Introduction to Dark Matter and Dark Energy

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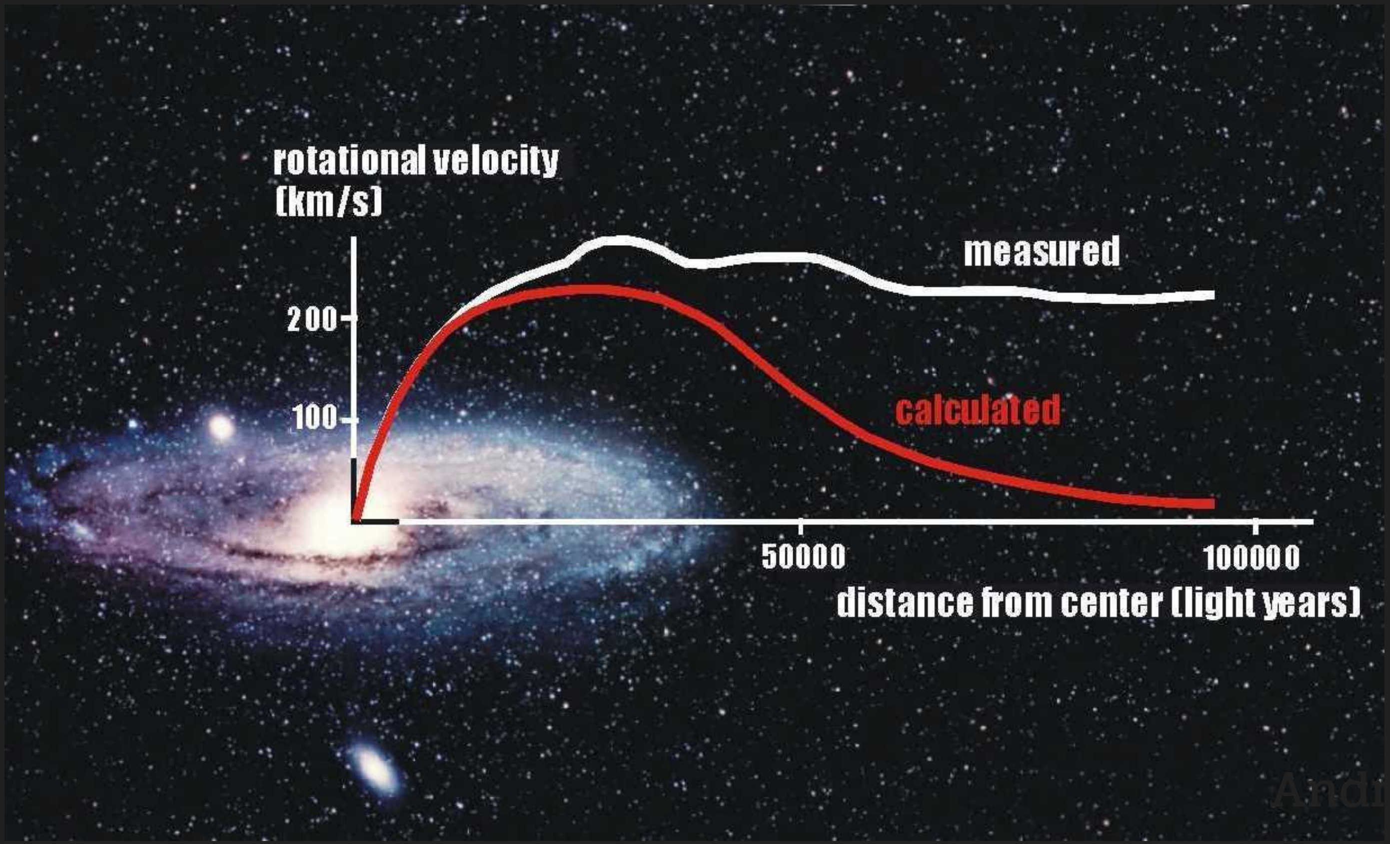
Khon Kaen University

8 October 2022

Why do we need Dark Matter?

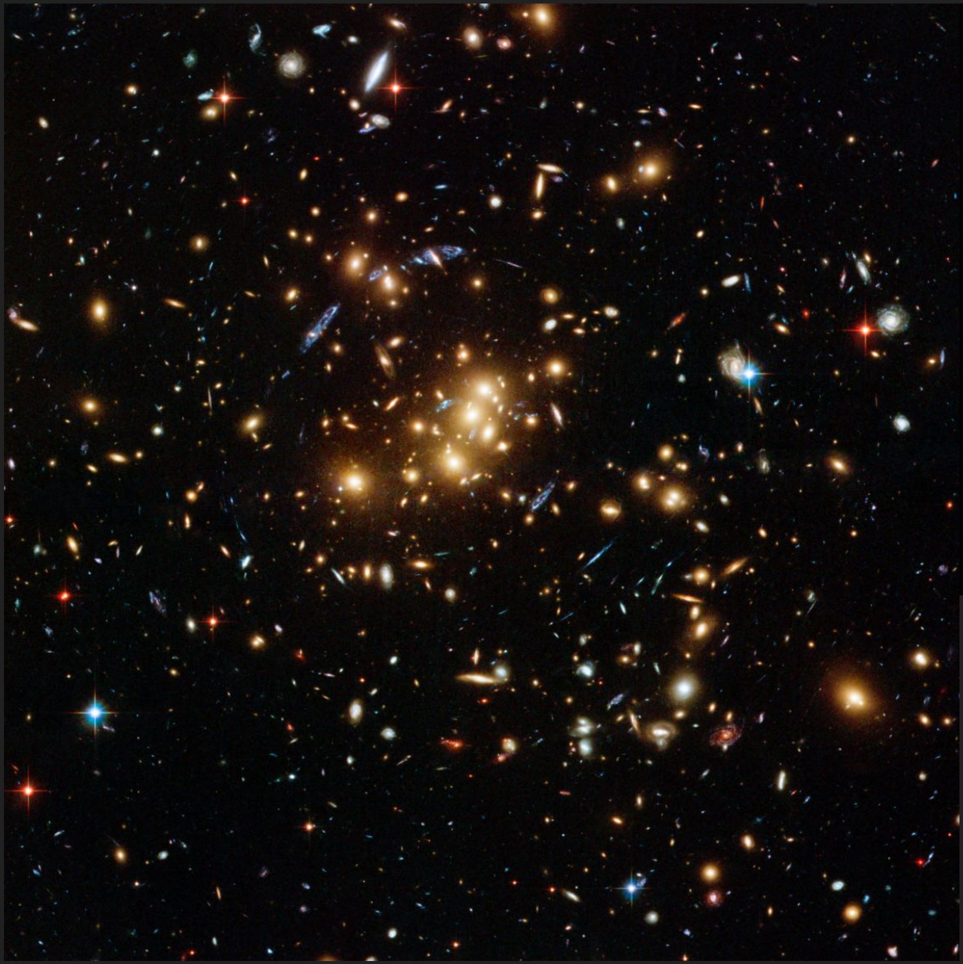
Evidence #1: Rotation curve



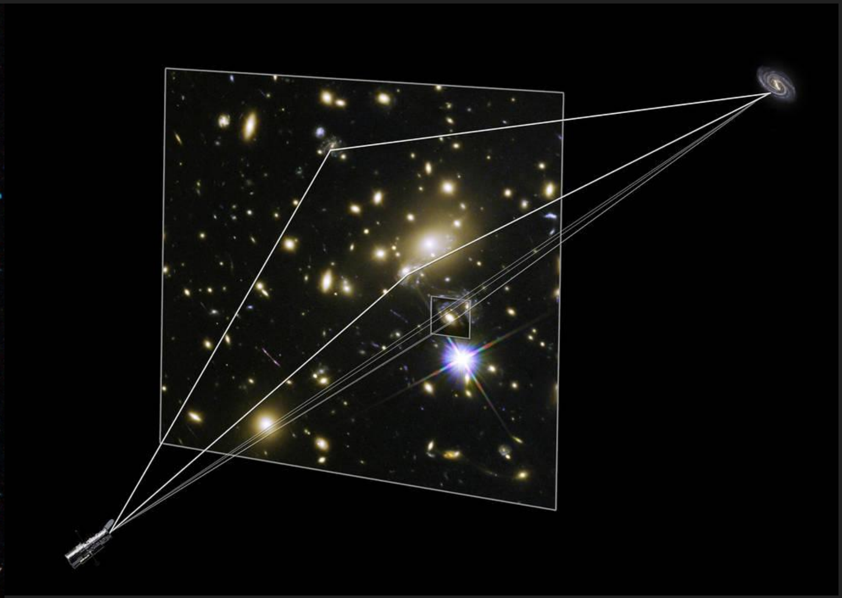
$$\frac{GM(r)m}{r^2} = \frac{mv^2}{r} \quad \Rightarrow \quad v = \sqrt{\frac{GM(r)}{r}}$$

Cr. Queens University

Evidence #2: Strong Gravitational Lensing

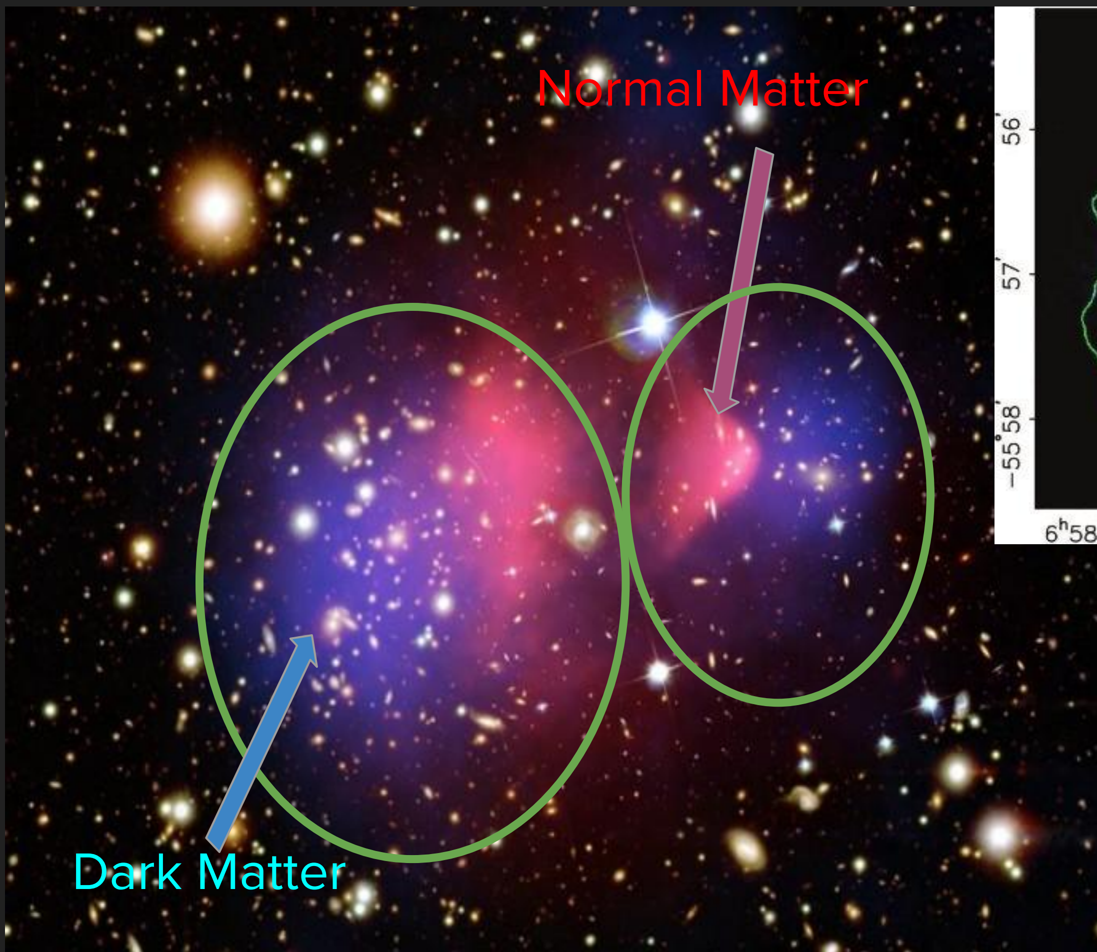


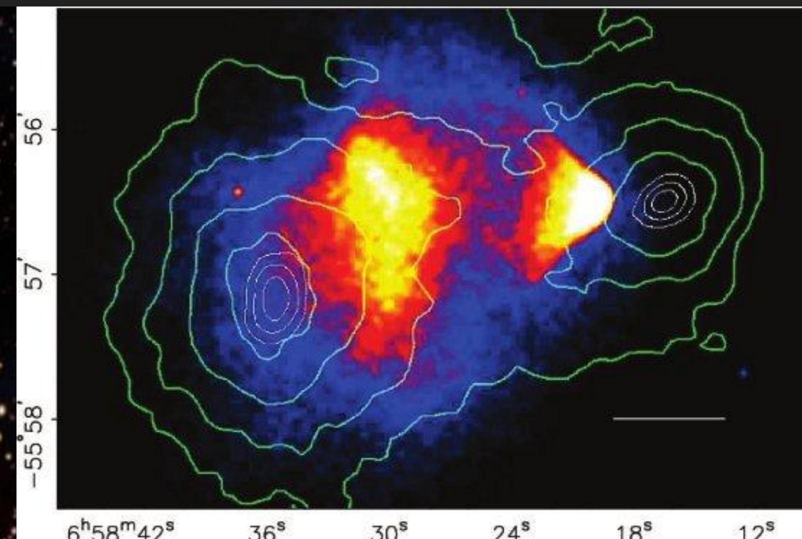
Galaxy cluster 0024+17



Cr. NASA

Evidence #3: Bullet Cluster (Weak Lensing)



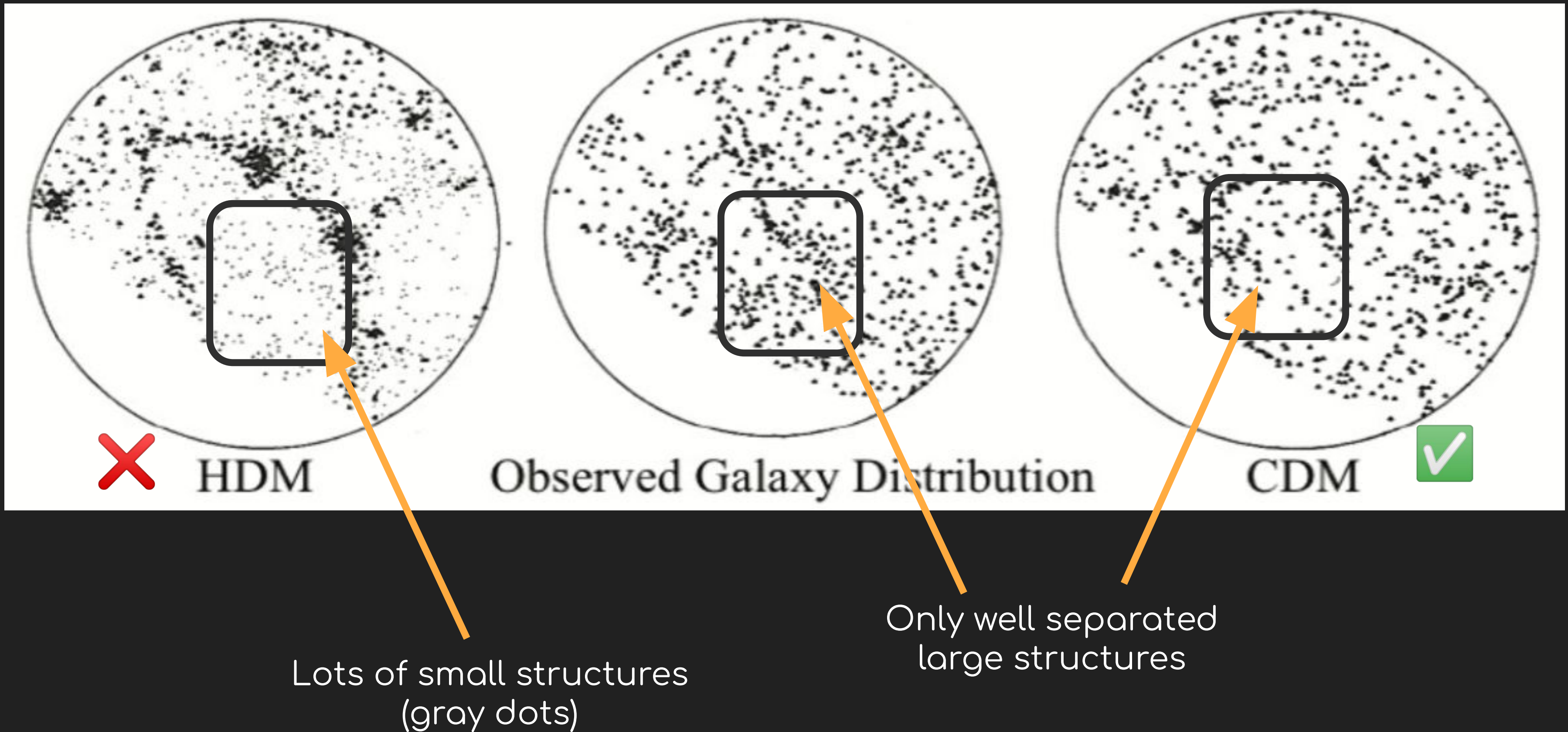


1305.0456

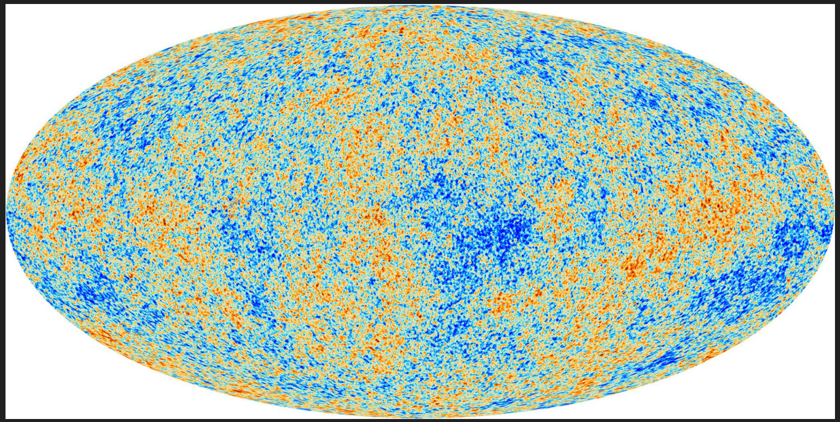
Cr. NASA

Evidence #4: Structure formation

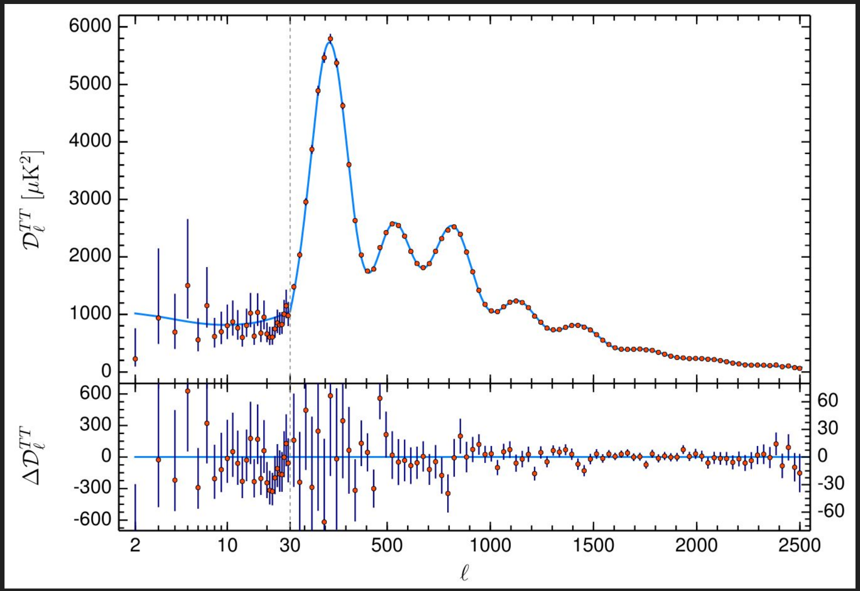
Kolb et al ‘86



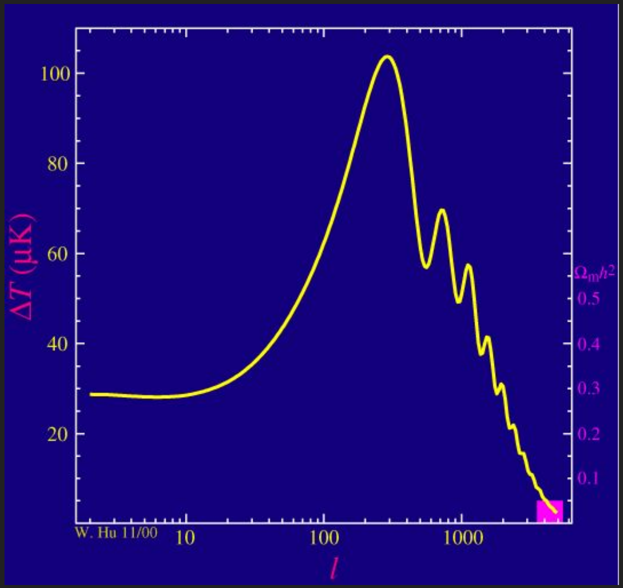
Evidence #5 CMB spectrum



Cr: Planck Collaboration



1807.06209



Wayne Hu's tutorial
http://background.uchicago.edu/~whu

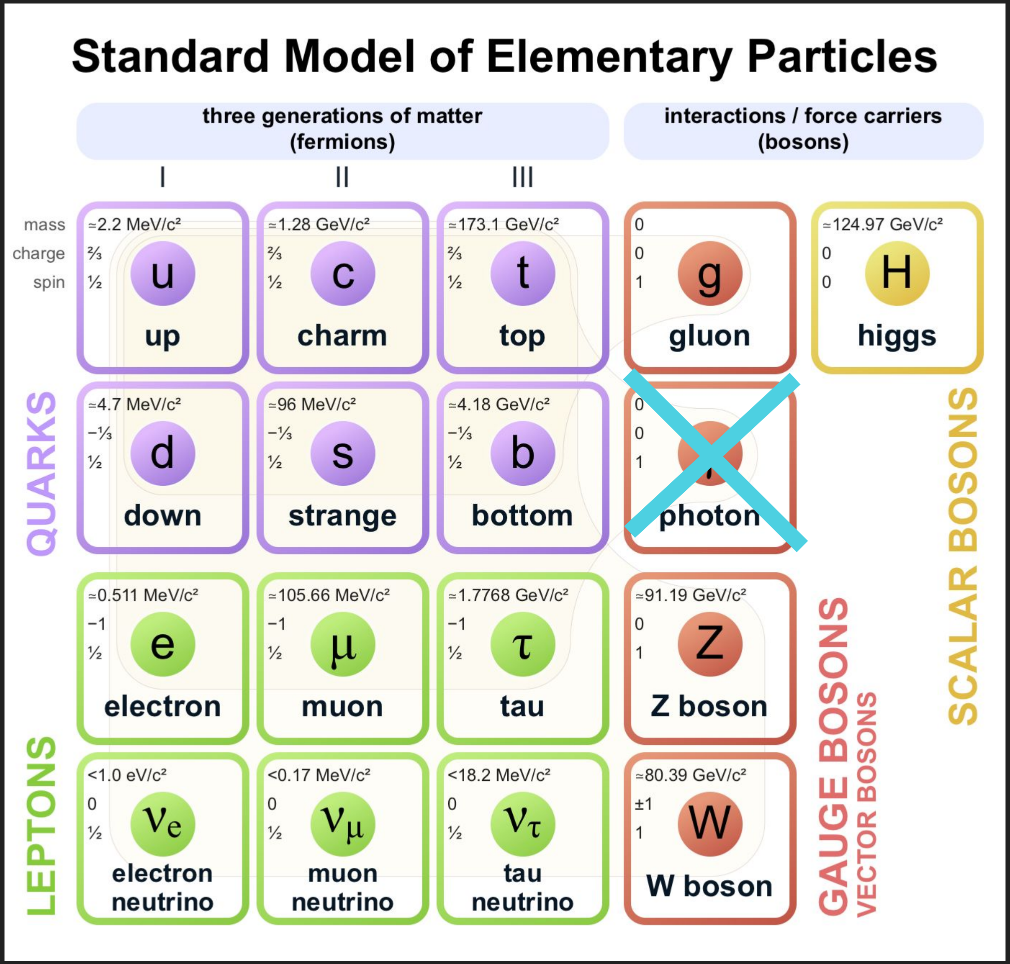
- Our universe is dominated by dark stuff
- Let's hunt them!!

Any clues?

Known DM Properties

- Massive
- Does not emit or reflect light (electrically neutral)
- Does not interact much with themselves and other
- Stable (from early Universe till now)
- Non-relativistic or “cold”

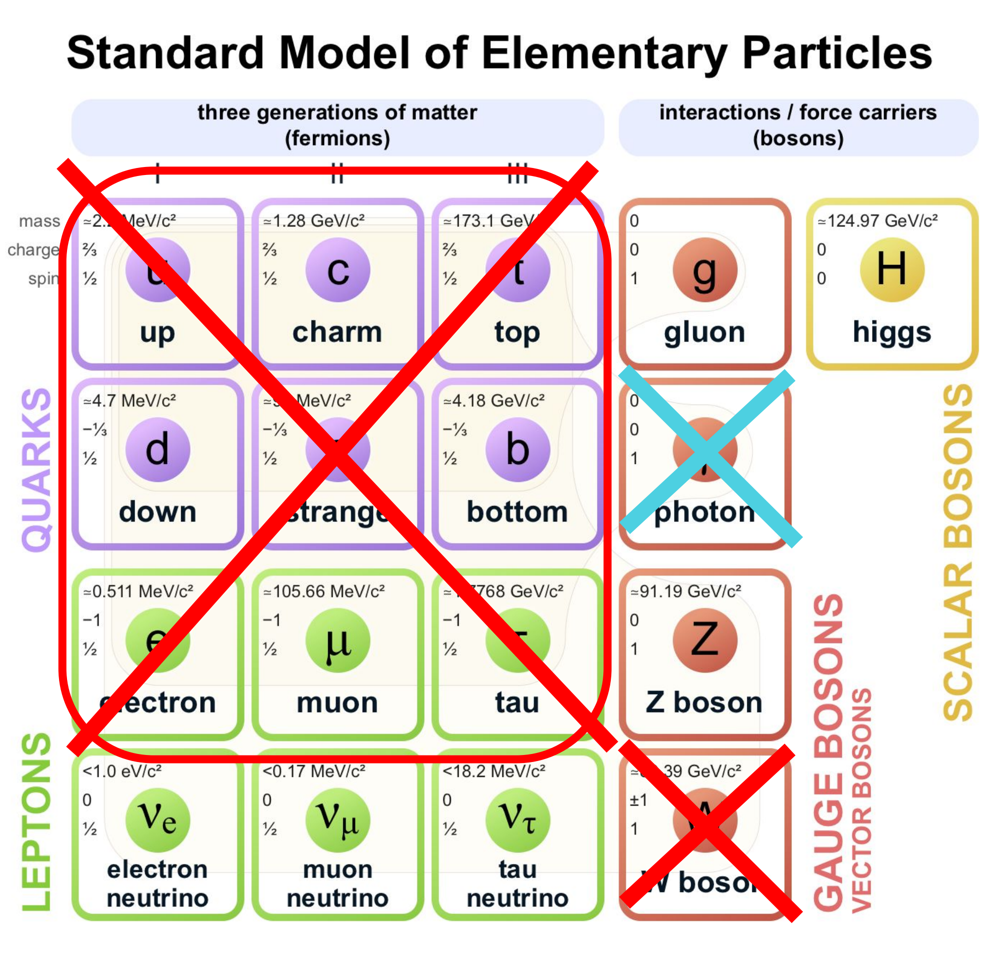
Dark Matter Candidate



Cr: Wikipedia

Dark Matter Candidate

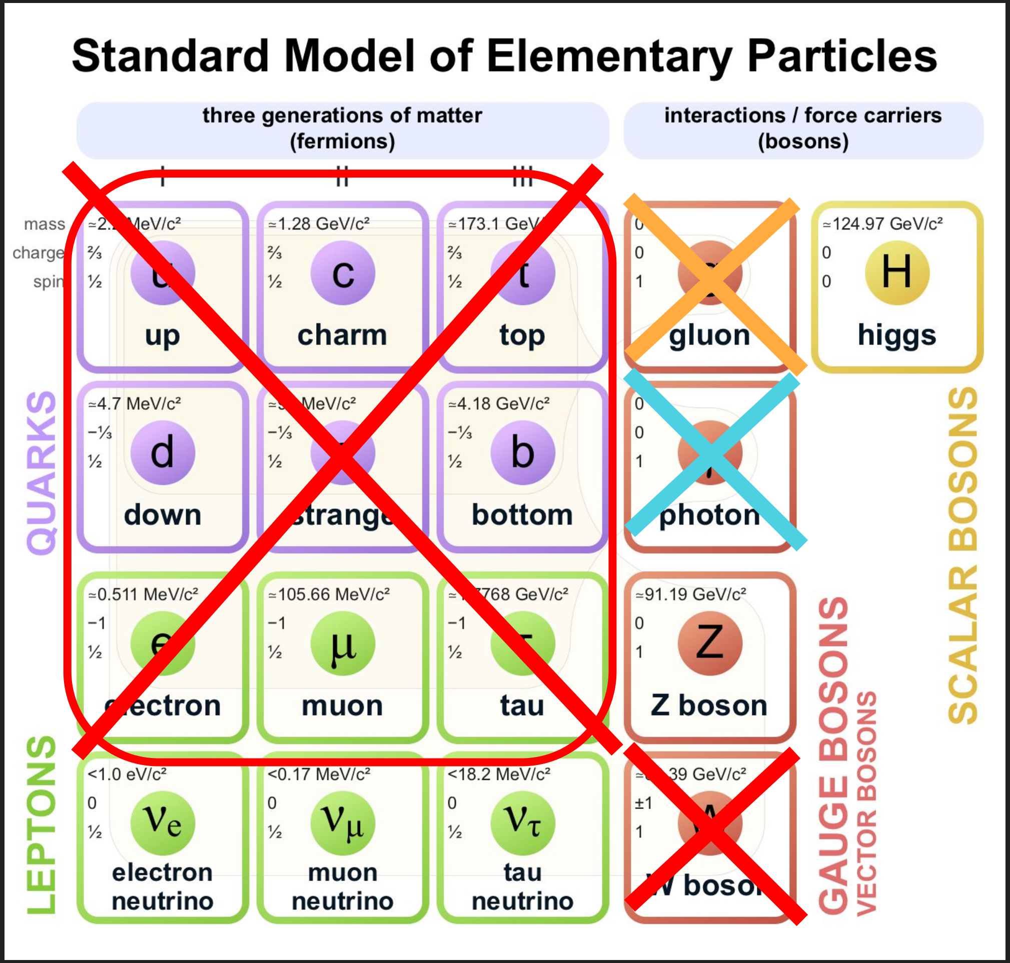
- Electrically neutral



Cr: Wikipedia

Dark Matter Candidate

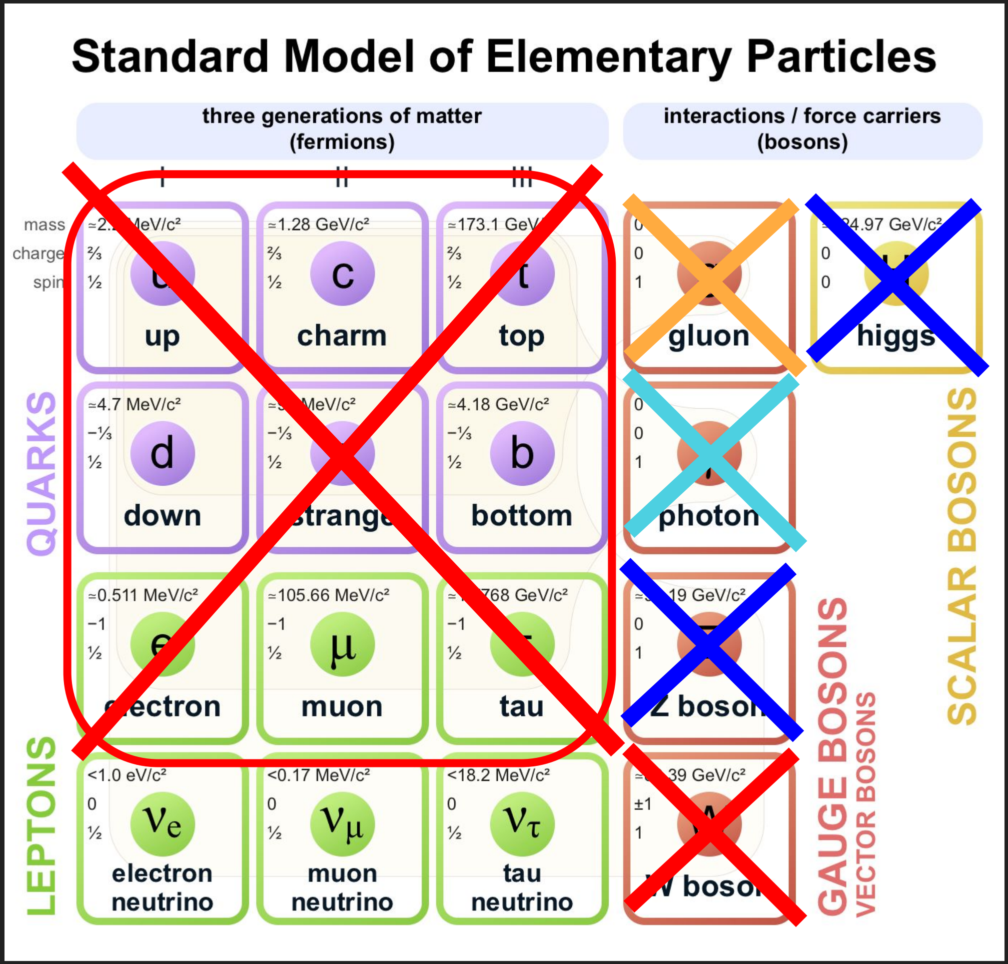
- Electrically neutral
- Interact weakly



Cr: Wikipedia

Dark Matter Candidate

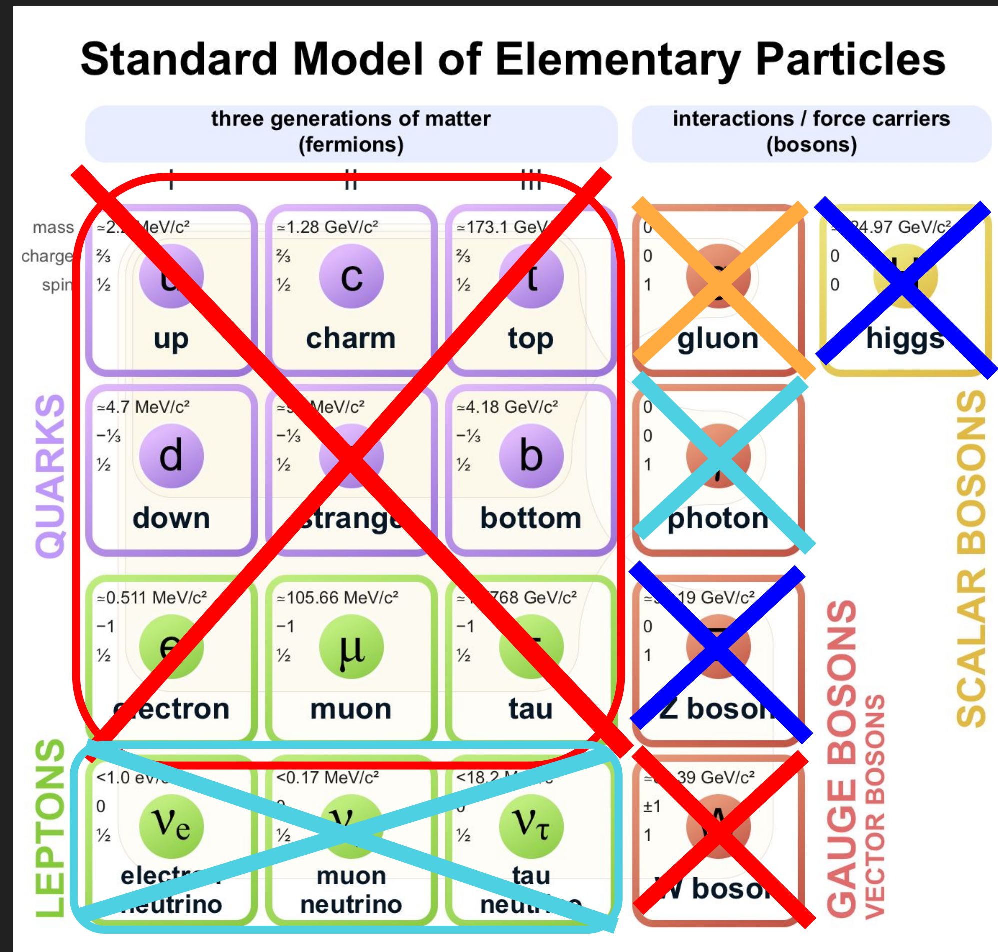
- Electrically neutral
- Interact weakly
- Stable



Cr: Wikipedia

Dark Matter Candidate

- Electrically neutral
- Interact weakly
- Stable
- Cold

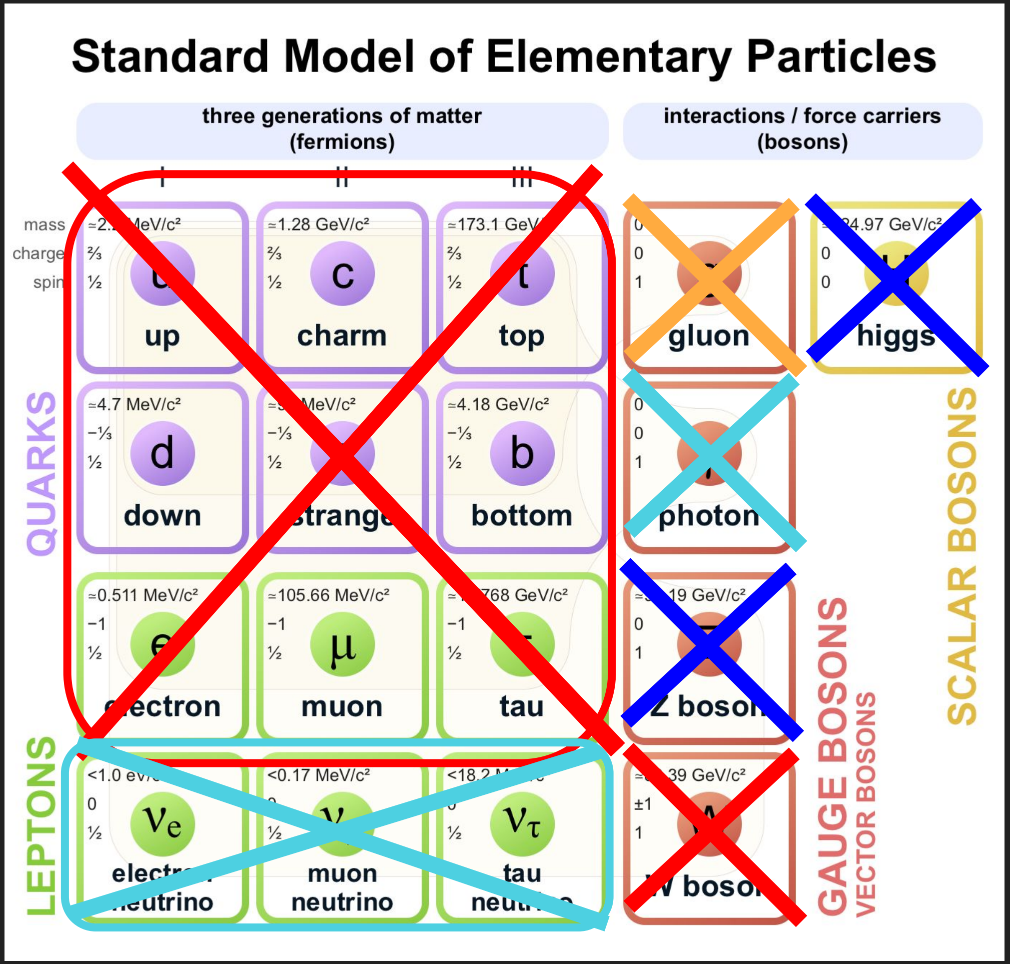


Cr: Wikipedia

Dark Matter Candidate

- Electrically neutral
- Interact weakly
- Stable
- Cold

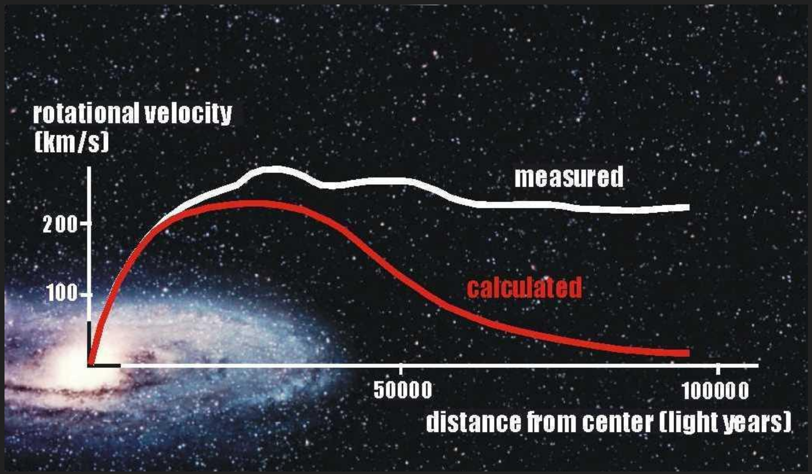
MUST BE NEW PARTICLES!

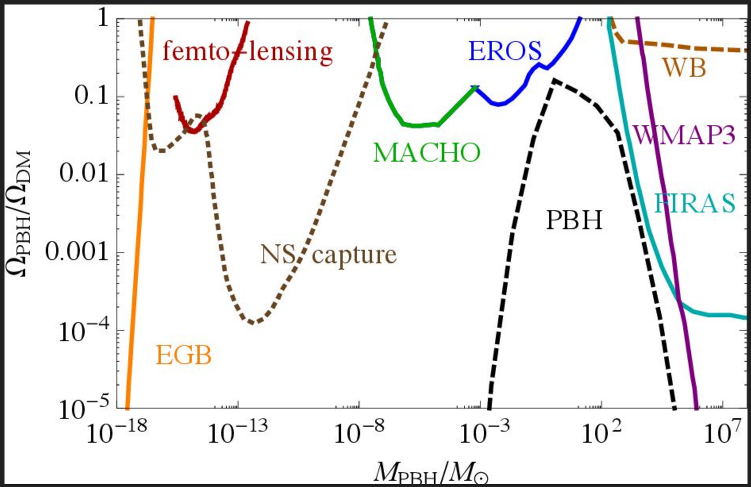


Cr: Wikipedia

***Caveat

- We will only talk about the dark matter scheme -> Particle Dark Matter
- Modified gravity -> often explain only the results at the galactic scale, i.e., rotation curve
- MACHOs (MAssive Compact Halo Objects) -> only small fraction of missing mass





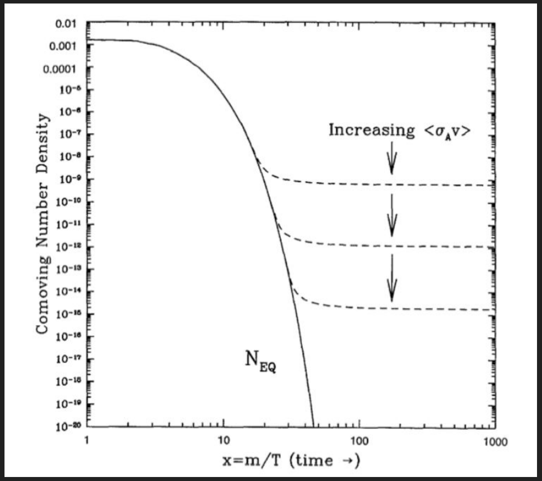
1702.08275

Dark Matter Scheme

- Thinking about dark matter as particles allows us to talk about
  - History of dark matter => production mechanism
  - How to detect => particles interaction
- Benefits:
  - One can relate the microscopic properties to the macroscopic properties
  - Strong, solid predictions from theories

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 - y\phi\bar{\chi}\chi$$

$$\frac{d\phi}{dE} = \frac{1}{8\pi}\frac{J}{m_\chi^2}\sum_i \frac{dN}{dE} < \sigma v >_i$$

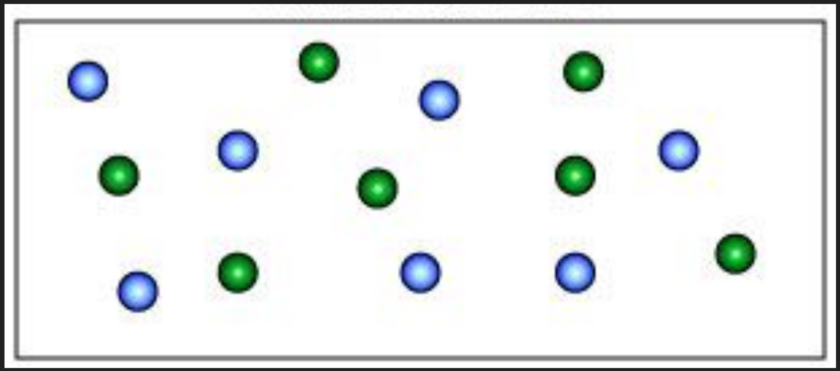


Where does Dark Matter come from?

Thermal Dark Matter

- At the beginning of the universe, we assume that dark matter is in thermal equilibrium with standard model particle soup

$$X + \overline{X} \leftrightarrow Y + \overline{Y}$$



Out of Equilibrium and Freeze out

- Equilibrium = 2-way process

$$X + \overline{X} \leftrightarrow Y + \overline{Y}$$

- When the temperature drops below the threshold, one process is less efficient → out of equilibrium

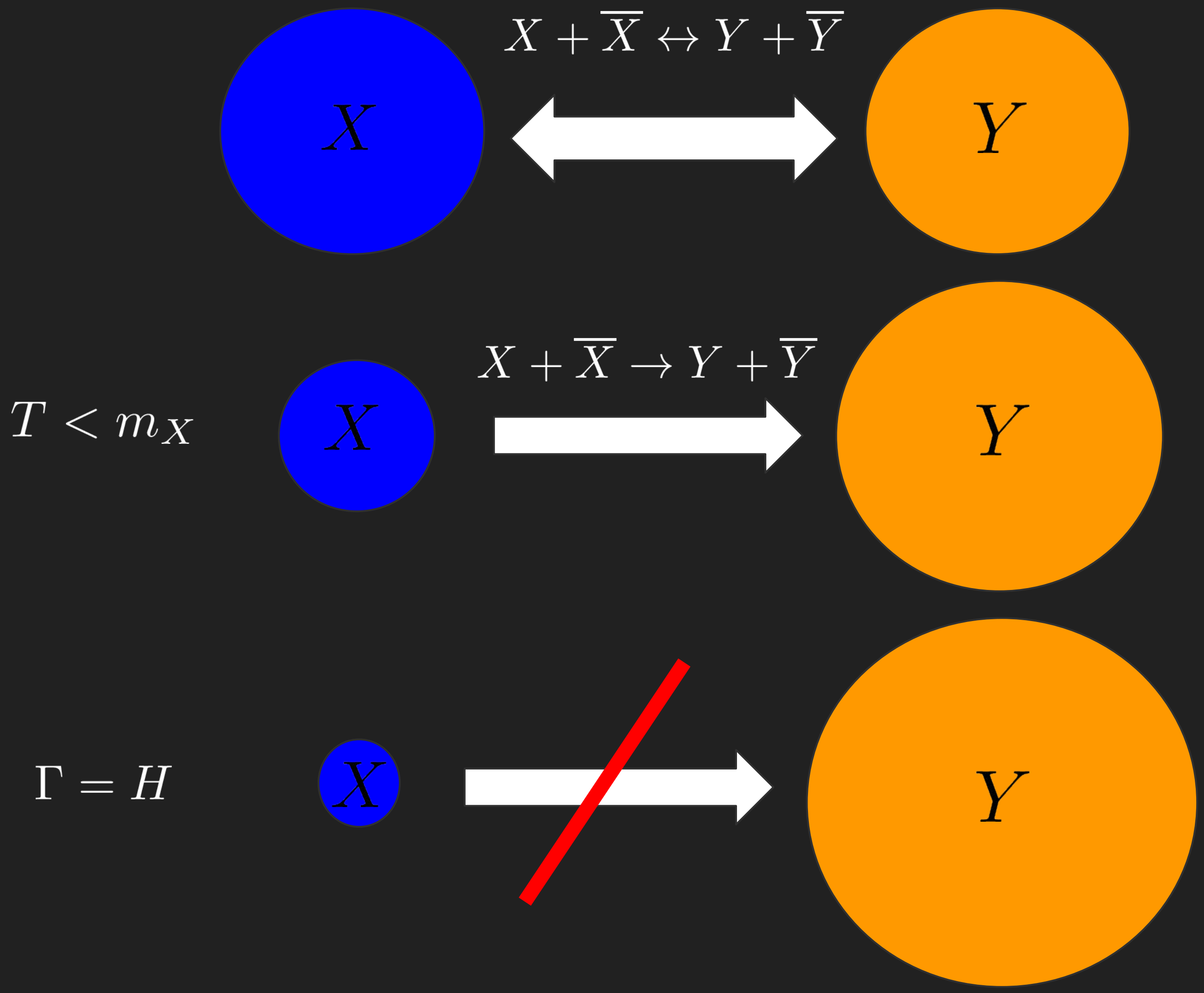
$$T < m_X \qquad\qquad X + \overline{X} \rightarrow Y + \overline{Y}$$

- The population of X decreases exponentially
- As the expansion rate of the universe is faster than the interaction rate then the process stops completely

$$\Gamma = H$$

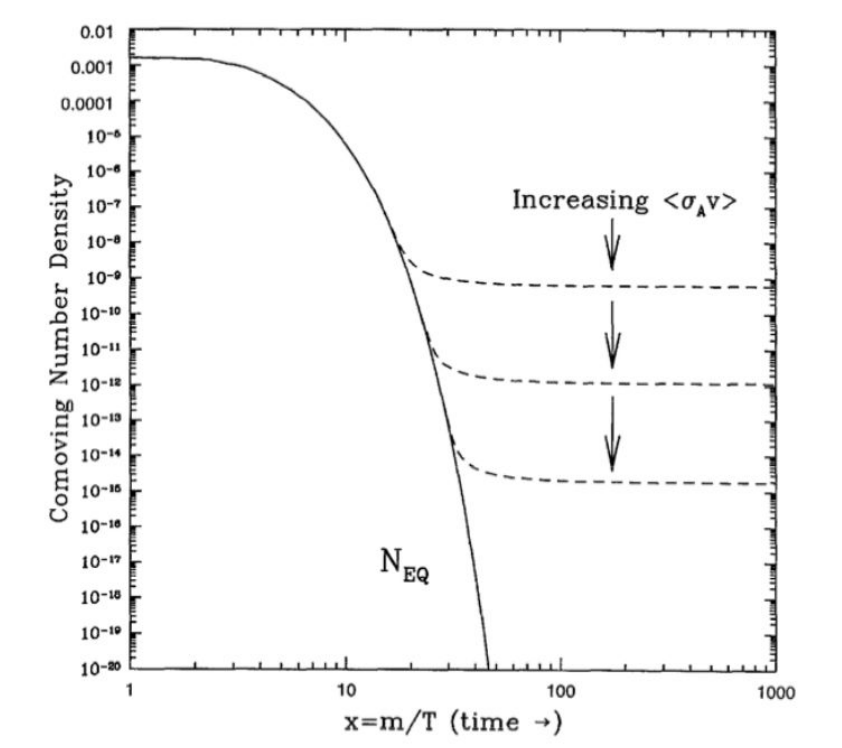
- X is out of thermal equilibrium

Out of Equilibrium and Freeze out



Dark Matter Freeze Out

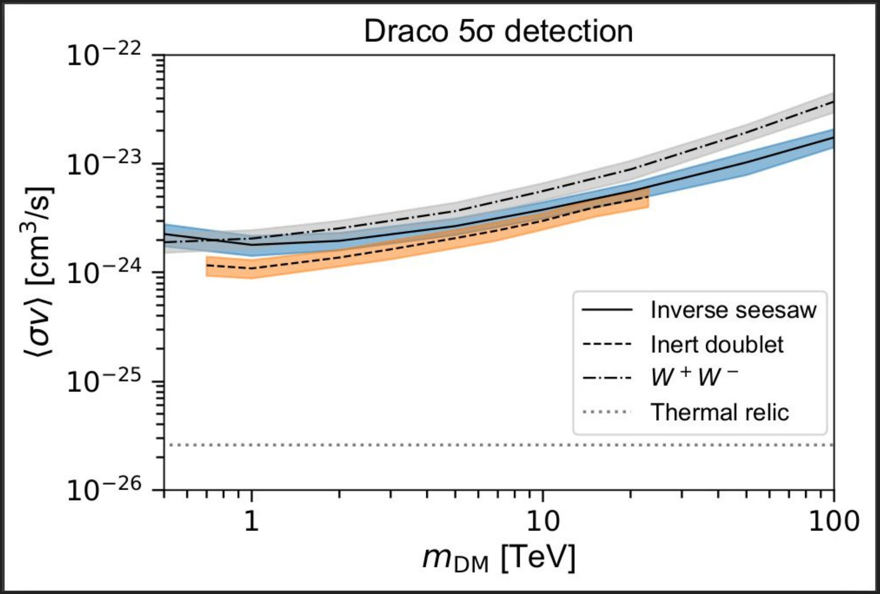
- The final relic density depends on the strength of dark matter annihilation



Kolb & Turner

WIMP Miracle

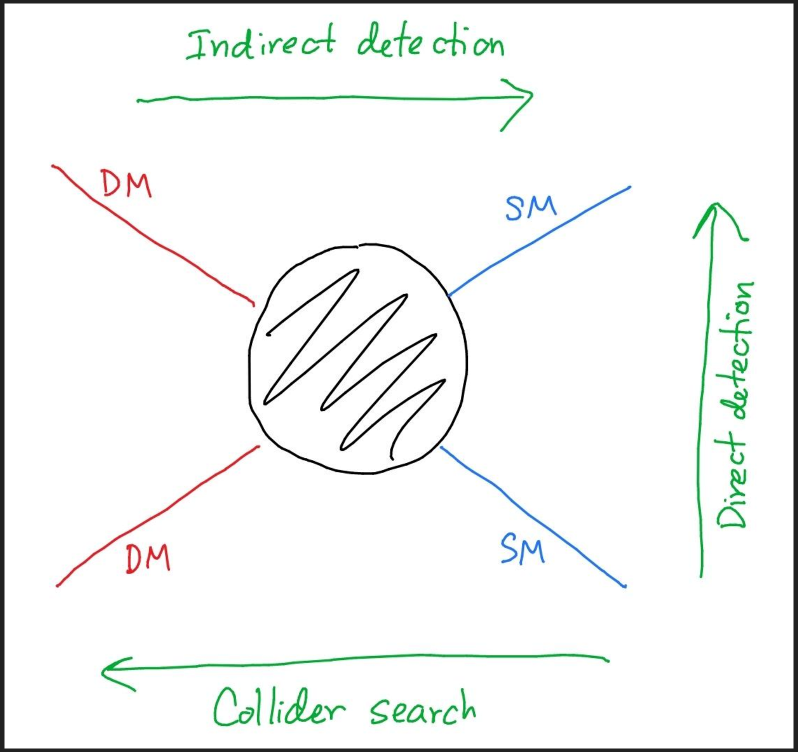
- Weakly Interacting Massive Particle is a well motivated class of models due to an agreement in order of magnitudes
- This cross section is called "thermal cross section"
- In general, connection between cross section and relic density gives a solid prediction of a beyond standard model theory

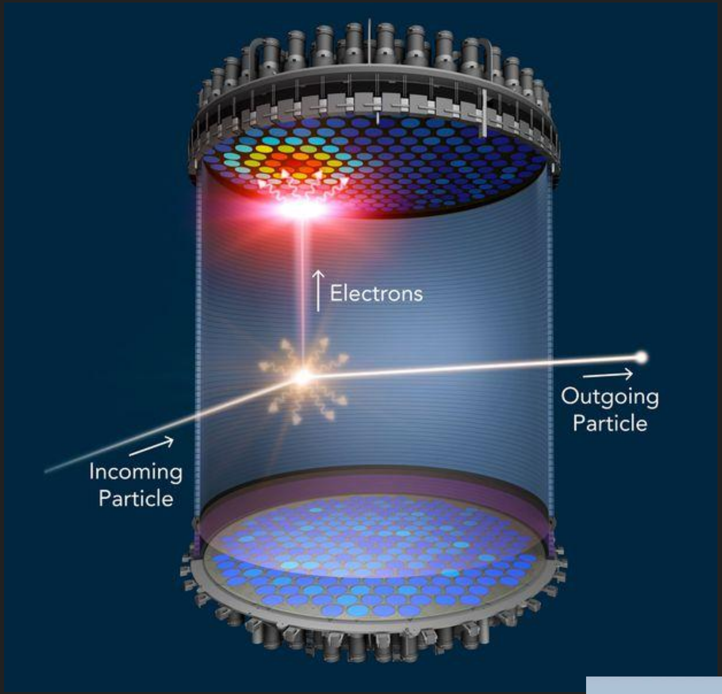


Let’s hunt them!!

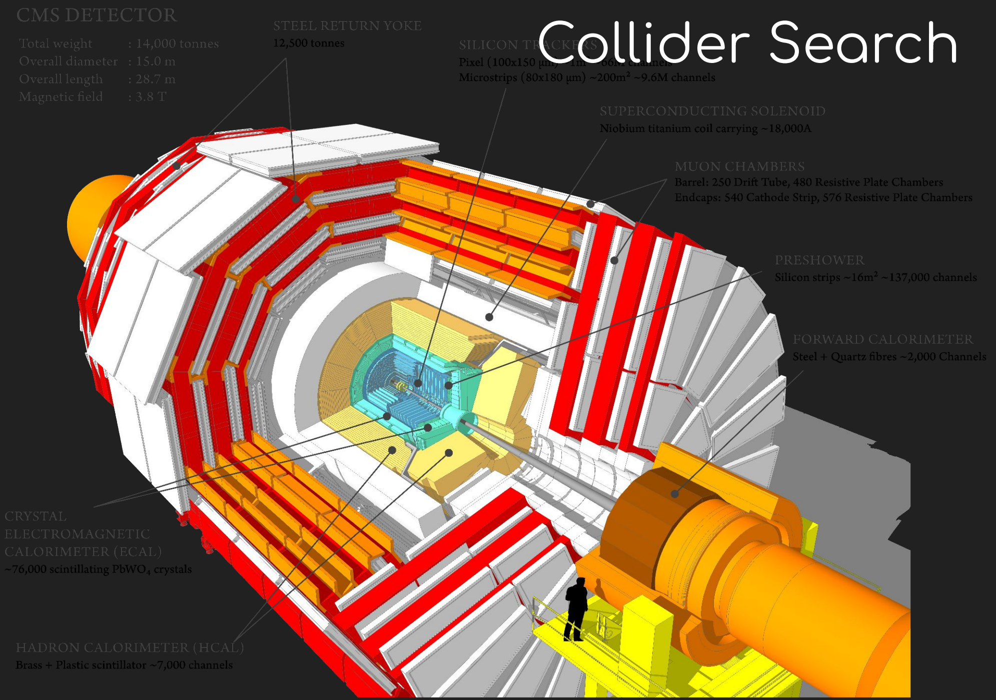
General scheme

- We can use dark matter scheme to relate microscopic properties with observations

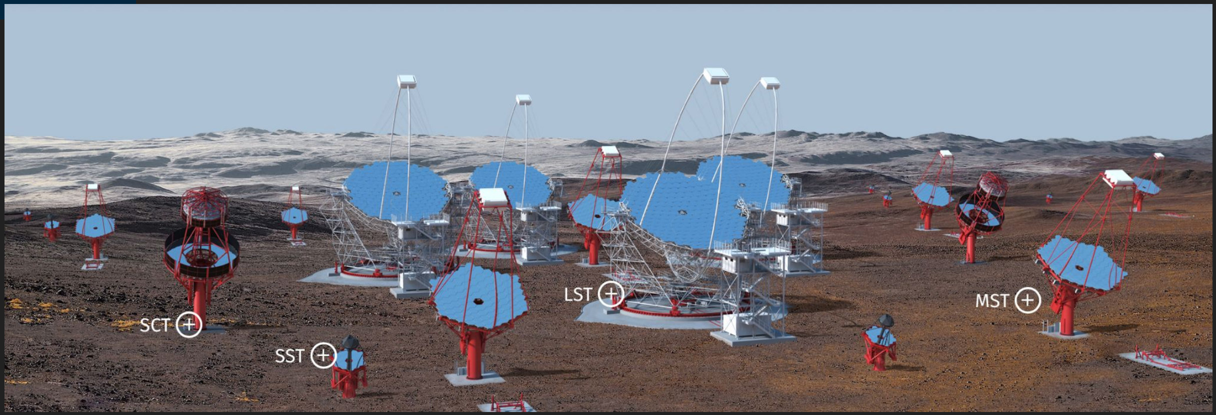




Collider Search

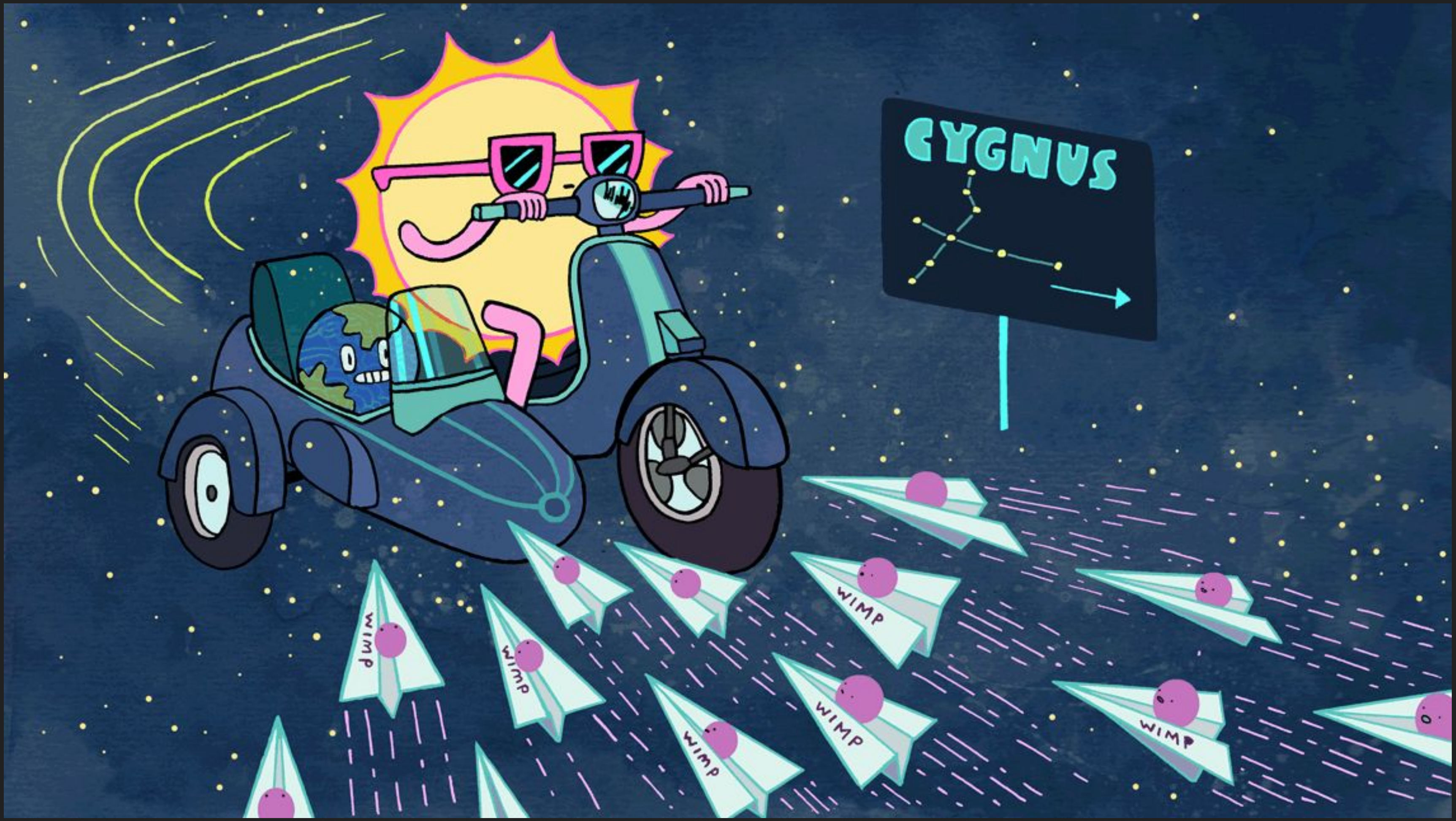


Direct Detection



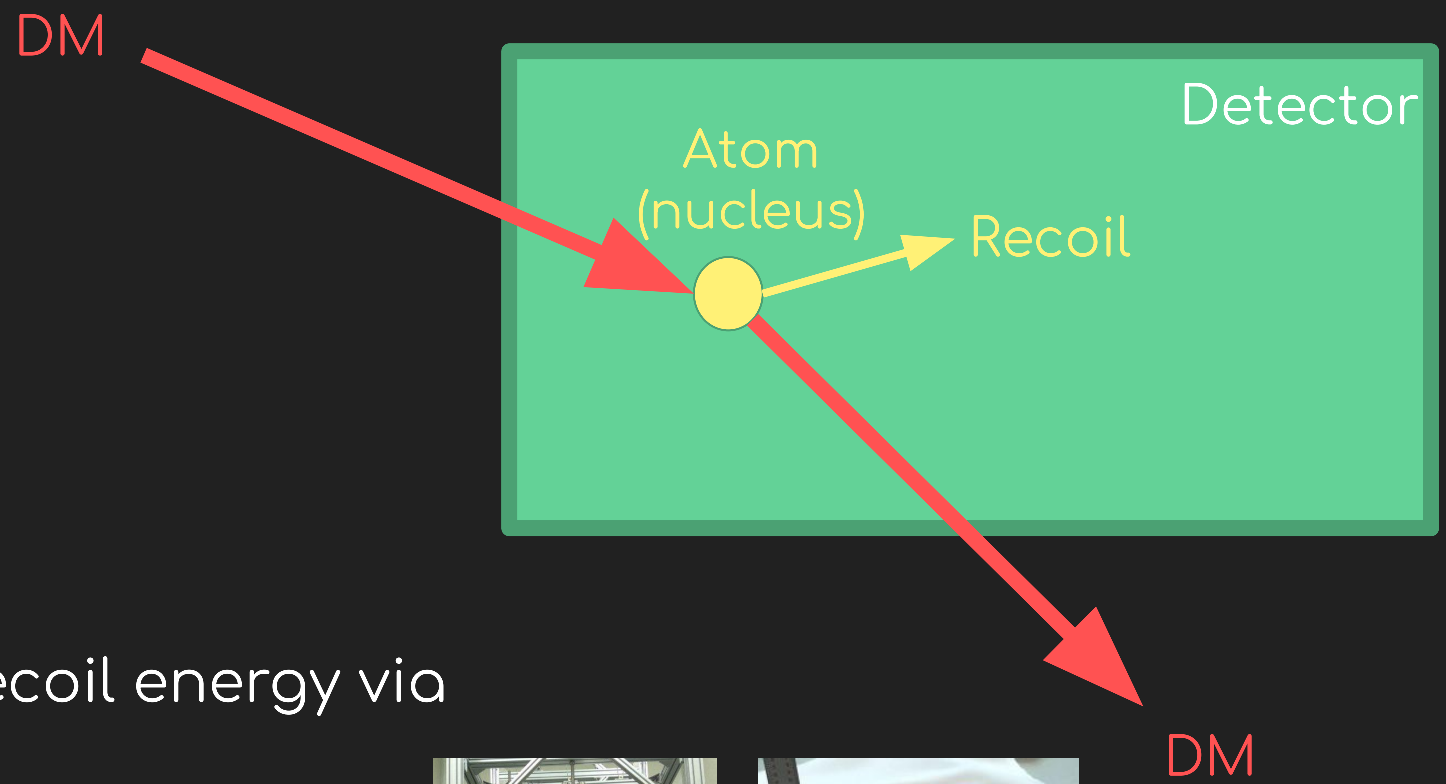
Indirect Detection

Direct Detection



Cr: Corinne Mucha, Sandbox Studio Chicago

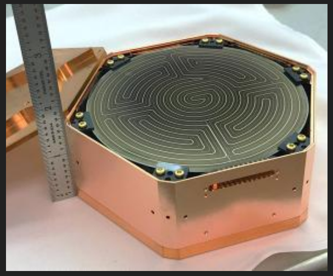
Direct Detection



Measure recoil energy via

- Light
- Vibration

PANDAX-II



SuperCDMS

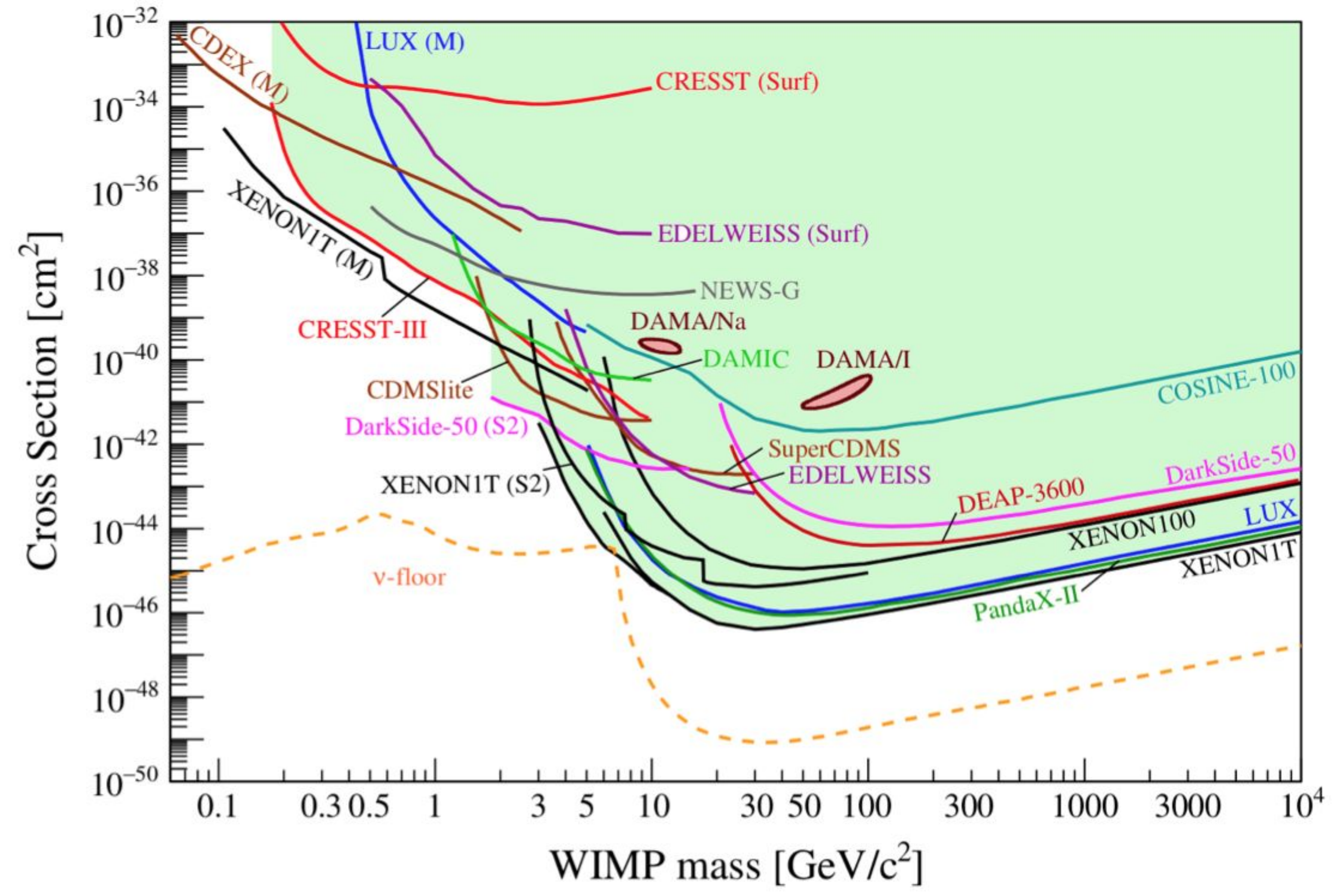
Direct Detection Experiments

Challenge: Many things can give a nucleus a kick
- cosmic rays
- radioactivity in/around the detector

Solutions:
1. Use the Earth as a shield
2. Use trigger to filter out background

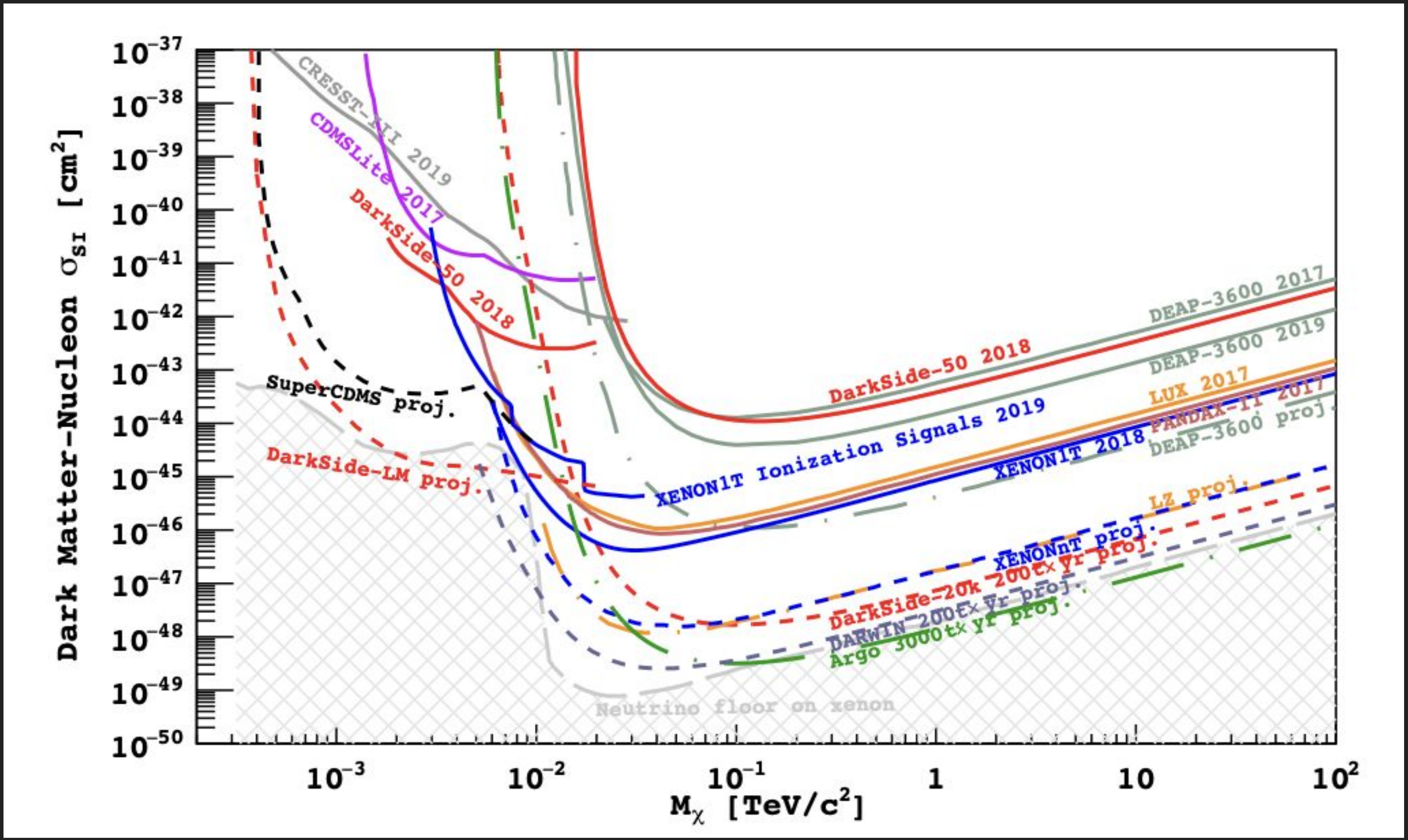
Experiment categories:
- Zero background
  XENONnT, LZ, PANDAX-III, Super-CDMS
- Annual modulation
  DAMA-Libra, COGENT

Direct Detection: Current Status



APPEC Committee Report [2104.07634]

Direct Detection: Future Projection

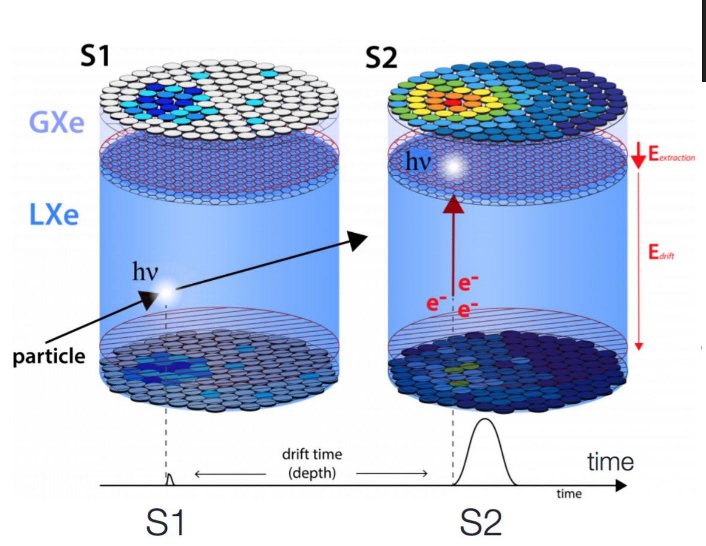


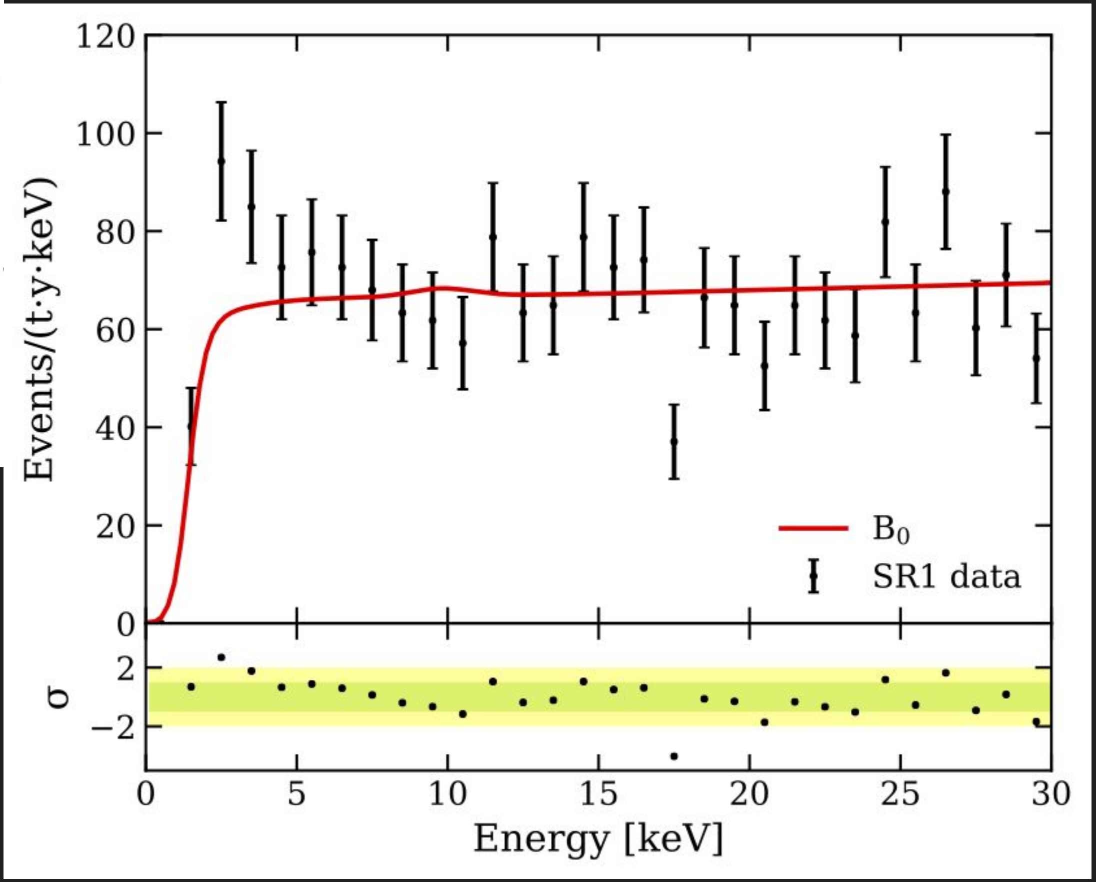
Physics Briefing Book.

European Strategy for Particle Physics Preparatory Group [1910.11775]

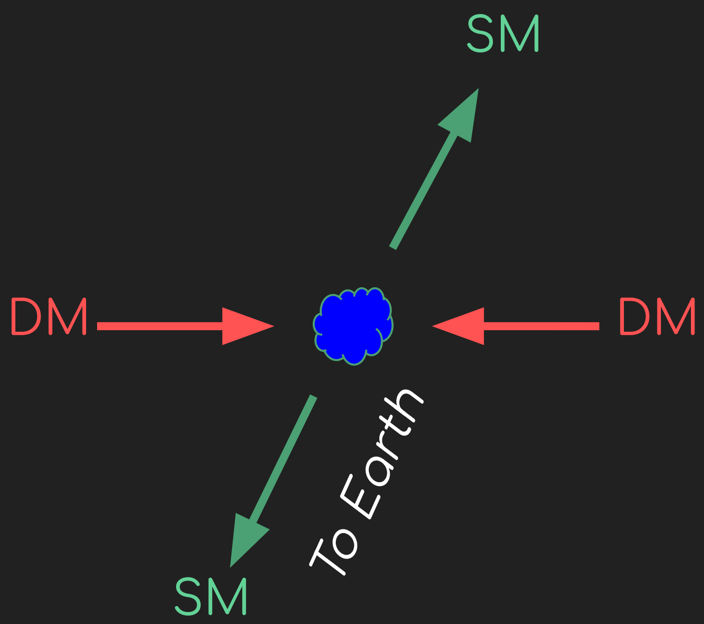
XENON1T Excess (Electronic Recoil)

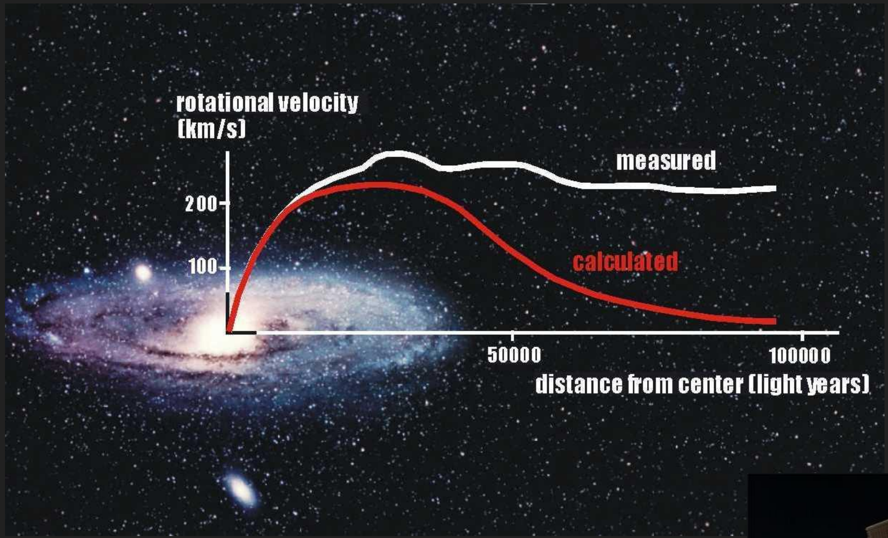
[2006.09721]

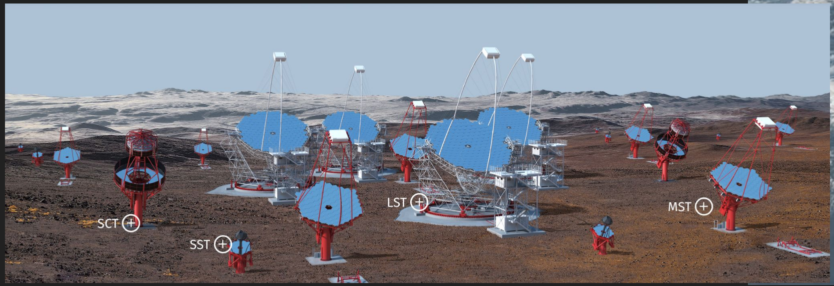


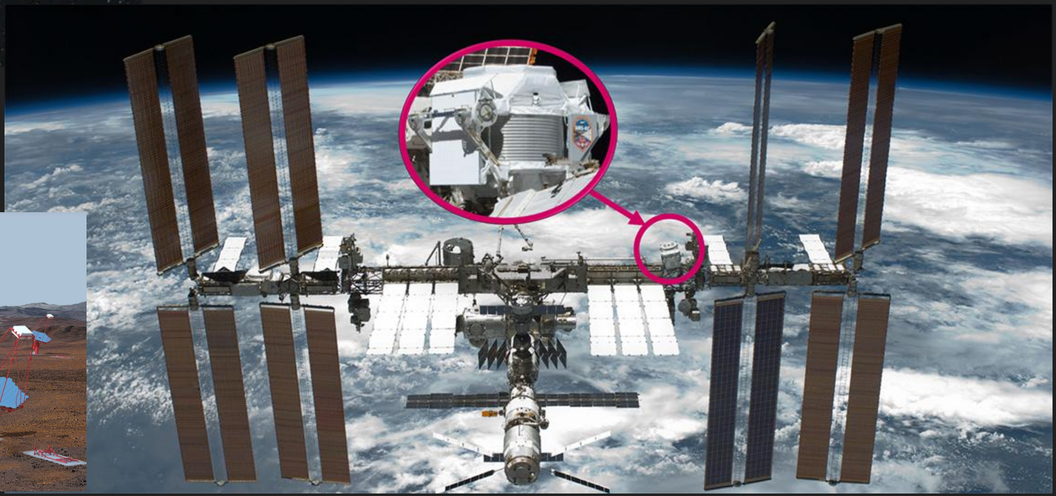


Indirect Detection





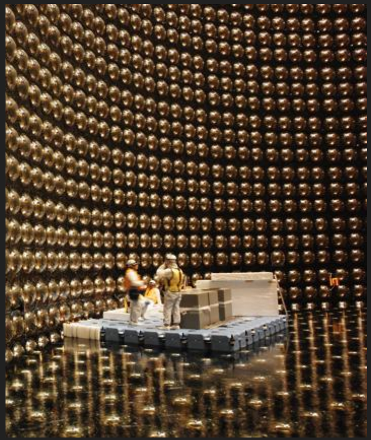




AMS-02 on ISS. cr: ESA

Indirect Detection: Experiments

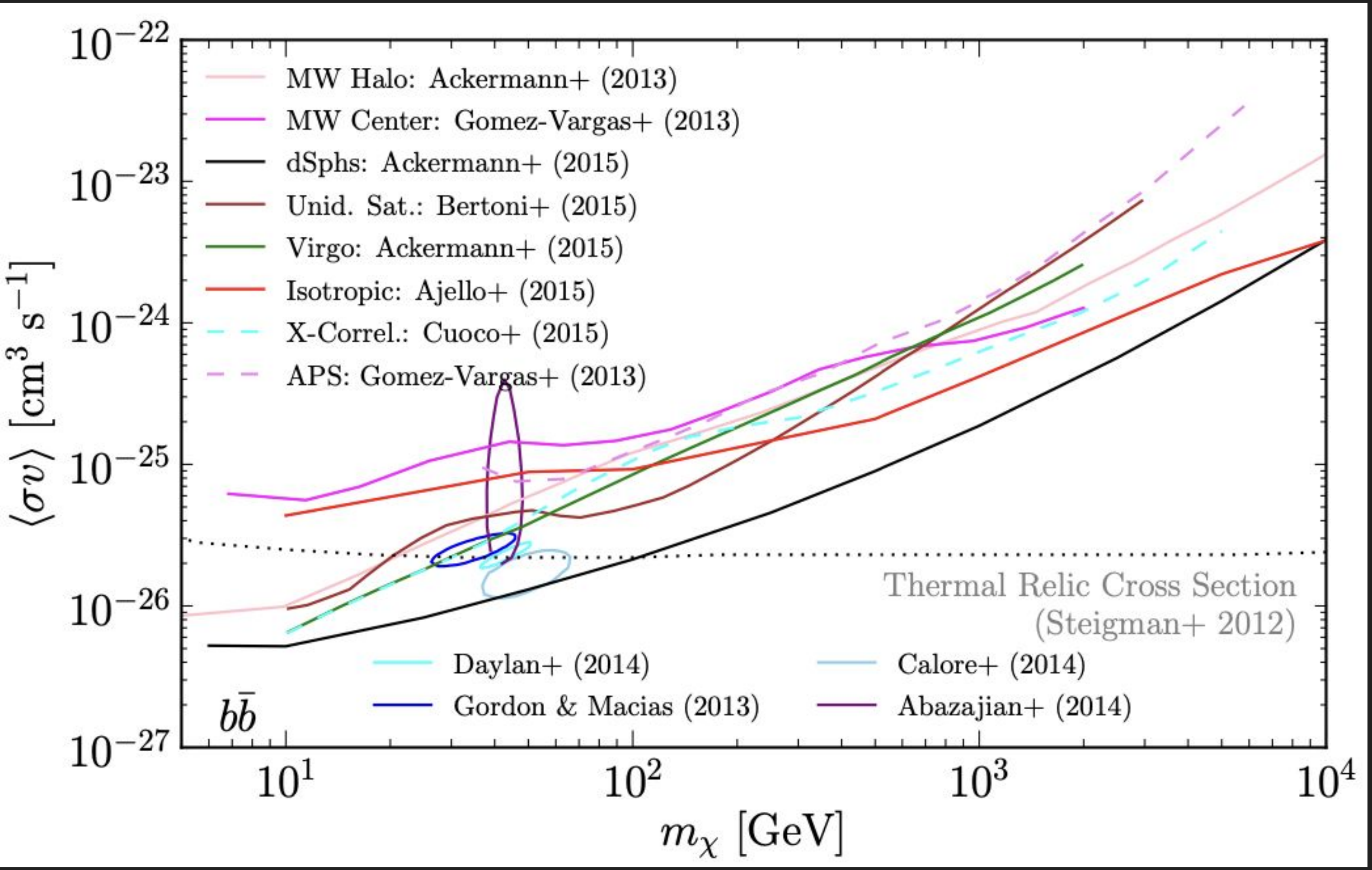
- DM particles self annihilate inside the Milky Way
  - Galactic center/dwarf galaxies
- Annihilation products travel to the Earth
  - e^+/e^-, photon, proton, neutrino, ...
- Detectors
  - Ground based
    - neutrino: IceCUBE, JUNO, SuperK, ...
    - gamma-ray: HESS, MAGIC, CTA, ...
  - Space based
    - e^+/e^-: AMS-02, DAMPE
    - x-ray: PLANCK, FERMI
- Challenges: Unknown astrophysical backgrounds.



Super-K

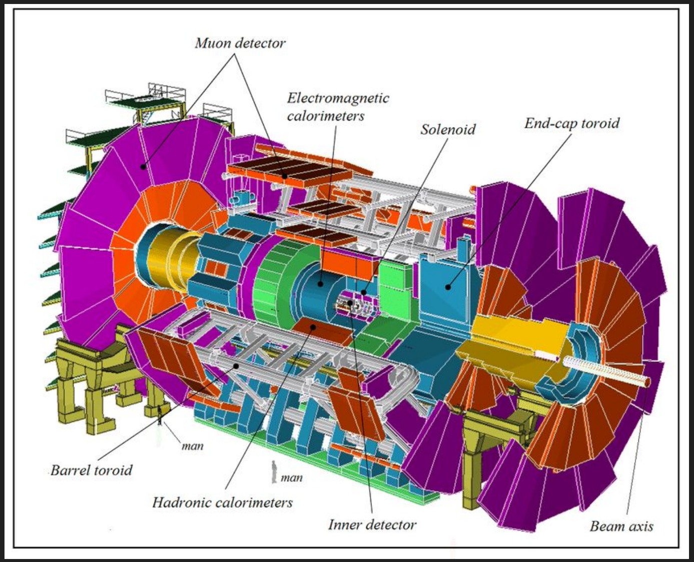
DAMPE

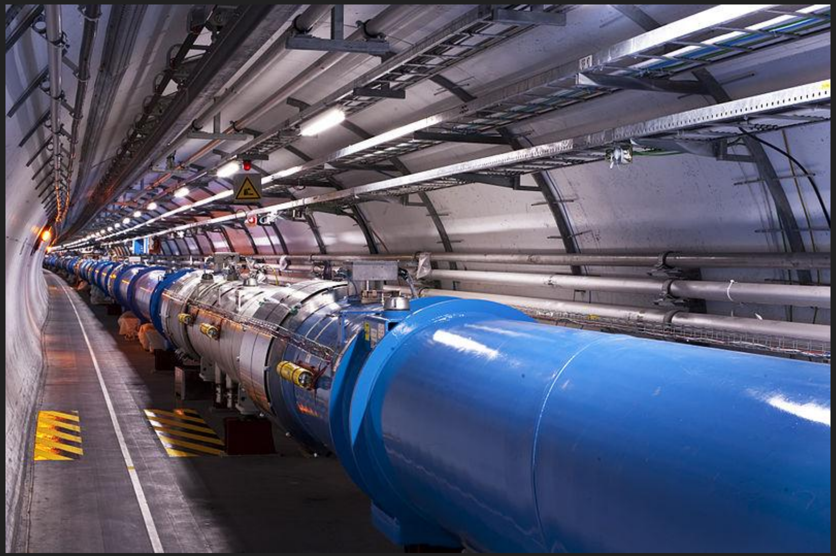
Indirect Detection: Current Status



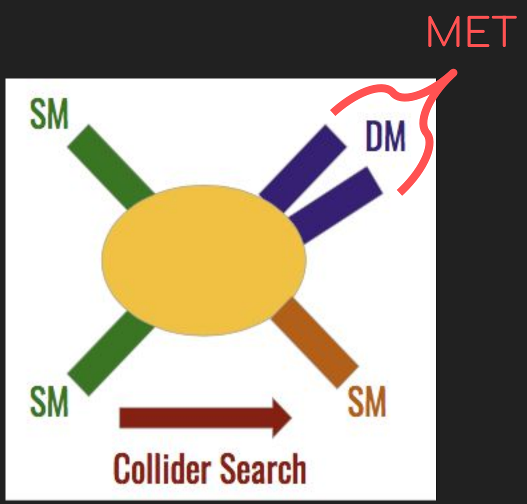
Limit from Fermi-LAT data [1605.02016]

Collider Search

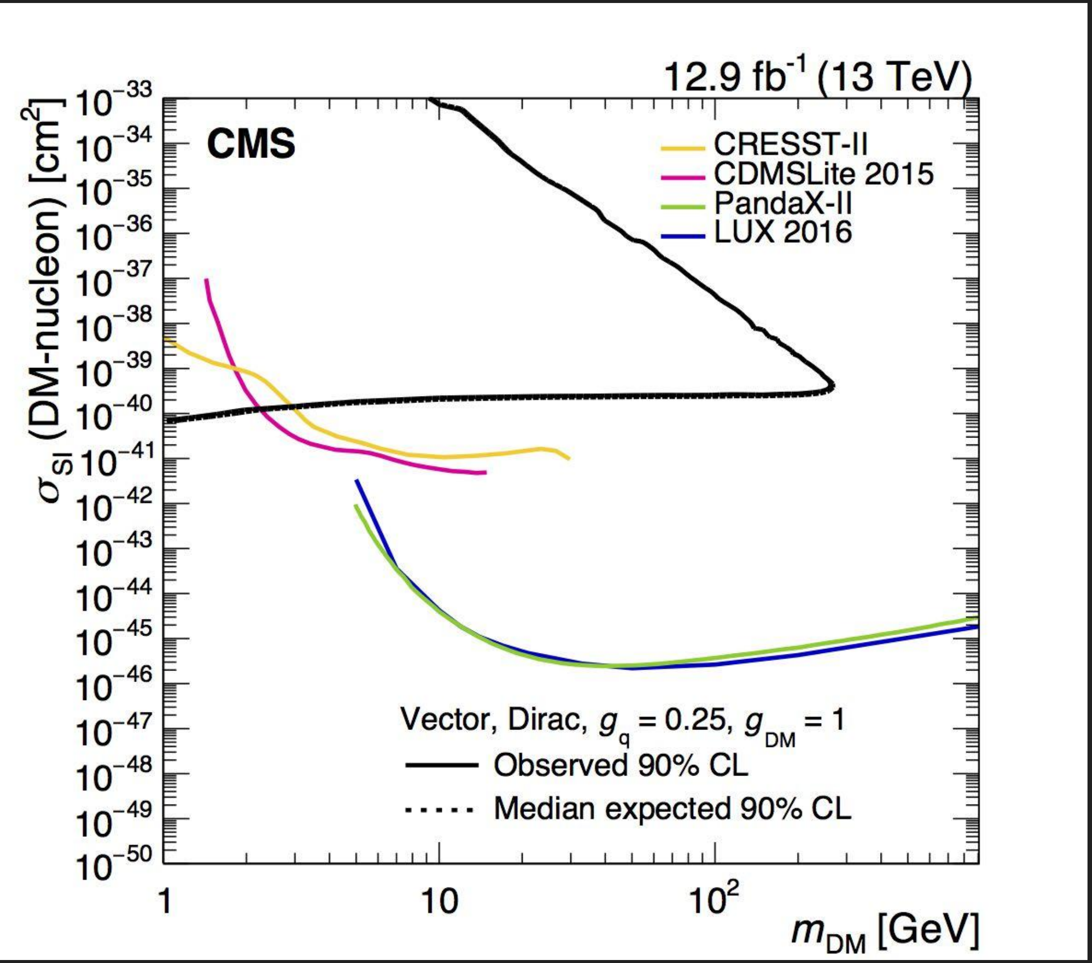




- DM leaves detector undetected
  - Missing energy/momentum
- Trigger on SM particles
  - Jet, photon, lepton

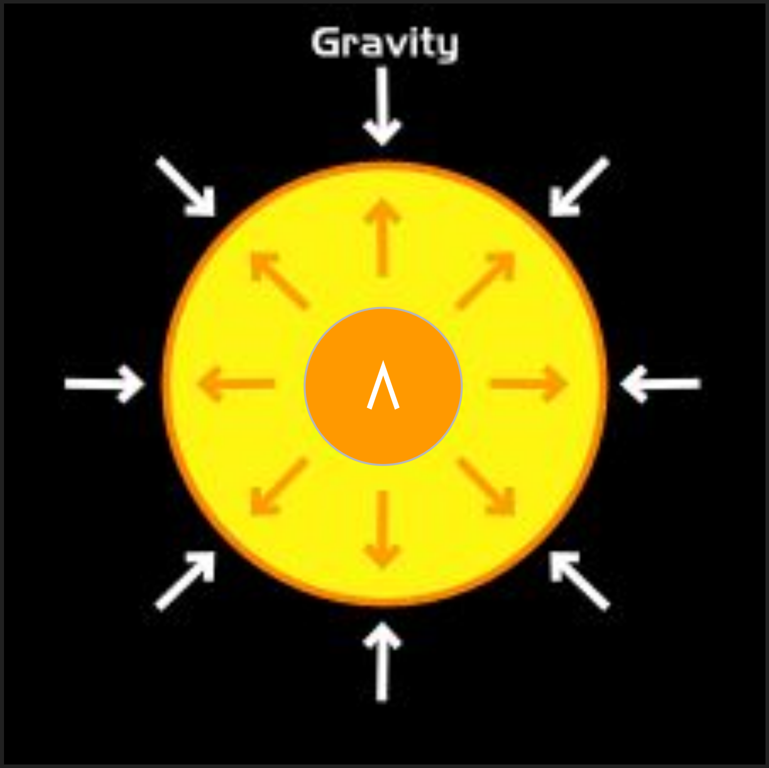


Example: Monophoton Signature



Why do we need Dark Energy?

Einstein's biggest blunder



We chose to believe that our universe is always static

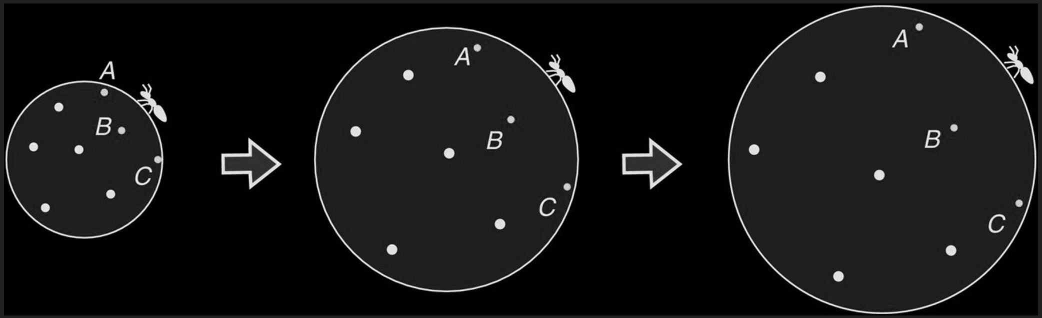
But the gravity is pulling stuff together

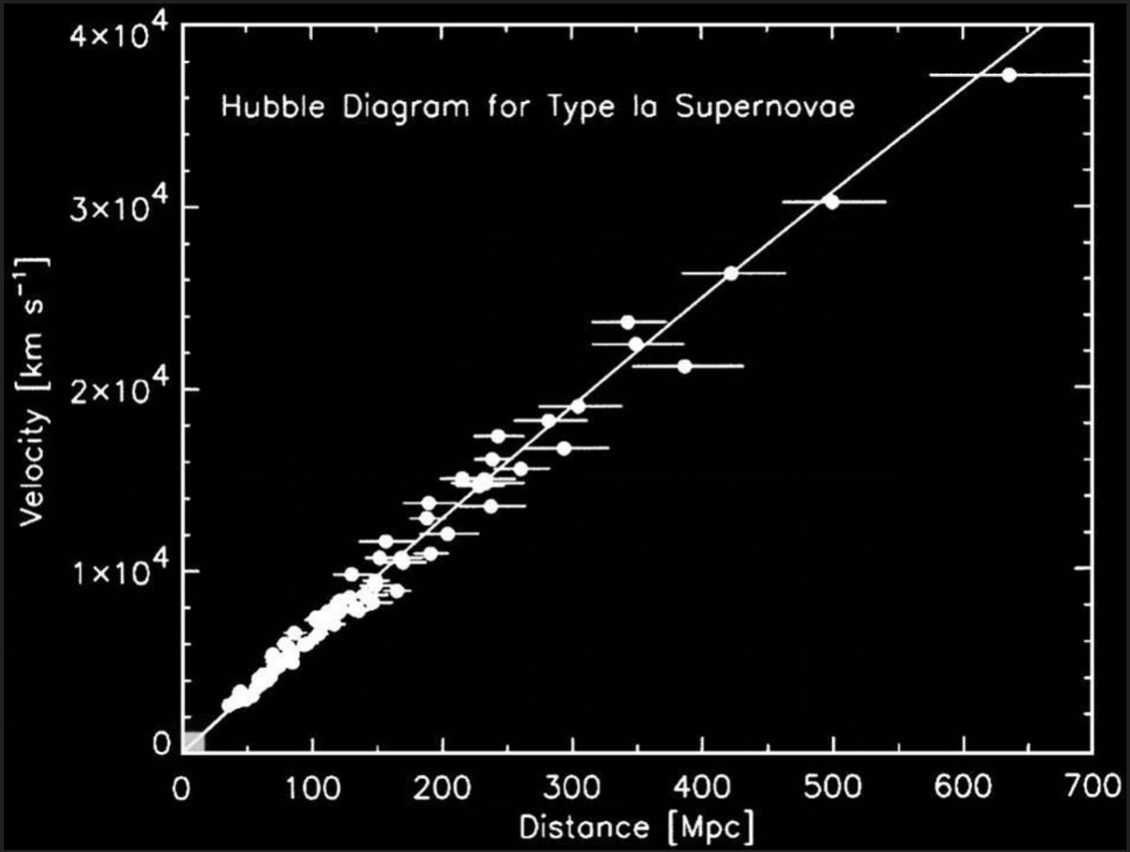
Einstein introduce the "push" → Cosmological constant

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}$$

The universe is expanding → Big Bang

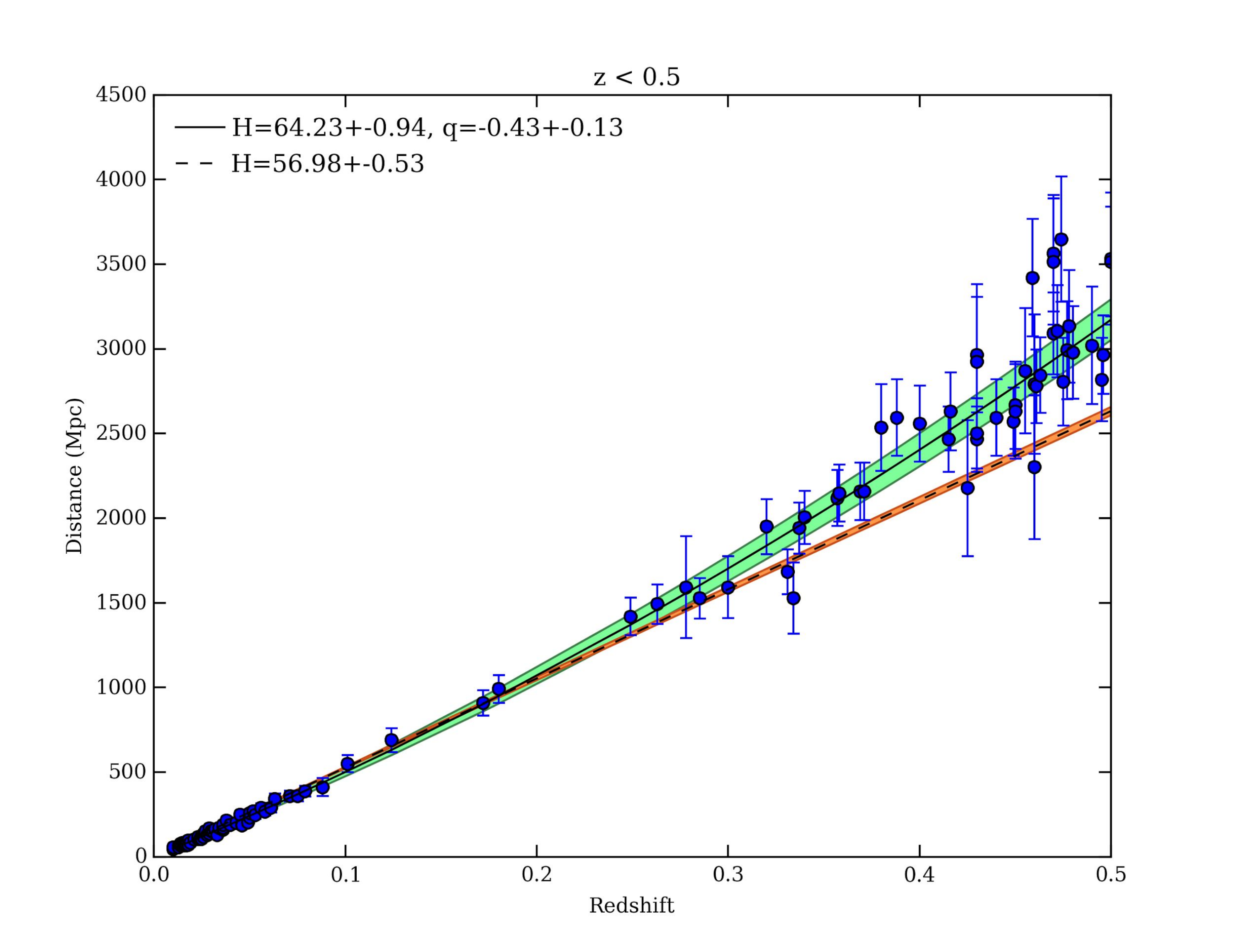
We can measure the speed and distance of galaxies





Big Bang – There is no need for a force (Λ) that pushing out

A c c e l e r a t i n g



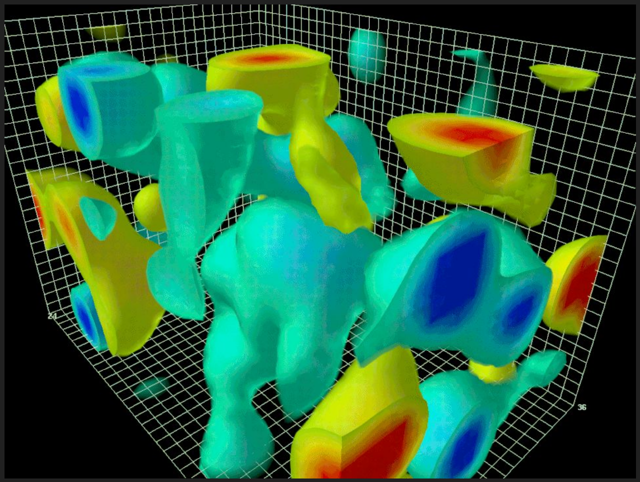
Cosmological constant coming back!

$$\Lambda$$

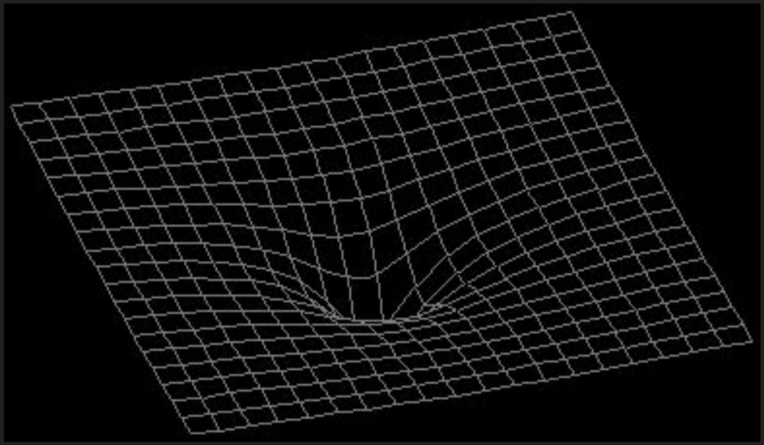
Where does this come from? Quantum field theory?

Vacuum is not empty

vacuum energy from quantum field =
100,000,000,000,000,000,000,000,000,000,000,000,000,000,000,0
00,000,000,000,000,000,000,000,000,000,000,000,000,000,000,00
0,000,000,000,000,000,000 ✖ cosmological constant



$$\approx 10^{120} \times$$



Not a clue → the real hunting has not even started

The best we can do is to conclude that...

- Most of the energy in the universe is not matter
- Most of the energy in the universe is not attractive
- We actually live in not so special place but a very special time
- The fate of our universe is at the hands of Dark Energy


Thank you

Back up

For a more complete review

- G. Jungman, M. Kamionkowski, K. Griest, Phys. Rept. 267, 195 (1996)
- G. Bertone, D. Hooper and J. Silk, Phys. Rept. 405, 279 (2005) [arXiv:hep-ph/0404175]
- M. Bauer and T. Plehn, Lect. Notes Phys. 959 (2019) [arXiv:hep-ph/1705.01987]

Where are they?

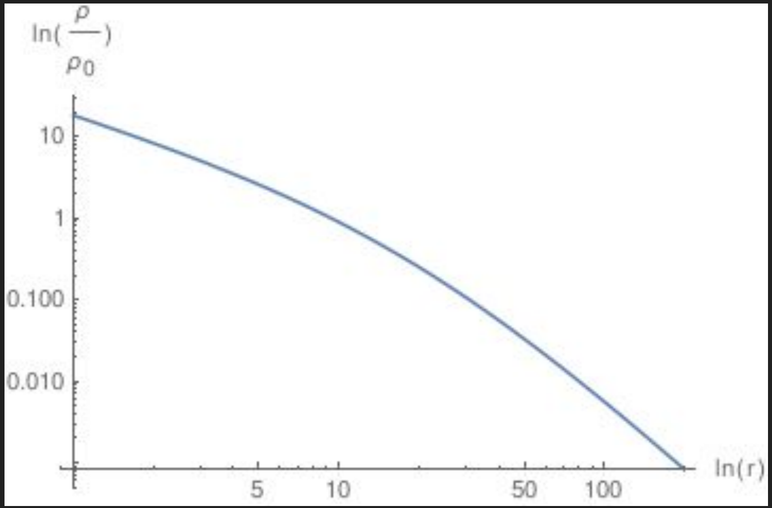
Local Density

- N-body simulation suggests a general density profile

NFW profile (Navarro, Frenk, and White)

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$$

$$\rho(r) \propto \frac{1}{r^2} \quad \text{at} \quad r \sim r_s$$



	α	β	γ	R (kpc)
Kra	2.0	3.0	0.4	10.0
NFW	1.0	3.0	1.0	20.0
Moore	1.5	3.0	1.5	28.0
Iso	2.0	2.0	0	3.5

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\left(\frac{r}{r_s}\right)^{\alpha}\right)^{(\beta-\gamma)/\alpha}}$$

0404175

Large uncertainties for small radii

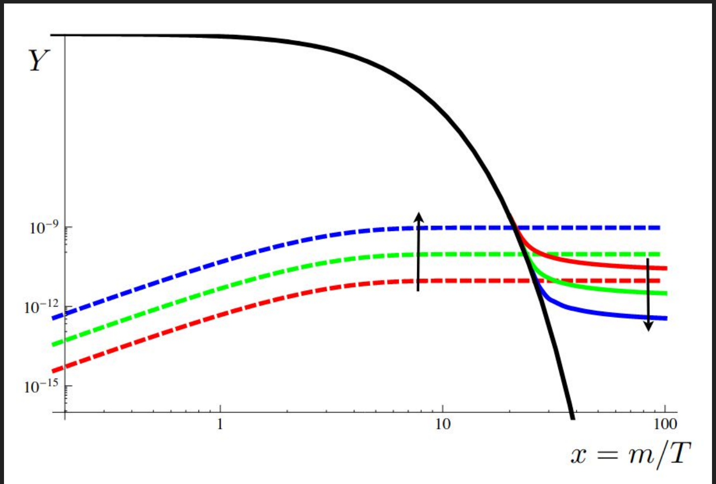
Other mechanisms

Freeze In Mechanism

- What if dark matter interactions are not strong enough to keep dark matter in thermal equilibrium at the beginning?
- We can produce dark matter slowly

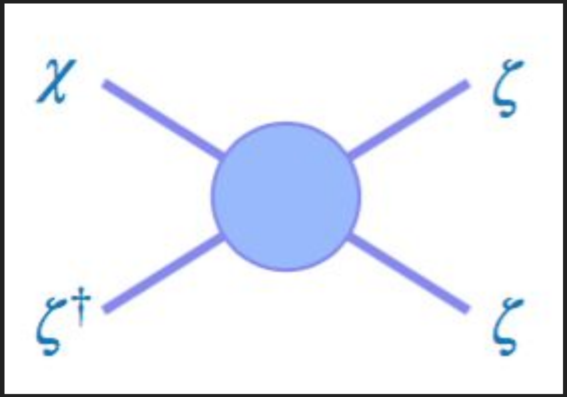
$$\mathrm{sm} + \mathrm{sm} \to \mathrm{dm} + \mathrm{sm}$$

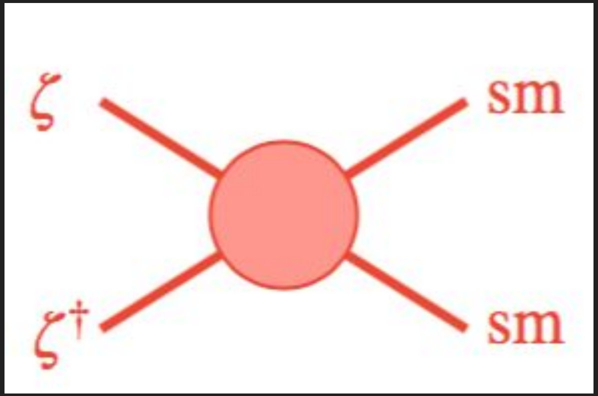
- And the process stops after the temperature falls below the threshold



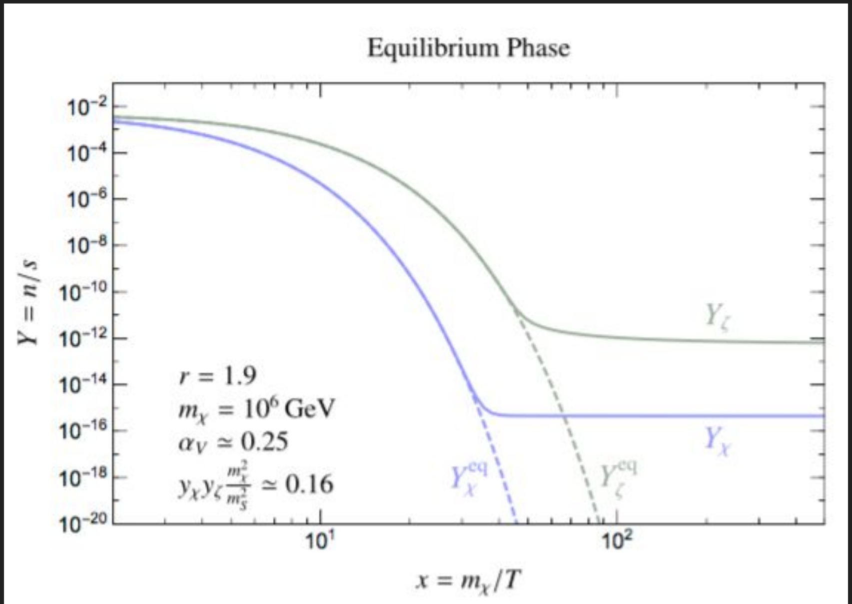
0911.1120

Zombie Dark Matter





- Zombie particle is out of equilibrium first
- Zombie starts to attack dark matter until the number density is too low
- Leftover dark matter = relic density



2003.04900

Asymmetric Dark Matter

- Borrow an idea from Baryogenesis
- Baryon *asymmetry* = A tiny *asymmetry* between baryon and antibaryon creates leftover to form protons and neutrons

$$\Omega_{\rm dm} \approx 5\Omega_b$$

- Density of dark matter and density of baryon is remarkably close
- One can connect the origin of *asymmetry* and obtain:

$$n_b - n_{\bar{b}} \approx n_X - n_{\bar{X}}$$

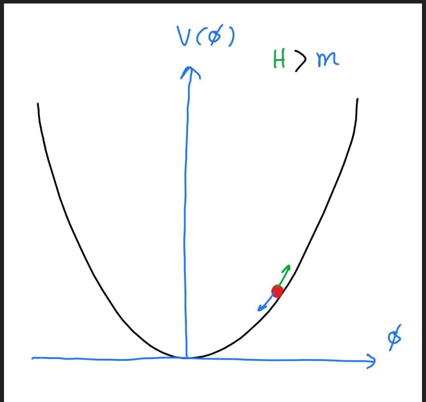
$$m_X \approx 5 m_p \approx 5 \text{ GeV}$$

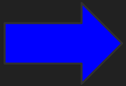
1308.0338

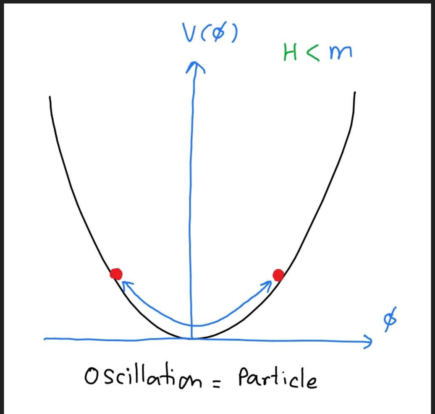
Misalignment Mechanism

- Starting from "misaligned" fields, the evolution of scalar field is frozen by the Hubble rate

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$







- After the Hubble rate becomes lower than the mass, the oscillation begins -> matter condensation
- Particles with very weak coupling such that they have never been in thermal equilibrium -> Axion