A general review of dark matter

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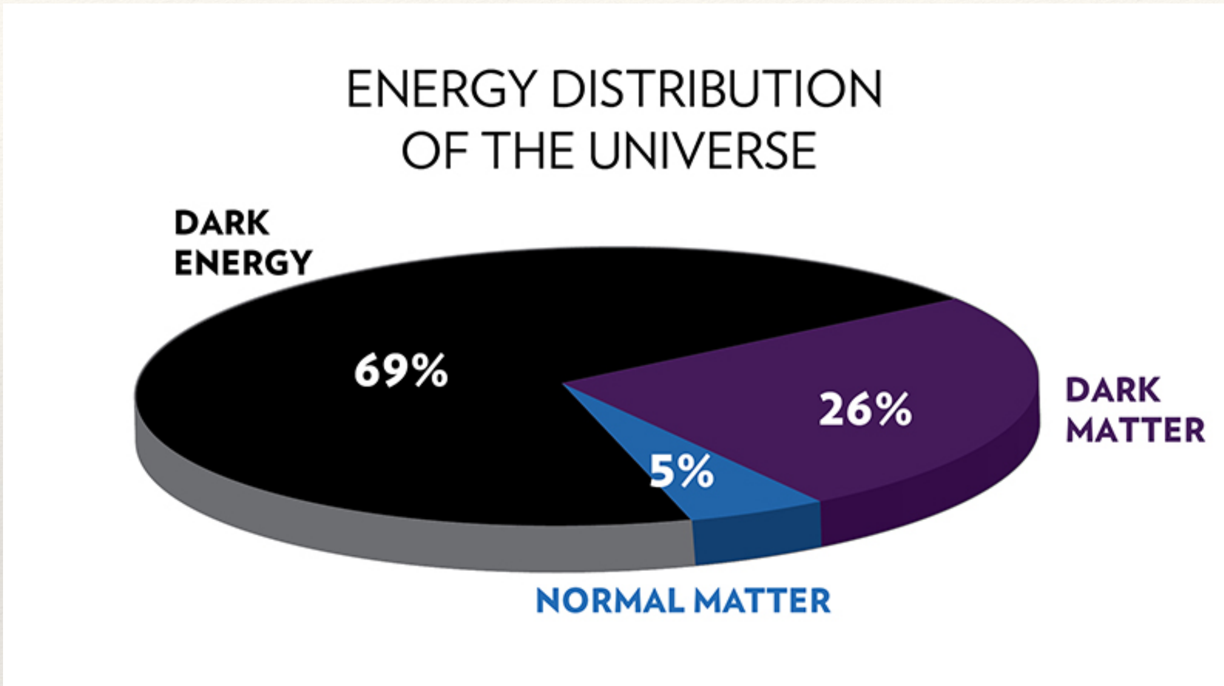
Outline

— Evidence for dark matter

— General considerations for dark matter models

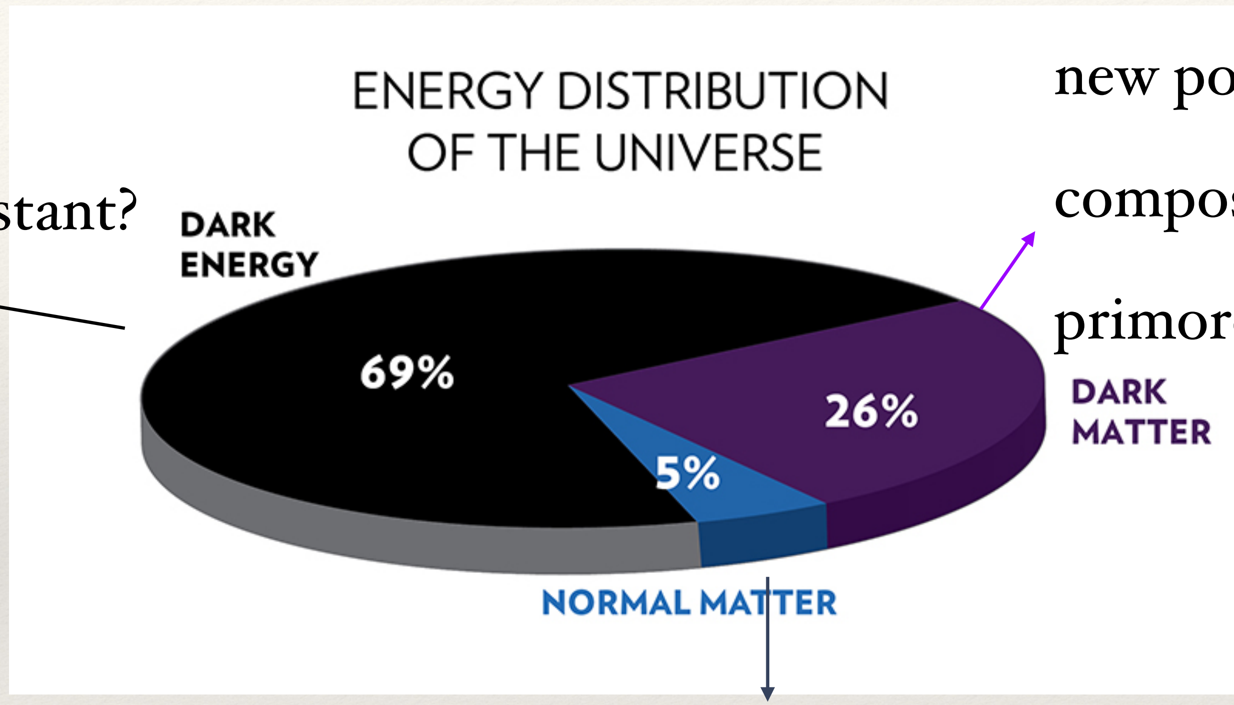
— Benchmark dark matter models

— General search strategies


ENERGY DISTRIBUTION OF THE UNIVERSE
DARK ENERGY
69%
26%
DARK MATTER
5%
NORMAL MATTER

cosmological constant?

a scalar field?



new point-like particle?

composite object?

primordial black hole?

Standard Model of particle physics

Evidence for dark matter

In spiral galaxies such as our Milky Way, most visible matter are in a galactic disk: $R_{\rm disk} \sim 10\,{\rm kpc}, h_{\rm disk} \sim 0.5\,{\rm kpc}$.

pc: parsec ~ 3.3 lightyears.

Rotation Curves

Newtonian gravity tells us that the circular velocities of stars

$$v_c(r) = \sqrt{\frac{GM}{r}}$$

GM → enclosed mass

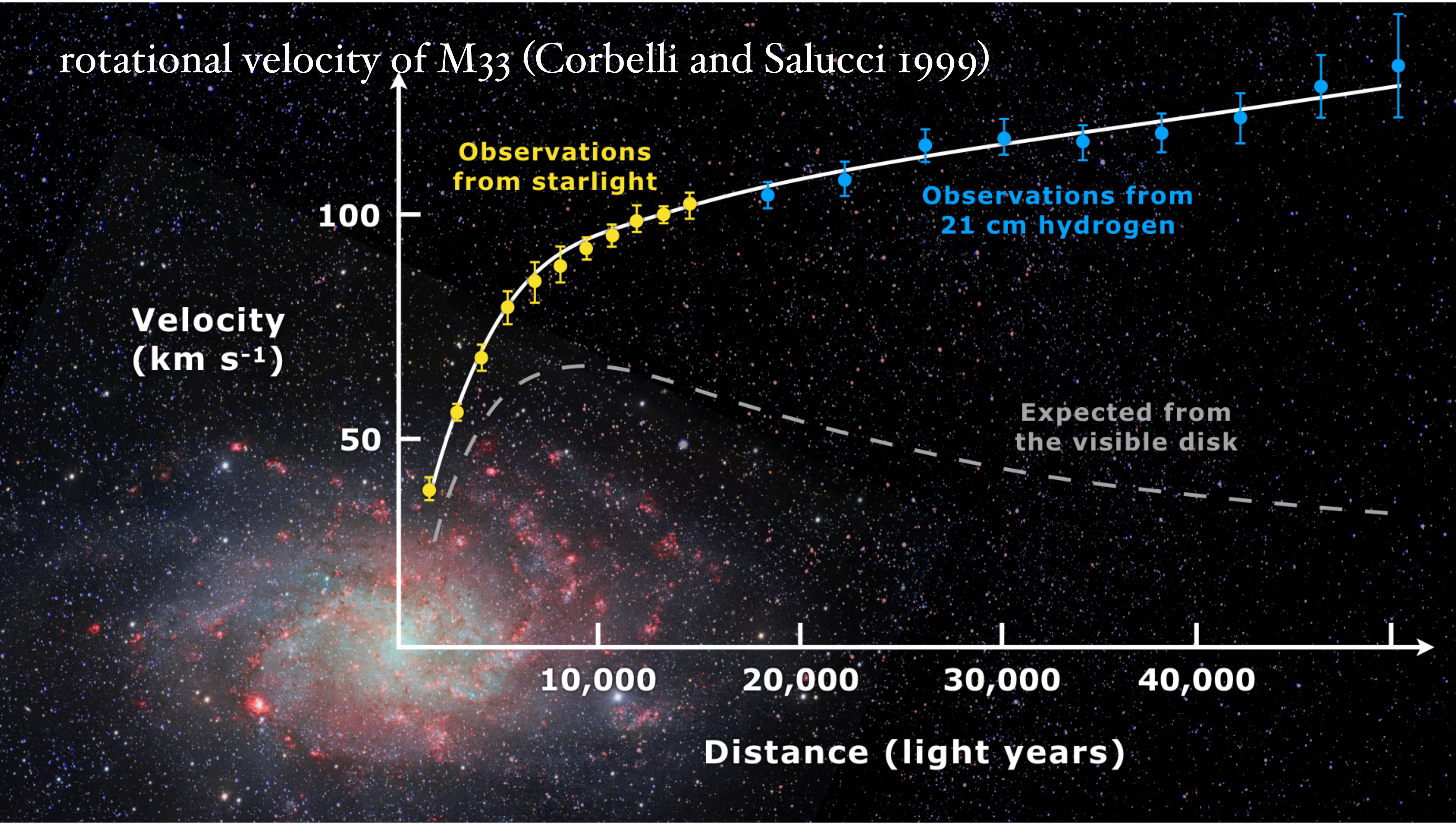
r → radial distance

When $r \gtrsim R_{\text{disk}}$, $M \sim$ a constant if all the mass is the visible matter mostly residing in the disk. The we expect $v_c \propto 1/\sqrt{r}$.

Yet at large r, $v_c \sim$ a constant $\Rightarrow M(r) \propto r$. More "invisible" matter out there!

Rubin, Ford 1970; Roberts, Whitehurst 1975; Rubin, Thonnard, Ford 1980; Bosma 1981; ....

rotational velocity of M33 (Corbelli and Salucci 1999)



Dark matter density is

$$\rho(r) \propto \frac{M(r)}{r^3} \sim \frac{1}{r^2}$$

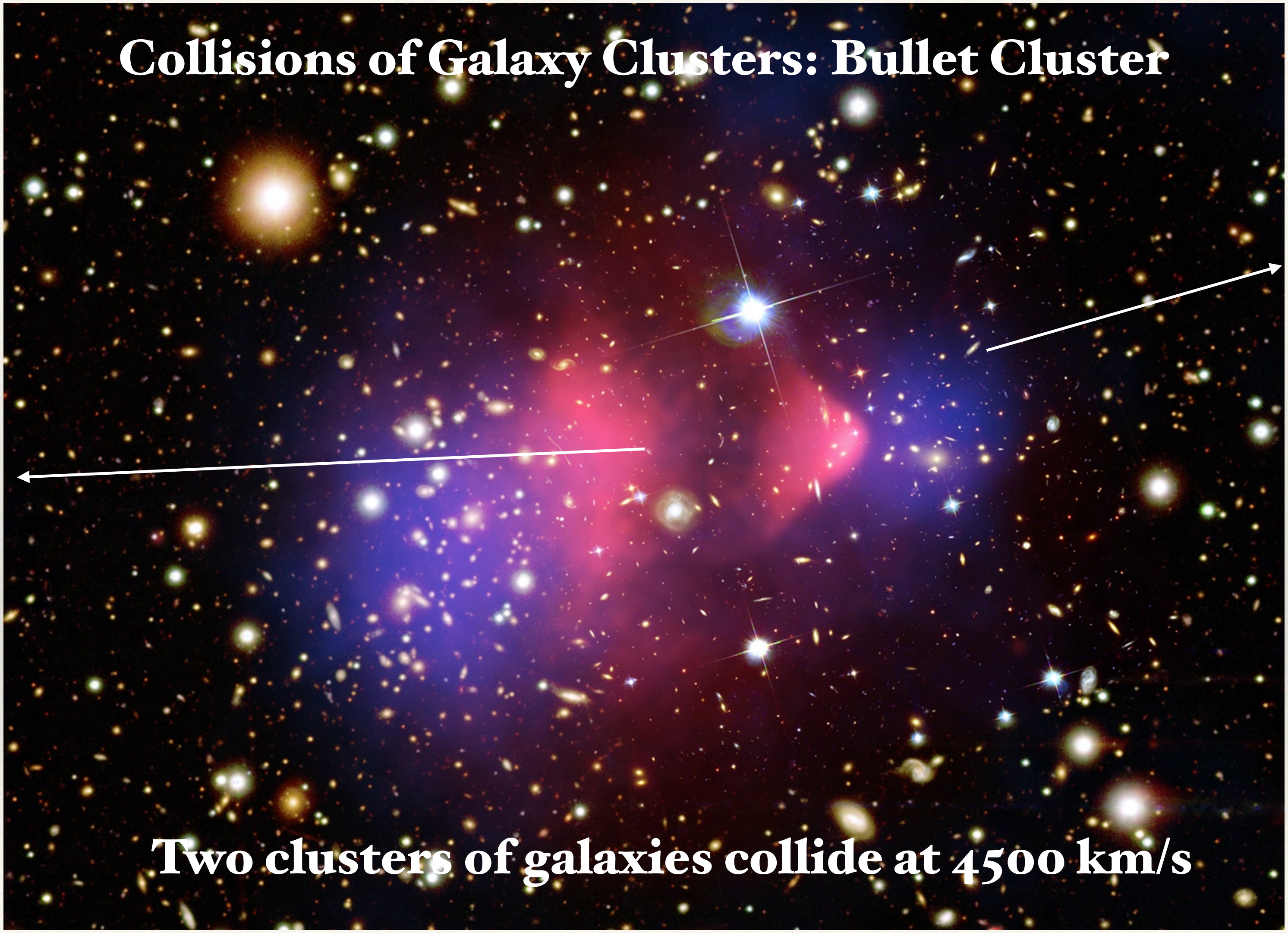
assuming that DM is distributed in a spherically symmetric halo.

Milky way: total mass $M_{\text{halo}} \sim 10^{12} M_\odot$ ($M_\odot$ solar mass), local DM density (in the solar system) $\sim 0.4\,\text{GeV/cm}^3$, then the halo radius

$M_{\text{halo}} \sim 4\pi \int_0^{R_{\text{halo}}} dr r^2 \rho(r) \Rightarrow R_{\text{halo}} \sim 100\,\text{kpc}$ **one order of magnitude above R_{disk}!**

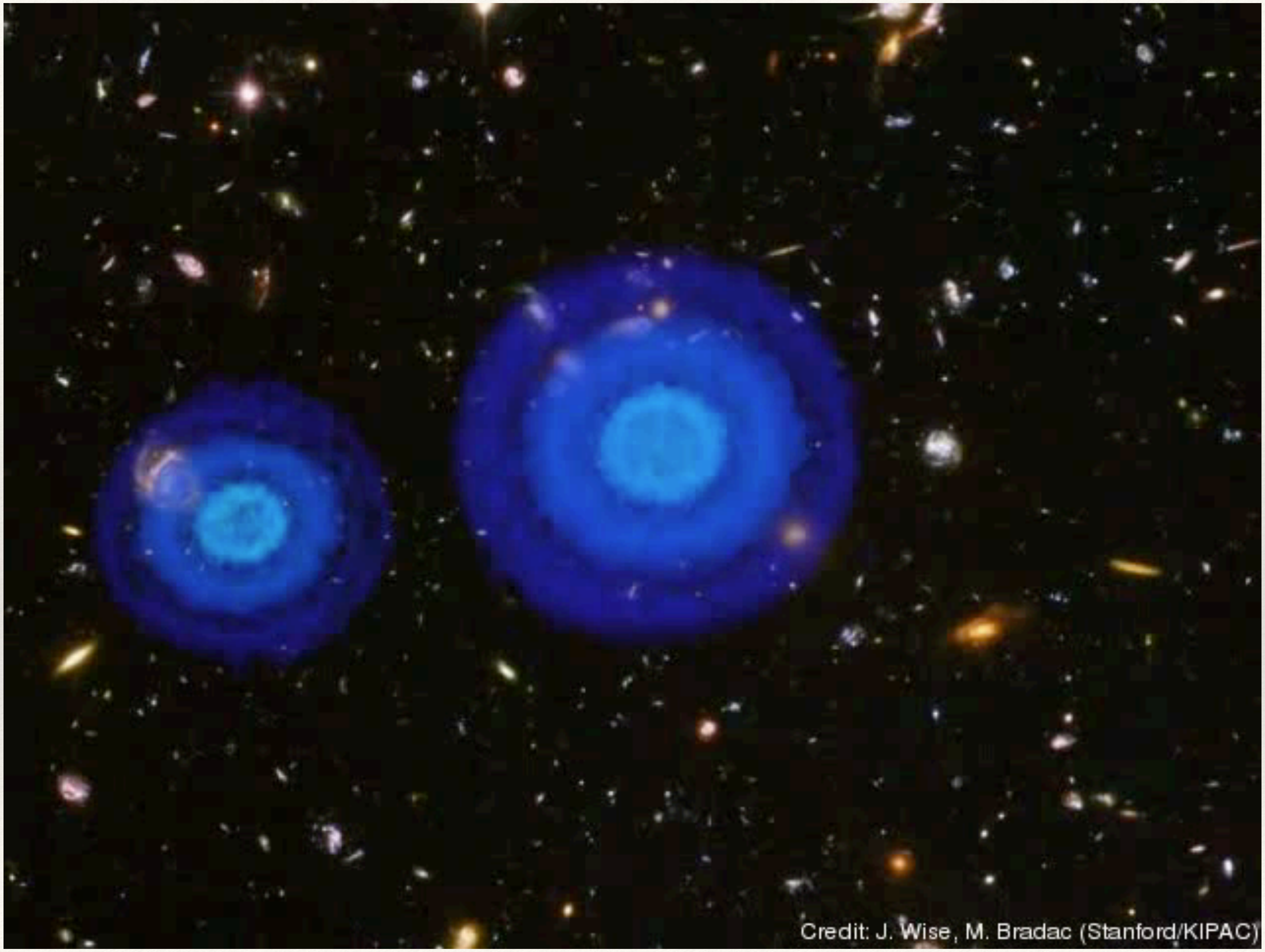
Average velocity of DM: $\langle v \rangle \sim \sqrt{\frac{GM_{\text{halo}}}{R_{\text{halo}}}} \sim 200\,\text{km/s}$ **Non-relativistic!**


Collisions of Galaxy Clusters: Bullet Cluster
Two clusters of galaxies collide at 4500 km/s

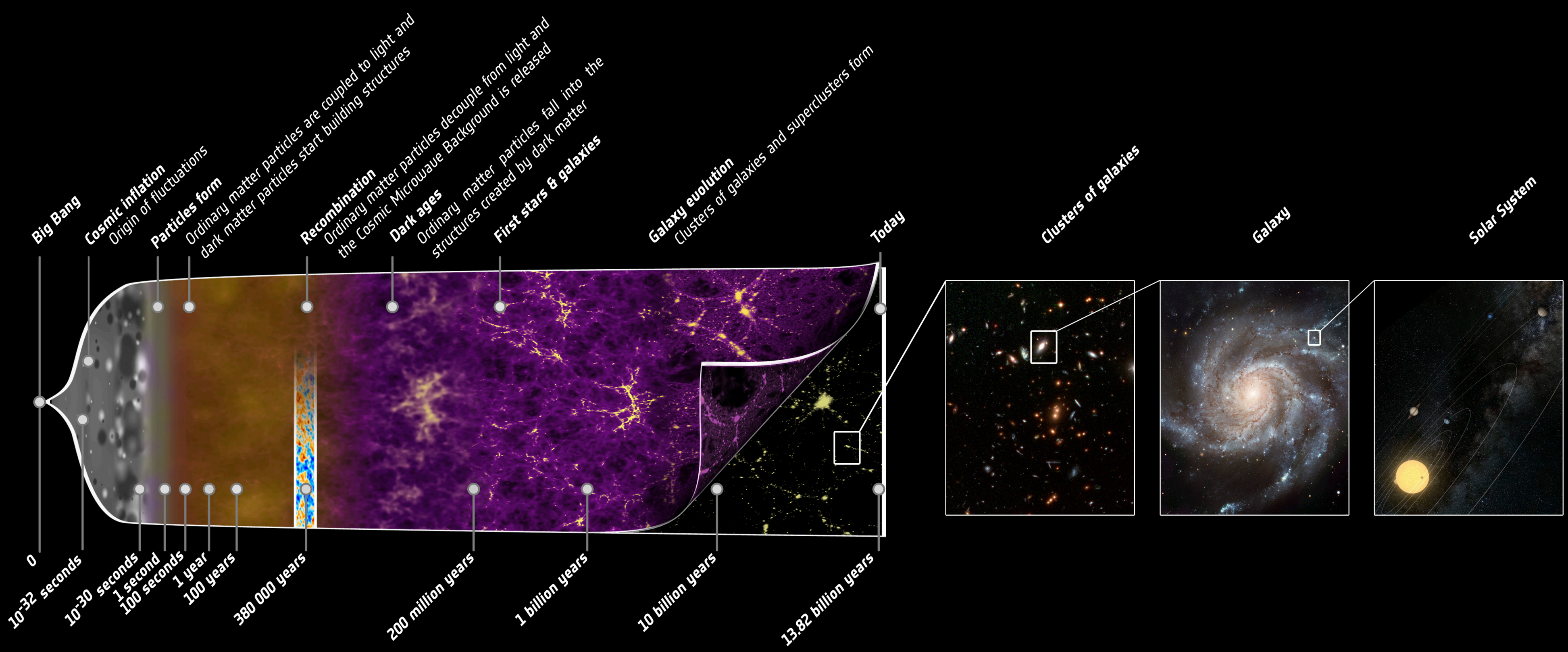


X-ray: hot gas

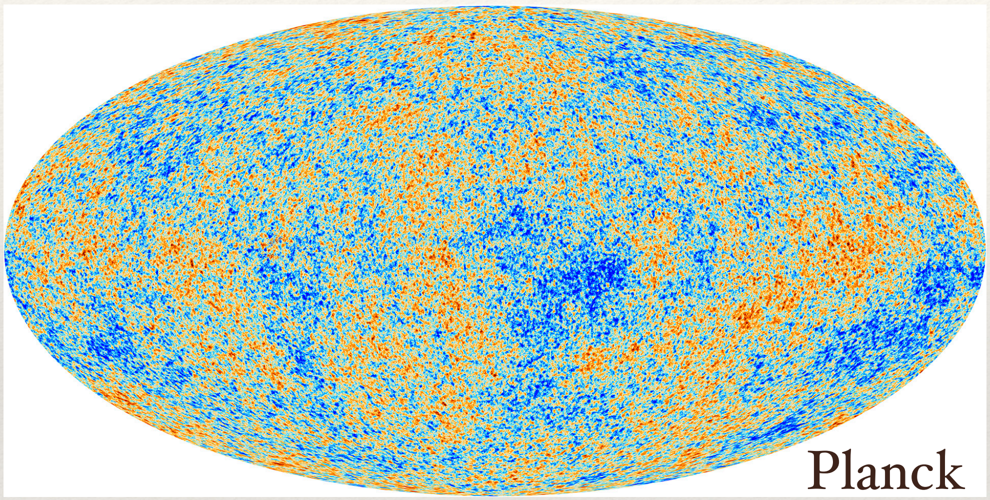
gravitational lensing: dark matter

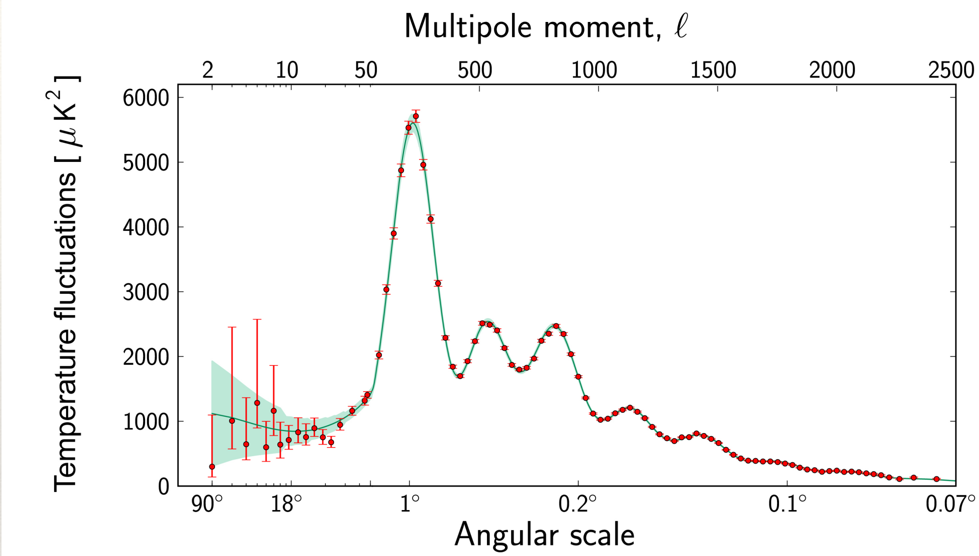

Credit: J. Wise, M. Bradac (Stanford/KIPAC)

Cosmic Microwave Background



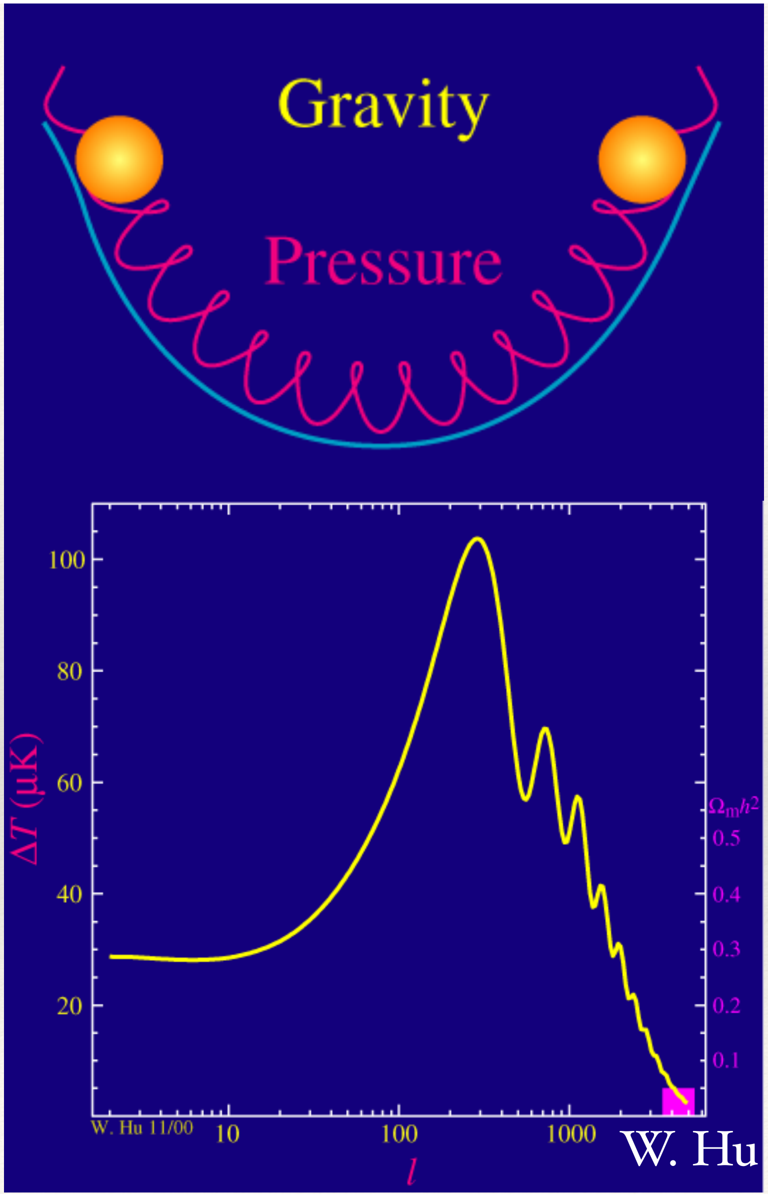
Snapshot of the oldest light in our universe imprinted on the sky when the universe was 380,000 years old.





$T_{\text{CMB}} = 2.7\text{K}$, fluctuation ~ 10^{-5}

Power spectrum, e.g., temperature fluctuations in the CMB at different angular scales on the sky.



Acoustic oscillations: radiation pressure resists gravitational compression ⇒ peaks and troughs in CMB spectrum.

CMB power spectra very well fit by ΛCDM— the standard model of cosmology with dark matter makes up ~80% of the matter today: $\Omega_{DM}h^2 = 0.12 \pm 0.001$.

For reviews, W. Hu's online lecture notes; TASI lecture "cosmological perturbations" J. Lesgourgues 2013;

We have tremendous astrophysical and cosmological evidence at all astrophysical scales (e.g., galaxy, galaxy cluster and CMB) for the existence of dark matter as the dominant component of matter in the universe.

General considerations for dark matter models

DM mass

Fermionic DM: a ***lower*** mass bound called "Tremaine-Gunn bound" Tremaine, Gunn 1979; Boyarsky, Ruchayskiy, and Iakubovskyi 2008

Escape velocity as an upper bound on the velocity of DM particles in galaxies + Pauli exclusion principle (one fermion per quantum state).

Consider a constant-density sphere of mass M and radius R made up of fermions with mass m_f . Fermi energy (highest energy level occupied by fermions):

$$E_f = \frac{1}{2m_f}\left(n_f 3\pi^2\right)^{2/3} = \frac{1}{2m_f}\left(\frac{9\pi}{4}\frac{M}{m_f R^3}\right)^{2/3}$$

n_f : fermion number density;

Fermi velocity: $E_f = \frac{1}{2} m_f v_f^2 \Rightarrow v_f = \frac{1}{m_f} \left(\frac{9\pi}{4} \frac{M}{m_f R^3} \right)^{1/3}$

Requiring $v_f \lesssim v_{\mathrm{esc}} = \sqrt{\frac{2GM}{R}}$, we have

$m_f \gtrsim 100\,\mathrm{eV}$ (from dwarf galaxies with $M \sim 5 \times 10^7\, M_\odot, R = 2.5\,\mathrm{kpc}$).

Warm dark matter limit: for sufficiently low mass DM, there is suppression in matter power spectrum (the spectrum of density fluctuations in matter). $m_f \gtrsim \mathrm{keV}$ (not a hard boundary though).

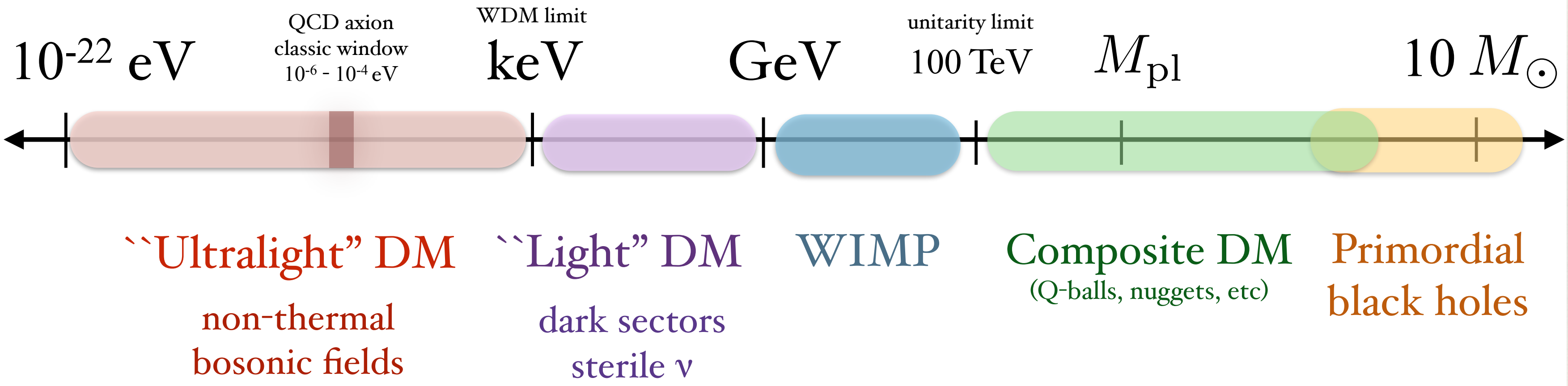
Bosonic DM:

A ***lower*** mass bound from uncertainty principle $\Delta x \Delta p \gtrsim 1/2$. Taking $\Delta x \sim R \sim 1\,\mathrm{kpc}$ (dwarf galaxy) and $\Delta p \sim m_\phi v$,

$$v \gtrsim \frac{1}{R m_\phi} \sim 20\,\frac{\mathrm{km}}{\mathrm{s}}\frac{10^{-22}\,\mathrm{eV}}{m_\phi}.$$

Requiring $v \lesssim v_{\mathrm{esc}} \Rightarrow m_\phi \gtrsim 10^{-22}\,\mathrm{eV}$ (fuzzy DM). Astrophysical bounds push this limit close to $(10^{-20} - 10^{-19})$ eV. e.g. Dalal and Kravtsov 2022; Goldstein, Koushiappas and Walker 2022.

A general ***upper*** bound on ***particle*** dark matter: $m_\chi \lesssim 10^{19}$ GeV (Planck scale). Above it, dark matter should be thought of as a finite-size black-hole or composite objects, instead of a point-like object. These are interesting possibilities though I will not talk about much in the rest of the lectures.



Lin TASI lecture, 2019

DM lifetime

DM produced in the early universe, probed by CMB and still needs to be around today. Age of universe $\sim 10\,\mathrm{Gyr} \approx 4 \times 10^{17}\,\mathrm{s}$. Thus any viable DM model should have a lifetime at least comparable to the age of the universe and a decay rate $\Gamma \lesssim 3 \times 10^{-18}\,\mathrm{s}^{-1}$!

Depending on how DM decays, the bound could be stronger! E.g., DM decays to dark radiation, lifetime of DM has to be above 250 Gyr if all DM decays.
Simon et.al 2022

DM self-interaction

Bullet cluster: DM did not undergo appreciable self-interactions during crossing.

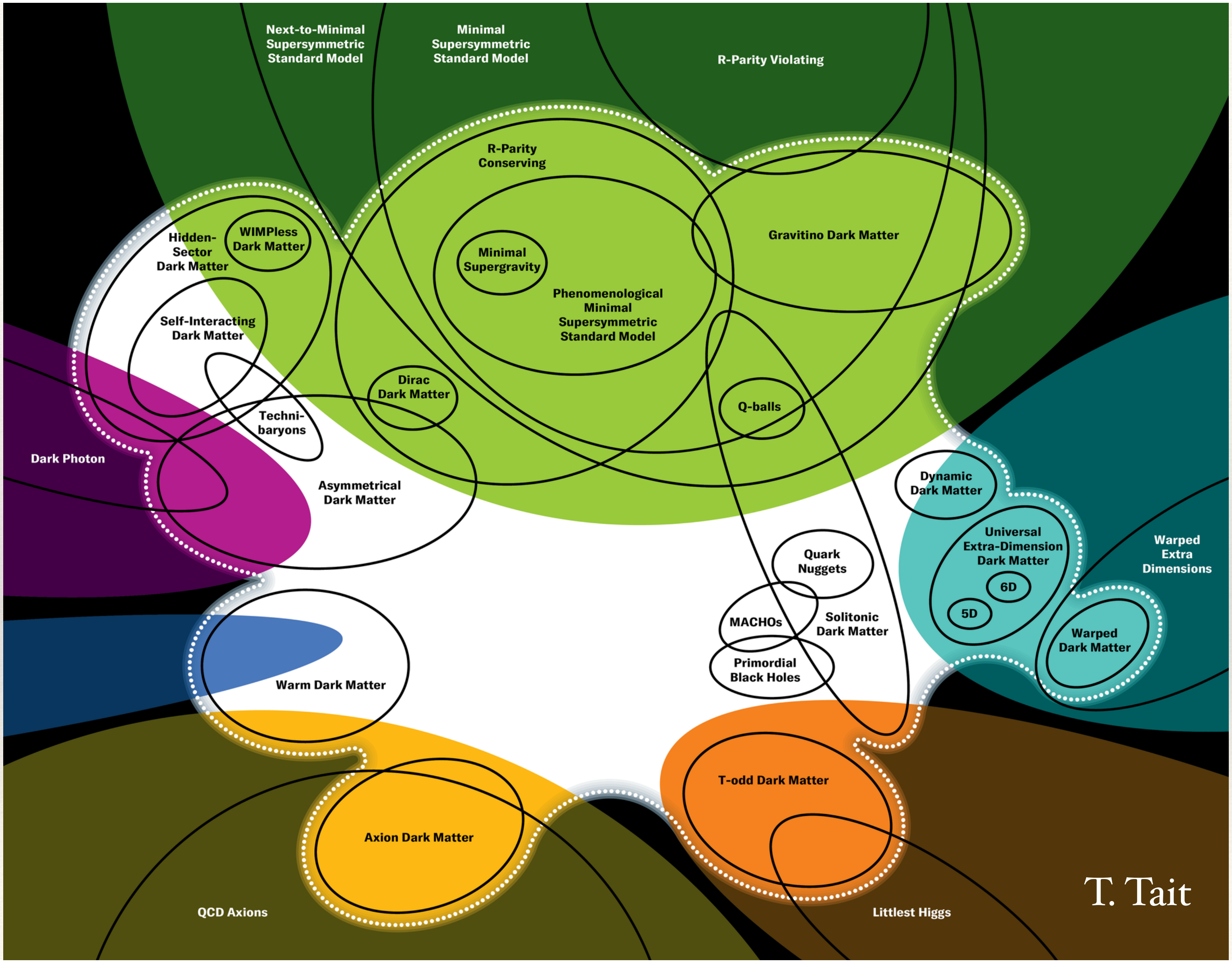
Probability of scattering $\sim n_\chi \sigma_{\rm DM} L < 1$ (n_χ : number density; σ_{DM}: DM scattering cross section; L :halo size). $n_\chi = M_{\rm halo}/(4/3\pi L^3)/m_\chi$

$$\sigma_{\rm DM}/m_\chi \lesssim 1\,{\rm cm}^2/{\rm g} \quad {\rm or} \quad \sigma_{\rm DM}/m_\chi \lesssim \left(\frac{1}{0.06\,{\rm GeV}}\right)^3$$

Comment: still possible to leave larger signatures of DM self-interaction in small-scale DM halos (i.e. dwarf galaxies) and still consistent with the bullet cluster bound, by invoking ***velocity-dependent*** self-interaction processes.

$\sigma_{\rm DM} \propto \frac{1}{v^n}$, more important in dwarf with lower v than in bullet cluster with higher v.

Benchmark DM models


Next-to-Minimal Supersymmetric Standard Model
Minimal Supersymmetric Standard Model
R-Parity Violating
R-Parity Conserving
Gravitino Dark Matter
Hidden-Sector Dark Matter
WIMPless Dark Matter
Minimal Supergravity
Phenomenological Minimal Supersymmetric Standard Model
Self-Interacting Dark Matter
Techni-baryons
Dirac Dark Matter
Q-balls
Dark Photon
Asymmetrical Dark Matter
Dynamic Dark Matter
Universal Extra-Dimension Dark Matter
6D
5D
Warped Extra Dimensions
Warped Dark Matter
Quark Nuggets
MACHOs
Solitonic Dark Matter
Primordial Black Holes
Warm Dark Matter
T-odd Dark Matter
Axion Dark Matter
QCD Axions
Littlest Higgs
T. Tait

WIMPs and thermal candidates (more in Lec. 2)

DM was in thermal equilibrium with the Standard Model thermal bath.

👍 Relic abundance determined by a few quantities;

👍 Interaction between DM and the SM: interesting and testable signatures.

Further categorization:

- 10 GeV - 10 TeV: weakly-interacting massive particles (WIMPs). ***WIMP miracle***: thermal DM candidate embedded in a scenario addressing the origin of the electroweak scale. Kill two birds with one stone.

Example: SUSY WIMPs: higgsinos, binos, winos.

- keV - 10 GeV: light dark matter (not ultralight bosonic dark matter).

Dark sector models

Dark sector —— mediator portal —— Standard Model

Higgs, dark photon, axion, sterile neutrino

What is an axion ? (more in Lec. 3)

a periodic compact pseudo-scalar field: realized as a Goldstone boson of a spontaneously breaking $U(1)$ symmetry, the Peccei-Quinn (PQ) symmetry.

$$a \cong a + 2\pi f_a$$

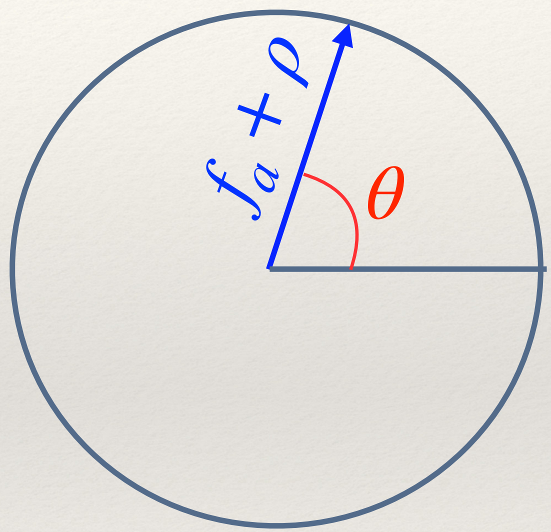
$$\theta \cong \theta + 2\pi$$

$$\theta \equiv \frac{a}{f_a}$$

$$V_\chi = \frac{\lambda}{2}\left(|\chi|^2 - \frac{f_a^2}{2} \right)^2$$

χ : complex Peccei-Quinn (PQ) scalar field

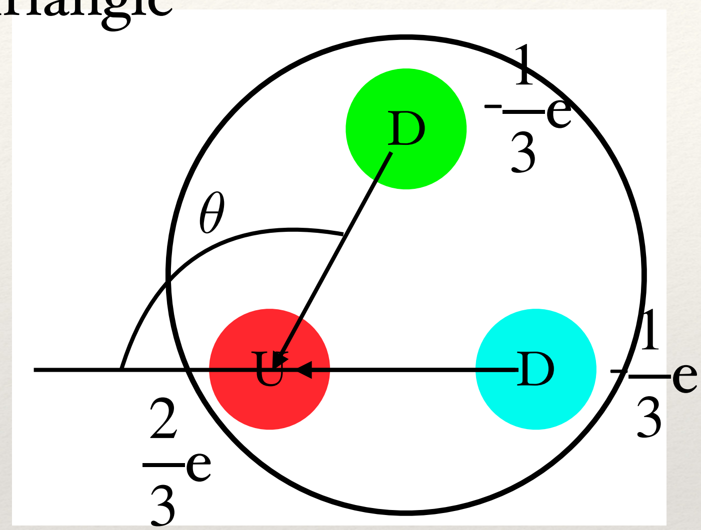
$$\chi = \frac{(f_a + \rho)}{\sqrt{2}} e^{ia/f_a} = \frac{(f_a + \rho)}{\sqrt{2}} e^{i\theta}$$



$$m_\rho = \sqrt{\lambda}\, f_a, \quad m_a = 0$$

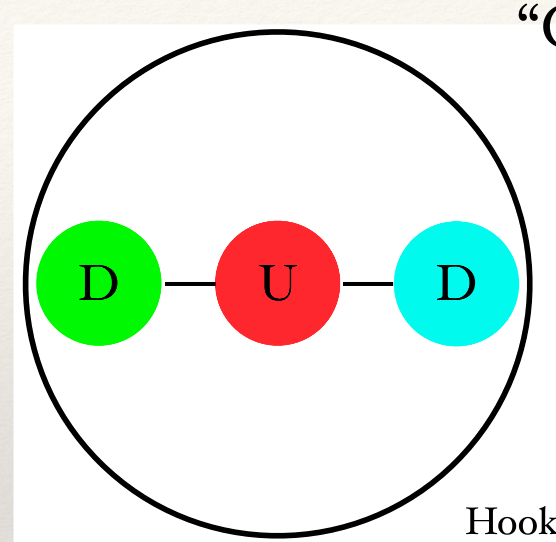
Strong CP problem: QCD axion

Triangle



$$\theta \rightarrow a$$
$$\longrightarrow$$

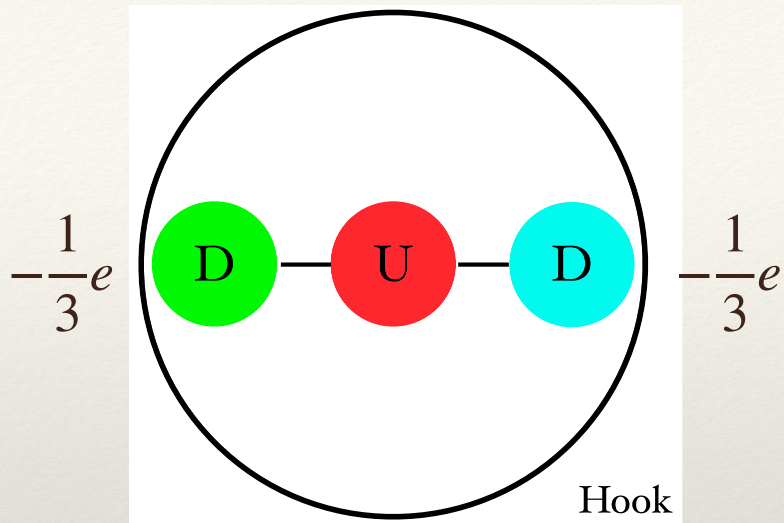
"CO_2"



Neutron electric dipole moment (EDM):

$$\vec{d} = \sum q\vec{r} \Rightarrow |d_n| \approx 10^{-13}\sqrt{1-\cos\theta}\ \mathrm{e\,cm}$$

Experimental result: $|d_n| \lesssim 10^{-26}\,\mathrm{e\,cm} \Rightarrow \theta \lesssim 10^{-13}$

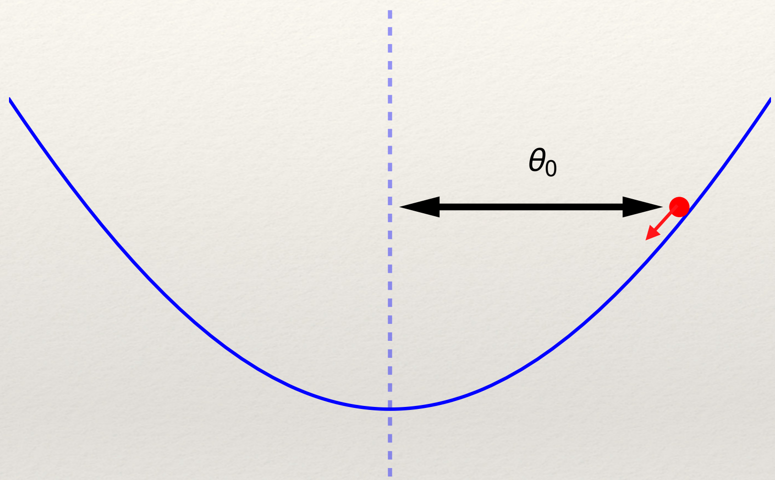


$$\overrightarrow{d} = \sum q\vec{r} = 0$$

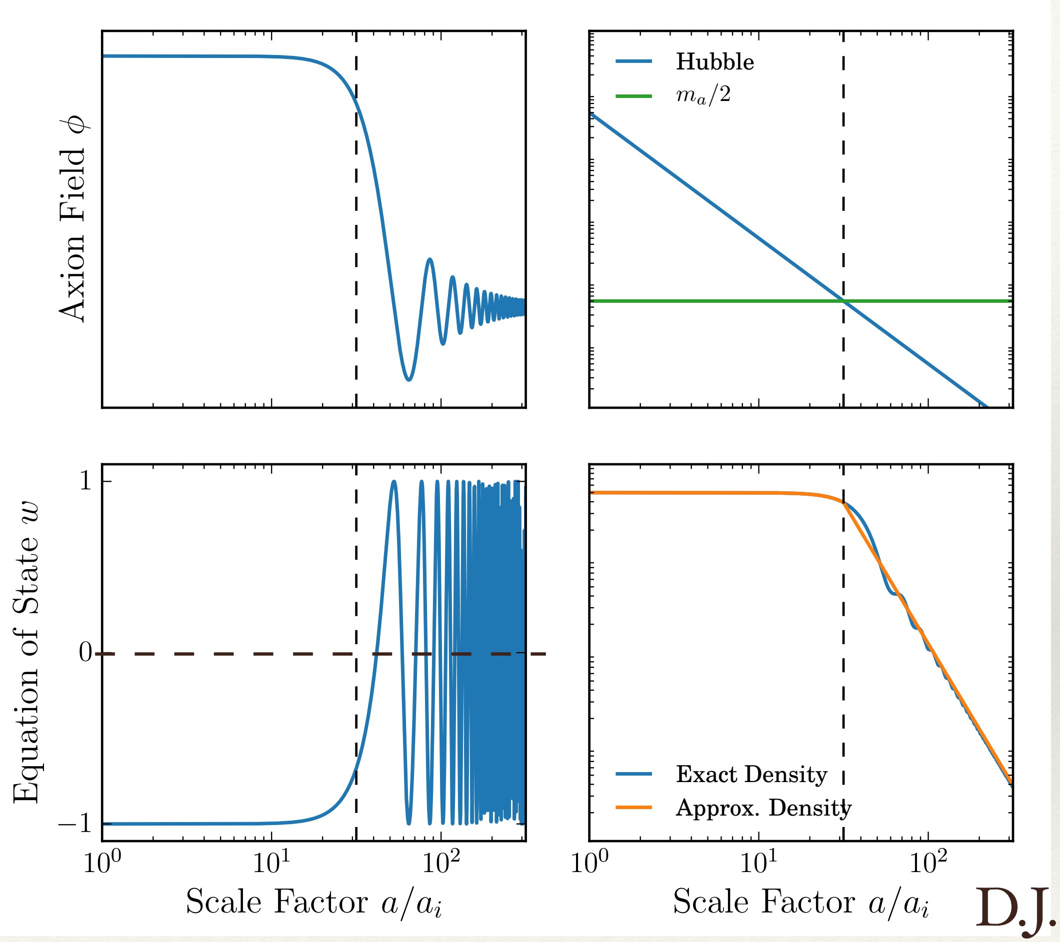
Peccei, Quinn; Weinberg; Wilczek; Kim; Shifman, Vainshtein, Zakharov; Zhitnitsky; Dine, Fischler, Srednicki 1977 - 1981

Axion dark matter through misalignment

Coherent oscillation of axion around the minimal of its potential



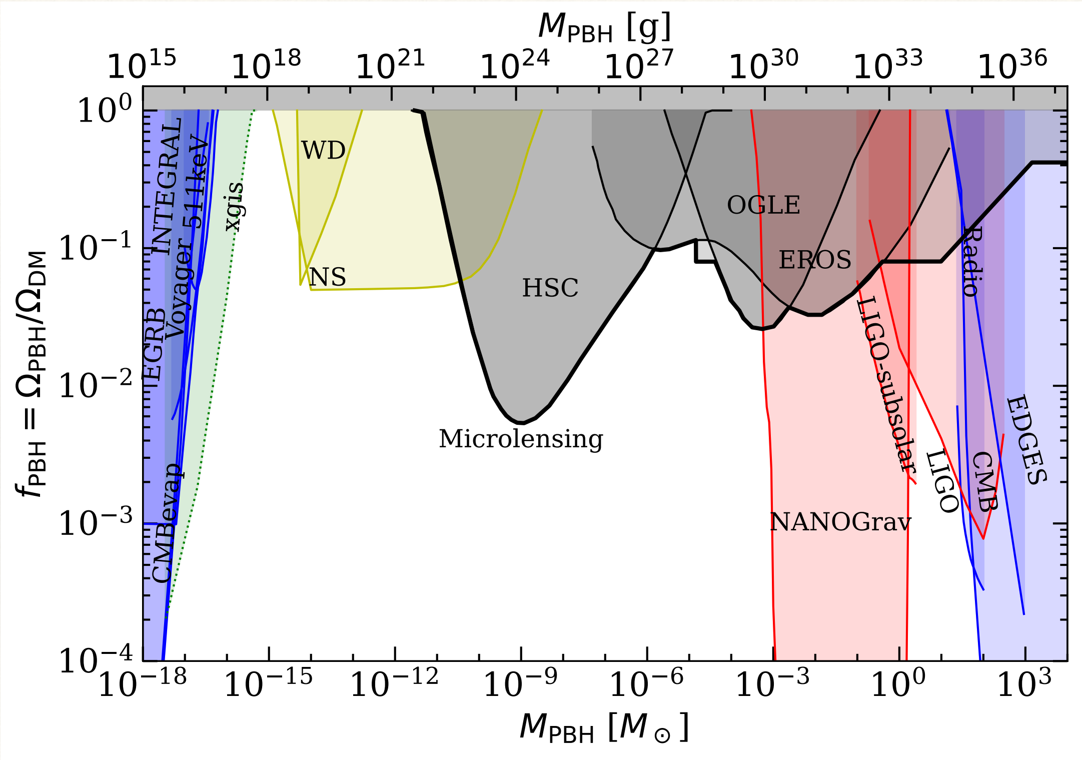
Preskill, Wise; Wilczek, Dine, Fischler; Abbott and Sikivie 1983;



D.J.E.Marsh, 2015

Others

Primordial black holes



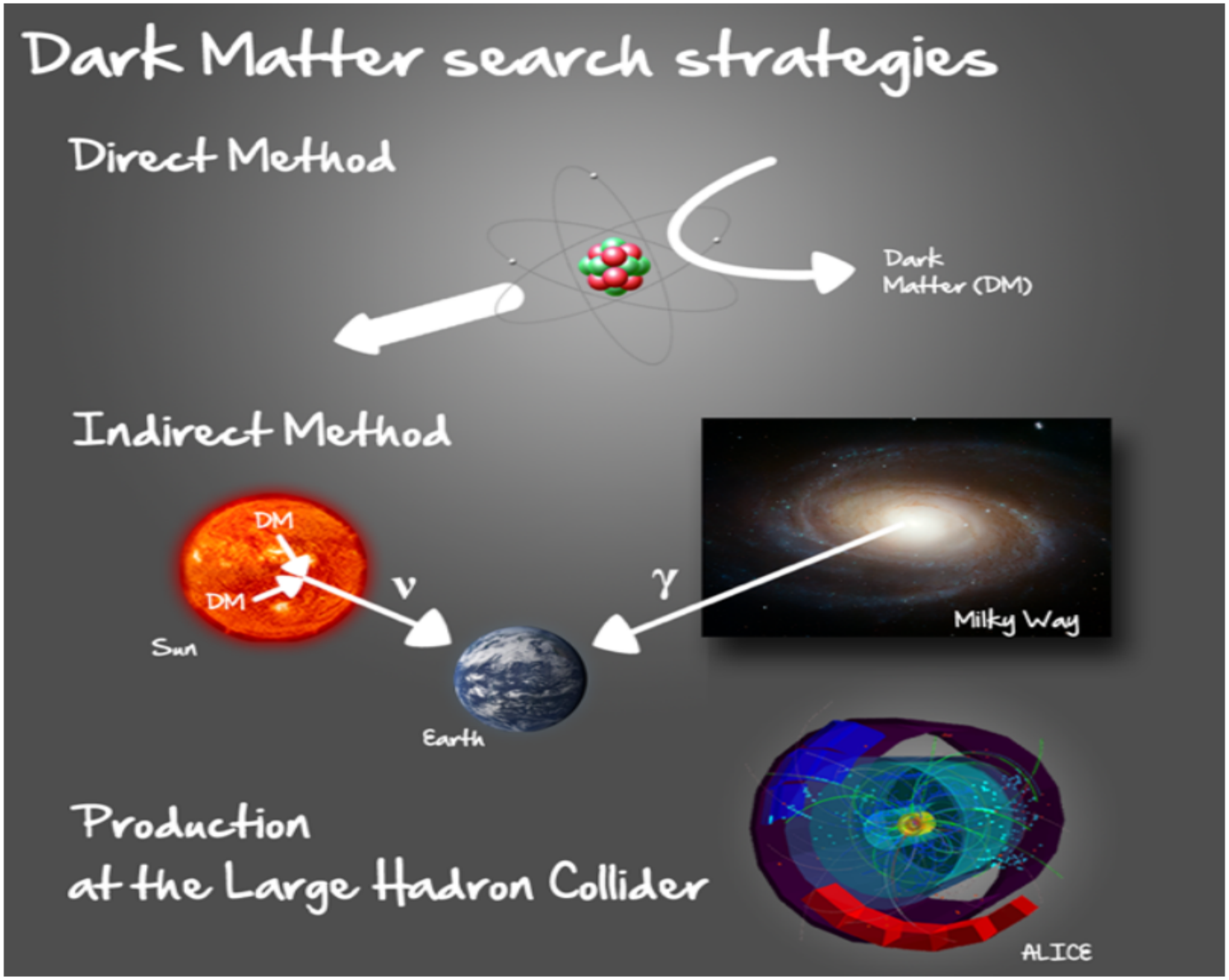
Malyshev et. al 2023 and refs therein

Superheavy candidates and composite objects:

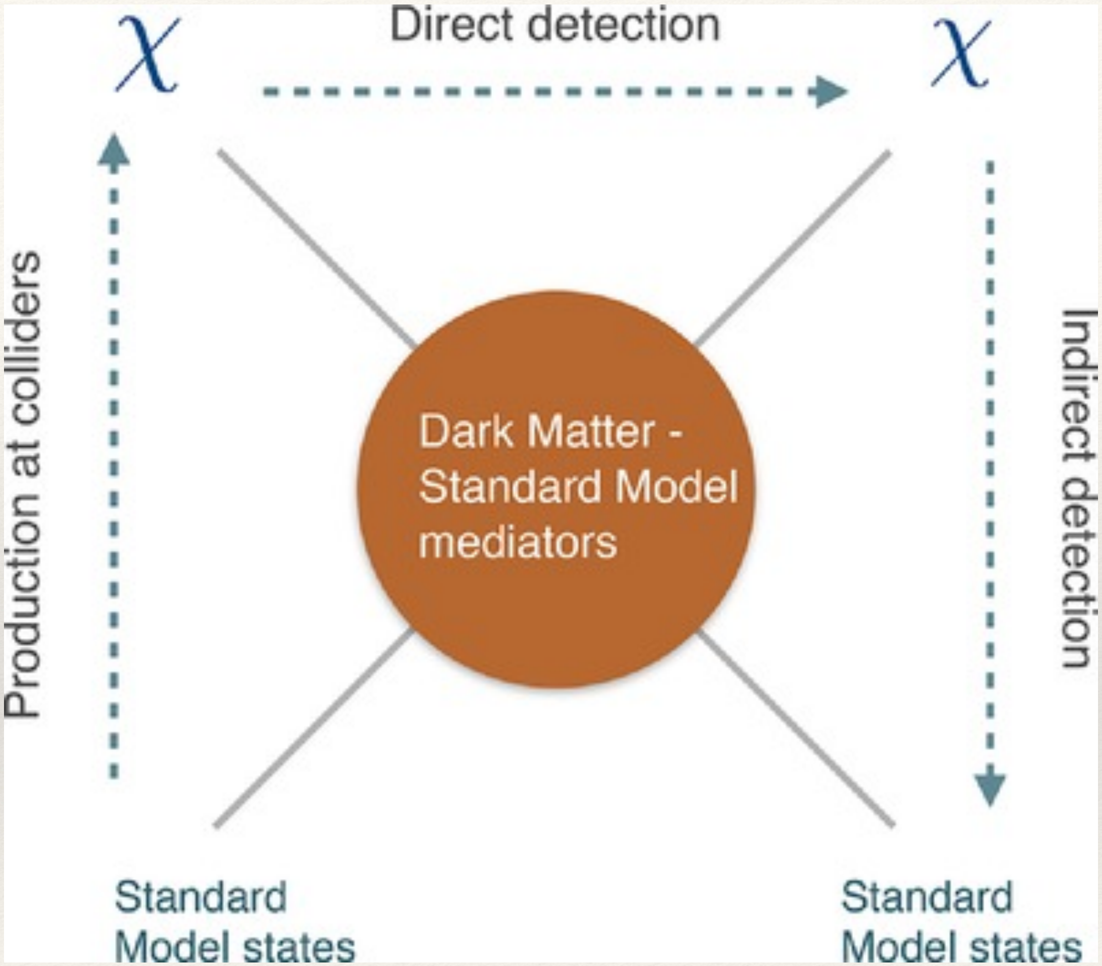
WIMPzillas: mass ~ (100 TeV - Planck scale); produced non-thermally (if produced thermally, the amount of DM would overclose the universe) or through gravitational particle production at the end of inflation;

For even larger masses, bound states or nuggets of fundamental particles.

General search strategies



How to detect dark matter (credit: HAP / A. Chantelauze)



χ
Direct detection
χ
Production at colliders
Indirect detection
Dark Matter - Standard Model mediators
Standard Model states
Standard Model states

More overview references

Lectures on dark matter physics, M. Lisanti, 1603.03793 [hep-ph];

TASI lectures on dark matter models and direct detection, T. Lin, 1904.07915 [hep-ph];

TASI lectures on particle physics and astrophysics of dark matter, B. Safdi, 2303.02169 [hep-ph].

Conclusions

No conclusions about dark matter now!

Just explore and have fun!