Fantastic Dark Matter and Where to Find It

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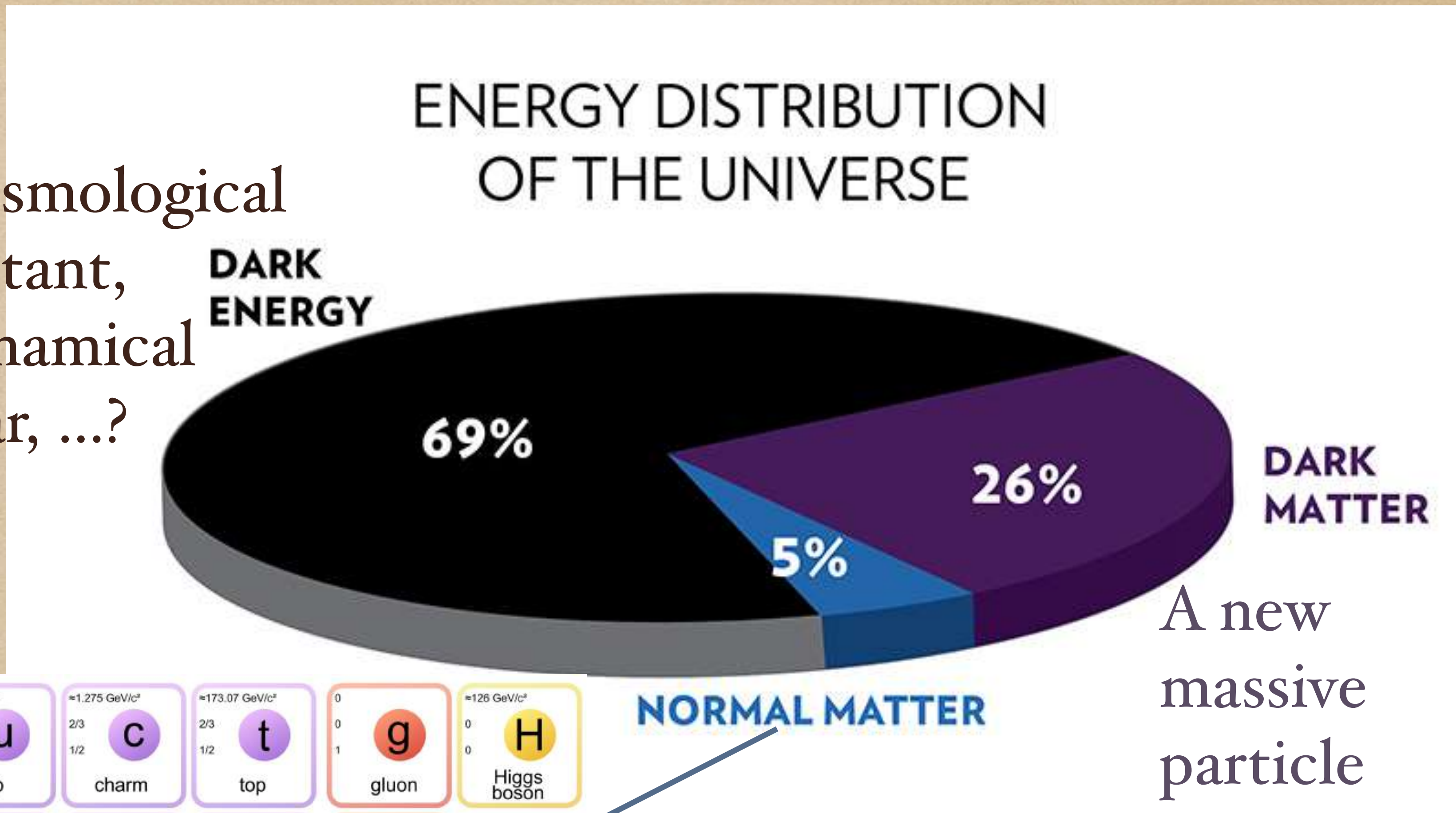
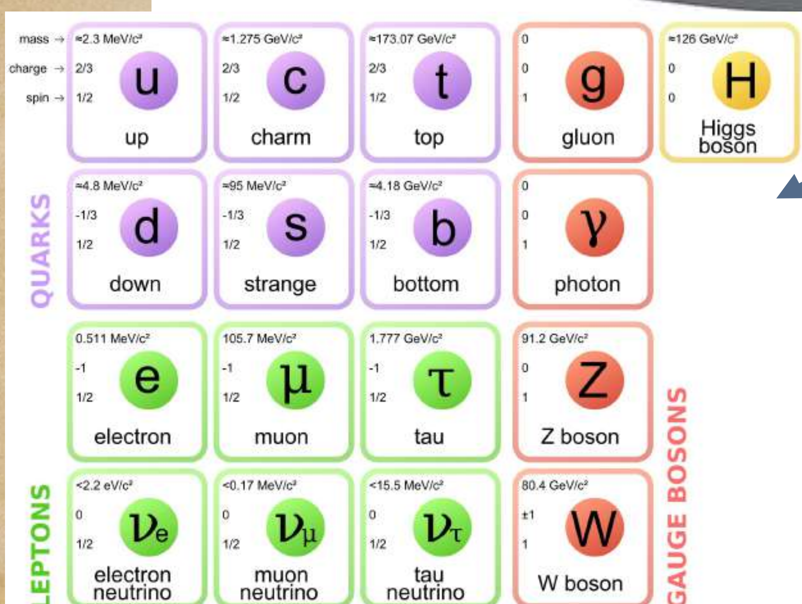
York University, Nov. 3, 2020

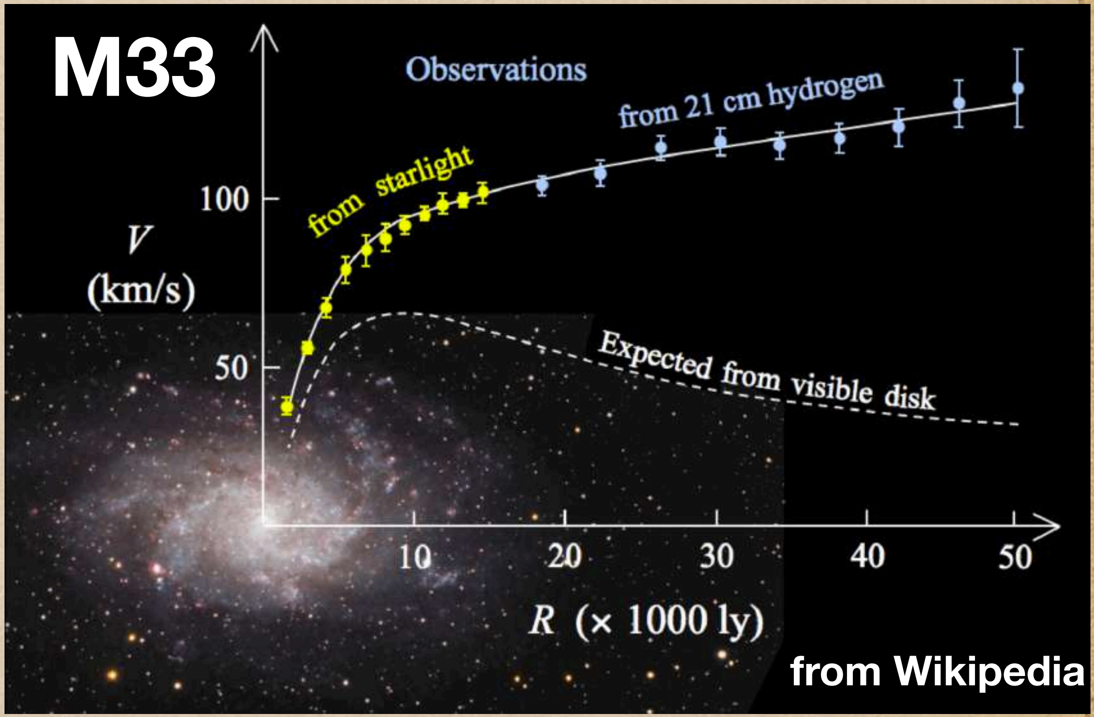


A cosmological constant,
a dynamical scalar, ...?

A new massive particle
or black hole?



Existence of Dark matter



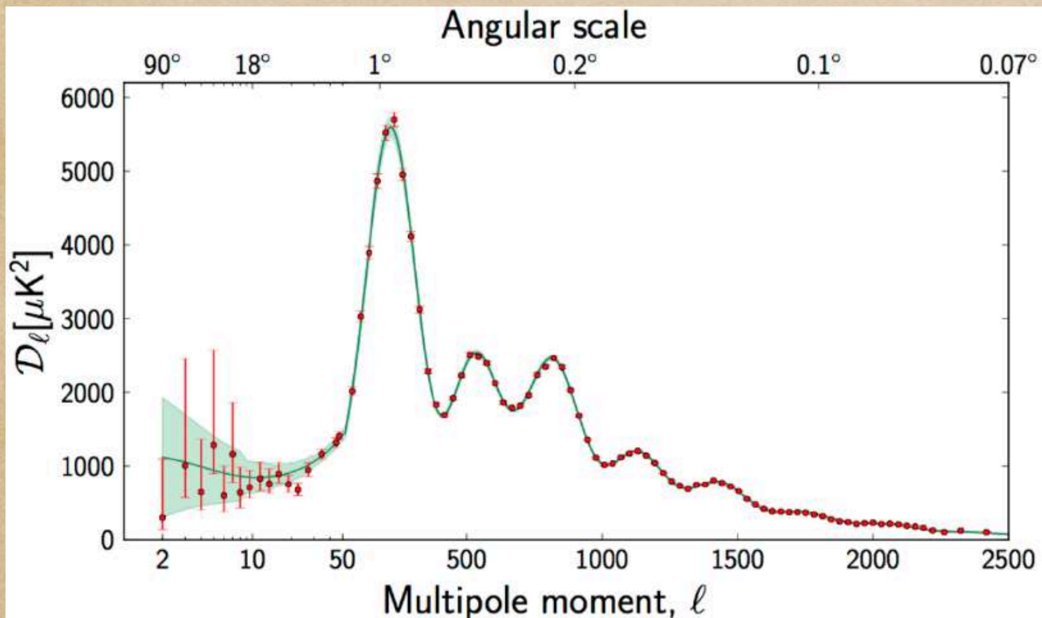
$$v \approx \sqrt{GM(R)/R}$$

Fritz Zwicky and Vera Rubin: dynamical evidence for invisible mass in galaxy clusters and galaxies


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


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

More Cosmological Evidence



Cosmic Microwave Background (radiation from recombination epoch)

Planck CMB TT power spectrum: fit by ΛCDM.

Dark matter distribution inferred from gravitational lensing in CL 0024+17 (blue shading)

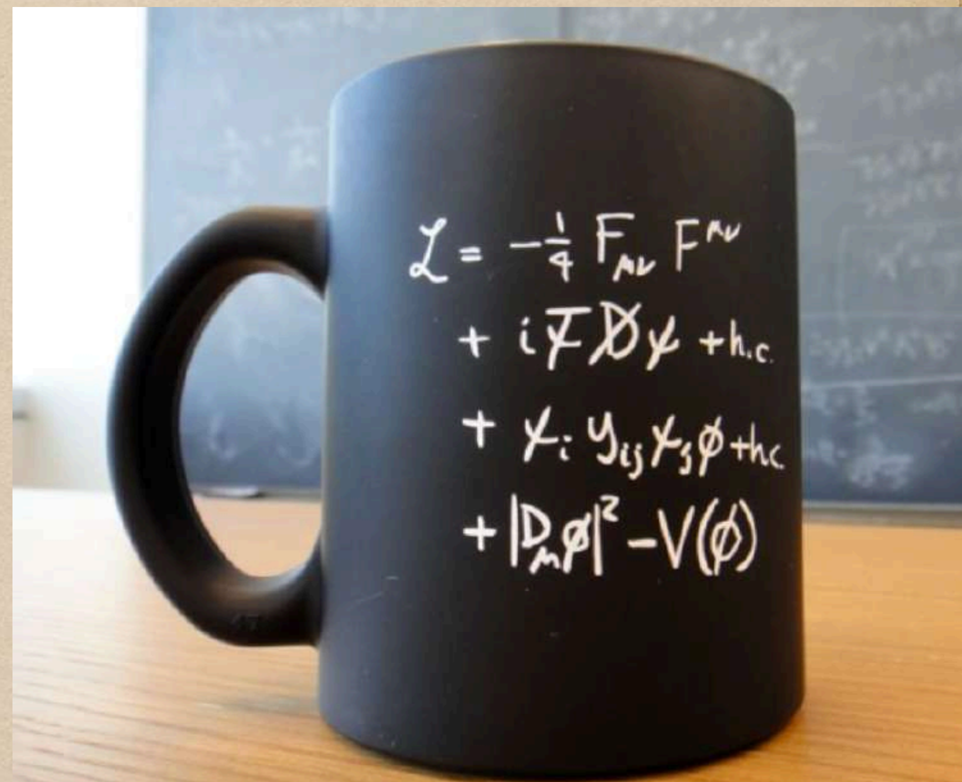
source: nasa.gov

The Dark Matter Abundance

The motion of stars in our galactic neighborhood tells us the local mass density in dark matter:

$$\rho \approx 0.3 \text{ GeV/cm}^3$$

DM particles are constantly passing through us unnoticed.



If dark matter is a type of weakly-interacting massive particle (WIMP), with mass around 100 GeV (100 × proton/nucleon mass), there is about **one** dark matter particle in every coffee-cup sized volume.

What do We Know about Dark Matter?

It exists and is about **85%** of the total matter in the Universe!

It is **stable** and interacts **gravitationally**.

It **interacts very little** with light: neither emits nor absorbs light.

It is (mostly) **collisionless**. On large scale, dark matter halos are roughly spherical, more precisely, triaxial; consistent with N-body collisionless, non-dissipative dark matter simulations.

Questions about Dark Matter

What is dark matter?

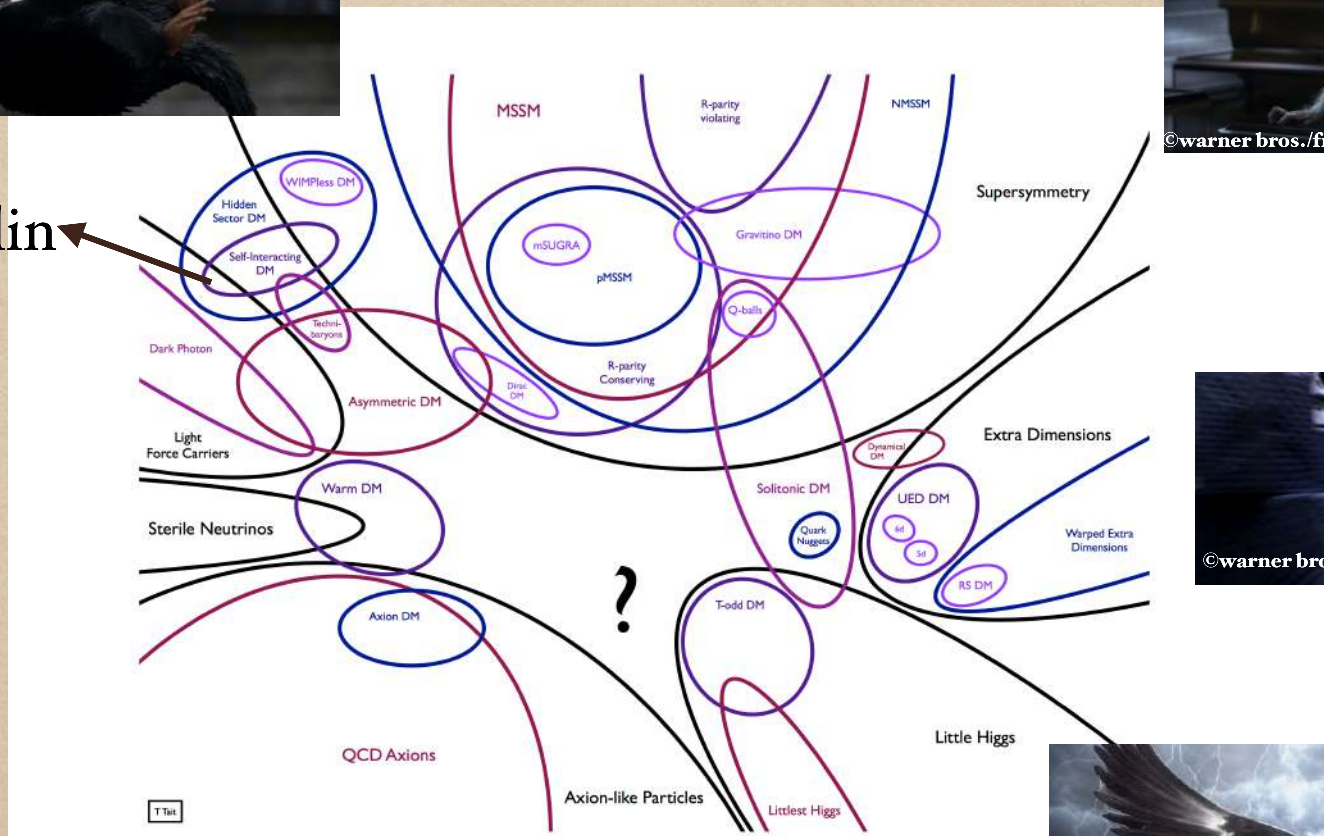
What are its properties? What is its mass? Does it interact beyond gravity?

How to explain its relic abundance?

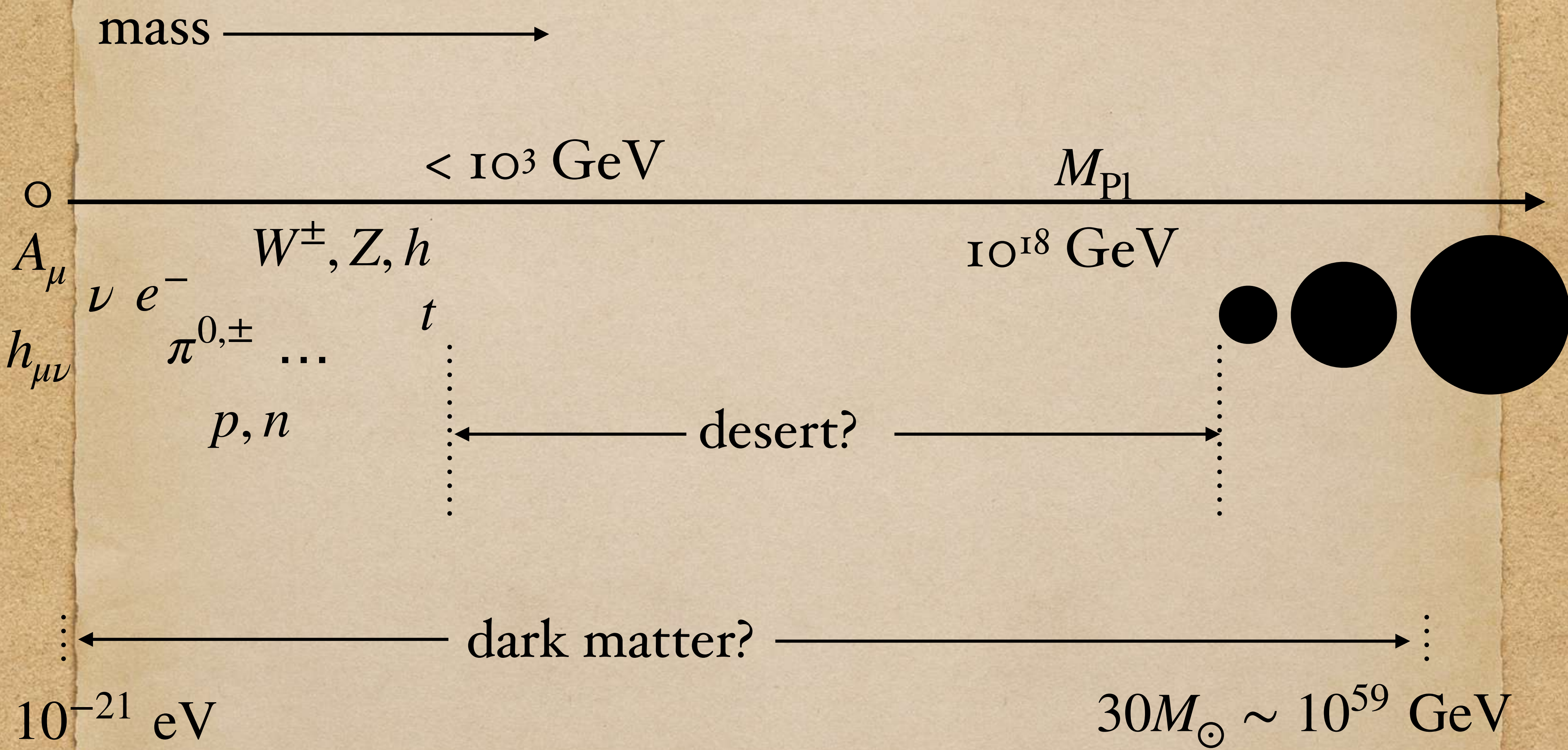
Is there only one species of dark matter? Or is there a dark world with multiple particles and forces? (don't forget the normal matter comes from a very complicated model — the Standard Model).

Zoo of Dark Matter Models

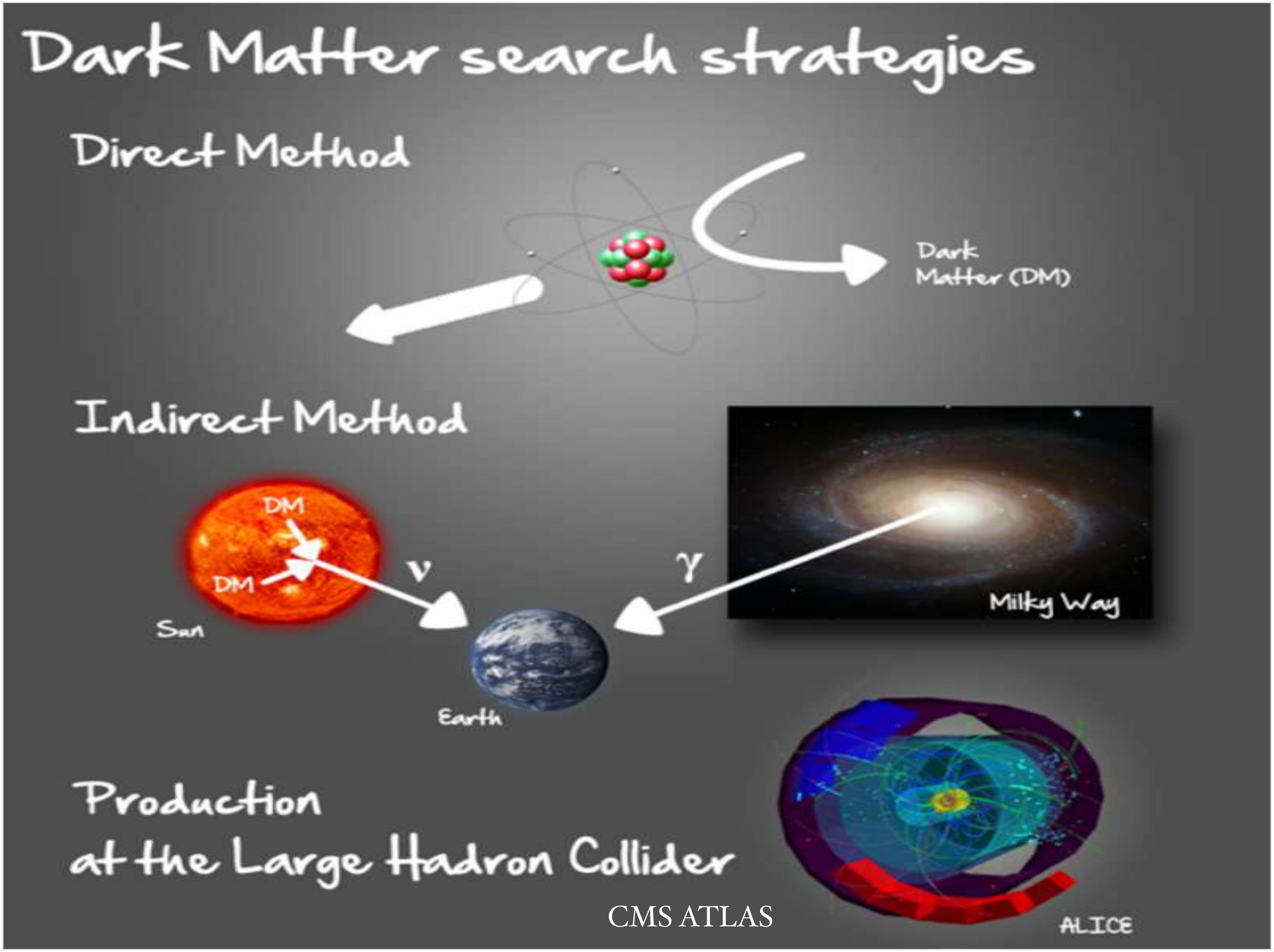
S.Tulin



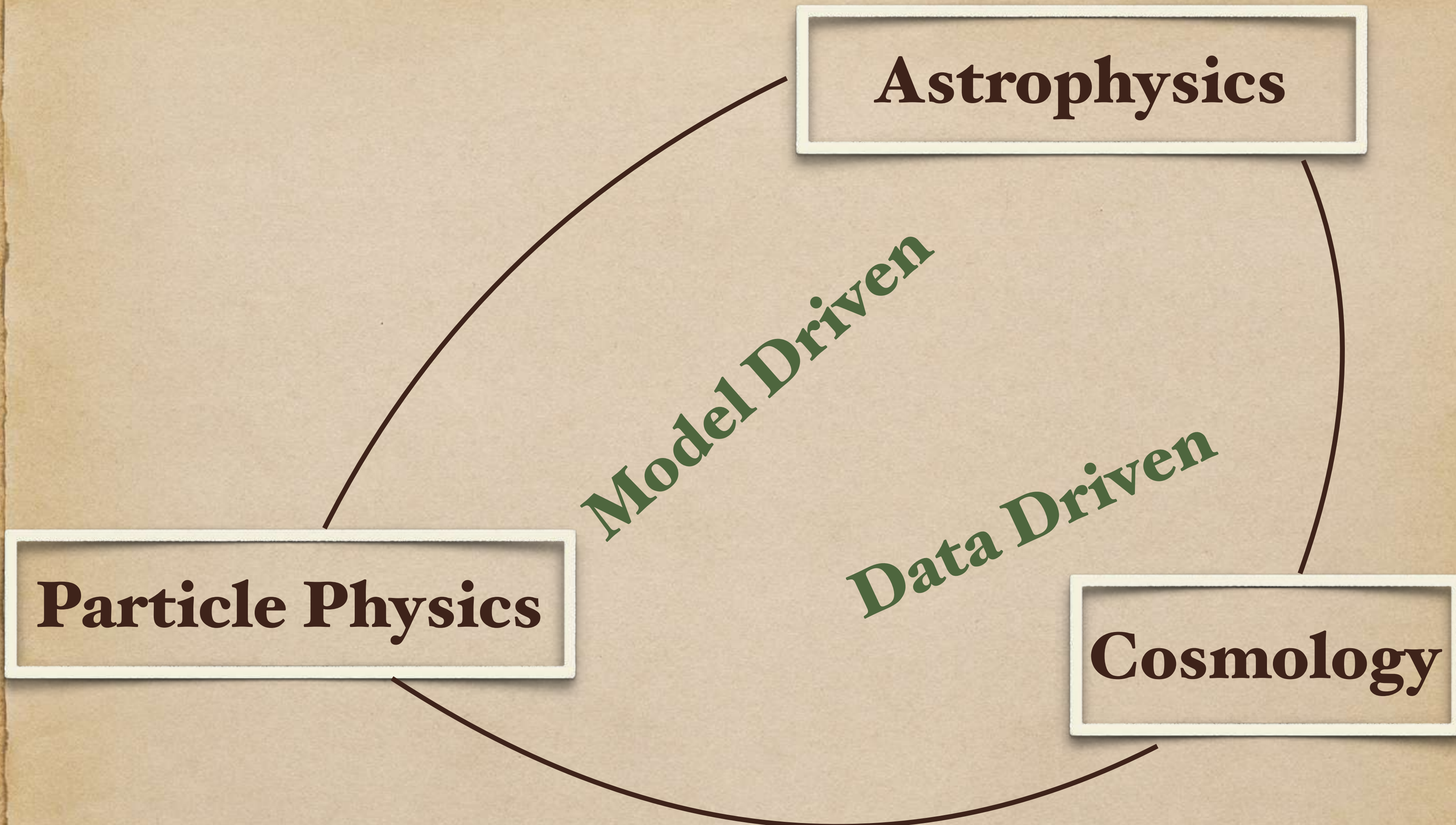
The Possible Mass Range of Dark Matter



Unit for mass: GeV = 10^9 eV; 1 GeV ~ 1 proton mass



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


Astrophysics
Model Driven
Data Driven
Particle Physics
Cosmology

Two Fantastic Dark Matter Beasts

connecting particle physics with cosmology and astrophysics

What if part of dark matter behaves like ordinary matter, dissipates energy and forms structure?

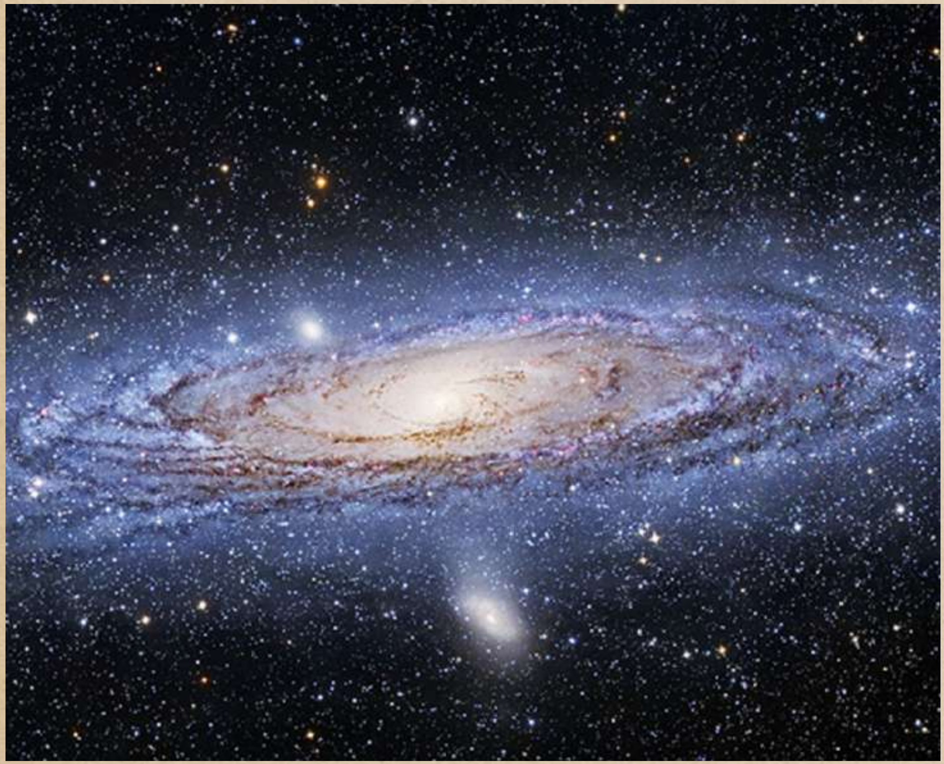
What if dark matter behaves more like waves than particles?

Double Disk Dark Matter

What if ***part of*** dark matter behaves like ordinary matter, ***dissipate*** energy and form structure?

It's clearly not a minimal scenario. Yet standard model is not even close to minimal with 6 quarks, 6 leptons, 4 gauge bosons and 1 Higgs boson. Among all the known sub-atomic particles, protons, electrons, photons, neutrinos are stable.

Dissipative Dynamics of Baryons

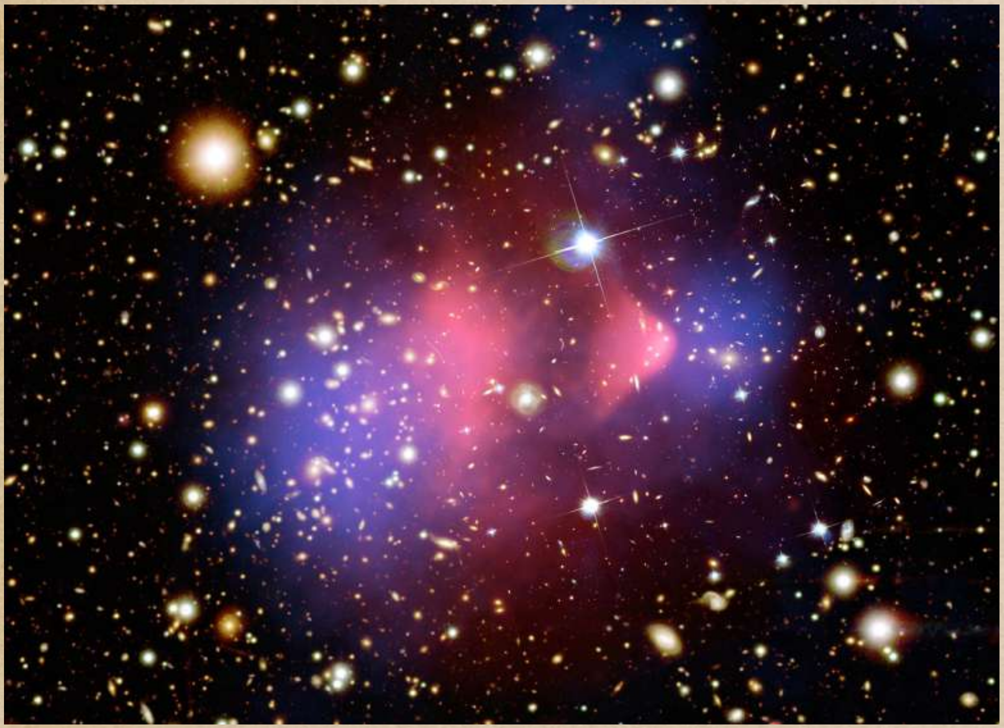


Spiral galaxies, such as our Milky Way, have a disk structure (the baryonic disk).

Scale height ~ 0.3 kpc, scale radius ~ 3 kpc
Why this flattened structure?

The answer lies in **energy dissipation** processes. Particles (protons, electrons, atoms) scatter and emit photons that **carry away kinetic energy but not (much) angular momentum**. Shrink but keep spinning: forced to form a disk.

Partially Interacting Dark Matter



Bullet Cluster (Markevitch et al. '03):

No more than ~1/3 of the DM remained behind in the center instead of passing into the lensing regions.

Could <1/3 of DM have very strong interactions, like baryons (or even stronger)? If a small fraction, will not have a dramatic effect on halo shapes.

Double Disk Dark Matter

JF, A. Katz, M. Reece and L. Randall, PRL, 2013; Phys. Dark Univ. 2013

A simple model: copy baryonic sector in the dark sector (the majority of dark matter is still a cold collisionless particle).

Proton X

Electron C

Photon γ_D

Double Disk Dark Matter

JF, A. Katz, M. Reece and L. Randall, PRL, 2013; Phys. Dark Univ. 2013

A simple model: copy baryonic sector in the dark sector (the majority of dark matter is still a cold collisionless particle).

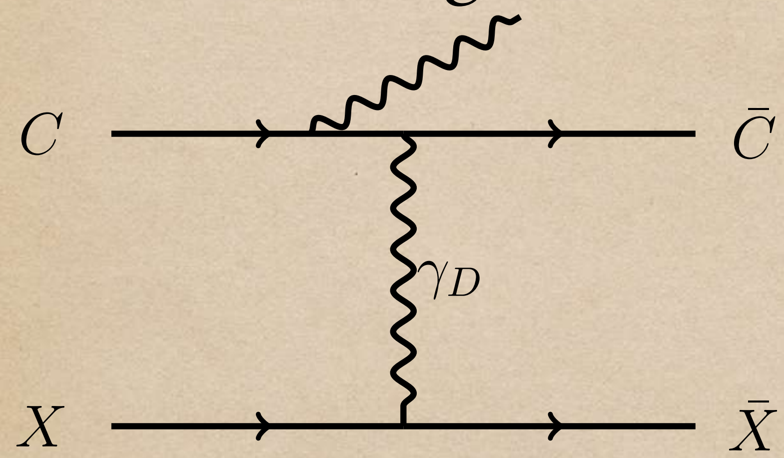
Dark Proton X

Dark Electron C

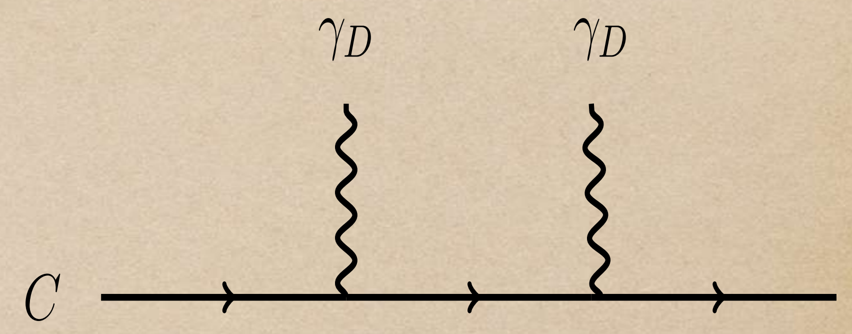
Dark Photon γ_D

Cooling (energy dissipation) processes:

Bremsstrahlung:



Compton scattering on the "dark CMB":

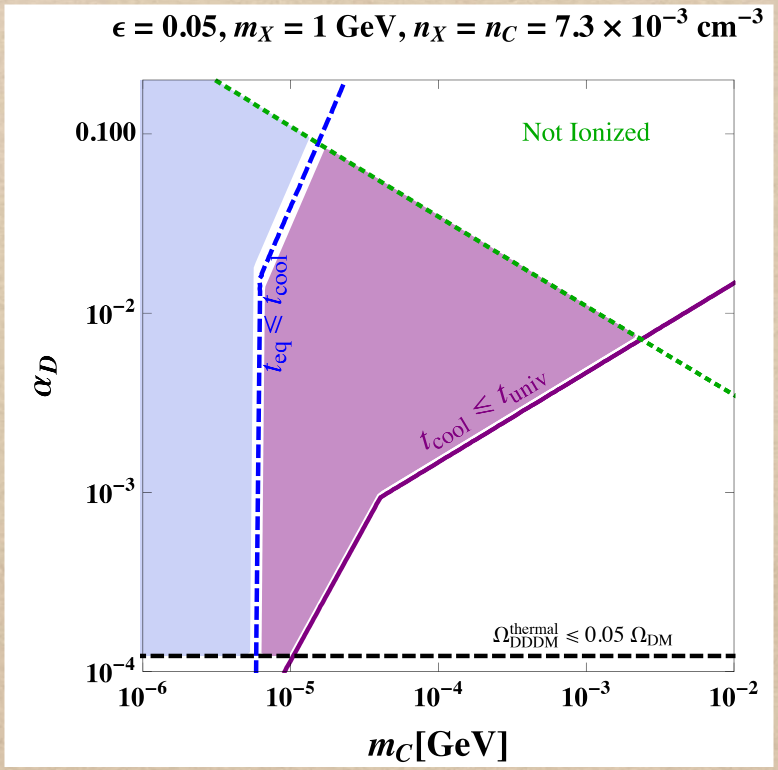


Once temperature of the dark sector is low, dark recombination happens (proton + electron form atoms) and atomic cooling processes are turned on.

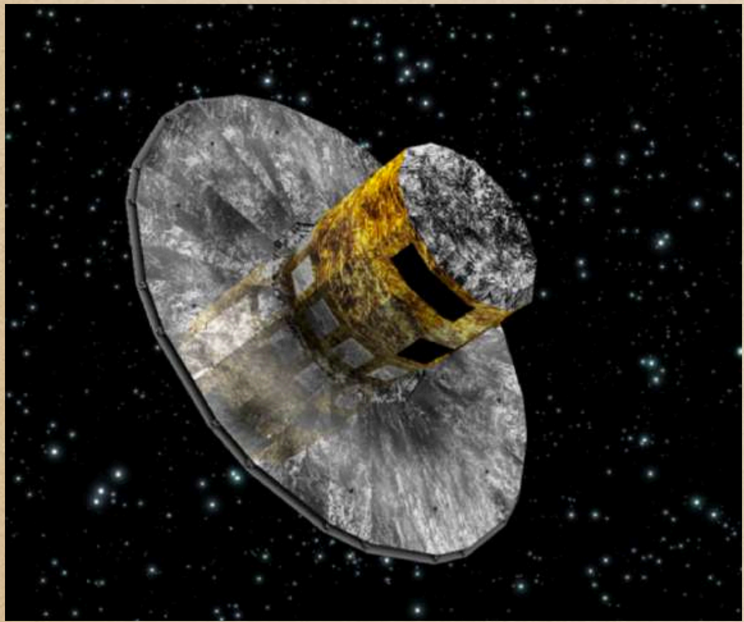
A complete computation of cooling rates including atomic processes: E.Rosenberg, JF, Phy. Rev. D, 2017

Viability of Double Disk Dark Matter

Purple regions cool calculably in age of universe with *5%* interacting DM.



Astrometry Probe of Dark Matter Structure
Gaia Satellite



A European Space Agency satellite that will provide position and velocity measurements for a *billion* stars in our galaxy.

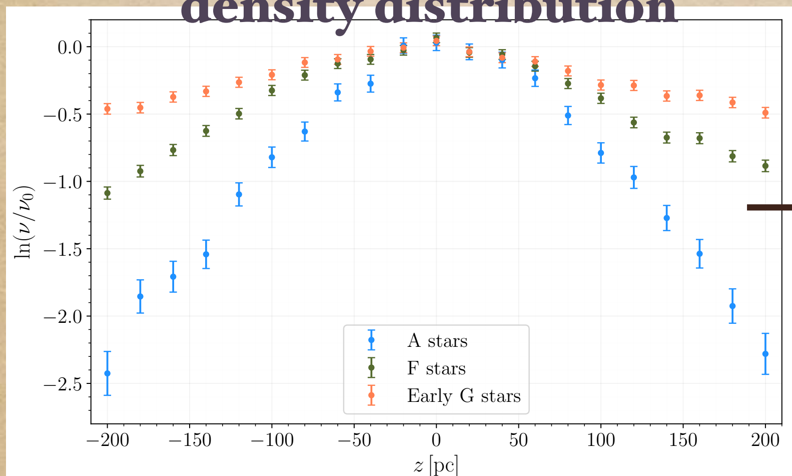
To infer the dark matter distribution, solve the Poisson equation and the Jeans equation (collisionless Boltzmann equation), assuming *tracer stars in equilibrium (not necessarily true)*:

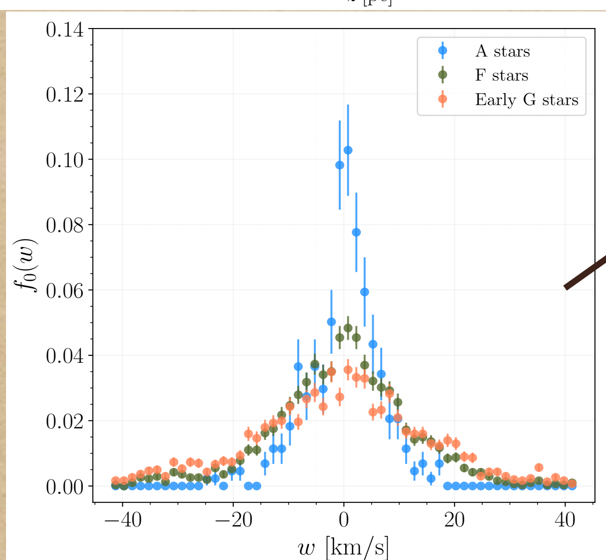
$$\frac{1}{r\nu_i}\frac{\partial}{\partial r}\left(r\nu_i\sigma_{rz;i}\right)+\frac{1}{r\nu_i}\frac{\partial}{\partial \phi}\left(\nu_i\sigma_{\phi z;i}\right)+\frac{1}{\nu_i}\frac{d}{dz}\left(\nu_i\sigma^2_{z;i}\right)=-\frac{d\Phi}{dz},$$

Astrometry Probe of Dark Matter Structure
Gaia Satellite

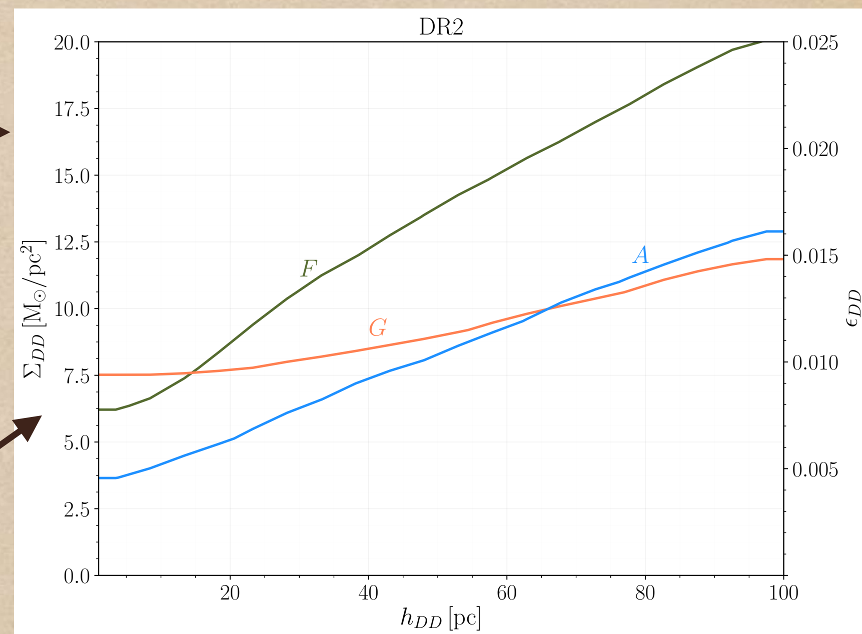
J. Buch, S. Leung and JF, JCAP, 2018

density distribution





velocity distribution



~ 1% of the total dark matter in the MW could be in a dark disk

Aside: power of Gaia

Local DM velocity distributions and substructures: Bozorgnia et. al 2018, 2019; Necib et.al 2018, 2019; still a lot of work to do to clear up the picture.

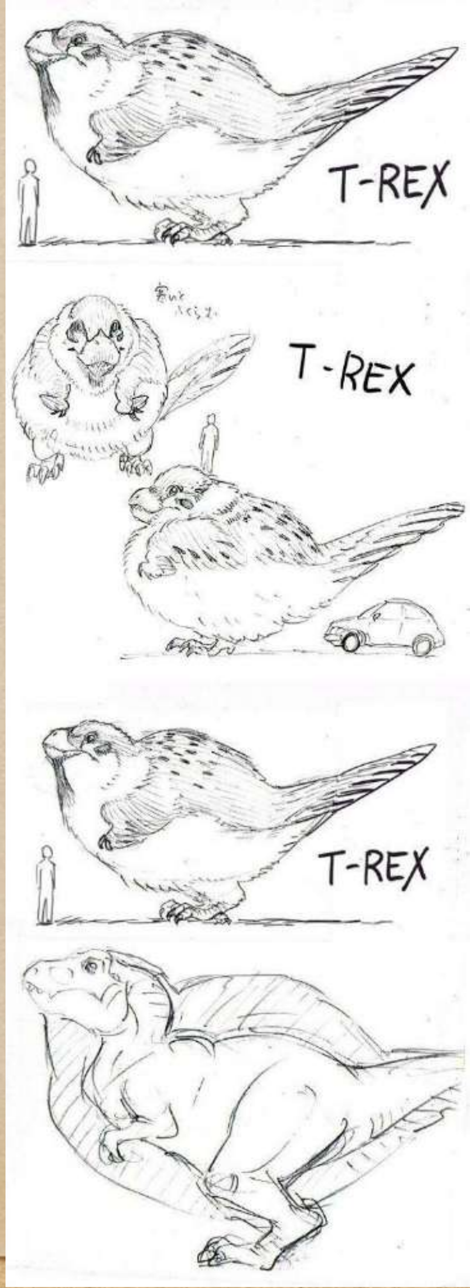
DM velocity distributions ⟷ Direct detection (nuclear scattering, electron scattering): J. Buch, M. Buen-Abad, JF, S.C. Leung 2019, 2020.

A Final Story for Entertainment: Comets and Solar Oscillation

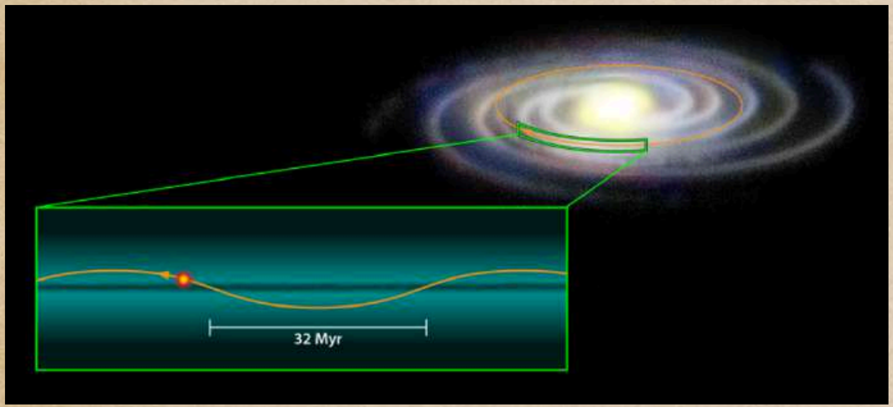
L. Randall and M. Reece, PRL, 2014

Large meteorite strikes on Earth cause big impact craters that are very likely responsible for some mass extinctions.

Crater record on earth: ~ 35 million year period (not statistically significant!).



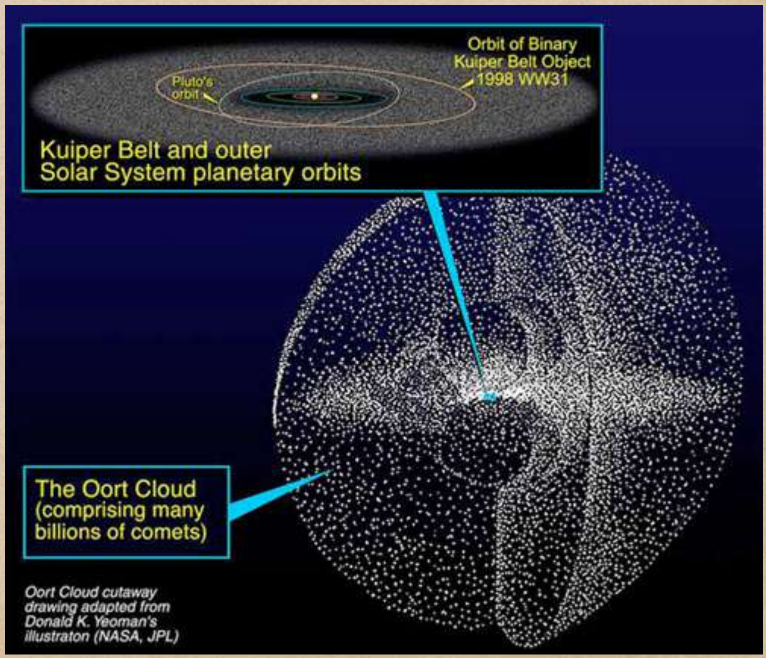
One explanation: Oort cloud comet more tidally perturbed as the Solar System passes through the galactic midplane.



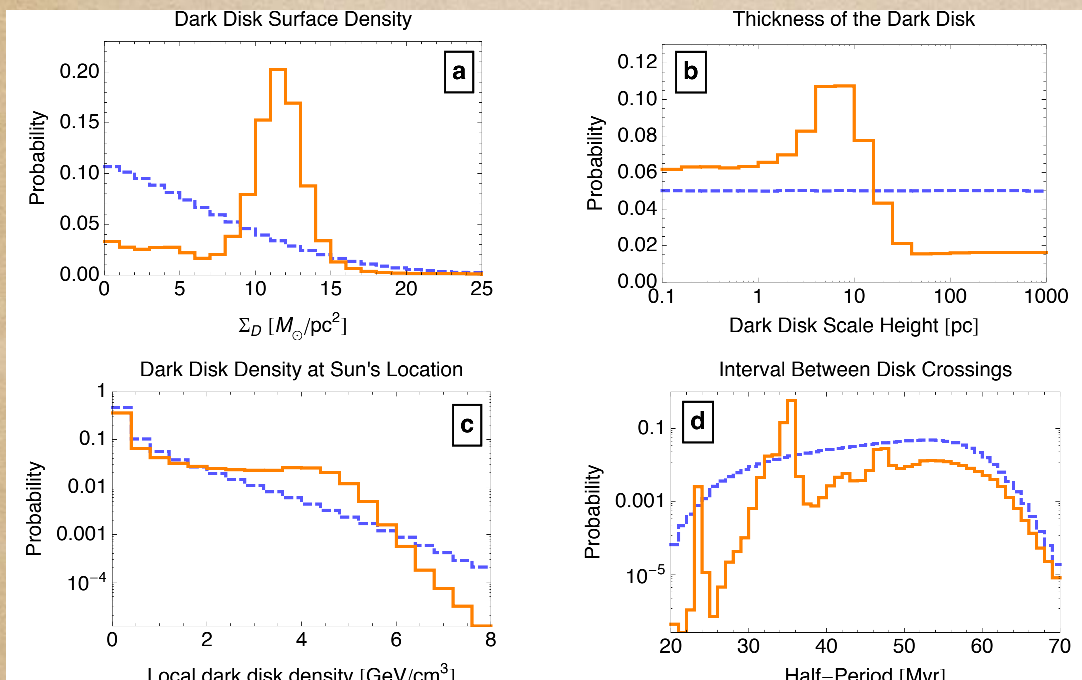
Solar oscillatory motion around the plane of the galaxy (artist's rendition from APS Physics Viewpoint, Alan Stonebraker)

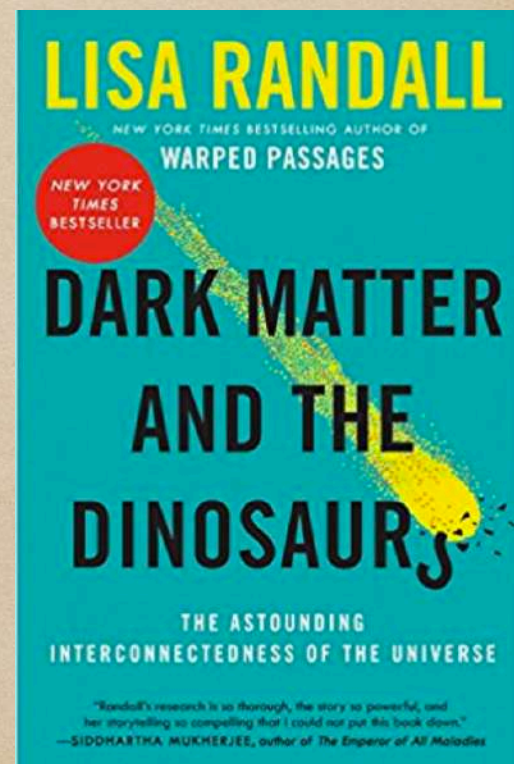
Many comets exist in the "Oort cloud" at distances ~ 10^4 AU. (Inferred—not directly observed.) They are perturbed by tidal forces.

The rate at which comets fall into the inner Solar System is proportional to the local density.



Yet the baryonic mid-plane is not dense enough to explain the 35 million year periodicity. Add gravity through adding a **very thin** dark disk (now in strong tension with Gaia data though there is caveat in the equilibrium analysis based on Gaia).





Other Possible Interesting Consequences

Direct detection and solar capture of dissipative dark matter, Fan, Katz, Shelton, JCAP, 2014;

Andromeda plane of satellites, Randall, Scholtz, JCAP, 2015;

Point sources of dissipative dark matter, Agrawal, Randall, JCAP, 2017;

Collapsed dark matter structures, Buckley, DiFranzo, PRL, 2017;

Accretion of dissipative dark matter onto active galactic nuclei, Outmezguine, Slone, Tangarife, Ubaldi, Volansky, JHEP, 2018;

Binary pulsars probing dark disk Caputo, Zavala, Blas Phy. Dark Univ. 2018;

………………………

Light Scalar Dark Matter

What if dark matter behaves more like waves than particles?

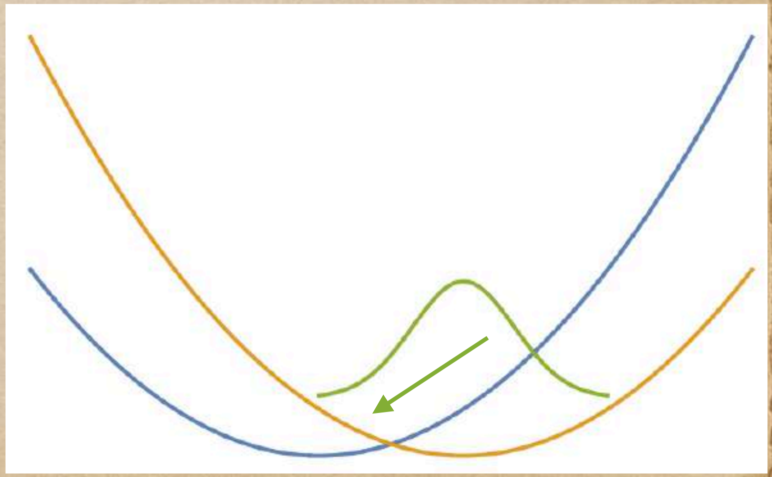
Fields and Particles

Usually we think dark matter as a collection of collisionless particles.

But if dark matter is very light, it has very high density (*large occupation number*) and it behaves like ***classical*** field (wave).

$$\phi(t) \approx \frac{\sqrt{\rho_{\rm DM}}}{m_\phi} \cos(m_\phi t)$$

Recall ***coherent state***: close to a classical solution with approximately well-defined particle number.



de Broglie wavelength > inter-particle spacing

$$\lambda_{\rm dB} \gtrsim \frac{1}{n_{\rm DM}^{1/3}} \Rightarrow \frac{1}{m_{\rm DM} v} \gtrsim \left(\frac{m_{\rm DM}}{\rho_{\rm DM}}\right)^{1/3}$$

Plug in $v \sim 200\ \mathrm{km/s}, \quad \rho \sim 0.3\ \mathrm{GeV/cm^3}$

$\Rightarrow m \lesssim 0.2\ \mathrm{eV}$ collective behavior

Such light dark matter must be a ***boson (such as a scalar)***: for fermions, Pauli exclusion requires a large Fermi velocity, inconsistent with observed dark matter distribution (Tremaine-Gunn bound).

Boson stars

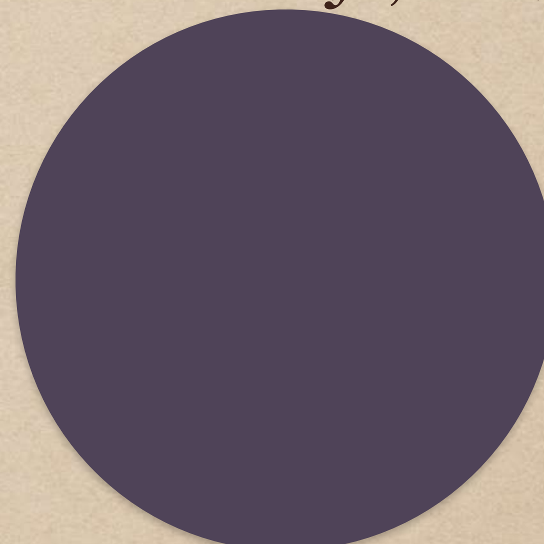
Light scalar dark matter may form smaller clumps, "***dark stars***". Properties depend on ***self-interactions*** of the bosons.

QCD axion with attractive self-interaction

$10^{-11} M_{\odot}$

$130\,\text{km}$

axion-like particle with repulsive self-interaction (JF, 2016)



$1 M_{\odot}$

$210\,\text{km}$

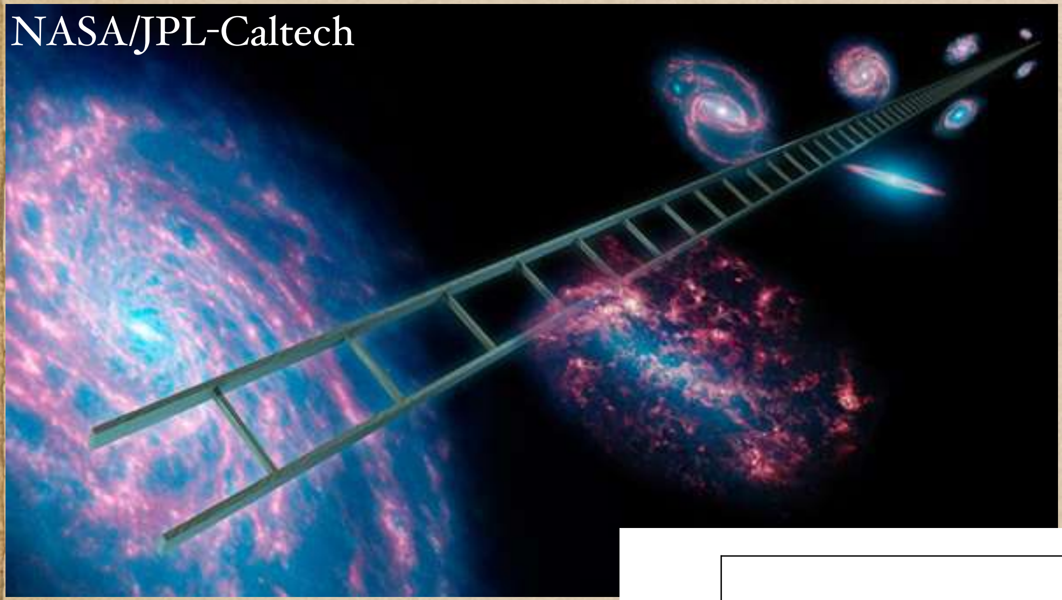
Visinelli, et.al; Schiappacasse, et.al; Eby et.al 2017

Mergers of binary may be detected at a ***gravitational wave*** detector such as LIGO.

Giudice et.al, 2016; Croon, JF, Sun, 2018

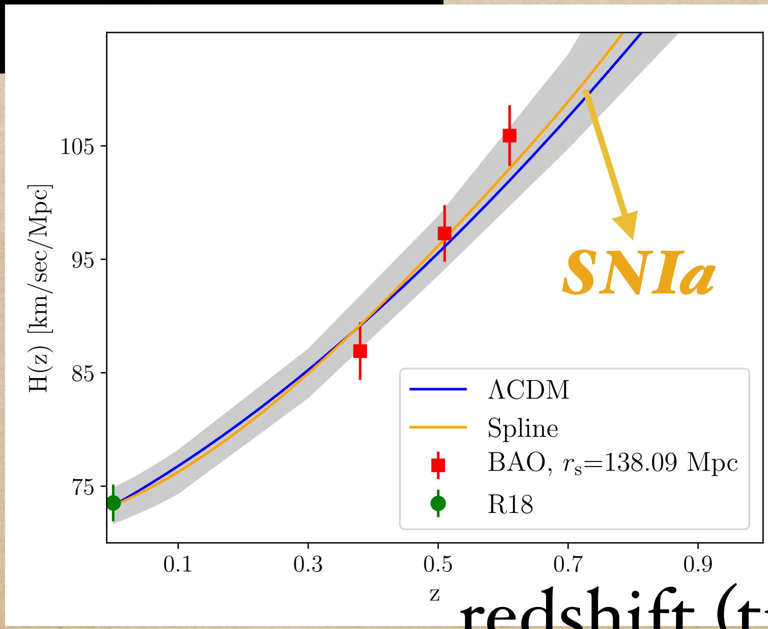
Modifying late-time Hubble diagram

cosmic distance ladder



Standard candle: Type-1a supernovae (SNIa)

Expansion rate

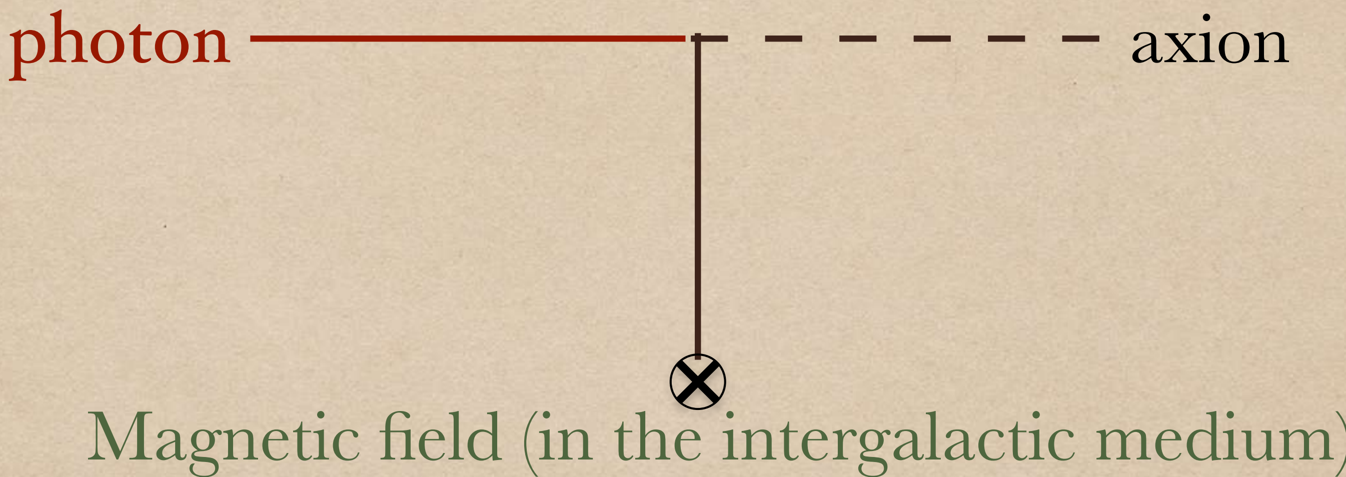


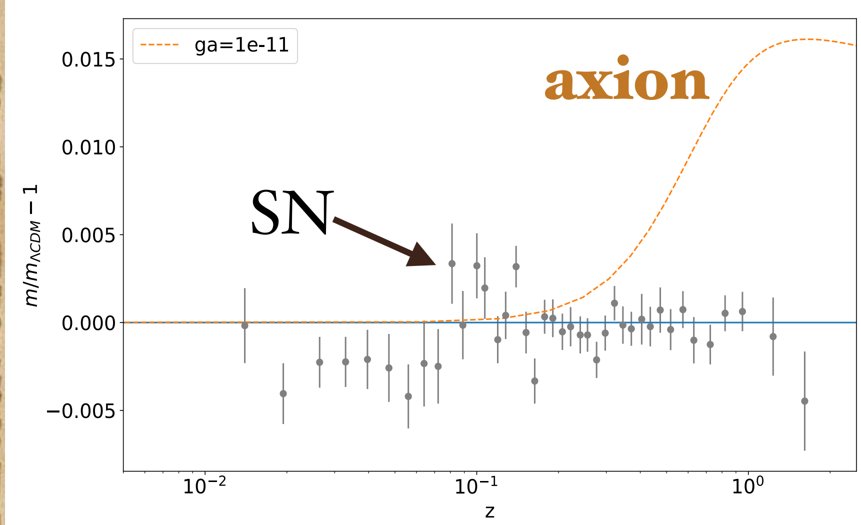
redshift (time)

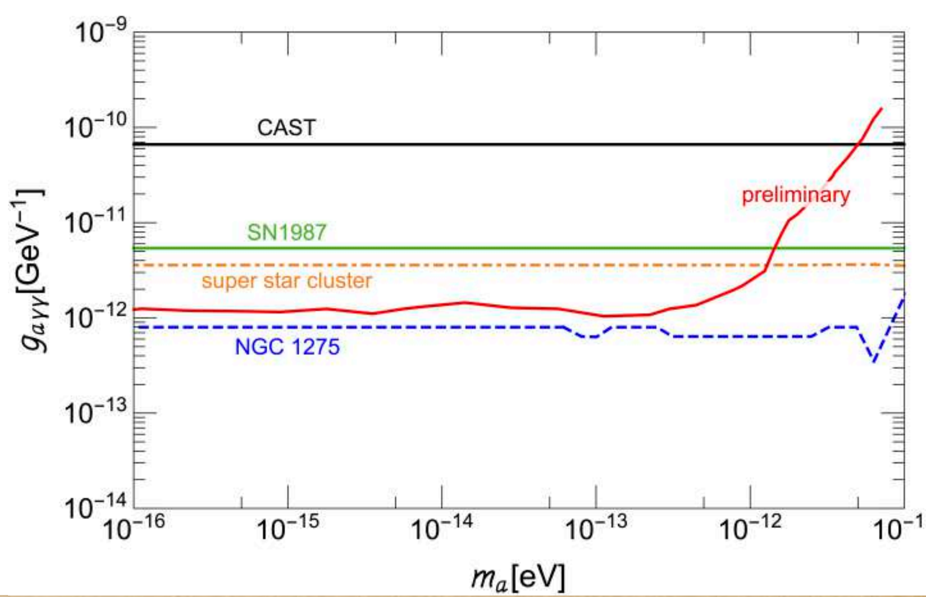
Aylor et.al 2018

axion-photon coupling: $-\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma\gamma}\ a\mathbf{E}\cdot\mathbf{B}.$

work to appear, M. Buen-Abad, JF and C. Sun







Conclusions

No conclusion yet! We still don't know what the majority of matter in the Universe is.

Two dark matter beasts from the zoo of dark matter scenarios:

— partially interacting dark matter and double disk dark matter;

— light scalar dark matter

They connect particle physics, cosmology, astronomy, gravitational waves and even meteorite impact!

More interdisciplinary fun coming and join the dark matter hunt!

Thank you!