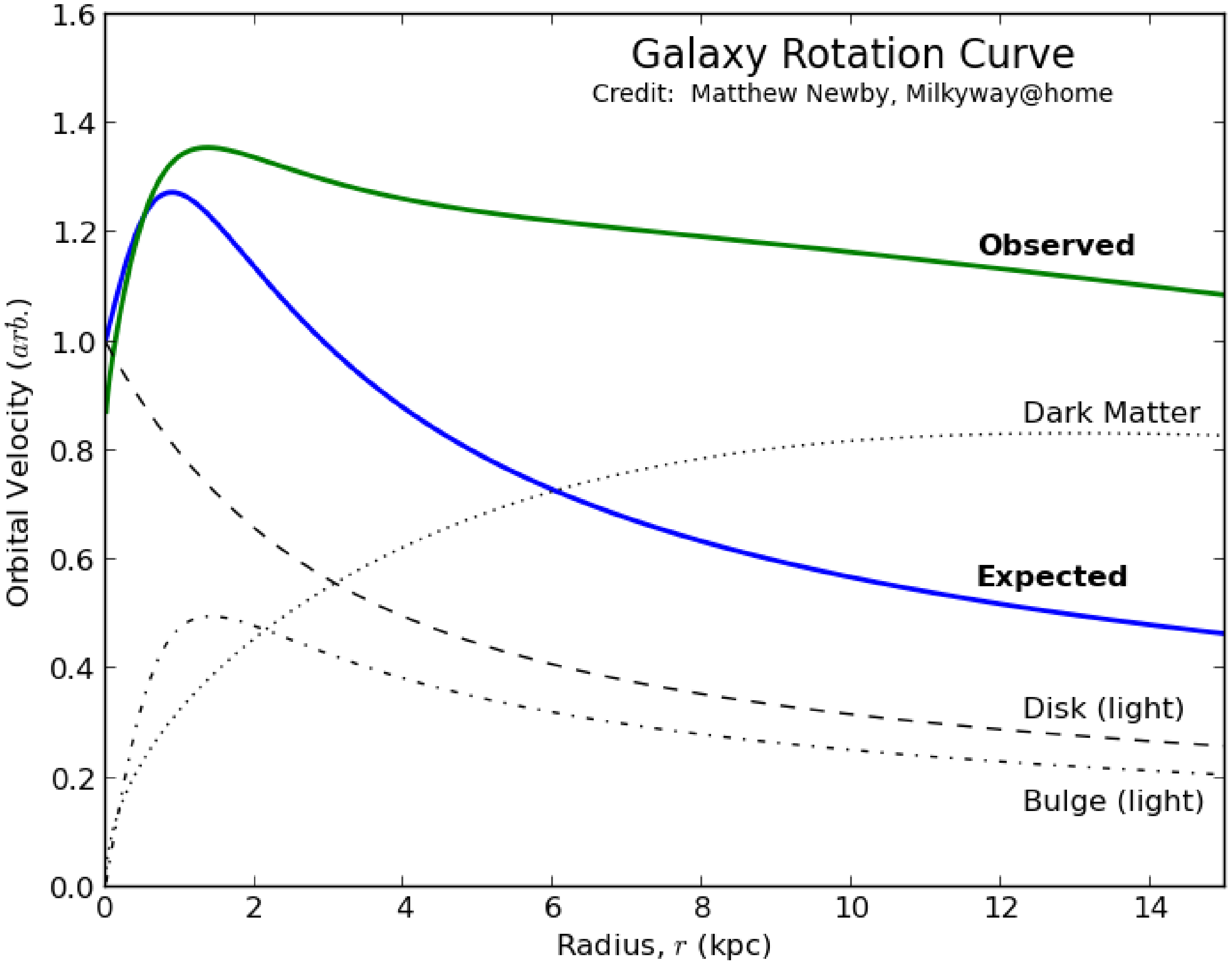
Dark Matter

- 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 $R > R_s$

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

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



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:

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

Using $P_{\rm gas} = \frac{\rho_{\rm gas} k T_{\rm gas}}{\mu}$ above, we get:

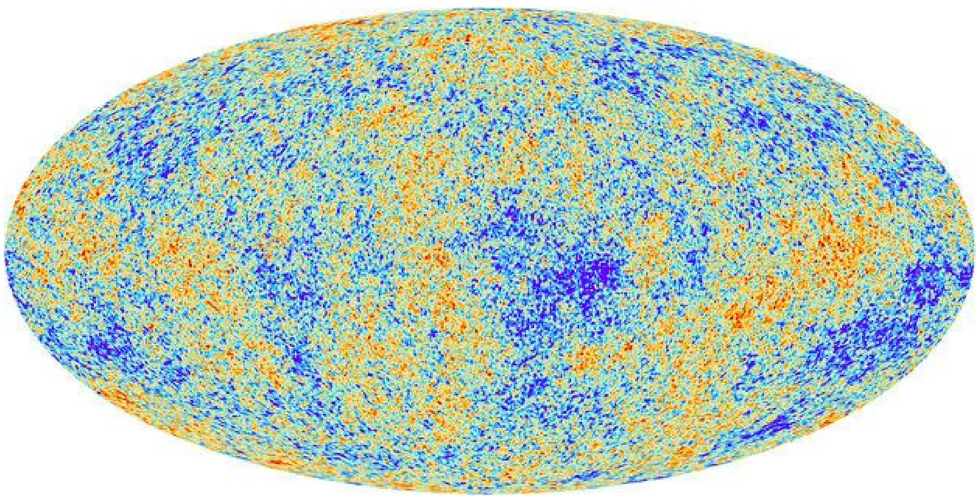
$$M(r) = \frac{kT_{\rm gas}(r)r}{G\mu}\left[-\frac{d\ln\rho_{\rm gas}}{d\ln r} - \frac{d\ln T_{\rm gas}}{d\ln r}\right]$$

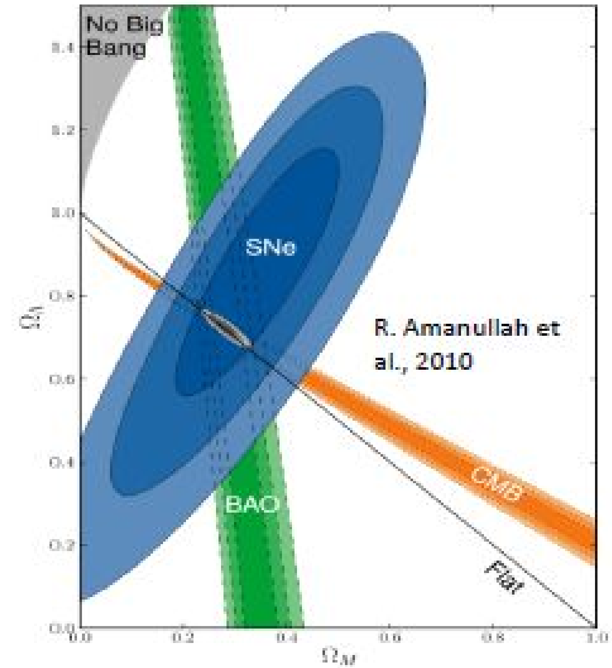
- X-ray data and modeling gives composition, temperature and density distribution of gas
- Eg: $M_{coma} \approx 1.3 \times 10^{15} M_\odot$

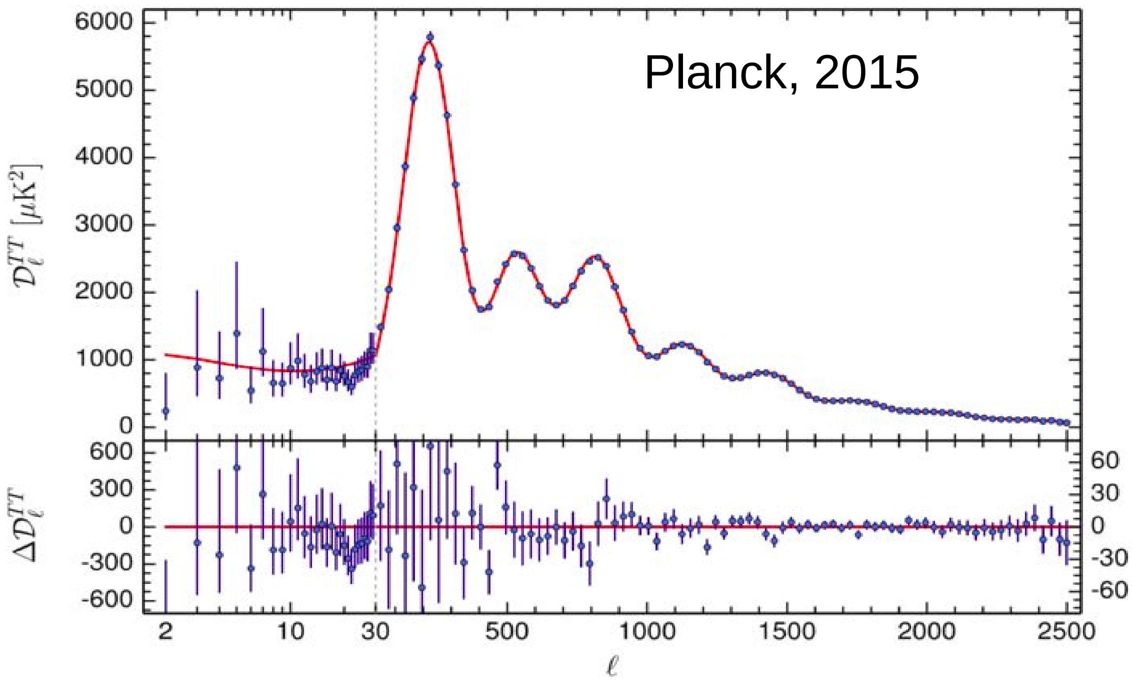
$$\boxed{\Omega_{\rm clus,0} \approx 0.2}$$

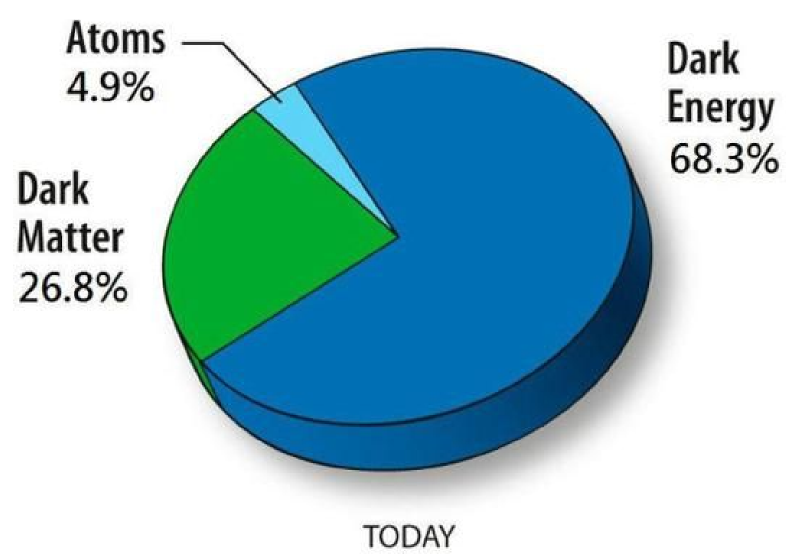
Evidence for Dark Matter

- Cosmic microwave background (CMB) observations, resulting in precise estimates (WMAP, Planck) supporting ΛCDM model



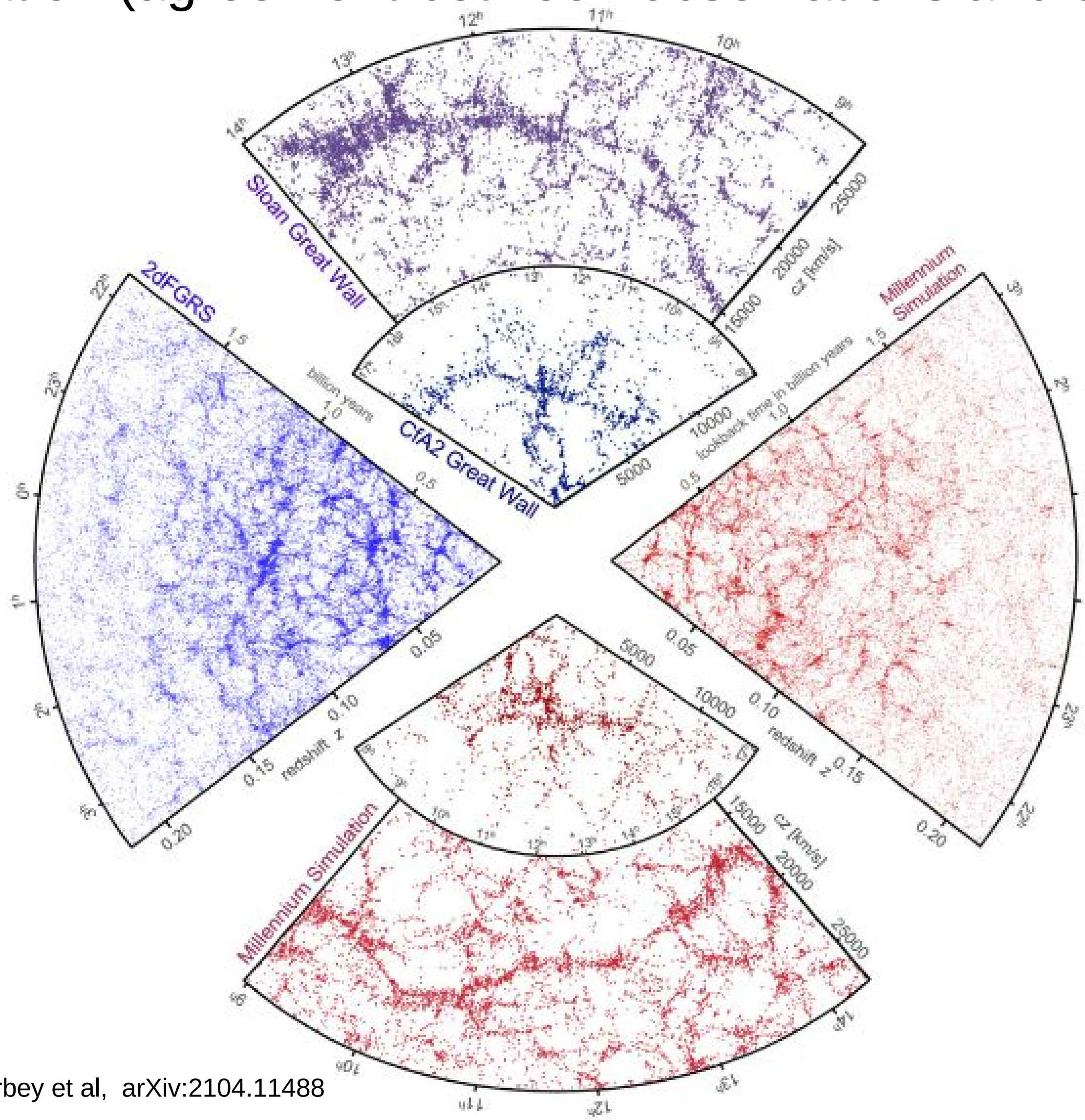






More evidence for Dark Matter

- Large scale formation (agreement between observations and simulation)

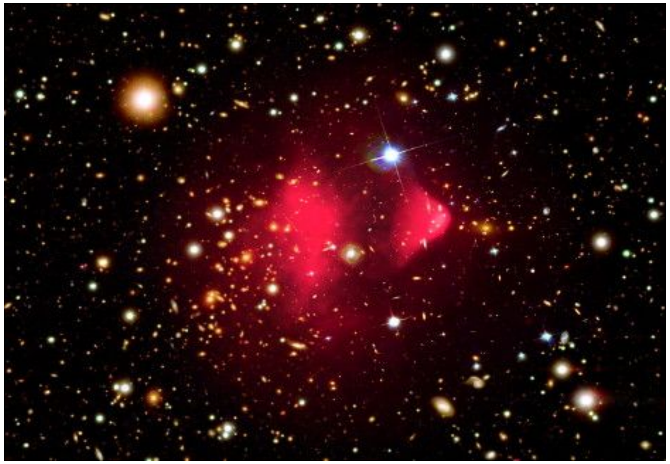


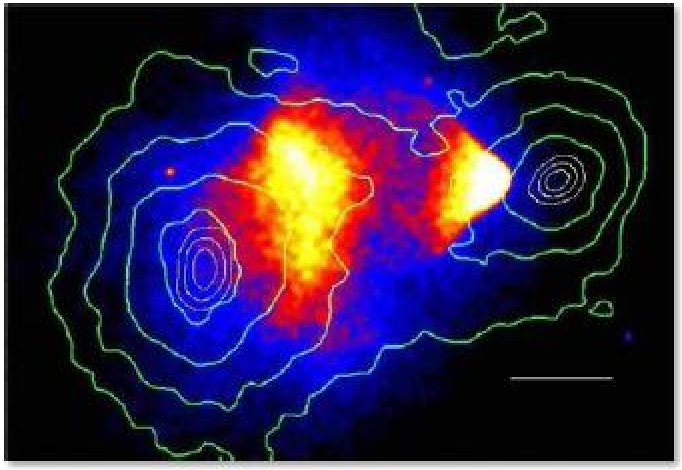
A. Arbey et al, arXiv:2104.11488

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].

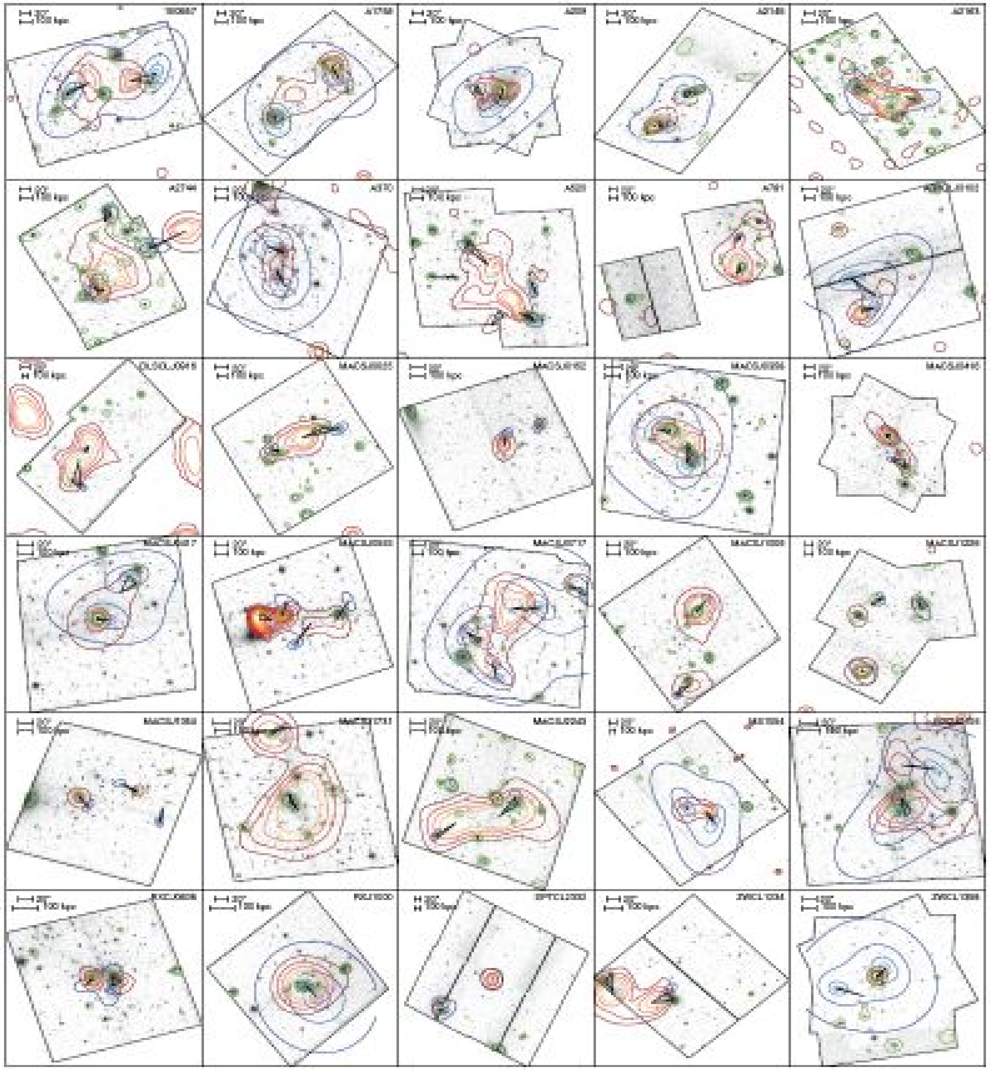
More evidence for Dark Matter

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





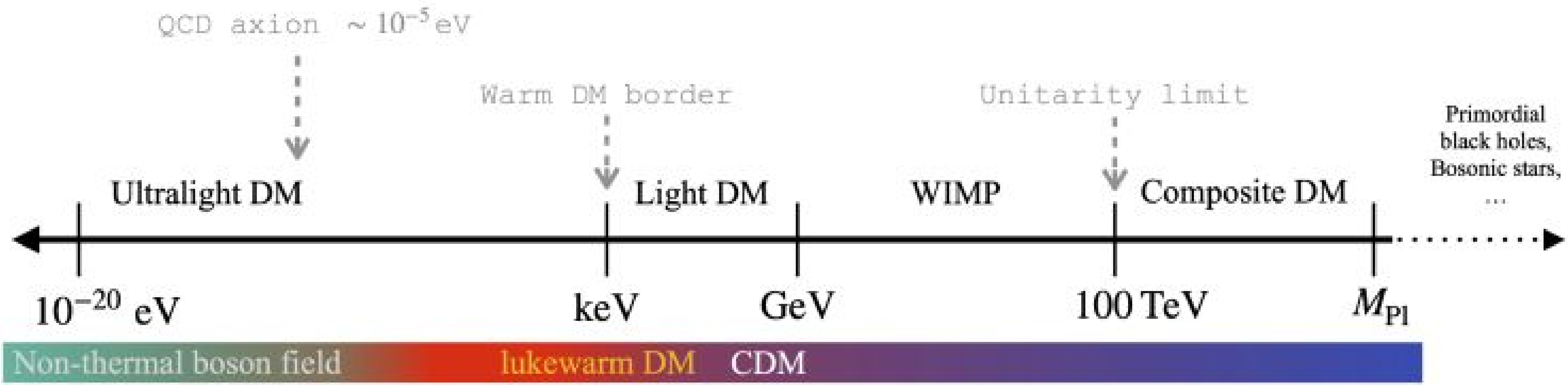
The bullet cluster, D. Clowe et al., 2006



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

What is Dark Matter?

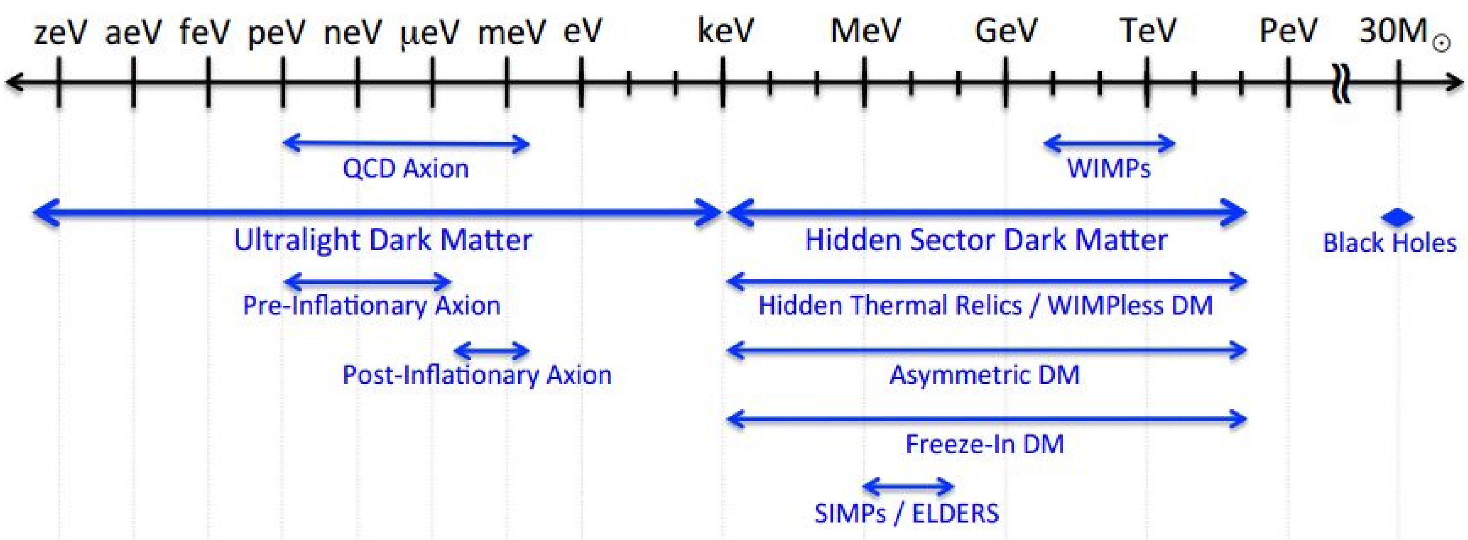
- A number of possibilities considered and excluded:
  - Modifications of the gravity law (MOND)
  - Massive compact halo objects (MACHOs)
- Primordial black holes
- New Particles. Options include:
  - Axions
  - Weakly Interacting Massive Particles (WIMPs)
  - ...



K. Tuominen, Symmetry 2021, 13, 1945

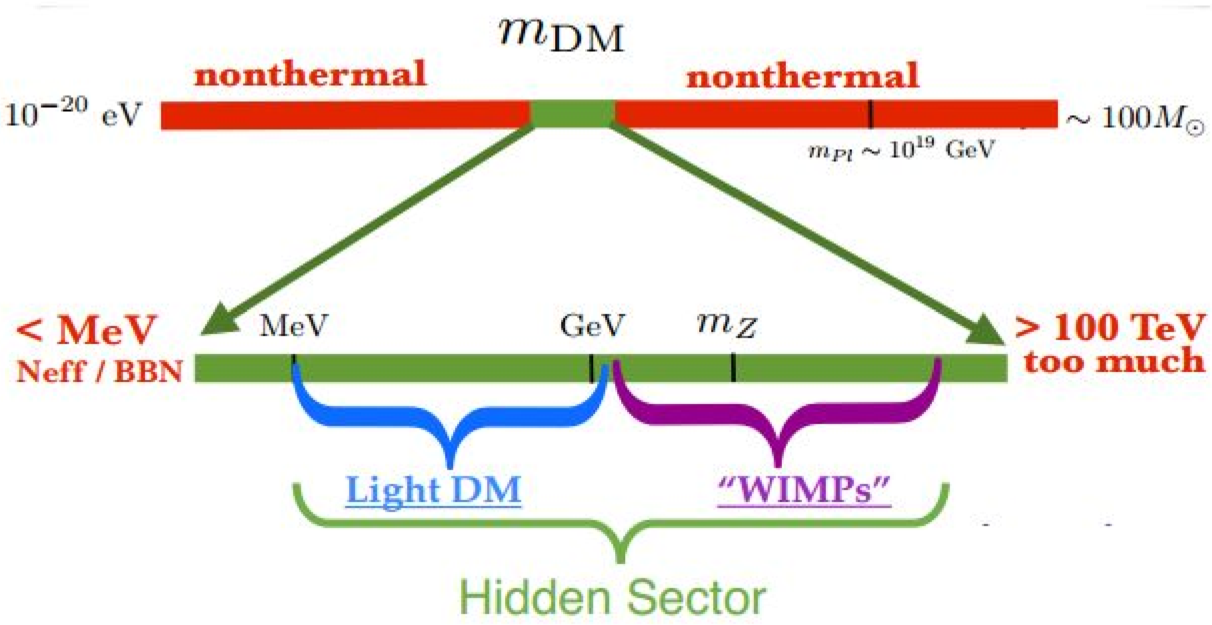
Mass scale

Too small mass
⇒ won't "fit"
in a galaxy!



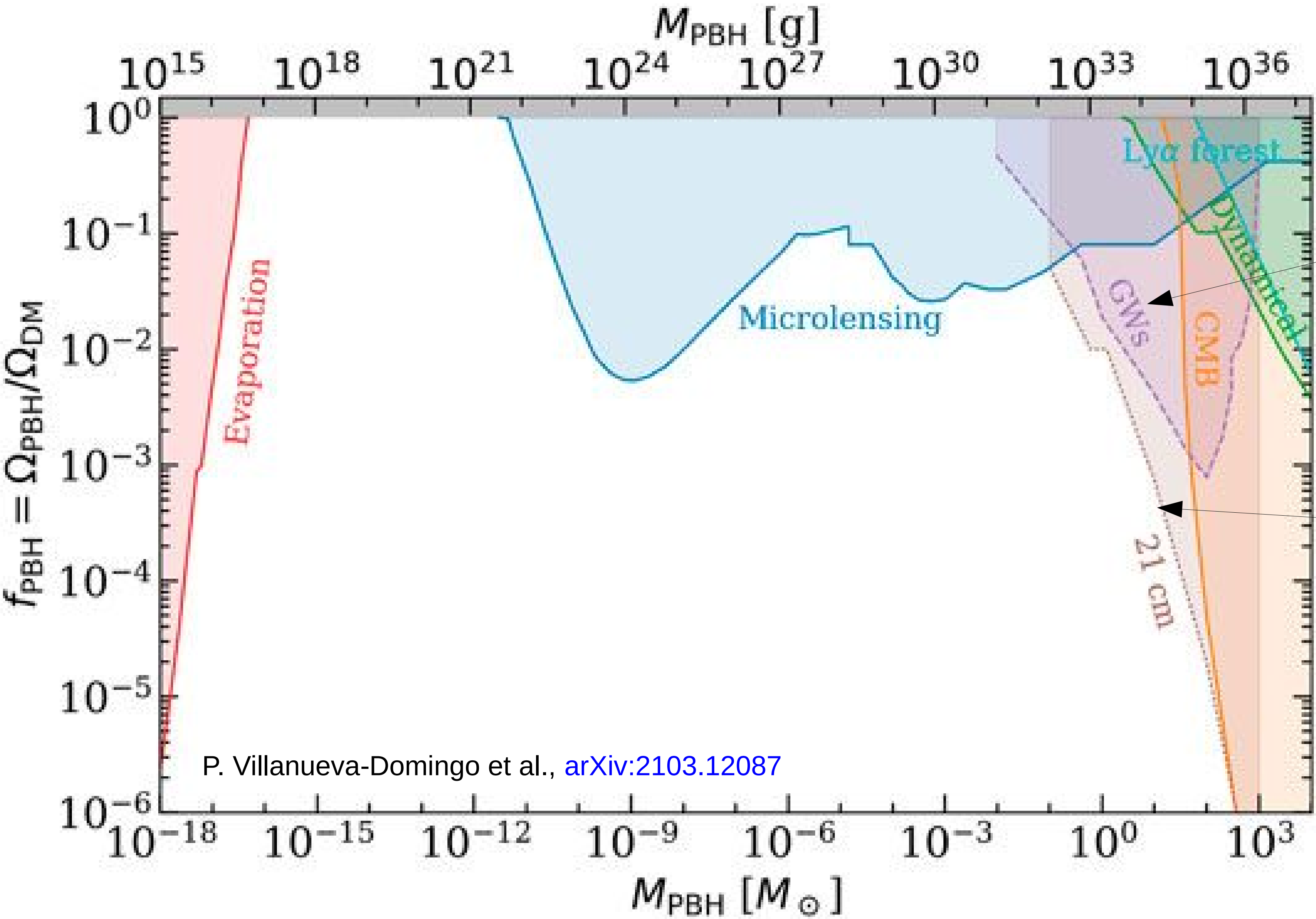
From MACHOs
searches

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

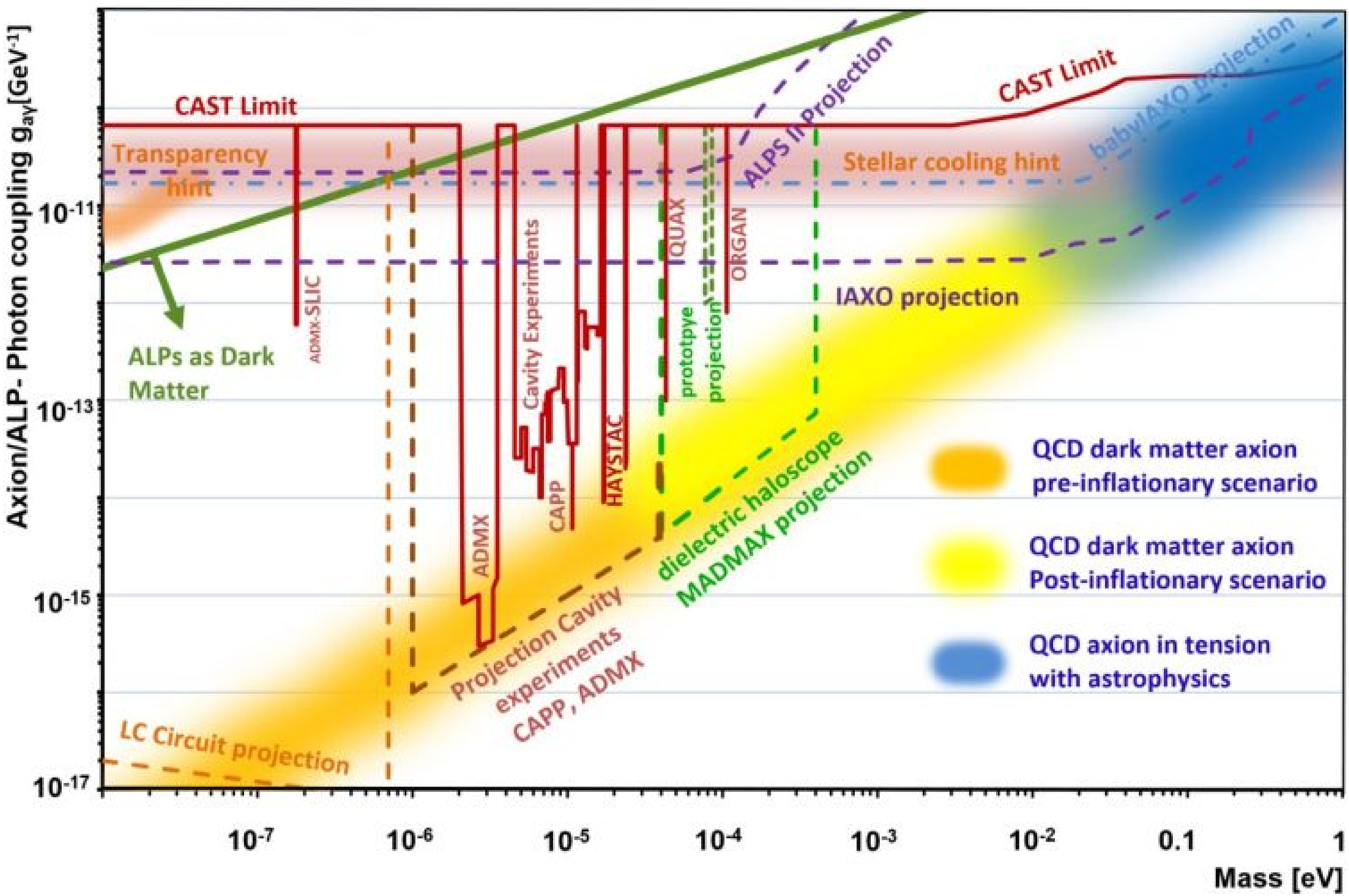
C. Bœhm et al JCAP03(2021)078

projected future sensitivity (SKA)

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

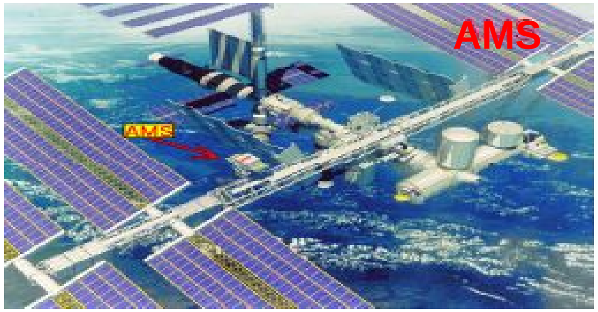
Heavily constrained as a primary DM component. But some room still exists...

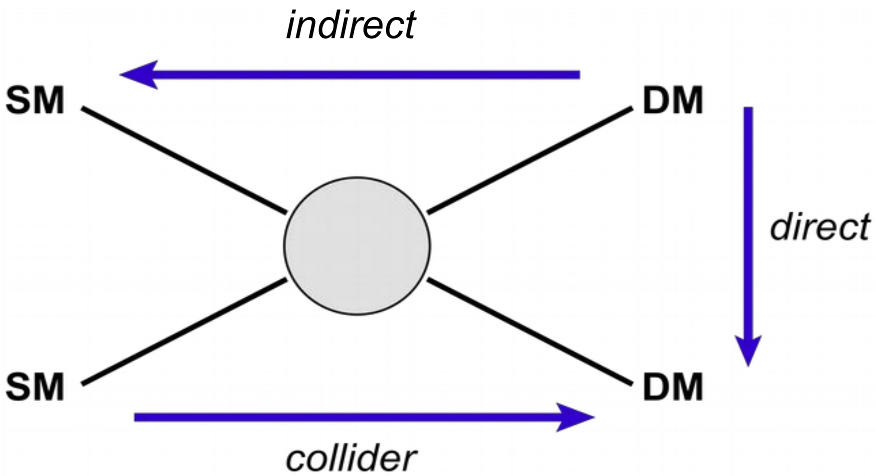
Axions and axion-like particles (ALPs)

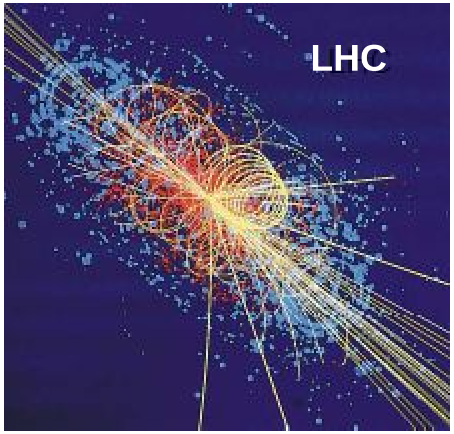


J. Billard et al., APPEC Committee Report, arXiv:2104.07634

Ways to look for Dark Matter particles



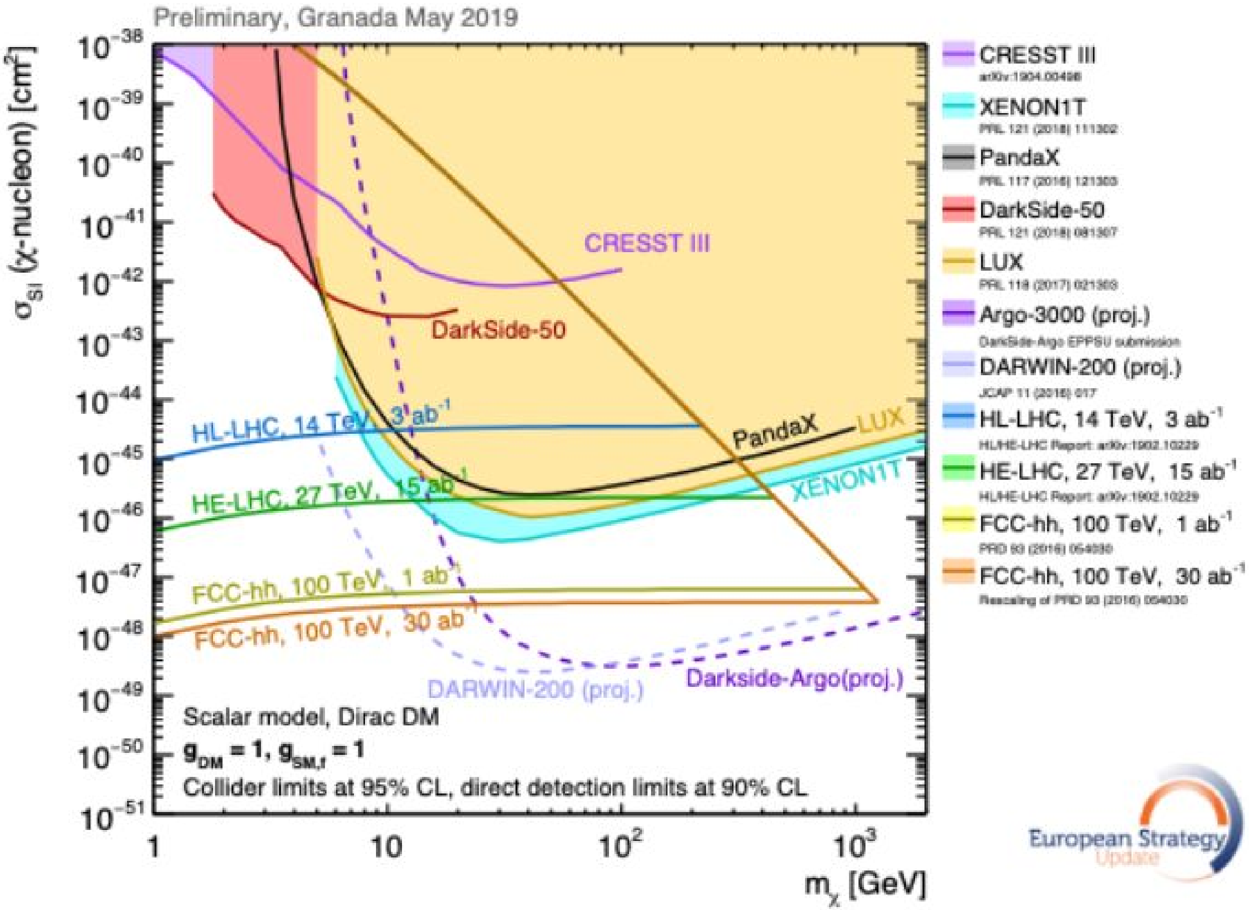




- Indirectly via their annihilation in Sun, Earth, Galaxy
  - Neutrinos (IceCube, Antares)
  - Positrons, antiprotons (AMS)
  - γ-rays (Fermi-LAT, CTA)
- <u>**Direct detection**</u>
- By producing them at accelerators (LHC, beam dump experiments)

Colider/direct detection complementarity

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

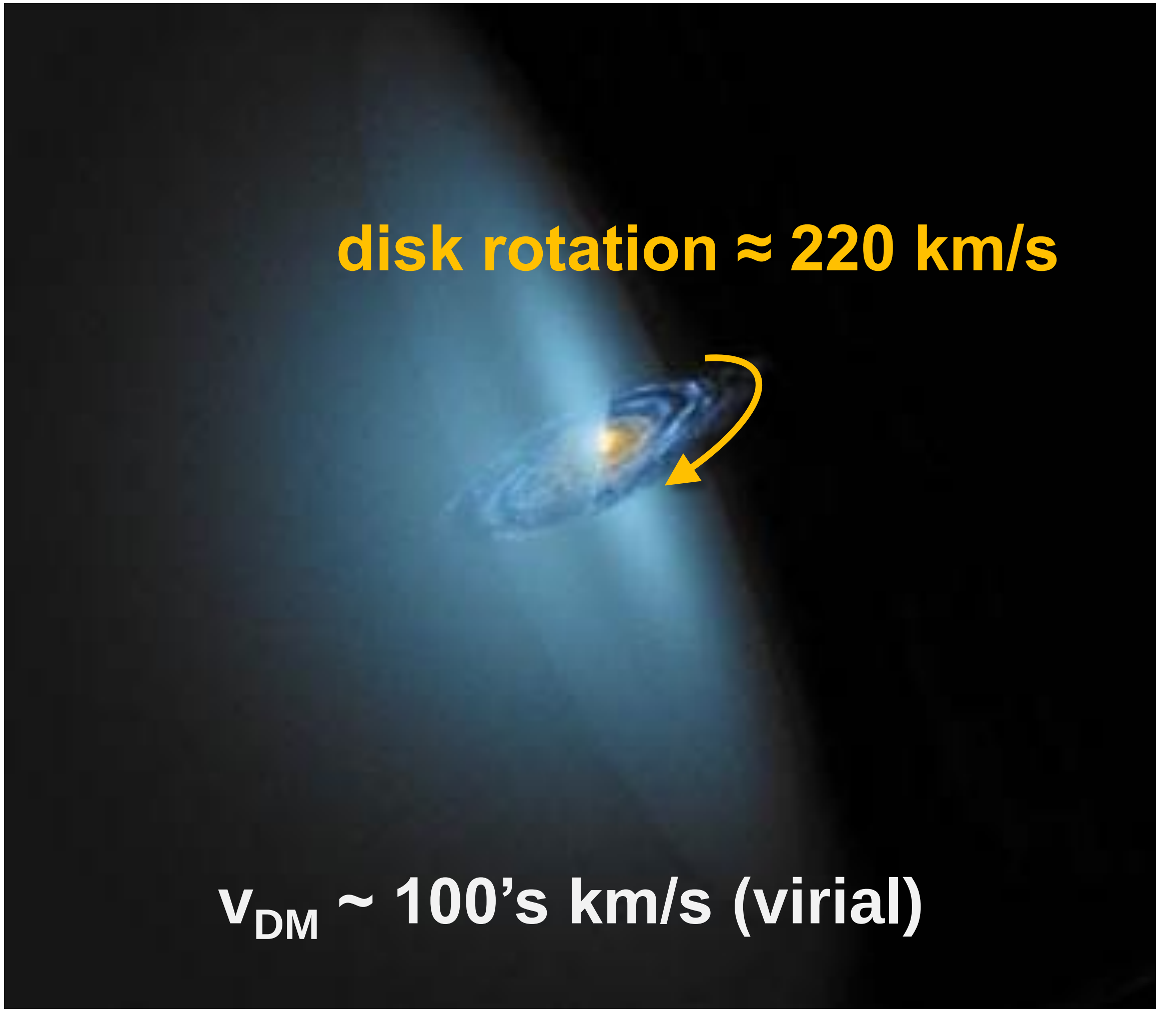


- A collider discovery will need confirmation from DD/ID for cosmological origin
- A DD/ID discovery will need confirmation from colliders to understand the nature of the interaction
- A future collider program that increases sensitivity to invisible particles coherently with DD/ID serves this purpose

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

Dark Matter Halo

D. Dixon, cosmographica.com



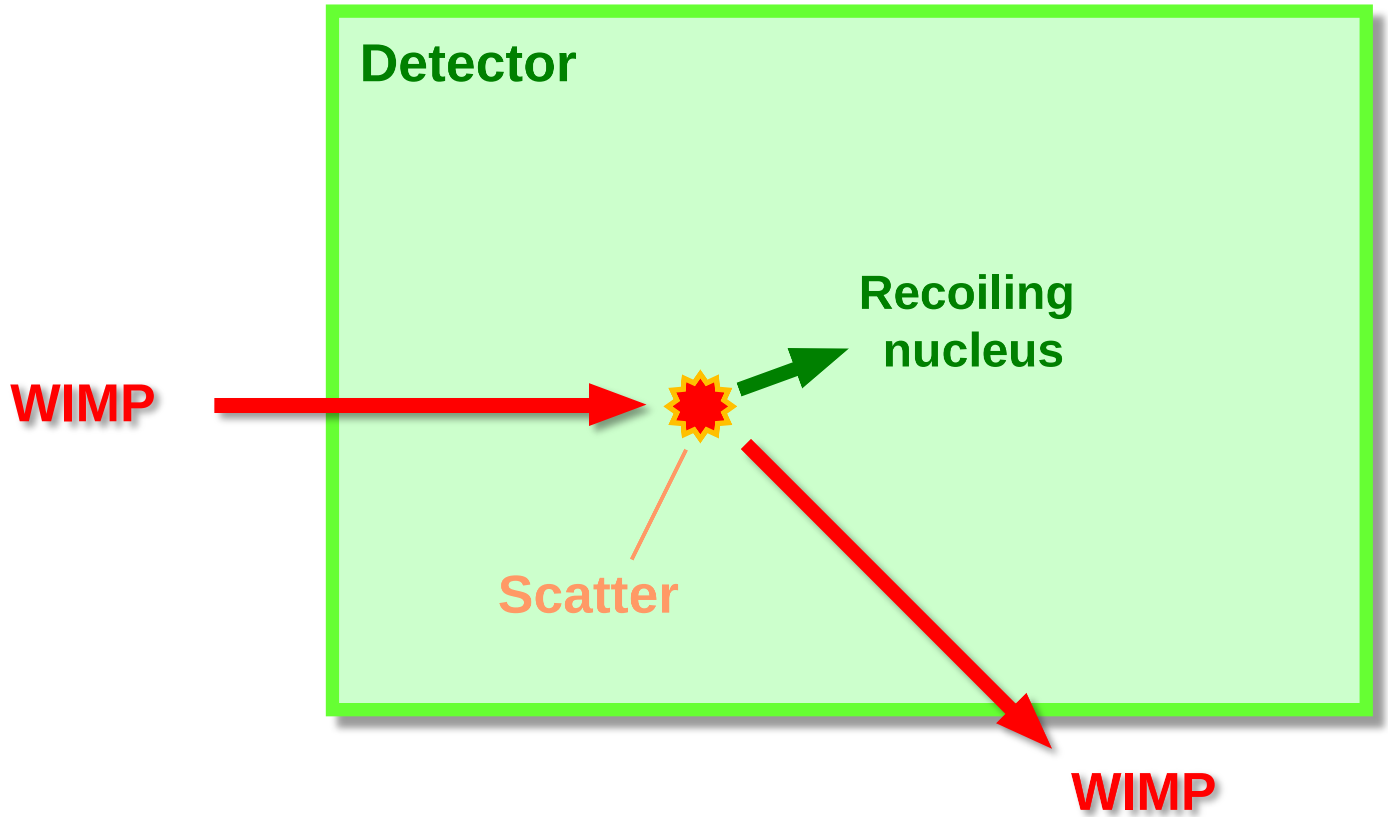
Direct Detection

Goodman & Witten (1985)

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

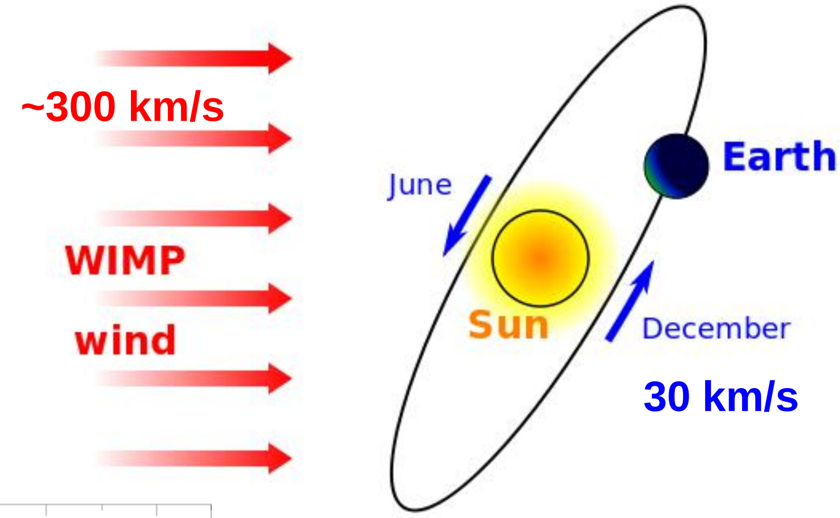
Review talk by Masiero

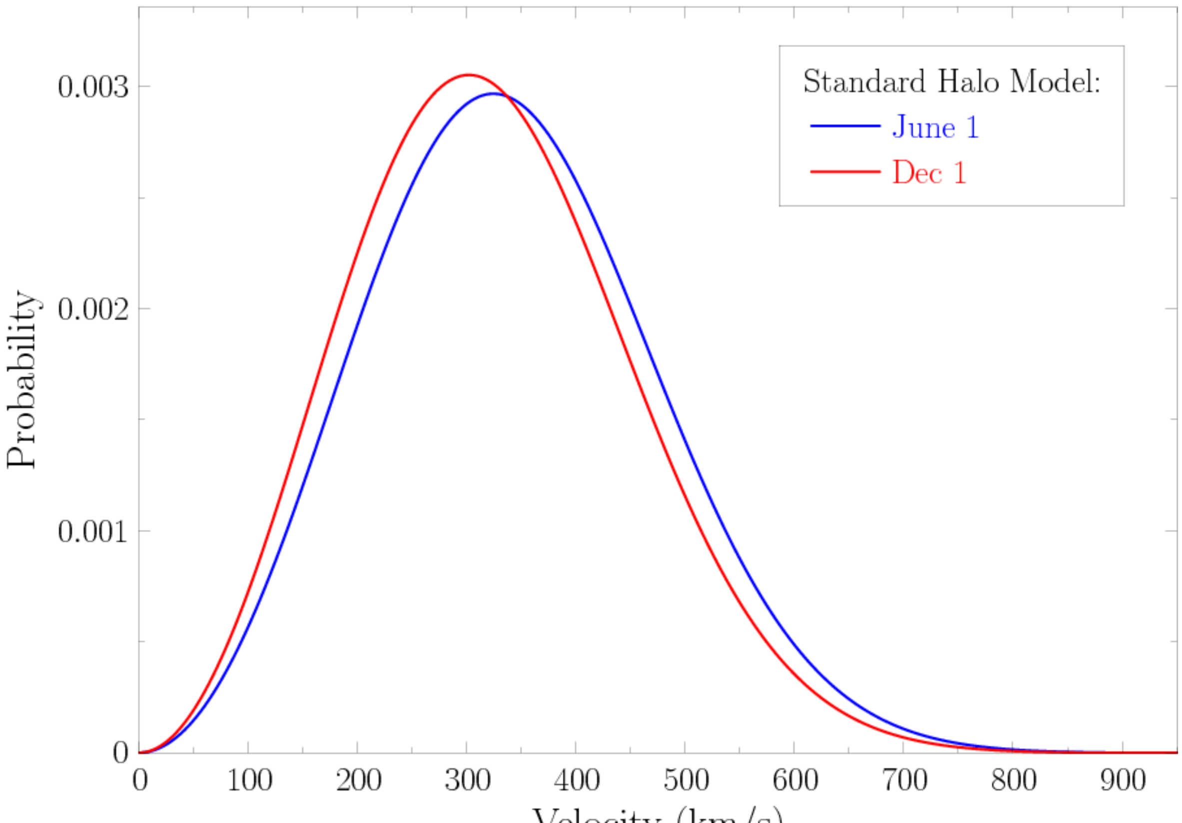
- Non-relativistic: elastic scattering of WIMP off detector nuclei → O(10 keV) recoil



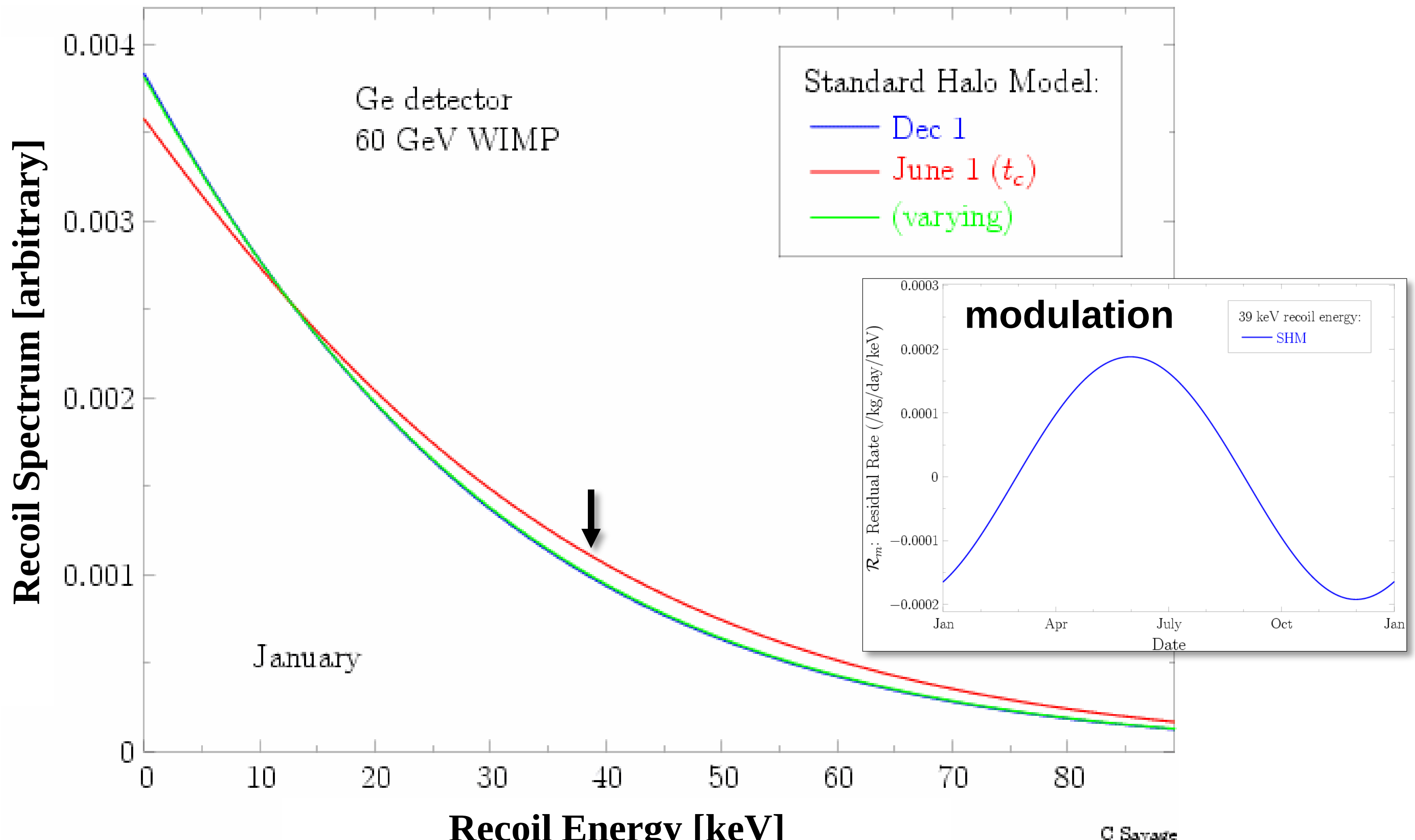
Annual Modulation

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,...

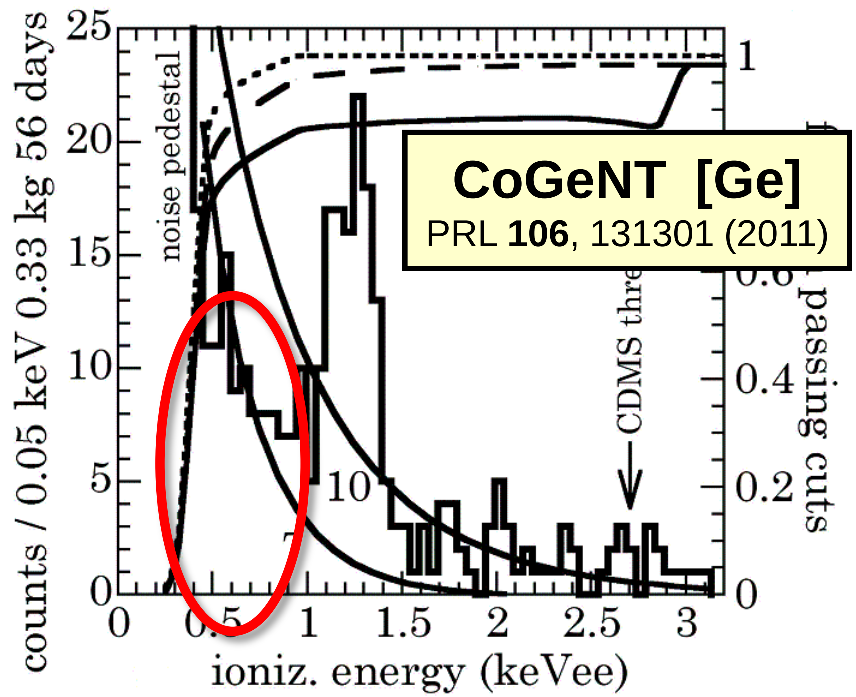
Ragazzi (Gran Sasso), D'Angelo (SABRE)

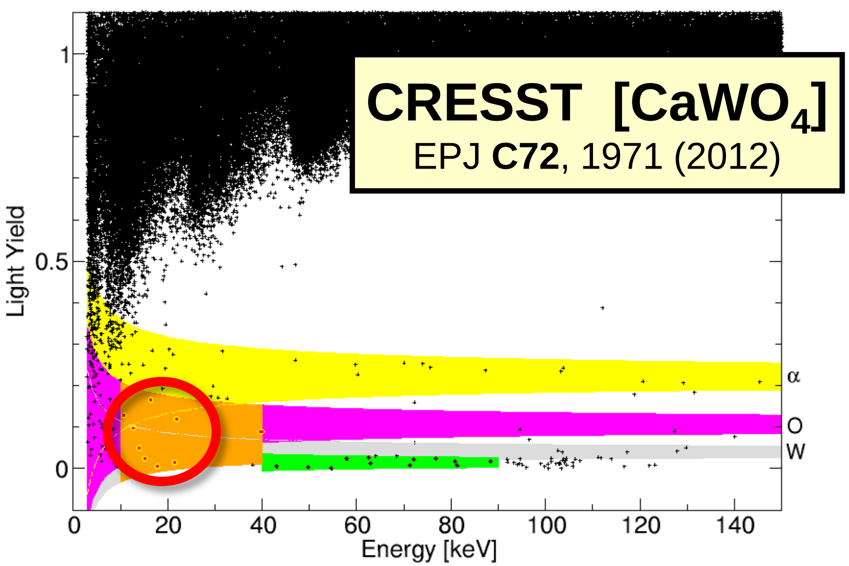
- Modulation: DAMA [+CoGeNT and above]

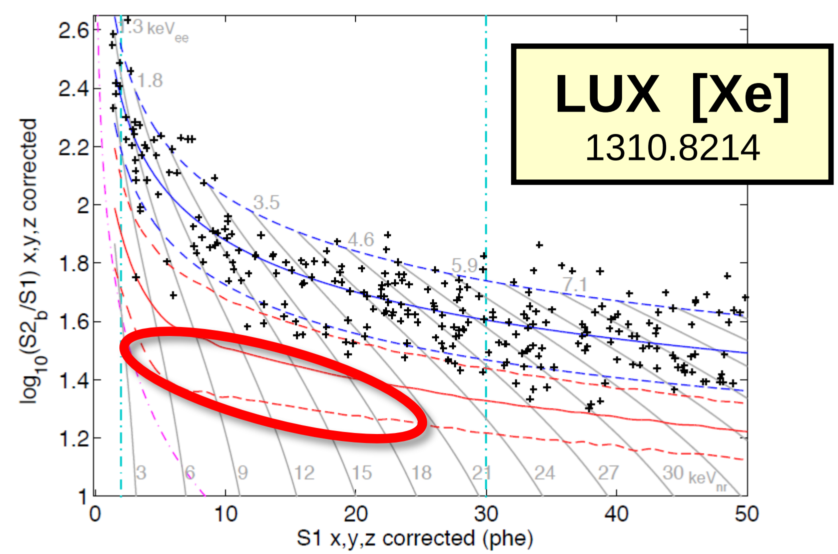
Foot

Experimental Results

- Potential signal:
  CDMS (Si), CoGeNT, CRESST, DAMA
- No signal:
  CDMS (Ge), LUX,…

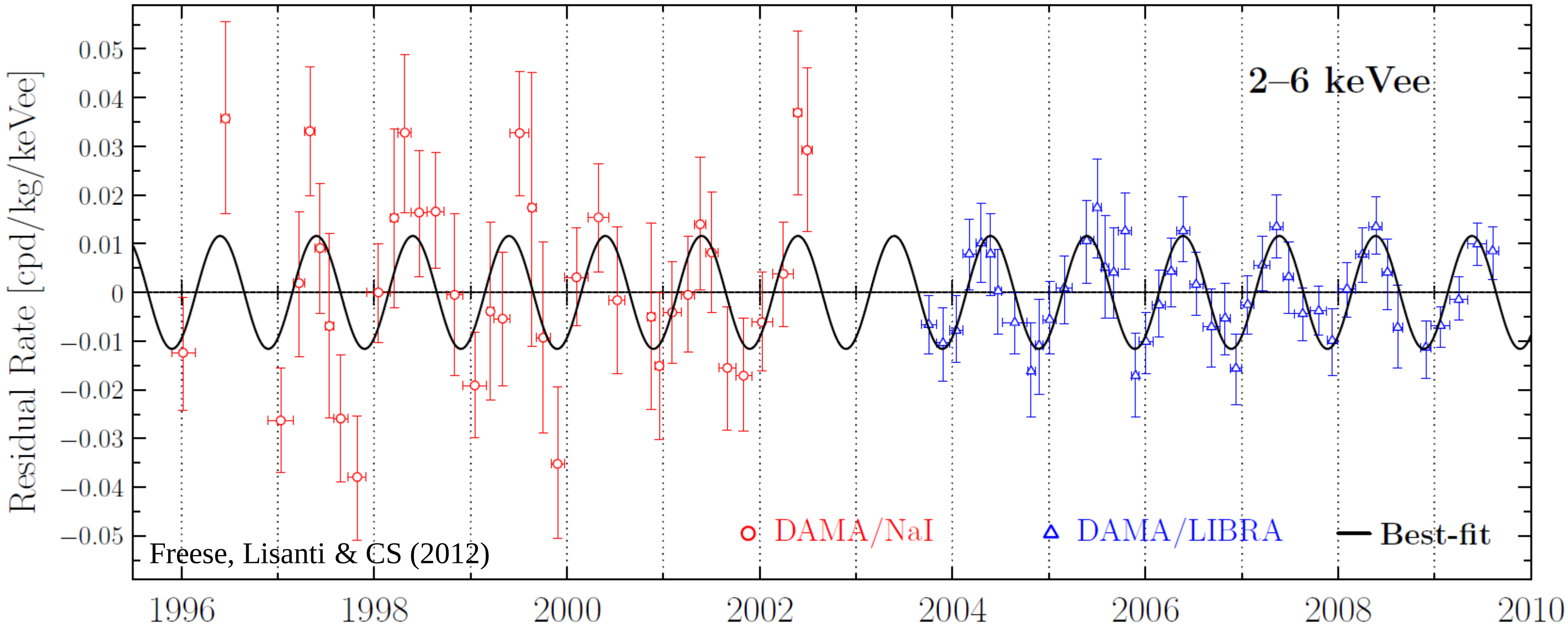






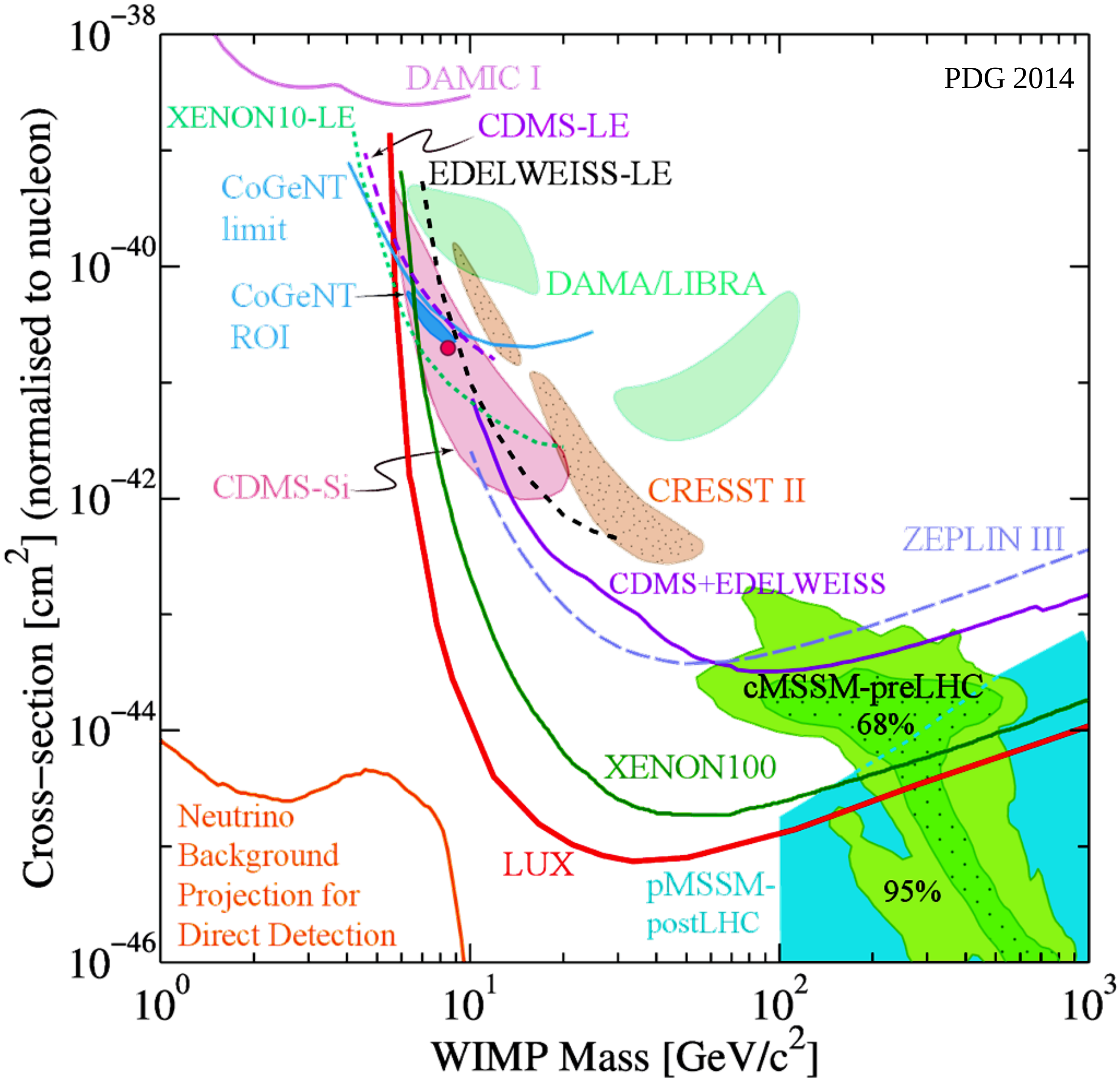
DAMA Results

- Modulation search using NaI crystals (scintillation only)
  - DAMA/NaI: 1996-2002 — R. Bernabei *et al.*, Riv. Nuovo Cim. **26N1**, 1 (2003)
  - DAMA/LIBRA: 2003-2009 — R. Bernabei *et al.*, Eur. Phys. J. **C67**, 039 (2010)



8.9σ annual modulation

Experimental Results



Direct Detection: Issues

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

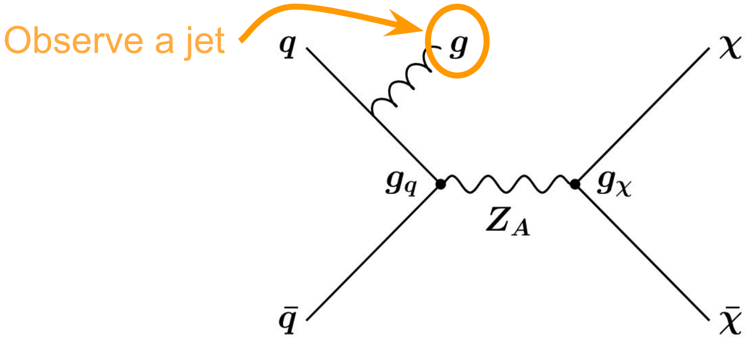
Issues affecting interpretation of results:

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

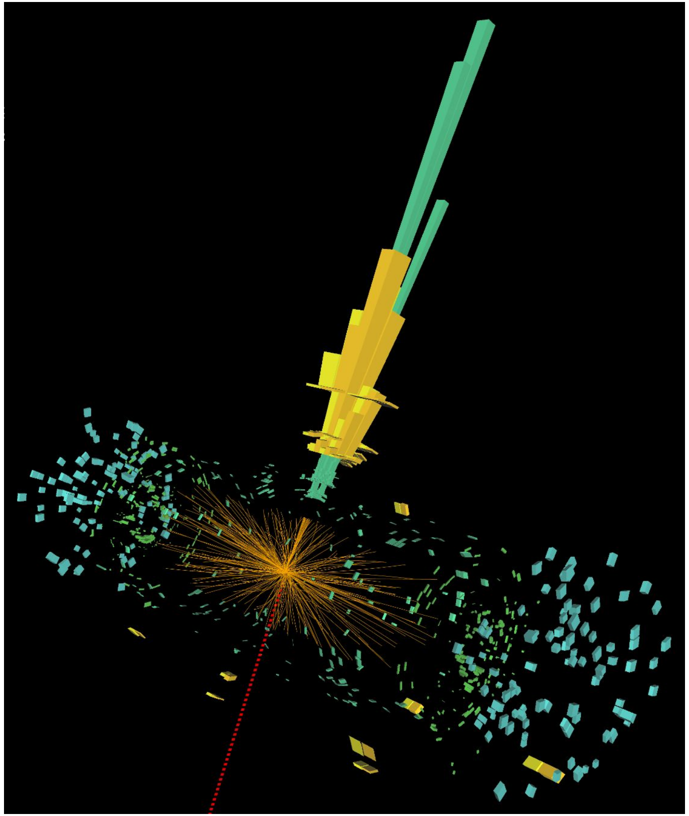
  e.g. nuclear physics [Underwood, Giedt, Thomas & Young (2012)]

Dark Matter Detection: Colliders

- Produce DM (χ), 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



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

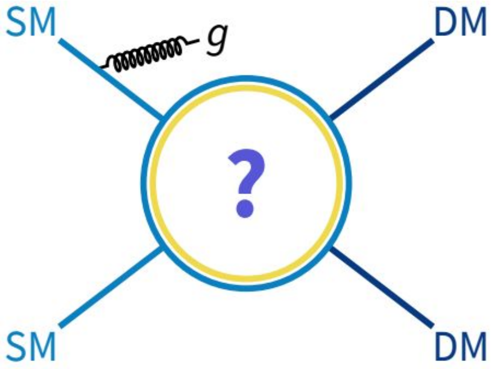
Missing transverse energy (MET/E_T^{miss})

Types of LHC DM Searches

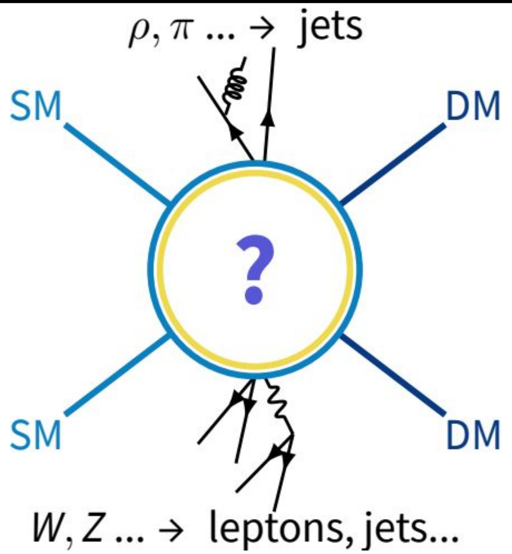
See Phys. Dark Univ. 26 (2019) 100371
& LHC DM Working Group

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

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



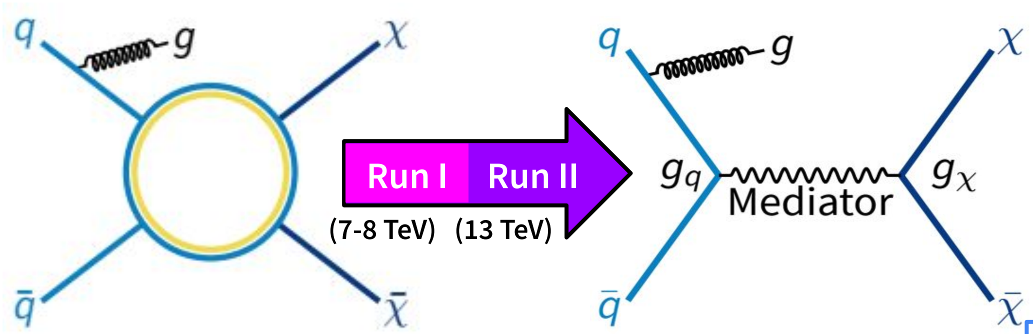
- Simple signals e.g. a single mediator
- Sizeable cross-sections
- Fewer assumptions on specific model parameters

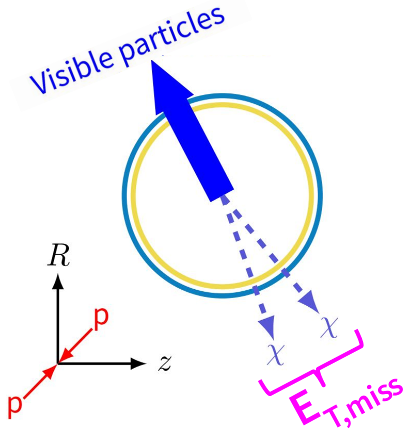


- More reliant on model assumptions
- E.g. supersymmetry, UV complete models

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_χ, m_{med}, g_q and g_χ



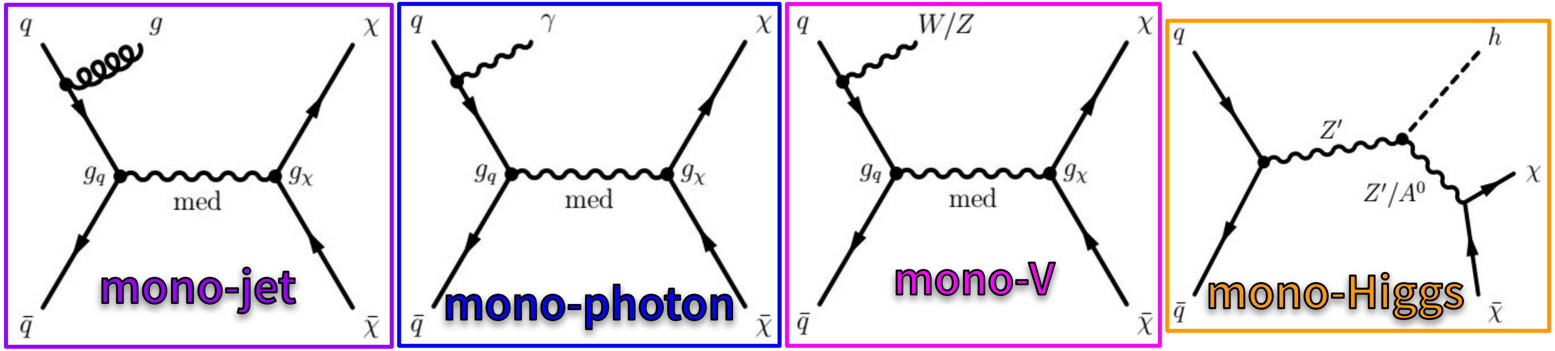


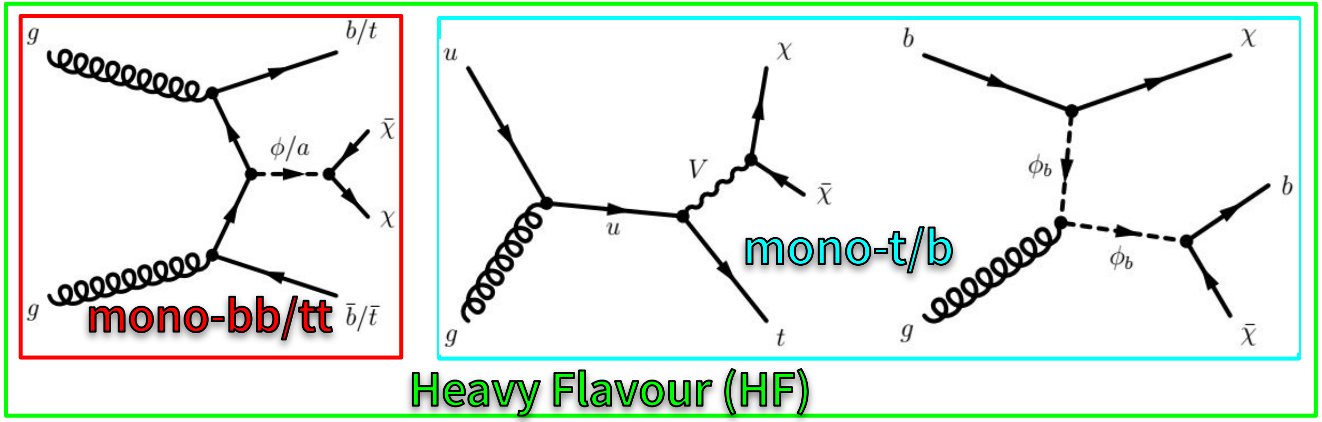
CERN-TH-2017-102

- Look for ‘mono-X’ signatures
  - ➥ Select events with ‘X’ (jet/γ/W/Z/t/H), veto other objects, precisely model backgrounds, check E_T^{miss}
  - ➥ Fix g_q, g_χ and exclude m_χ, m_{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.) ...

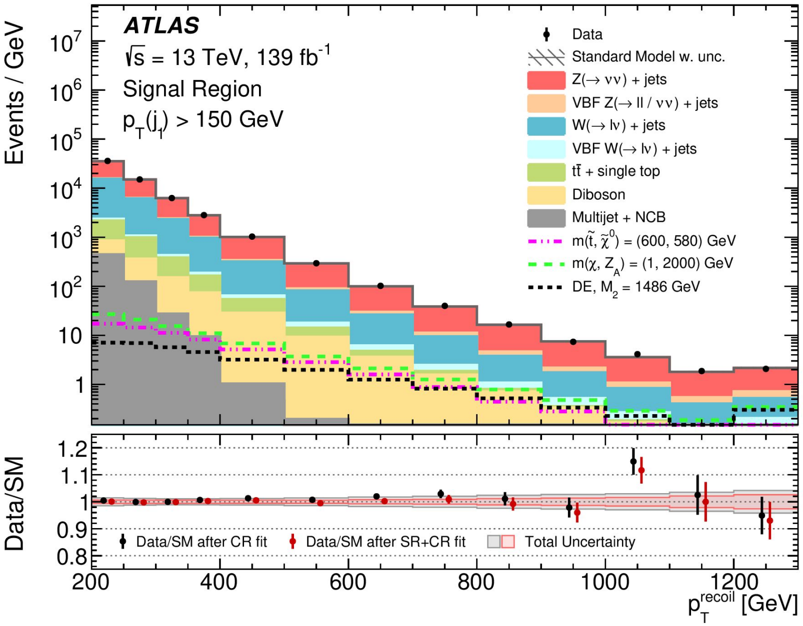
Via (axial-)vector or (pseudo-)scalar mediators...

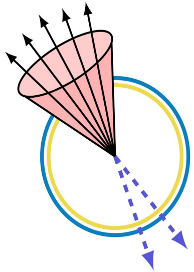
And with different couplings, depending on the benchmark

Mono-jet

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

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



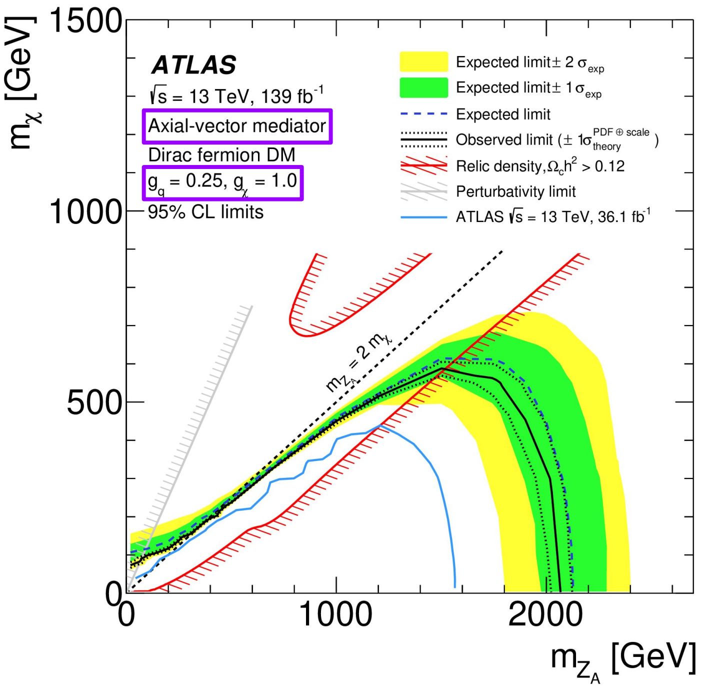


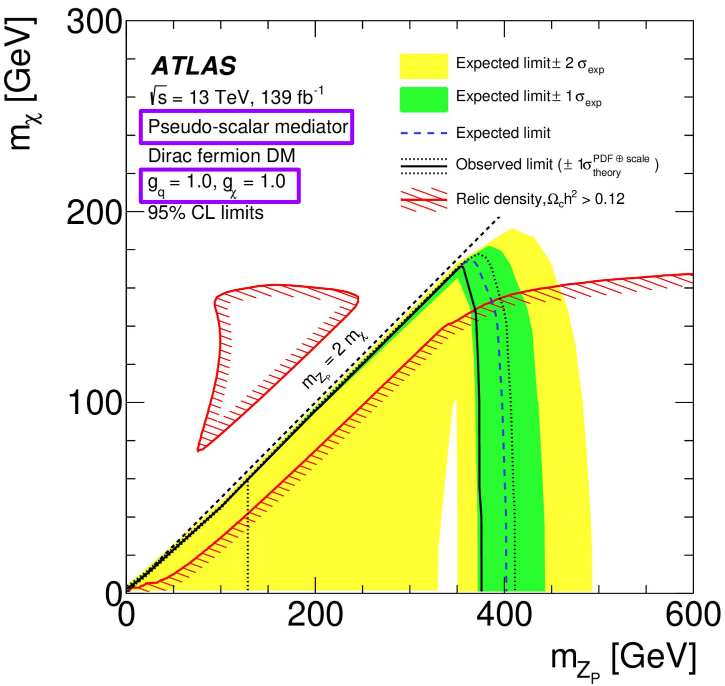
- Signal Selections
  - >1 jet with p_T > 150 GeV
  - E_T^{miss} > 200 GeV
  - Define signal regions (SRs) in bins of E_T^{miss}
- Define control regions (CRs) to constrain SM BGs
  - W→μν, W→eν, Z→μμ, Z→ee, top
- Perform simultaneous binned bg-only likelihood fit
  - Apply normalisation factors extracted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

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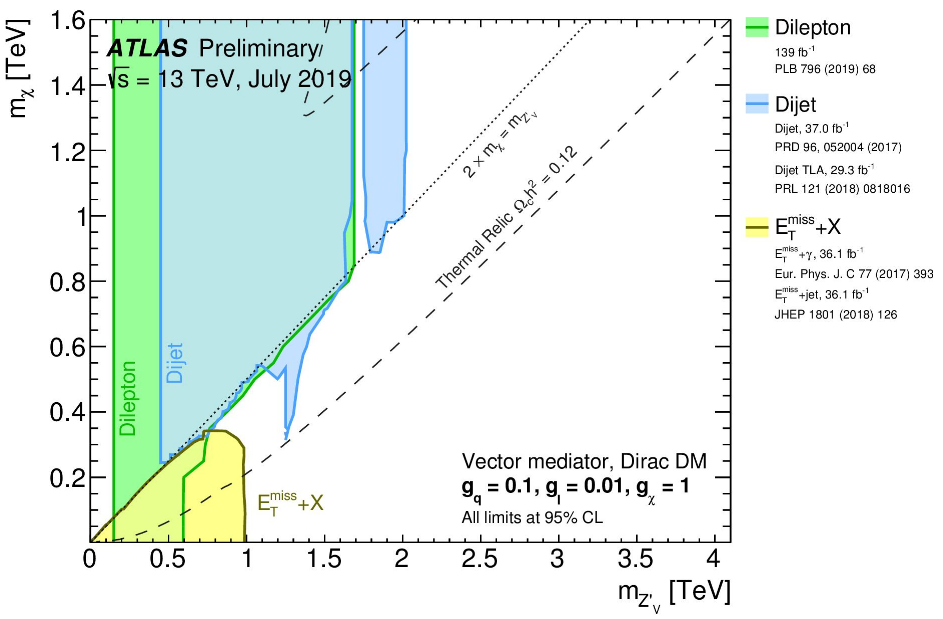
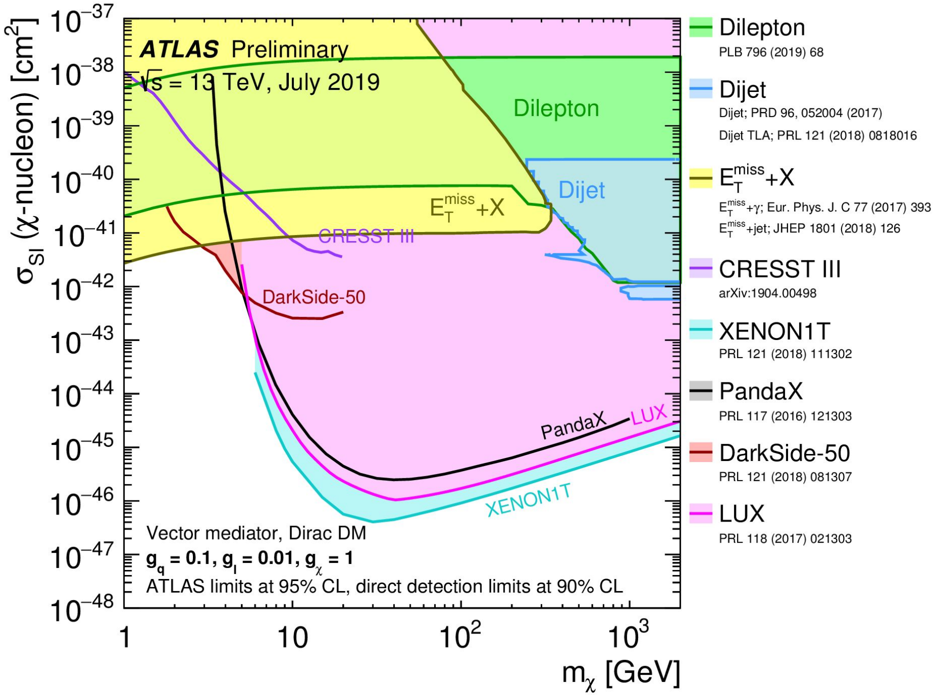
- SI WIMP-nucleon scattering cross-section, Dirac DM, $g_\chi = 1$, $g_q = 0.1$, $g_l = 0.01$
  - ➥ For these couplings in this model, the mono-jet search has higher sensitivity than DD at low m_χ!





Heavy Neutral Leptons

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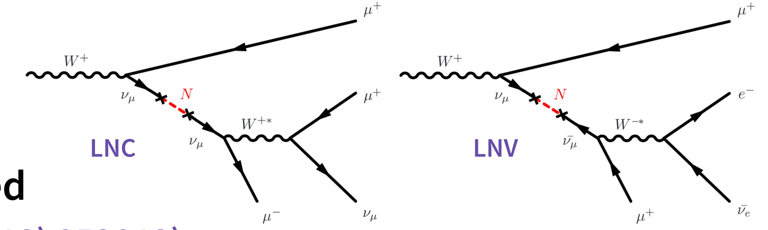
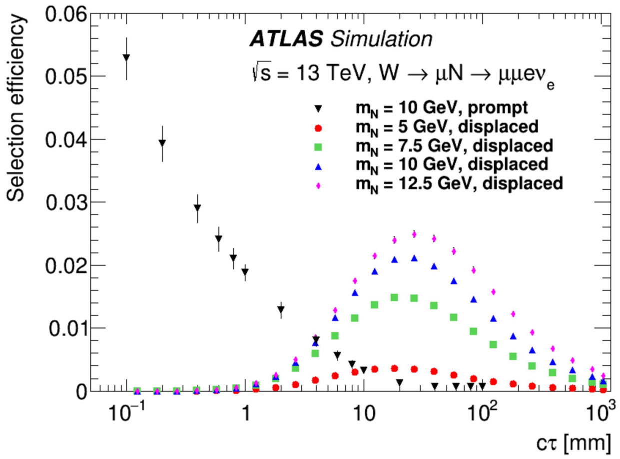
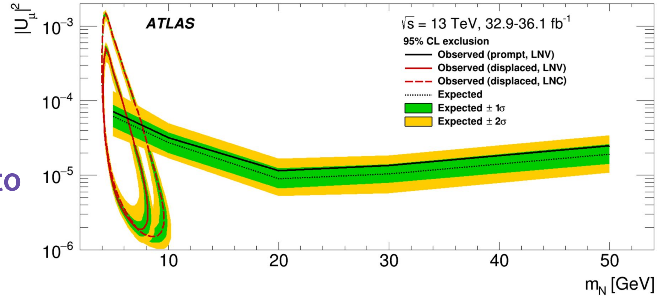
- Postulate new right-handed neutrinos with Majorana masses below the EW scale
  - ➥ Explain neutrino masses, matter-antimatter asymmetry, DM…
  - ➥ Decays may be lepton number violating (LNV) or conserving (LNC), depending on nature of neutrinos
- Both prompt & displaced leptonic decay signatures studied
  - ➥ Displaced vertex reconstruction algorithm (Phys. Rev. D 97 (2018) 052012)





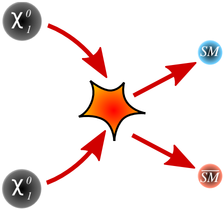
- ➥ Set limits on mass and coupling strength for prompt & displaced
- ➥ Displaced limit contour oblique ellipse approximately corresponds to HNL proper decay lengths in the range 1-30 mm



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

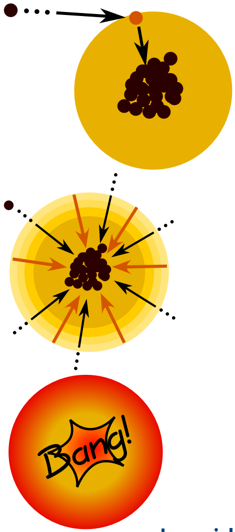


Imperial College London

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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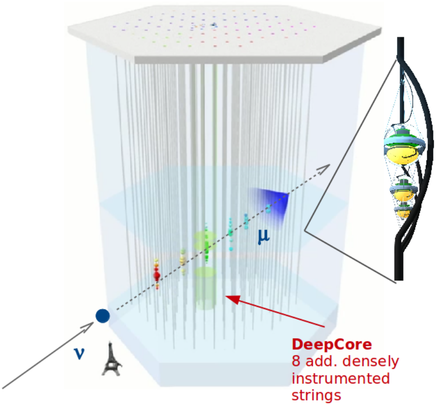
The IceCube Neutrino Observatory

- 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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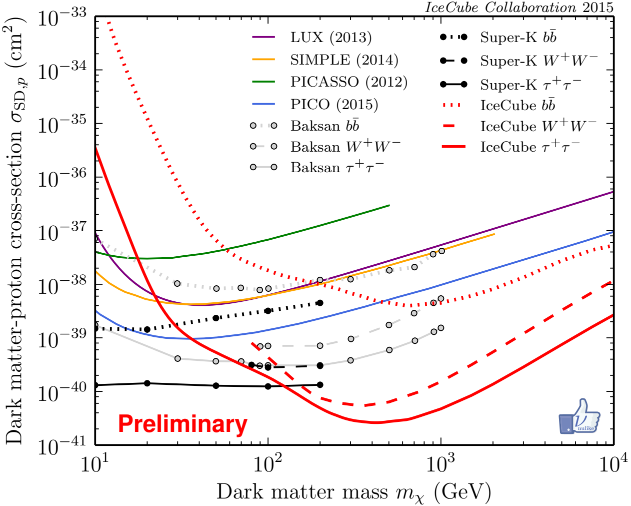

IceCube Collaboration (+PS, Savage, Edsjö) *in prep*
nulike: model-independent unbinned limit calculator for generic BSM models

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