Two Lectures on

The Standard Cosmology

Rocky Kolb—University of Chicago

The observed universe

The cosmic symphony

Where to start?

- The beginning and work forward?
- Today and work backwards?
- Historical developments?

Classical issues with the Standard Model

- Age
- Flatness
- Unwanted relics
- Why homo/iso

Inflation

- Density perturbations and gravitational waves
- Reheating

Dark Matter

- Evidence
- Particle Dark Matter
- Freeze-in/Freeze-out
- Axions, Axion-like particles

Dark Energy

- Evidence
- If Λ, why so small?

BBN

- Limits on neutrino properties

CMB

- Temperature
- Sound Horizon

Relativistic Cosmology

- Lightning Review of GR
- The Cosmological Principle
- Einstein's Static Universe
- Friedmann Blows Up the Universe
- Friedmann Equation
- Lemaitre rediscovers Friedmann
- Einstein Becomes a Big Banger

Thermal History

- A primer on Thermodynamics

The Program

Rocky I

The Universe Observed
Energy and pressure
The Friedmann equation
<u>Primordial</u> origin of Dark Matter #

Rocky II

<u>Primordial</u> Inflation
Baryo/Leptogenesis
CMB*
Dark Energy †

Matt Pyle
* Adrian Lee
† Dave Schlegel

Some Reference Texts

Baumann, *Cosmology*

Dodelson, *Modern Cosmology*

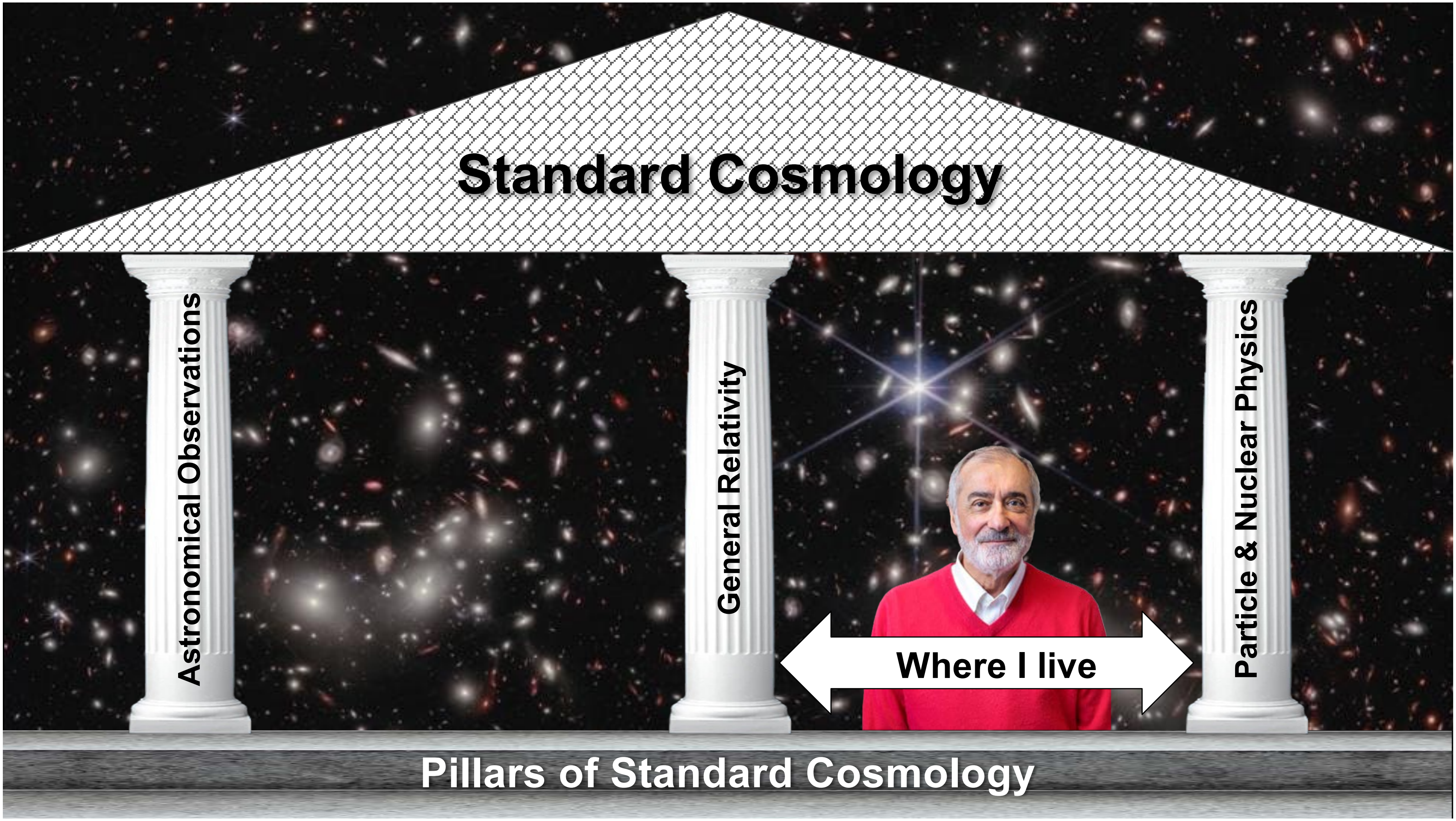
Hooper, *Particle Cosmology & Astrophysics*

Kolb & Turner, *The Early Universe*

Lyth and Liddle, *The Primordial Density Perturbation*

Mukhanov, *Physical Foundations of Cosmology*

Weinberg, *Cosmology*


Standard Cosmology
Astronomical Observations
General Relativity
Particle & Nuclear Physics
Where I live
Pillars of Standard Cosmology

The Standard Cosmology (ΛCDM)

- Gravity described by General Relativity.
- Big Bang: Universe emerged from a state of high density, energy, and temperature a finite time in the past, expanding according to Einstein's equations.
- Λ: Einstein's Cosmological Constant (dark energy).
- CDM: Cold Dark Matter.
- An inflationary era very early in the expansion history that set the primordial temperature and density perturbations.
- The standard model of particle and nuclear physics (+ DM + DE + inflation).
- Primordial density perturbations grew via gravitational instability (aided by dark matter) to form large-scale structure.

Cosmic Symphony (Harmonice Mundi)

expansion tempo	movement	epoch	relic
pizzicato	string	$t_{\text{Planck}} = 10^{-43}\text{s}$	???
presto	inflation	$t_{\text{inflation}} = 10^{-35}\text{s}$	CMB fluctuations gravitational waves seeds of structure
allegro	radiation	earlier than 60,000 years	abundances of the light elements
andante	matter	later than 60,000 years	growth of structure: galaxies, clusters,…
largo	inflation	day before yesterday	acceleration of the universe

The Standard Cosmology (ΛCDM)

- Most predictive cosmological model, in agreement with (almost) all observational data.

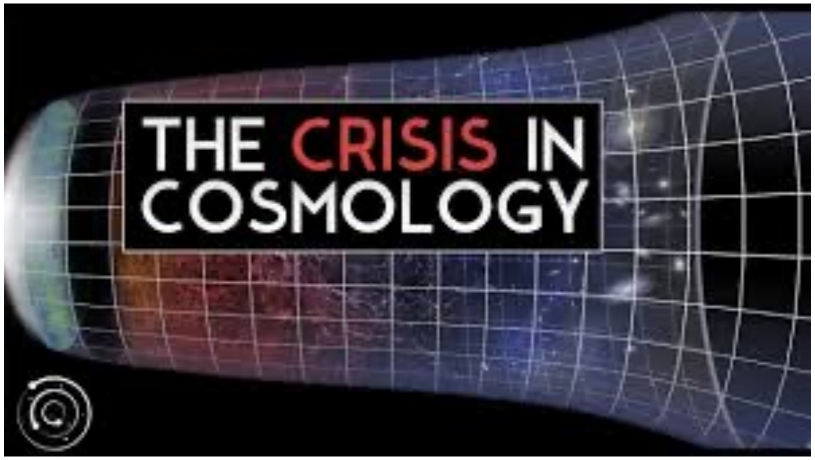
- But not without issues and questions:

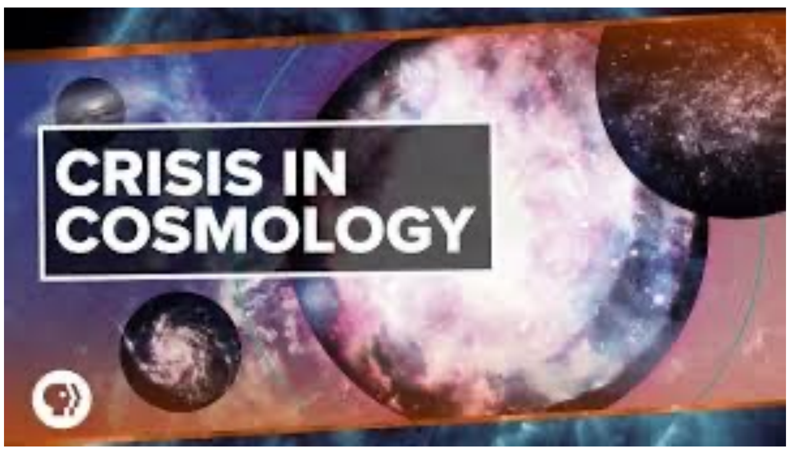
  - 95% of the present universe is dark energy and dark matter, which we don't understand. (Beyond the Standard Model of particle physics.)

  - Cosmic inflation is phenomenological success, but without grounding in a fundamental theory. (Beyond the Standard Model of particle physics.)

  - Why is there a universe, why are there only 3 spatial dimensions, why did structure form so early, …?

- But premature to say, "Cosmology is in Crisis."


THE CRISIS IN
COSMOLOGY


CRISIS IN
COSMOLOGY


PBS
THE NEW CRISIS
IN COSMOLOGY

The New York Times

OPINION

GUEST ESSAY

The Story of Our Universe May Be Starting to Unravel

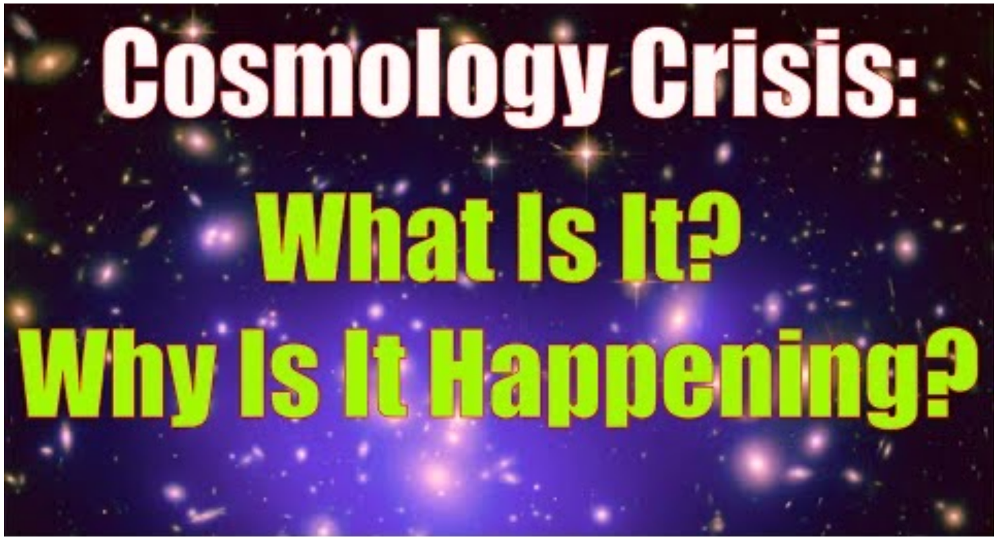
Sept. 2, 2023

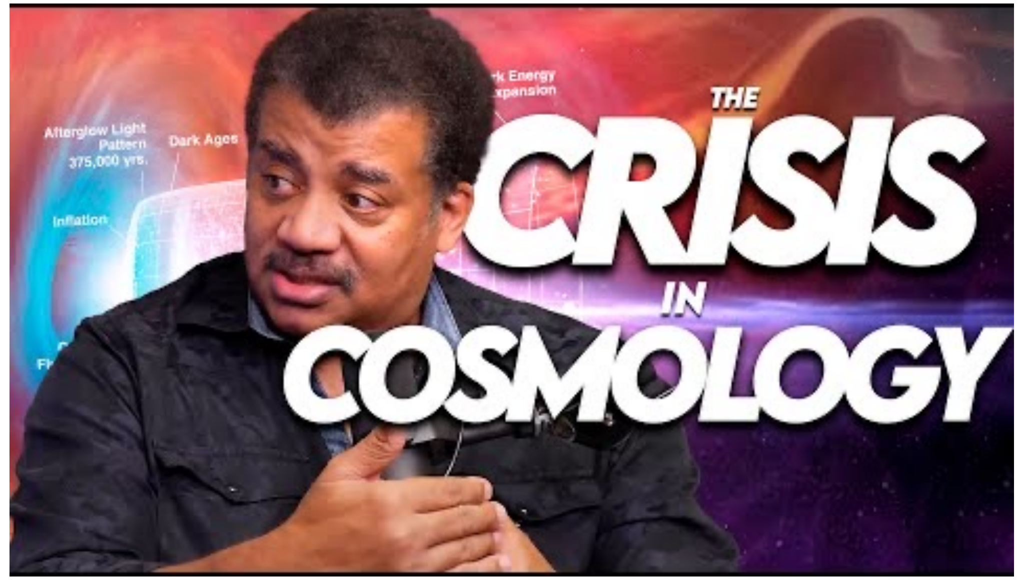
Virginia Gabrielli

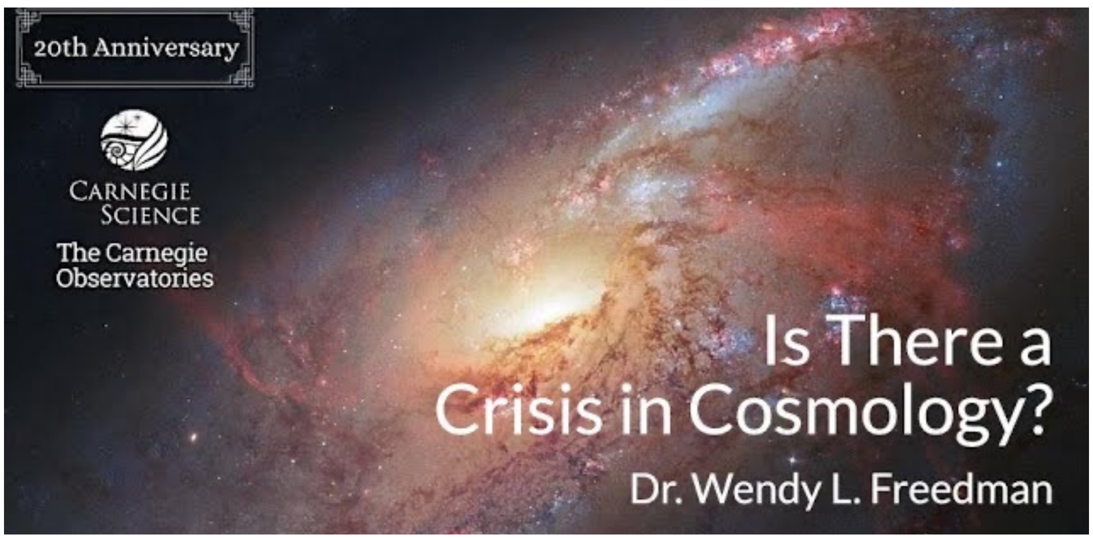
By Adam Frank and Marcelo Gleiser

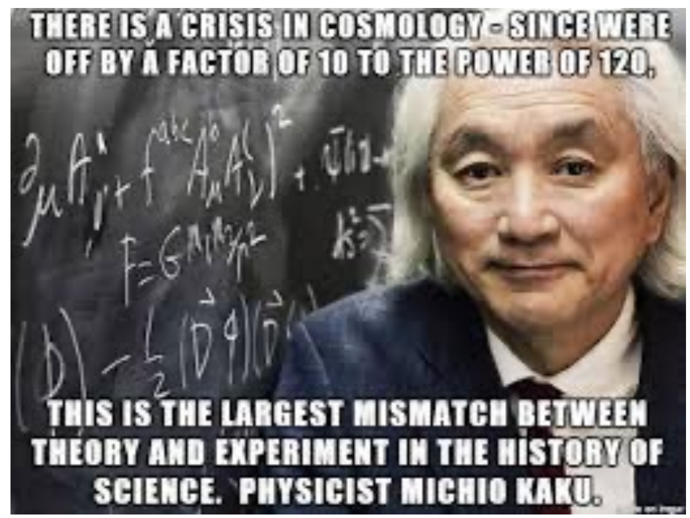
Dr. Frank is an astrophysicist at the University of Rochester.

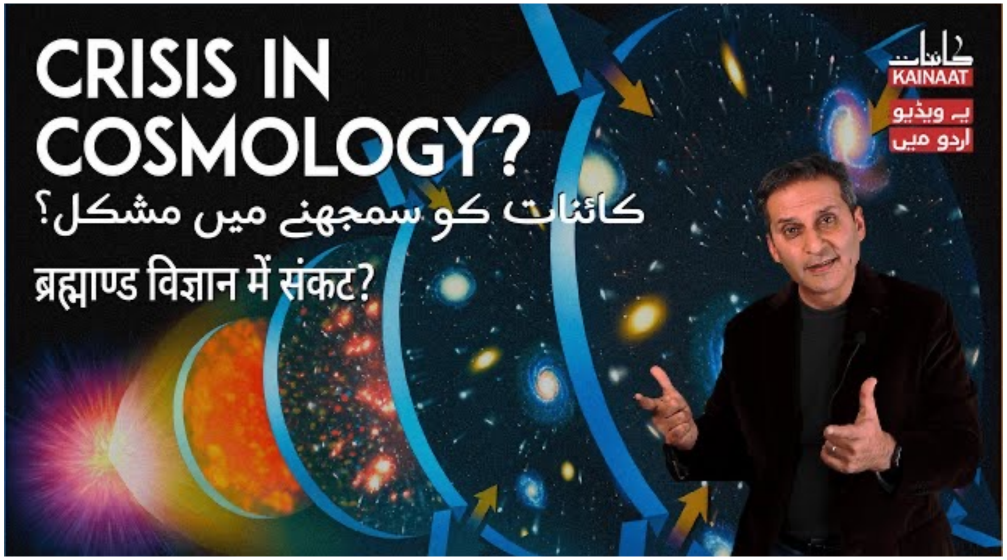
Dr. Gleiser is a theoretical physicist at Dartmouth College.

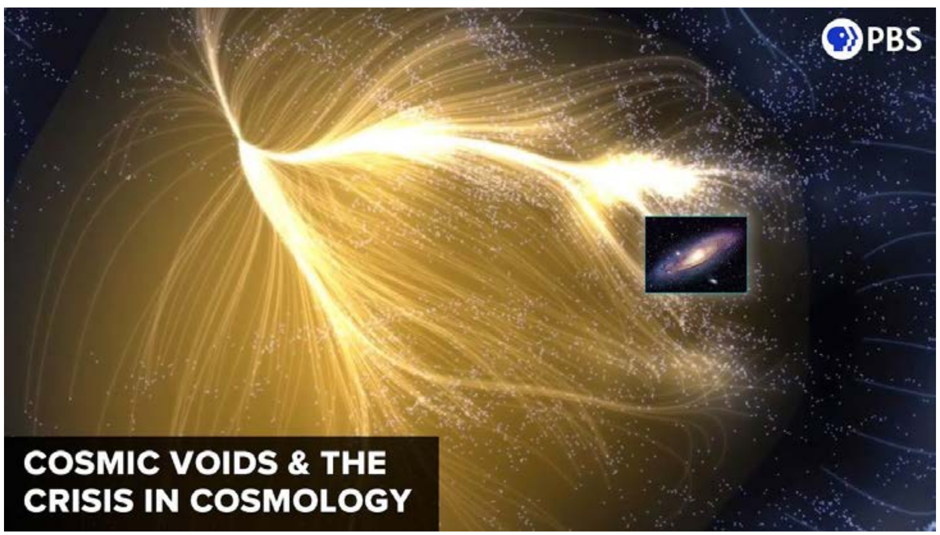

Cosmology Crisis:
What Is It?
Why Is It Happening?

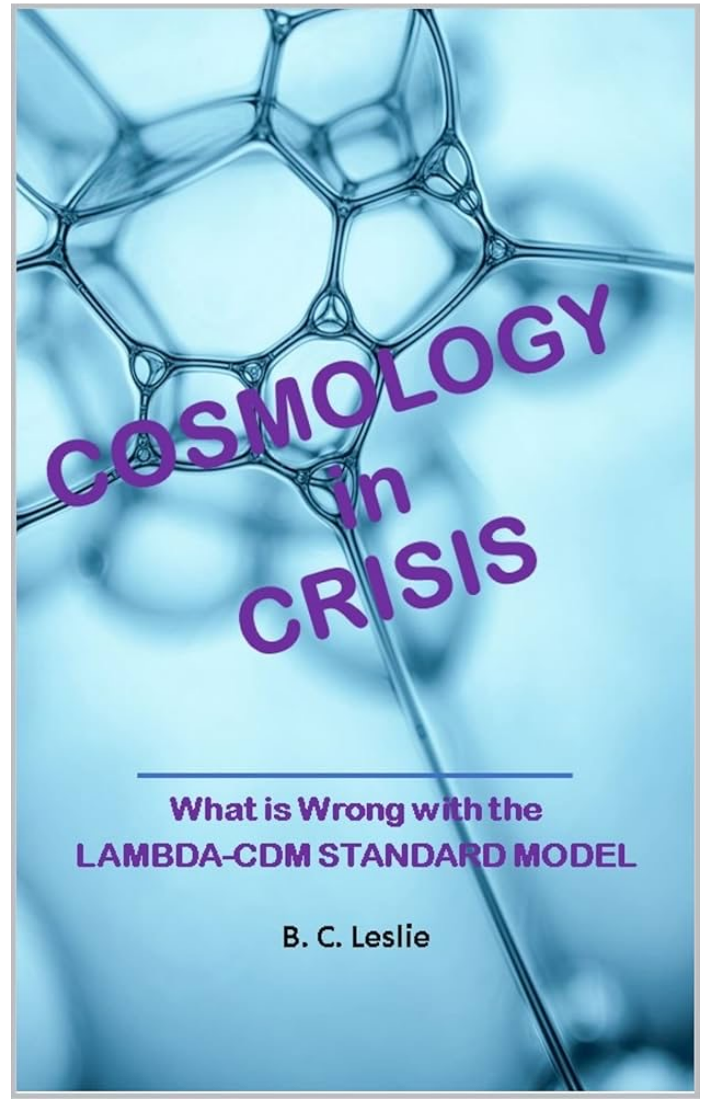

Afterglow Light Pattern 375,000 yrs.
Dark Ages
Inflation
THE
CRISIS
IN
COSMOLOGY

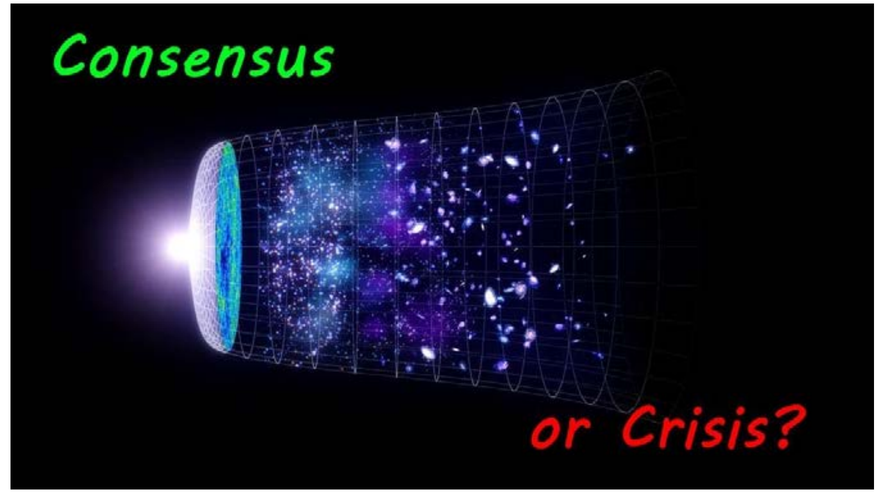

20th Anniversary
CARNEGIE SCIENCE
The Carnegie Observatories
Is There a Crisis in Cosmology?
Dr. Wendy L. Freedman


THERE IS A CRISIS IN COSMOLOGY - SINCE WERE OFF BY A FACTOR OF 10 TO THE POWER OF 120.
THIS IS THE LARGEST MISMATCH BETWEEN THEORY AND EXPERIMENT IN THE HISTORY OF SCIENCE. PHYSICIST MICHIO KAKU.

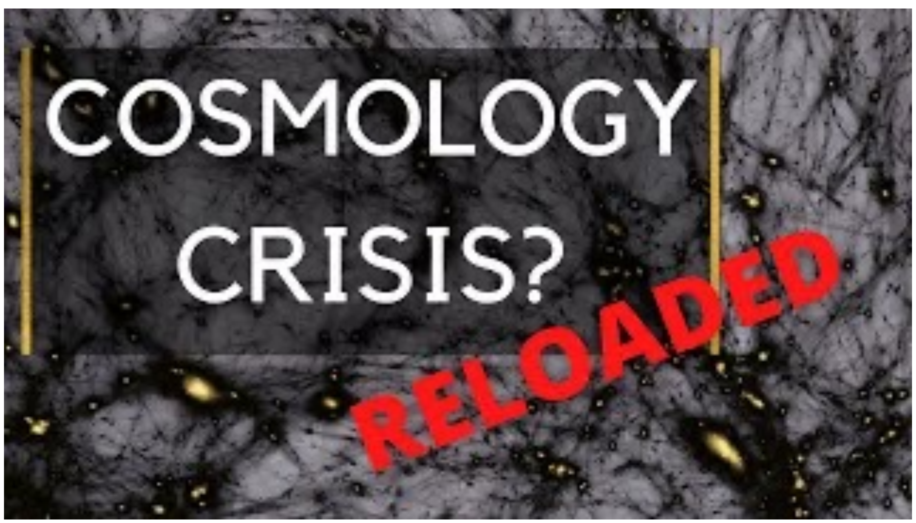

CRISIS IN COSMOLOGY?
کائنات کو سمجھنے میں مشکل؟
ब्रह्माण्ड विज्ञान में संकट?
KAINAAT
یہ ویڈیو
اردو میں


PBS
COSMIC VOIDS & THE CRISIS IN COSMOLOGY


COSMOLOGY in CRISIS
What is Wrong with the LAMBDA-CDM STANDARD MODEL
B. C. Leslie



The “crisis in cosmology” is
pure exaggeration Ethan Siegel



Subscribe
Latest Issues
SCIENTIFIC AMERICAN.
Sign In | Newsletters

Save 20% on digital! Subscribe

SPACE & PHYSICS

How a Dispute over a Single Number Became a Cosmological Crisis

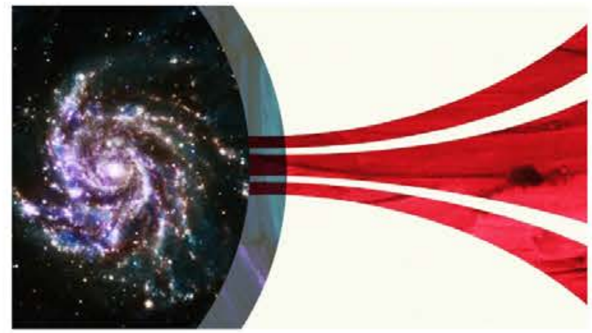
Two divergent measurements of how fast the universe is expanding cannot both be right. Something must give—but what?

By Richard Panek on March 1, 2020

13.8 — MAY 4, 2023

Some scientists speak of a "crisis in cosmology." They have a good reason

The standard model of cosmology has a big new problem: Some galaxies seem to be too old.



Credit: Annelisa Leinbach / Big Think; NASA

KEY TAKEAWAYS

● Just like atoms are the building blocks of chemistry, galaxies are the building blocks of cosmology. ● The standard model of cosmology gives astronomers a way to link observed distances to objects with their age. ● However, new images from the James Webb Space Telescope found galaxies far more distant (and, hence, far older) than what the standard model of cosmology predicts. The new data provide compelling evidence that the model might need to be updated.

EXPERT VOICES OP-ED & INSIGHTS

News > Science & Astronomy

Why is there a 'crisis' in cosmology?

By Paul Sutter published October 30, 2021

Click here for more Space.com videos...

Paul M. Sutter is an astrophysicist at SUNY Stony Brook and the Flatiron Institute, host of "Ask a Spaceman" and "Space Radio," and author of "How to Die in Space." Sutter contributed this article to Space.com's Expert Voices: Op-Ed & Insights.

Is there really a 'crisis' in cosmology?

By Paul Sutter last updated February 21, 2022

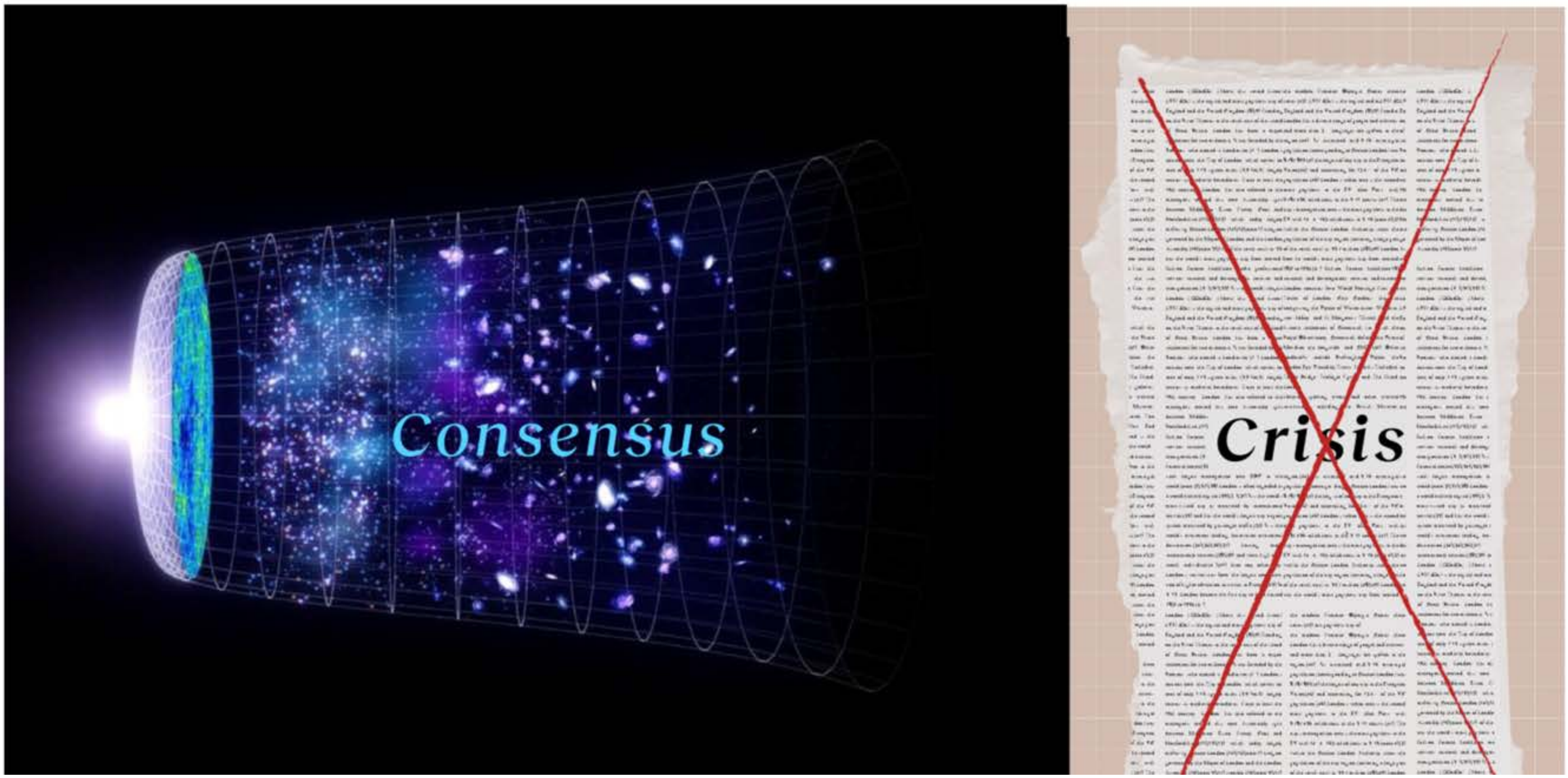
Maybe we just don't understand some cosmic phenomena as well as we think we do.

The Crab Nebula as seen by the Hubble Space Telescope and ground-based telescopes in a composite view. The nebula is the aftermath of a brilliant supernova spotted in 1054. (Image credit: NASA, ESA, NRAO/AUI/NSF and G. Dubner (University of Buenos Aires))

STARTS WITH A BANG — SEPTEMBER 6, 2023

The "crisis in cosmology" is pure exaggeration

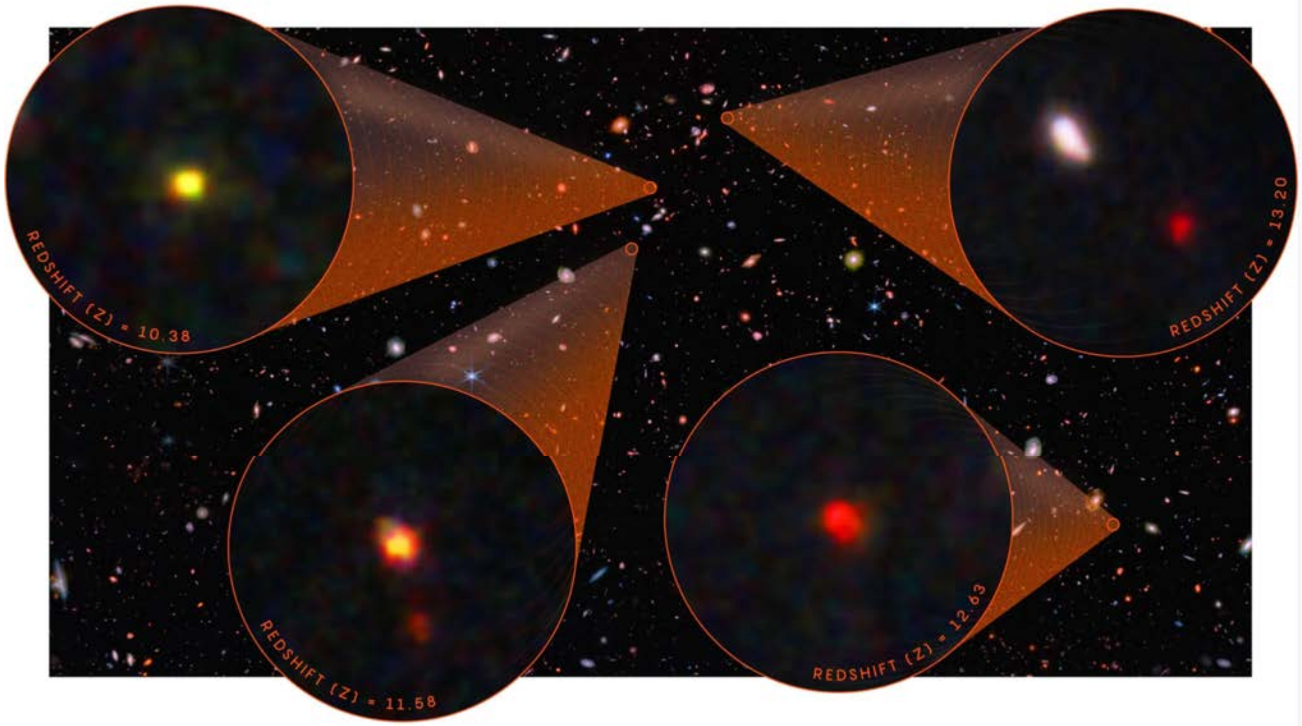
There are a few clues that the Universe isn't completely adding up. Even so, the standard model of cosmology holds up stronger than ever.



ASTROPHYSICS

Standard Model of Cosmology Survives a Telescope's Surprising Finds

Reports that the James Webb Space Telescope killed the reigning cosmological model turn out to have been exaggerated. But astronomers still have much to learn from distant galaxies glimpsed by Webb.



The Webb telescope has spotted galaxies surprisingly far away in space and deep in the past. These four, studied by a team called JADES, are all seen as they appeared less than 500 million years after the Big Bang.

Samuel Velasco/Quanta Magazine; source: NASA

Rebecca Boyle

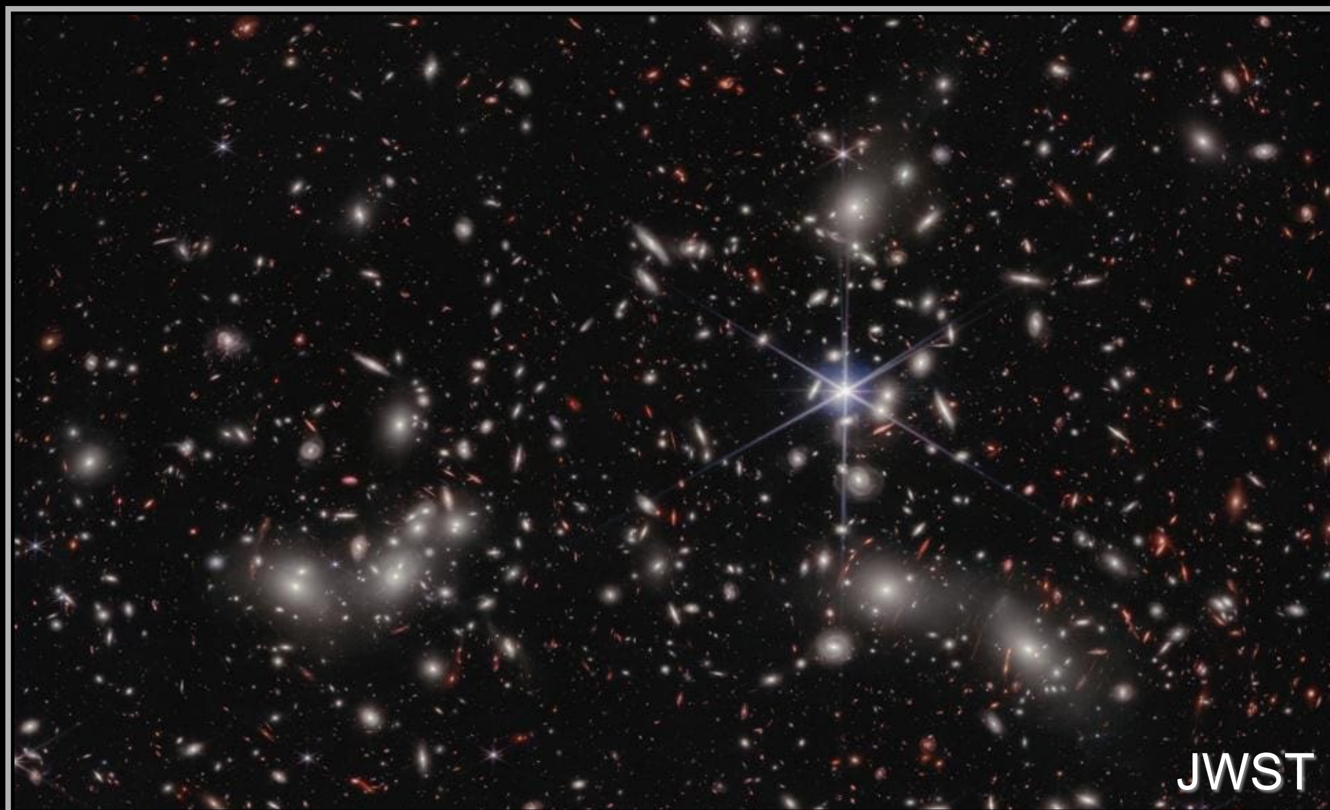
The cracks in cosmology were supposed to take a while to appear. But when the James Webb Space Telescope (JWST) opened its lens last spring, extremely distant yet very bright galaxies immediately shone into the telescope's field of view. "They were just so stupidly bright, and they just stood out," said Rohan Naidu, an

Share this article

Newsletter

January 20, 2023

Observer’s View of the Universe



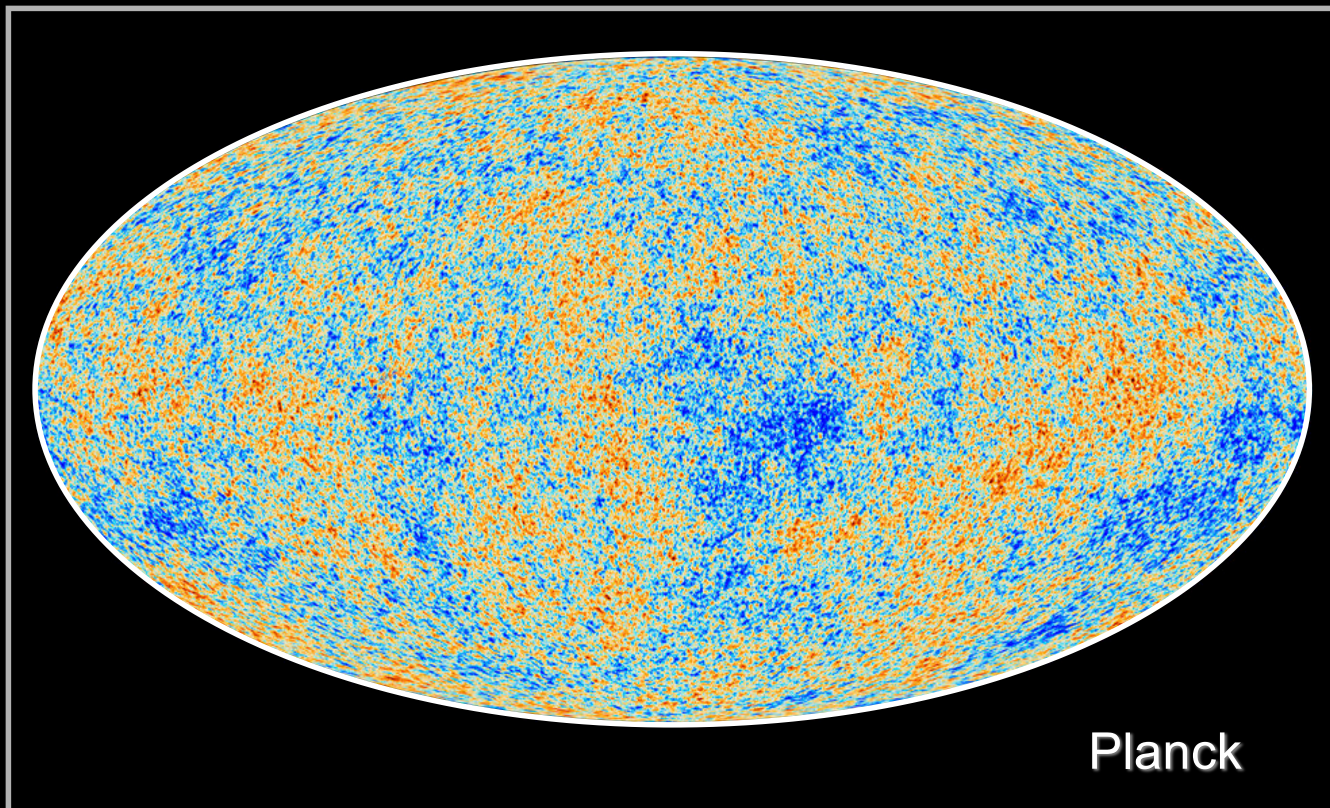
Inhomogeneous, rich structure,
full of stars, black holes, galaxies, clusters, ….

Theorist's View of the Universe

Actual image of dark matter

smooth (homogeneous and isotropic)
full of dark matter and dark energy

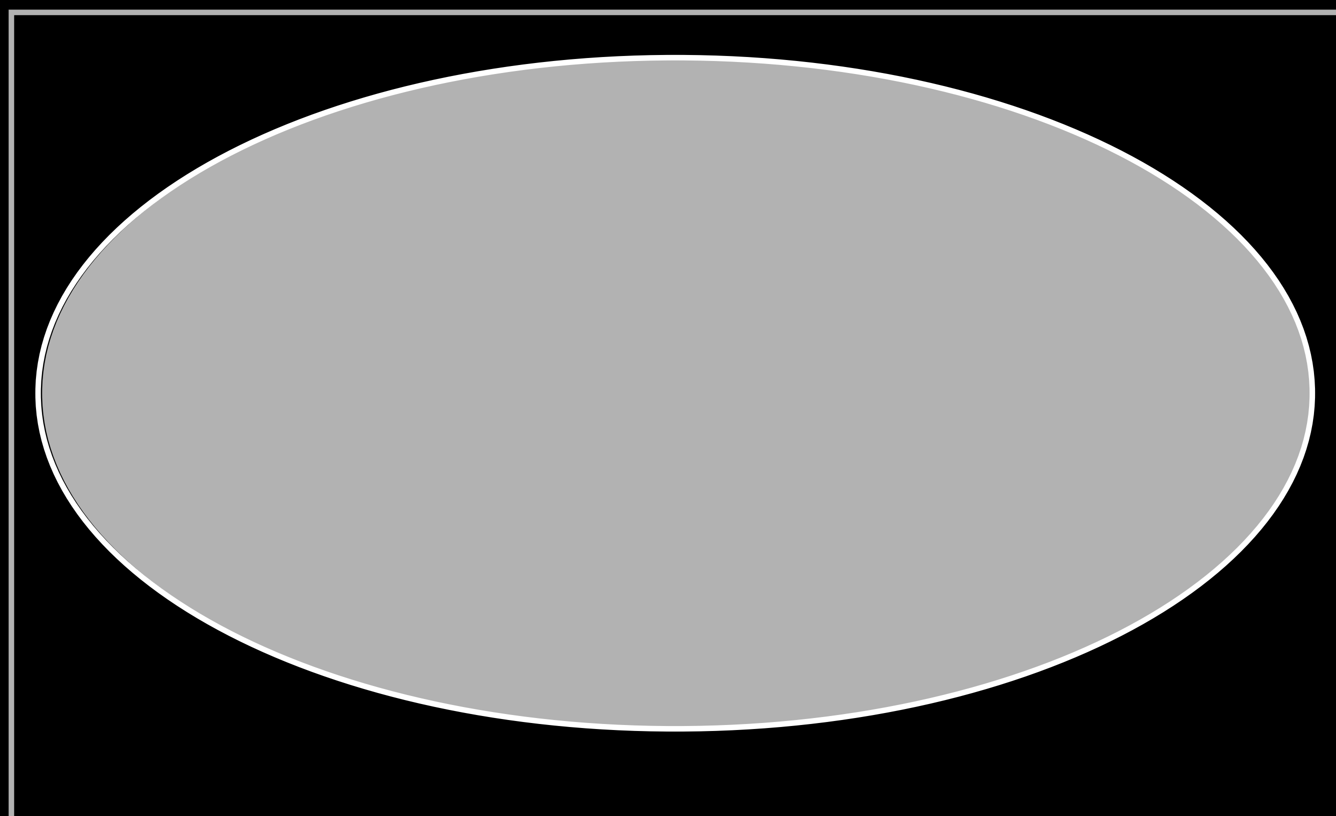
Observer's View of the Universe



Temperature fluctuations $\mathcal{O}(10^{-5})$ in the CMB

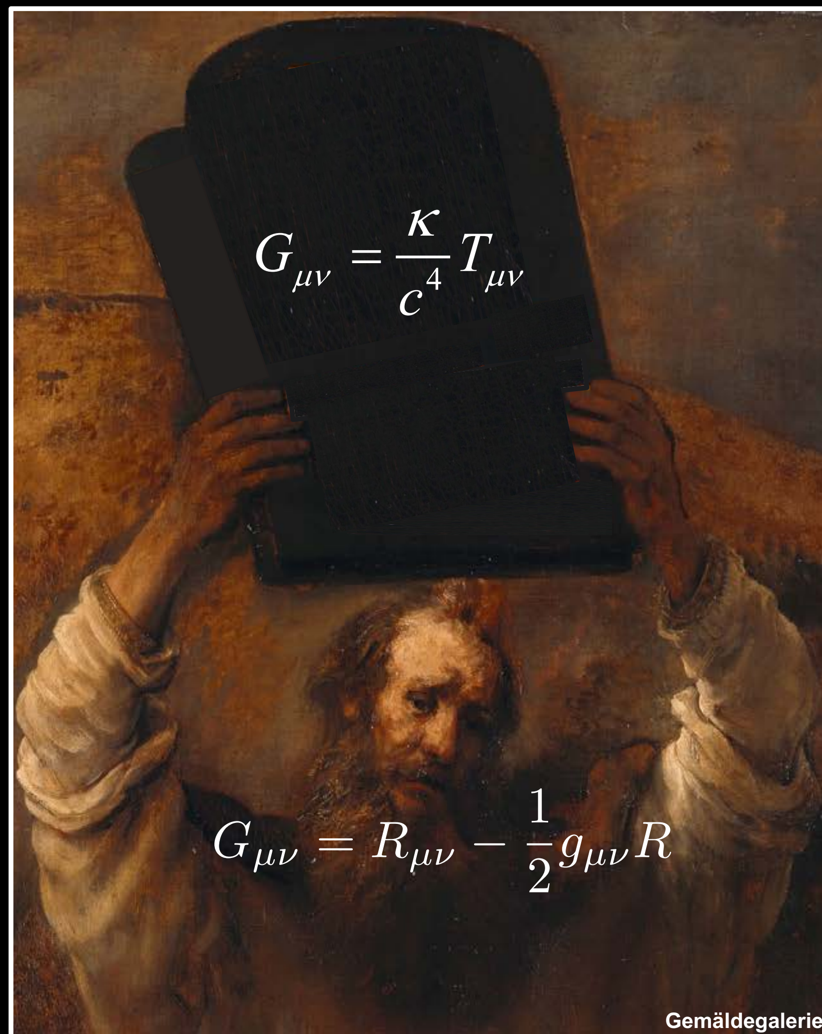
What is their origin? Inflation!

Theorist's View of the Universe



Temperature remarkably uniform
Why so smooth? Inflation!

Ten Commandments of Modern Genesis



Einstein's 1917 Static World Model

1. Assumed the cosmological principle: "All locations in the universe are equivalent; in particular the locally averaged density of stellar matter should therefore be the same everywhere."

2. Assumed the universe was spherical (finite volume), space curved. Boundary condition on space: space has no boundary.

3. Assumed the universe is "static" (no beginning, no end): Boundary condition on time: time has no boundary.

Einstein's 1917 Static World Model

1. "All locations in the universe are equivalent; in particular the locally averaged density of stellar matter should therefore be the same everywhere."
2. Space is finite, hence spherical.
3. "Spatial structure and density should be constant over time."
4. Dynamics determined by Einstein field equations of general relativity.

   1. Implies there is one dynamical variable, constant in space: the scale factor "$P(t)$"
   2. Implies that P is the "radius of the universe."
   3. Implies that P is constant in time
   4. Implies that P satisfies the system of equations

$$2\frac{P''}{P} + \frac{P'^2}{P^2} + \frac{c^2}{P^2} = 0$$

$$\frac{3P'^2}{P^2} + \frac{3c^2}{P^2} = \kappa c^2 \rho$$

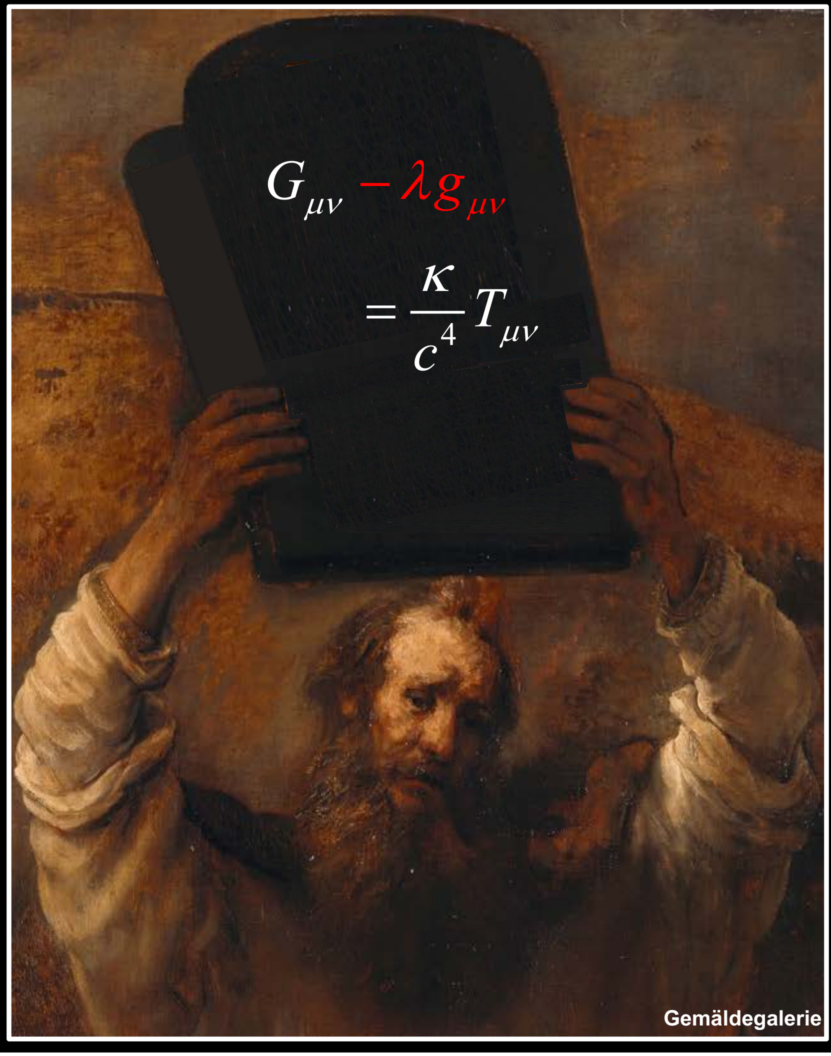
P = scale factor (radius of universe)
P'' = acceleration
P' = velocity
$\kappa = 8\pi G_N$
ρ = mass density

Einstein's 1915-1916 field equations <u>do not</u> admit a static solution.

Ten Commandments of Modern Genesis

Left-hand side

cosmological constant λ



Right-hand side

Einstein's 1917 Static World Model

Starting with a universe full of stars

Assumed

1. the cosmological principle: "All locations in the universe are equivalent; in particular the locally averaged density of stellar matter should therefore be the same everywhere."
2. the universe was spherical (finite volume), space curved.
3. the universe is "static."

Original field equations do not admit a static solution.

Added a cosmological constant.

Could calculate the volume of the universe in terms of λ and the stellar density.

Einstein's 1917 Static World Model

1. "All locations in the universe are equivalent; in particular the locally averaged density of stellar matter should therefore be the same everywhere." [Cosmological Principle]
2. "Spatial structure and density should be constant over time."
3. Space is finite, hence spherical.
4. Dynamics determined by Einstein field equations of general relativity.

   1. Implies there is one dynamical variable, constant in space: the scale factor "$P(t)$"
   2. Implies that P is the "radius of the universe."
   3. Implies that P is constant in time
   4. Implies that P satisfies the system of equations

$$2\frac{P''}{P} + \frac{P'^2}{P^2} + \frac{c^2}{P^2} - \lambda = 0$$

$$\frac{3P'^2}{P^2} + \frac{3c^2}{P^2} - \lambda = \kappa c^2 \rho$$

P = scale factor (radius of universe)
P' = velocity
P'' = acceleration
κ = $8\pi G$
ρ = mass density

Einstein's 1915-1916 field equations do not admit a static solution.

They do with the introduction of λ.

$$\lambda = \frac{c^2}{P^2} \qquad \frac{2c^2}{P^2} = \kappa c^2 \rho$$

Einstein's 1917 Static World Model

1. "All locations in the universe are equivalent; in particular the locally averaged density of stellar matter should therefore be the same everywhere." [Cosmological Principle]
2. "Spatial structure and density should be constant over time."
3. Space is finite, hence spherical.
4. Dynamics determined by Einstein field equations of general relativity.

    1. Implies there is one dynamical variable, constant in space: the scale factor "$P(t)$"
    2. Implies that P is constant in time
    3. Implies that P is the "radius of the universe."
    4. Implies that P satisfies the system of equations

$$\frac{c^2}{P^2} - \lambda = 0$$

$$\frac{3c^2}{P^2} - \lambda = \kappa c^2 \rho$$

P = scale factor (radius of universe)
P' = velocity
P'' = acceleration
κ = $8\pi G$
ρ = mass density

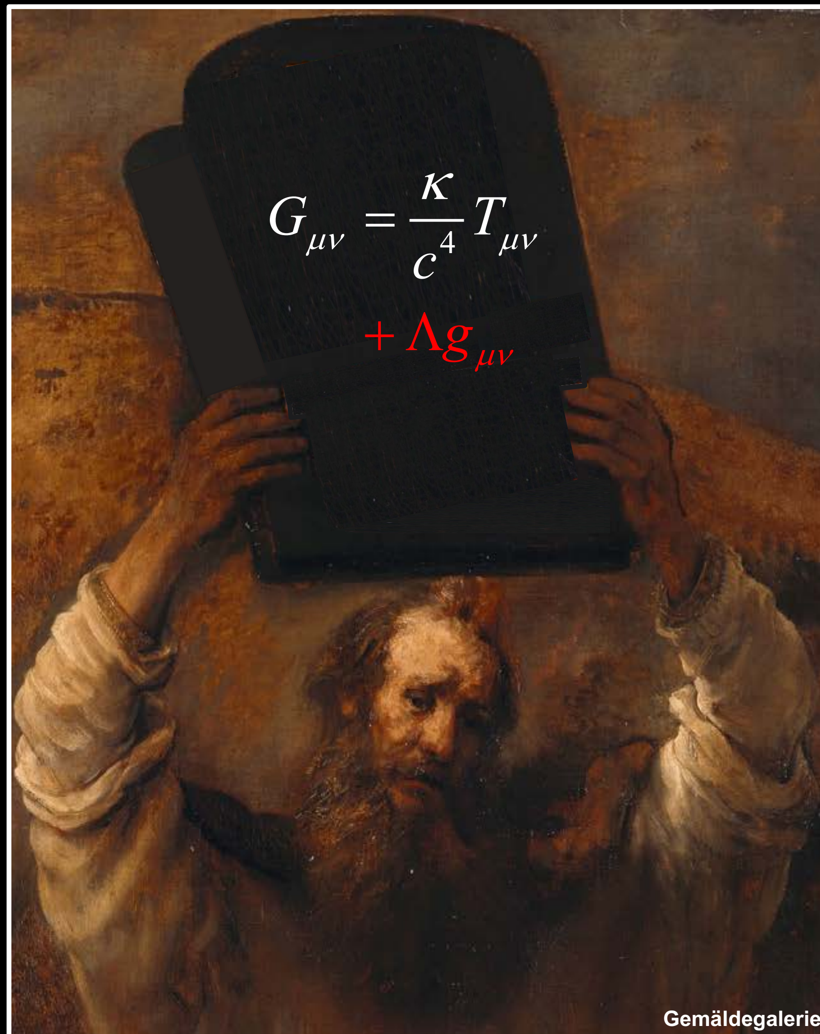
Einstein's 1915-1916 field equations do not admit a static solution.

They do with the introduction of λ.

$$\lambda = \frac{c^2}{P^2} \qquad \frac{2c^2}{P^2} = \kappa c^2 \rho$$

Ten Commandments of Modern Genesis

Left-hand side



$$G_{\mu\nu} = \frac{\kappa}{c^4} T_{\mu\nu}$$

$$+ \Lambda g_{\mu\nu}$$

Right-hand side

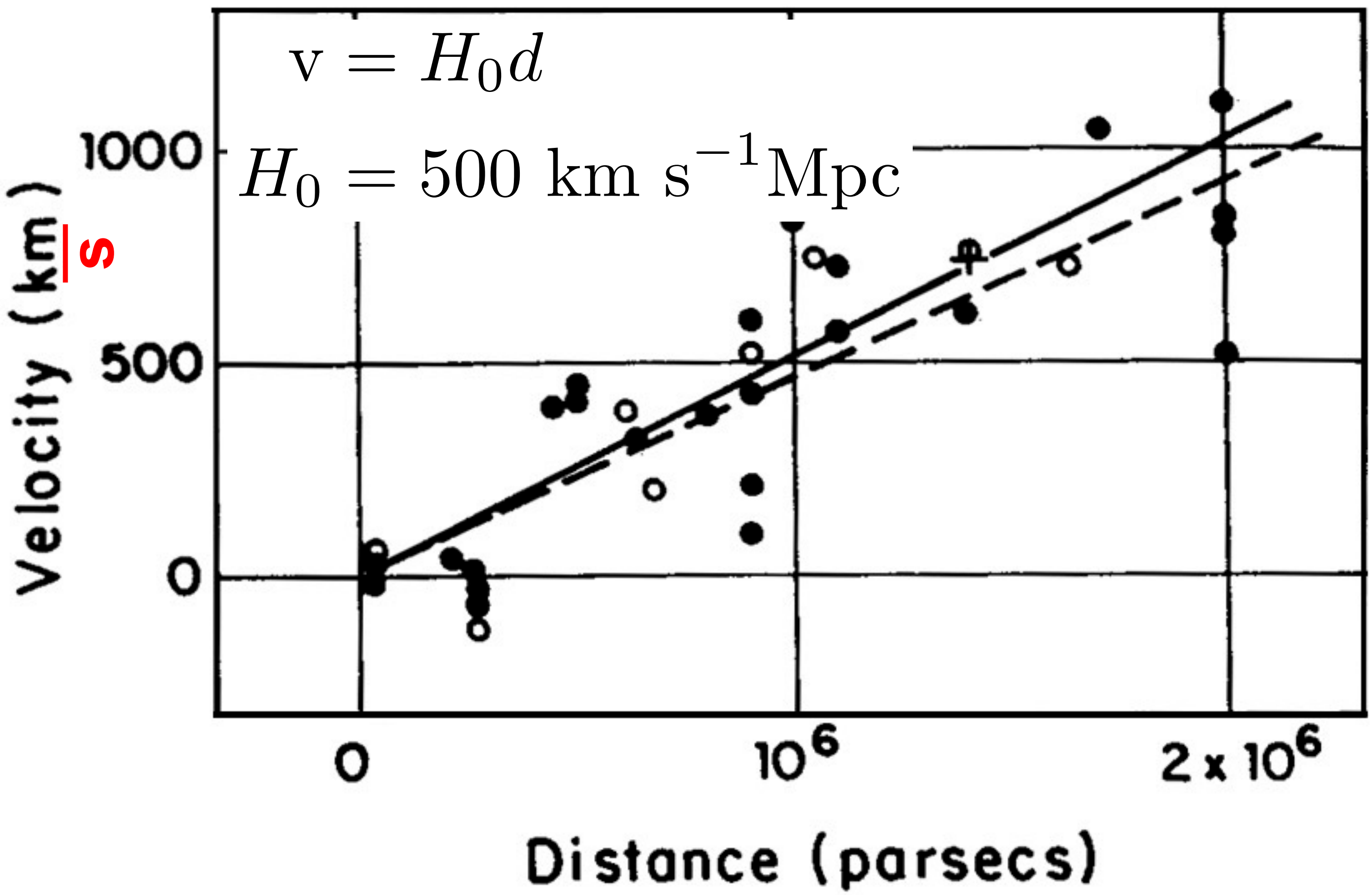
dark energy Λ

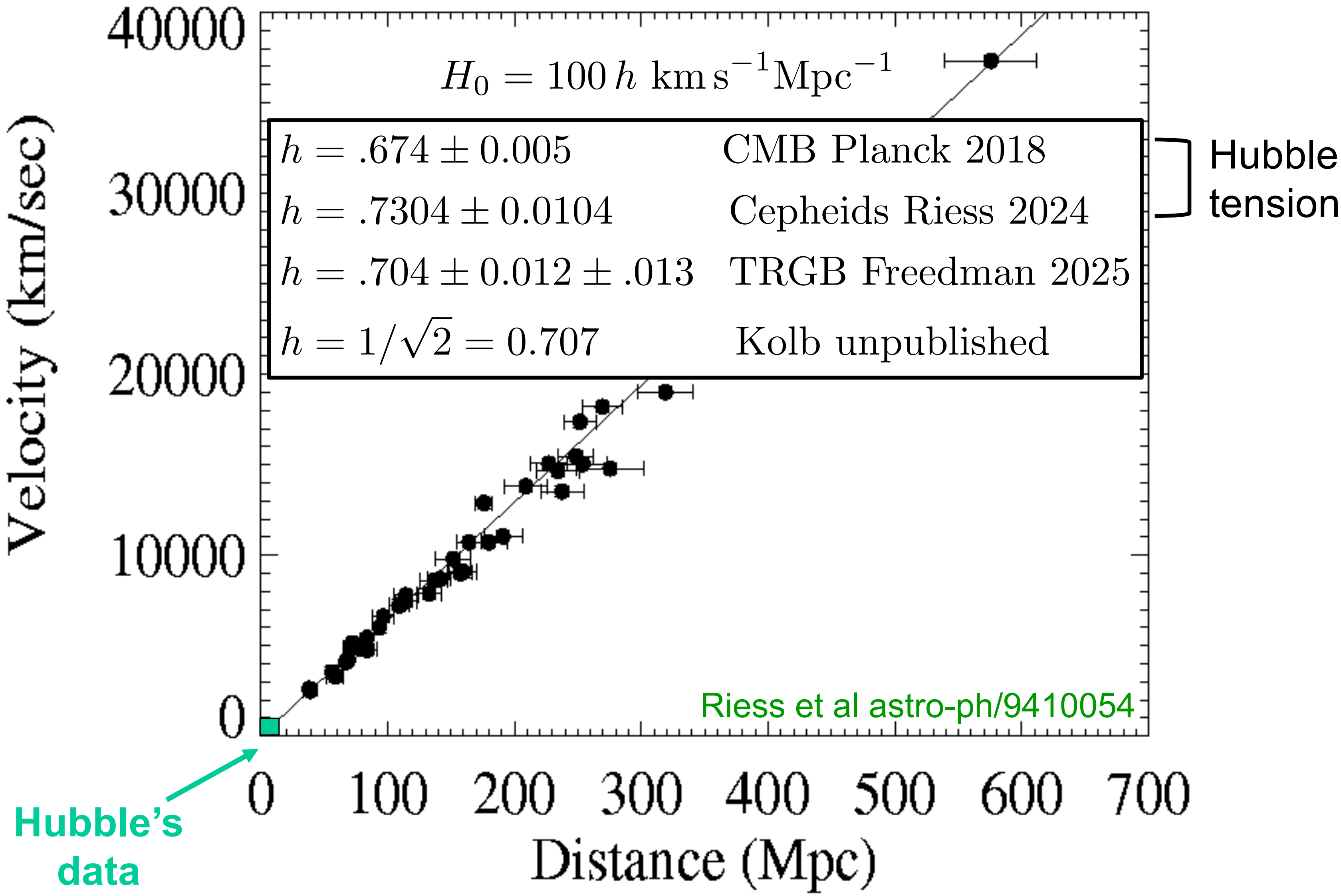

Hubble
INTERCOLLEGIATE
1909
CHAMPIONS
University of Chicago 1909 National Champions

Hubble Recommendation Letters From the UChicago Archives

"… physically, he is a splendid specimen…"
"… magnificent physique …."
"… manly …"
"… loveable character …"

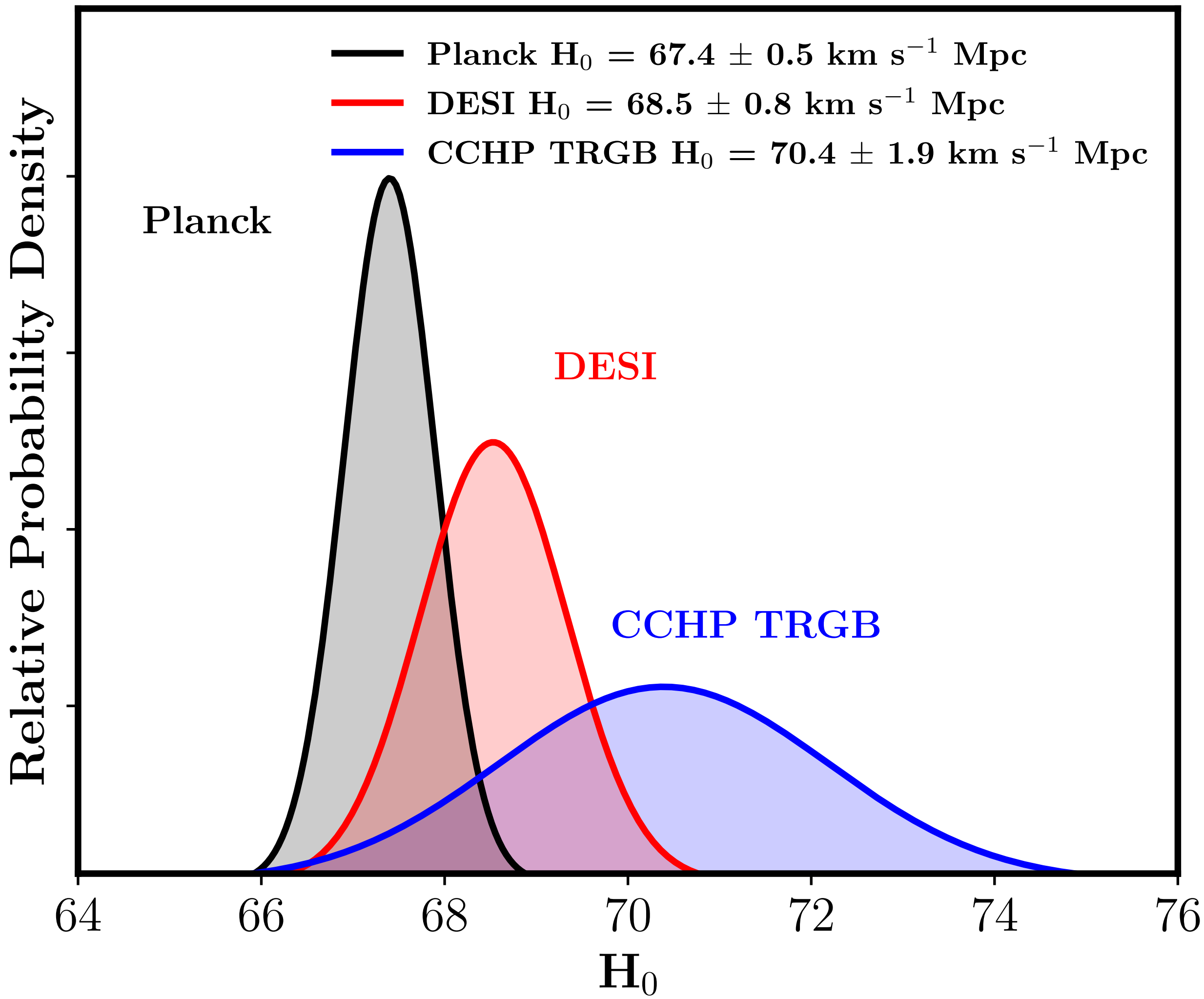
Hubble's 1929 Discovery Paper





$H_0 = 100\,h$ km s^{-1}Mpc^{-1}
$h = .674 \pm 0.005$ CMB Planck 2018
$h = .7304 \pm 0.0104$ Cepheids Riess 2024
$h = .704 \pm 0.012 \pm .013$ TRGB Freedman 2025
$h = 1/\sqrt{2} = 0.707$ Kolb unpublished
Hubble tension
Velocity (km/sec)
40000
30000
20000
10000
0
0
100
200
300
400
500
600
700
Distance (Mpc)
Riess et al astro-ph/9410054
Hubble's data

Freedman et al. (2025) 2408.06153v2



Using only JWST + SNe

$H_0 = 68.81 \pm 1.79 \pm 1.32$ TRGB

$H_0 = 67.80 \pm 2.17 \pm 1.64$ JAGB

Using HST +JWST + SNe

$H_0 = 70.4 \pm 1.2 \pm 1.3$ TRGB

"Our results are consistent with the current standard LCDM model without the need for the inclusion of new physics."

Big-Bang Theory

Robertson-Walker metric ⇐ $G_{\mu\nu} = 8\pi G_N T_{\mu\nu}$ ⇒ **Perfect-fluid stress tensor**

$a(t)$ = cosmic scale factor

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

$k = +1, -1, 0$ for spherical, hyperbolic, or flat 3–spaces.

Often convenient to use conformal time η

$$dt = a\, d\eta$$

$$ds^2 = a^2(\eta)(d\eta^2 + d\vec{x}^2)$$

$\rho =$ energy density

$p =$ pressure

$$T^{\mu}_{\ \nu} = \mathrm{diag}(\rho, p, p, p)$$

Robertson-Walker Metric

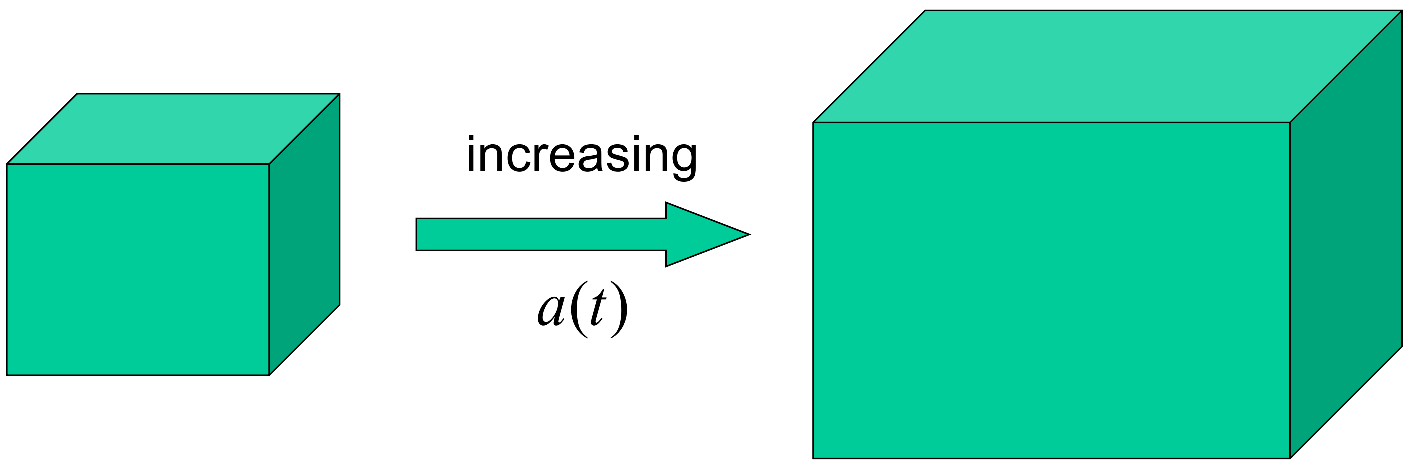
$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

$k = 0$ (spatially flat)

$$ds^2 = dt^2 - a^2(t)\left(dr^2 + r^2 d\Omega^2\right) = dt^2 - a^2(t)\left(d\vec{x}^2 + d\vec{y}^2 + d\vec{z}^2\right)$$

(comoving coordinates: $\vec{x}, \vec{y}, \vec{z}$)

(physical distance: $d\vec{l}^{\,2} = a^2(t)\left(d\vec{x}^2 + d\vec{y}^2 + d\vec{z}^2\right)$



Perfect-Fluid Stress-Energy Tensor

- Must specify energy and pressure content of the Universe
- Assume pressure is related to energy density: $p_i = w_i \rho_\iota$
- Conservation of stress-energy tensor: $T^{\mu\nu}{}_{;\nu} = 0 \rightarrow \rho_i \propto a^{-3(1+w_i)}$

$T^{\mu\nu}$: fluids with different w

Kination:	$p_K = \rho_K$	$w = 1$	$\rho_K \propto a^{-6}$
Radiation:	$p_R = \rho_R/3$	$w = 1/3$	$\rho_R \propto a^{-4}$
Matter:	$p_M = 0$	$w = 0$	$\rho_M \propto a^{-3}$
Curvature:	$p_k = -\rho_k/3$	$w = -1/3$	$\rho_k \propto a^{-2}$
Vacuum (Λ):	$p_V = -\rho_V$	$w = -1$	$\rho_V \propto a^0$

Dynamics From Field Equations

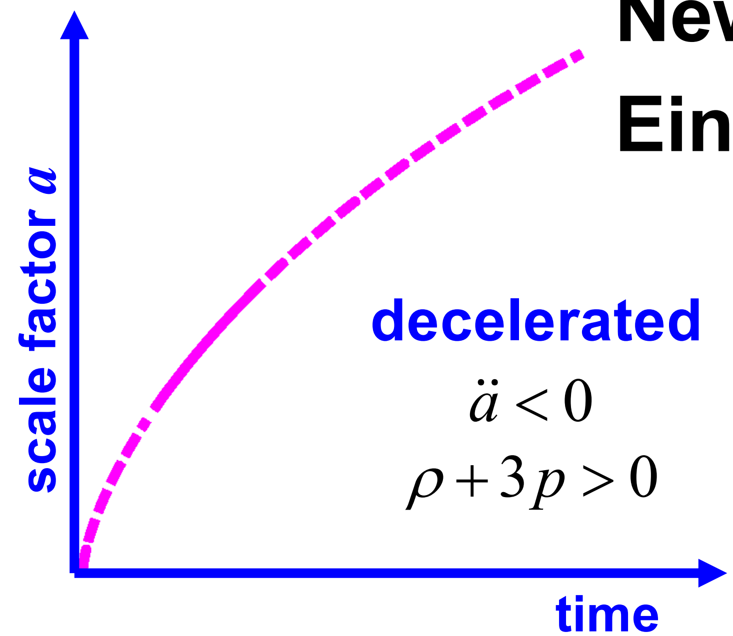
(00) $$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho$$ Friedmann Equation

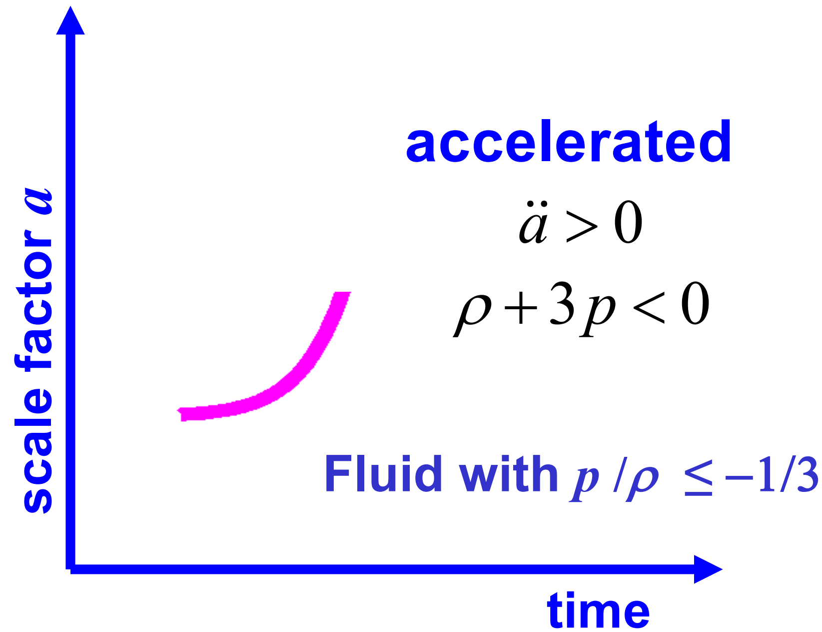
(00) − (ii) $$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3p\right)$$ Deceleration equation

$$H \equiv \frac{\dot{a}}{a} =$$ expansion rate

Newton
Einstein

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





Expansion Rate Is A Key Quantity

Friedmann equation ($G_{00} = 8\pi G T_{00}$) : Expansion rate $H(z)$

$\Omega_i \equiv \rho_i / \rho_C \qquad \rho_C \equiv 3H_0^2 / 8\pi G_N \qquad 1 + z = a_0/a$

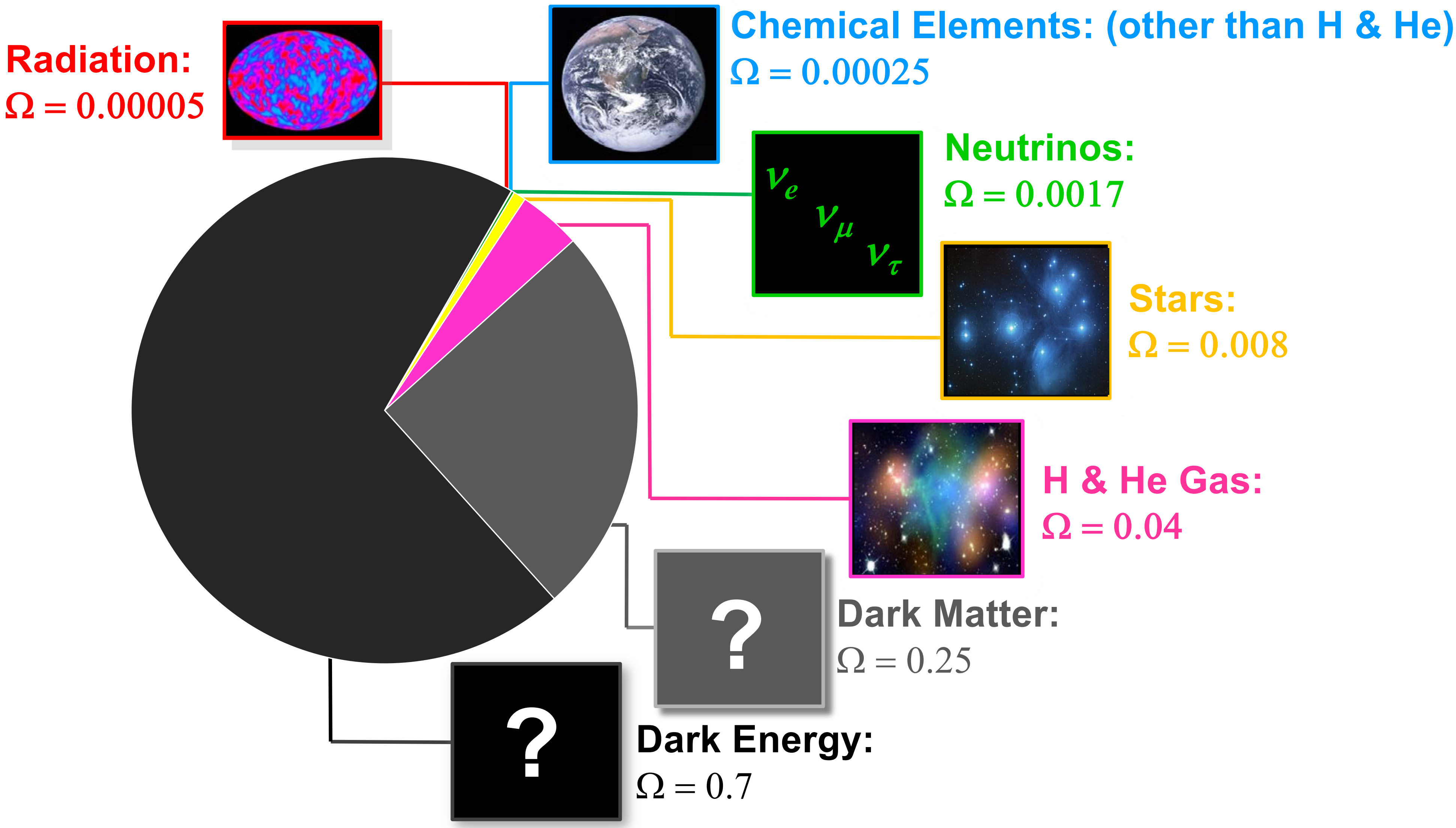
Hubble const. radiation matter curvature dark energy

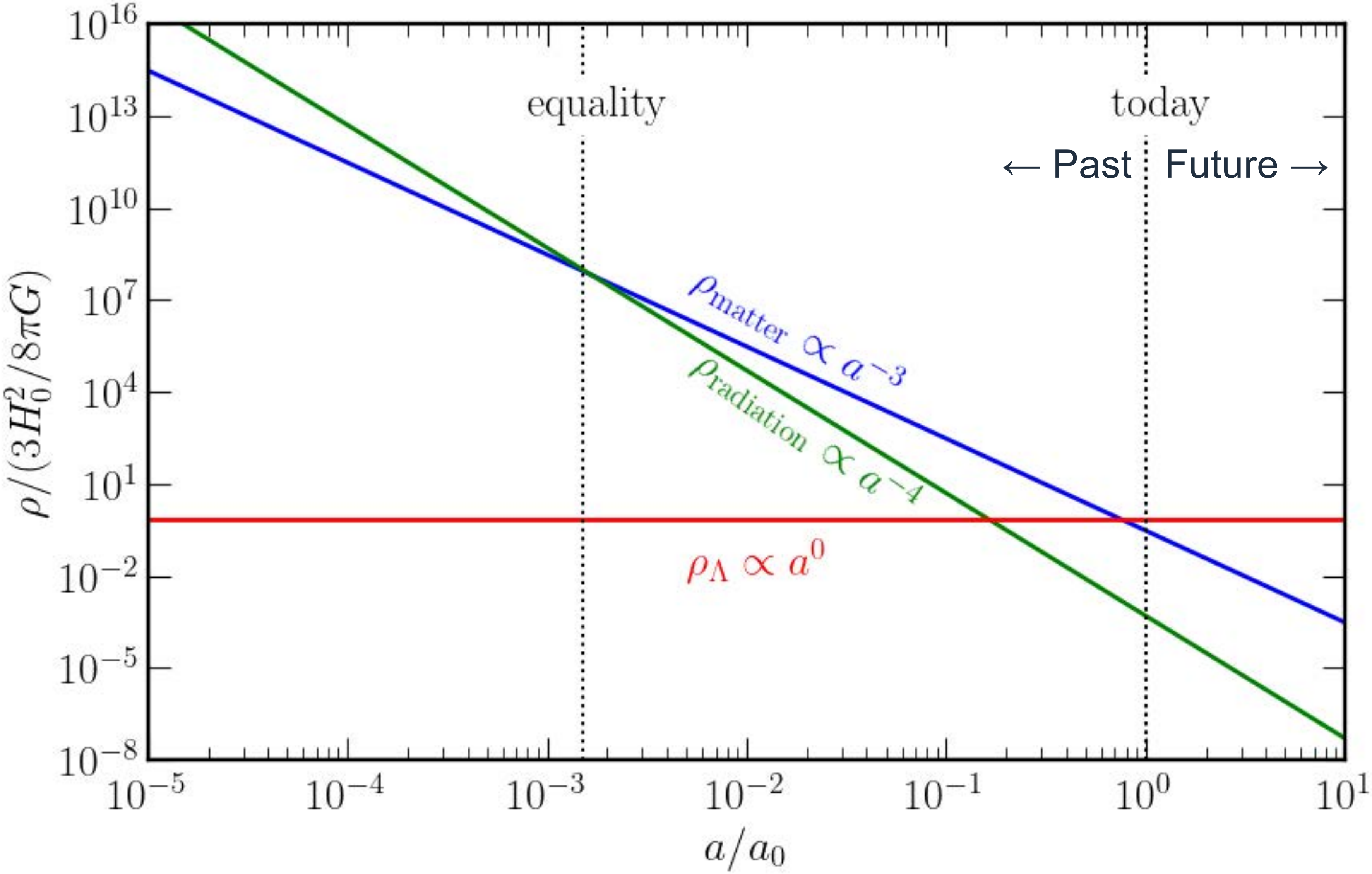
$$H^2(z) = H_0^2 \left[\Omega_R (1+z)^4 + \Omega_M (1+z)^3 + (1 - \Omega_{\text{TOTAL}})(1+z)^2 + \Omega_w (1+z)^{3(1+w)} \right]$$

CMB LSS CMB $H(z)$

Equation of state parameter: $w = P/\rho,\ \rho_i \propto a^{-3(1+w_i)}$

$w =$		ρ
1	kination	a^{-6}
$1/3$	radiation	a^{-4}
0	matter	a^{-3}
$-1/3$	curvature	a^{-2}
-1	Λ	a^{0}


Radiation:
Ω = 0.00005
Chemical Elements: (other than H & He)
Ω = 0.00025
Neutrinos:
Ω = 0.0017
νe νμ ντ
Stars:
Ω = 0.008
H & He Gas:
Ω = 0.04
?
Dark Matter:
Ω = 0.25
?
Dark Energy:
Ω = 0.7



equality
today
← Past
Future →
$\rho_{matter} \propto a^{-3}$
$\rho_{radiation} \propto a^{-4}$
$\rho_\Lambda \propto a^0$
$\rho/(3H_0^2/8\pi G)$
a/a_0
10^{16}
10^{13}
10^{10}
10^{7}
10^{4}
10^{1}
10^{-2}
10^{-5}
10^{-8}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

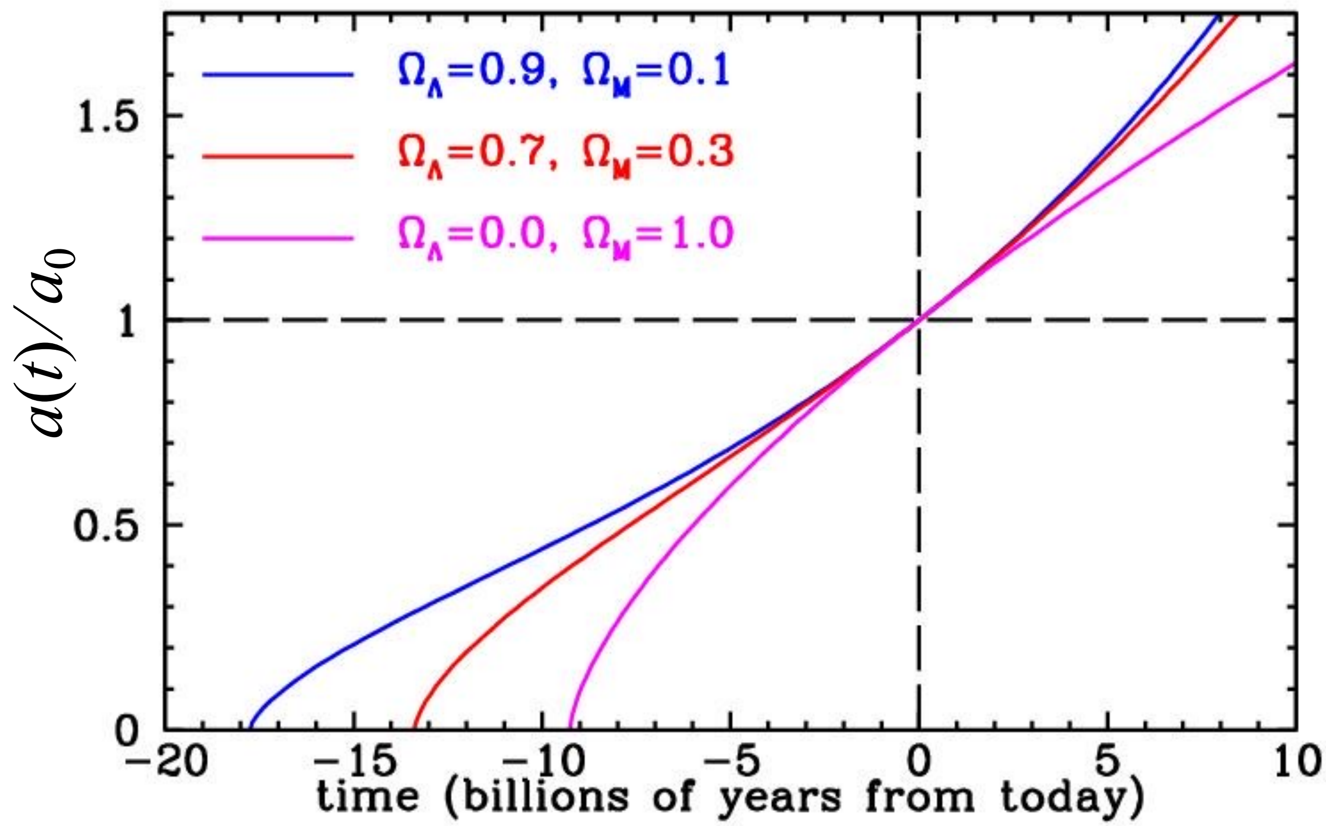
Dynamics ⟹ Evolution

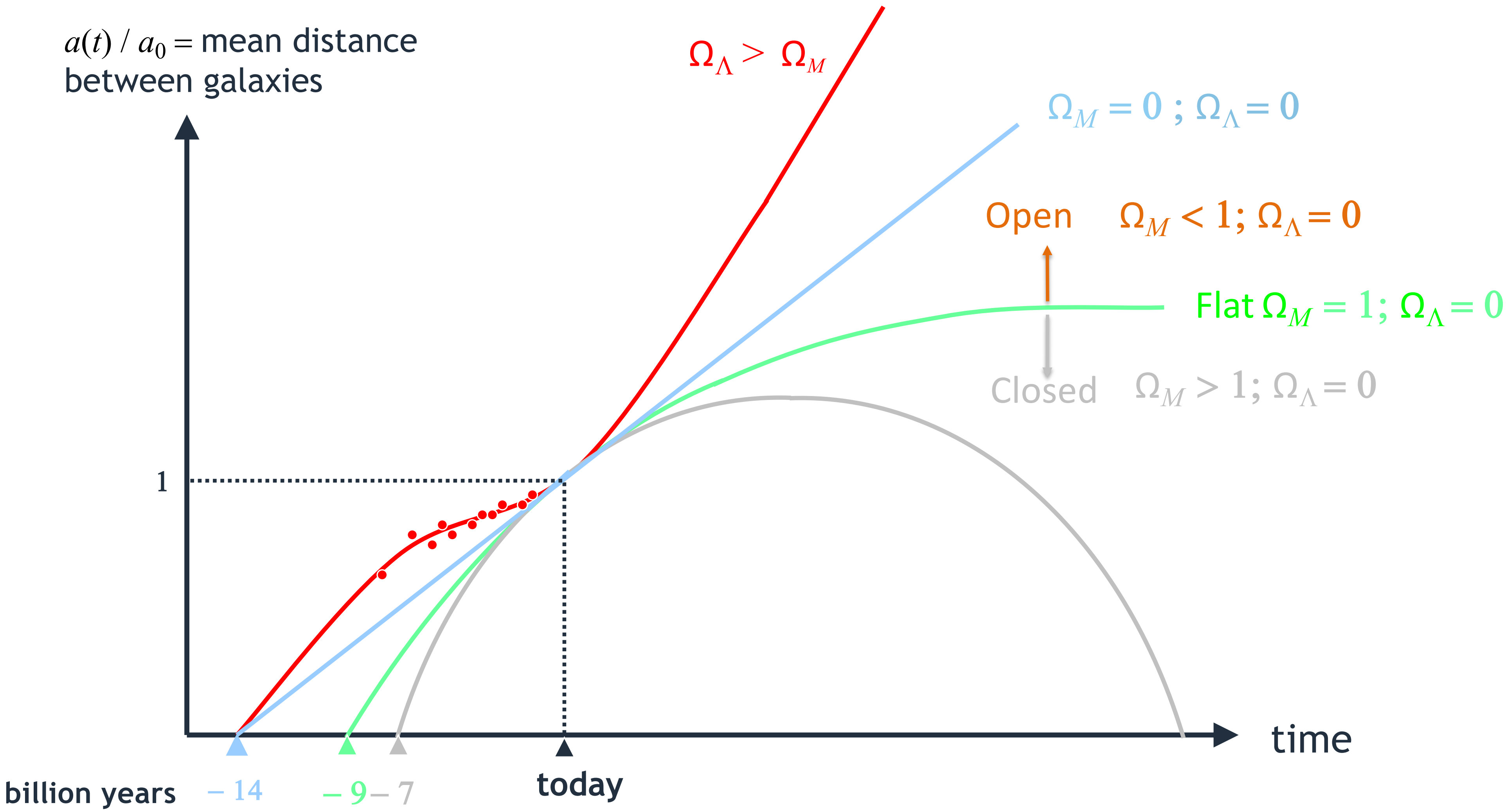
$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho \qquad \rho = \rho_M\left(a\right) + \rho_R\left(a\right) + \rho_\Lambda + \ldots$$

- $a(t)$ & $H(t)$ depend on matter/energy content
- $a(t)$ measurable via redshift
- Redshift z is a proxy for time or scale factor: $1 + z = a_0/a(t)$

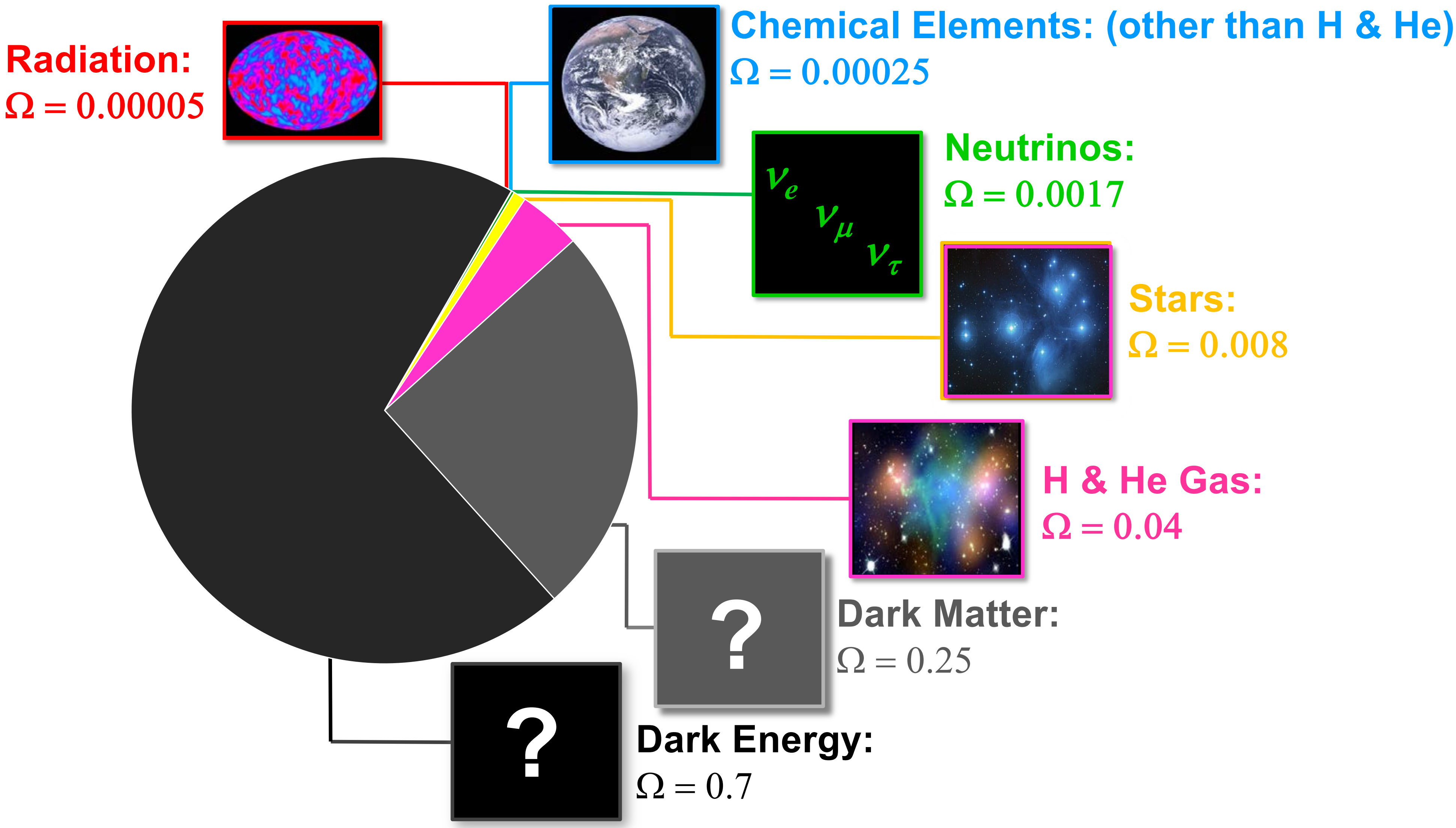
Evolution of *a*(*t*) for Matter + Λ Flat Models

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_M\left(\frac{a_0}{a}\right)^3 + \Omega_\Lambda\right]$$





From B. Leibundgut



Radiation:
Ω = 0.00005
Chemical Elements: (other than H & He)
Ω = 0.00025
Neutrinos:
Ω = 0.0017
ν_e ν_μ ν_τ
Stars:
Ω = 0.008
H & He Gas:
Ω = 0.04
Dark Matter:
Ω = 0.25
?
Dark Energy:
Ω = 0.7
?

Ninety-three Years of Dark Matter

Sun: 2×10^{27} tons; 4×10^{26} watts $\rightarrow$ Mass/Luminosity = 5 tons/watt

Oort 1932 Local Neighborhood Dim 10–15 tons/watt

Jan Oort

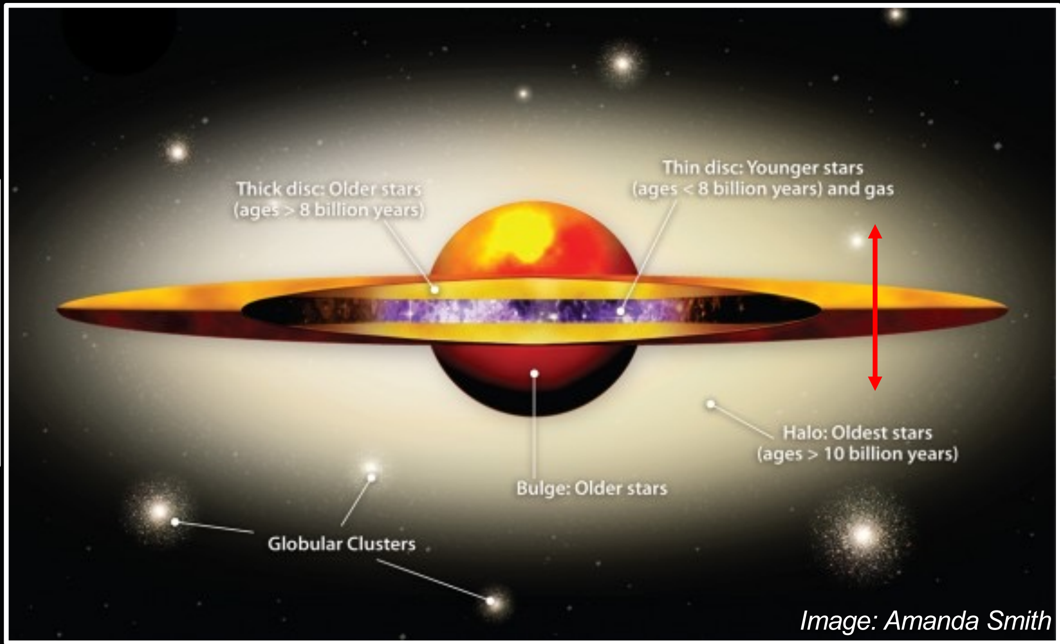
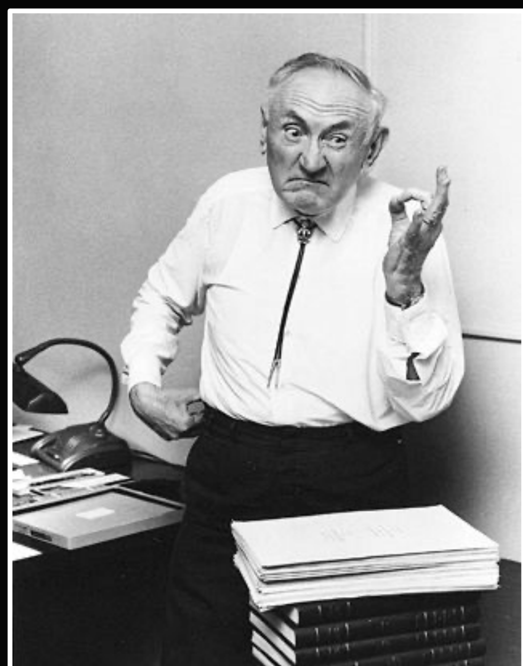


Image: Amanda Smith

Fritz Zwicky



Described his colleagues as
"spherical bastards"

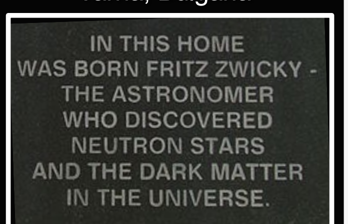
Ninety-three Years of Dark Matter

Sun: 2×10^{27} tons; 4×10^{26} watts $\rightarrow$ Mass/Luminosity = 5 tons/watt

Oort	1932	Local Neighborhood Dim	10–15 tons/watt
Zwicky	1937	Galaxy Clusters Really Dark	2,500 tons/watt


Fritz Zwicky

Varna, Bulgaria



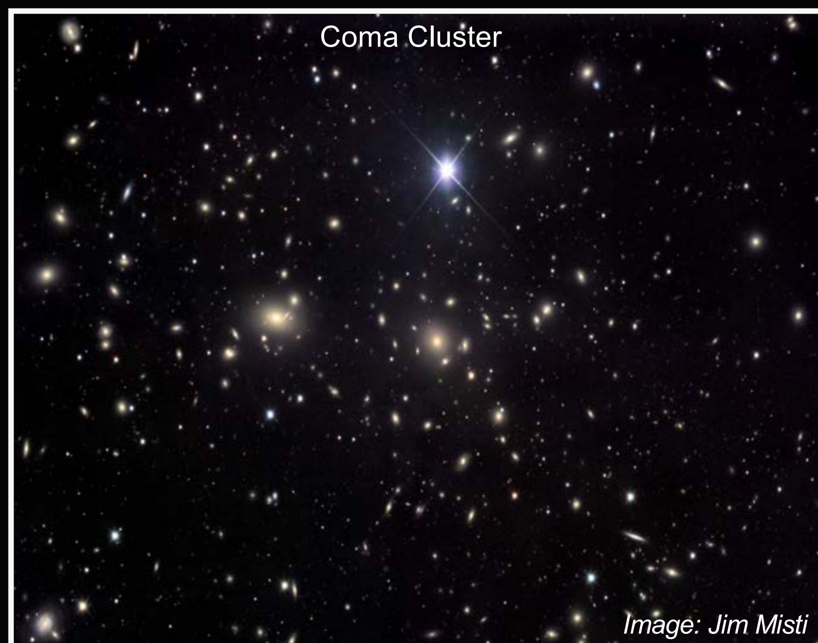
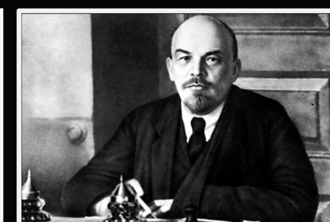
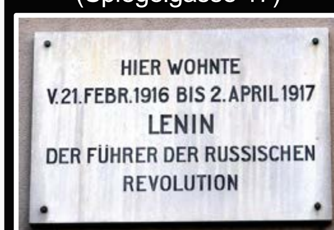

Coma Cluster

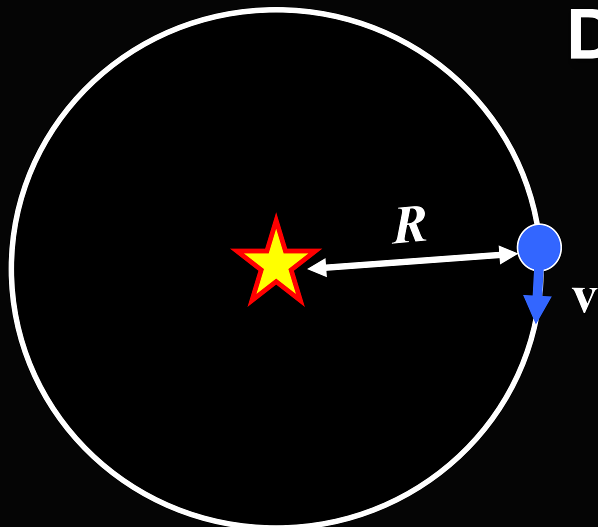
Image: Jim Misti


Vladimir Lenin 1916

Zurich, Switzerland
(Spiegelgasse 17)

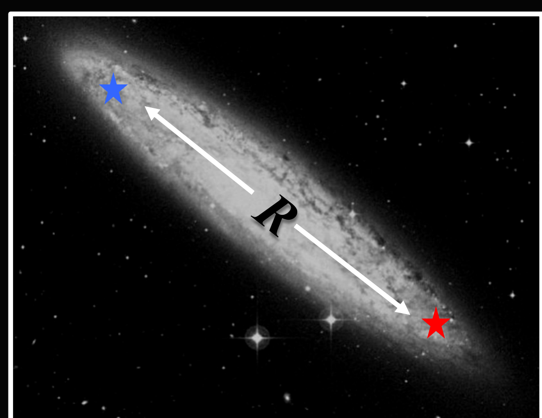


Dark Matter



$$\frac{G_N m M_\odot}{R^2} = m\frac{\mathrm{v}^2}{R} \qquad (F = ma)$$

measure v & R → $M_\odot$



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

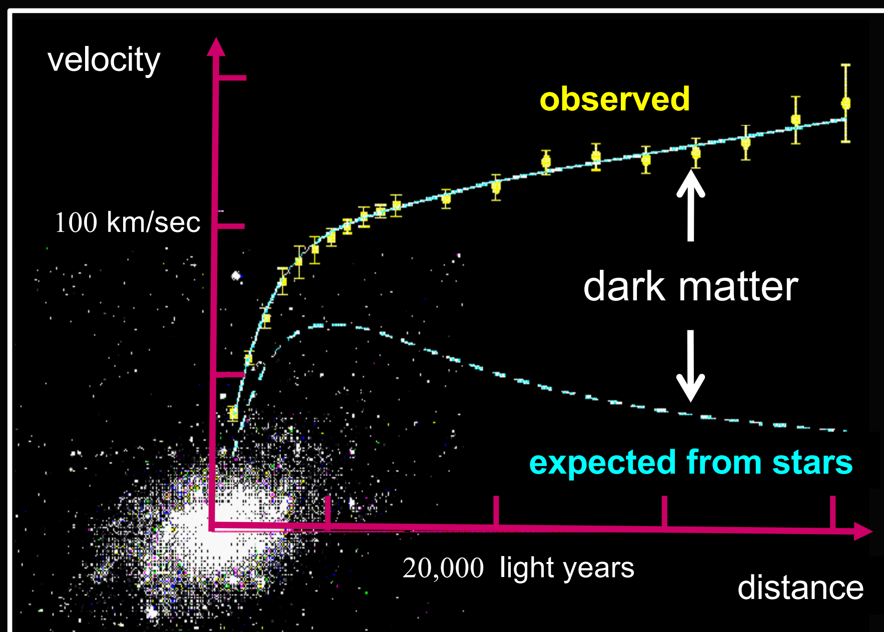
measure v & $R \rightarrow M_{<R}$

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

Ninety-three Years of Dark Matter

Sun: 2×10^{27} tons; 4×10^{26} watts $\rightarrow$ Mass/Luminosity = 5 tons/watt

Oort	1932	Local Neighborhood Dim	10–15 tons/watt
Zwicky	1937	Galaxy Clusters Really Dark	2,500 tons/watt
Rubin, Ford & others	1970s	Individual Galaxies Also Dark	300 tons/watt

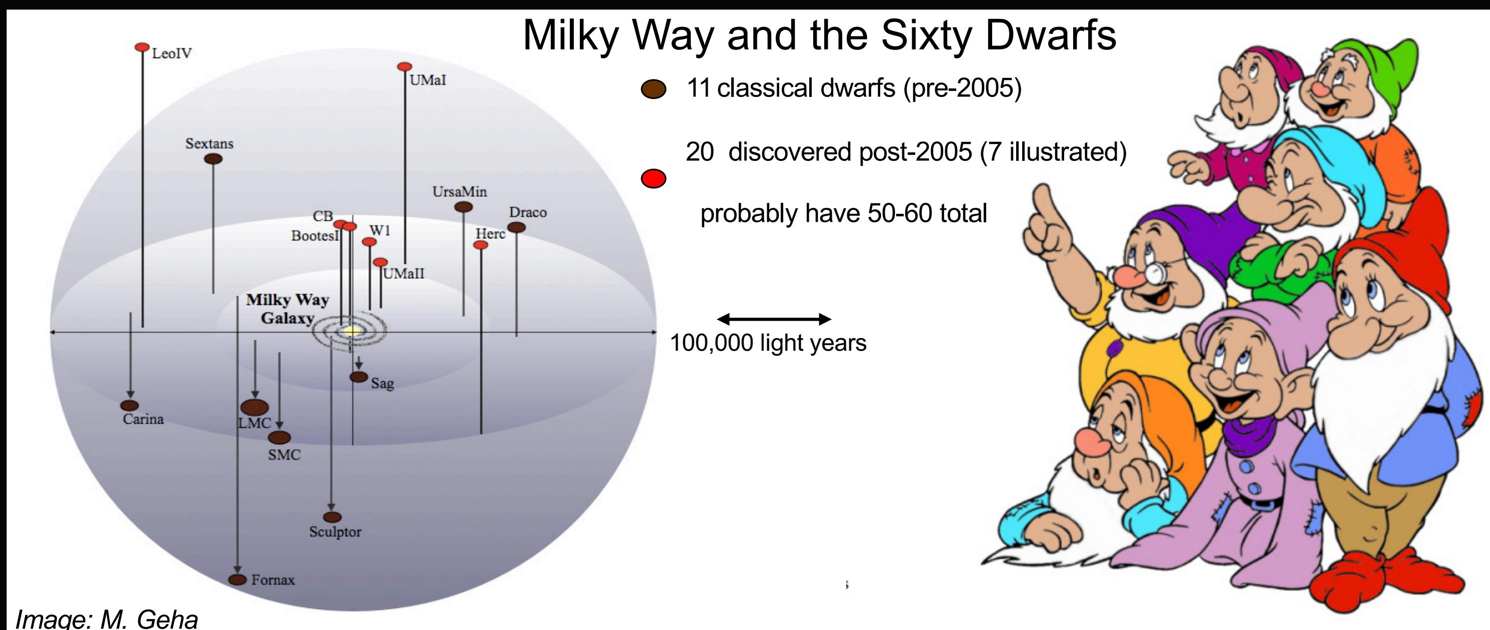


Vera Rubin

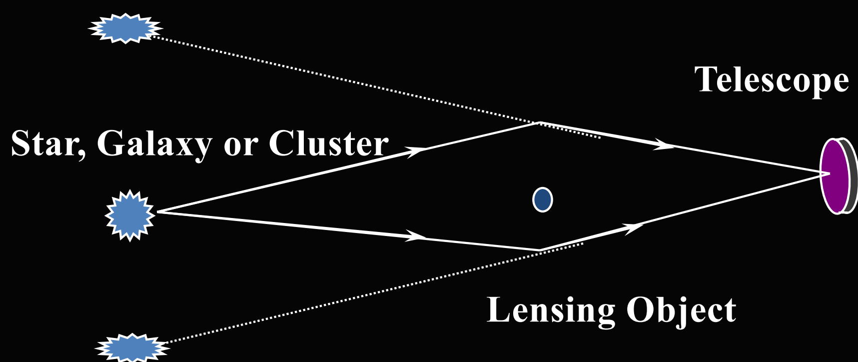
Ninety-three Years of Dark Matter

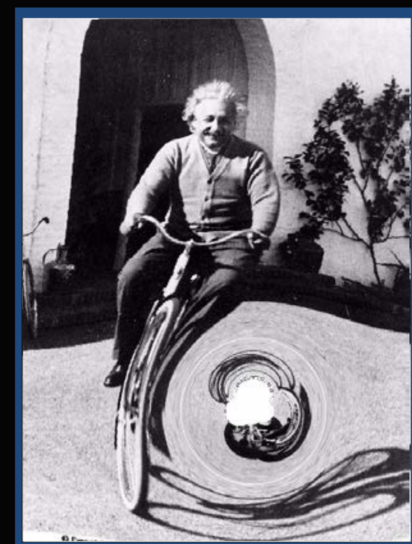
Sun: 2×10^{27} tons; 4×10^{26} watts → Mass/Luminosity = 5 tons/watt

Oort	1932	Local Neighborhood Dim	10–15 tons/watt
Zwicky	1937	Galaxy Clusters Really Dark	2,500 tons/watt
Rubin, Ford & others	1970s	Individual Galaxies Also Dark	300 tons/watt
Dwarf Observers	1990s	Dwarf Galaxies Darker Still	15,000 tons/watt



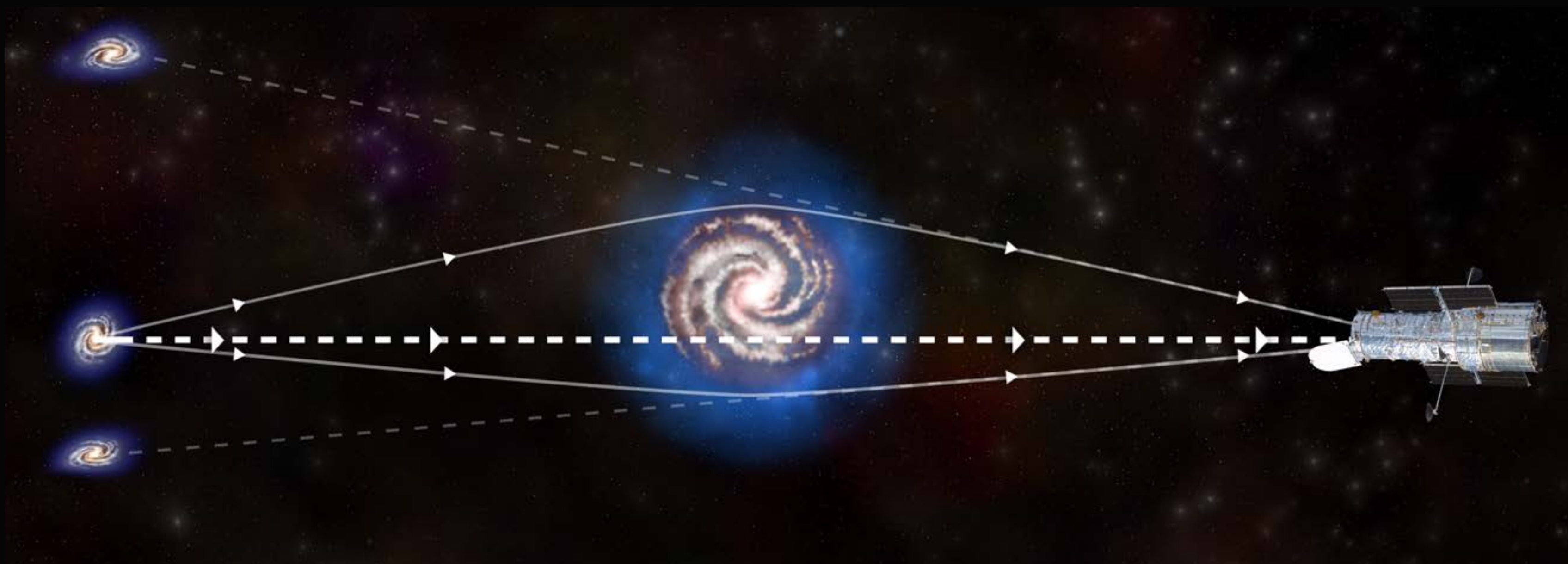
Gravitational Lensing





Gravitational Lensing

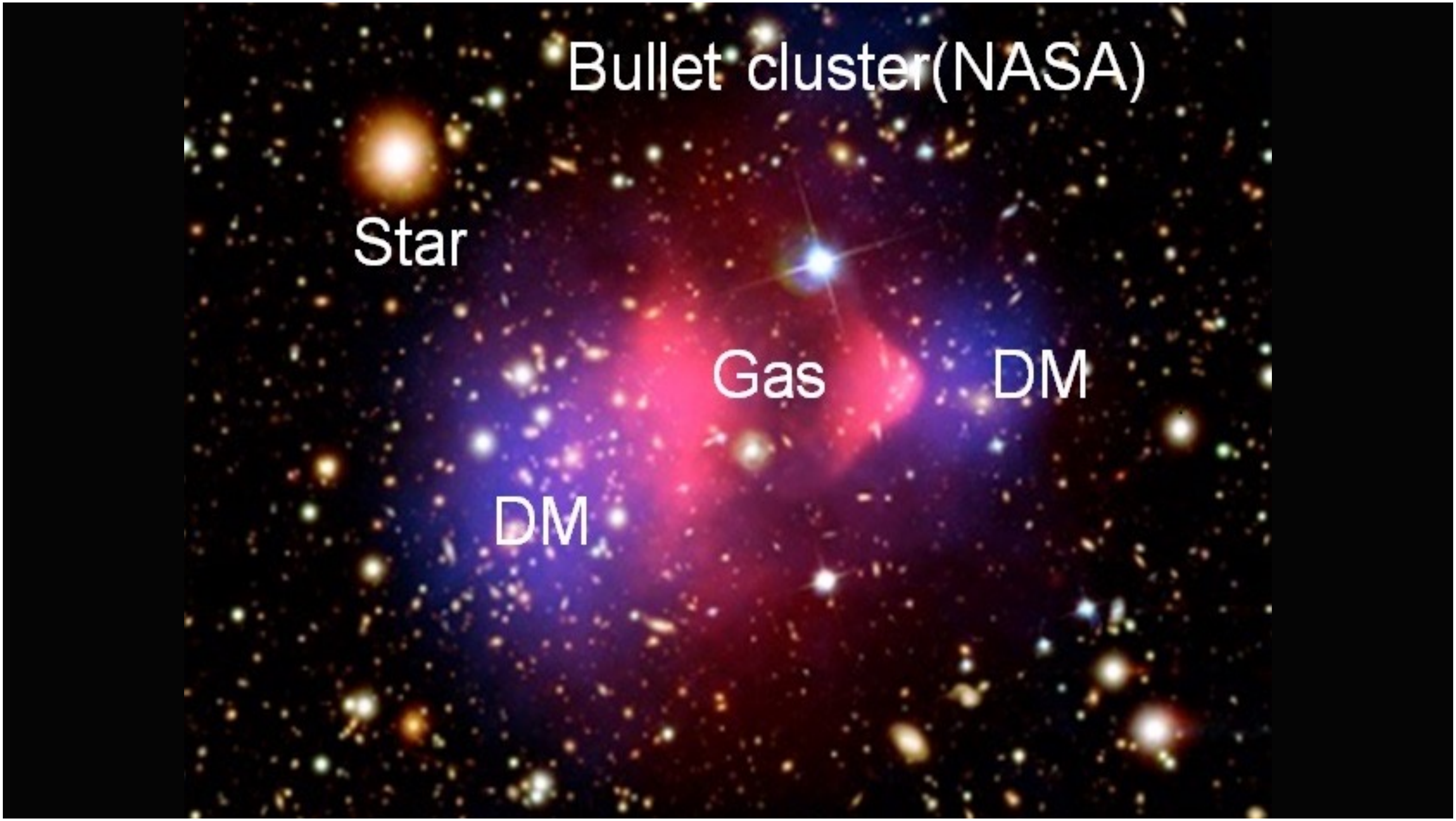
The bending of light by gravity makes it possible to measure the mass of a galaxy (scale of 10 kiloparsec) or cluster of galaxies (scales of dozens of megaparsec)

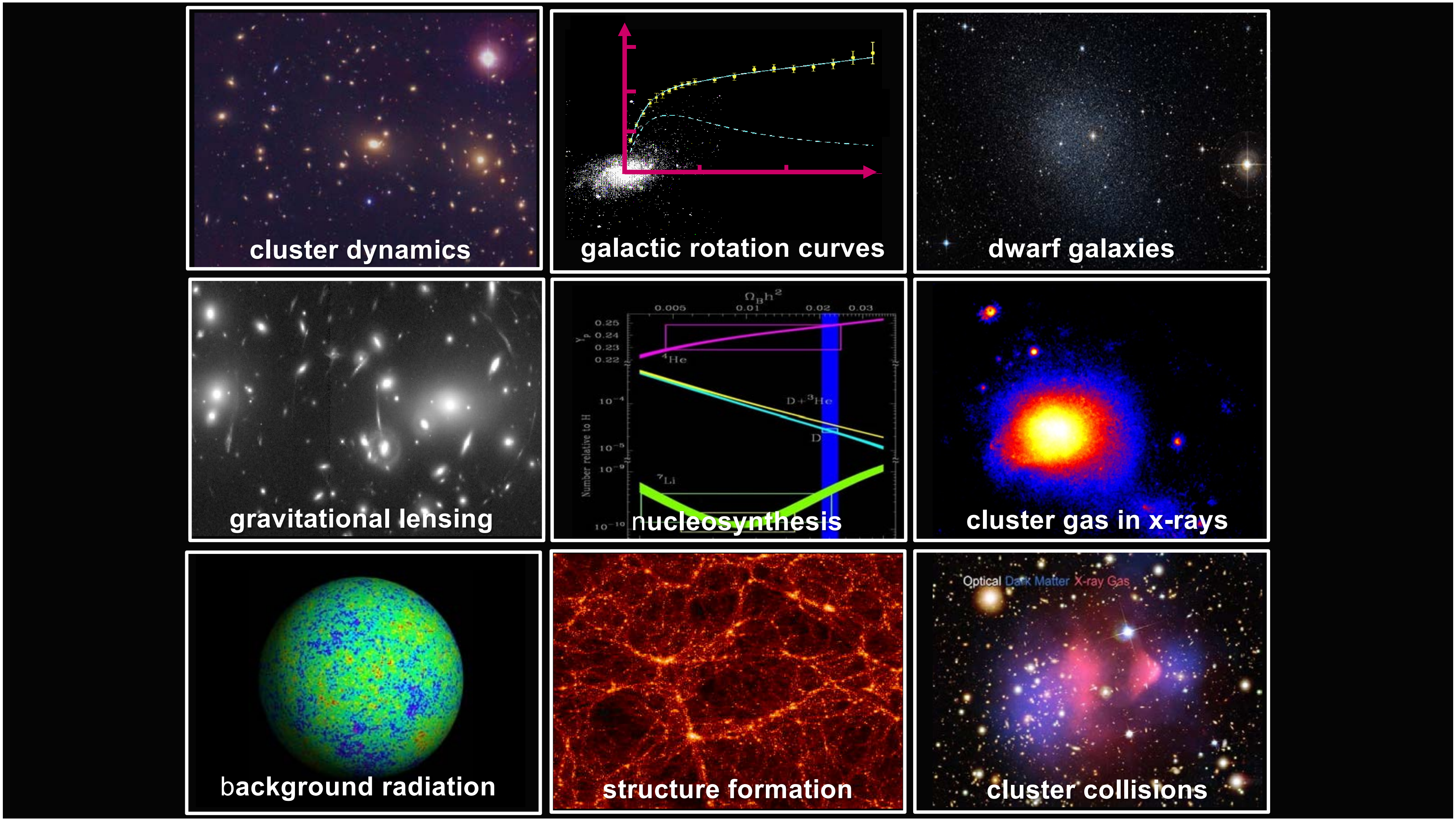


Gravitational Lensing

Hubble Space Telescope

Galaxy Cluster Abell 2218


Bullet cluster(NASA)
Star
Gas
DM
DM


cluster dynamics
galactic rotation curves
dwarf galaxies
gravitational lensing
nucleosynthesis
cluster gas in x-rays
background radiation
structure formation
Optical Dark Matter X-ray Gas
cluster collisions

What is a Simulation?

Oxford English Dictionary

Lost for Words?

simulation

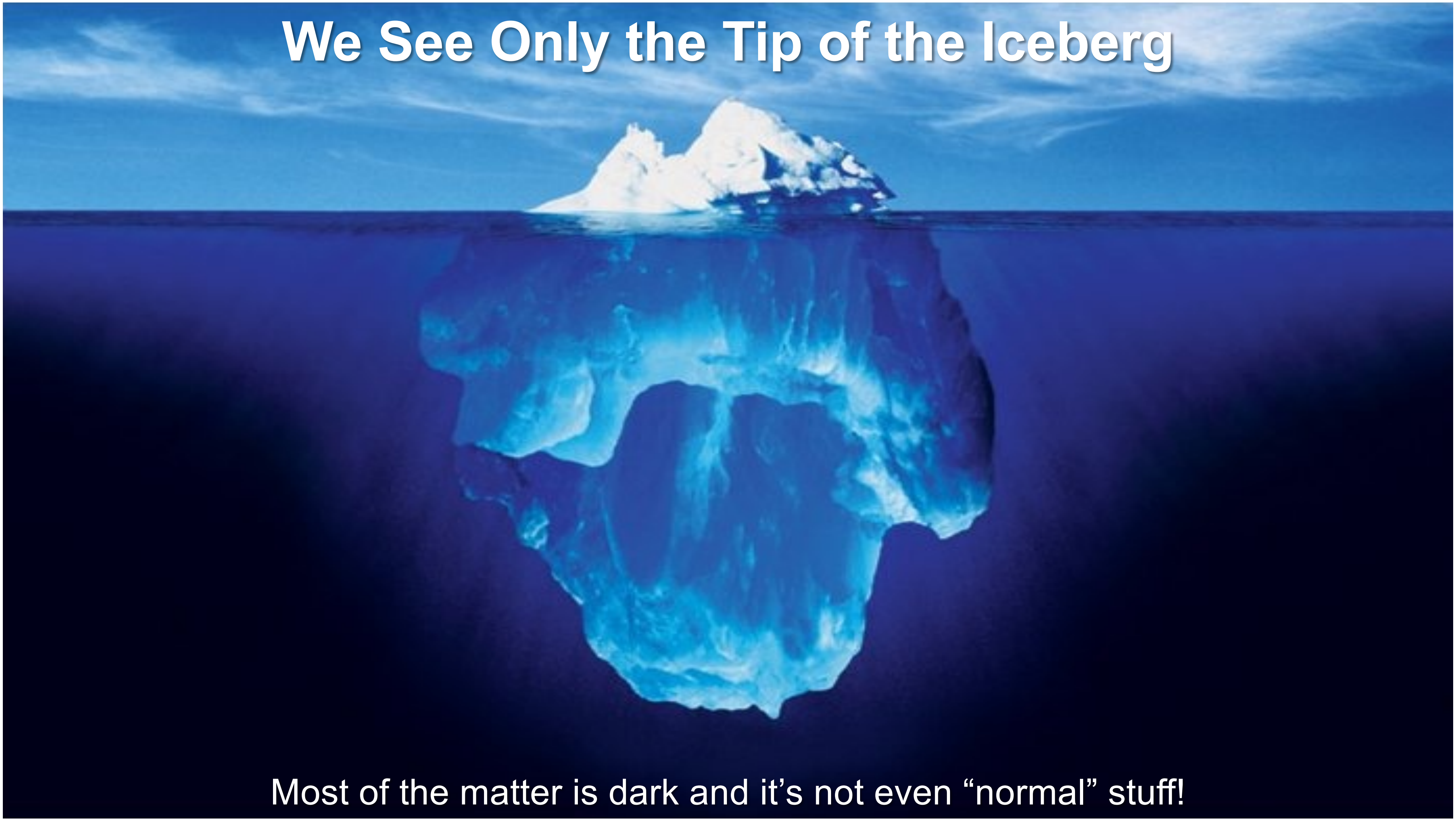
Find Word

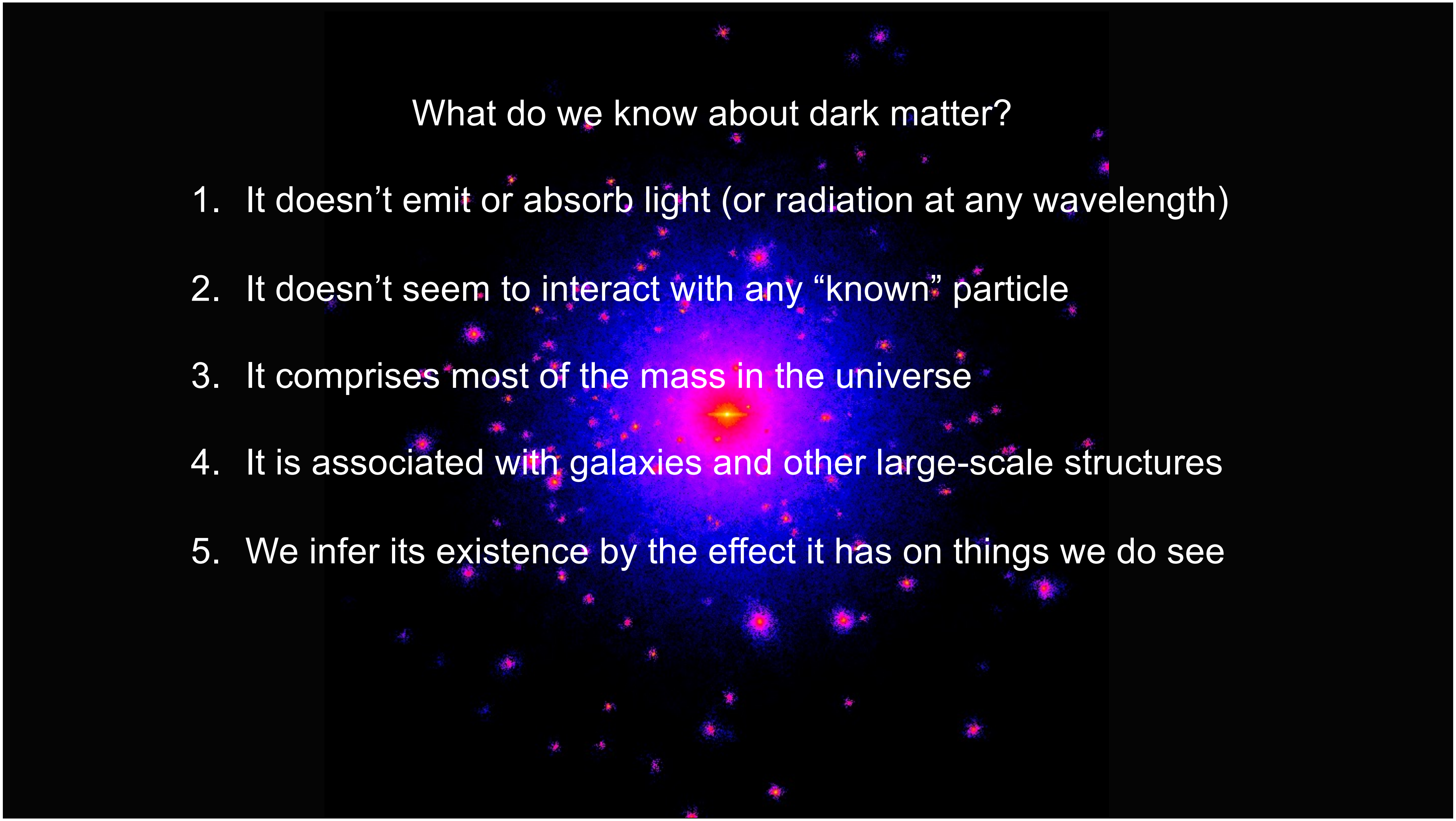
simulation

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.


We See Only the Tip of the Iceberg
Most of the matter is dark and it’s not even “normal” stuff!


What do we know about dark matter?
1. It doesn’t emit or absorb light (or radiation at any wavelength)
2. It doesn’t seem to interact with any “known” particle
3. It comprises most of the mass in the universe
4. It is associated with galaxies and other large-scale structures
5. We infer its existence by the effect it has on things we do see

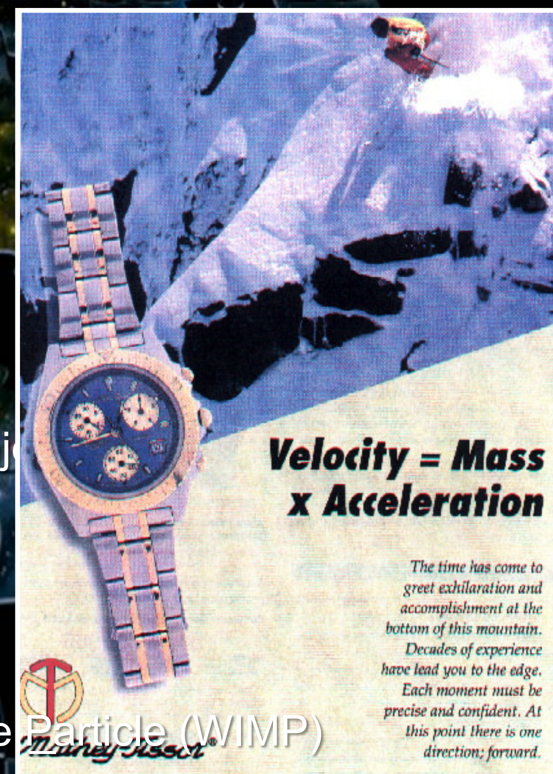
Dark Matter

- Einstein or Newton didn't have the last word
  - Modified Gravity
  - MOND (Modified Newtonian Dynamics, *i.e.*, $F \neq m\,a$)

- Rocky Rogue Planets
- Mass Challenged Stars
- Black Holes

} Massive Compact Halo Obj

- Unknown Particle Species — Weakly Interagting Massive Particle (WIMP)



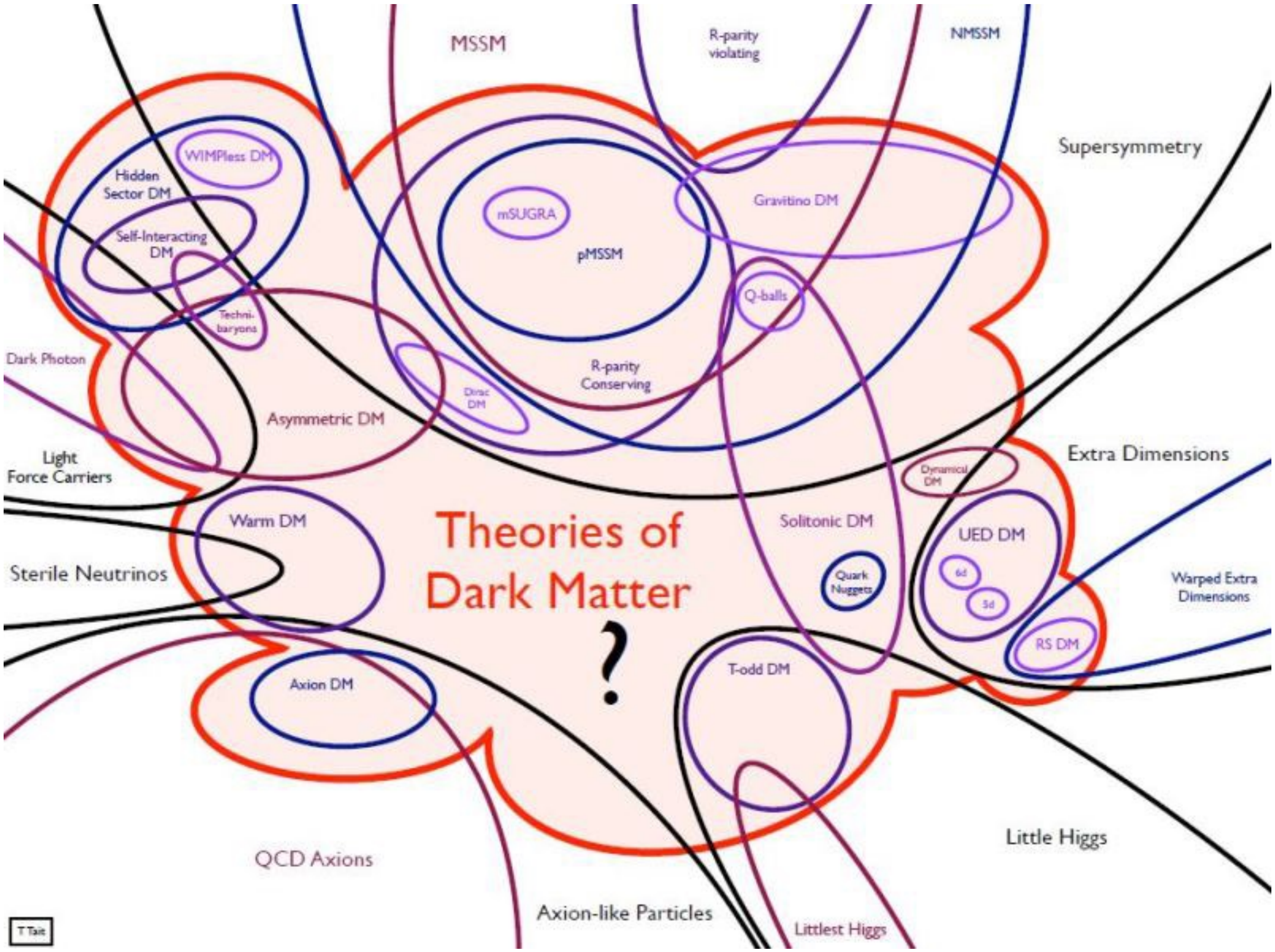
Known Particle Species

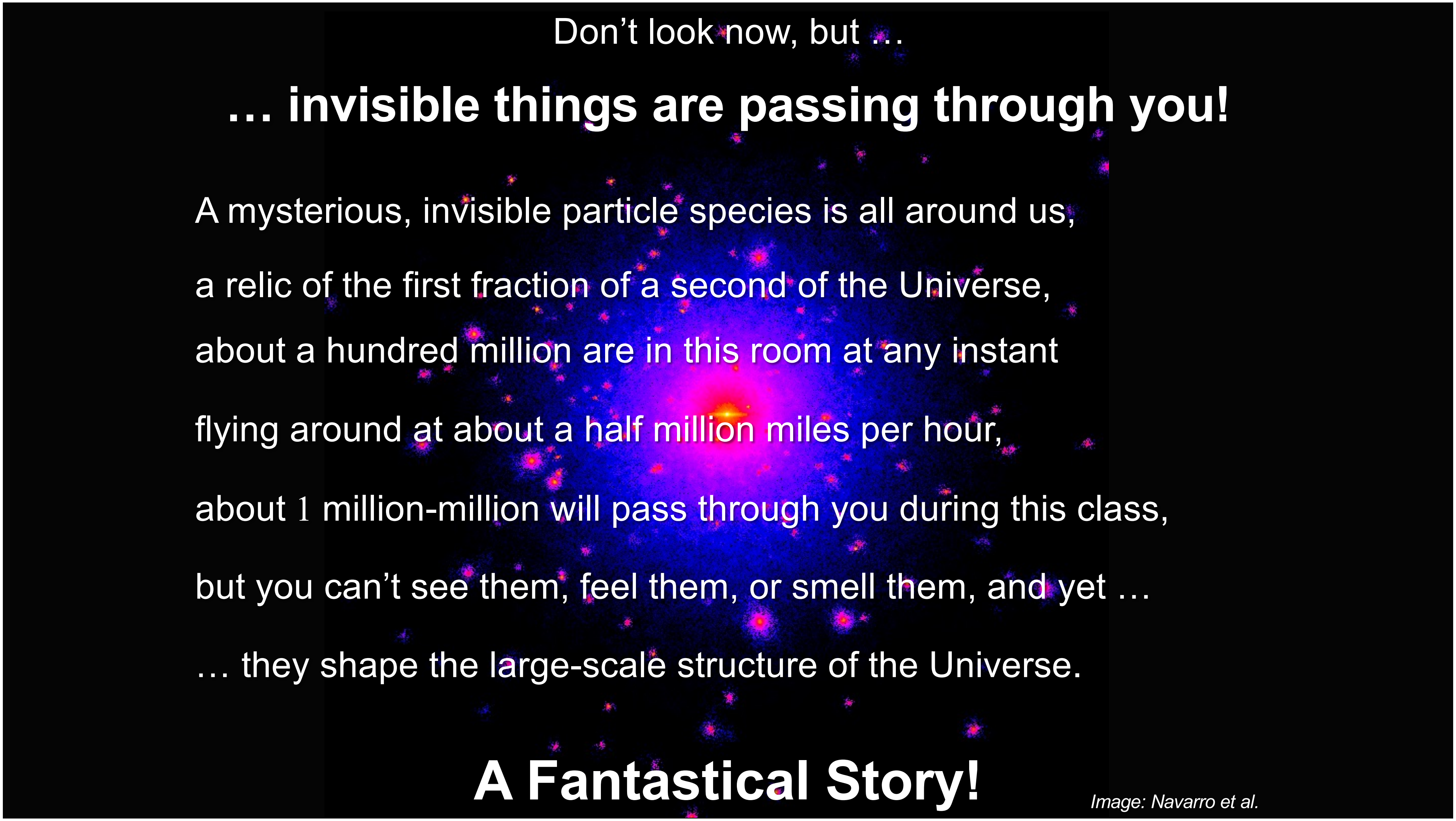
?

Dark particle must be stable and massive and interact weakly

Dark particle must be “Beyond the Standard Model” (BSM)

Let 10^3 flowers bloom?




Don’t look now, but …
… invisible things are passing through you!
A mysterious, invisible particle species is all around us,
a relic of the first fraction of a second of the Universe,
about a hundred million are in this room at any instant
flying around at about a half million miles per hour,
about 1 million-million will pass through you during this class,
but you can’t see them, feel them, or smell them, and yet …
… they shape the large-scale structure of the Universe.
A Fantastical Story!
Image: Navarro et al.

Particle Dark Matter Bestiary

- sub-eV mass neutrinos (WIMPs exist!) (hot)
- sterile neutrinos, gravitini (warm)
- lightest supersymmetric particle (cold)
- lightest Kaluza-Klein particle (cold)

} thermal relics or decay of or oscillation from thermal relics

- Bose-Einstein condensates
- axions, axion clusters
- solitons (Q-balls, B-balls, …)

} from phase transitions

- supermassive wimpzillas — from inflation

} nonthermal relics

<u>Mass</u>	
$10^{-22}\,\mathrm{eV}$ $(10^{-56}\,\mathrm{g})$	Bose-Einstein
$10^{-8}\,M_\odot$ $(10^{+25}\,\mathrm{g})$	axion clusters

<u>Interaction Strength</u>
only gravitational: wimpzillas
strongly interacting: B balls

Freeze Out

Details in classic paper of Gondolo and Gelmini NPB360 (1991) 145

Consider a massive particle species χ, with mass m.

Assuming M-B statistics with phase-space density $f(p_\chi)$
(no stimulated emission or Pauli blocking)

Creation and annihilation of χ through interaction with a light field ψ

$$\psi_1 + \psi_2 \leftrightarrow \chi_1 + \chi_2$$

Boltzmann equation for evolution of n_Ψ (in absence of scattering, $n_\chi \propto a^{-3}$)

$$\dot{n}_\chi + 3Hn_\chi = \frac{1}{(2\pi)^8}\int \frac{d^3p_{\psi_1}}{2E_{\psi_1}} \int \frac{d^3p_{\psi_2}}{2E_{\psi_2}} \int \frac{d^3p_{\chi_1}}{2E_{\chi_1}} \int \frac{d^3p_{\chi_2}}{2E_{\chi_2}} \left[f(p_{\psi_1})f(p_{\psi_2}) - f(p_{\chi_1})f(p_{\chi_2})\right]$$

$$\times \left|\mathcal{M}_{\chi_1\chi_2\to\psi_1\psi_2}\right|^2 \; \delta^4(p_{\psi_1} + p_{\psi_2} - p_{\chi_1} - p_{\chi_2})$$

Have assumed $\left|\mathcal{M}_{\psi_1\psi_2\to\chi_1\chi_2}\right|^2 = \left|\mathcal{M}_{\chi_1\chi_2\to\psi_1\psi_2}\right|^2$

Freeze Out

Kinetic Equilibrium and Chemical Equilibrium of a particle X:

Kinetic equilibrium if rate of reactions that change the energy of a particle is $\gg H$, e.g.,

$$\Gamma(\gamma + X \leftrightarrow \gamma + X) \gg H$$

$$f_X(p_X) = e^{-(E_X-\mu)/T} = e^{\mu/T} f_X^{\mathrm{EQ}}(p_X)$$

Chemical equilibrium if rate of reactions that change the number of particles is $\gg H$, e.g.,

$$\Gamma(X + X \leftrightarrow \gamma + \gamma) \gg H \Rightarrow \mu_X = \mu_\gamma = 0$$

$$f_X(p_X) = e^{-E_X/T} = f_X^{\mathrm{EQ}}(p_X)$$

In almost all cases, rate for kinetic equilibrium $\gg$ rate for chemical equilibrium

Freeze Out

$$\dot{n}_\chi + 3Hn_\chi = \frac{1}{(2\pi)^8}\int \frac{d^3p_{\psi_1}}{2E_{\psi_1}} \int \frac{d^3p_{\psi_2}}{2E_{\psi_2}} \int \frac{d^3p_{\chi_1}}{2E_{\chi_1}} \int \frac{d^3p_{\chi_2}}{2E_{\chi_2}} \left[f(p_{\psi_1})f(p_{\psi_2}) - f(p_{\chi_1})f(p_{\chi_2})\right]$$
$$\times \left|\mathcal{M}_{\chi_1\chi_2\to\psi_1\psi_2}\right|^2 \ \delta^4(p_{\psi_1} + p_{\psi_2} - p_{\chi_1} - p_{\chi_2})$$

Assume light particle in chemical equilibrium: $f_\psi(p) = e^{-E_\psi/T}$

$$f_\psi(p_{\psi_1})f_\psi(p_{\psi_2}) = e^{-E_{\psi_1}/T}e^{-E_{\psi_2}/T}, \quad \delta^4 \Rightarrow e^{-E_{\psi_1}/T}e^{-E_{\psi_2}/T} = e^{-E_{\chi_1}/T}e^{-E_{\chi_2}/T} = f_\chi^{\mathrm{EQ}}(p_{\chi_1})f_\chi^{\mathrm{EQ}}(p_\chi)$$

$$\dot{n}_\chi + 3Hn_\chi = \frac{1}{(2\pi)^8}\int \frac{d^3p_{\psi_1}}{2E_{\psi_1}} \int \frac{d^3p_{\psi_2}}{2E_{\psi_2}} \int \frac{d^3p_{\chi_1}}{2E_{\chi_1}} \int \frac{d^3p_{\chi_2}}{2E_{\chi_2}} \left[f^{\mathrm{EQ}}(p_{\chi_1})f^{\mathrm{EQ}}(p_{\chi_2}) - f(p_{\chi_1})f(p_{\chi_2})\right]$$
$$\times \left|\mathcal{M}_{\chi_1\chi_2\to\psi_1\chi_2}\right|^2 \ \delta^4(p_{\psi_1} + p_{\psi_2} - p_{\chi_1} - p_{\chi_2})$$

Rearrange:

$$\dot{n}_\chi + 3Hn_\chi = \frac{1}{(2\pi)^8}\int d^3p_{\chi_1} \int d^3p_{\chi_2} \left[f^{\mathrm{EQ}}(p_{\chi_1})f^{\mathrm{EQ}}(p_{\chi_2}) - f(p_{\chi_1})f(p_{\chi_2})\right]$$
$$\times \frac{1}{2E_{\chi_1}}\frac{1}{2E_{\chi_2}} \int \frac{d^3p_{\psi_1}}{2E_{\psi_1}} \ \frac{d^3p_{\psi_2}}{2E_{\psi_2}} \ \left|\mathcal{M}_{\chi_1\chi_2\to\psi_1\psi_2}\right|^2 \ \delta^4(p_{\psi_1} + p_{\psi_2} - p_{\chi_1} - p_{\chi_2})$$

Freeze Out

$$\dot{n}_\chi + 3Hn_\chi = \frac{1}{(2\pi)^8}\int d^3p_{\chi_1}\int d^3p_{\chi_2}\left[f^{\rm EQ}(p_{\chi_1})f^{\rm EQ}(p_{\chi_2}) - f(p_{\chi_1})f(p_{\chi_2})\right]$$
$$\times\frac{1}{2E_{\chi_1}}\frac{1}{2E_{\chi_2}}\int\frac{d^3p_{\psi_1}}{2E_{\psi_1}}\;\frac{d^3p_{\psi_2}}{2E_{\psi_2}}\;\left|\mathcal{M}_{\chi_1\chi_2\to\psi_1\psi_2}\right|^2\;\delta^4(p_{\psi_1}+p_{\psi_2}-p_{\chi_1}-p_{\chi_2})$$

Annihilation cross section for $\chi_1 + \chi_2 \to \psi_1 + \psi_2$:

$$\sigma_A = \frac{1}{(2\pi)^2}\frac{1}{\sqrt{(p_{\chi_1}\cdot p_{\chi_2})^2 - m_\chi^4}}\int\frac{d^3p_{\psi_1}}{2E_{\psi_1}}\;\frac{d^3p_{\psi_2}}{2E_{\psi_2}}\;\left|\mathcal{M}_{\chi_1\chi_2\to\psi_1\psi_2}\right|^2\;\delta^4(p_{\psi_1}+p_{\psi_2}-p_{\chi_1}-p_{\chi_2})$$

$$\dot{n}_\chi + 3Hn_\chi = \frac{1}{(2\pi)^8}\int d^3p_{\chi_1}\int d^3p_{\chi_2}\left[f^{\rm EQ}(p_{\chi_1})f^{\rm EQ}(p_{\chi_2}) - f(p_{\chi_1})f(p_{\chi_2})\right]\;\frac{\sqrt{(p_{\chi_1}\cdot p_{\chi_2})^2 - m_\chi^4}}{2E_{\chi_1}2E_{\chi_2}}\sigma_A$$

Freeze Out

$$\dot{n}_\chi + 3Hn_\chi = \frac{1}{(2\pi)^8}\int d^3p_{\chi_1}\int d^3p_{\chi_2}\left[f^{\rm EQ}(p_{\chi_1})f^{\rm EQ}(p_{\chi_2}) - f(p_{\chi_1})f(p_{\chi_2})\right]\ \frac{\sqrt{(p_{\chi_1}\cdot p_{\chi_2})^2 - m_\chi^4}}{2E_{\chi_1}2E_{\chi_2}}\sigma_A$$

Now assume χ in Kinetic Equilibrium: $f_\chi(p) = e^{\mu/T}e^{-E/T}$

$$\dot{n}_\chi + 3Hn_\chi = \frac{\left[1 - e^{2\mu/T}\right]}{(2\pi)^8}\int d^3p_{\chi_1}\int d^3p_{\chi_2}e^{-E_{x_1}/T}e^{-E_{x_2}/T}\ \frac{\sqrt{(p_{\chi_1}\cdot p_{\chi_2})^2 - m_\chi^4}}{2E_{\chi_1}2E_{\chi_2}}\sigma_A$$

$$\frac{\sqrt{(p_{\chi_1}\cdot p_{\chi_2})^2 - m_\chi^4}}{2E_{\chi_1}2E_{\chi_2}} \equiv |v_{\rm Moller}|$$ = Moller velocity

$$\dot{n}_\chi + 3Hn_\chi = \left[1 - e^{2\mu/T}\right]\int d^3p_{\chi_1}\int d^3p_{\chi_2}e^{-E_{x_1}/T}e^{-E_{x_2}/T}\ |v_{\rm Moller}|\ \sigma_A$$

Freeze Out

$$\dot{n}_\chi + 3Hn_\chi = \left[1 - e^{2\mu/T}\right] \int d^3p_{\chi_1} \int d^3p_{\chi_2} e^{-E_{x_1}/T} e^{-E_{x_2}/T} \; |v_{\text{Moller}}| \; \sigma_A$$

$$\dot{n}_\chi + 3Hn_\chi = \underbrace{\int d^3p'_{\chi_1} \int d^3p'_{\chi_2} f^{\text{EQ}}(p'_{\chi_1}) f^{\text{EQ}}(p'_{\chi_2}) \left[1 - e^{2\mu/T}\right]}_{\left[(n_\chi^{\text{EQ}})^2 - n_\chi^2\right]} \underbrace{\frac{\int d^3p_{\chi_1} \int d^3p_{\chi_2} e^{-E_{x_1}/T} e^{-E_{x_2}/T} \; |v_{\text{Moller}}| \; \sigma_A}{\int d^3p'_{\chi_1} \int d^3p'_{\chi_2} f^{\text{EQ}}(p'_{\chi_1}) f^{\text{EQ}}(p'_{\chi_2})}}_{\langle |v_{\text{Moller}}| \; \sigma_A \rangle}$$

$$\boxed{\dot{n}_\chi + 3Hn_\chi = \left[(n_\chi^{\text{EQ}})^2 - n_\chi^2\right] \langle |v_{\text{Moller}}| \; \sigma_A \rangle}$$

Freeze Out

$$\dot{n}_\chi + 3Hn_\chi = \left[(n_\chi^{\mathrm{EQ}})^2 - n_\chi^2\right] \langle |v_{\mathrm{Moller}}|\ \sigma_A \rangle$$

- I lost factors of 2π along the way, but the result is right.
- Have to account for identical particles in initial and final states.
- Take account of spin states.
- Need initial conditions
  - If at high temperatures ($T \gg m$) $n_\chi = n_\chi^{\mathrm{EQ}}$ then "Freeze OUT"
  - If at high temperatures ($T \gg m$) $n_\chi \ll n_\chi^{\mathrm{EQ}}$ then "Freeze IN"
- When $\mathrm{Max}\left[n_\chi,\ n_\chi^{\mathrm{EQ}}\right] \langle |v_{\mathrm{Moller}}| \sigma_A \rangle \ll H,\ n_\chi \propto a^{-3}$ and $n_\chi a^{-3}$ frozen.
- More details in Goldolo and Gelmini.

Freeze Out

$$\dot{n}_\chi + 3Hn_\chi = \left[(n_\chi^{\mathrm{EQ}})^2 - n_\chi^2\right] \left\langle \left| v_{\mathrm{Moller}} \right| \sigma_A \right\rangle$$

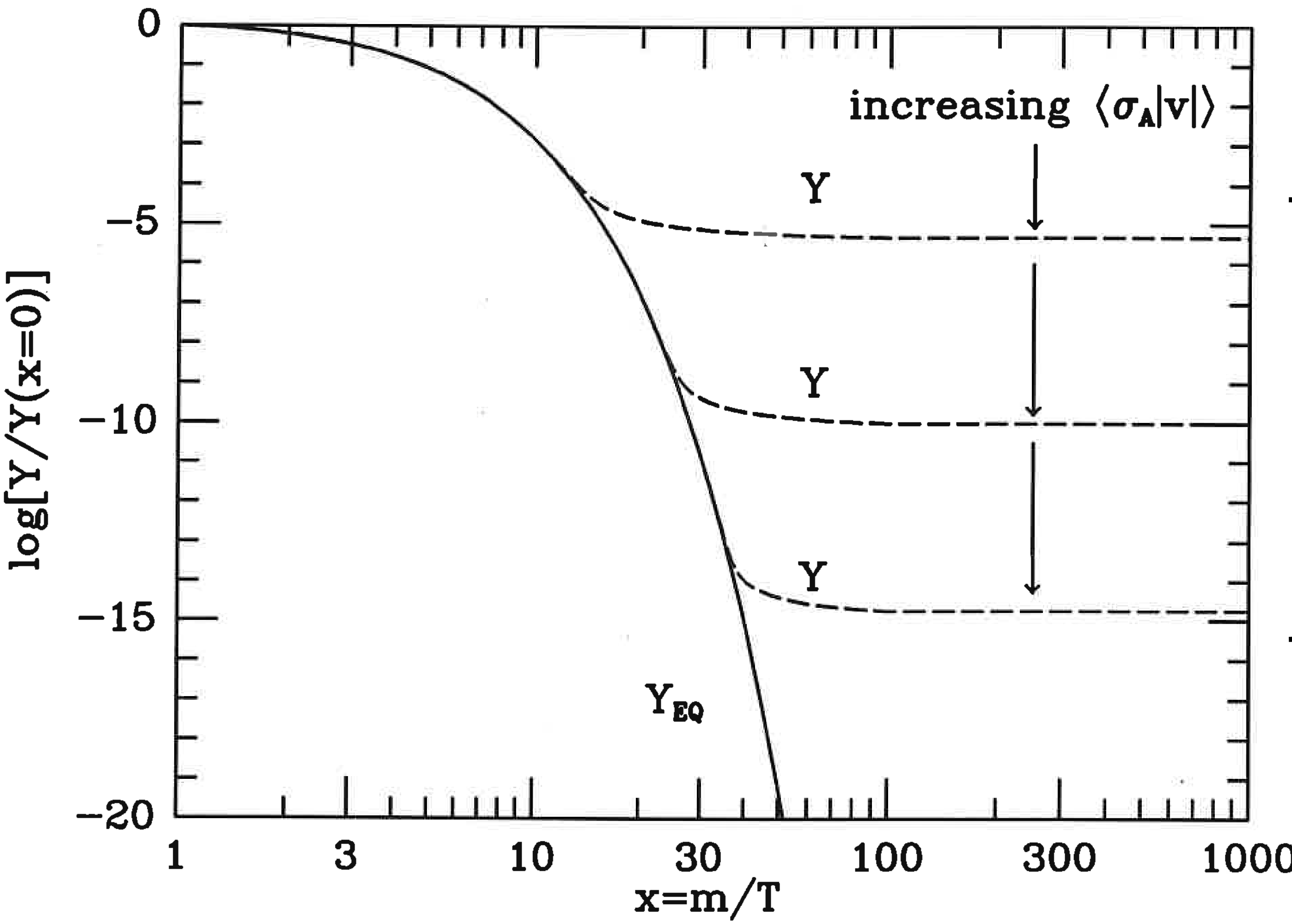
- Convenient to track $Y_\chi = n_\chi / s$, s is the entropy density

$$s = \frac{\rho + P}{T} = \frac{2\pi^2}{45} g_{*s} T^3 \qquad \text{where} \quad g_{*s} = \sum_{i=\mathrm{bosons}} \left(\frac{T_i}{T}\right)^3 + \frac{7}{8} \sum_{i=\mathrm{fermions}} \left(\frac{T_i}{T}\right)^3$$

For most of history of the universe all species at same temperature and $g_{*s} = g_*$

- And track evolution in $x = m/T$ rather than time

Freeze Out of a Cold Thermal Relic



$$Y_\infty \propto \frac{1}{m m_{\rm Pl} \langle \sigma_A | v_{\rm Moller} | \rangle}$$

Freeze-out value of Y determines present mass density

$$\Omega \propto m Y_\infty$$

$$\propto \frac{1}{\langle \sigma_A | v_{\rm Moller} | \rangle}$$

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

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

Here n is the actual number density of heavy neutrinos at time t; R is the cosmic scale factor; <σv> 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]:

$$n_0(T) = \ldots \quad (3)$$

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

$\langle\sigma_A v\rangle =$ NR annihilation cross section × Møller flux (thermal avg.)

$$\Omega h^2 \approx 0.11 \times \frac{10^{-36}\ \mathrm{cm}^2}{\langle\sigma_A v\rangle}$$

$$10^{-36}\ \mathrm{cm}^2 = \frac{\alpha^2}{(150\ \mathrm{GeV})^2}$$

weak scale!

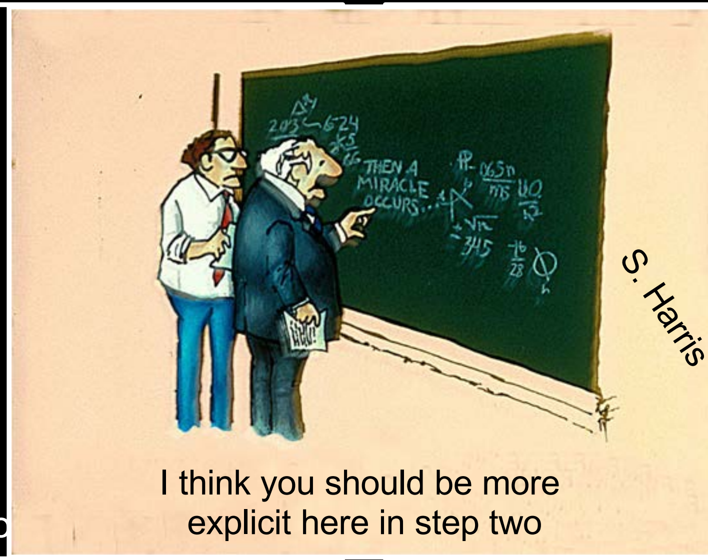
Not quite so clean:

- velocity dependence
- resonances
- co-annihilation
- $\log$ dependence on M
- decay production
- spin-dependence
- asymmetries
- …

The WIMP "Miracle"

Merriam-Webster OnLine

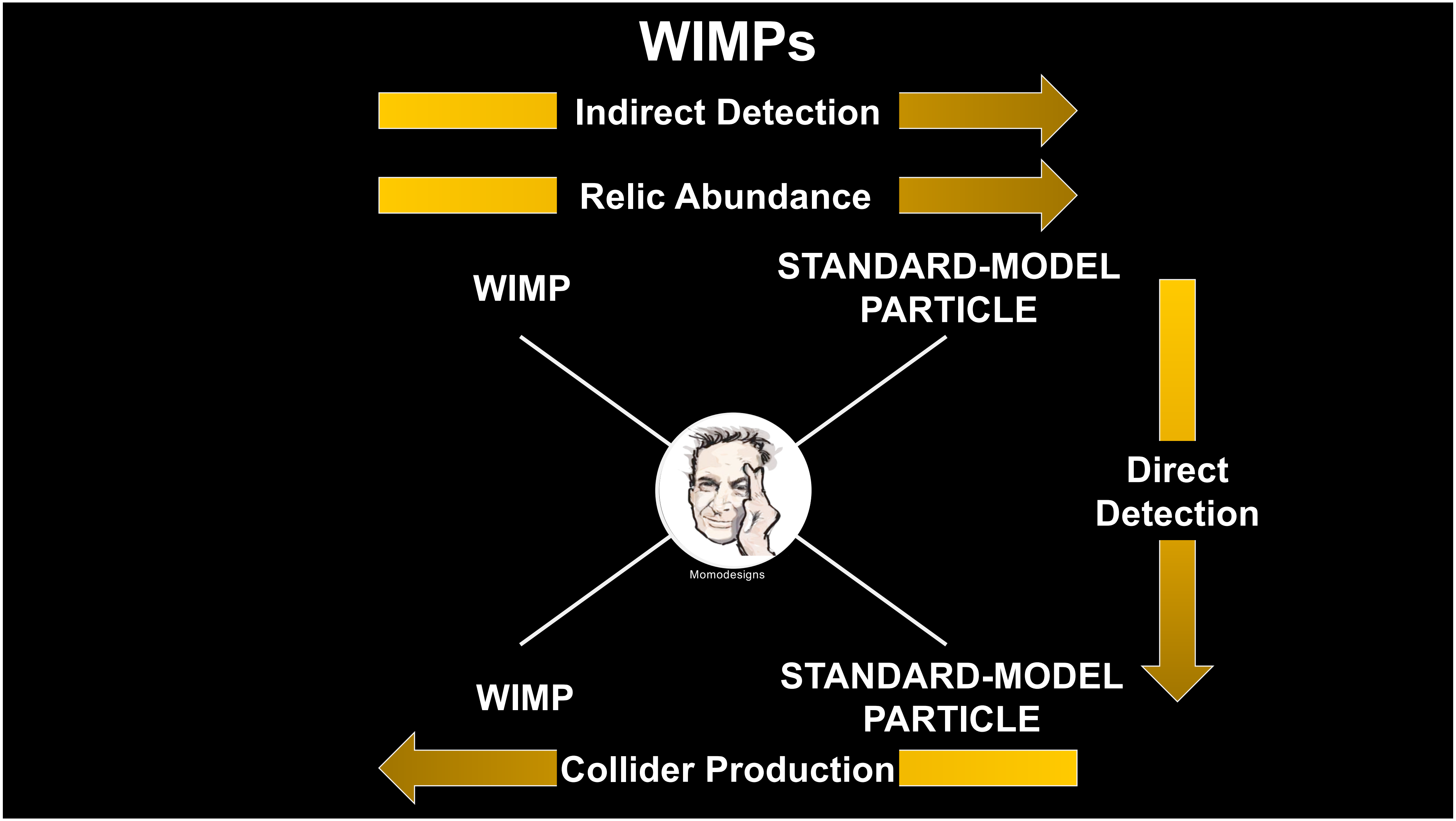
1 : an extraordinary
divine interventio



encyclopedia

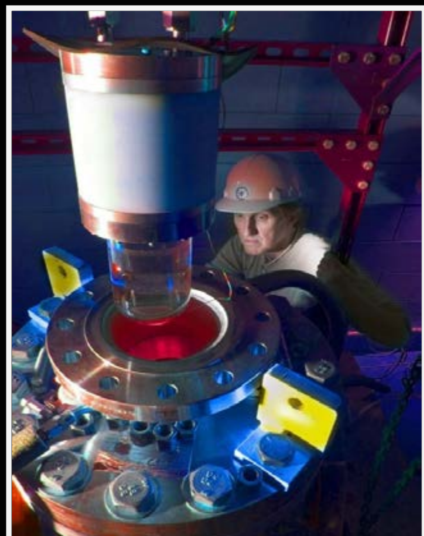
. often used to give an
npression of great and
nusual value in a trivial
ontext …

WIMPs:
BSM (but not far BSM)
Interact with Standard Model particles (but "weakly")

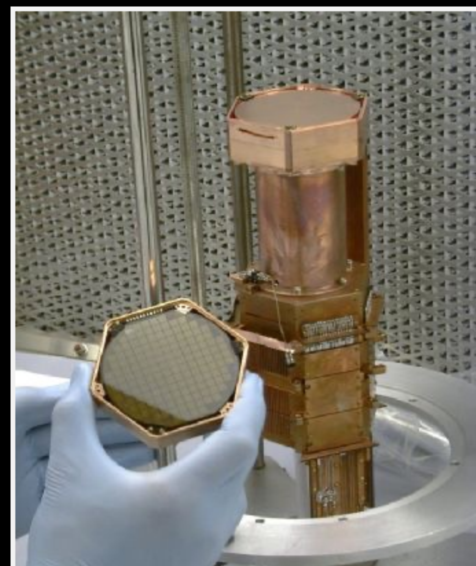

WIMPs
Indirect Detection
Relic Abundance
WIMP
STANDARD-MODEL PARTICLE
Direct Detection
Momodesigns
WIMP
STANDARD-MODEL PARTICLE
Collider Production

Direct Detection (Matt Pyle)

COUPP



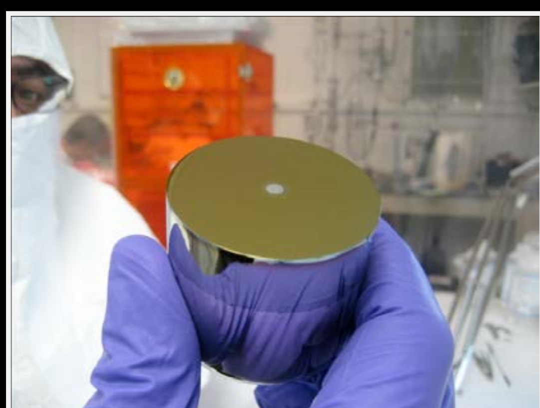
CDMS



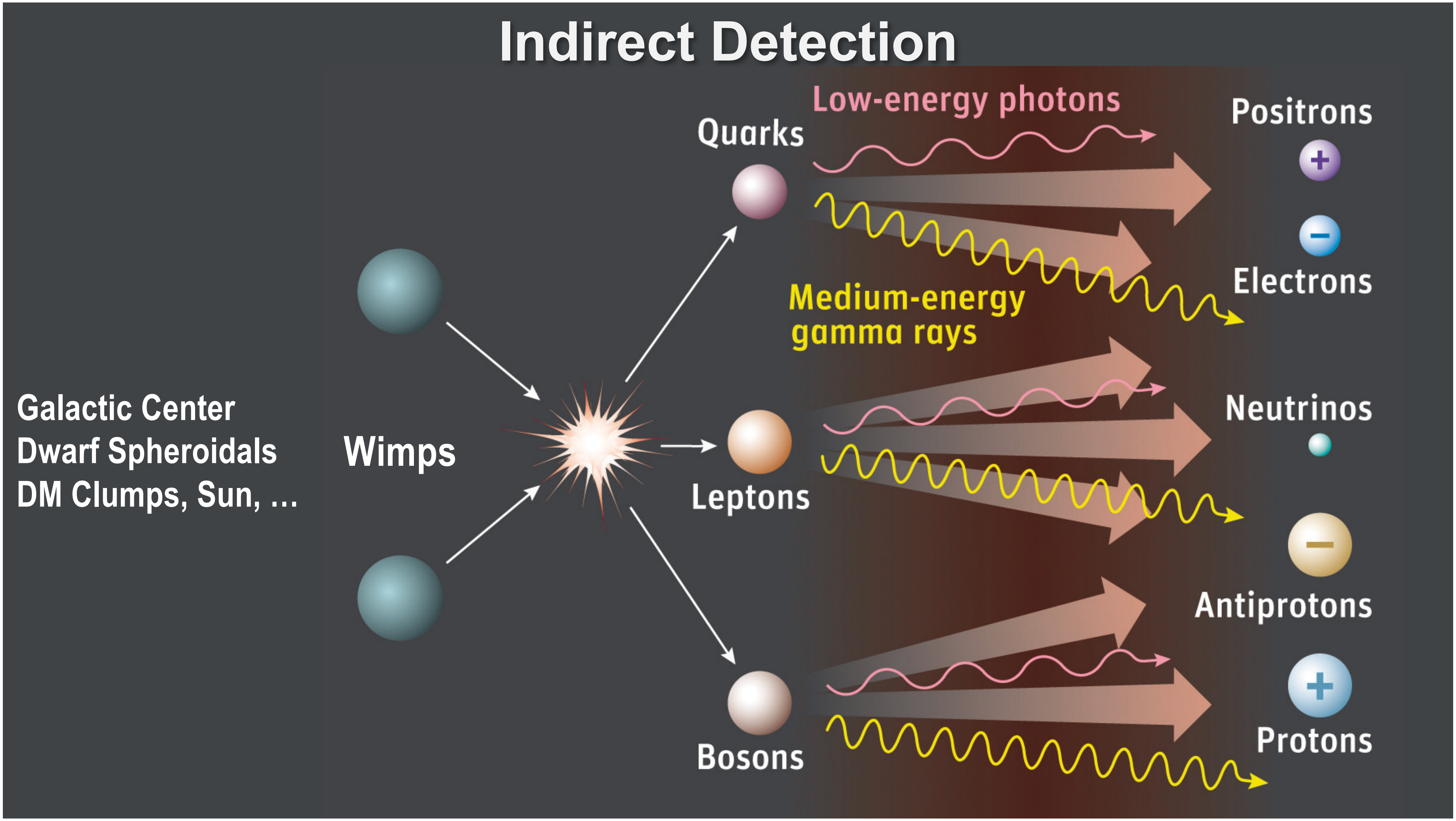
CRESST

Xenon

CoGeNT



(+ EDELWEISS, DAMA, EURECA, ZEPLIN, DEAP, ArDM, WARP, LUX, SIMPLE, PICASSO, DMTPC, DRIFT, KIMS, LUX, ARDM, ANAIS, CDEX PandaX, DarkSide, DAMA/LIBRA …)


Indirect Detection
Low-energy photons
Quarks
Positrons
Electrons
Medium-energy gamma rays
Galactic Center
Dwarf Spheroidals
DM Clumps, Sun, ...
Wimps
Neutrinos
Leptons
Antiprotons
Protons
Bosons

Indirect Detection

$$\Phi_{\gamma,e^+,n,\ldots}(E,\hat{n}) = \frac{1}{4\pi}\left[\frac{\langle\sigma v\rangle}{2m_\chi^2}\frac{dN_{\gamma,e^+,n,\ldots}}{dE}\right]\left[\int_{\text{line of sight}}\rho_\chi^2\,dl\right]$$

$\Phi_{\gamma,e^+,n,\ldots}(E,\hat{n}) =$ [particle physics] [J factor (astronomy)]

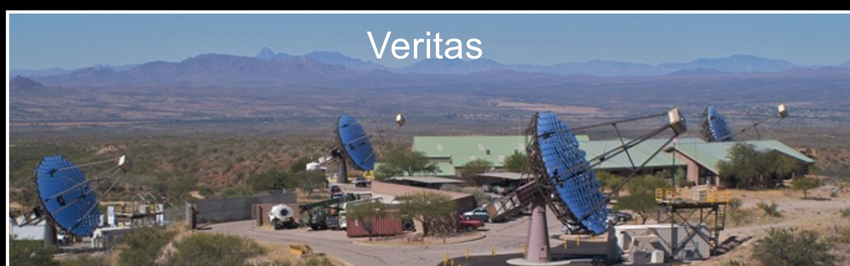
What to look for

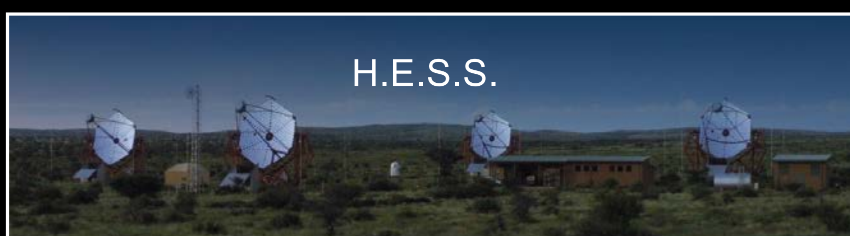
- Charged particles: $\bar{p}$, high-energy $e^- e^+$
  - astronomical backgrounds
  - easy to detect
  - bent by magnetic field
- Continuum photons, neutrinos
  - astronomical backgrounds
  - γ easy to detect
  - ν hard to detect/often not dominant
- Monoenergetic photon line ($\bar{\chi}\chi \rightarrow \gamma\gamma$)
  - low background
  - (probably) low signal
  - "golden" detection channel

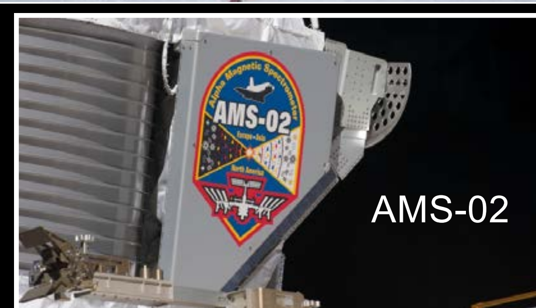
Where to look for it

- Galactic Center
  - know where to look
  - largest signal
  - largest backgrounds
- Nearby subclumps
  - don't know where to look
  - signal down 10^{-3}
  - clean: no baryons
- Dwarf spheroidals $(\mathcal{M}/\mathcal{L}) > 3000$
  - know where to look (about 20)
  - signal down another 10^{-3}
  - clean: very few baryons

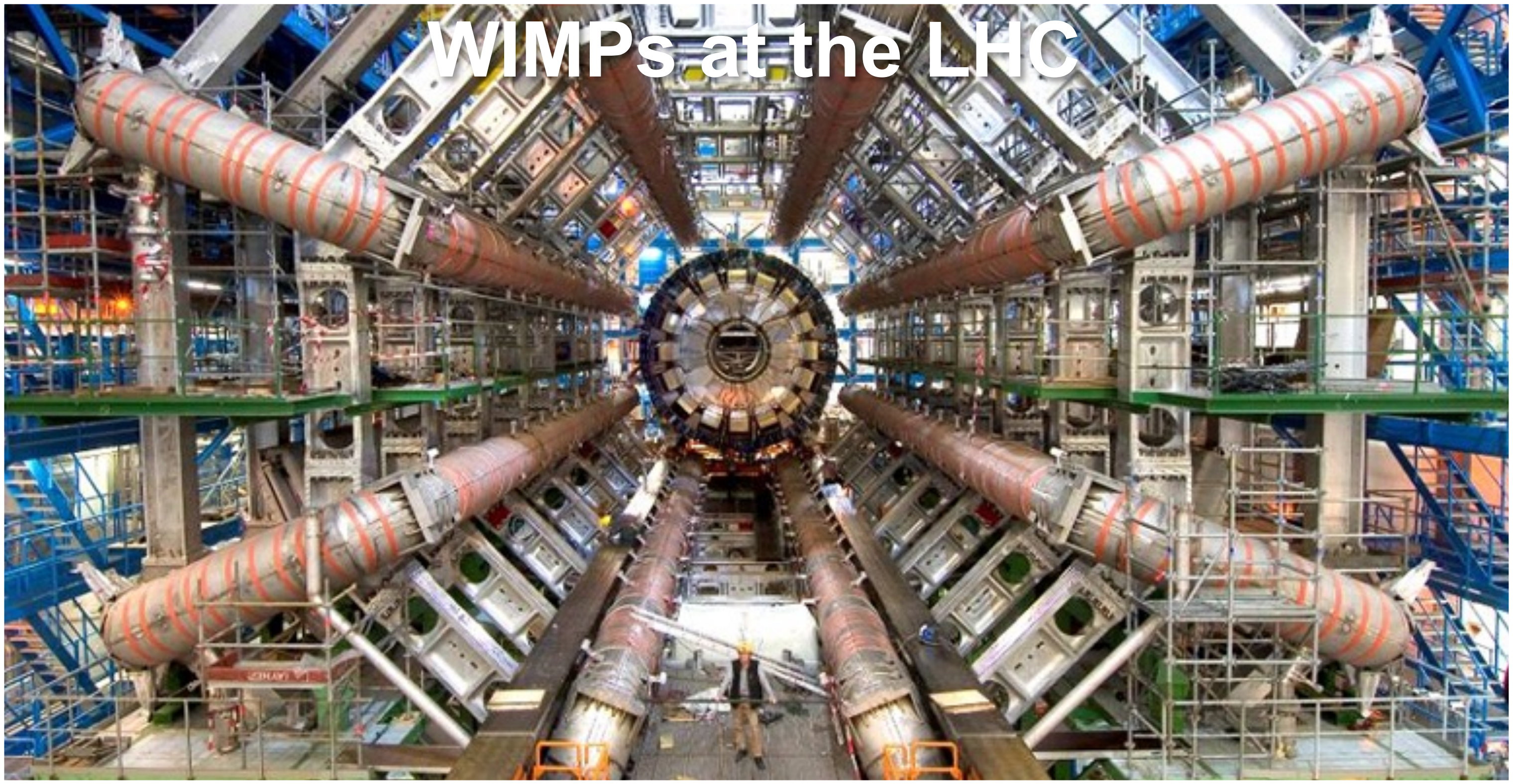
Indirect Detection

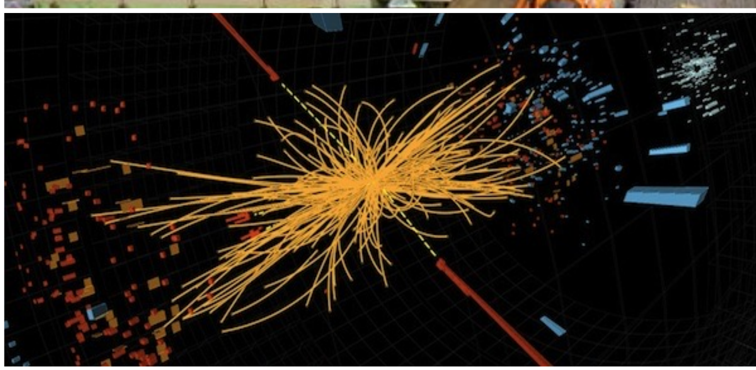






WIMPs at the LHC

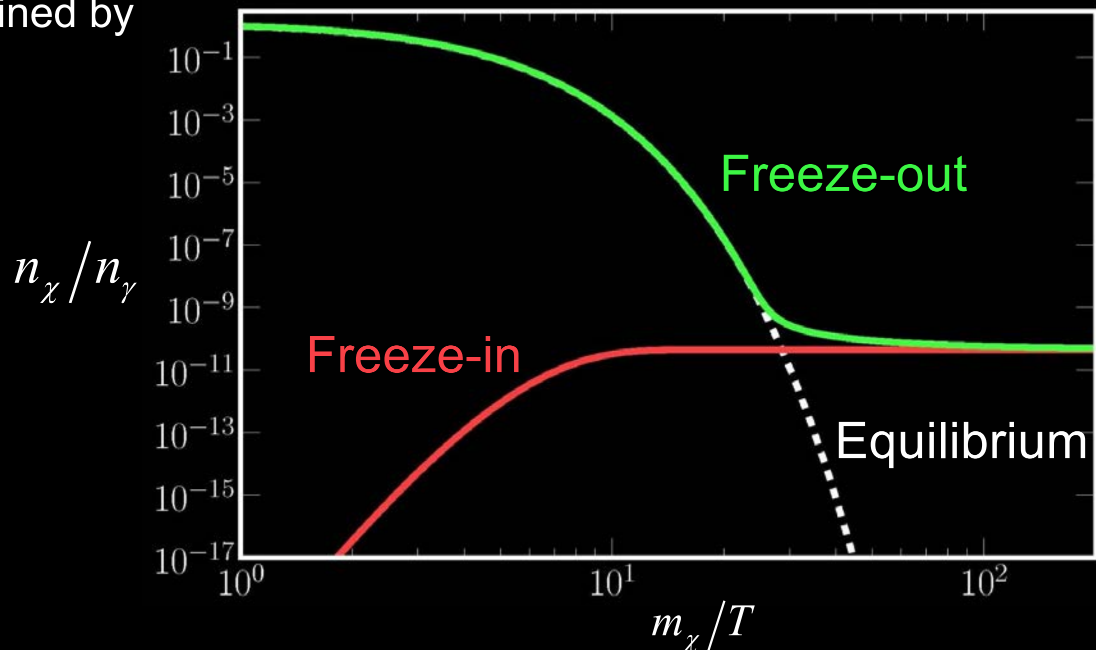




Looking for an
invisible
needle in a haystack

Most popular paradigm: cold thermal relic*

- DM abundance set by creation/annihilation with standard-model particles
- Equilibrium abundance of DM determined by M / T (no asymmetry)
- DM species final abundance determined by
  "freeze-out" of equilibrium, or
  "freeze-in" to final abundance



- Freeze-out/in: interplay between
  particle physics (DM—SM interactions) and cosmology (expansion rate)

* An object of particular veneration.

Direct, Indirect, Accelerator

Where is the WIMP?

No signal in direct (DAMA?), indirect (galactic center $\gamma-$ ray excess?), or accelerator searches.

Even more troubling, no sign of BSM physics at LHC.

This doesn't seem to be the decade of the WIMP!!!

(Perhaps) DM is NOT a WIMP (cold thermal relic), time to focus elsewhere

⬇	⬇	⬇	⬇
go lighter dark sector	go ultralight axion, dark photon	go ultraheavy WIMPzilla	boldly go where no one has gone before

Dark Matter particle mass range

<u>Mass Range for Particle Dark Matter</u>

$m \geq 10^{-22}$ eV: de Broglie wavelength smaller than dark-matter dominated objects

$m \leq 10^{19}$ GeV: mass less than Planck mass

$m \geq$ few eV: if fermion (exclusion principle)

<u>If thermal freeze-out</u>

$m \geq m_e$: annihilation to SM particles

$m \leq 100$ TeV: annihilation cross section too small for larger masses

<u>Is Dark Matter a Particle Or a Wave?</u>

$m \leq 1$ eV: occupation number in de Broglie-wavelength volume $\geq 1 \rightarrow$ WAVE

$m \geq 1$ eV: occupation number in de Broglie-wavelength volume $\leq 1 \rightarrow$ PARTICLE

Dark Matter particle mass range (mere 41 orders of magnitude)

Plancktons: $m \sim m_{\text{Planck}} = 10^{19}$ GeV

WIMPzillas: $m \sim m_{\text{inflaton}} = 10^{10} - 10^{13}$ GeV

Supermassive: $m > 100$ TeV

WIMP range (e.g., neutralino): $m_{\text{proton}} < m < 1$ TeV

Light dark matter (e.g., dark photon): $m_{\text{electron}} < m < m_{\text{proton}}$

Ultralight dark matter (e.g., axion): $m < 1$ eV

Fuzzy dark matter: $m \sim 10^{-22}$ eV

Is Dark Matter Really a WIMP?

- Observation/experiment will tell!
- So far, after 30 years of effort nothing definite seen.
- KEEP
  CALM
  AND
  CARRY ON SEARCHING
  FOR
  DARK MATTER
- or, …
- Pursue other ideas.
- Hope for a disruptive discovery.

The Universe Observed

- Cosmological parameters (just numbers)

  $H_0 \rightarrow$ the present expansion rate (Hubble's constant)

  $\Omega_i \rightarrow$ the present cosmic food chain

  $(\ \Omega_{\mathrm{TOTAL}},\ \Omega_M,\ \Omega_B,\ \Omega_\Lambda,\ \Omega_\gamma,\ \Omega_\nu,\ \ldots)$

  $T_0 \rightarrow$ the present temperature of the Universe

  $t_0 \rightarrow$ the present age of the Universe

- Power spectra–characterization of perturbations:

  Galaxies: $P(k)$ Radiation: C_ℓ