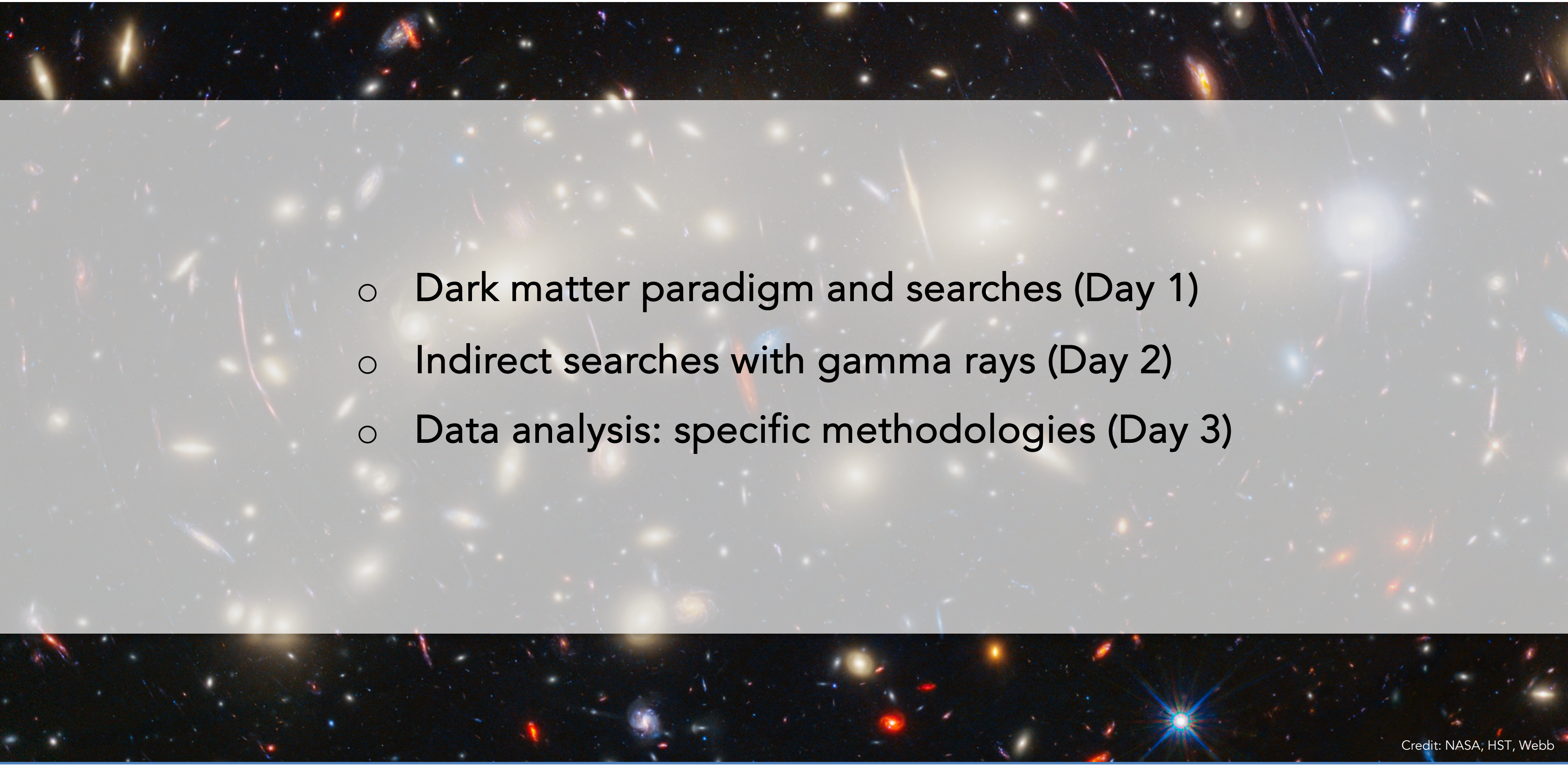
Indirect detection of dark matter

HEPAP-DAS 2023
SAHA Institute of Nuclear Physics

Daniel Nieto
(d.nieto@ucm.es)
Institute for Particle and Cosmos Physics
IPARCOS-UCM

https://apod.nasa.gov/apod/ap200724.html

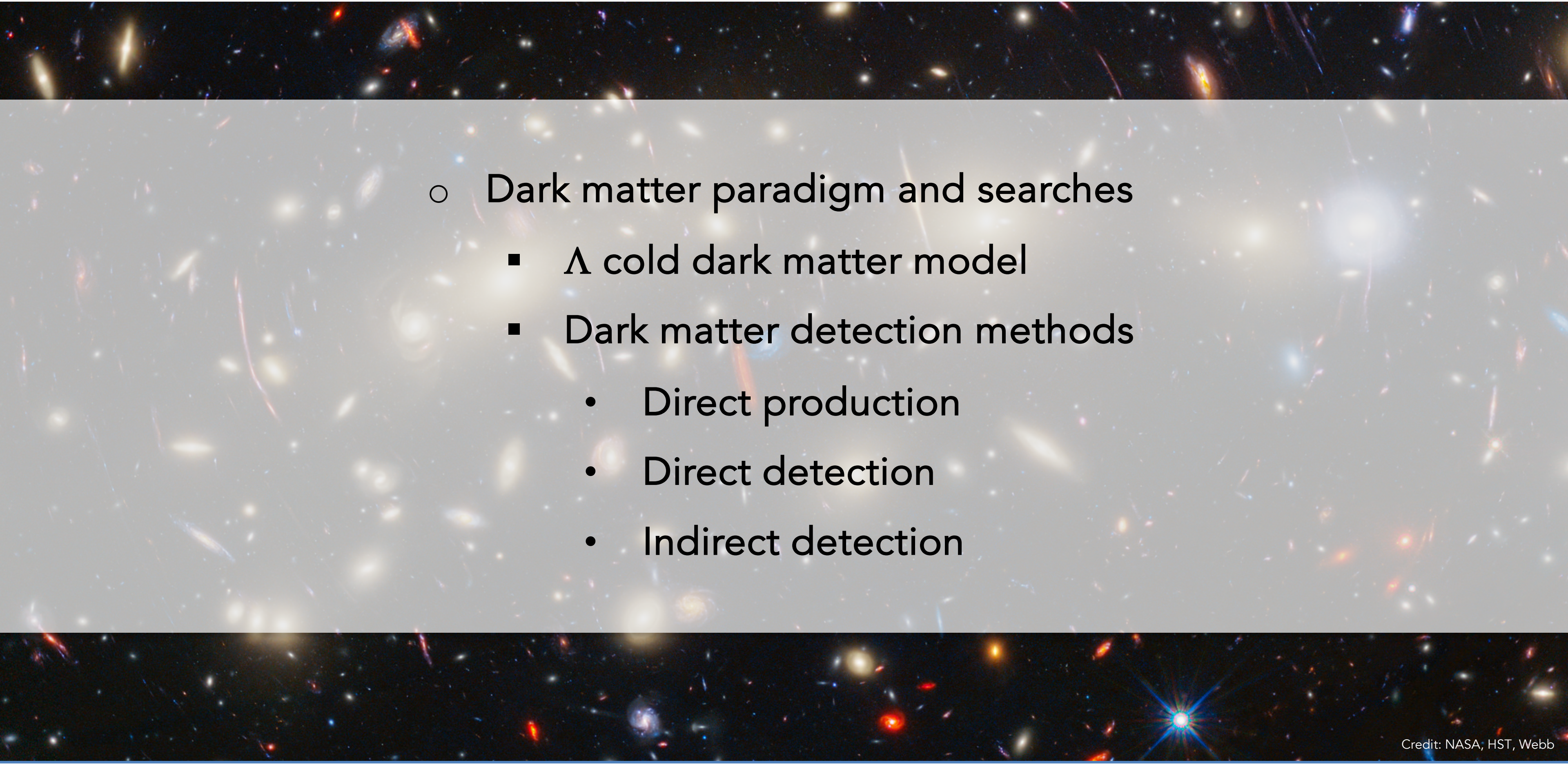
Syllabus



- Dark matter paradigm and searches (Day 1)
- Indirect searches with gamma rays (Day 2)
- Data analysis: specific methodologies (Day 3)

Credit: NASA, HST, Webb

Syllabus: Day 1

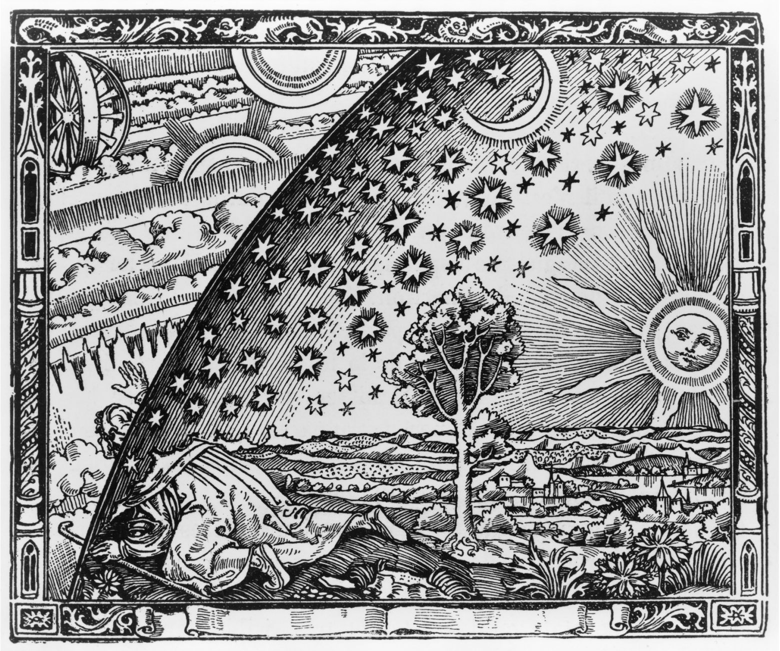


Credit: NASA, HST, Webb

- Dark matter paradigm and searches
  - Λ cold dark matter model
  - Dark matter detection methods
    - Direct production
    - Direct detection
    - Indirect detection

Cosmology

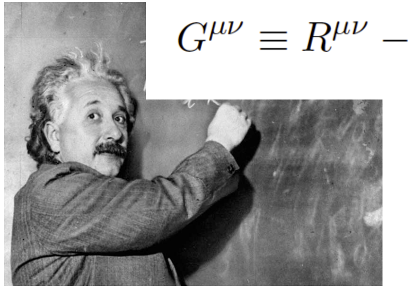
- Cosmology is the scientific study of the Universe as a whole: its origin, evolution and ultimate fate
- It involves theories and hypotheses that can be tested with observations
- Theories are revisited, extended or abandoned based on the observations
- Observations rely on the detection of light and particles (and gravitational waves)



Standard Cosmological Model

The foundations:

General Relativity



$$G^{\mu\nu} \equiv R^{\mu\nu} - \frac{1}{2}g^{\mu\nu}R = -\frac{8\pi G}{c^4}T^{\mu\nu} - \Lambda g^{\mu\nu}$$

- Newton's gravity (c. 1680):
  Field, only valid at low energies
- Einstein's gravity (1916):
  Distortion of space-time
  Valid at "all energies"

"Matter tells space how to curve,
and space tells matter how to move"

J. Wheeler

New description of gravity ➔ New description of the dynamics of the Universe

First question: How is the matter in the Universe distributed?

Standard Cosmological Model

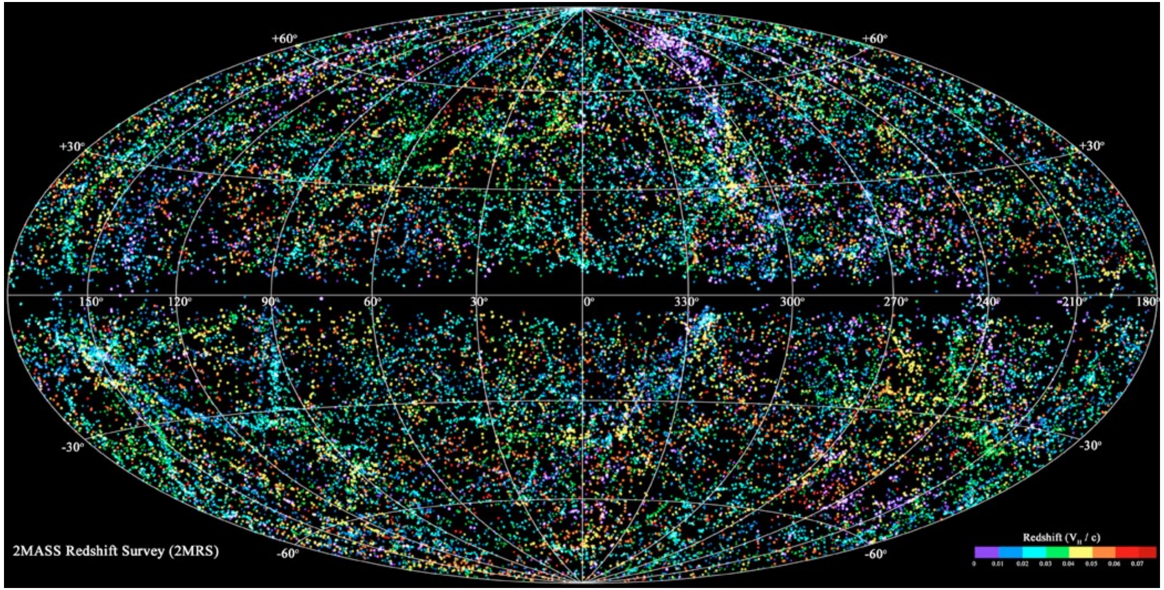
The foundations:

Cosmological Principle

Simplest assumption: the distribution of matter appear roughly the same everywhere and in every direction

The distribution of matter in the Universe is*: homogeneous isotropic

In agreement with observations



*(at large scales!)

Standard Cosmological Model

The foundations:

General Relativity
+
Cosmological
Principle

➔

Friedmann solution:

- ➢ Fix the geometry: it is determined by the Universe energy-density content
- ➢ Fix the dynamics: The Universe is not static!

Hubble parameter

curvature

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G \rho_{tot}}{3} - \frac{kc^2}{R^2}$$

expansion parameter

Temporal development of the Universe

total energy-density

radiation

$$\rho_{tot} = \rho_m + \rho_r + \rho_\Lambda$$

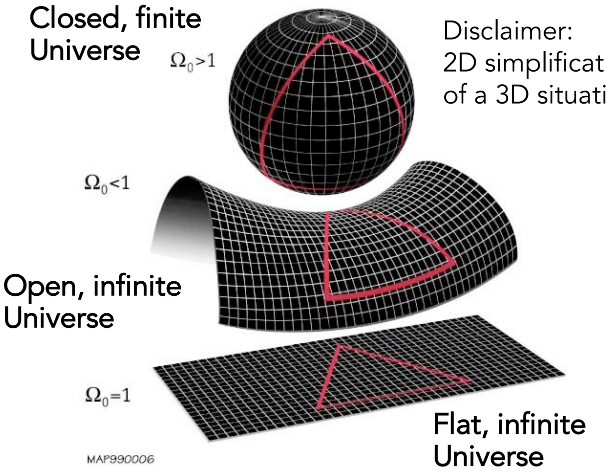
dark matter
baryonic matter

dark energy
(cosm. constant)

$$\rho_c = \frac{3}{8\pi G} H_0^2$$

➔ Critical density:
~ 6 H/m³ (~ 9.6 x 10^{-27} kg/m³)

$$\Omega \equiv \frac{\rho_{tot}}{\rho_c} = \Omega_m + \Omega_r + \Omega_\Lambda = 1 + \frac{kc^2}{(H_0 R)^2}$$



Disclaimer:
2D simplification
of a 3D situation

Standard Cosmological Model

The foundations:

General Relativity
+
Cosmological Principle

➔

Friedmann solution:

- Fix the geometry: it is determined by the Universe energy-density content
- Fix the dynamics: The Universe is not static!

Hubble parameter

curvature

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho_{tot}}{3} - \frac{kc^2}{R^2}$$

expansion parameter

← Temporal development of the Universe

total energy-density

radiation

$$\rho_{tot} = \rho_m + \rho_r + \rho_\Lambda$$

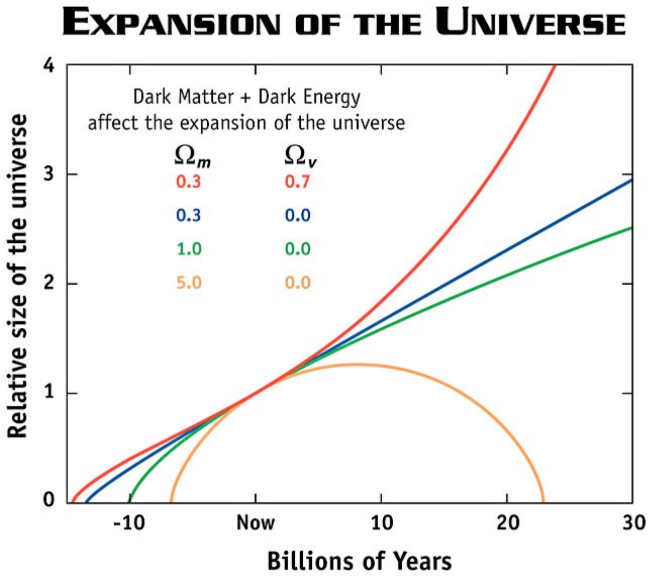
dark matter
baryonic matter

dark energy
(cosm. constant)

$$\rho_c = \frac{3}{8\pi G}H_0^2$$

➔ Critical density:
~ 6 H/m³ (~ 9.6 x 10^{-27} kg/m³)

$$\Omega \equiv \frac{\rho_{tot}}{\rho_c} = \Omega_m + \Omega_r + \Omega_\Lambda = 1 + \frac{kc^2}{(H_0 R)^2}$$



Standard Cosmological Model

The foundations:

General Relativity
+
Cosmological
Principle

➔

Friedmann solution:

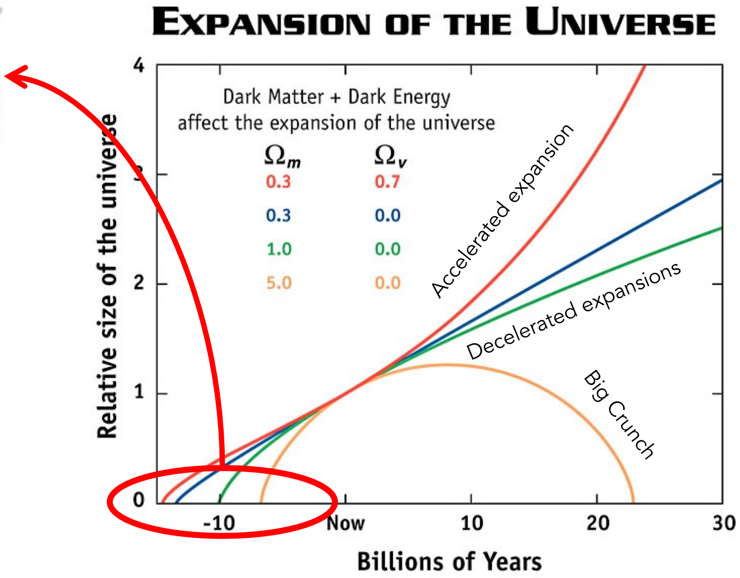
- Fix the geometry: it is determined by the Universe energy-density content
- Fix the dynamics: The Universe is not static!

$$\Omega \equiv \frac{\rho_{tot}}{\rho_c} = \Omega_m + \Omega_r + \Omega_\Lambda = 1 + \frac{kc^2}{(H_0 R)^2}$$

Today, Ω_r is negligible, thus the fate of the Universe will be driven by Ω_m and Ω_Λ

One of the main challenges of modern cosmology is to accurately determine the cosmological parameters that define our Universe

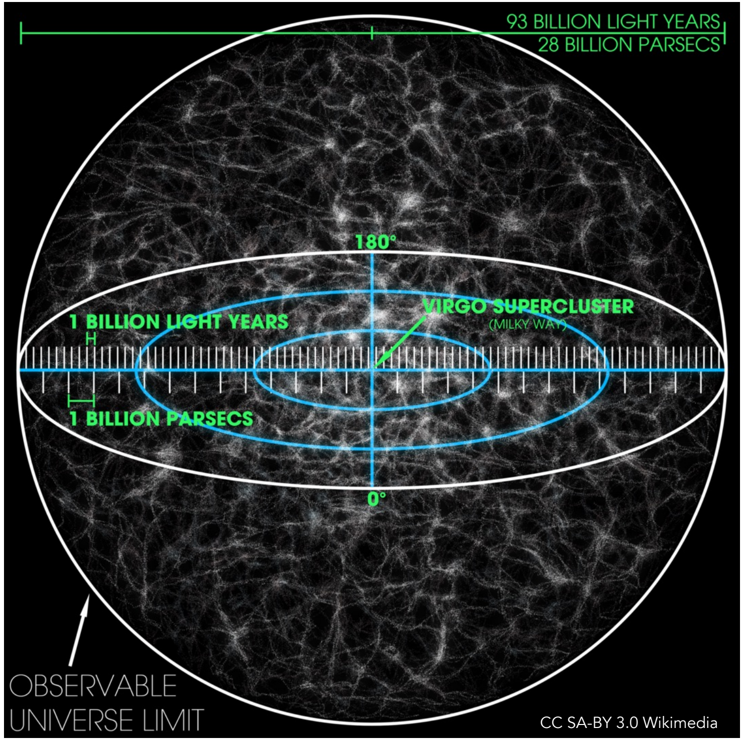
the BIG BANG THEORY



Standard Cosmological Model

Some remarks about the Big Bang theory:

- The Universe has a finite age (~13.7 billion years) and we can only see a finite distance into space: ~46 billion light years, our visible Universe
- The theory says nothing about what happens beyond the visible Universe horizon
- The Big Bang did not occur at a single point is space: it is the simultaneous appearance of space everywhere in the Universe
- If the Universe is infinite it was born infinite
- If the Universe is closed and finite, it was born with zero volume
- There is no such a thing as a "center of expansion"



CC SA-BY 3.0 Wikimedia

Testing the Big Bang theory

The Big Bang theory predicts several phenomena that have been confirmed by a number of crucial observations:

- The expansion of the Universe
- The abundance of light elements
- The cosmic microwave background

Standard Cosmological Model

Testing the Big Bang theory: the expansion of the Universe

Edwin Hubble

Mt. Wilson 100″ telescope

1929: the Universe is… expanding!

Hubble's law: $v = H \times d$

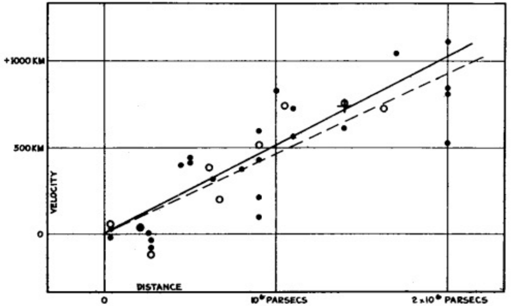
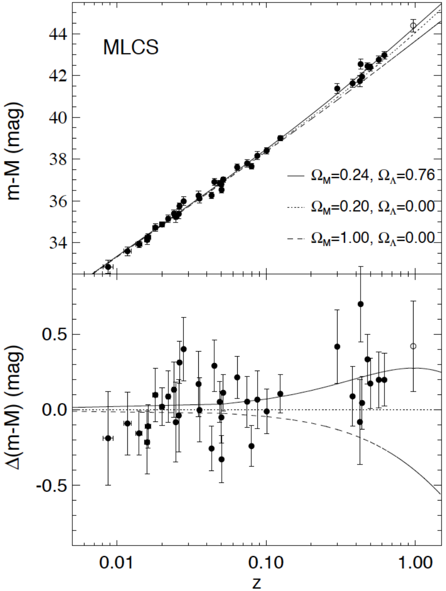


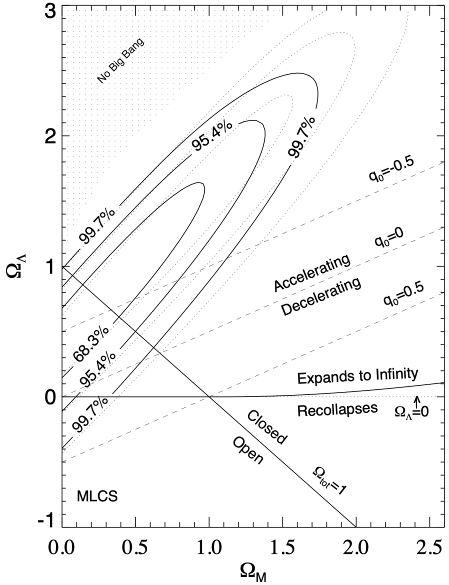
FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.

1998: the Universe is… in accelerated expansion!





Adam G. Riess *et al* 1998 *AJ* **116** 1009

Testing the Big Bang theory: the abundances of light elements

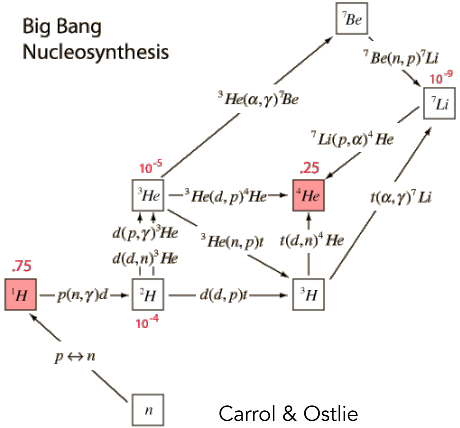
➢ The early Universe was a very hot place:

- 1s after the Big Bang T = 10 billion K
- Sea of baryonic matter and radiation:
  neutrons, protons, electrons, photons, neutrinos…

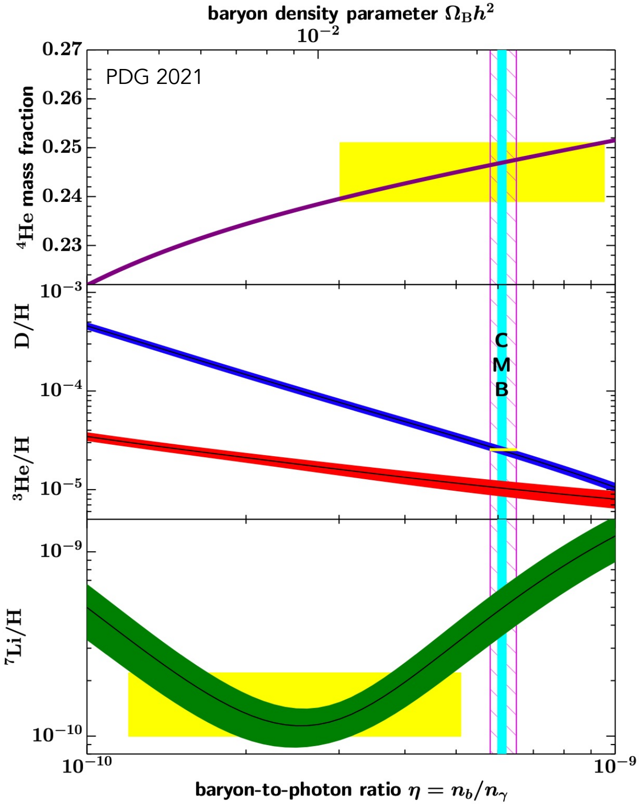
➢ As it cooled down, light elements formed:

- H, Deuterium, He & Li

Big Bang Nucleosynthesis



Carrol & Ostlie

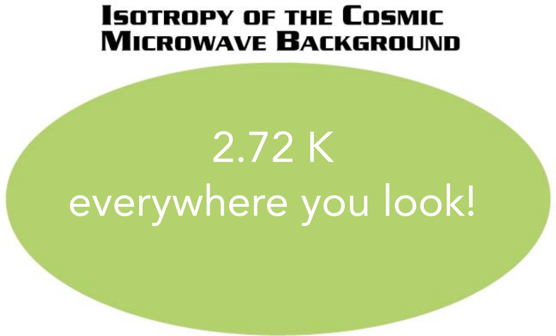


Testing the Big Bang theory: the cosmic microwave background

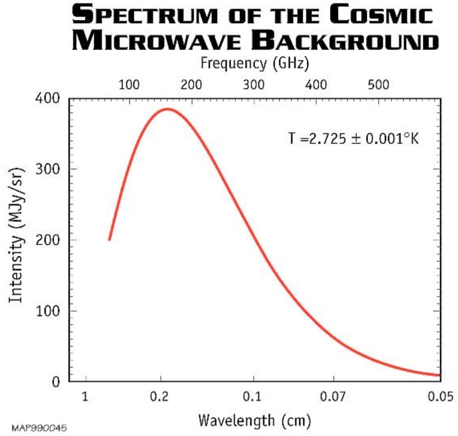
- ➢ At the early Universe baryonic matter and radiation were entangled

- ➢ As the Universe cooled down…
- 300.000 yrs / 3000 K
- Baryonic matter decoupled from radiation
- Universe expansion up to today cooled that radiation down to 2.72 K

- ➢ That radiation has been observed!
- Cosmic microwave background
- Same temperature everywhere
- However, there are extremely tiny fluctuations in the cosmic microwave background of the order of 10^{-3} K



Map of the Universe in Galactic coordinates



Standard Cosmological Model

The Big Bang theory is far from complete…

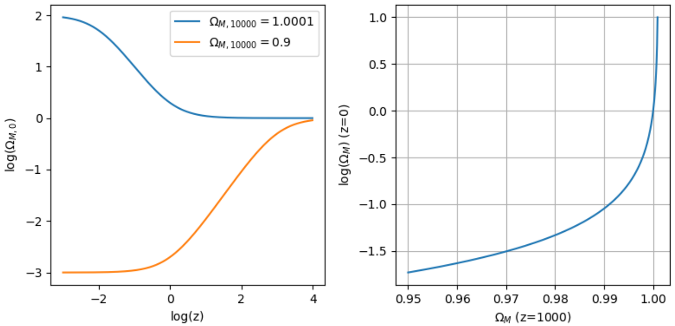
What the Big Bang theory can not explain

- Formation of structures in the Universe
- Fluctuations in the cosmic microwave background

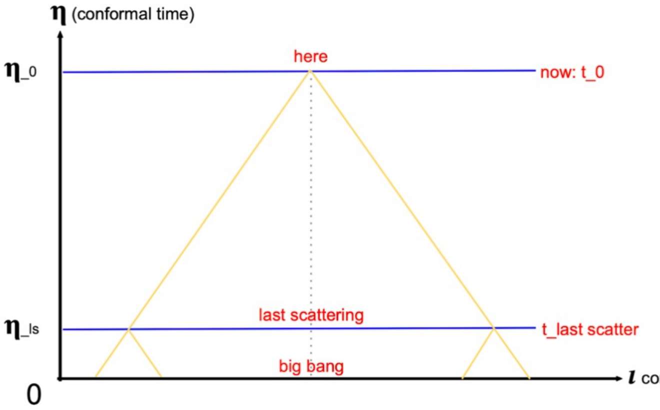
The Big Bang theory problems

- Horizon problem: regions not in causal contact are very similar
- Flatness problem: today's flatness require fine-tuning of conditions in the past
- Big Bang theory predicts stable "magnetic monopoles"

So now… What?



burro.case.edu



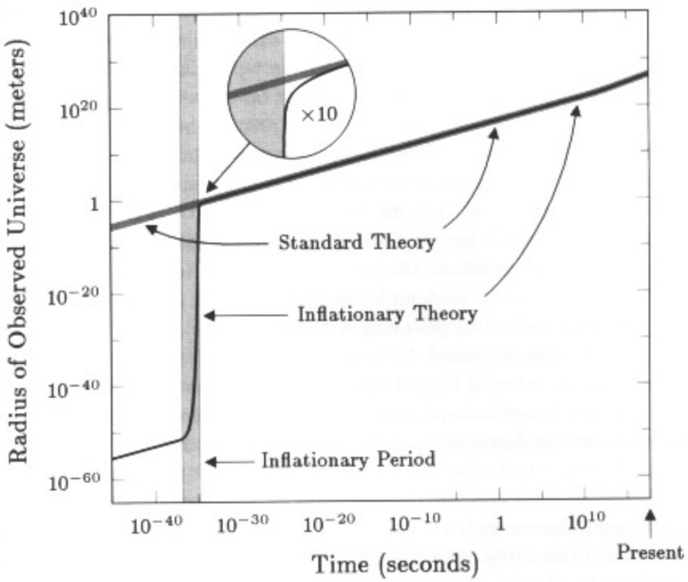
Wikimedia Commons

Standard Cosmological Model

Inflation Theory

- First epoch after the Big Bang
- There were neither matter, nor radiation, nor dark energy
- Inflaton field: a kind of vacuum energy
- Extremely brief epoch of the Universe: 10^{-37}s to 10^{-32}s
- Extremely rapid expansion of the Universe (exponential)

Universe size increased by a factor 10^{26}
almost instantaneously!



It solves

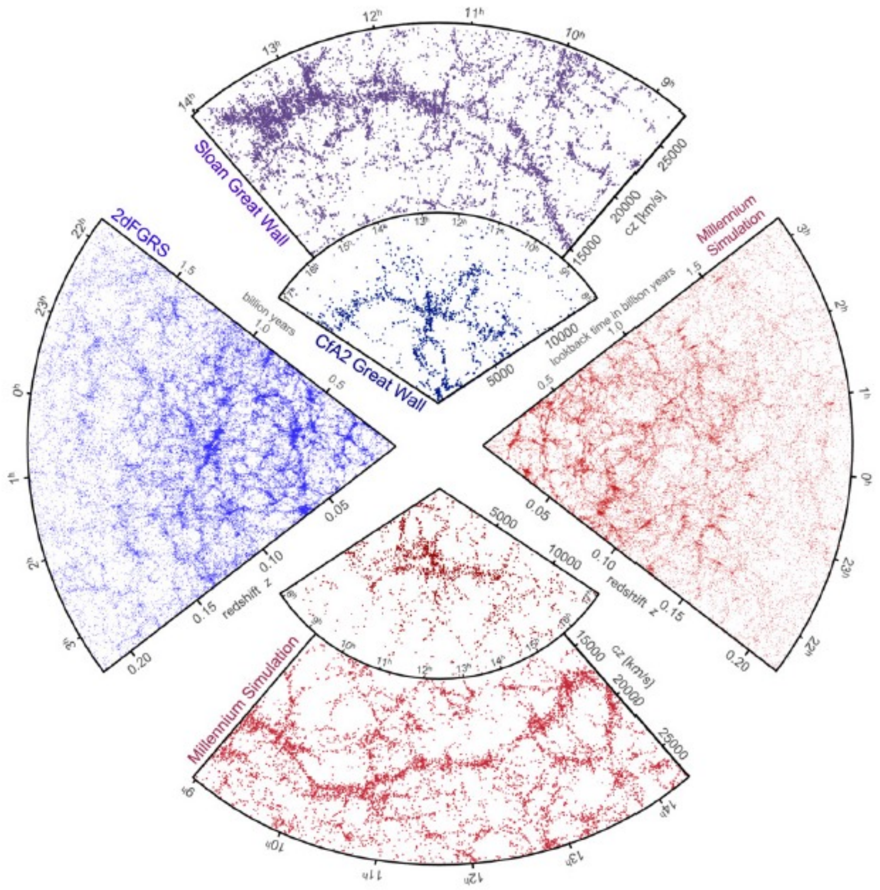
Flatness problem   Horizon problem   Magnetic monopoles

And it explains

- Formation of structures
- Fluctuations in the cosmic microwave background

as the consequence of augmented quantum fluctuations of the inflaton field

Standard Cosmological Model



Structure formation

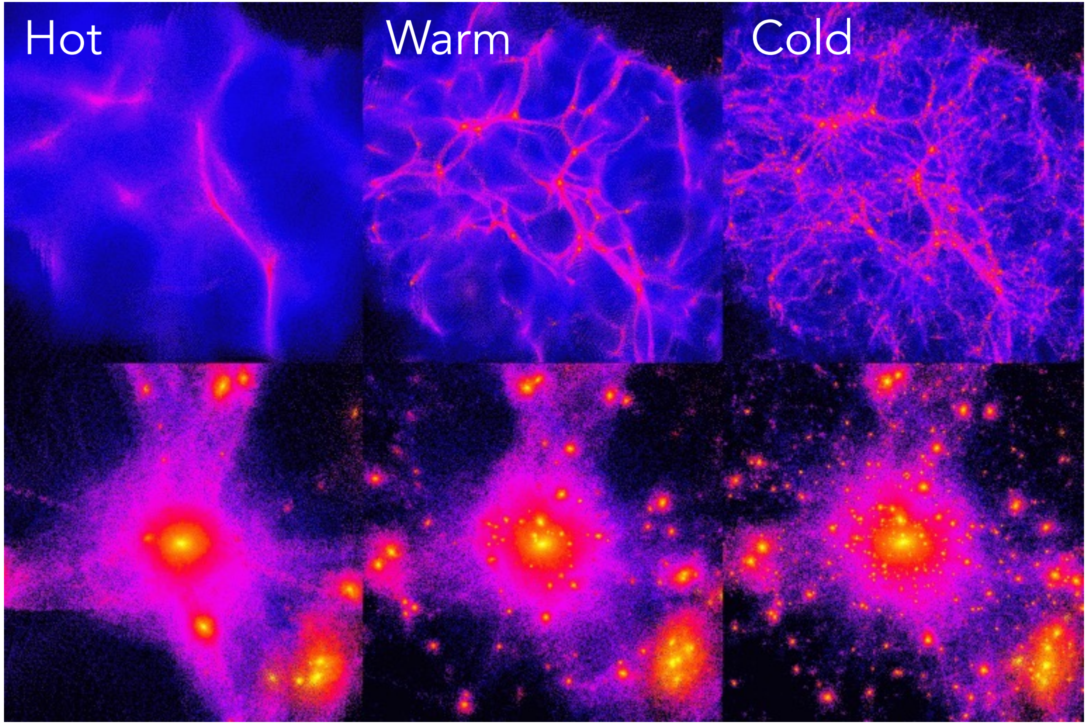
- Quantum fluctuations of the inflaton field imprints fluctuations in the primordial matter+radiation fluid
- Dark matter decouples from the primordial fluid and those fluctuations are amplified as the Universe expands
- Structure formation simulations agree with observations at the large scale (and also at smaller scales)

Standard Cosmological Model

Structure formation

Bottom-up hierarchical structure formation and abundance of substructure favored by observations:

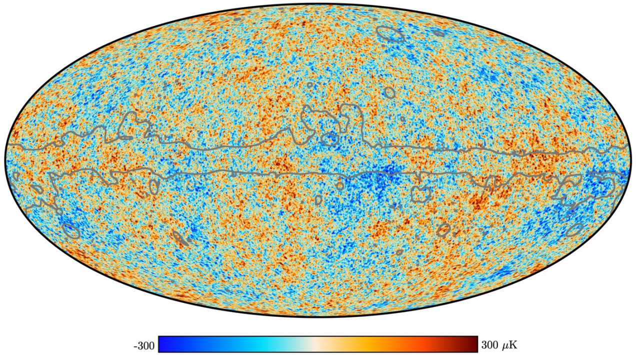
Cold dark matter

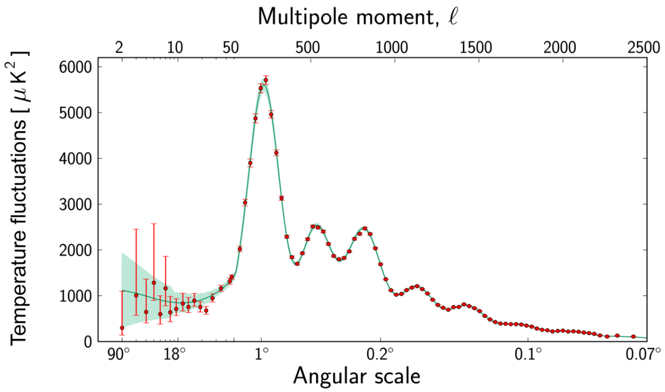


Standard Cosmological Model

Standard Cosmological Model: Big Bang + Inflation (a.k.a. Λ – Cold Dark Matter Model)

Cosmological parameters are obtained as the best fit to the combination data from different experiments: Planck, BAO, SnIa





Parameter	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02242 ± 0.00014
$\Omega_c h^2$	0.11933 ± 0.00091
$100\theta_{MC}$	1.04101 ± 0.00029
τ	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.047 ± 0.014
n_s	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}]	67.66 ± 0.42
Ω_Λ	0.6889 ± 0.0056
Ω_m	0.3111 ± 0.0056
$\Omega_m h^2$	0.14240 ± 0.00087
$\Omega_m h^3$	0.09635 ± 0.00030
σ_8	0.8102 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$	0.825 ± 0.011
$\sigma_8 \Omega_m^{0.25}$	0.6051 ± 0.0058
z_{re}	7.82 ± 0.71
$10^9 A_s$	2.105 ± 0.030
$10^9 A_s e^{-2\tau}$	1.881 ± 0.010
Age [Gyr]	13.787 ± 0.020
z_*	1089.80 ± 0.21
r_* [Mpc]	144.57 ± 0.22
$100\theta_*$	1.04119 ± 0.00029
z_{drag}	1060.01 ± 0.29
r_{drag} [Mpc]	147.21 ± 0.23
k_D [Mpc^{-1}]	0.14078 ± 0.00028
z_{eq}	3387 ± 21
k_{eq} [Mpc^{-1}]	0.010339 ± 0.000063
$100\theta_{s,eq}$	0.4509 ± 0.0020
f_{2000}^{143}	29.4 ± 2.7
$f_{2000}^{143\times217}$	32.1 ± 1.9
f_{2000}^{217}	106.9 ± 1.8

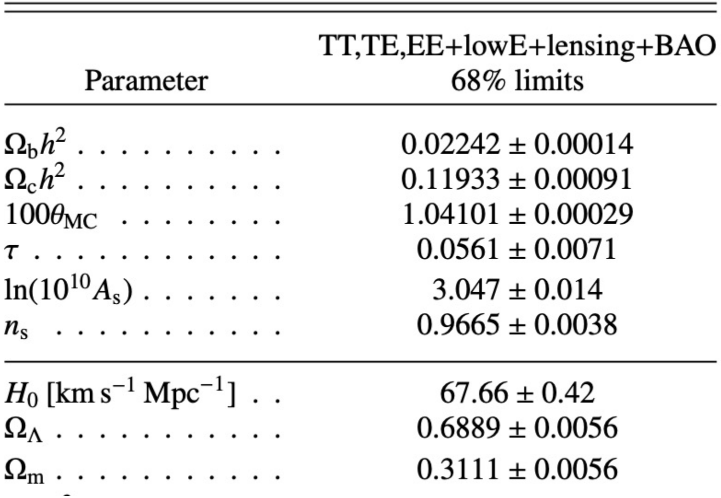
Planck Collaboration 2018

Standard Cosmological Model

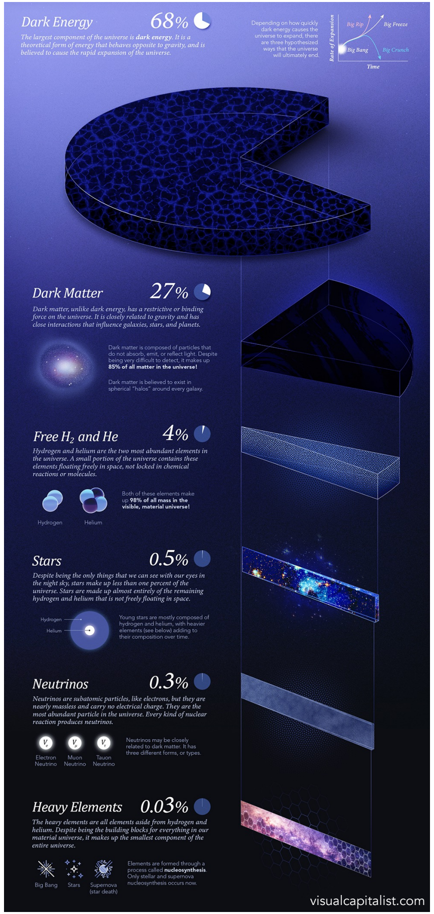
We have obtained the cosmological parameters with an astonishing accuracy, never ever dreamt by early XXth century cosmologists.

However…

95% of today's Universe content remains completely unknown!



Parameter	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02242 ± 0.00014
$\Omega_c h^2$	0.11933 ± 0.00091
$100\theta_{MC}$	1.04101 ± 0.00029
τ	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.047 ± 0.014
n_s	0.9665 ± 0.0038
H_0 [km s^{-1} Mpc^{-1}] . .	67.66 ± 0.42
Ω_Λ	0.6889 ± 0.0056
Ω_m	0.3111 ± 0.0056



Dark Energy 68%

*The largest component of the universe is **dark energy**. It is a theoretical form of energy that behaves opposite to gravity, and is believed to cause the rapid expansion of the universe.*

Depending on how quickly dark energy causes the universe to expand, there are three hypothesized ways that the universe will ultimately end.

Dark Matter 27%

Dark matter, unlike dark energy, has a restrictive or binding force on the universe. It is closely related to gravity and has close interactions that influence galaxies, stars, and planets.

Dark matter is composed of particles that do not absorb, emit, or reflect light. Despite being very difficult to detect, it makes up **85% of all matter in the universe!**

Dark matter is believed to exist in spherical "halos" around every galaxy.

Free H_2 and He 4%

Hydrogen and helium are the two most abundant elements in the universe. A small portion of the universe contains these elements floating freely in space, not locked in chemical reactions or molecules.

Both of these elements make up **98% of all mass in the visible, material universe!**

Stars 0.5%

Despite being the only things that we can see with our eyes in the night sky, stars make up less than one percent of the universe. Stars are made up almost entirely of the remaining hydrogen and helium that is not freely floating in space.

Young stars are mostly composed of hydrogen and helium, with heavier elements (see below) adding to their composition over time.

Neutrinos 0.3%

Neutrinos are subatomic particles, like electrons, but they are nearly massless and carry no electrical charge. They are the most abundant particle in the universe. Every kind of nuclear reaction produces neutrinos.

Neutrinos may be closely related to dark matter. It has three different forms, or types.

Heavy Elements 0.03%

The heavy elements are all elements aside from hydrogen and helium. Despite being the building blocks for everything in our material universe, it makes up the smallest component of the entire universe.

Elements are formed through a process called **nucleosynthesis**. Only stellar and supernova nucleosynthesis occurs now.

visualcapitalist.com

Dark Matter

- Evidences for the existence of the dark matter
- What could be the dark matter be made of?
- How can we detect the dark matter?

Dark Matter: evidences

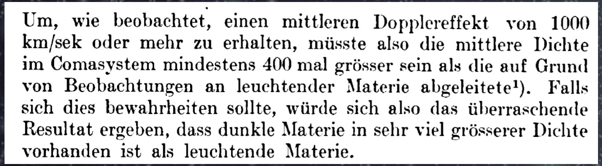
The evidences for Dark Matter are numerous and stem from robust astrophysical observations:

- ➢ Key element in the Standard Cosmological Model
  - Cosmic Microwave Background
  - Big Bang Nucleosynthesis
  - Structure Formation
- ➢ Dynamics of galaxies and galaxy clusters
- ➢ Gravitational lensing

Dark Matter: evidences

Dynamics of galaxies and galaxy clusters

In 1933, Zwicky found a “little” deficit of ~90% in mass in the Coma cluster, lately confirmed in other clusters and galaxies…



Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte vorhanden ist als leuchtende Materie.

Helvetica Physica Acta, Vol. 6, p. 110-127, 1933

In order to obtain, as observed, a medium-sized Doppler effect of 1000 km/s or more, the average density in the Coma system would have to be at least 400 times greater than that derived on the basis of observations of luminous matter If this should be verified, it would lead to the surprising result that dark matter exists in much greater density than luminous matter.

Dark Matter: evidences

If Newtonian dynamics apply:

Centripetal force

Gravitational force

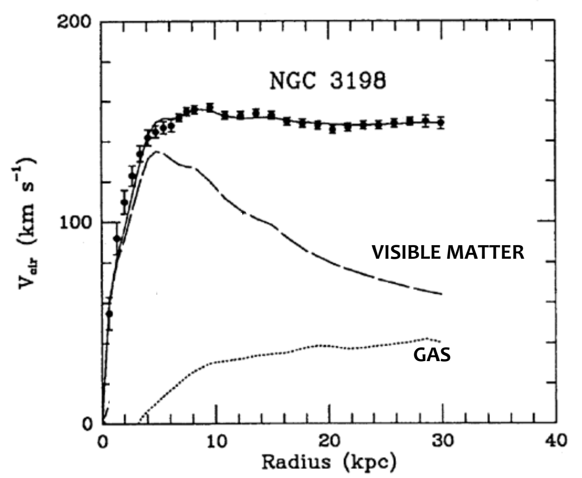
$$\frac{mv^2}{r} = \frac{mM(r)G}{r^2} \Rightarrow v = \sqrt{\frac{M(r)G}{r}}$$

Inner system:

$$M(r) \propto r^3 \Rightarrow v \propto r$$

Outer system:

$$M(r) \approx const \Rightarrow v \propto \frac{1}{\sqrt{r}}$$



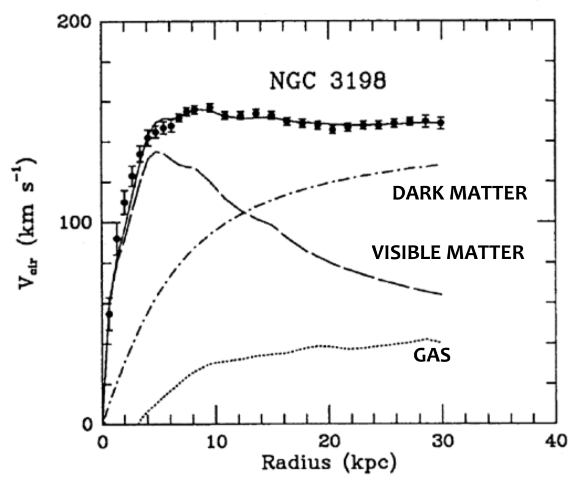
Dark Matter: evidences

If Newtonian dynamics apply:

Centripetal force

Gravitational force

$$\frac{mv^2}{r} = \frac{mM(r)G}{r^2} \Rightarrow v = \sqrt{\frac{M(r)G}{r}}$$

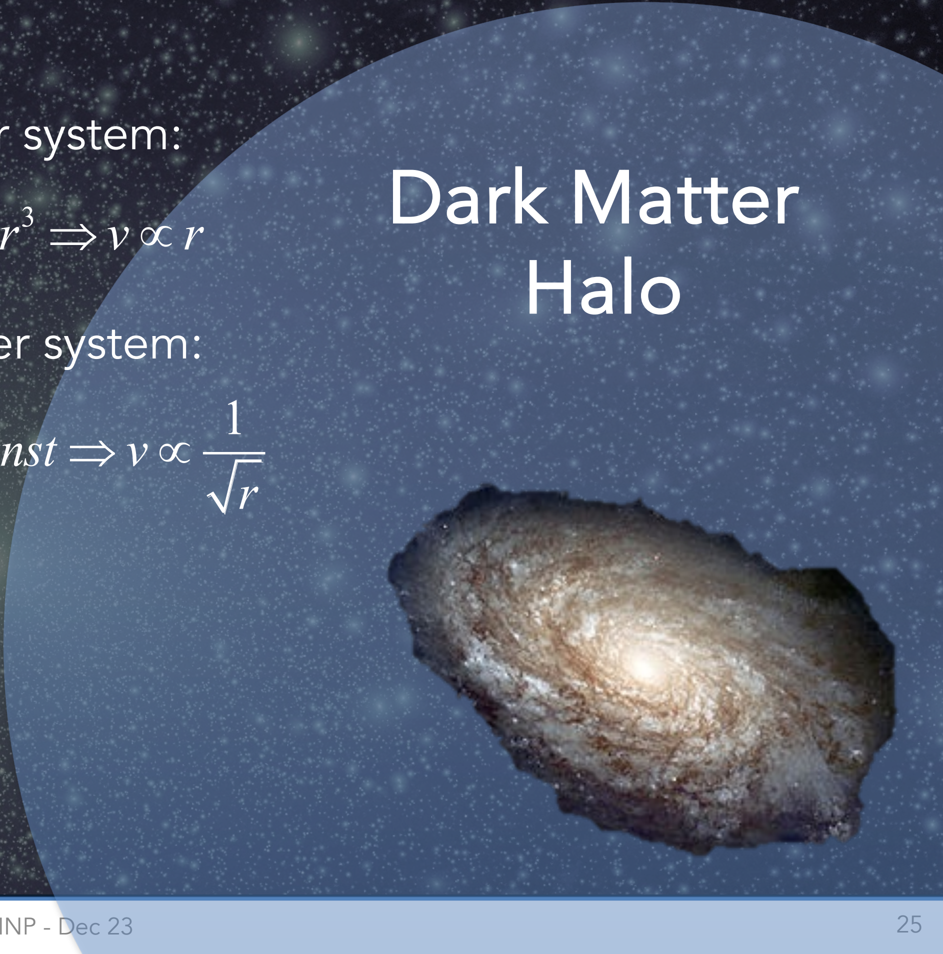


Inner system:

$$M(r) \propto r^3 \Rightarrow v \propto r$$

Outer system:

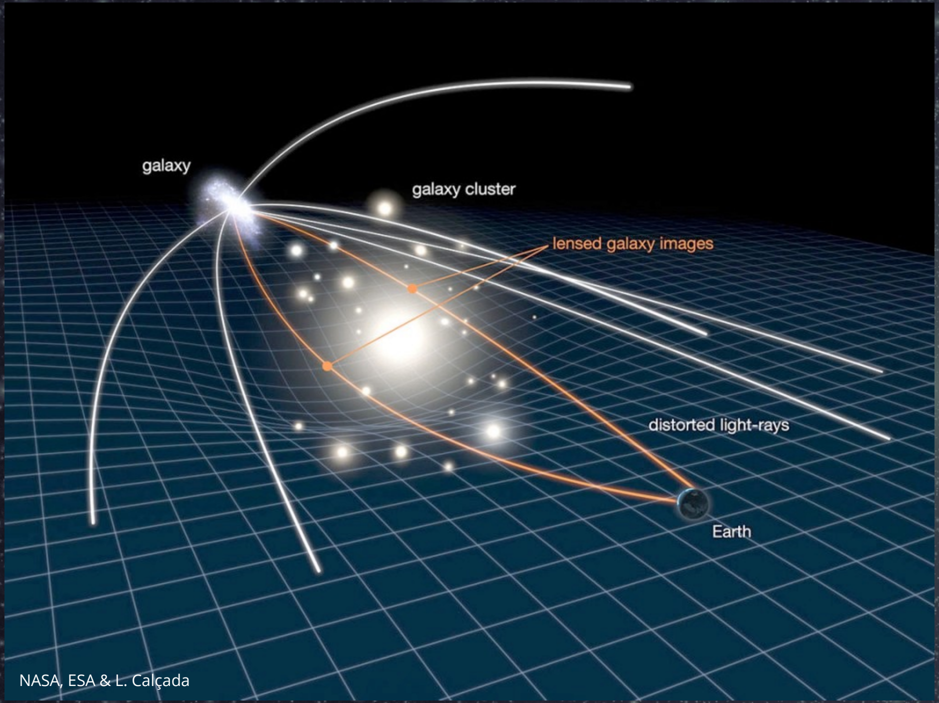
$$M(r) \approx const \Rightarrow v \propto \frac{1}{\sqrt{r}}$$



Dark Matter: evidences

Gravitational Lensing

As a fundamental consequence of general relativity, light bends in a gravitational field proportionally to the mass that produces it.



NASA, ESA & L. Calçada

The lensing object can change the shape and multiply images of foreground objects

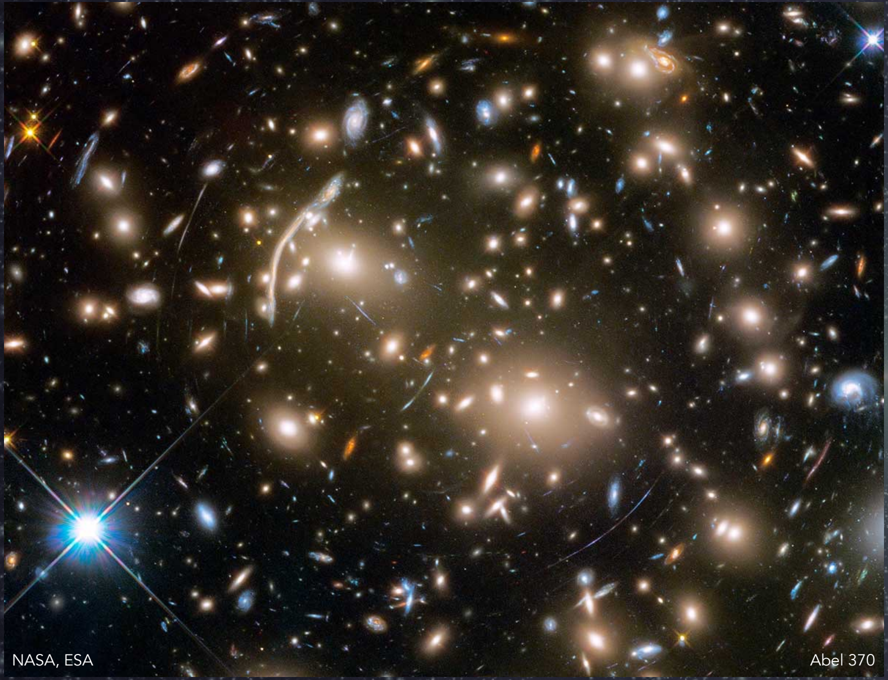
From the lensed image one can infer the properties of the lense, and thus its mass

The inferred masses are always dominated by dark matter

Dark Matter: evidences

Gravitational Lensing

As a fundamental consequence of general relativity, light bends in a gravitational field proportionally to the mass that produces it.



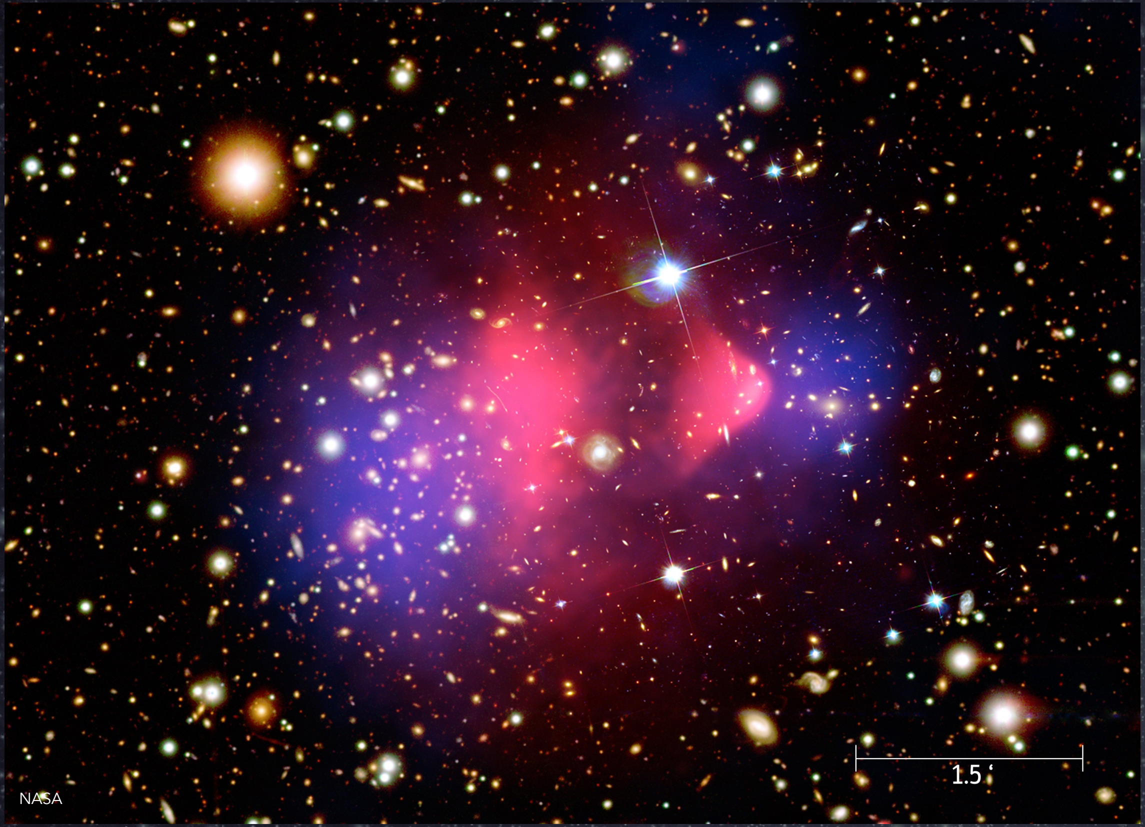
The lensing object can change the shape and multiply images of foreground objects

From the lensed image one can infer the properties of the lense, and thus its mass

The inferred masses are always dominated by dark matter

Dark Matter: evidences

Bullet Cluster



Visible spectrum from Magellan and Hubble Space Telescope images.

Pink overlay shows the x-ray emission recorded by Chandra Telescope (intracluster gas).

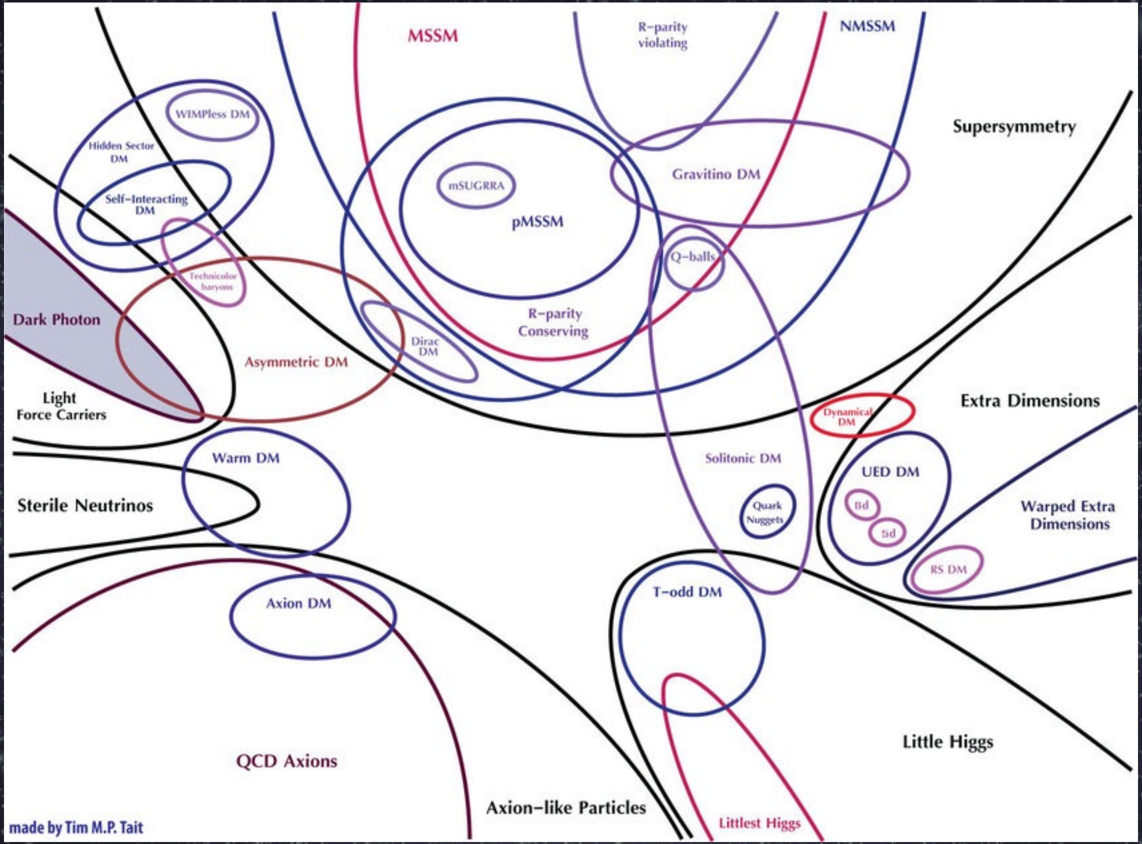
Blue overlay represents the mass distribution of the clusters calculated from gravitational lens effects (dark matter and galaxies).

Dark Matter: candidates

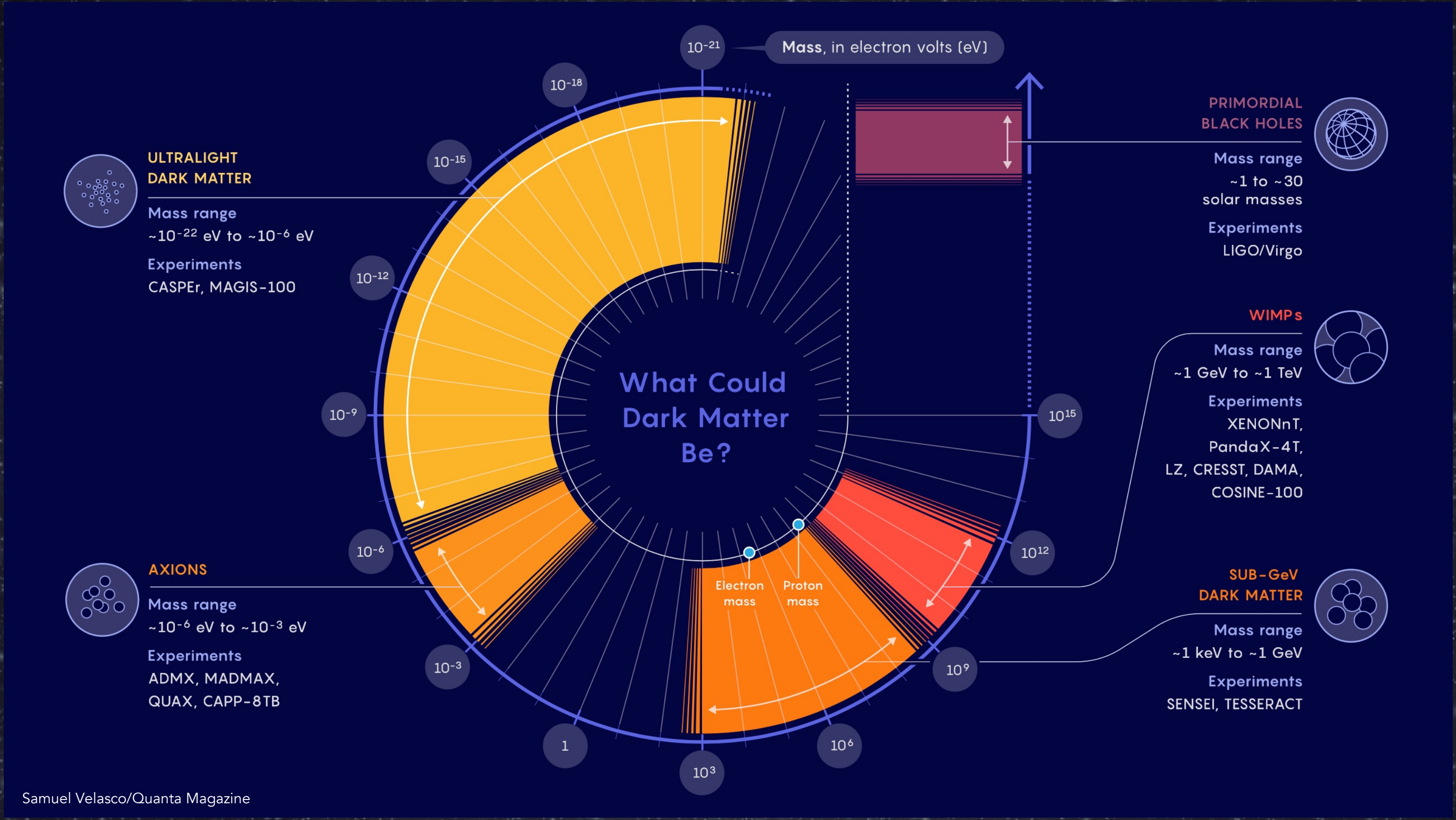
Dark matter particle requisites:

- To match the relic abundance (density of particles at decoupling)
- To be stable at Universe lifetime scale
- Massive particle, gravitationally interacting
- Weak interactions, no EM interactions (no light emission/absorption)
- To leave BBN unchanged
- To leave stellar evolution unchanged
- To be able to reproduce structure formation
- To be experimentally verifiable!

Dark Matter: candidates



Dark Matter: candidates



ULTRALIGHT DARK MATTER

Mass range
~10^{-22} eV to ~10^{-6} eV

Experiments
CASPEr, MAGIS-100

AXIONS

Mass range
~10^{-6} eV to ~10^{-3} eV

Experiments
ADMX, MADMAX, QUAX, CAPP-8TB

PRIMORDIAL BLACK HOLES

Mass range
~1 to ~30 solar masses

Experiments
LIGO/Virgo

WIMPs

Mass range
~1 GeV to ~1 TeV

Experiments
XENONnT, PandaX-4T, LZ, CRESST, DAMA, COSINE-100

SUB-GeV DARK MATTER

Mass range
~1 keV to ~1 GeV

Experiments
SENSEI, TESSERACT

Samuel Velasco/Quanta Magazine

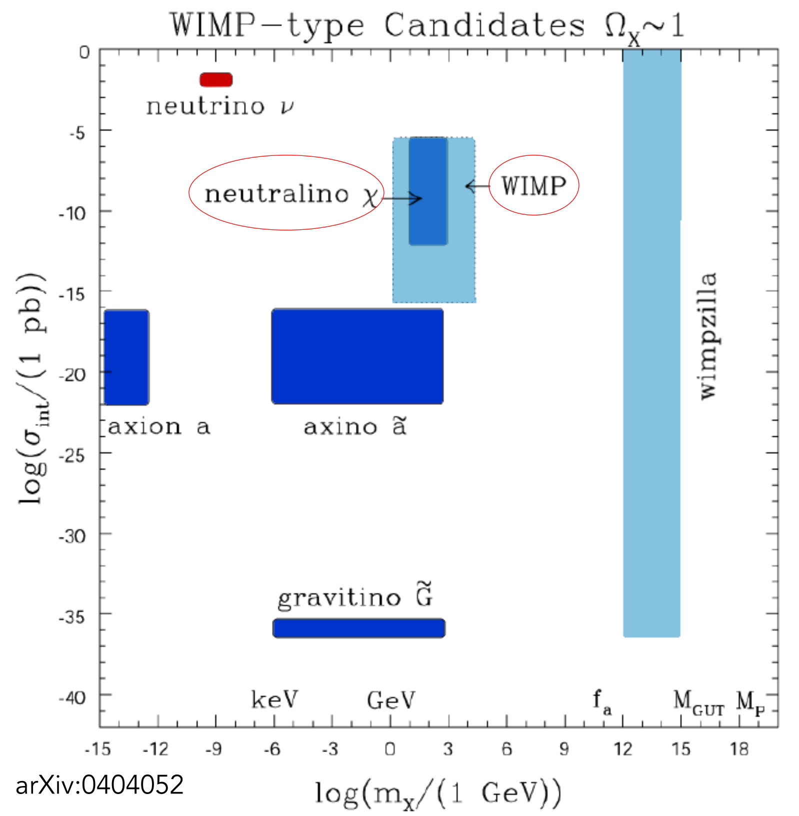
Dark Matter: candidates

Weakly Interacting Massive Particles: a good candidate

- Why **WIMPs**?
  - Neutral in color & electric charge
  - Gravitational & weak interaction
  - Cosmologically stable & massive
- Which **WIMP**? → e.g. ***Neutralino***
  - Lightest stable **SUSY** particle
  - Natural candidate
  - Compatible relic abundance
  - *WIMP Miracle:*

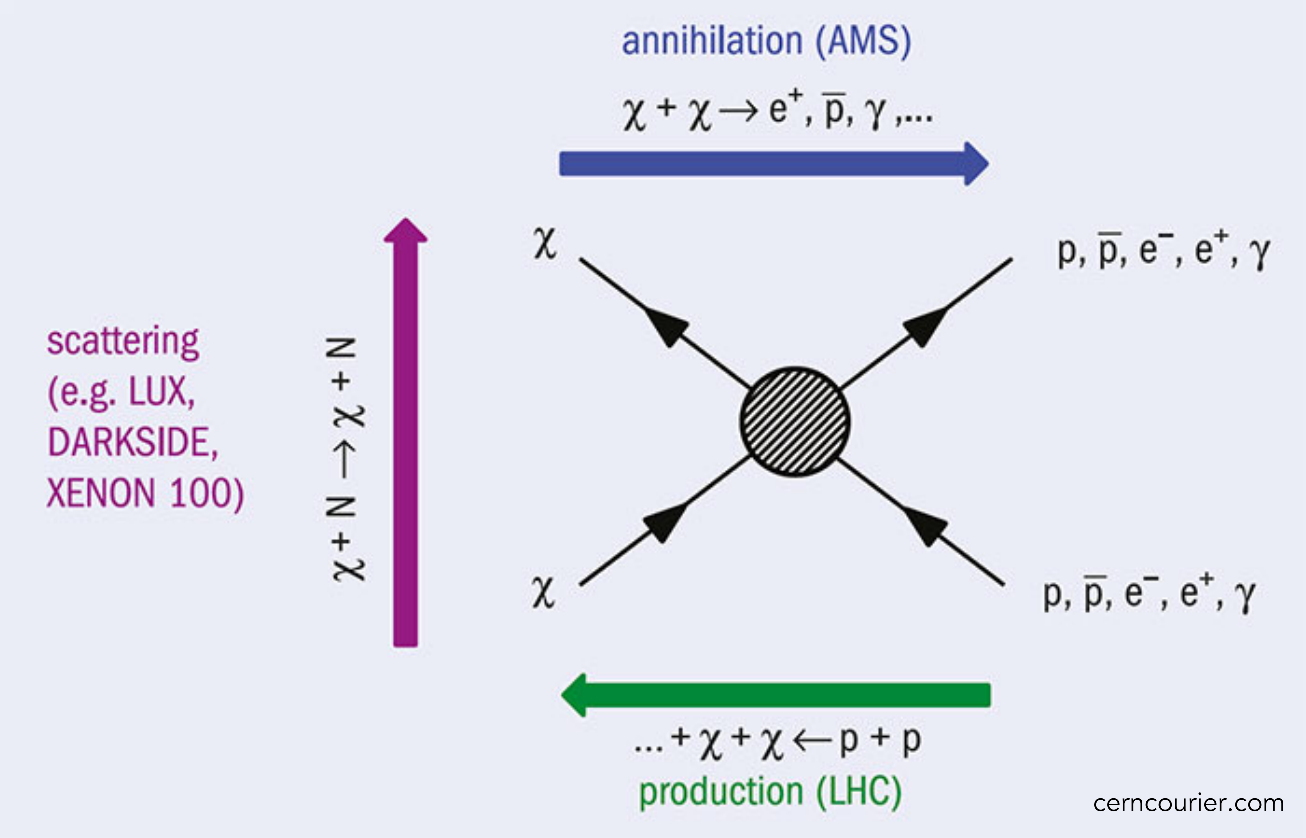
$$\Omega_{DM} = \frac{s_0}{\rho_c/h^2}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{m_{DM}}{T_0 M_{Pl}}\frac{1}{\langle\sigma_{ann}v\rangle}$$

  - Cold Dark Matter candidate
  - m_χ > 50 GeV up to TeV scale



arXiv:0404052

Dark Matter: detection



cerncourier.com

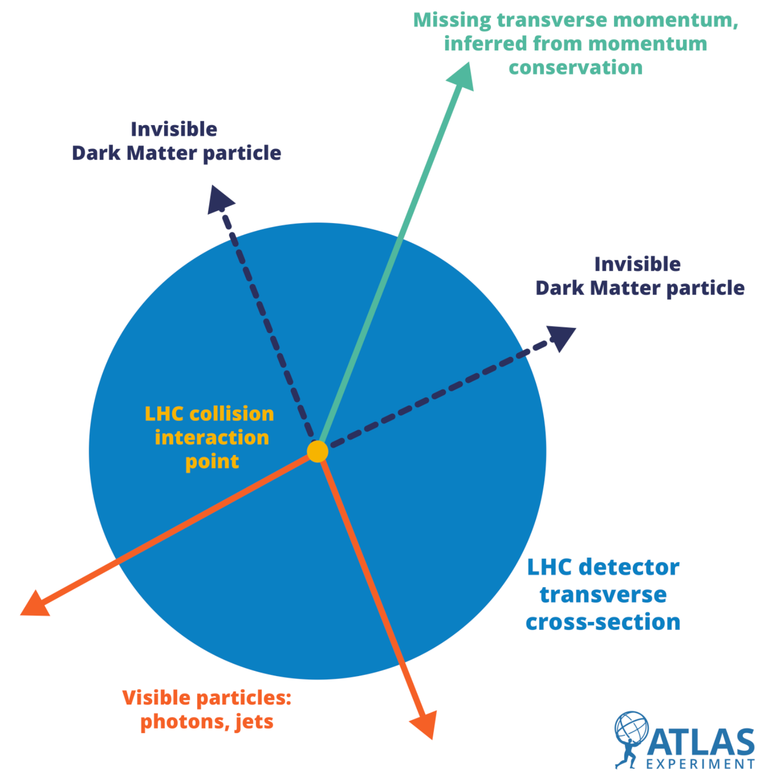
Dark Matter: direct production

Direct production

- Assuming that the dark matter is a particle, it would be subject to detection at particle accelerators with sufficient center-of-mass energy and luminosity
- The dark matter would be detected through its associated missing momentum

$$E_0 \neq \sum E_{products}$$

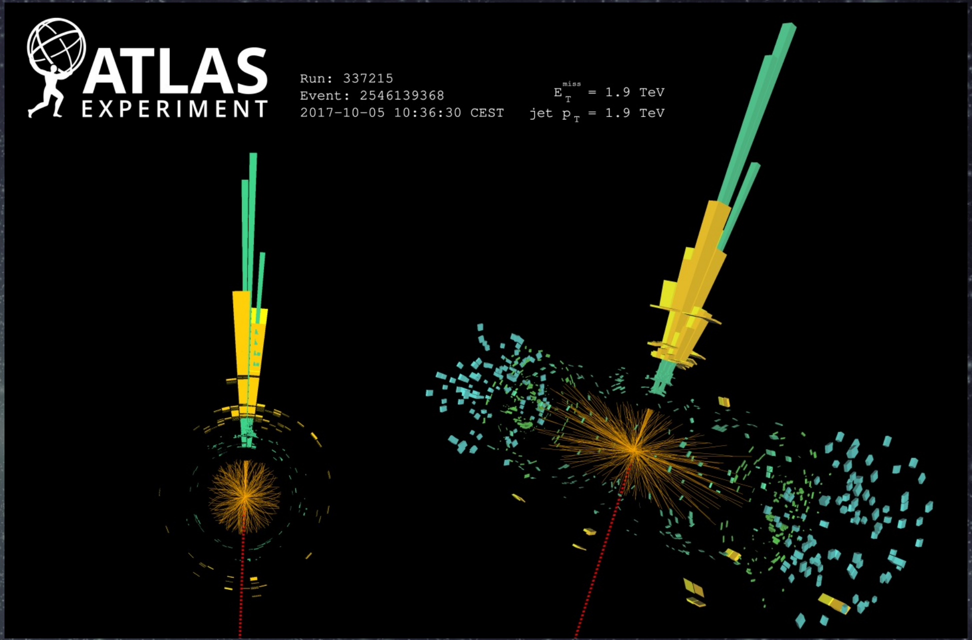
- This technique suffers from a very large background



Dark Matter: direct production

Direct production

- Assuming that the dark matter is a particle, it would be subject to detection at particle accelerators with sufficient center-of-mass energy and luminosity



- The dark matter would be detected through its associated missing momentum

$$E_0 \neq \sum E_{products}$$

- This technique suffers from a very large background

Dark Matter: direct production

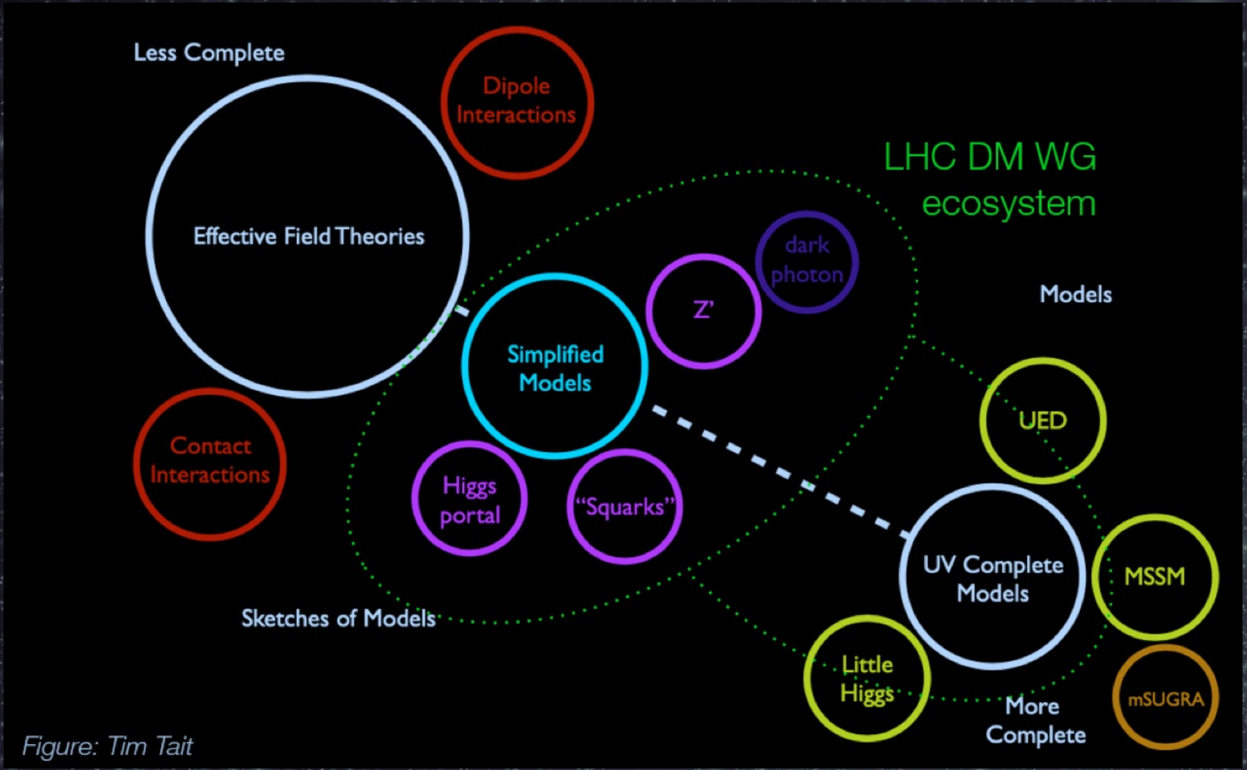
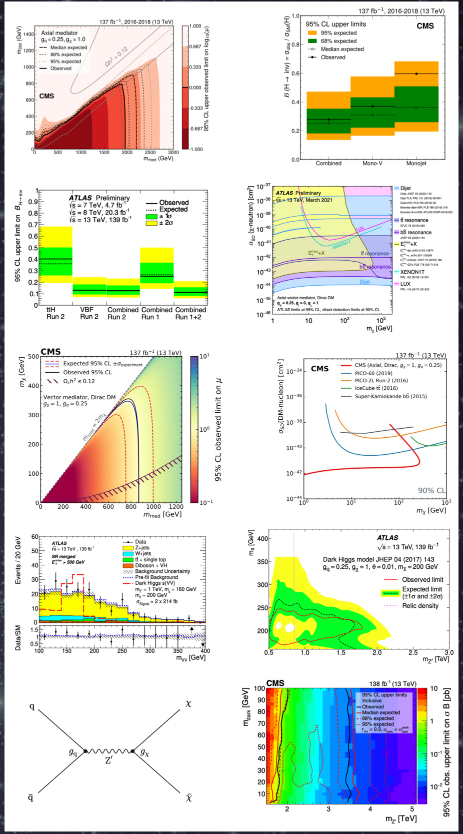


Figure: Tim Tait



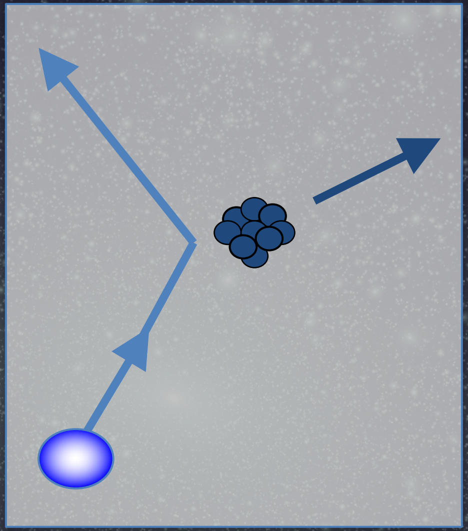
ATL-PHYS-PROC-2022-003

Dark Matter: direct detection

Direct detection: Principle

DM elastically scatter off nuclei

- Direct interaction of the DM halo with the detector. Typical nucleus recoil energy: **E_R~1-100 keV**.
- The rate of the DM interactions depends on the local DM density and relative DM velocity.

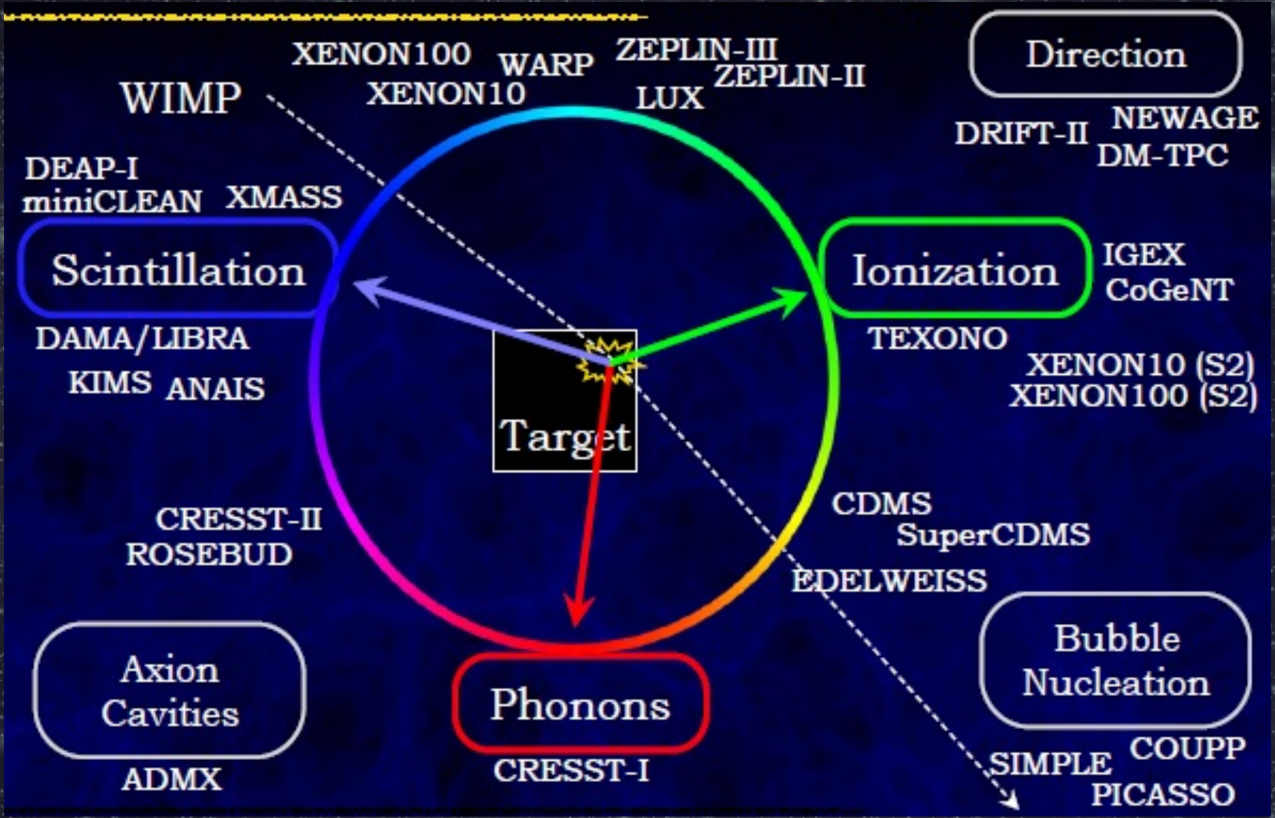


Nuclear recoils

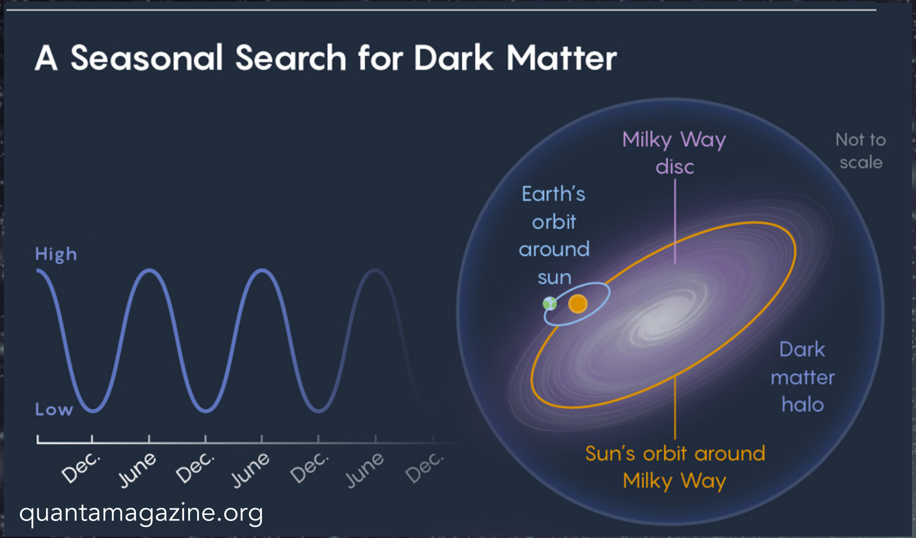
⬇

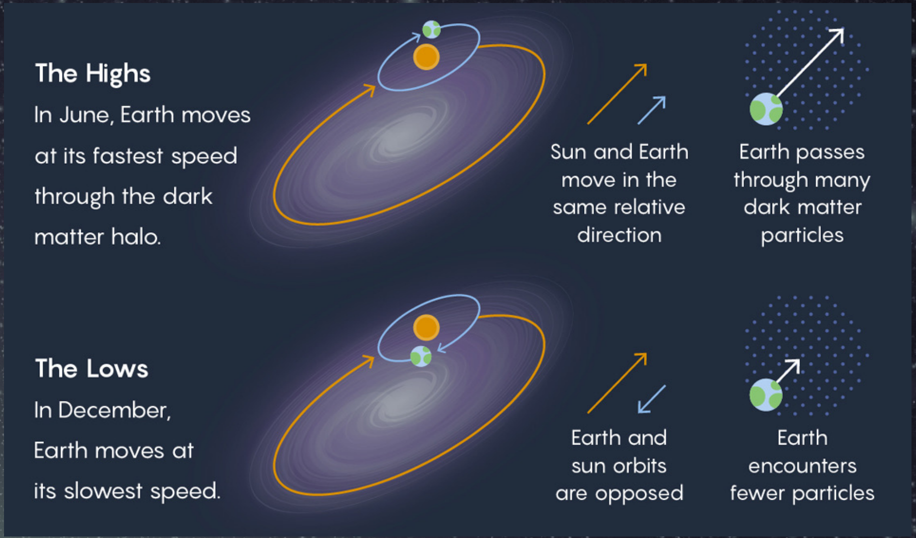
Measure recoil energy spectrum

Direct detection: Particle detection channels



Dark Matter: direct detection





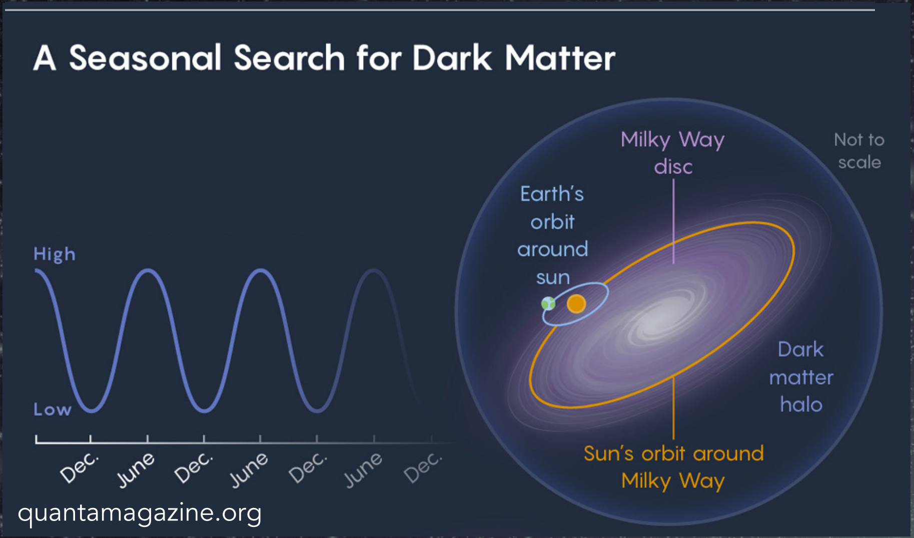
The Highs

In June, Earth moves at its fastest speed through the dark matter halo.

The Lows

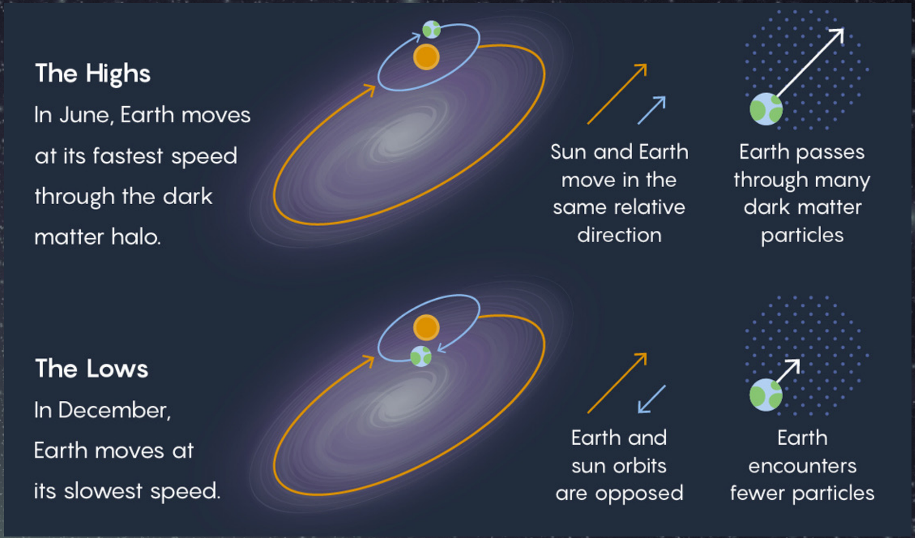
In December, Earth moves at its slowest speed.

Dark Matter: direct detection



A Seasonal Search for Dark Matter

quantamagazine.org



The Highs

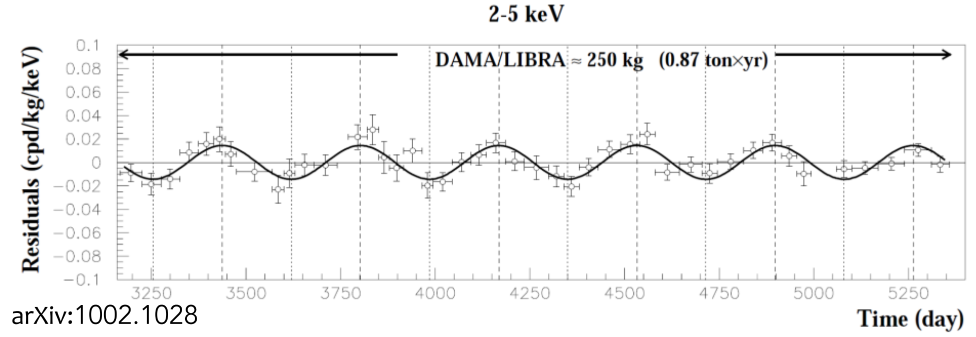
In June, Earth moves at its fastest speed through the dark matter halo.

The Lows

In December, Earth moves at its slowest speed.

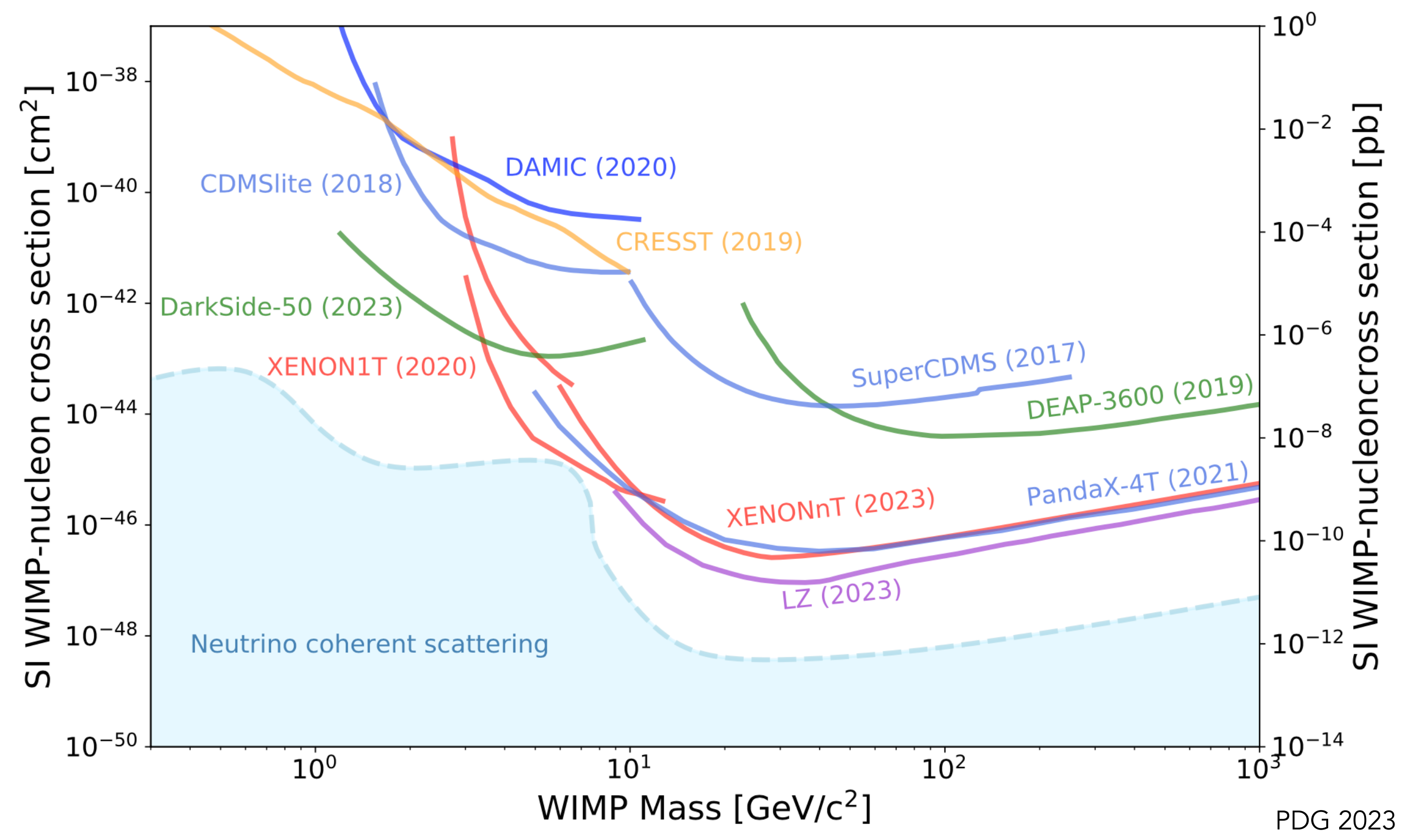
DAMA-LIBRA

- Some hints
- Never confirmed and incompatible with rest of experiments



arXiv:1002.1028

Dark Matter: direct detection

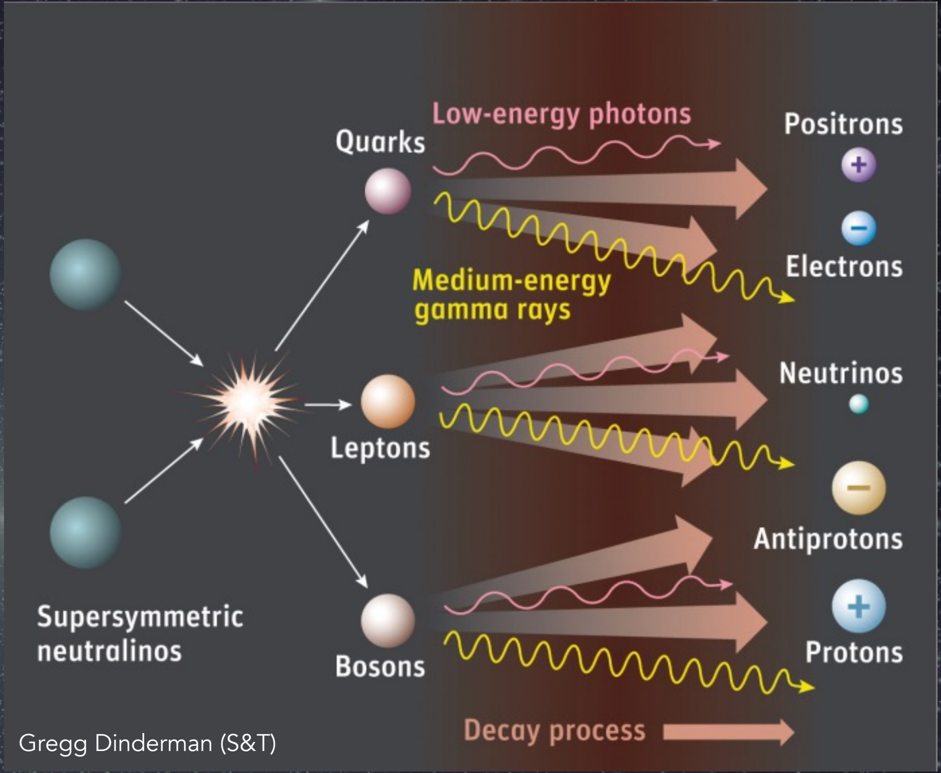


PDG 2023

Dark Matter: indirect detection

Indirect detection:

- Basis: Detection of DM annihilation or decay products (SM particles)
- In most cases, entangled with cosmic rays and subdominant
- Photons are privileged messengers
    - No deflection by B-fields
    - Trace back to source
    - Astrophysical targets



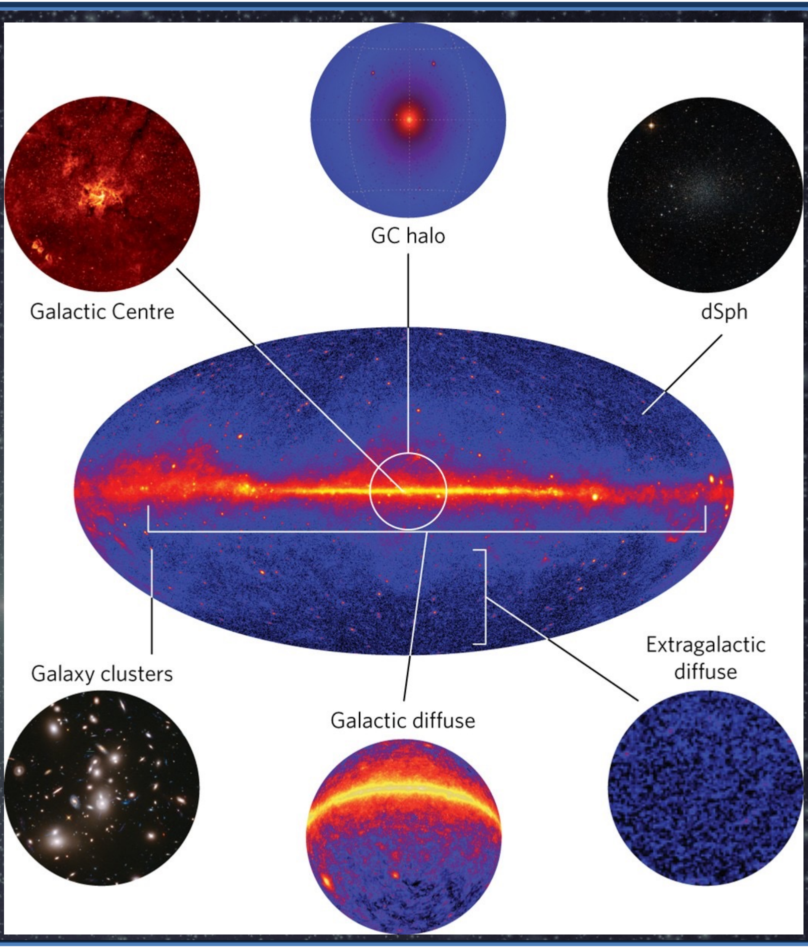
Gregg Dinderman (S&T)

PDG 2023

Dark Matter: indirect detection

Indirect detection:

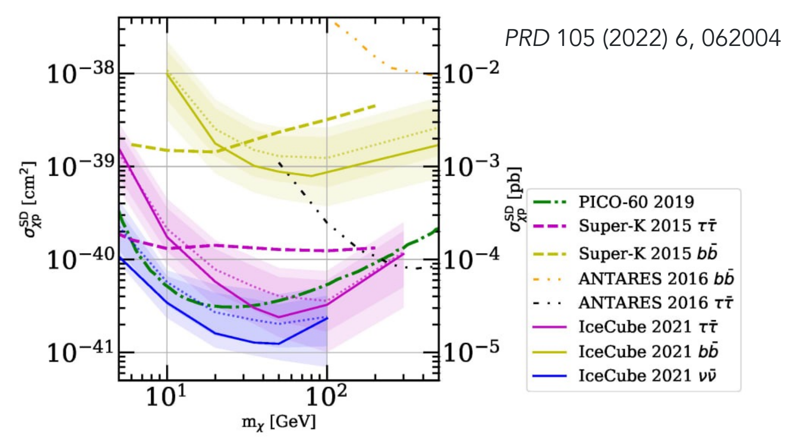
- Basis: Detection of DM annihilation or decay products (SM particles)
- In most cases, entangled with cosmic rays and subdominant
- Photons are privileged messengers
  - No deflection by B-fields
  - Trace back to source
  - Astrophysical targets



Dark Matter: indirect detection

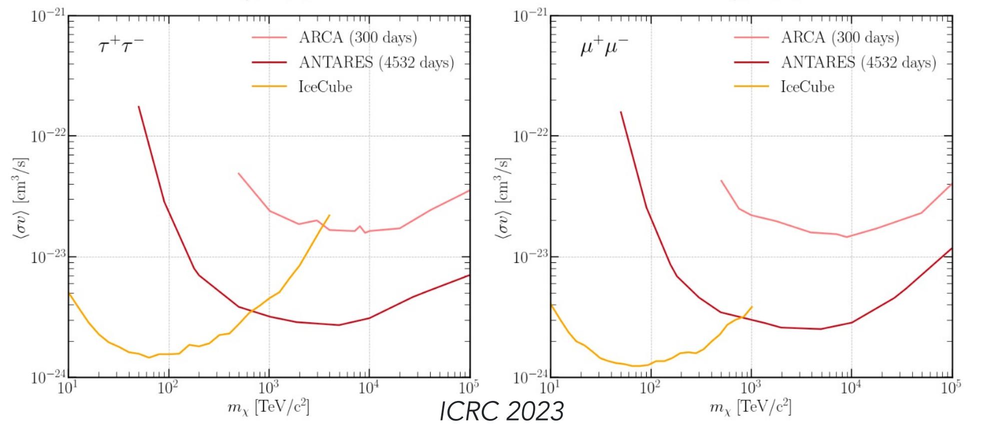
Indirect detection: neutrinos

Neutrinos from the Sun



PRD 105 (2022) 6, 062004

Neutrinos from the Gal. Center



ICRC 2023

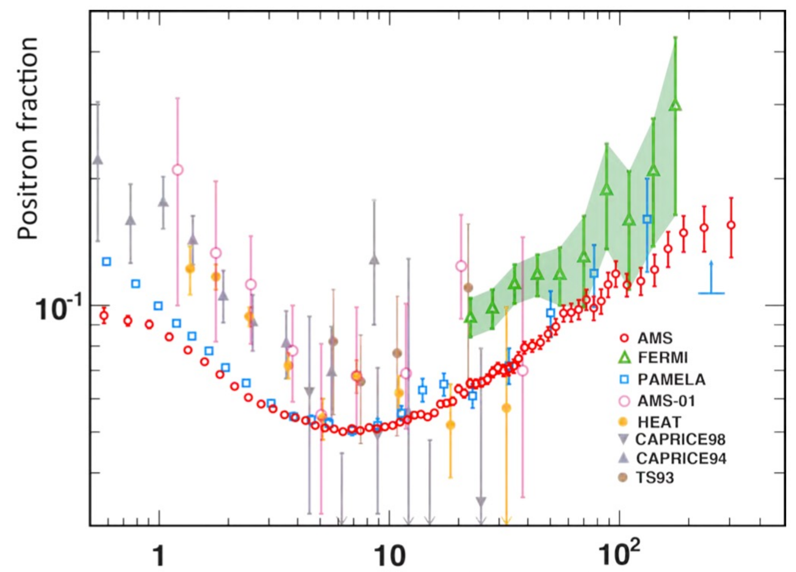
PDG 2023

Dark Matter: indirect detection

Indirect detection: cosmic rays

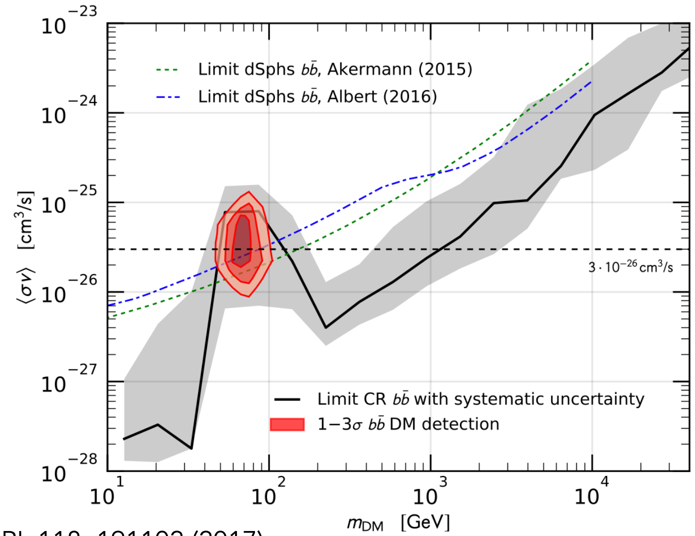
AMS-02

Positrons



Phys. Rep. 894, 1-116 (2021)

Antiprotons



PRL 118, 191102 (2017)

PDG 2023

Dark Matter: indirect detection

Indirect detection: gamma rays

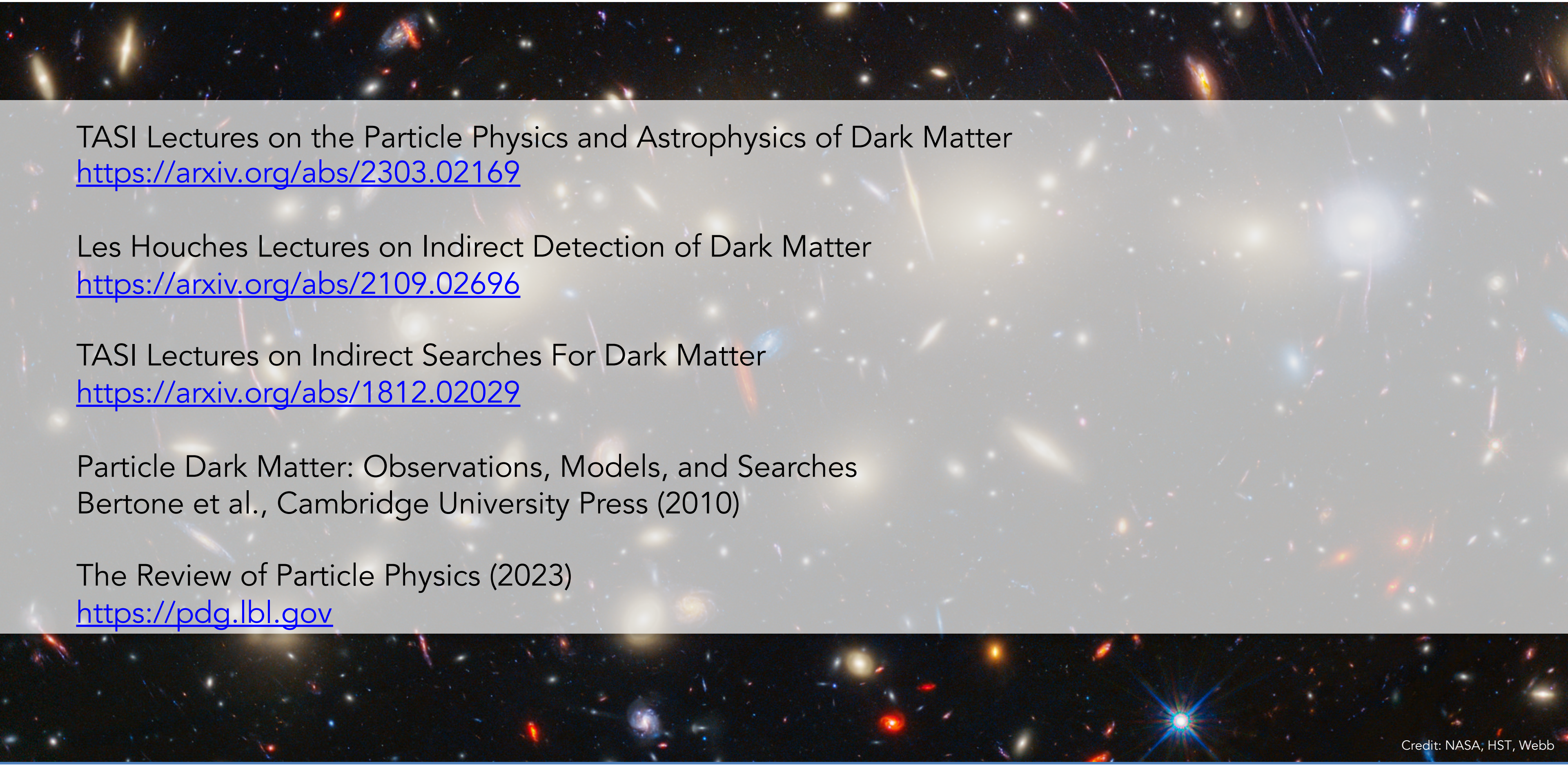
tomorrow

[tuh-mawr-oh] ***noun***

a mystical land where 99% of all human productivity, motivation and achievements are stored.

PDG 2023

Further readings



TASI Lectures on the Particle Physics and Astrophysics of Dark Matter
https://arxiv.org/abs/2303.02169

Les Houches Lectures on Indirect Detection of Dark Matter
https://arxiv.org/abs/2109.02696

TASI Lectures on Indirect Searches For Dark Matter
https://arxiv.org/abs/1812.02029

Particle Dark Matter: Observations, Models, and Searches
Bertone et al., Cambridge University Press (2010)

The Review of Particle Physics (2023)
https://pdg.lbl.gov

Credit: NASA, HST, Webb