Review of dark matter searches (other than LHC)

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Dark matter (indirectly) detected!

Plenty of (gravitational) evidence for non-baryonic cold (or coldish - as opposed to hot) DM being the building block of all structures in the Universe. E.g.:

- classical tests of galactic dynamics using gas rotation curves or stellar velocity dispersion profiles;
- 3-D mass reconstruction of cluster mass profiles via strong lensing and of the cosmic web via weak lensing;
- gravitational support for early Universe photon-baryon acoustic oscillations as seen in the CMBR or in galaxy correlation function;
- a consistent theory for structure formation itself;
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Relying on the assumption that GR is the theory of gravity; still, it is very problematic to explain them all, covering so different length scales, in a single alternative theory of gravity and matter made of baryons only.

Particle physics and the DM problem (?)

The standard model for cosmology and structure formation, the ΛCDM model does not aim to address questions regarding the nature of the DM component.

The DM term is treated as a classical, cold, pressure-less fluid subject to gravitational interactions only (no coupling to ordinary matter or photons, no self-coupling); tests of such gravitational coupling determine its mean density with exquisite accuracy:

$$\Omega_c h^2 = 0.120 \pm 0.001$$ *[Planck +, arXiv:1807.06209]*

as well as the spectrum of its perturbations (nearly scale invariant, as expected from inflation).

Indeed, reformulating the DM problem in terms of elementary particles in the dilute limit (two-body interactions dominating over multi-body interactions) is **an assumption**, and not the only possible extrapolation!

Observations and particle properties of DM

Assuming a particle formulation, astro/cosmo observables provide mainly informations on the properties that DM does not have, e.g.: it needs to be non-baryonic, non-relativistic at the phase of matter-radiation equality, ... This is enough to say that **DM is NOT within the SM of particle physics**.

At the same time, loose bounds on the properties which are crucial for devising a detection strategy for DM particles - the **mass** and **coupling to ordinary matter**.

The **mass scale is essentially unconstrained**, allowing for:
i) ultralight bosons - as light as 10^{-22} eV for the so-called **fuzzy DM** (when the DM de Broglie wavelength gets as large as about 1 kpc, *[Hu, Barkana, Gruzinov, PRL 85 (2000)]*); *ii)* fermions as light as about 1 keV (Gunn-Tremaine bound, based on phase space density limits as connected to the Pauli exclusion principle). Upper bounds are irrelevant from a particle physics perspective.

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Regarding the **interaction scale**, there are: *i)* **very tight limits with photons** (DM millicharge, electric and magnetic dipole moments need to be severely suppressed); *ii)* **significant limits with baryons**; *iii)* **relatively weak limits for self-interactions** (from galaxy clusters morphologies and mergers, such as from the Bullet cluster).

Insights from small-scale CDM "crisis"?

A few issues with the ΛCDM model on small scales (i.e. sub galactic) in the deeply non-linear regime (where numerical N-body simulations of hierarchical clustering are needed):

- **cusp/core problem** (simulations find ~1/r scalings at the center of halos - the NFW profile -, some observations for dwarf galaxies favour density profiles with a flat inner core);
- **missing satellite problem** (# of substructures in the CDM simulations much larger than # of satellites observed in real galaxies, like the Milky Way);
- **the too-big-to-fail problem** (the observed satellites of the Milky Way are not massive enough to be consistent with predictions from CDM).

Possibly a sign that there is too much power on small scales in the ΛCDM model. Another option is that baryonic components / baryonic feedback are not properly treated in the simulations.

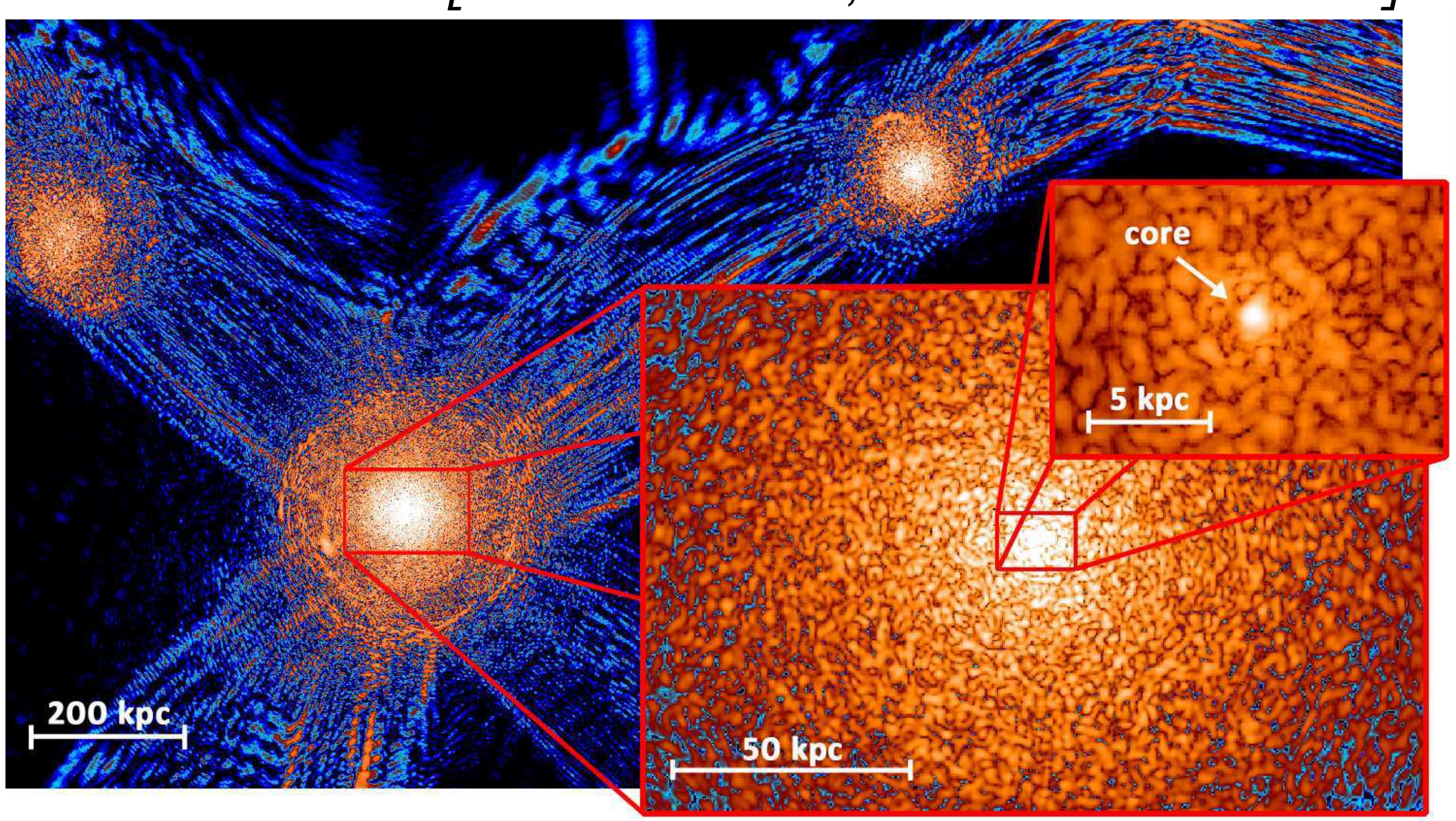
Particle DM and the small-scale CDM "crisis"

You can remove power on small scales by introducing a new physical scale associated to DM particles:

- a **free-streaming scale** (warm DM, e.g.: keV sterile neutrinos)
- a **self-interaction scale** (self-interacting DM, e.g.: states in a dark/hidden sector interacting via a light mediator)
- a **"quantum" scale** (e.g.: fuzzy DM, DM forming a BEC)
- …

[Schive et al., arXiv:1406.6586]

Scenarios that are getting more popular, partially because N-body simulations in these cases are becoming available. E.g.: for ultra-light scalar DM



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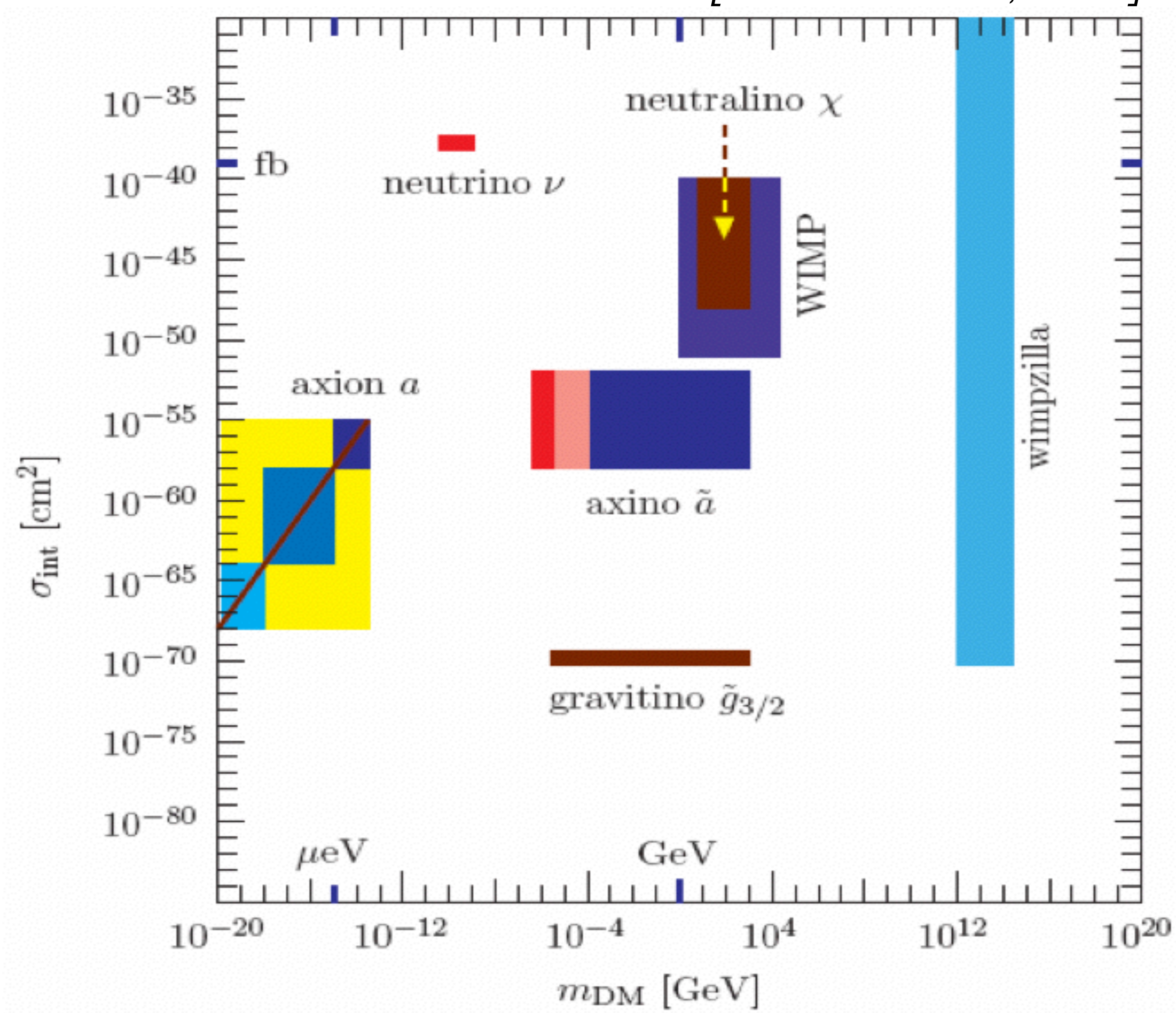
A chance to detect DM particles via identifying one of such features, comparing structure formation predictions in these scenarios against cosmological/astrophysical observations?

Note: the full DM puzzle is more complicated than the single pieces! E.g.: Lyα forest (absorption pattern in the spectra of distant quasars due to Lyα transitions of hydrogen along the line of sight) is also probing small scales, and seems to disfavour sharp small-scale suppressions ➡ $m > 10^{-21}$ eV *[Kobayashi et al., arXiv:1708.00015]*.

The DM Particle zoo

Viable particle frameworks span huge ranges in masses and interaction scales:

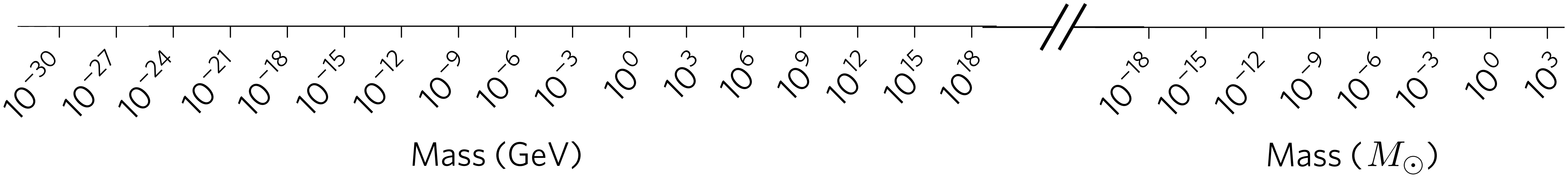
[Kim & Carosi,2010]



from gravitational interactions for gravitinos, to weakly interacting DM candidates, or mirror DM with strong self-interactions

from sub-eV axions, to keV sterile neutrinos, GeV-TeV WIMPs, up to supermassive DM close to the Planck scale

Find your way in a 49 (89) order of magnitude journey



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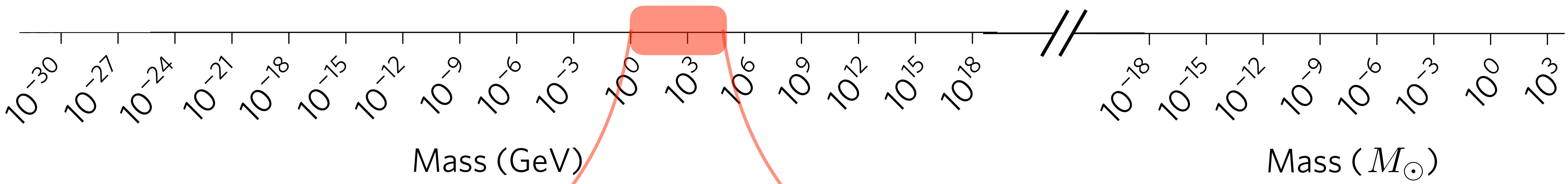
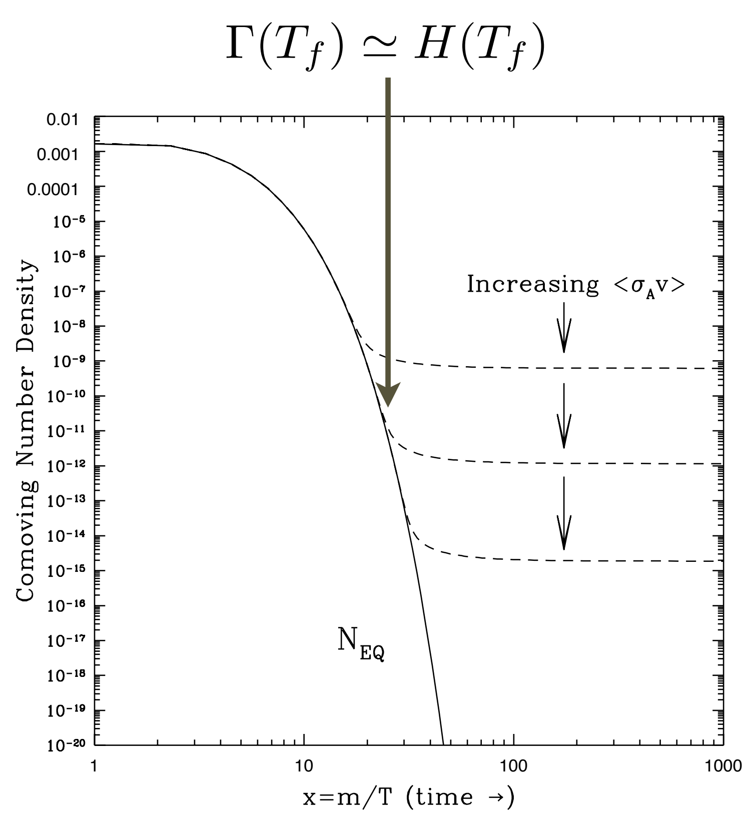


Thermal relics directly coupled to the baryon/photon primordial bath: $\chi\,\bar{\chi} \leftrightarrow \mathrm{SM}\ \overline{\mathrm{SM}}$ (with SM is some lighter Standard Model state)



$$\Omega_\chi h^2 \simeq \frac{3 \cdot 10^{-27} \mathrm{cm}^{-3} \mathrm{s}^{-1}}{\langle \sigma_A v \rangle_{T=T_f}}$$

WIMP miracle: “fixed” DM pair annihilation cross section into “visible” particles.

A recipe that can work below about **100 TeV** (unitarity limit *[Griest & Kamionkowski 1990]*; in realistic models up to about 15 TeV) and gets inefficient below about **1 GeV**.

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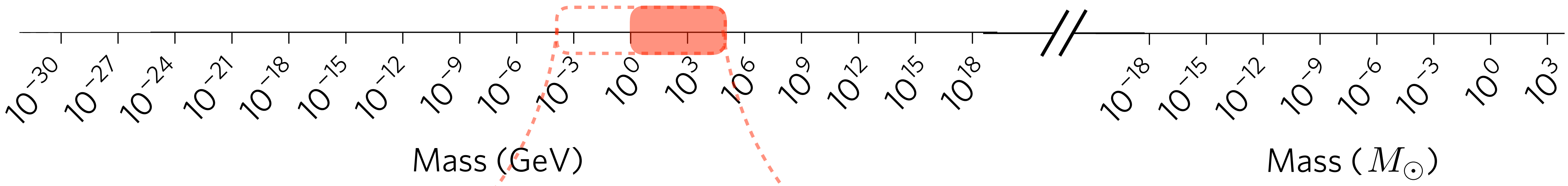
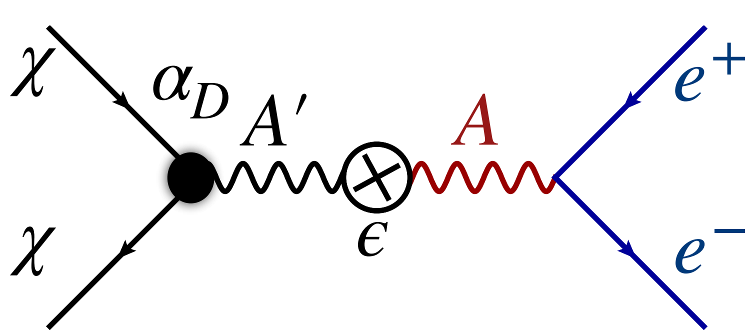


Thermal relics in a sector different from the SM sector - say a **hidden DM sector** - communicating to the baryon/photon primordial bath via some mediator - say an hidden photon with kinetic mixing with the SM photon:



Analogous to WIMPs, but with more freedom in the choice of the dark force in the hidden sector: it can work down to **sub-MeV** masses. The coupling ϵ to "visible" particles is one of the parameters in the model.

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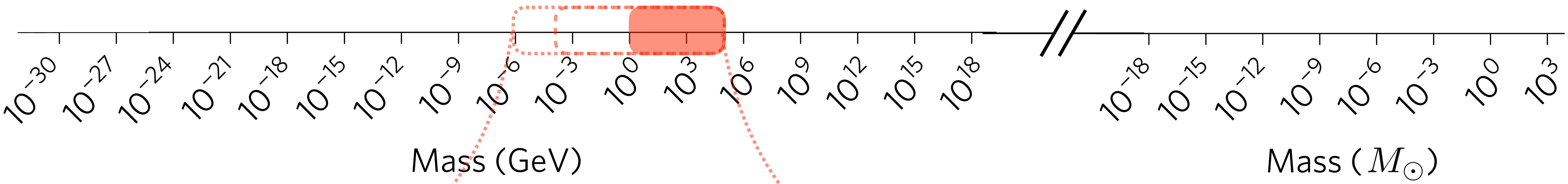
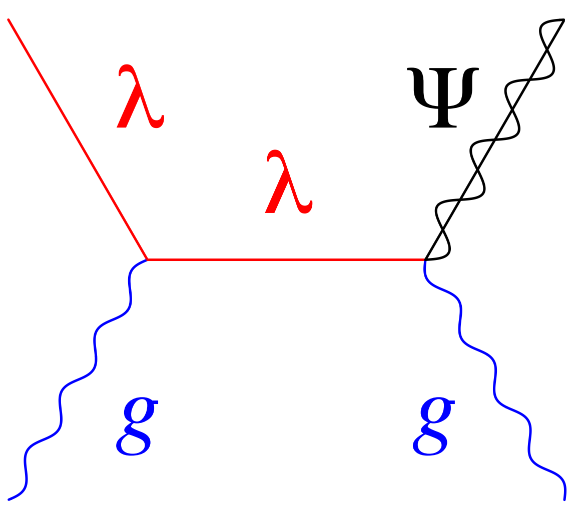
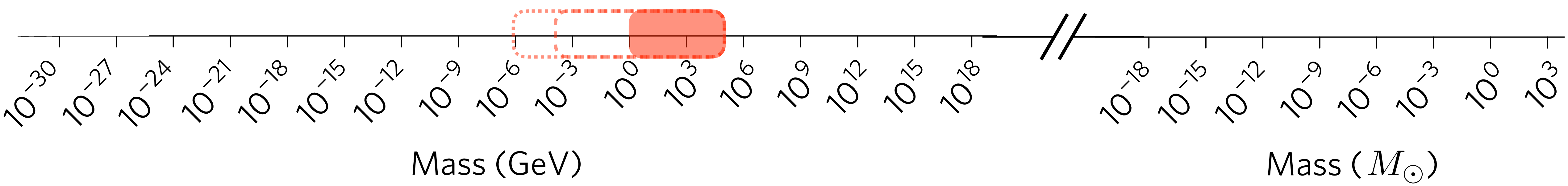


Non-thermal relics generated **from** inelastic scatterings or decays of **thermal states**, eventually in the hidden sector.
Typical example: gravitinos **Ψ** in supergravity theories sourced by the thermal population of SUSY states **λ**, e.g. via: $g\lambda \to g\Psi$



Ψ can be much lighter than **λ**, still paying attention that you do not get HOT DM, i.e. it needs to be at least above the **keV** (depending on production details). The coupling of **Ψ** to "visible" particles can be very suppressed (even gravitationally) but there is the "visible" counterpart **λ**.

Find your way in a 49 (89) order of magnitude journey



Three generic schemes, populating a fairly large DM mass range, and with three fairly generic patterns for detection phenomenology:

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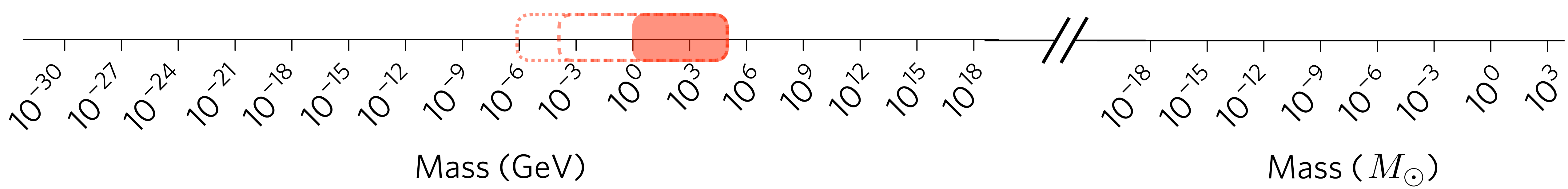

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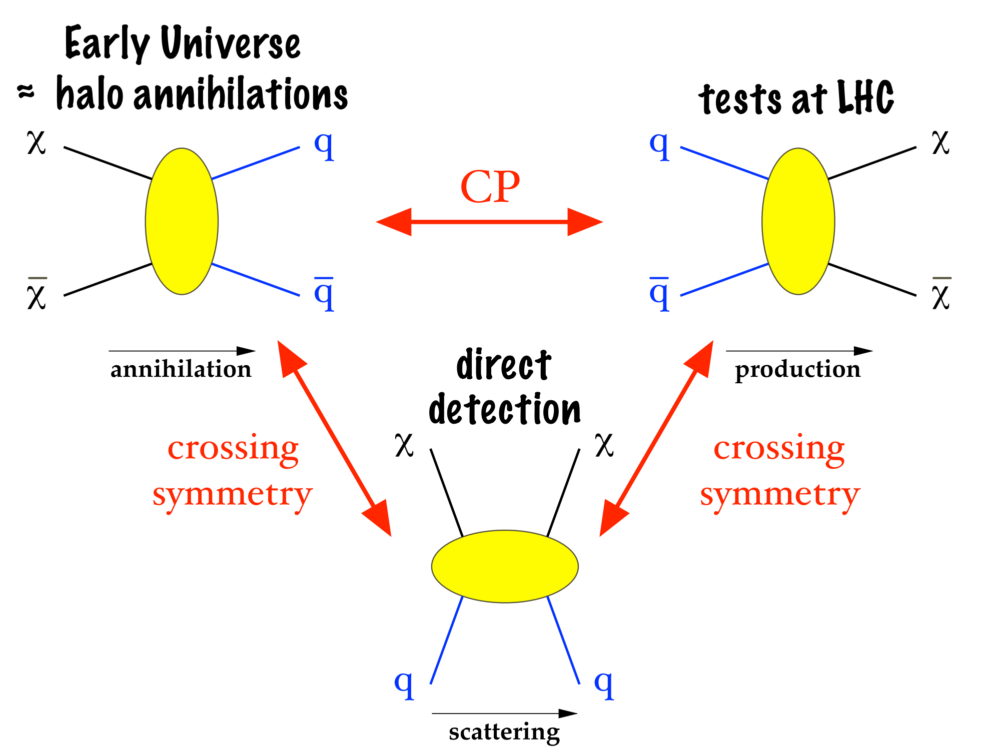
Thermal relics: the familiar and beloved scheme



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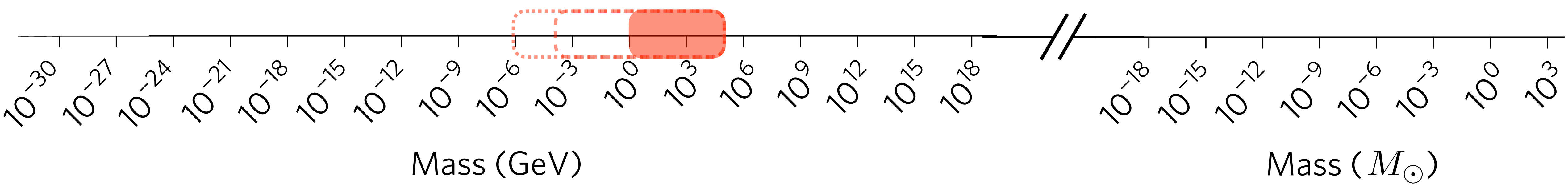

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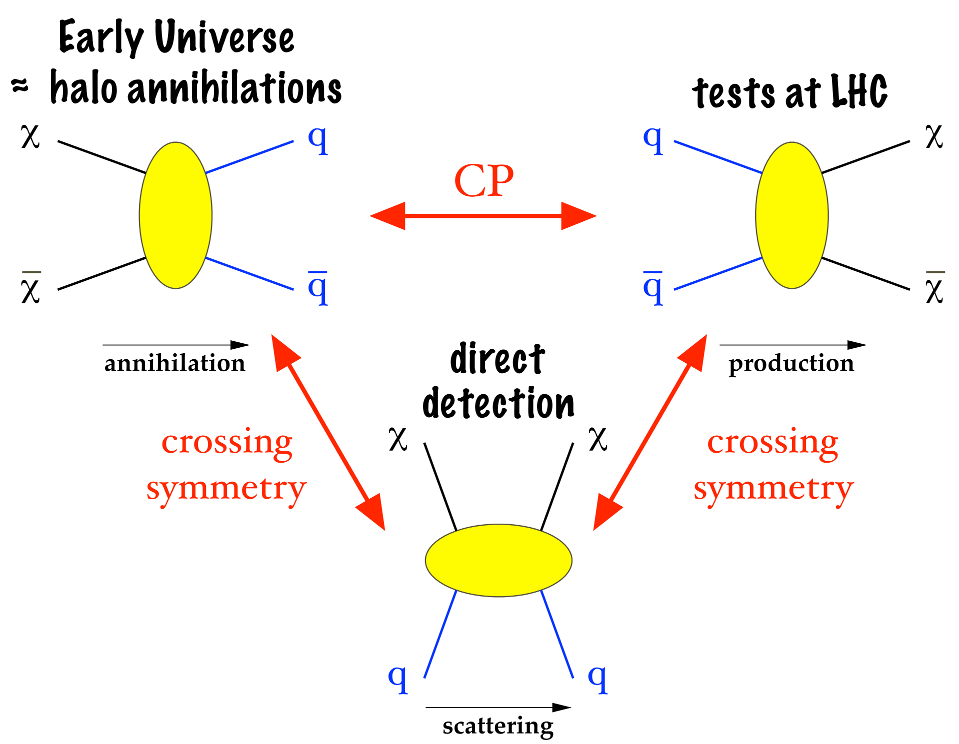

Thermal relics in hidden DM sector: (possibly) analogous to the thermal relic cases + all the phenomenology related to the new dark forces and the dark mediators!

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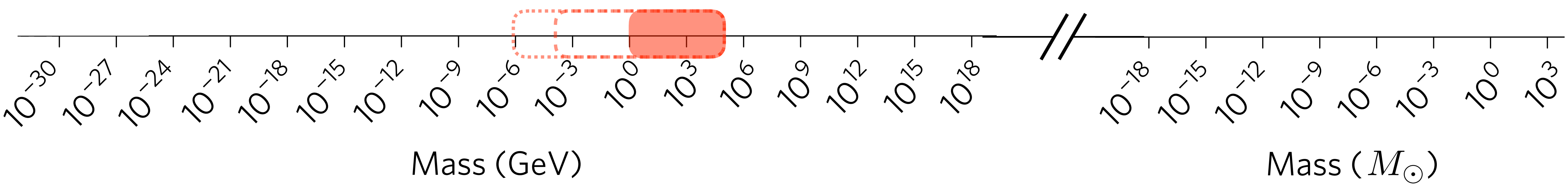

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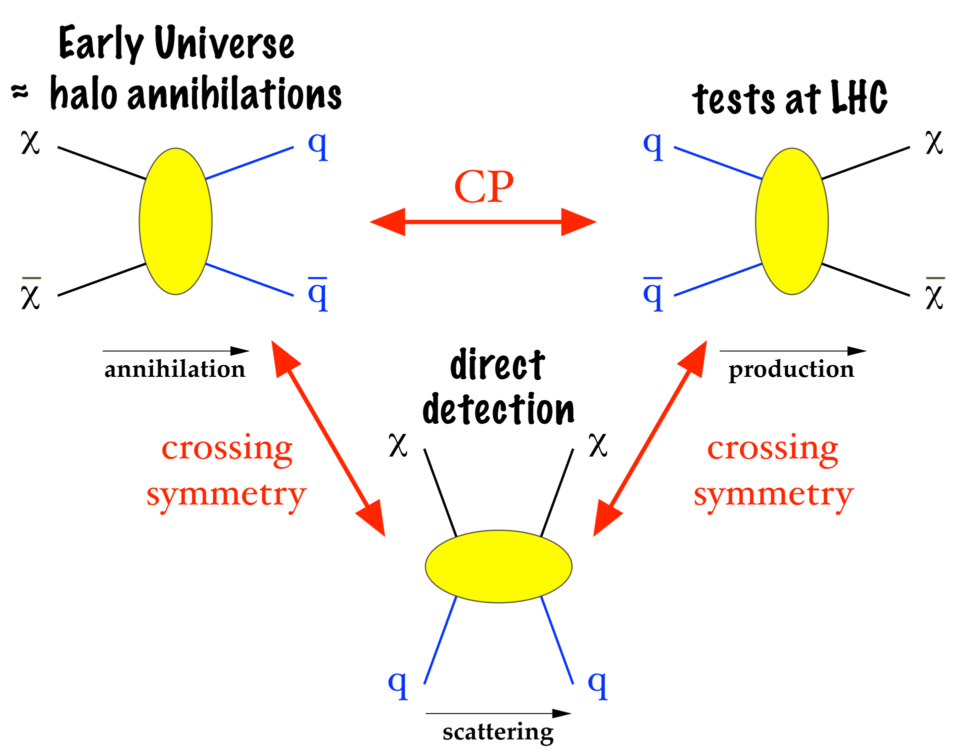

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Non-thermal relics from thermal states: Ψ may be impossible to detect, but there is all the phenomenology connected to λ, maybe with some definite peculiarities, e.g., long lived NLSP.

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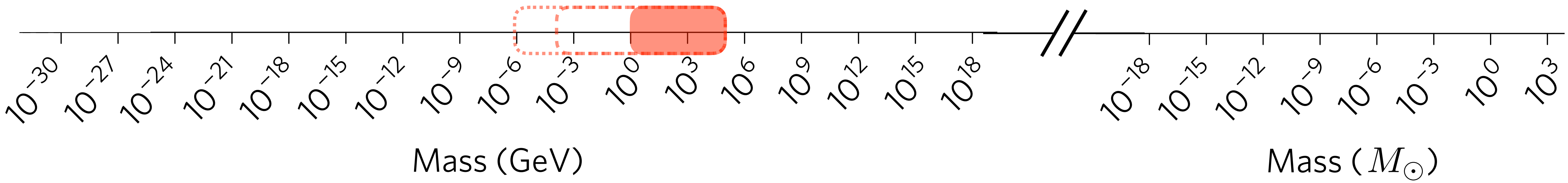

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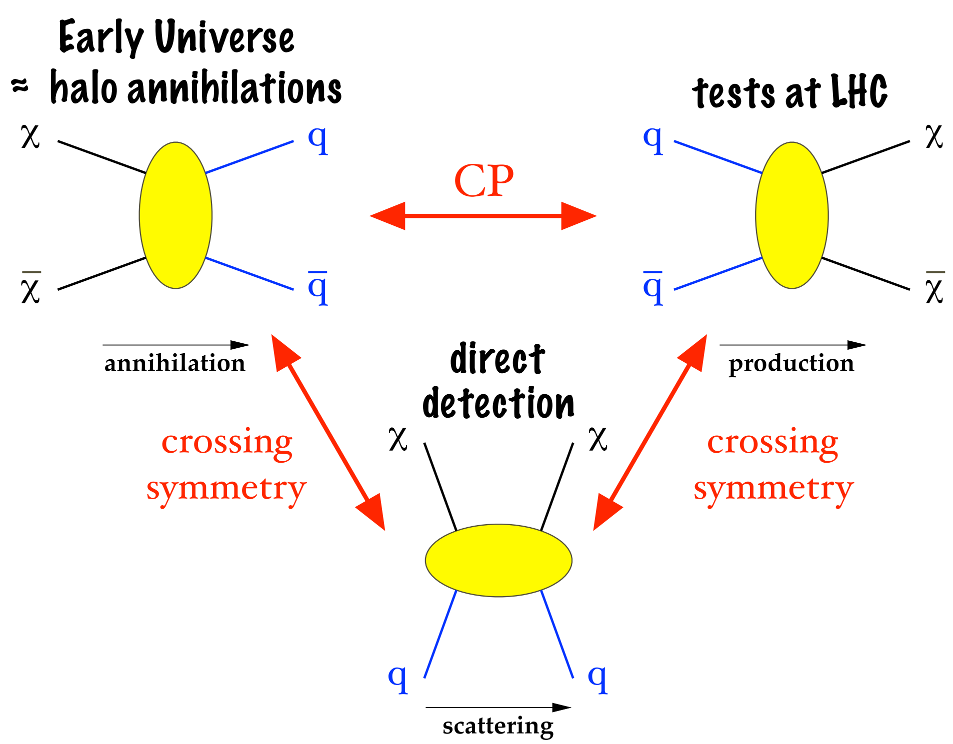

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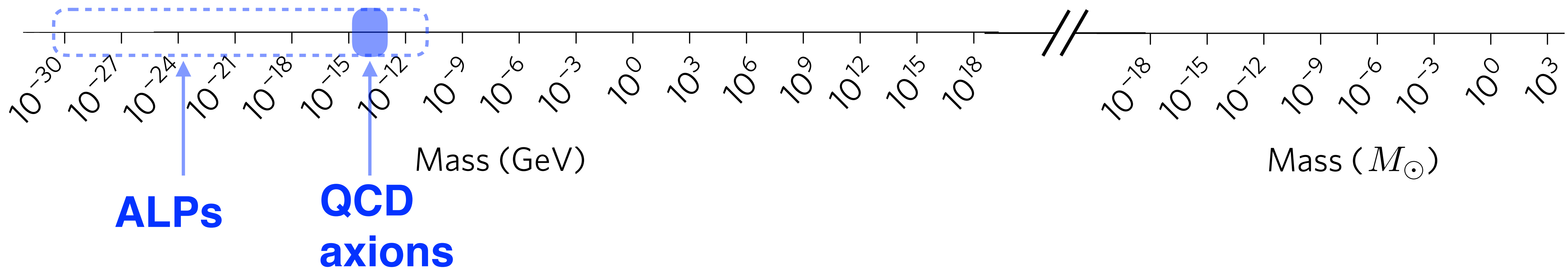
Pretty much everything else is a case by case business!

E.g.: QCD axions and Axion-Like Particles (ALPs)



Misalignment production: very light scalars trapped in modes with coherent oscillations, which behave cosmologically as CDM. Possible **contributions** to energy density **from decays of strings and domain walls**.

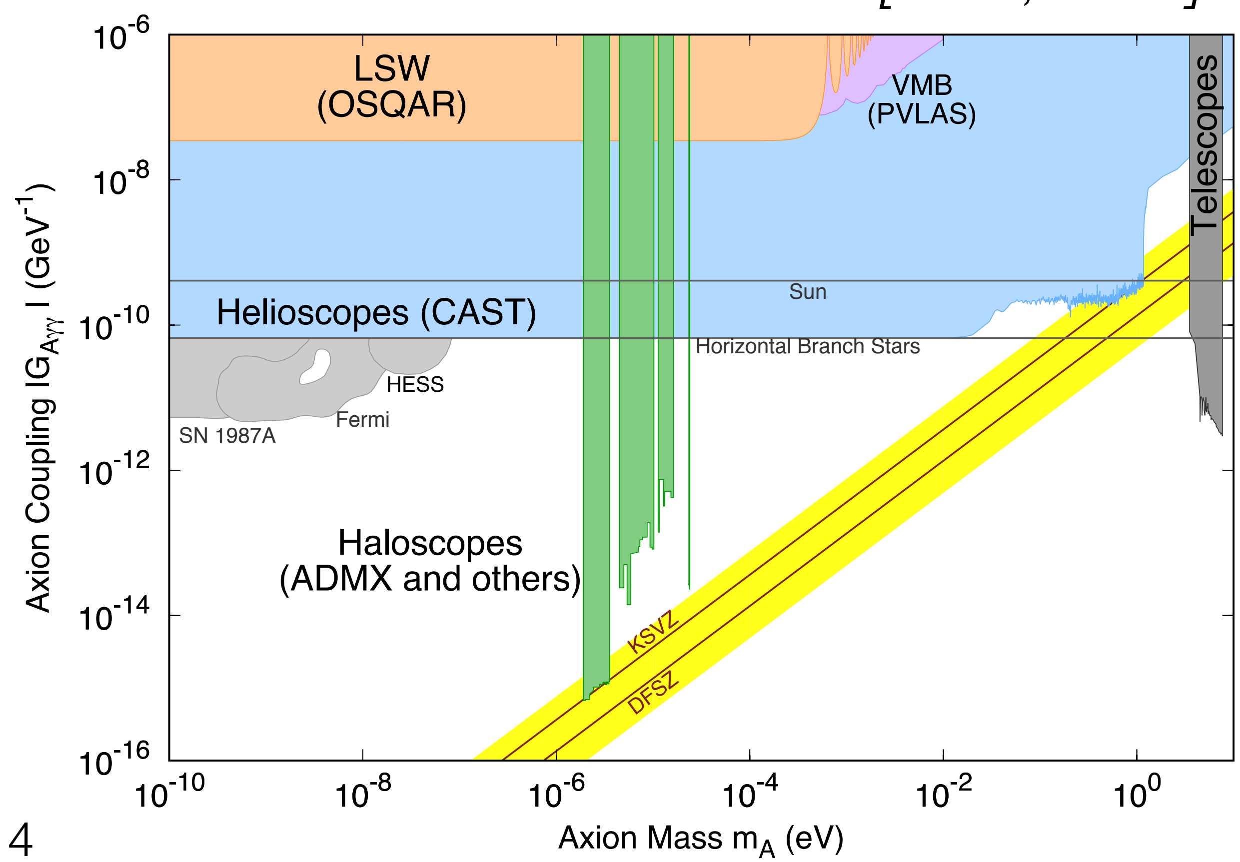
[PDG, 2018]

The phenomenology mostly based on the axion coupling with photons:

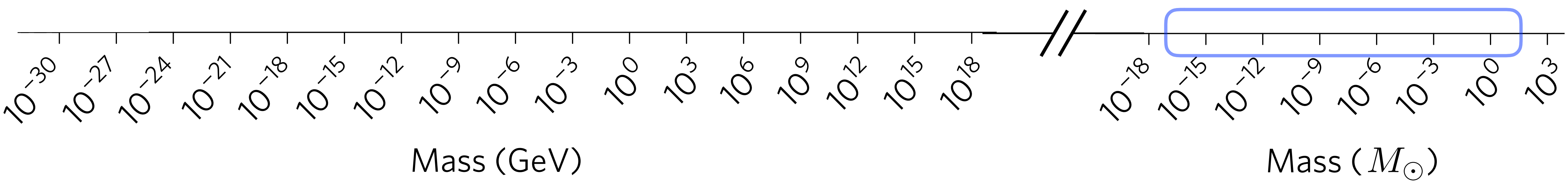
$$\mathcal{L}_{A\gamma\gamma} = -\frac{G_{A\gamma\gamma}}{4} F_{\mu\nu}\tilde{F}^{\mu\nu}\phi_A = G_{A\gamma\gamma}\mathbf{E}\cdot\mathbf{B}\,\phi_A$$

with:

$$G_{A\gamma\gamma} = \frac{\alpha}{2\pi f_A}\left(\frac{E}{N} - 1.92(4)\right) = \left(0.203(3)\frac{E}{N} - 0.39(1)\right)\frac{m_A}{\mathrm{GeV}^2}$$

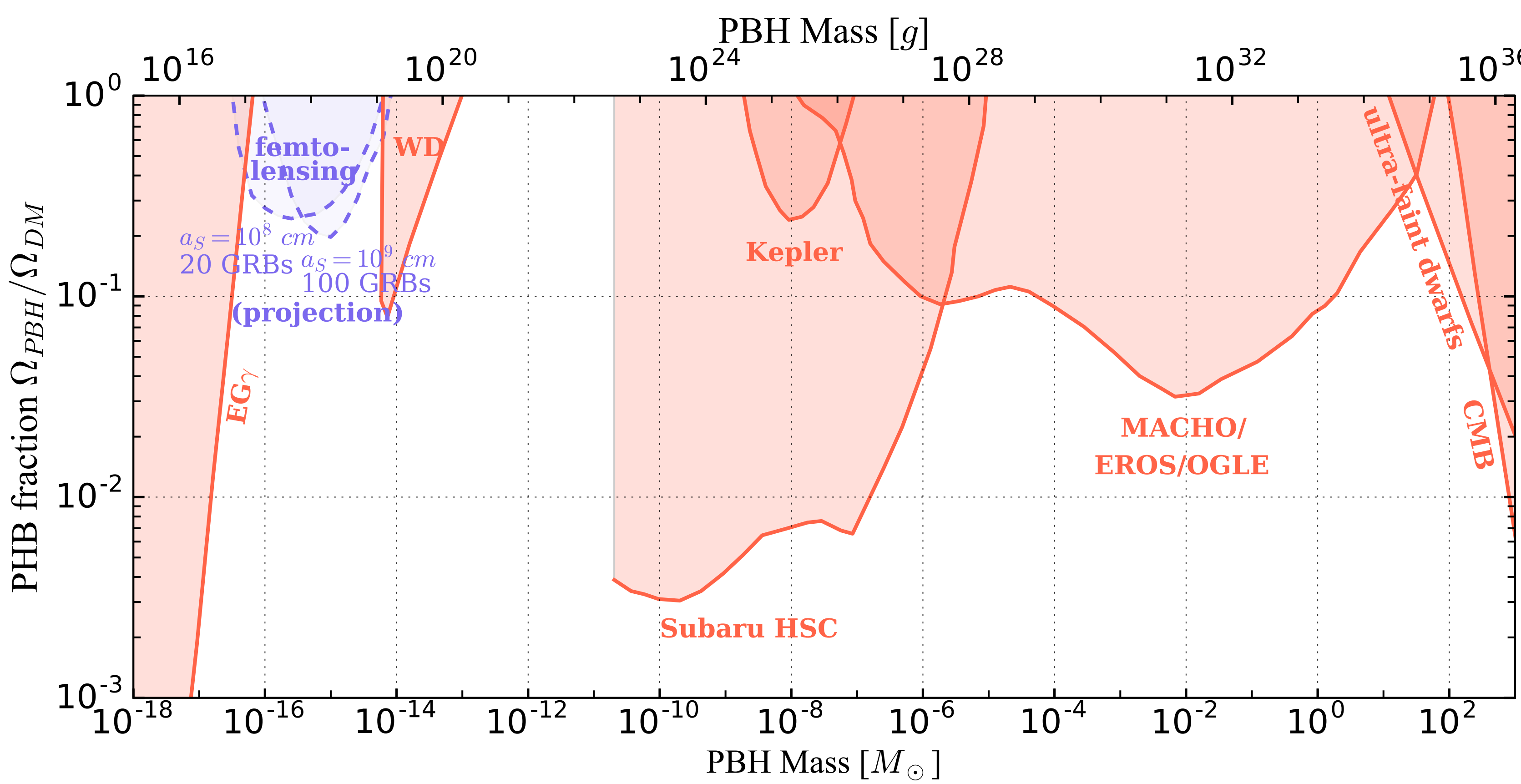


E.g.: Primordial Black Holes as DM



The only DM candidate within the SM of particle physics (but definitely not in terms of elementary particles in the dilute limit). **Primordial spectrum** after inflation which needs to be very much boosted compared to the spectrum on large scales, but that you can fit into the desired mass range. Revival after LIGO detection of merging binary BH systems.

Introducing a macroscopic perturber in galaxies, the early/late Universe, … All sort of constraints:



[Katz et al., arXiv:1807.11495]

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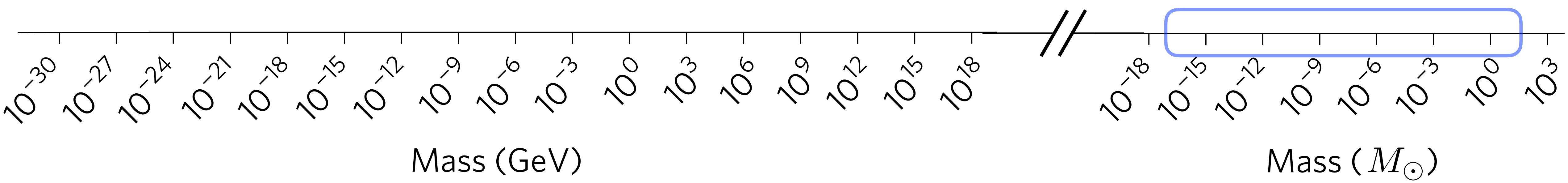

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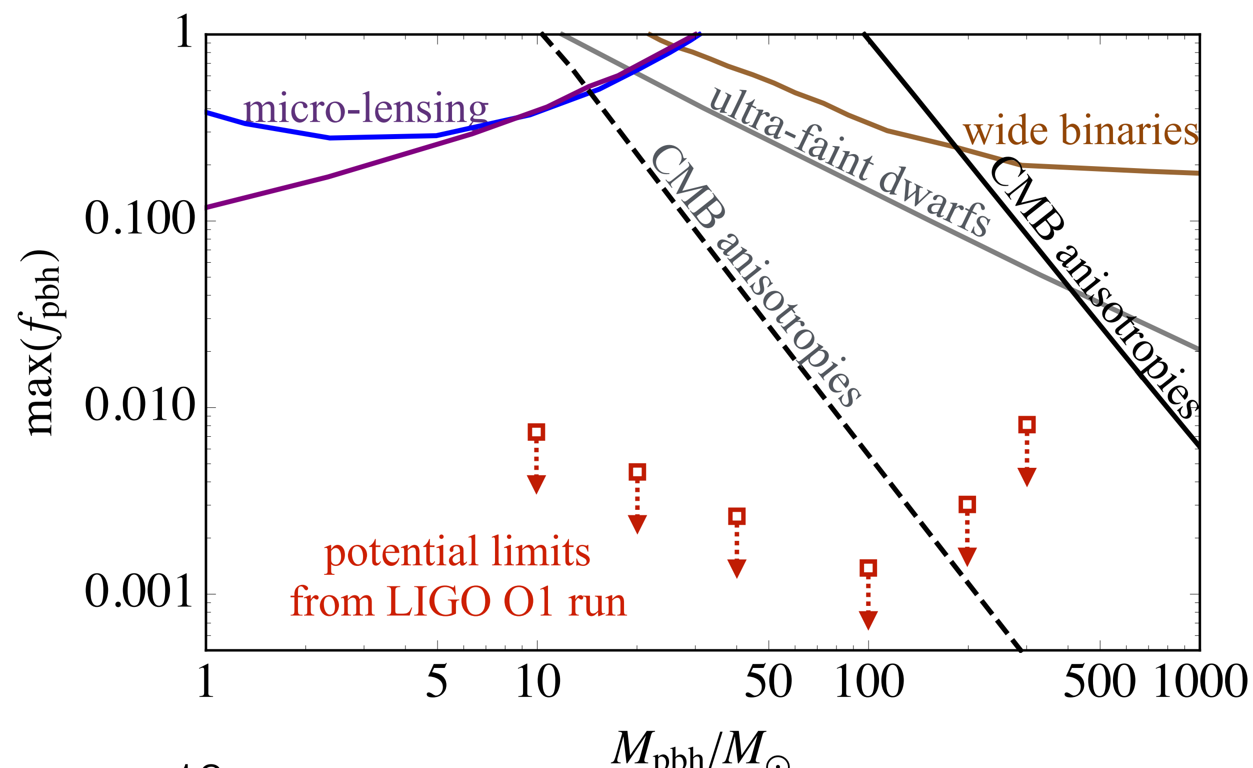
In the mass range of interest for the LIGO detections, limits and projected sensitivities are strongly model-dependent. More investigations to understand whether this is a viable scenario.

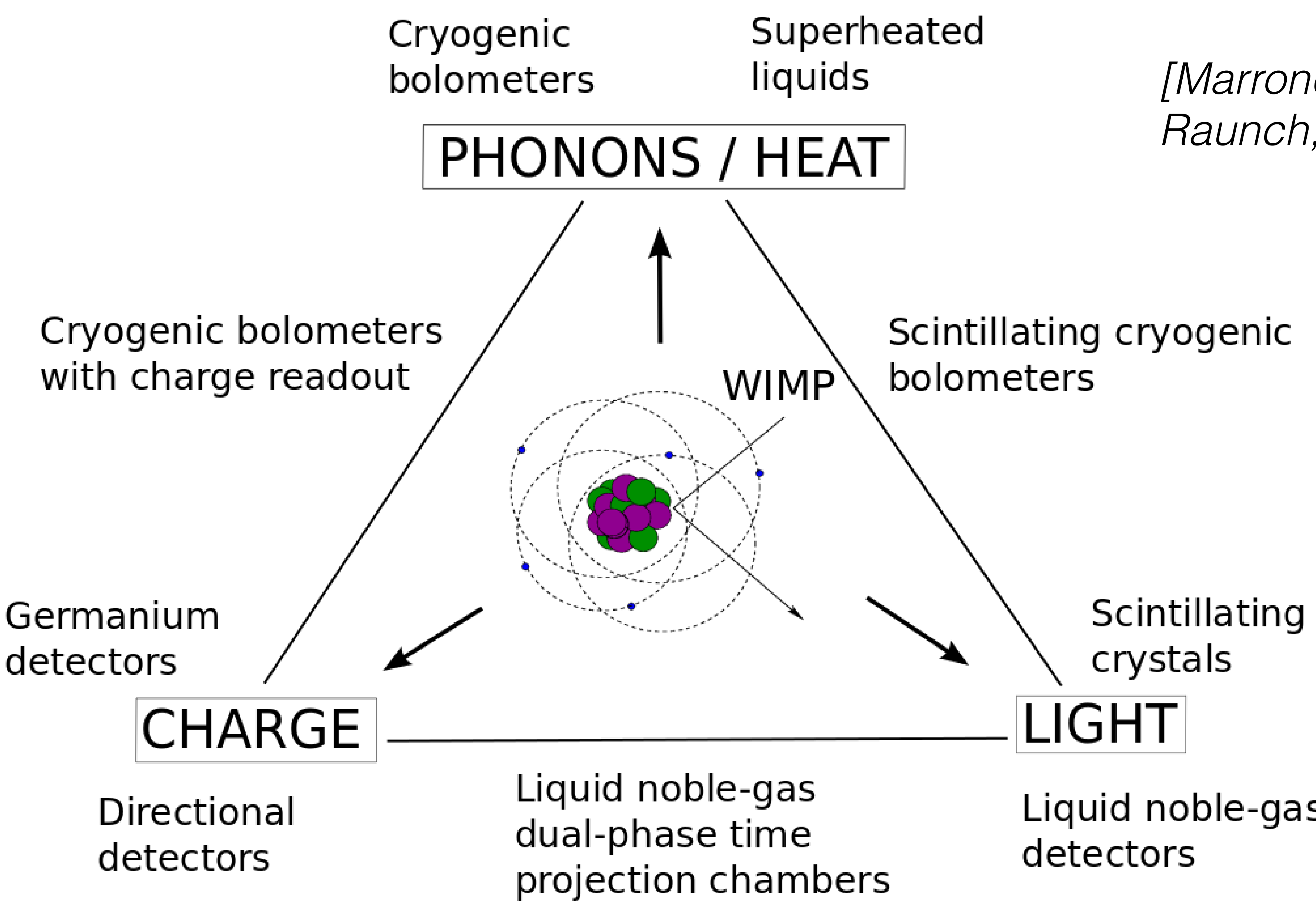
[Ali-Häımoud et al., arXiv:1709.06576]



Direct detection

Elastic scatterings on target nuclei of DM particles making the Milky Way halo. Possible signals and background rejections depending on the technology in use:

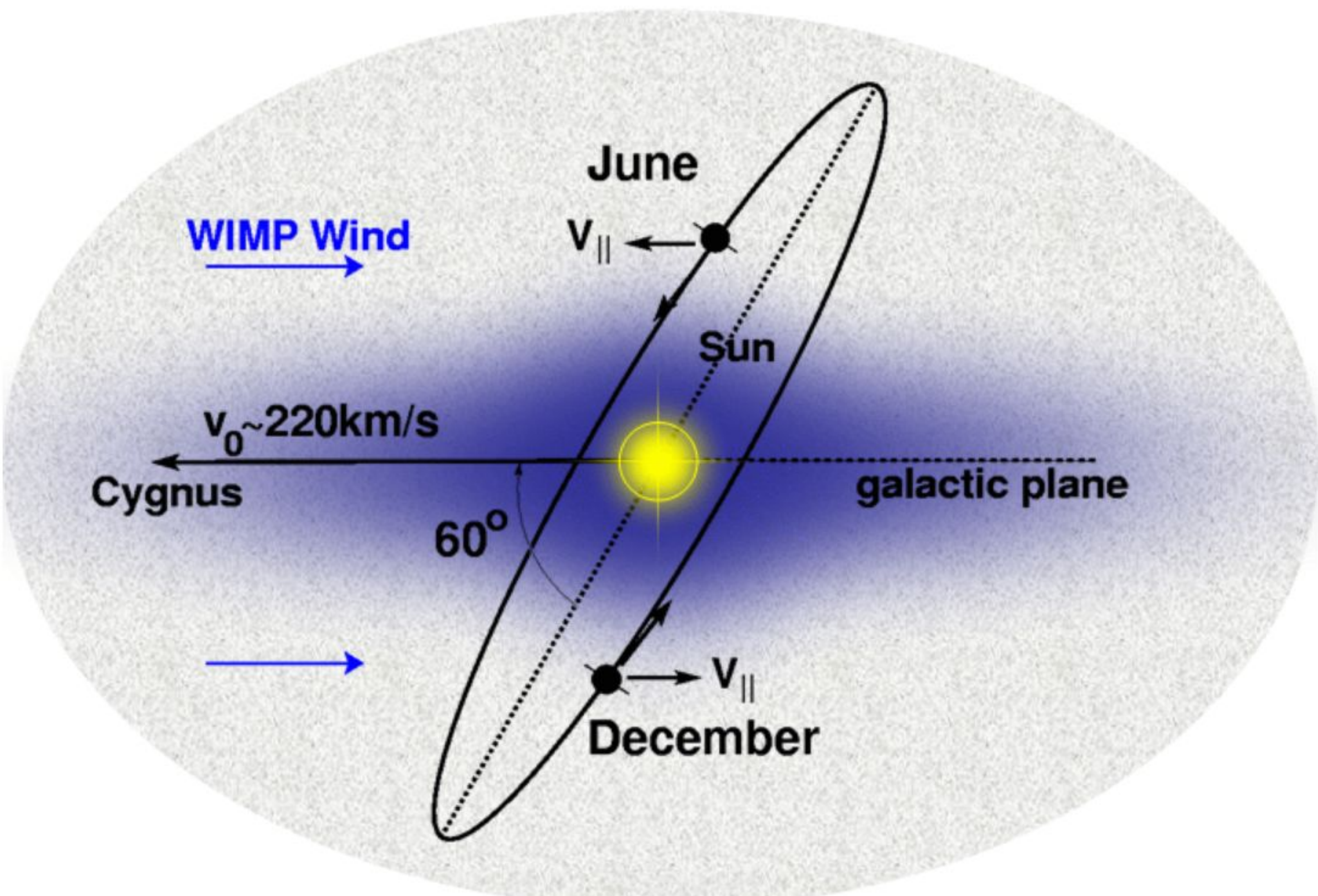
[Marrondán Undagoitia & Raunch, arXiv:1509.08767]



Annual modulation signature

Modulation in the event rate due to the orbit of the Earth around the Sun: *[Drukier, Freese & Spergel, 1986]*

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cdot\cos\left(\frac{2\pi(t-t_0)}{T}\right)$$



The relative speed of DM particles is larger in the summer, increasing the number of nuclear recolis above threshold.

[http://www.hep.shef.ac.uk/research/dm/intro.php]

The DAMA/LIBRA annual modulation result

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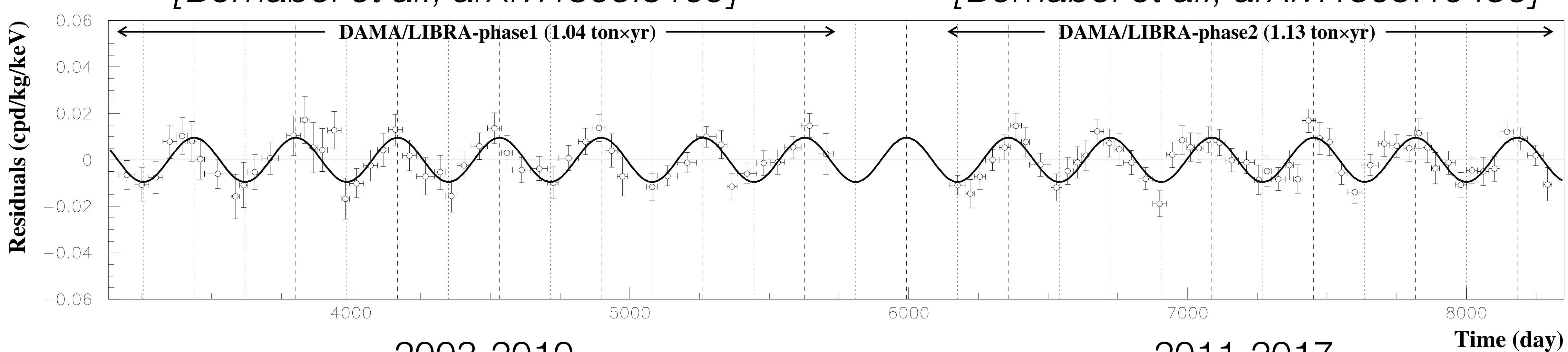
DAMA/LIBRA detects scintillation signals in NaI cristals; no nuclear/electronic recoil discrimination but sensitivity to the modulation:

[Bernabei et al., arXiv:1308.5109] *[Bernabei et al., arXiv:1805.10486]*



2003-2010 2011-2017

+ DAMA/NaI (1996-2002): after the last update from DAMA/LIBRA phase2, with lower energy threshold, 12.9 σ significance!

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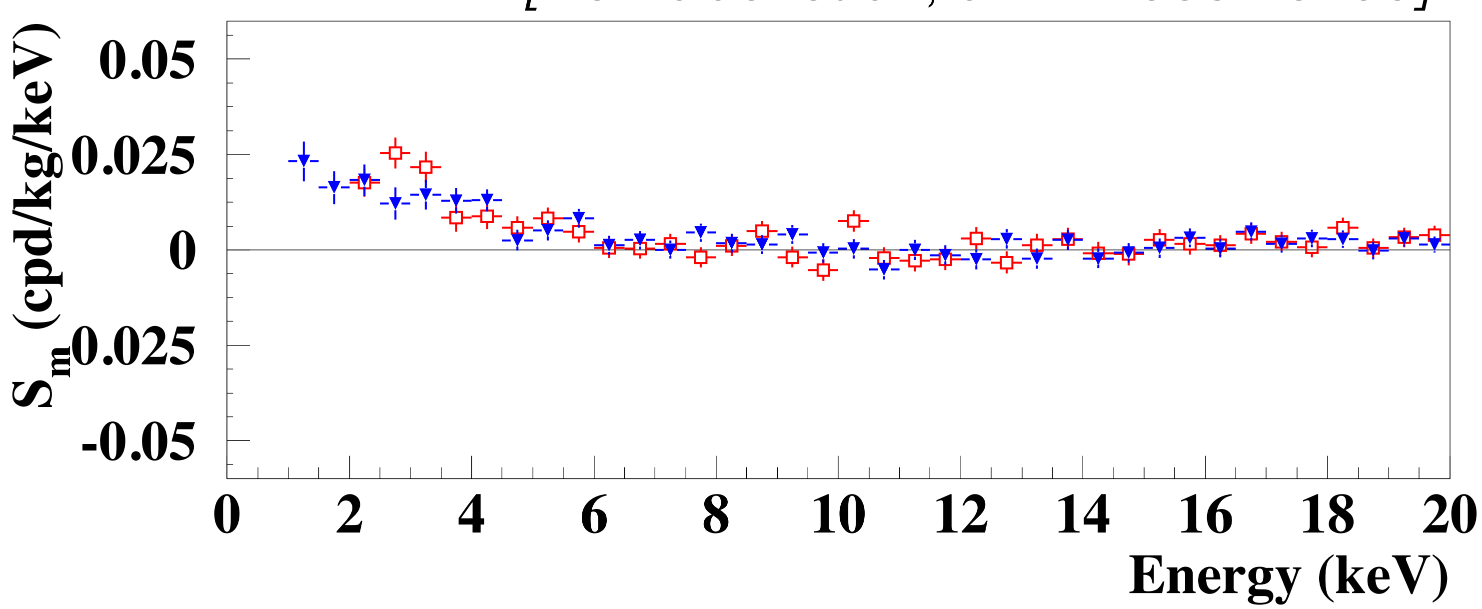


Red: DAMA/NaI+ DAMA/LIBRA phase1

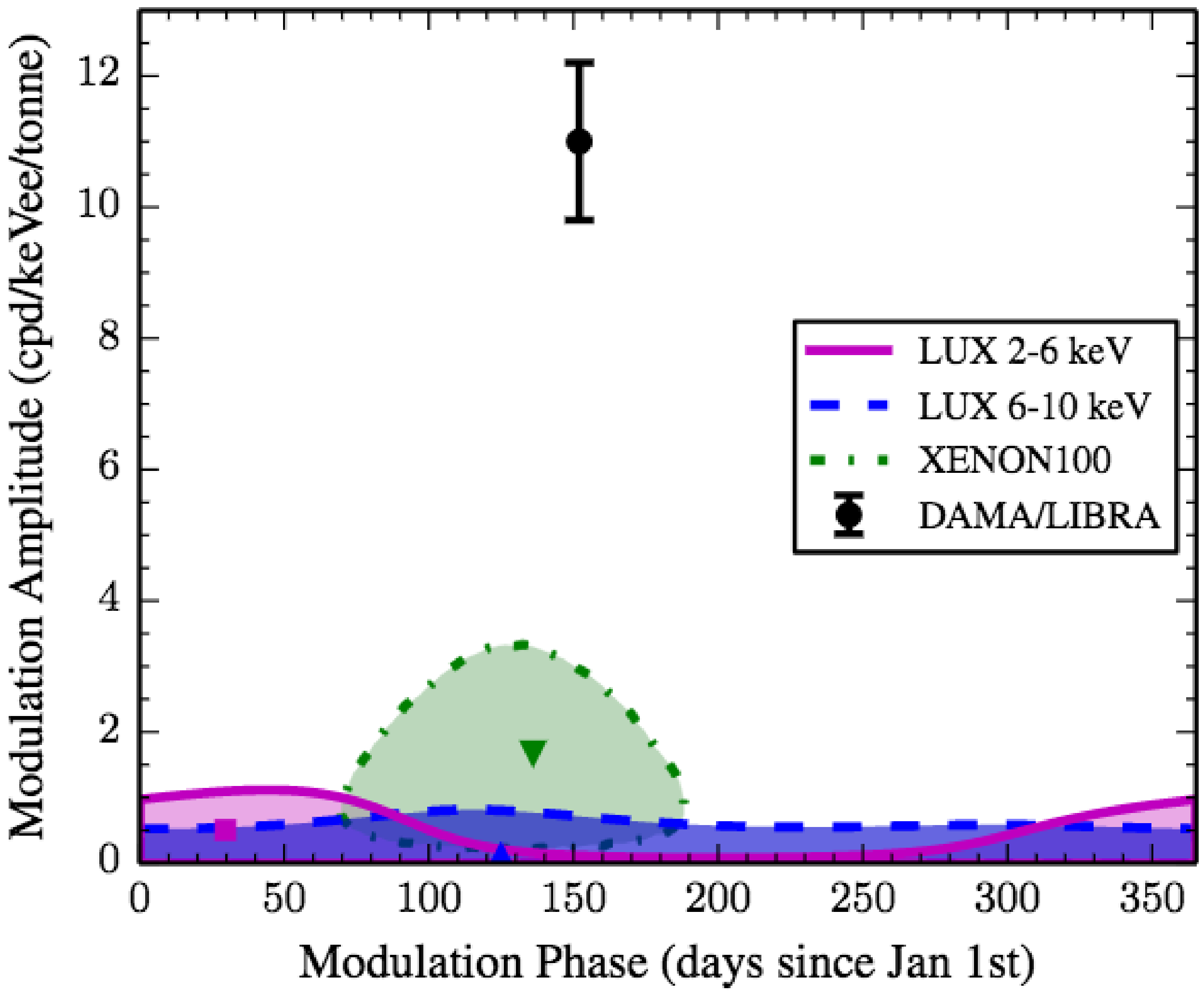
Blue: DAMA/LIBRA phase2

WIMP interpretations (Spin Independent, Spin Dependent, Isospin-Violating, …) in very sharp tension with results from other targets!

Annual modulation in liquid Xe detectors

A model dependence is introduced - some extent - when comparing different targets. Model independent checks desirable:

Electron recoils expected for leptophilic models; test annual modulation for this case with liquid Xe detectors:



interpretation excluded at:

- 3 σ by **XMASS**, *[arXiv:1801.10096]*
- *5.7* σ by **XENON100**, *[arXiv:1701.00769]*
- *9.2* σ by **LUX**, *[arXiv:1807.07113]*

Testing DAMA/LIBRA with other NaI detectors

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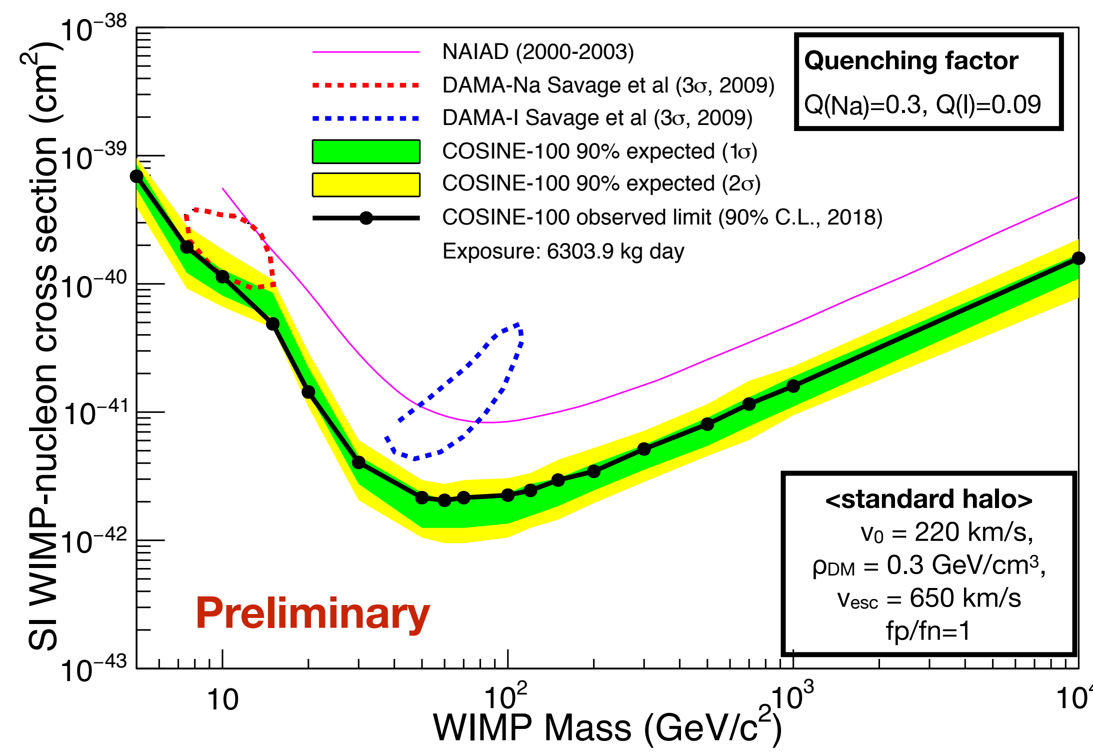
Several NaI experiments are currently running, under construction or in R&D phase:

- **COSINE-100** (@Yangyang, in physics run since September 2016) *[arXiv: 1710.05299]*
- **ANAIS-112** (@Canfranc, taking data since August 2017, 3 σ significance on modulation in 5 years) *[arXiv:1704.06861]*
- **SABRE-5** (@LNGS, proof of principle 2018) + **SABRE-50** (@SUPL, Australia, scheduled 2019) *[arXiv:1806.09340]*
- **PICO-LON** (@kamioka) [arXiv:1512.046445]
- **COSINUS** (@LNGS) *[arXiv:1603.02214]*
- **DAMA/LIBRA phase 3** (@LNGS, R&D for 1 ton)

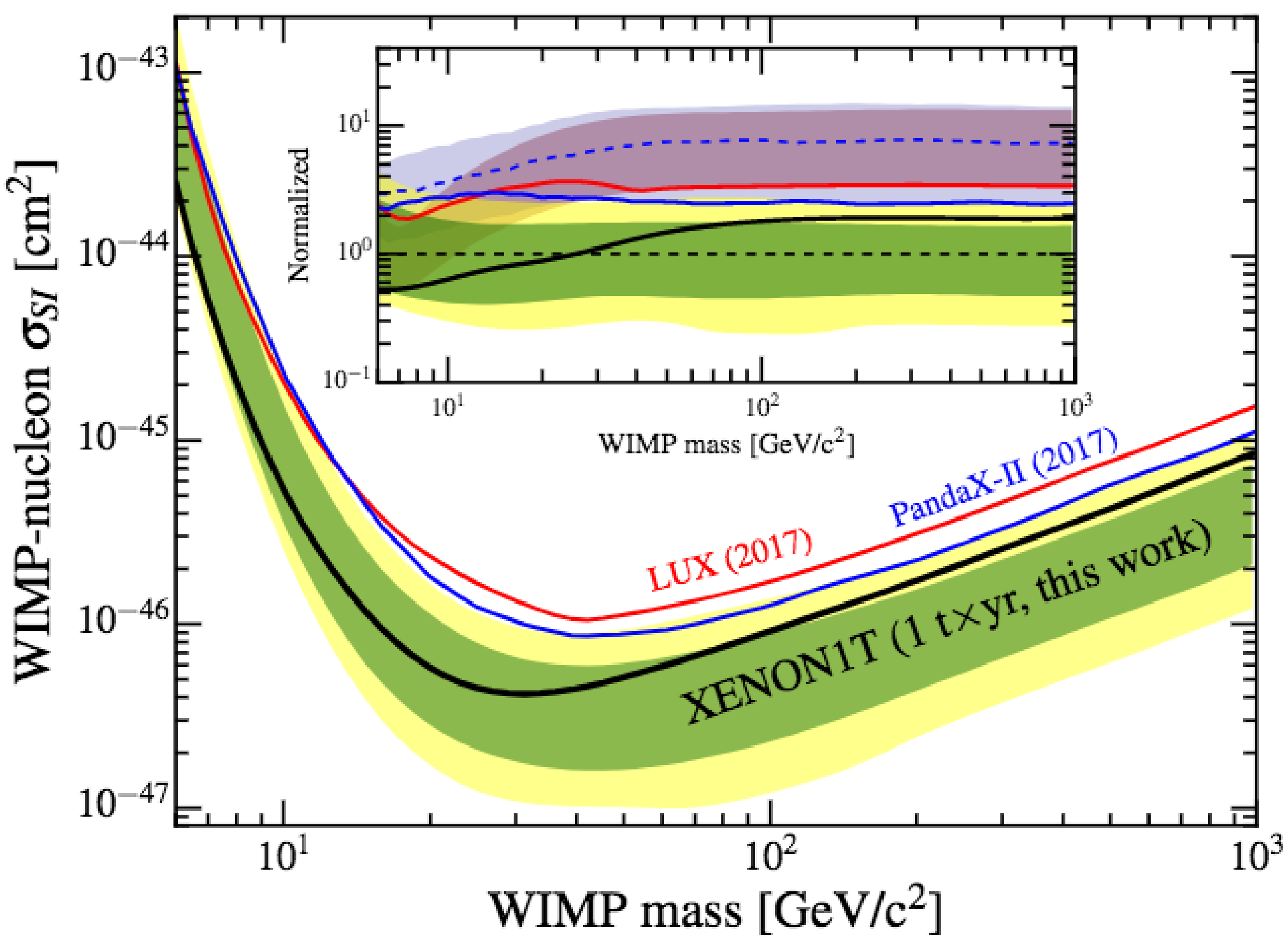
preliminary result of COSINE-100 presented @ IDM2018, based on count rate



5-yr of data for testing annual modulation

The run with noble gasses towards the ν floor

With noble gasses you can scale to large masses, keeping 3D reconstruction. Single phase detectors using pulse shape discrimination: first results from **DEAP** (LAr @SNOLAB, *[arXiv: 1707.08042]*) and new result from **XMASS** (LXe @ Kamioka *[arXiv: 1808.06177]*). Two phase TPCs have taken the lead in the latest years:

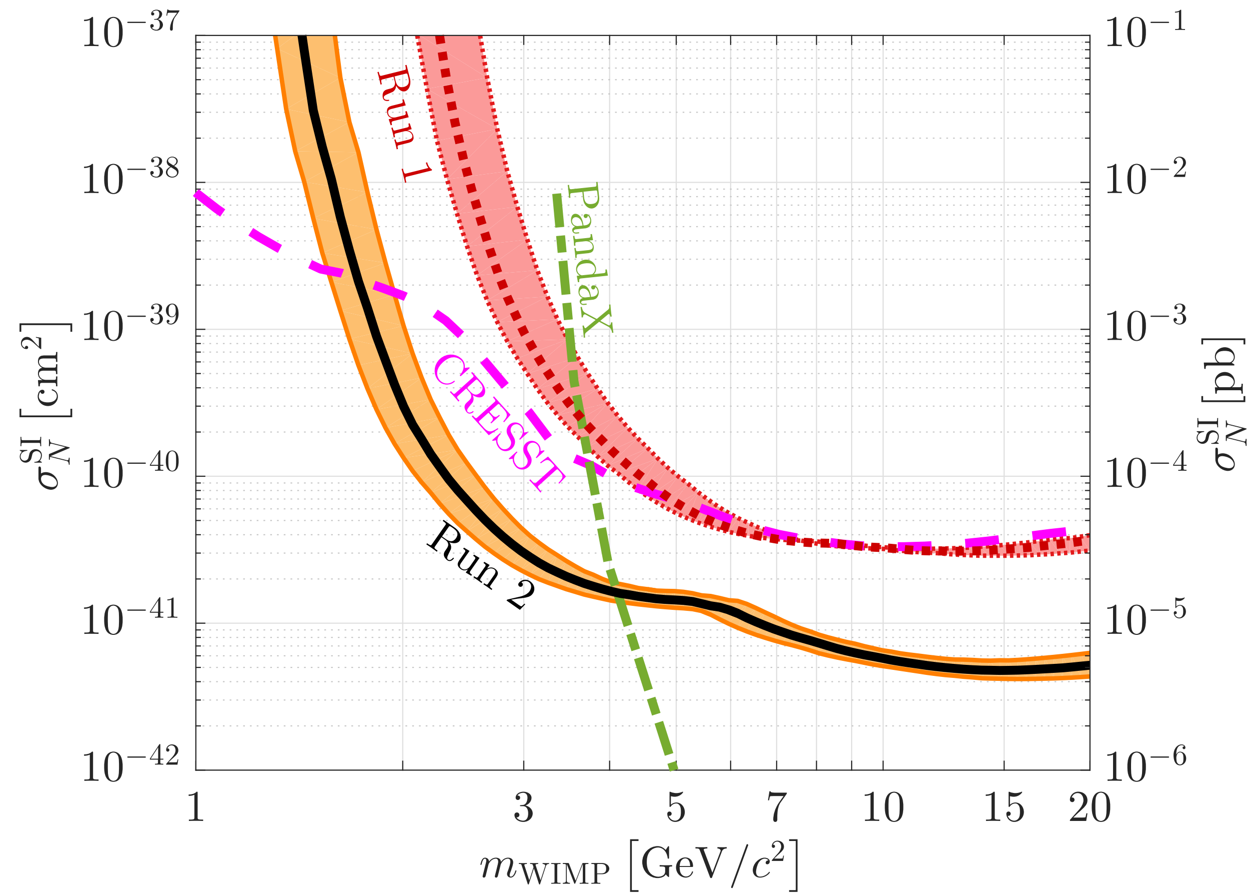


- **LUX** (33.5 ton×day exposure, latest results 2016, decommisioned) *[PRL 118, 021303 (2017)]*
- **PANDAX-II** (54 ton×day exposure, latest results 2017, running) *[PRL 119, 181302 (2017)]*
- **XENON1T** (365 ton×day exposure, latest results 2018, running) *[arXiv:1805.12562]*

the next steps: **LZ**, **PANDAX-4T** and **XENONnT** (+ LAr **DarkSide**), in commissioning in 2019-2020

The light mass window (1-10 GeV) …

In general cryogenic bolometers tend to be more sensitive: Latest results from **CDMSLite** [arXiv: 1707.01]



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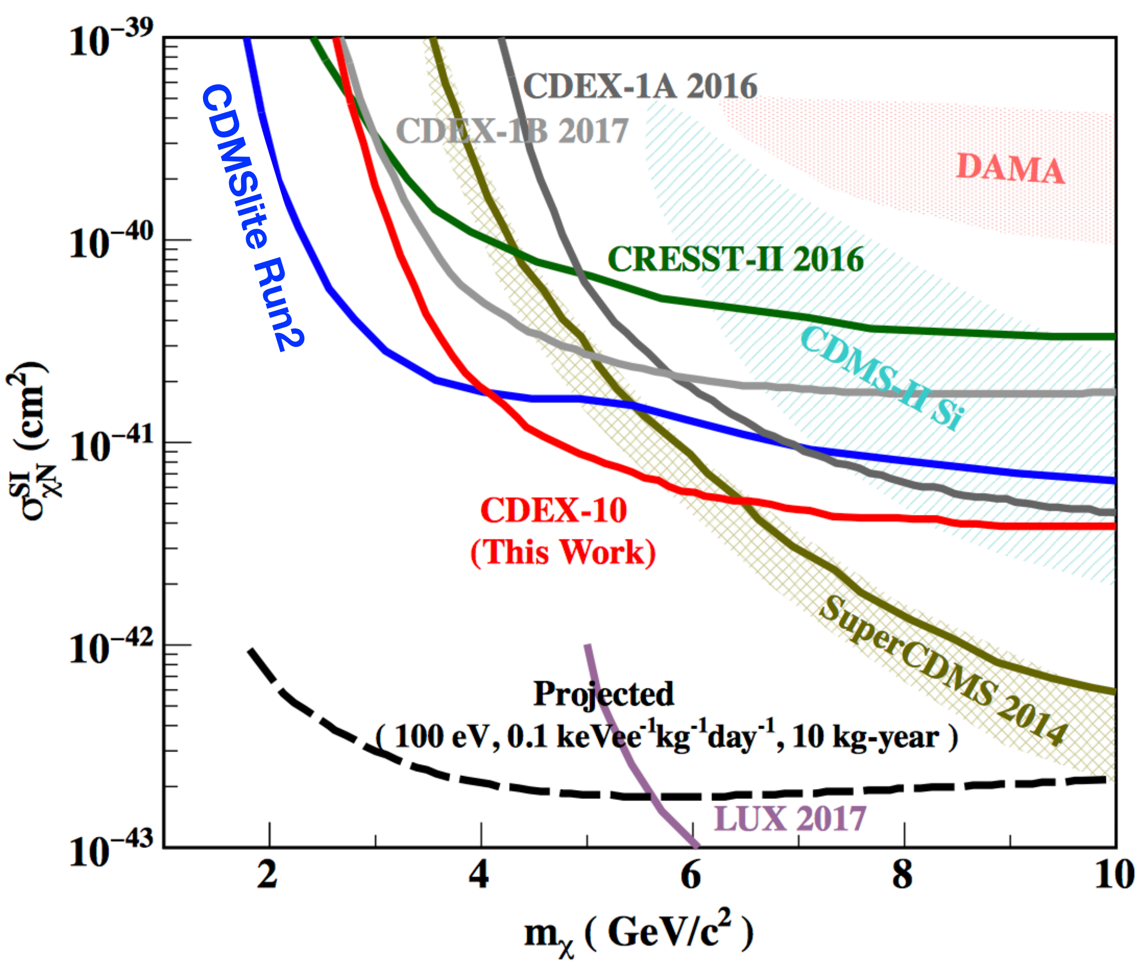

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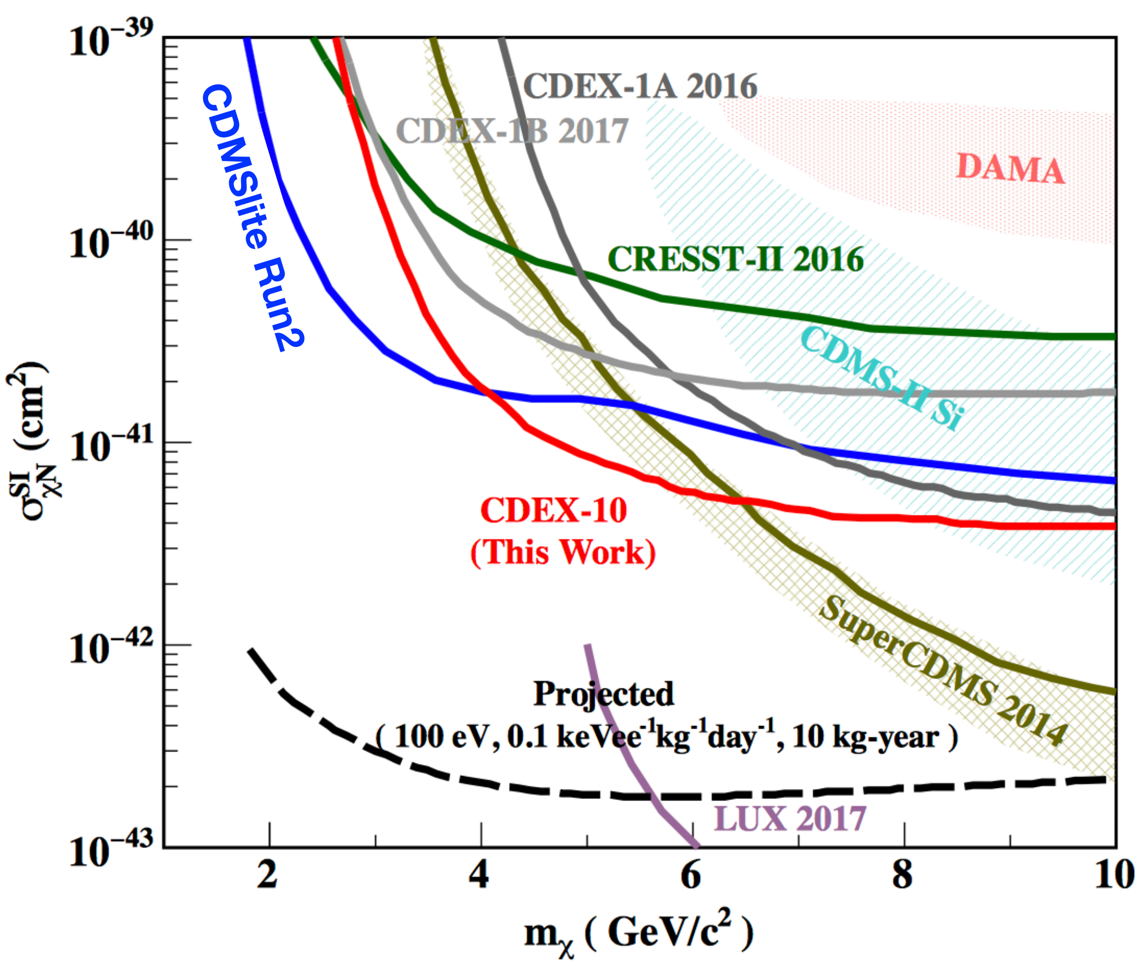
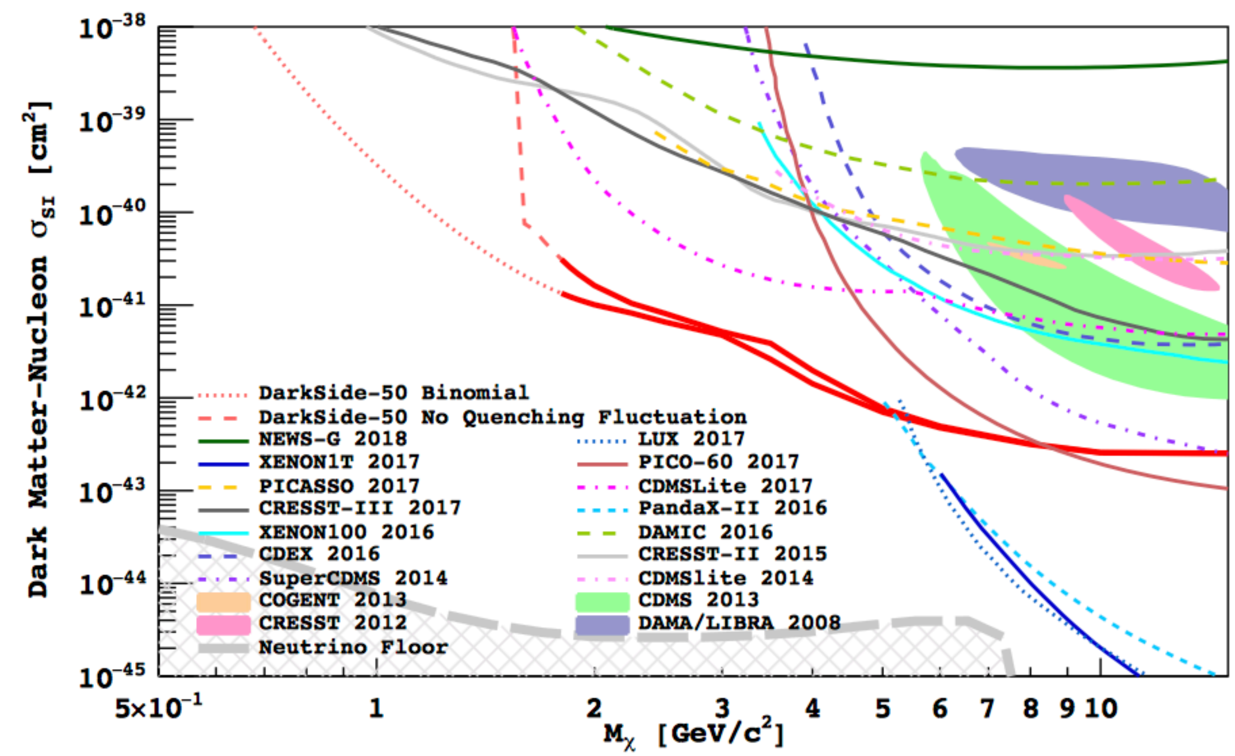
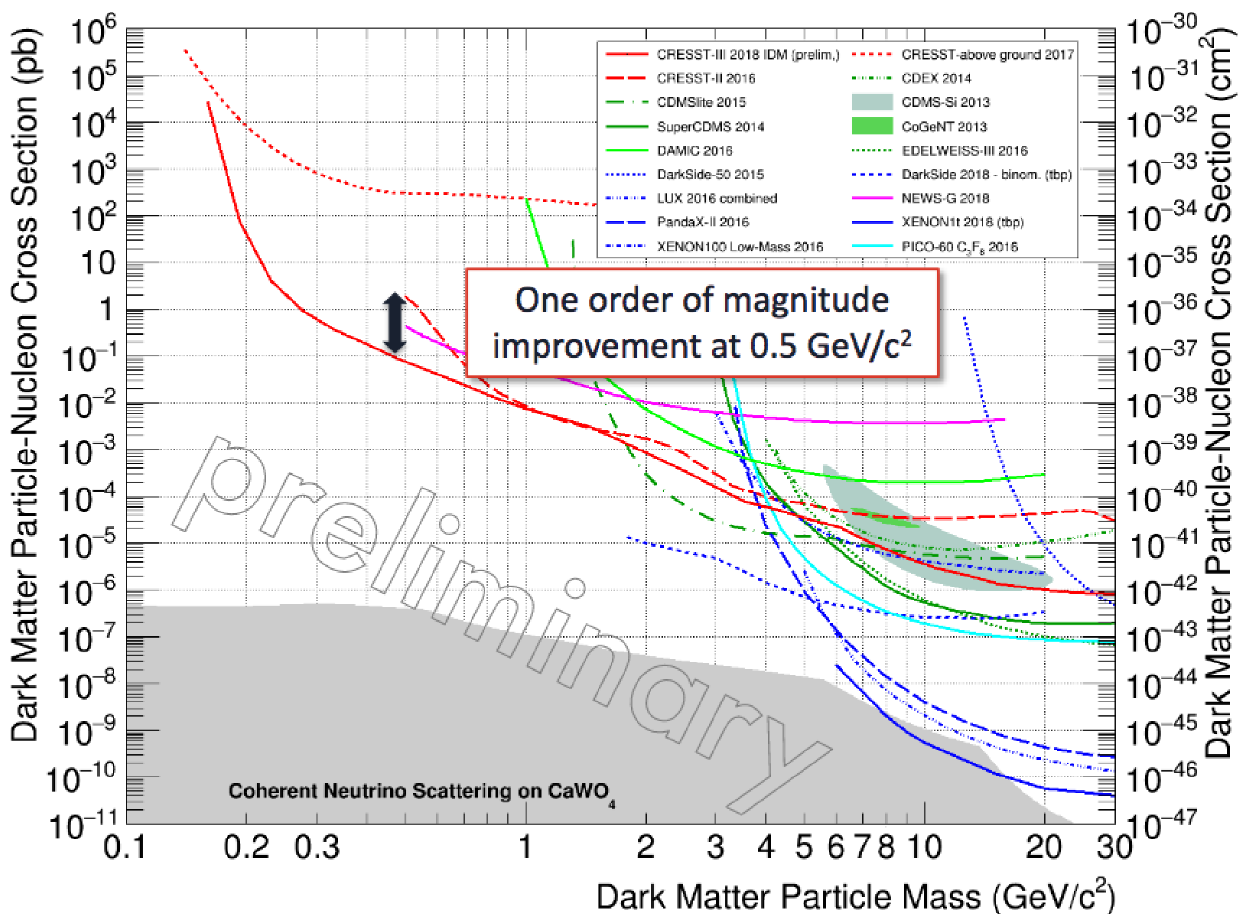
… but a big improvement has been obtained with noble gas TPCs, using S2 only: Latest results from **DarkSide-50** [arXiv: 1802.06994]





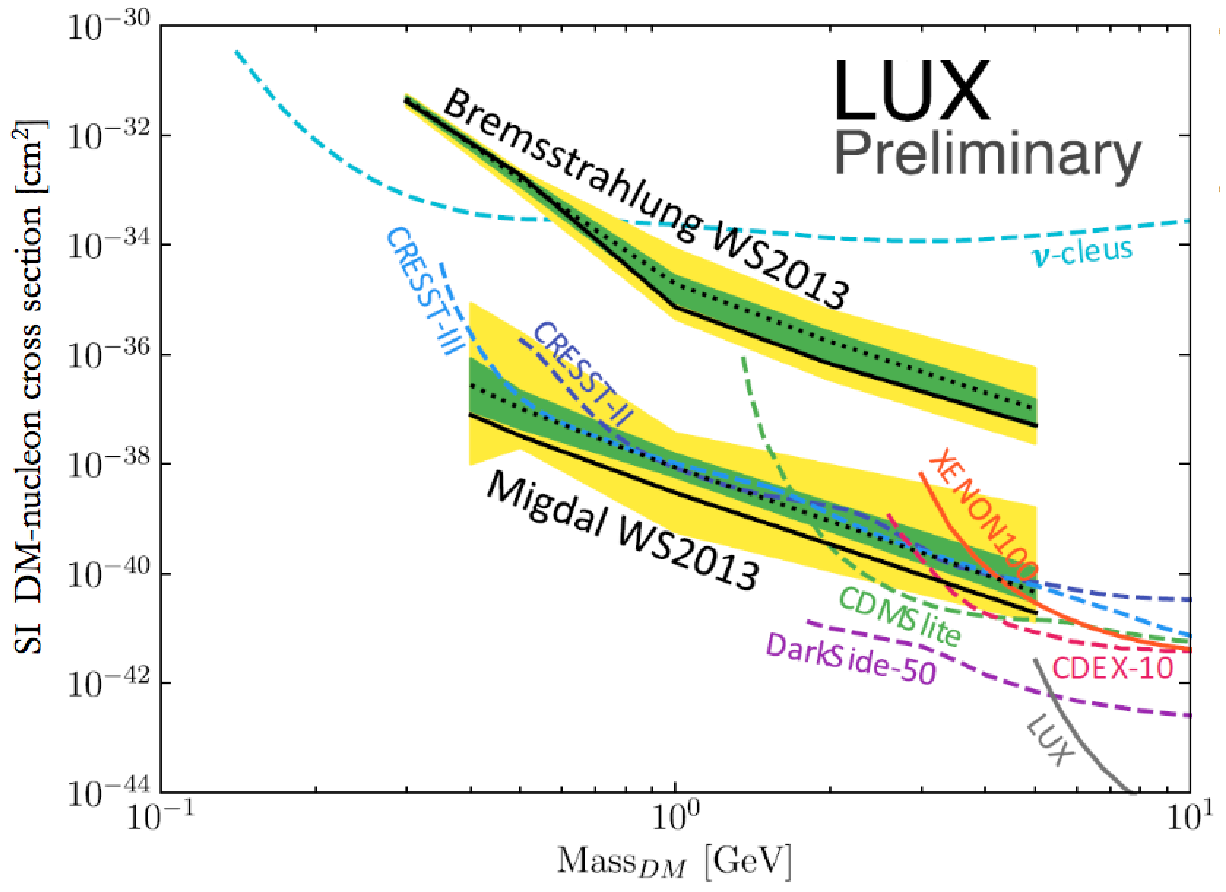
… and going to even lighter masses

… sub-GeV for DM-nuclei interactions: Latest results from **CRESST-III** [talk @ IDM2018 + arXiv:1711.07692]



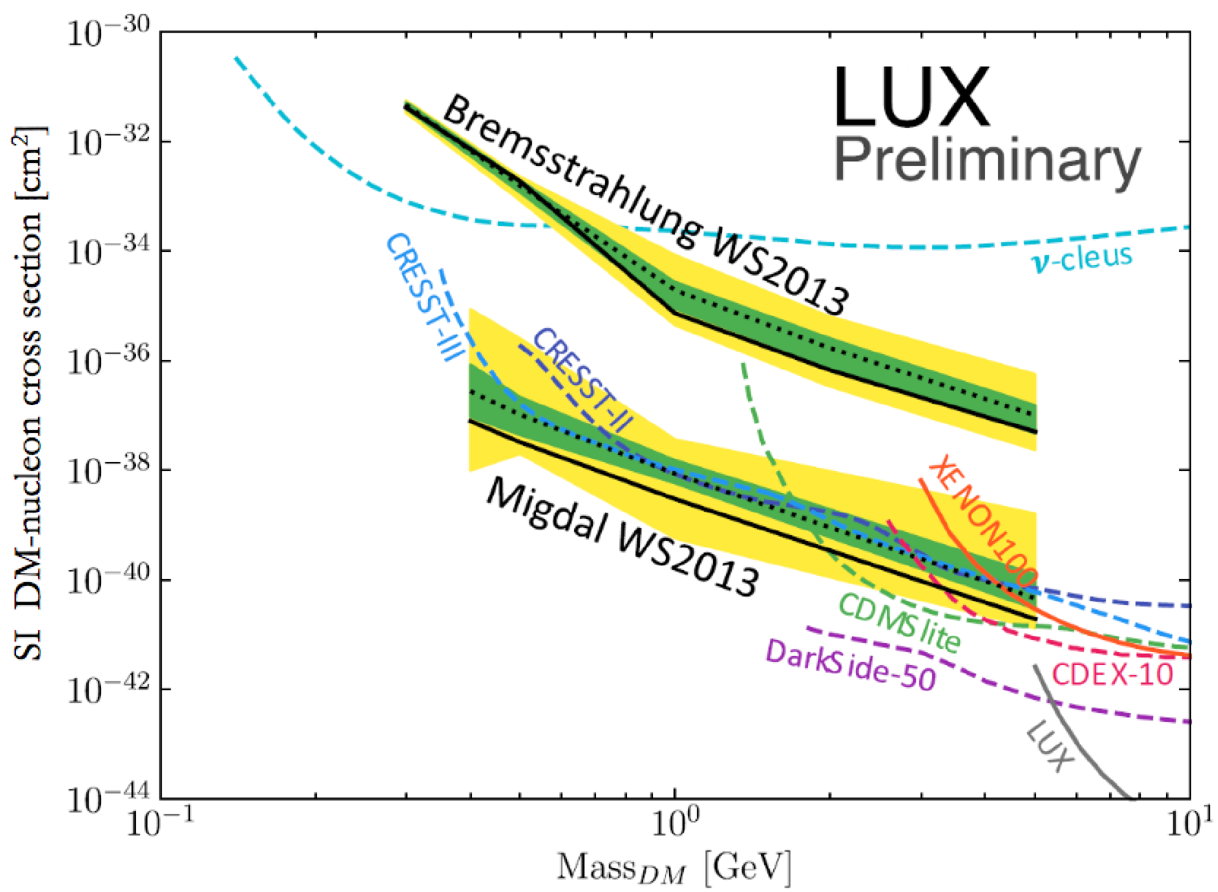
… and going to even lighter masses

… sub-GeV for DM-nuclei interactions: Latest results from **CRESST-III** [talk @ IDM2018 + arXiv:1711.07692] and **LUX** [talk @ IDM2018]

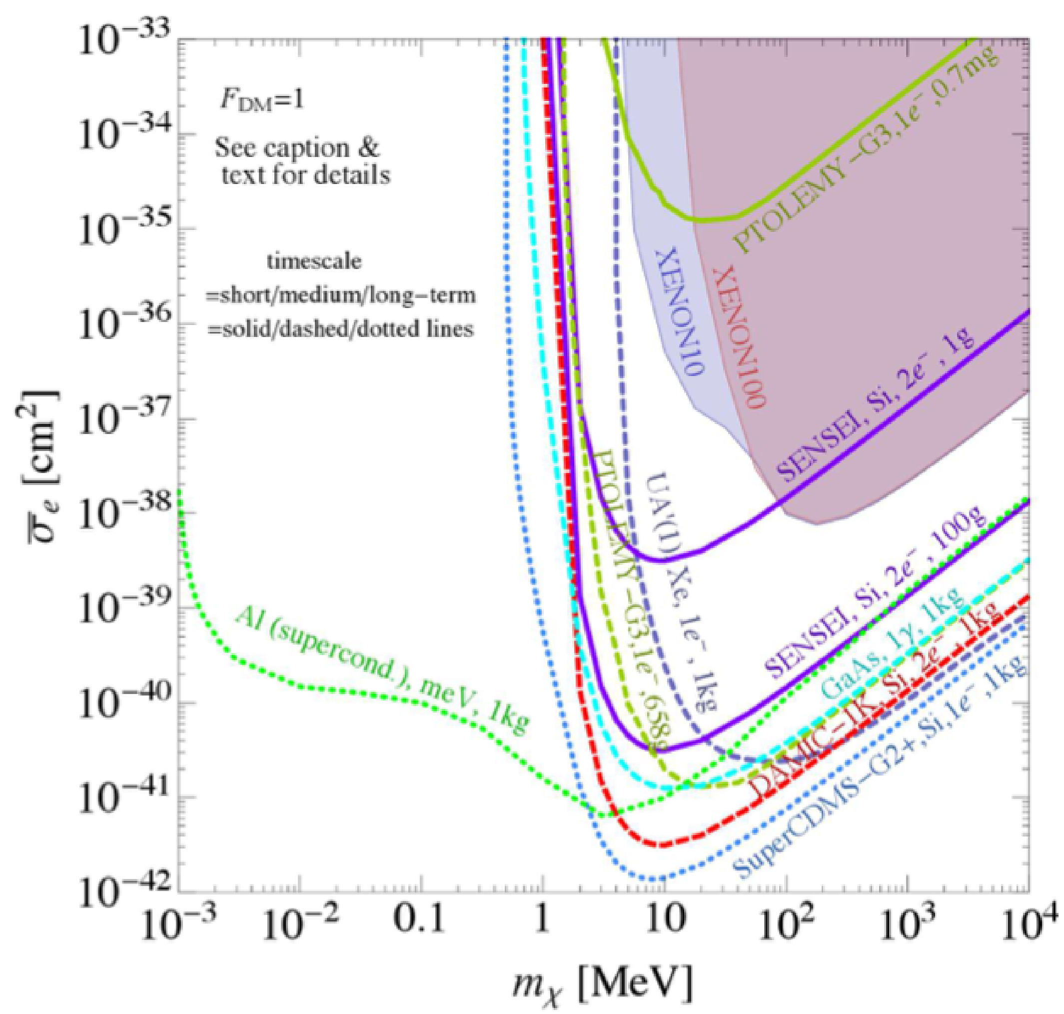


… and going to even lighter masses

… sub-GeV for DM-nuclei interactions: Latest results from **CRESST-III** [talk @ IDM2018 + arXiv:1711.07692] and **LUX** [talk @ IDM2018]

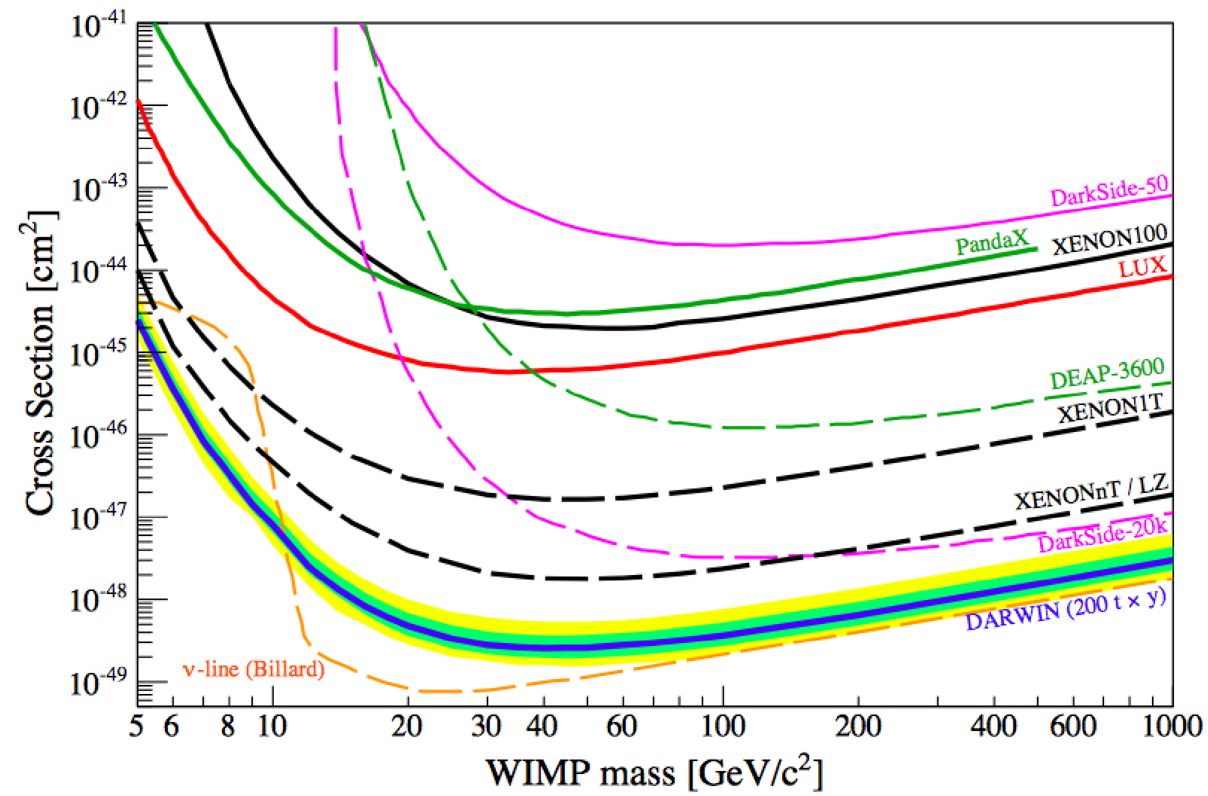


… down to 1 MeV and below for DM-electron interactions: **XENON10** & **XENON100** limits and number of new proposals **DAMIC**, **SENSEI**, **DANAE**, using CCD technology:



The ν floor as ultimate goal for WIMP searches

Steady progresses towards an ultimate experiment **DARWIN** (40t LXe for an exposure target of 200+ ton×year) *[arXiv:1606.07001]* :



Possibly a objective for various detectors and various techniques:

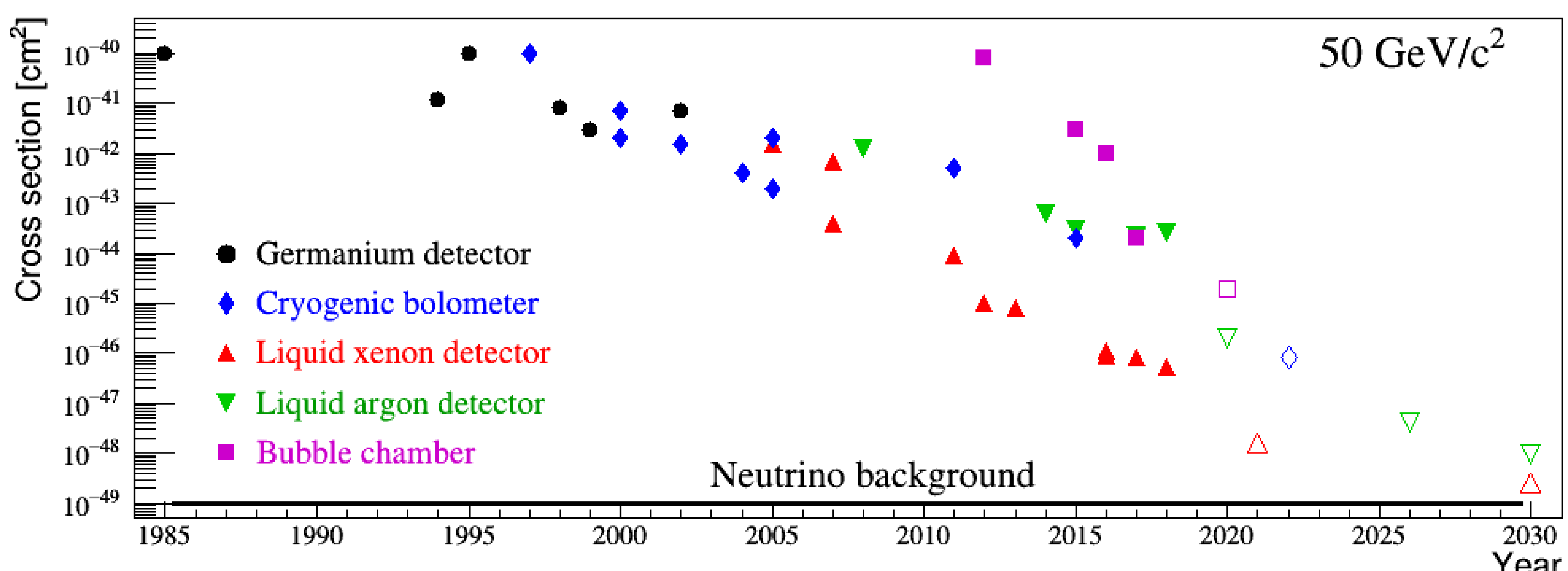


Figure updated from J. Phys. G43 (2016) 1, 013001

Marrondán Undagoitia, 2018

Indirect DM detection at an unsettled stage

A wide range of targets and wavelengths explored for contributions due to DM particle pair annihilations or decays. Some results are indeed compatible with a particle DM signal, e.g.:

- an excess at about a GeV in the γ-ray flux measured by Fermi Gamma-ray Space Telescope towards the Galactic center (first analyses in 2009);
- the excess of positrons at high energy in the locally measured cosmic-ray flux (long-standing: PAMELA, Fermi, AMS-02);
- a 3.5 keV line possibly identified by X-ray surveys on a number of DM dominated targets (since 2014; some DM dominated object did NOT show it);
- a (very weak) excess at 10-20 GeV in CR antiproton flux measured by AMS-02 *[Cuoco et al., 2017]*;
- a (again very weak) Fermi excess towards some ultra-faint MW dwarf satellites, newly discovered by DES *[Fermi+DES, 2017]*.

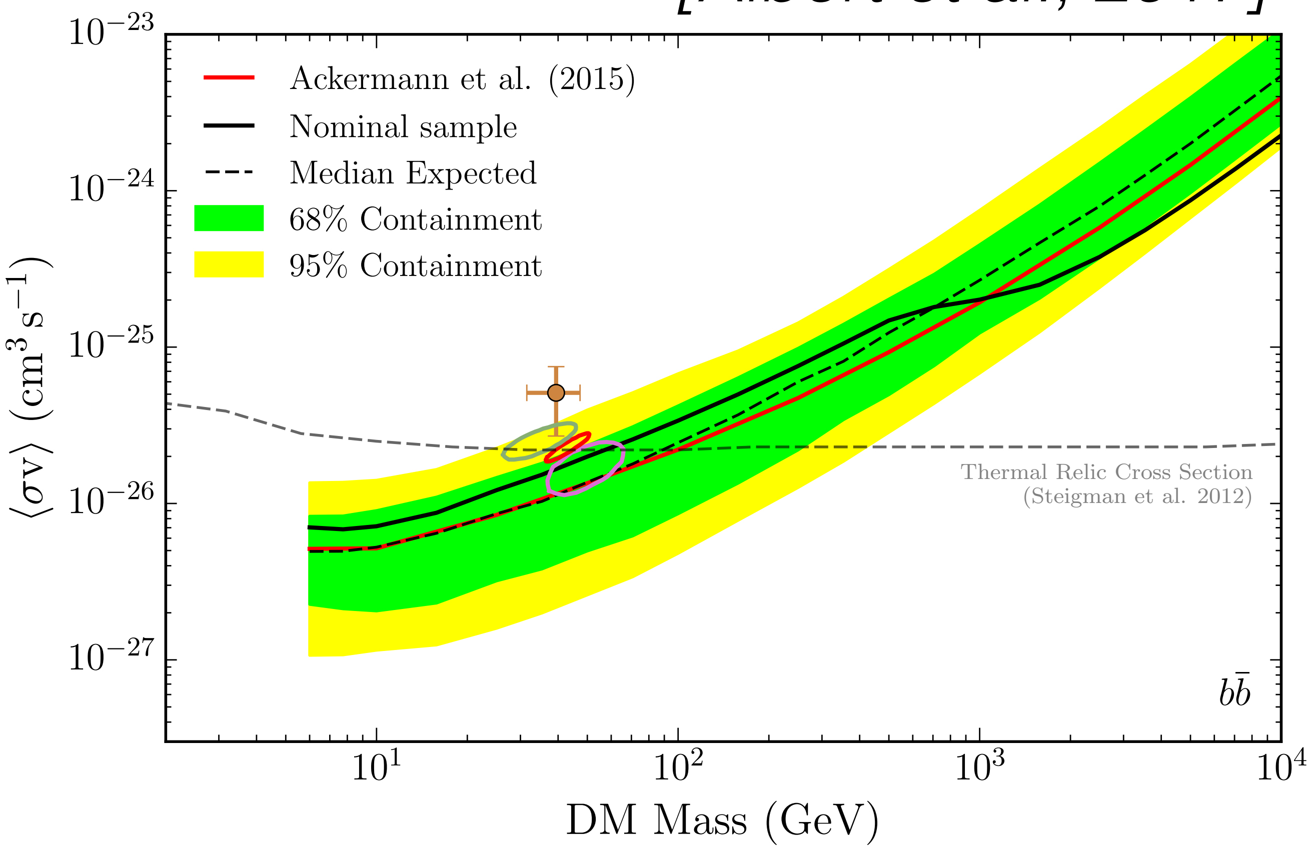
Unfortunately, there are severe caveats in uniquely and unambiguously associating any of these to a definite particle physics scenario. E.g.:

[Bartels et al., 2018] & *[Macias et al., 2018]* find both that a boxy template to be associated to the Galactic bulge fits the GeV excess better than a spherically symmetric DM template.

Indirect DM detection at an unsettled stage

On the other hand in some channels upper limits have been pushed quite far. The tightest constraint by Fermi from the stacking analysis on MW dwarfs:

[Albert et al., 2017]



DM thermal relics lighter than about 100 GeV excluded!

Are there hidden underlying assumption? Should we trust these exclusion limits at face value? See, e.g. *[PU & Valli, 2017]*.

In lack of smoking gun signals (gamma-ray lines or antideuterons still an option), research is concentrating on pinning down signal uncertainties and refining background estimates.

Summary

- From cosmological/astrophysical evidence for dark matter to cosmological/astrophysical evidence for dark matter particles.
- A few frameworks in which the dark matter particle detection phenomenology has fairly generic patterns.
- Still the space of viable dark matter models is populated also by cases requiring dedicated efforts.
- Steady progresses in direct searches, with the DAMA/LIBRA result still to be understood.
- More puzzling the situation with searches for dark matter particle pair annihilations or decays.