Particle Physics Foundations of Dark Matter, Dark Energy, and Inflation

Rocky I:	Dark Matter	(Wednesday, 11:00)
Rocky II:	Dark Energy	(Thursday, 11:00)
Rocky III:	Inflation	(Friday, 11:00)

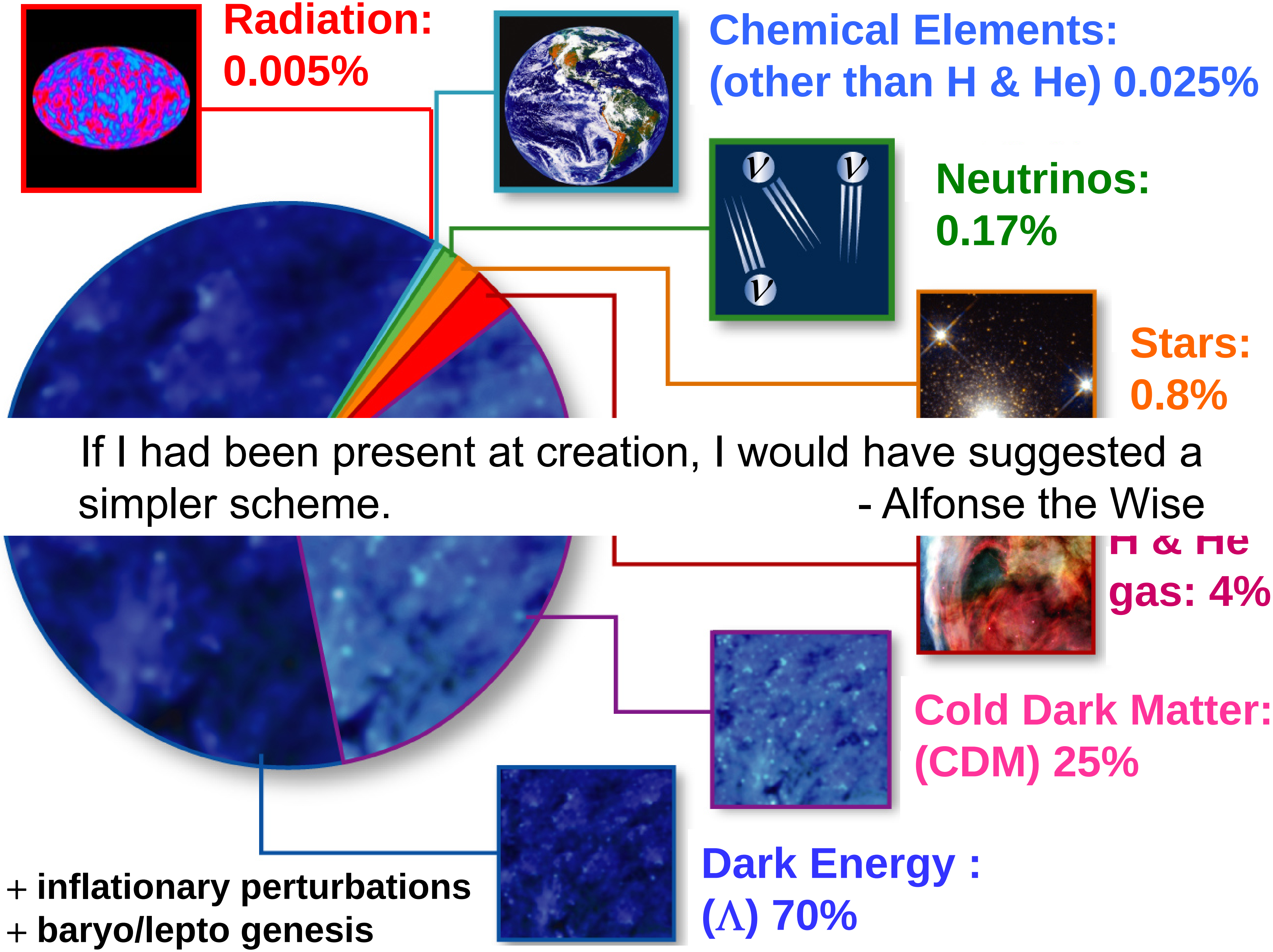
Rocky Kolb
University of Chicago

ΛCDM: The Standard Model

"How helpful is astronomy's pedantic accuracy, which I used to secretly ridicule!"

Einstein's to Arnold Sommerfeld on December 9, 1915 (measurements of the perihelion advance of Mercury)

Beyond Standard Model Physics



If I had been present at creation, I would have suggested a simpler scheme.

- Alfonse the Wise

Ninty-Five Percent of the Universe

Dark Matter (25%)

Pulls things together

Attractive gravity

New particle species?

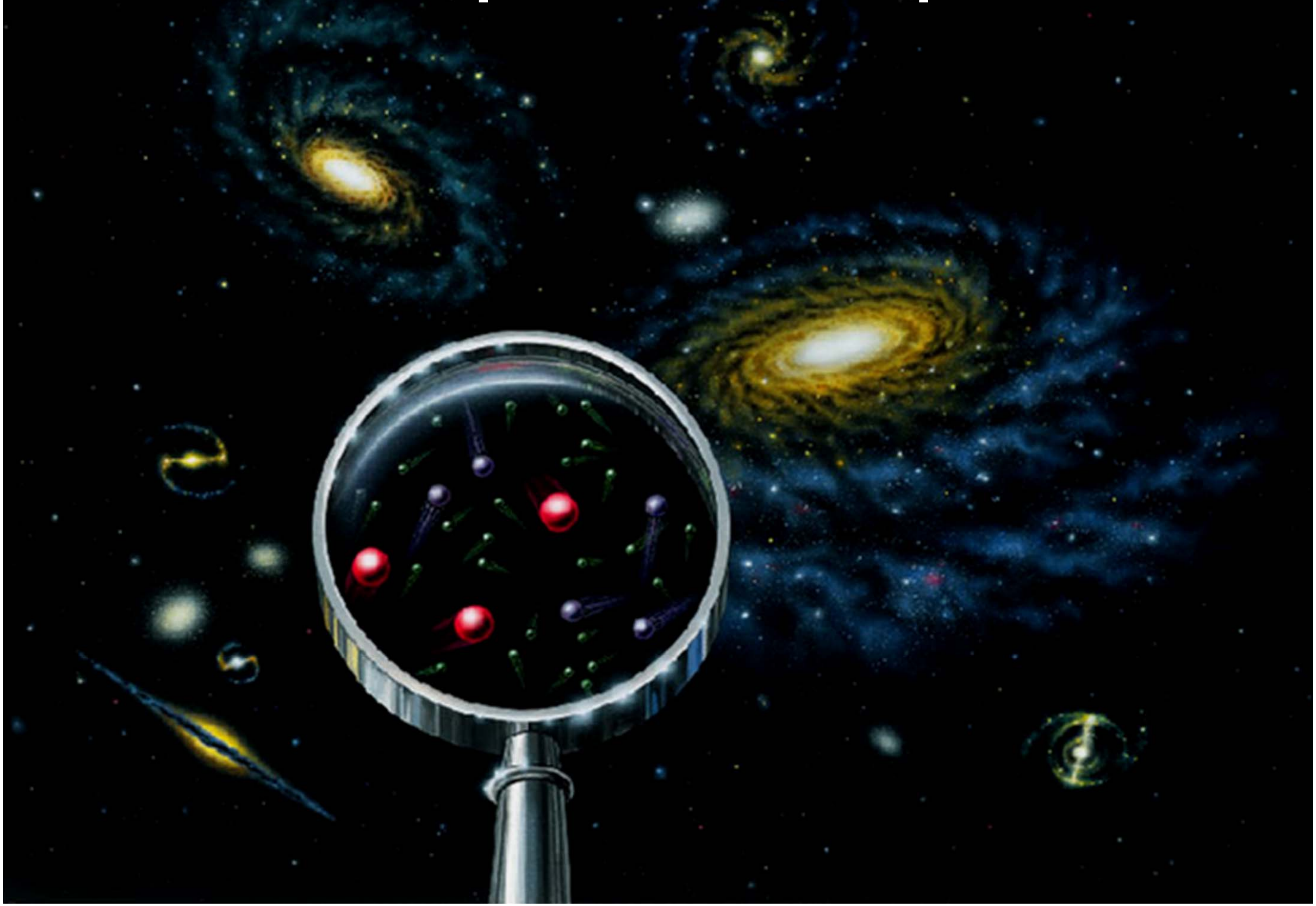
Dark Energy (70%)

Pushes things apart

Repulsive gravity

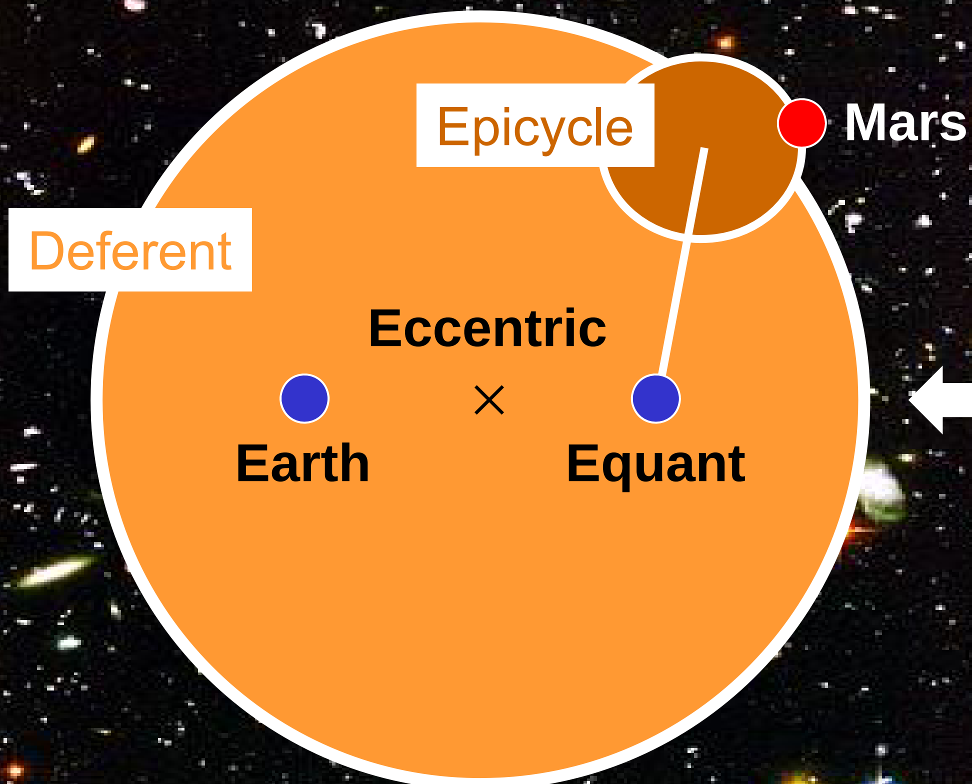
Weight of space?

Inner Space / Outer Space



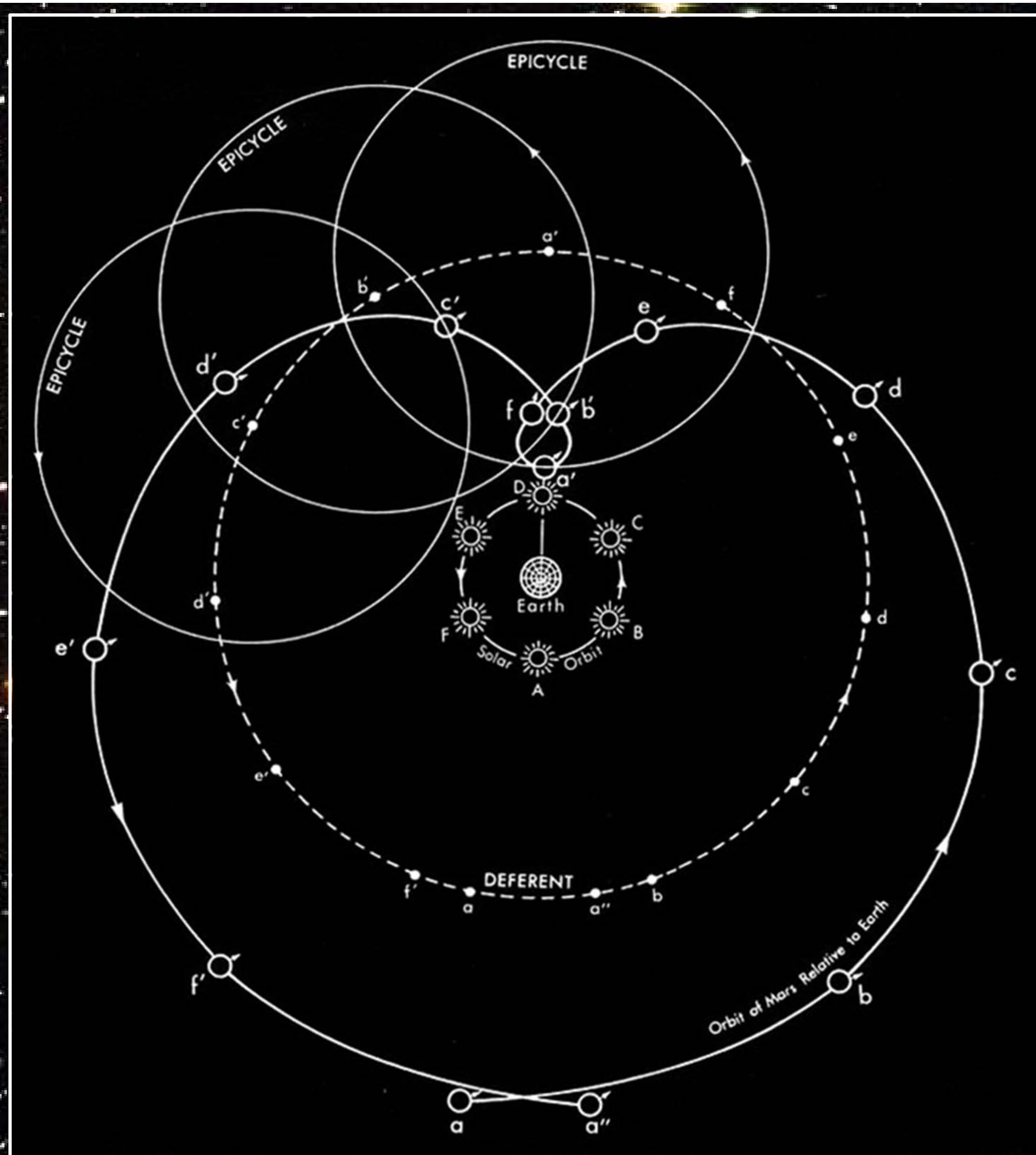
The construction of a model…consists of snatching from the enormous and complex mass of facts called reality a few simple, easily managed key points which… becomes for certain purposes a substitute for reality itself.

Evsey Domar
20th-century economist

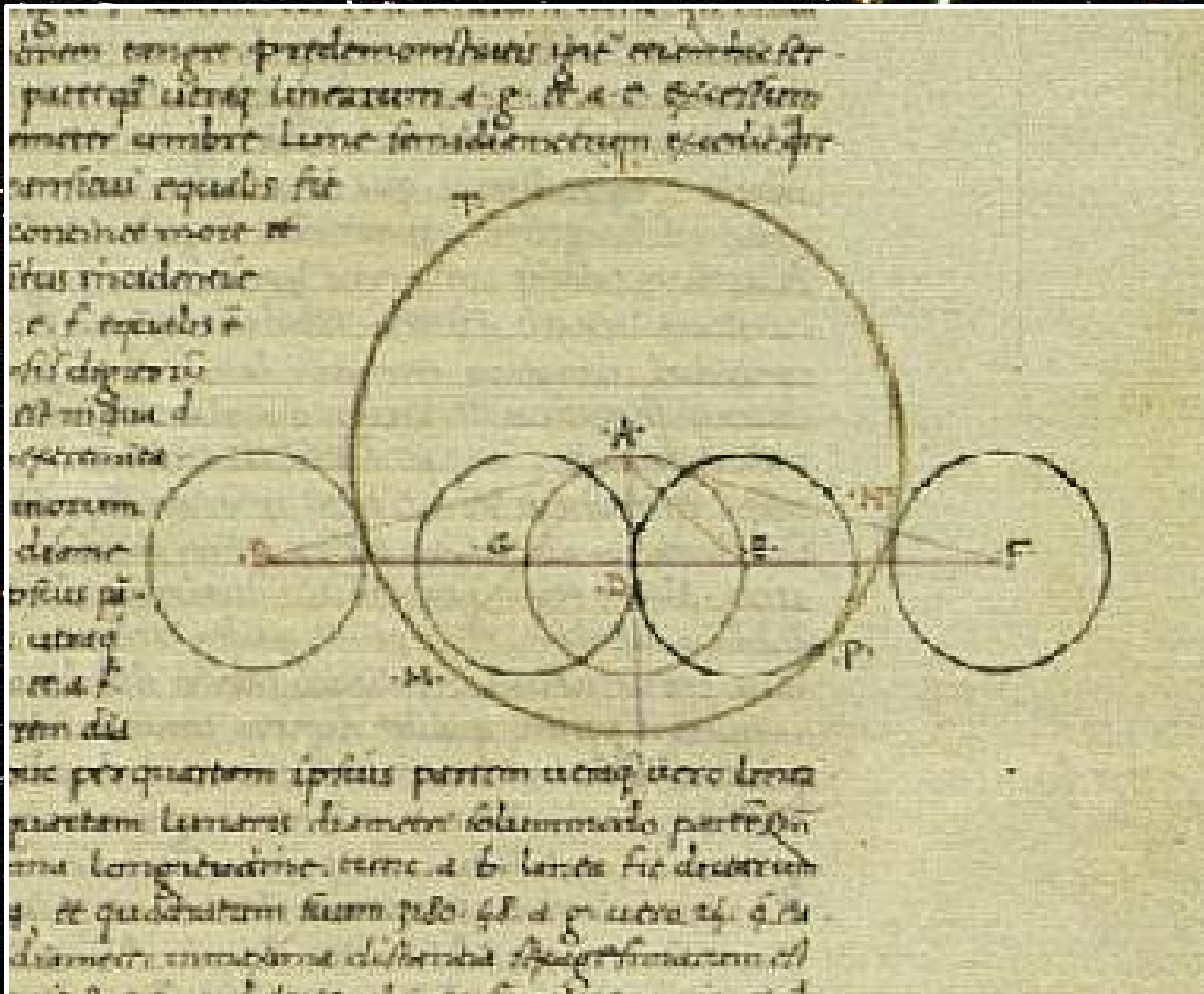


This cosmological model agreed with observations for 1300 years!

A Previous
Consensus
Convergence
Dominant
Best-Fit
Standard
Cosmological
Model

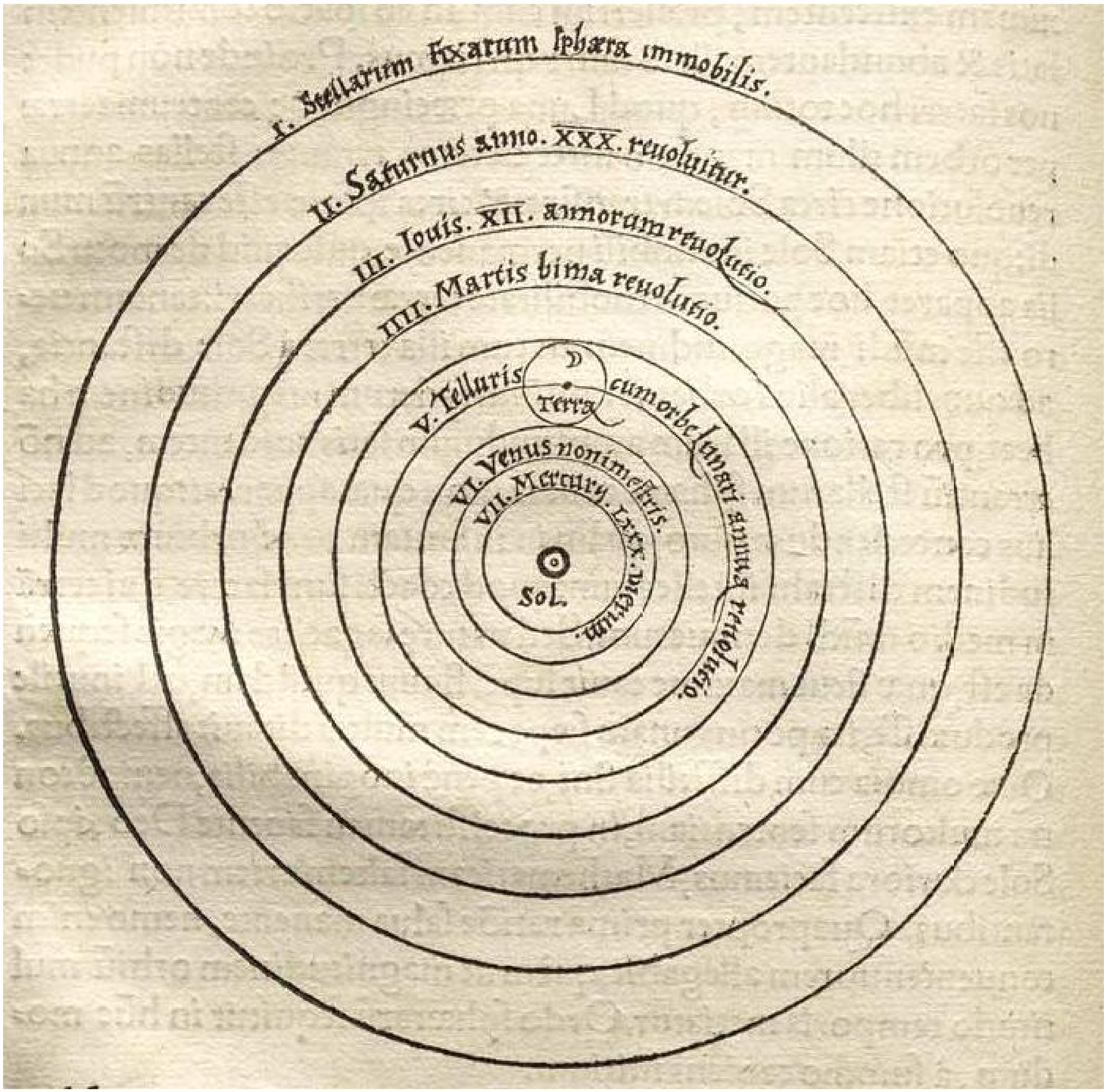


Ptolemaic System
The Almagest



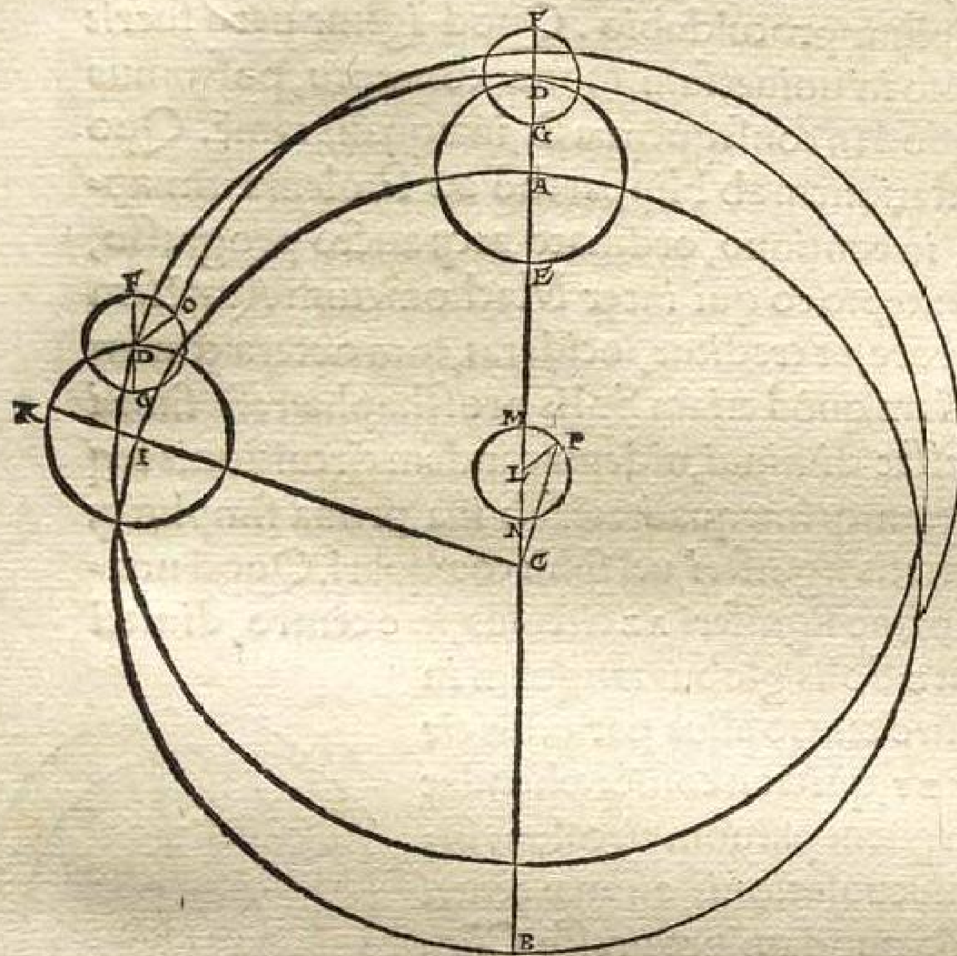
George Trebizond's Latin translation (ca. 1451) of Almagest

Copernican System
De *Revolutionibus* Book I



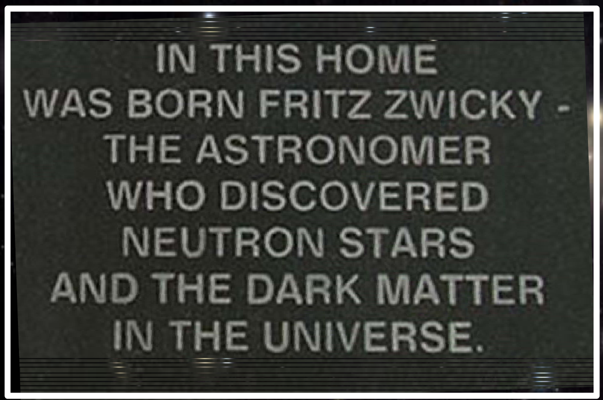
Copernican System
De Revolutionibus, Book III

quoq; epicyclum hoc modo. Sit mundo ac Soli homocentrus AB, & ACB diameter, in qua ſumma abſis contingat. Et facto in A centro epicyclus deſcribatur DE, ac rurſus in D centro epicyclium FG, in quo terra uerſetur, omniaq; in eodem plano zodiaci.



Sitq; epicycli primi motus in ſuccedētia, ac annuus ferè, ſecūdi quoq;, hoc eſt D, ſimiliter annuus, ſed in præcedentia, amborumq; ad AC lineam pares ſint reuolutiones. Rurſus cētrum terræ ex F in præcedentia addat parumper ipſi D. Ex hoc manifeſtū eſt quòd cum terra fuerit in F, maximum efficiet Solis apogeum, in G minimum: in medijs autem circumferentijs ipſius FG epicyclij faciet ipſum apogeum præcedere uel ſequi, auctum dimi

Dark Matter



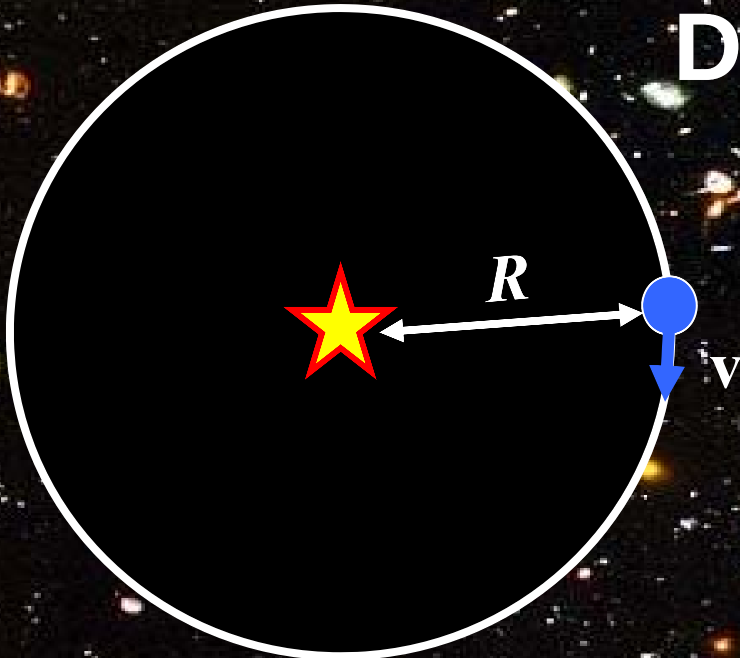
Varna, Bulgaria

Fritz Zwicky 1930s

Swiss ETHZ
Weyl & Scherrer

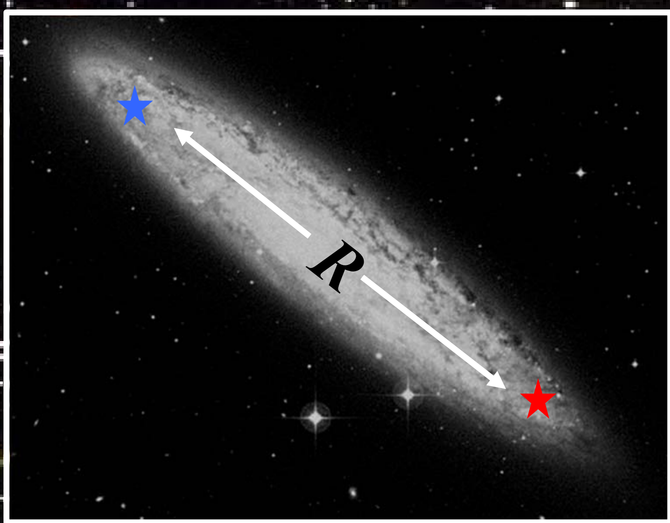
Galaxy Clusters (e.g., Coma)

Dark Matter



$$v^2 = \frac{G_N M_\odot}{R}$$

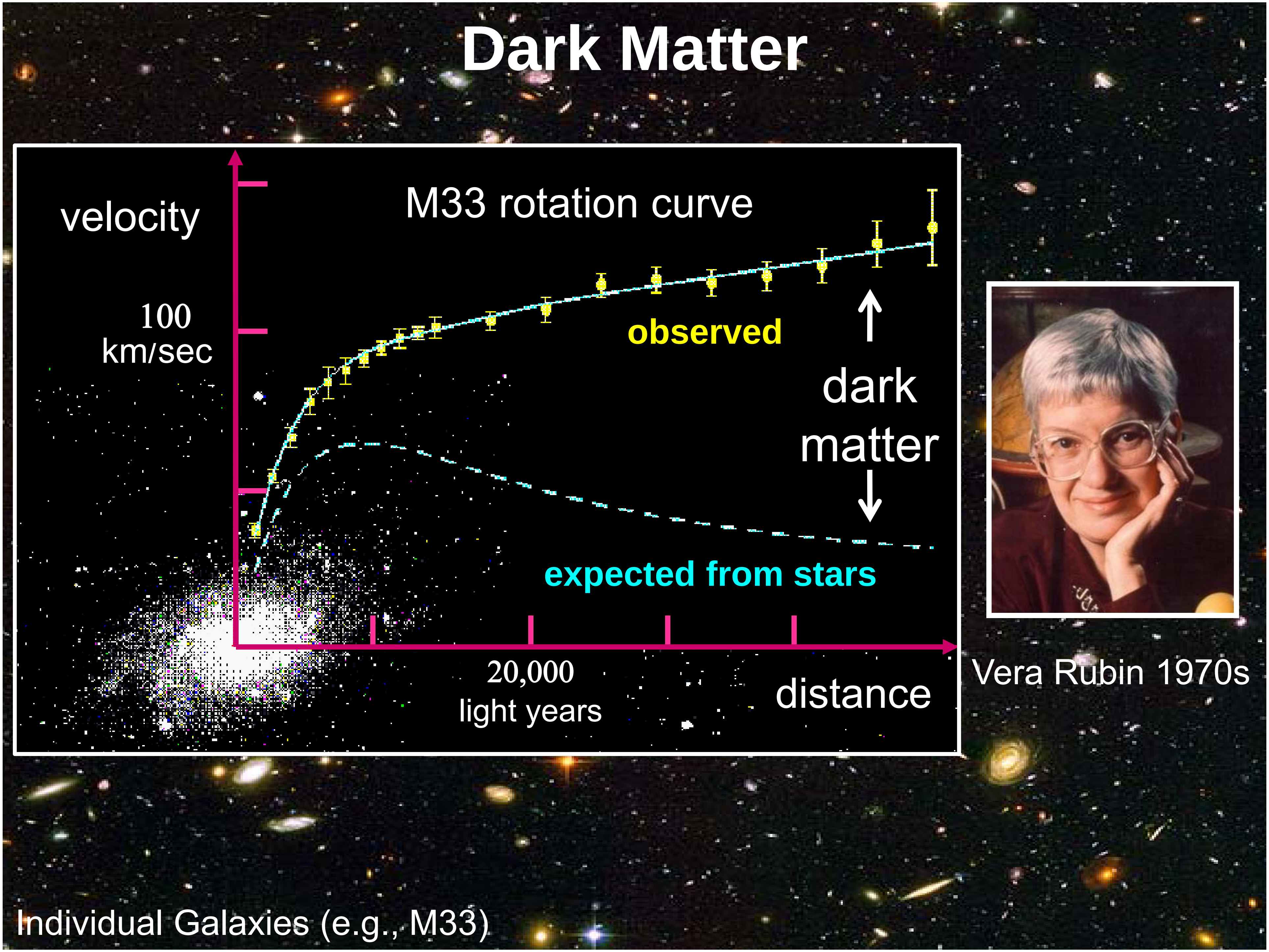
measure v **&** $R \rightarrow M_\odot$



$$v^2 = \frac{G_N M_{<R}}{R}$$

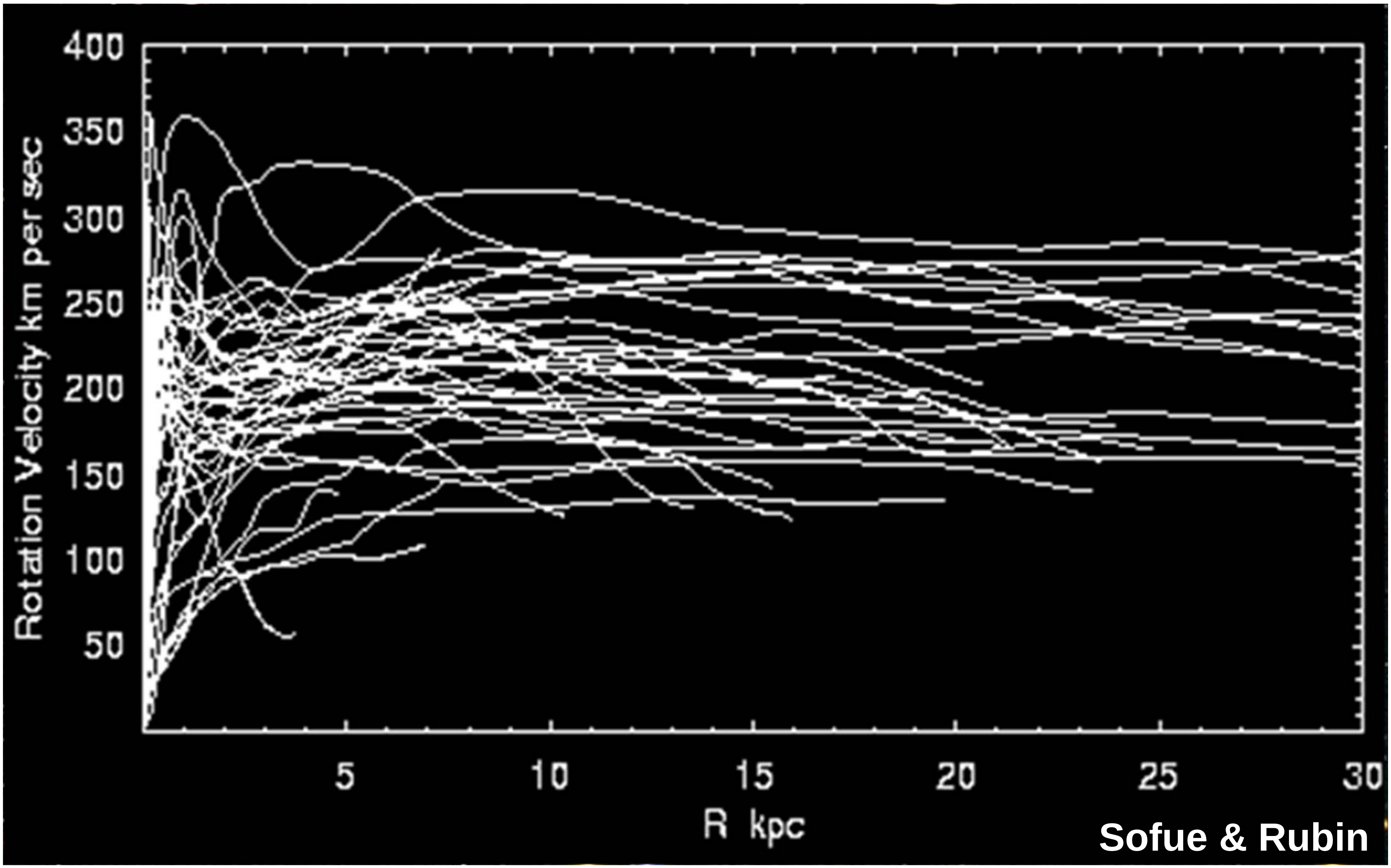
measure v **&** $R \rightarrow M_{<R}$

"outside" of galaxy, measure v **&** $R \rightarrow M_{\mathrm{GALAXY}}$


Dark Matter
M33 rotation curve
velocity
100
km/sec
observed
dark
matter
expected from stars
20,000
light years
distance
Vera Rubin 1970s
Individual Galaxies (e.g., M33)

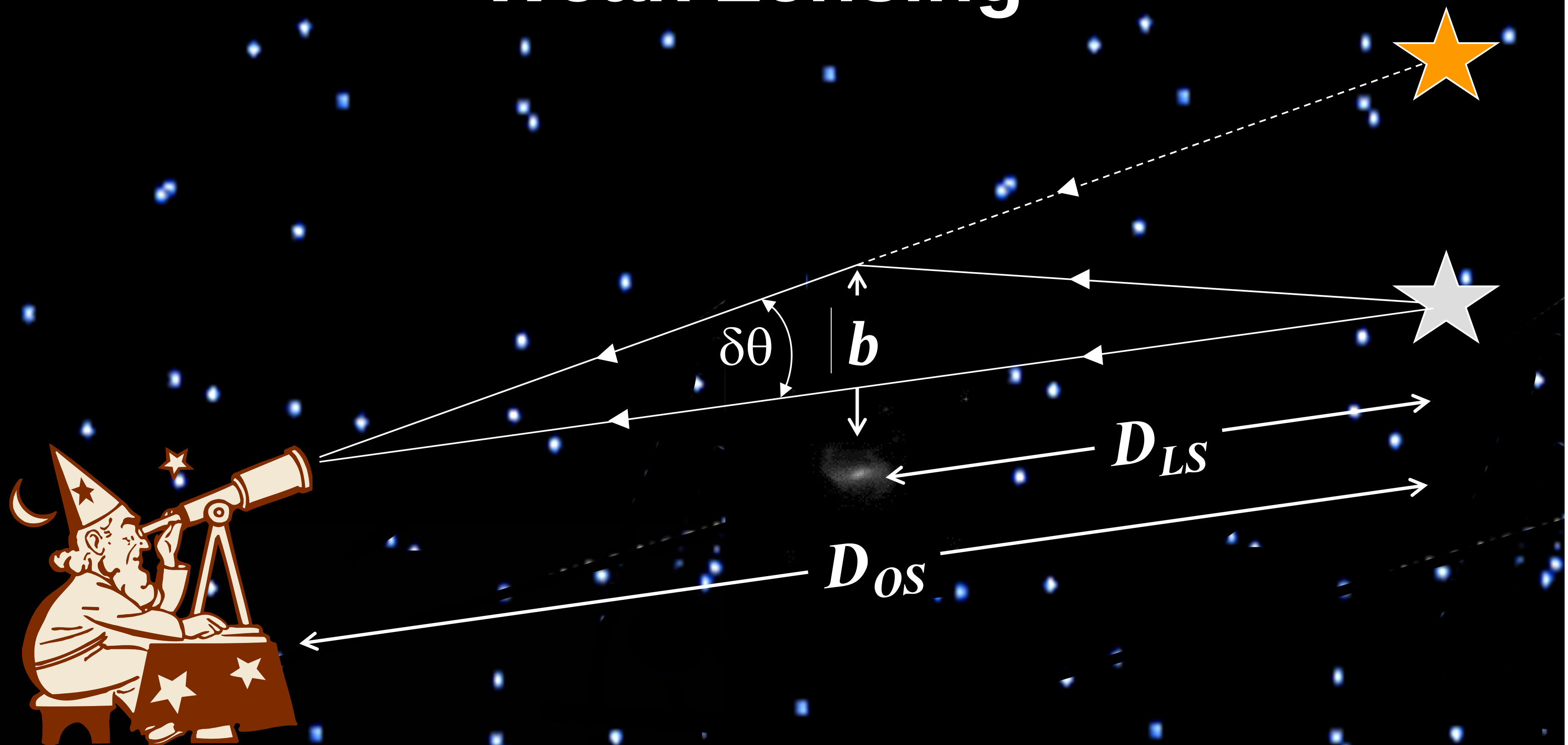
Dark Matter

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



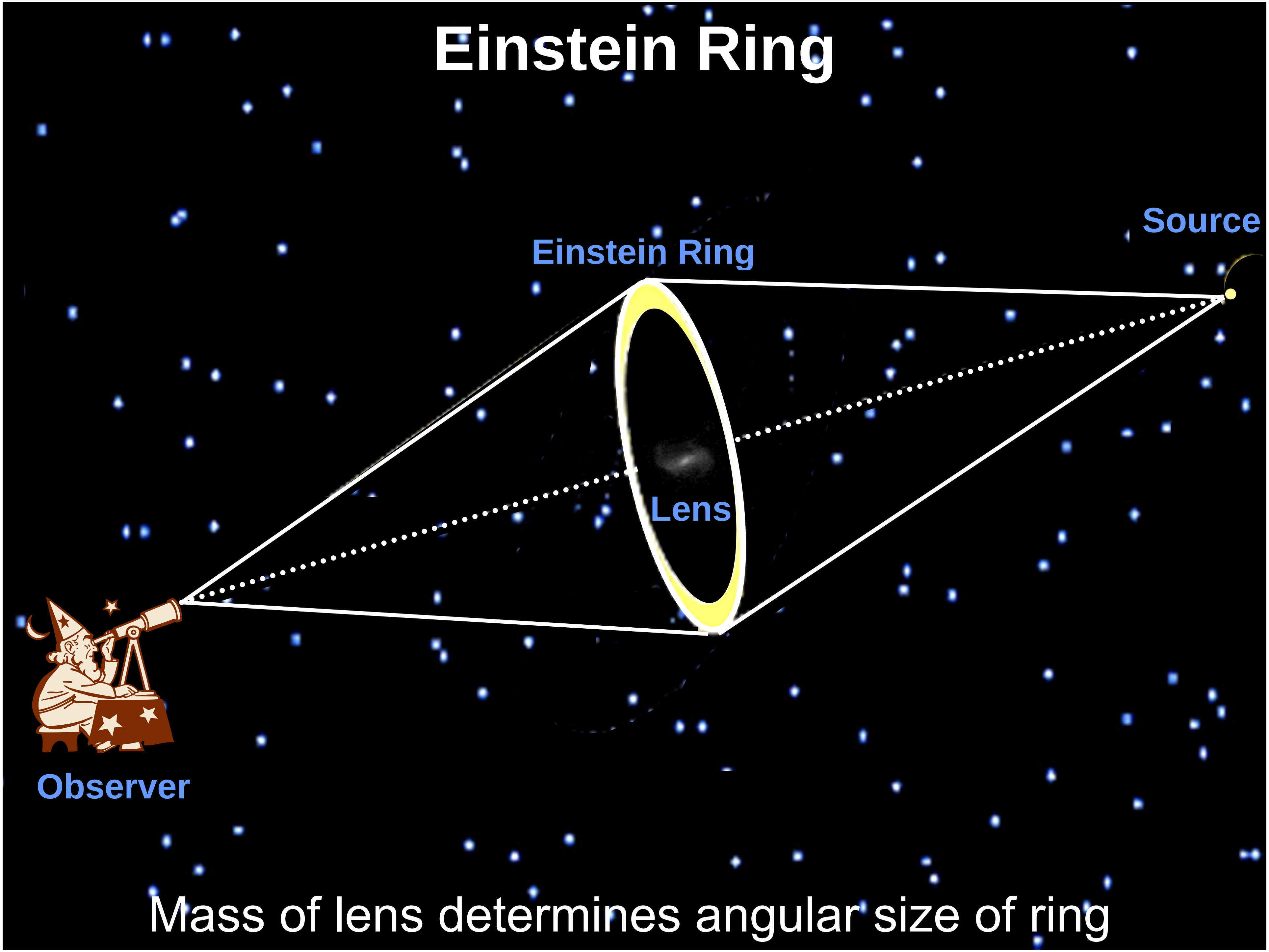
Sofue & Rubin

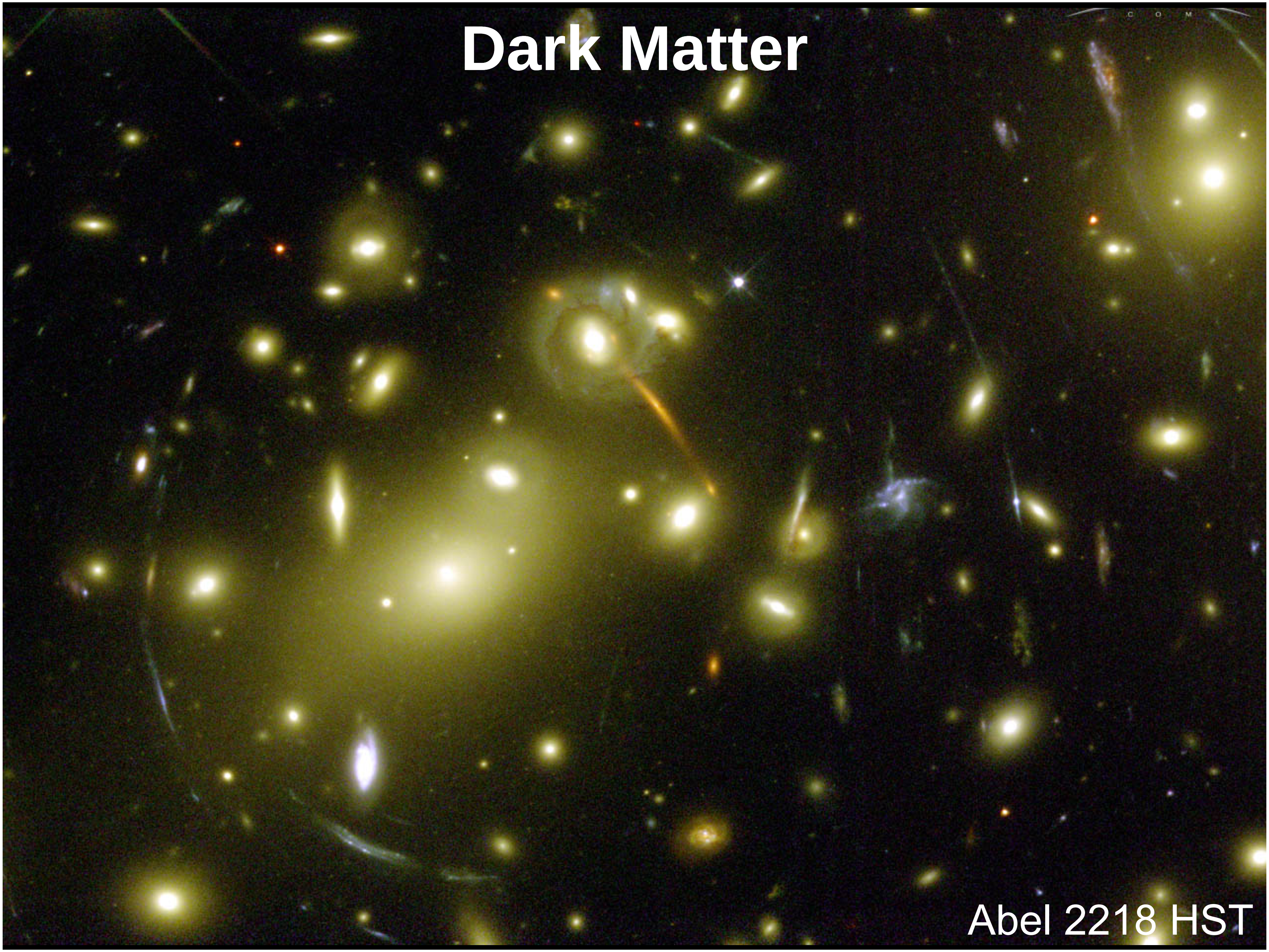
Weak Lensing



observe deflection angle

$$\delta\theta = \frac{4GM}{b}\frac{D_{LS}}{D_{OS}}$$


Einstein Ring
Source
Einstein Ring
Lens
Observer
Mass of lens determines angular size of ring

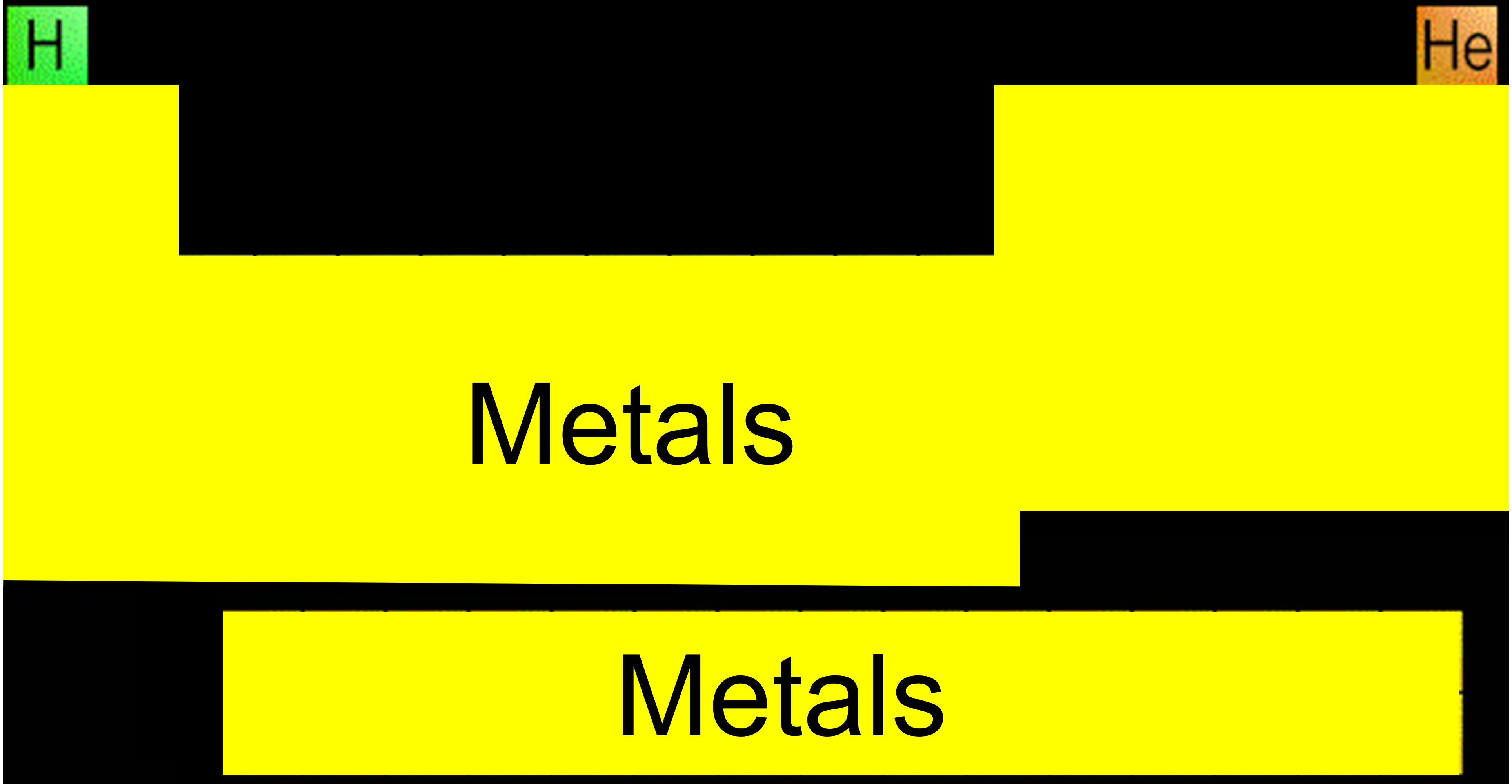

Dark Matter
Abel 2218 HST

Periodic Table – Chemist

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Periodic Table – Cosmologist



The Universe Today

73%   **Hydrogen**   (10^{-5} ^{2}H-deuterium)
26%   **Helium**   (10^{-5} ^{3}He)
1%   **Metals**

The Universe 3 minutes AB

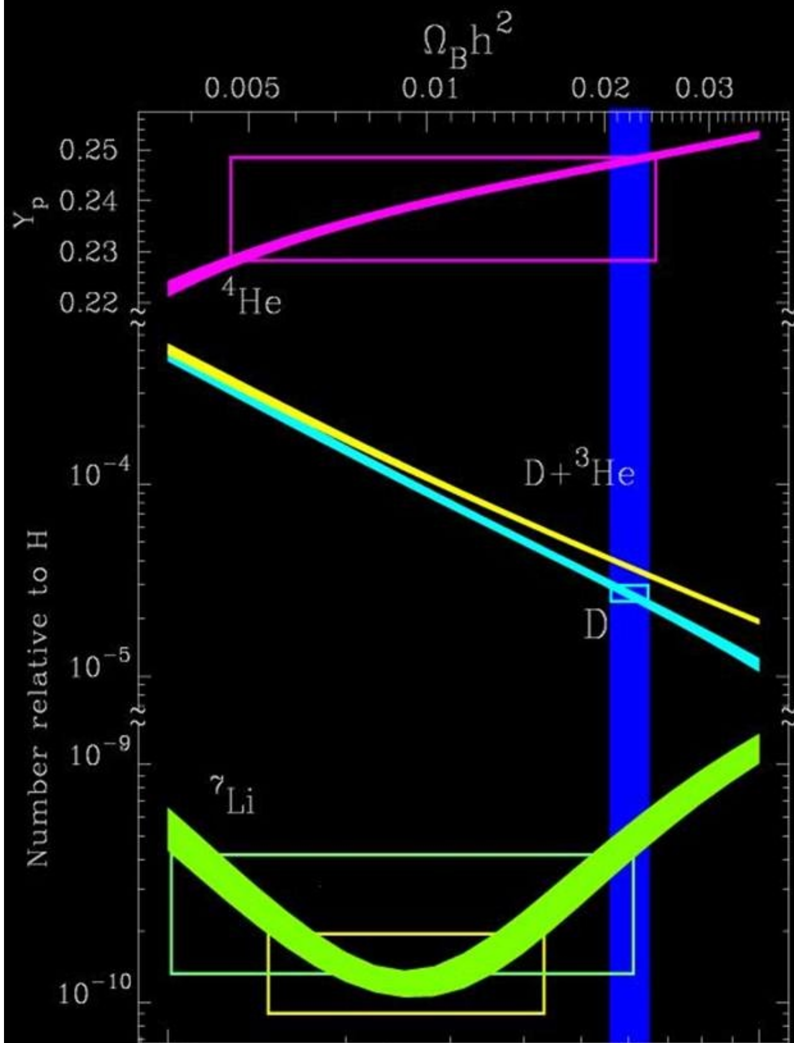
76%   **Hydrogen**   (10^{-5} ^{2}H- deuterium)
24%   **Helium**   (10^{-5} ^{3}He)
10^{-8}% **Lithium**

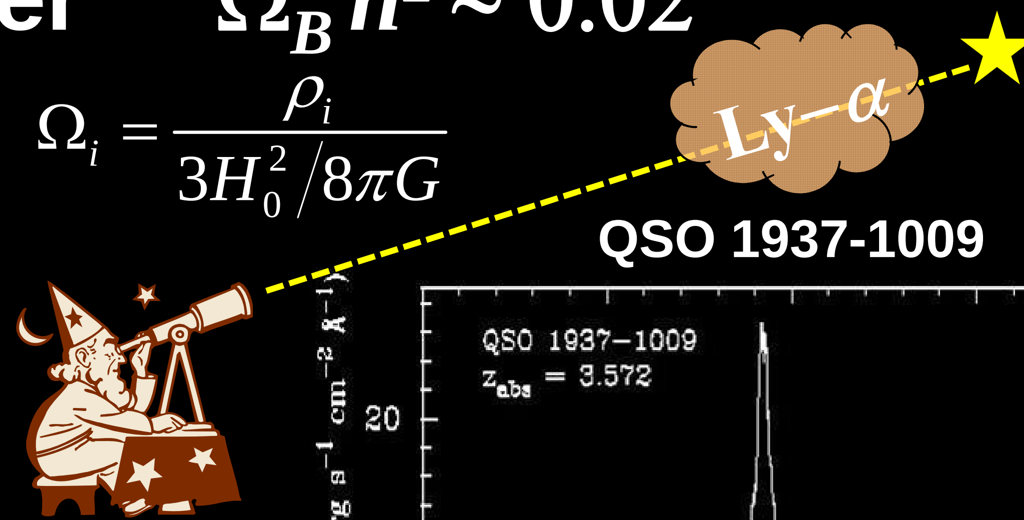
Big Bang Nucleosynthesis (BBN)

Dark Matter $\Omega_B h^2 \sim 0.02$

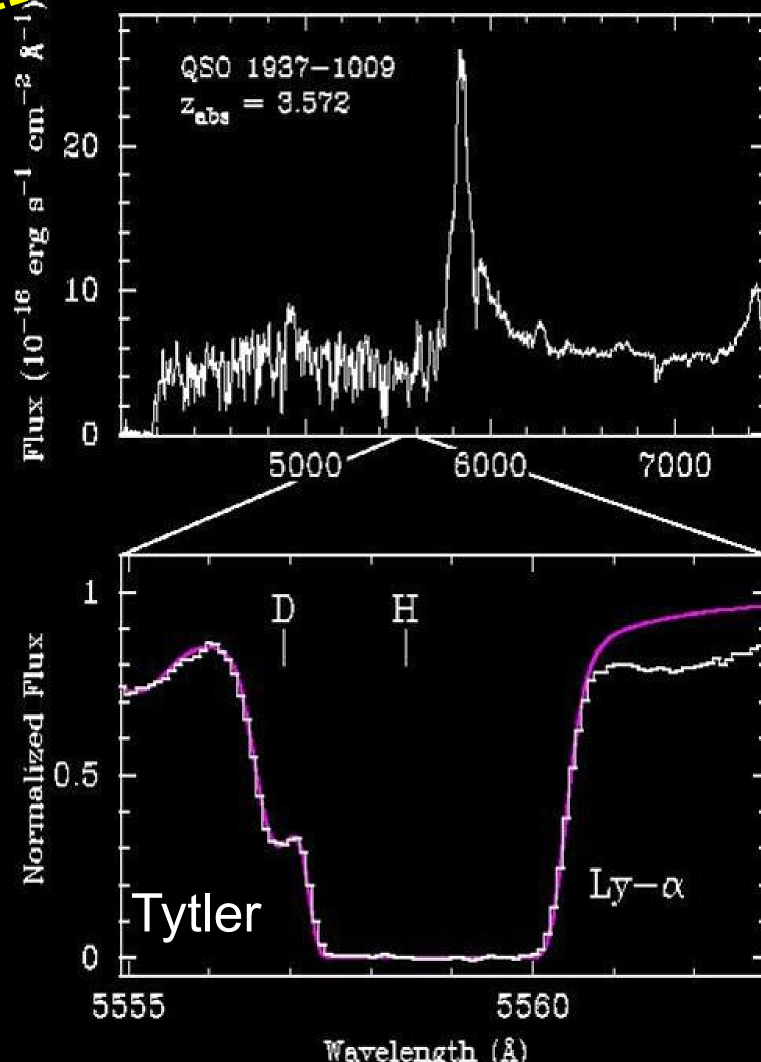
$H_0 = 100h$ km s^{-1} Mpc^{-1}

$$\Omega_i = \frac{\rho_i}{3H_0^2/8\pi G}$$



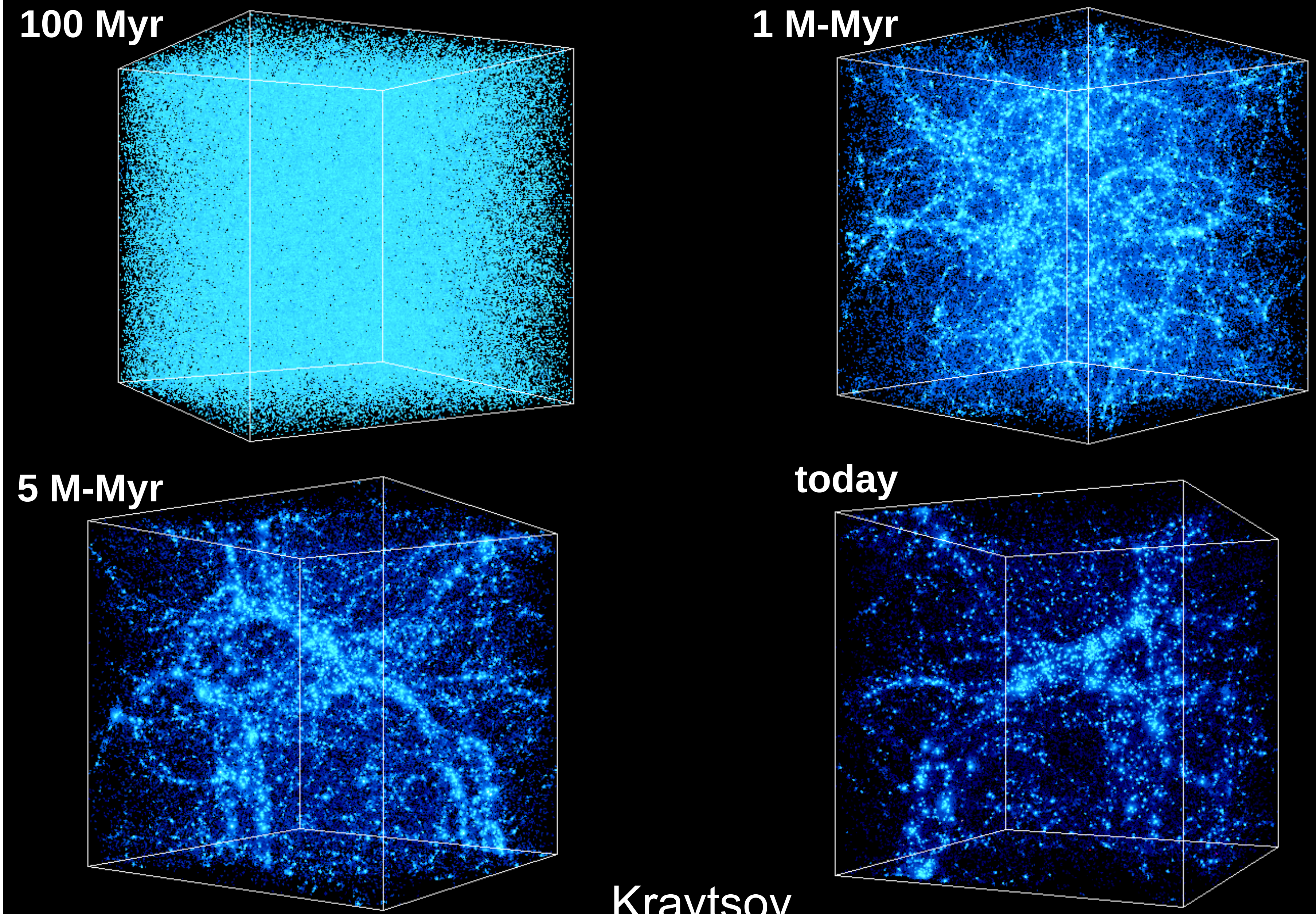


QSO 1937-1009



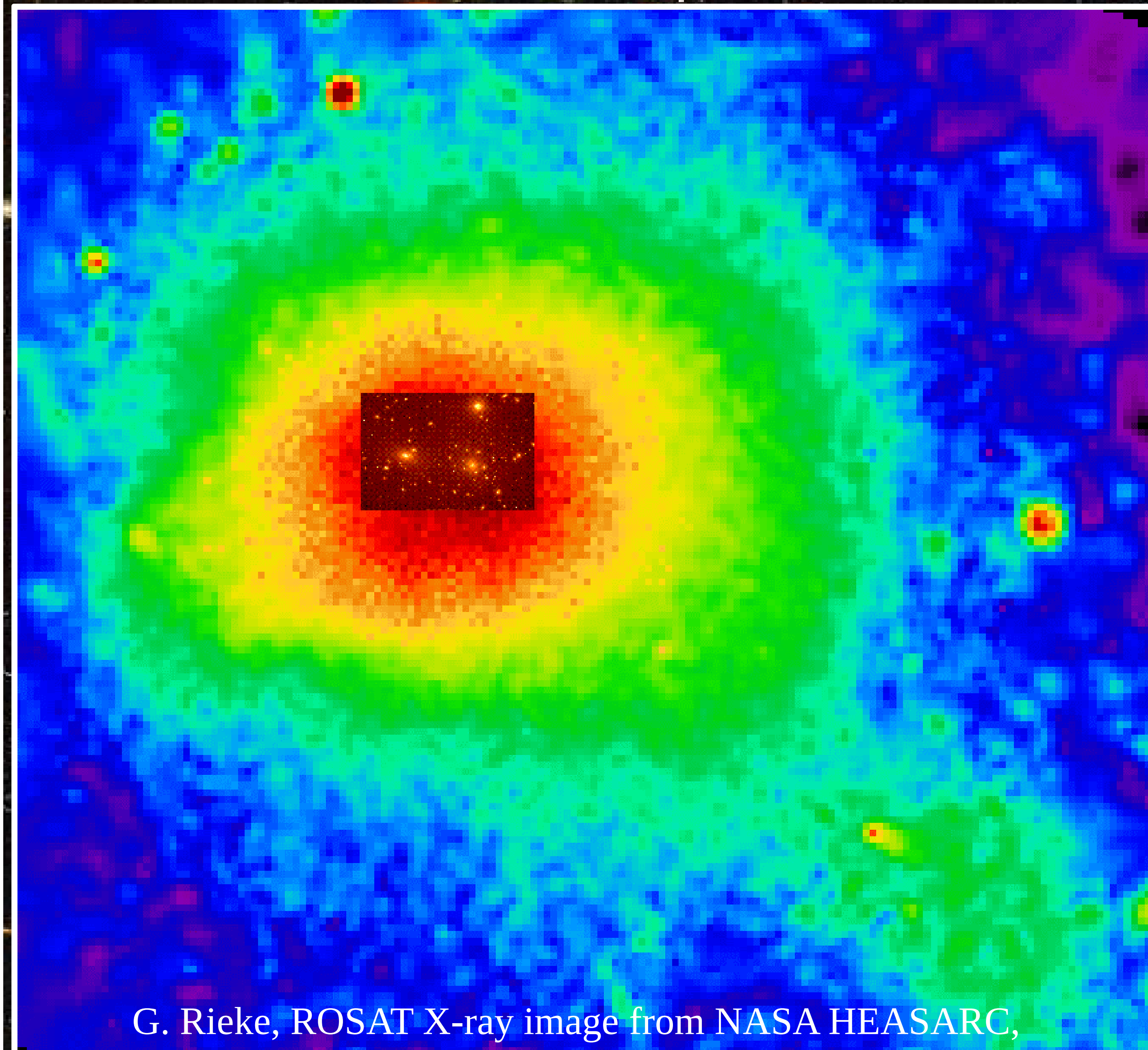
WMAP: $\Omega_B h^2 = 0.0229 \pm 0.00073$

Structure Formation



Kravtsov

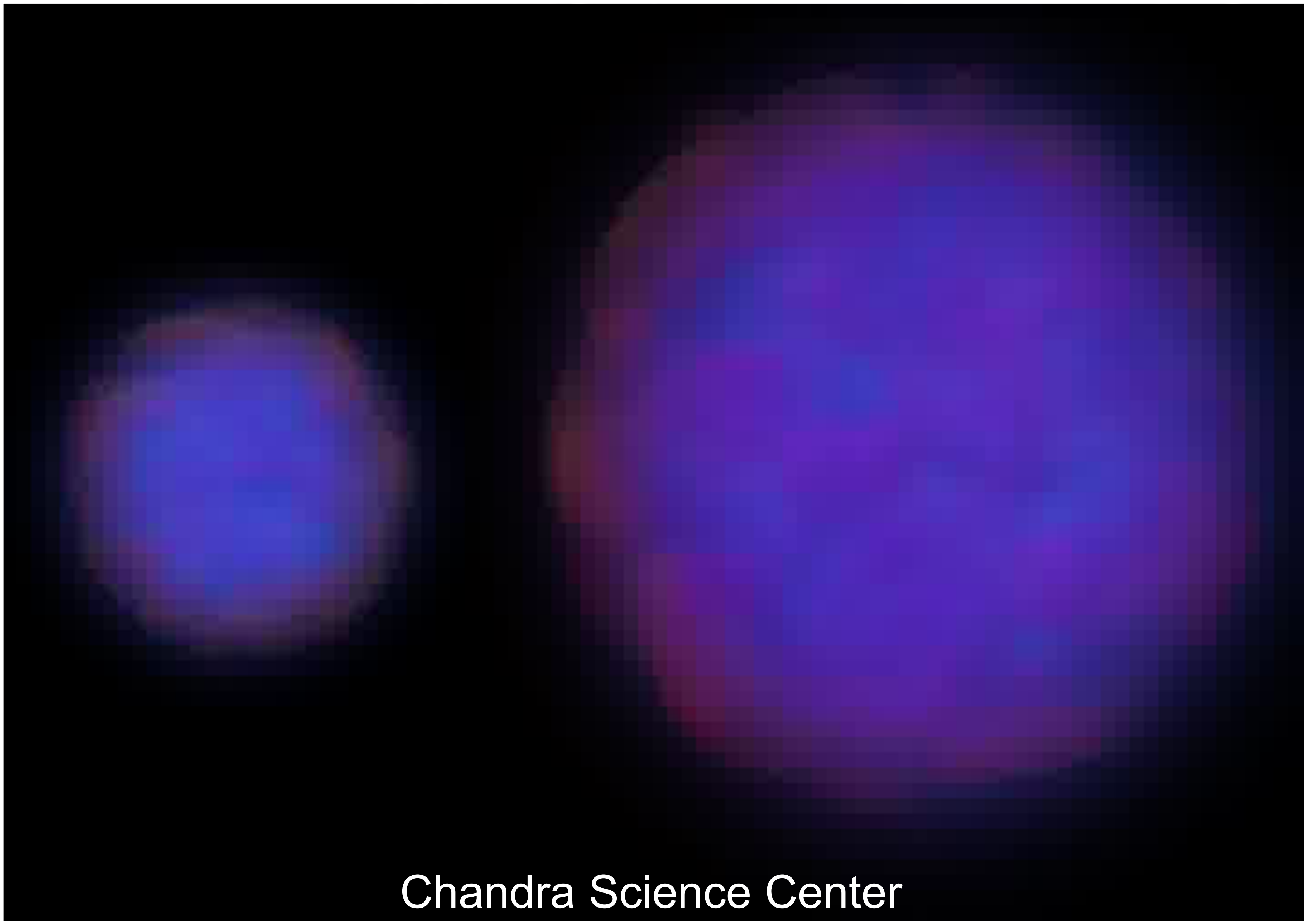
X-Ray Temperature of Galaxy Clusters



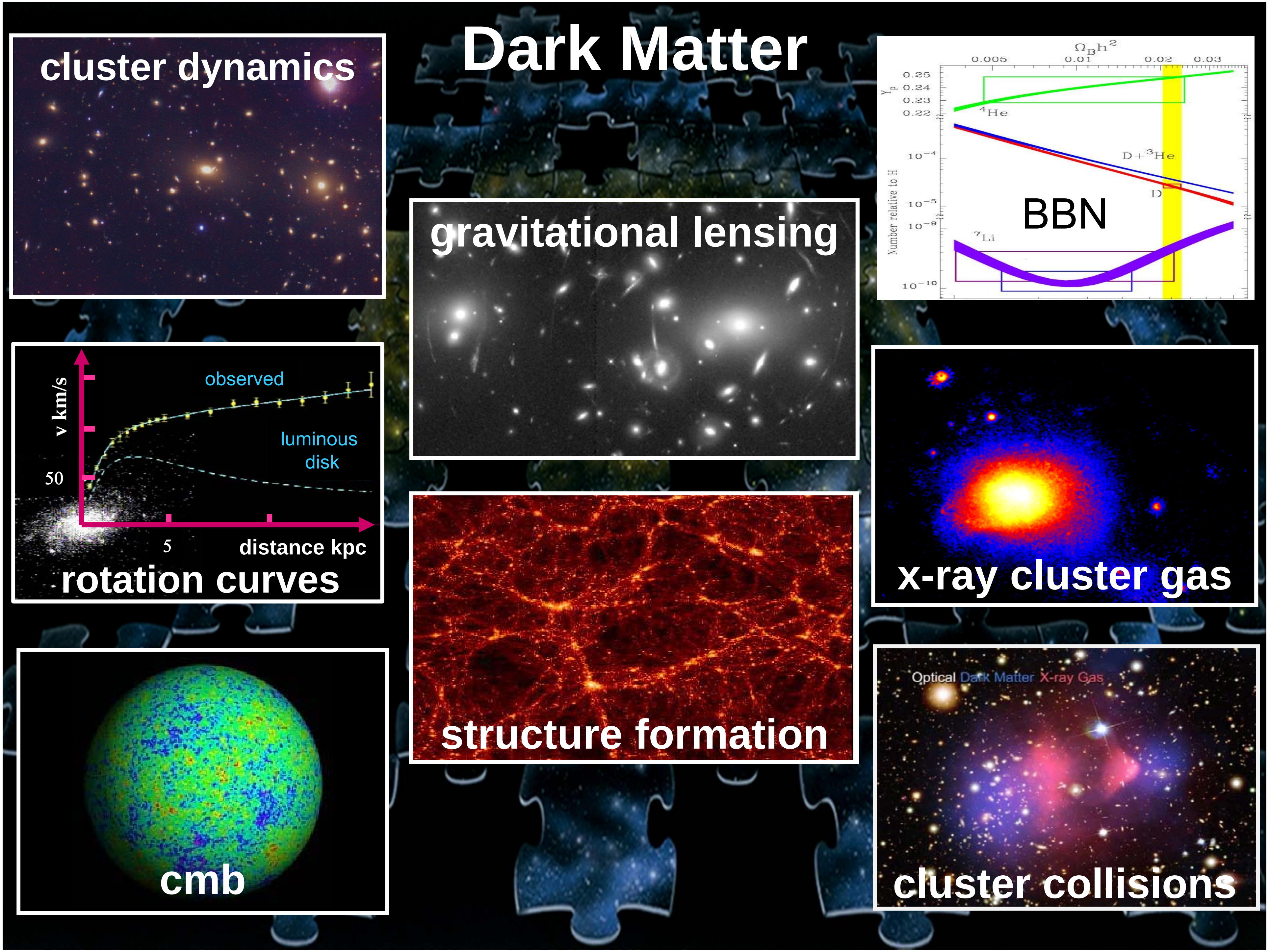
Coma cluster in X rays with visual image superimposed

X-Ray temperature measures depth of gravitational potential

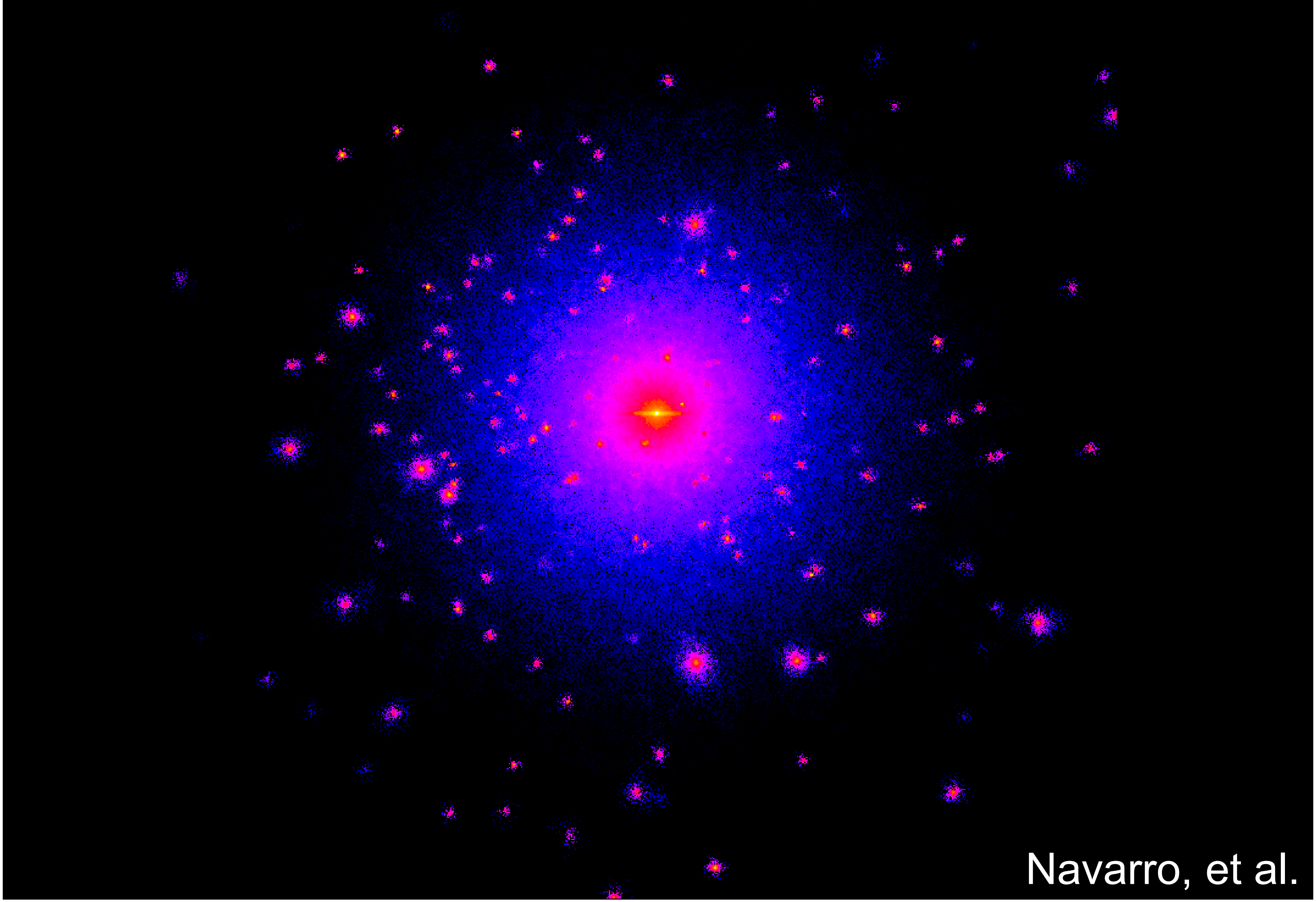
Dark Matter



Chandra Science Center


Dark Matter
cluster dynamics
gravitational lensing
ΩBh2
0.005
0.01
0.02
0.03
Yp
0.25
0.24
0.23
0.22
4He
10−4
D+3He
D
10−5
10−9
Number relative to H
7Li
10−10
BBN
v km/s
observed
luminous
disk
50
5
distance kpc
rotation curves
x-ray cluster gas
structure formation
cmb
Optical Dark Matter X-ray Gas
cluster collisions

Dark Matter



Navarro, et al.

simulation

SECOND EDITION 1989

Pronunciation | Spellings | Etymology | Quotations | Date chart

1. a. The action or practice of simulating, with intent to deceive; false pretence, deceitful profession.

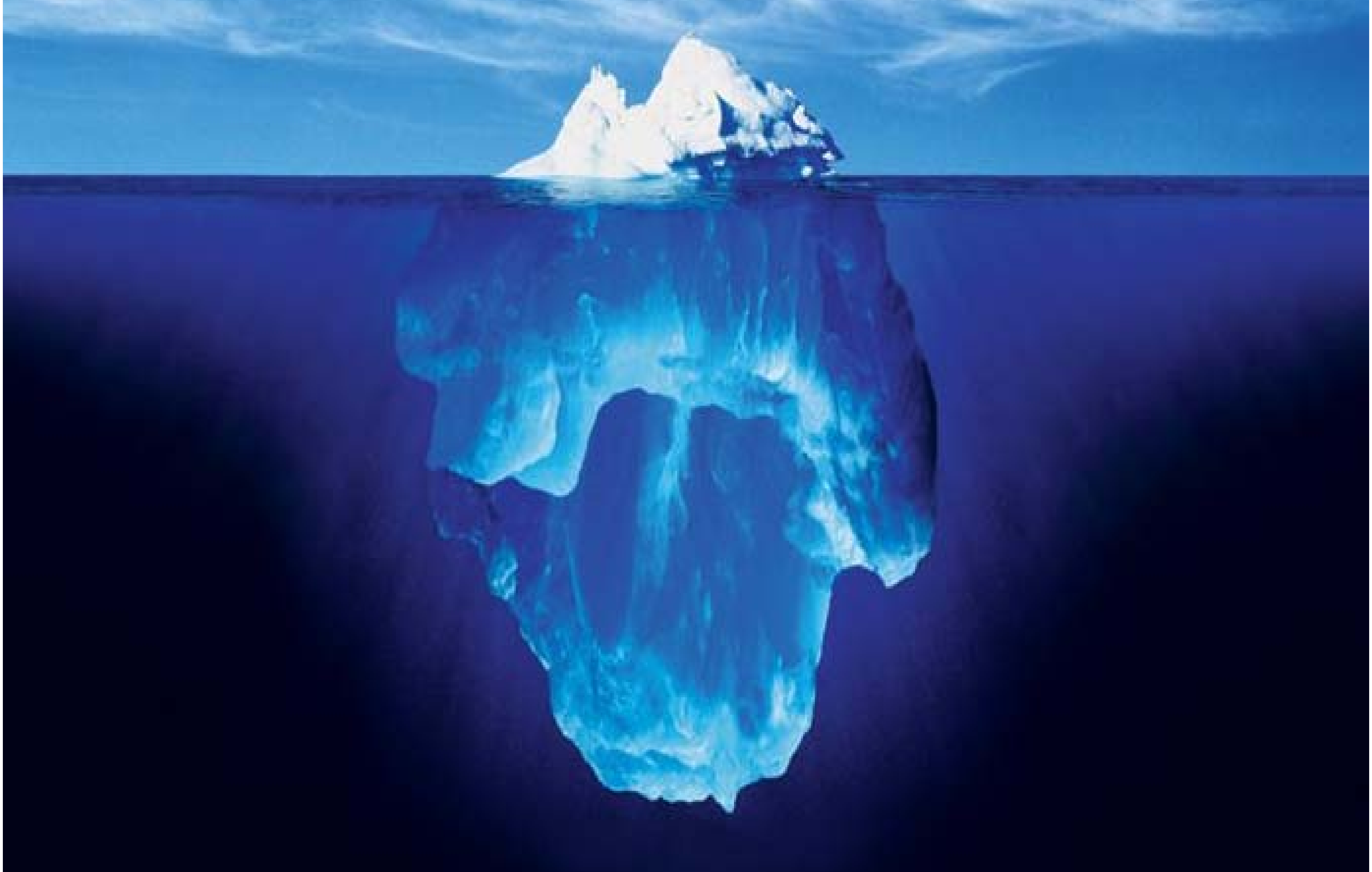
1340 *Ayenb.* 23 And þerof wexeþ uele zennes, ase ariȝthalf; þet is to wytene: lozengerie, simulacion. **c1400** *Rom. Rose* 7230 He nys no full good champioun That dredith such similacioun. **1412-20** LYDG. *Chron. Troy* IV. 4504 Amonge hem silfe to bringe in tresoun, Feyned trouþe and symulacioun. **1542** UDALL *Erasm. Apoph.* 170 He..did with mutual simulacion on his partie cover & kepe secrete the colorable dooyng of the saied feloe. **1577** tr. *Bullinger's Decades* (1592) 319 This precept doth commaunde vs..that..wee doe our neighbor harme..neither by simulation nor dissimulation. **1611** SPEED *Hist. Gt. Brit.* VI. (1632) 114 His nature relishing too much of the Punick craft and simulation. **1692** SOUTH *Serm.* (1697) I. 525 A Deceiving by Actions, Gestures, or Behaviour, is called Simulation, or Hypocrisie. **1711** STEELE *Tatler* No. 213 ¶1 Simulation is a Pretence of what is not, and Dissimulation a Concealment of what is. **1788** WESLEY *Wks.* (1872) VII. 43 Simulation is the seeming to be what we are not; dissimulation, the seeming not to be what we are. **1836** LANDOR *Pericles & Aspasia* Wks. 1846 II. 379, I wish he were as pious as you are: occasionally he appears so. I attacked him on his simulation. **1872** SHIPLEY *Gloss. Eccl. Terms* 71 Fraud.., whether it consists in simulation or dissimulation.

b. Tendency to assume a form resembling that of something else; unconscious imitation.

1870 MARCH *Anglo-Saxon Gram.* 28 *Simulation.* The feigning a connection with words of similar sound is an important fact in English and other modern languages: asparagus > sparrow-grass.

2. A false assumption or display, a surface resemblance or imitation, *of* something.

Dark Matter



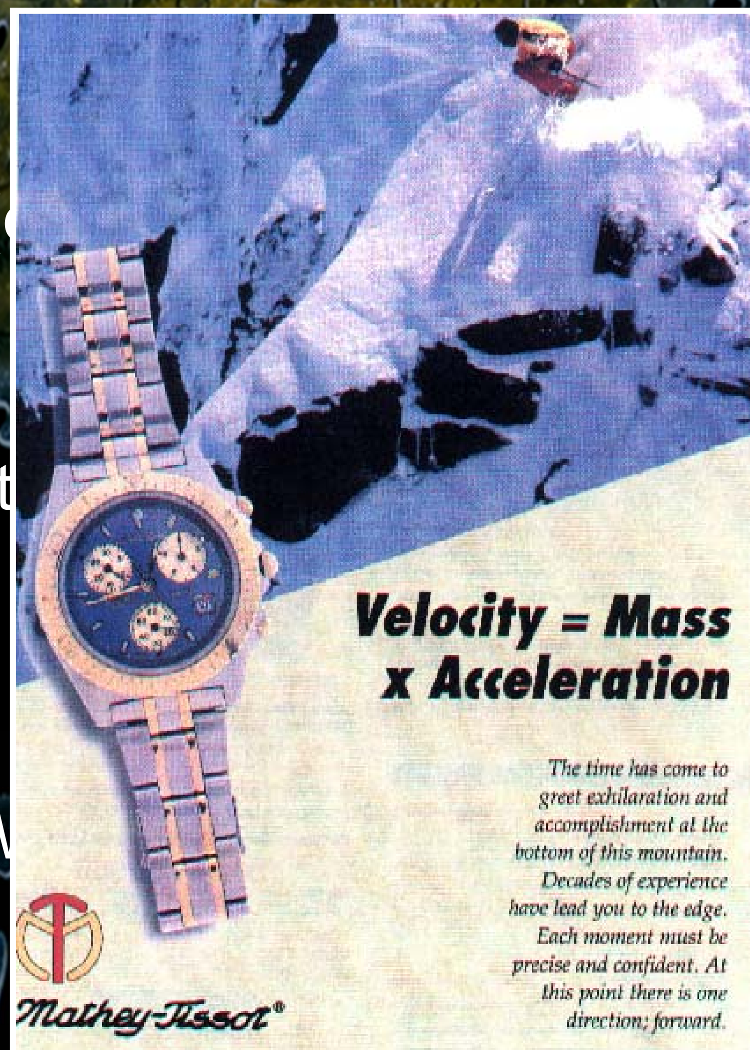
Most of the matter is dark and it's not even "normal" stuff!

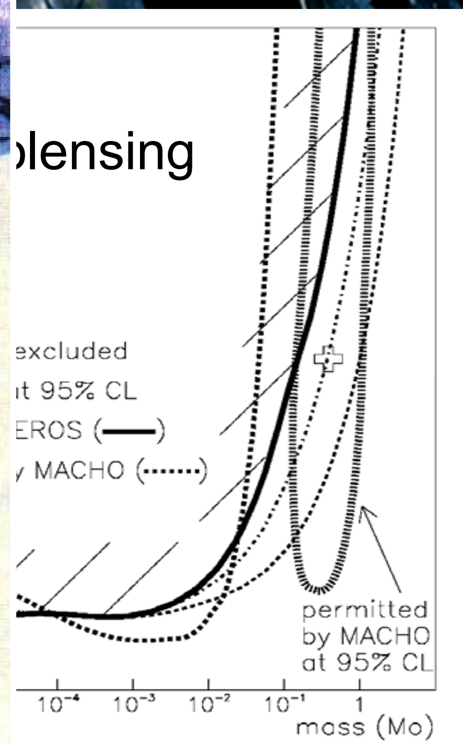
Dark Matter

- Modified Newtonian Dynamics
- Rogue Planets
- Mass challenged (c
- Black holes
- Particle relic from t

lensing

The W





Particle Dark Matter

- 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

Mass range

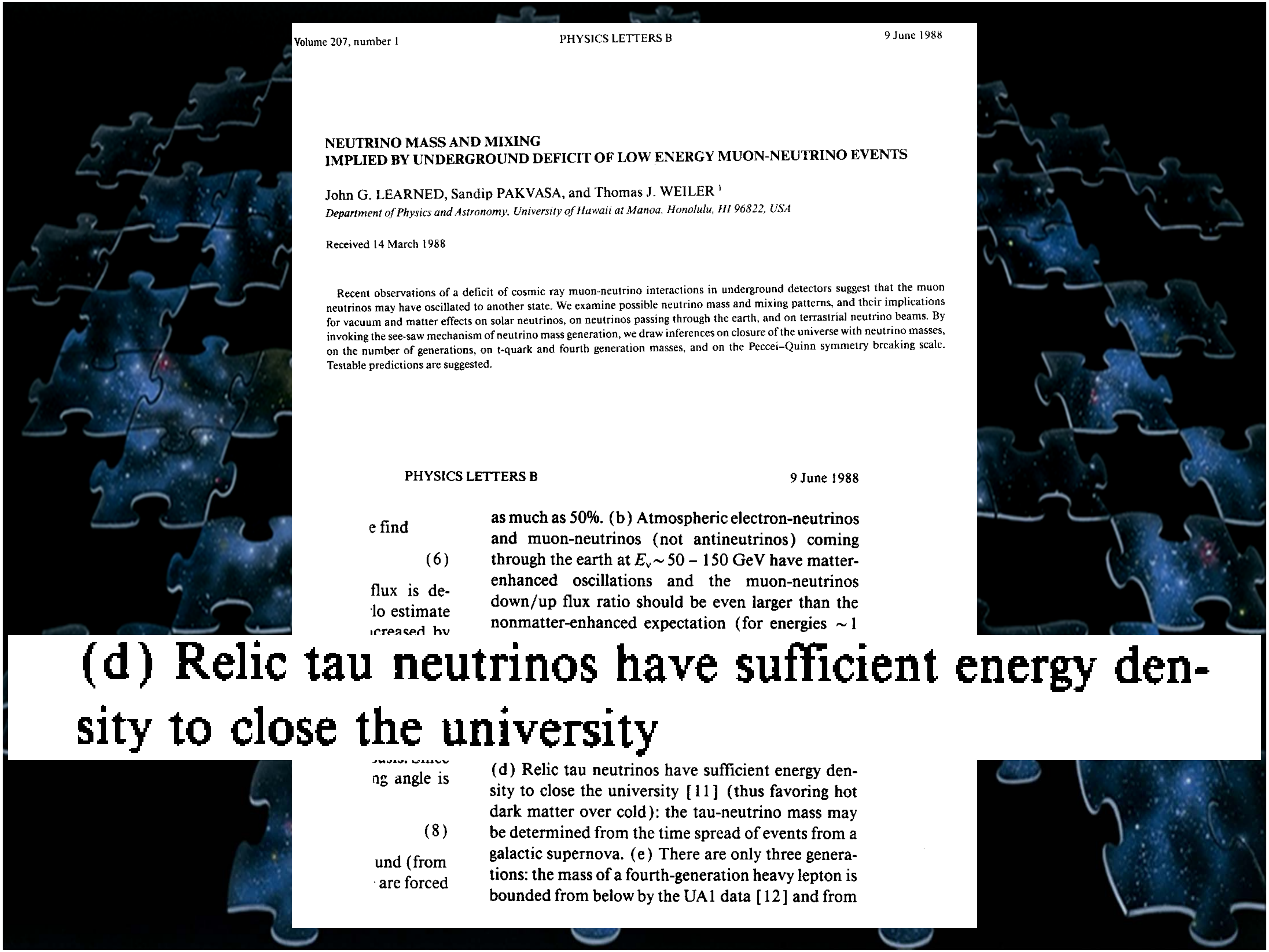
10^{-22} eV (10^{-56} g) B.E.C.s

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

Interaction strength range

Only gravitational: 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.

e find

(6)

flux is de-
lo estimate
creased by

ng angle is

(8)

und (from
are forced

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

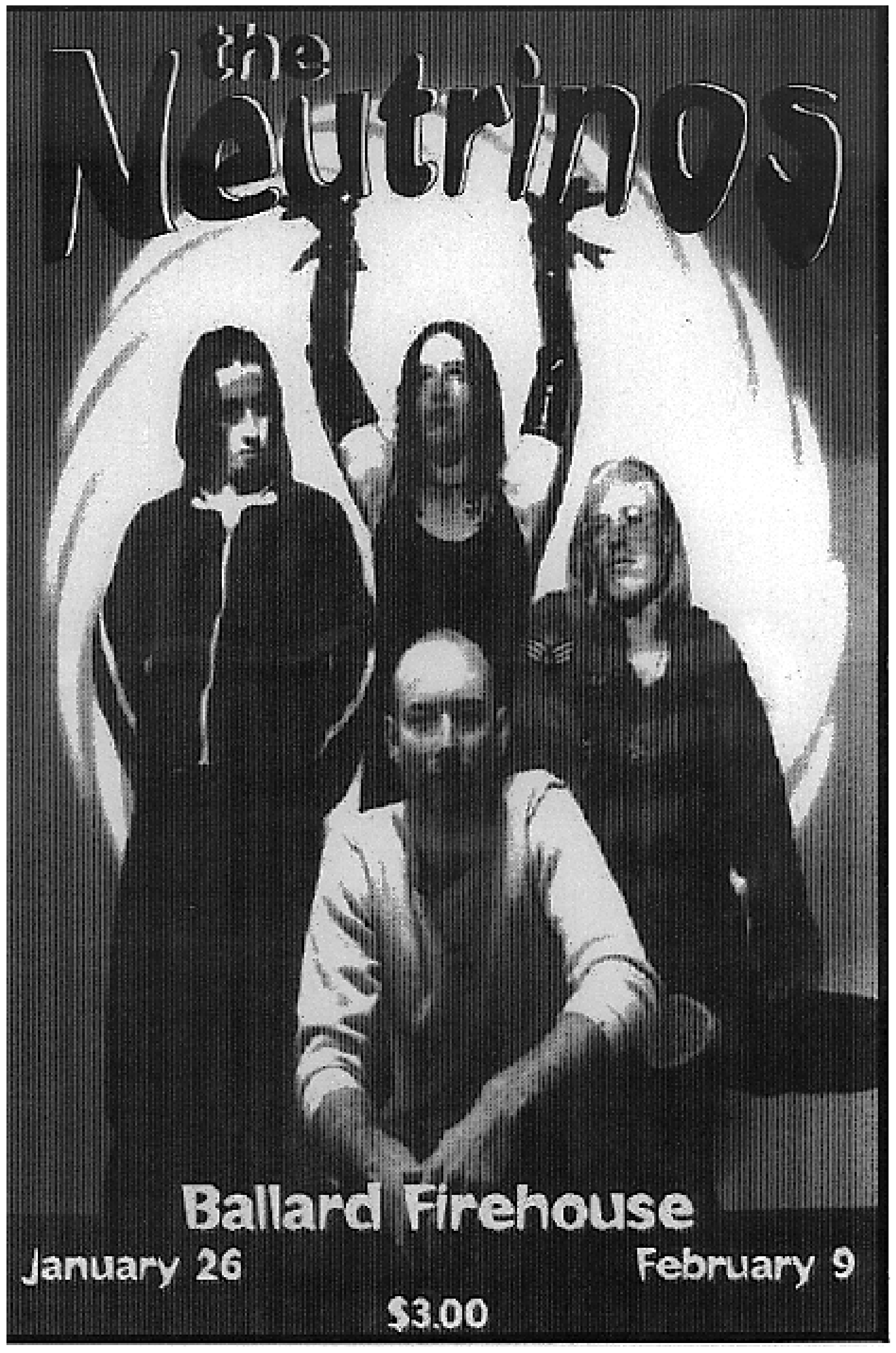
(d) Relic tau neutrinos have sufficient energy den-sity to close the university [11] (thus favoring hot dark matter over cold): the tau-neutrino mass may be determined from the time spread of events from a galactic supernova. (e) There are only three generations: the mass of a fourth-generation heavy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

WIMPy Neutrinos

- Neutrinos exist:
  three active + sterile?
- Neutrinos have mass:
  - Atmospheric (10^{-2} eV)
  - Solar (10^{-3} eV)
- Contribute to Ω
  hot thermal relic:

$$\Omega_{\nu\nu} \approx \frac{m_\nu}{47\ \text{eV}}$$

- Not most of dark matter
  too light! too hot!



Particle Dark Matter

- 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

Mass range

10^{-22} eV (10^{-56} g) B.E.C.s

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

Interaction strength range

Only gravitational: wimpzillas

Strongly interacting: B balls

WIMPy Sterile Neutrinos (or Gravitinos)

- weaker interactions
- decouple earlier
- diluted more
- can have larger mass
- smaller velocity than neutrinos: “warm”

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

Particle Dark Matter

- 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

Mass range

10^{-22} eV (10^{-56} g) B.E.C.s

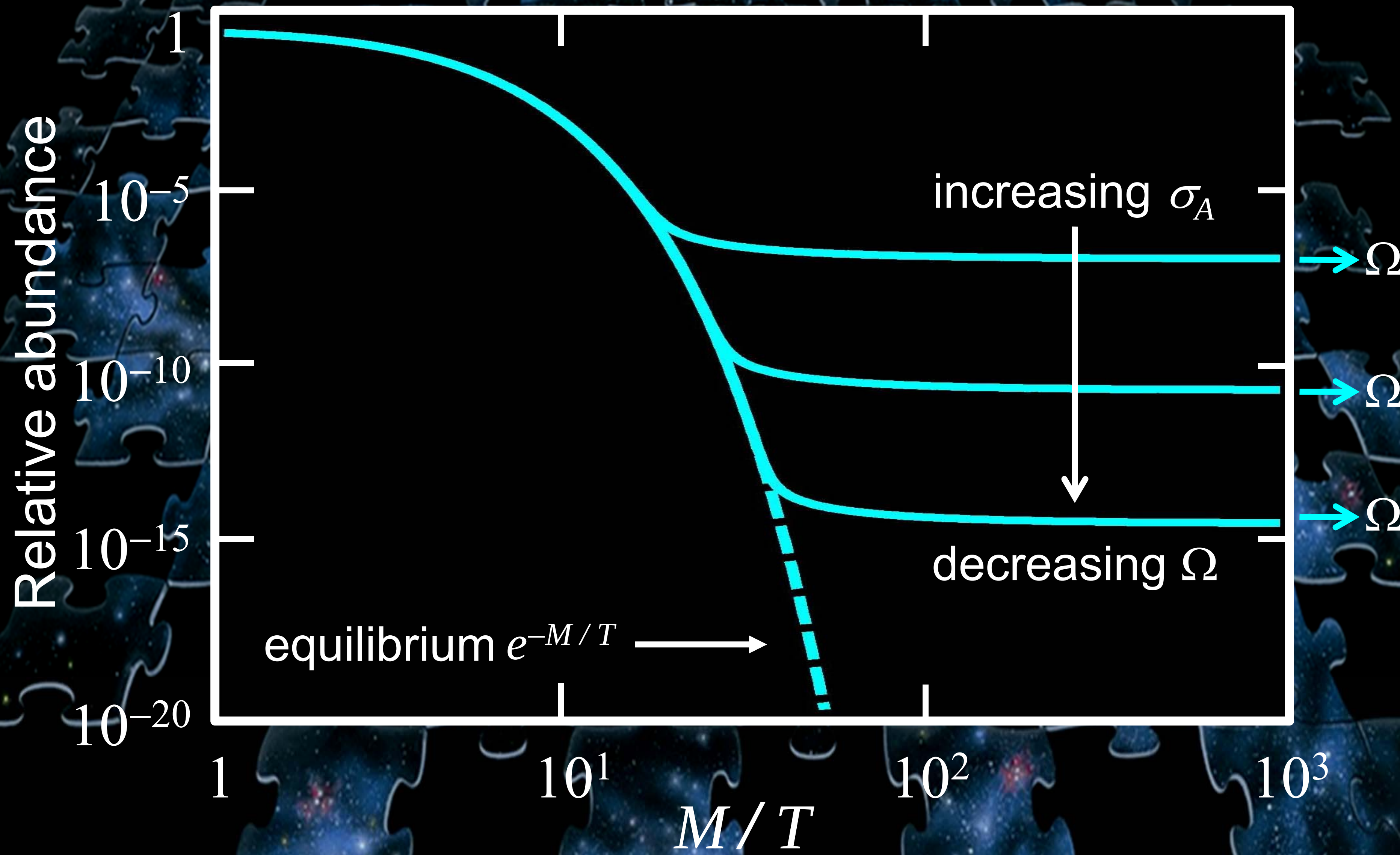
$10^{-8} M_{\odot}$ (10^{+25} g) axion clusters

Interaction strength range

Only gravitational: wimpzillas

Strongly interacting: B balls

Cold Thermal Relics*



* An object of particular veneration.

Fermi National Accelerator Laboratory

FERMILAB-Pub-77/41-THY
May 1977

Cosmological Lower Bound on

Heavy Neutrino Masses

BENJAMIN W. LEE *
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

AND

STEVEN WEINBERG **
Stanford University, Physics Department, Stanford, California 94305

ABSTRACT

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.

** On leave 1976-7 from Harvard University.

* Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration

Ben Lee (1935 — June 1977)

Steve Weinberg

$$\frac{dn}{dt} = -\frac{3\dot{R}}{R}\,n - \langle\sigma v\rangle n^2 + \langle\sigma v\rangle n_0{}^2 \; . \qquad (2)$$

Here n is the actual number density of heavy neutrinos at time t; R is the cosmic scale factor; $\langle\sigma v\rangle$ is the average value of the $L^0\bar{L}^0$ annihilation cross-section times the relative velocity and n_0 is the number density of heavy neutrinos in thermal (and chemical) equilibrium[6]:

$$n_0(T) = \frac{2}{(2\pi)^3}\int_0^\infty 4\pi p^2 dp\left[\exp\left((m_L{}^2+p^2)^{\frac{1}{2}}/kT\right)+1\right]^{-1} \; . \qquad (3)$$

(We use units with $\hbar$=c=1 throughout.)

At the temperatures we are considering here, the energy

$$\frac{dn}{dt} = -\frac{3\dot{R}}{R}\,n - \langle\sigma v\rangle n^2 + \langle\sigma v\rangle n_0{}^2$$

where ρ is the energy density

$$\rho = N_F a T^4 = N_F \pi^2 (kT)^4/15 \qquad (5)$$

with N_F an effective number of degrees of freedom, counting ½ and 7/16 respectively for each boson or fermion species and spin state. For temperatures in the range of 10-100 MeV (which most concern us here) we must include just $\gamma, \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, e^-$, and e^+, so N_F = 4.5, a value we will adopt for most purposes. However, if current ideas about the strong interactions are correct, then N_F rises steeply at a temperature of order 500 MeV to a value[7] $N_F \approx 30$.

To estimate $\langle\sigma v\rangle$, we note that the heavy neutrinos must be quite non-relativistic at the temperature T_f where they freeze

$$\langle \sigma v \rangle \approx G_F^2 m_L^2 N_A / 2\pi$$

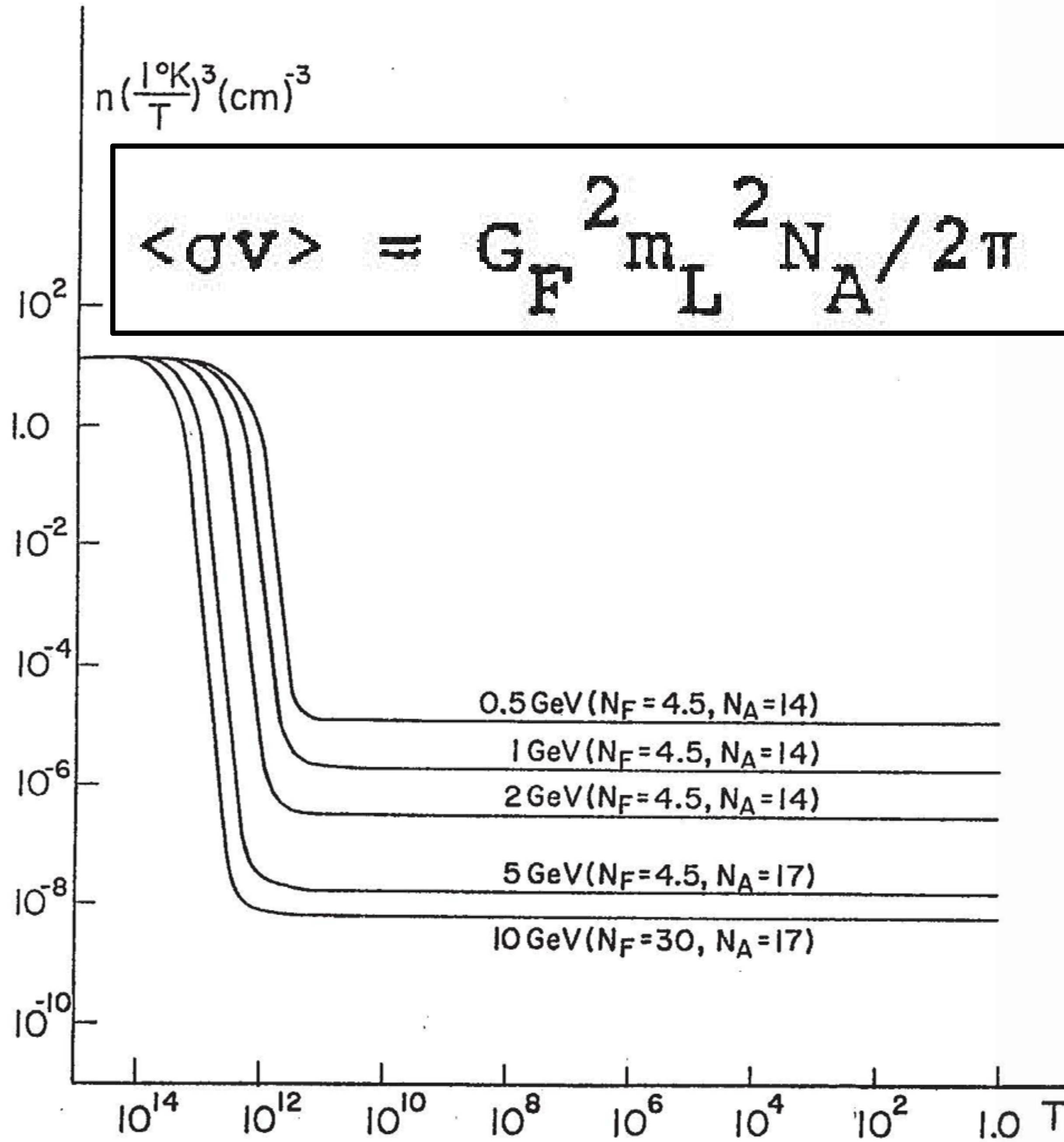


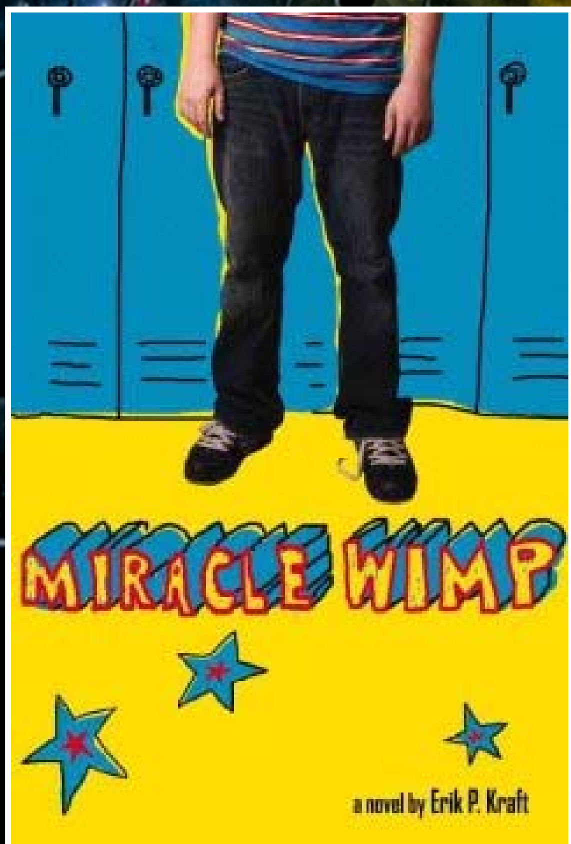
FIG. 1

Cold Thermal Relics Are WIMPs

$\Omega \Rightarrow$ Cross section (& mass ?) of order weak scale

WIMP (Weakly Interacting Massive Particle)

The WIMP Miracle



Merriam-Webster
Merriam-Webster OnLine

mir·a·cle
\ˈmir-i-kəl \
noun

1 : an extraordinary event manifesting divine intervention in human affairs

Coincidence or Causation?

WIMPs

Goal: Discover dark matter and its role in shaping the universe

Particle Physics:

Discover dark matter and learn how it is …

… grounded in physical law

… embedded in an overarching physics model/theory

Astro Physics:

Understand the role of dark matter in …

… formation of structure

… evolution of structure

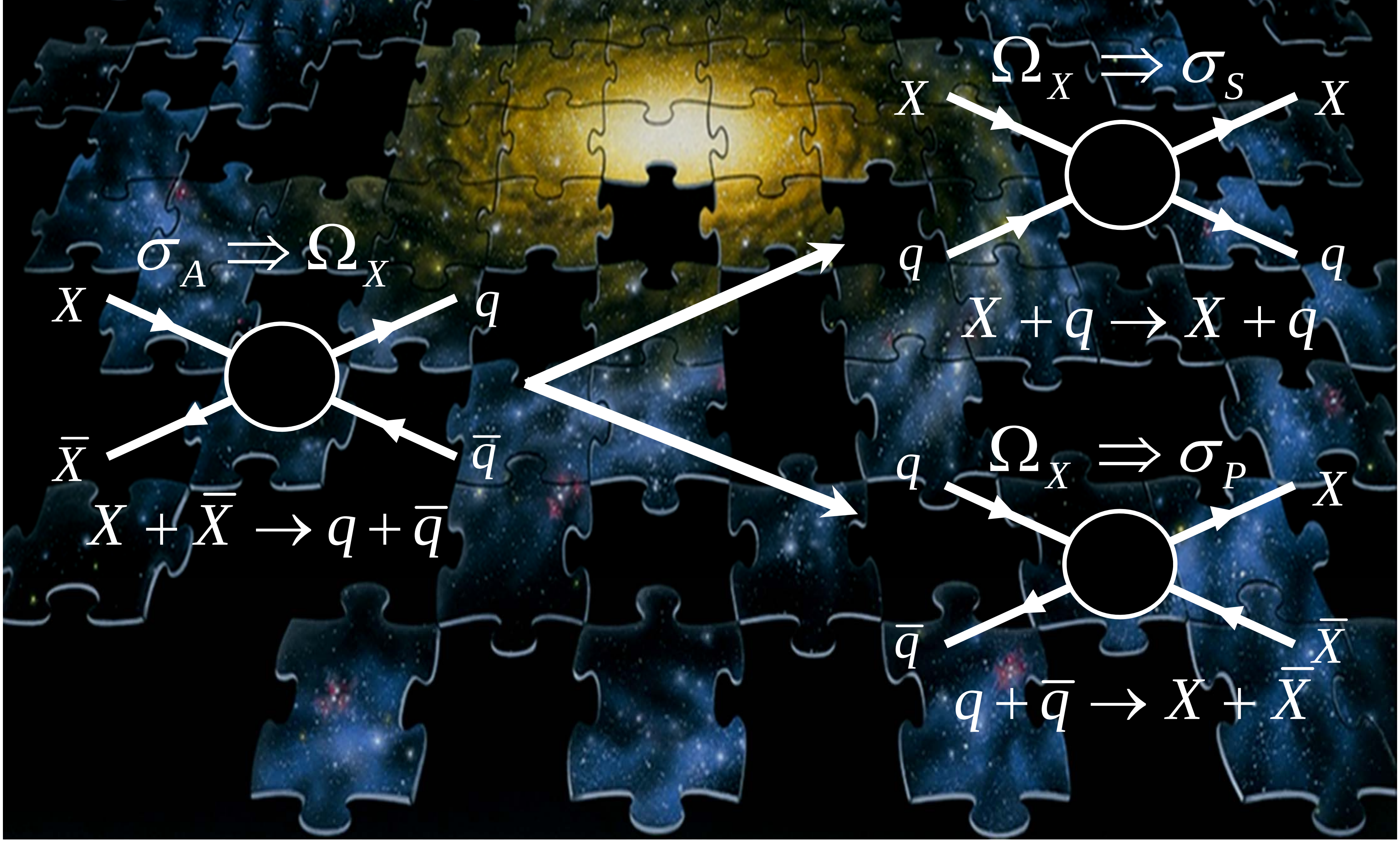
WIMPs:

massive, stable, “weakly” interacting, $SU(3)_C \times U(1)_{EM}$ singlet

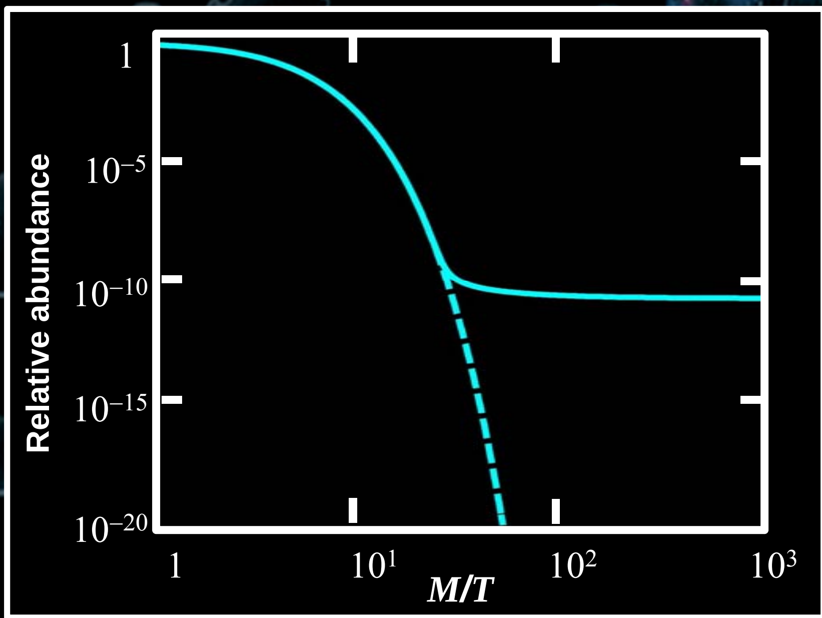
WIMP must be a *BSM* (but perhaps not far BSM) particle.

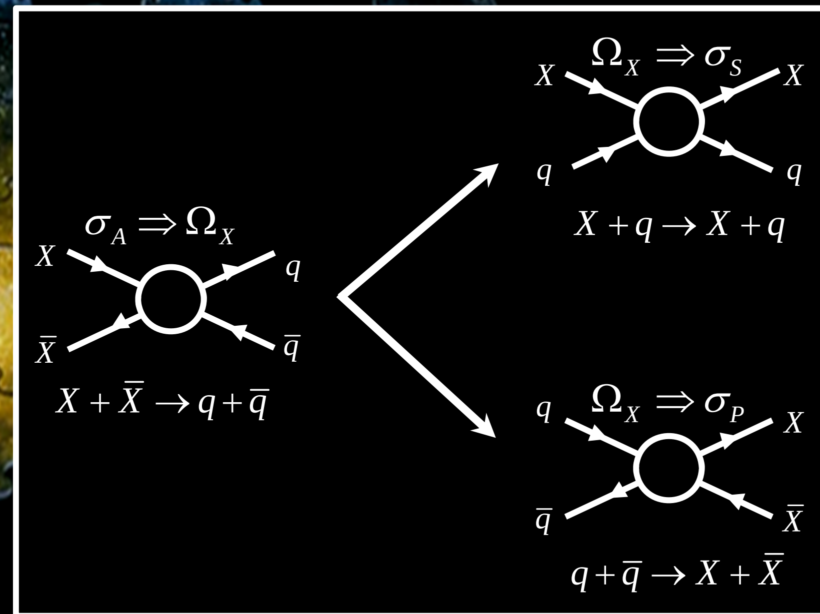
WIMPs

Too good to be true?



WIMPs





Not quite so simple:

- velocity dependence
- co-annihilation
- resonances
- superwimps
- dependence on M, g_*,
- …

Not quite so simple:

- velocity dependence
- local phase-space density
- flavor dependence
- co-production
- Sommerfield enhancement
- …

Nuclear Physics B238 (1984) 453–476

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

John ELLIS and J. S. HAGELIN

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, USA

D. V. NANOPOULOS, K. OLIVE[†], and M. SREDNICKI[‡]

CERN, CH-1211 Geneva 23, Switzerland

Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predomi-

SUSY WIMPs

Favorite cold thermal relic: the neutralino

Neutralino:

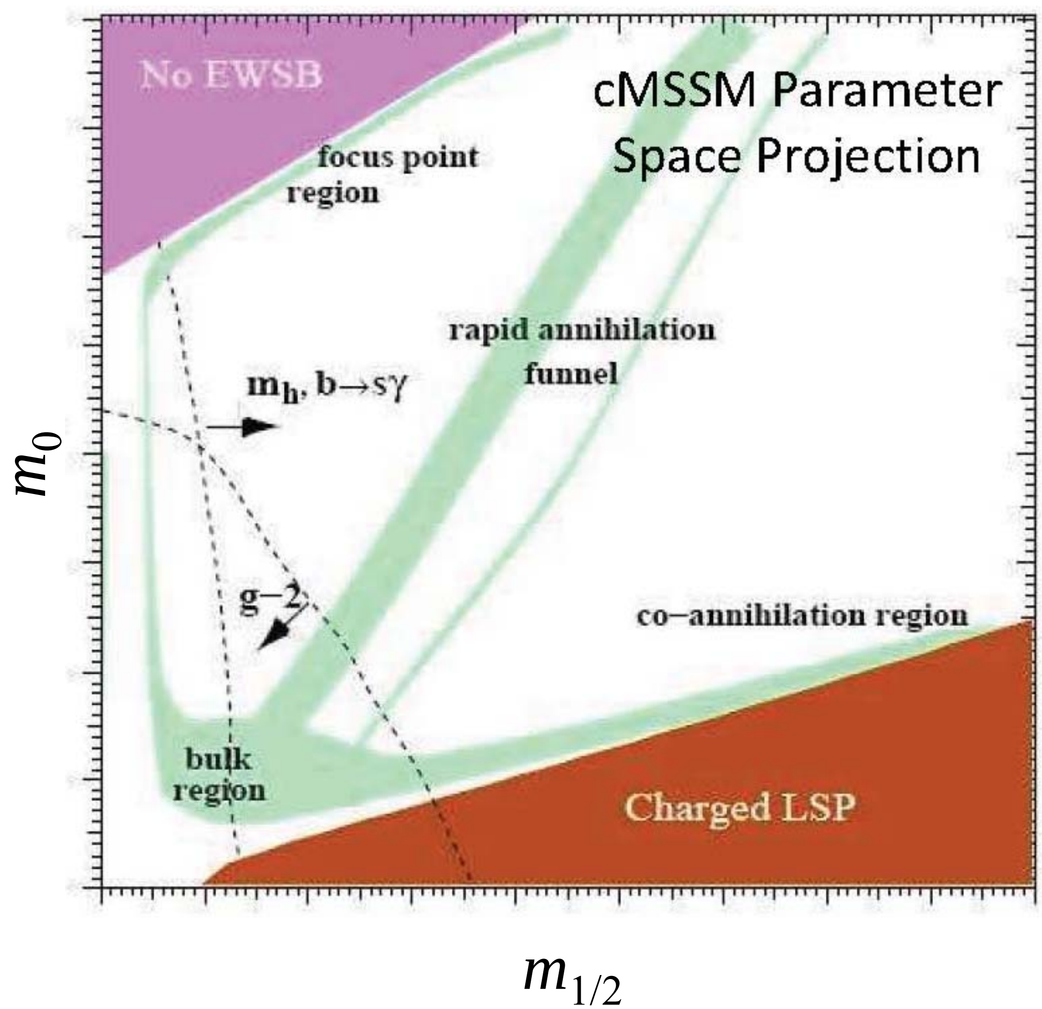
$$\tilde{\chi}^0 = \alpha \tilde{B} + \beta \tilde{W}^3 + \gamma \tilde{H}_1^0 + \delta \tilde{H}_2^0$$

$m_{\tilde{\chi}^0}$ and interactions:

100+ parameters of SUSY

cMSSM

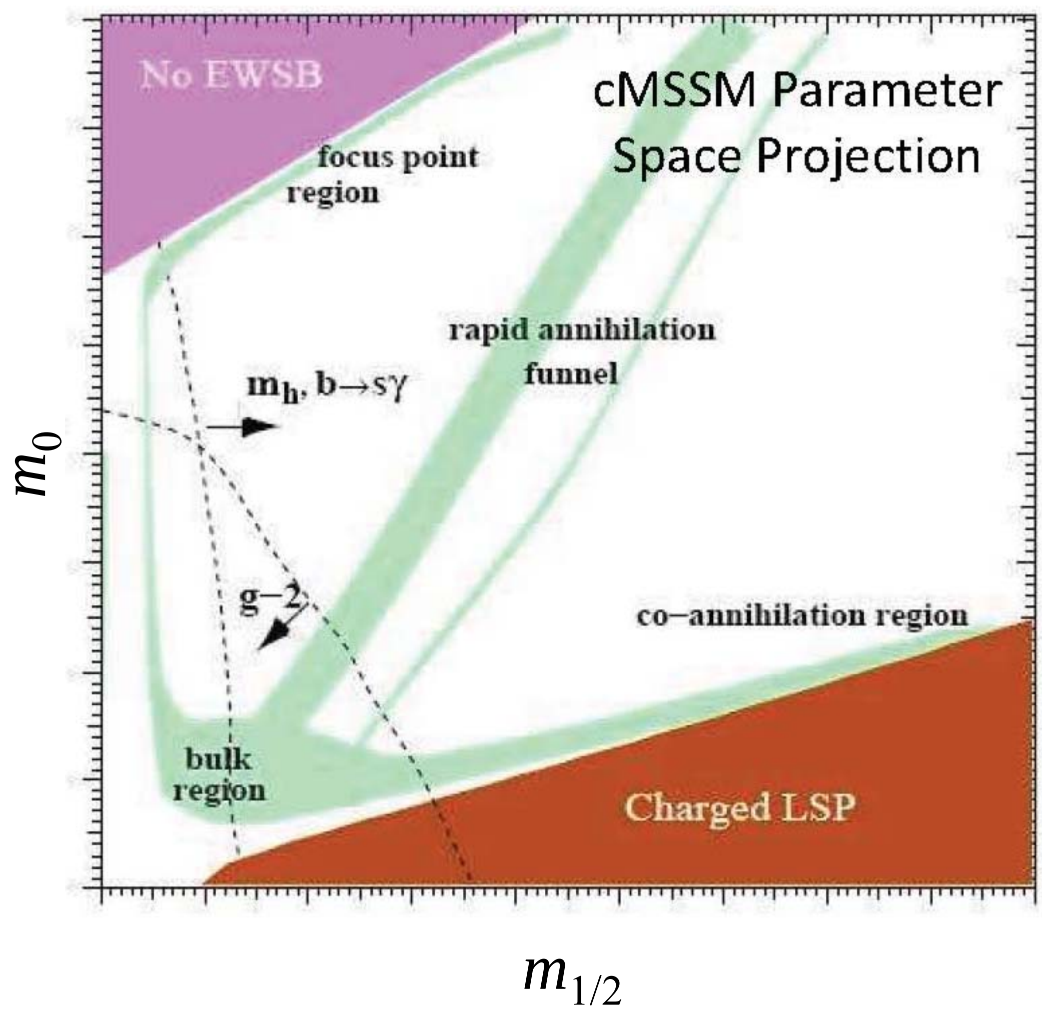
m_0 , $m_{½}$, $\tan\beta$, A_0 , sign μ



Ellis, Olive, Santoso, Spanos 2003

SUSY WIMPs

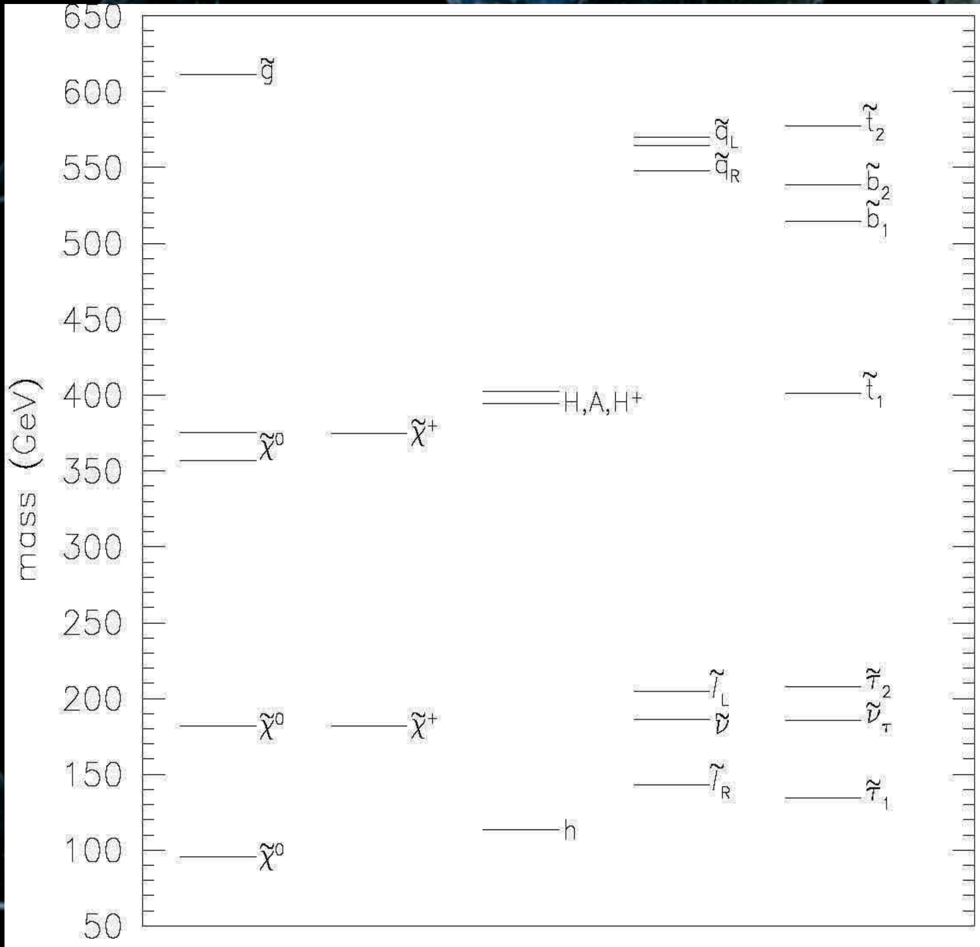
- Typical SUSY models consistent w/ collider and other HEP data have too small annihilation cross section → too large Ω
- Need chicanery to increase annihilation cross section
  - s-channel resonance through light H and Z poles
  - co-annihilation with $\tilde{\tau}$ or $\tilde{t}$
  - large tanβ (s-channel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

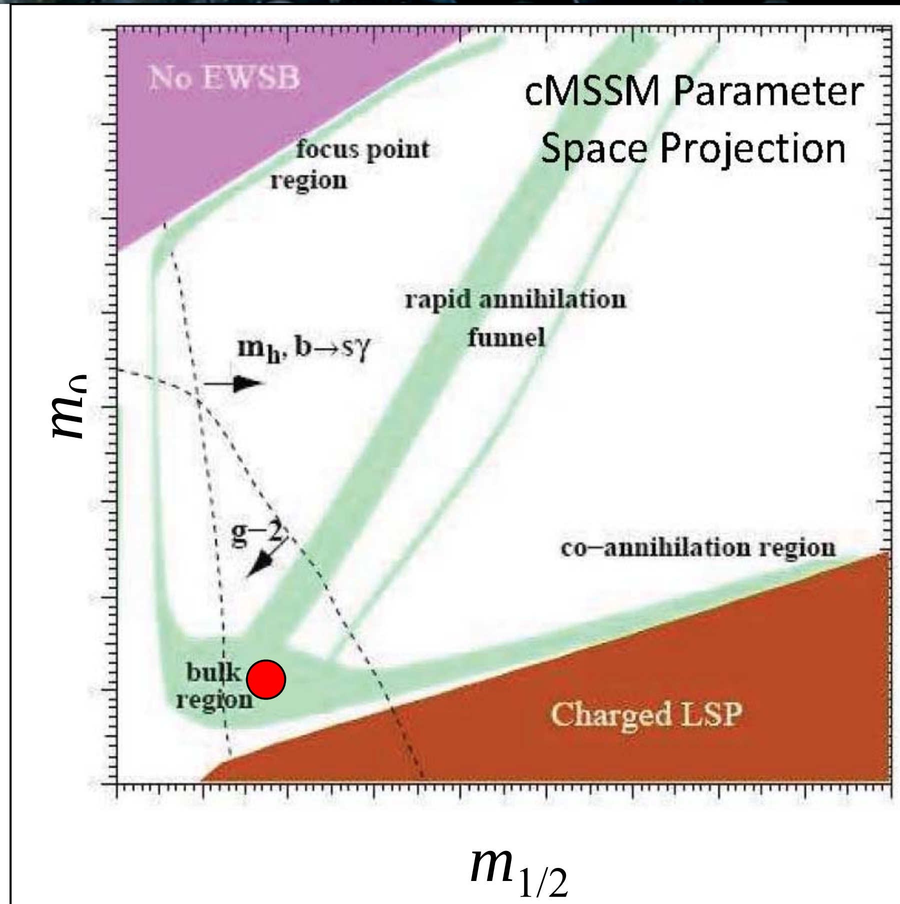


Ellis, Olive, Santoso, Spanos

SUSY WIMPs

Bulk Region: light superpartners





Ellis, Olive, Santoso, Spanos

LHC chewing away at allowed region, but too early to throw in the towelino.

Kaluza-Klein WIMPs

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

$S^1 \times M^4$

Quantized Kaluza-Klein excitations

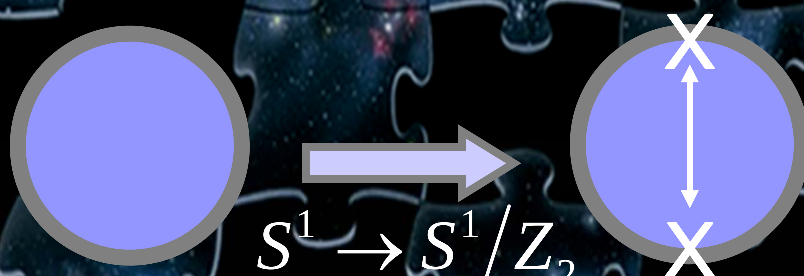
$$E^2 = \vec{p}^{\,2} + p_5^2 = \vec{p}^{\,2} + M_n^2$$

$$p_5^2 = n^2/R^2 \qquad M_n^2 = n^2/R^2$$

Conservation of momentum ⟶ conservation of KK mode number

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

need chiral fermions



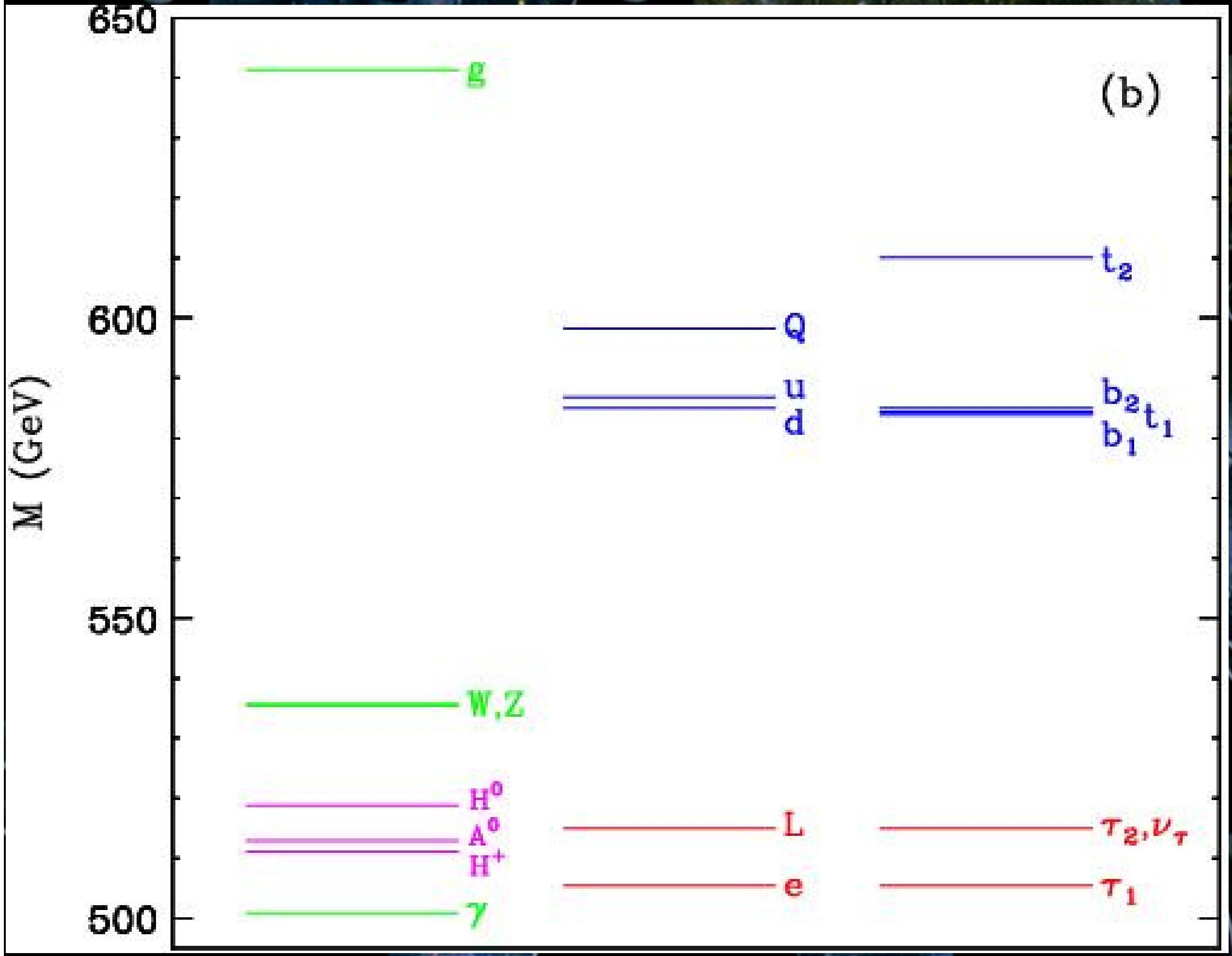
$S^1 \to S^1/Z_2$

KK quantum number ⟶ KK parity

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

Kaluza-Klein WIMPs

$R^{-1} = 500$ 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

LHC chewing away at allowed region