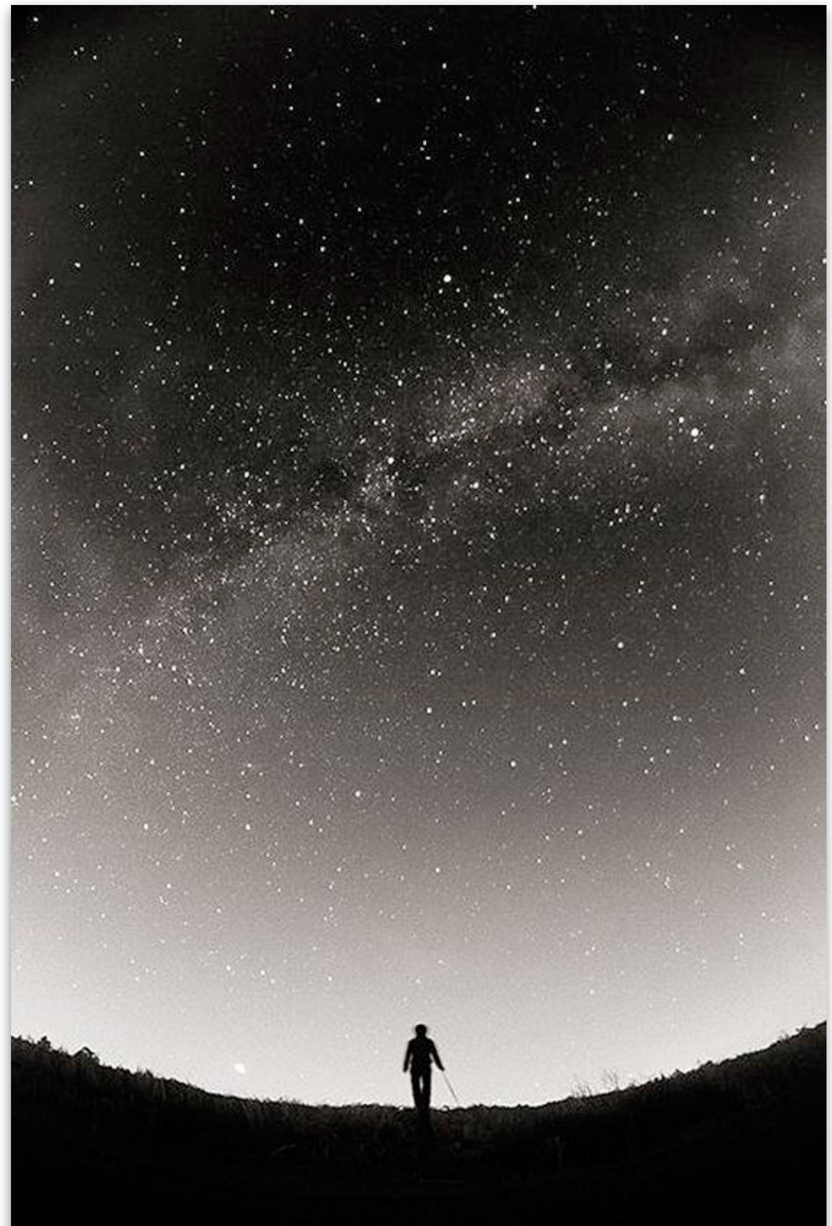
QUO VADIS, MATERIA NIGRA ?



Pasquale Dario Serpico (Annecy, France)
GSSI - 28/11/2018

Outline

Introduction

- Why is the dark matter problem peculiar & so intriguing?
- The most popular, traditional particle physics answer to DM… and its failure (till now)

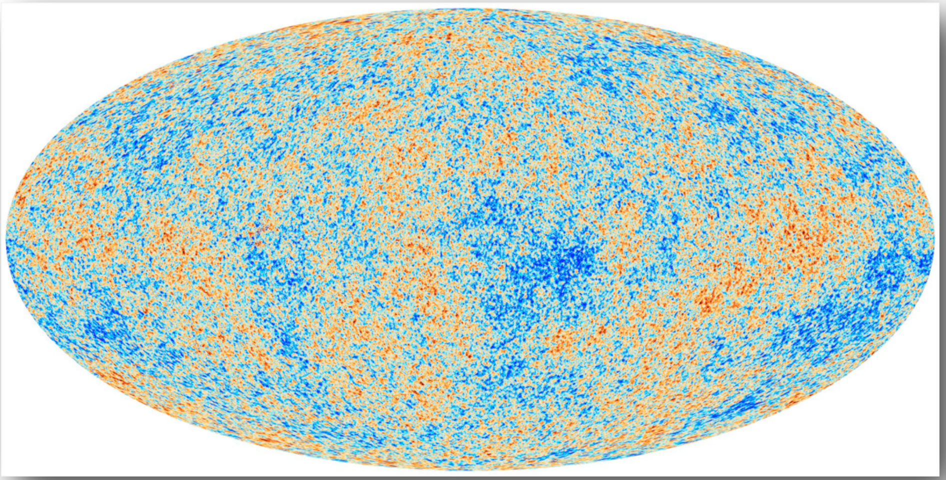
A few strategies currently pursued and their "rationale"

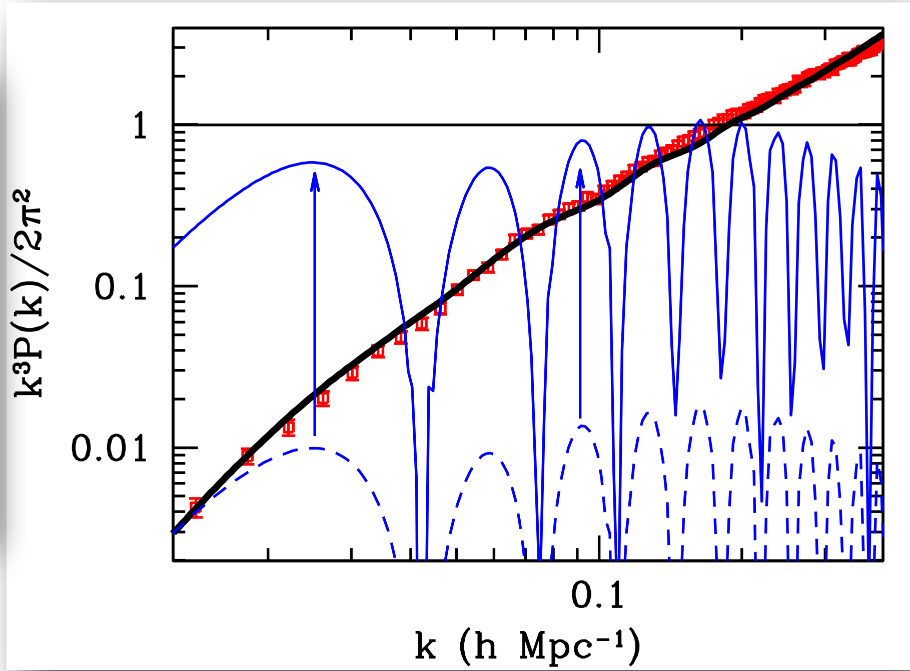
- The "small-scale", phenomenological inspiration for model building
- The "large σ way": some implications via a couple of production mechanisms
- Some "quantum" alternatives

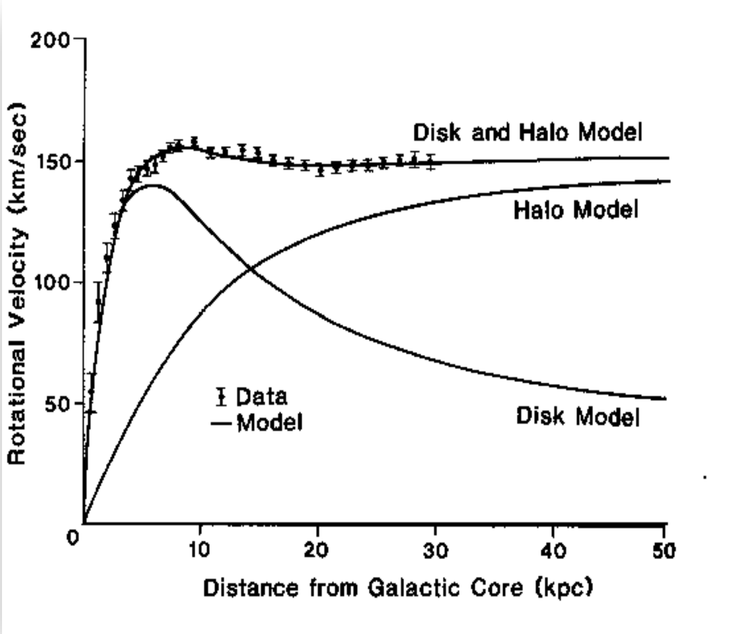
Some perspectives & outline

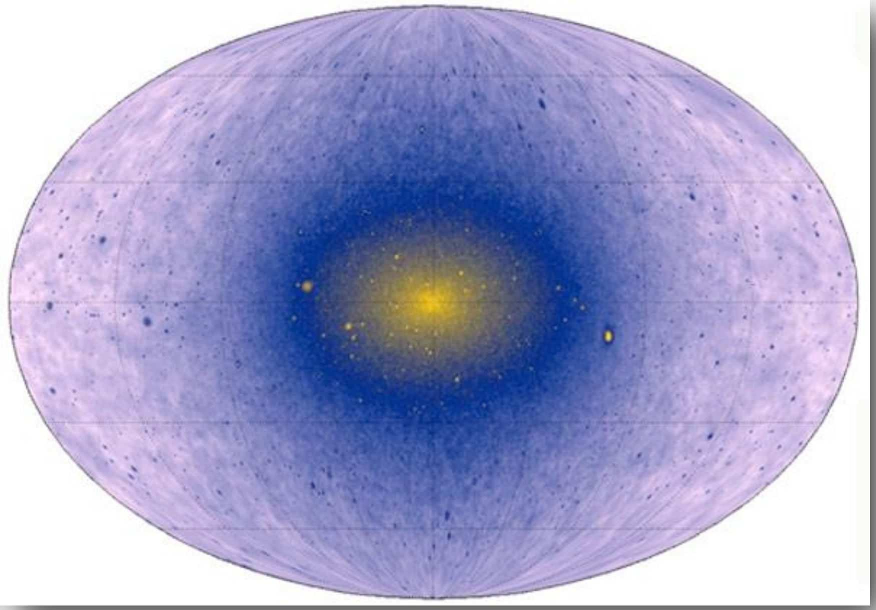
Disclaimer: I'll present my understanding of the current context & (some) directions of research.
Please do not hold me responsible for the research choices & tastes of (some) colleagues.

The “Dark Matter” Phenomenon









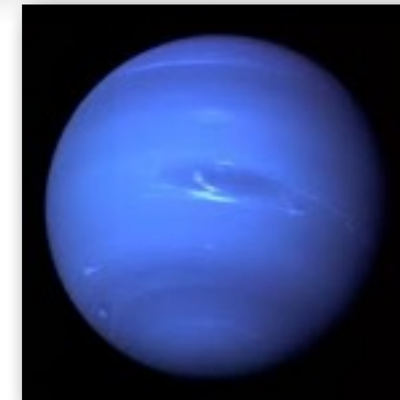
A number of astrophysical & (above all!) cosmological observations only makes sense if adding (≧1) extra ingredient beyond current model of particle physics + general relativity

“Dark Matters” common in astrophysics

Should you be shocked that one infers the presence of “extra stuff” only via gravity?

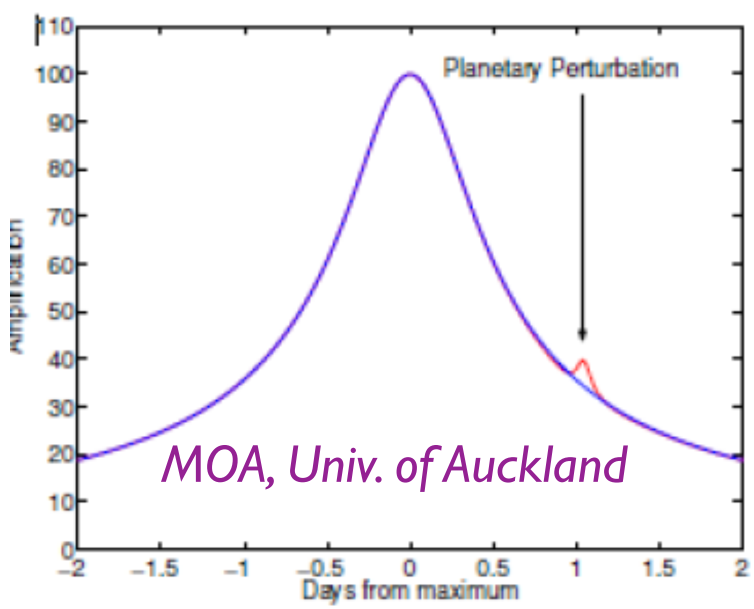
Le Verrier and independently Adams interpreted irregularities in Uranus orbit as due to perturbation by a yet unknown planet, calculating its orbital elements “by inversion”

On September 24, 1846 Galle found that “the planet whose place you [Le Verrier] have [computed] *really exists*” (“indirect DM detection”)



Indirect detection of Solar System DM by Voyager 2

Microlensing routinely used to discover e.g. brown dwarfs (or exoplanets!)



MOA, Univ. of Auckland

Large fraction of the “baryonic budget” is missing (probably hidden in warm-hot intergalactic medium), looked for with SZ effect, see e.g.

A. de Graaff, Y. C. Cai, C. Heymans and J. A. Peacock, 1709.10378

Inferring the existence of objects from their gravitational effect is familiar in astrophysics!

Crucial role of cosmological evidence!

this is the new element, compared to the other "astro dark stuff"!

I. *Evidence from exact solutions or linear perturbation theory applied to simple physical systems (gravity, atomic physics...): credible and robust!*

II. *Can be at least effectively described as an additional <u>matter</u> species.*

III. *Tells us that the (largest fraction of) required dark matter is non-baryonic, rather than brown dwarf stars, planets, etc.*

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III. ***Tells us that the (largest fraction of) required dark matter is non-baryonic, rather than brown dwarf stars, planets, etc.***

This implies that <u>DM requires new physics,</u> beyond the theories known today. Only a handful of similar indications exists: explains the interest of particle physicists!

<u>Problem</u>

Gravity is universal: no particle identification! **discovery via other channels** is needed **to clarify <u>particle physics</u>** framework (*if not merely gravitationally coupled*)
But **what to look for is model-dependent!**

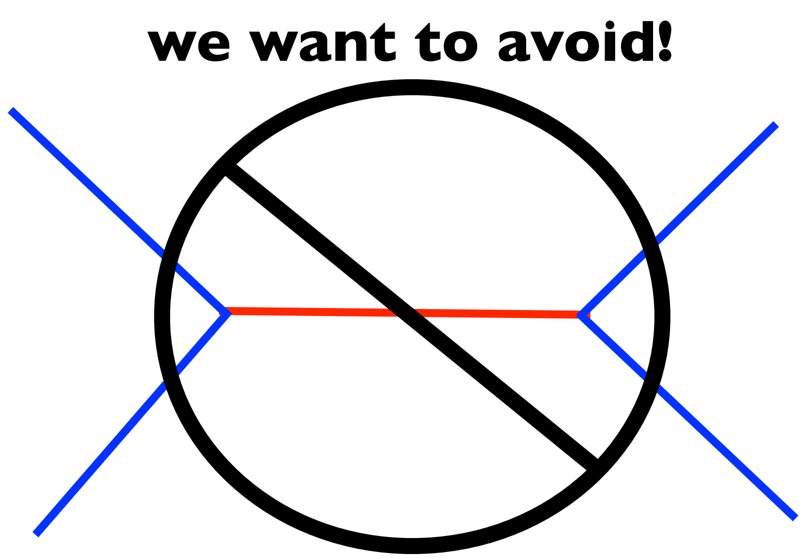
“Traditional” link DM-particle physics

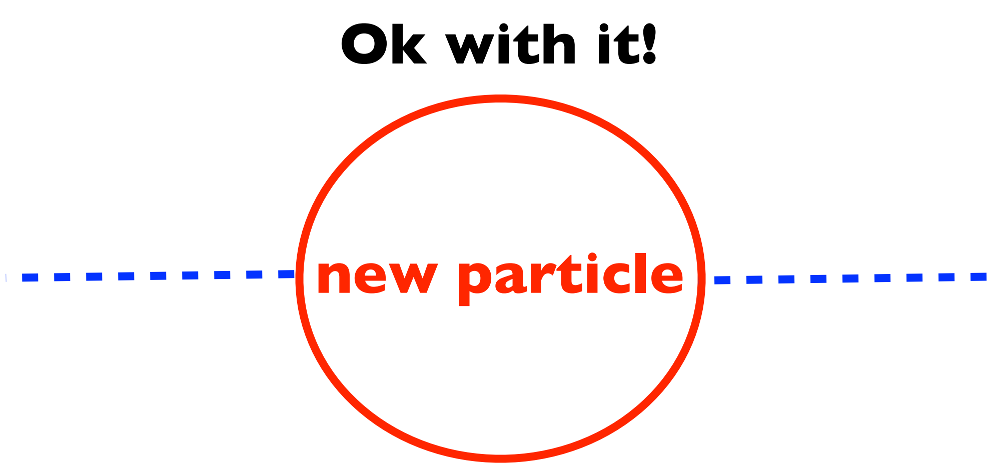
Strong <u>prior for TeV-scale BSM (with SM-like couplings)</u> **to cure “the hierarchy problem”:**

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!





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

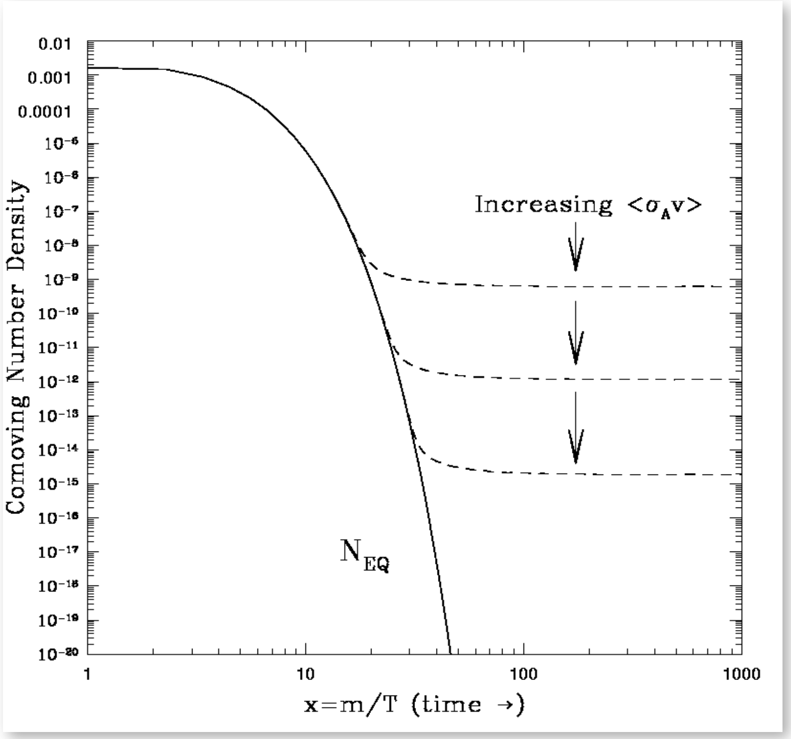
Cosmology tells us that the early universe was a hot plasma, with all "thermally allowed" species populated. Notion tested up to T~ few MeV (BBN, cosmo ν's):

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...



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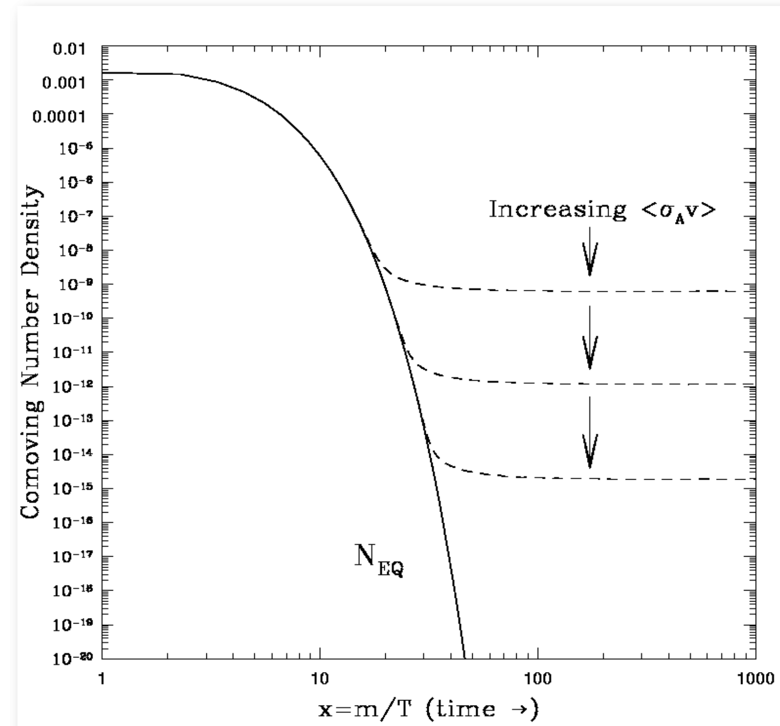
$$\frac{dn}{dt} + 3H\,n = -\langle\sigma v\rangle[n^2 - n_{\rm eq}^2]$$

Set $Y \equiv (n/s)$ [$s \sim T^3$ is the entropy density] & start from $Y = Y_{eq} \sim e^{-m/T}$

$$\frac{dY}{dx} = -\frac{x\,s\langle\sigma v\rangle}{H(T=m)}[Y^2 - Y_{\rm eq}^2]$$



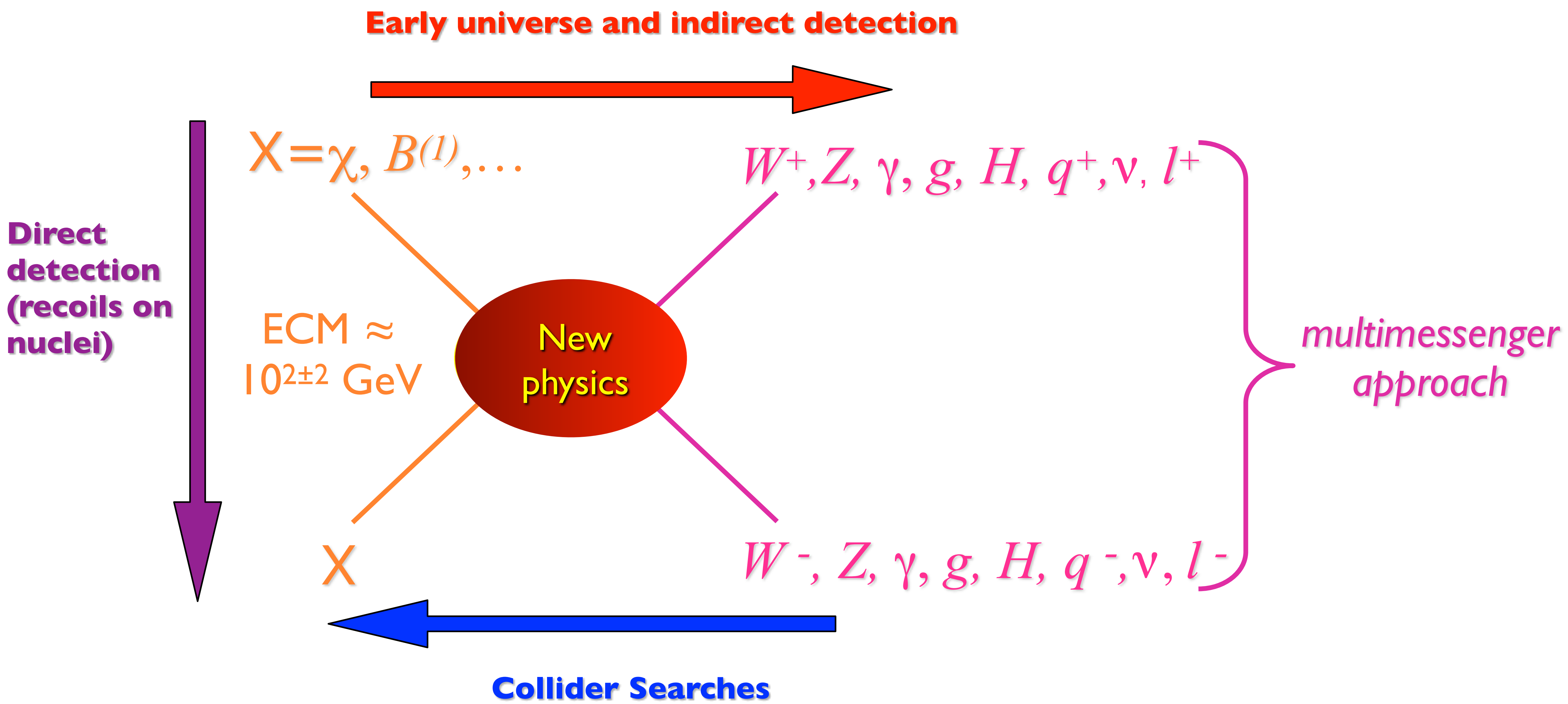
Textbook calculation yields the current average cosmological energy density

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

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

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

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

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.

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

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

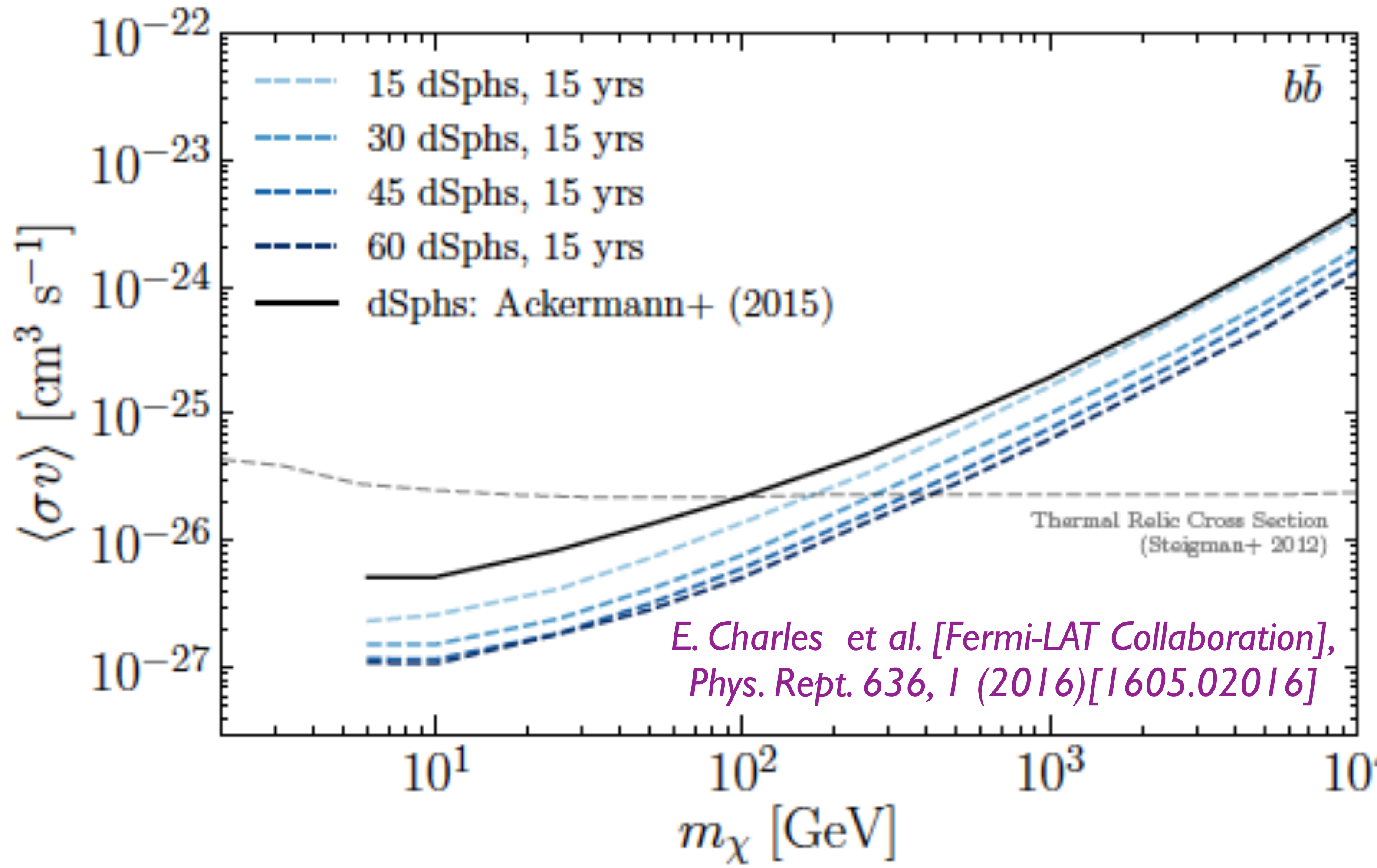
Surveys (e.g. LSST) could discover **hundreds (?) of new Dwarf Spheroidals.** Even assuming only ~60 with acceptable determination of DM distribution ("J-factors"), plus ~8 more years of Fermi data taking, improvement of a factor of 2-5 expected by the end of Fermi lifetime

- 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

F. Calore, P.D. Serpico, B. Zaldivar JCAP 10 (2018) 029 [1803.05508]

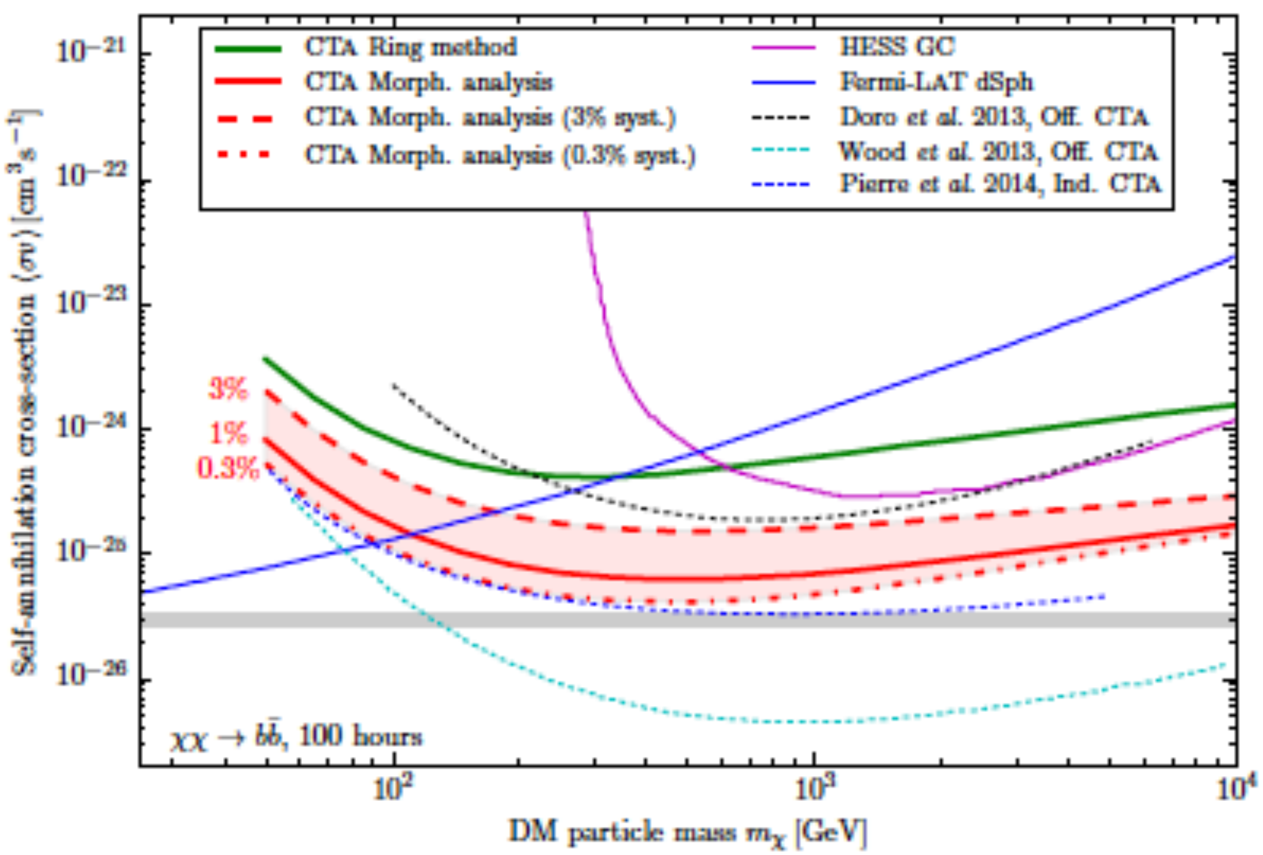
- further **refinements in J-factor** determinations from **surveys** (shrinking errors)



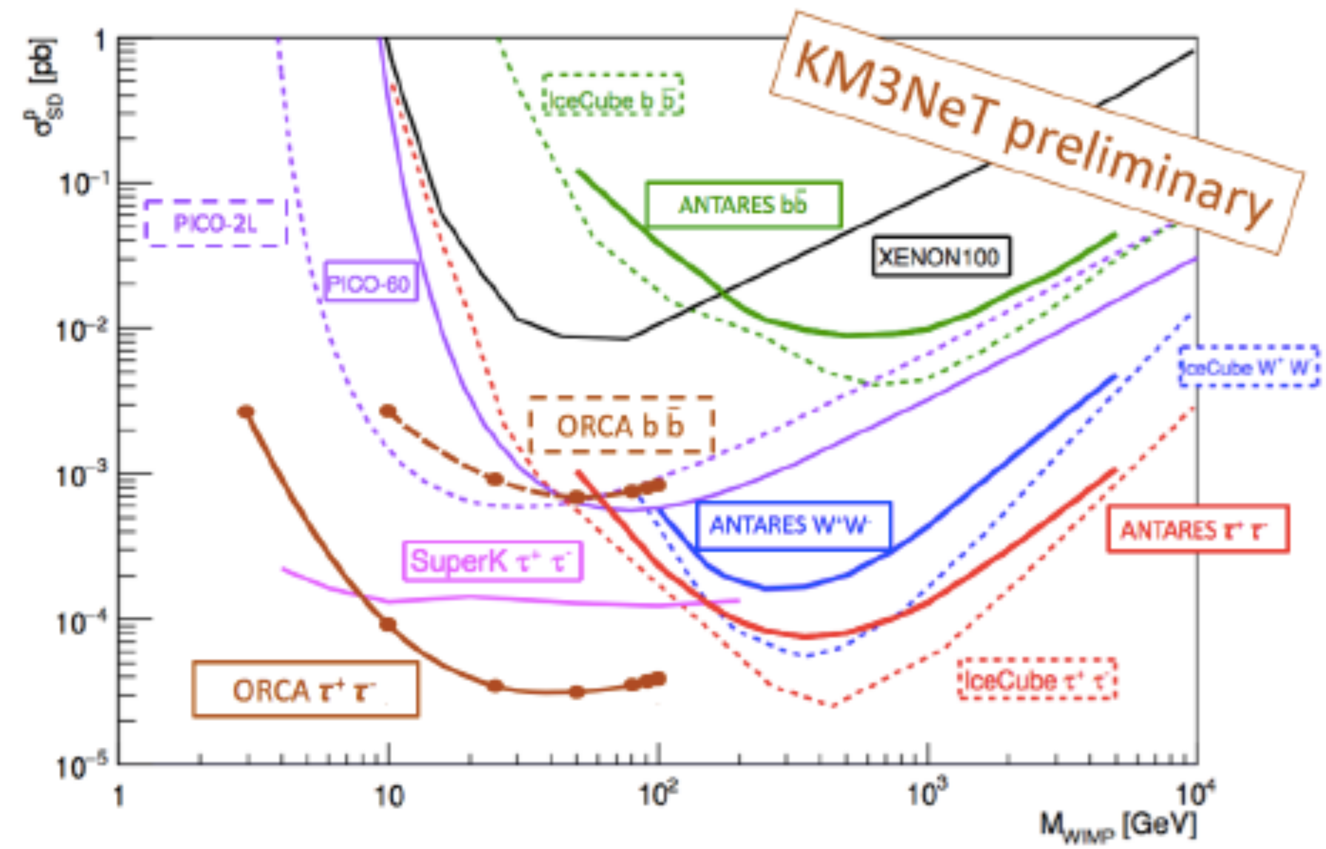
E. Charles et al. [Fermi-LAT Collaboration], Phys. Rept. 636, 1 (2016)[1605.02016]

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

Lessons

look for particles interacting “less-than-weakly” with the SM
[but not necessarily with themselves!]

Alone, this would basically explain the lack of detection at colliders and in underground experiments (not to speak of indirect detection, which is only starting to explore the WIMP region now)

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DM production mechanism becomes one meaningful classification criterion

The possibly too weak interaction with SM motivates one to look for purely gravitational signatures

Do we have any "gravitational" hint that may motivate alternative models?

Gravitational probes of DM at small scales

- Most **DM models** are degenerate in their LSS predictions, but lead to **different expectations** for structures at sufficiently **small scales** (linked to **microphysics**)
- Up to now, these scales only be probed in the **non-linear regime**, involving "virialized halos" rather than small perturbations of the homog. density field: **simulations** needed!
- Simulations can only handle in a "**first principle**" way **purely gravitational** interactions, hence robust predictions at small scales concern **DM-only** simulations.

Within these limitations, some "expectations" obtained for "Cold DM":

- Bottom-up halo assembly history & ~ ***universal properties*** (basically 1 parameter= mass)
- DM *profiles* of individual halos are ***cuspy and dense*** (density ~NFW, inner scaling $\sim r^{-1}$)
- ***Many more small halos than large ones***, with scaling $dn/dM \sim M^{-1.9}$

Problem nr. 1

we cannot "observe DM", only baryons (but for lensing reconstruction)

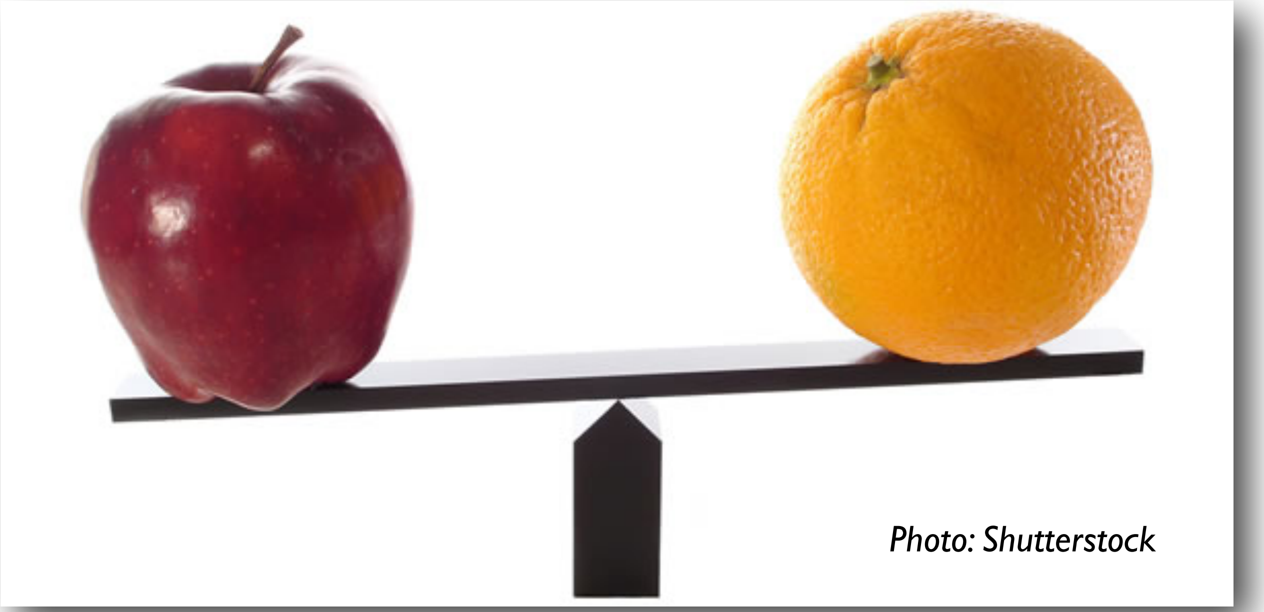
Problem nr. 2

(How) does the inclusion of baryons alters the previous expectations?

“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]



(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 (+ issues in going from observations → interpretation)

Option nr. 2

Exotics: “special” DM properties, departing from CDM paradigm

Lately… Dark Forces are popular

In particular, "problems" could be solved via strong DM-DM elastic scattering ($\sigma/m \sim 1$ cm^2/g=1.8 b/GeV)

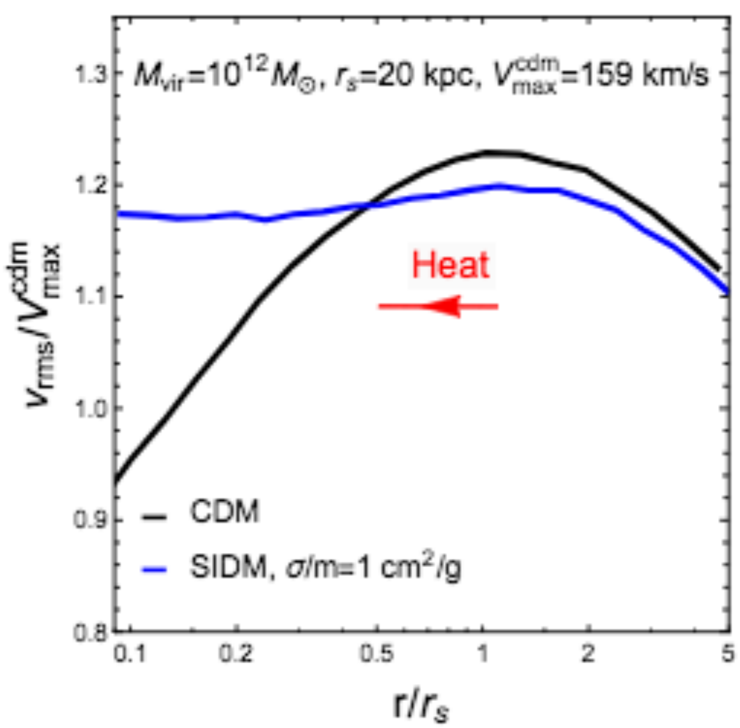
Idea of **Self-Interacting DM** goes back to:

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

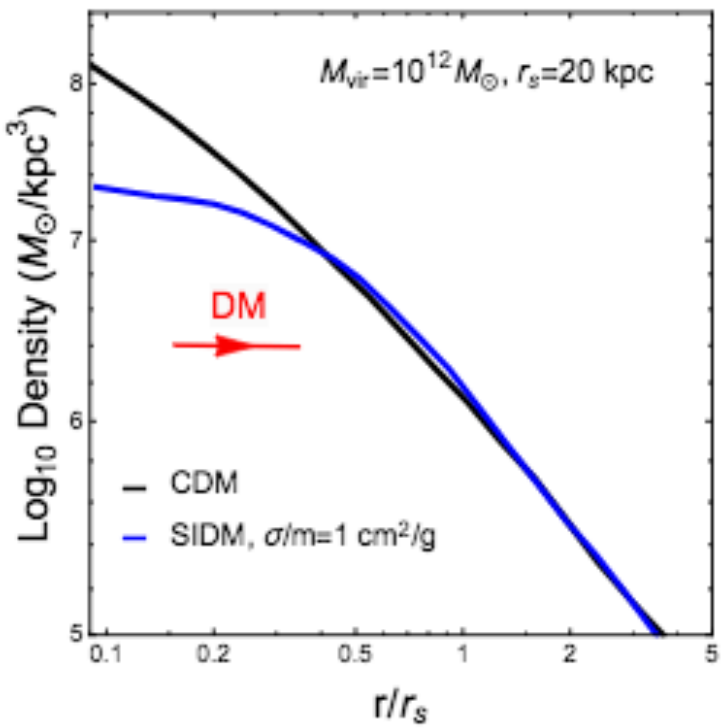
Major revival in recent years, for a review & refs.

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

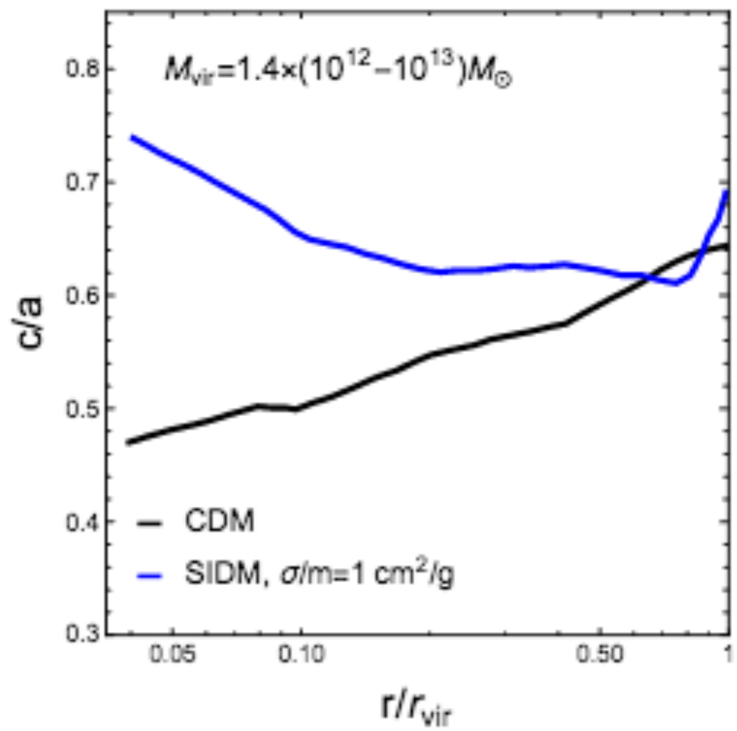
In inner halos, elastic scatterings lead to DM "thermalization" (momentum redistribution)



more uniform & isotropic v-dispersion



cored profiles & suppressed DM density



more spherical inner halos

Model building implications

It has been realized for instance that:
freeze-in *(with light mediators)*
cannibalization *(in a colder-than-SM dark sector)*
are frameworks allowing one to realize **strongly self-interacting DM**,
while fulfilling constraints.

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]

Examples of Constraints

for the light mediator case:

- BBN (must not be spoiled by disintegration byproducts of unstable mediator decay)
- CMB anisotropy not disrupted (via alterations to the ionization rate)
- direct bounds from X-ray observations
- direct detection in underground detectors

For the cannibal scenario:

- Ly-alpha (cannot be too hot!)

Additional pheno arguments may require extra ingredients in the dark sector.

Example of "new" production mechanism: Freeze-in

One usually solves the Boltzmann eq. for WIMPs (at RHS rewritten in terms of $Y=n/s$ and $x=m/T$) under the *assumption* of initial equil. abundance, $Y(x<<1)=Y_{eq}$

$$\frac{dn}{dt} + 3H\,n = -\langle\sigma v\rangle[n^2 - n_{\rm eq}^2] \qquad \frac{dY}{dx} = -\frac{x\,s\langle\sigma v\rangle}{H(T=m)}[Y^2 - Y_{\rm eq}^2]$$

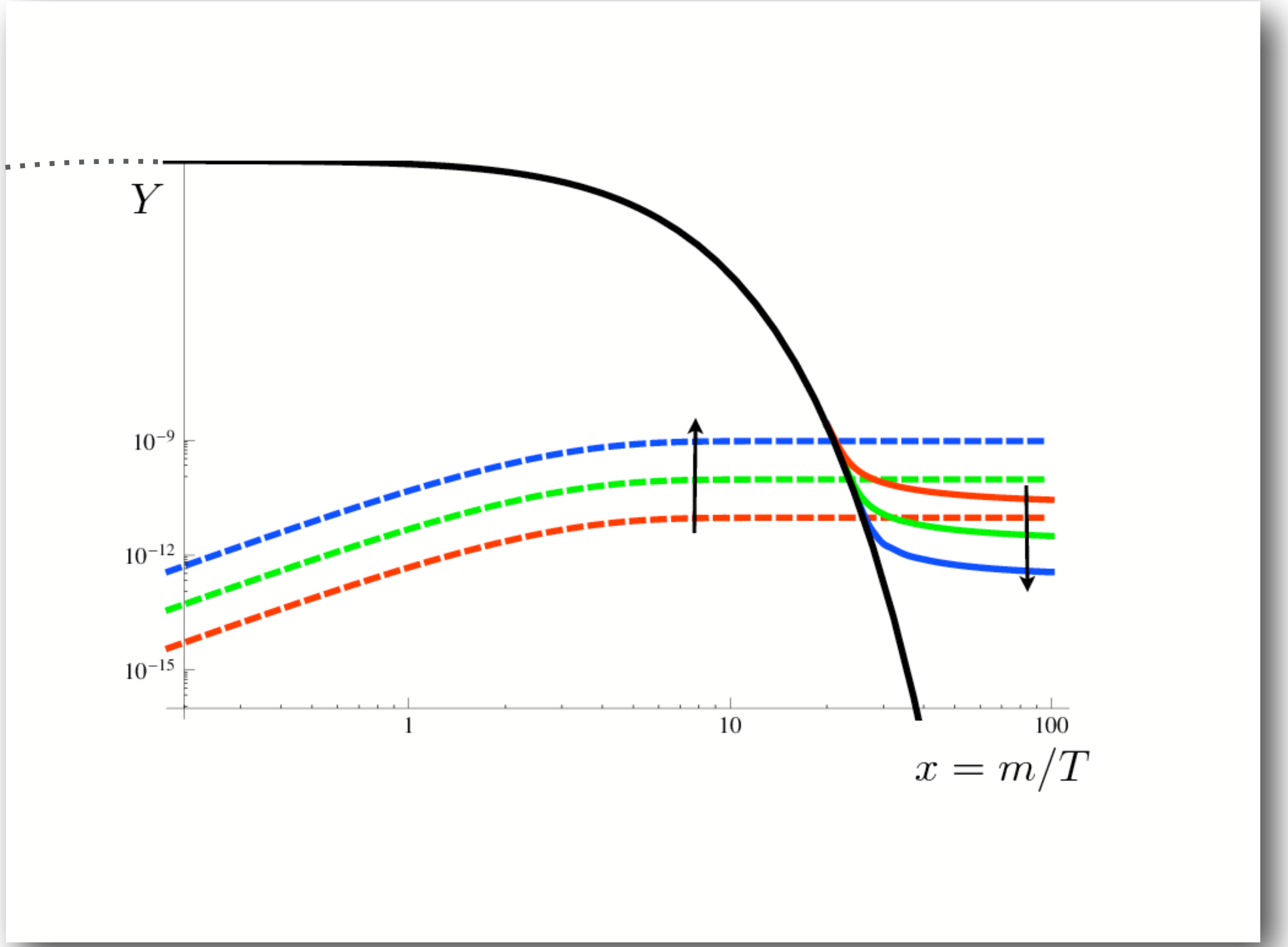
This is unnecessary: had we started with $Y(x_0<<1)=0$, provided that $\Gamma_{eq} / H = K>>1$ the equation

$$\frac{x}{Y_{\rm eq}}\frac{dY}{dx} = -\frac{\Gamma_{\rm eq}}{H}\left[\left(\frac{Y}{Y_{\rm eq}}\right)^2 - 1\right] \quad \text{with} \quad \Gamma_{\rm eq} = \langle\sigma v\rangle n_{\rm eq}$$

admits the solution $Y \sim Y_{eq}\, K \ln(x/x_0)$ *[assuming K constant…which is not!]* so equilibrium is attained when $x \sim x_0 \exp(1/K)$, i.e. only a 10% increase wrt x_0 for K=10!

Freeze-in, continued

However, if Γ_{eq}/H =K<<1 (i.e., ***feeble*** coupling!) it never attains equilibrium: yet it can match the required DM value via the residual production from the plasma



L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West, "Freeze-In Production of FIMP Dark Matter," JHEP 1003, 080 (2010) [0911.1120]

That's called "***Freeze In***", since it's the "reverse" of freeze out

Freeze-in, continued

In the eq., we can then neglect Y wrt Y_{eq}

$$\frac{dY}{dx} \simeq \frac{x\, s \langle \sigma v \rangle}{H(m)} Y_{\rm eq}^2$$

Assuming negligible initial abundance

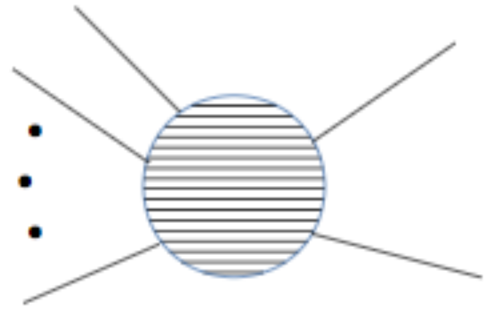
$$Y_\infty \simeq \int_{x_0}^{\infty} dx' \frac{x'\, s\, \langle \sigma v \rangle}{H(m)} Y_{\rm eq}^2$$

- Note that now $Y_\infty \propto \langle \sigma v \rangle$ **inverse dependence** wrt WIMP freeze-out
- Can check that ***Y* saturates at smaller *x*** (order 1) wrt x_{fo}~20-30 (early universe history more important)
- Y_∞ sensitive to **initial conditions** (reheating temperature, yield coming directly from inflation…)

In this "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*

Another example: Cannibalism

Defining property: relic abundance fixed by N→2 processes among DM (N>2)



goes back to

E. D. Carlson, M. E. Machacek and L. J. Hall, Astrophys. J. 398, 43 (1992)

(but 'their' cosmology is not viable!)

Resurrected in *Y. Hochberg, E. Kuflik, T. Volansky, J. G. Wacker, PRL 113, 171301 (2014) [1402.5143]*

New, lighter mass scale for DM (sub-GeV)!

Key-reason: Different scalings

WIMPs

From the freeze-out condition $\Gamma = H$ one derives $Y_\infty \propto \dfrac{1}{m\, M_{Pl} \langle \sigma v \rangle}$

In terms of the equality temperature

$$T_{\rm eq} \sim \left.\frac{\rho_r}{s}\right)_{\rm eq} = \left.\frac{\rho_m}{s}\right)_{\rm eq} = m\, Y_\infty$$

From the WIMP scaling

$$\langle \sigma v \rangle \simeq \frac{\alpha^2}{m^2}$$

one derives $m \sim \alpha [T_{\rm eq} M_{\rm Pl}]^{1/2}$

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SIMPs ("cannibalism")

due to the modifications

$$\Gamma_{N\to 2} = n^{N-1} \langle \sigma v^{N-1} \rangle \qquad \langle \sigma v \rangle \simeq \frac{\alpha_{\rm eff}^N}{m^{3N-4}}$$

one derives $m \sim \alpha_{\rm eff} [T_{\rm eq} M_{\rm Pl}^{N-1}]^{1/N}$

The original idea… is not so "cool"!

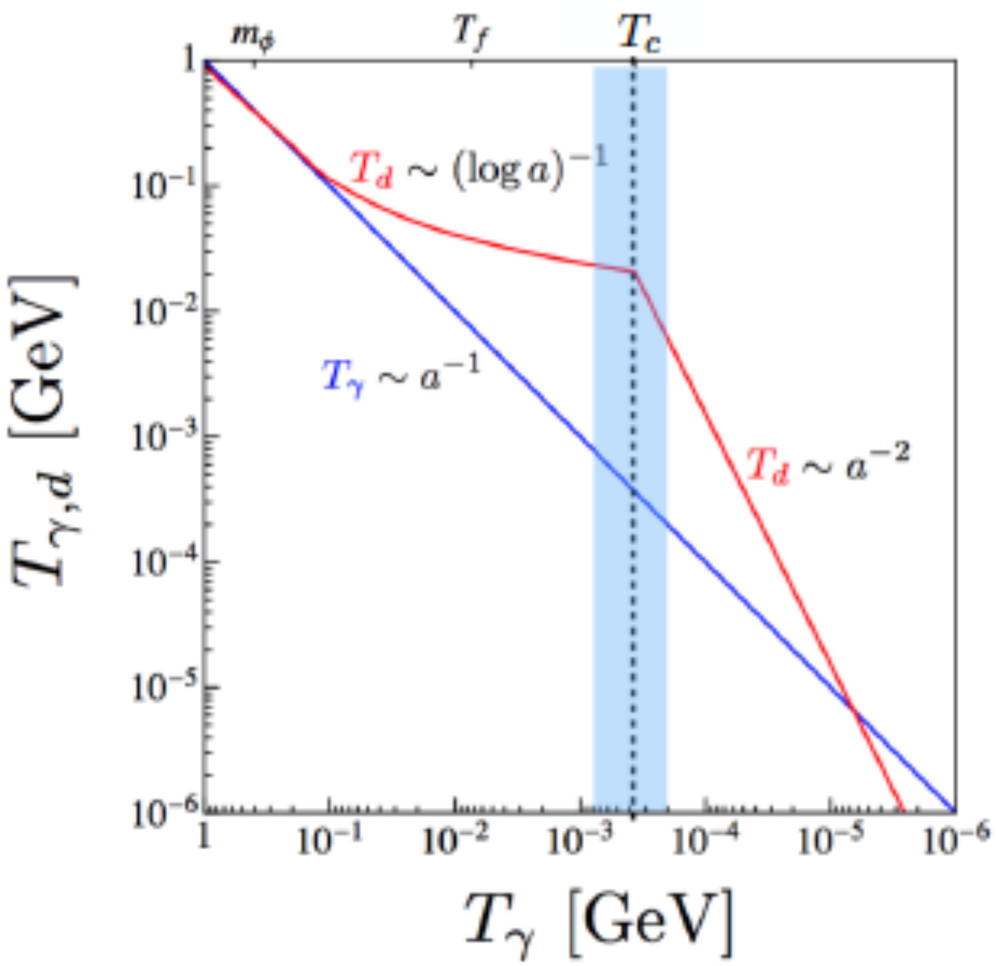
By 'eating' their fellows, the residual SIDM cool down very inefficiently, compared to radiation!

Conservation of entropy in the dark sector requires

$$const. \simeq s\,a^3 \simeq \frac{\rho_d}{T_d} \propto m\,(mT_d)^{3/2}\,e^{-m/T_d}a^3$$

$$T_d \propto \frac{m}{\log a}$$

Only after freeze-out of cannibalism, $T_d \propto a^{-2}$

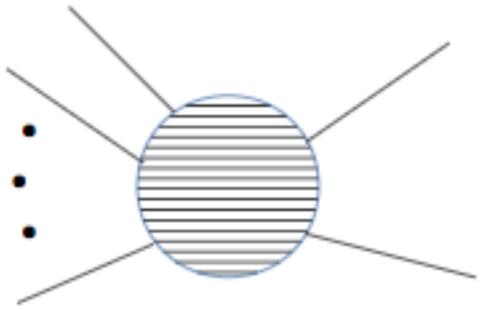


This is **usually lethal for models**, **unless** *some coupling is retained with the SM, so that the SIMP is in* **kinetic** *equilibrium with it!*

Typically, a "portal-type" interaction is added by hand, which is crucial for non-gravitational searches

Summary: Cannibalism

Defining property: relic abundance fixed by N→2 processes among DM (N>2)



goes back to

E. D. Carlson, M. E. Machacek and L. J. Hall, Astrophys. J. 398, 43 (1992)

(but 'their' cosmology is not viable!)

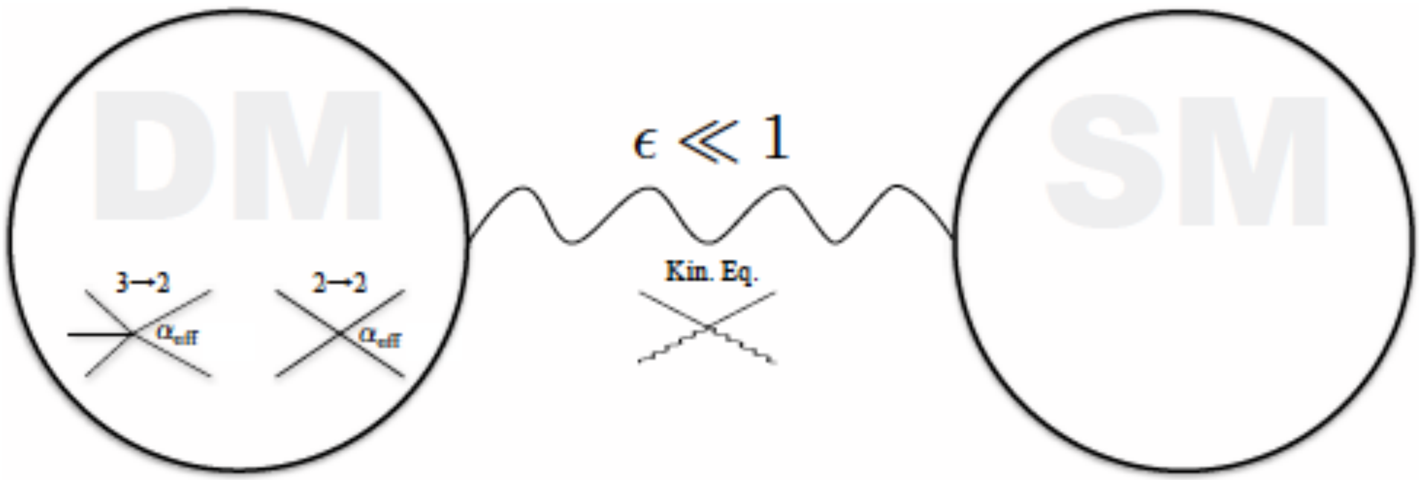
Resurrected in *Y. Hochberg, E. Kuflik, T. Volansky, J. G. Wacker, PRL 113, 171301 (2014) [1402.5143]*

New, lighter mass scale for DM (sub-GeV)

$m_{\rm DM} \sim \alpha_{\rm ann} \left(T_{\rm eq} M_{\rm Pl}\right)^{1/2} \sim$ TeV replaced by $m_{\rm DM} \sim \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100$ MeV

But requires delicate balance:

- *chemical* freeze-out via 3→2 in the Dark sector requires 2→2 towards SM suppressed
- Yet, must be in *kinetic* equil. with SM (otherwise "hot" DM); achieved via portal operator with *different* scale

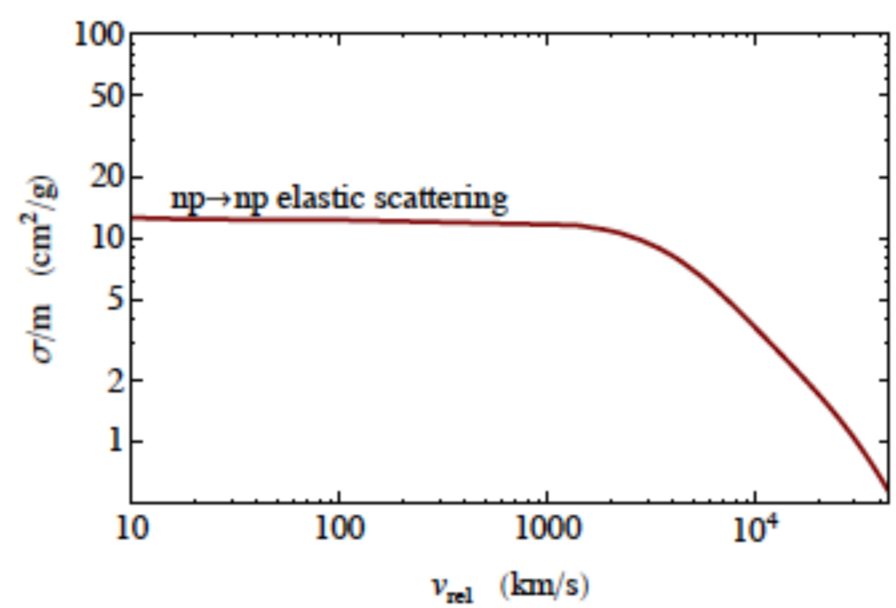


Further complications: Observations require $\sigma=\sigma(\mathbf{v})$

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	$\sim 0.1\ cm^2/g$	1500 km/s	Stellar dispersion, lensing	[116, 126]
Abell 3827 subhalo merger	$\sim 1.5\ cm^2/g$	1500 km/s	DM-galaxy offset	[127]
Abell 520 cluster merger	$\sim 1\ cm^2/g$	$2000 - 3000$ 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 requires 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"!

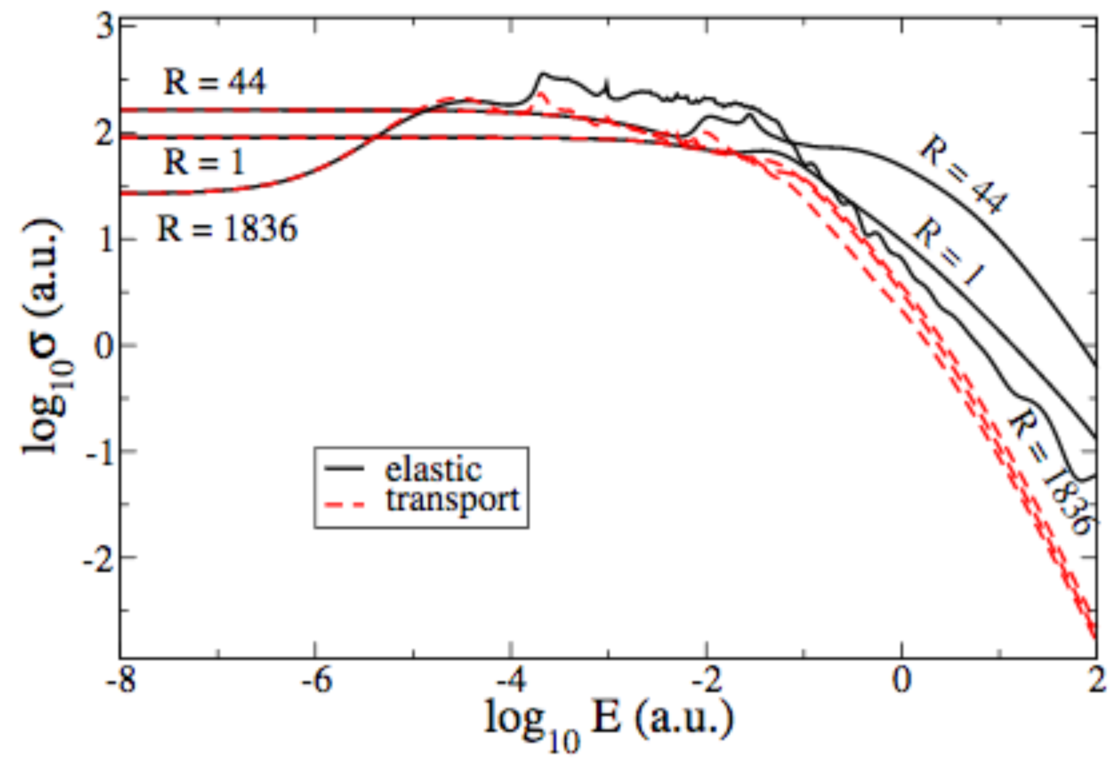
possibly related to *some degree* of "dissipative" effects in the dark sector

Detour: (Quasi-)massless mediators?

Naively: too steep xsec dependence (Rutherford) ***~v⁻⁴***

However, considered in scenarios with **rich Dark Sector**, including **≧2 stable massive particles** (e.g."dark proton" and "dark electron", mass ratio=*R*). There one can have "**dark atoms**" & get an acceptable scattering. E.g.

J. M. Cline, Z. Liu, G. Moore and W. Xue, "Scattering properties of dark atoms and molecules," PRD 89, 043514 (2014) [1311.6468]



In this case (some) DM is "dissipative"!
Danger, notably for the dinosaurs

J. Fan, A. Katz, L. Randall and M. Reece, "Dark-Disk Universe," PRL 110, 211302 (2013) [1303.3271]

Typically **only a small fraction of DM can have such properties**, due to astro-cosmo bounds.

numerical simulations have started to appear…

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

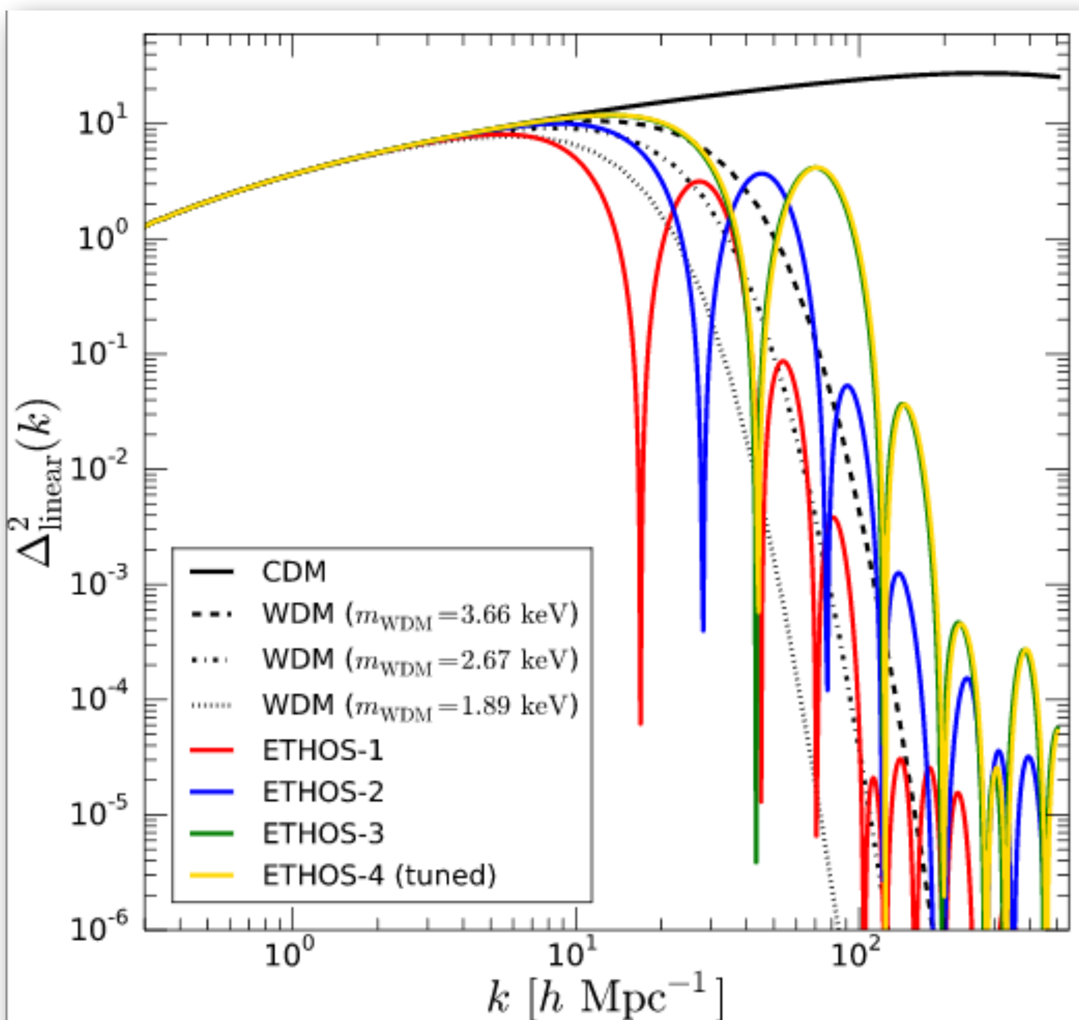
Dark Oscillations

The fraction of DM coupling to new BSM relativistic particles:

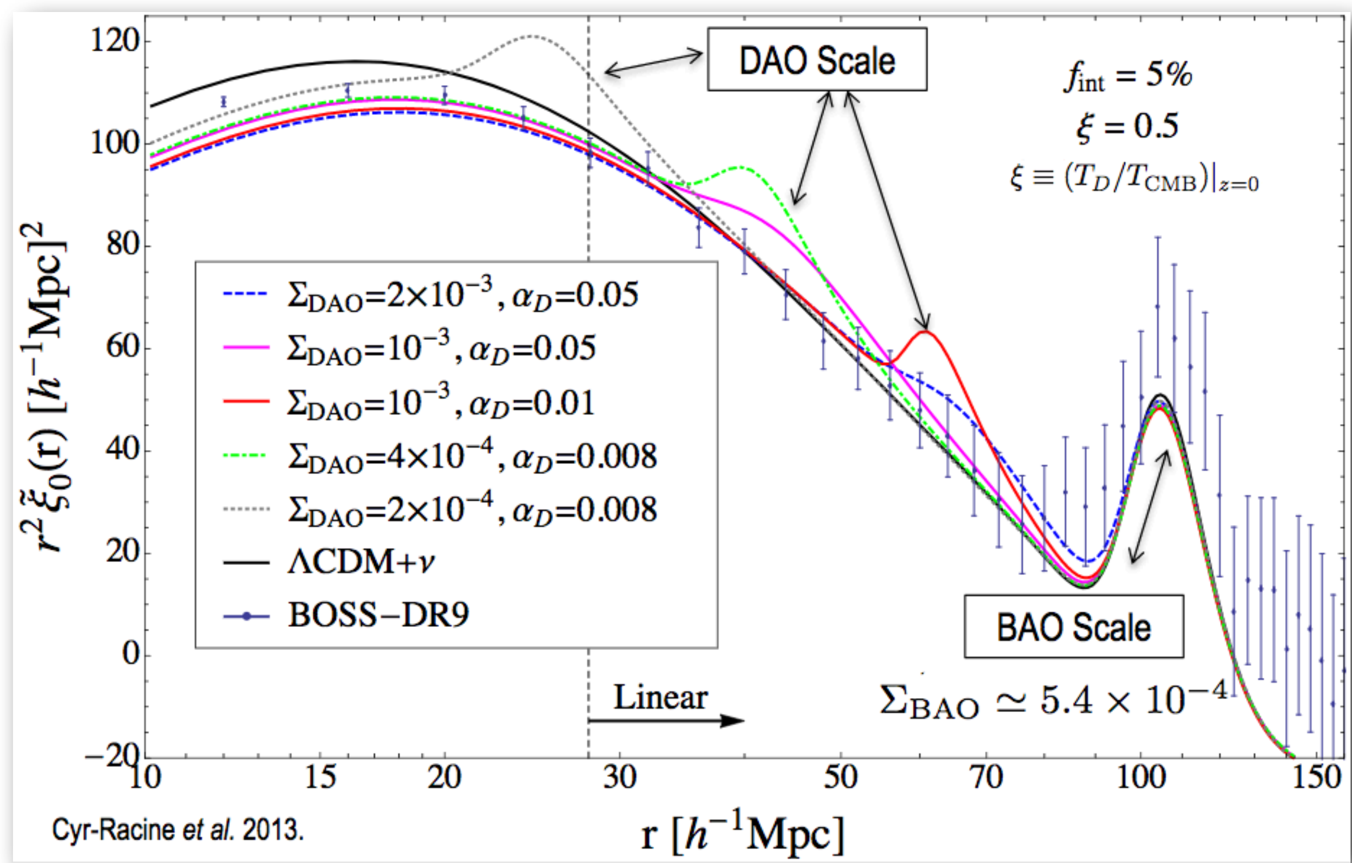
i) leads to non-vanishing sound speed & provides pressure support against gravitational collapse
ii) Has a relatively late epoch of kinematic decoupling

Leads to small-scale damping of DM power spectrum (like WDM) + "dark oscillations", analogous to BAO

e.g. *F.Y. Cyr-Racine, R. de Putter, A. Raccanelli, K. Sigurdson, "Constraints on Large-Scale Dark Acoustic Oscillations from Cosmology," PRD 9 063517 (2014)[1310.3278]*



CMB & LSS constraint this **DM fraction to below 5%**



Dark Radiation

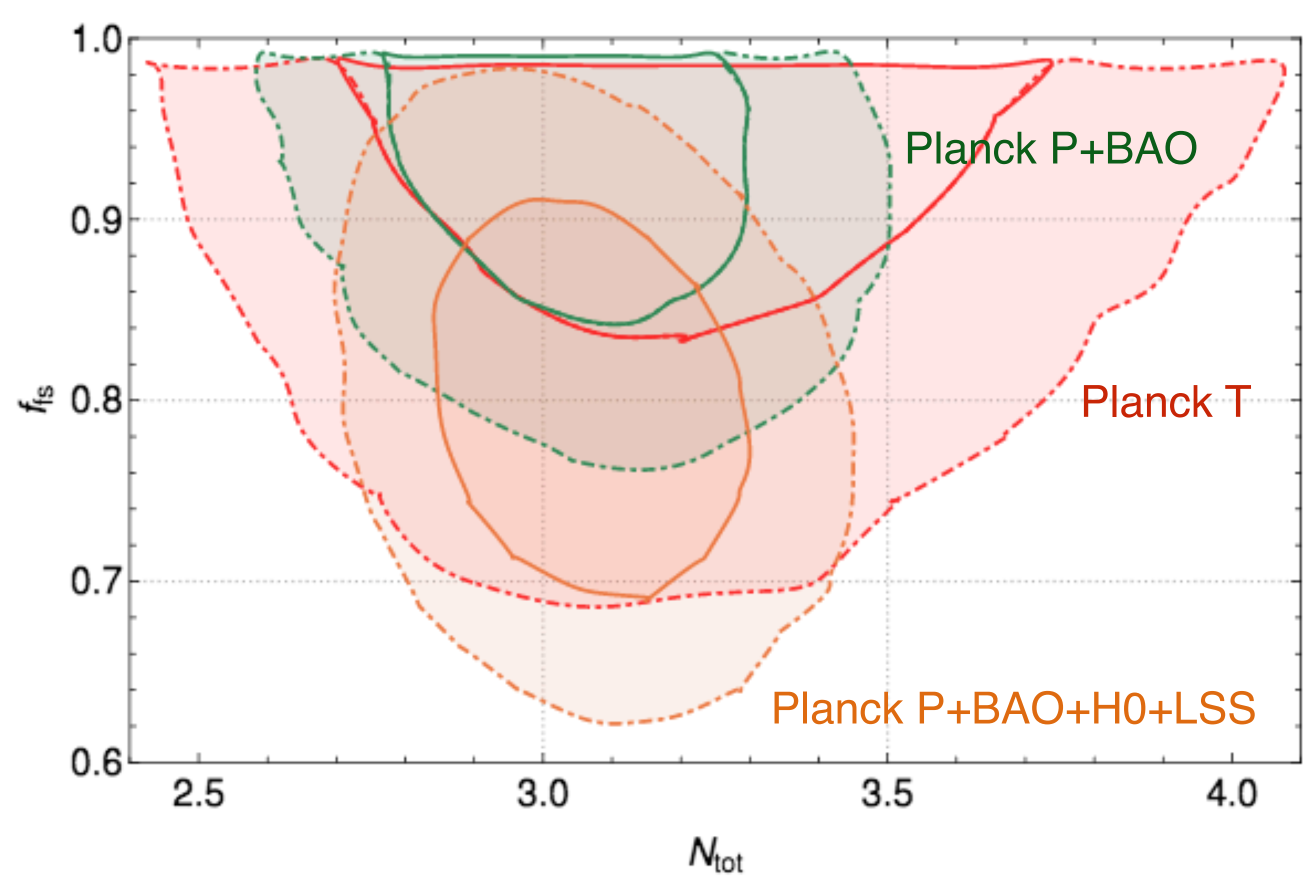
The light/massless mediator is typically stable or very long-lived, contributing to the amount of relativistic degrees of freedom (Dark Radiation) in the early Universe, and is subject to constraints from Big Bang Nucleosynthesis (BBN) and CMB

BBN *alone* gives $\Delta N_{eff}<1$ at about 3 σ with standard assumptions (*R. H. Cyburt, et al. Rev. Mod. Phys. 88, 015004 (2016) [1505.01076]*) or at about 2 σ relaxing virtually all assumptions on He chemical evolution, apart from actual He not smaller than primordial (*G. Mangano and PS, Phys. Lett. B 701, 296 (2011) [1103.1261]*)

For CMB, the fraction of DR which is free-streaming also matters, studied in

C. Brust, Y. Cui and K. Sigurdson, JCAP 1708, 020 (2017) [1703.10732]

bounds from comparable to twice as strong as from BBN (but different epoch! E.g. what's relativistic at BBN might not be at CMB…)



Some “quantum” alternatives

“Mass (Colder Darker Matter)”
Cornelia Parker 1997

Alternative small-scale fix: Quantum DM effects

Fuzzy Dark Matter: extremely light bosons ($m\sim10^{-22}$ eV) hence with kpc-sized De Broglie wavelength

Introduced by *W. Hu, R. Barkana and A. Gruzinov, PRL 85, 1158 (2000) [astro-ph/0003365]*

Revived by *L. Hui, J.P. Ostriker, S. Tremaine and E. Witten, PRD 95, 043541 (2017) [1610.08297]*

Halo cutoff at low masses and profile flattening due to "uncertainty principle"

"semiclassical" Schrödinger-Poisson eq. for ***quantum gravitational effects*** *(do not open the Pandora box!)*

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2\,m}\nabla^2\psi + m\Phi\psi \qquad \nabla^2\Phi = 4\pi G\, m|\psi|^2$$

only halos fulfilling $\frac{\lambda_{DB}}{2\pi} \lesssim \frac{GM_{\rm halo}}{v_{\rm vir}^2}$ can exist. Or better, radius containing 1/2 mass of a spherically symmetric, time-independent, self-gravitating system of FDM satisfies

$$r_{1/2}\,M_{\rm halo} \geq 3.925\frac{\hbar^2}{G\,m^2} \simeq 0.3\,{\rm kpc}\frac{10^9\,M_\odot}{M}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)^2$$

actually, one finds a central soliton (saturating the above ineq.: S-P eq. implies a conserved particle number; the soliton solution minimizes the energy for a given particle number) +NFW-like halo

Phenomenologically interesting region at odds with observations: time-dependent oscillations on scales λ_{DM}/v_{vir} e.g. incompatible with star clusters observed in Eridanus II core, see *Marsch & Niemayer, 1810.08543*

The best (worst?) of two worlds

Bose-Einstein Condensate DM:

- light bosons (m< eV) whose wavefunctions overlap in Galaxies
- with sizable interactions (**σ/m> 0.1 cm²/g**) so to thermalize

Idea occasionally proposed in the literature, e.g. *Silverman and Mallet CQG 2001, Gen. Rel. Grav. 2002*

But has become recently popular after articles like

L. Berezhiani and J. Khoury, "Theory of dark matter superfluidity," PRD 92, 103510 (2015) [1507.01019]
J. Khoury, PRD 93 103533 (2016) [1602.05961]

showed that one can simultaneously achieve

- CDM-like behaviour at supra-galactic scales (cosmo and cluster successes recovered)
- At (sub)Galactic scales, recover "MONDian" behaviour $a = \sqrt{a_N\, a_0} \simeq \sqrt{\frac{a_N H_0}{6}} \quad (a_N \ll a_0)$

obtained either as "fifth-force" between baryons mediated by phonons, or higher-gradient corrections in the superfluid effective theory (then MOND force law applies to both baryons and DM)

Fair to say that the "theories" thus obtained appear rather ad hoc; not easily conceived how they emerge from UV. Maybe some hope for phenomenological validation? Link with Dark Energy? As in

E. G.M. Ferreira, G. Franzmann, J. Khoury and R. Brandenberger, "Unified Superfluid Dark Sector," 1810.09474

Beyond gravitational signatures: Some ideas in indirect detection

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

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)

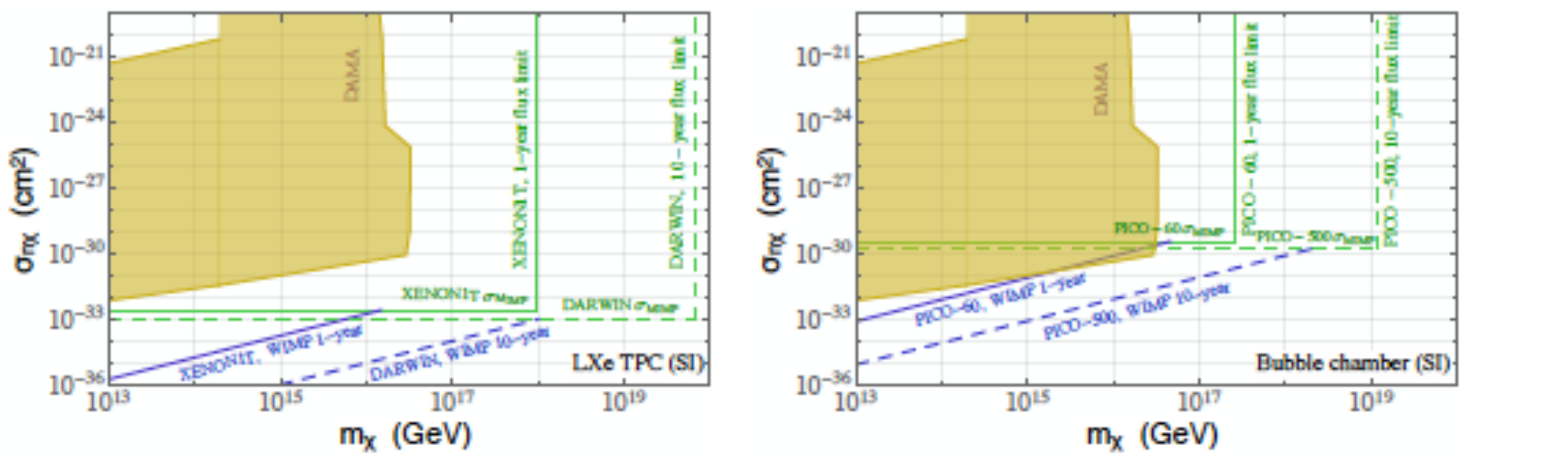
R.T. D'Agnolo, D. Pappadopulo and J.T. Ruderman, "Fourth Exception in the Calculation of Relic Abundances,"' Phys. Rev. Lett. 119, 061102 (2017) [1705.08450]

Beyond gravitational signatures:
Some ideas at colliders & direct detection

Some directions at colliders

- long tracks of metastable DM “progenitors”
- displaced vertices
- Higgs $\to$ invisible (e.g. following in cannibals from kinetic eq. with SM…)

Direct detection, I



use “standard’ experiment to look in different ranges/observables, e.g. at high-masses for “multiple-scattering” signatures

J. Bramante, B. Broerman, R. F. Lang and N. Raj, “Saturated Overburden Scattering and the Multiscatter Frontier: Discovering Dark Matter at the Planck Mass and Beyond,” Phys. Rev. D 98, no. 8, 083516 (2018) [1803.08044]

Direct detection, II

kinematically "light" regime (sub-GeV) can be probed notably via electron scatterings
(lots of experimental proposals based on new techniques!)

Main Science Goal	Experiment	Target	Readout	Estimated Timeline
Sub-GeV Dark Matter (Electron Interactions)	SENSEI	Si	charge	ready to start project (2 yr to deploy 100g)
	DAMIC-1K	Si	charge	ongoing R&D 2018 ready to start project (2 yr to deploy 1 kg)
	UA′(1) liquid Xe TPC	Xe	charge	ready to start project (2 yr to deploy 10kg)
	Scintillator w/ TES readout	GaAs(Si,B)	light	2 yr R&D 2020 in sCDMS cryostat
	NICE; NaI/CsI cooled crystals	NaI CsI	light	3 yr R&D 2020 ready to start project
	Ge Detector w/ Avalanche Ionization Amplification	Ge	charge	3 yr R&D 1 yr 10kg detector 1 yr 100kg detector
	PTOLEMY-G3, 2d graphene	graphene	charge directionality	1 yr fab prototype 1 yr data
	supercond. Al cube	Al	heat	10+ yr program
Sub-GeV Dark Matter (Nucleon Interactions)	Superfluid helium with TES readout	He	heat, light	1 yr R&D; 2018 ready to start project; 2022 run
	Evaporation & detection of He-atoms by field ionization	superfluid helium, crystals with long phonon mean free path (e.g. Si, Ge)	heat	3 yr R&D; 2020 ready to start project R&D
	color centers	crystals (CaF)	light	R&D effort ongoing
	Magnetic bubble chamber	Single molecule magnet crystals	Spin-avalanche (Magnetic flux)	R&D effort ongoing

M. Battaglieri et al., "US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report," 1707.04591

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 detection 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,*** notably from small-scale “problems” in DM (Strong self-interacting DM, dark forces, light mediators…)

- No guaranteed signal, but accrued **interest to significantly explore new windows**:
  - MeV gamma-ray sky
  - Gravitational Waves (e.g. “dark sector” phase transitions in the early universe)
  - 21 cm
  - CMB spectral distortions
  - improved X-ray sensitivity
  - $\gtrsim$100 TeV gamma-ray sky (ground based)

  - Light mass frontier in direct DM detection
  - Portal-related pheno at colliders: tracks due to metastable progenitors, displaced vertices, invisible Higgs decay…