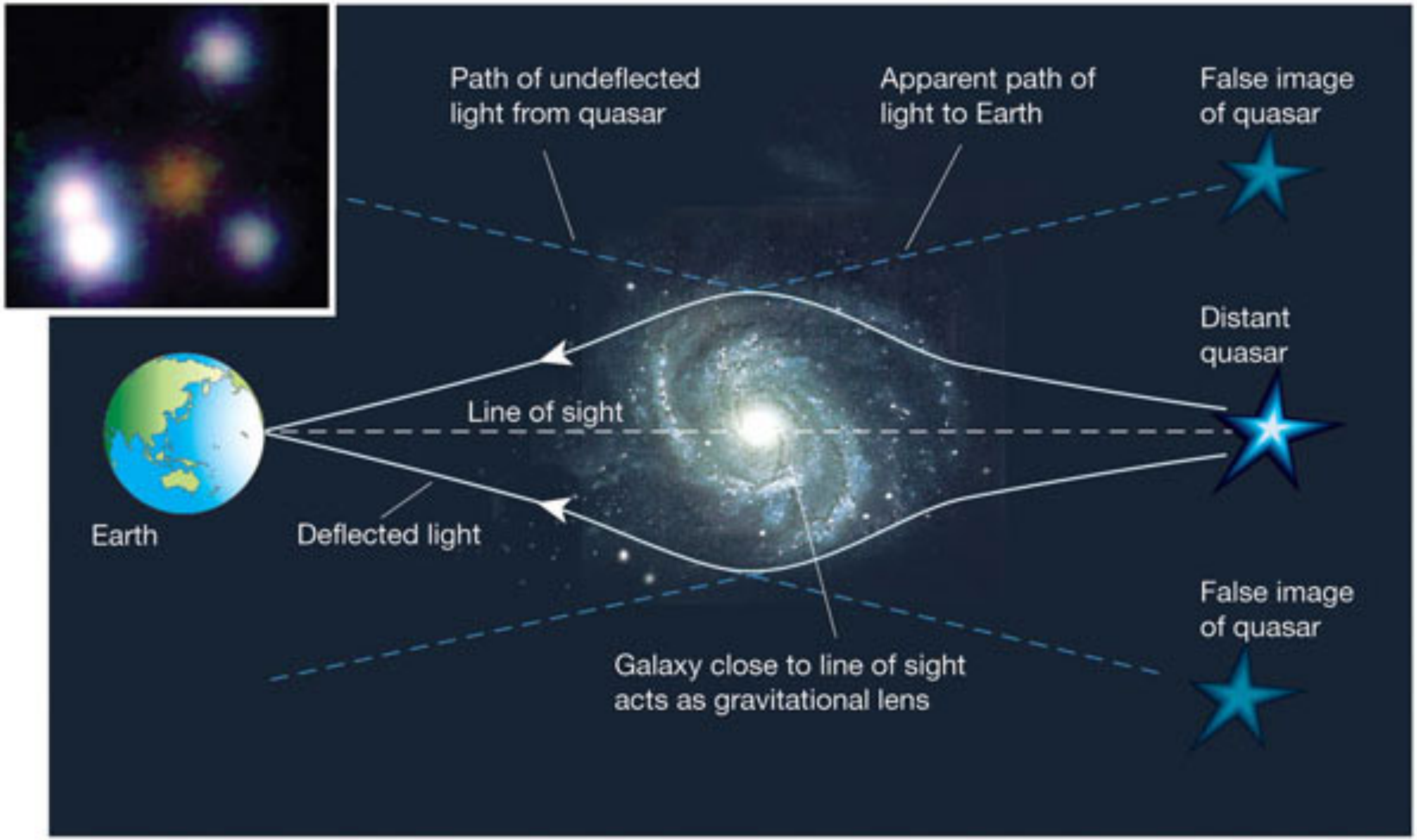
Evidence on Large Scales

Clusters of galaxies



$$f_B h^{3/2} = 0.08 \pm 0.03 \quad \Rightarrow \quad \frac{\Omega_B}{\Omega_M} \approx 0.15 \quad \text{for} \quad h = 0.7$$

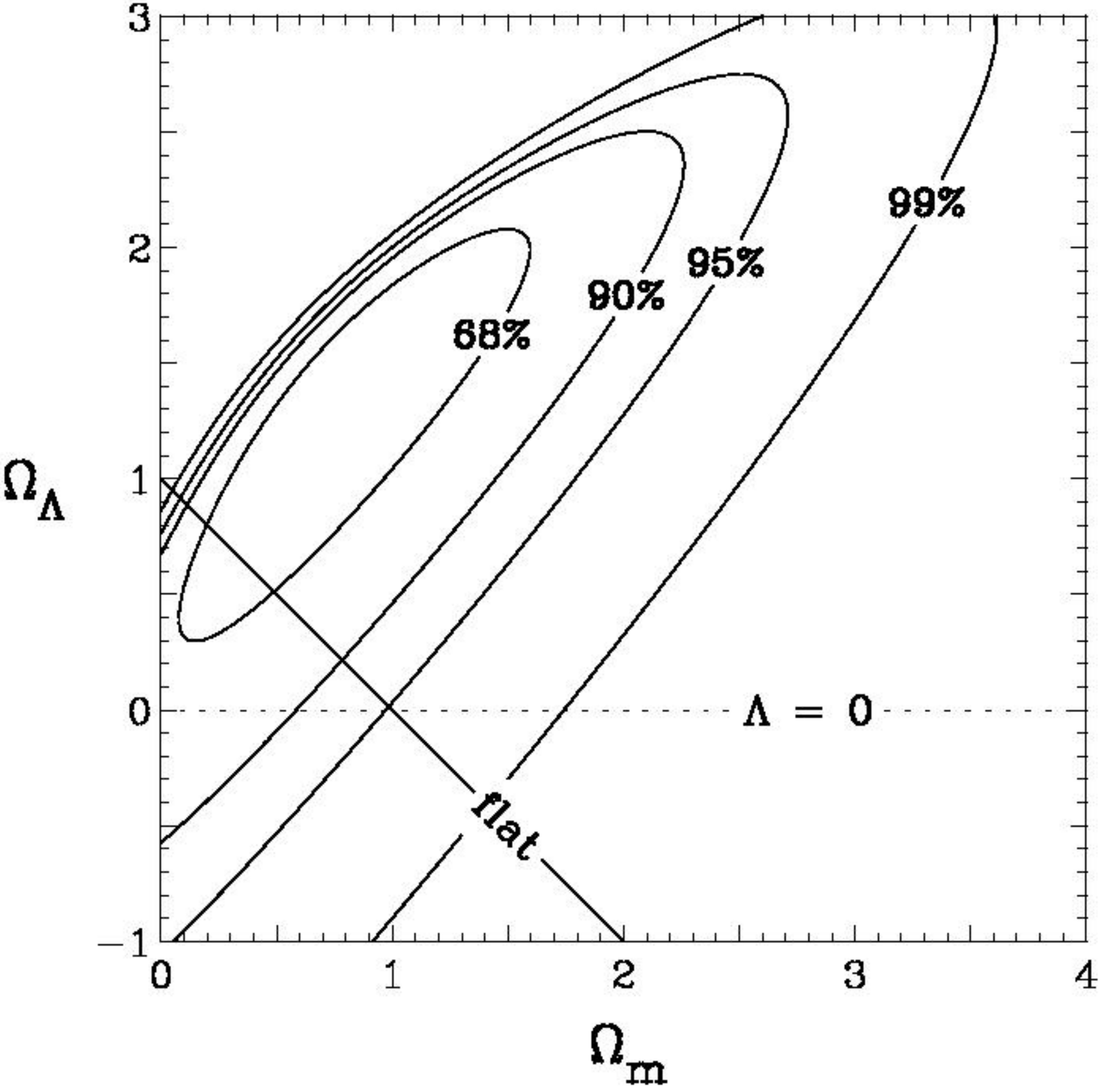
Gravitational Lensing



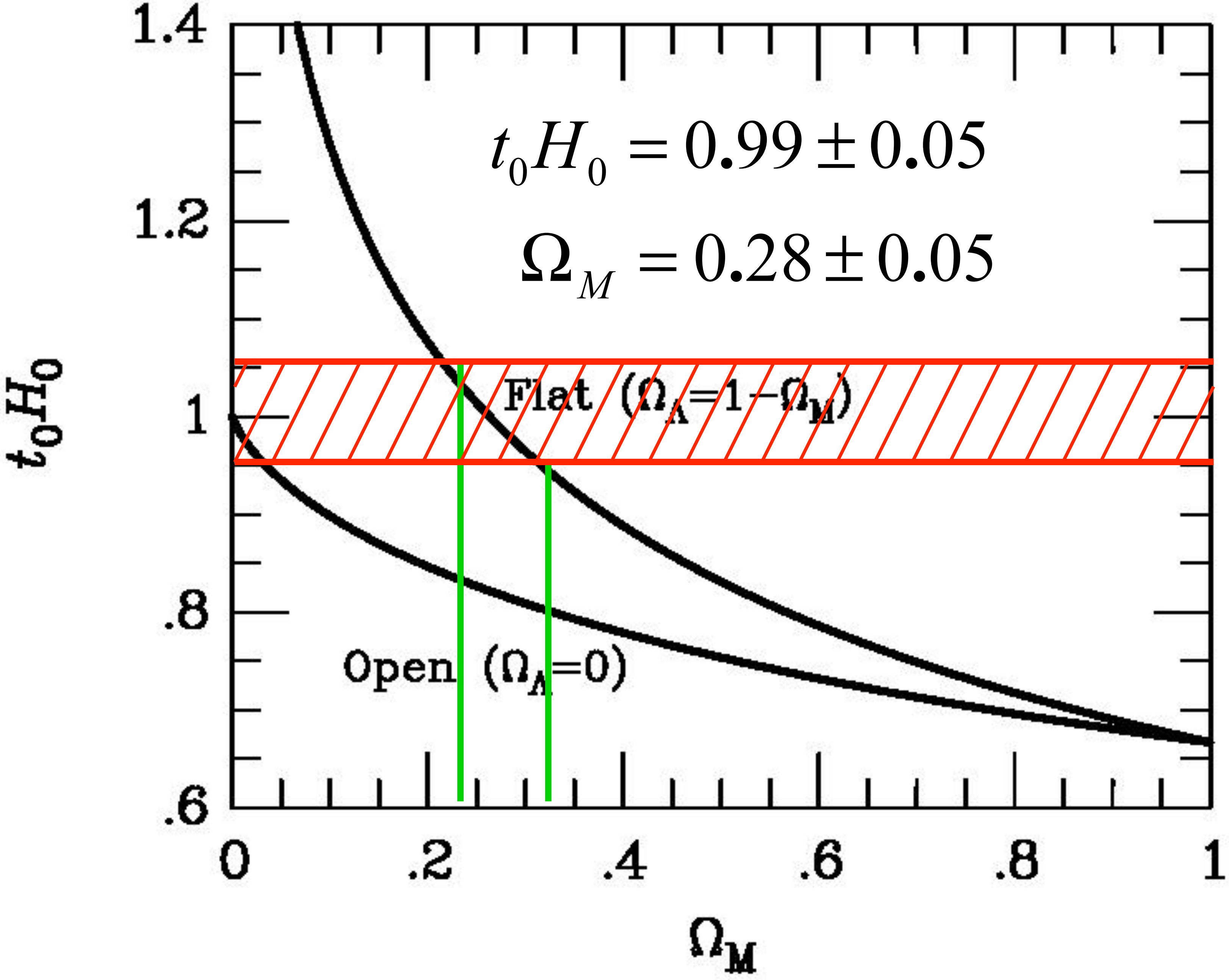
Gravitational Lens in Abell 2218 HST · WFPC2

PF95-14 · ST ScI OPO · April 5, 1995 · W. Couch (UNSW), NASA

Gravitational Lensing



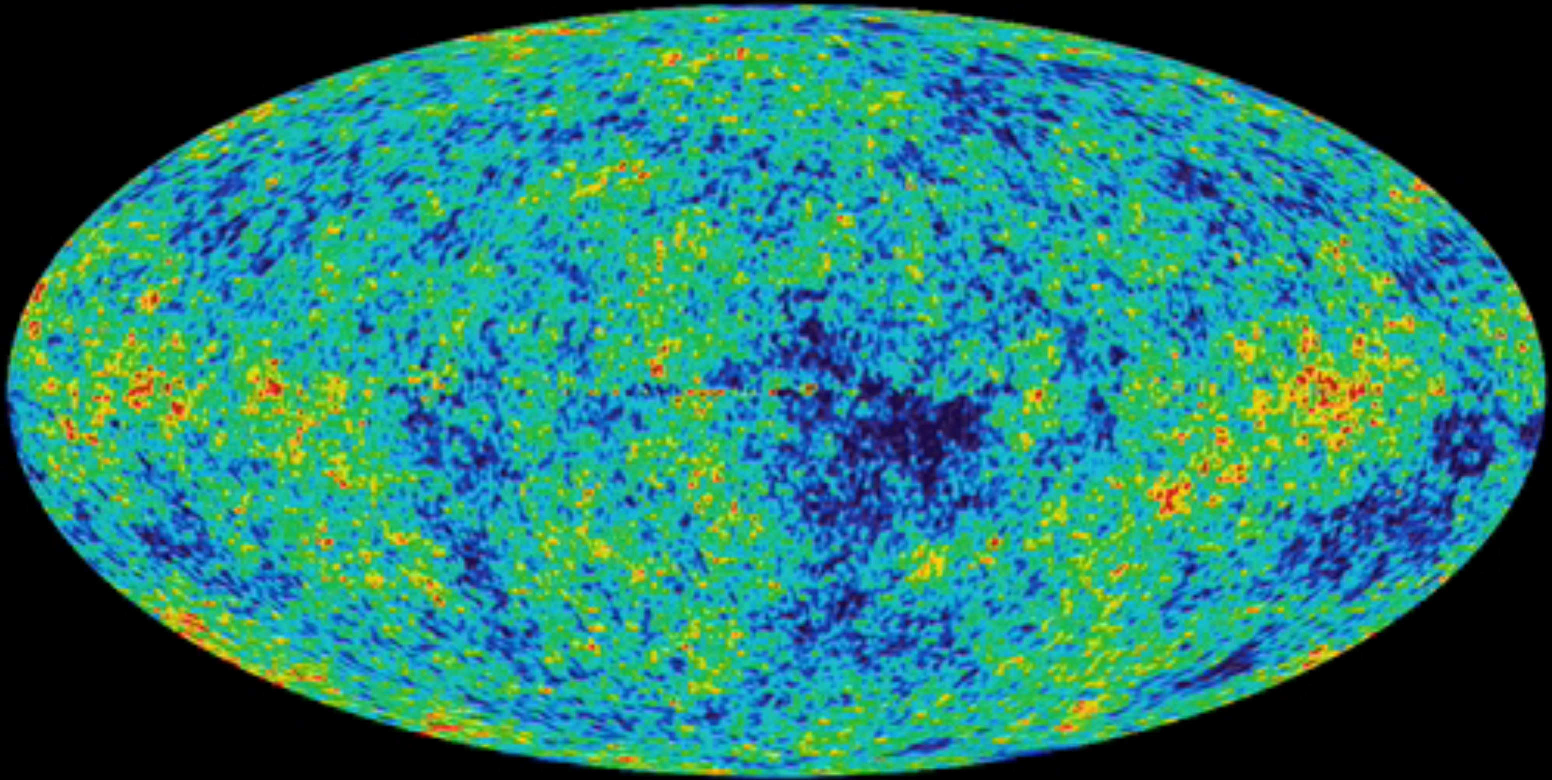
Further Cosmological Evidence

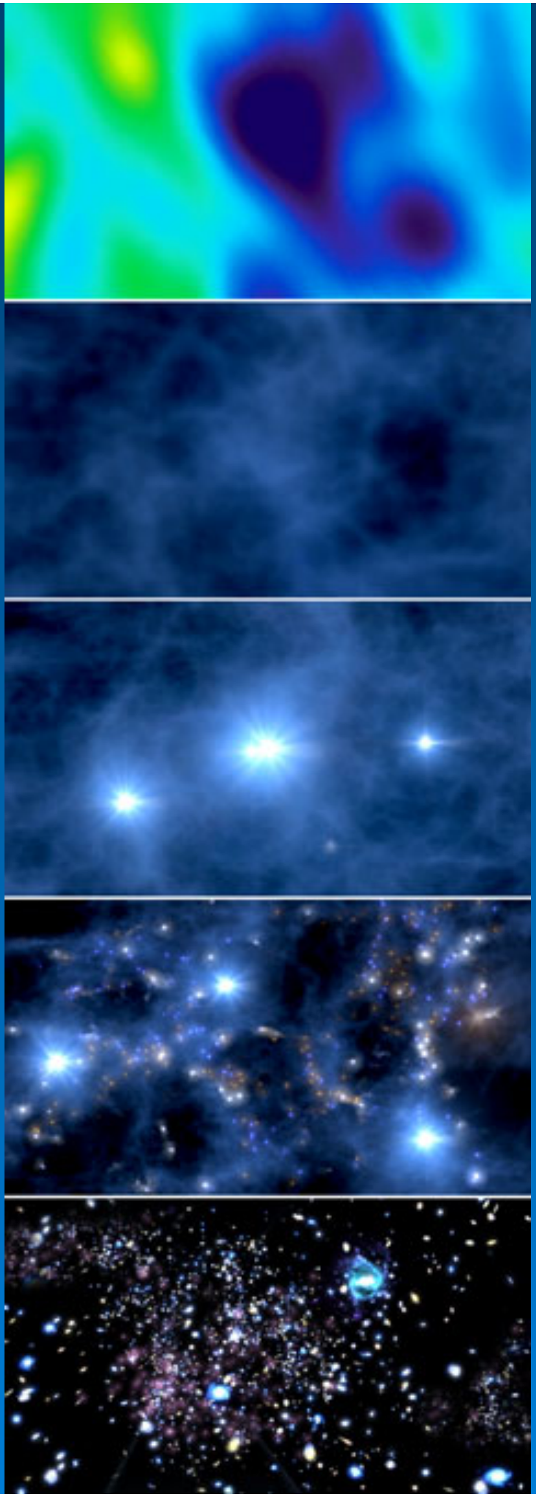


$$t_0 H_0 = 0.99 \pm 0.05$$

$$\Omega_M = 0.28 \pm 0.05$$

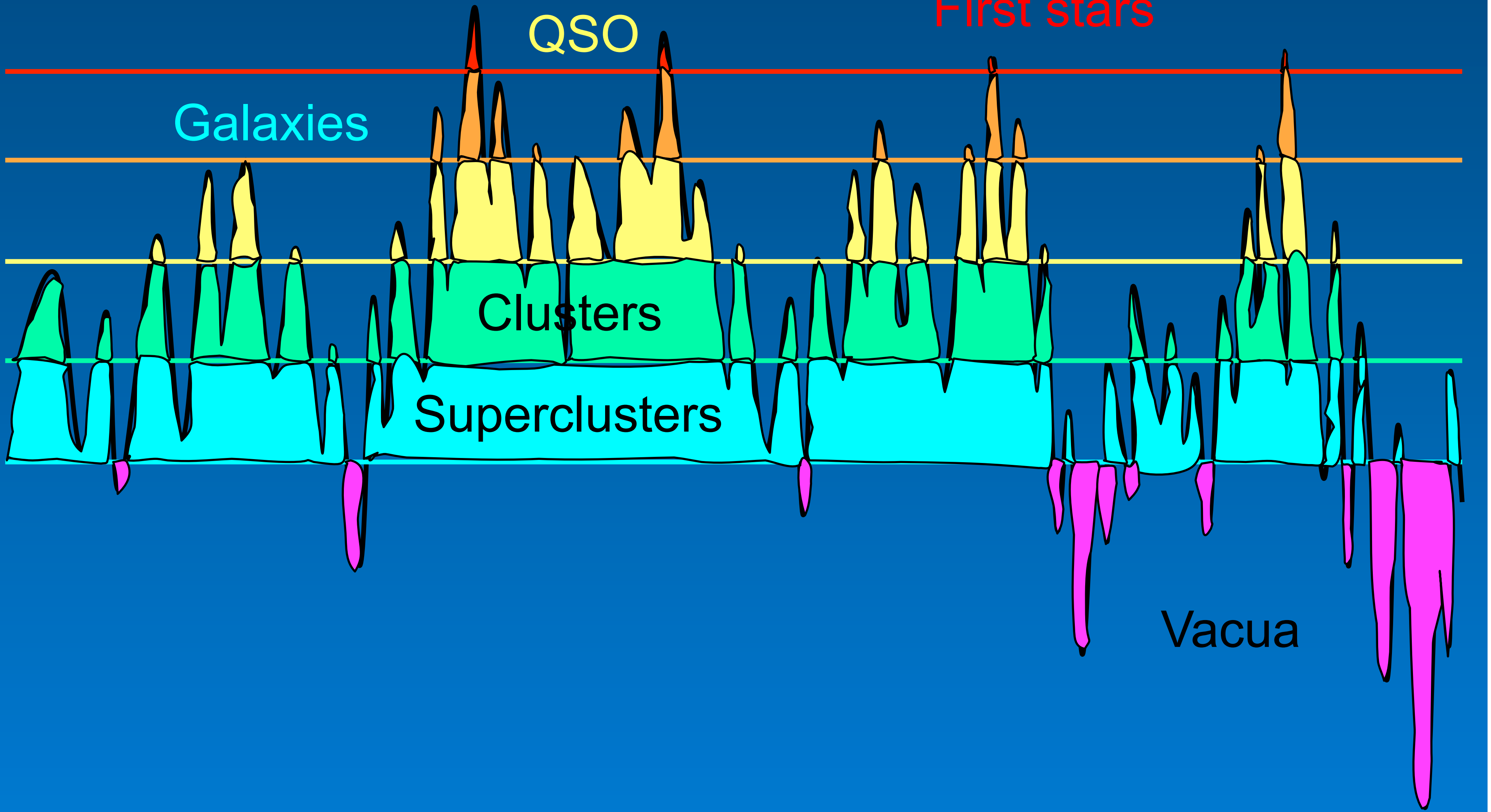
Large Scale Structure Formation



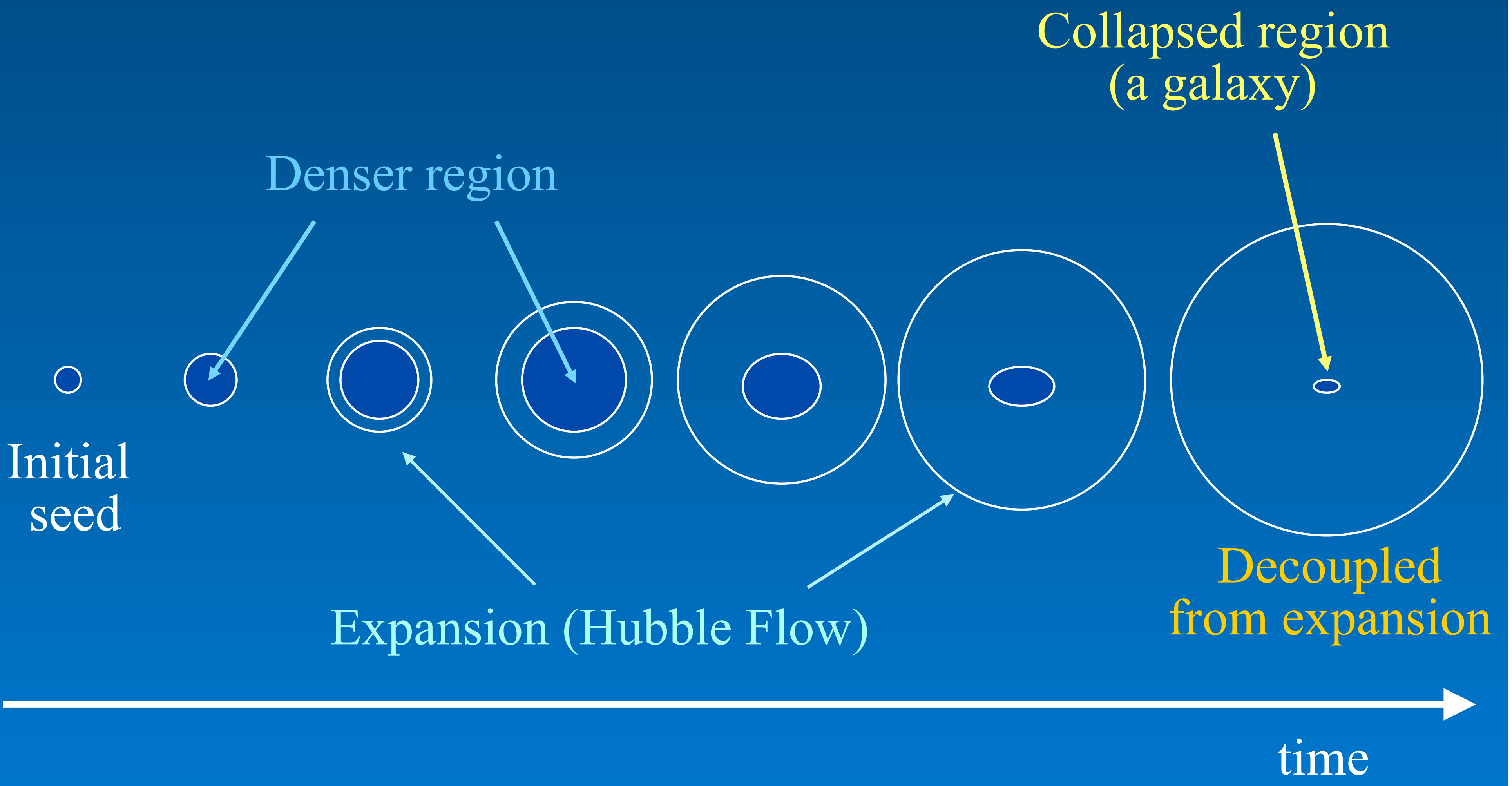


$z \approx 1100$	CMB Anisotropies
$z \approx 100$	Dark epoch
$z \approx 20$	First stars
$z \approx 10$	Galaxies & Quasars
$z \approx 1$	Clusters & Superclusters

Density contrast thresholds



Gravitational Collapse



Collapsed region
(a galaxy)

Denser region

Initial
seed

Expansion (Hubble Flow)

Decoupled
from expansion

time

Matter
Power
Spectrum

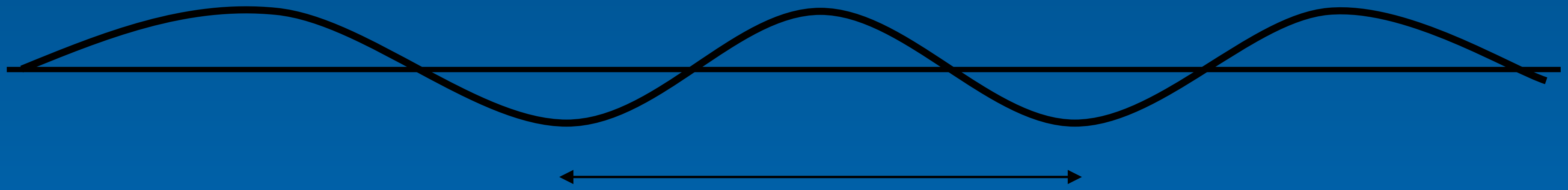
$$\delta(\vec{x},a) = \frac{\rho(\vec{x},a) - \rho(a)}{\rho(a)}$$ density contrast

$$\rho(a) = \rho_0\, a^3$$ average density

$$\delta(x,a) = \int d^3k\, \delta_{\mathrm{k}}(a)\, e^{ikx}$$

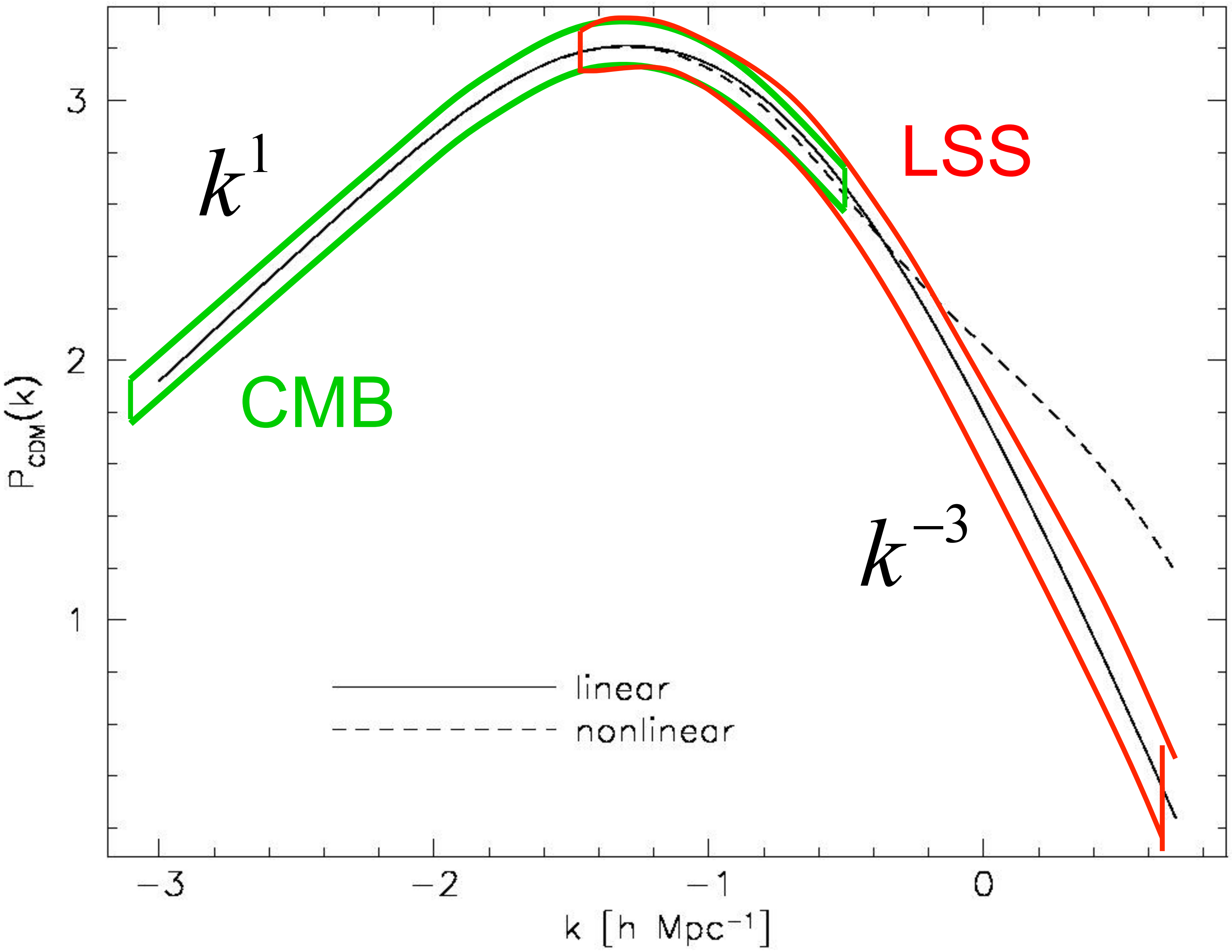
$$\mathrm{P(k)} \equiv \left\langle \left|\delta_{\mathrm{k}}\right|^2 \right\rangle \approx A\, k^n$$ Power Spectrum

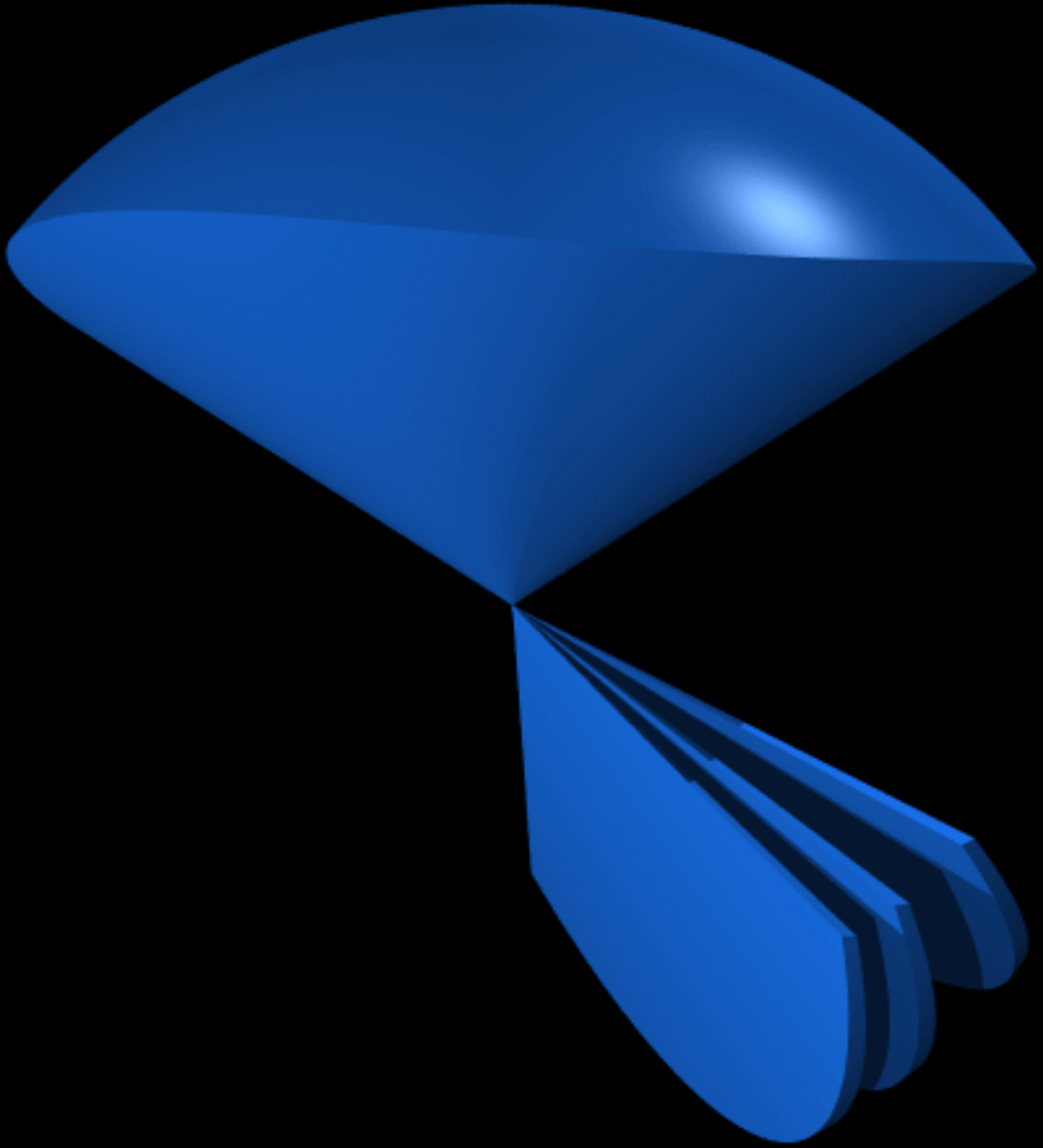
$$\delta_k(a)$$



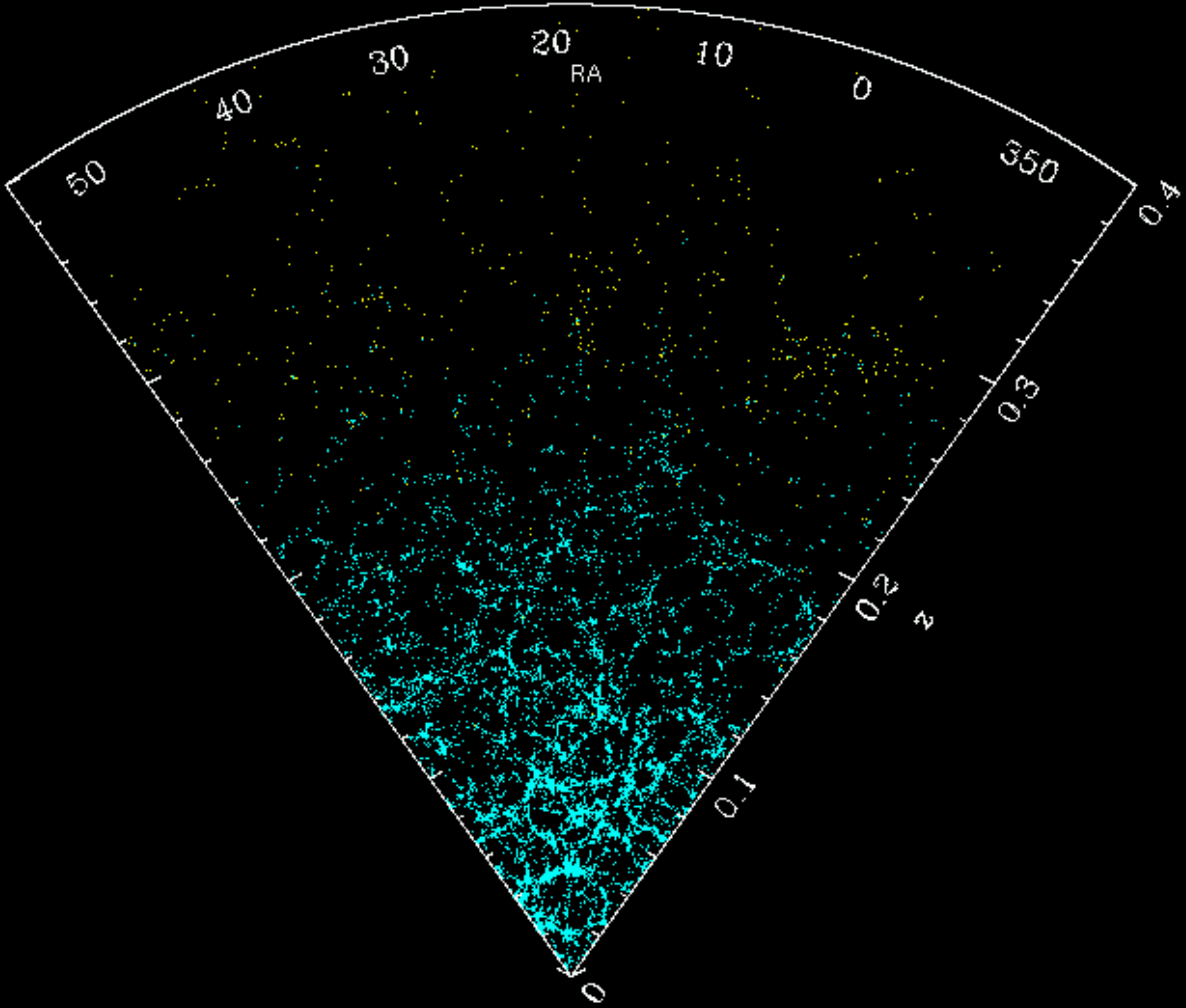
$$\lambda = \frac{2\pi}{k}$$

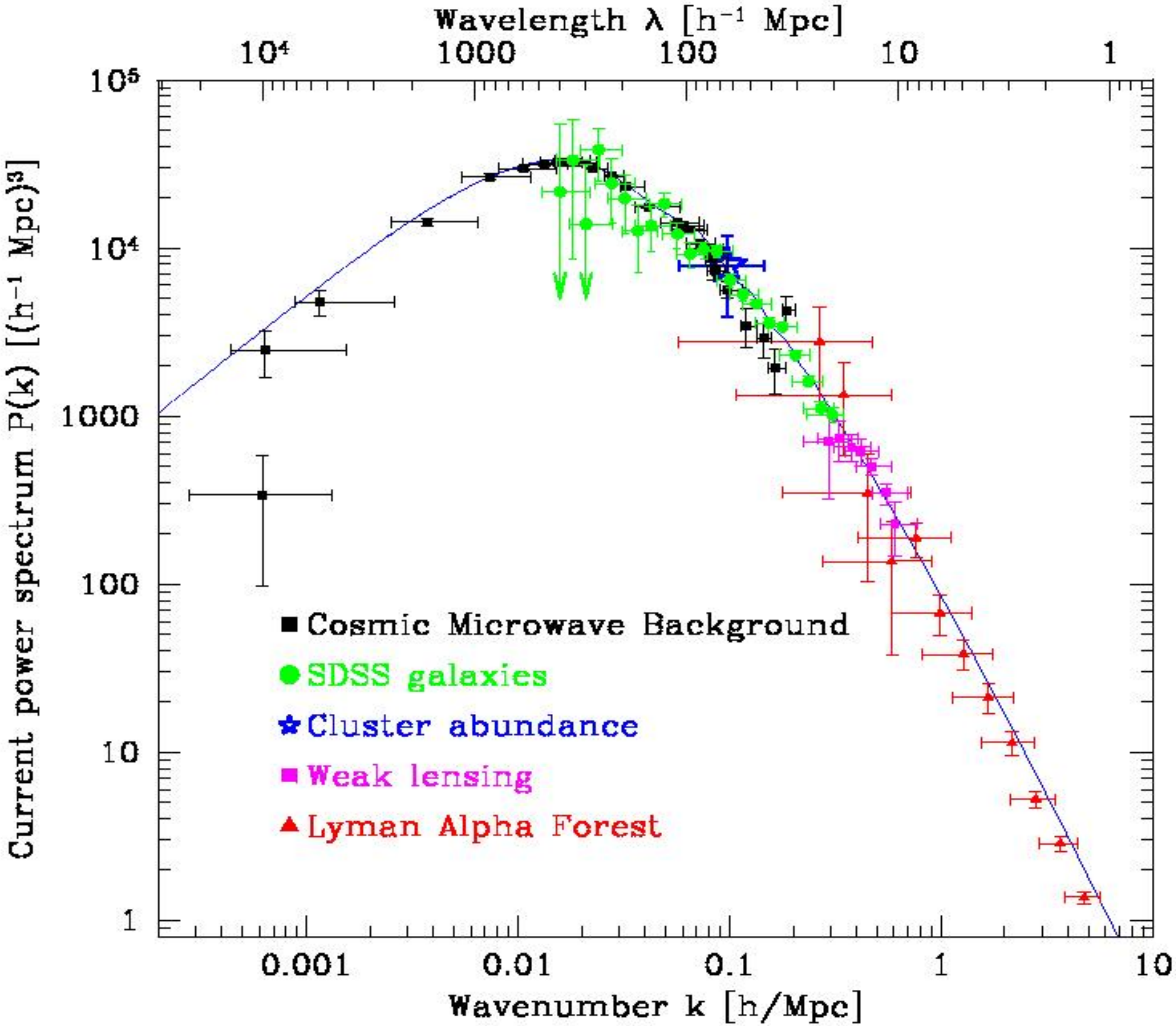
$$\mathrm{P(k)} \equiv \left\langle \left|\delta_{\mathrm{k}}\right|^2 \right\rangle \approx A\, k^n$$





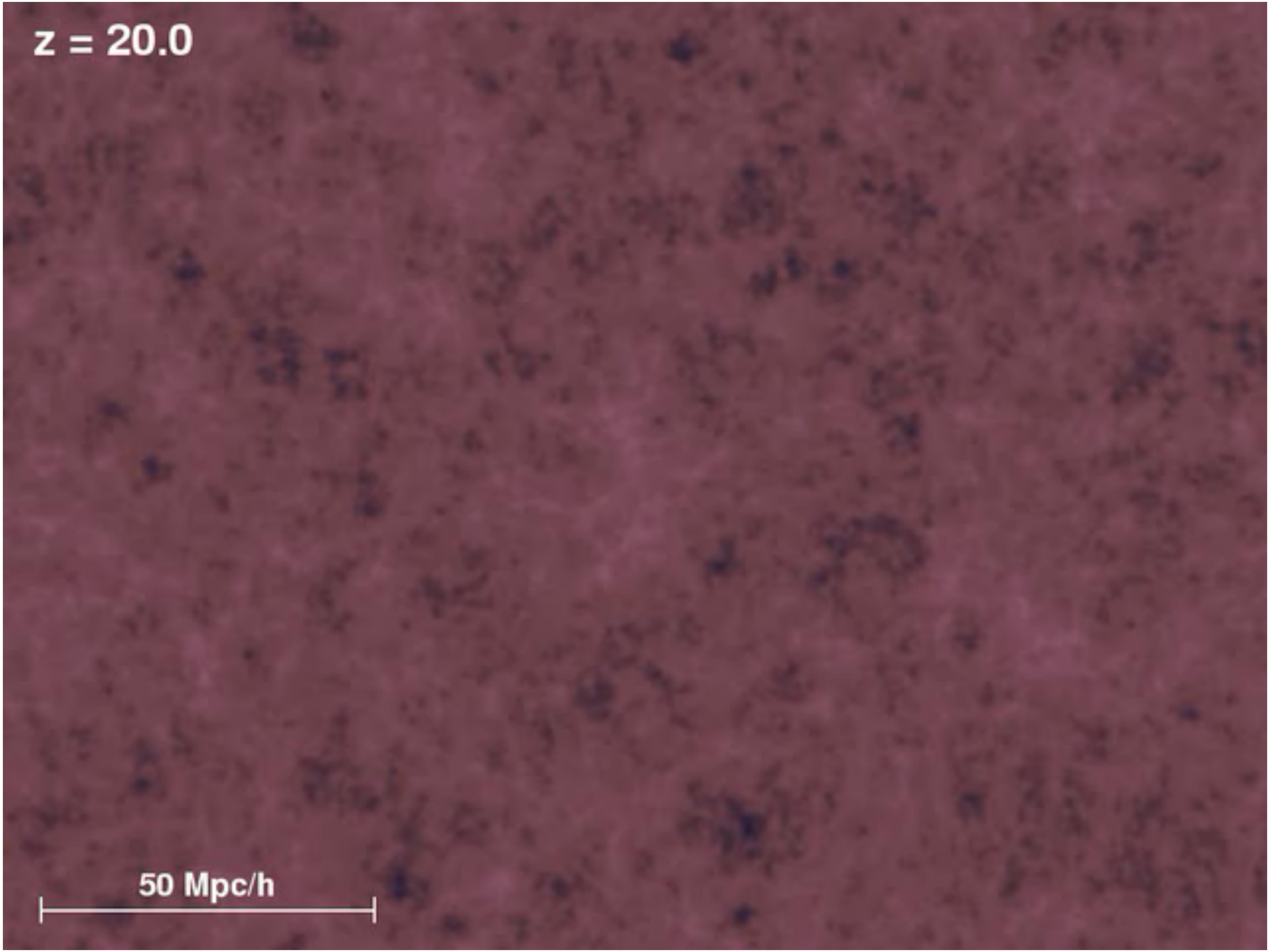
SDSS

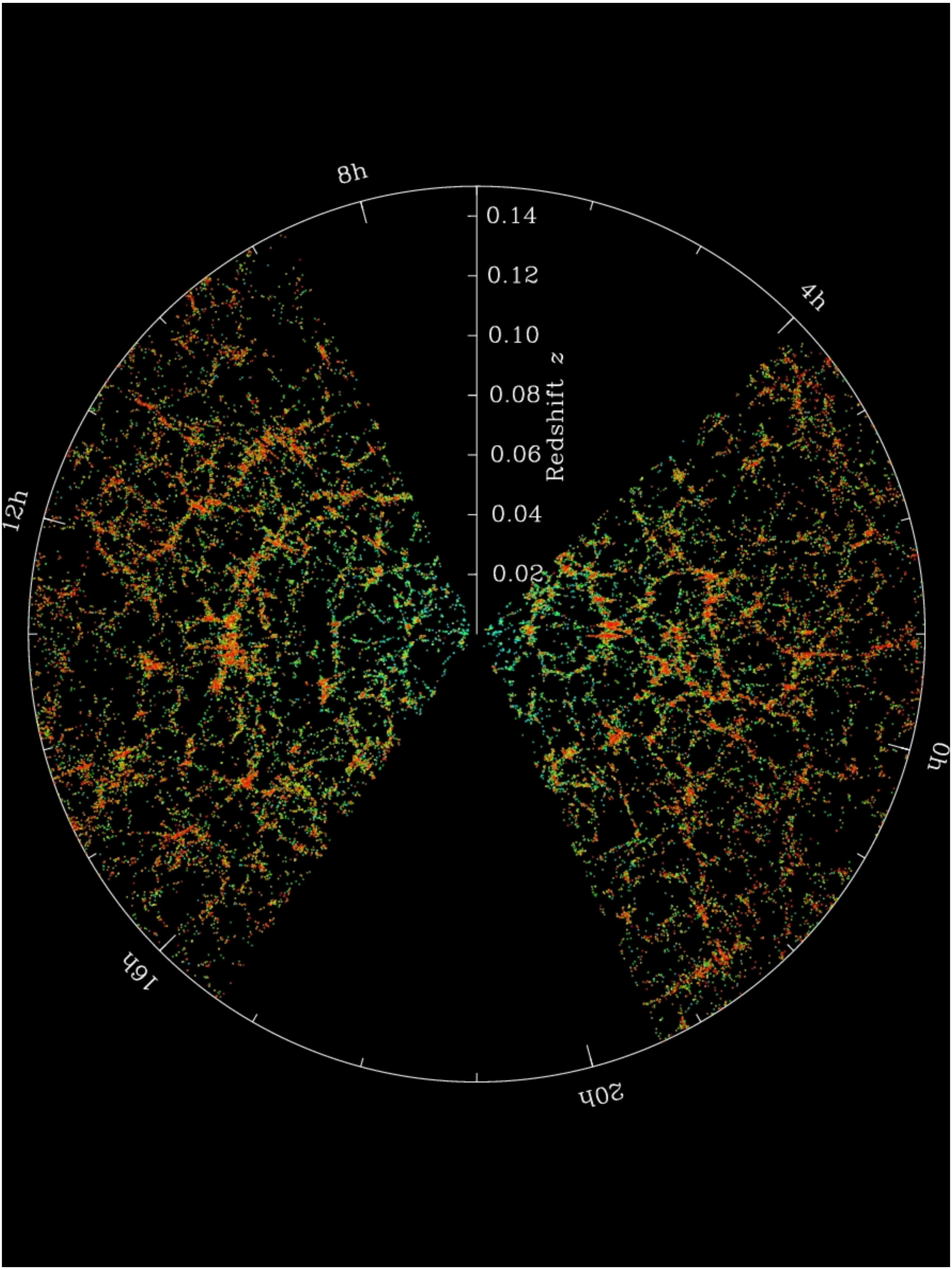

50
40
30
20
RA
10
0
350
0.4
0.3
0.2
z
0.1
0

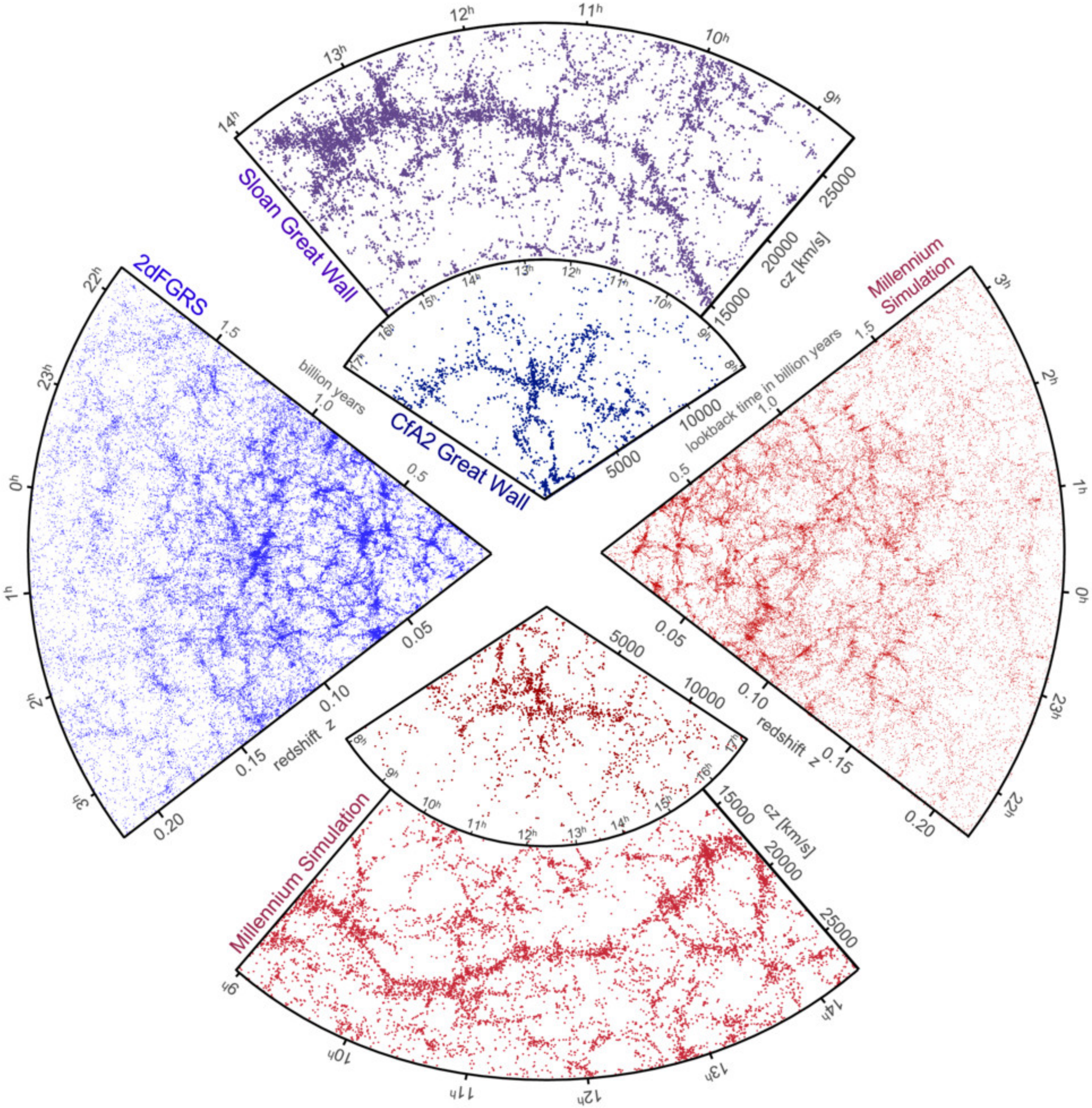

Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]
■ Cosmic Microwave Background
● SDSS galaxies
★ Cluster abundance
■ Weak lensing
▲ Lyman Alpha Forest

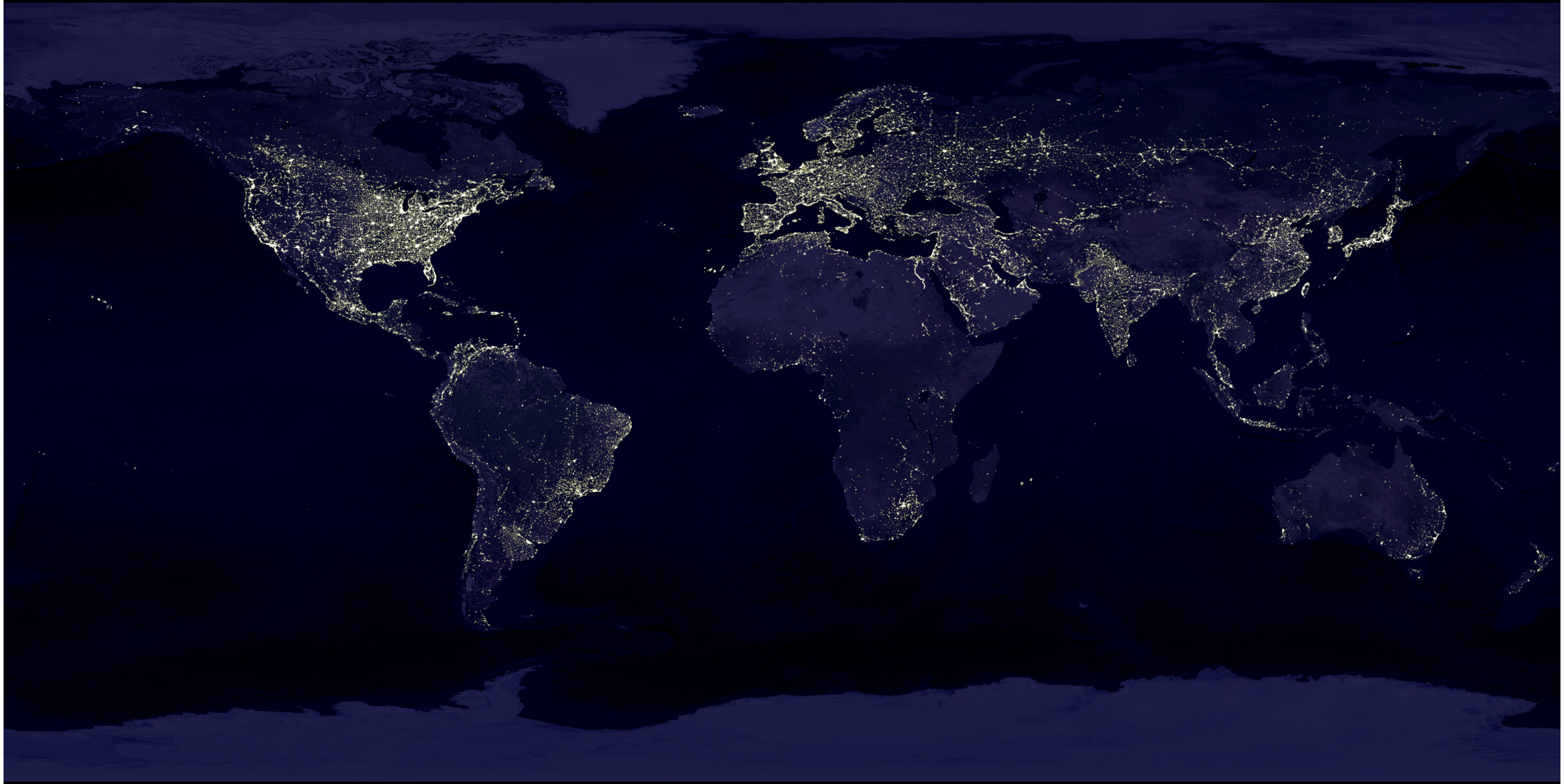
Numerical Simulations

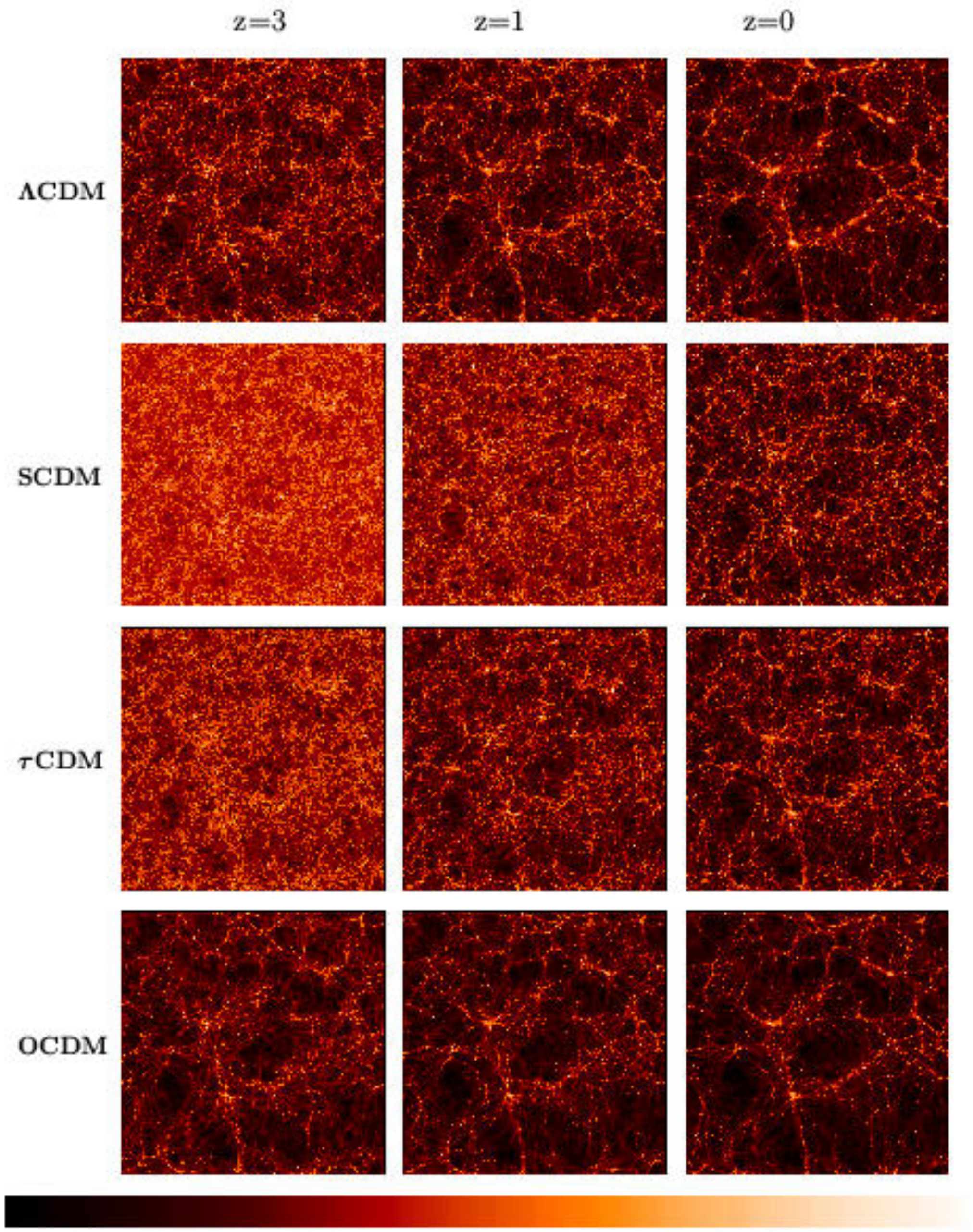
(beyond pert. Theory)


z = 20.0
50 Mpc/h


8h
4h
12h
0h
16h
20h
0.14
0.12
0.10
0.08
0.06
0.04
0.02
Redshift z


Sloan Great Wall
CfA2 Great Wall
2dFGRS
Millennium Simulation
Millennium Simulation
cz [km/s]
5000
10000
15000
20000
25000
billion years
lookback time in billion years
0.5
1.0
1.5
redshift z
0.05
0.10
0.15
0.20
8h
9h
10h
11h
12h
13h
14h
15h
16h
17h
22h
23h
0h
1h
2h
3h



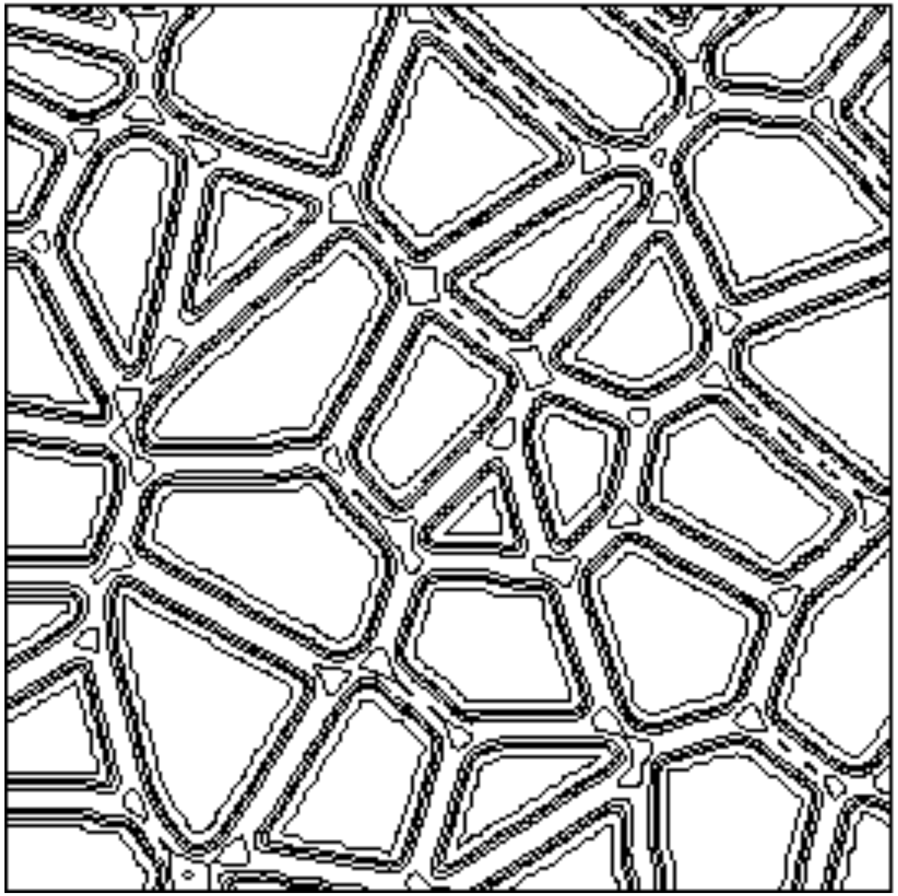


The VIRGO Collaboration 1996

Large Scale Structure Simulations (1996)

Non Gaussianities

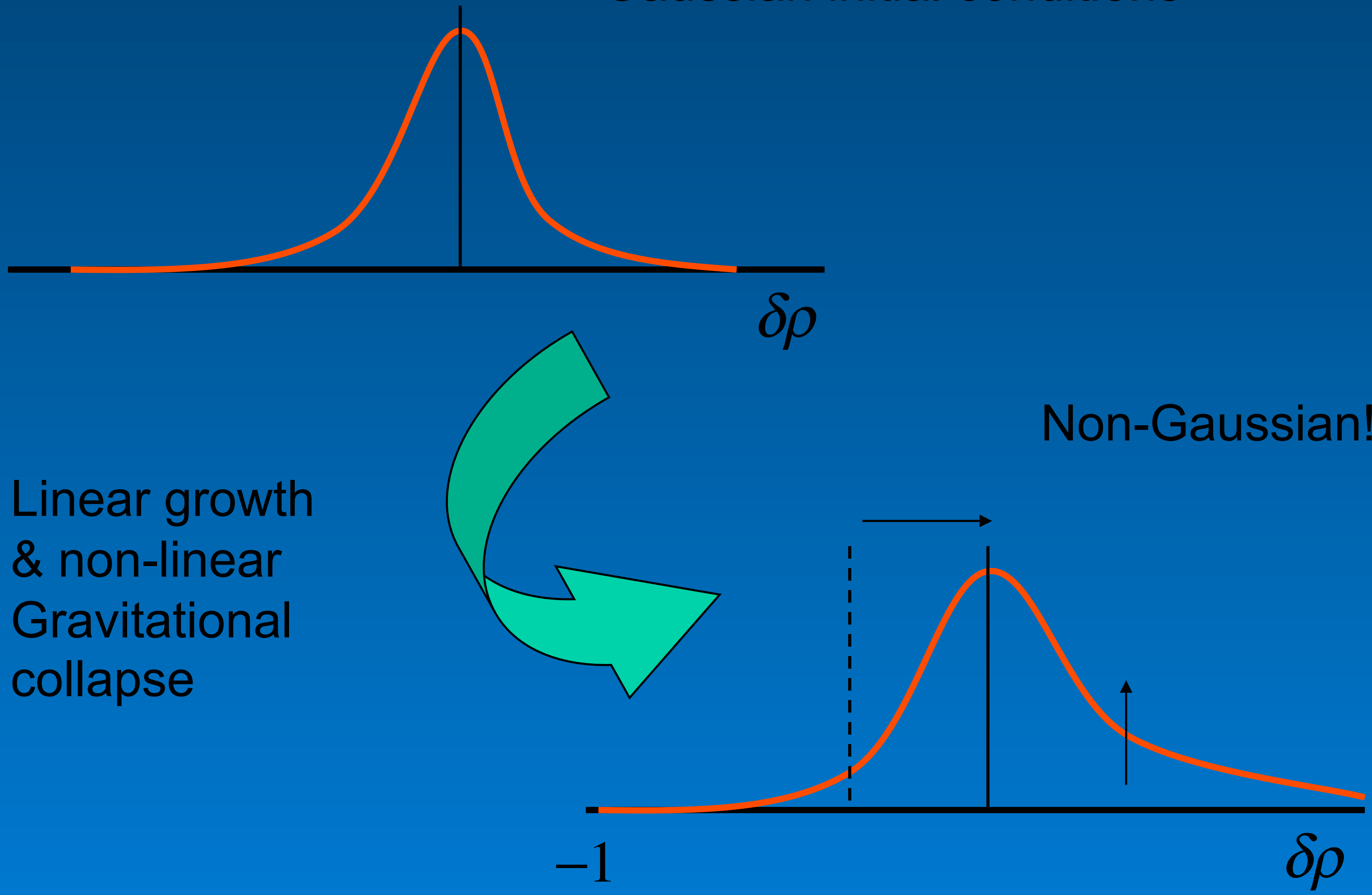
Voronoi foam, smoothed original



Voronoi foam, random phases

Same Power Spectrum P(k)

Gaussian initial conditions



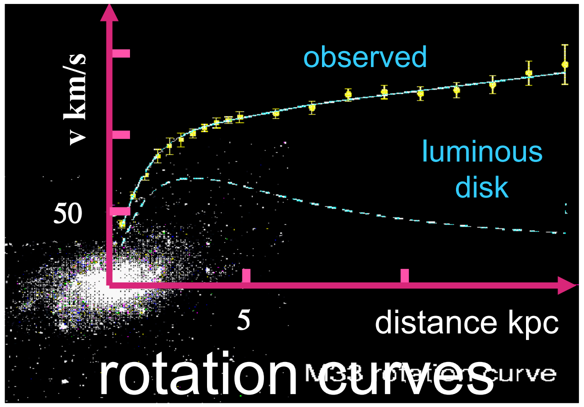
Linear growth
& non-linear
Gravitational
collapse

Non-Gaussian!

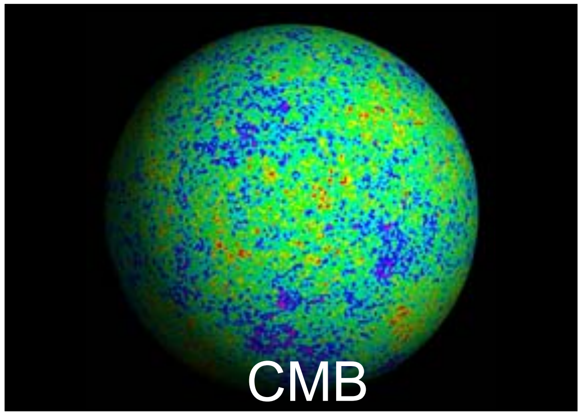
Summary of Dark Matter Content

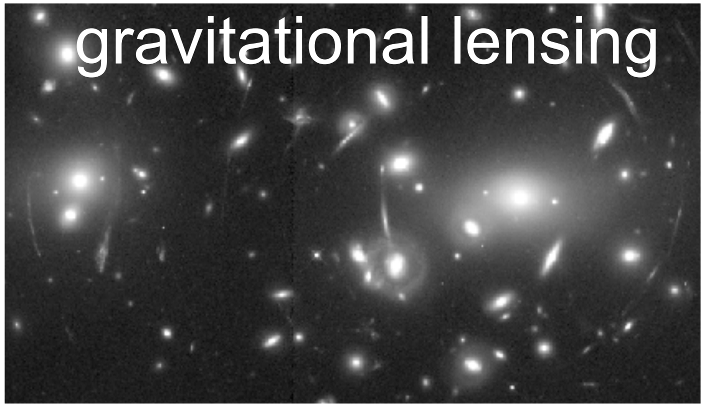
Dark Matter

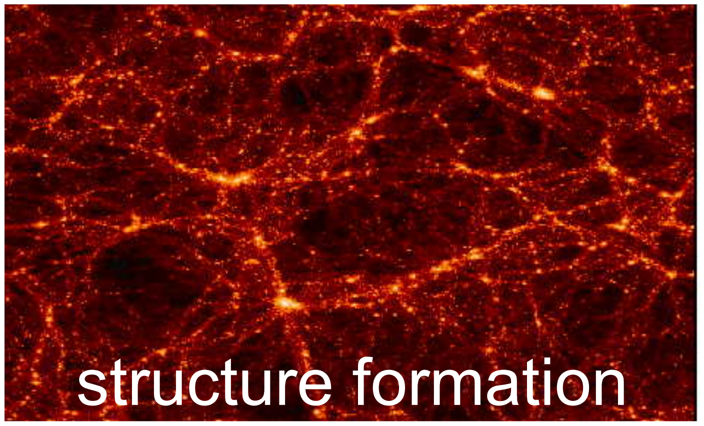

cluster dynamics

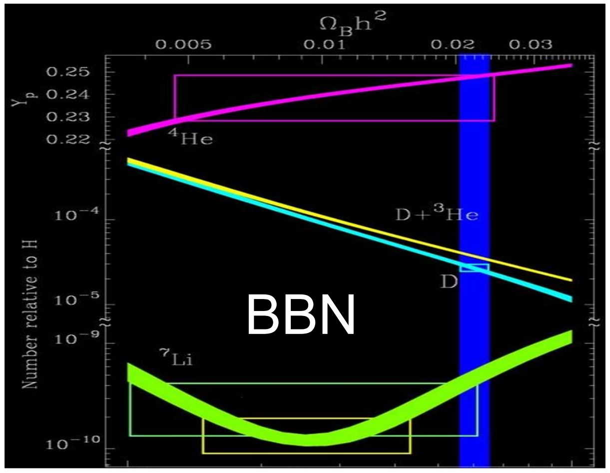


rotation curves

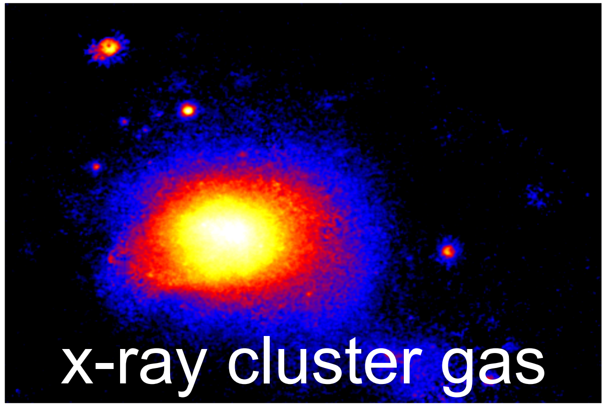

CMB


gravitational lensing

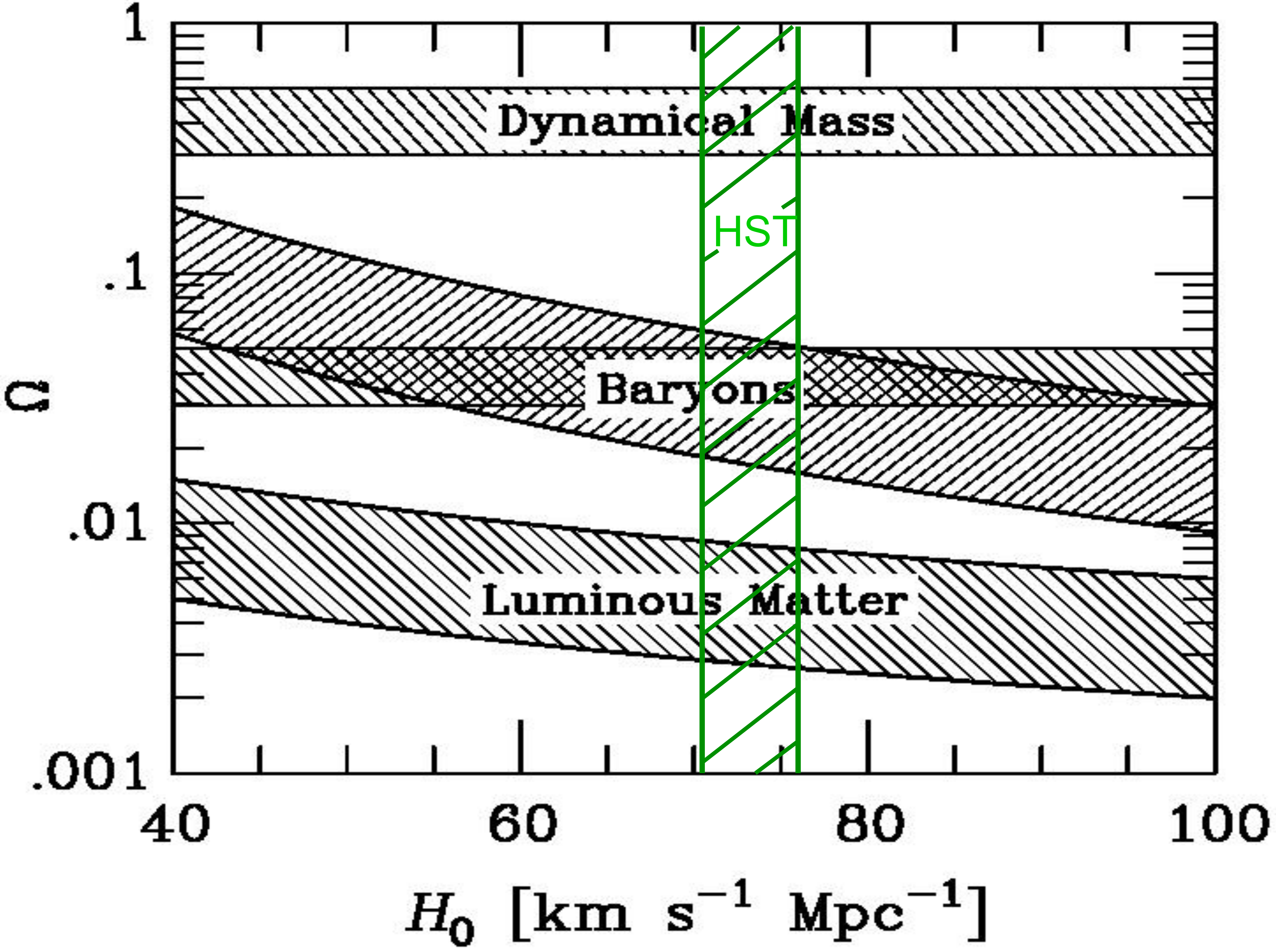

structure formation



BBN


x-ray cluster gas

cluster collisions


1
.1
.01
.001
Ω
Dynamical Mass
HST
Baryons
Luminous Matter
40
60
80
100
H_0 [km s^{-1} Mpc^{-1}]

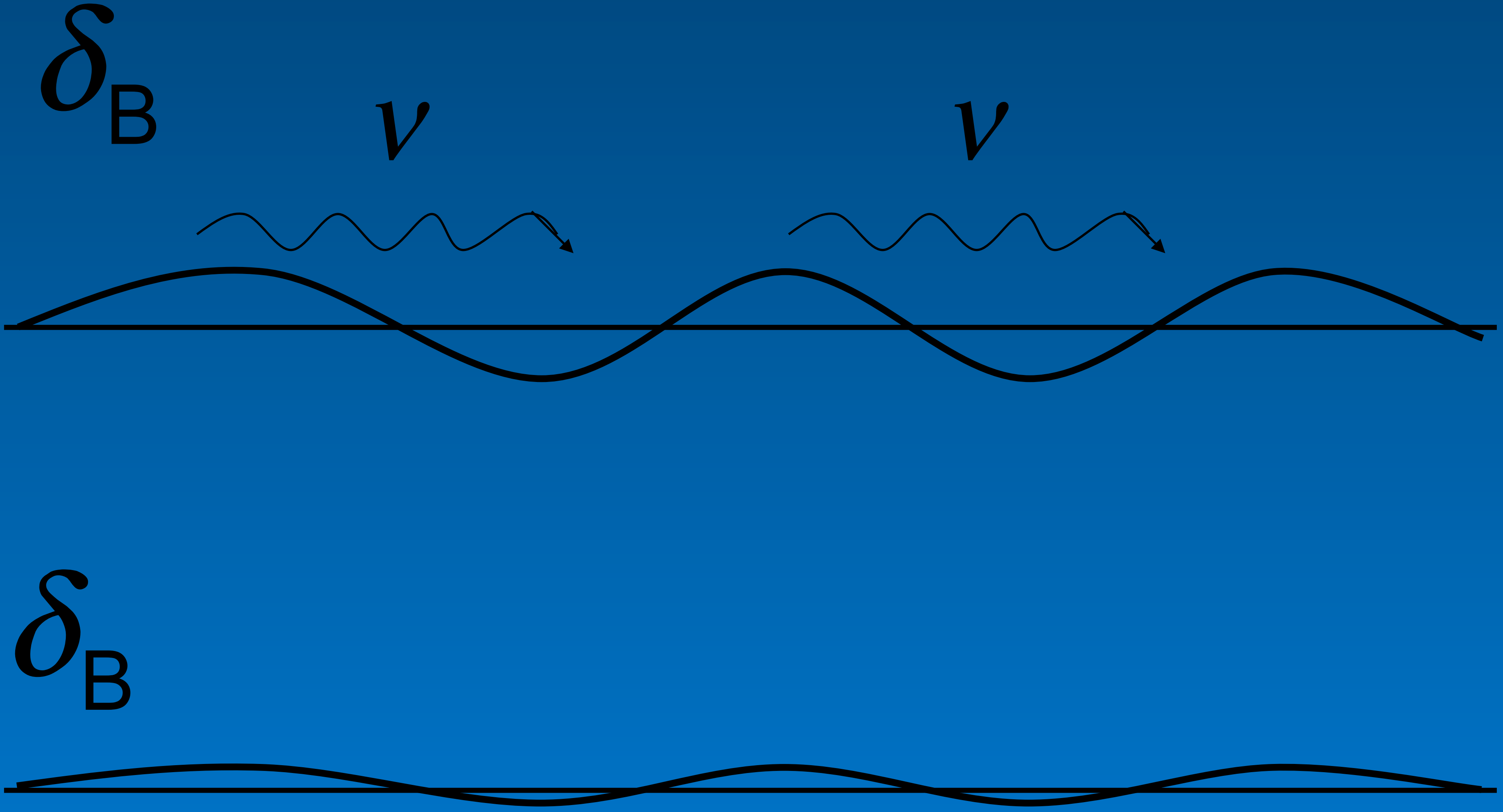
What constitutes Dark Matter?

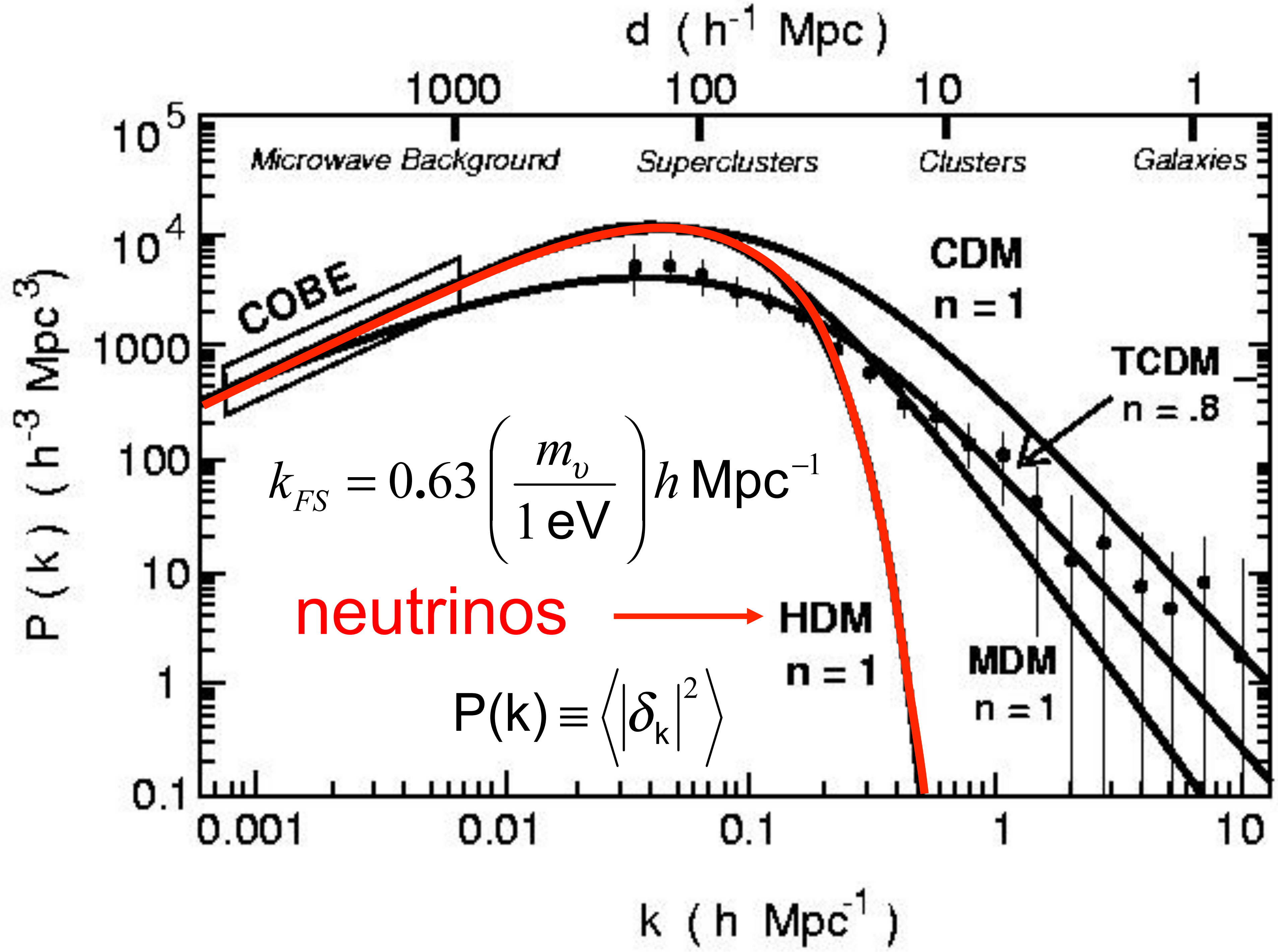
- Planets?
- Brown dwarfs?
- Primordial Black Holes?
- Relic Particles from the Big Bang?
  - Neutrinos
  - Axions
  - Neutralinos
  - Wimpzillas

Really, we have no idea…

Could neutrinos be the Dark Matter?

Free Streaming

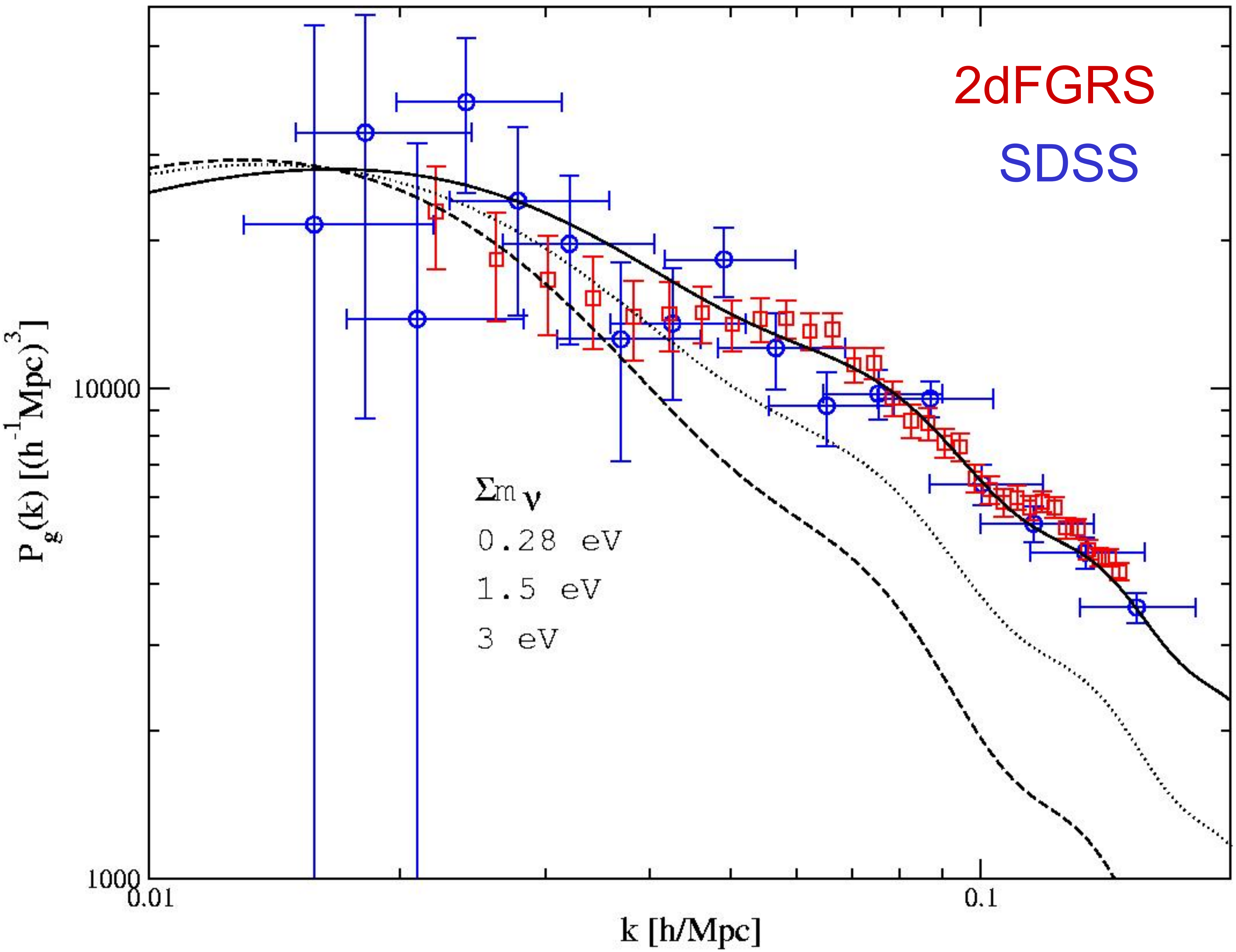


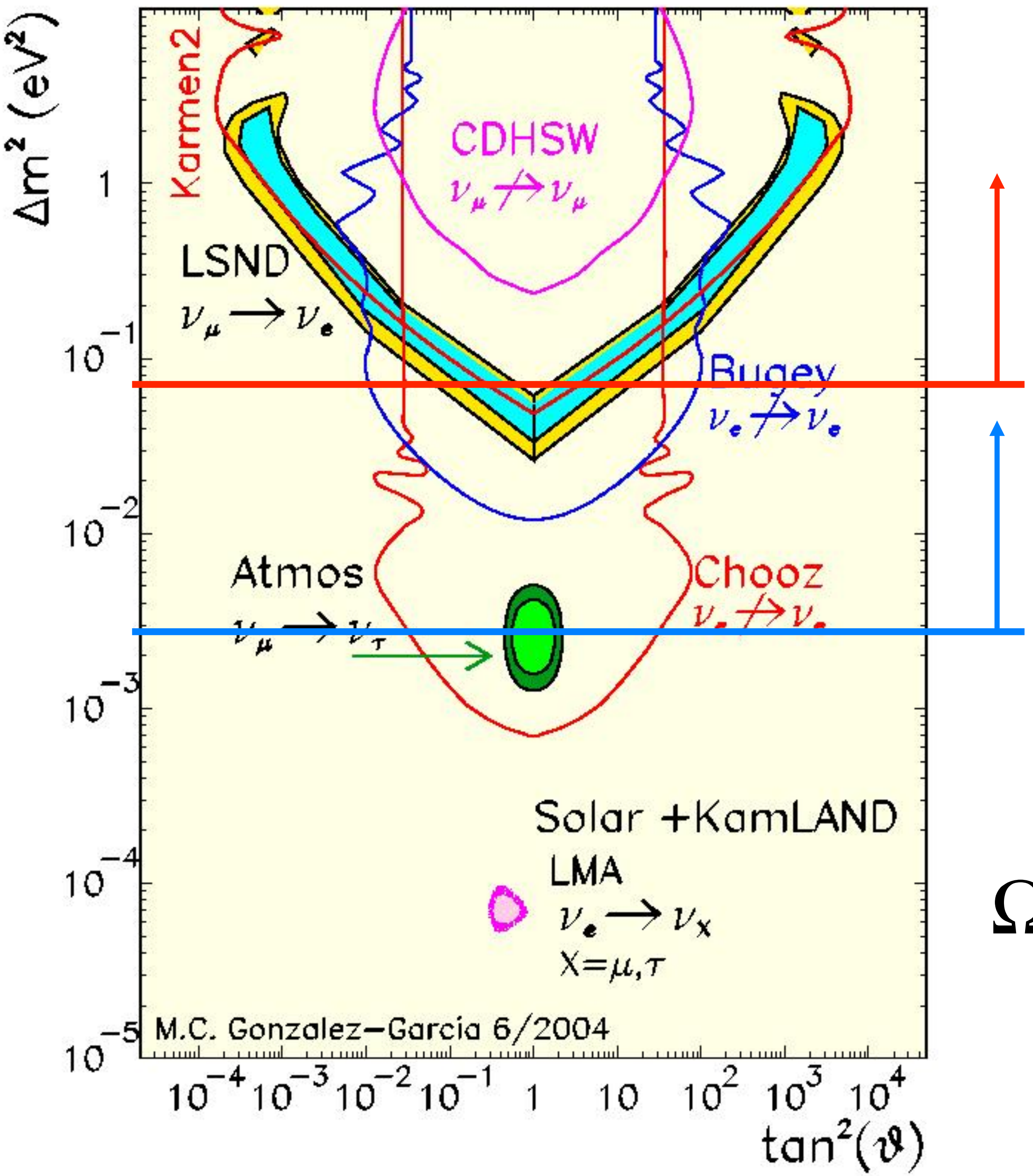


$$k_{FS} = 0.63\left(\frac{m_\upsilon}{1\,\mathrm{eV}}\right) h\,\mathrm{Mpc}^{-1}$$

neutrinos → HDM

$$\mathrm{P(k)} \equiv \left\langle \left|\delta_\mathrm{k}\right|^2 \right\rangle$$


2dFGRS
SDSS
Σm_ν
0.28 eV
1.5 eV
3 eV
$P_g(k)$ [$(h^{-1}$Mpc$)^3$]
10000
1000
0.01
0.1
k [h/Mpc]



Cosmologically
Excluded
(WMAP/SDSS)

Cosmologically
Detectable
(Planck)

$$\Omega_\upsilon = \frac{\sum m_\upsilon \, h^{-2}}{93.2 \text{ eV}}$$

WIMPS

WIMPs: Cold Thermal Relics

- neutrinos (hot)
- sterile neutrinos, gravitinos (warm)
- Lightest supersymmetric particle (cold)
- Lightest Kaluza-Klein particle (cold)

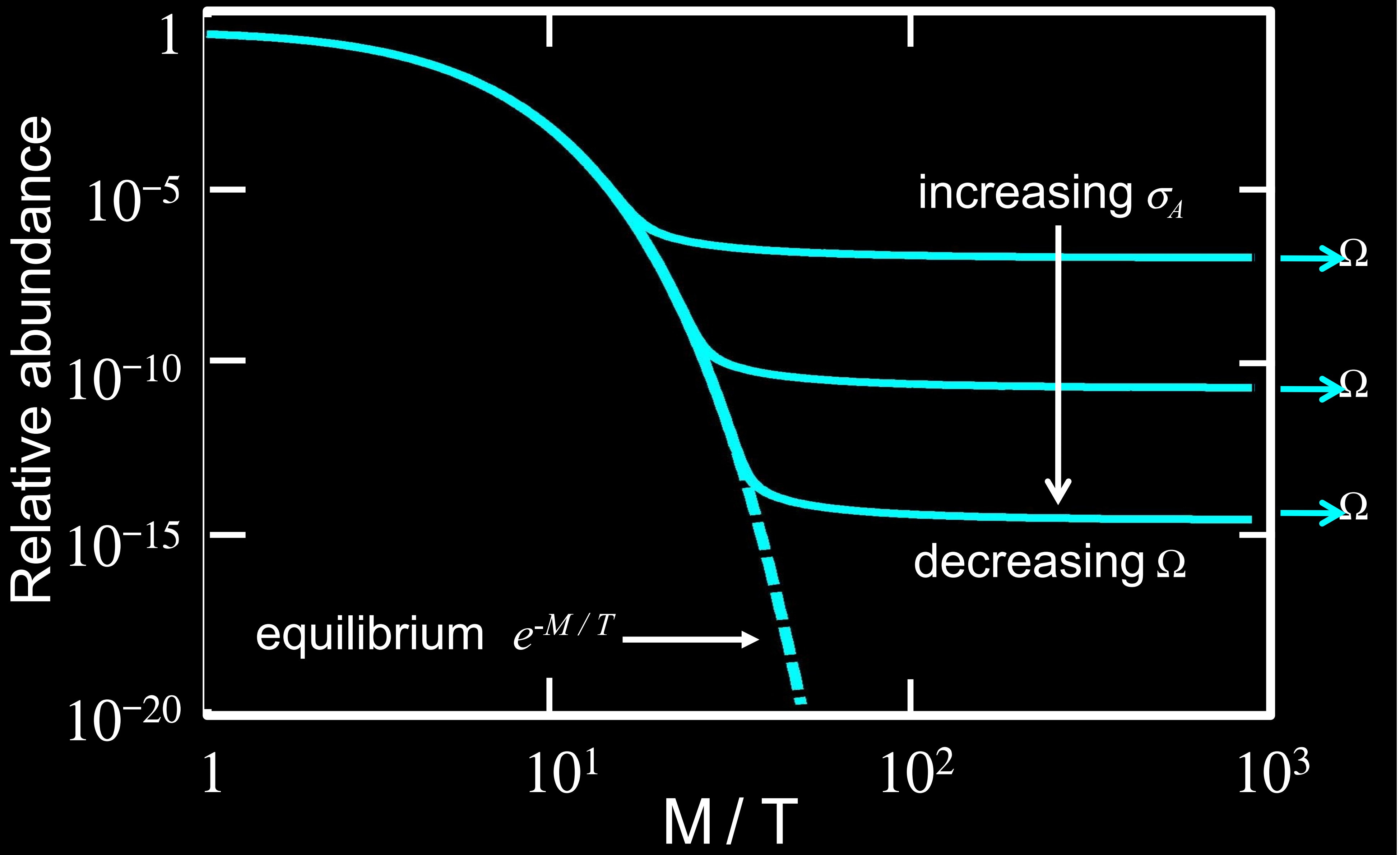
thermal relics

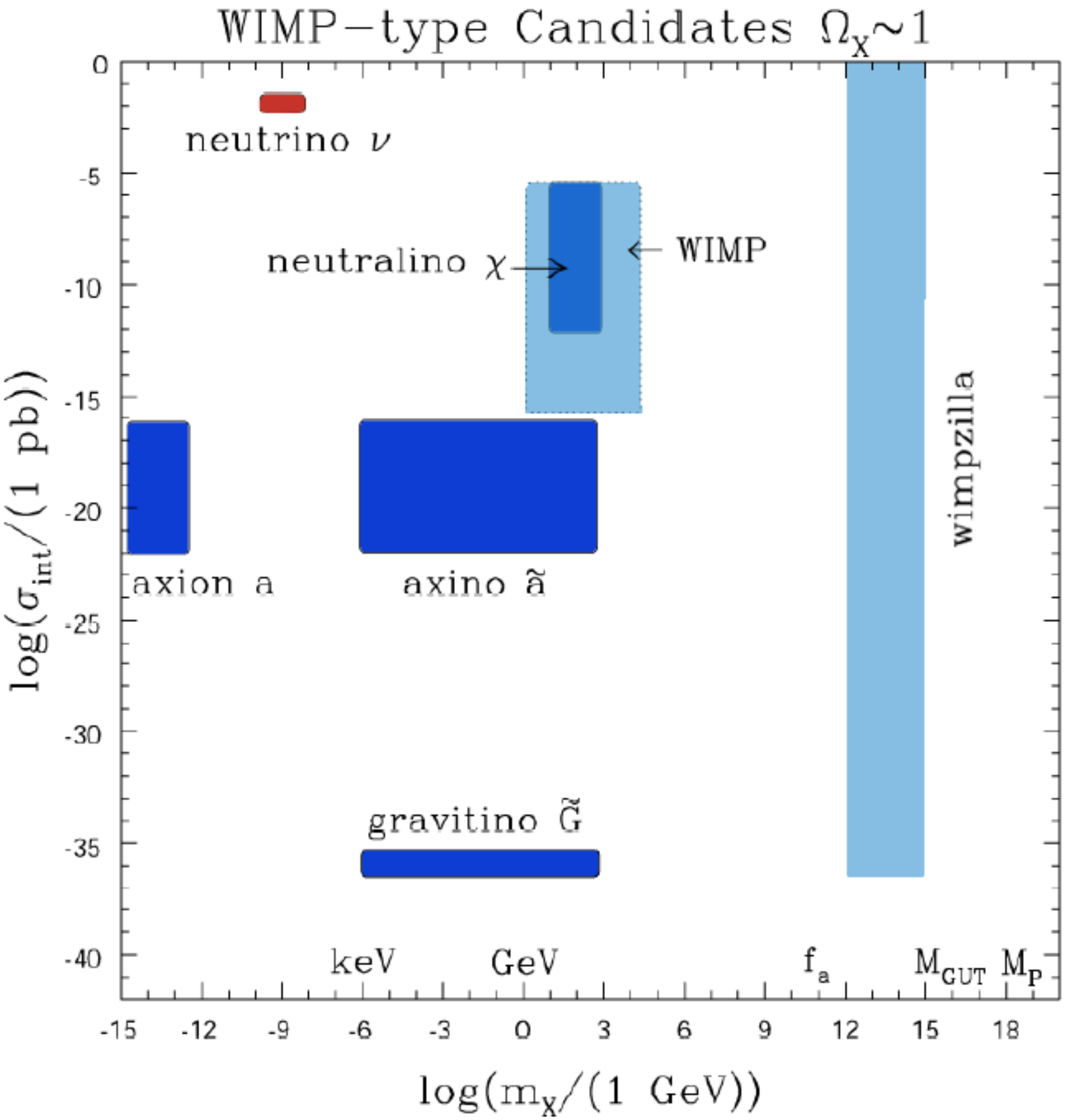
- B.E.C.s, axions, axion clusters
- solitons (Q-balls, B-balls, odd-balls, …)
- supermassive wimpzillas

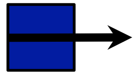
nonthermal relics

$$\Omega_{\mathrm{PDM}} h^2 \sim \frac{G^{3/2} T_0^3 h^2}{H_0^2 \langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle} = \frac{3 \times 10^{-27}\ \mathrm{cm}^3\ \mathrm{s}^{-1}}{\langle \sigma_{\mathrm{ann}} v_{\mathrm{rel}} \rangle}$$

Cold Thermal Relics




WIMP−type Candidates Ω_X~1
neutrino ν
neutralino χ
WIMP
wimpzilla
axion a
axino $\tilde{a}$
gravitino $\tilde{G}$
keV
GeV
f_a
M_{GUT}
M_P
0
-5
-10
-15
-20
-25
-30
-35
-40
-15
-12
-9
-6
-3
0
3
6
9
12
15
18
$\log(\sigma_{int}/(1\ pb))$
$\log(m_X/(1\ GeV))$



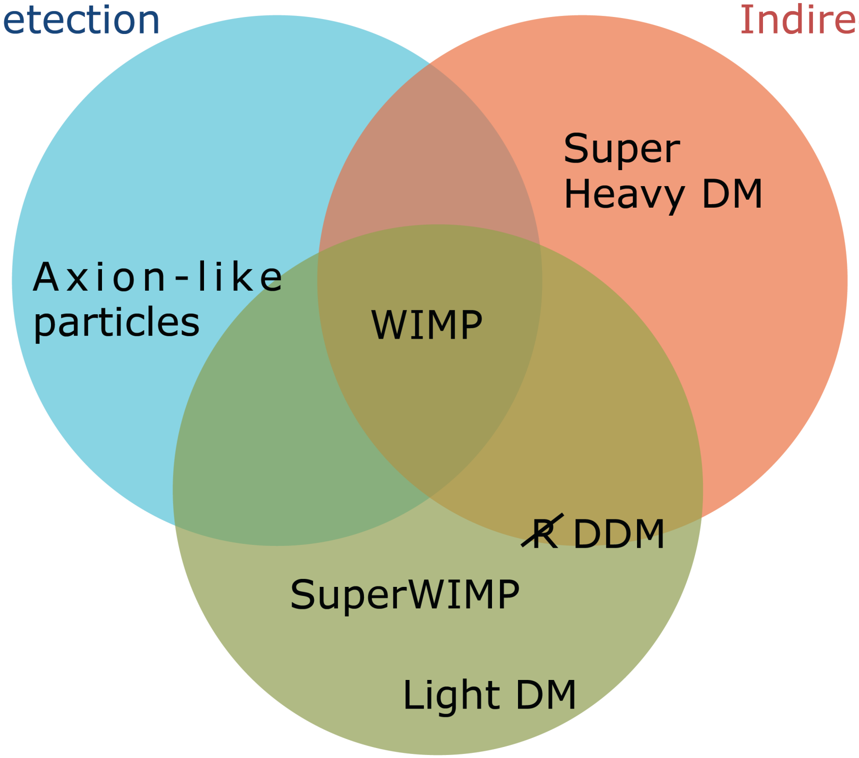
PBH

Direct Search for Dark Matter Particles

Complementarity of DM searches

Direct Detection

DAMA/LIBRA
CDMS
XENON
KIMS
COUPP
ZEPLIN
CoGeNT
CRESST
ANAIS
SIMPLE
…



Indirect Detection

PAMELA
Fermi
MAGIC
AMS
ANTARES
IceCube
CTA
WMAP
…

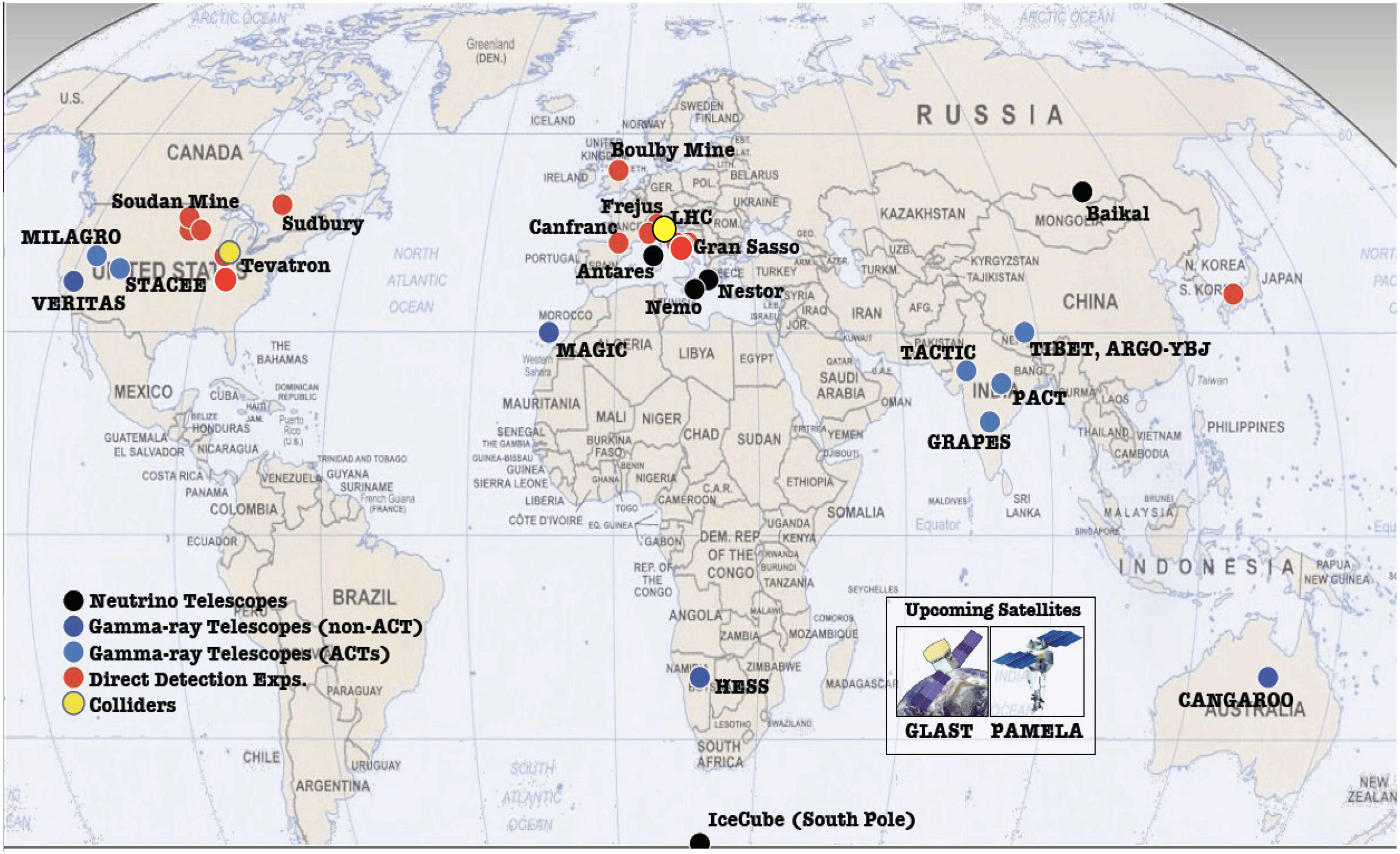
Accelerator searches

LHC (ILC)

Many DM models can be probed by the different experimental techniques

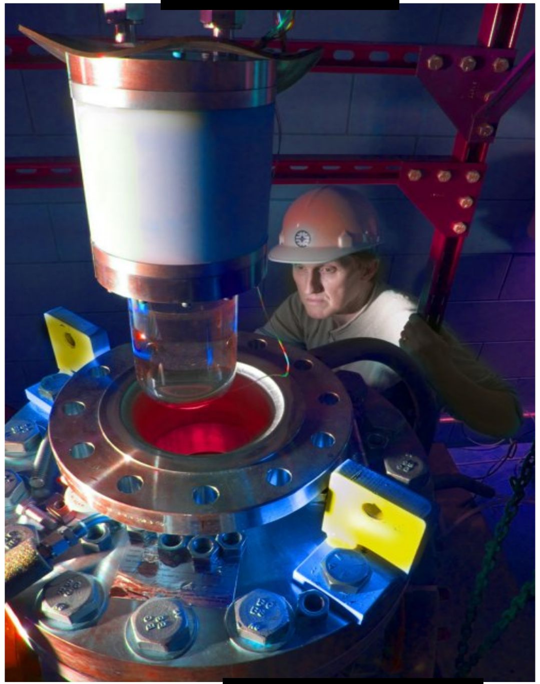
“Redundant” detection can be used to extract DM properties

DM experiments (2007)

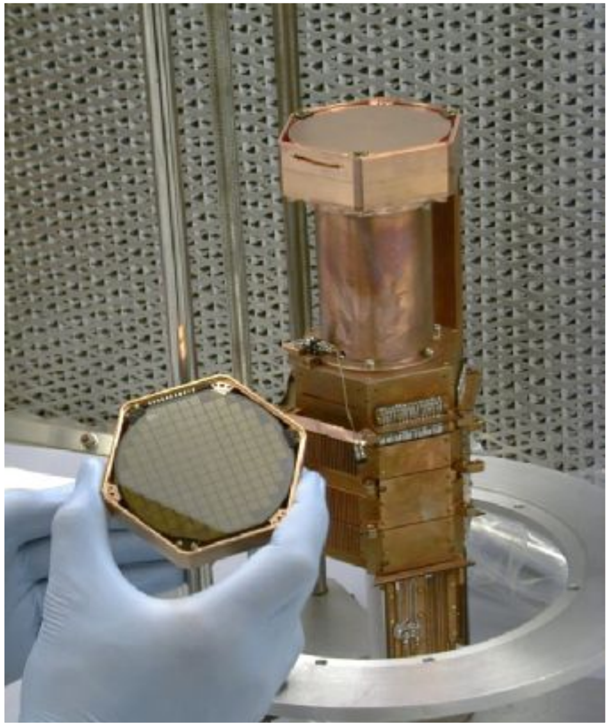


Direct Detection

COUPP

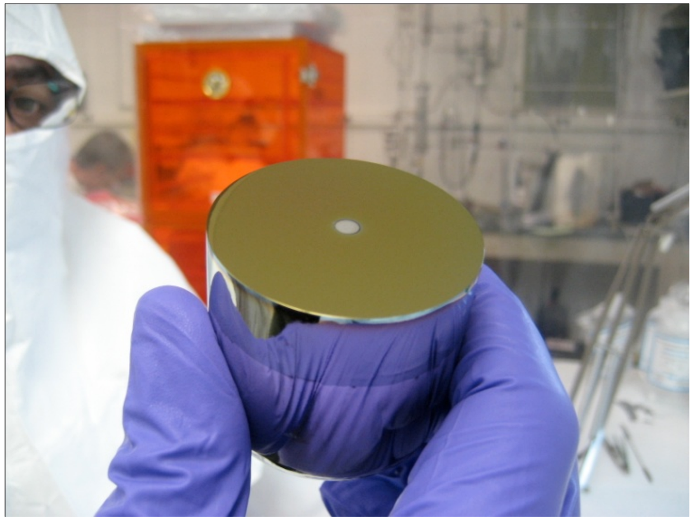


CDMS



CRESST

CoGeNT



(+ EDELWEISS,
XENON, EURECA,
ZEPLIN, DEAP, ArDM,
WARP, LUX, SIMPLE,
PICASSO, DMTPC,
DRIFT, KIMS, …)

DAMA

Direct Detection

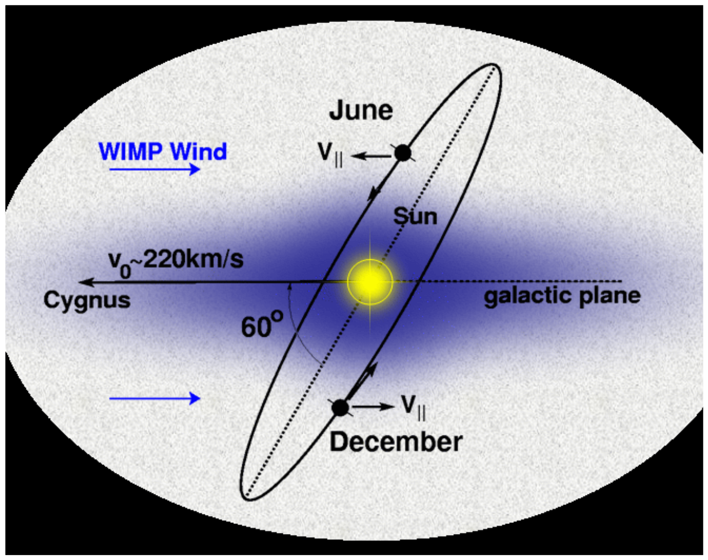
- Depends on local WIMP phase-space density
- Usual assumption: $\rho_{DM} = 0.3\,\mathrm{GeV\ cm}^{-3}$
- Usual assumption: Maxwellian velocity distribution
  in galactic rest frame

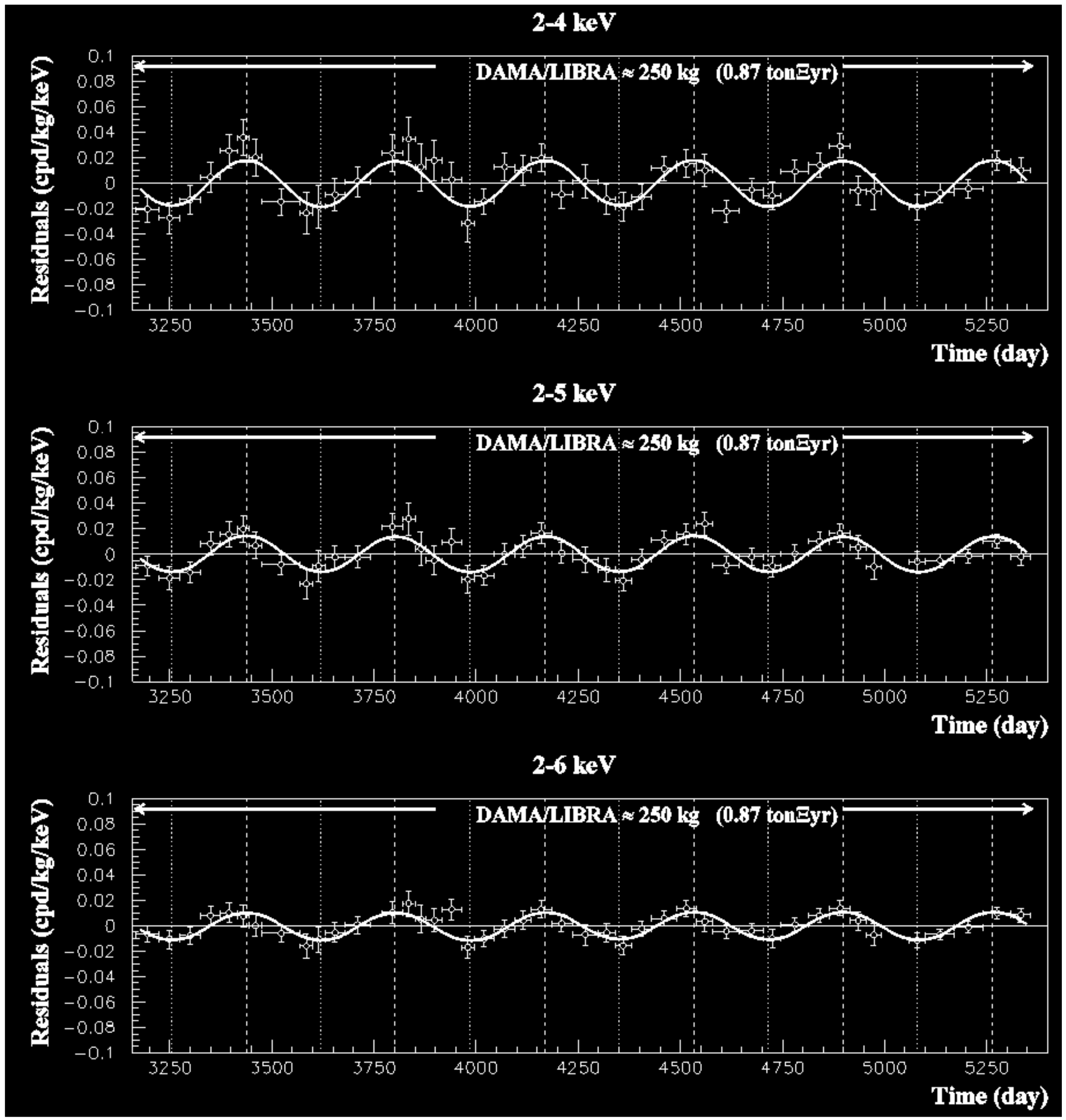
DAMA/LIBRA

$\cos \omega(t - t_0)$

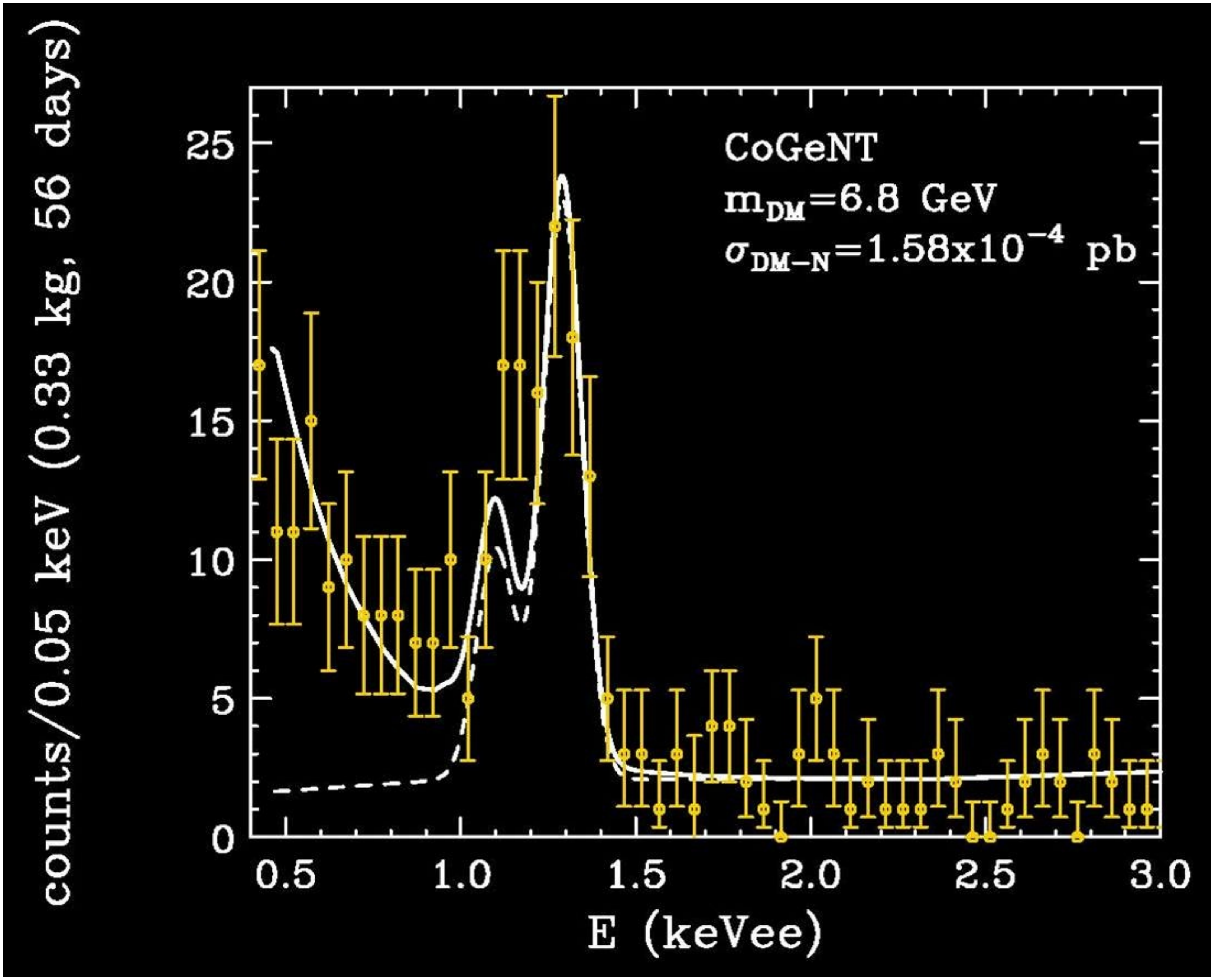
$T = 2\pi/\omega = 1$ year

$t_0 = 152.5^d$ (2nd June)

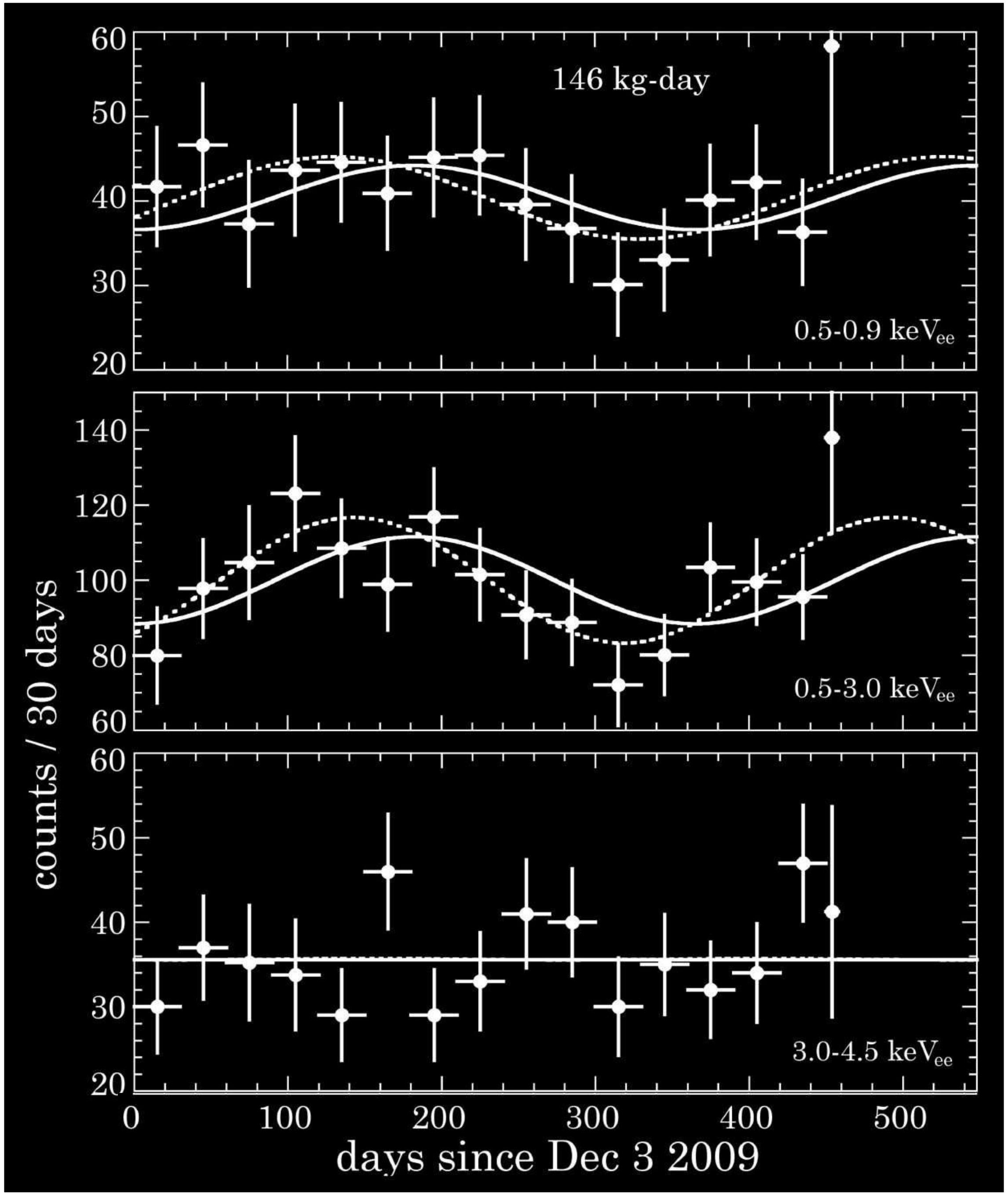




CoGeNT

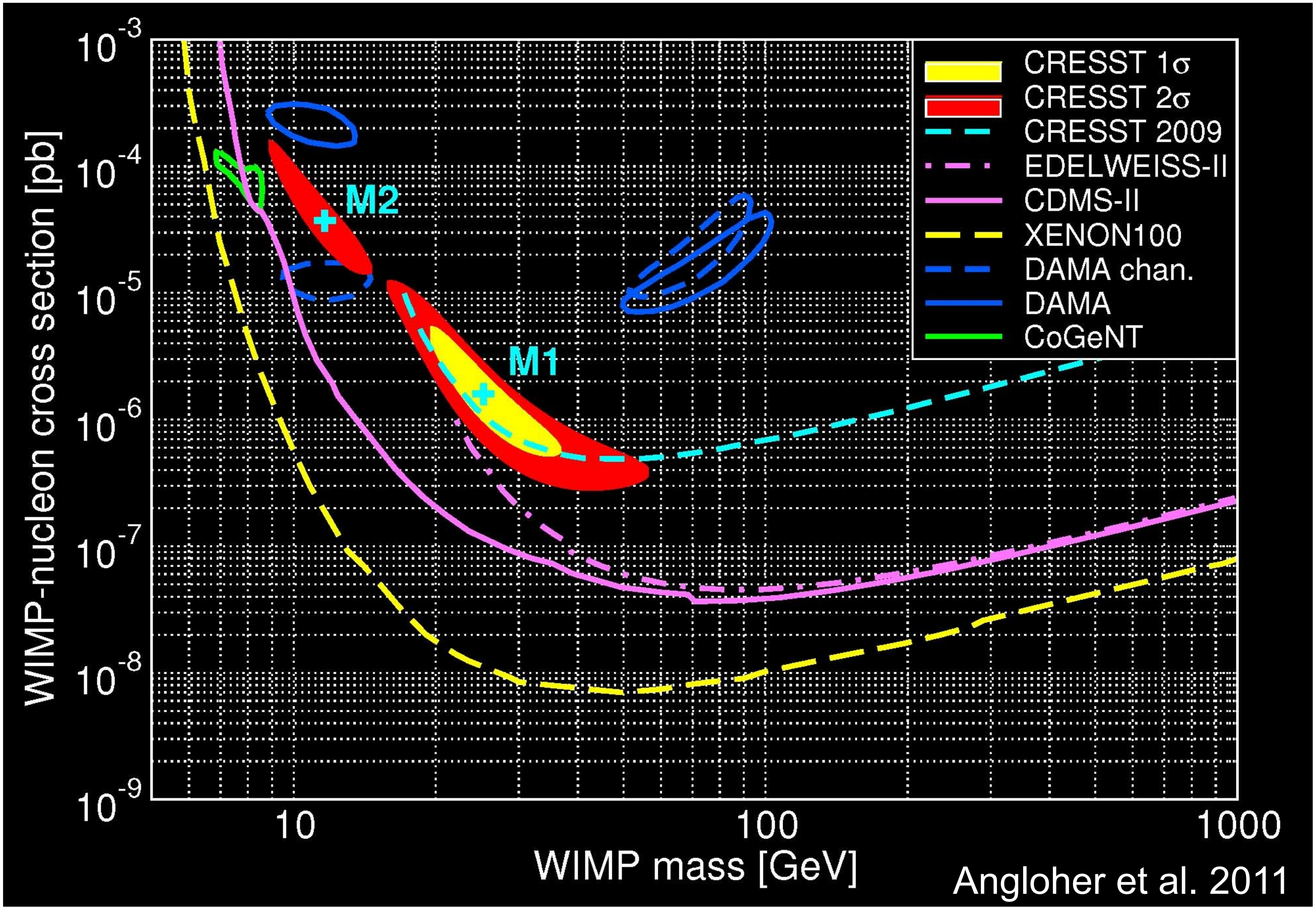

CoGeNT
m_{DM}=6.8 GeV
σ_{DM-N}=1.58x10^{-4} pb
counts/0.05 keV (0.33 kg, 56 days)
E (keVee)
0
5
10
15
20
25
0.5
1.0
1.5
2.0
2.5
3.0

CoGeNT



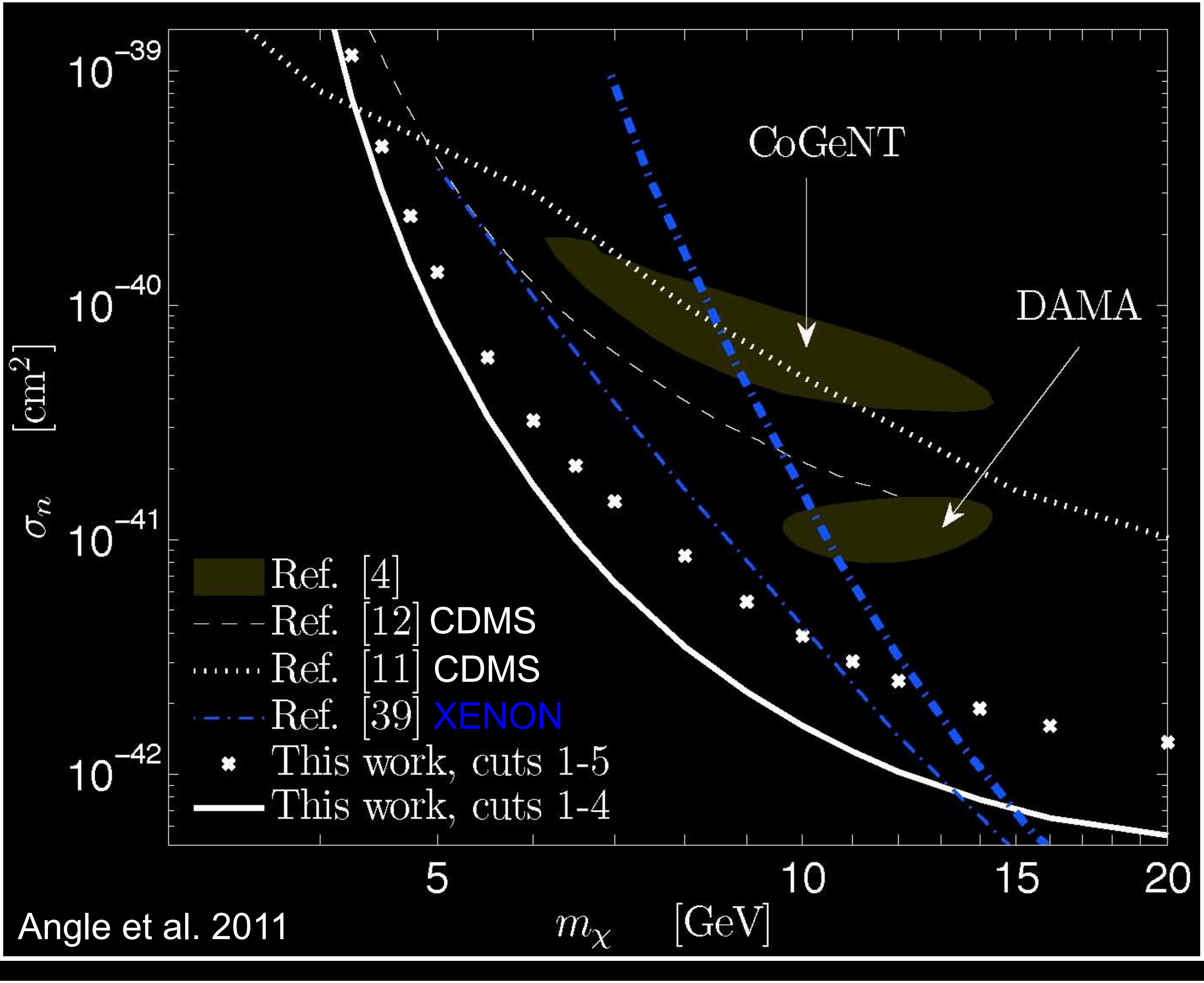
annual modulation
at 2.8 σ
Aalseth et al. 2011

CRESST



Angloher et al. 2011

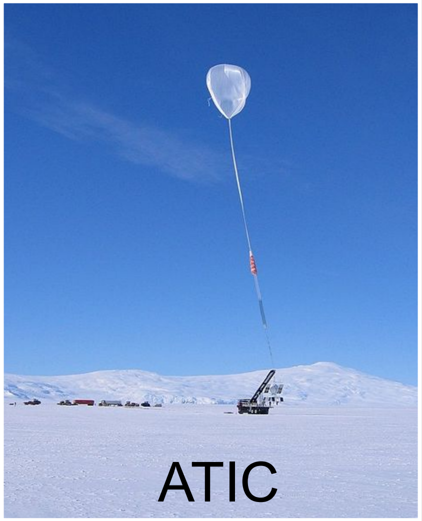
XENON/CDMS

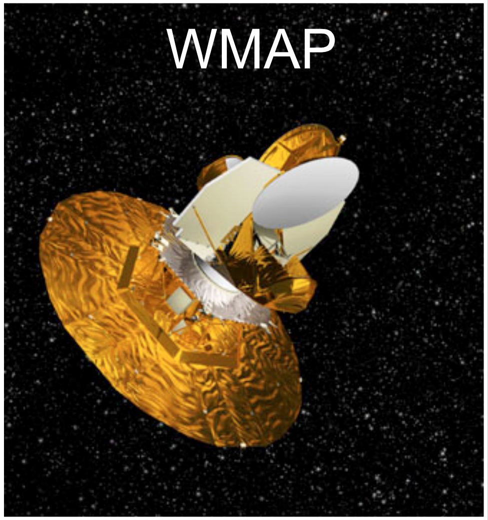


Angle et al. 2011

Indirect Search for Dark Matter Particles

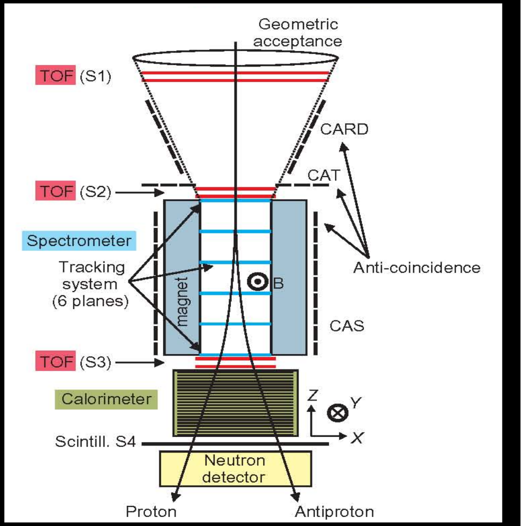
Indirect Detection


ATIC


WMAP


Fermi/GLAST

PAMELA



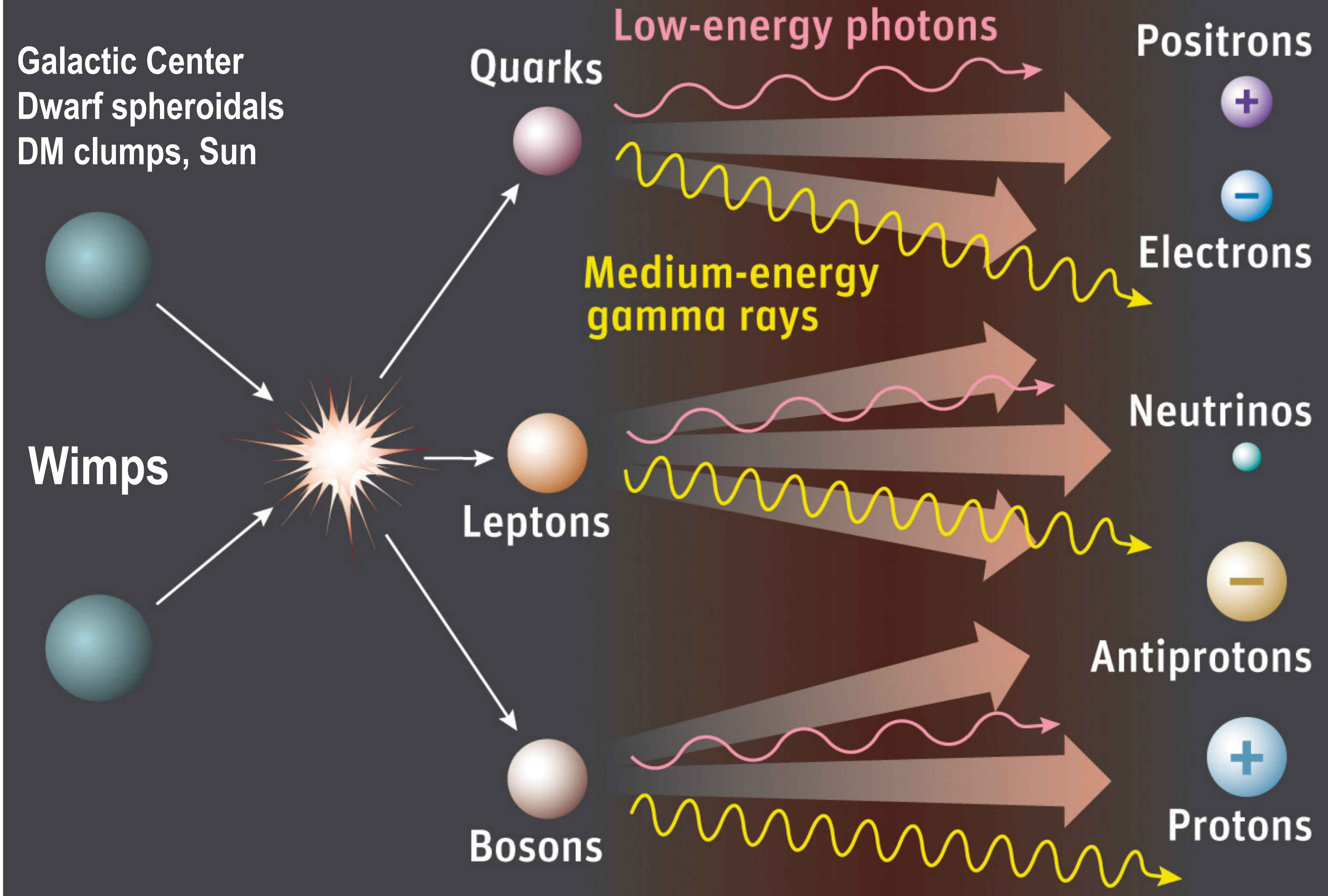

VERITAS


IceCube

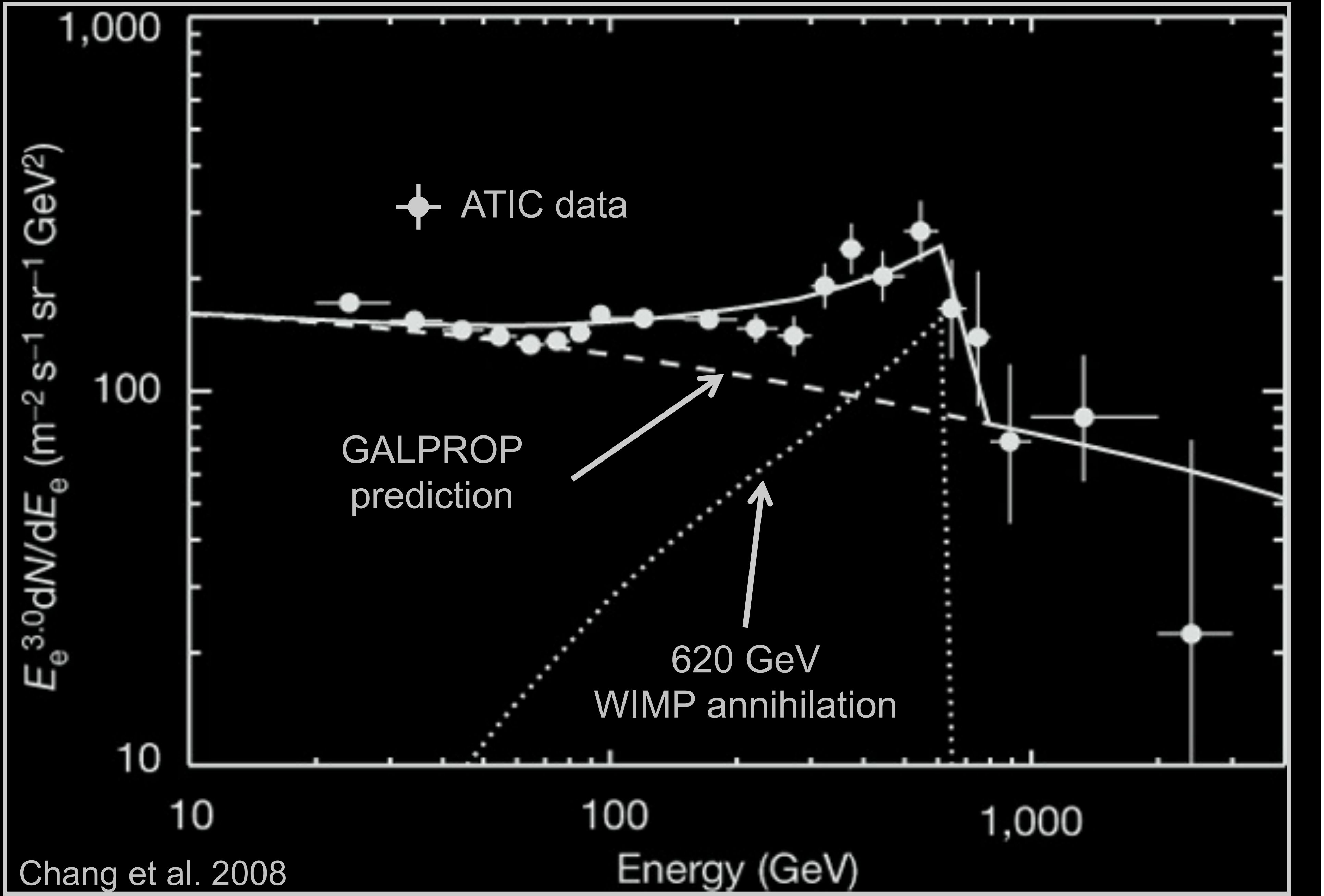

H.E.S.S.

AMS

Indirect Detection

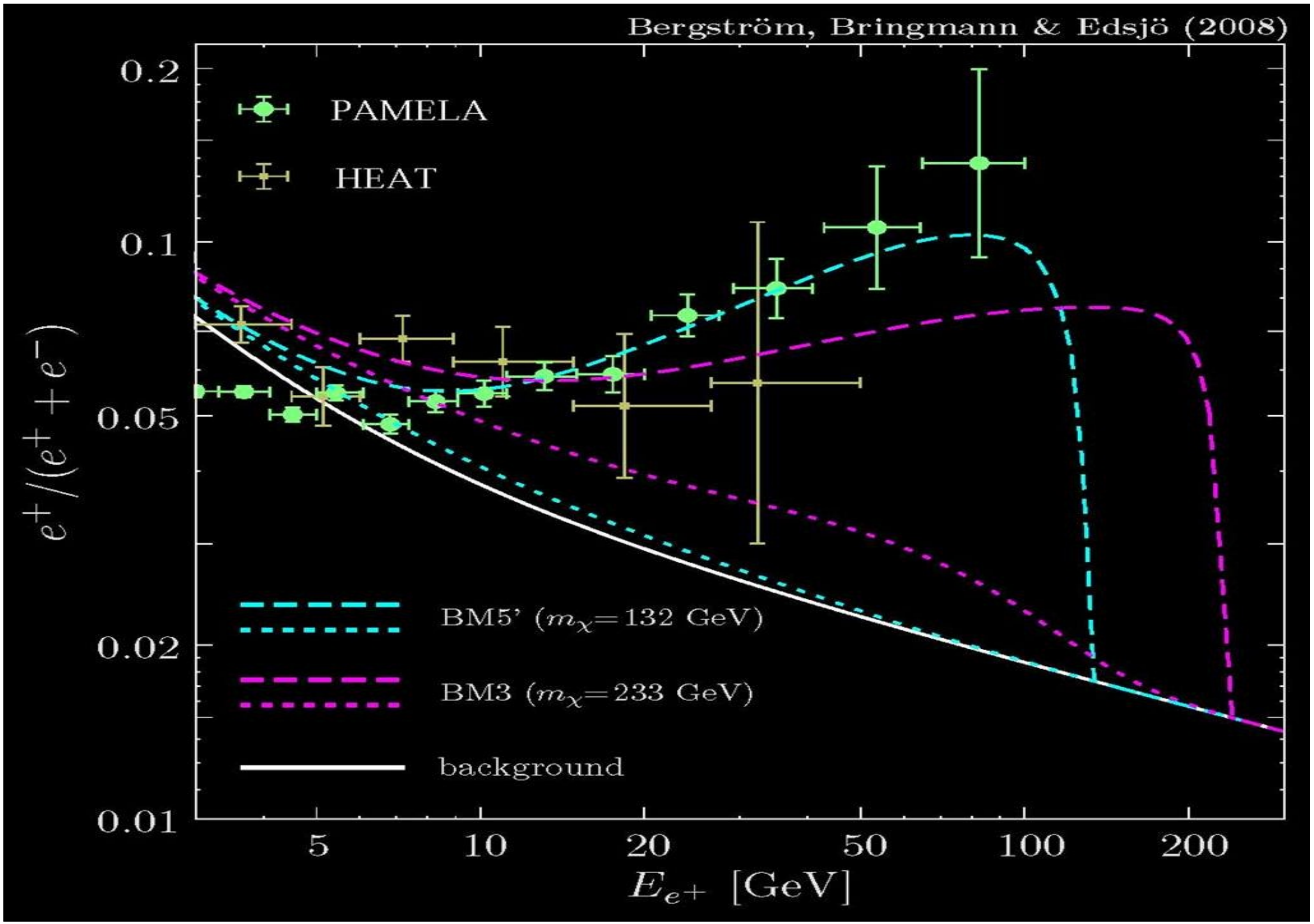


ATIC

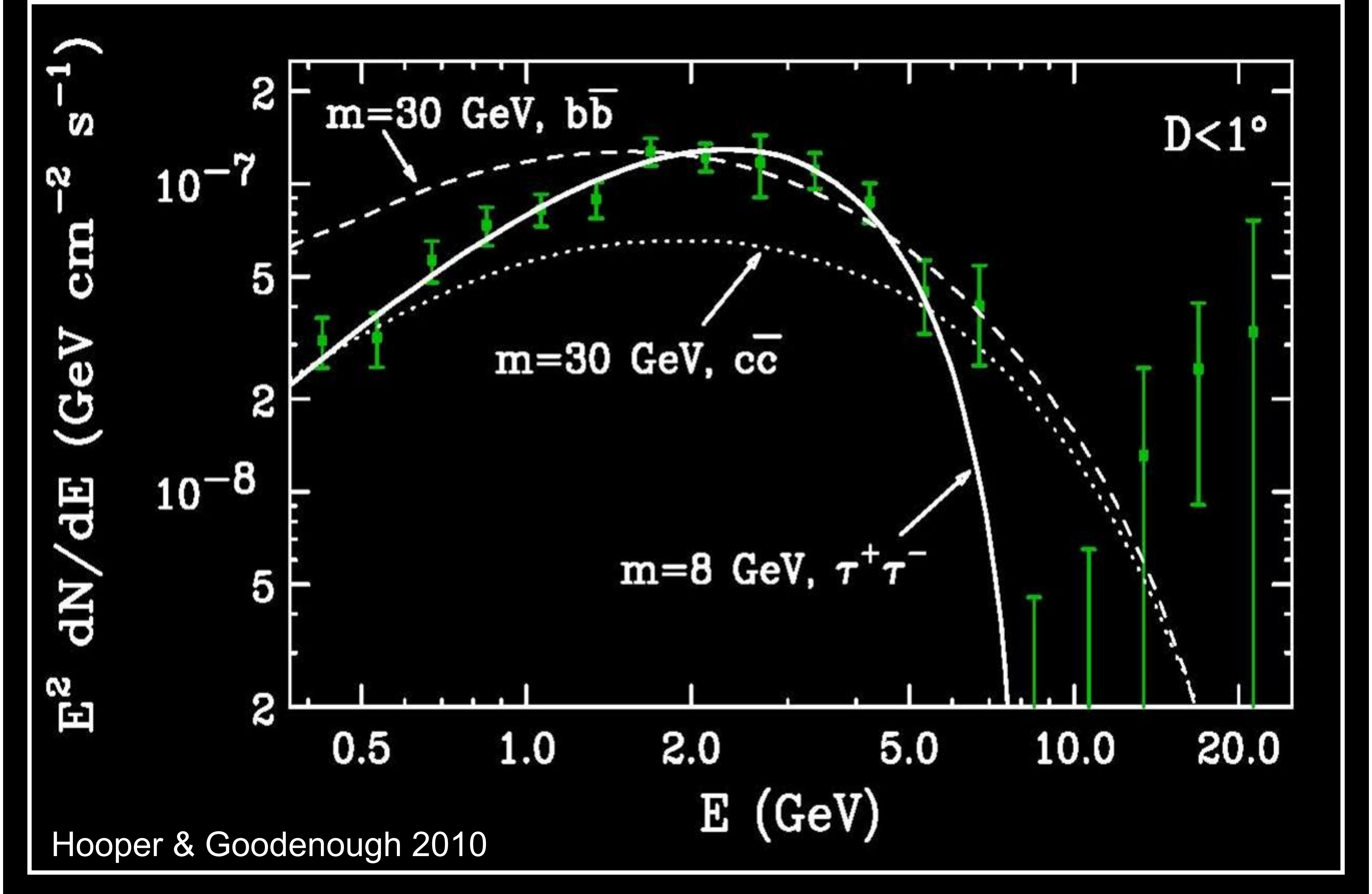


Chang et al. 2008

PAMELA

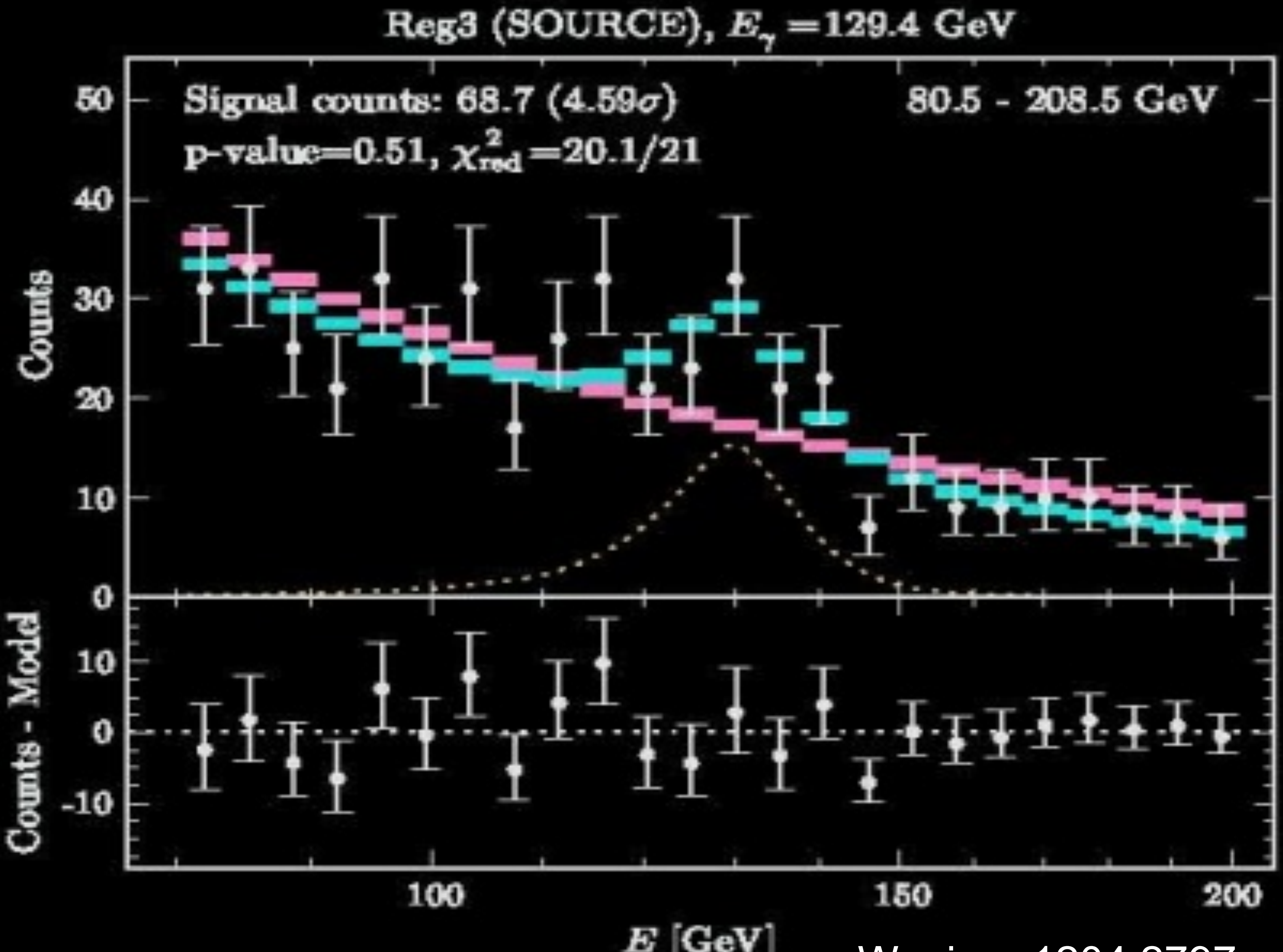

Bergström, Bringmann & Edsjö (2008)
PAMELA
HEAT
BM5' (m_χ=132 GeV)
BM3 (m_χ=233 GeV)
background
0.2
0.1
0.05
0.02
0.01
$e^+/(e^+ + e^-)$
5
10
20
50
100
200
E_{e+} [GeV]

Fermi/GLAST Feature



Hooper & Goodenough 2010

Fermi/GLAST Line

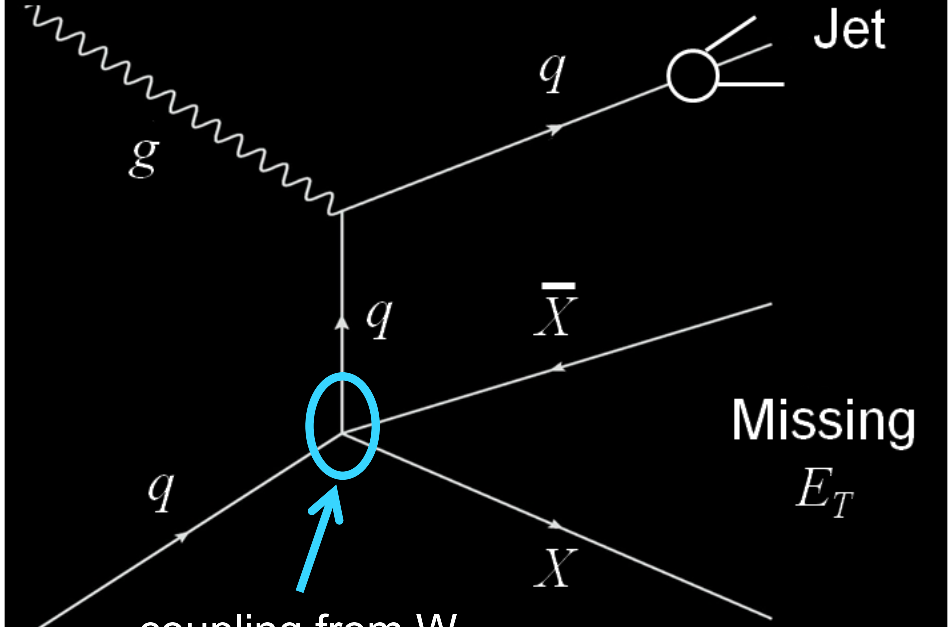


Weniger 1204.2797

Collider Searches

Collider Searches

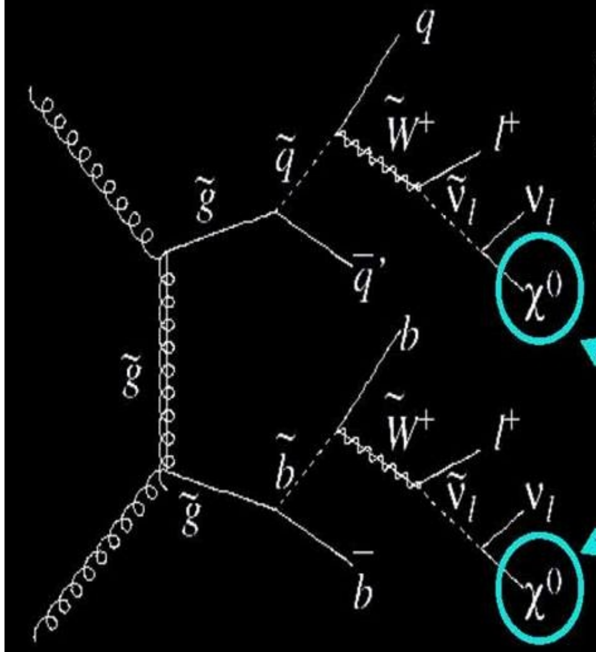
Maverick WIMPs



coupling from W
or direct/indirect

Backgrounds (neutrino, QCD, …)

Social WIMPs



$\tilde{g}$-pair production with subsequent cascade decays

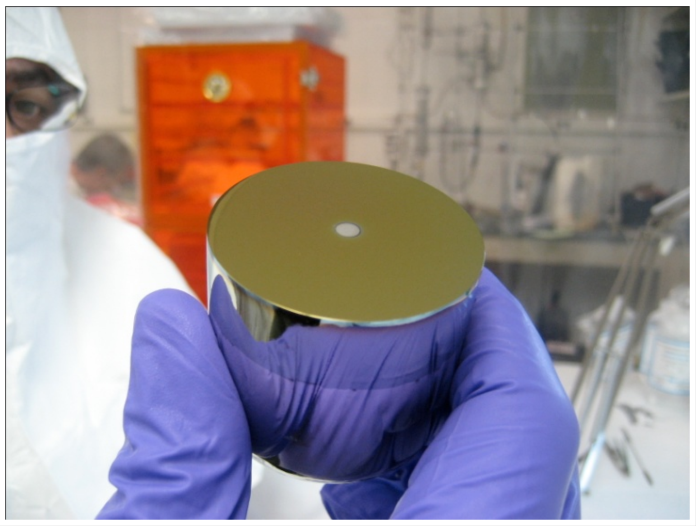
χ^0s escape undetected: missing E_T

Complicated decay chain

Beltran, Hooper, Kolb, Krusberg, Tait 1002.5137
Rajaraman, Shepherd, Tait, Wijangco 1108.1196
Fox, Harnik, Kopp, Tsai 1109.4398

WIMPs

CoGeNT



nonrelativistic

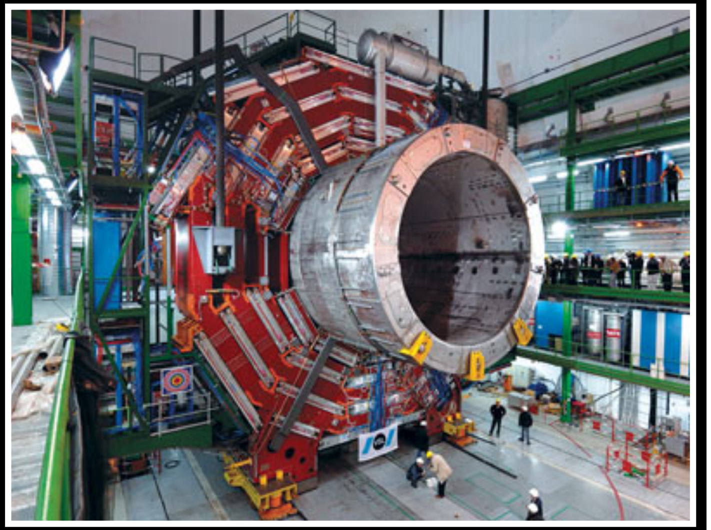
$\chi + N \rightarrow \chi + N$

10^{-4} pb – 10^{-6} pb

Described by
Effective field theory

Model Dependent

LHC

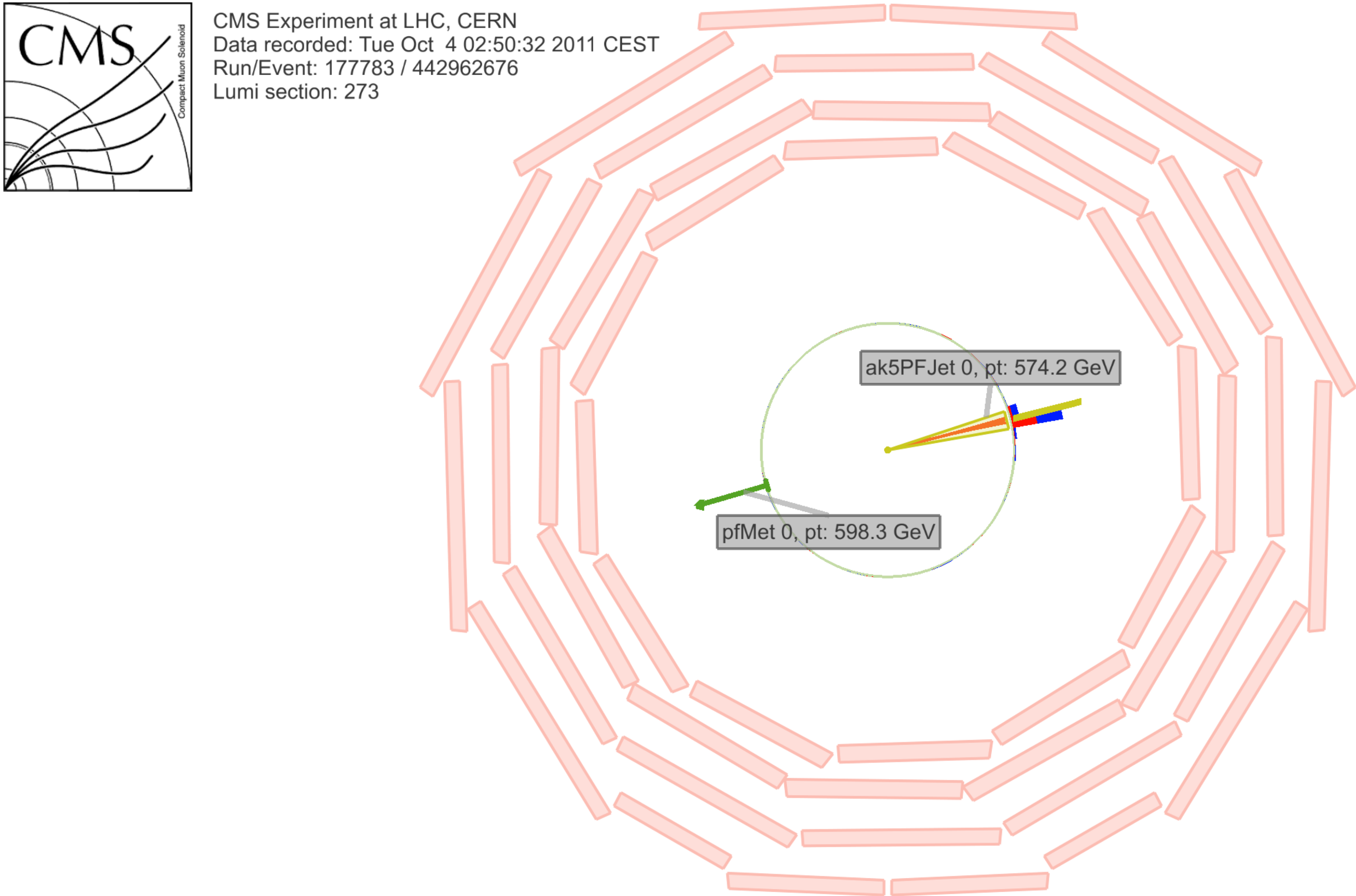


relativistic

$q + \bar{q} \rightarrow \chi + \chi$

Assume described by
effective field theory

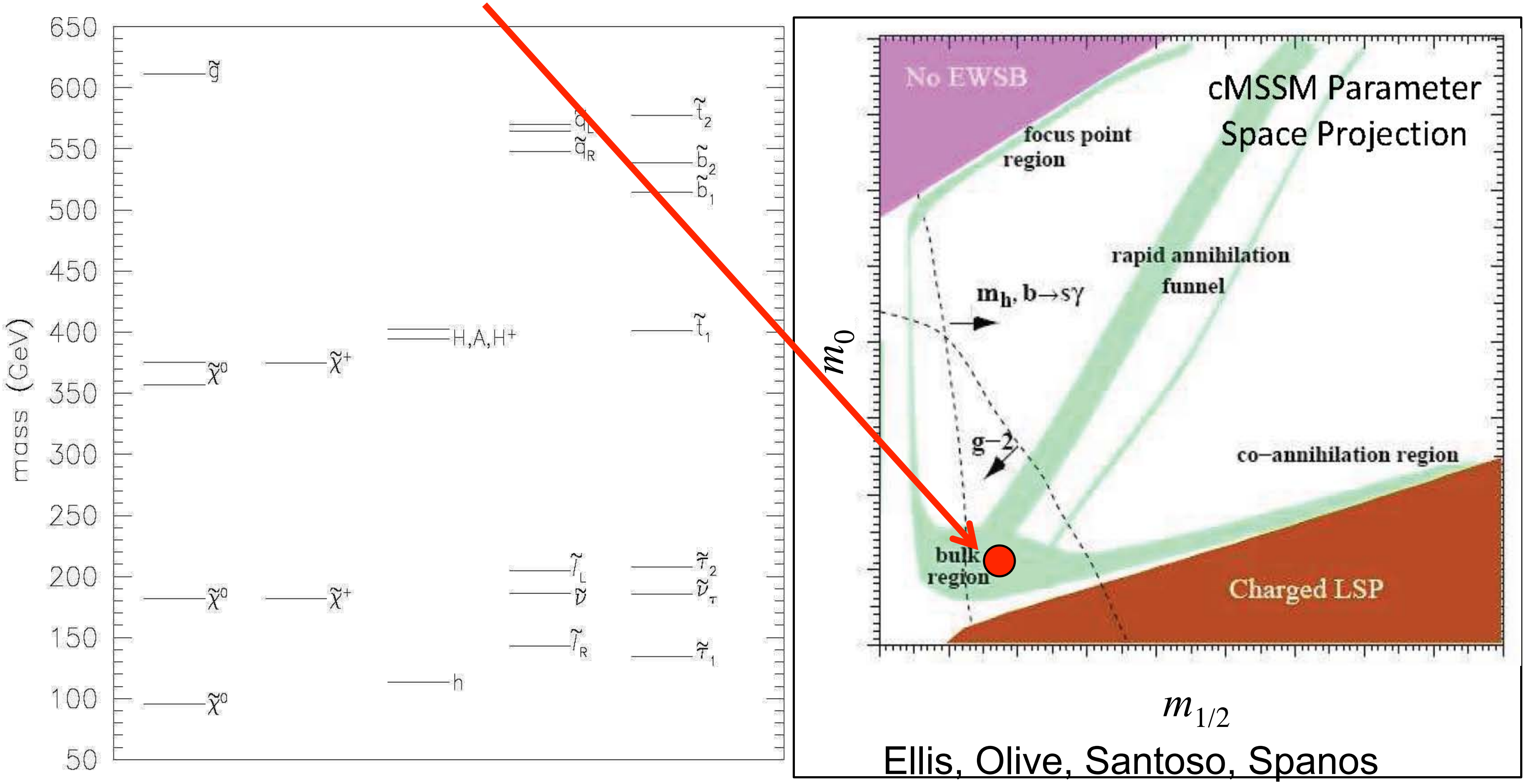
Missing Momentum = Missing Mass?



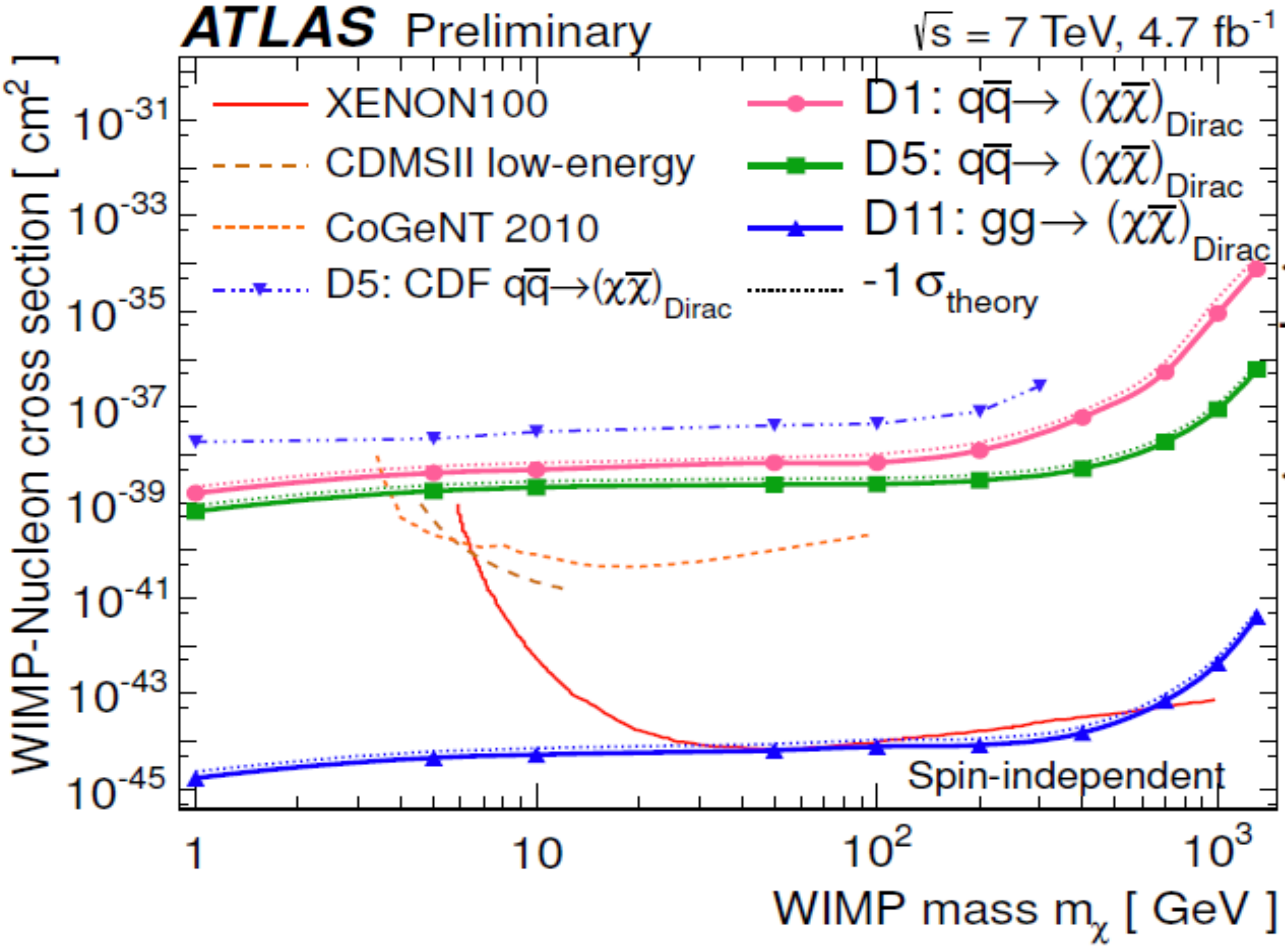
CMS Experiment at LHC, CERN
Data recorded: Tue Oct 4 02:50:32 2011 CEST
Run/Event: 177783 / 442962676
Lumi section: 273

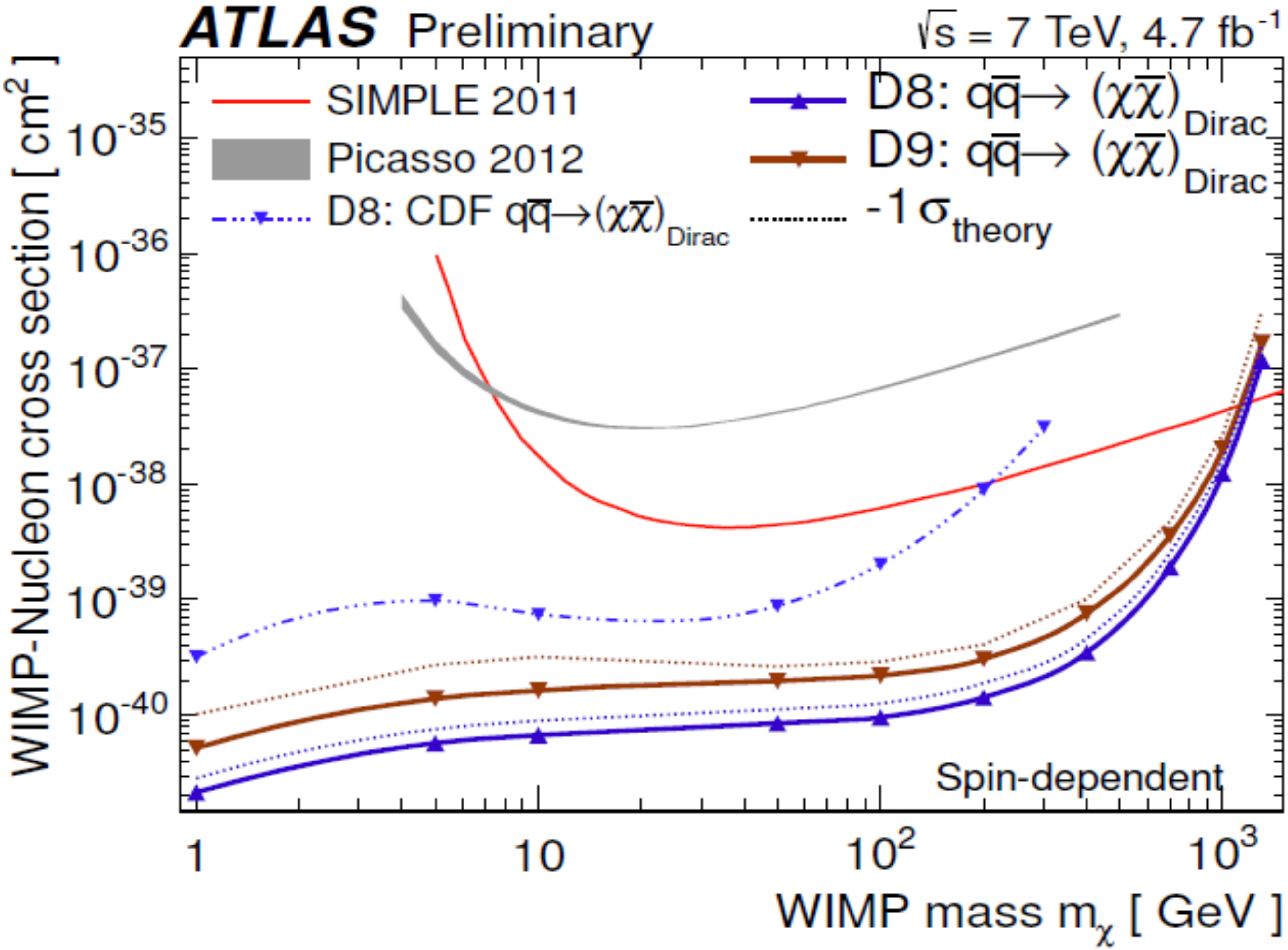
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO11059Winter2012

Bulk Region: light superpartners



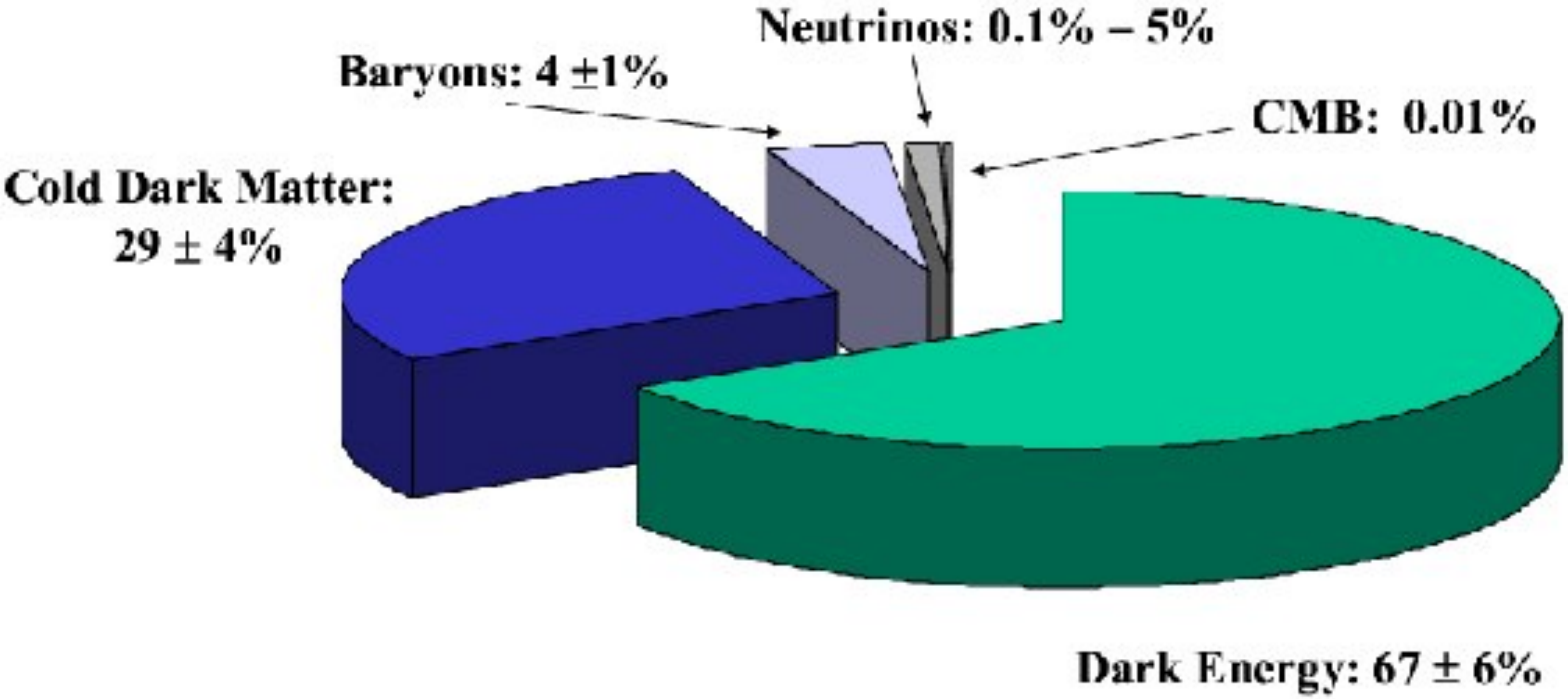
Ellis, Olive, Santoso, Spanos

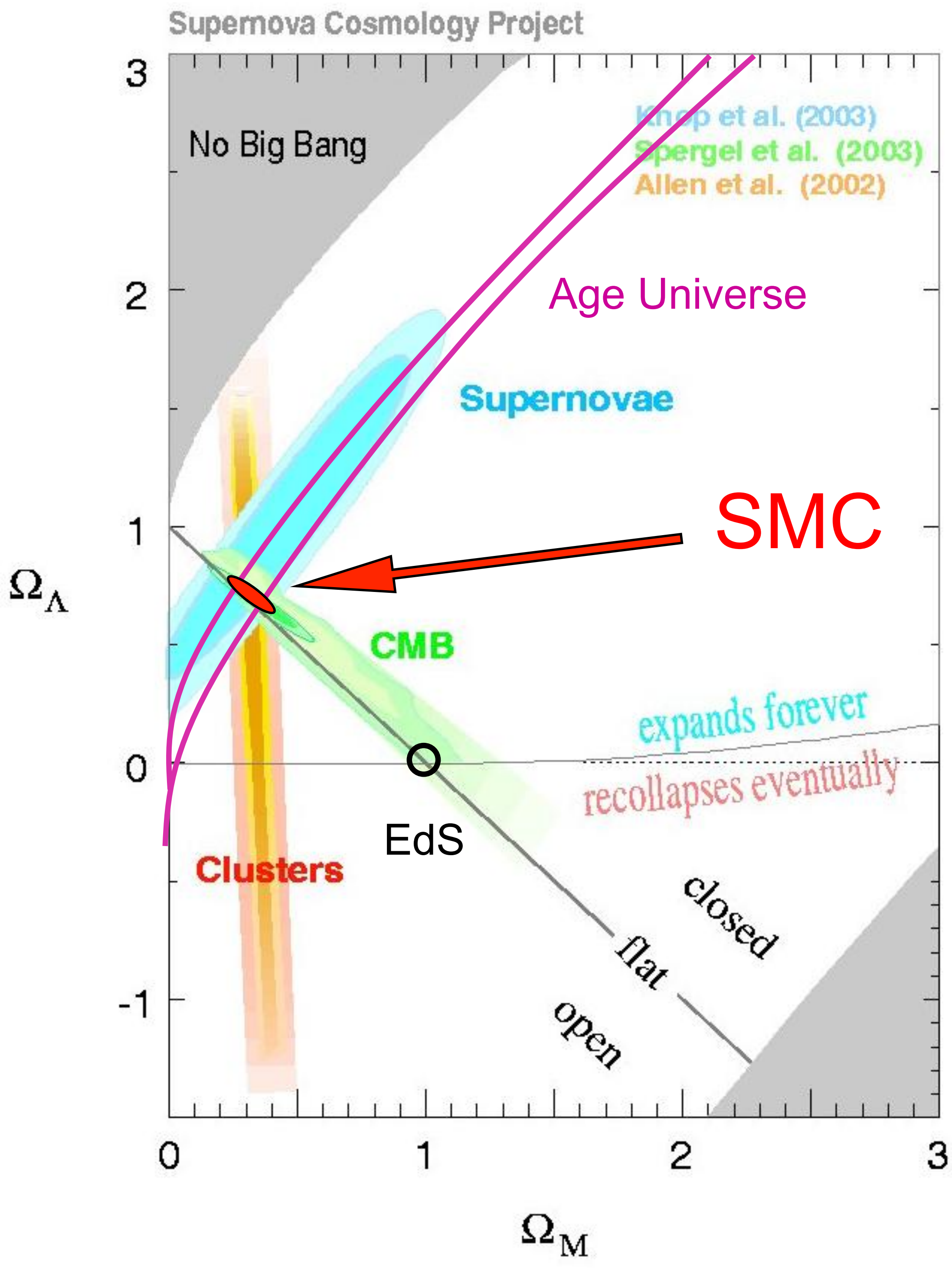

ATLAS Preliminary
√s = 7 TeV, 4.7 fb^-1
XENON100
CDMSII low-energy
CoGeNT 2010
D5: CDF qq̄→(χχ̄)Dirac
D1: qq̄→ (χχ̄)Dirac
D5: qq̄→ (χχ̄)Dirac
D11: gg→ (χχ̄)Dirac
-1 σtheory
Spin-independent
WIMP-Nucleon cross section [cm^2]
10^-31
10^-33
10^-35
10^-37
10^-39
10^-41
10^-43
10^-45
1
10
10^2
10^3
WIMP mass mχ [GeV]


ATLAS Preliminary
√s = 7 TeV, 4.7 fb⁻¹
SIMPLE 2011
Picasso 2012
D8: CDF qq̄→(χχ̄)Dirac
D8: qq̄→ (χχ̄)Dirac
D9: qq̄→ (χχ̄)Dirac
-1 σtheory
Spin-dependent
WIMP-Nucleon cross section [cm²]
10⁻³⁵
10⁻³⁶
10⁻³⁷
10⁻³⁸
10⁻³⁹
10⁻⁴⁰
1
10
10²
10³
WIMP mass mχ [GeV]

Summary

Matter and Energy in the Universe: A Strange Recipe





STANDARD MODEL OF COSMOLOGY

$$\Omega_M = 0.27 \pm 0.03$$

$$\Omega_\Lambda = 0.73 \pm 0.03$$

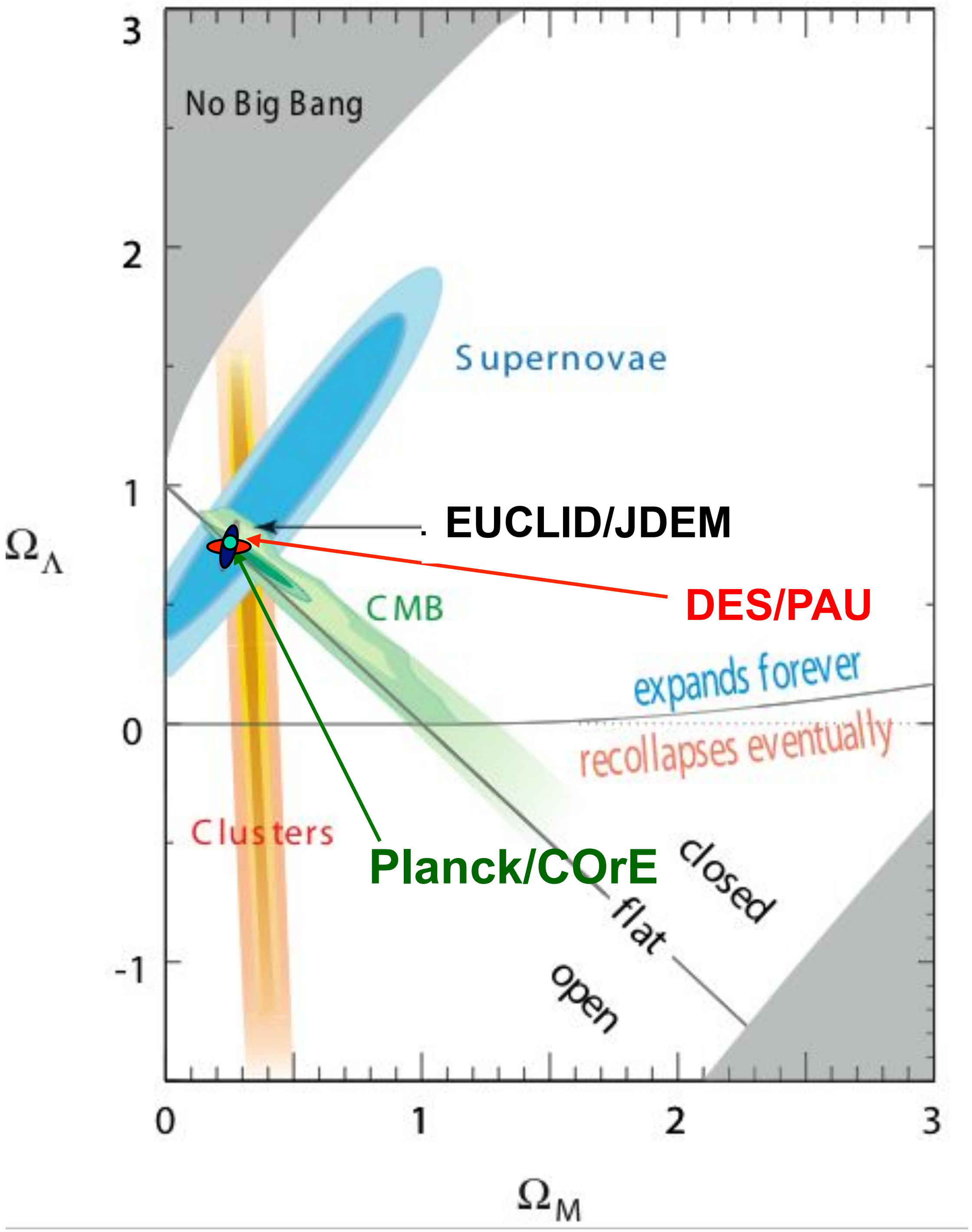
$$\Omega_0 = 1.002 \pm 0.005$$

$$\Omega_B = 0.0445 \pm 0.0033$$

$$H_0 = 72 \pm 3 \text{ km/s/Mpc}$$

$$t_0 = 13.7 \pm 0.3 \text{ Gyr}$$

“Precision Cosmology”
errors < few%



THE FUTURE?

A standard
model of
Cosmology
(2010-2015)

precision
<1%

DM? DE?

A   SUMMARY

Dark Matter is real:

- galaxies
- clusters
- large scale structure
- cosmic microwave background

We still do not know what it is:

- Direct detection has unconfirmed hints
- Indirect detection has tantalizing hints
- Collider searches see nothing yet

But we may have surprises…

The future is bright!