# Cosmology

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lectures given at PAPS 2017

# What is cosmology?

- History of the Universe, as inferred from observation+physical theory

# Particle Physics, also known as High Energy Physics

**Aim to answer two basic questions:**

- What are the fundamental constituents of matter?
- What are the fundamental forces that control their behavior?

**(fundamental = short distances = high energies!)**

# I am a particle physicist; why am I interested in cosmology?

**Cosmological observation + theory depends on**

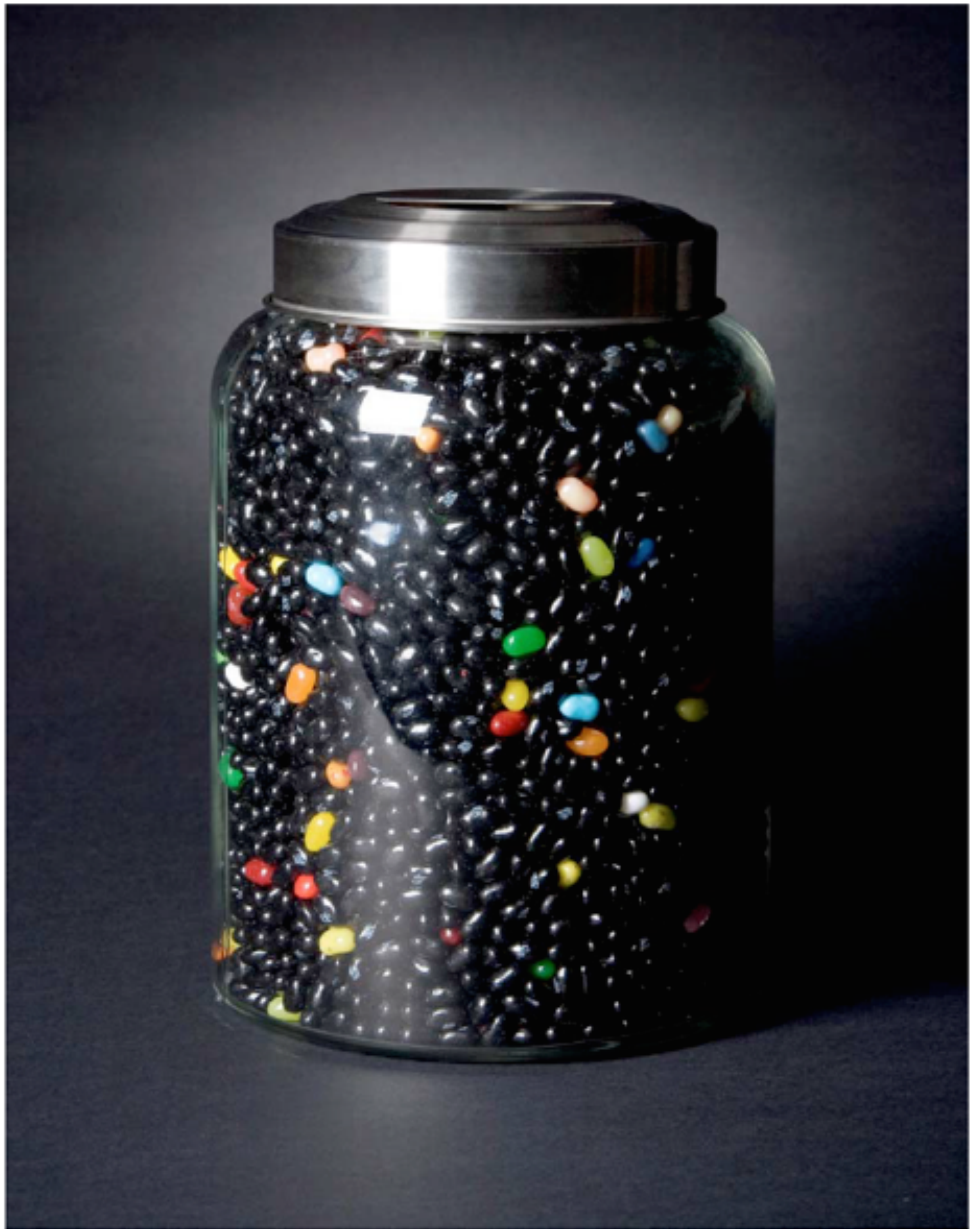
- **What are the fundamental constituents of matter?**
- **What are the fundamental forces that control their behavior?**

**Do the same particles and forces of the Standard Model of particle physics, confirmed in our laboratory experiments, agree with observation?**

**Mostly, but Not completely!!!! clues to physics beyond the standard model.**

# Our understanding of the universe has been transformed during the past 20 years

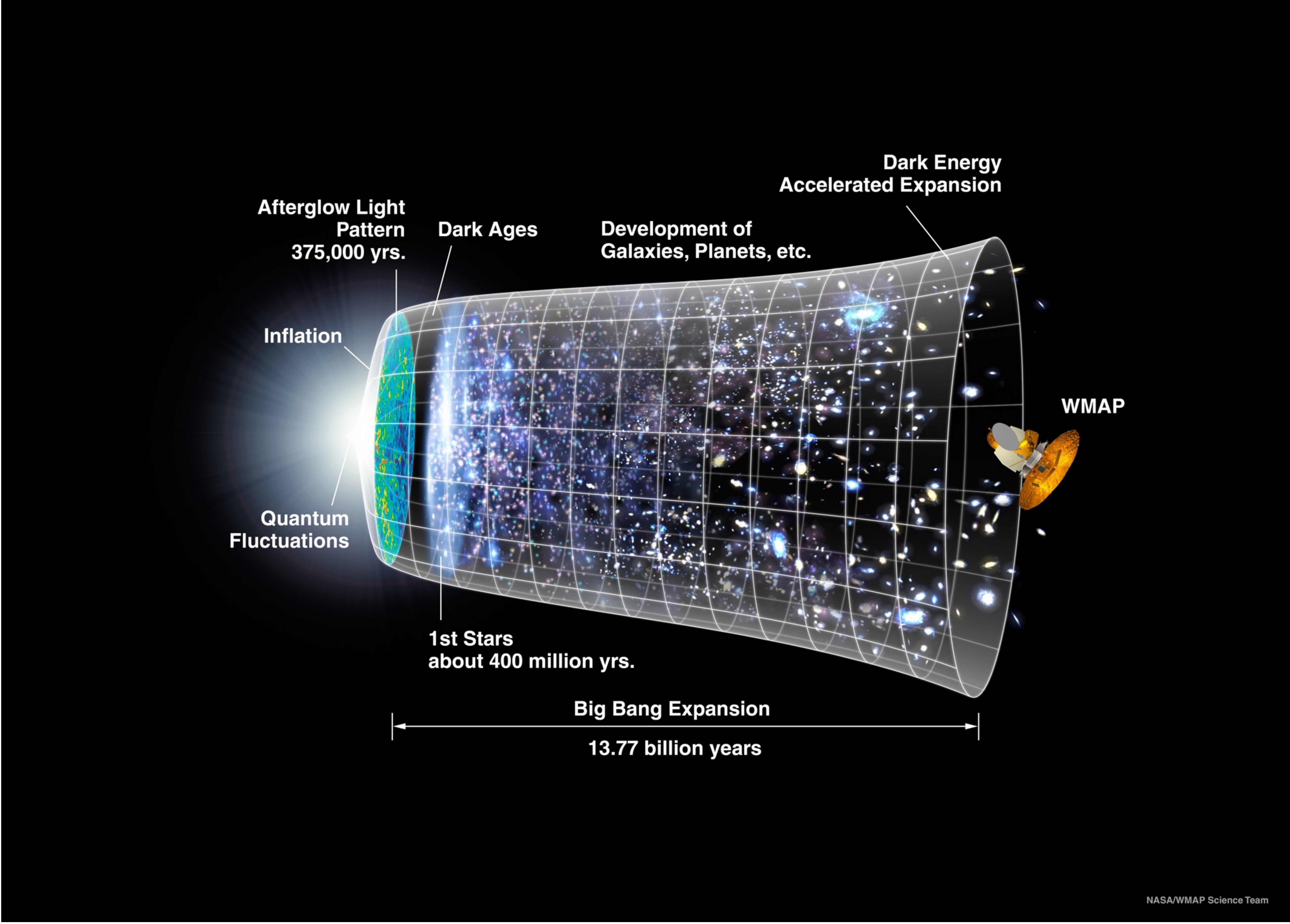
- We are developing a quantitative, consistent, testable theory of everything in the universe and the universe itself
- Most of the matter in the universe is "dark matter" likely a new particle
- "empty" space has a tendency to expand—likely due to a bizarre form of stuff called "dark energy", which cannot be diluted or made to go away
- the very early universe at some point likely went through a period of rapid expansion that would have diluted all the ordinary matter—yet here we are! whatever created the ordinary matter created more matter than antimatter, despite the near perfect matter-antimatter symmetry of the laws of the standard model
- inflation is becoming a well tested theory of the beginning of the universe



# Topics of these lectures:

- Basics: Big Bang and Friedmann-Lemaitre-Robertson-Walker metric. Recommended reading: Mark Whittle's lecture notes at http://people.virginia.edu/~dmw8f/astr5630/Topic16/Lecture_16.html
- dark matter
- baryogenesis
- dark energy, inflation

# Basics

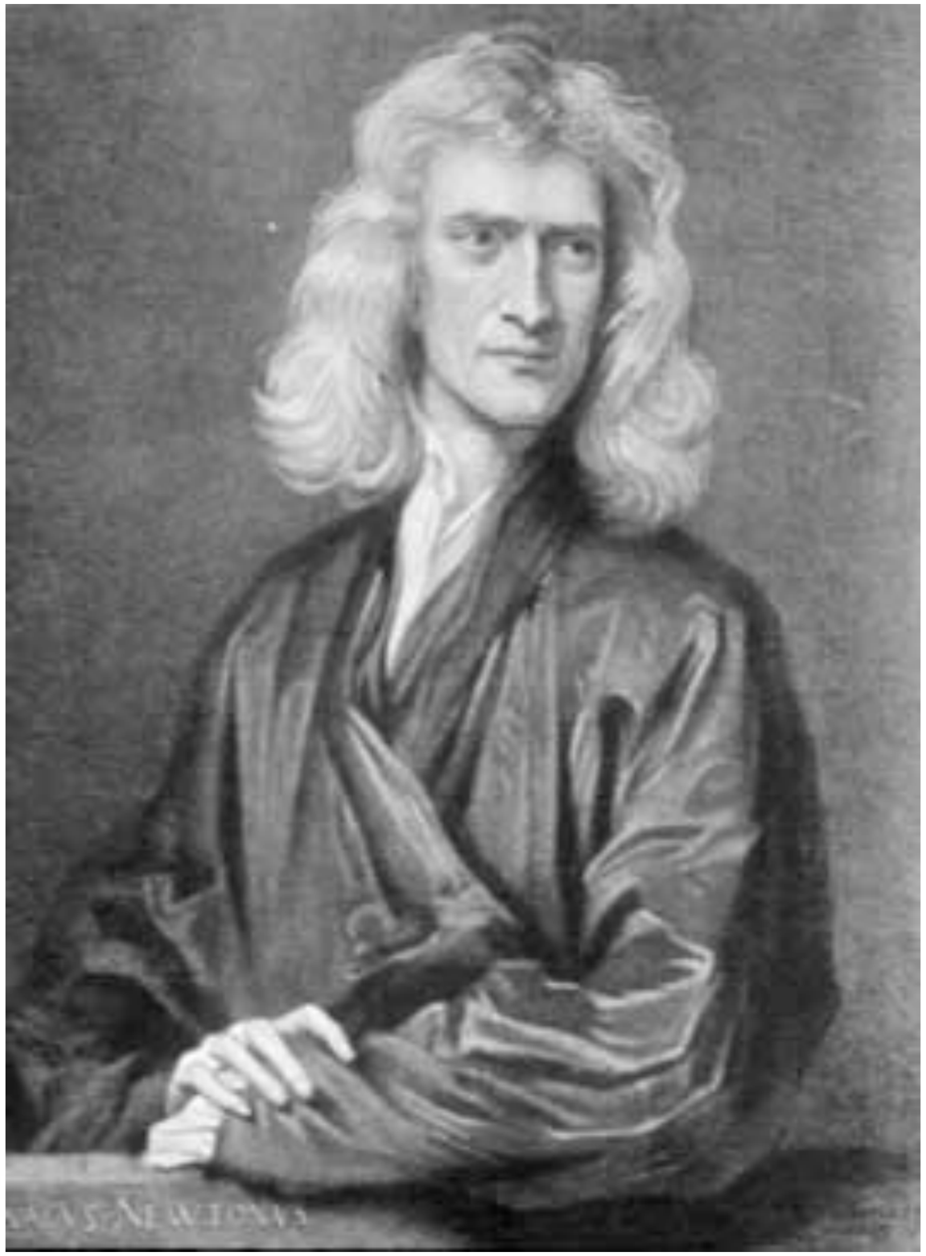

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years
NASA/WMAP Science Team

# What does it mean for ‘space to expand?’

lets start with gravity

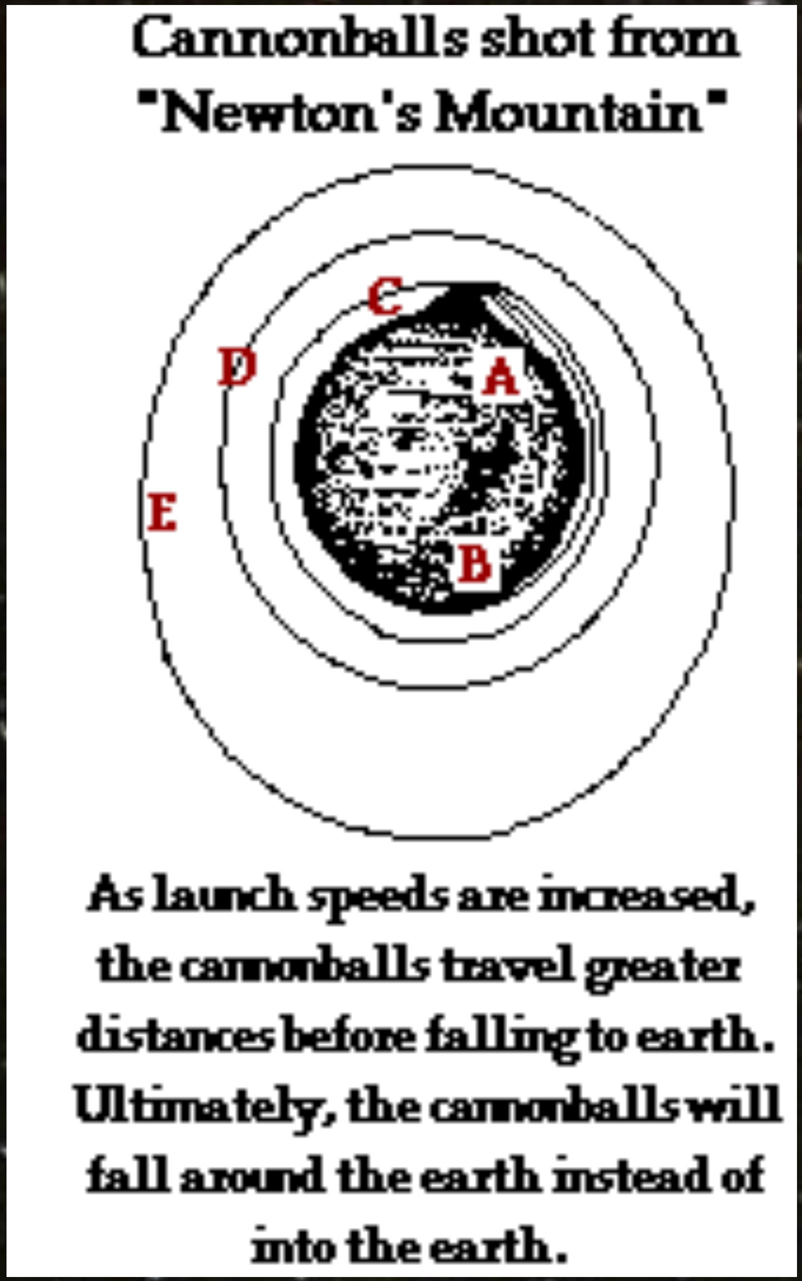
# Newton

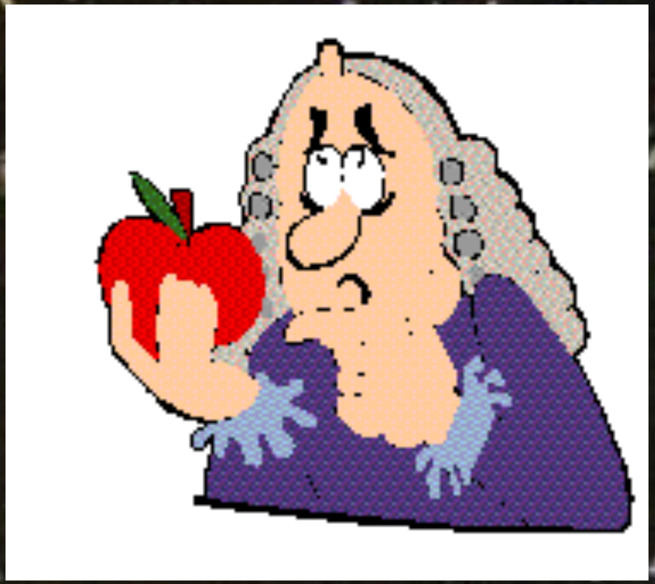
- founding examplar of modern physical science
- ground breaking experimentalist and mathematician
- discovered universal gravitation

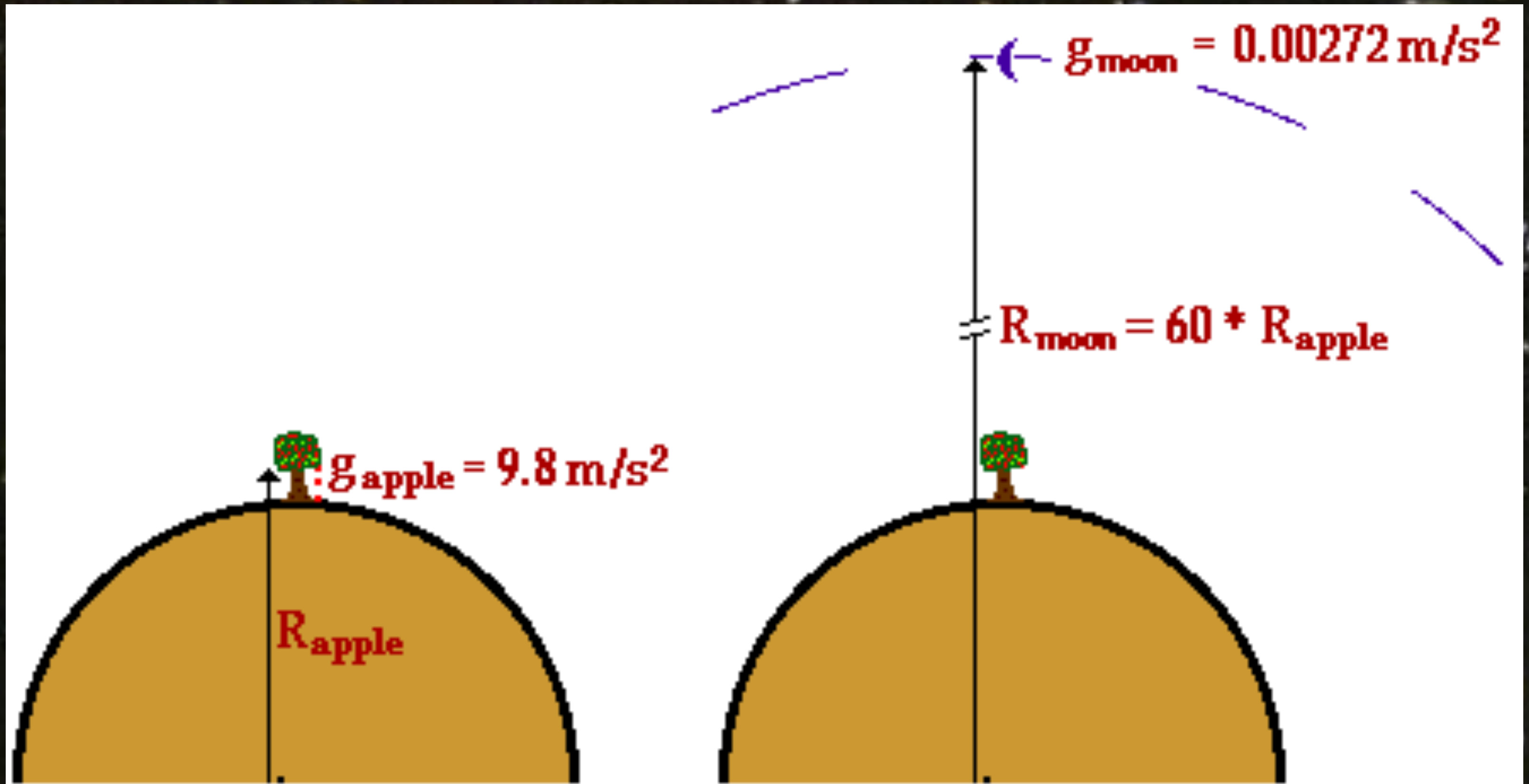


*" No great discovery was ever made without a bold guess"*

# Newton: Same Physical Laws for Heaven and Earth!





# Newtonian Gravity

- Basic law of motion: An object in uniform motion (straight line, constant speed) will remain in uniform motion Unless acted on by a Force
- Gravitational force between two objects is proportional to the product of their masses and inversely proportional to the distance between their centers (for spheres)

# Einstein

- Time Magazine's "Man of the Century"
- Newtonian ideas about gravity, reality, matter, space, time overthrown
- General Relativity unified relativity with gravity, inconsistent with Quantum Mechanics
- Dreamed of unified theory of everything

*"The eternal mystery of the world is its comprehensibility."*

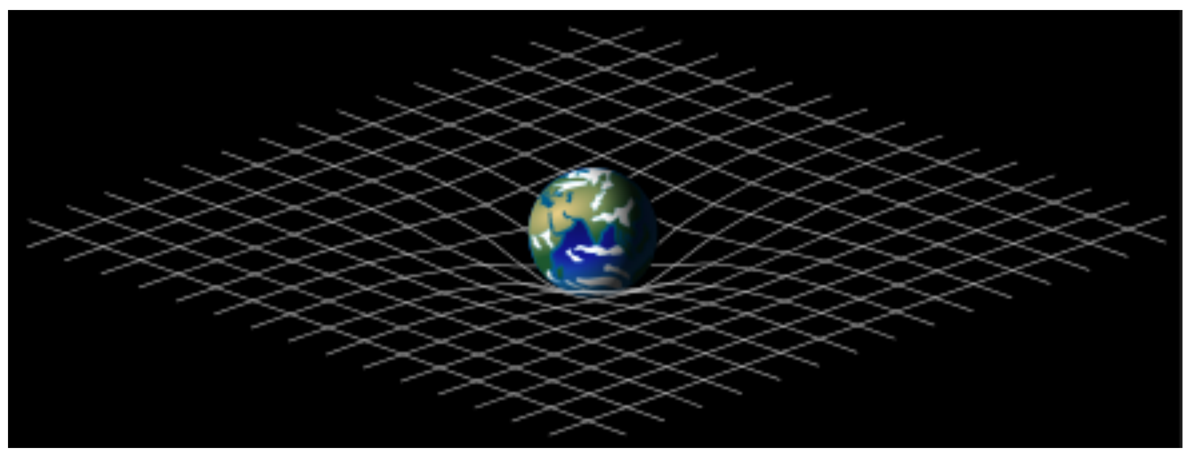
*"The happiest thought of my life. I was sitting in a chair when all of a sudden a thought occurred to me: if a person falls <u>freely</u> he or she will not feel their own weight. I was startled. This simple thought made a deep impression on me."*

-Einstein

# Equivalence Principle

- All falling objects fall at same rate in vacuum (feathers, lead weights)
- In newtonian gravity this is due to an apparent coincidental equivalence between gravitational and inertial mass

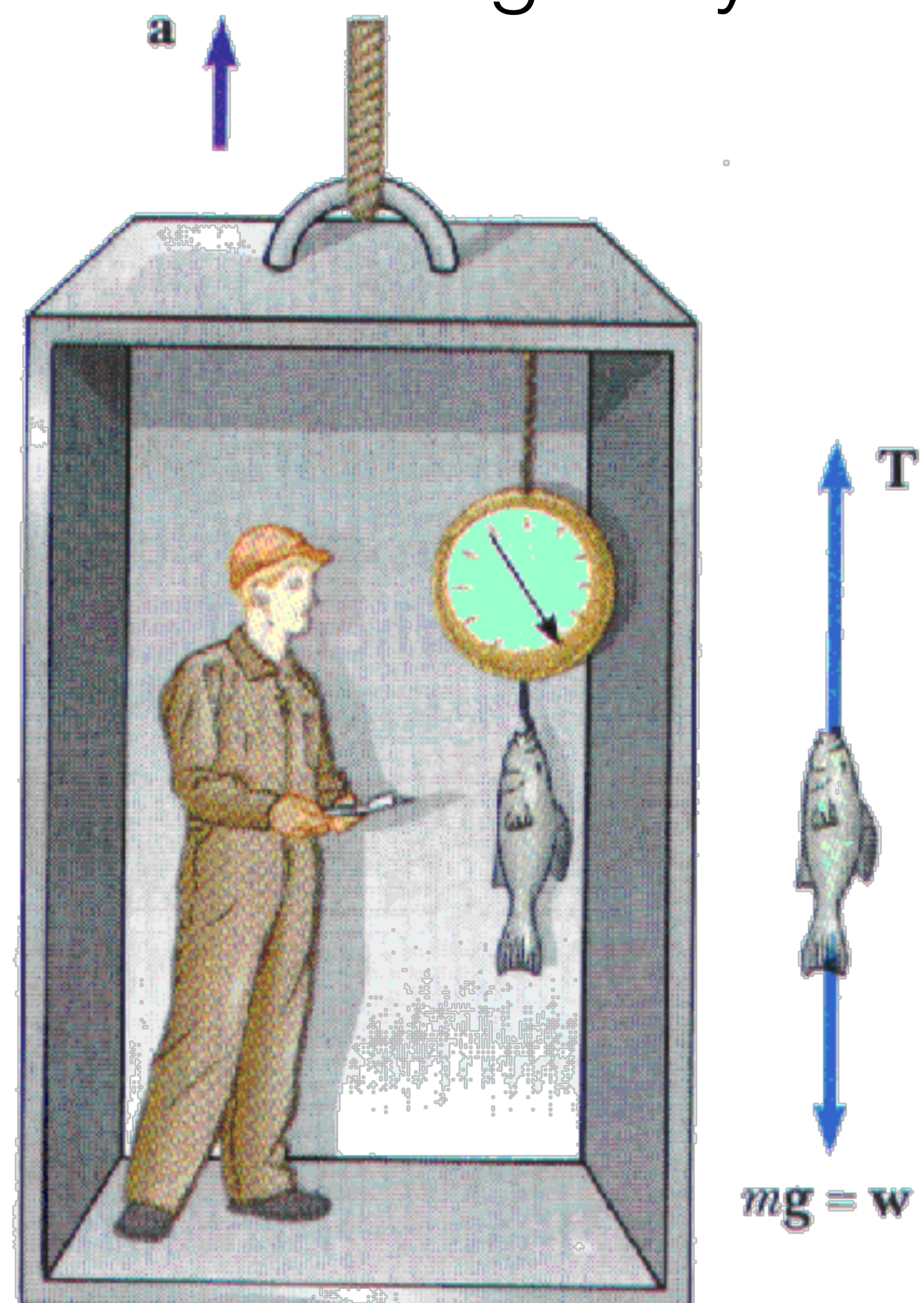
# General Relativity: a theory about the Dynamics of Space-time



Matter changes ("curves") space-time

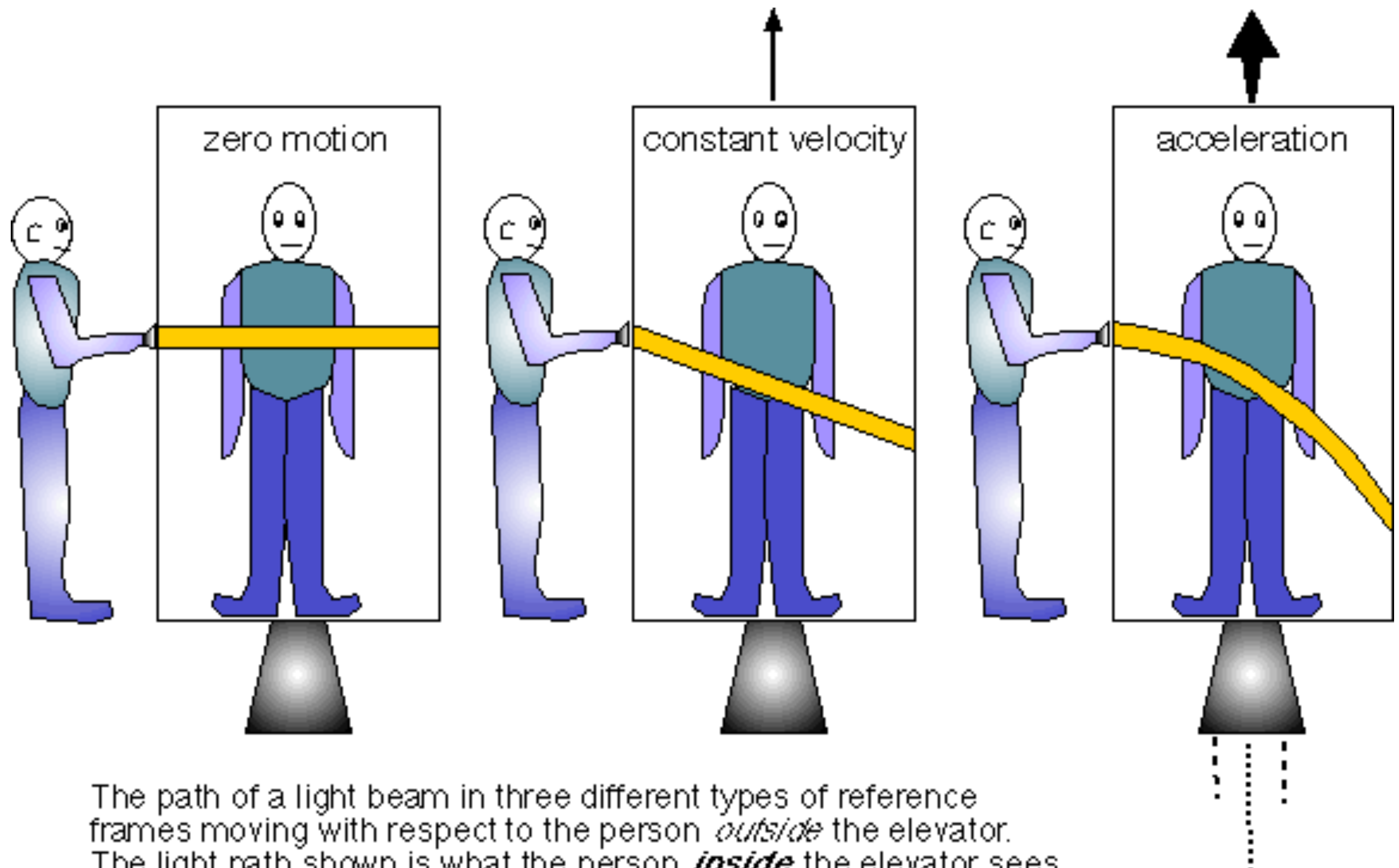
# General Relativity

- Equivalence between gravity and acceleration



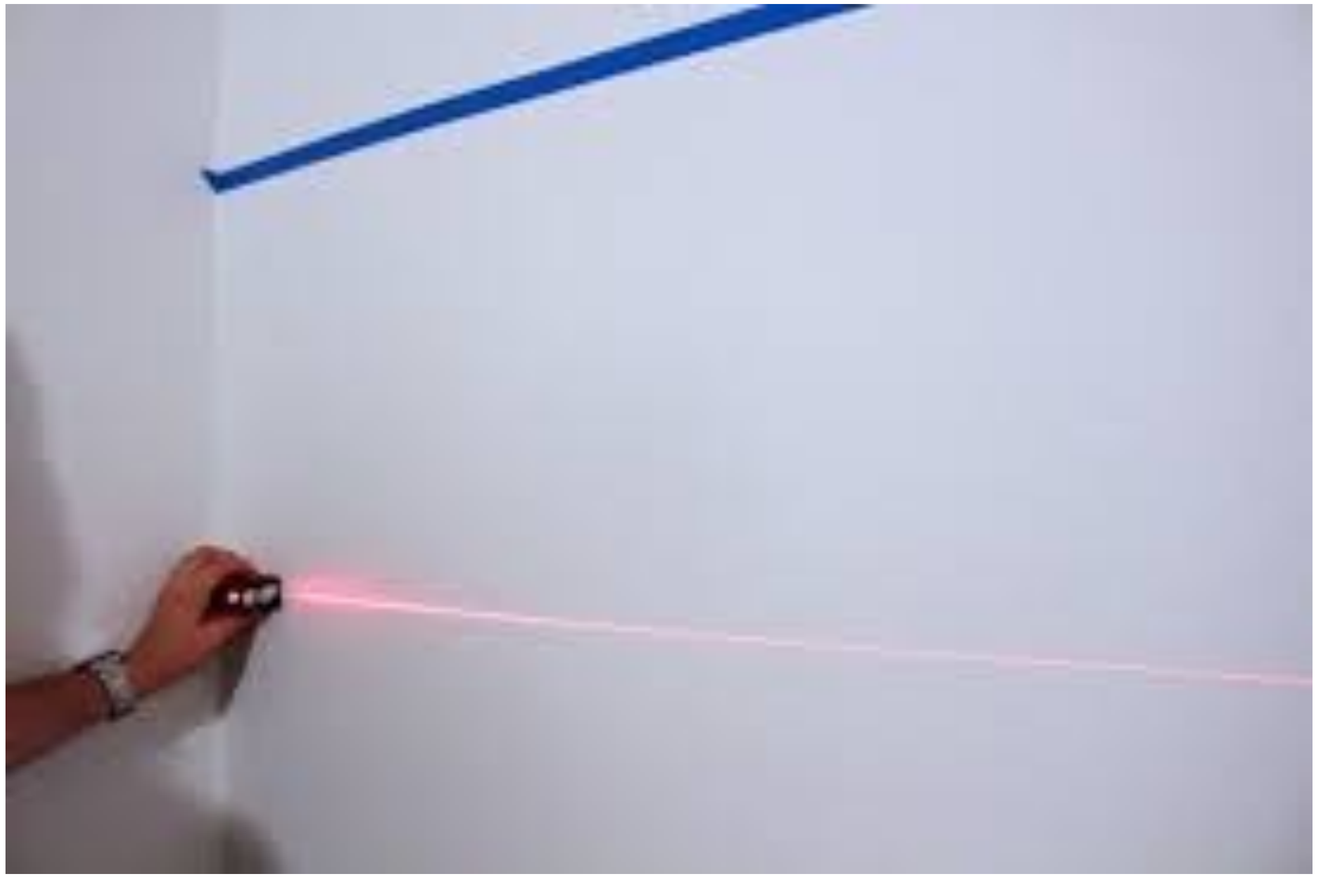
# turning off gravity=free fall


# Does gravity bend light?



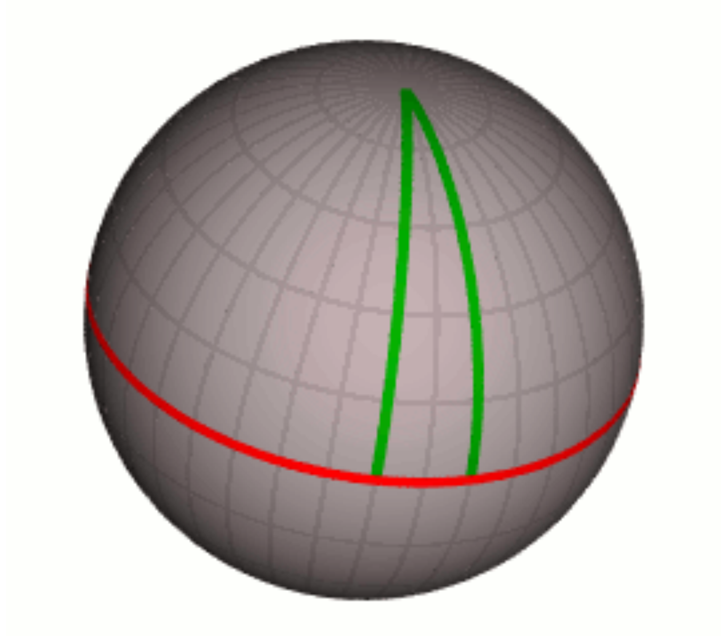

The path of a light beam in three different types of reference frames moving with respect to the person *outside* the elevator. The light path shown is what the person ***inside*** the elevator sees. Under large acceleration, the beam of light will curve downward. It should also do that in a region of strong gravity.

# What is a straight line?



# particles, light follow geodesics in curved space-time

geodesic: path which locally minimizes distance.
generalization of “straight line” to curved space



geodesics on surface of earth-
great circles. Note that angles of triangle sum to
>180° due to curvature of surface

Key Idea of General Relativity (GR): "Matter tells spacetime how to curve. Curved spacetime tells matter how to move."

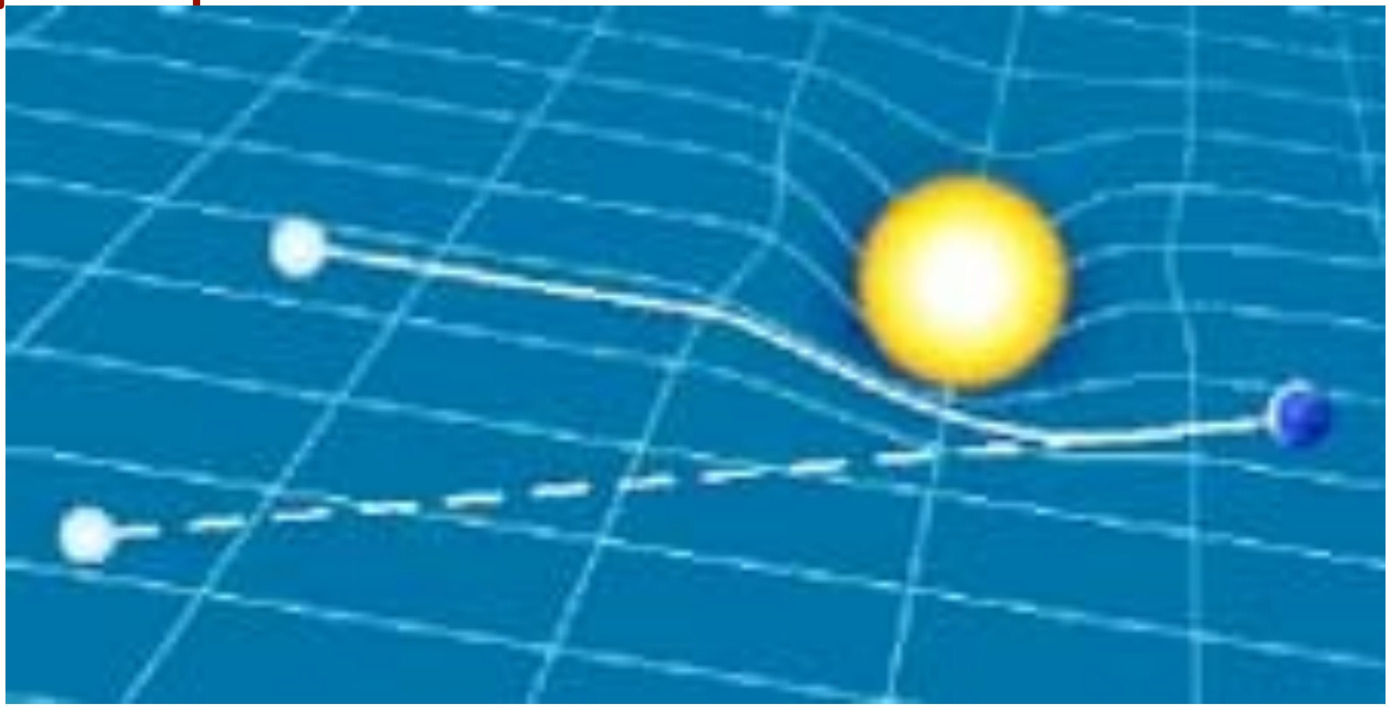
-Wheeler

Some Key Tests of General Relativity:

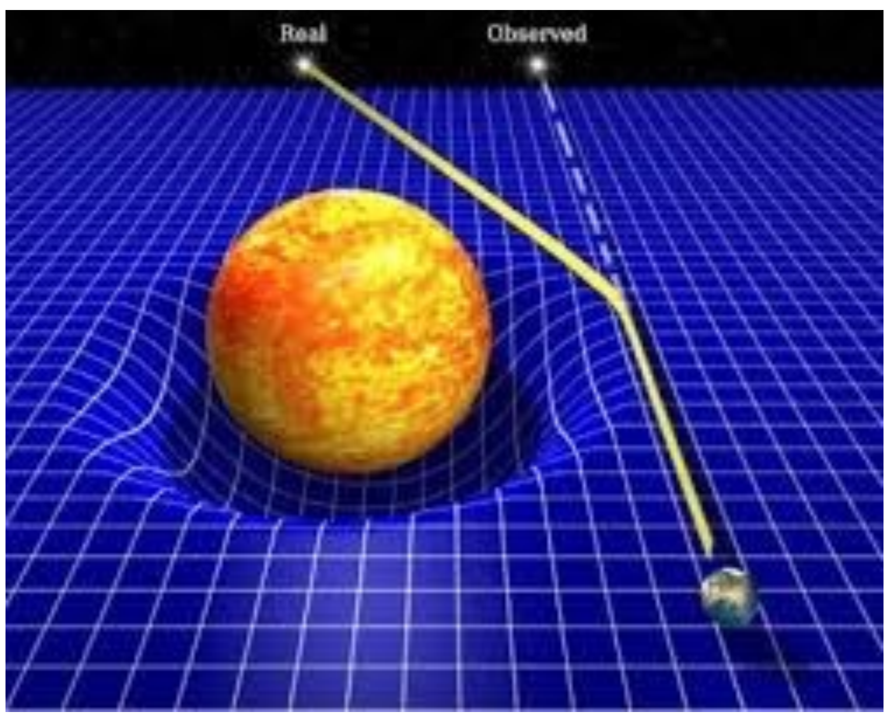
- Perihelion Precession of Mercury
- Bending of Starlight near the Sun
- The Binary Pulsar (Gravitational Waves)
- The equivalence principle

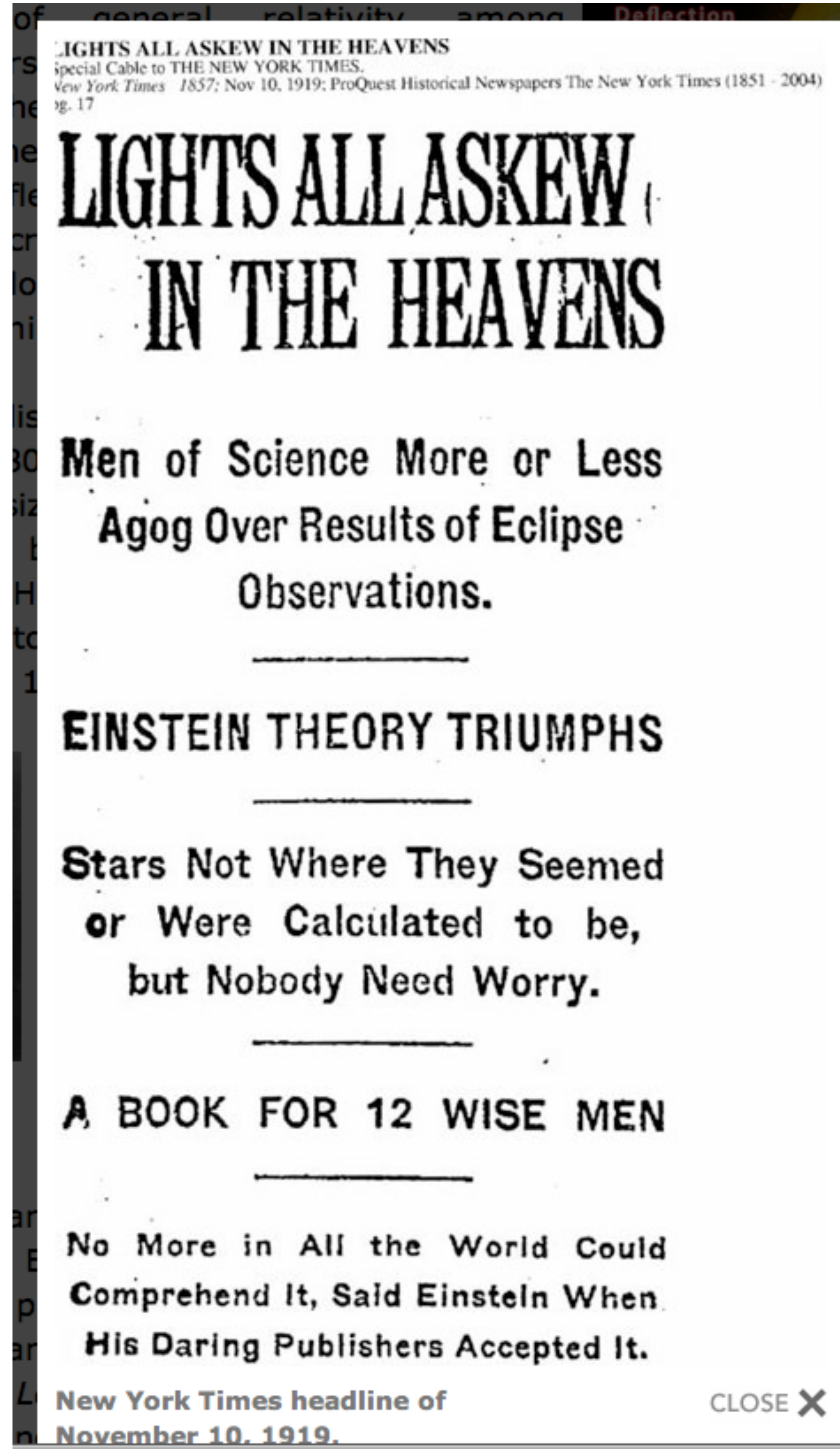
Newton's laws are approximations of GR.

- Work accurately in the "everyday" world of speeds slower than light, weak fields.
- Are mathematically much simpler.
- Are inadequate for many practical applications, e.g. GPS⇒GR crucial for modern technology.



# Confirmation of General Relativity: 1919



LIGHTS ALL ASKEW IN THE HEAVENS
Special Cable to THE NEW YORK TIMES.
*New York Times (1857);* Nov 10, 1919; ProQuest Historical Newspapers The New York Times (1851 - 2004)
pg. 17

## LIGHTS ALL ASKEW IN THE HEAVENS

**Men of Science More or Less Agog Over Results of Eclipse Observations.**

**EINSTEIN THEORY TRIUMPHS**

**Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.**

**A BOOK FOR 12 WISE MEN**

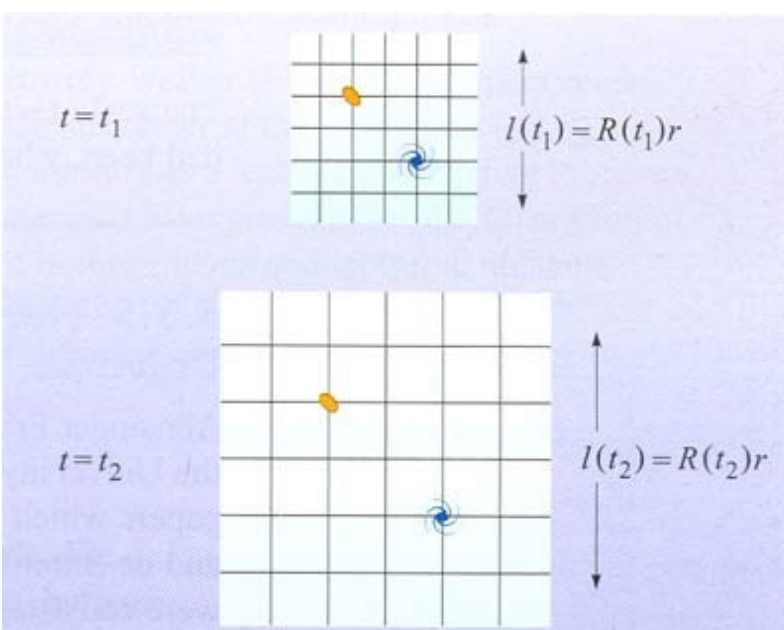
**No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.**

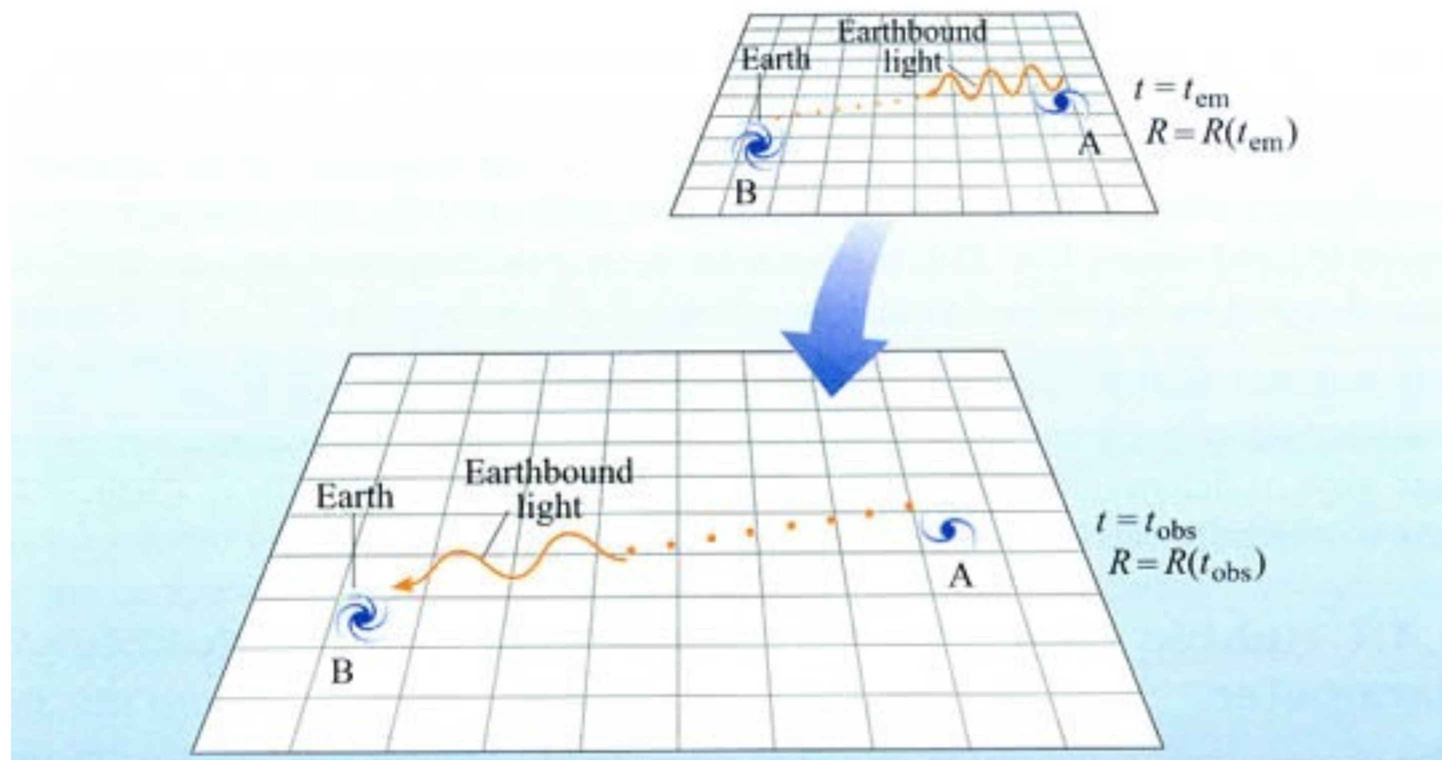
New York Times headline of November 10, 1919.

CLOSE ✕

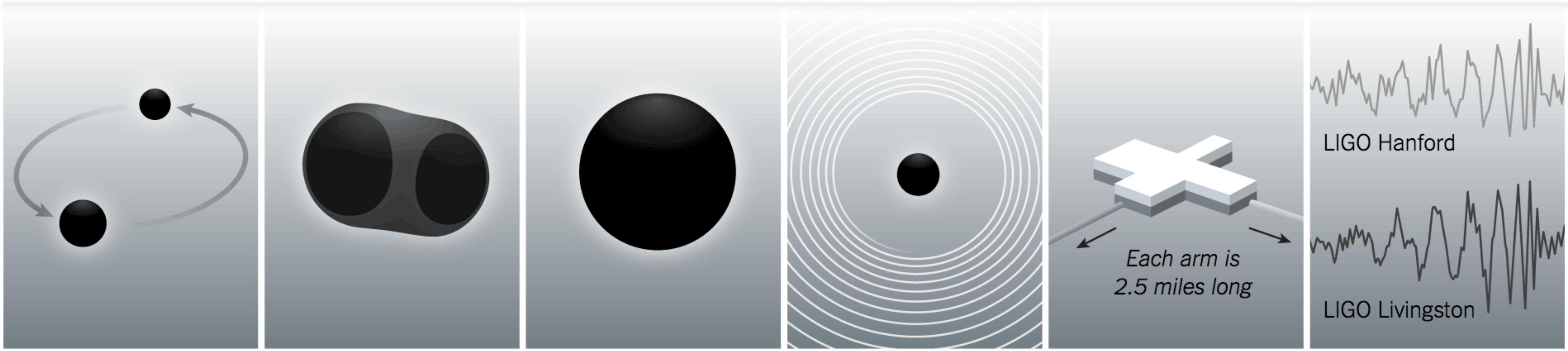
# 1925: Hubble discovery of expanding universe

"redshifted" (longer wavelength) spectra
of distant galaxies



# Gravitational Wave detection:announced 2016




**TWO BLACK HOLES**
About 1.2 billion years ago in a distant galaxy, a pair of black holes circled each other. The larger black hole was 36 times the mass of our sun, and the smaller one 29 times.

**COLLISION**
The intense gravity accelerated the black holes to half the speed of light, pulling them closer and carving distortions in space and time. In a fraction of a second, the pair collided and merged into an irregular shape.

**RING DOWN**
The unstable blob smoothed itself into a sphere, a process called ring down. Three solar masses' worth of energy were vaporized in a storm of gravitational waves, distorting space and time and leaving a new black hole 62 times the mass of the sun.

**GRAVITATIONAL WAVES**
The invisible waves rippled outward at the speed of light. But waves fade with distance, and when they finally reached Earth, the distortions were too small to be measured above the heat, noise and other vibrations of our planet.

**DETECTION**
LIGO is a pair of L-shaped observatories 1,900 miles apart. Ultra-pure mirrors at the ends of each arm are isolated from vibrations. Passing gravitational waves push and pull the arms, changing the length of tunnels by less than the width of a proton.

**A CHIRP**
On Sept. 14, LIGO's detectors measured their first vibrations from a gravitational wave. Translated to sound, it was a short chirp, the billion-year-old echo of the collision of those two black holes.

# recap so far

- Einstein: gravity=dynamical space time
- Energy distorts space and time according to Einstein's equations
- all stuff follows geodesics in same spacetime
- Equivalence principle follows
- gravitational field indistinguishable from accelerated reference frame

# lets get  slightly more technical

# what is being minimized in free fall: The "interval"

- in relativity, it is convenient to use units with speed of light, c=1 . e.g. measure time in seconds and distance in light-seconds.
- s= interval between space-time points in flat space-time (Minkowski space)—same for all observers
- space time point "event" coordinates $x_i, y_i, z_i, t_i$
- flat space: $s^2 = -(t_2 - t_1)^2 + (x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2$

# interval in curved space time

- introduce metric tensor $g_{\mu\nu}$. $\mu,\nu=0,1,2,3$. $t=x^0, x=x^1, y=x^2, z=x^3$
- ds =infinitesimal interval
- $ds^2=\Sigma_{\mu\nu=0,1,2,3}(g_{\mu\nu}\, dx^\mu dx^\nu)$
- can use generalized (e.g. spherical, or cylindrical, or moving) coordinates— appearance of metric changes but ds, s are same for all observers and coordinate systems. "general coordinate invariance"

# Friedman-Robertson-Walker-Lemaitre universe

- spatially homogenous and isotropic (cosmological principle) which is true on largest scales (beyond~150 Mpc)
- spherical coordinates:

  $ds^2=-dt^2+a(t)^2(dr^2/(1-kr^2)+r^2(d\theta^2+\sin^2\theta d\phi^2))$

  - a(t)=scale factor
  - k=0:flat space (our universe is apparently flat)
  - k=1: constant positive curvature
  - k=-1: constant negative curvature

# FRW in flat space

$ds^2 = -dt^2 + a(t)^2(dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)) =$
$-dt^2 + a(t)^2(dx^2 + dy^2 + dz^2)$

$t_0$=now

convention: $a(t_0)=1$, here $r=0$

past: $a<1$, future $a>1$

Hubble parameter $H=(da/dt)/a$

$H(t_0)=H_0$

x,y,z called comoving coordinates

physical distance $a(t)(\Delta x^2+\Delta y^2+\Delta z^2)^{1/2}$ changes

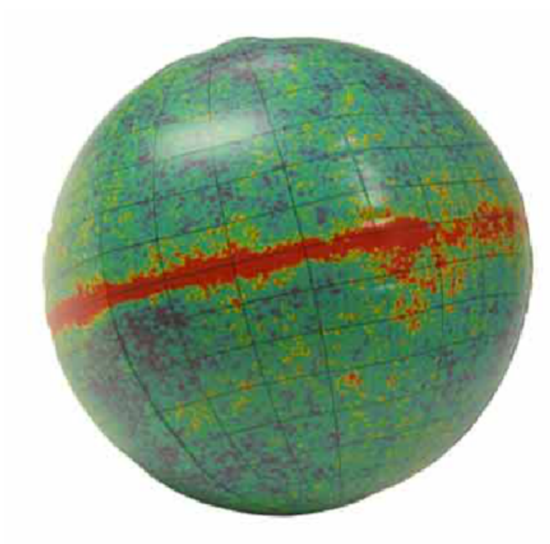
# Redshift z

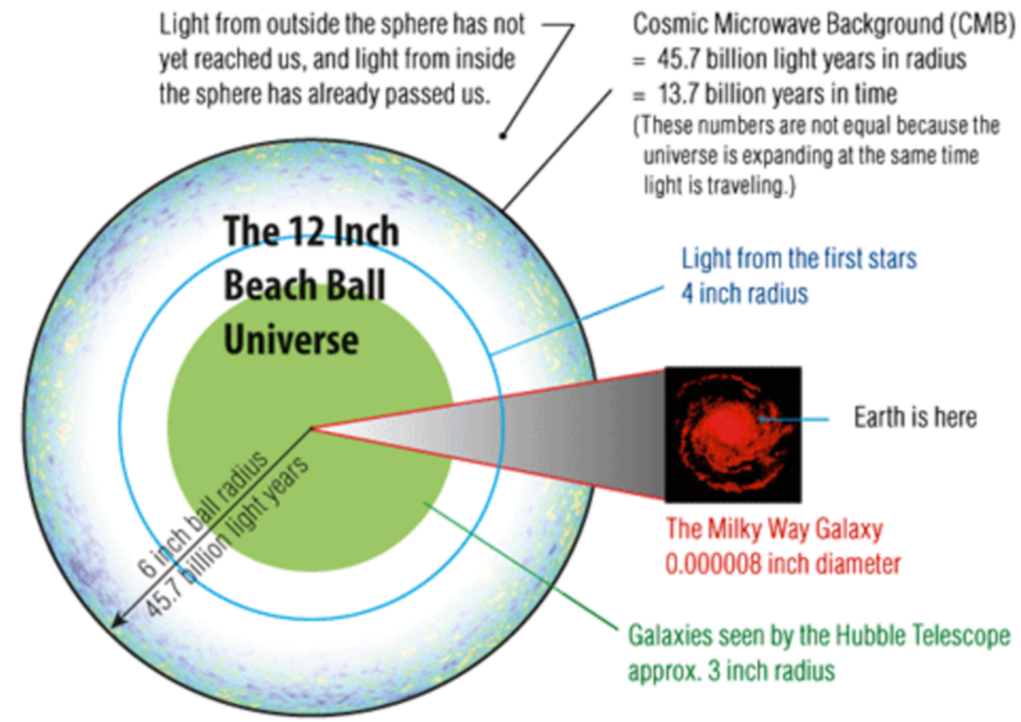
- wavelength of light expands along with space
- $1+z=\lambda_{observed} / \lambda_{emitted}$
- $(1+z)=a(t_0)/(a(t_{emitted}))$
- distant galaxies recede with velocity $v \sim H_0\, r$
- $r=10$ Mpc $\Rightarrow v \sim 10^3$ km/s
- $r = 1000$ Gpc $\Rightarrow v \sim 10^8$ km/s
- galaxies recede faster than c at critical distance $r=c/H_0 \sim 4200$ Gpc $\Rightarrow$ edge of *observable* universe

# examples

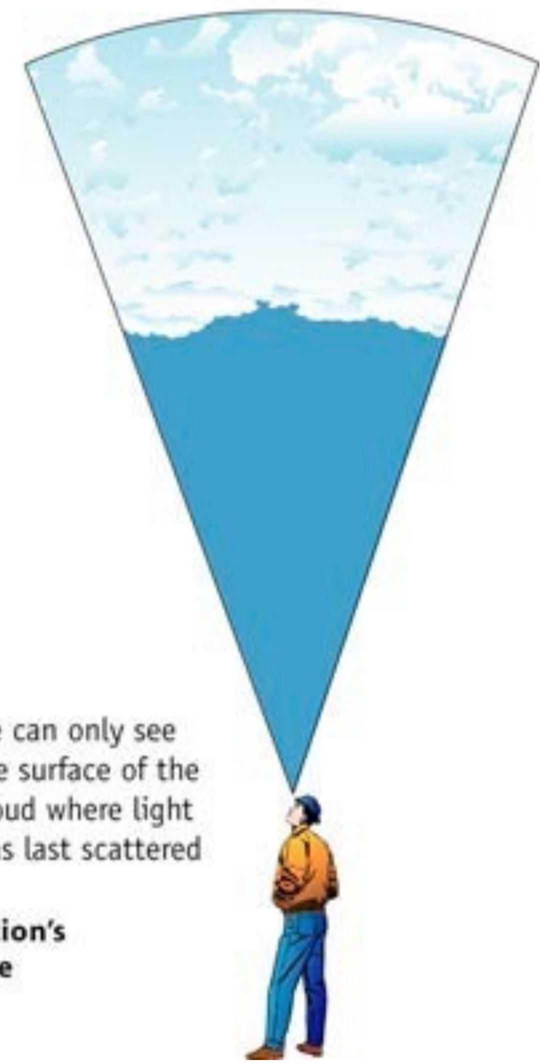
- $z = 0.1$ $a(t_e) = 1/1.1 = 0.909$
- $z = 1$, $a = 0.5$ galaxies were half their current separation ($8 \times$ the current density)
- at $z = 6$, $a = 0.14$ (currently, the most distant QSOs)
- at $z = 1000$, $a = 0.001$ ($10^9 \times$ denser)

# Hot big bang






- we currently see a cosmic microwave background of photons filling space with temperature $T_0=2.7^oK=6.6\times10^{-4}$ eV
- "surface of last scattering" universe became transparent at z=1100 (hydrogen atom formed)
- $T_{emitted}=(1+z)\ T_0=0.7$ eV$=3000^o$ K
- CMB radiation near perfectly uniform black body but small temperature deviations~a part in $10^{-4}$


**The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.**

# recap so far

- describe space-time dynamics using metric tensor
- matter, light follow geodesics given by metric
- GR+cosmological principle+observation=Friedmann–Lemaître–Robertson–Walker expanding universe
- distant galaxies receding
    - redshifted light
    - scale factor a(t) increasing in time
- most distant ‘object’ we observe is cosmic microwave background surface of last scattering

# ISSUES

- extrapolation implies finite time until a=0 (initial singularity)
- why is CMB thermal, uniform? (thermalization implies interaction but not enough time since beginning of universe?)
- a(t)?

# Dynamical equations to determine a(t)

- Applying Einstein's equations to determine the FLRW metric leads to same equations as we can derive from a simplified picture
- Energy Conservation: $dE=-pdV \Longrightarrow d(\varepsilon\, a^3) = -p\, d(a^3)$
- "analog Energy Conservation (with gravity)"

  $(1/2)(da/dt)^2 \;-\; (4\pi G/3)a^3\, \varepsilon/a \;=\; -kc^2/(2R_0)$

  "Kinetic energy"+ "gravitational potential energy"="total energy"

  $R_0$= curvature scale , $k=0 \Longrightarrow$ perfect balance

  critical energy density: $\Omega_c=H^2/(8\pi G/3)$

# equation of state

- $p = w\,\varepsilon$
- “dust” (cold particles) w=0
- radiation (massless particles) w=1/3
- “vacuum” (Lorentz invariant stress tensor) w=-1

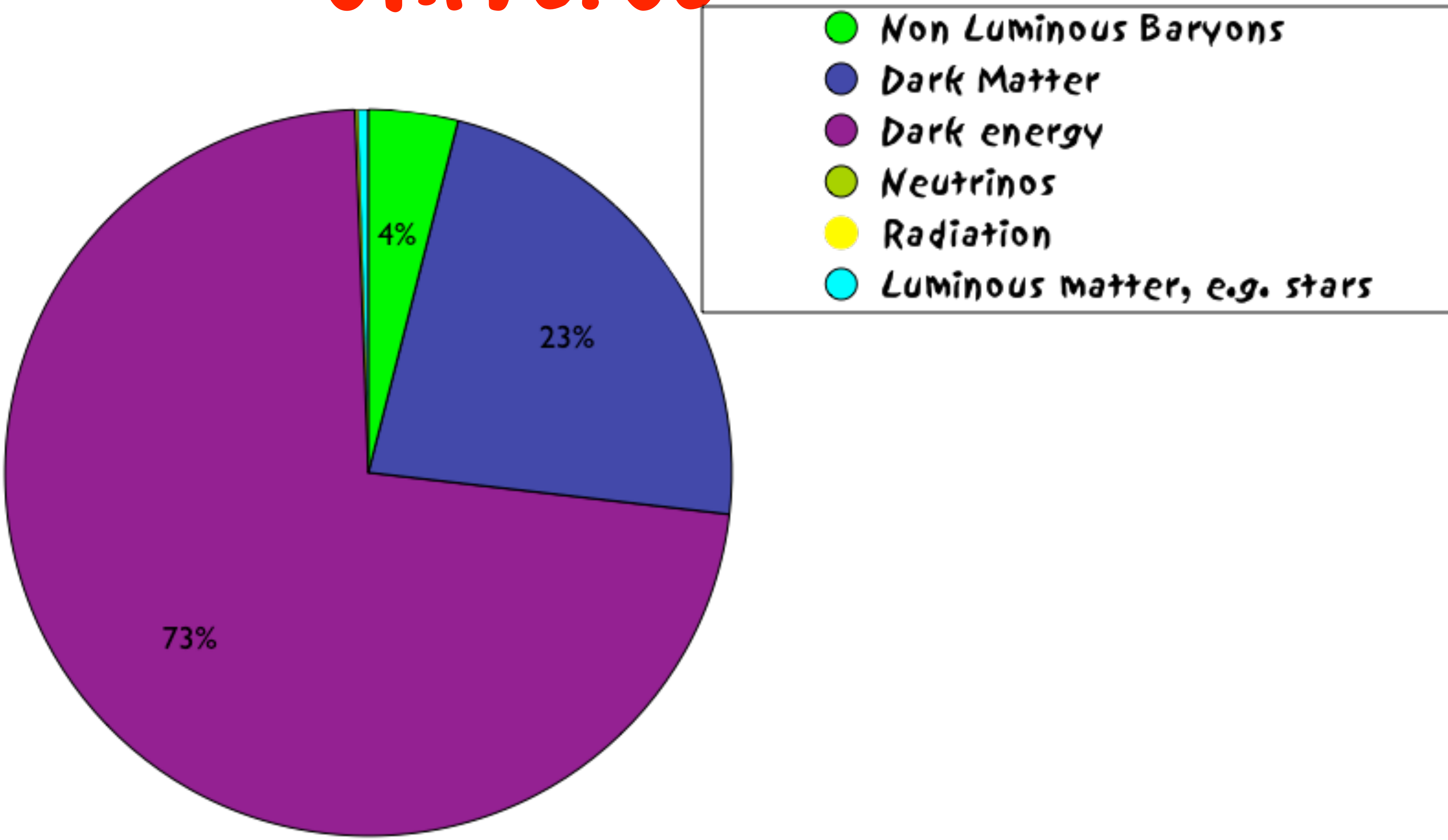
# solutions:

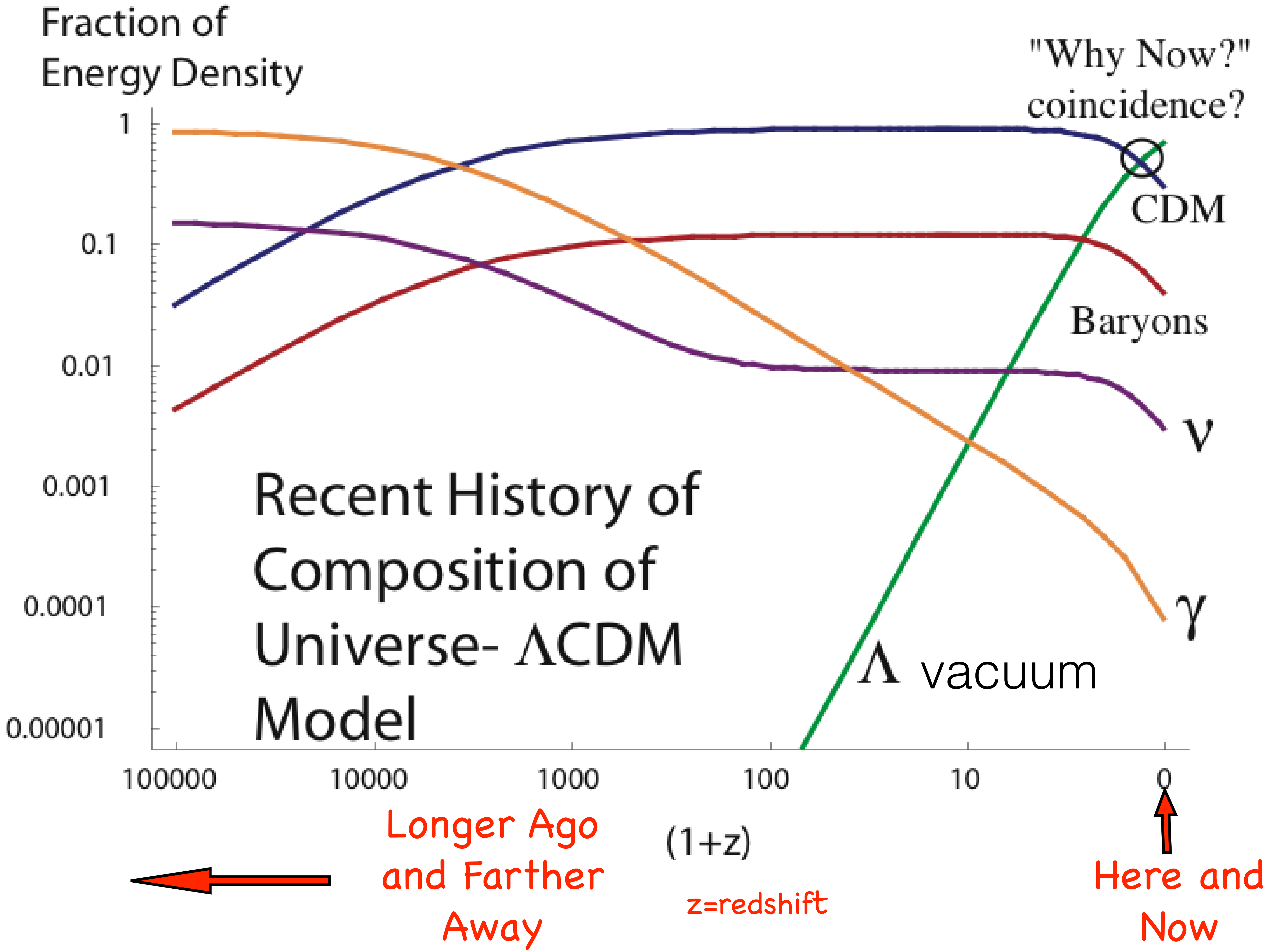
- w=0 (dust) $\Longrightarrow$ $\varepsilon \sim 1/a^3$, $a \sim t^{2/3}$
- w=1/3 (radiation) $\Longrightarrow$ $\varepsilon \sim 1/a^4$, $a \sim t^{1/2}$
- w=-1 (vacuum) $\Longrightarrow$ $\varepsilon \sim$ constant, $a \sim e^{Ht}$

also known as “cosmological constant” ($\Lambda$)

or “dark energy”

# "ΛCDM model" of Our Universe




Fraction of
Energy Density
1
0.1
0.01
0.001
0.0001
0.00001
"Why Now?"
coincidence?
CDM
Baryons
ν
γ
Λ vacuum
Recent History of
Composition of
Universe- ΛCDM
Model
100000
10000
1000
100
10
0
Longer Ago
and Farther
Away
(1+z)
z=redshift
Here and
Now

# key ideas of first lecture

gravity is a theory of space and time
energy warps space-time
free-fall=follow geodesics minimizing interval
expansion of universe
redshift
evolution of size, temperature,
composition of universe

tommorrow: dark matter

# lecture 2

dark universe, dark matter

# Dark Matter: proposed in 1930's
# Reproposed in 1970's

# Zwicky's evidence for dark matter

**Astrophysicist Fritz Zwicky calculated that the Coma cluster, one of the densest known galaxy clusters, needed to contain about 400 times its apparent mass--otherwise it would fly apart.**

*Courtesy of: Jim Misti, Misti Mountain Observatory*

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**Astrophysicist Fritz Zwicky calculated that the Coma cluster, one of the densest known galaxy clusters, needed to contain about 400 times its apparent mass--otherwise it would fly apart.**

*Courtesy of: Jim Misti, Misti Mountain Observatory*

# Most of the Galaxy is Dark

*Image credit: NASA, ESA, and T. Brown and J. Tumlinson (STScI).*

# We can use gravitational lensing to detect dark matter

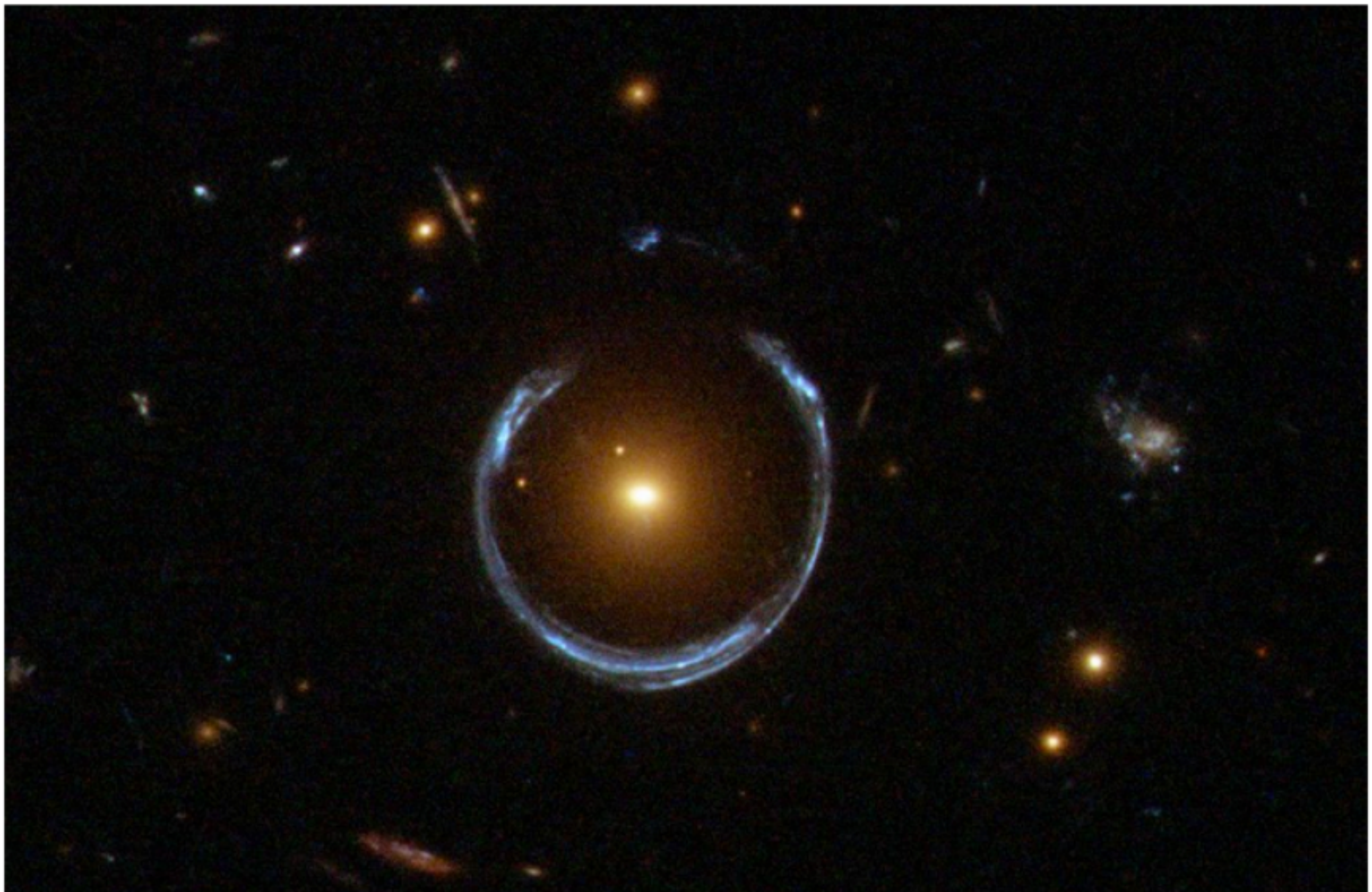

Image credit: ESA/Hubble & NASA.

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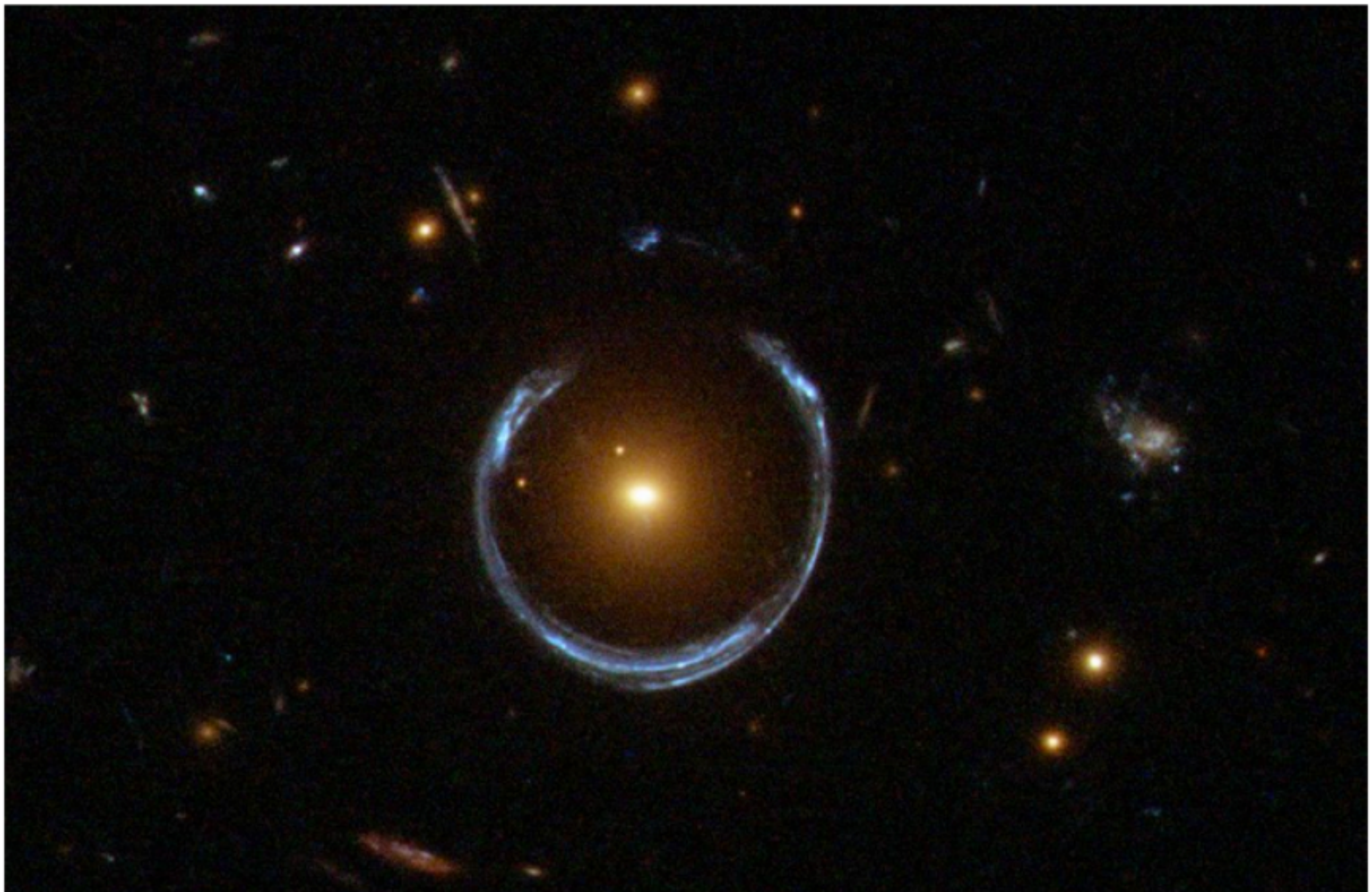
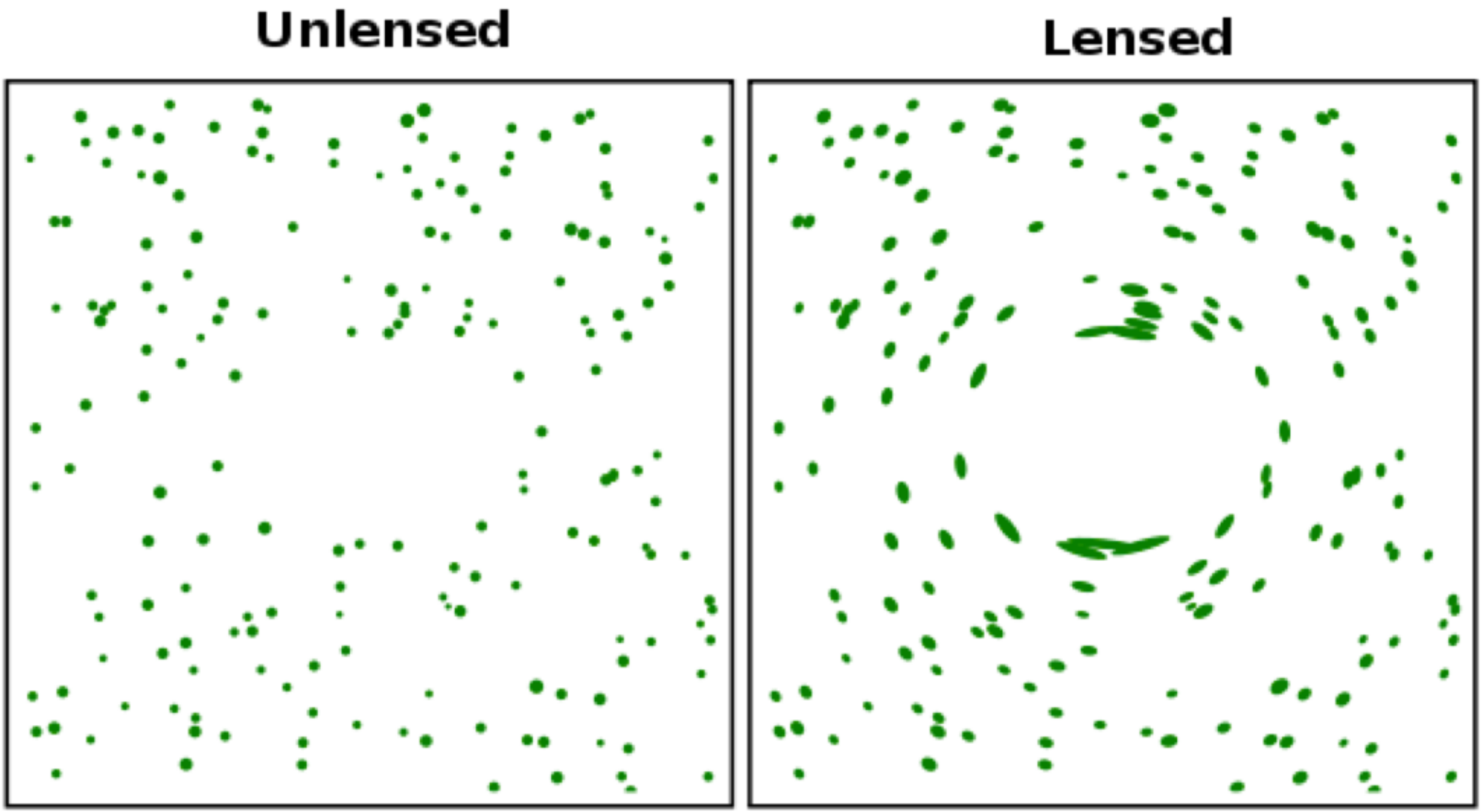


Image credit: ESA/Hubble & NASA.

# Detecting dark matter with lensing



# Ordinary Dark Matter, Modified Gravity or new kind of particle?

- Most ordinary matter doesn't shine (hydrogen gas clouds)
- We could imagine changing laws of gravity at large distances instead of a new form of matter
- Dark matter is different from ordinary matter: Collisionless?
- How can we test collisional properties of dark matter?

# Dark Matter evidence

**Collision of two galaxy clusters**

**pink: intergalactic gas from X-ray $\rightarrow$ Ordinary Matter, most mass from ordinary particles**

**DM concentrated where galaxies are**
**blue: mass inferred from gravitational lensing $\rightarrow$ Dark Matter**

# “Bullet Cluster”: colliding galaxy clusters

# Trainwreck Cluster

Image credit: X-ray: NASA/CXC/UCDavis/W.Dawson et al; Optical: NASA/STScI/UCDavis/W.Dawson et al.

# Musket Ball Cluster

# We have discovered Dark Matter

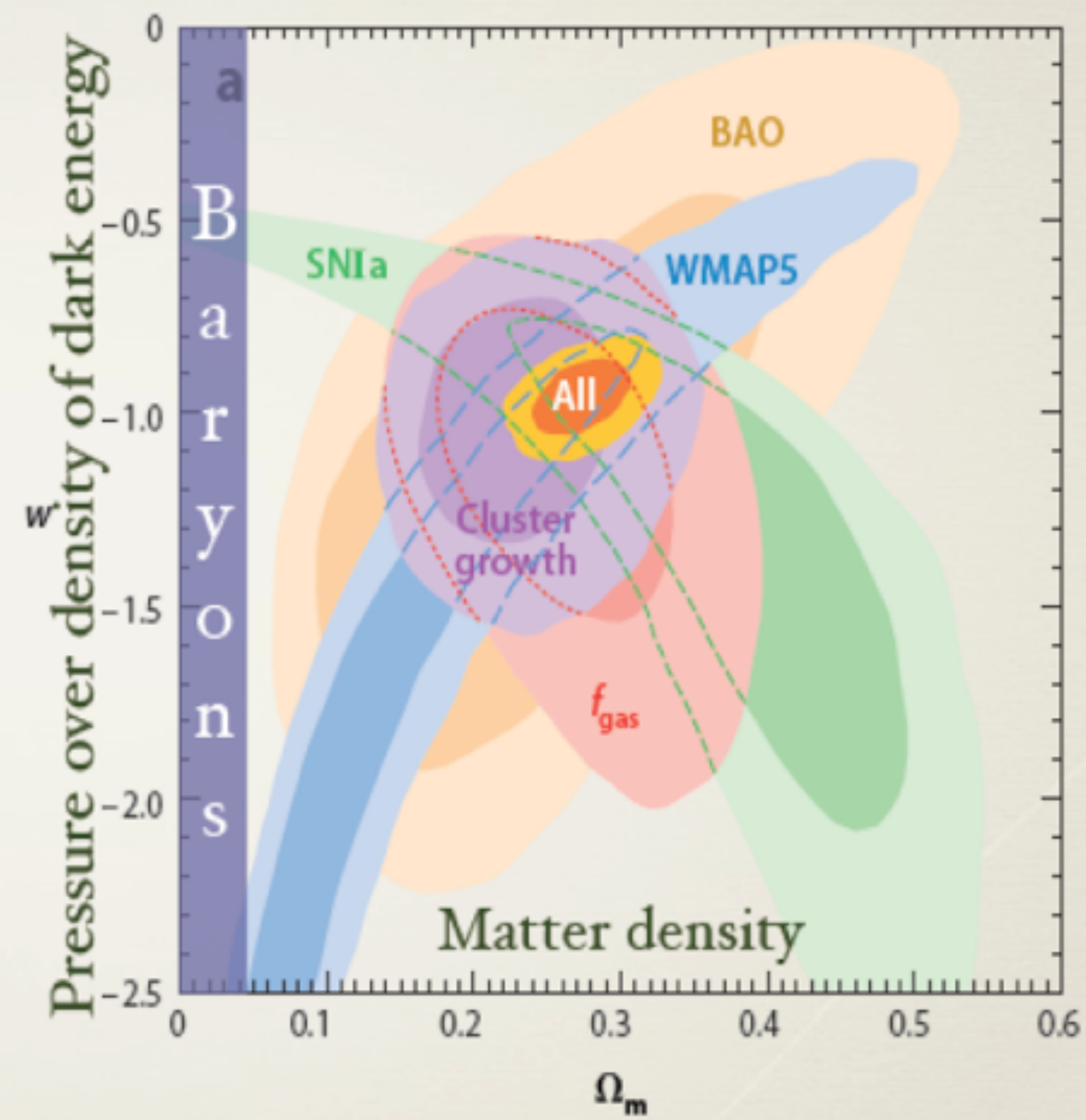
- There is an unseen source of gravitating matte which is collisionless (at least, small collision cross section compared to gas)
- Not made of atoms!
- Beyond the standard model of particle physics
- Gravity is only known portal
- Can we find others?

# A new particle (or particles?)

Dark Matter=Some stuff that gravitates, is pressureless=cold (not moving very fast) collection of weakly interacting particles

# DARK MATTER

- Dark matter has **already been discovered** through
  - Galaxy clusters
  - Galactic rotation curves
  - Weak lensing
  - Strong lensing
  - Hot gas in clusters
  - Bullet Cluster
  - Supernovae
  - CMB
- We are entering the **decade of dark matter identification**




Allen et al, Annual Review of Astronomy and Astrophysics, vol. 49, pp. 409-470 (2011)

Mantz et al, Monthly Notices of the Royal Astronomical Society, Volume 406, Issue 3, pp. 1759-1772 (2010)

# We don't know much more

# Recap: Dark Matter

- Very strong gravitational evidence
- No nongravitational effects seen yet
- Could be almost anything except what we already know
  - Nearly pressureless, collisionless (weakly interacting nonrelativistic particles)
  - No electromagnetic interactions (caveats)
  - No strong interactions (caveats)

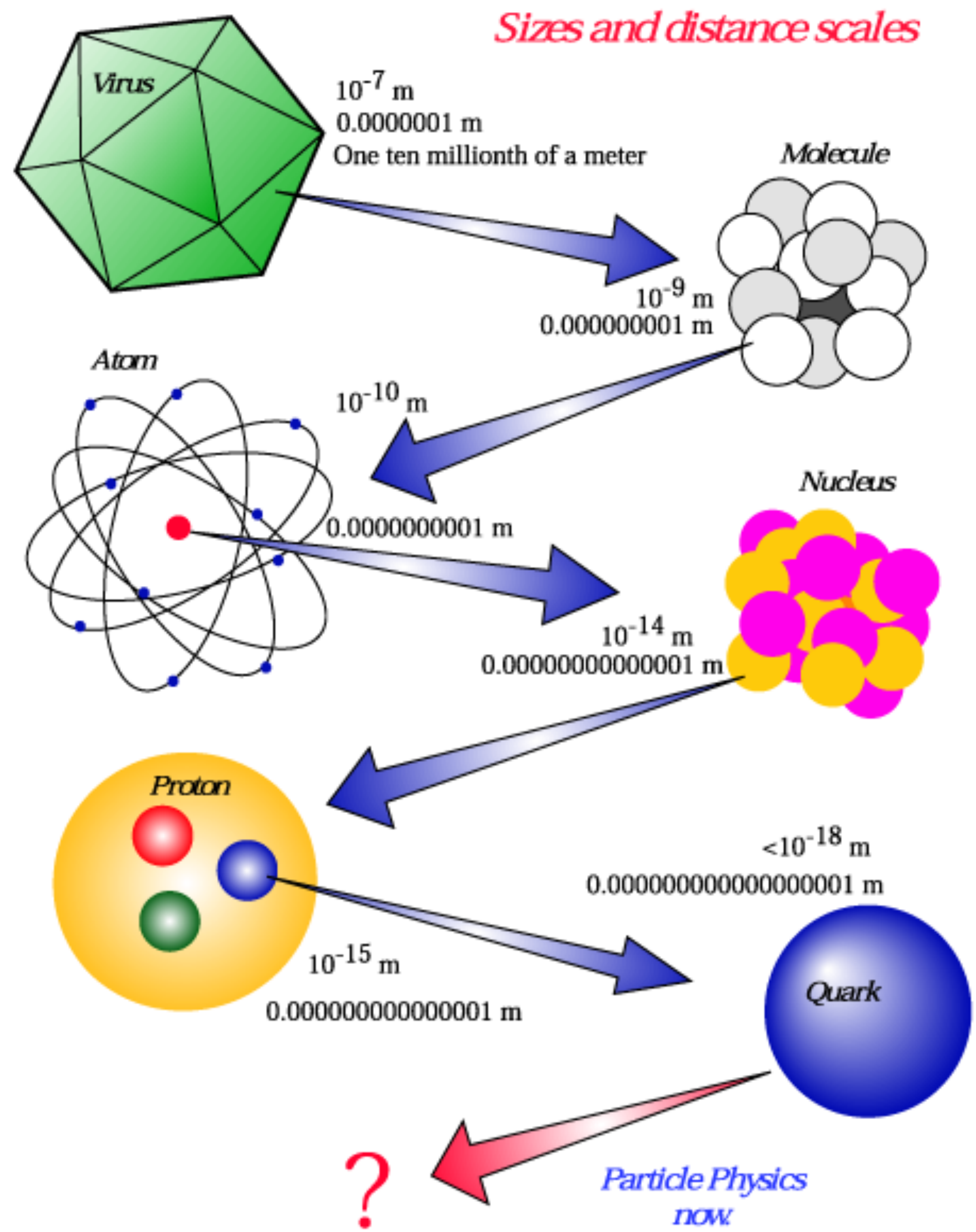
# Dark matter and particle physics

what is the standard model of particle physics and how could dark matter fit?

# Constituents of Matter

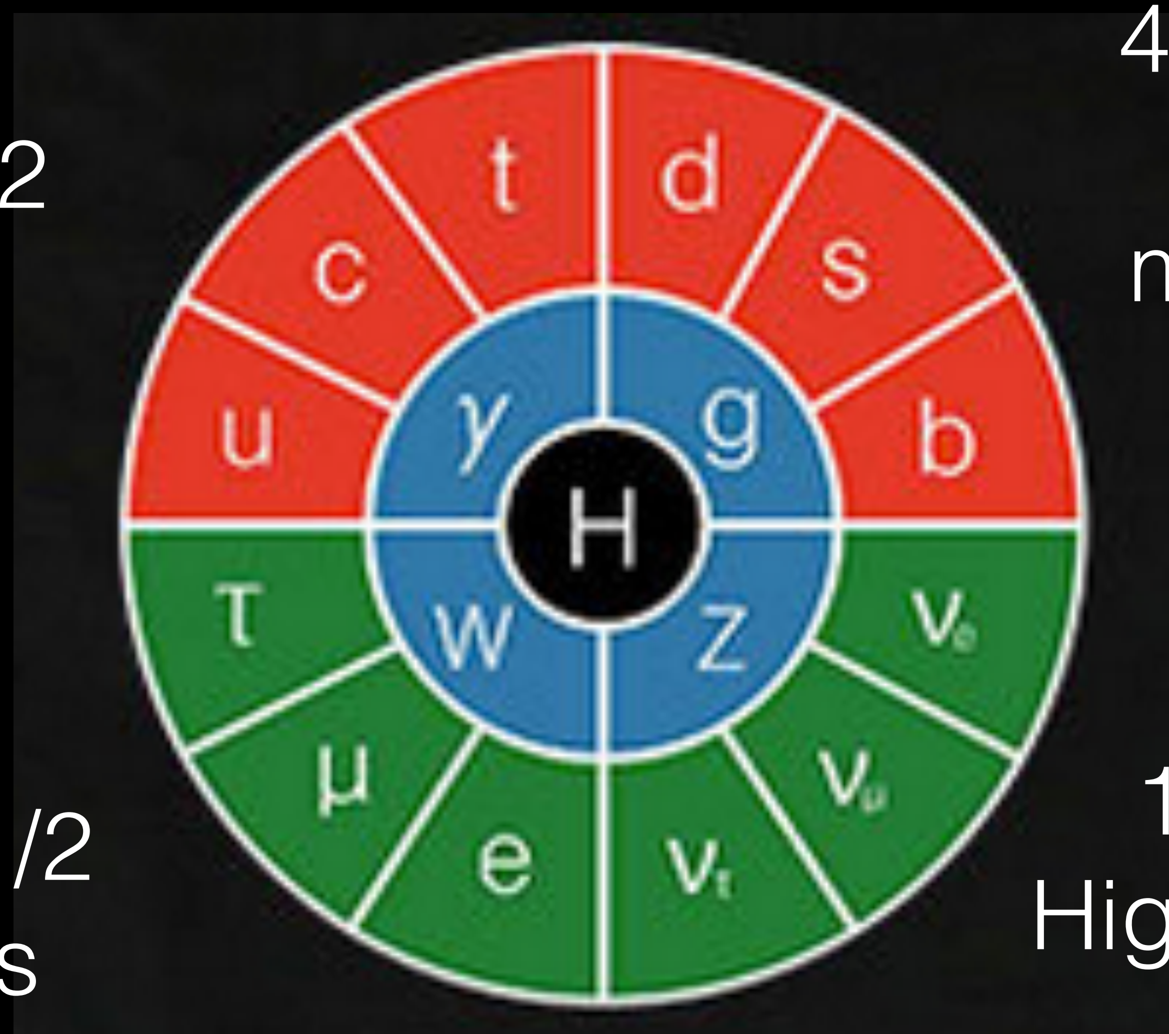
## At shorter and shorter distances

## Physics by DE-construction = Particle Physics



# 17 elementary particles of the Standard Model

6 spin 1/2
quarks




4 spin one
force
mediators

6 spin 1/2
leptons

1 spin 0
Higgs boson

## By their transformations thou shalt distinguish fermions and bosons!

**Rotate by 360°**

$$\phi \xrightarrow{\text{Rotate } 360°} \phi$$

**Boson (integer spin)**

$$\psi \xrightarrow{\text{Rotate } 360°} (-1)\psi$$

**Fermion (half-integer spin)**

**Phases (minus signs) matter in the quantum world!**

⇒ **bosons (forces) are highly "social" and are happy to be in the same state, e.g., lasers (coherent photons)**

⇒ **fermions (quarks and leptons) are highly "anti-social" and no two can be in exactly the same state, e.g., the electrons in an atom cannot be in the same orbit (more electrons means a larger atom)**

# Fundamental Forces

| Force | Relative Strength | Mediated by Bosons | Acting on: Particles | Acting on: "Charge" |
| --- | --- | --- | --- | --- |
| Strong | 1 | Gluons | Quarks & Gluons | Color |
| Electromagnetic | $10^{-2}$ | Photons | Quarks & Charged Leptons | Electric Charge |
| Weak | $10^{-6}$ | W and Z bosons | Quarks & Leptons | Weak Charge |
| Gravity | $10^{-40}$ | Gravitons (theoretical) | All forms of energy | Energy |

**Coupling of W and Z bosons to quarks and leptons same as coupling of photons to quarks and leptons: Electroweak**

# Particle Physics and Dark matter

- Is the dark matter in the standard model?
- not electrically charged
- stable
- only neutral stable standard model particle is the neutrino (if neutrinos have sufficient mass)
  - neutrinos are very light, and fermions$\Longrightarrow$can't pack them densely enough to be the dark matter observed in small galaxies
- Dark matter is new particle not in Standard Model!
- Most popular and well motivated:
  - Weakly Interacting Massive Particle
  - Axion

# Weakly Interacting Massive Particle (WIMP)

- Consider a particle which is similar to a neutrino, but heavy.
  - weak interactions associated with a fundamental mass scale
    - $G_F$= Fermi constant
    - $G_F^{-1/2}$~300 GeV (ħ=c=1 units)
    - weak boson masses 80, 91 GeV
    - guess ~300 GeV is a 'typical' scale for particle masses
    - 1 pb=$10^{-36}$ $cm^2$ 'typical' weak cross section at that energy
    - 'zoo' of new particles at around that mass scale????
    - supersymmetry (susy) predicts fermion parters for every boson and boson partner for every fermion—are the susy partners at the weak scale?
    - stability: a discrete conserved charge (analagous to parity, called "r-parity") $(-1)^{(2S+3(B-L))}$
    - all known particles have r-parity = +1
    - lightest r-odd particle would be stable
      - if neutral, dark matter candidate

# early universe WIMP thermodynamics

- in early universe, Temperature T very hot and WIMPS in thermal equilibrium
- density of WIMPS $\rho \sim 1/(e^{m/T} \pm 1) \cong e^{-m/T}$ at low T

  (+ for fermions, - for bosons)

- As T decreases, staying in thermal equilibrium requires that particles annihilate into lighter standard model particles
- annihilation rate=flux x cross section
- flux ~ $\rho$ v
- cross section ~ weak cross section ~ $10^{-36}$ $cm^2$
- age of universe ~ $H^{-1}$

# WIMP Freezeout in early universe

- flux x cross section x time=#annihilations
- In thermal equilibrium, for $T \ll m$, WIMP flux$\sim (m/T)T^3 e^{-m/T}$
- T decreasing as 1/a, flux decreasing rapidly!
- age of universe $\sim H^{-1}$
- Universe radiation dominated: $H \sim T^2 G_N^{1/2}$
- $(m/T)T^3 e^{-m/T} \sigma/(T^2 G_N^{1/2}) < 1 \Longrightarrow$ fewer than 1 annihilation per particle during age of universe
- Particles stop annihilating, abundance is "frozen"
- After this "freezeout", abundance is diluted by expansion of space, ratio of dark matter particle density to entropy density does not change

from thesis presentation of Ali Ovgun at Eastern Mediterranean University

# FREEZE OUT: QUALITATIVE

(1) Assume a new heavy particle $X$ is initially in thermal equilibrium:

$$XX \leftrightarrow \bar{q}q$$

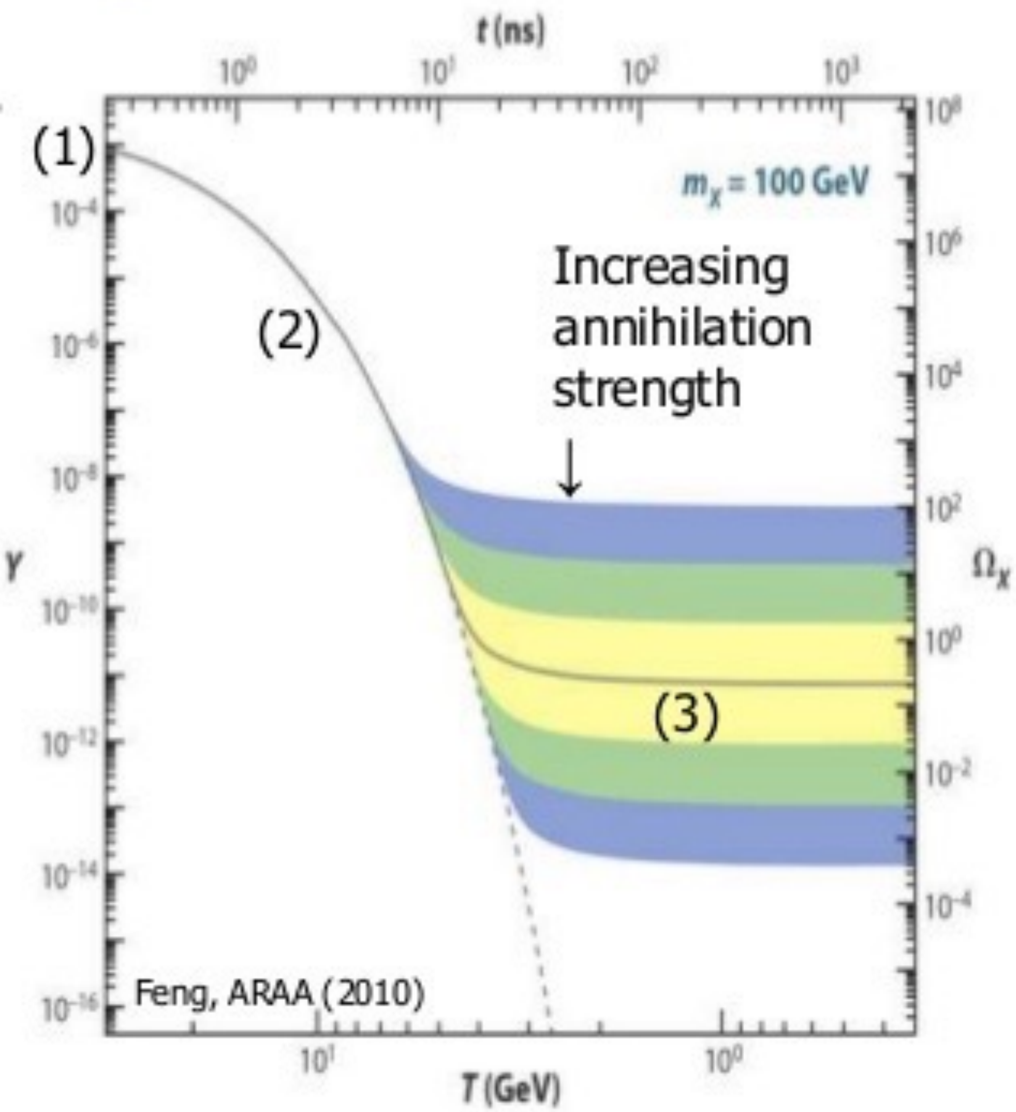
(2) Universe cools:

$$XX \not\leftarrow \bar{q}q \quad (\rightarrow \text{ only})$$

(3) Universe expands:

$$XX \not\rightleftarrows \bar{q}q$$

Zeldovich et al. (1960s)



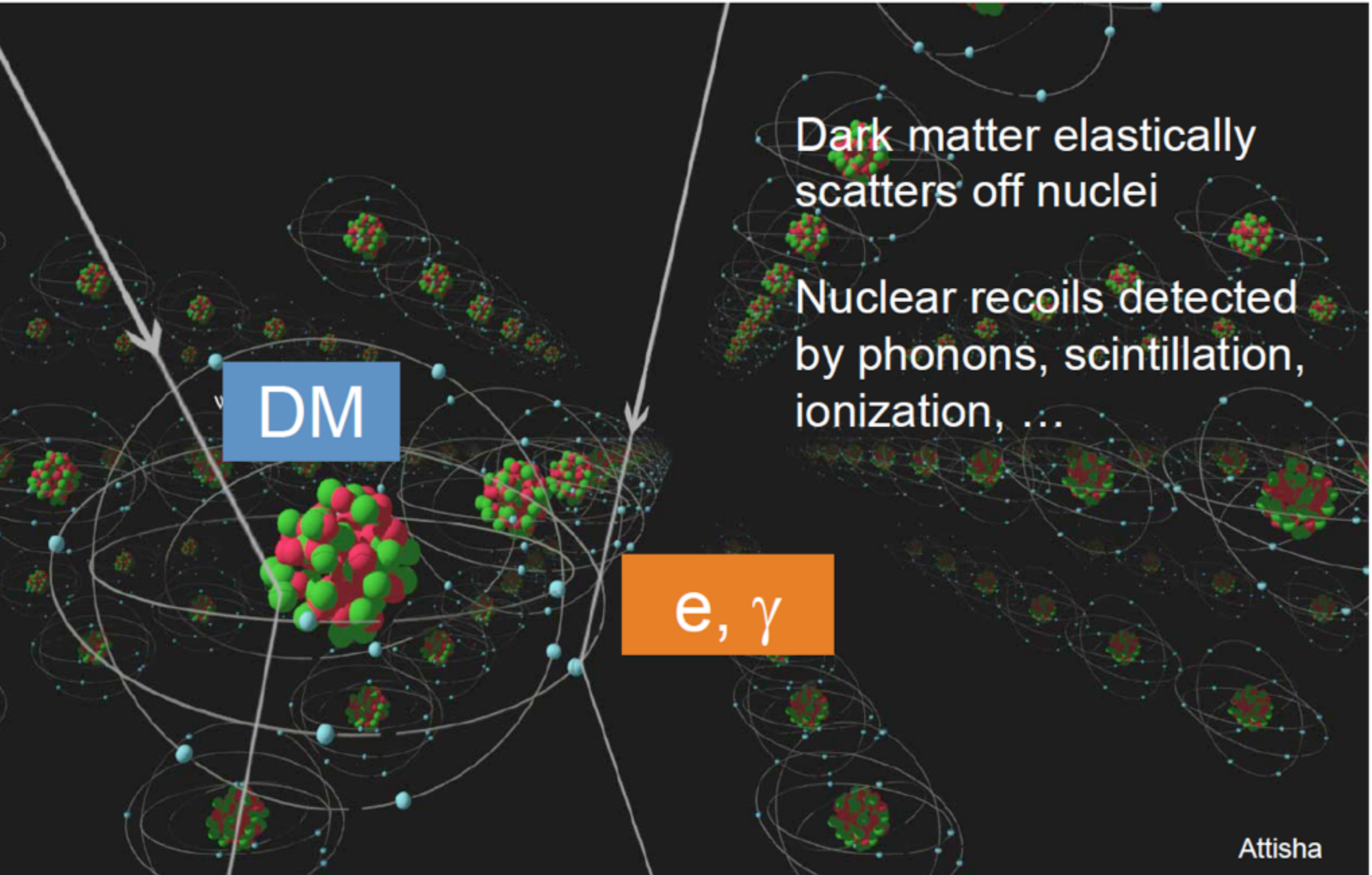

$\Omega_\chi$= fraction of critical density provided by dark matter

decreasing temperature→

# Wimp ‘miracle’

- **If the dark matter abundance is determined by the freezeout temperature, it depends on the mass and the annihilation cross section**
- **A mass near the weak scale (5-1000 GeV) and a cross section of similar size to the weak cross section gives the observed abundance!**
- **Coincidence or clue?**

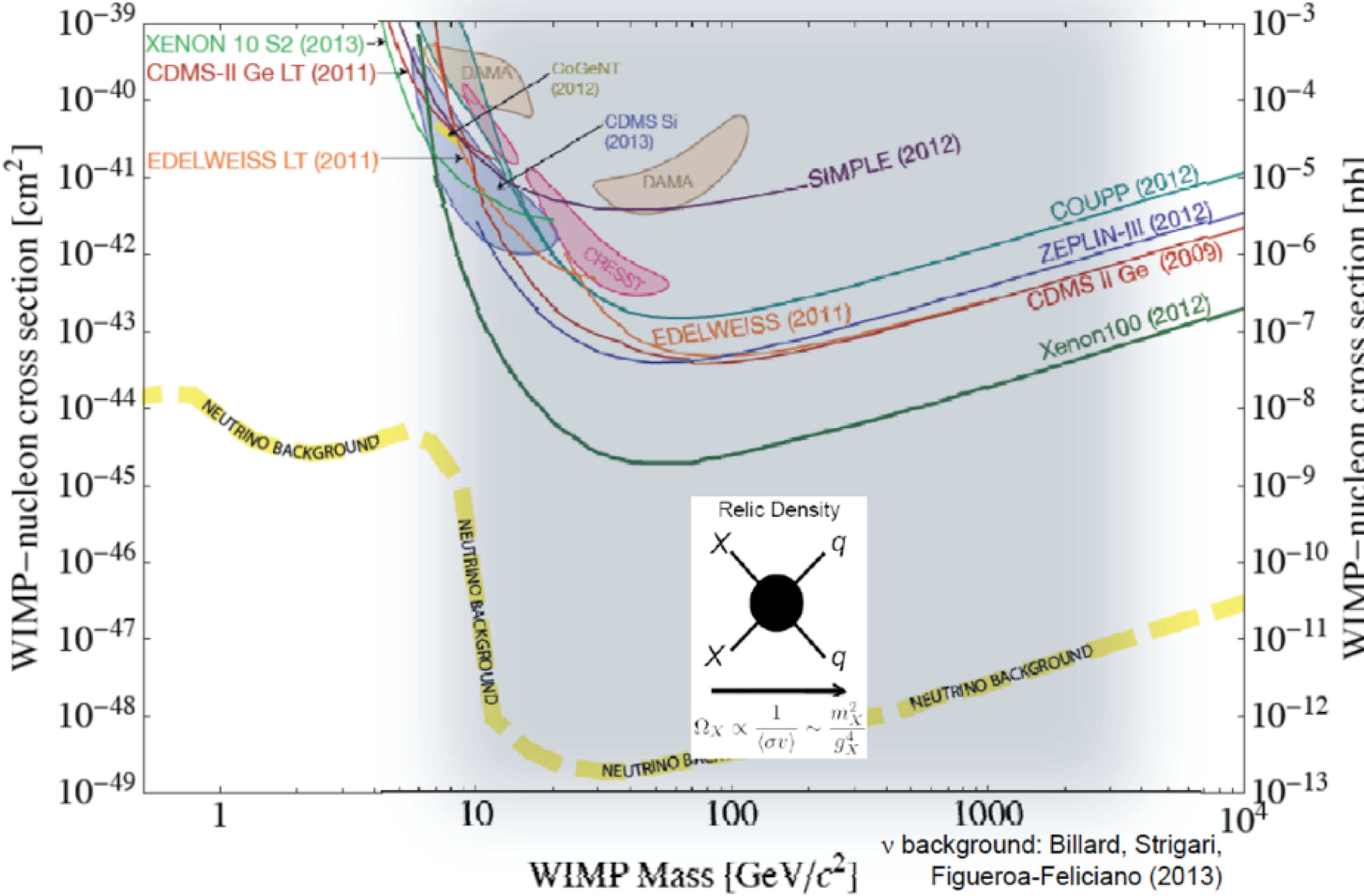
# DIRECT DETECTION




Dark matter elastically scatters off nuclei

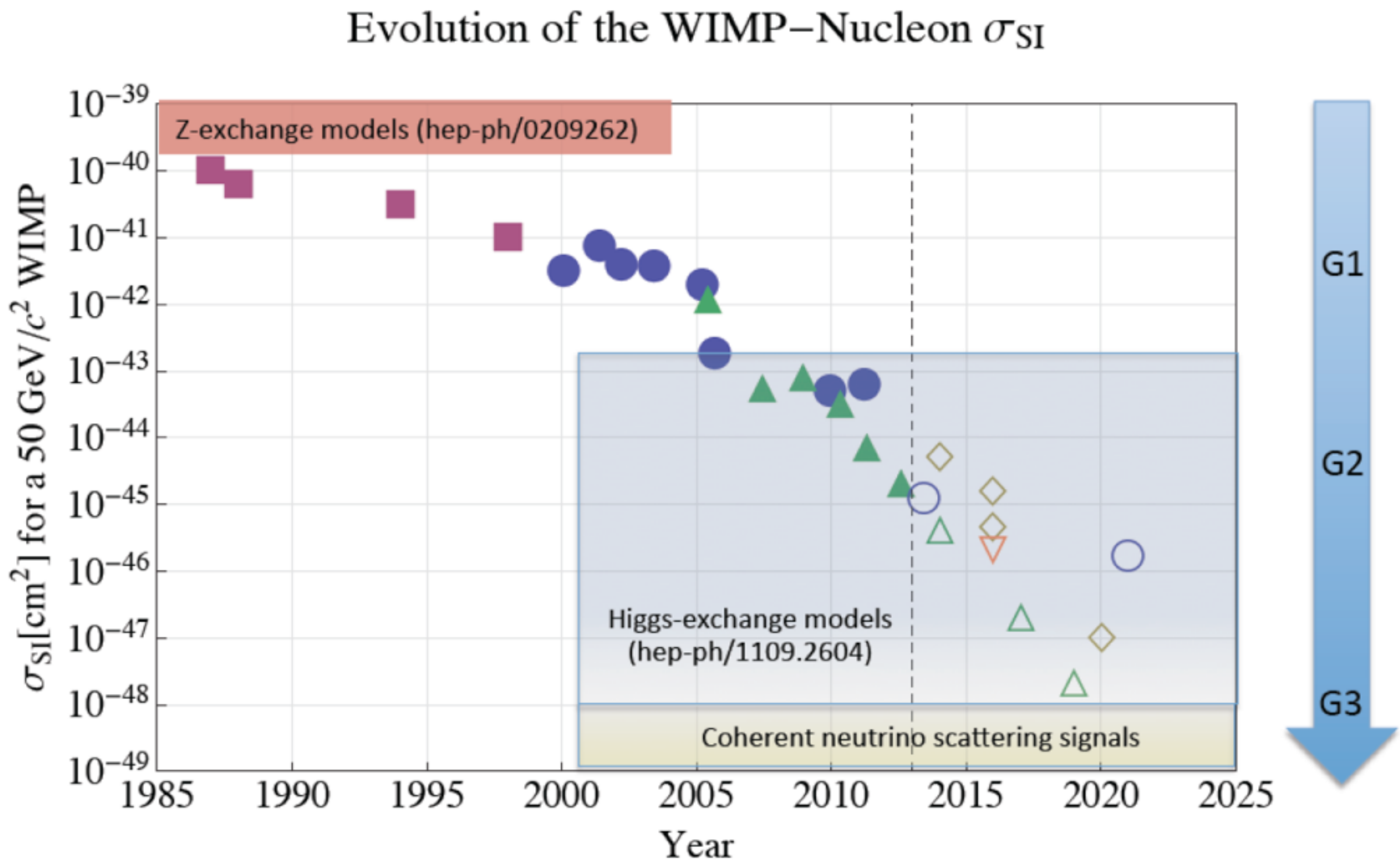
Nuclear recoils detected by phonons, scintillation, ionization, …

# CURRENT STATUS AND FUTURE PROSPECTS




ν background: Billard, Strigari, Figueroa-Feliciano (2013)

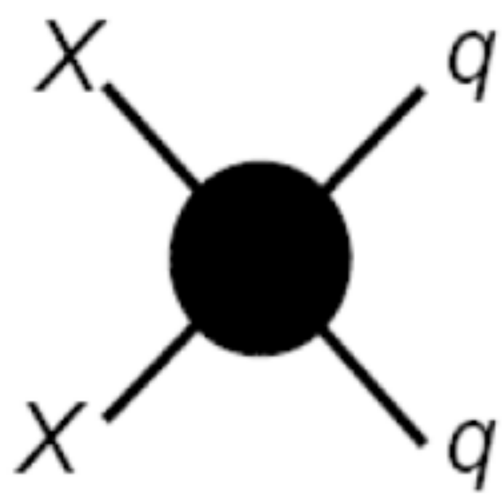
# MOORE'S LAW FOR DARK MATTER



# 2 Km underground in Sudbury

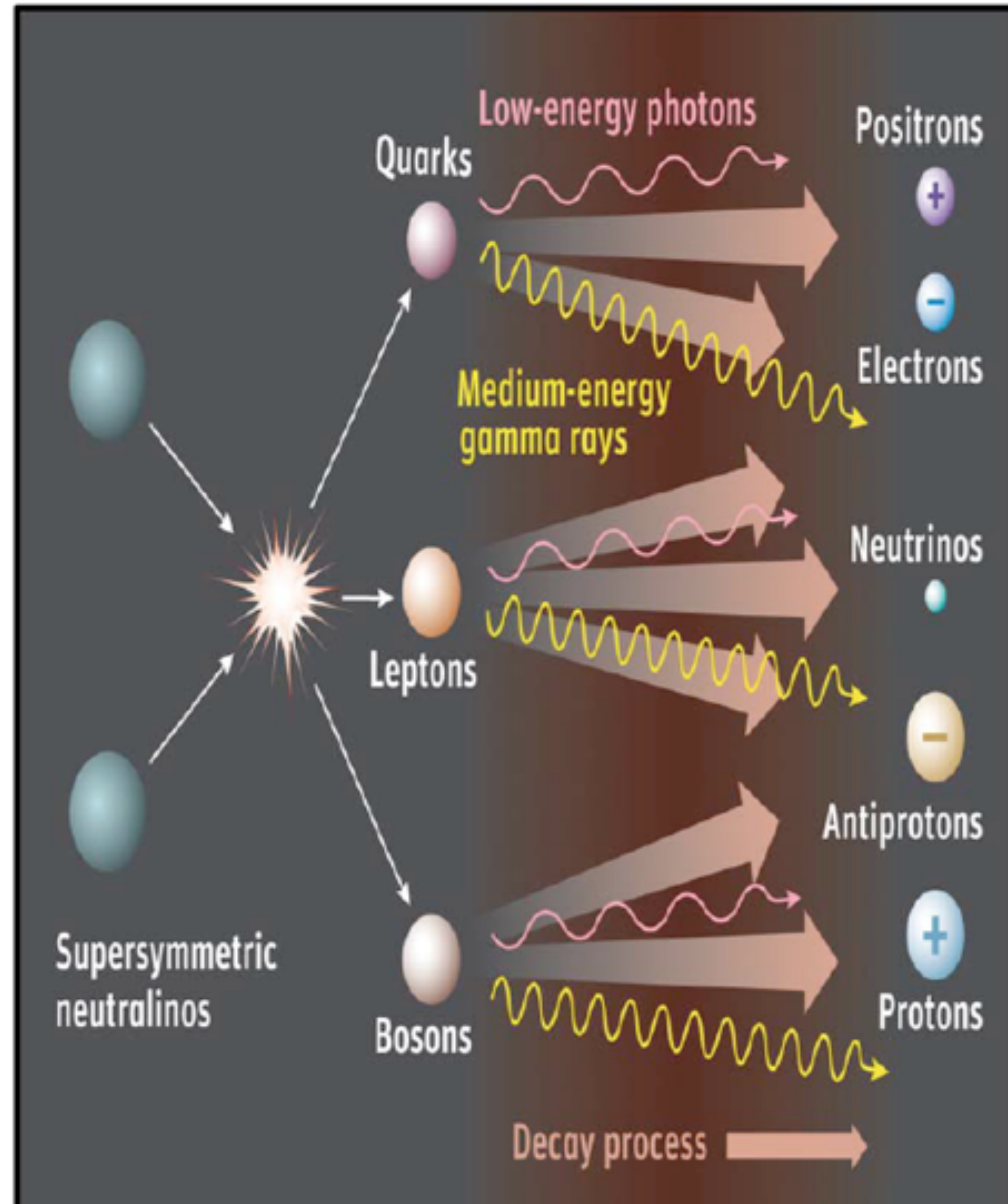
# INDIRECT DETECTION

- Dark matter may pair annihilate in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons



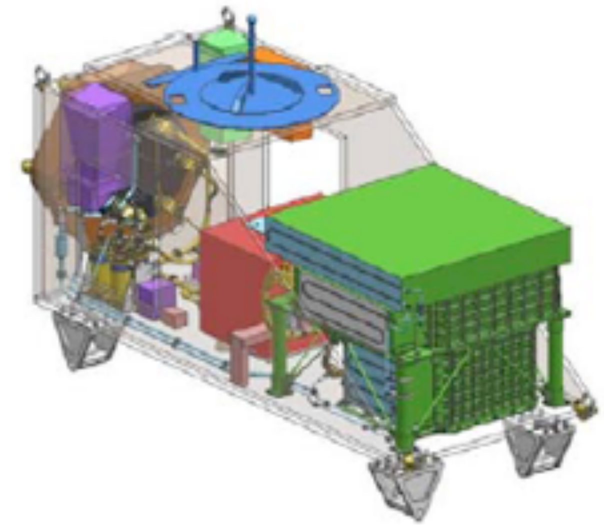

- The relic density provides a target annihilation cross section

$$\langle \sigma_A v \rangle \sim 3 \times 10^{-26} \text{ cm}^3\text{/s}$$



# INDIRECT DETECTION: ANTI-MATTER

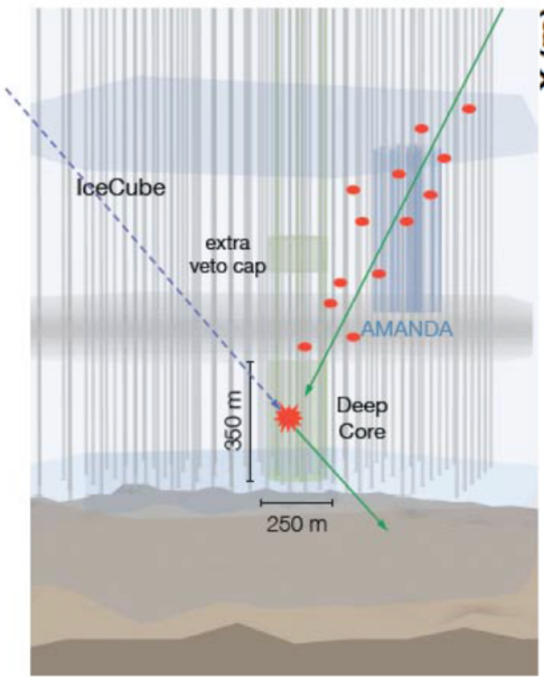
- Positrons (PAMELA, Fermi-LAT, AMS, CALET)
- Anti-Protons (PAMELA, AMS)
- Anti-Deuterons (GAPS)

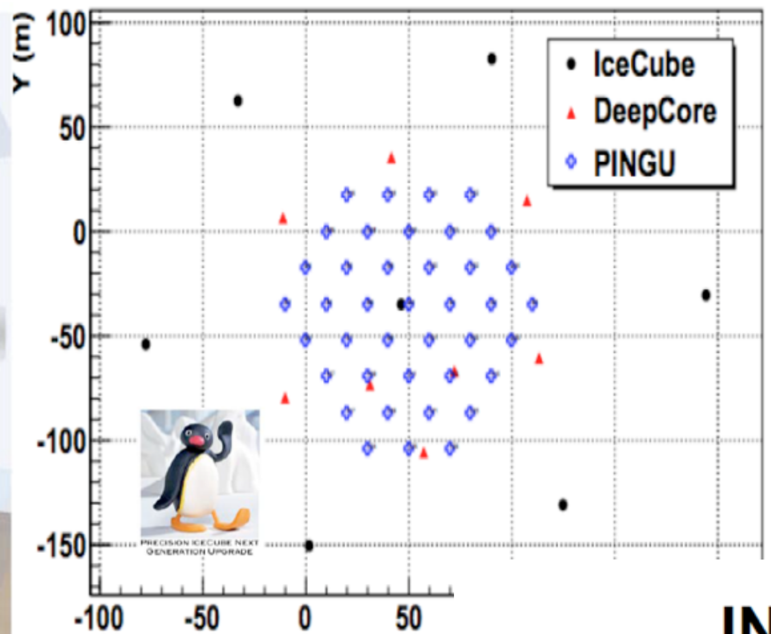



## INDIRECT DETECTION: NEUTRINOS

Current: IceCube/DeepCore, ANTARES

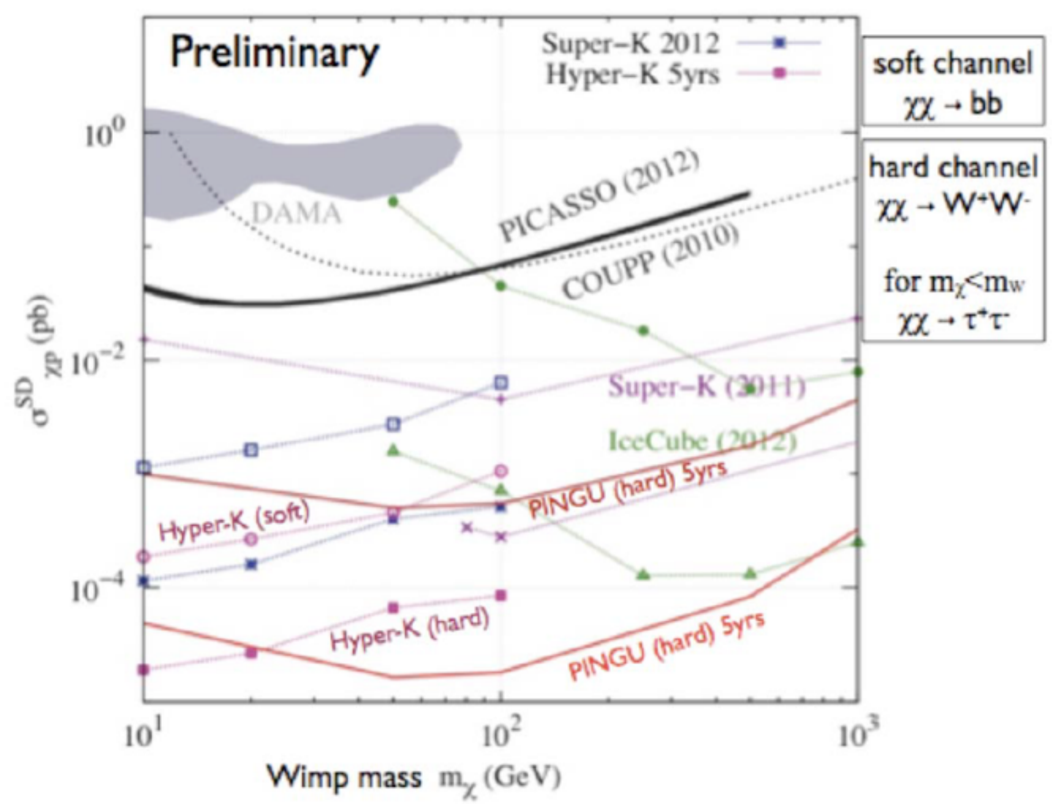
Future: PINGU

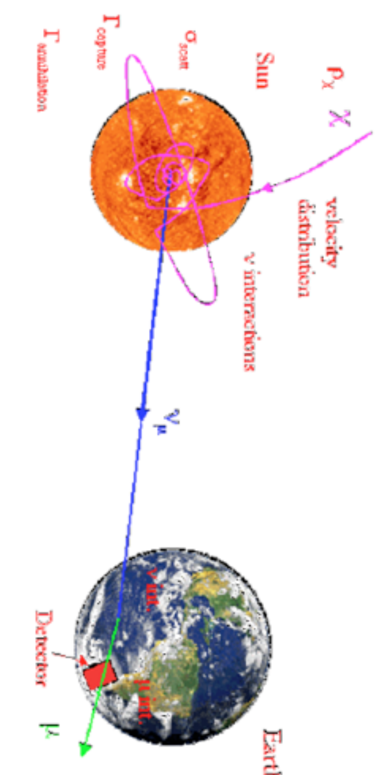





## INDIRECT DETECTION: NEUTRINOS




Future experiments like PINGU may discover the smoking-gun signal of HE neutrinos from the Sun, or set stringent $\sigma_{SD}$ limits, extending the reach of IceCube/DeepCore

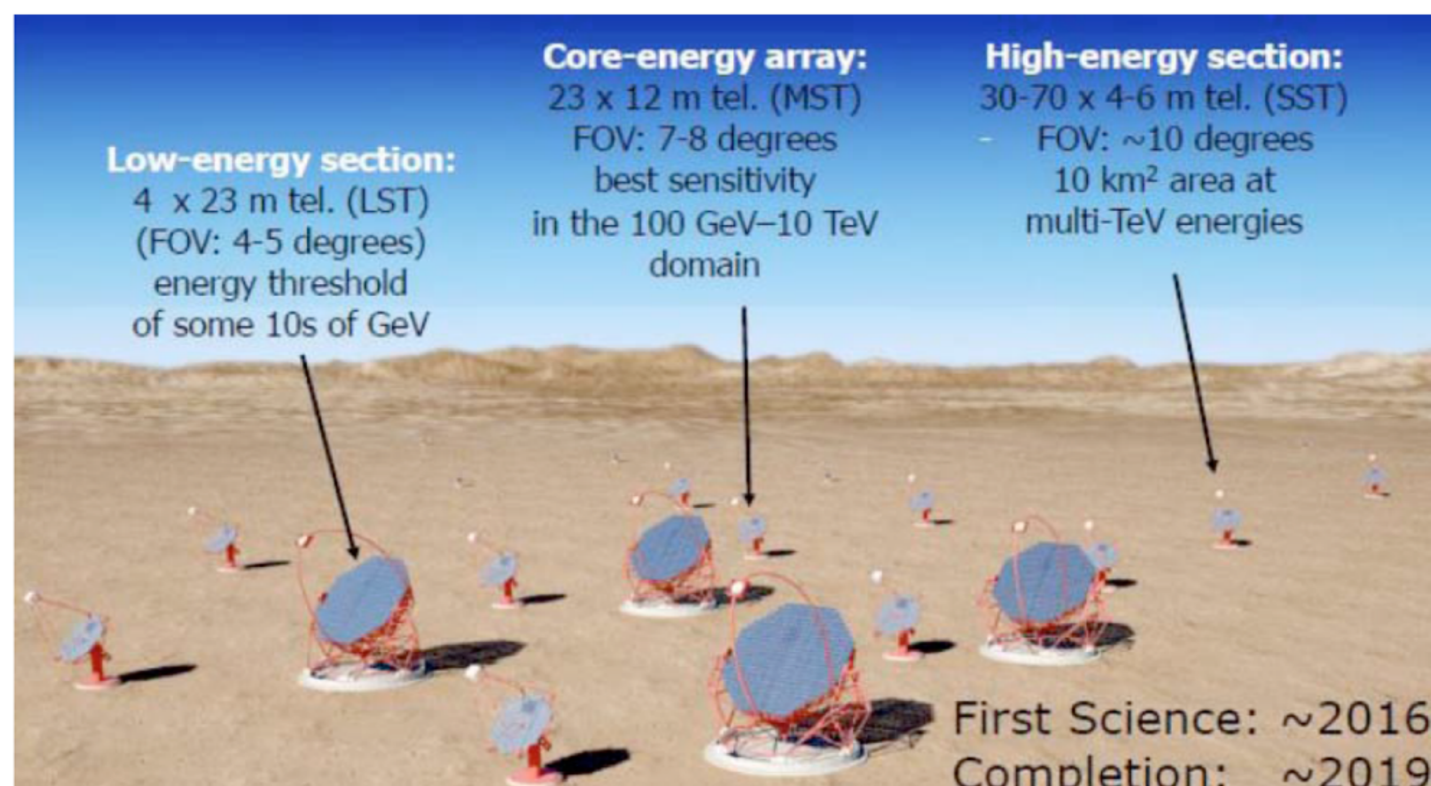
# INDIRECT DETECTION: PHOTONS

Current: Veritas, Fermi-LAT, HAWC, and others

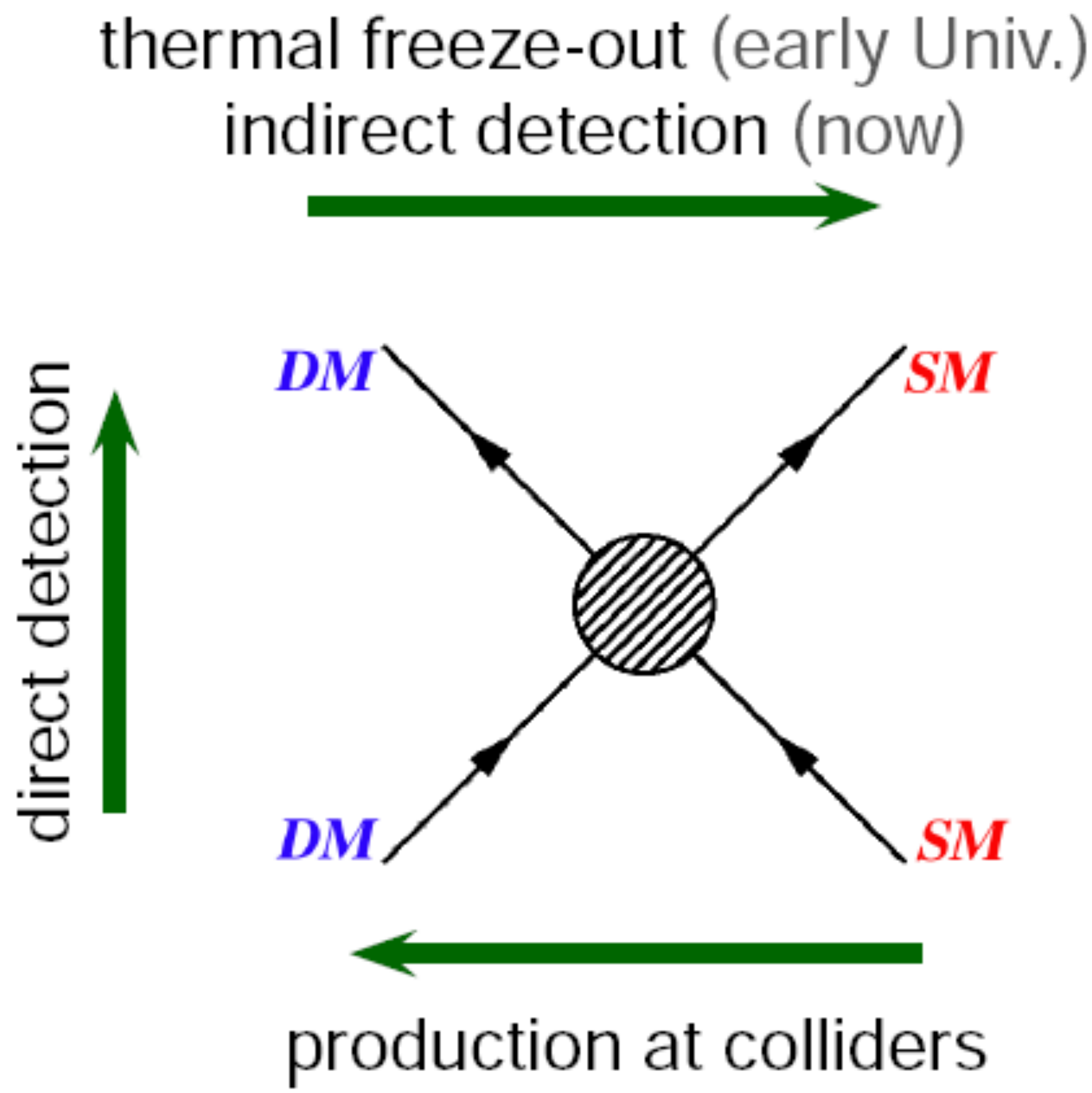



# INDIRECT DETECTION: PHOTONS

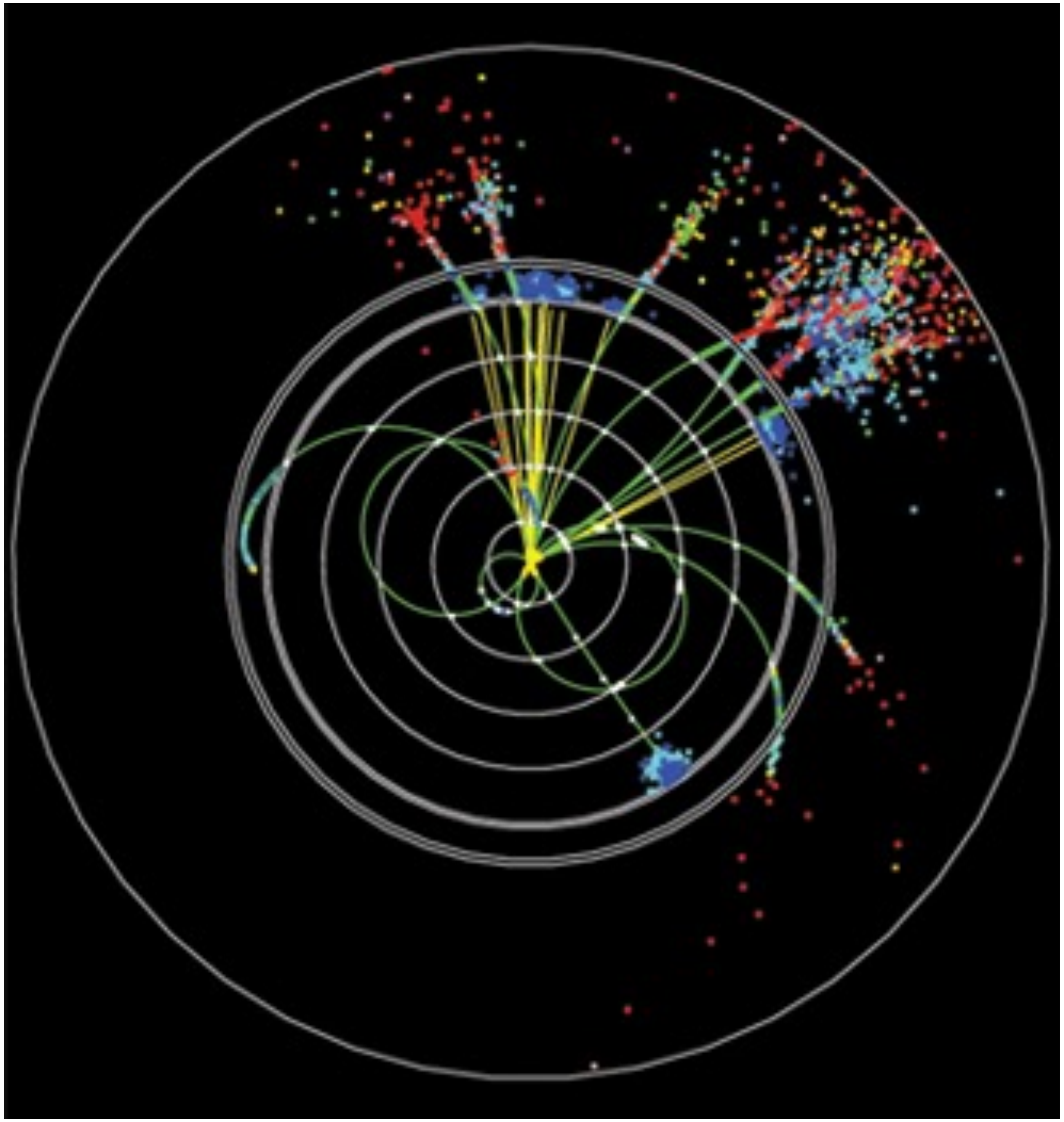
Future: Cerenkov Telescope Array



# dark matter in colliders



# Potential LHC collider signature: ‘missing’ transverse momentum



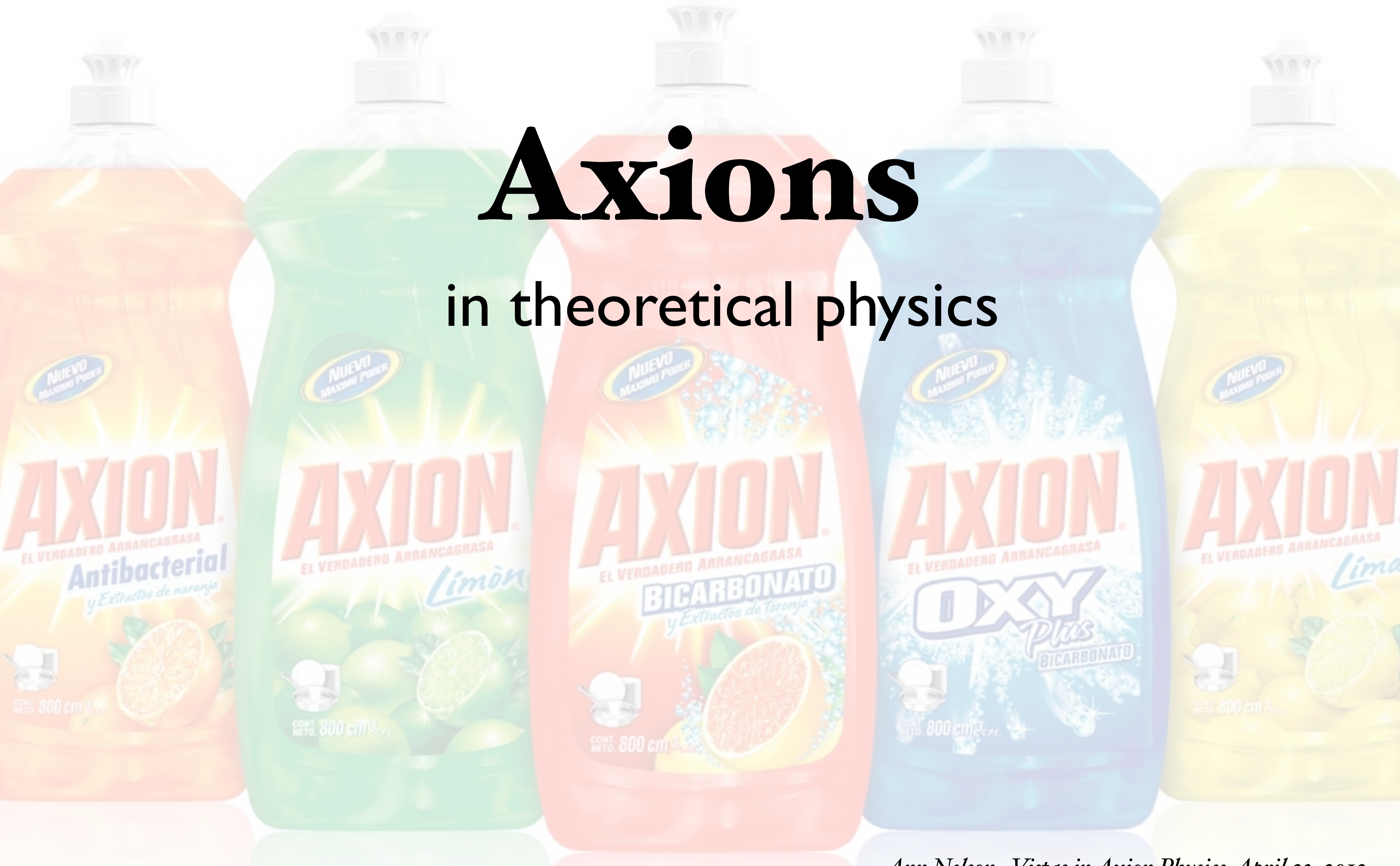
# recap: WIMPS

- motivated by potential new type of conservation law in susy

- wimp miracle-freezeout gives correct abundance with typical weak scale mass and annihilation cross section
- Direct Detection searches see nothing yet
- Indirect detection-ambiguous (astrophysical sources may produce similar signals)
- Collider searches see nothing yet

# Axions

## in theoretical physics




*Ann Nelson, Vistas in Axion Physics, April 23, 2012*

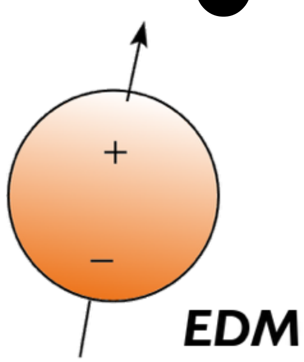
# Strong CP Problem

- QCD theta term violates P, T, CP

$$\mathcal{L}_{CPV} = \bar{\theta}\frac{\alpha_s}{8\pi}G\tilde{G}$$

- renormalized in Standard Model, short distance sensitive ("divergent")

- Electric dipole moment of neutron ~ $3 \times 10^{-16}\bar{\theta}$ forces fine-tuning to part in ~$10^{-9}$ to satisfy experimental bound




- elegant solution by Peccei and Quinn: $\bar{\theta}$ dynamical, ≈ 0

$$\mathcal{L}_{axion} = \frac{a}{f}\frac{\alpha_s}{8\pi}G\tilde{G}$$

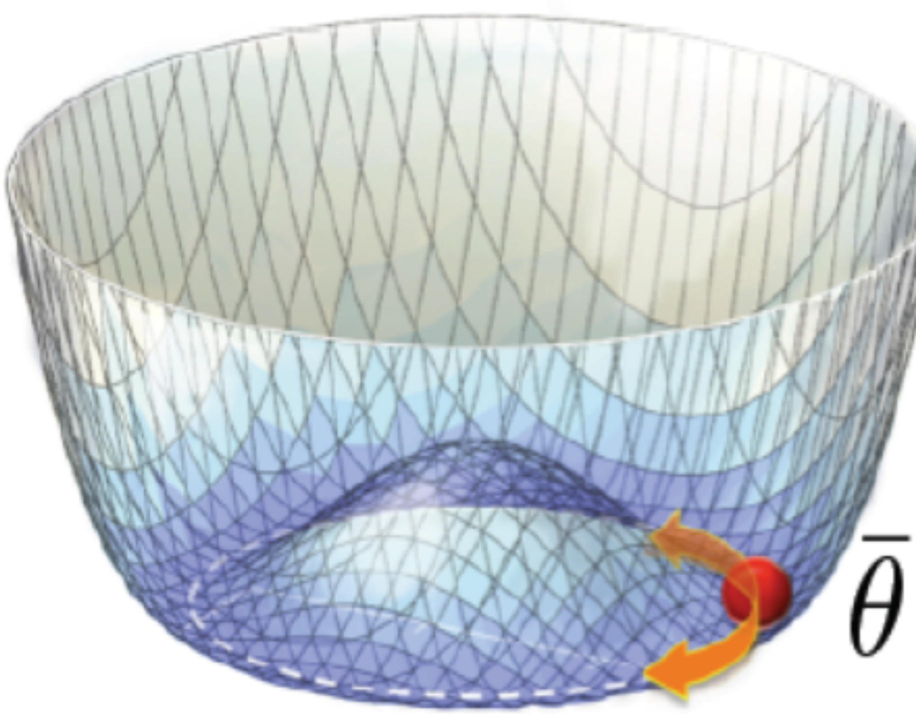
- Weinberg, Wilczek: PQ mechanism

Observation of Peccei & Quinn (1977):

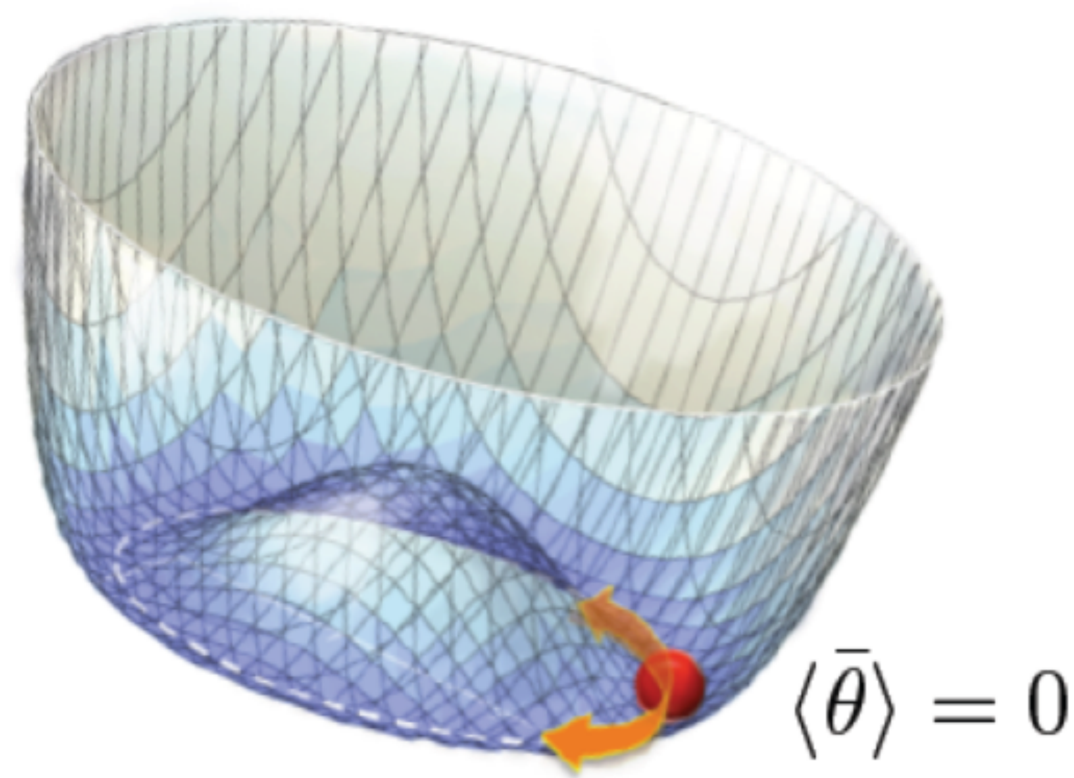
If a complex boson is

- coupled to quarks in the right way,
- and spontaneously breaks a U(1) symmetry,

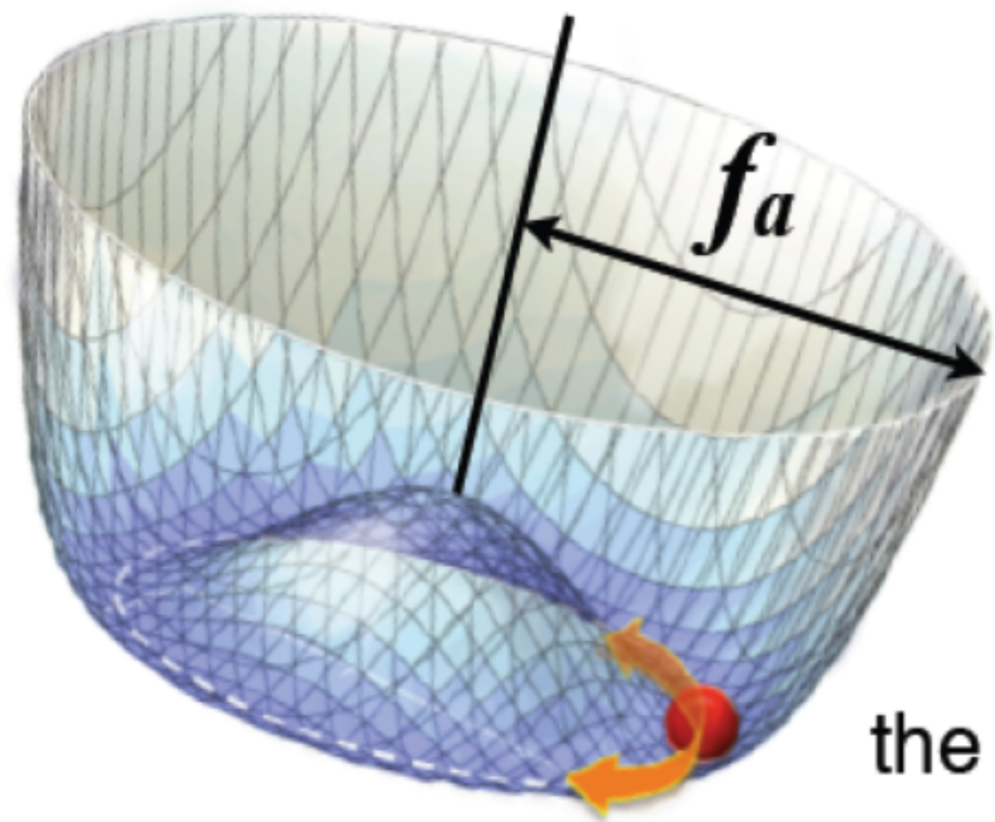
the phase of the field dynamically determines $\bar{\theta}$ ...




... known that the QCD violates the U(1) symmetry and vacuum energy is minimized for $\bar{\theta}$ =0



Weinberg, Wilczek (1978): oscillations about minimum = new particle

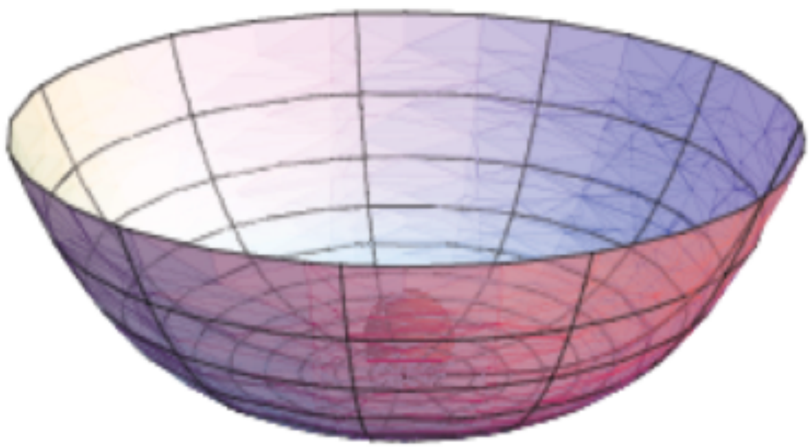



the axion

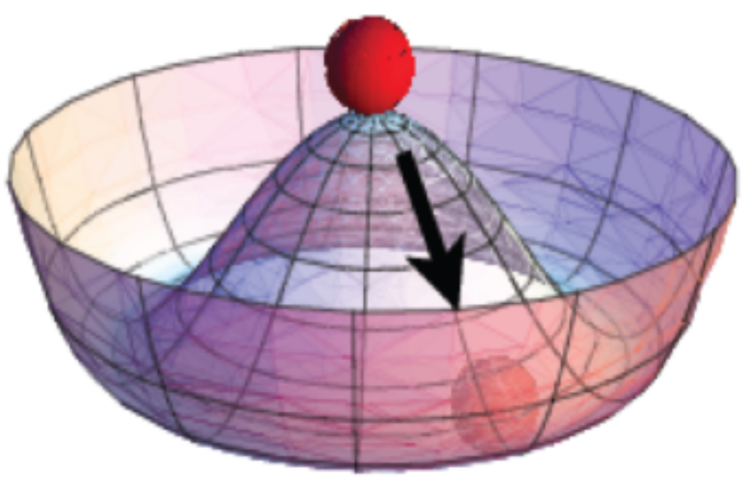
axion physics set by energy scale $f_a$

axion mass: $m_a \sim \dfrac{(100\ \mathrm{MeV})^2}{f_a}$

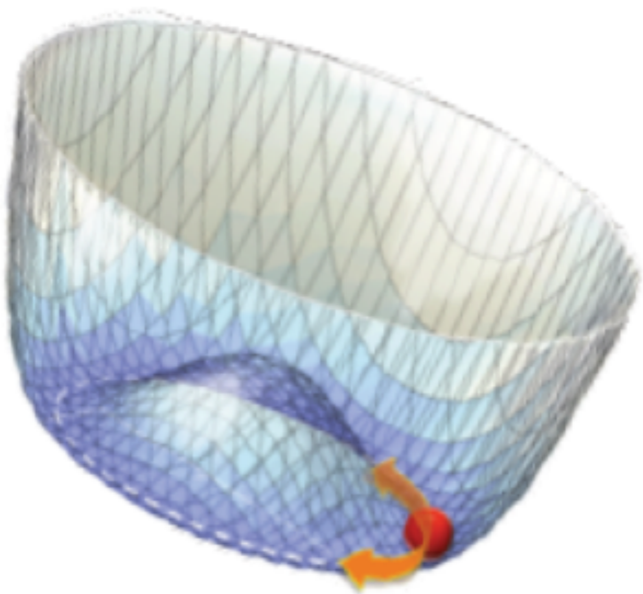
# Big-bang axion cosmology



Temperature $T > f_a$: Peccei-Quinn symmetry unbroken



$T \sim f_a$: Peccei-Quinn symmetry spontaneously breaks



$T \sim 100\ MeV$: QCD tips the potential and the axion field starts oscillating

# Remember this equation

- In early universe, radiation dominated, simple relation between Hubble constant and temperature

$$H \approx \frac{T^2}{M_P}$$

*$M_P$=Planck mass/energy*

# And this one

- Age of universe ~ $H^{-1}$
- Valid for radiation, matter dominance
- Not valid for inflation, dark energy dominance (but dark energy has only become important recently so is true today)

# And finally

- Temperature ~ 1/(scale factor)
  - (also affected by changes to number of relativistic degrees of freedom or nonequilibrium processes)
- Pressureless matter $\rho_{DM}$~/(scale factor)^3
- In/near equilibrium, entropy density $s$~1/(scale factor)^3
- Now easy to do back of the envelope dark matter computations to see if you have something close to todays value

$$\frac{\rho_{DM}}{s} \sim 1\text{eV}$$

# Oscillating fields and Cold Dark Matter

Equation for spatially smooth field in expanding universe with Hubble constant $H$

Damping term

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$$H \approx \frac{T^2}{M_P}$$

# At late times: Oscillating axion

$$E = \frac{1}{2}(\dot{a}^2 + m_a^2 a^2)$$

$$P = \frac{1}{2}(\dot{a}^2 - m_a^2 a^2)$$

Pressureless! (Virial Theorem <kinetic>=<potential>)

# Energetic, pressureless...

A fluid of noninteracting, very cold particles!

Energy density $= m_a^2 \langle a \rangle^2$

(number density $= m_a \langle a \rangle^2$)

# Rough estimate

- Energy density in axions today:

$$\frac{\rho_{\text{axion}}}{\rho_{DM}} \sim \left(\frac{f_a}{10^{11}\text{GeV}}\right)^{\frac{3}{2}}$$

# More refined estimate

- Including finite temperature effects, numbers.

$$\frac{\rho_{\text{axion}}}{\rho_{DM}} \sim 7 \left( \frac{f_a}{10^{12}\text{GeV}} \right)^{1.18}$$

- UPPER bound on $f_a$

# Theory Origin of Axion

- Could have "accidental" Peccei-Quinn approximate symmetry
  - corrections to axion potential from PQ symmetry breaking highly constrained
- String theory predicts "model independent axion"

(in large class of models) with $f_a \sim 10^{16}$ GeV

- String theory compatible with any $f_a < 10^{19}$ GeV
- string theory axion solves strong CP problem in large class of models

# Alternatives to Axions

- No anthropic explanation for size of strong CPV!
- massless up quark incompatible with lattice, chiral sym
- alternative solution to strong CP problem: spontaneously broken P or CP plus some mechanism for weak CP without large strong CP (e.g. Nelson-Barr)
- axion is only solution to strong CP problem compatible with nonminimal flavor or CP violation at weak scale

# Axion implies Axion Cold Dark Matter

*Preskill, Wise, Wilczek; Abbot, Sikivie; Dine, Fischler*

- Cosmological Axion equation of motion

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

- resembles damped Harmonic Oscillator
- $H > m_a$ $\Rightarrow$overdamped, a~ constant
- $H < m_a$ $\Rightarrow$underdamped, a oscillates and loses energy to cosmological "Hubble friction"
- $H < m_a \Rightarrow$ axion is pressureless Cold Dark Matter!
  - potentially too much for $f > 10^{12}$ GeV, $m_a < \mu$eV

# Axion dark matter continued

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

- $a \sim a_{initial}$ until $H(T_i) \sim m_a(T_i)$ at redshift "$z_i$"
- larger $f_a \Rightarrow$ smaller $m_a\ (T_i) \Rightarrow$ smaller $z_i$ (Note: axion mass temperature dependence currently estimated, could be computed on lattice)
- "typical" size of $a_{initial} \sim f_a$
- "typical" initial energy density $a^2_{initial} m_a^2 \sim m_\pi^2 f_\pi^2$
- $\alpha_i \equiv a_{initial}/f_a$ (Note: axion+inflation$\Rightarrow$"landscape" of initial conditions)
- subsequent energy density: $\alpha_i^2 m_\pi^2 f_\pi^2 (1/(1+z_i))^3$
- Assuming $\alpha_i \sim 1$, obtain observed dark matter abundance for $f_a \sim$ few $10^{11}$ GeV

# Over 5000 papers

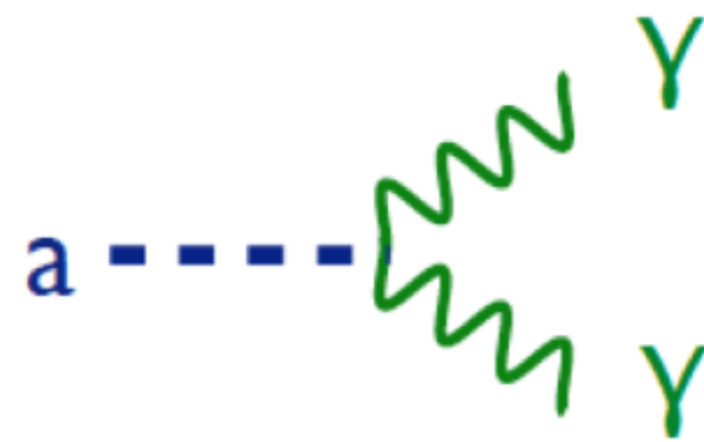
- why so much fascination with a speculative idea?
- “a perfect storm”
  - potential to solve  2 major problems
  - “model independent” in string theory
  - potential to create several major problems
  - lots of compelling, cool theory
  - some compelling, cool, feasible experiments

# Hunt for the dark matter axion

If axions are the dark matter, they are all around us. How can we detect them?

ADMX experiment @ the UW:

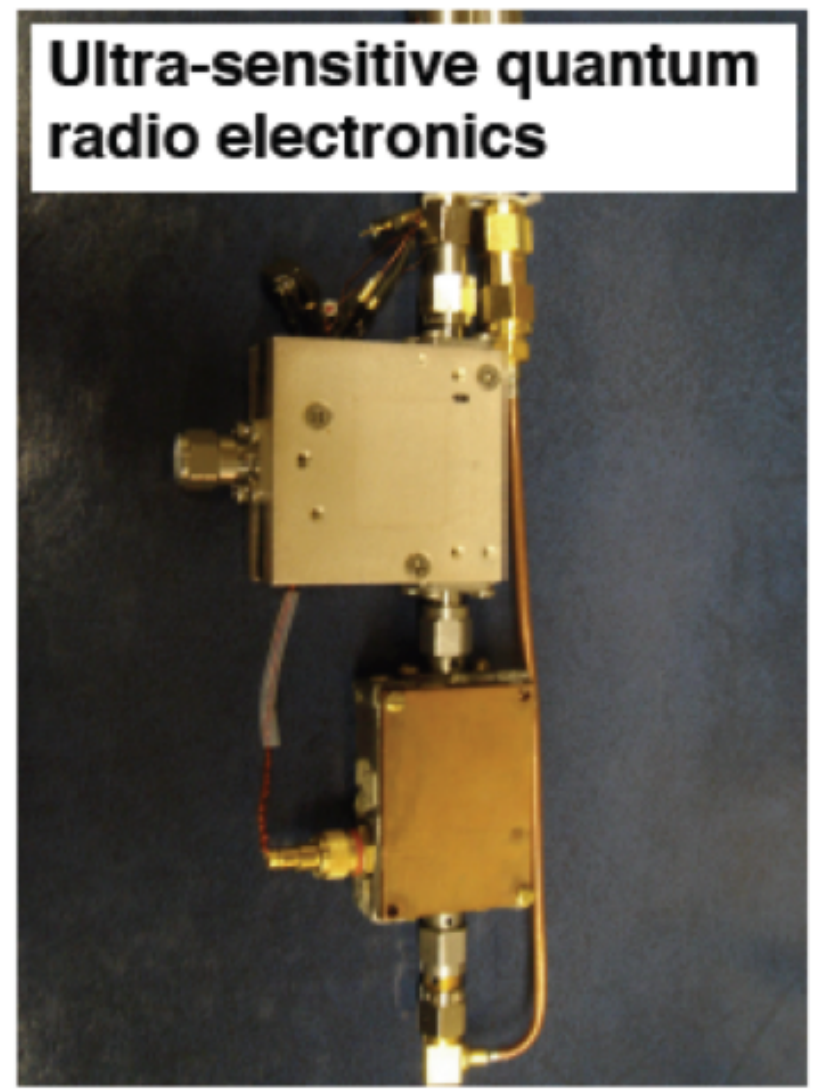
Sikivie-type cavity experiment:
makes use of axion - 2 photon coupling (E.B)




- High Q tuneable EM cavity
- High B field (8 Tesla)
- cosmic axion + B field stimulates emission into E mode photon
- Search for E mode excitation, scanning cavity resonance frequenc
through possible values for $m_a/2$.

## ADMX: The Axion Dark Matter eXperiment, an ultra-sensitive search for dark-matter axions


The magnet and microwave cavity convert Milky Way axions into a very weak radio signal




The weak radio signal is detected by electronics so sensitive it would easily provide your cell phone 4 bars on Jupiter

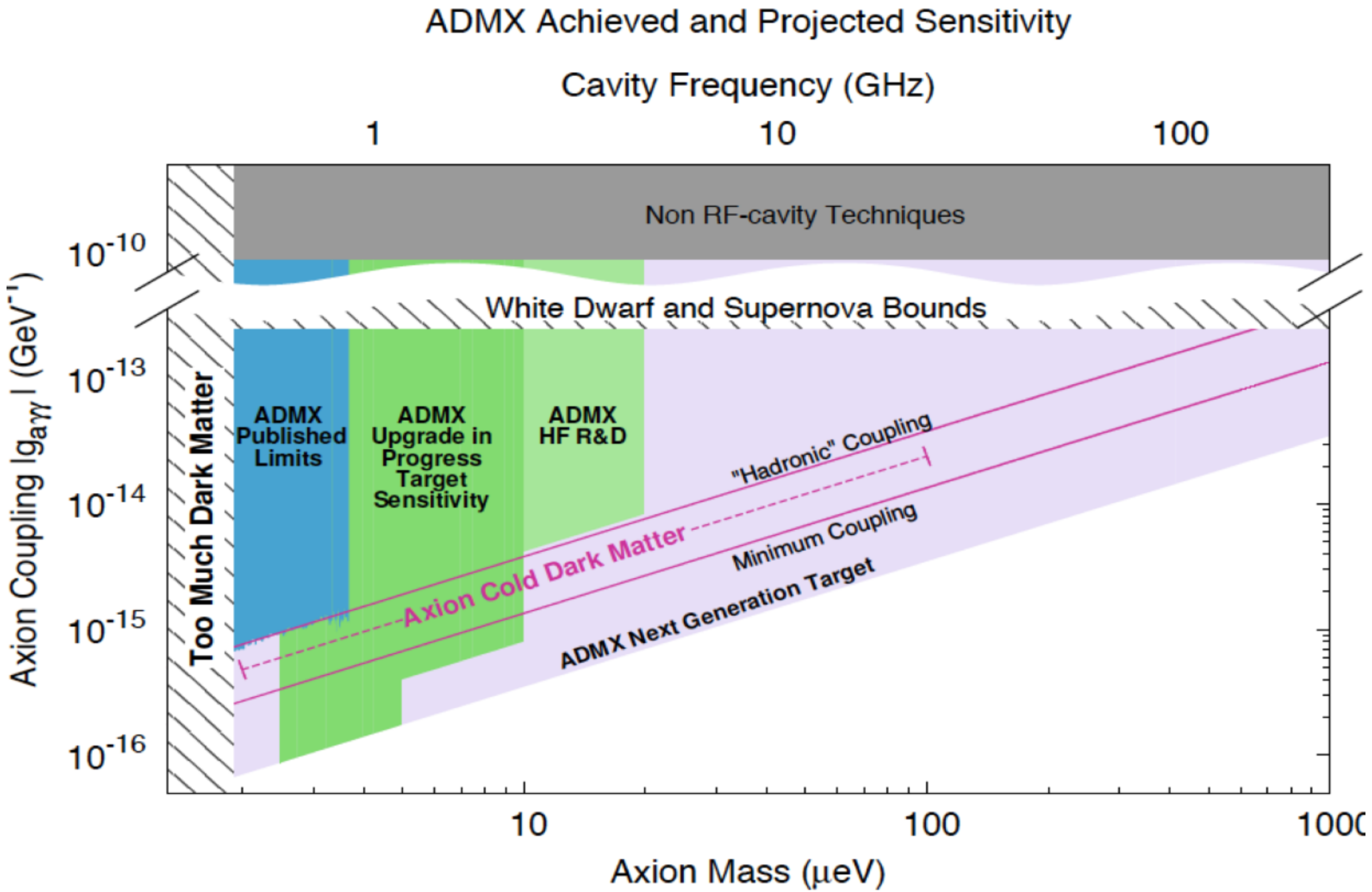
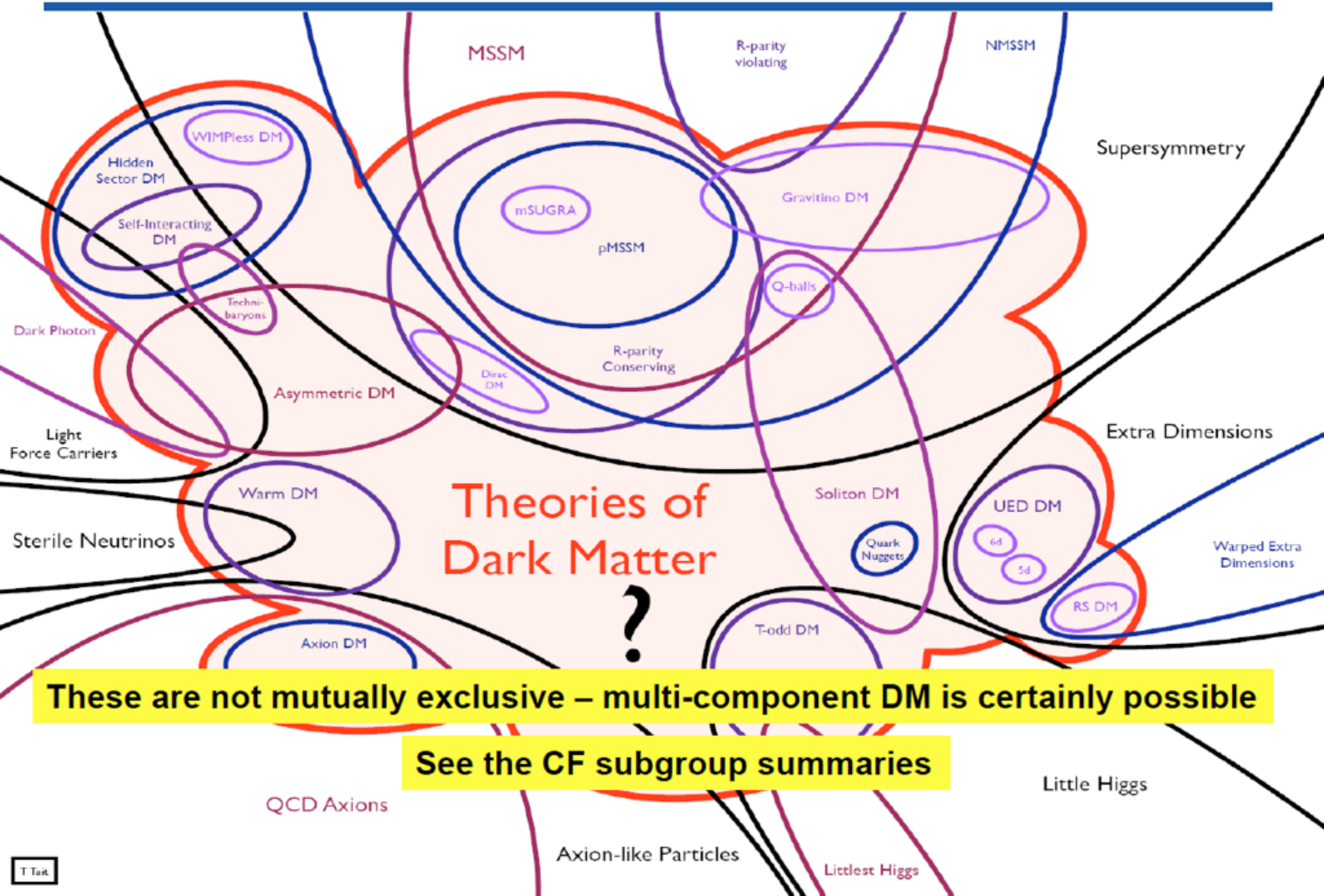



**Figure 2.** *The search reach of the ADMX RF-cavity experiments over the next 3 years. The first decade of allowed axion mass will be explored at "definitive" sensitivity to QCD axions over the next year. The middle decade will be explored at over the following two years. These two decades are expected to encompass the mass of the dark matter axion.*

# But wait, there’s more!

too much more!

# NON-WIMP DARK MATTER




**These are not mutually exclusive – multi-component DM is certainly possible**

**See the CF subgroup summaries**

# Dark Matter Experimental landscape (from Snowmass)

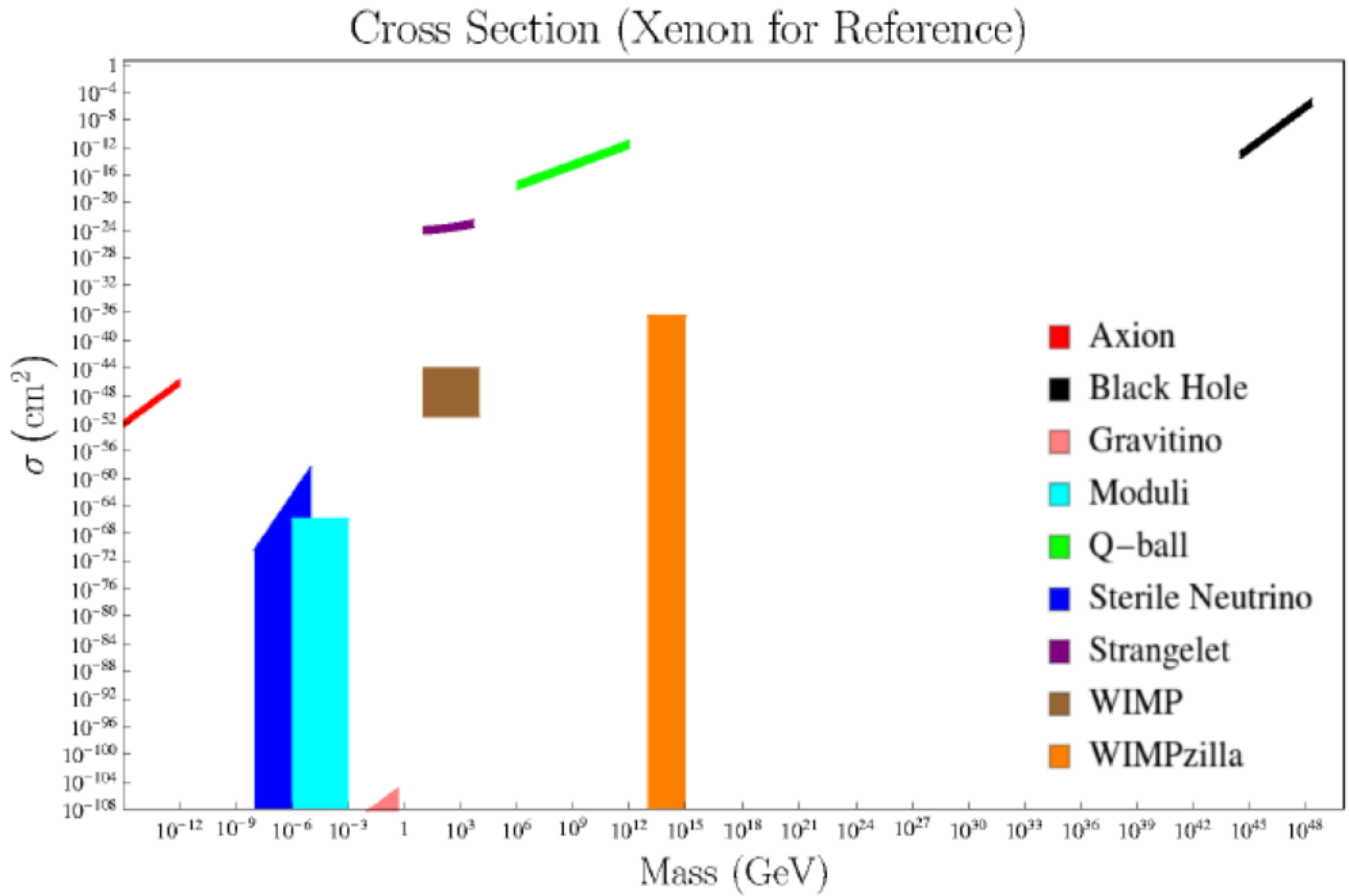



**Figure 1.** *Graphical representation of the (incomplete) landscape of candidates. Above, the landscape of dark matter candidates due to T. Tait. Below, the range of dark matter candidates' masses and interaction cross sections with a nucleus of Xe (for illustrative purposes) compiled by L. Pearce. Dark matter candidates*

# recap of lecture 2

dark matter-a new particle?
not in standard model
motivated extensions: supersymmetry which can give WIMPS
Peccei-Quinn symmetry to solve strong CP problem can give axions
something else? VERY many possibilities

tommorrow: baryogenesis