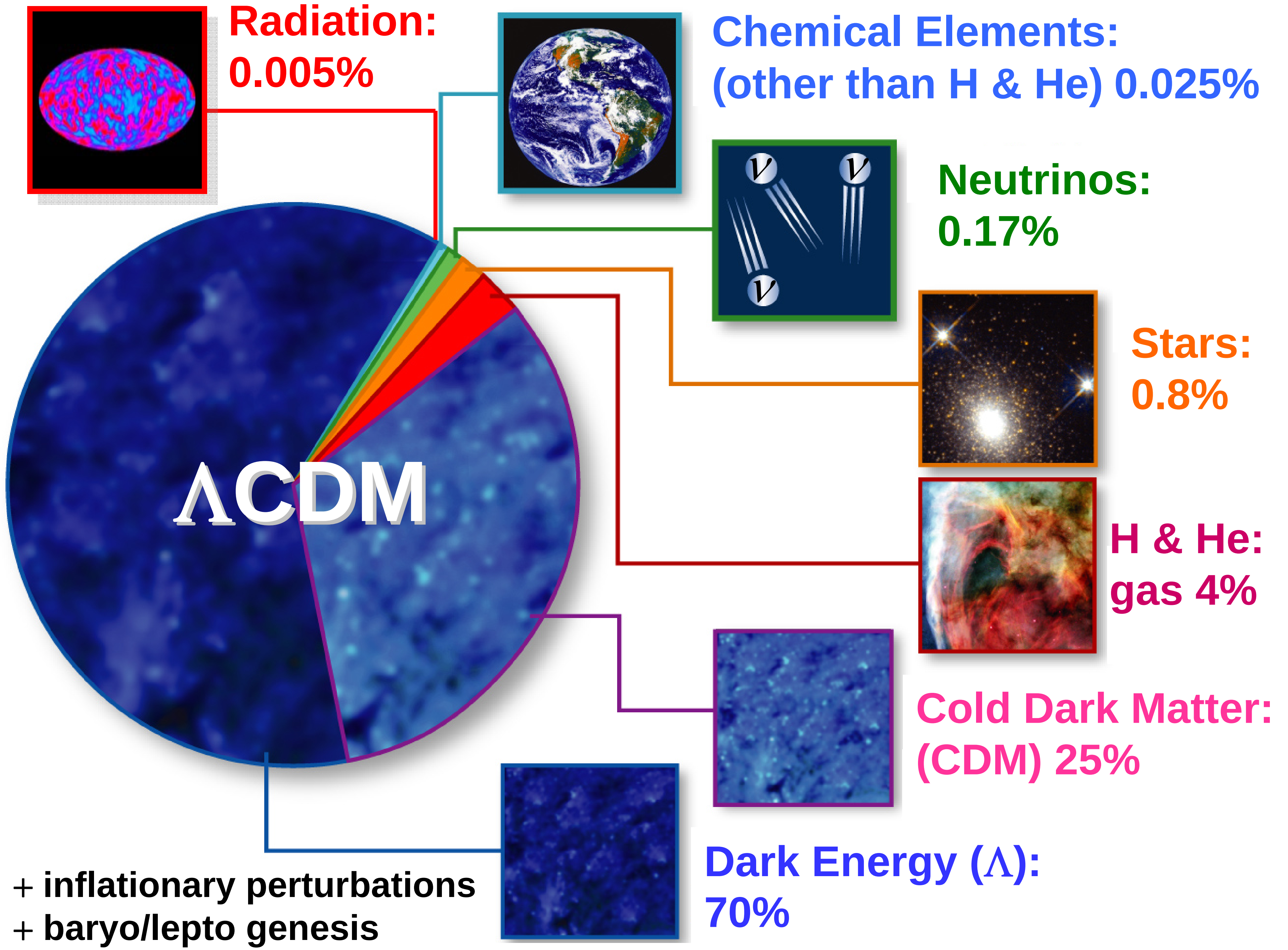
The Dark Universe: Dark Matter and Dark Energy

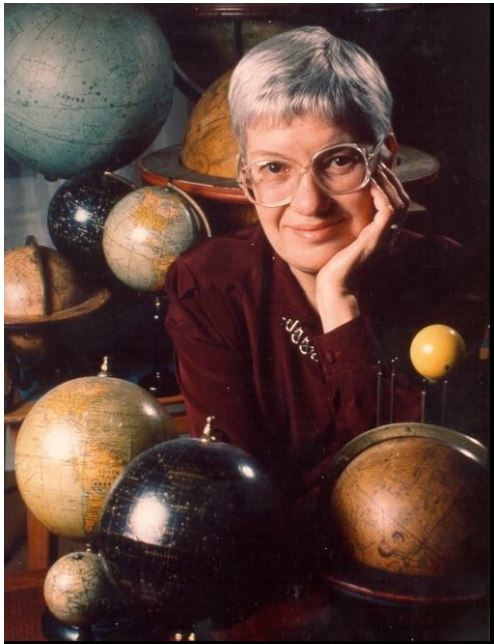
Rocky I:	The Universe Observed	Monday
Rocky II:	Inflation	Tuesday
Rocky III:	Dark Matter	Wednesday
Rocky IV:	Dark Energy	Thursday

CERN Academic Training Lectures January 2008

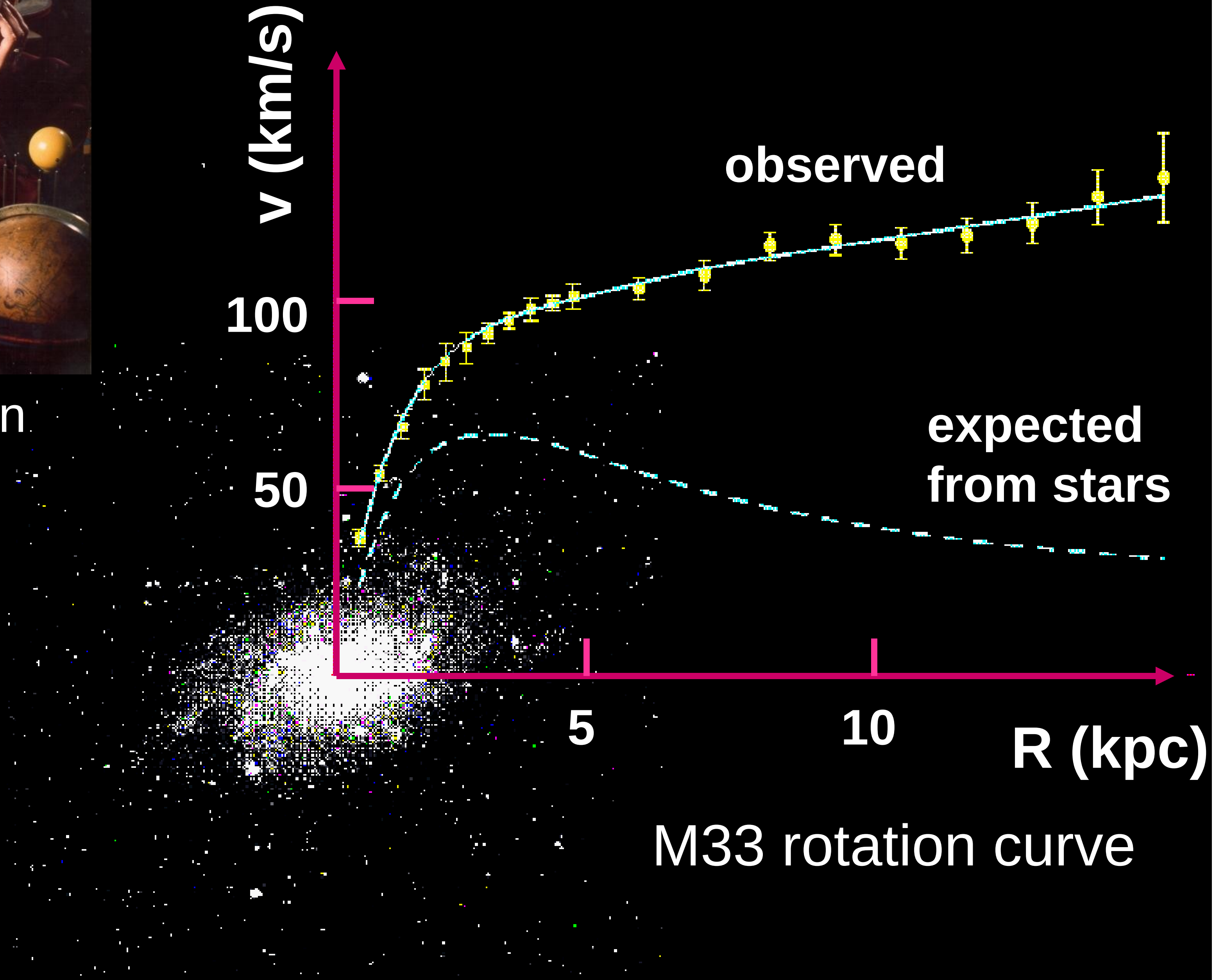
Rocky Kolb *The University of Chicago*


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
Stars:
0.8%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM
+ inflationary perturbations
+ baryo/lepto genesis

The Dark Universe



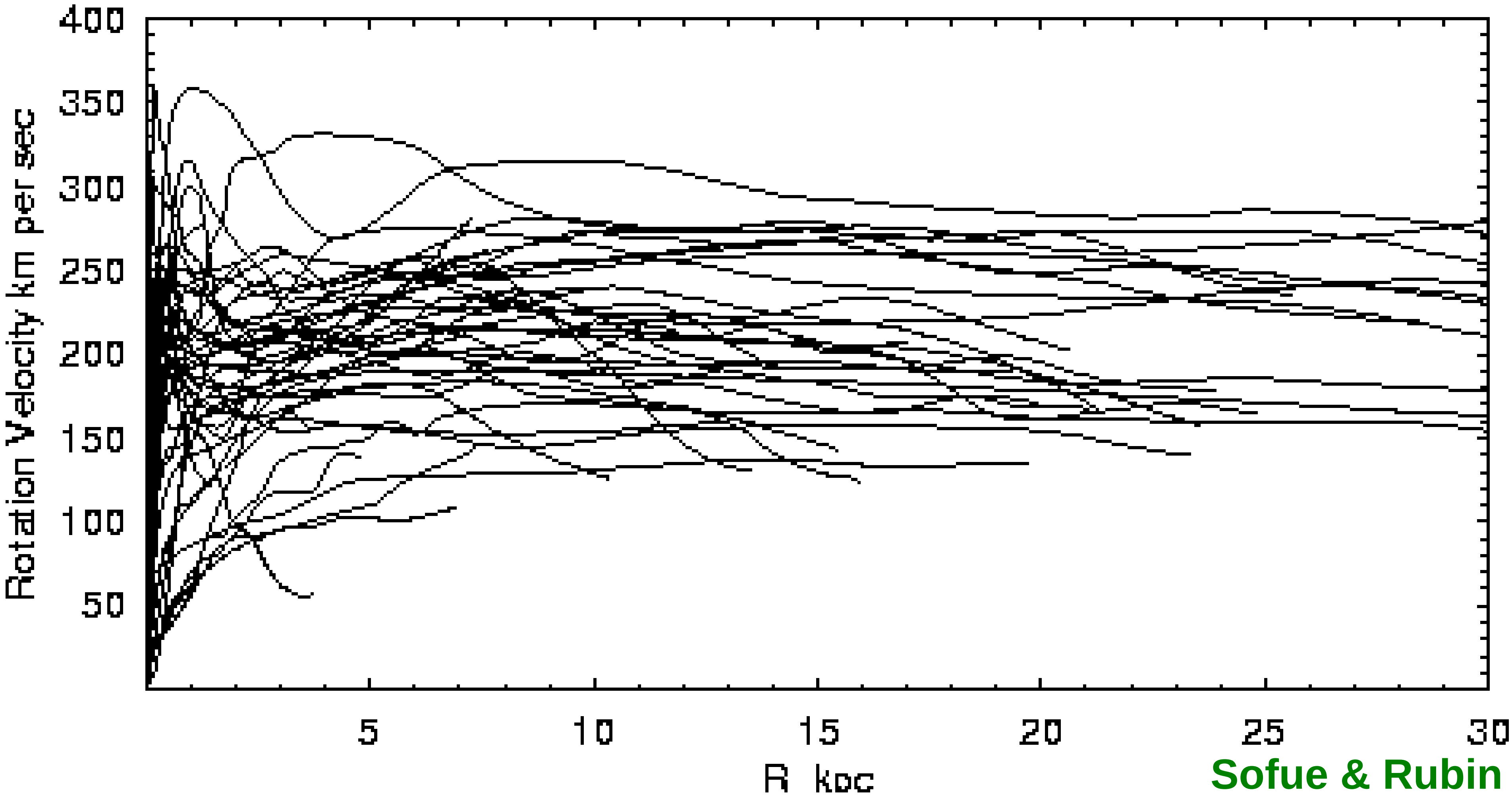
Vera Rubin



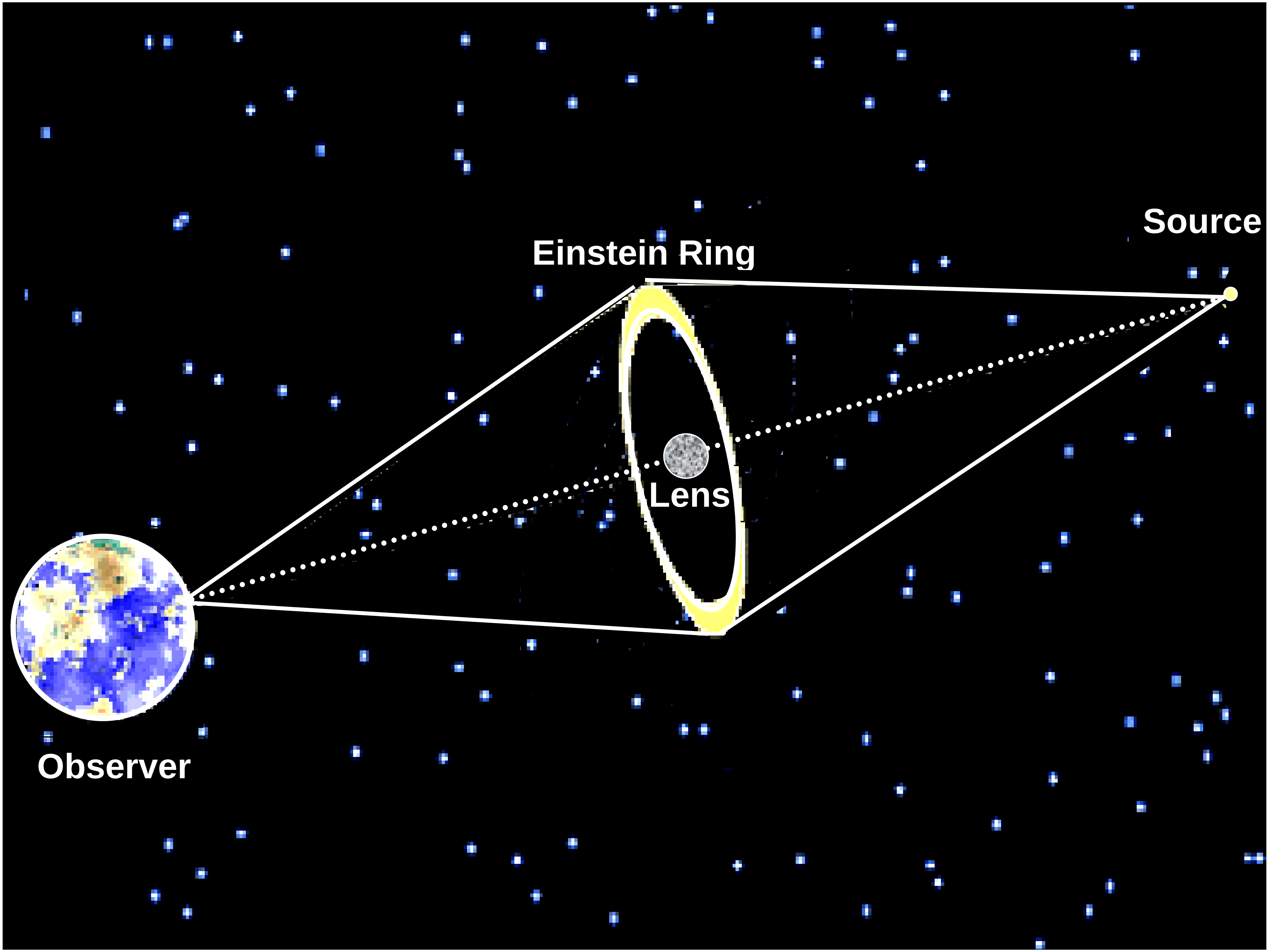
M33 rotation curve

Rotation Curves

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



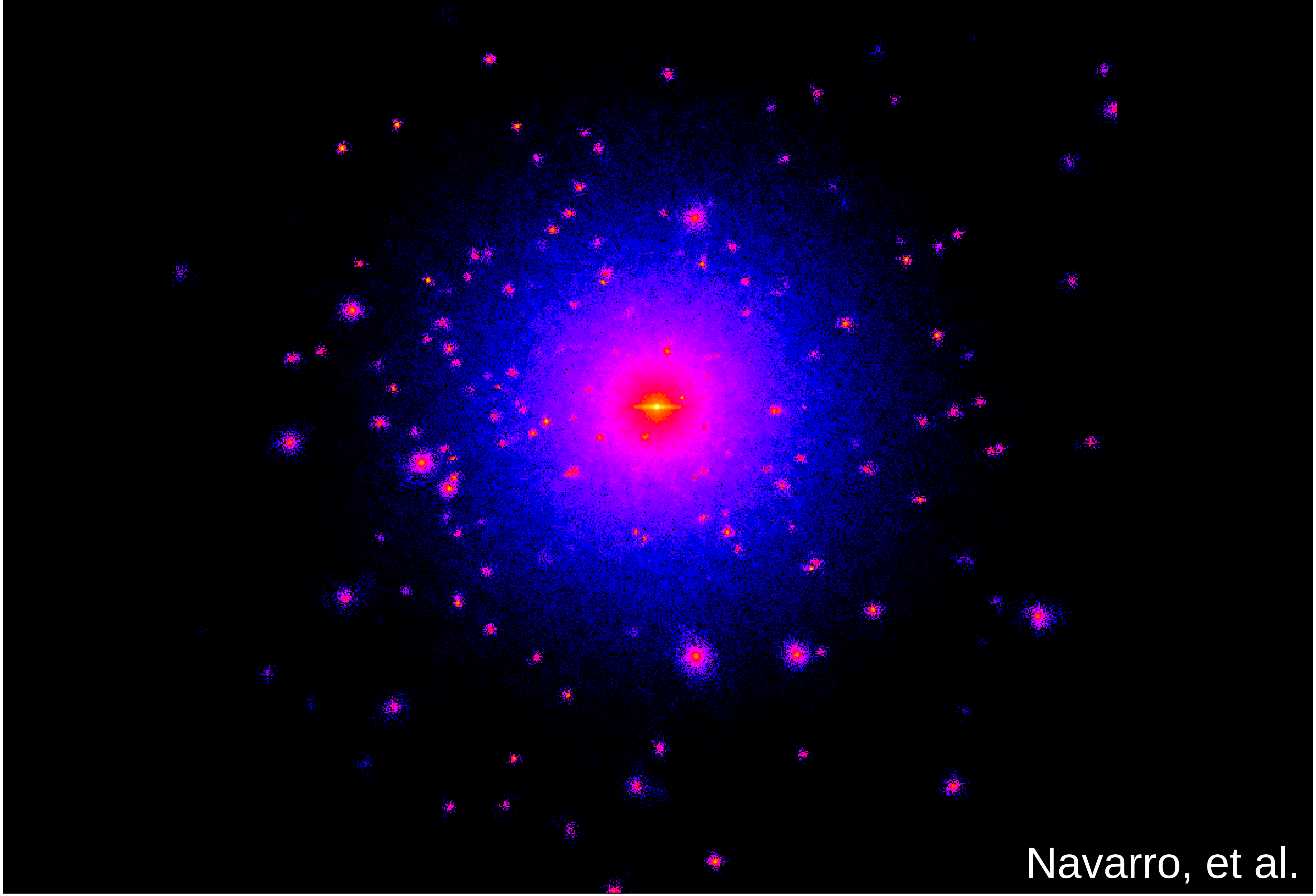
Sofue & Rubin



Einstein Ring
Source
Lens
Observer

The Dark Universe

The Dark Universe



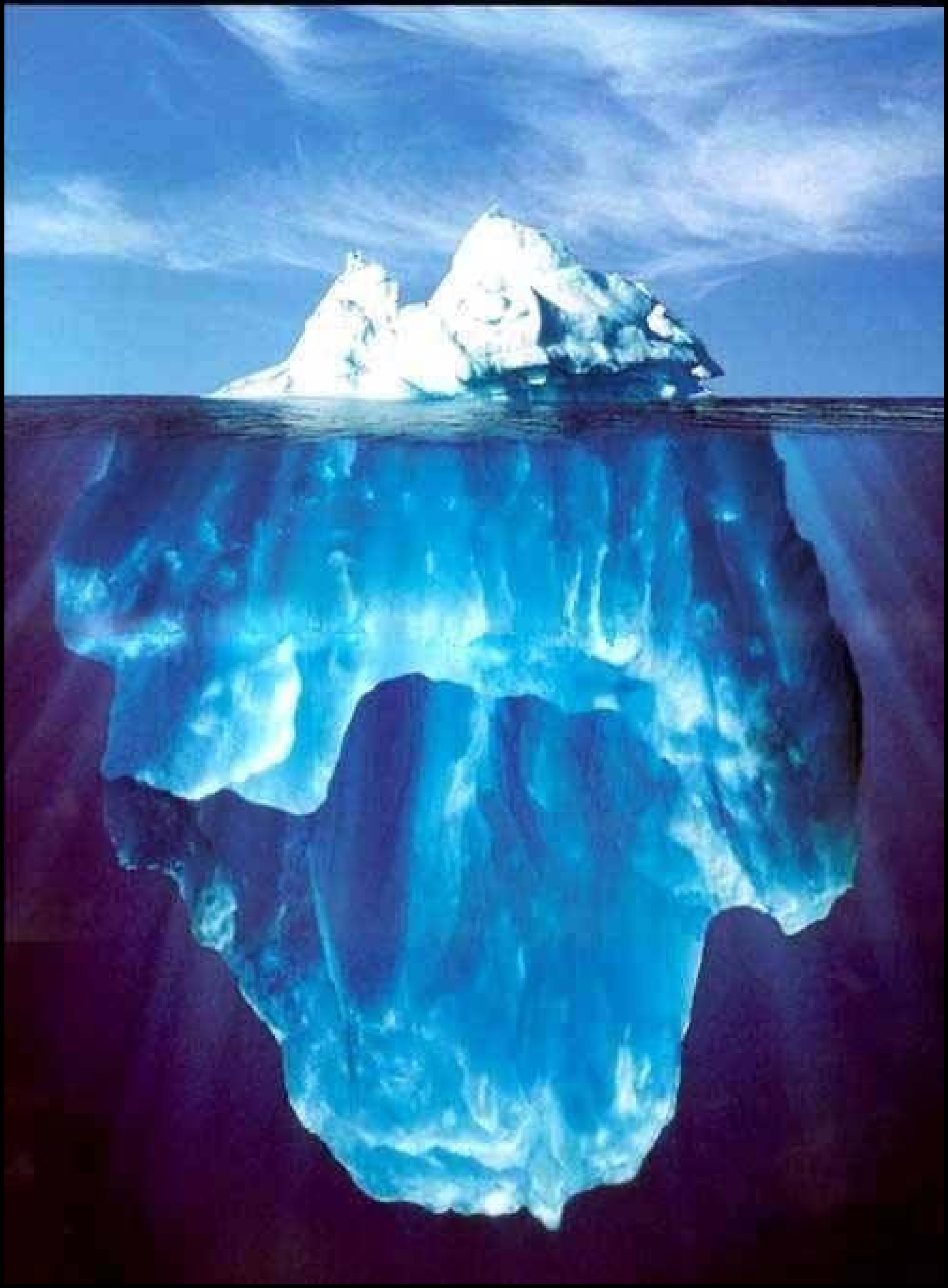
Navarro, et al.

Dark Matter

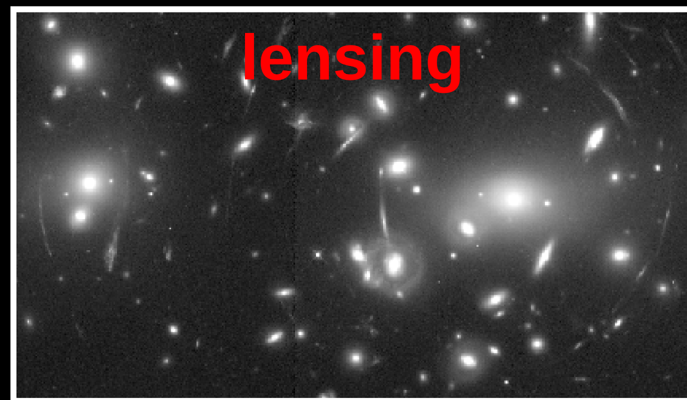
We only see the tip of the iceberg—most of the matter is dark!

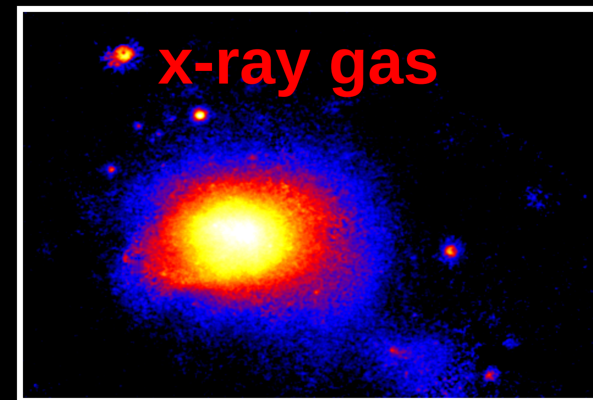
Some of the dark matter is a hot gas of hydrogen & helium

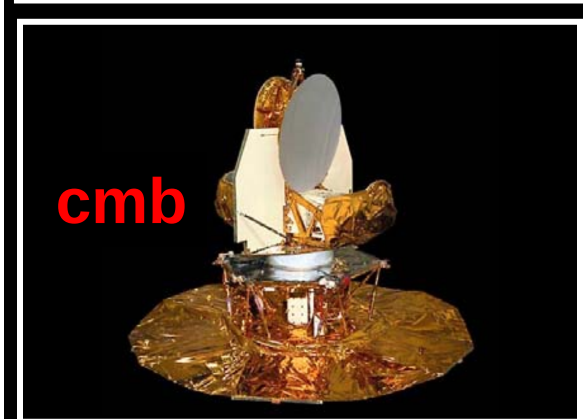
But *most* of it doesn't seem to be "normal" matter.

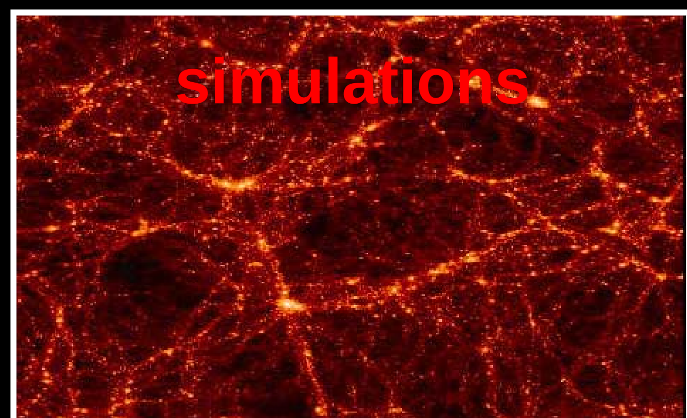


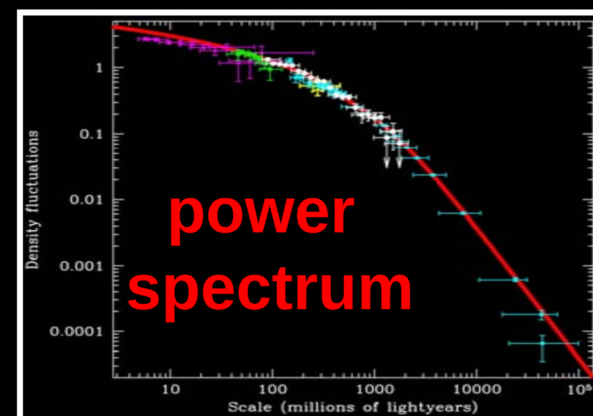
$\Omega_M \sim 0.3$



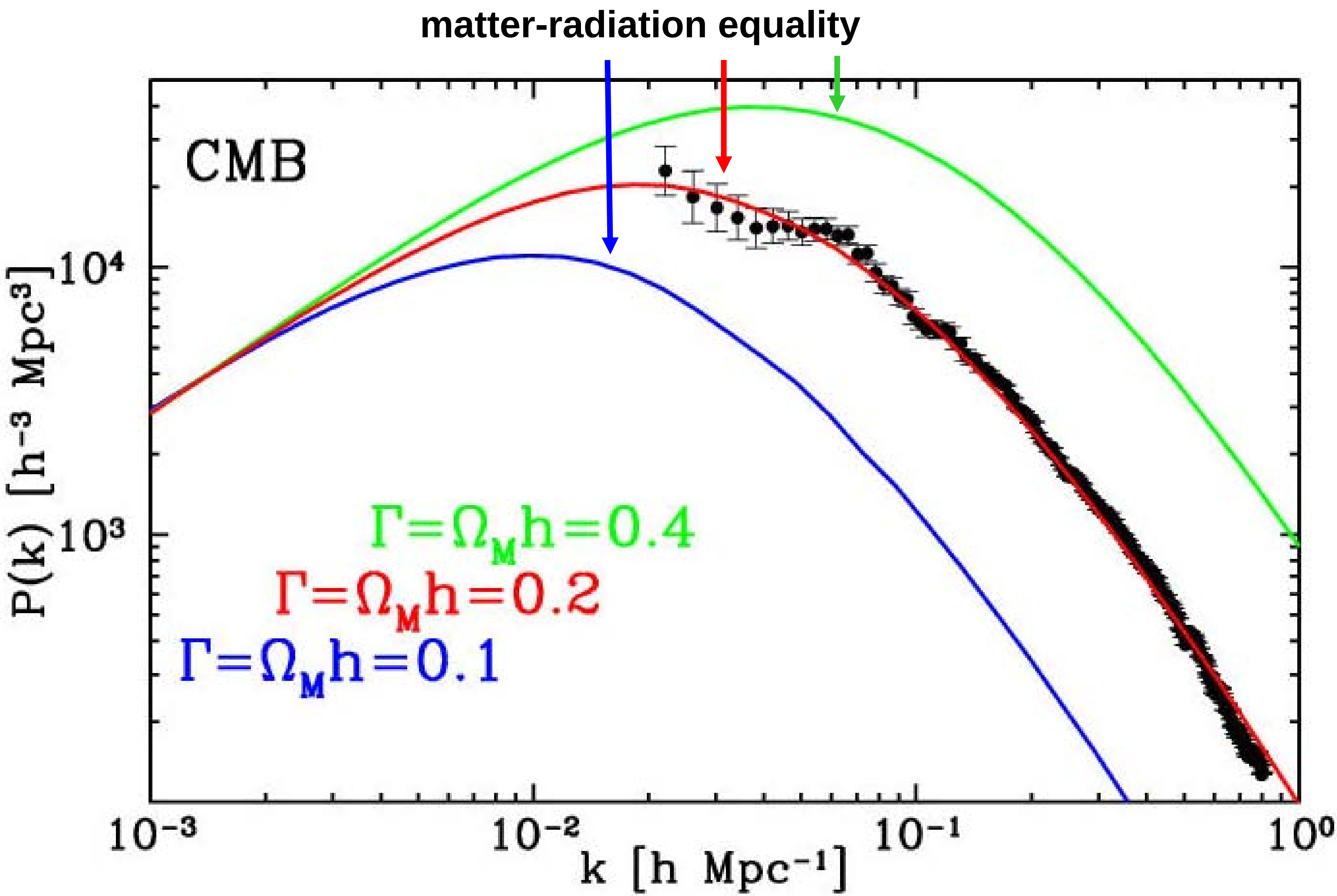




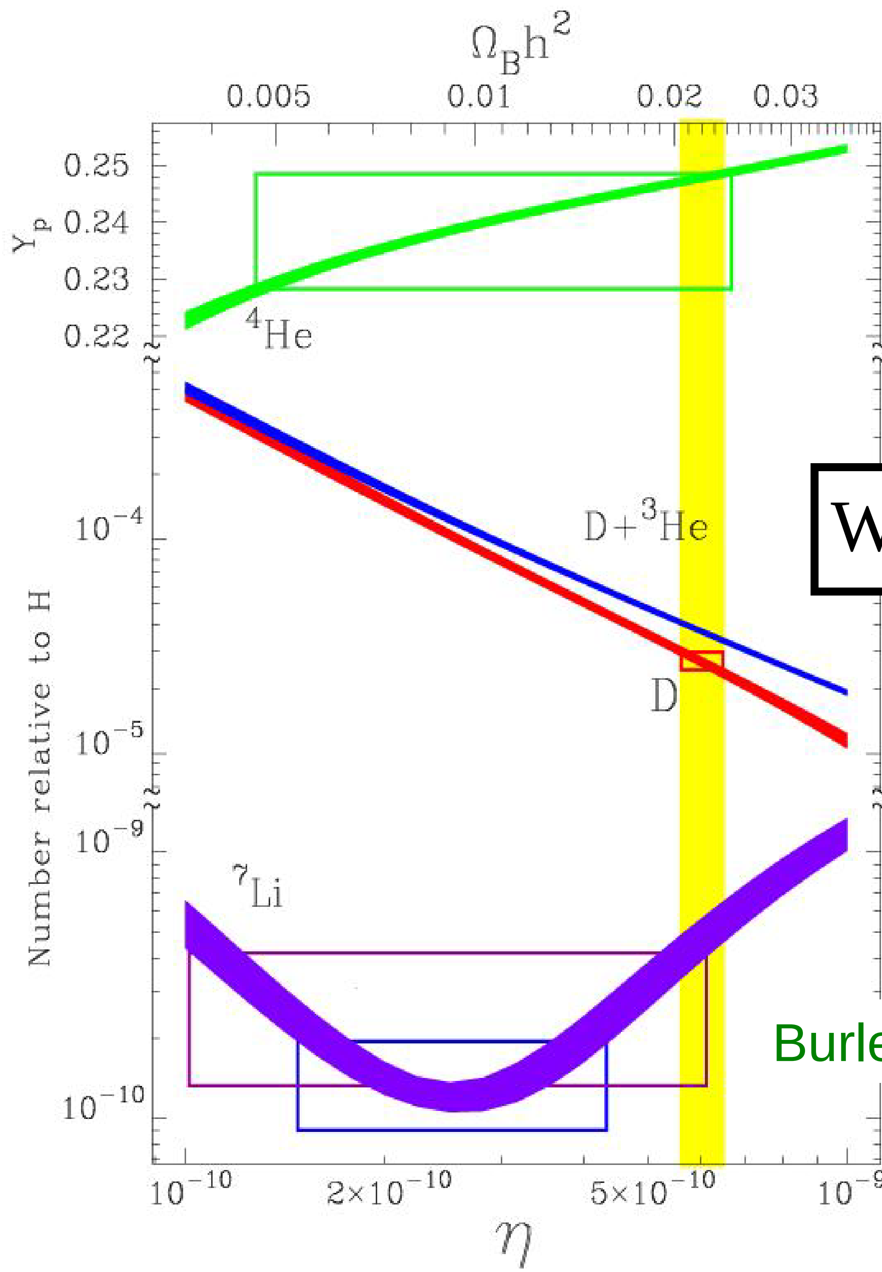




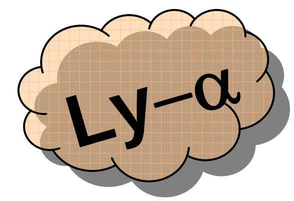
Power spectrum for CDM



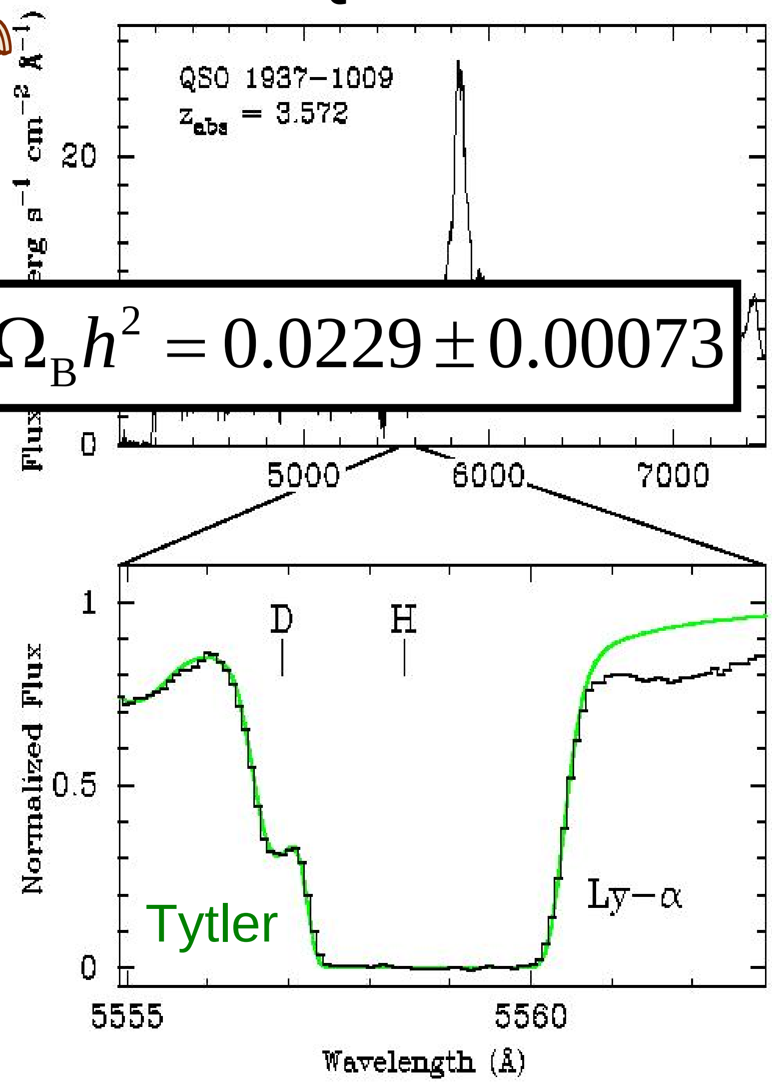
Baryons $\Omega_B h^2 \sim 0.02$



Burles et al.



QSO 1937-1009



$$\text{WMAP:}\ \ \Omega_B h^2 = 0.0229 \pm 0.00073$$

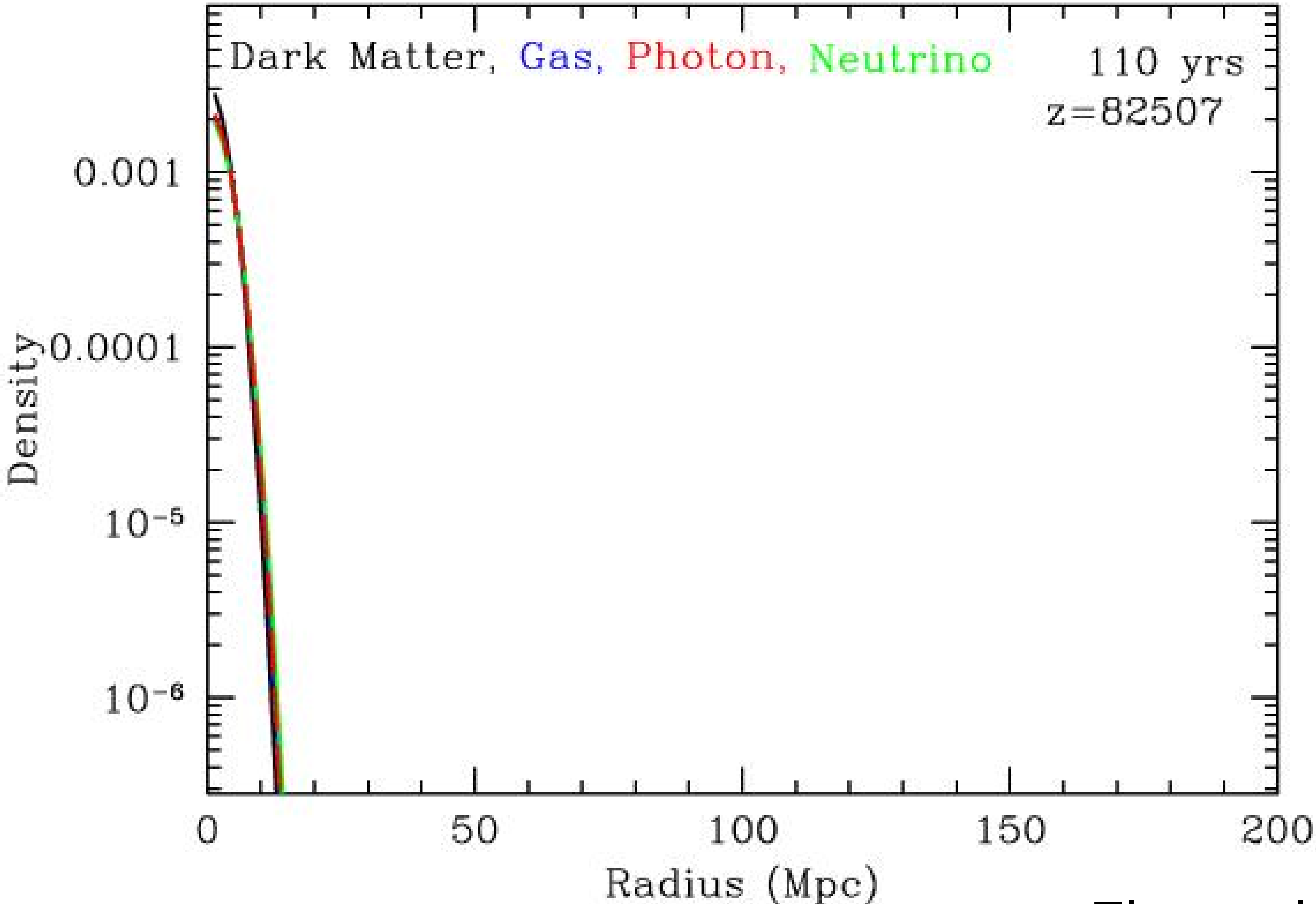
Tytler

Dissipative Processes

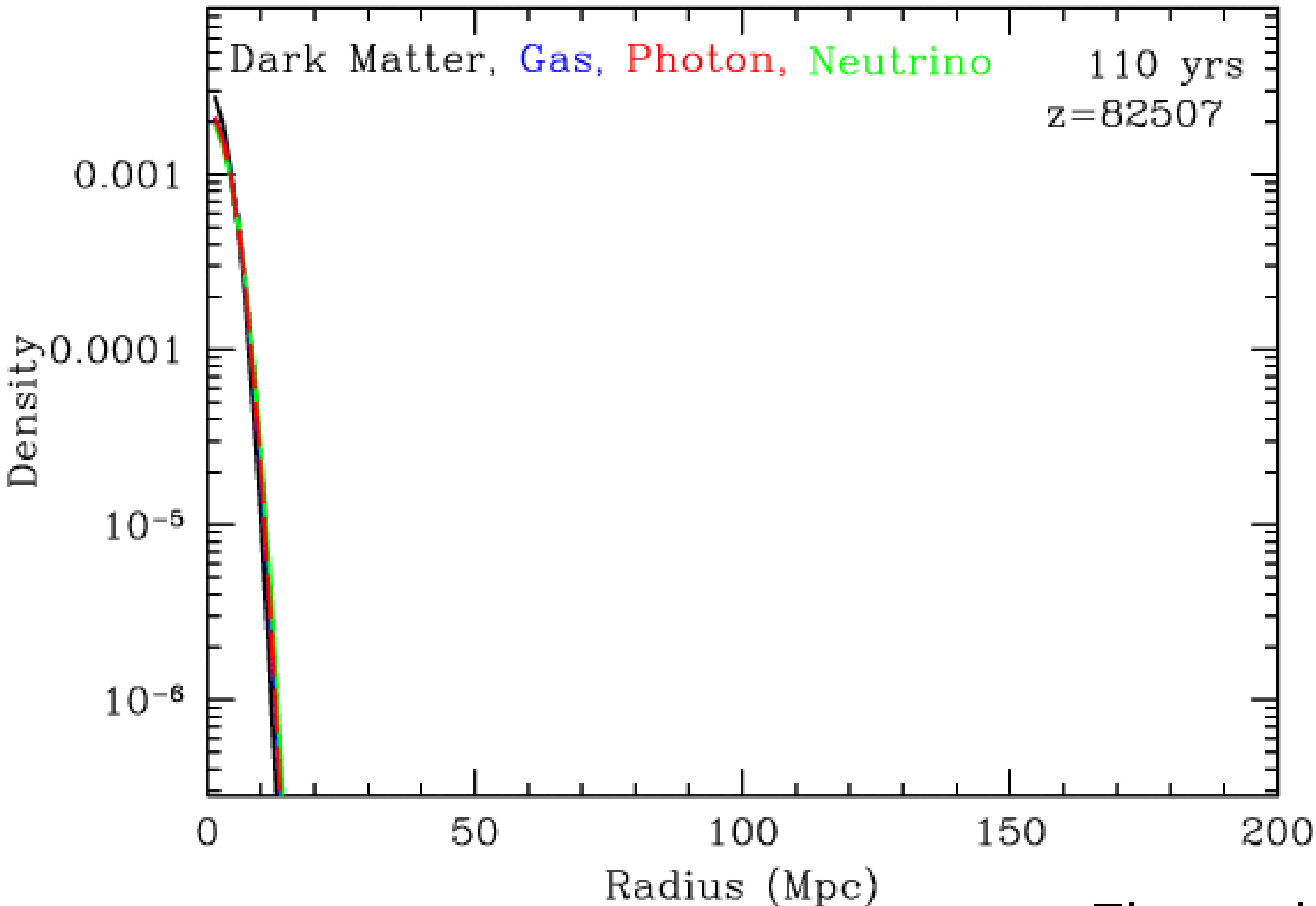
Collisional damping – Silk damping

As baryons decouple from photons, the photon mean-free path becomes large. As photons escape from dense regions, they can drag baryons along, erasing baryon perturbations on small scales.

Baryon-photon fluid suffers damped oscillations.


Dark Matter, Gas, Photon, Neutrino
110 yrs
z=82507
0.001
0.0001
10^{-5}
10^{-6}
Density
0
50
100
150
200
Radius (Mpc)

Eisenstein



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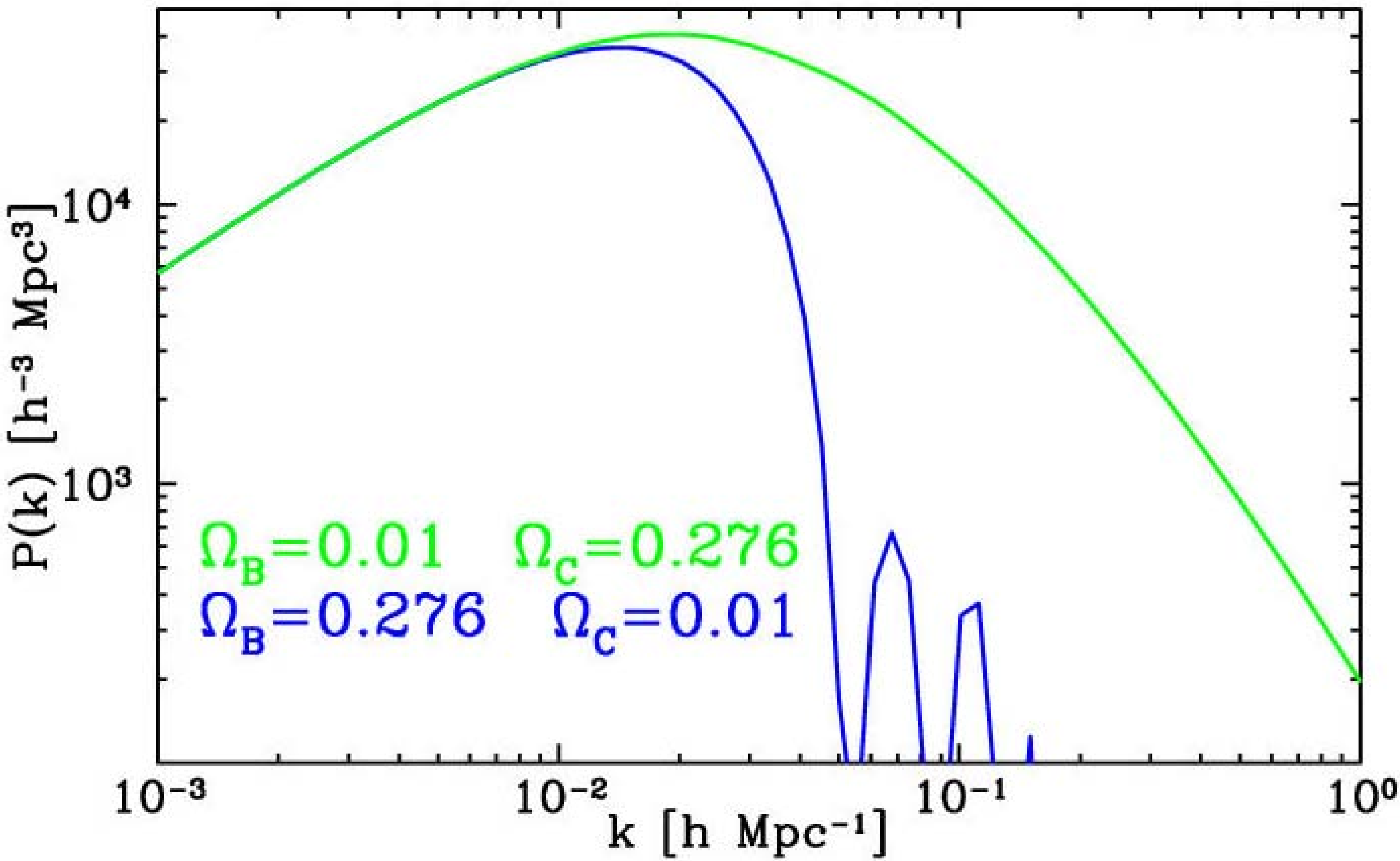
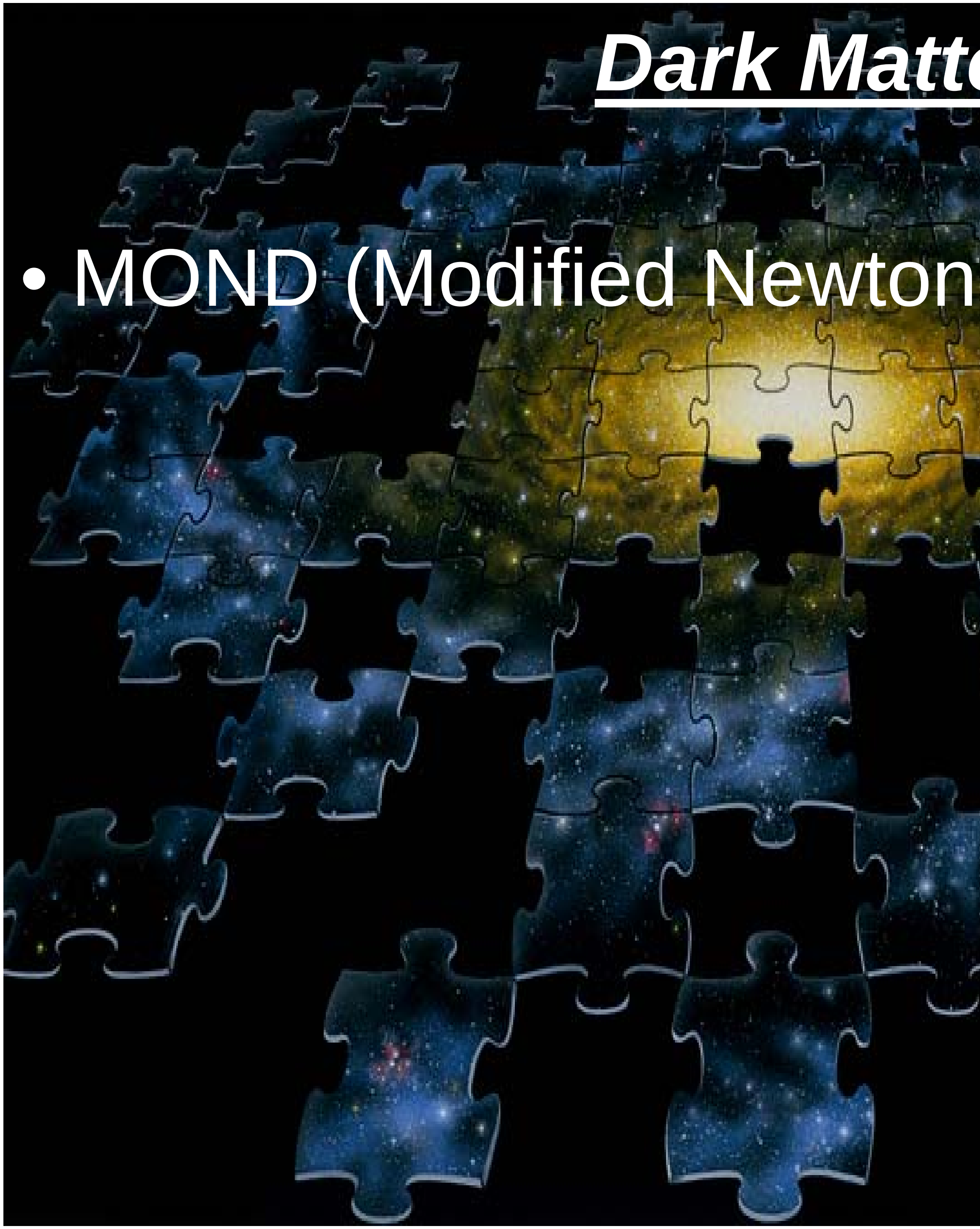
Eisenstein

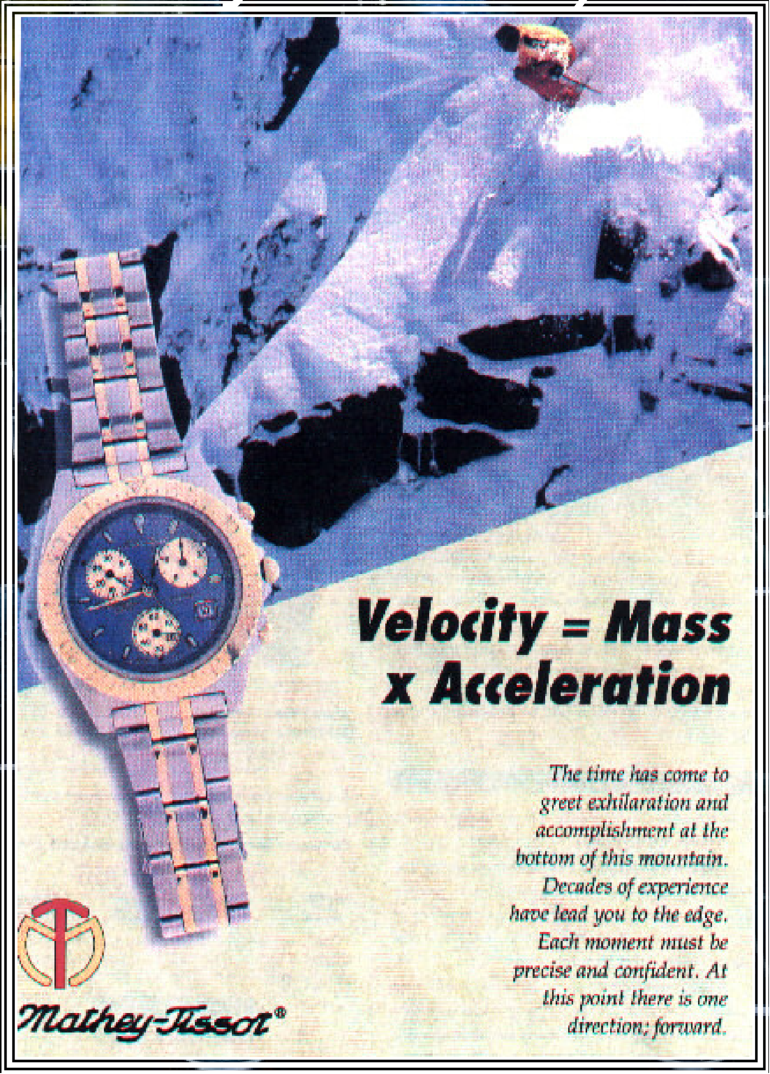
The Evolved Spectrum



Dark Matter

- MOND (Modified Newtonian Dynamics)





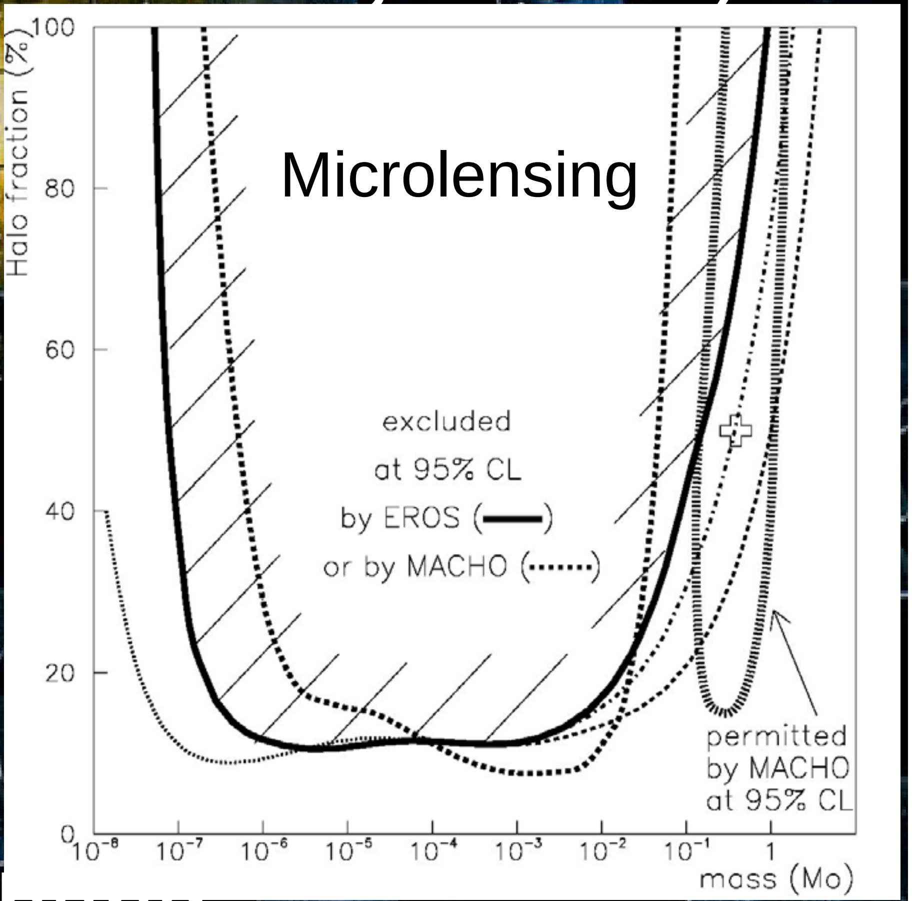
Dark Matter

- MOND (Modified Newtonian Dynamics)

The Bullet Cluster

Dark Matter

- MOND (Modified Newtonian Dynamics)
- Planets
- Dwarf stars
  Size challenged stars
  brown red white
- Black holes
- Particle relic from the bang



Particle Relic From The Bang

- **neutrinos** **(hot dark matter)**
- **sterile neutrinos, gravitinos** **(warm dark matter)**
- **LSP (neutralino, axino, …)** **(cold dark matter)**
- **LKP (lightest Kaluza-Klein particle)**
- **axions, axion clusters**
- **solitons (Q-balls; B-balls; Odd-balls, ….)**
- **supermassive wimpzillas**

<u>Mass range</u>

$10^{-6}\,\mathrm{eV}\ \ (10^{-40}\,\mathrm{g})$ axions

$10^{-8}\,M_{\odot}\ \ (10^{25}\,\mathrm{g})$ axion clusters

<u>Interaction strength range</u>

Noninteracting: wimpzillas

Strongly interacting: B balls

Volume 207, number 1 PHYSICS LETTERS B 9 June 1988

NEUTRINO MASS AND MIXING
IMPLIED BY UNDERGROUND DEFICIT OF LOW ENERGY MUON-NEUTRINO EVENTS

John G. LEARNED, Sandip PAKVASA, and Thomas J. WEILER [1]
Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822, USA

Received 14 March 1988

Recent observations of a deficit of cosmic ray muon-neutrino interactions in underground detectors suggest that the muon neutrinos may have oscillated to another state. We examine possible neutrino mass and mixing patterns, and their implications for vacuum and matter effects on solar neutrinos, on neutrinos passing through the earth, and on terrastrial neutrino beams. By invoking the see-saw mechanism of neutrino mass generation, we draw inferences on closure of the universe with neutrino masses, on the number of generations, on t-quark and fourth generation masses, and on the Peccei–Quinn symmetry breaking scale. Testable predictions are suggested.

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(8)

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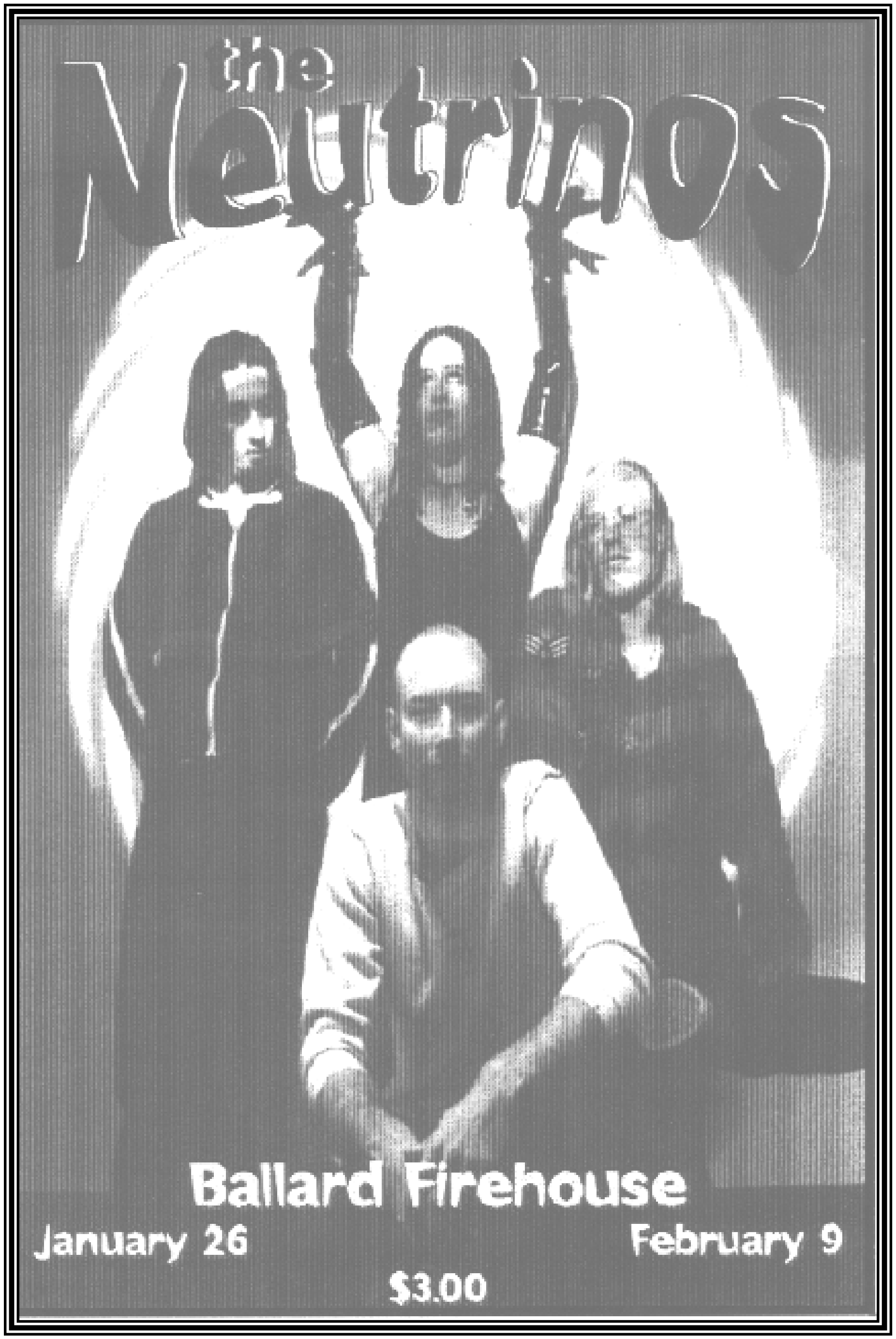
as much as 50%. (b) Atmospheric electron-neutrinos and muon-neutrinos (not antineutrinos) coming through the earth at $E_\nu \sim 50-150$ GeV have matter-enhanced oscillations and the muon-neutrinos down/up flux ratio should be even larger than the nonmatter-enhanced expectation (for energies ~ 1

(d) Relic tau neutrinos have sufficient energy density to close the university [11] (thus favoring hot

(d) Relic tau neutrinos have sufficient energy density to close the university [11] (thus favoring hot dark matter over cold): the tau-neutrino mass may be determined from the time spread of events from a galactic supernova. (e) There are only three generations: the mass of a fourth-generation heavy lepton is bounded from below by the UA1 data [12] and from

Neutrinos

- Neutrinos exist:
  three active + sterile?
- Neutrinos have mass:
  Atmospheric (10^{-2} eV)
  Solar (10^{-3} eV)
- Contribute to Ω
  hot thermal relic:
  $$\Omega_{\nu\bar{\nu}} h^2 \simeq \frac{m_\nu}{93\ \mathrm{eV}}$$
- Not most of dark matter
  too light!
  too hot!

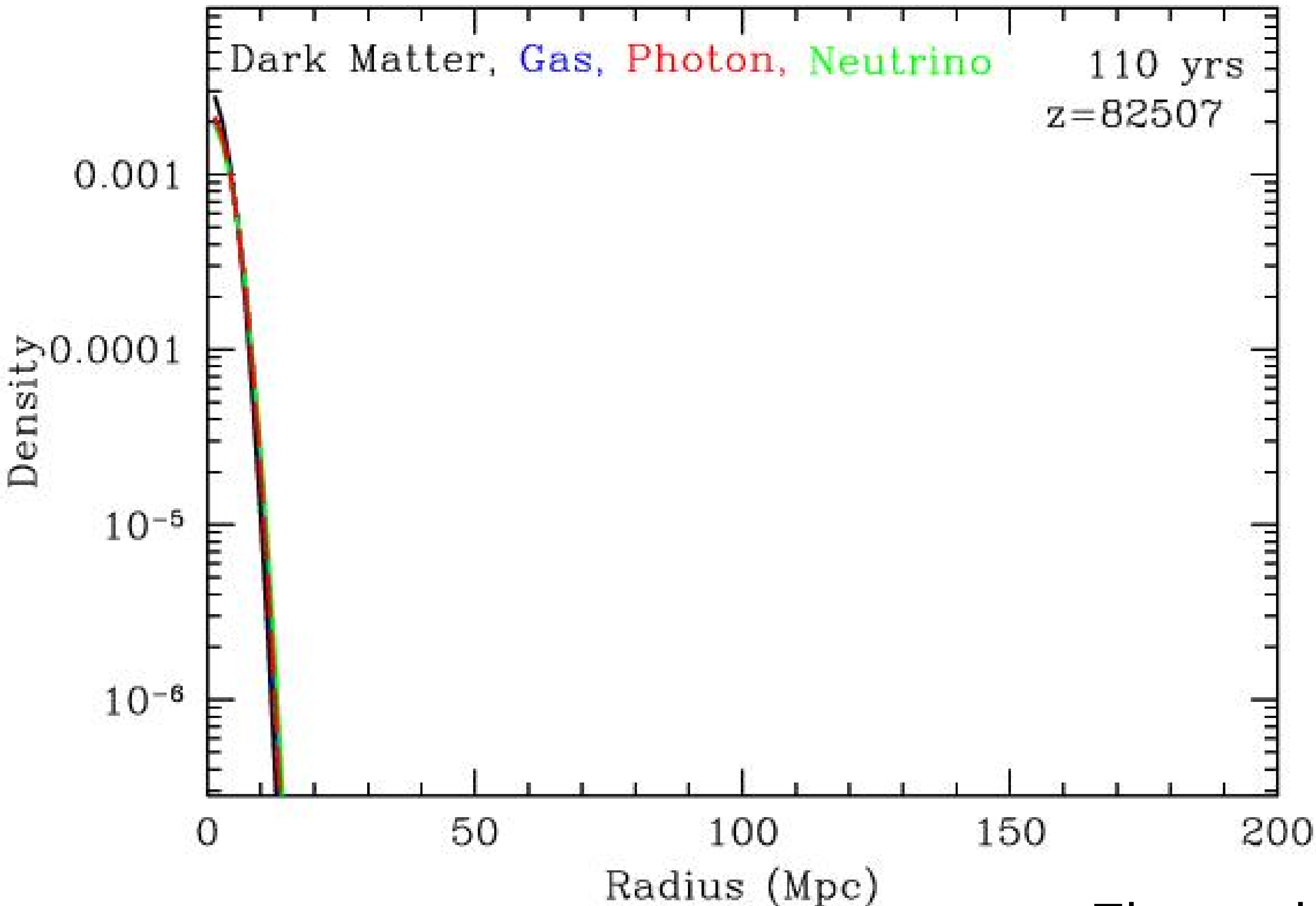


Dissipative Processes

Collisionless phase mixing – free streaming

If dark matter is relativistic or semi-relativistic particles can stream out of overdense regions and smooth out inhomogeneities. The faster the particle the longer its free-streaming length.

Quintessential example: eV-range neutrinos



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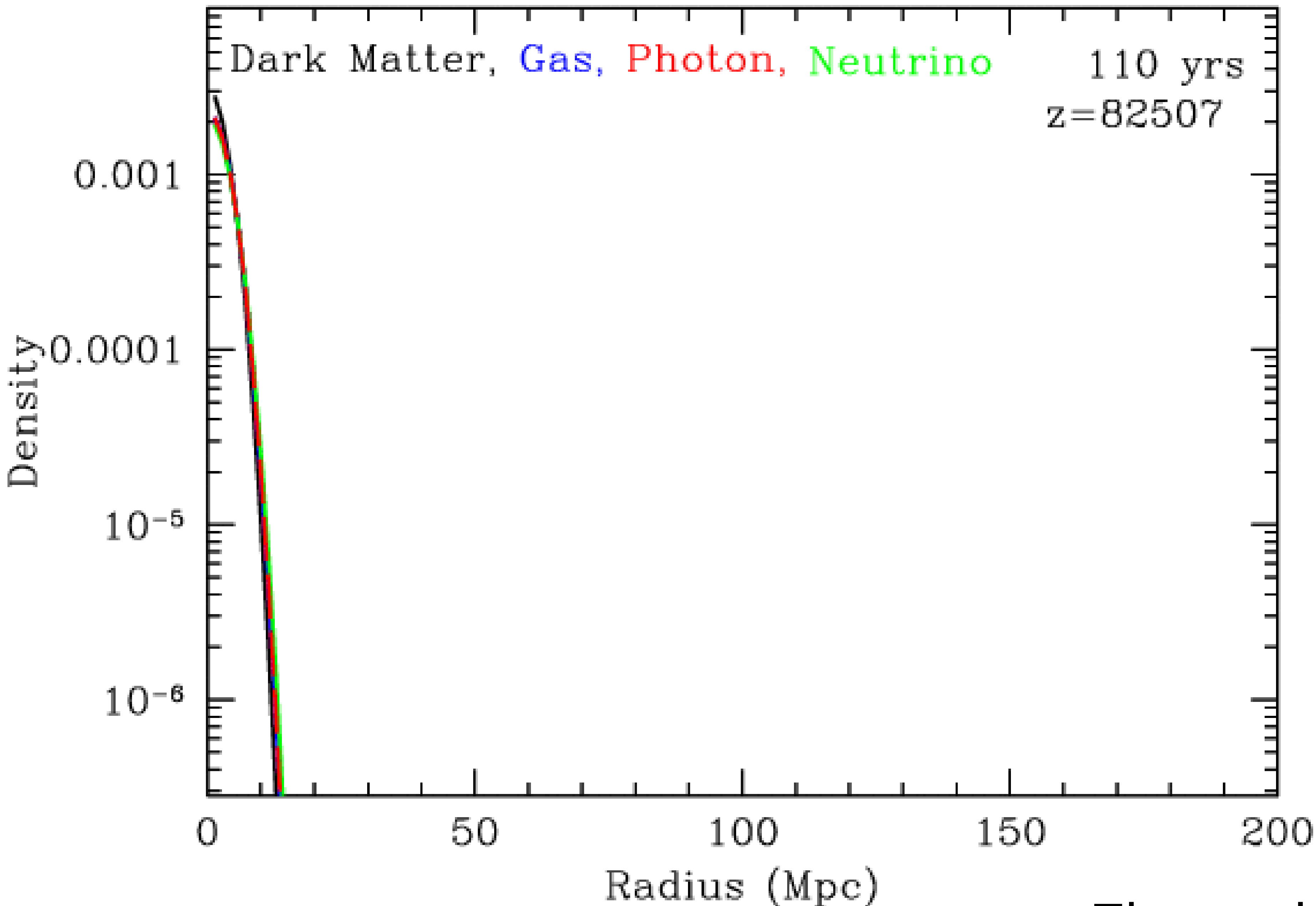
Eisenstein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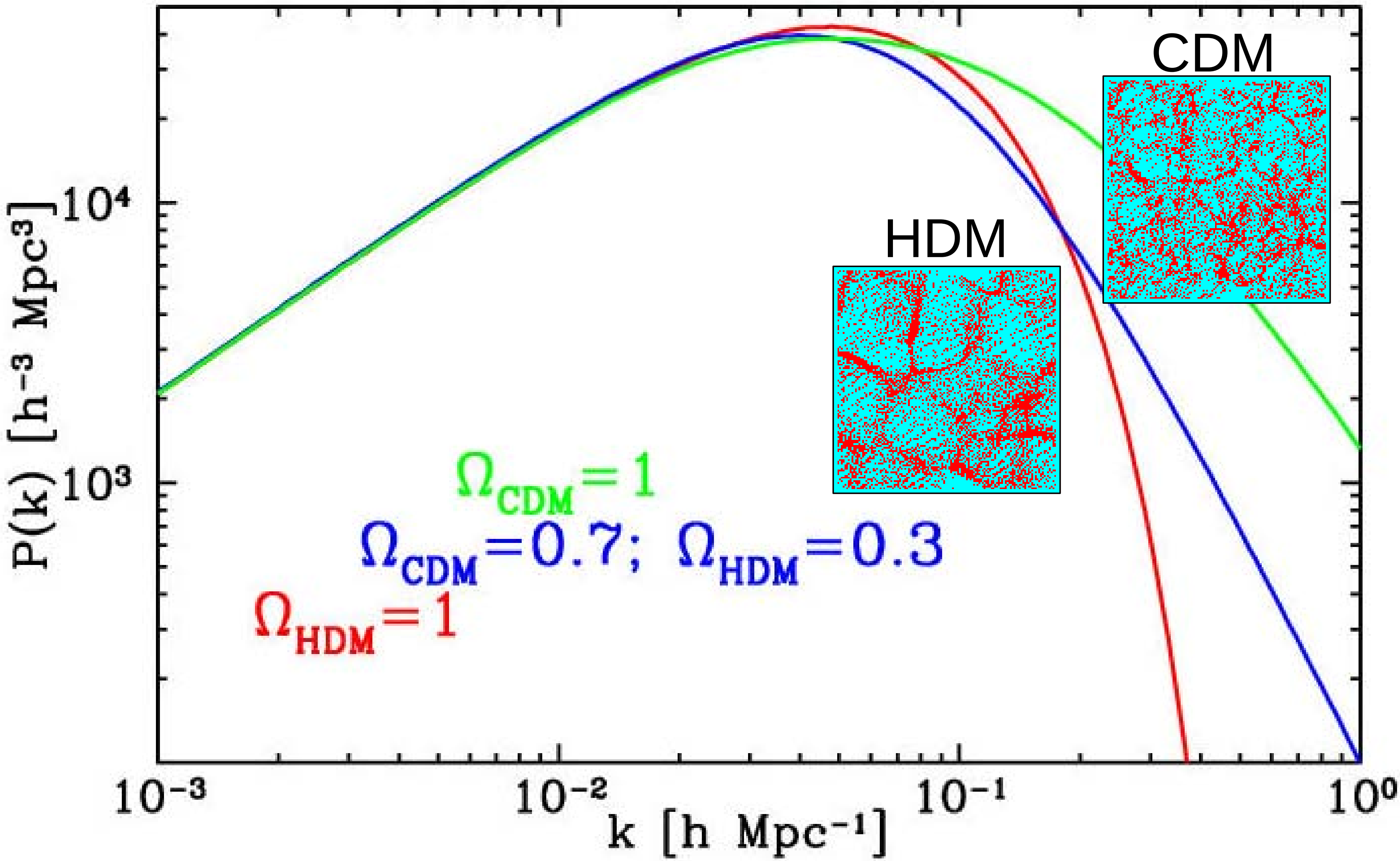
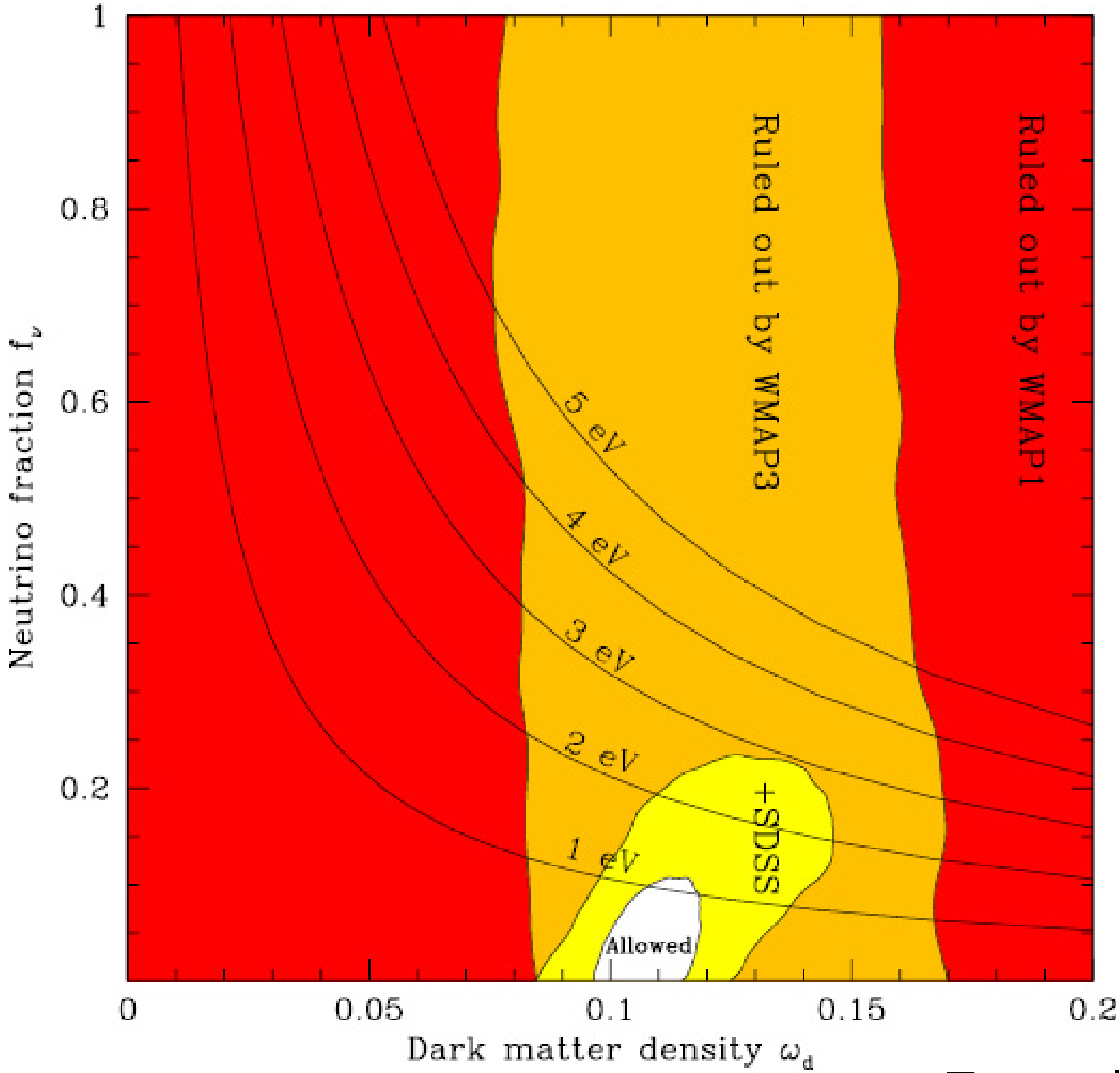
Collisionless damping

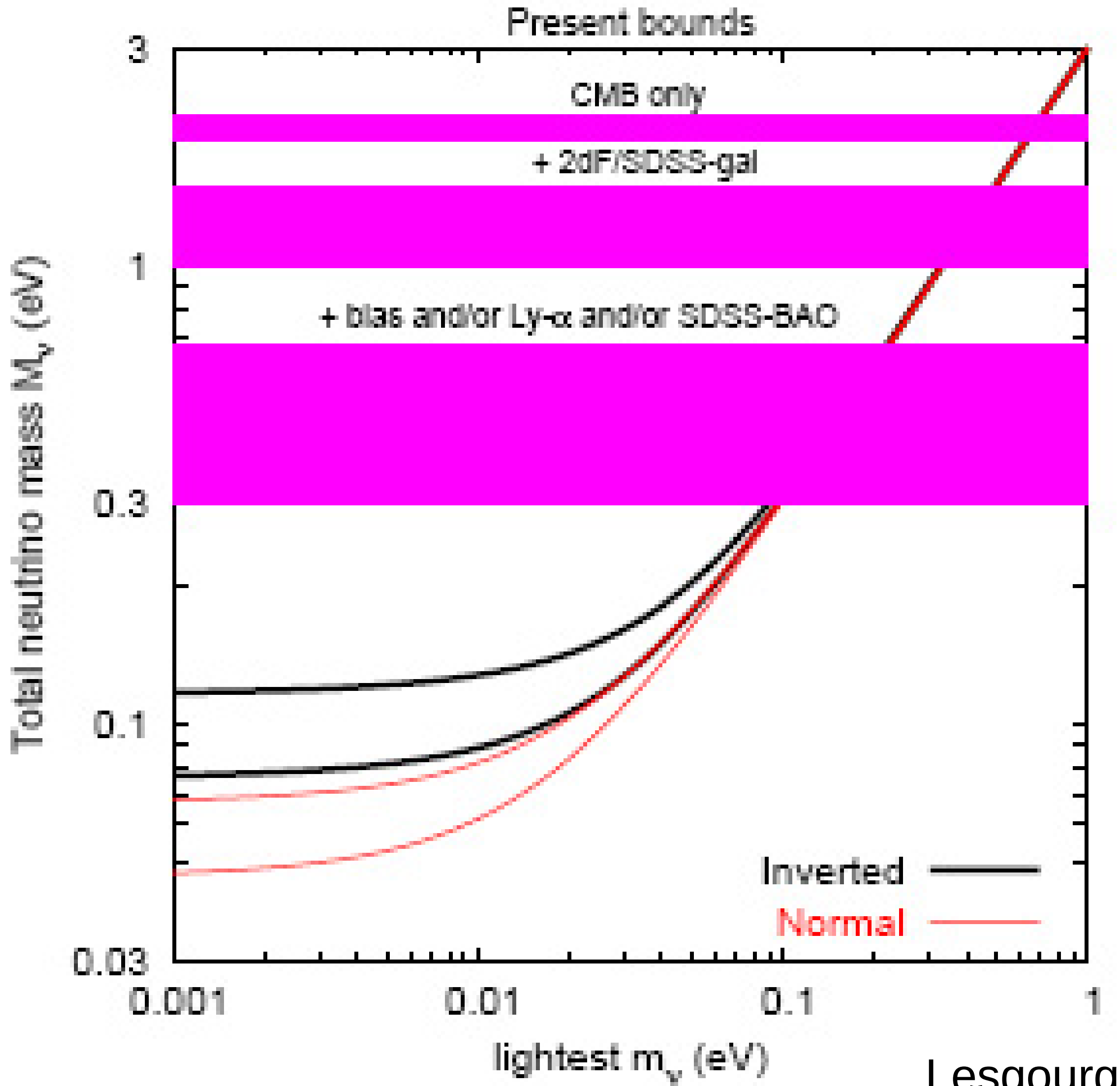


WMAP + LSS



Tegmark et al., SDSS

WMAP + LSS



Lesgourgues & Pastor

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Interaction strength range

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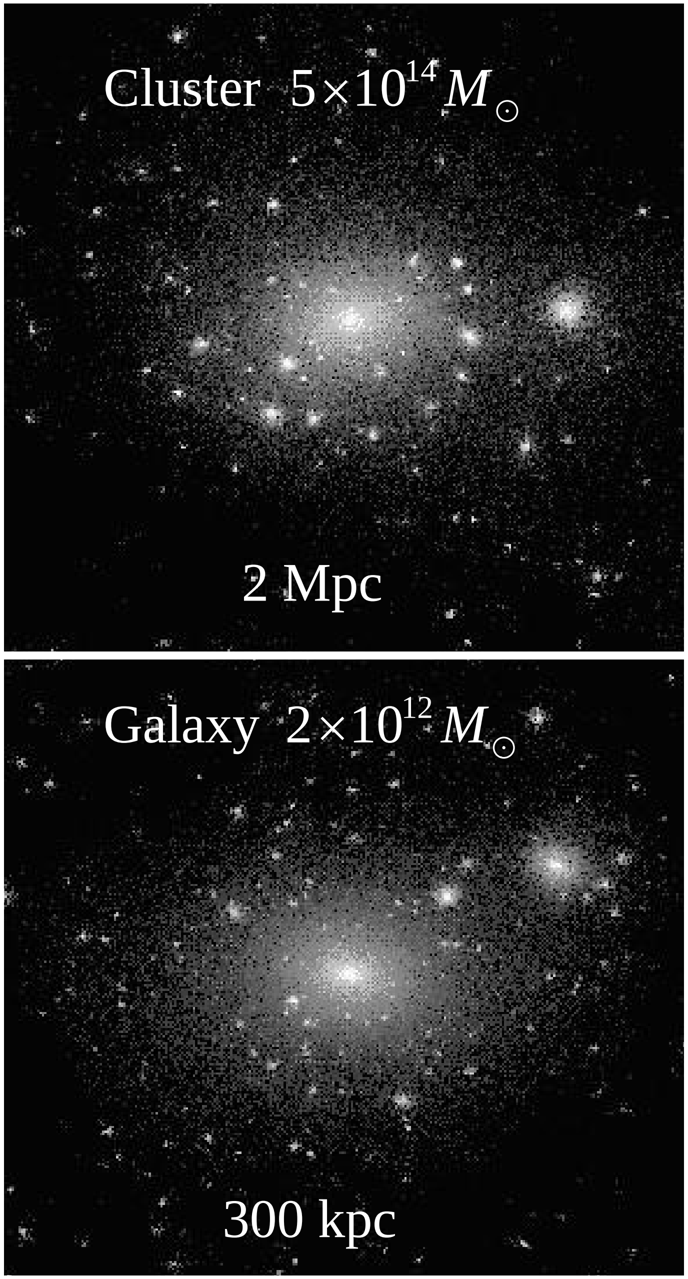
Strongly interacting: B balls

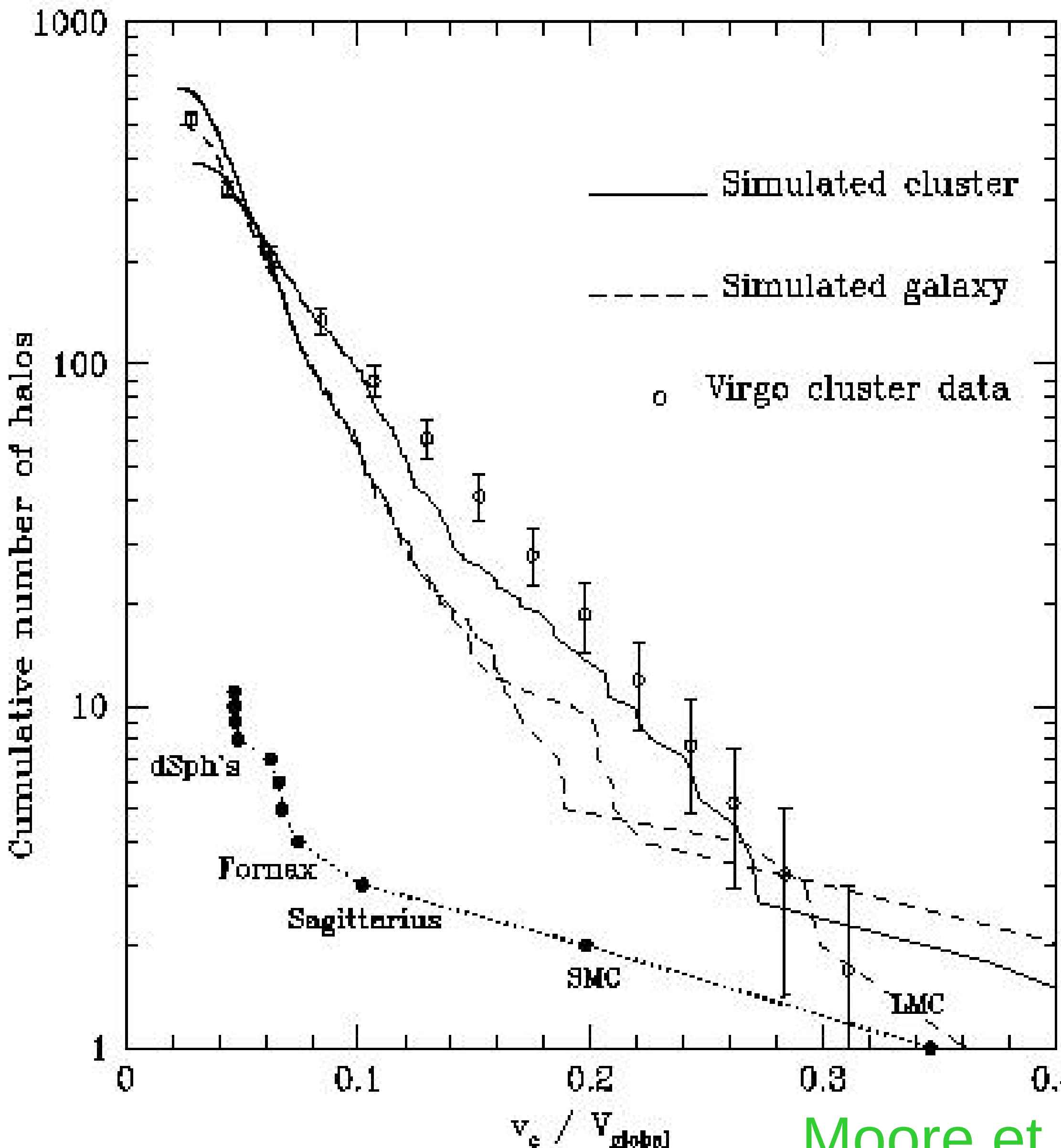
Sterile Neutrinos & Gravitinos

- weaker interactions
- decouple earlier
- diluted more
- can have larger mass
- smaller velocity
- “warm”
- satellite & cusp problem?

Particle models with sterile neutrinos or gravitinos in desired mass range are “unfashionable.”

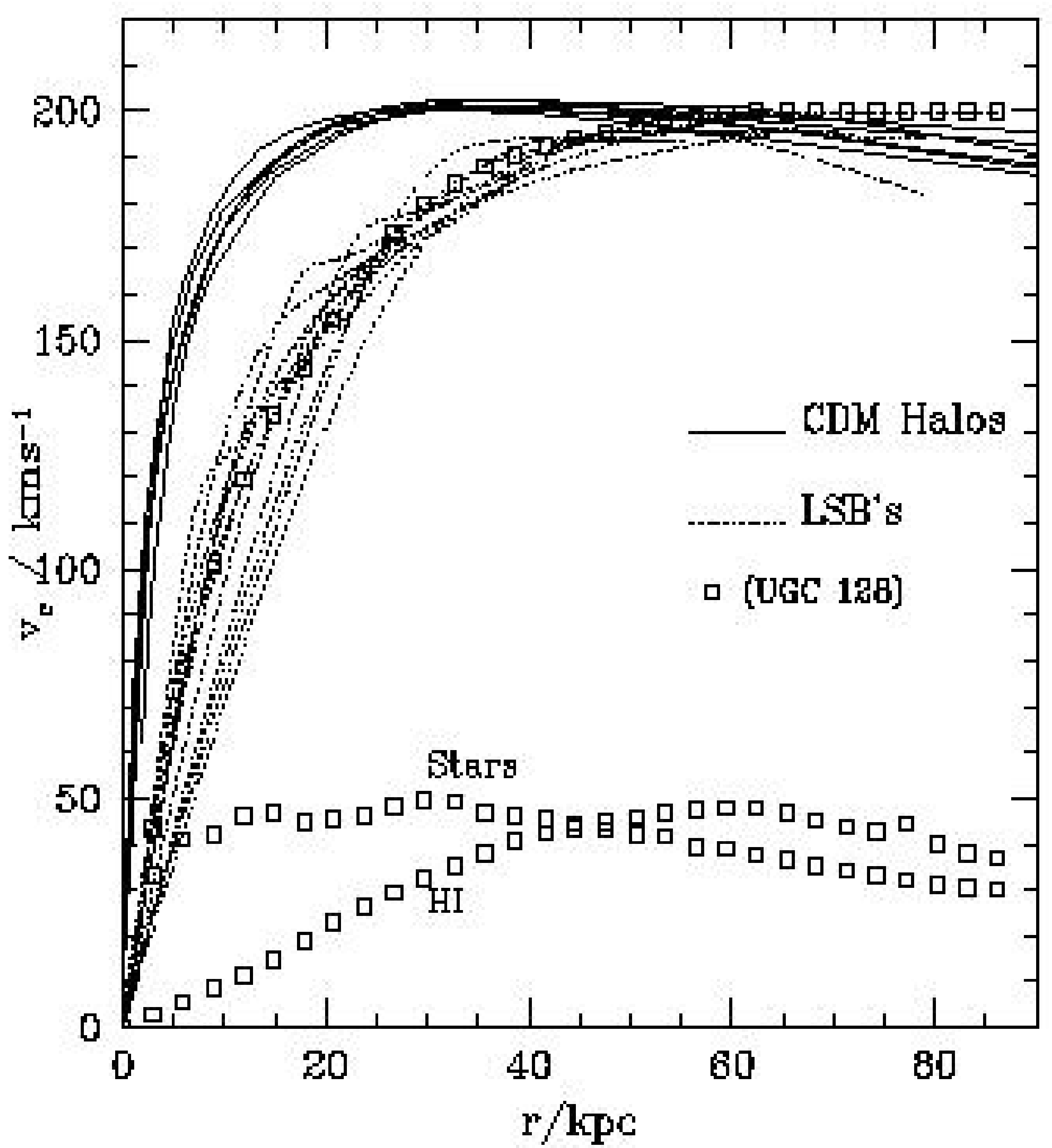
Small-Scale Structure





Moore et al.

Small-Scale Structure



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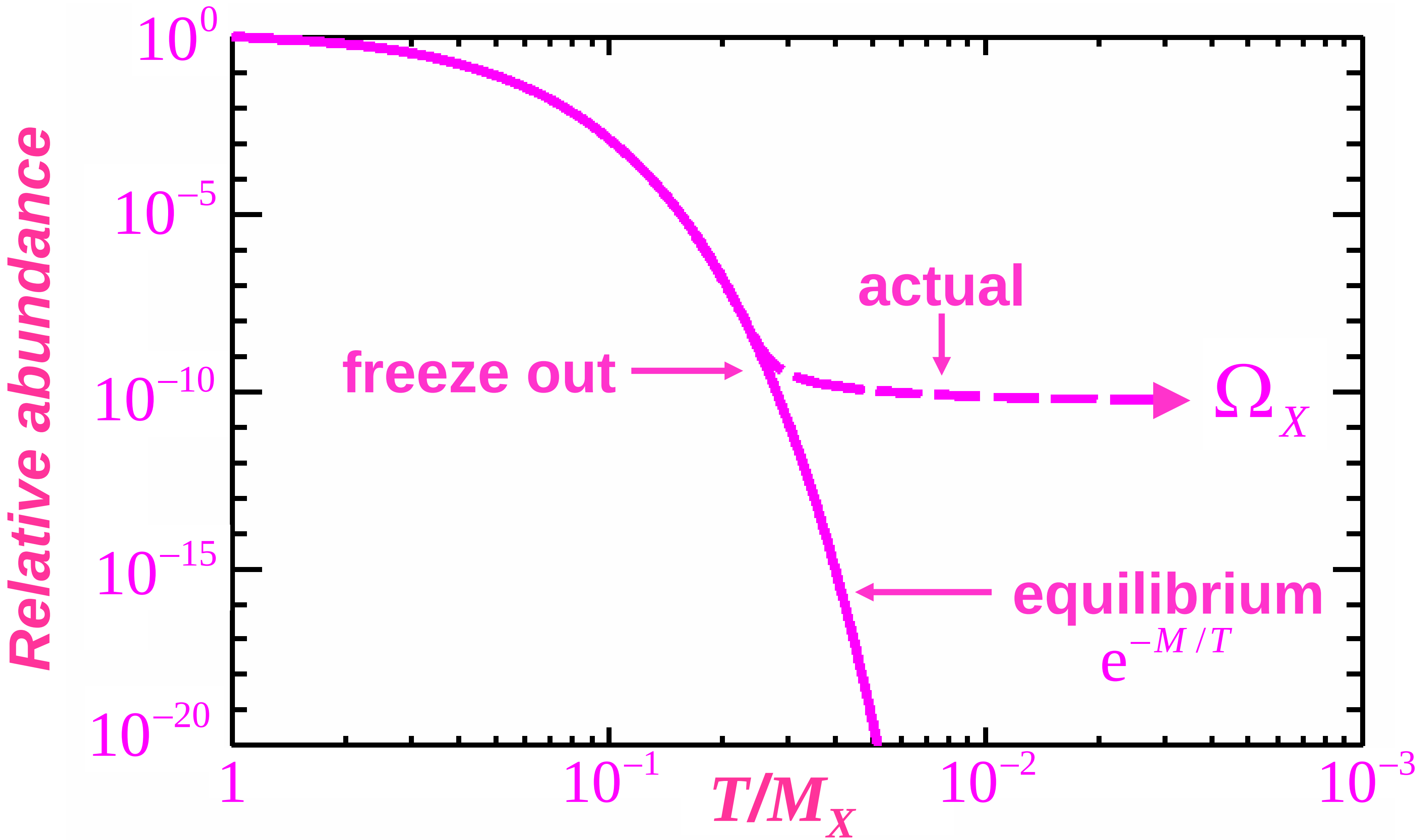
Cold Thermal Relics*

- Particle is stable (or at least has a lifetime greater than t_0)
- There is no associated chemical potential (no asymmetry)
- Particle is in LTE at temperatures greater than its mass
- Particle remains in LTE until $M < T$ (cold)
- Particle annihilates with thermal-average cross section

$$\langle \sigma \mathrm{v} \rangle = \sigma_0 \, (T/M)^n$$

*** An object of particular veneration.**

Cold Thermal Relics*



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$$\langle \sigma \mathrm{v} \rangle = \sigma_0 \, (T/M)^n$$

- Freeze-out at $M/T_F \simeq (n+1)\ln\left(M M_{Pl}\sigma_0\right)$
- Freeze-out abundance relative to entropy density (or γ density)

$$\frac{n_X}{s} \simeq \frac{\left(M/T_F\right)^{n+1}}{M M_{Pl}\sigma_0}$$

- Contributing $\Omega \propto M \dfrac{n_X}{s} \propto \sigma_0^{-1}$

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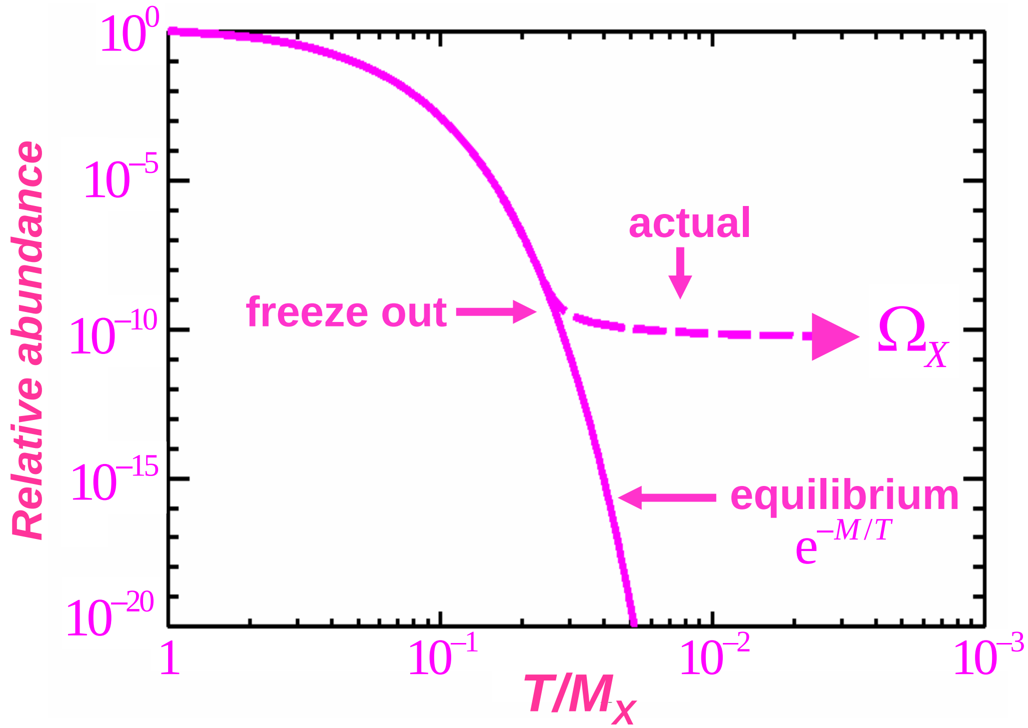
Cold Thermal Relics*



Not quite so clean:

- s-wave or p-wave?
- annihilation or scattering cross section?
- co-annihilation?
- sub-leading dependence on mass, g_*, etc.

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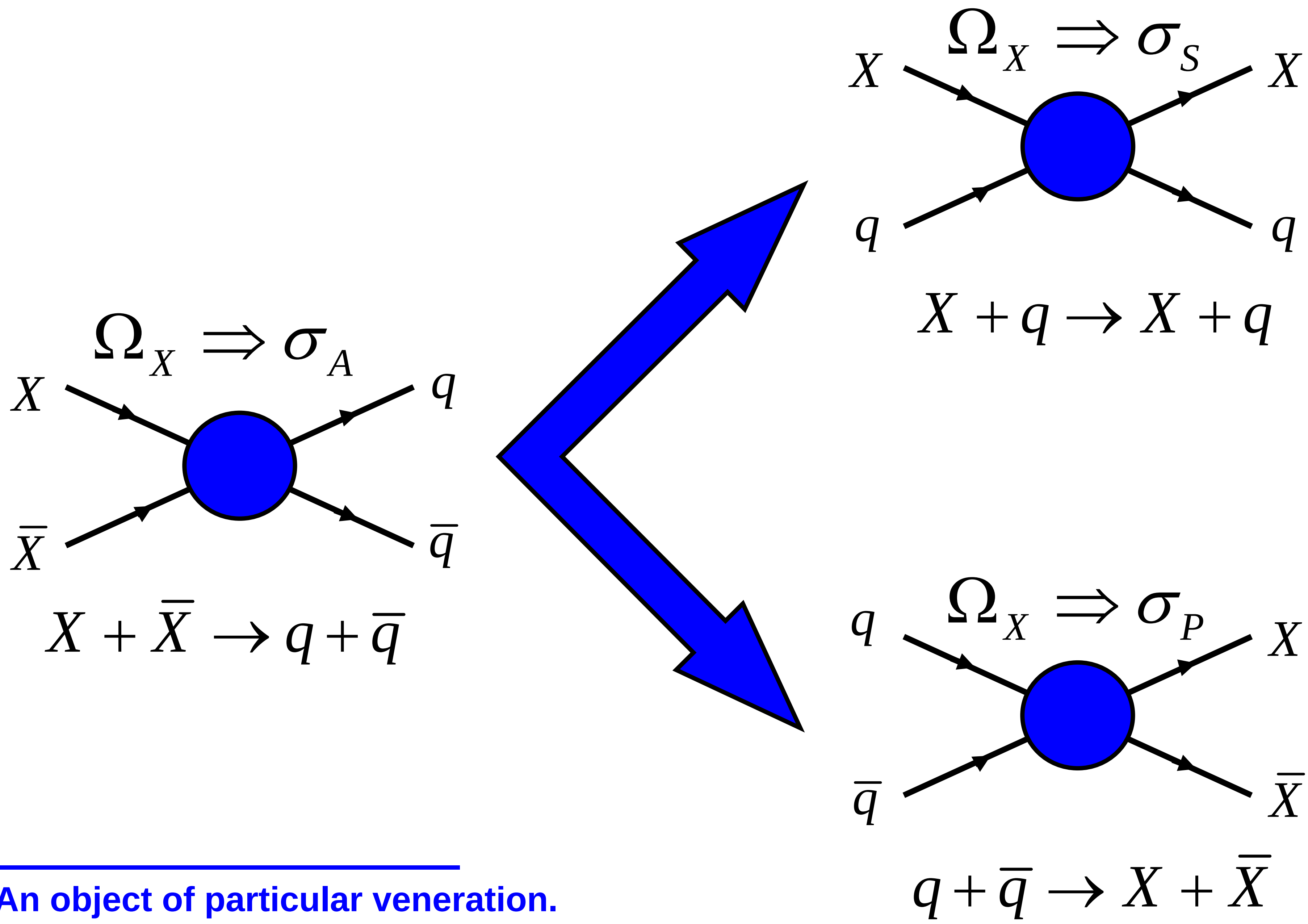
Cold Thermal Relics*



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* An object of particular veneration.

Cold Thermal Relics*

- Direct detection (σ_S)

  More than a dozen experiments

- Indirect detection (σ_A)

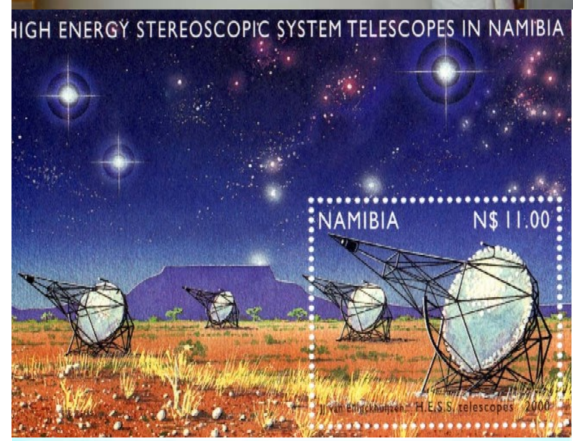
  Annihilation in sun, Earth, galaxy. . .

  neutrinos, positrons,

  antiprotons, γ rays, . . .

- Accelerator production (σ_P)

  Tevatron, LHC, …



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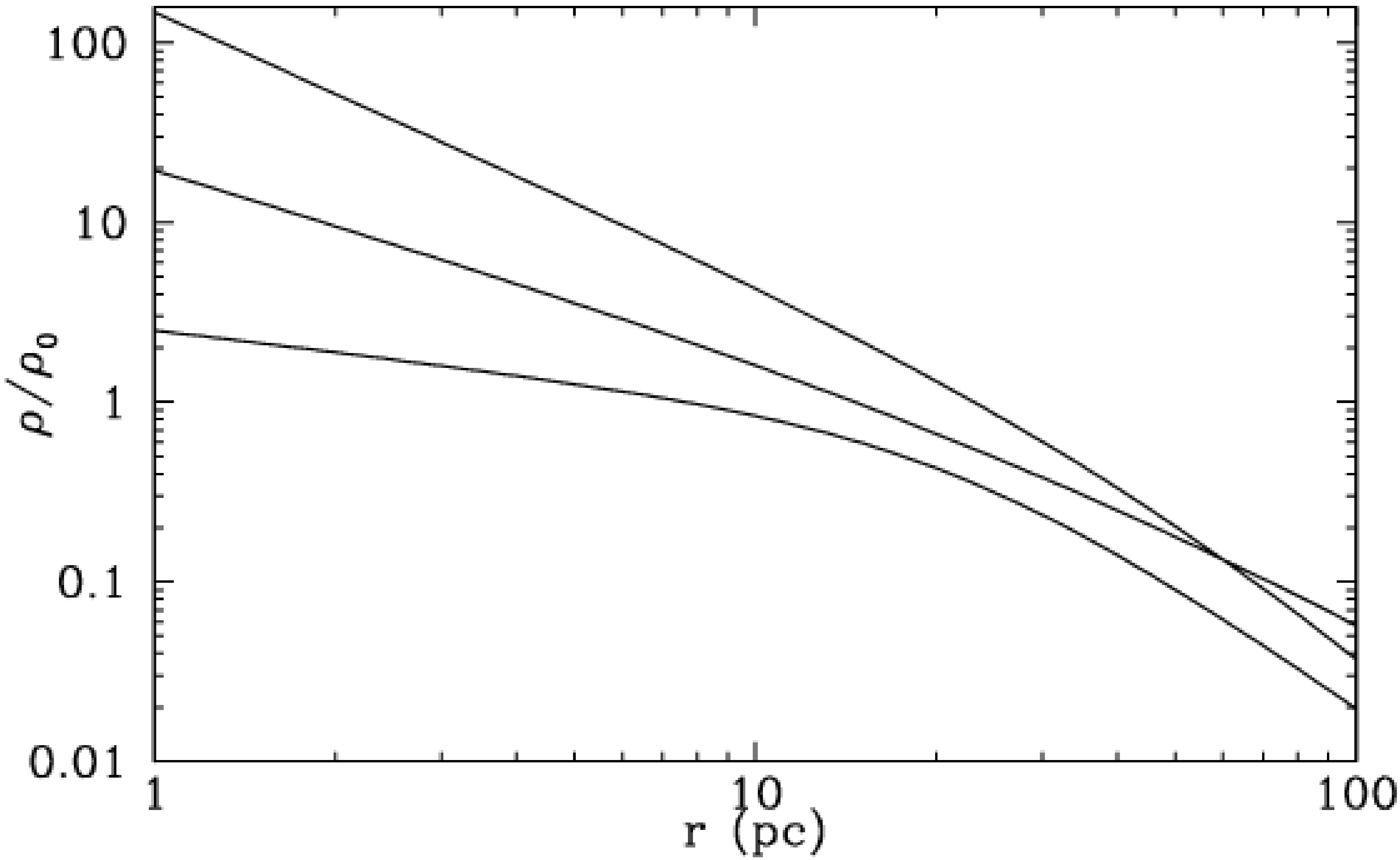
Indirect Detection

- Neutrinos from the sun or Earth
- Anomalous cosmic rays and γ rays
  from galactic halo(s)
- Neutrinos, γ rays , radio waves from
  our galactic center
- Role of halo substructure [rate $\propto$ (density)^2]

Galactic center: spike cusp, ???
Black hole in the galactic center

Small-Scale Structure



Cold Thermal Relics*

Favorite cold thermal relic: the neutralino

- Study "constrained" MSSM models
- Typical SUSY models consistent w/ collider data have too small annihilation cross section $\rightarrow$ too large Ω
- Need chicanery to increase annihilation cross section
  - s-channel resonance through light H and Z poles
  - co-annihilation with $\tilde{\tau}$ or $\tilde{t}$
  - large tanβ (s-channel annihilation via broad A resonance)
  - high values of m_0–LSP Higgsino-like & annihilates into W & Z pairs (focus point)
  - …
  - or, unconstrained

*** An object of particular veneration.**

*Cold Thermal Relics**

Favorite cold thermal relic: the neutralino

- Direct detectors, indirect detectors, & colliders race for discovery
- Suppose by 2010 have credible signals from all three???

How will we know we all seeing the same phenomenon?

- Lots of opinions (papers)
  – Will learn enough from LHC (Arnowitt & Dutta)
  – Need ILC (Baltz, Battaglia, Peskin, Wizansky)
  – Depends where in SUSY space (Chung, Everett, Kong, Matchev)
  – …
- *Let's hope for this problem!!!!*

*** An object of particular veneration.**

Cold Thermal Relics*

Favorite cold thermal relic: the neutralino

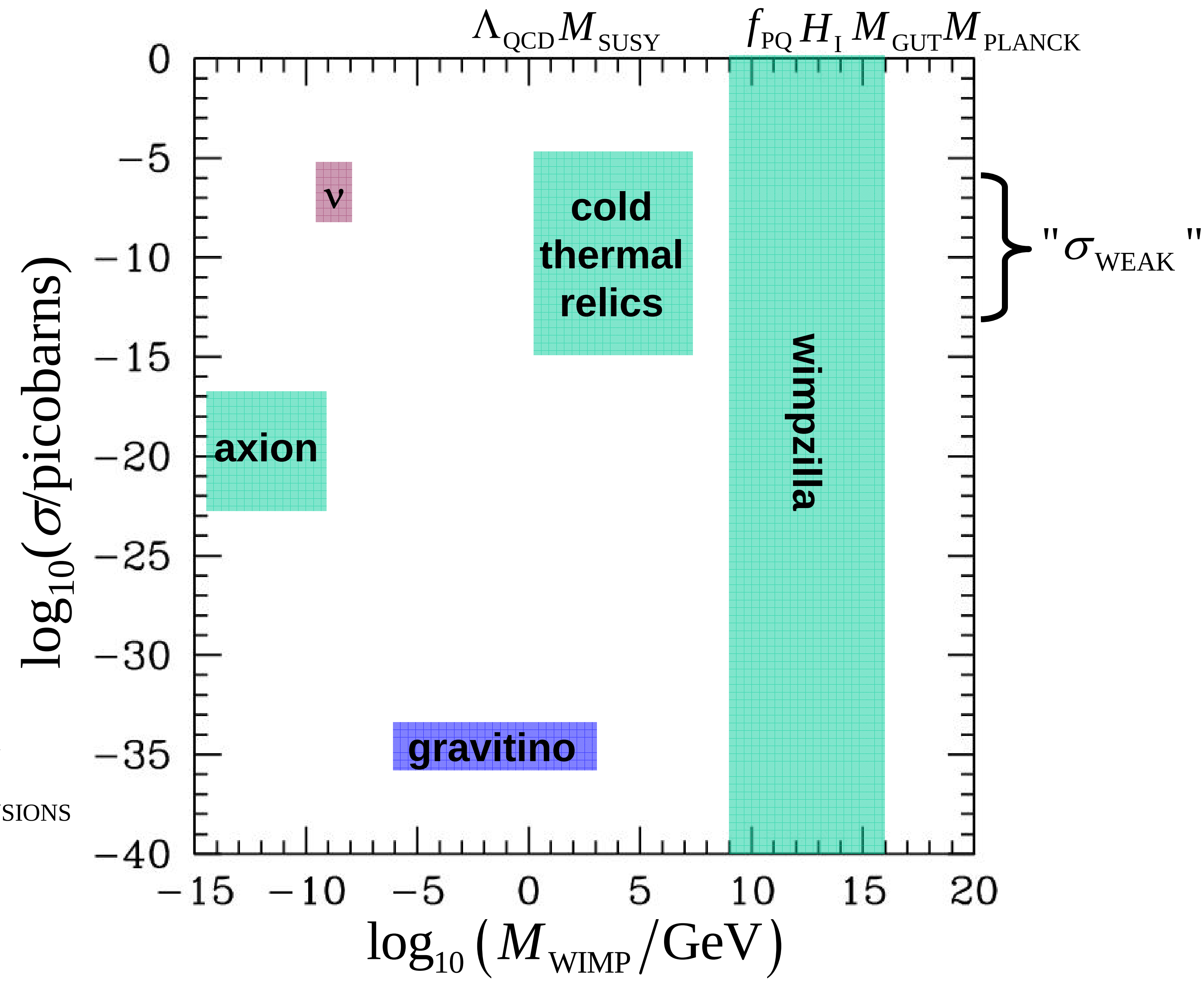
"a simple, elegant, compelling explanation for a complex physical phenomenon"

"For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation."

- Tommy Gold

*** An object of particular veneration.**

Particle Dark Matter Candidates



Other Scales:

M_{EWK}

$M_{STERILE}$

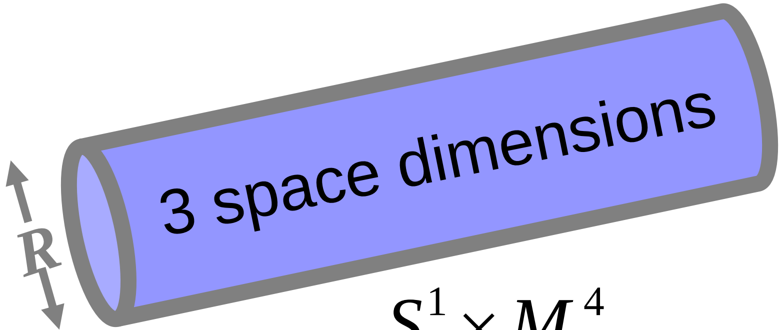
M_{STRING}

$M_{TECHNICOLOR}$

$M_{EXTRA\ DIMENSIONS}$

Kaluza-Klein Particles

Kolb & Slansky (84); Servant & Tait (02); Cheng, Feng & Matchev (02)



$S^1 \times M^4$

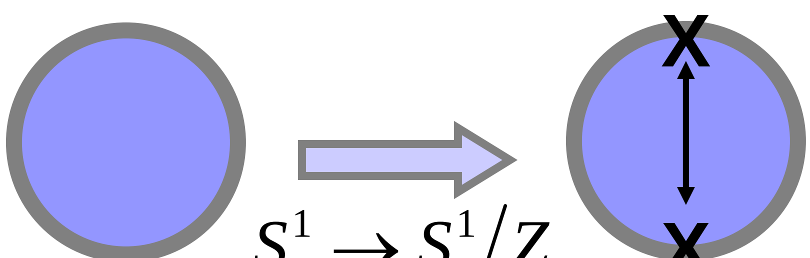
Quantized Kaluza-Klein excitations

$$E^2 = \vec{p}^{\,2} + p_5^2 = \vec{p}^{\,2} + M_n^2 \qquad p_5^2 = n^2/R^2 \qquad M_n^2 = n^2/R^2$$

Conservation of momentum $\longrightarrow$ conservation of KK mode number

First excited mode $(n=1)$ **stable, mass** R^{-1}

need chiral fermions



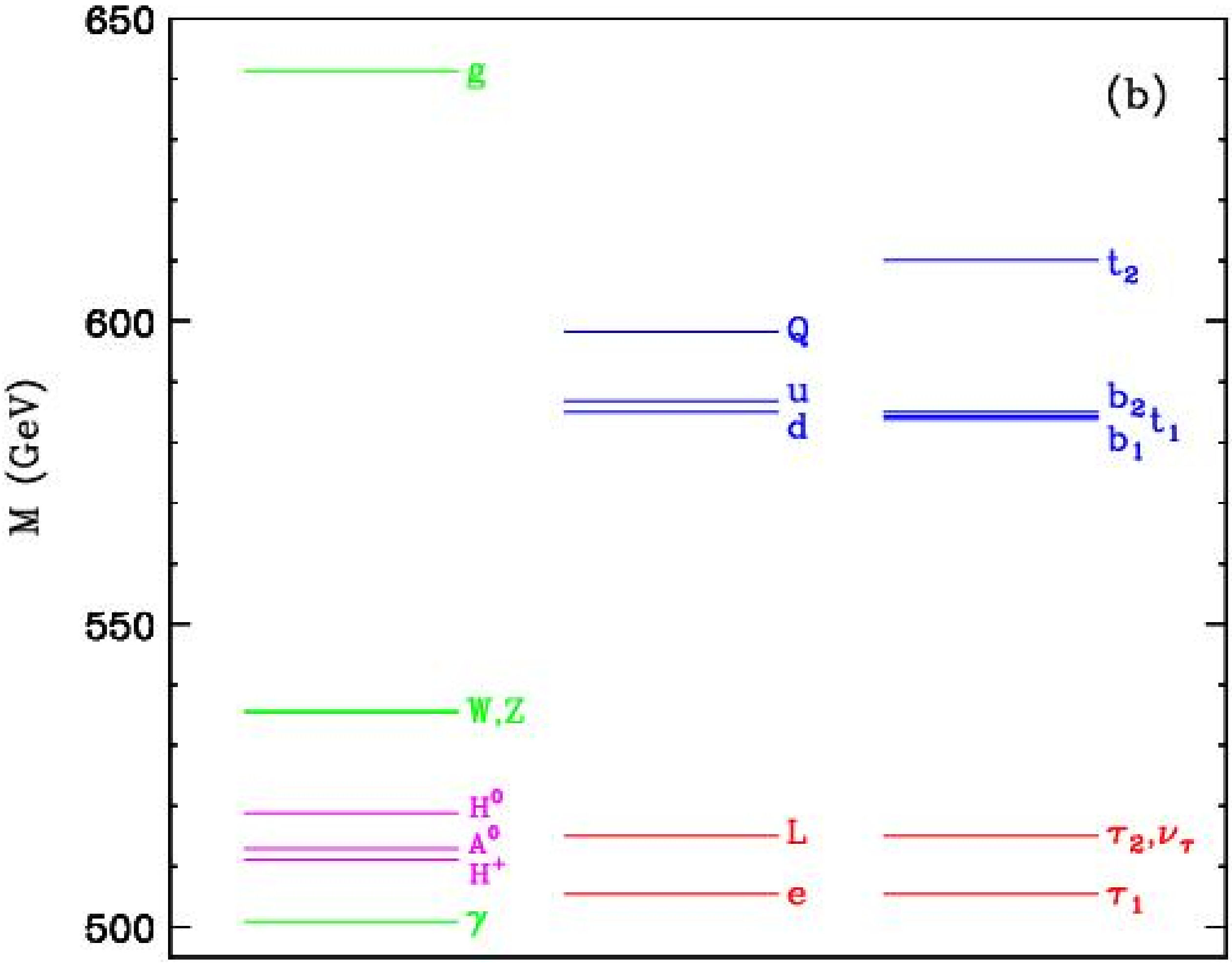
$S^1 \to S^1/Z_2$

KK quantum number $\longrightarrow$ KK parity

First excited mode $(n=1)$ **stable, mass** R^{-1}

Kaluza-Klein Particles

$$R^{-1} = 500 \text{ GeV}$$



- LKP = KK photon
  Cheng, Matchev & Schmaltz
- Looks like SUSY
  Cheng, Matchev & Schmaltz
- Beware KK graviton
  Kolb, Servant & Tait
- Direct detection
  Servant & Tait
  Cheng, Feng & Matchev
- Indirect detection
  Bertrone, Servant, Sigl

Axion Dark Matter

. . . about to be ruled out or closing in on detection

- Pseudo-Nambu-Goldstone boson
- Axion mass: $m_a = \frac{\Lambda^2}{f_{PQ}} = 1\ \mathrm{eV}\ \frac{10^7\,\mathrm{GeV}}{f_{PQ}}$
- Pseudoscalar
- Couples to two photons through the anomaly
- Very weakly interacting with matter
- Origin of axions

    phase transition

    decay of axion strings

Balls

- **Q-balls (non-topological solitons):** S. Coleman; T.D. Lee

Scalar field with conserved global charge "Q" ⇒ Ground state is a Q-ball, lump of coherent scalar condensate

$E \propto Q^{3/4}$: can't decay to Q free particles

- **Q-ball production and evolution:**

Solitogenesis — Frieman, Gelmini, Gleiser & Kolb

Solitosynthesis — Frieman, Olinto, Gleiser & Alcock; Greist & Kolb

Statistical fluctuations — Greist, Kolb & Masssarotti

Condensate fragmentation — Kusenko & Shaposhnikov

Balls

- **Q-balls exist in MSSM** Kusenko, Shapashnikov & Tinyakov

  scalars = squarks & sleptons

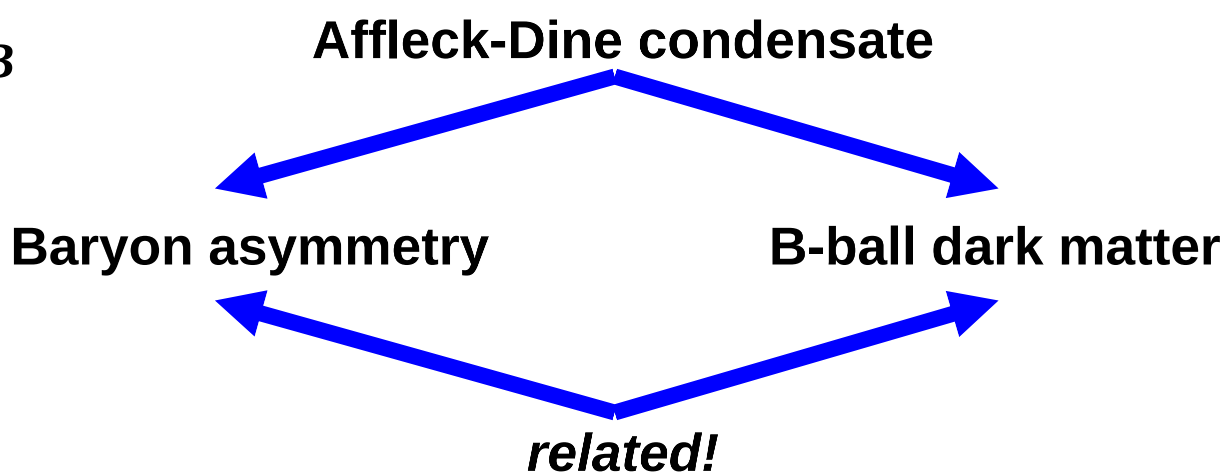
$$M_B \sim (1\ \mathrm{TeV}) \times B^{3/4} \quad \left(\text{stable for } B \geq 10^{12}\right)$$

- **Fragmentation of** Kusenko & Shapashnikov

  Affleck-Dine condensate

$$M_B \sim 10^{-3}\ \mathrm{g} \quad \left(B \simeq 10^{24}\right)$$

- **Relates Ω_{DM} to Ω_B**



Nonthermal Dark Matter (Supermassive Relics)

Production Mechanisms:

- Reheating — Chung, Kolb, Riotto
- Preheating — Chung
- Bubble collisions — Chung, Kolb, Riotto
- Gravitational — Chung, Kolb, Riotto; Kuzmin & Tkachev

Expanding Universe → Particle Creation

Discovery: Schrödinger (1939) ***The Proper vibrations of the expanding universe***
"the alarming phenomenon"

It's a bug!

First application: **density perturbations, gravitational waves from inflation**

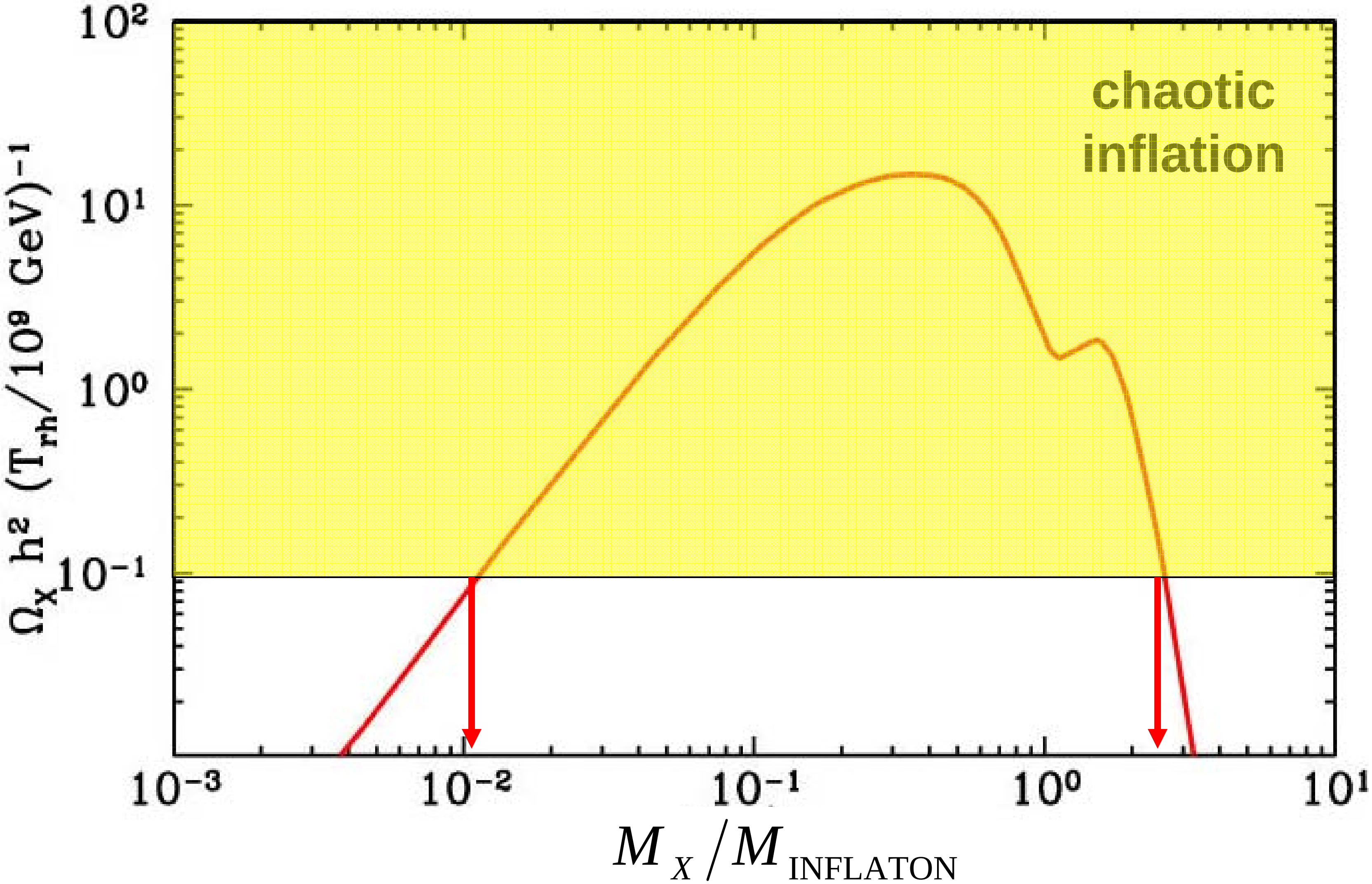
1983—present: It's a feature!

New application: **dark matter**

(Chung, Kolb, & Riotto; Kuzmin & Tkachev)

Particle Production

Chung, Kolb& Riotto; Kuzmin & Tkachev)



$$\Omega_X \approx 1 \quad \text{for} \quad M_X / M_{\text{INFLATON}} \approx 1 \Rightarrow M_X \approx 10^{10} \text{ to } 10^{15} \text{GeV}$$

Superheavy Particles

Inflaton mass (in principle measurable from gravitational wave background, guess 10^{12} GeV) may signal a new mass scale in nature.

Other particles may exist with mass comparable to the inflaton mass.

Conserved quantum numbers may render the particle stable.

Wimpzilla Characteristics

- supermassive: $10^9 - 10^{19}$ GeV (~ 10^{12} GeV ?)
- abundance may depend only on mass
- abundance may be independent of interactions
  - sterile?
  - electrically charged?
  - strong interactions?
  - weak interactions?
- lifetime $\gg$ age of the universe

Wimpzillas

- Origin of inflationary perturbations from creation of particles in the expanding universe

- Beautiful ideas often have other applications

  Nature uses only the longest threads to weave her patterns…

  — Feynman

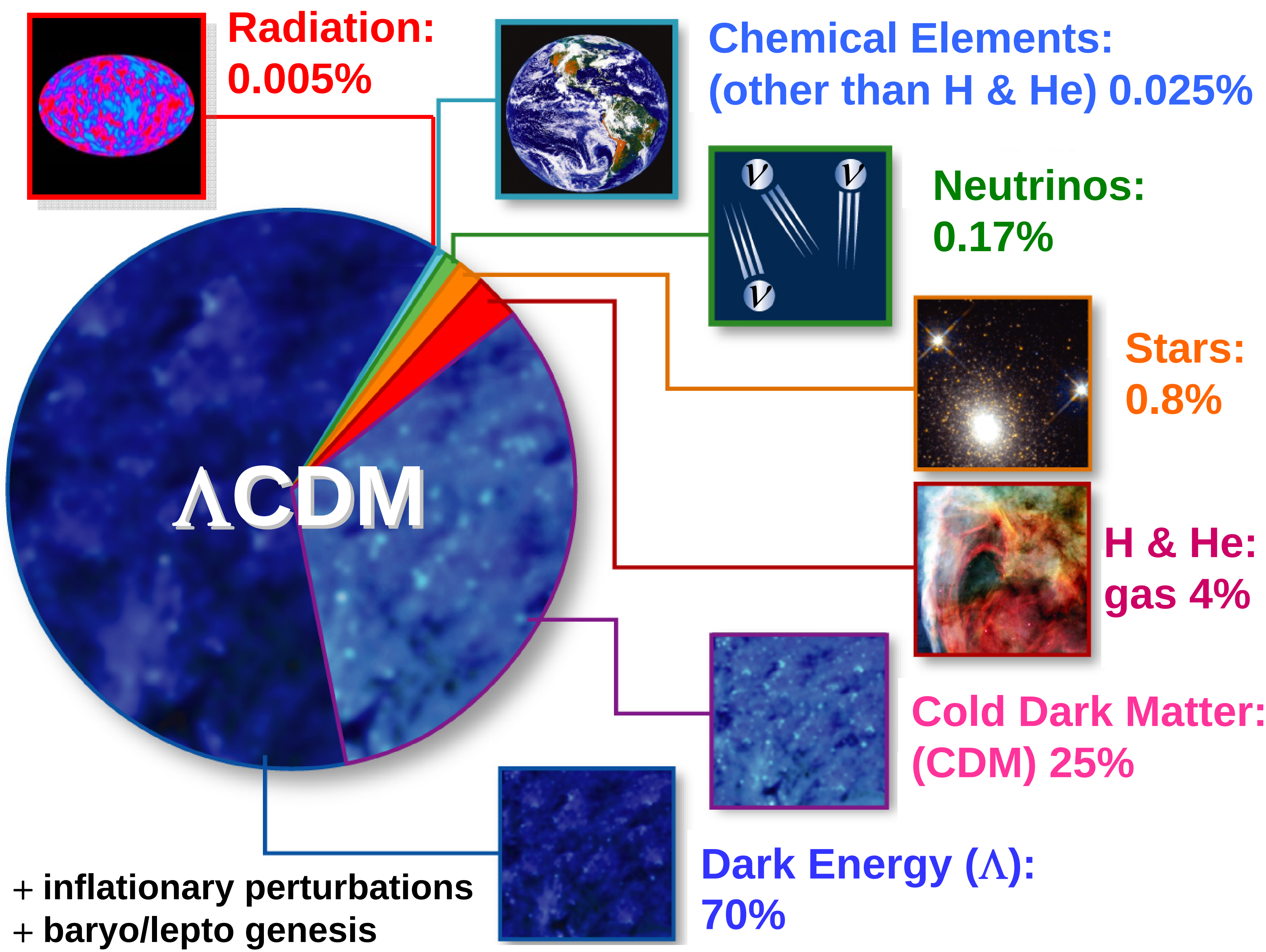
- Perhaps origin of dark matter also from creation of particles in the expanding universe (it's a long thread!)

- Dark matter may have only gravitational interactions—no accelerator production, no direct detection, no indirect detection (an inconvenient truth)

Dark Matter

WIMP

WIMPZILLA


Radiation:
0.005%
Chemical Elements:
(other than H & He) 0.025%
Neutrinos:
0.17%
Stars:
0.8%
H & He:
gas 4%
Cold Dark Matter:
(CDM) 25%
Dark Energy (Λ):
70%
ΛCDM
+ inflationary perturbations
+ baryo/lepto genesis

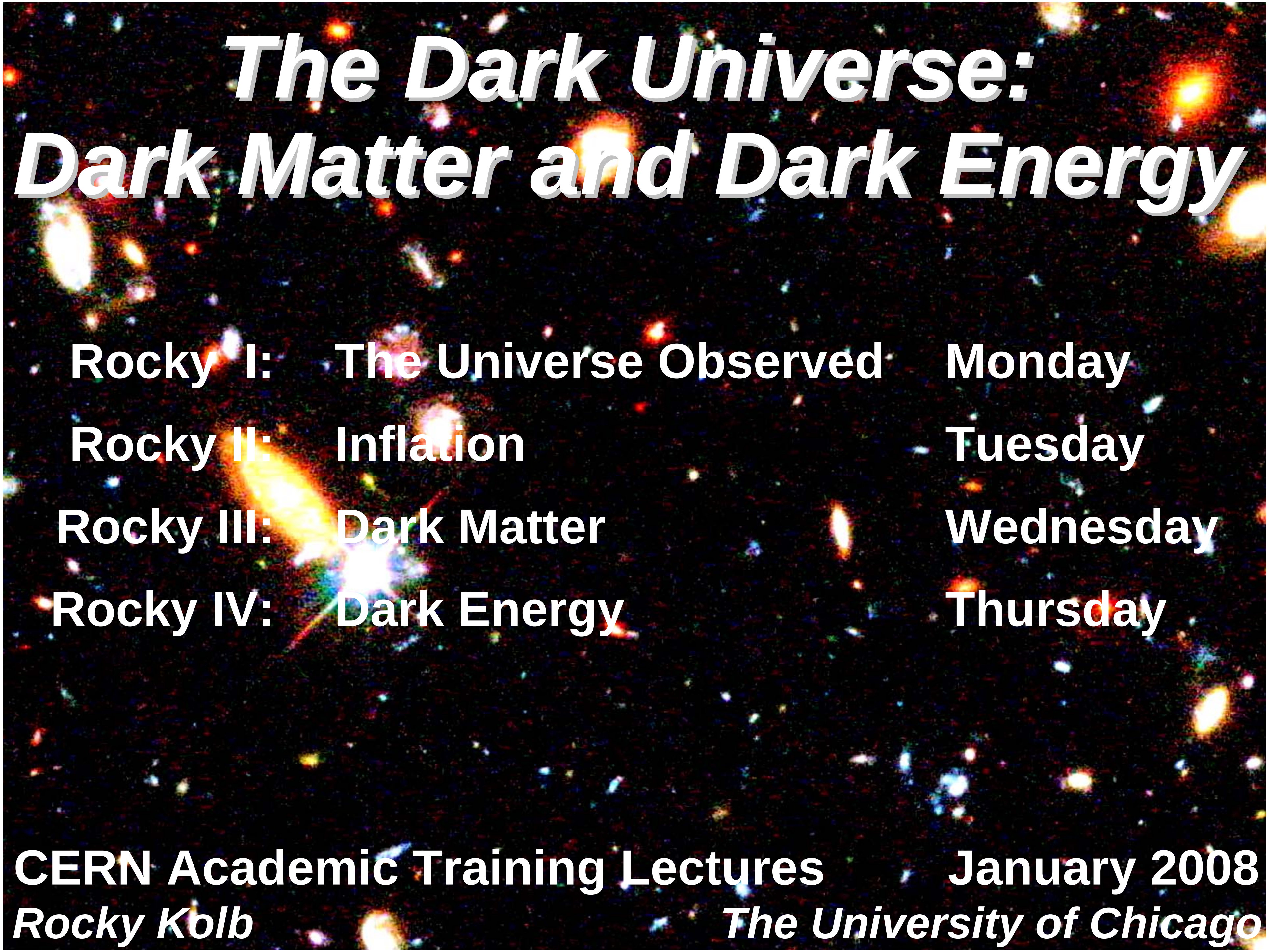
Suggested reading:

Origin of (particle) species
The Early Universe, Kolb & Turner

Neutrinos in cosmology
Julien Lesgourgues & Sergio Pastor
Phys.Rept.429,2006.

Dark Matter Direct & Indirect Detection
Gianfranco Bertone, Dan Hooper, Joseph Silk
Phys.Rept.405:279,2005.

Other references
Cosmology and the Unexpected.
Edward W. Kolb.
e-Print: arXiv:0709.3102


The Dark Universe:
Dark Matter and Dark Energy
Rocky I: The Universe Observed Monday
Rocky II: Inflation Tuesday
Rocky III: Dark Matter Wednesday
Rocky IV: Dark Energy Thursday
CERN Academic Training Lectures January 2008
Rocky Kolb The University of Chicago