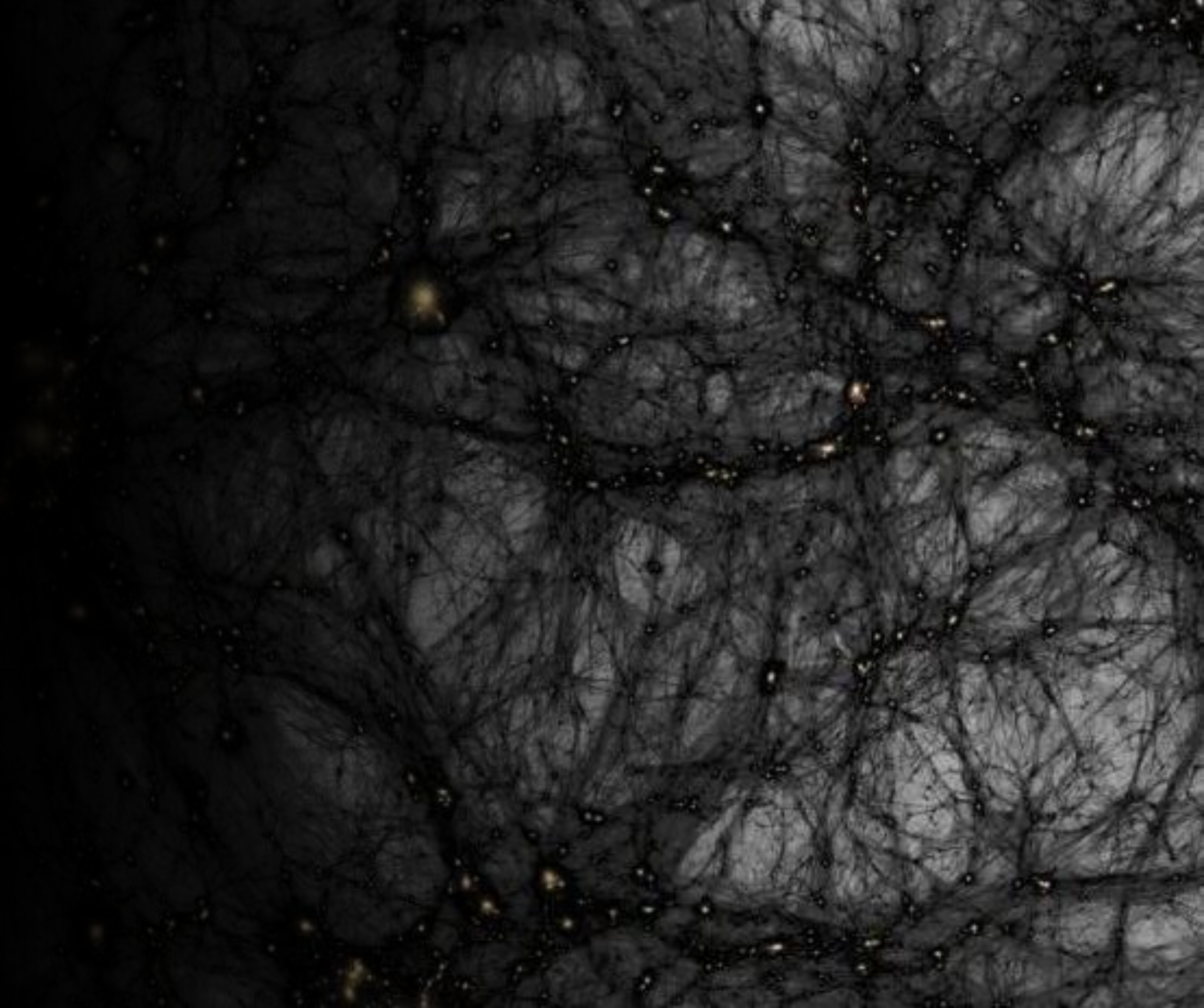
# Dark Matter Searches

Aman Sahoo

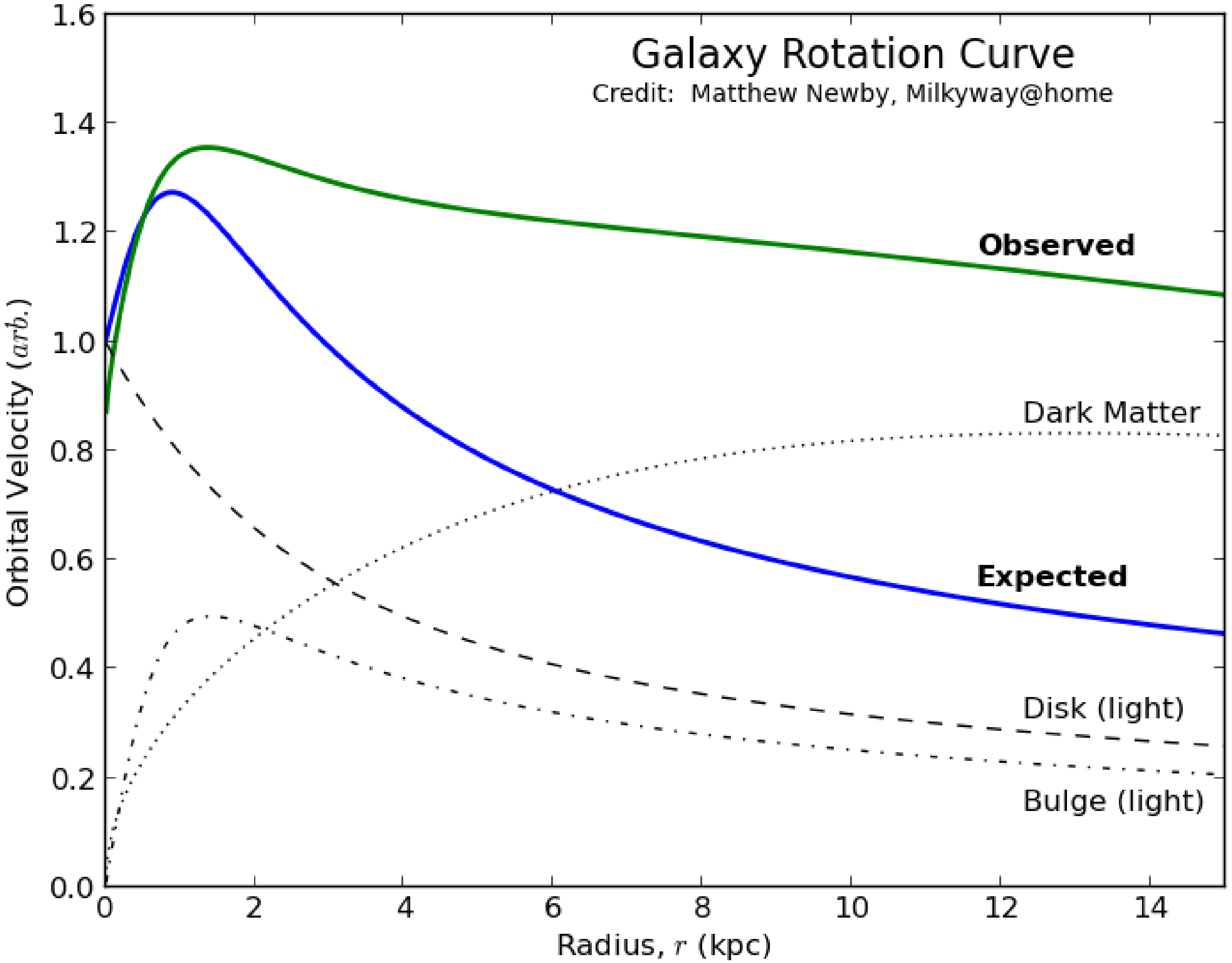


# Dark Matter

- Interacts through gravity and not EM
- Existence predicted by observing galaxy rotation.
- $v = \sqrt{\frac{GM(R)}{R}}$ Keplerian Prediction
- $I(R) = I(0)\exp\left(-\frac{R}{R_s}\right)$ Star brightness from centre of galaxy
- So $v \propto R^{-1/2}$ for $R > R_s$

$$M(R) = \frac{v^2 R}{G} = 1.05 \times 10^{11}\,\mathrm{M_\odot}\left(\frac{v}{235\,\mathrm{km\,s^{-1}}}\right)^2\left(\frac{R}{8.2\,\mathrm{kpc}}\right)$$

$$\langle M/L_V\rangle_{\mathrm{gal}} \approx 64\,\mathrm{M_\odot}/\mathrm{L_{\odot,V}}\left(\frac{R_{\mathrm{halo}}}{100\,\mathrm{kpc}}\right)$$



# Dark Matter in Galaxy Clusters

Virial Theorem: For a cluster of mass M

- $K = \frac{1}{2}M\langle v^2\rangle$ & $W = -\frac{G}{2}\sum_{\substack{i,j \\ j\neq i}} \frac{m_i m_j}{|\vec{x}_j - \vec{x}_i|} \Rightarrow W = -\alpha\frac{GM^2}{r_h}$
- $\ddot{I} = 2\sum_i m_i(\vec{x}_i \cdot \ddot{\vec{x}}_i + \dot{\vec{x}}_i \cdot \dot{\vec{x}}_i) \Rightarrow \ddot{I} = 2W + 4K$
- In steady state: $\ddot{I} = 0 \Rightarrow K = -\frac{W}{2} \therefore M = \frac{\langle v^2\rangle r_h}{\alpha G}$
- Using observational data, $\langle v^2\rangle$ & $\mathrm{r_h}$ can be estimated with certain assumptions
- Eg: $M_{coma} = 2 \times 10^{15} M_\odot$

Hydrostatic equilibrium:

$$\frac{dP_{\text{gas}}}{dr} = -\frac{GM(r)\rho_{\text{gas}}(r)}{r^2}$$

Using $P_{\text{gas}} = \frac{\rho_{\text{gas}} kT_{\text{gas}}}{\mu}$ above, we get:

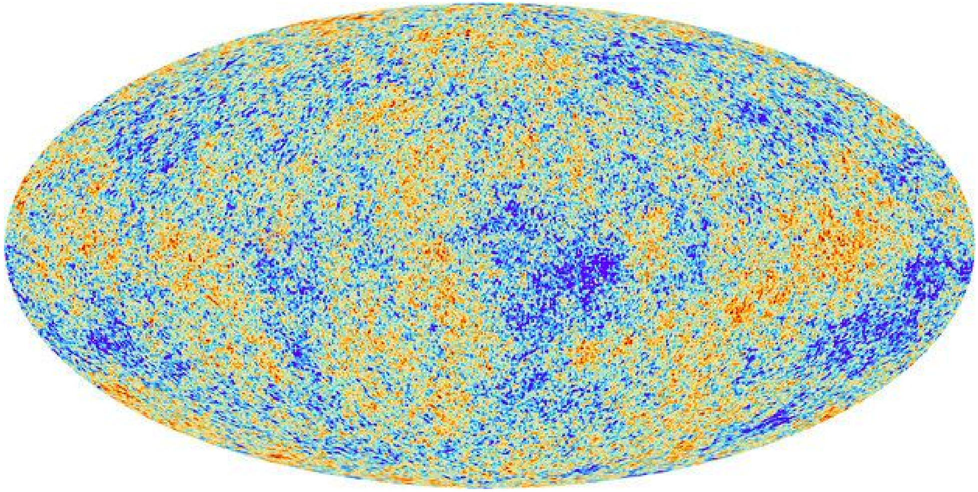
$$M(r) = \frac{kT_{\text{gas}}(r)r}{G\mu}\left[-\frac{d\ln\rho_{\text{gas}}}{d\ln r} - \frac{d\ln T_{\text{gas}}}{d\ln r}\right]$$

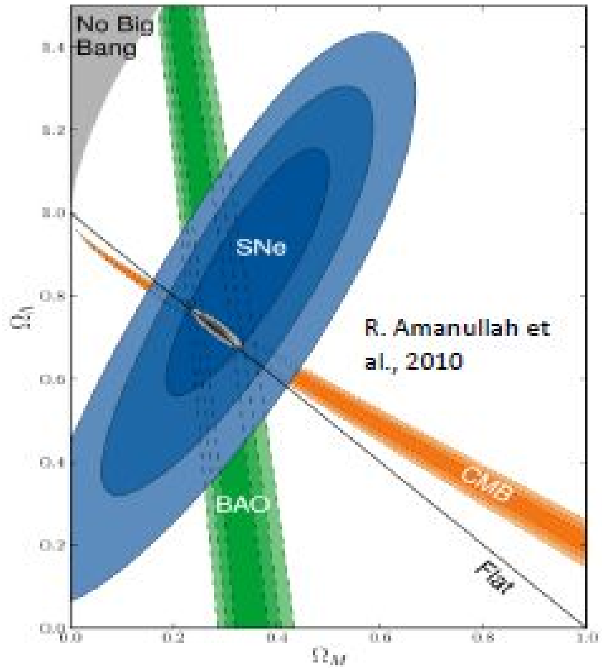
- X-ray data and modeling gives composition, temperature and density distribution of gas
- Eg: $M_{coma} \approx 1.3 \times 10^{15} M_\odot$

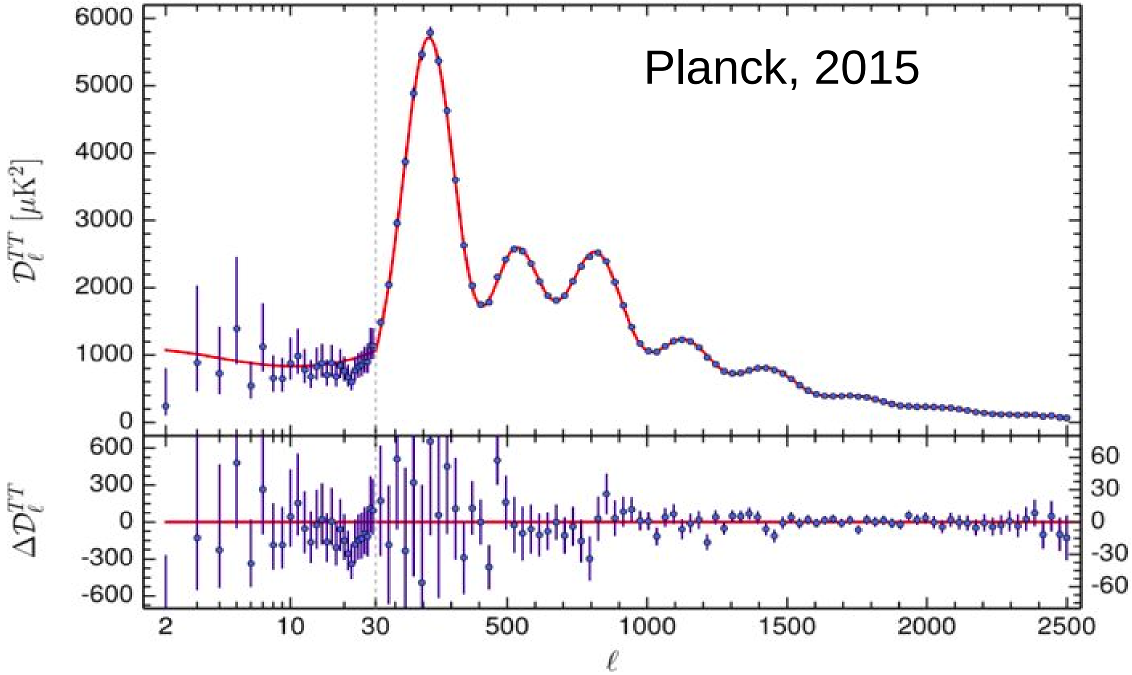
$$\boxed{\Omega_{\text{clus},0} \approx 0.2}$$

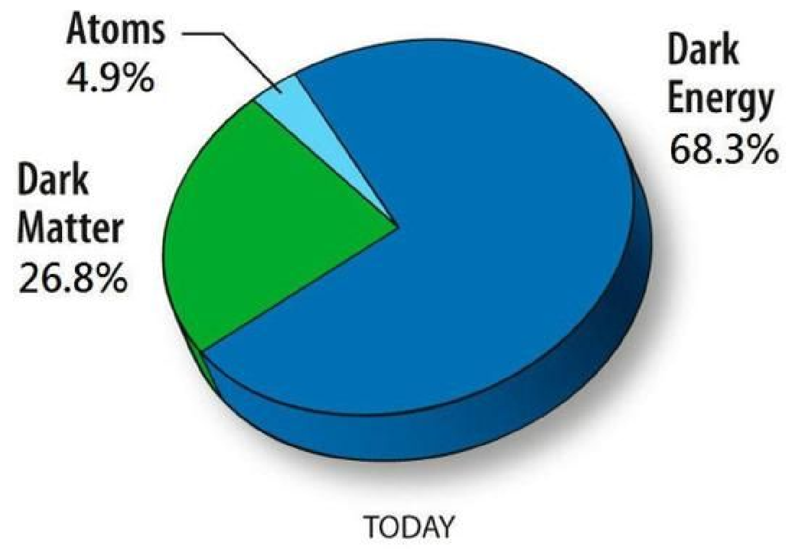
# Evidence for Dark Matter

- Cosmic microwave background (CMB) observations, resulting in precise estimates (WMAP, Planck) supporting $\Lambda$CDM model



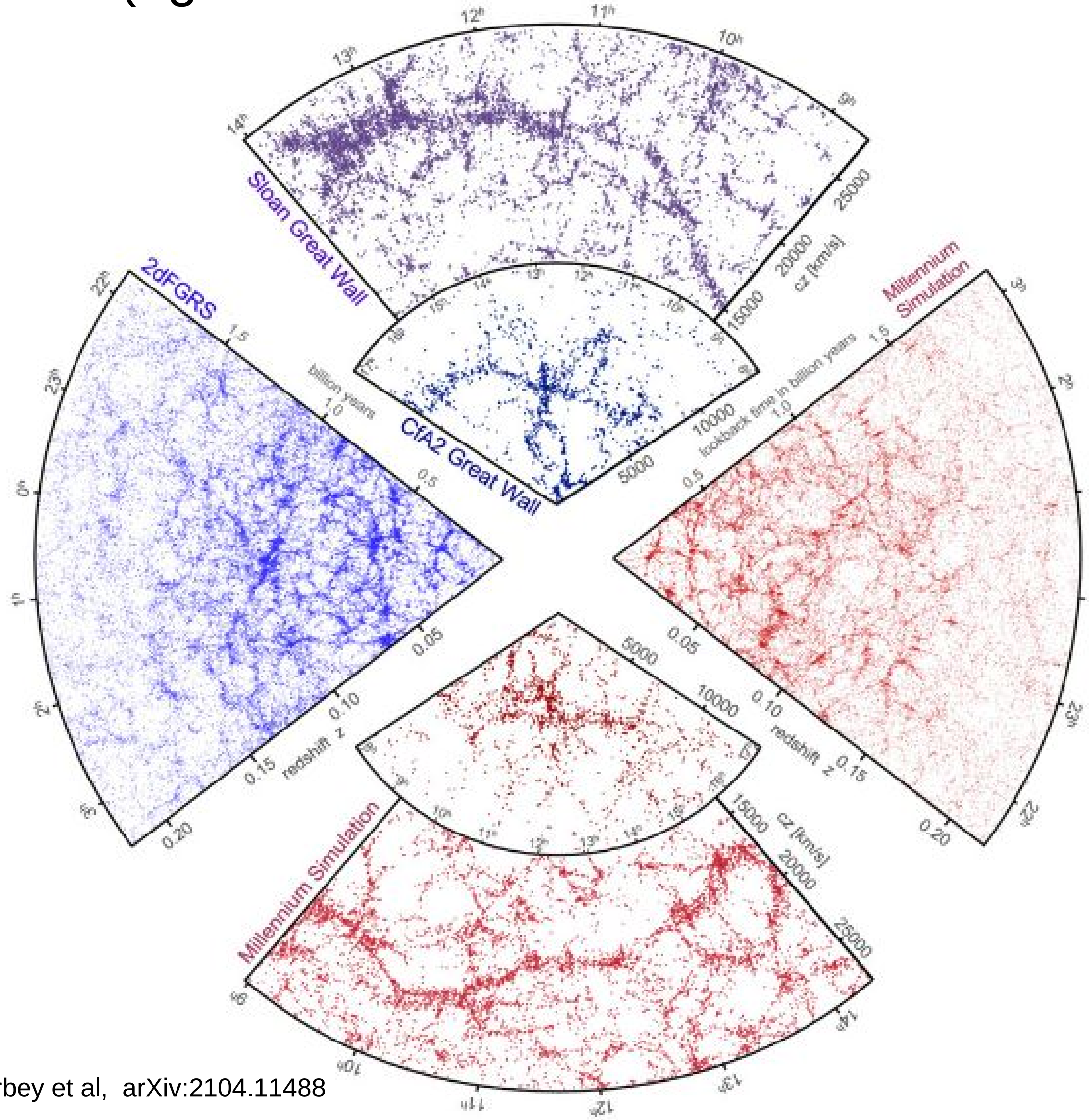


# More evidence for Dark Matter

- Large scale formation (agreement between observations and simulation)

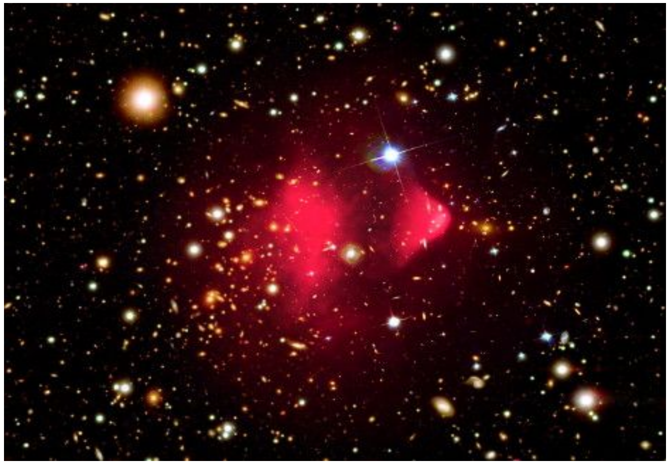


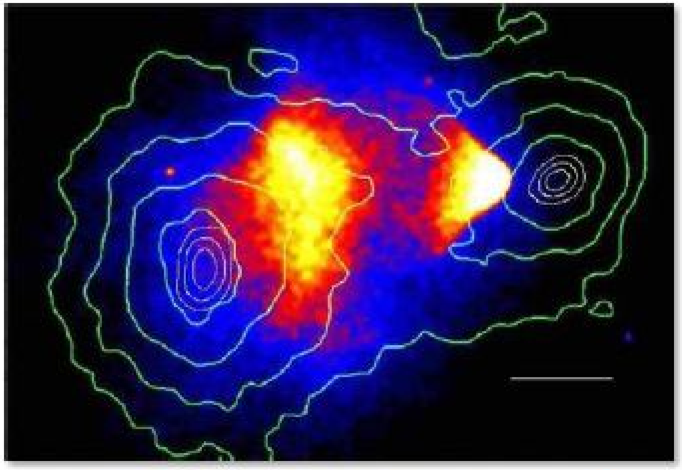

A. Arbey et al, arXiv:2104.11488

Figure 6: Simulated distribution of structures from the Millenium simulation (in red) to be compared to the observed distributions by CfA2 [16], 2dFGRS [17] and SDSS [18]. From [19].

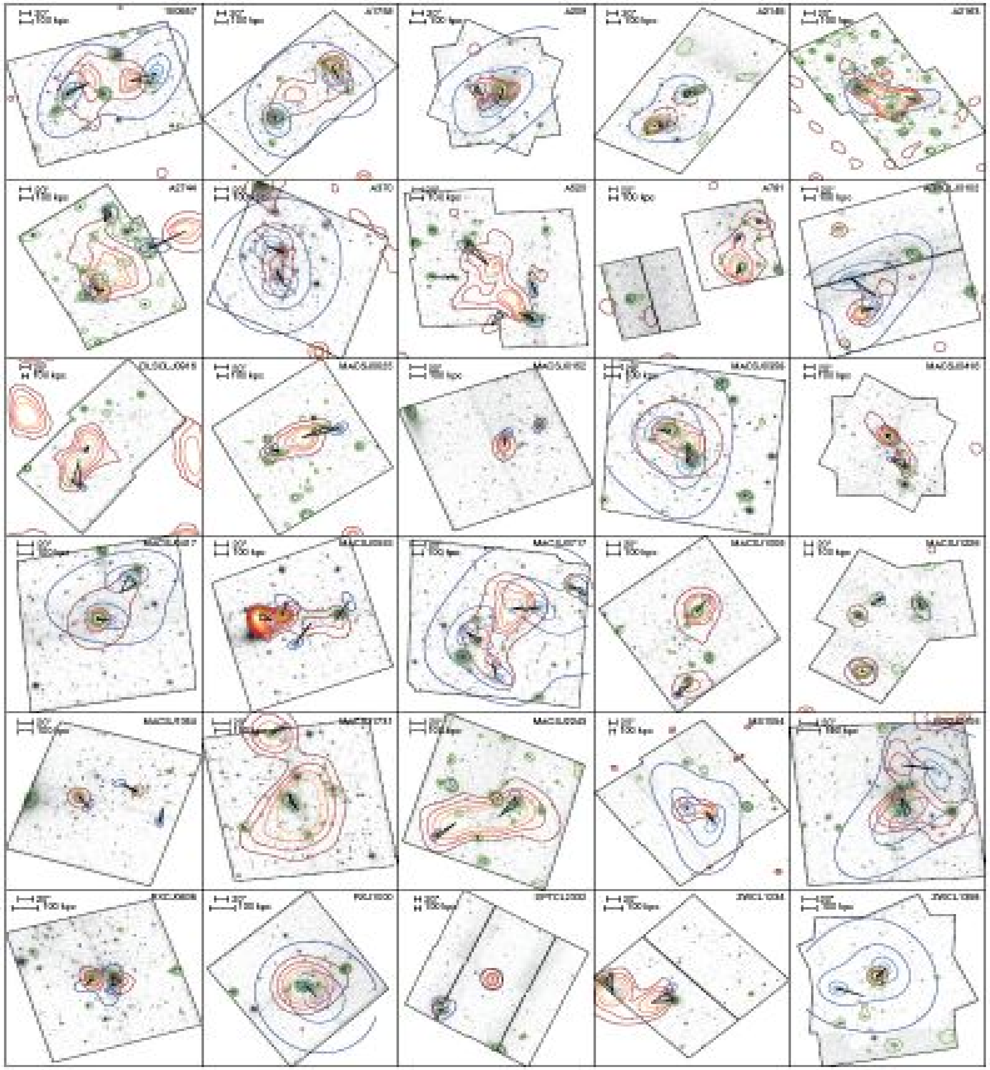
# More evidence for Dark Matter

- Gravitational lensing observations (Bullet Cluster, ...)





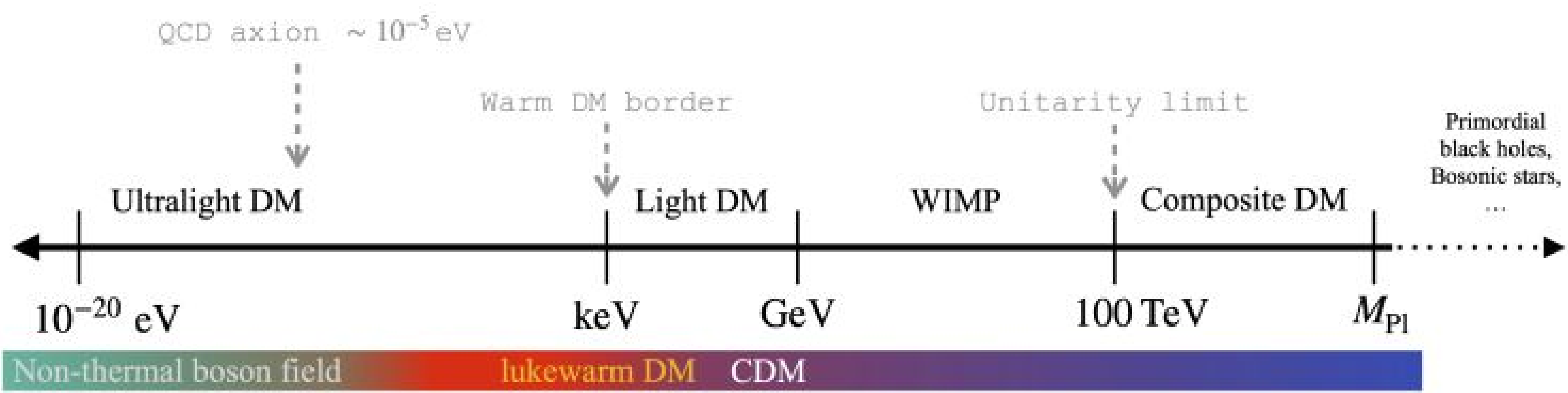
The bullet cluster, D. Clowe et al., 2006



D. Harvey & al., Science, March 27, 2015.
72 new colliding systems! (Also gives bounds on self-interacting DM.)

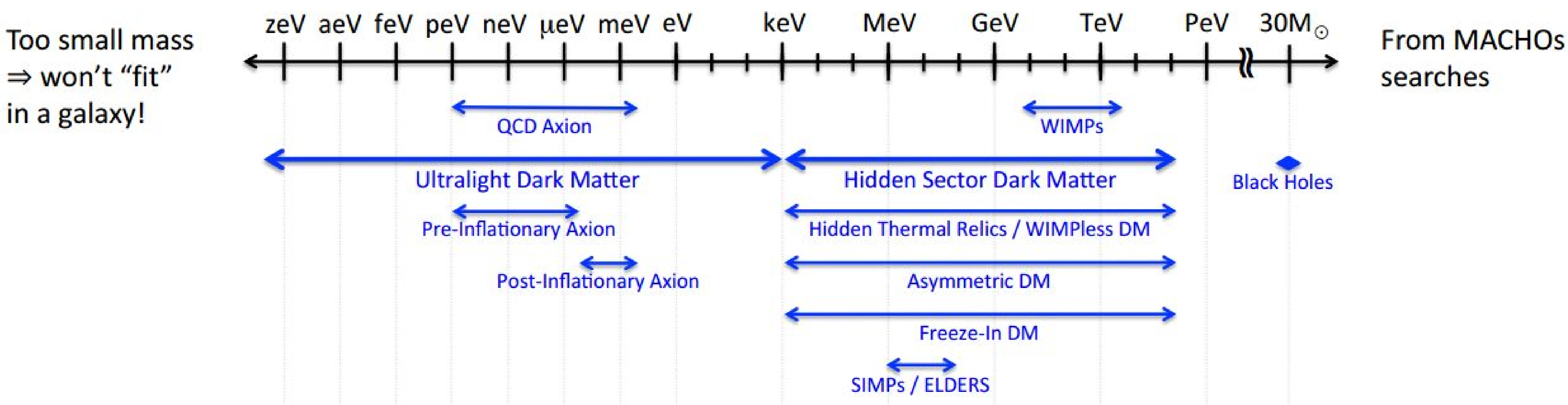
# What is Dark Matter?

- A number of possibilities considered and excluded:
  - Modifications of the gravity law (MOND)
  - Massive compact halo objects (MACHOs)
- Primordial black holes
- New Particles. Options include:
  - Axions
  - Weakly Interacting Massive Particles (WIMPs)
  - ...

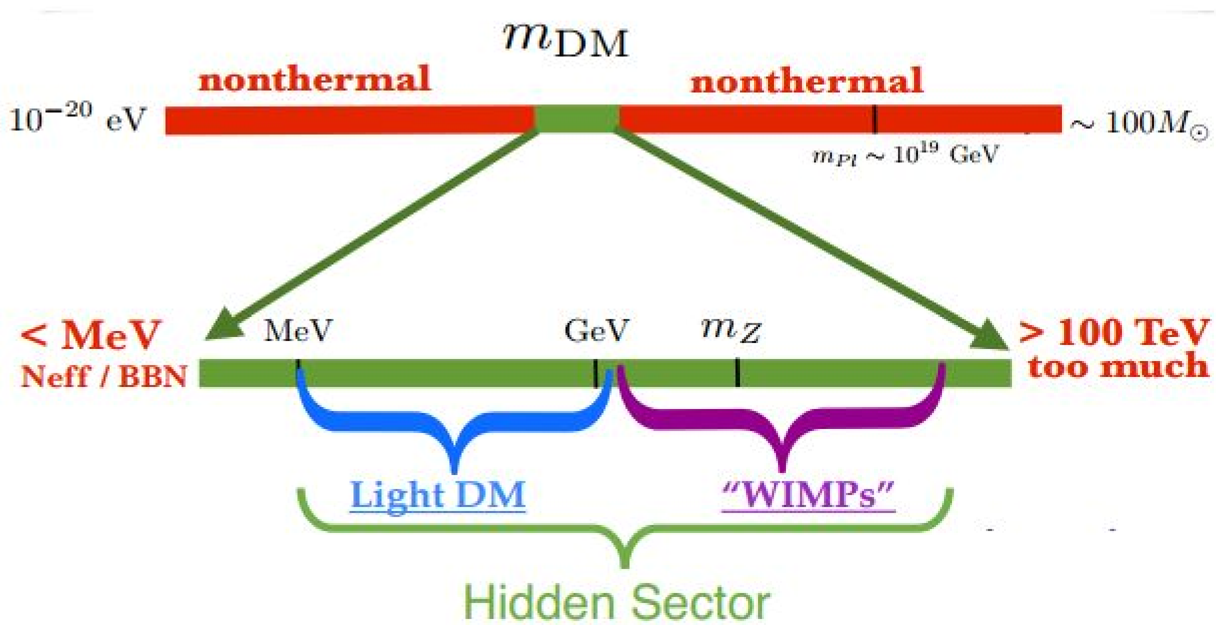



K. Tuominen, Symmetry 2021, 13, 1945

# Mass scale

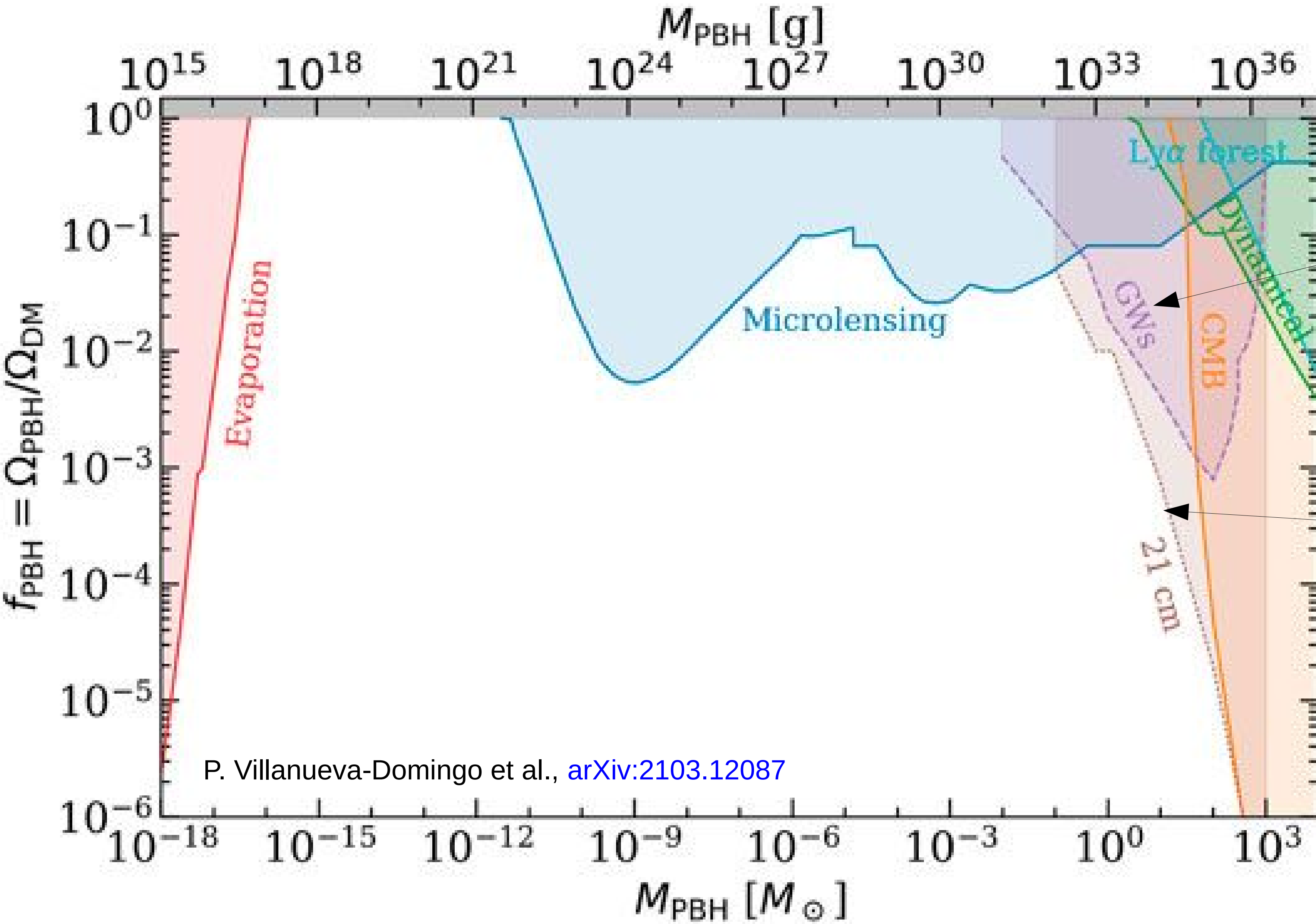



Thermal Equilibrium in early Universe narrows the viable mass range




*(M. Carena, ESPPU 2019 Dark Sectors Summary Talk)*

# Primordial black holes




B. Kavanagh et al., Phys. Rev. D 98, 023536 (2021)

debated

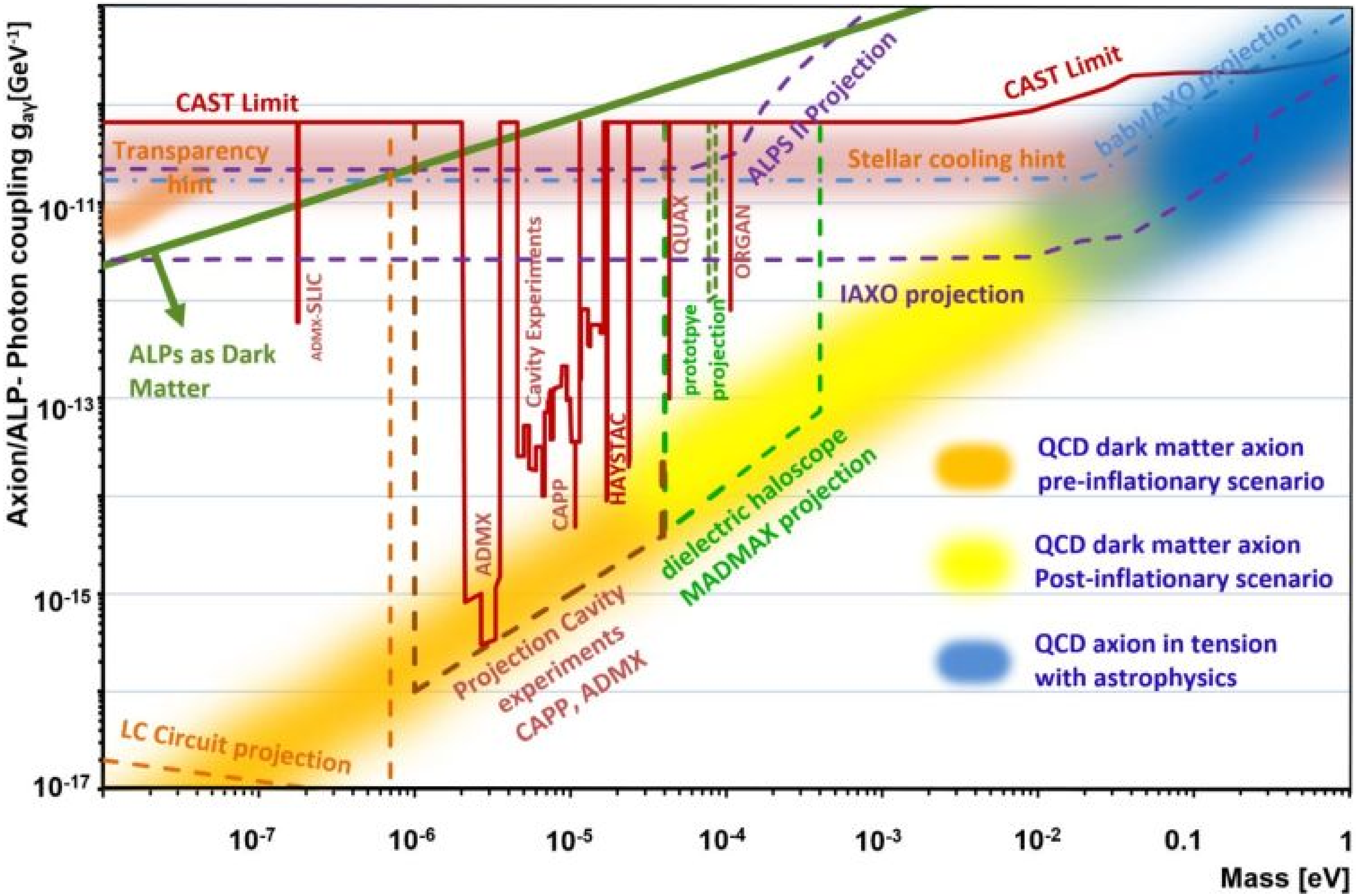
C. Bœhm et al JCAP03(2021)078

projected future sensitivity (SKA)

O. Mena et al., Phys. Rev. D 100, 043540 (2019)

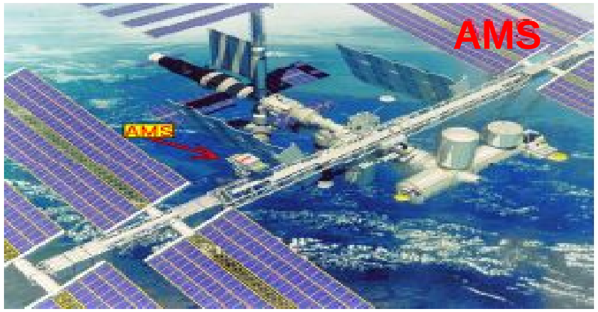
**Heavily constrained as a primary DM component.** But some room still exists...

# Axions and axion-like particles (ALPs)

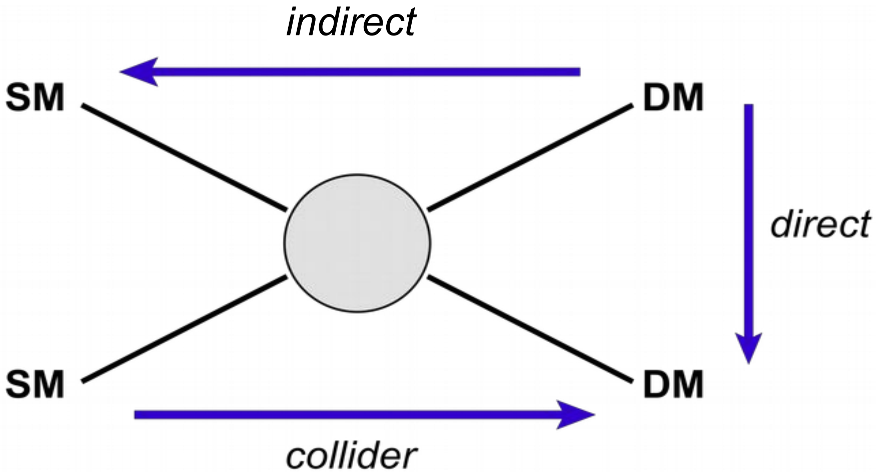


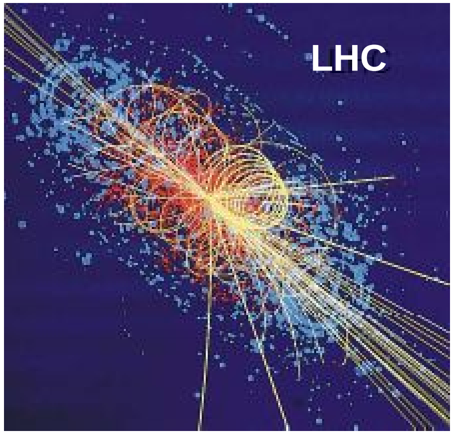

J. Billard et al., APPEC Committee Report, arXiv:2104.07634

# Ways to look for Dark Matter particles



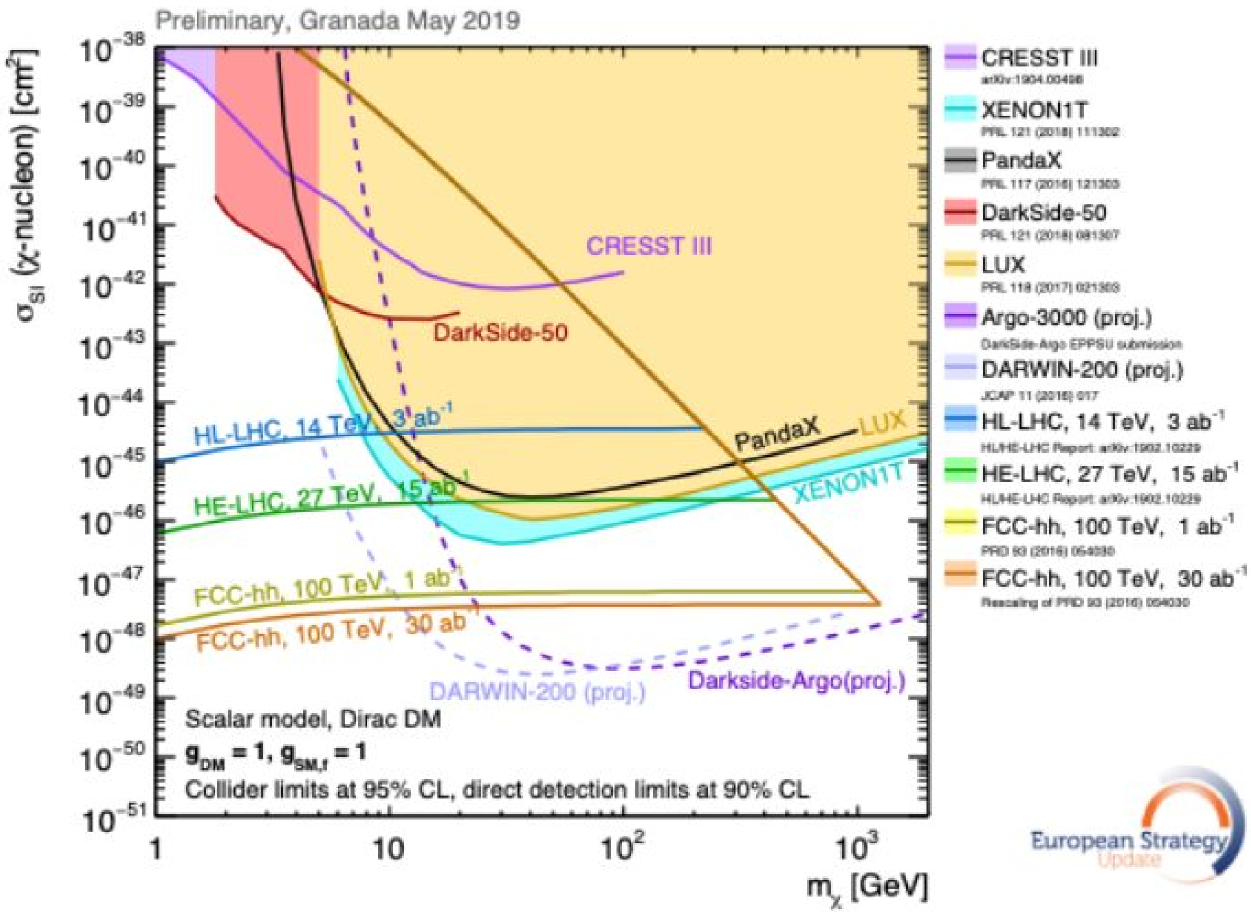




- Indirectly via their annihilation in Sun, Earth, Galaxy
  - Neutrinos (IceCube, Antares)
  - Positrons, antiprotons (AMS)
  - $\gamma$-rays (Fermi-LAT, CTA)
- <u>**Direct detection**</u>
- By producing them at accelerators (LHC, beam dump experiments)

# Colider/direct detection complementarity

Example of Complementary reach for future colliders and future DD for benchmarks considered (this case: scalar mediator)

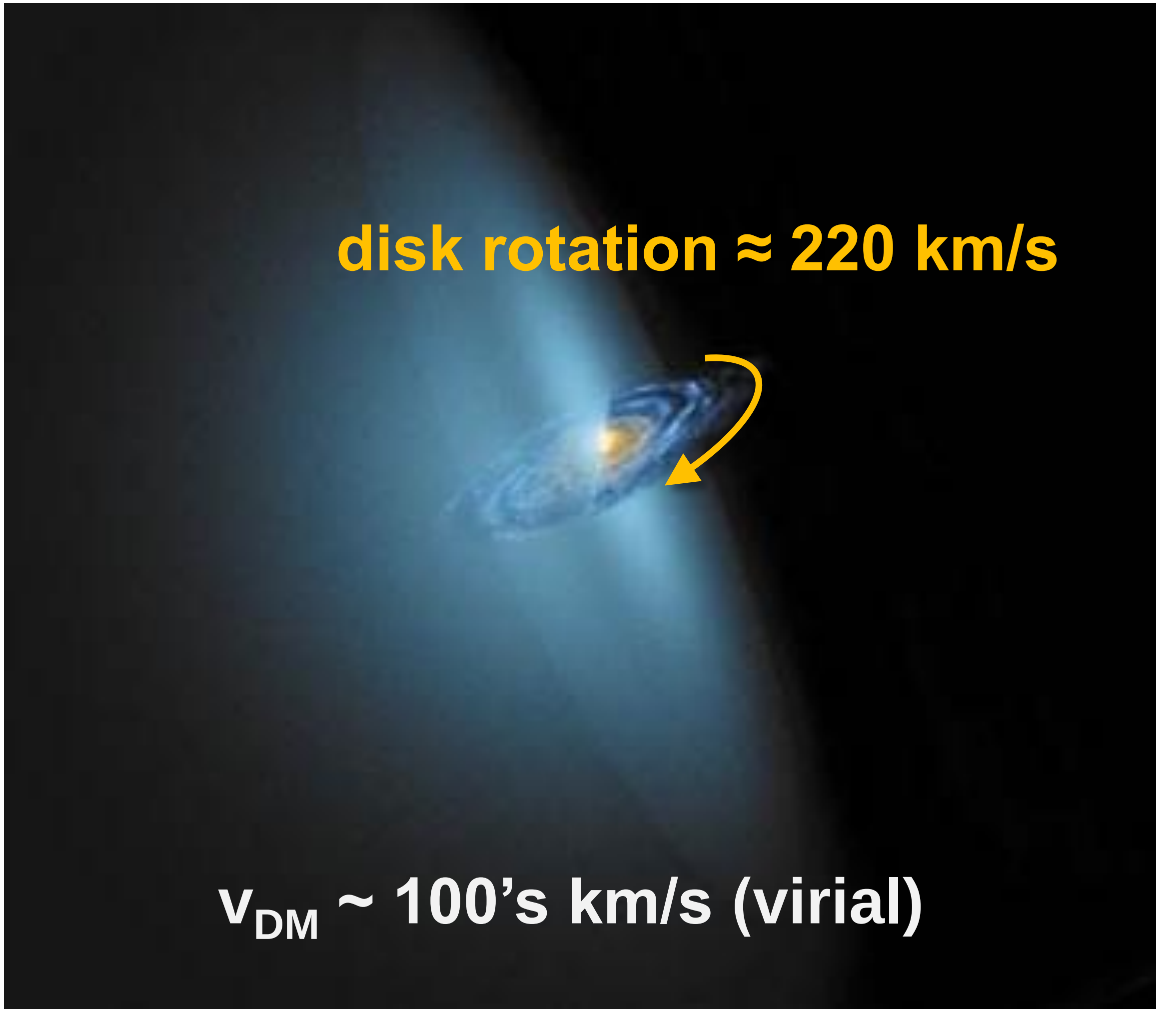



- A collider discovery will need confirmation from DD/ID for cosmological origin
- A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
- A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose

*(M. Carena, ESPPU 2019 Dark Sectors Summary Talk)*

# Dark Matter Halo

D. Dixon, cosmographica.com



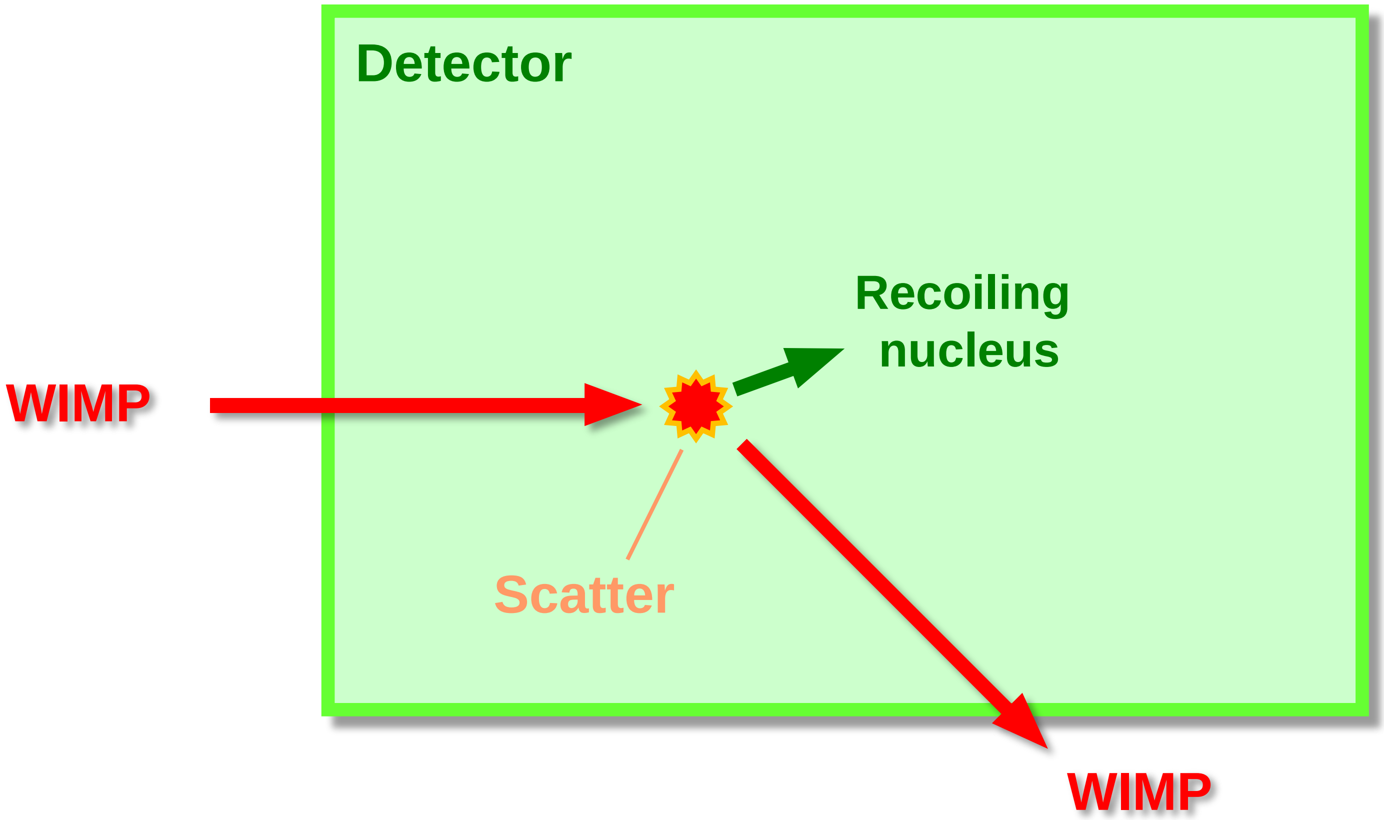
# Direct Detection

Goodman & Witten (1985)

See Freese, Lisanti & CS (2012) for a review

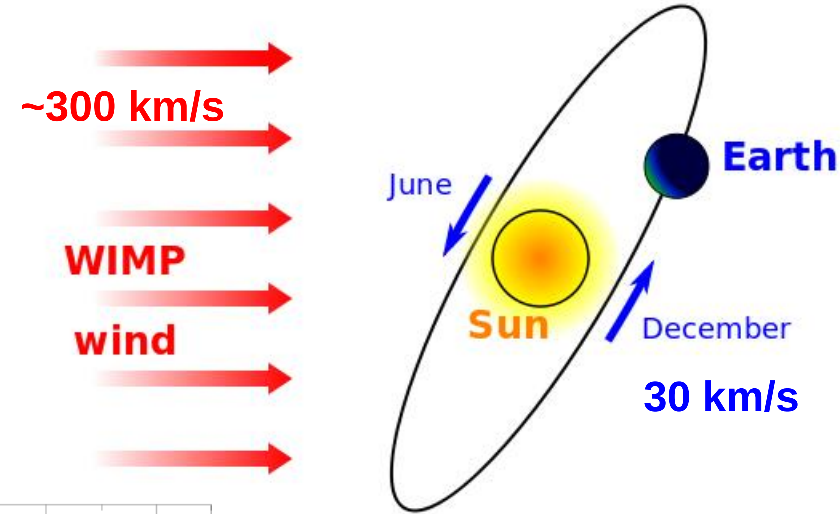
Review talk by Masiero

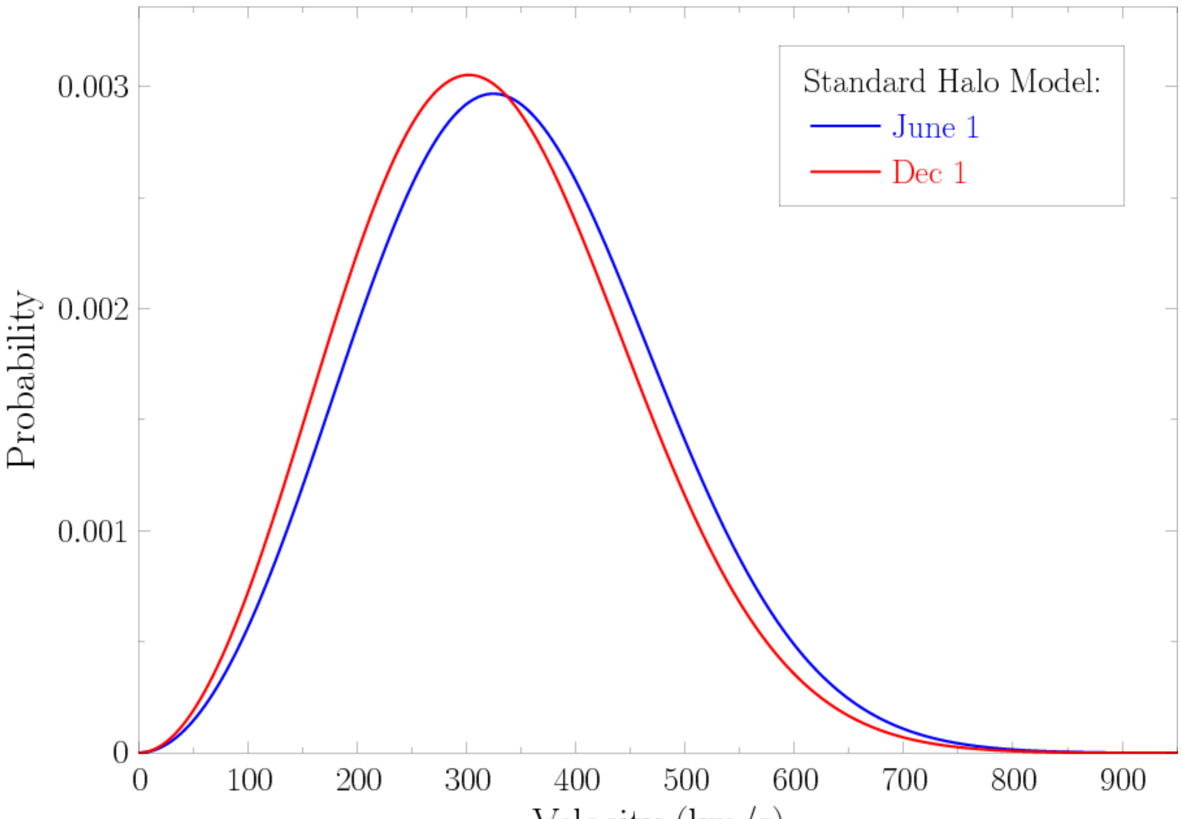
- Non-relativistic: elastic scattering of WIMP off detector nuclei $\rightarrow$ O(10 keV) recoil



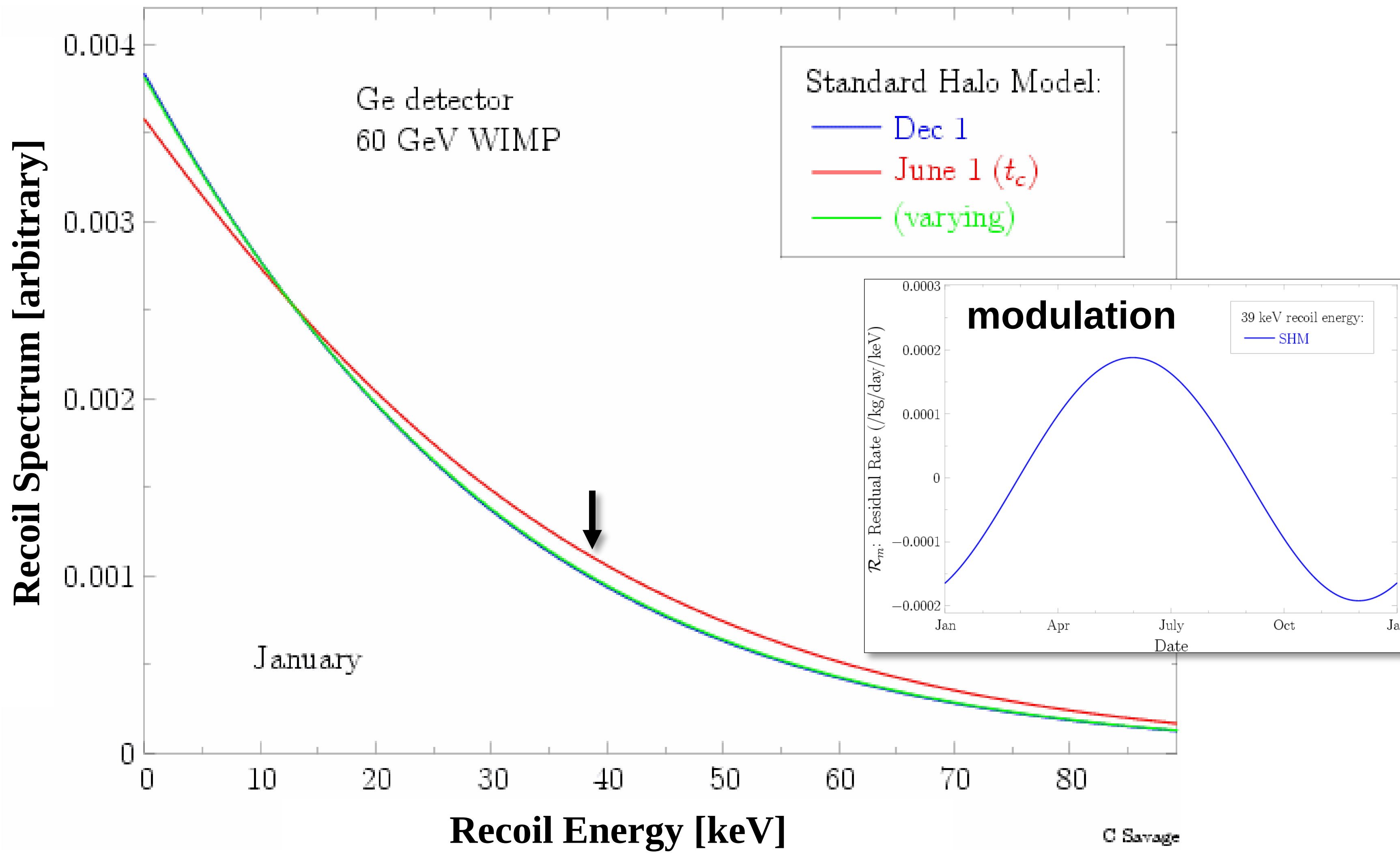
# Annual Modulation

Drukier, Freese & Spergel (1986)



# Recoil Spectrum



# Experiments

## Difficulties

- Low energies $\Rightarrow$ very sensitive detectors
- Backgrounds $\Rightarrow$ material selection/screening (radioactive contaminants), deep underground (cosmic rays)

Tomei & Barberio/Volpi

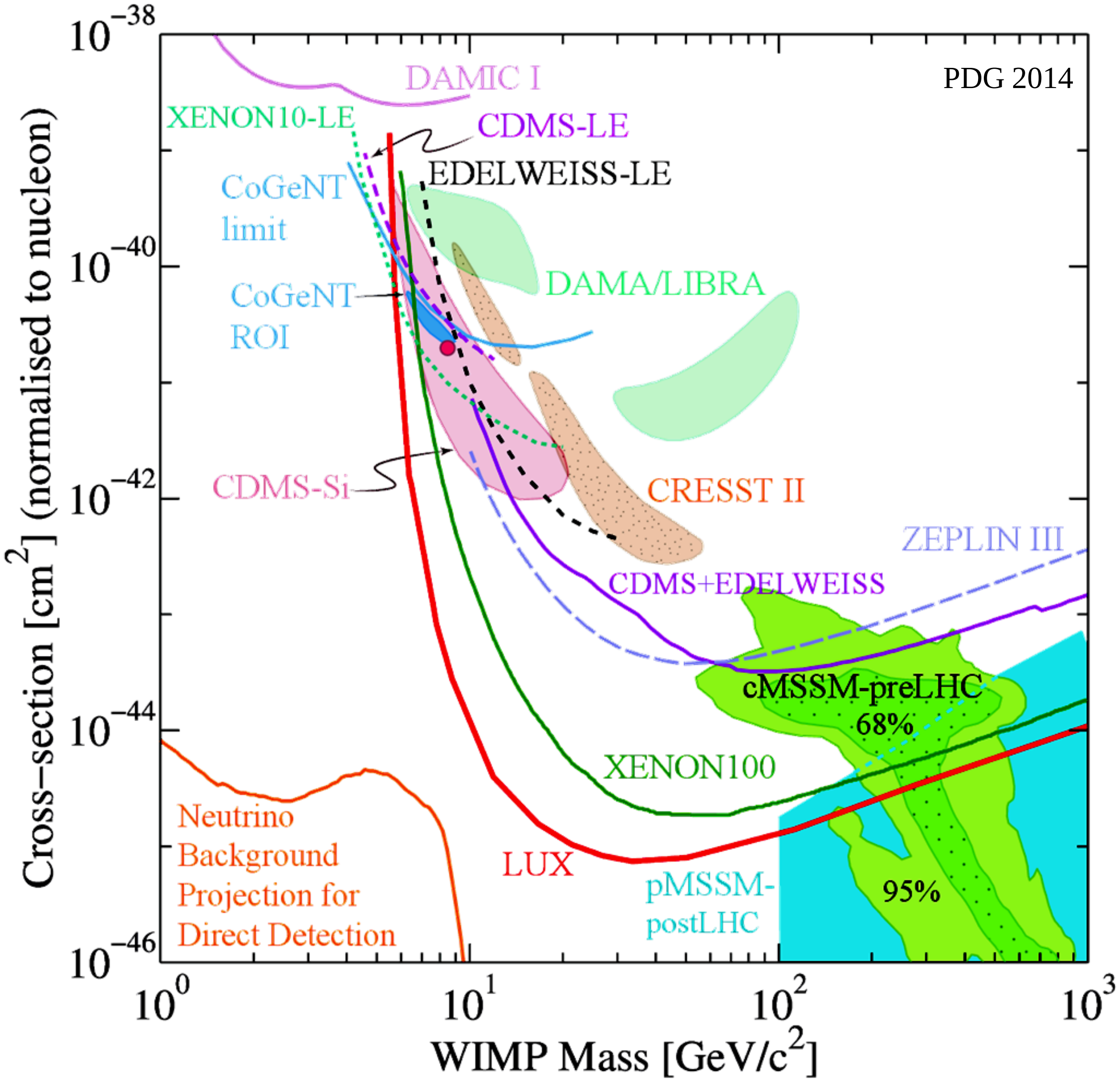
- Counting: CDMS, CoGeNT, COUPP, CRESST, DM-Ice, LUX, SABRE, XENON,…

Ragazzi (Gran Sasso), D'Angelo (SABRE)

- Modulation: DAMA [+CoGeNT and above]

Foot

# Experimental Results



# Direct Detection: Issues

Assumptions: neutralino-like w/ scalar interaction,
Standard Halo Model,…

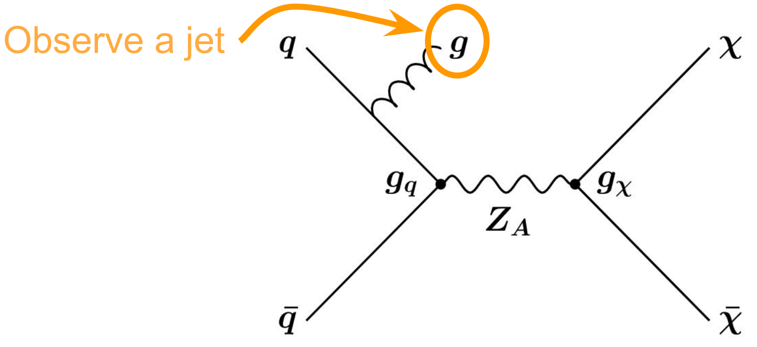
Issues affecting interpretation of results:

- Particle physics (interactions)
- Astrophysical uncertainties (halo)
- Poorly understood/unknown backgrounds
- Statistical analysis
- Detector energy calibrations
- Theoretical issues

  e.g. nuclear physics [Underwood, Giedt, Thomas & Young (2012)]

# Dark Matter Detection: Colliders

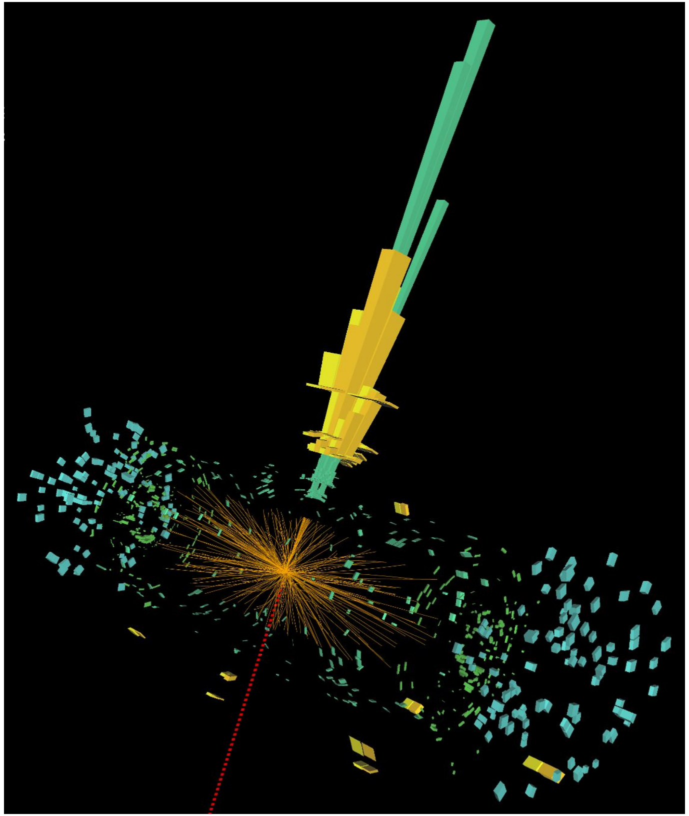
- Produce DM ($\chi$), imitating big-bang conditions




- If DM only interacts through gravity… how do we detect it?
  - ➥ Momentum is conserved ∴ can infer missing momentum by measuring all detected particles

$$E_{\mathrm{T}}^{\mathrm{miss}} = \left| -\sum_{\mathrm{reconstructed}} \vec{p}_T \right| = -\sum_{\mathrm{calo}} \vec{E}_T^{\mathrm{calo}} - \sum_{\mathrm{MS}} \vec{E}_T^{\mathrm{MS}}$$

Missing transverse energy (MET/$E_T^{miss}$)

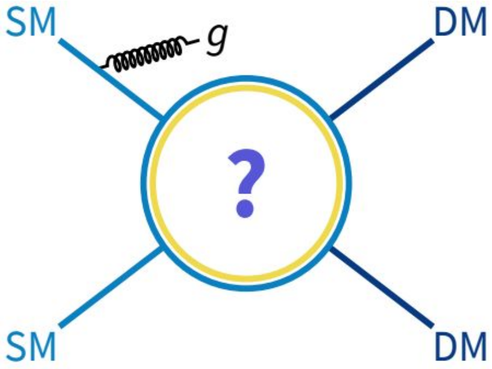


# Types of LHC DM Searches

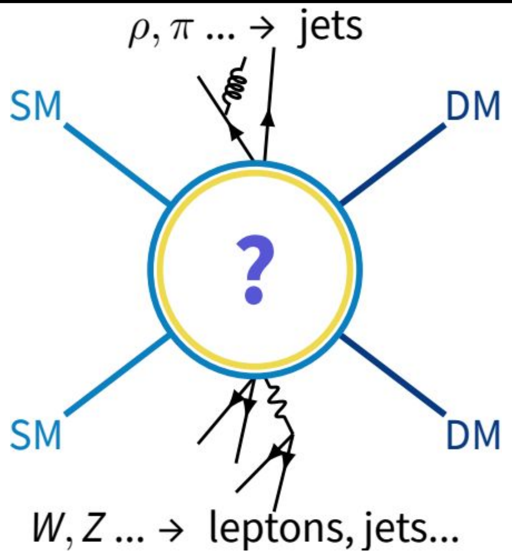
See Phys. Dark Univ. 26 (2019) 100371
& LHC DM Working Group

Dark matter is invisible to our detectors → look for associated production of visible (SM) particles

Generic Searches & Simpler Models ⟷ Specific Searches & More Complete Models



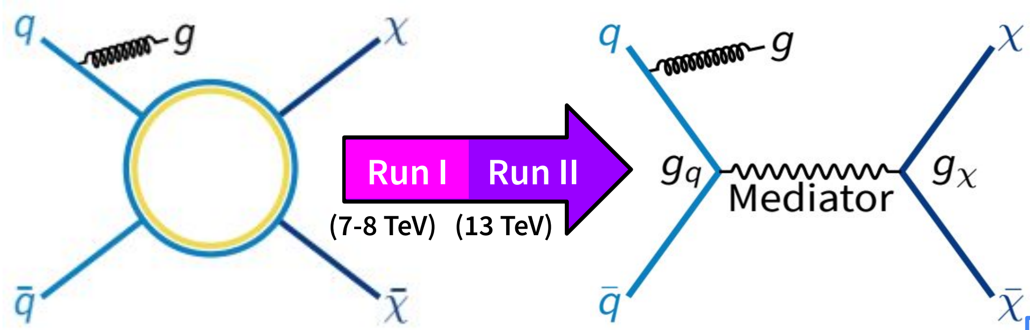

- Simple signals e.g. a single mediator
- Sizeable cross-sections
- Fewer assumptions on specific model parameters

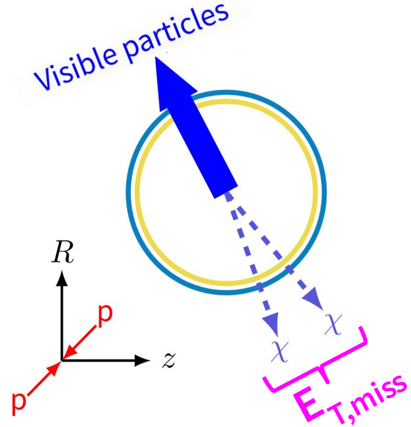



- More reliant on model assumptions
- E.g. supersymmetry, UV complete models

# Simplified Models - ‘Mono-X’

- The most general models involve contact interaction operators in Effective Field Theories (EFTs)
- These become invalid at large momentum transfer, $Q^2$, which is problematic for Run-II
  - ➥ Favour ‘simplified’ models with a mediator, introducing $m_\chi$, $m_{\text{med}}$, $g_q$ and $g_\chi$



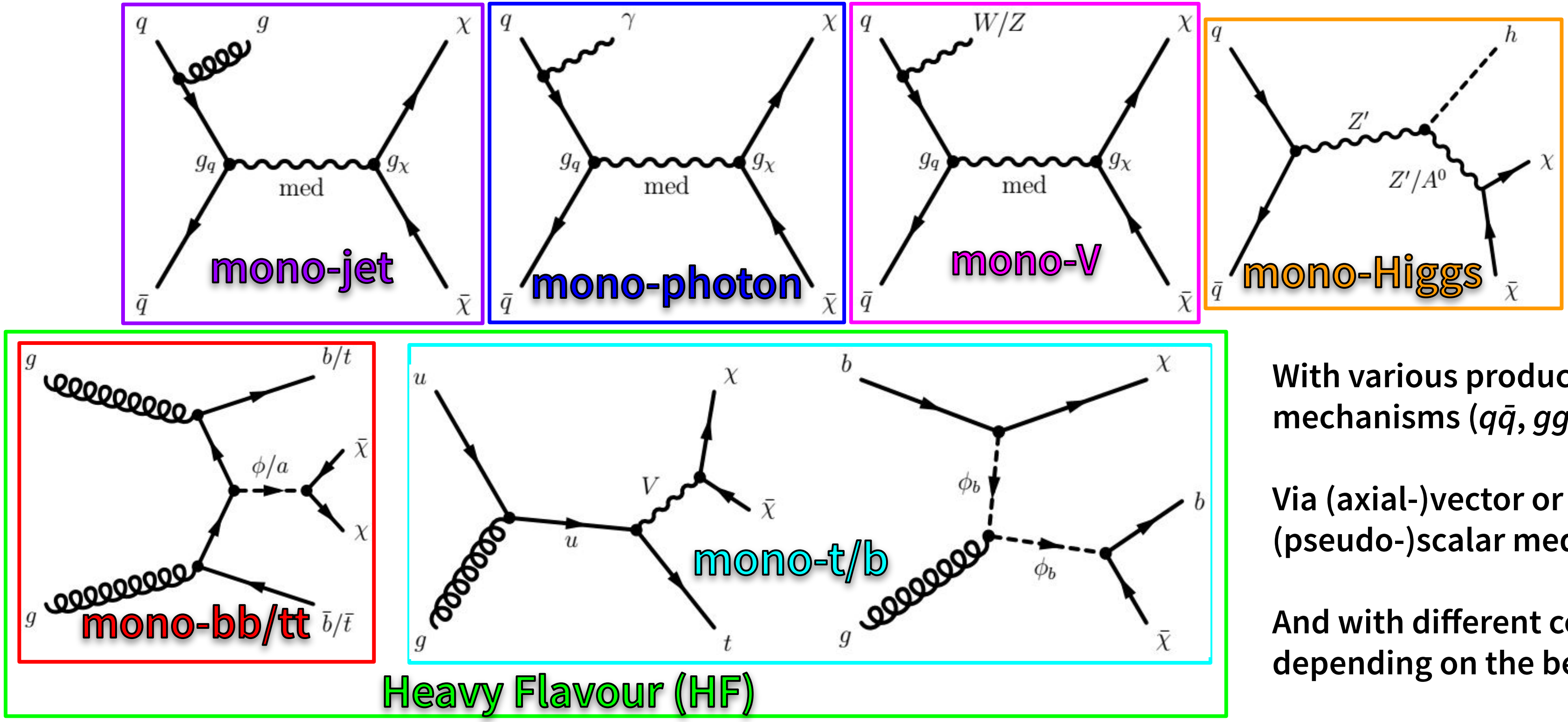




CERN-TH-2017-102

- Look for ‘mono-X’ signatures
  - ➥ Select events with ‘X’ (jet/$\gamma$/$W$/$Z$/$t$/$H$), veto other objects, precisely model backgrounds, check $E_T^{miss}$
  - ➥ Fix $g_q$, $g_\chi$ and exclude $m_\chi$, $m_{\text{med}}$ → CERN-LPCC-2016-001
- Also look for visible decays of the mediator to complement these searches → CERN-LPCC-2017-01
  - ➥ Re-interpret other analyses as mediator searches

# Mono-X Signatures

There is a wealth of mono-X final states to be investigated at the LHC...



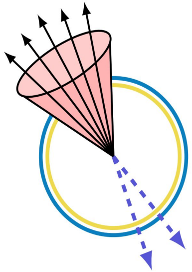

With various production mechanisms ($q\bar{q}$, $gg$ etc.) ...

Via (axial-)vector or (pseudo-)scalar mediators...

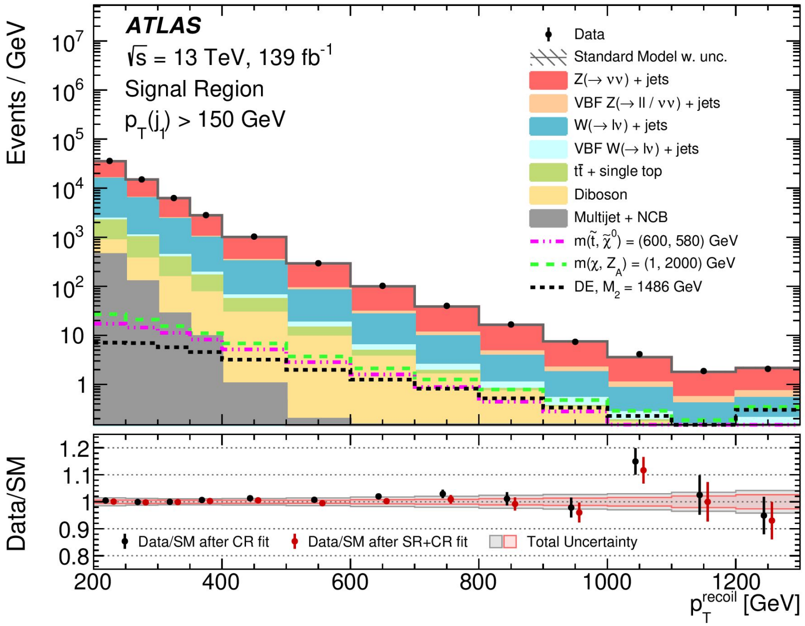
And with different couplings, depending on the benchmark

# Mono-jet

[Phys. Rev. D 103, 112006 (2021)](#)



- Gluon ISR is by far the most prevalent at the LHC!

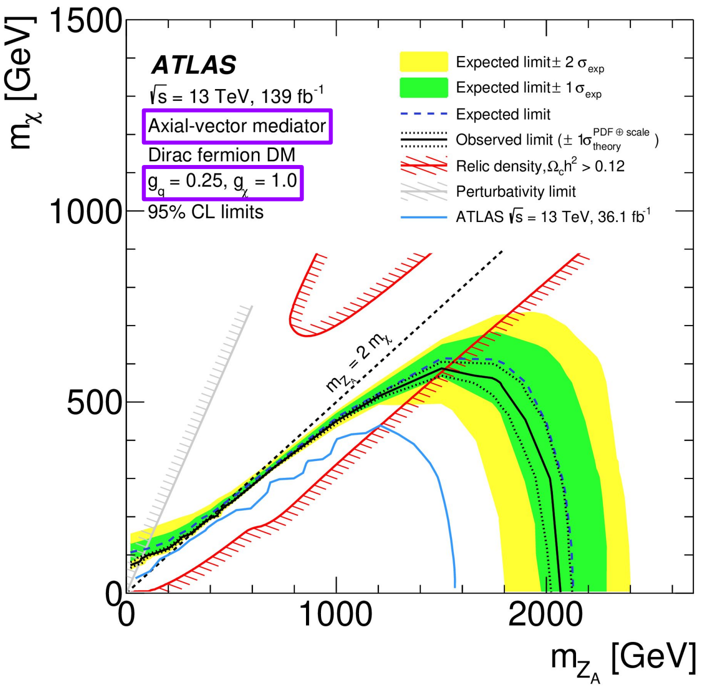


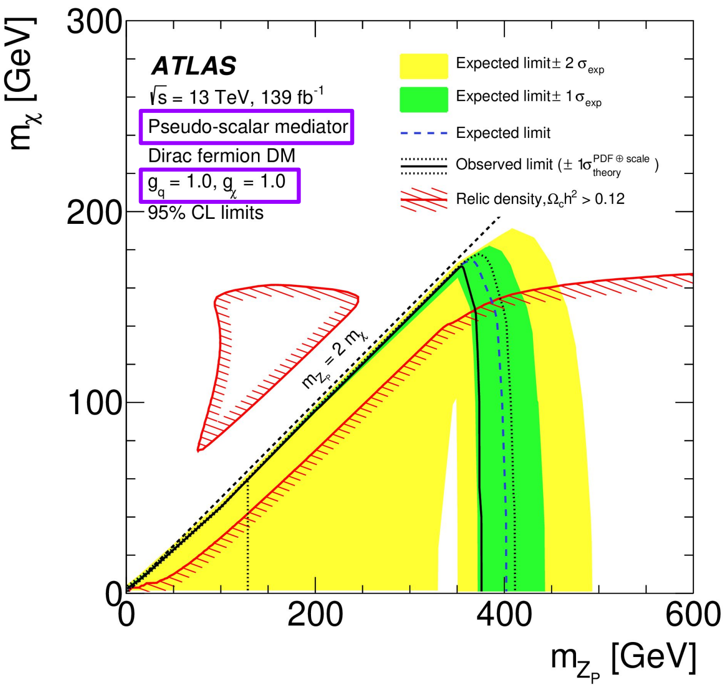

- **Signal Selections**
  - >1 jet with $p_T$ > 150 GeV
  - $E_T^{miss}$ > 200 GeV
  - Define signal regions (SRs) in bins of $E_T^{miss}$
- **Define control regions (CRs) to constrain SM BGs**
  - W→μν, W→eν, Z→μμ, Z→ee, top
- **Perform simultaneous binned bg-only likelihood fit**
  - Apply normalisation factors extracted from this fit to SM predictions

# Mono-jet

Phys. Rev. D 103, 112006 (2021)

- No observed excess ∴ set limits on signal cross section

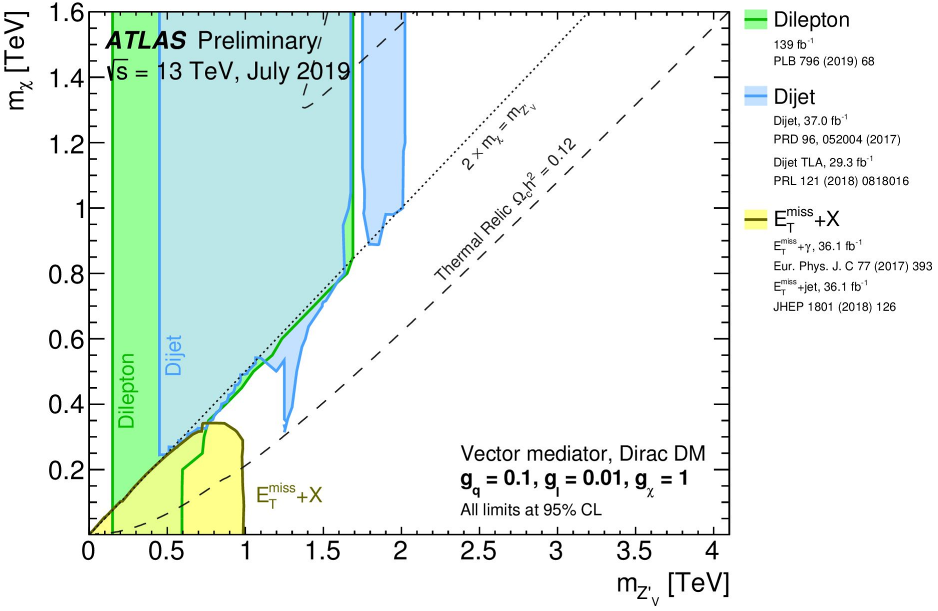


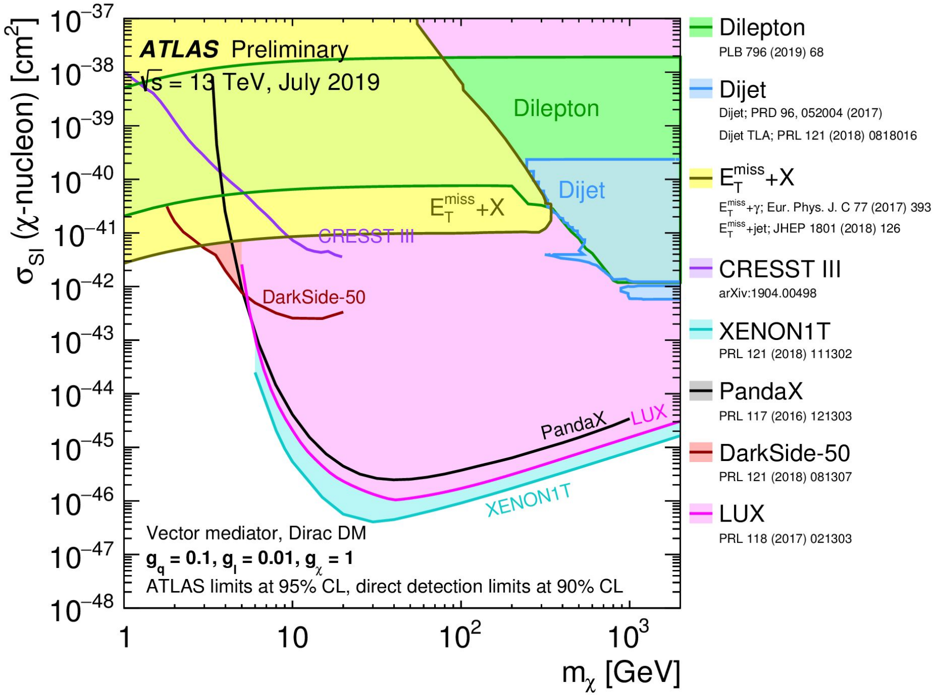



# Combined Results

JHEP 05 (2019) 142

- SI WIMP-nucleon scattering cross-section, Dirac DM, $g_\chi = 1$, $g_q = 0.1$, $g_l = 0.01$
  - For these couplings in this model, the mono-jet search has higher sensitivity than DD at low $m_\chi$!

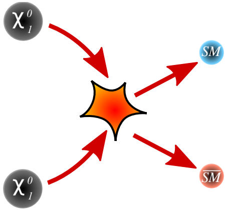


# What is indirect detection?

Looking for Standard Model particles produced by dark matter annihilation or decay.

- neutrinos – IceCube, Super-K, KM3NET
- anti-protons – PAMELA, AMS-02, CALET
- anti-deuterons – AMS-02, GAPS
- $e^+e^-$ – PAMELA, Fermi, AMS-02, CALET
  $\rightarrow$ secondary radiation: inverse Compton, synchrotron, bremsstrahlung
- gamma-rays – Fermi-LAT, HESS, CTA
- secondary impacts on the CMB, reionisation
- ‘indirect direct detection’ $\rightarrow$ impacts on solar and stellar structure

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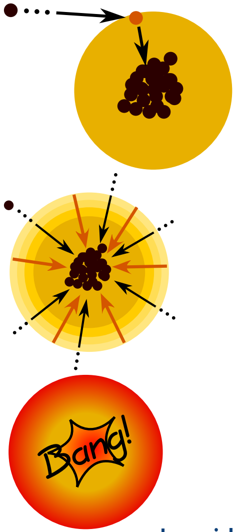
# Neutrinos – how does it work?

The cartoon version:

1. Halo WIMPs crash into the Sun
2. Some lose enough energy in the scatter to be gravitationally bound
3. Scatter some more, sink to the core
4. Annihilate with each other, producing neutrinos
5. Propagate+oscillate their way to the Earth, convert into muons in ice/water
6. Look for Čerenkov radiation from the muons in **IceCube**, ANTARES, etc

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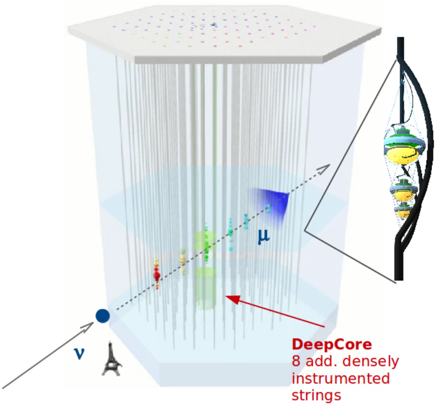
# The IceCube Neutrino Observatory

- 86 strings
- 1.5–2.5 km deep in Antarctic ice sheet
- $\sim$125 m spacing between strings
- $\sim$70 m in DeepCore (10$\times$ higher optical detector density)
- 1 km$^3$ instrumented volume (1 Gton)

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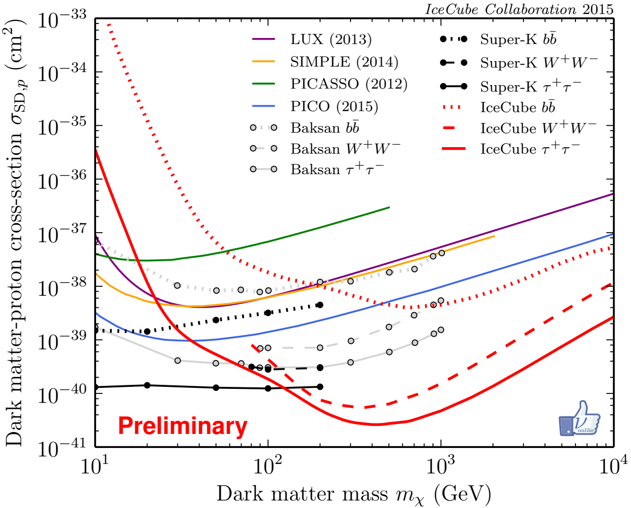
# Neutrinos – IceCube, Super-K et al




IceCube Collaboration (+PS, Savage, Edsjö) *in prep*

`nulike`: model-independent unbinned limit calculator for generic BSM models

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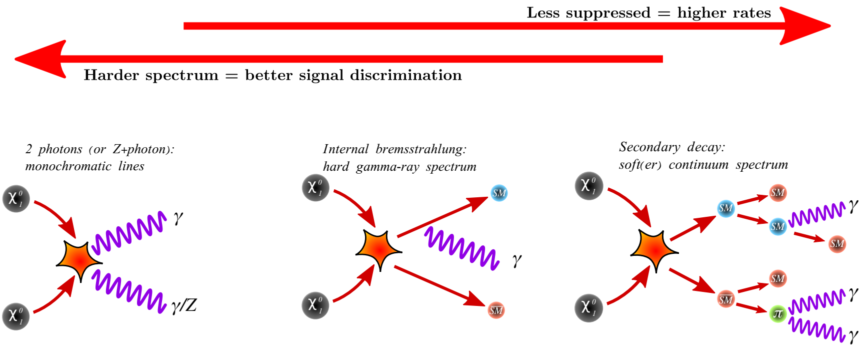
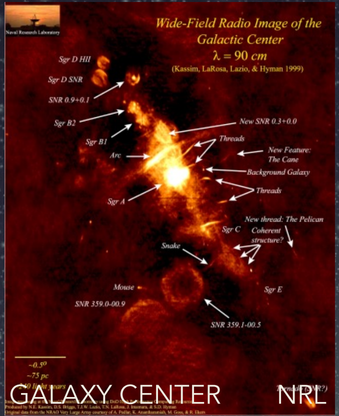
# Types of gamma-ray spectra



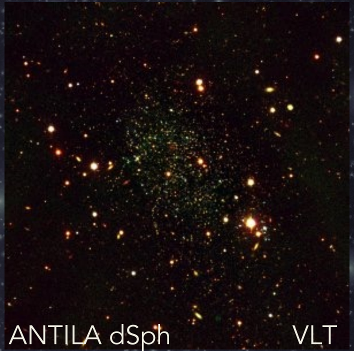

- 3 main gamma-ray channels:
  - monochromatic lines
  - internal bremsstrahlung (FSR + VIB)
  - continuum from secondary decay

# Targets

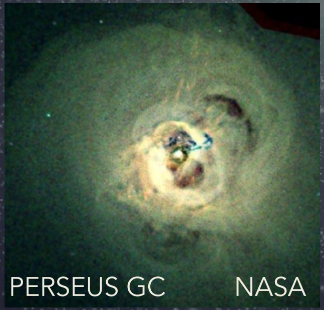
- Galactic Center
- High flux
- Huge background




- Dwarf Galaxies
- Large M/L
- No background
- Low flux



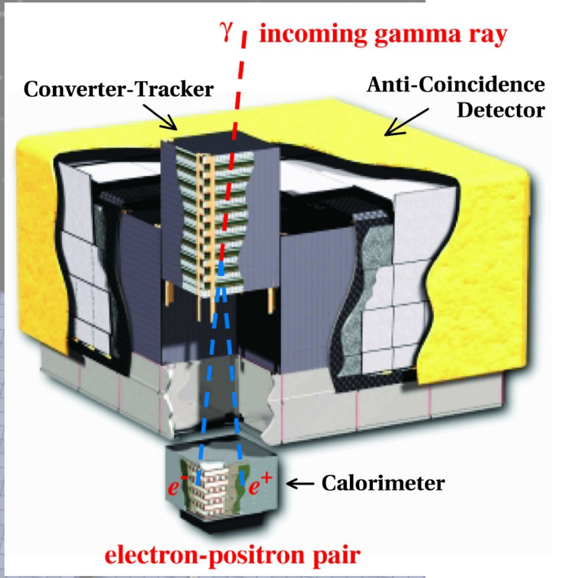

- Galaxy Clusters
- Huge DM content
- Large distance
- High background




- *DM subhalos*
- *Irregular dSph*
- *Spiral galaxies*
- *…*

Fermi Gamma-ray Space Telescope

- Fermi-GST
  - Fermi-LAT and Fermi-GBM
- Fermi-LAT
  - Precision Si-strip tracker
  - Hodoscopic CsI calorimeter
  - Energy range: 20 MeV - 300 GeV
  - Large FoV ~2.4 sr
  - Full sky coverage every two orbits (~3h)
  - Collection area: ~1m$^2$




fermi.gsfc.nasa.gov

# Indirect Dark Matter Searches: Detectors

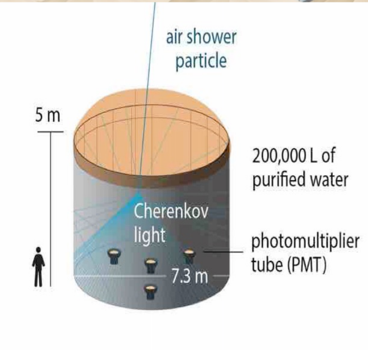
- Two telescope array
- La Palma Island (Spain)
    - 2200 m a.s.l.
- Reflectors: 2 x 17 m Ø
- Cameras: 3.5° FoV
    - 1039 PMT
- Energy
    - Threshold: 50 GeV
    - Resolution: 15%
- Angular resolution ~ 0.07°
- Sensitivity ~0.8 % C.U.
- Light Carbon Fiber struc.

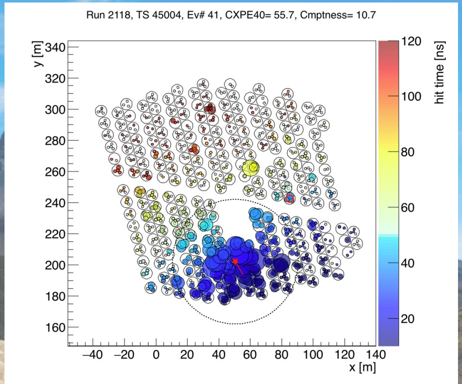
- Four telescope array
- Tucson (USA)
    - 1268 m a.s.l.
- Reflectors: 4 x 12 m Ø
- Cameras: 3.5° FoV
    - 499 PMT
- Energy
    - Threshold: 100 GeV
    - Resolution: 15%
- Angular resolution ~ 0.1°
- Sensitivity ~0.7 % C.U.

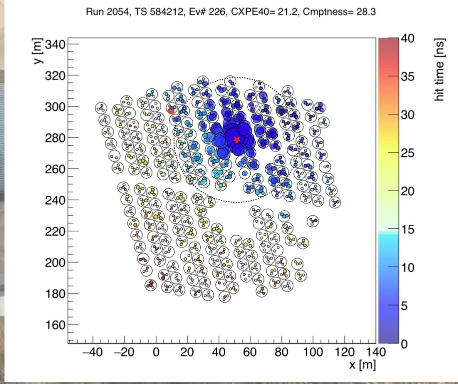
- 4+1 telescope array
- Namibia
    - 1800 m a.s.l.
- Reflectors:
    - 4 x 13 m Ø
    - 1 x 28 m Ø
- Cameras:
    - 4 x 960 PMT, 5° FoV
    - 1 x 2048 PMT, 3.2° FoV
- Energy
    - Threshold: 100 GeV
    - Resolution: 15%
- Angular resolution ~ 0.08°
- Sensitivity ~0.7 % C.U.

## High Altitude Water Cherenkov gamma-ray Observatory

- 4100 m asl, Sierra Negra, Mexico
- Large FoV (15% sky)
- Covers 2/3 sky in 24h
- 90% duty cycle
- 300 4.5m x 7.3m tanks (4 PMTs)
- Energy range: 0.5 TeV – 100 TeV

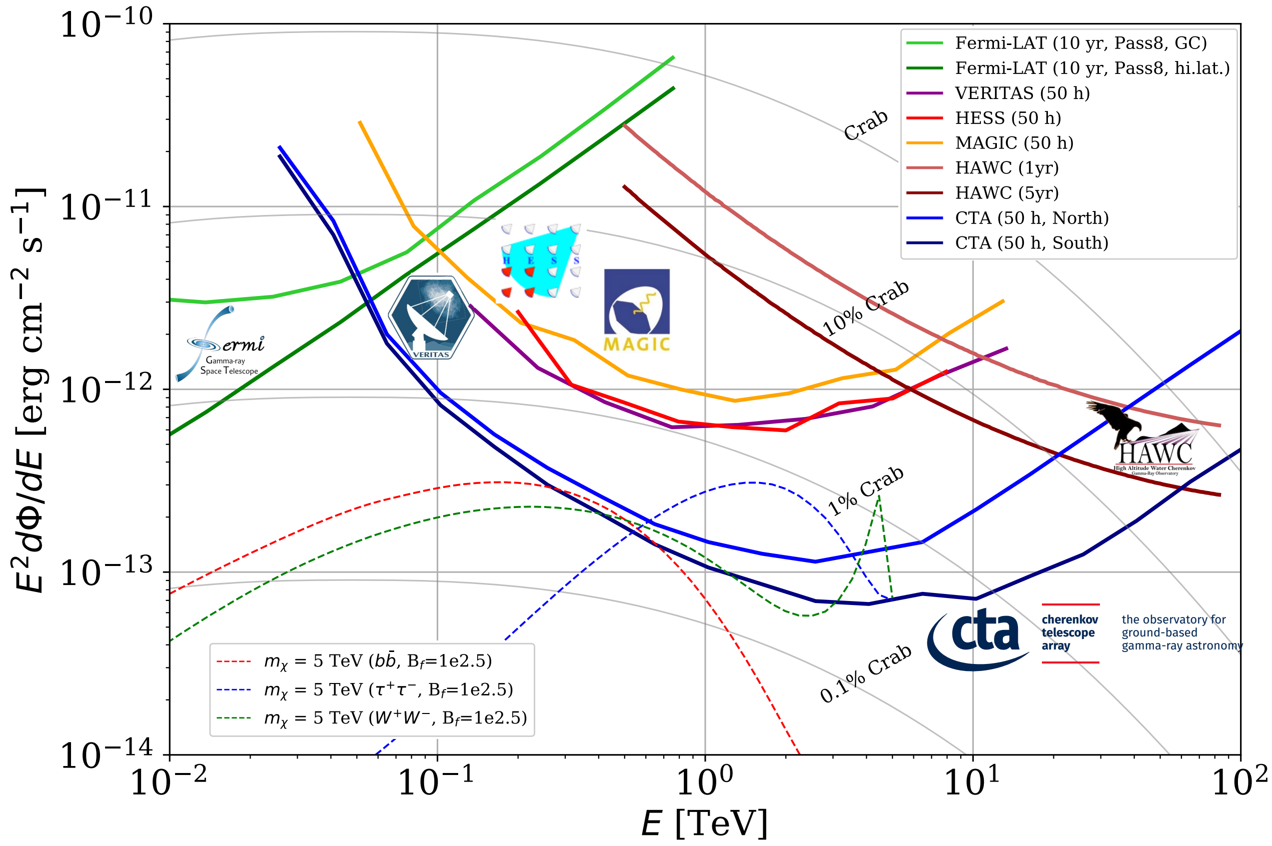



www.hawc-observatory.org

# Indirect Dark Matter Searches: Detectors



# References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- C. Savage CoEPP-CAASTRO Workshop: Dark Matter Direct Detection
- Ellis Kay, Baltic School of High-Energy Physics and Accelerator Technologies 2021
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# Thank You!