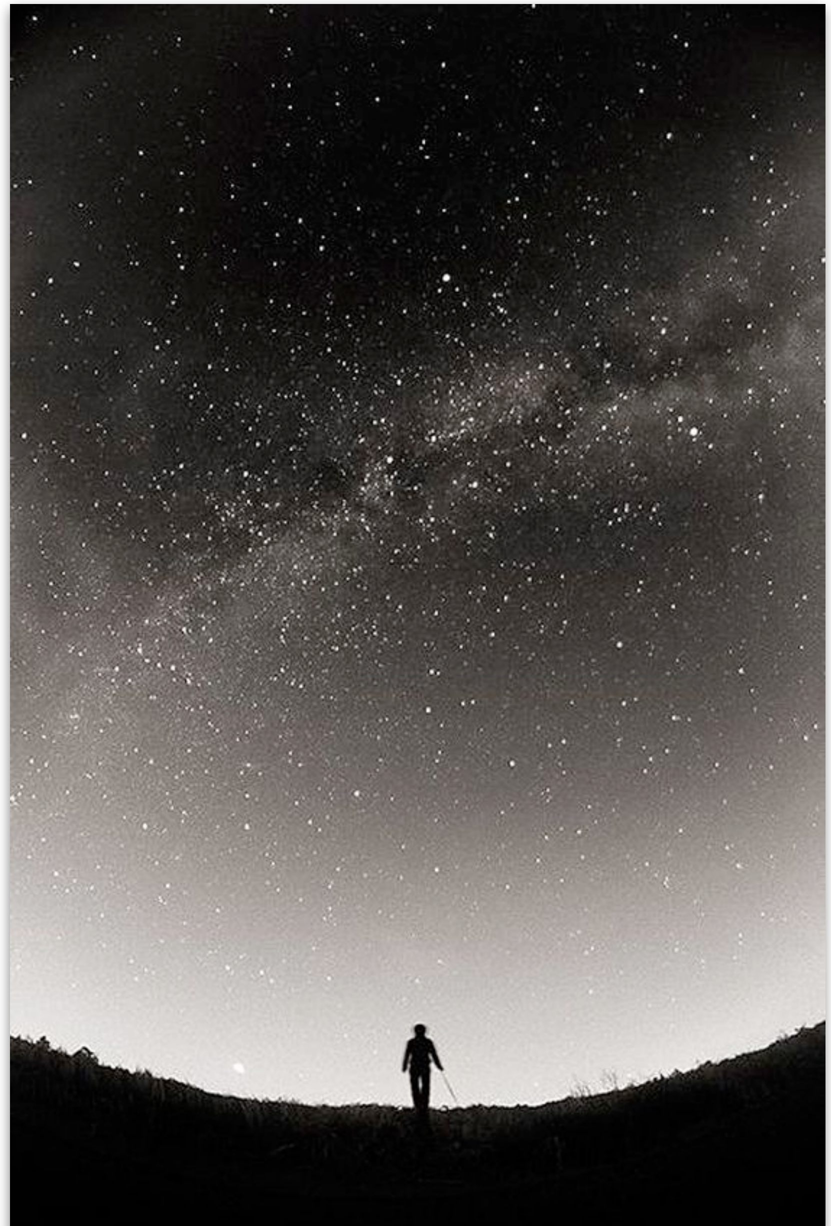
QUO VADIS, MATERIA NIGRA ?



Pasquale Dario Serpico (Annecy, France)

Journées Théorie PNHE - 01/10/2018

Mon cahier des charges, répondre à:

- quels modèles/scénarios [de matière noire] restent dans la course ?
- avec quelles motivations théoriques ?
- quelles sont les signatures les plus prometteuses dans le ciel à haute énergie s'il en reste ?
- quelles sont les complémentarités avec les autres observables astrophysiques et celles sondées dans les expériences sur Terre ?
- Où faut-il investir l'effort ces prochaines années ?

(un grand merci à Julien Lavalle)

"My two cents"

“Traditional” link DM-particle physics

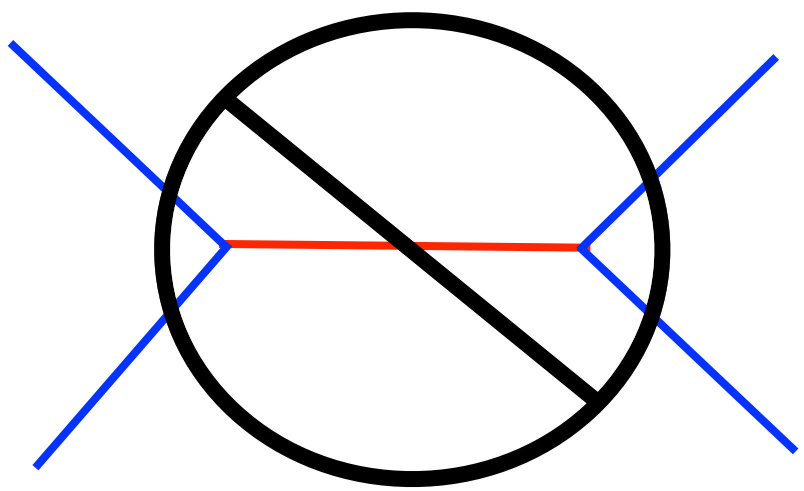
Strong **prior for TeV-scale BSM (with SM-like couplings)** to cure **“the hierarchy problem”:**

why is weak scale (notably Higgs mass) insensitive to quantum effects from physics at some much higher energy scale Λ_{UV} (e.g. gravity)?

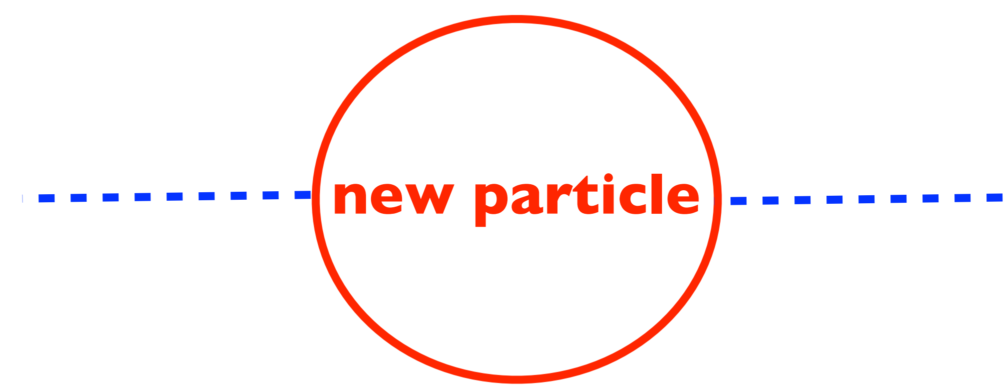
Conjecture: there is some symmetry (e.g. SUSY) @ E~O(TeV), “shielding” low-E pheno from UV.

Precision data (e.g. from LEP) suggest that tree-level couplings SM-SM-BSM should be avoided!

we want to avoid!



Ok with it!



One straightforward solution is to impose **some symmetry** (often “parity-like”, relic from some UV-sym): SUSY R-parity, K-parity in ED, T-parity in Little Higgs. New particles only appear in pairs!

➡ Automatically makes **lightest new particle stable!**
➡ It has other benefits, e.g. respect **proton stability** bounds!

The WeaklyInteractingMassiveParticle Paradigm

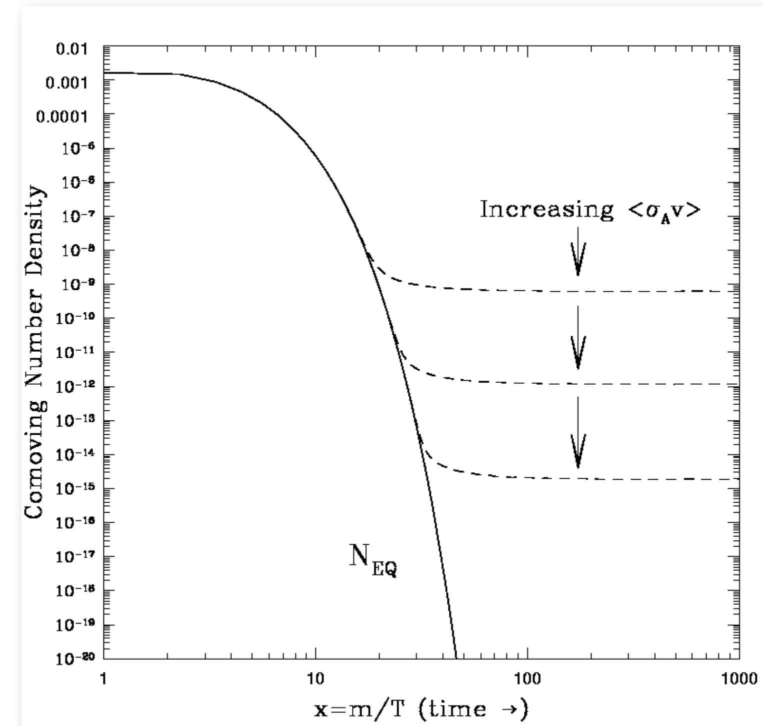
Cosmology tells us that the early universe was a hot plasma, with all "thermally allowed" species populated. Notion tested up to T~ few MeV (BBN, cosmo ν's):

What if we extrapolate further backwards, introducing this new particle?

$$X\bar{X} \longleftrightarrow \ell\bar{\ell}$$

Add to SM a ***stable massive particle*** in ***chemical equilibrium with the SM*** via ***EW-strength interactions*** in the early universe down to *T*<<*m* (required for **cold** DM, i.e. non-relativistic distribution function!). It suffers exponential suppression of its abundance

What is left of it depends on the decoupling time, or their annihilation cross section: the weaker, the more abundant...



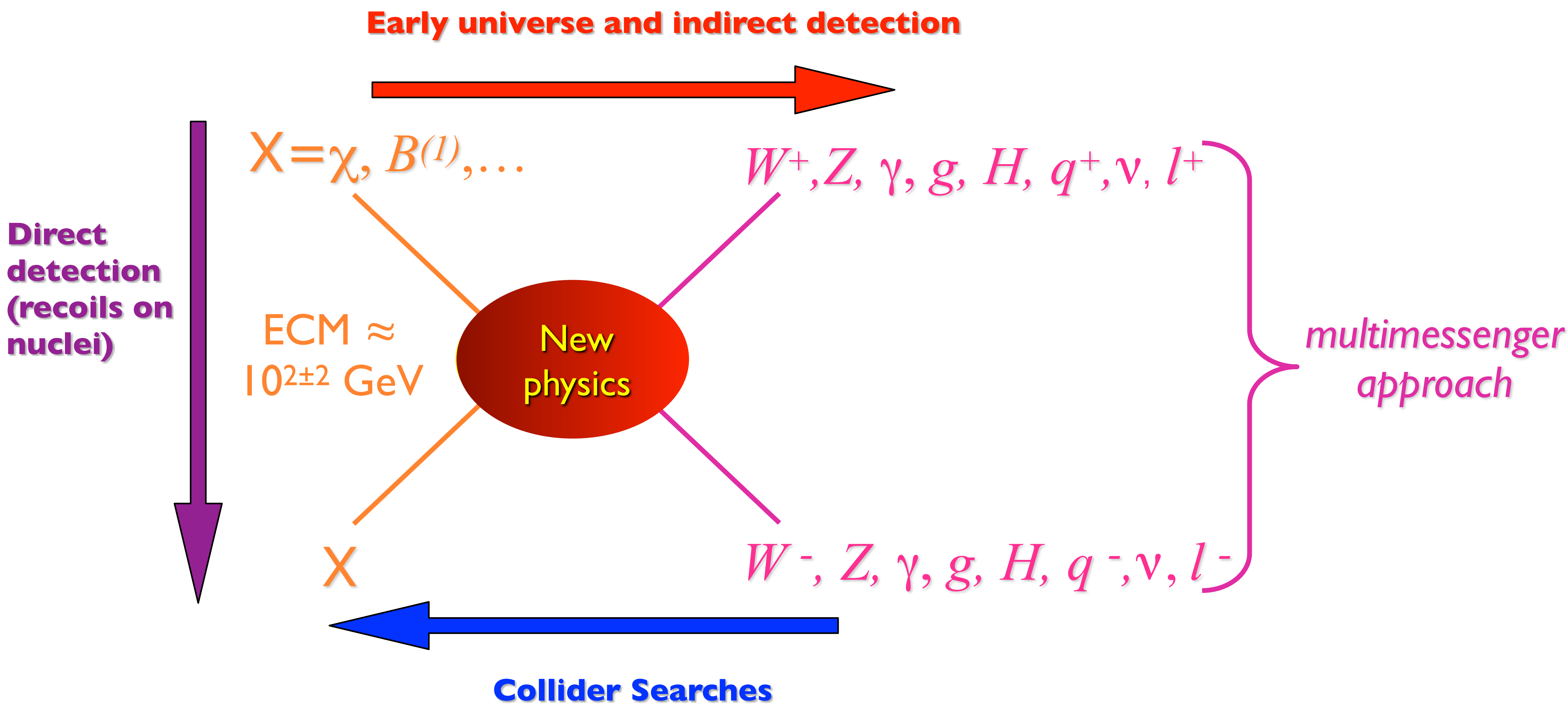
Textbook calculation yields the current average cosmological energy density

$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}$$

Observationally inferred $\Omega_{DM}h^2$~0.1 recovered for EW scale masses & couplings (aka ***WIMP miracle***)!

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m^2} \simeq 1\,\mathrm{pb}\left(\frac{200\,\mathrm{GeV}}{m}\right)^2$$

WIMP (not generic DM!) search program



✓ demonstrate the "particle physics" nature of astrophysical DM (locally, via DD; remotely, via ID)

✓ Possibly, create DM candidates in the controlled environments of accelerators (but not enough! Neither stability nor relic density "directly tested", for instance…)

✓ Find a consistency between properties of the two classes of particles. Ideally, we would like to calculate abundance and DD/ID signatures → link with cosmology/test of production

Status of multi-messenger WIMP identification program

Null results till now *(in none of the channels)*

+

a number of more or less hyped claims

(notably in indirect detection, none of which confirmed independently, admitting alternative astrophysical or instrumental explanations)

Paradigm of the m-m program
"The blind men & the elephant"
Mughal painting, ~ 1600 AD

In our case, it seems that the men are not blind, but the elephant is invisible

What is left? What's the current attitude?

Loosely speaking, I can identify a few conceptual directions:

A. "Keep faith": our ideas were correct, but we are a bit unlucky, some "mild" unexplained fine-tuning is present, e.g.:

1. BSM particles (slightly) too heavy to be produced at LHC, DM may be (multi)TeV, too…
2. … or accidentally light (after all, 1st gen. mass scale<< Higgs vev)
3. Almost mass-degenerate states

B. "The patch": agnostic on the UV, just "explain" why no physics up to TeV scale (aka just care about the "little hierarchy")

4. dark color gauge groups, hidden sector & new forces, links to the Higgs via "portal interactions"…

C. "Forget it": at least DM unrelated to hierarchy prob., find inspiration in pheno or different theory

5. BSM too light and/or weakly coupled with the SM (in the latter case, possibly heavy). Sufficient to explain lack of direct detection as well (outside currently probed kin. range, loop or mixing suppressed couplings…) Motivations from neutrino physics? Axions from strong-CP and axion-like particles maybe from strings?

If sticking to WIMPs…

An important comment (of interest for PNHE)

Indirect detection is very far from a "critical coverage", even for "vanilla WIMPs"!

many models at few hundreds GeV scale still ok. The **pessimism on WIMPs is not driven by IDM**. If interested in pursuing a WIMP search program independently from negative results of colliders and DD, there is plenty of room in parameter space to justify it!

However, "traditional" WIMP indirect searches are limited by the systematic error with which we know (or can know, even in principle!) the "backgrounds" (*astrophysical signals*)

A commendable effort consists in "trying to squeeze the best we can", with (sometimes computationally painful) theoretical improvements.

An important comment (of interest for PNHE)

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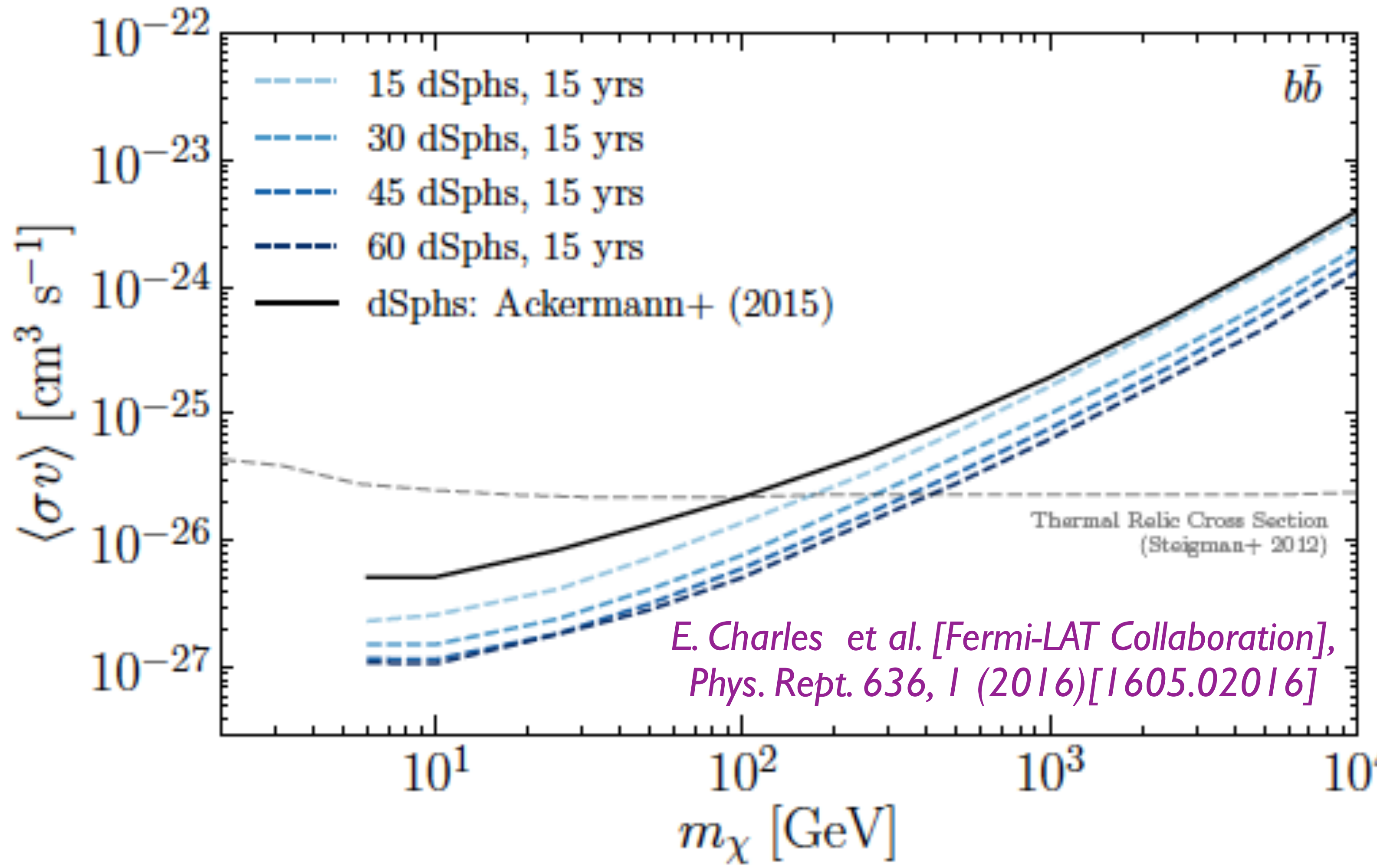
i.e. WIMP IDM searches are not dead
but the ***"return"*** *in explored parameter space over the* ***"investment"*** *(theory and experiments) is shrinking*

Take advantage of the existing/planned, ex. 1

Surveys (e.g. LSST) could discover **hundreds (?) of new Dwarf Spheroidals** even assuming only ~60 with acceptable determination of DM abundance/J-factor, plus ~8 more years of Fermi data taking, improvement of a factor of 2-5 expected by the end of Fermi lifetime

- should allow e.g. definitive check of WIMP DM interpretation of the Gal. Center excess
- eventually (already now?) **background limited**, e.g. uncertainty in diffuse flux & unresolved sources along the l.o.s. (interest in alternative, data-driven techniques, see e.g.…)
- further **refinements in J-factor** determinations from **surveys** (shrinking errors)

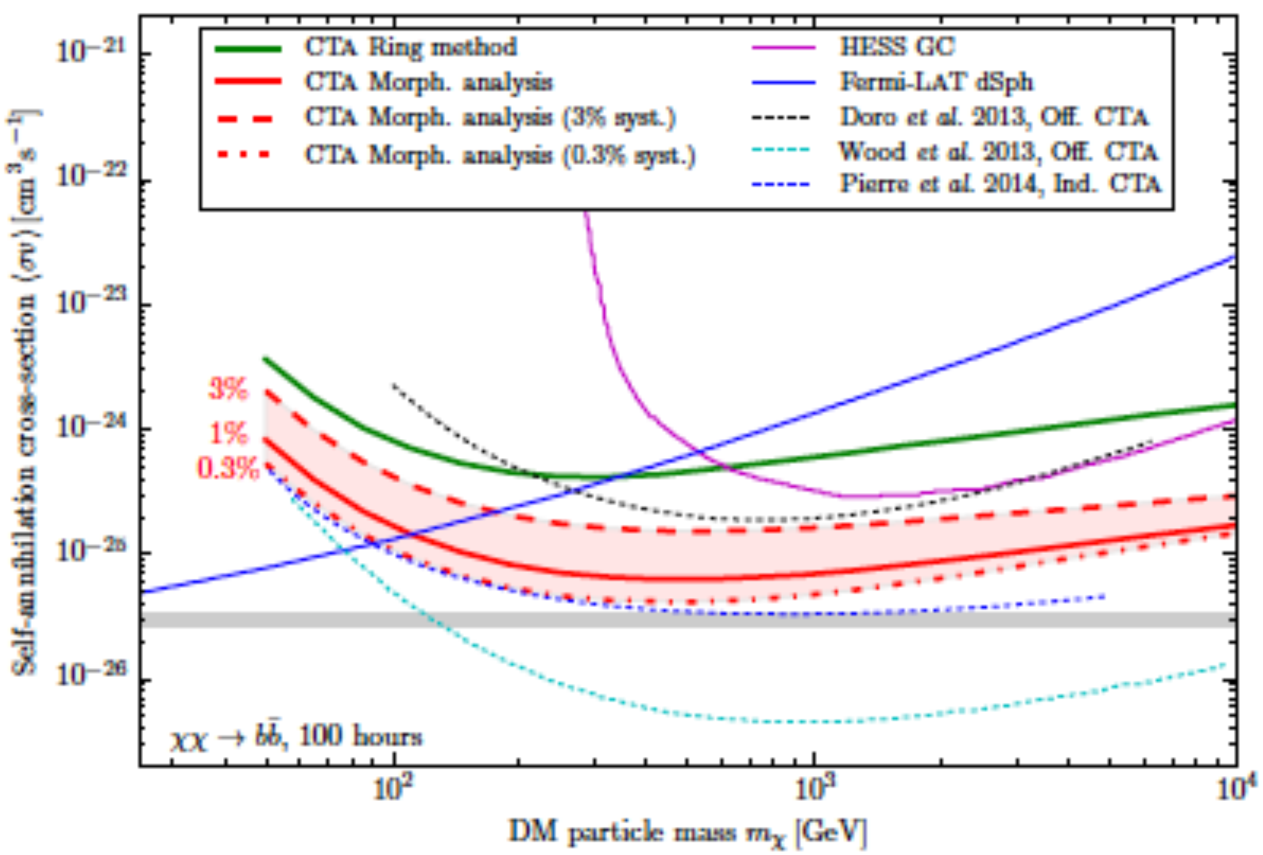


E. Charles et al. [Fermi-LAT Collaboration], Phys. Rept. 636, 1 (2016)[1605.02016]

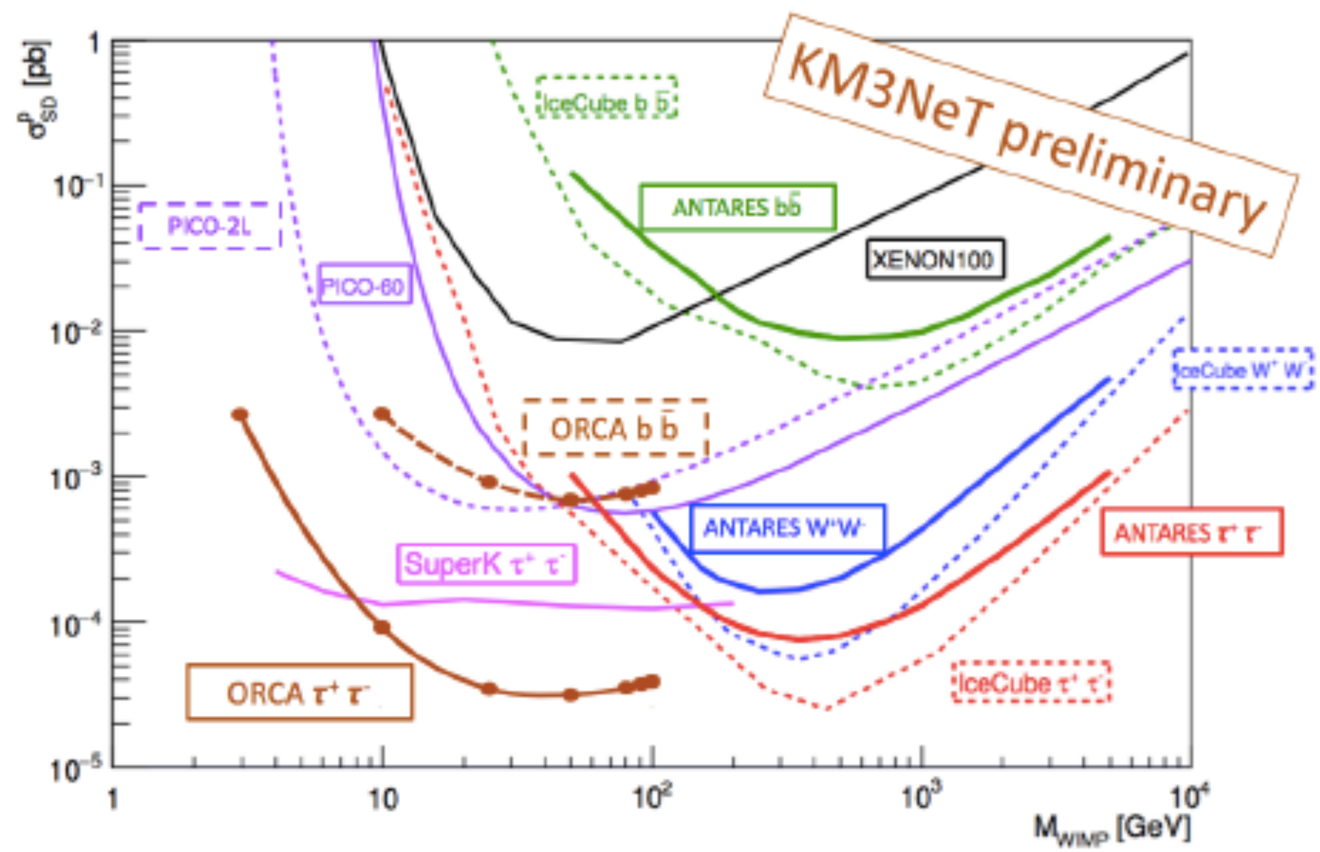
see talk by F. Calore for more details

Take advantage of the existing/planned, ex. II

will be complemented by **CTA**, which will make us access to ~"vanilla" WIMP x-sections in (multi)TeV mass range; improved sensitivity to WIMP spin-dependent cross section at low masses via the **ORCA/PINGU** ν telescopes low energy extension (ν's from the sun from WIMP capture and annihilation)…



H. Silverwood, C. Weniger, P. Scott and G. Bertone,
"A realistic assessment of the CTA sensitivity to dark matter annihilation,"
JCAP 1503, 055 (2015)



P. Coyle [KM3NeT Collaboration],
"KM3NeT-ORCA: Oscillation Research with Cosmics in the Abyss,"
J. Phys. Conf. Ser. 888, no. 1, 012024 (2017)
[1701.01382]

If not WIMP, what else?

We cannot give up on (meta)stability if we want DM. Relax the condition of relic being in **equilibrium with SM** in the early universe.

Alone, this likely explains negative results at LHC, see for instance:

F. Kahlhoefer, "On the LHC sensitivity for non-thermalised hidden sectors," 1801.07621

"under rather general assumptions, *hidden sectors that never reach thermal equilibrium in the early Universe are also inaccessible for the LHC [...]* particles that can be produced at the LHC must **either** have been in **thermal equilibrium** with the Standard Model at some point **or** must be **produced via the decays of another** hidden sector **particle that has been in thermal equilibrium**"

whenever $\Gamma(T) < H(T) = \sqrt{\frac{4\pi^3 g_*}{45}}\frac{T^2}{M_{\rm pl}}$ where $\Gamma \equiv \langle \sigma v \rangle n^{\rm eq} = \int \frac{N_c\, s^2\, K_1(\sqrt{s}/T)}{4\pi^2\, T^2}\sigma(\sqrt{s})\, {\rm d}\sqrt{s}\,,$

It turns out that $N_{\rm LHC} = \int {\rm d}\sqrt{s}\, \frac{{\rm d}x}{x} f_1(x)\, f_2\left(\frac{s}{s_{\rm tot}\, x}\right) \frac{2\,\mathcal{L}\sqrt{s}}{s_{\rm tot}}\sigma(\sqrt{s})$ is negligible

While not being a water-proof theorem (e.g. standard cosmology valid up to EW temperatures assumed), it is a valid guide in how to move beyond

E.g.: Feebly interacting DM (FIMPs)

Usually, name given to DM produced via processes (possibly involving new mediators) which are not fast enough to attain equilibrium with SM, notably:

*1) Decays of BSM particles, themselves either at equilibrium **(super-WIMPs)** or not*

Typically associated to non-negligible velocity dispersion of the daughter particles, i.e. DM is not as "cold" as in WIMP scenarios

*2) "Inefficient" 2→2 collisions from bath into DM/BSM **(freeze-in)***

Like a "suppressed" WIMP scenario: It is harder to compute the relic abundance & more model dependent. But there are efforts in easing that task! E.g. *G. Bélanger, F. Boudjema, A. Goudelis, A. Pukhov and B. Zaldivar, "micrOMEGAs5.0 : freeze-in," 1801.03509*

*3) "Dark freeze-out", notably via **cannibalism** (e.g. 3→2 processes)*

It has been realized for instance that 2) and/or 3) are almost the unavoidable choice to realize **strongly self-interacting DM**, see *N. Bernal, X. Chu, C. Garcia-Cely, T. Hambye and B. Zaldivar, "Production Regimes for Self-Interacting Dark Matter," JCAP 1603, 018 (2016) [1510.08063]*

And why would you want to do that? Either for theory reasons (e.g. path B), or…

One reason: DM "problems" at small scales

naive comparison data vs DM-only simulation shows disagreements!

J. S. Bullock and M. Boylan-Kolchin, "Small-Scale Challenges to the ΛCDM Paradigm," Ann. Rev. Astron. Astrophys. 55, 343 (2017) [1707.04256]

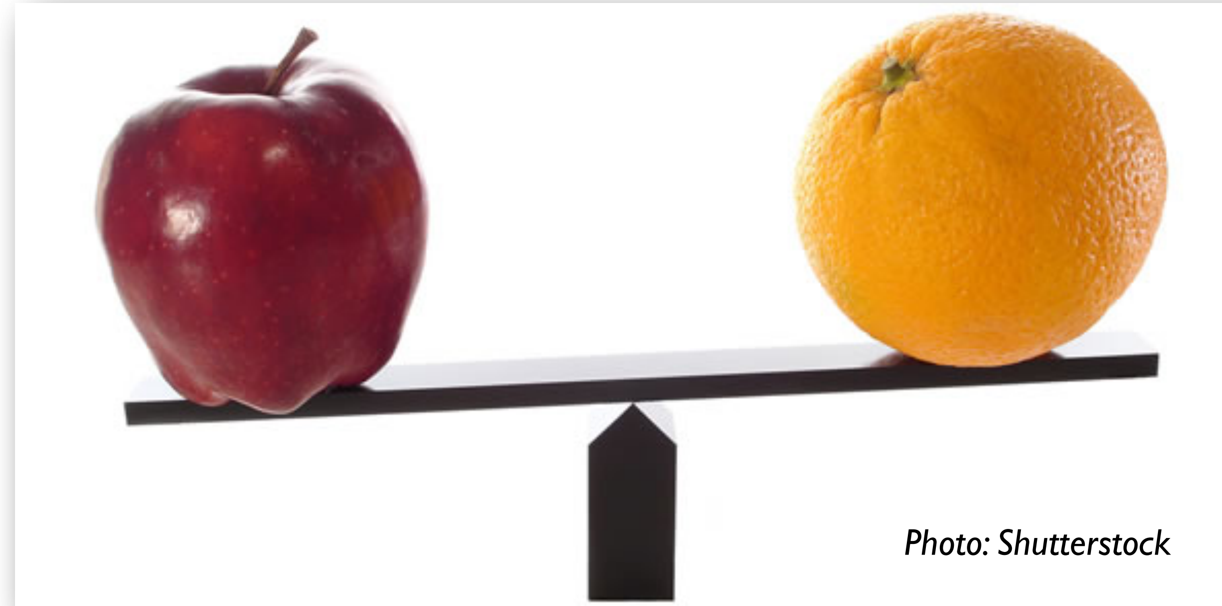


Photo: Shutterstock

(In?)complete list of claimed problems

- **Missing satellite** problem: *Many more halos than Galaxies*
- **Cusp/core** controversy: *too little DM and too cusp in DM dominated Galaxies*
- **Too big to fail**: *"intermediate" mass halos without apparent associated Galaxy?*
- **Diversity problem**: *galaxies with similar associated halo mass (proxy) remarkably diverse*
- **Tully-Fisher relation** (& relatives): *tight correlation between baryonic & "halo" properties*
- **Satellite alignment planes**

Possible Solutions

Option nr. 1

Baryons act non-trivially (+observations → interpretation issues)

Option nr. 2

Exotics: "special DM properties"?

Lately… Dark Forces are popular

In particular, "problems" could be solved via strong DM-DM elastic scattering (**$\sigma/m \sim 1$ cm²/g=1.8 b/GeV**)

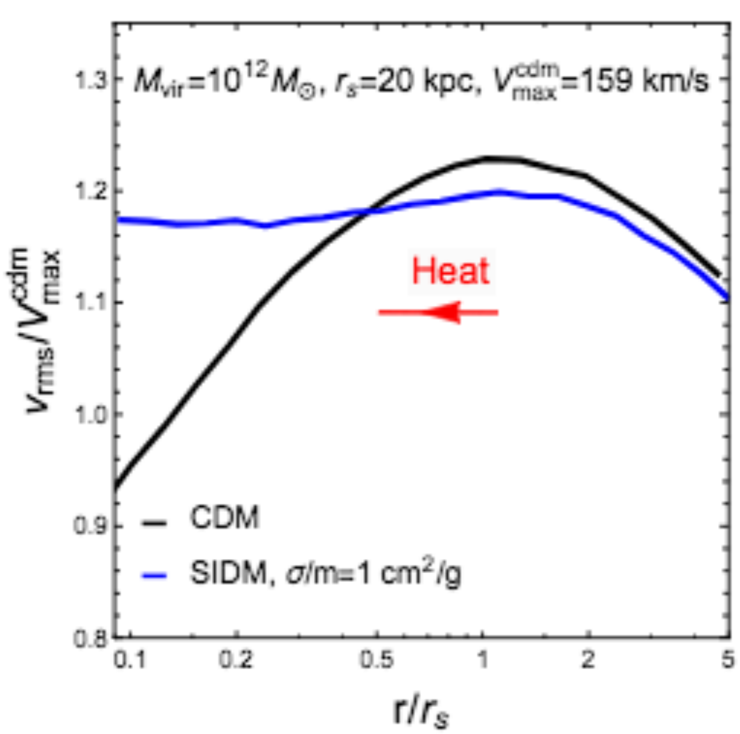
Idea of **Self-Interacting DM** goes back to:

D. N. Spergel & P. J. Steinhardt, "Observational evidence for selfinteracting cold dark matter," PRL 84, 3760 (2000) [astro-ph/9909386]

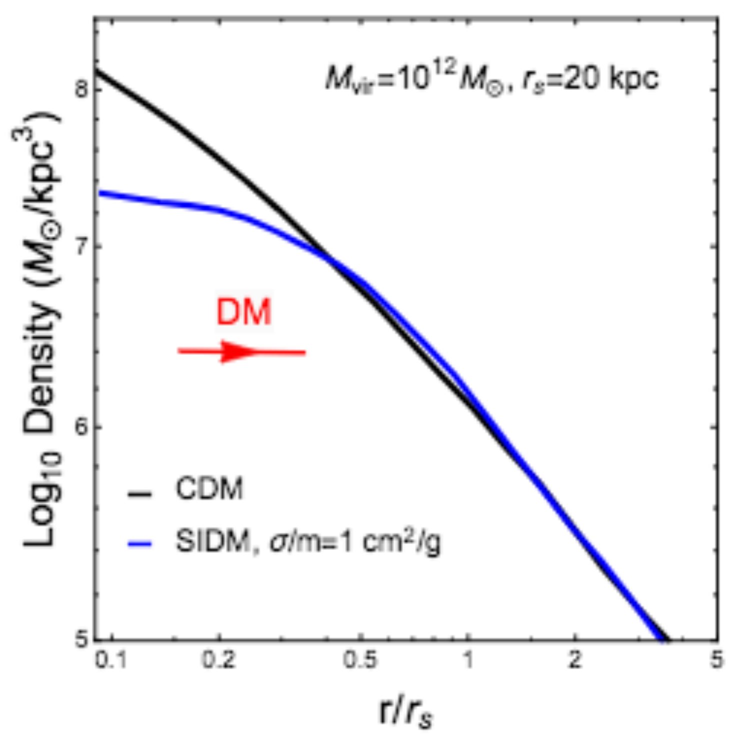
Major revival in recent years, for a review & refs.

S. Tulin and H. B. Yu, "Dark Matter Self-interactions and Small Scale Structure," Phys. Rept. 730 , 1 (2018) [1705.02358]

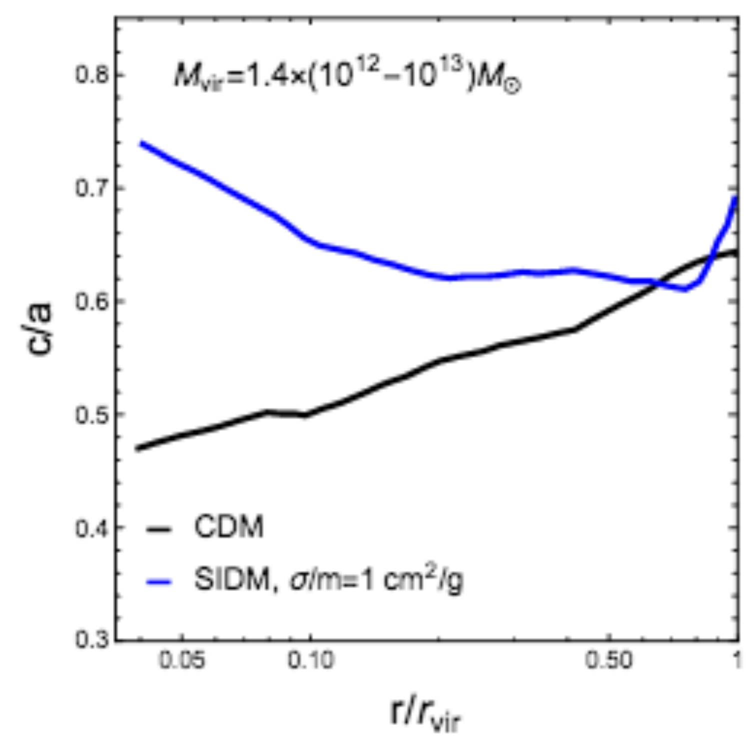
In inner halos, scatterings lead to DM "thermalization"



more uniform & isotropic v-dispersion



cored profiles & suppressed DM density



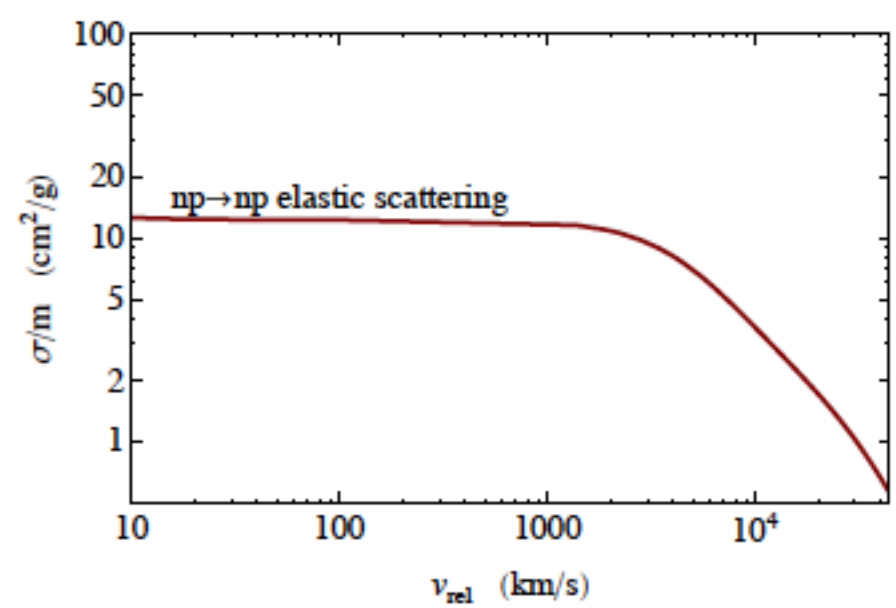
more spherical inner halos

Observational constraints require σ=σ(v)

Positive observations	σ/m	v_{rel}	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1$ cm^2/g	30 – 200 km/s	Rotation curves	[102, 116]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6$ cm^2/g	50 km/s	Stellar dispersion	[110]
Local Group	$\gtrsim 0.5$ cm^2/g	50 km/s	Stellar dispersion	[111]
Cores in clusters	~ 0.1 cm^2/g	1500 km/s	Stellar dispersion, lensing	[116, 126]
Abell 3827 subhalo merger	~ 1.5 cm^2/g	1500 km/s	DM-galaxy offset	[127]
Abell 520 cluster merger	~ 1 cm^2/g	2000 – 3000 km/s	DM-galaxy offset	[128, 129, 130]
Constraints				
Halo shapes/ellipticity	$\lesssim 1$ cm^2/g	1300 km/s	Cluster lensing surveys	[95]
Substructure mergers	$\lesssim 2$ cm^2/g	$\sim$ 500 – 4000 km/s	DM-galaxy offset	[115, 131]
Merging clusters	$\lesssim$ few cm^2/g	2000 – 4000 km/s	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
Bullet Cluster	$\lesssim 0.7$ cm^2/g	4000 km/s	Mass-to-light ratio	[106]

In particular, clusters are in much better agreement with pure CDM predictions (some improvement only for 1 o.o.m. smaller cross sections)

Decreasing with relative velocity (as in nucleon scattering)



Do models with 1 dof work? Not really!

$$\frac{\sigma}{m} \simeq 1\frac{\mathrm{cm}^2}{\mathrm{g}} \simeq \left(\frac{60}{\mathrm{MeV}}\right)^3$$

One can in principle get large σ with a model as simple as a self-interacting scalar field

$$\mathcal{L} = -\frac{g}{4}\phi^4 \qquad \sigma_{\phi\phi} \simeq \frac{g^2}{64\pi m_\phi^2}$$

e.g. OK for *g~1* and *m~10 MeV*

note how light…

M. C. Bento, O. Bertolami, R. Rosenfeld and L. Teodoro, Phys.Rev. D 62, 041302 (2000) [astro-ph/0003350]

v-dependence require at least 2 dofs/scales!

E.g. scalar interaction with a light mediator ϕ

$$\mathcal{L}_{\rm int} = g_\chi \bar{\chi}\chi\phi$$

yielding a Yukawa potential

$$V(r) = \pm\frac{\alpha_\chi}{r}\exp(-m_\phi r)$$

and x-section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha_\chi^2 m_\chi^2}{[m_\chi^2 v_{\rm rel}^2 \sin^2(\theta/2) + m_\phi^2]^2}$$

Systematic exploration of regimes for light mediators

S. Tulin, H. B. Yu and K. M. Zurek, PRD 87, 115007 (2013)[1302.3898]

Idea of "Dark photons"!

New forces in common with scenarios of type B as well

A generic lesson from non-thermal DM: mass range broadens, pheno too!

- Can have very heavy DM via freeze-in, e.g. ~10 PeV-scale (usually metastable)

What's the best probe of that? Currently, ν telescopes!

A. Esmaili, S. K. Kang and P. D. S., "IceCube events and decaying dark matter: hints and constraints," JCAP 1412, 054 (2014) [1410.5979]

Possibly, in the future, ground-based gamma-ray telescopes for ~100 TeV range, type LHAASO

A. Esmaili and P. D. S., "Gamma-ray bounds from EAS detectors and heavy decaying dark matter constraints," JCAP 1510, 014 (2015) [1505.06486]

- Can have light DM, sub-GeV scale in the problem

also true for small splittings (scenarios A3, possibly scenarios of type B…)

F. D'Eramo and S. Profumo, "Sub-GeV Dark Matter Shining at Future MeV Gamma-Ray Telescopes," Phys.Rev.Lett. 121, 071101 (2018) [1806.04745].

New, ad hoc technologies being developed in direct detection. In IDM, the soft gamma ray range remains a "juicy" almost unexplored target of opportunity (e.g. e-ASTROGAM), also for a number of astrophysical questions

X-rays: "The importance of old friends"

Desiderata:

Increased exposure, improved angular and spectral resolution (or both!), low-background orbits

T. E. Jeltema and S. Profumo, "Dark Matter Detection with Hard X-ray Telescopes," MNRAS 421, 1215 (2012) [1108.1407]

Why?

E.g. to look for decay lines possibly associated to sterile ν's $\nu_s \to \nu + \gamma$

(independently of what you think, the 3.5 keV story is a "proof of principle" of a discovery!)

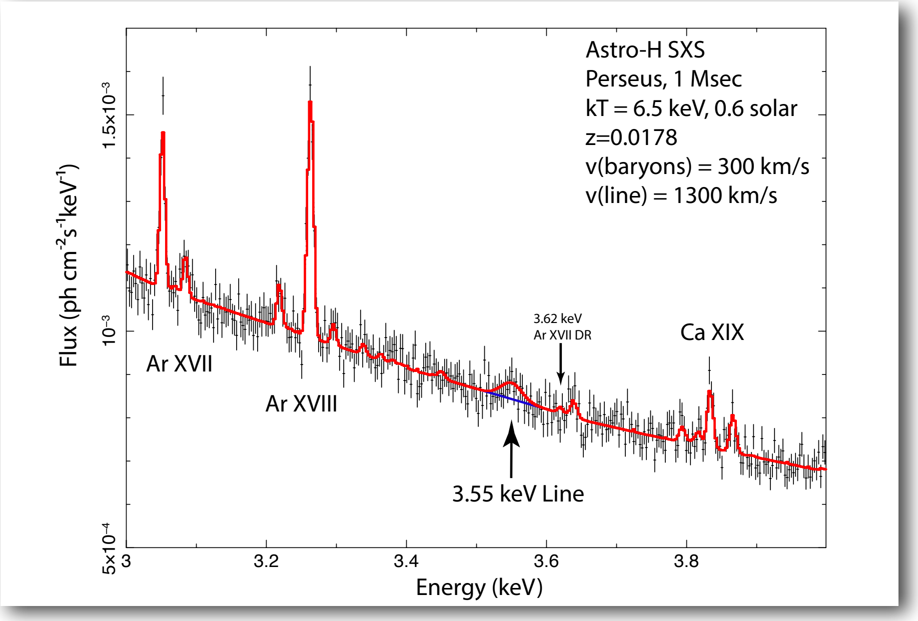
Checks with sufficient resolution & sensitivity:

whether the line weakens toward the edges of a cluster matching predicted DM density profiles.

if line widths broad, as from Doppler broadening of virialised halos, or narrow as from atomic transitions

E. Bulbul et al., "Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters," ApJ 789 (2014) 13 [1402.2301]

A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, "An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster," 1402.4119, PRL 113 (2014) 251301



But also to check for de-excitation lines in DM models with multiple states with small splitting, e.g.

Finkbeiner & Weiner ``X-ray line from exciting dark matter," Phys. Rev. D 94, no. 8, 083002 (2016) [1402.6671]

X-rays: "The importance of old friends", cont'd

axion-like particles (mix with photons in B-fields) in compact objects; astro advantage due to large coh. lengths

$$\frac{P_{\gamma\to a}^{\text{laboratory experiments}}}{P_{\gamma\to a}^{\text{celestial objects}}} \simeq \left(\frac{B_{\rm lab}}{B}\right)^2 \left(\frac{R_{\rm lab}}{R}\right)^2 \simeq \left(\frac{R_{\rm obj}}{R_s}\right)^2 \frac{B_{\rm lab}^2 R_{\rm lab}^2}{c^4/8G} \ll 1$$

D. Chelouche et al. "Spectral Signatures of Photon-Particle Oscillations from Celestial Objects," ApJ. Suppl. 180, 1 (2009) [0806.0411]

Simple Schrödinger-like mixing equation leads to rich & complicated pheno due to medium properties

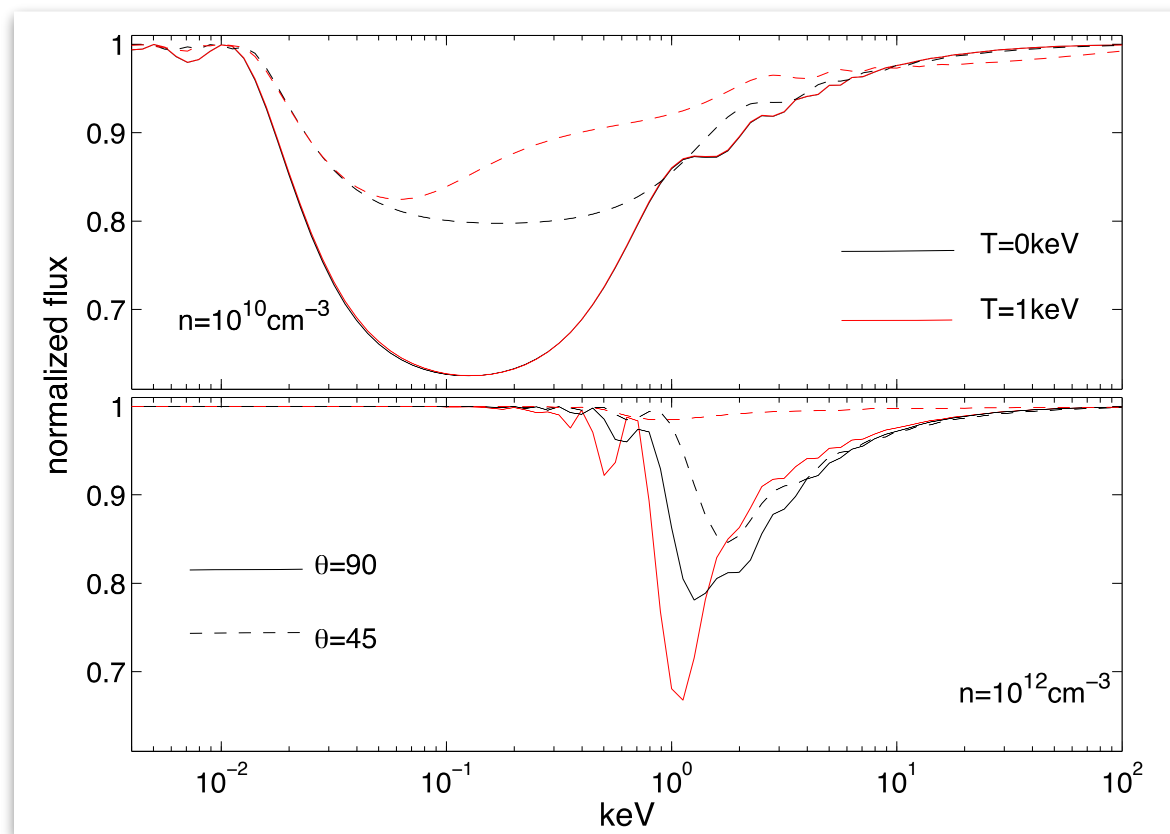
$$\left(\omega - i\partial_\gamma + \Delta\right)\mathfrak{A} = 0$$

e.m. field components & axion field (acting as "additional polarization state")

$$\begin{bmatrix} A_\perp \\ A_\parallel \\ a \end{bmatrix}$$

Polarization-dependent refraction indexes, mass (& effective plasma mass) term, Faraday rotation, birefringence term…

$$\begin{vmatrix} \Delta_{\perp\perp} & \Delta_{\perp\parallel} & 0 \\ \Delta^\star_{\perp\parallel} & \Delta_{\parallel\parallel} & \Delta_{\parallel a} \\ 0 & \Delta_{\parallel a} & \Delta_{aa} \end{vmatrix}$$

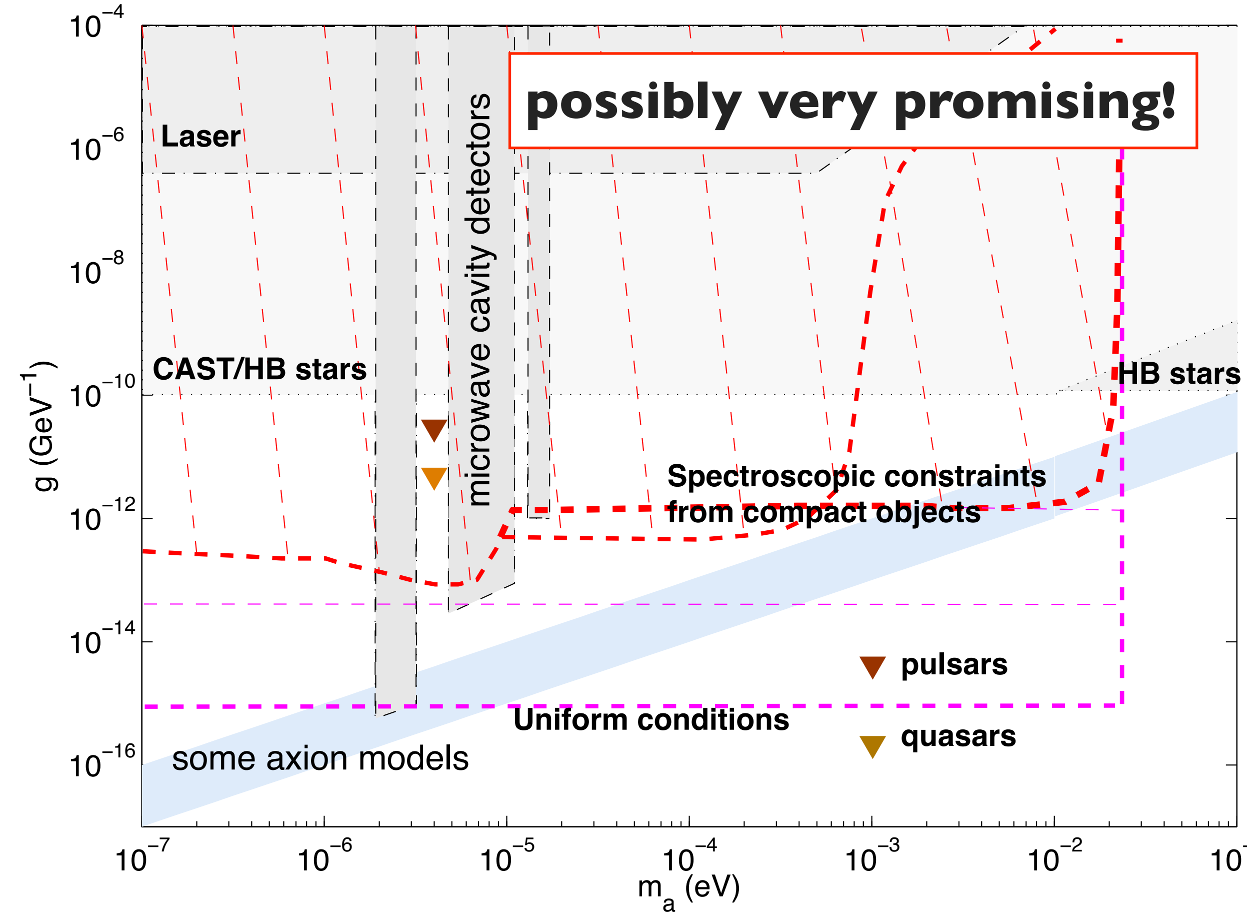


ex.: **X-ray binary** "conversion dips" at different n & T

X-rays: "The importance of old friends", cont'd

Challenges:

1) to see them (sensitivity, resolution, etc.)
2) to identify them as ALP-induced (dependence of rest-equivalent width/signal from variables is different from corresponding atomic lines: peculiar shape and variability features expected!)



Or "simply" for good-old tracing purposes, notably in combination with lensing, also useful to check ideas related to dark forces, e.g.

T. Sepp et. al. "Simulations of Galaxy Cluster Collisions with a Dark Plasma Component" arXiv:1603.07324

When don't know what to do, general rule: go for something unexplored!

Take the **opening of the Gravitational Wave window**

Although almost ruled out, revisiting primordial black hole as DM candidates was a healthy exercise!

GW170817 may also remembered as a turning point (blow?) in modified gravity research

Similarly, sizably discovery potential associated to opening new windows, like

21 cm astrophysics see e.g. some exploratory study in *V. Poulin, J. Lesgourgues, PS, JCAP 1703, 043 (2017) [1610.10051]*

(or the literature inspired by the putative EDGES detection)

CMB spectral distortions (e.g. via DM upscattering into states which late decays)

R.T. D'Agnolo, D. Pappadopulo and J.T. Ruderman, "Fourth Exception in the Calculation of Relic Abundances,"' Phys. Rev. Lett. 119, 061102 (2017) [1705.08450]

(Personal) Overview & Conclusions

- **"Traditional" arguments** relating the DM phenomenon to BSM physics at the EW scale **(WIMPs) have not lead to a discovery**, neither at Direct Det. nor at colliders.

- The **indirect WIMP detection** techniques have recently reached "meaningful" exploration power, **start digging into interesting parameter space**.

- **Improving on this path is possible and will be pursued**, widening the reach in parameter space (e.g. CTA, ORCA). Road ahead however uphill to reduce systematics in astro backgrounds & theory (**reduced incremental return over investment**, notably for charged CRs, which also require new x-sec measurement campaigns)

- **Alternatives (non-thermal DM candidates) are considered more** & more. More modest modeling requirements, sometimes pheno inspired. Some general trends:
  - Decaying DM more appealing
  - Lighter and heavier masses need to be looked up
  - Strong self-interacting DM, dark forces, light mediators, etc.

- Accrued **interest to significantly improve X-ray sensitivity & explore new windows**:
  - MeV gamma-ray sky
  - Gravitational Waves (e.g. "dark sector" phase transitions in the early universe)
  - 21 cm
  - CMB spectral distortions
  - $\gtrsim$100 TeV gamma-ray sky (ground based)