The “gravitational window” for dark matter: motivations and models

LAPTh

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cnrs

Structure of my talk (& apologies)

- Introduction
- Life beyond WIMPs
- Problems at small scales (notions)
  - *Review of the problems*
  - *Baryonic effects to the rescue?*

Covered by Aseem Paranjape earlier this afternoon

- Possible DM microphysics explanations: from warm DM to Self-Interacting DM
  - Detour on (quasi-)massless mediators
- SIDM addressing large-scale cosmology anomalies?
- Some alternative: cold(er) cases
- Conclusions

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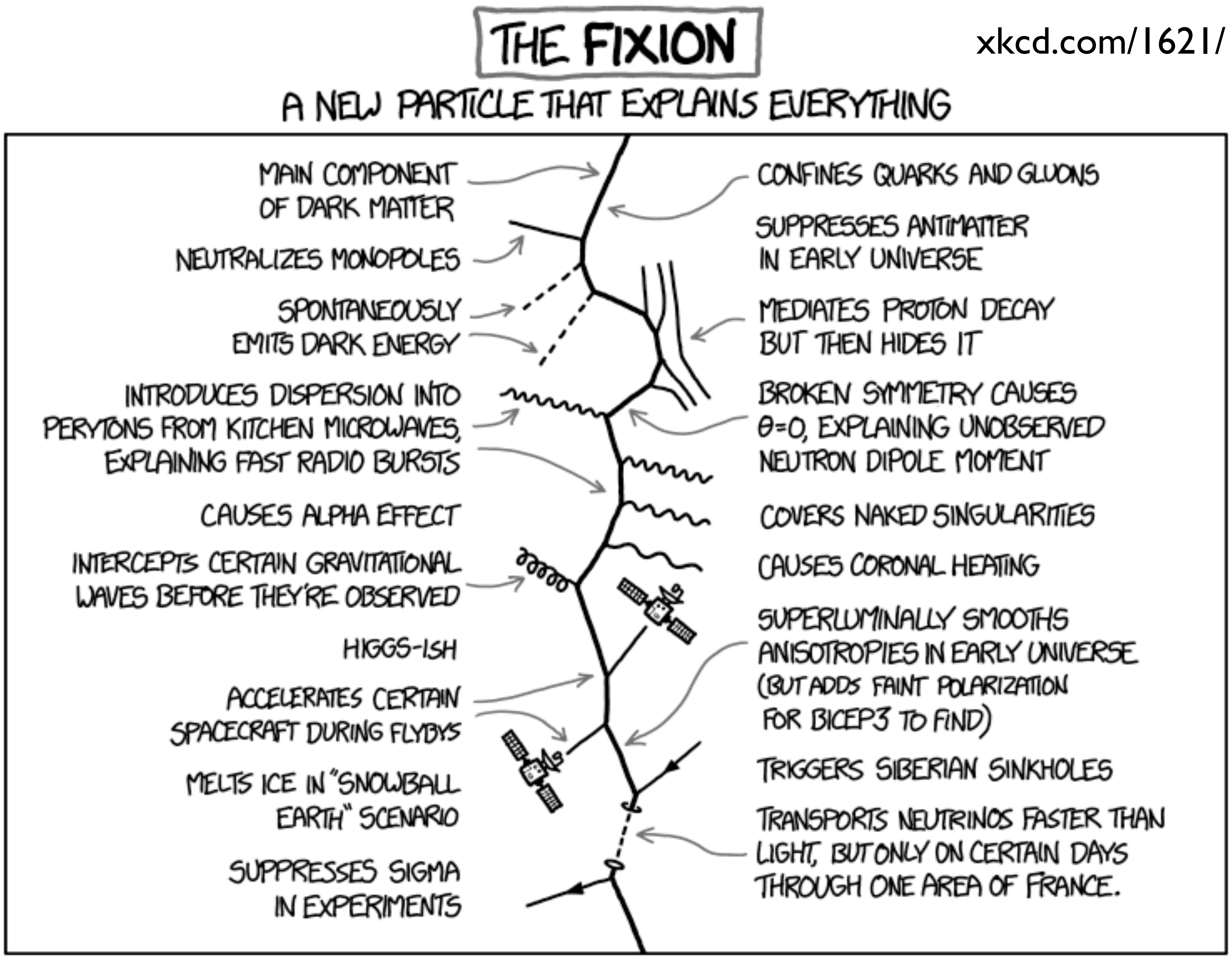
Disclaimer I: **Will only talk of "gravitational" implications & signatures, say nothing about e.m. searches in cosmo, nor the Lab. For *some (only some!) they are peculiar & interesting.***

Disclaimer II: **I'm not expert on at least half of the topics covered. Apologies to those who are. On those topics, take my talk as educated (?) outsider's view**

Introduction

lessons (?!?) *from* theorists *on* fundamental dof's

xkcd.com/1621/



Introduction

lessons (?!?) *from* colliders *on* fundamental dof's

Experimentalists' message:

Standard Model*

It's the ~~economy~~, stupid!

* plus massive neutrinos...

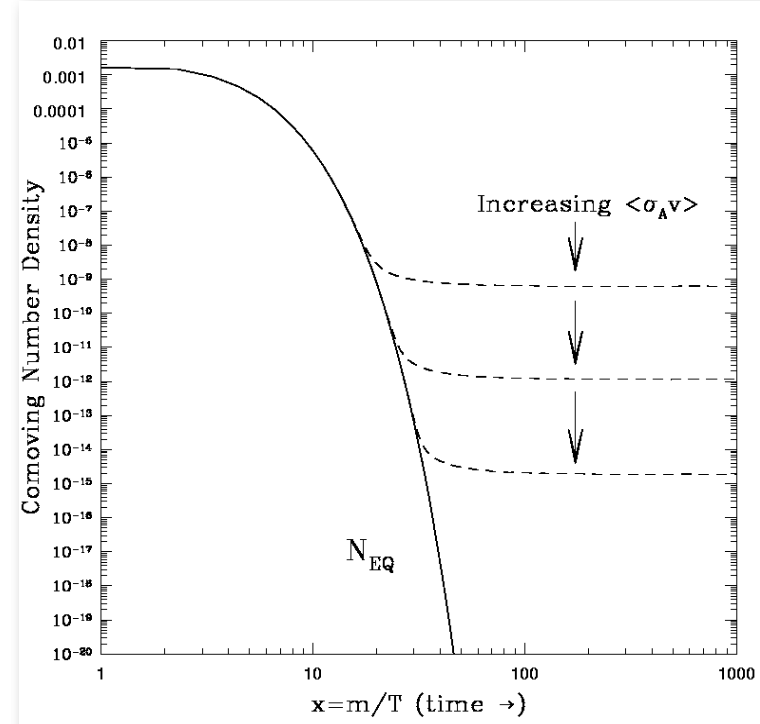
This (temporary?) failure also includes the leading (according to particle physicists) class of candidates to the dark matter

The Weakly Interacting Massive Particle Paradigm

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

Add to SM a ***stable massive particle*** in ***chemical equilibrium with the SM*** via ***EW-strength interactions*** in the early universe down to $T \ll m$ (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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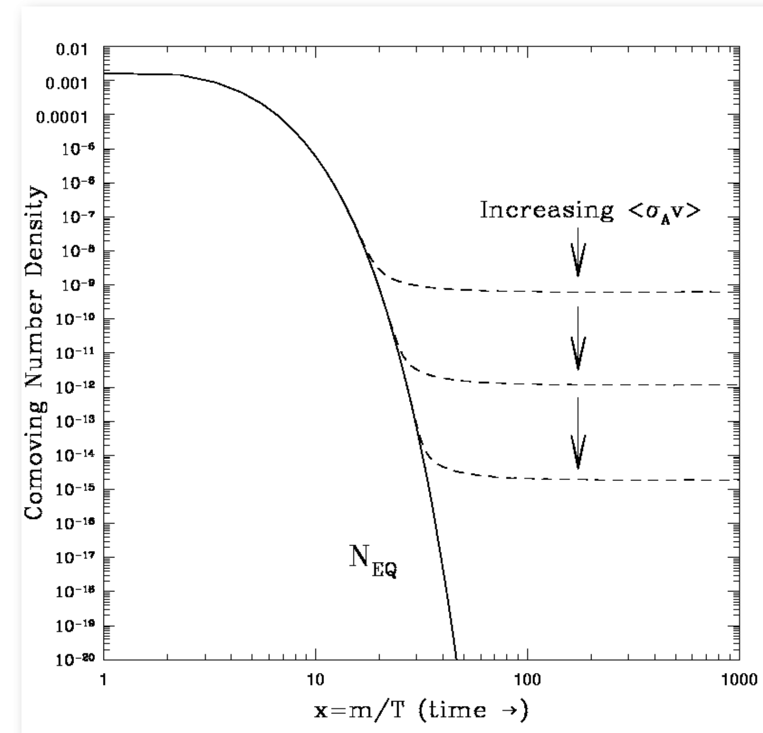


Textbook calculation yields the current average cosmological energy density

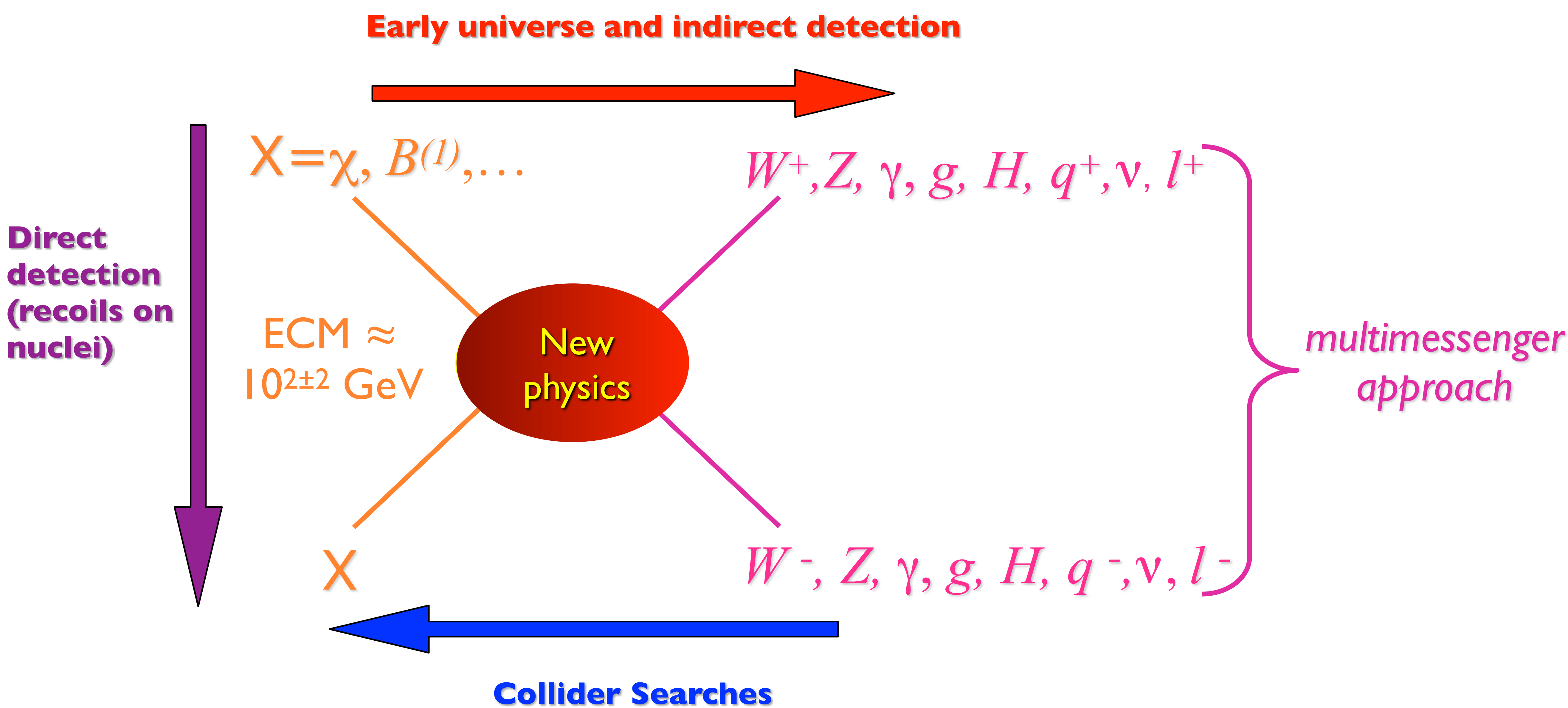
$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle\sigma v\rangle}$$

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

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

- ***Stability*** may result from the same ***discrete "parity" symmetry*** easing p-decay bounds, no signs of new physics at LEP, etc.
- Matches ***theoretical prior for BSM at EW scale*** from hierarchy problem
- Leads to a number of interesting, testable phenomenological consequences

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

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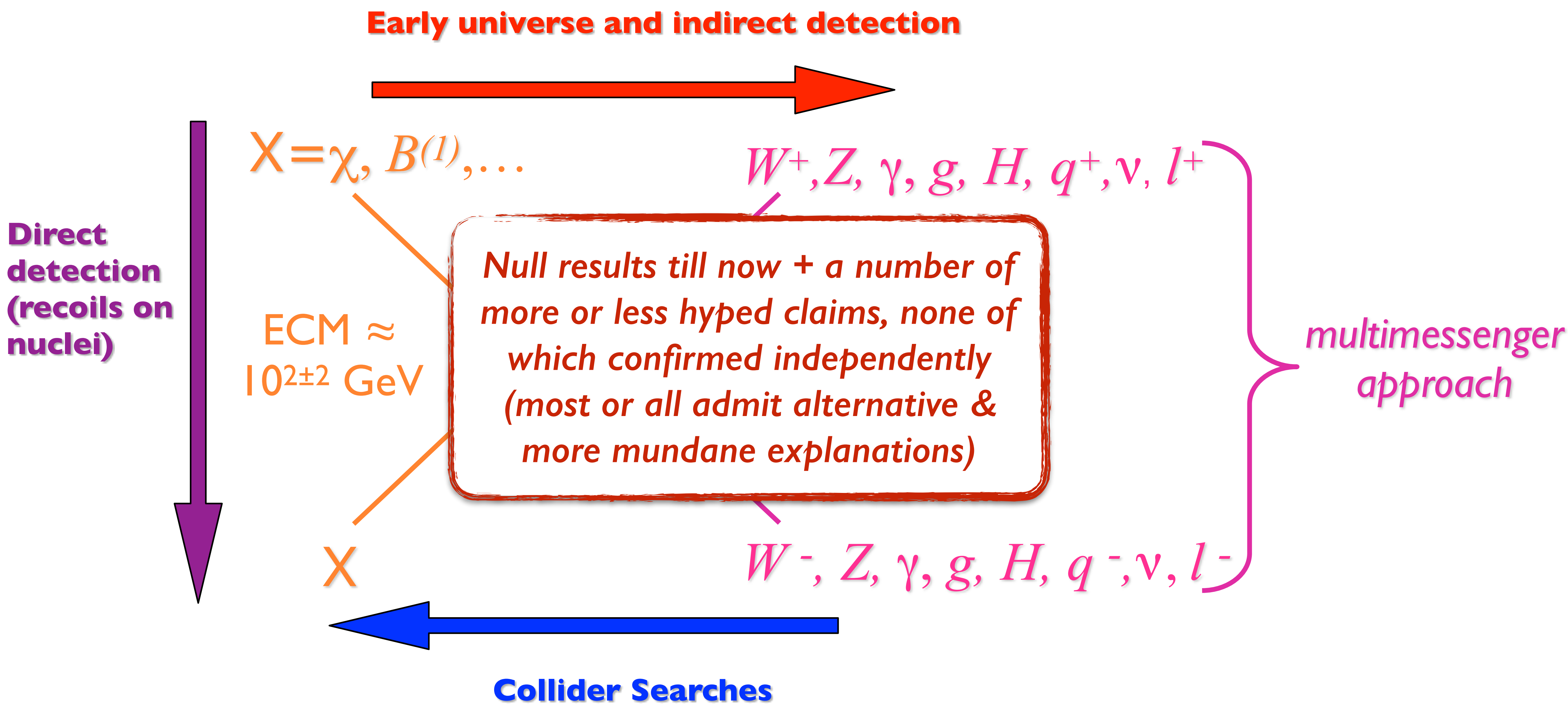

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In the meanwhile…

…lessons *from* the Universe *on* fundamental (?!) dof's

- Dark matter
- Baryon asymmetry
- Inflation
- Dark Energy *(at least if not cosmological constant)*

"Who ordered ***that***?"

but also, less well remembered:

"I think physicists are the Peter Pans of the human race. They never grow up…"

Let's keep an open mind and open attitude, trying to learn from Nature rather than our prejudice.

But why should cosmology reserve us surprises, notably on DM, given negative results from the Lab searches?

I can propose a few reasons:

1. Most obvious ways to go beyond WIMPs are more likely probed via astro/cosmo
2. There might be already astro/cosmo "anomalies", possibly involving DM beyond WIMPs
3. Unexplored cosmo windows (GW, 21 cm, CMB spectral distortions,…) remain much more easily accessible than, say, the next oom improvement in collider CoM energy

Part I: Losing equilibrium

What's next, for DM searches?

We cannot give up on (meta)stability if we want DM. Easiest requirement to relax is 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 (of course, while continuing to improve WIMP-like searches!)

Feebly interacting DM (FIMPs) with the SM

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: this can have a gravitational signature! *Mostly degenerate with old well-known warm DM*, albeit different parametric dofs

Textbook example of gravitational probes of DM microphysics

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***

more on this later, since it probably requires some justification…

It has been realized for instance that 2) and/or 3) are almost the unavoidable choice to realize 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]*

Textbook example

1) DM v-distribution: free-streaming length

In terms of the characteristic (e.g. rms) velocity of the species, the comoving **free-streaming** horizon is

$$\lambda_{\rm fs} = \int_{t_{\rm dec}}^{t_0} {\rm d}t \frac{v(t)}{a(t)}$$

$v(t)$ → masses

$a(t)$ → history of universe, t_{eq}

$t_{\rm dec}$ → interactions (e.g. decay rate)

associated to a free-streaming mass scale

$$M_{\rm fs} = \frac{4}{3}\bar{\rho}\left(\frac{\lambda_{\rm fs}}{2}\right)^3$$

below which growth of structures is suppressed

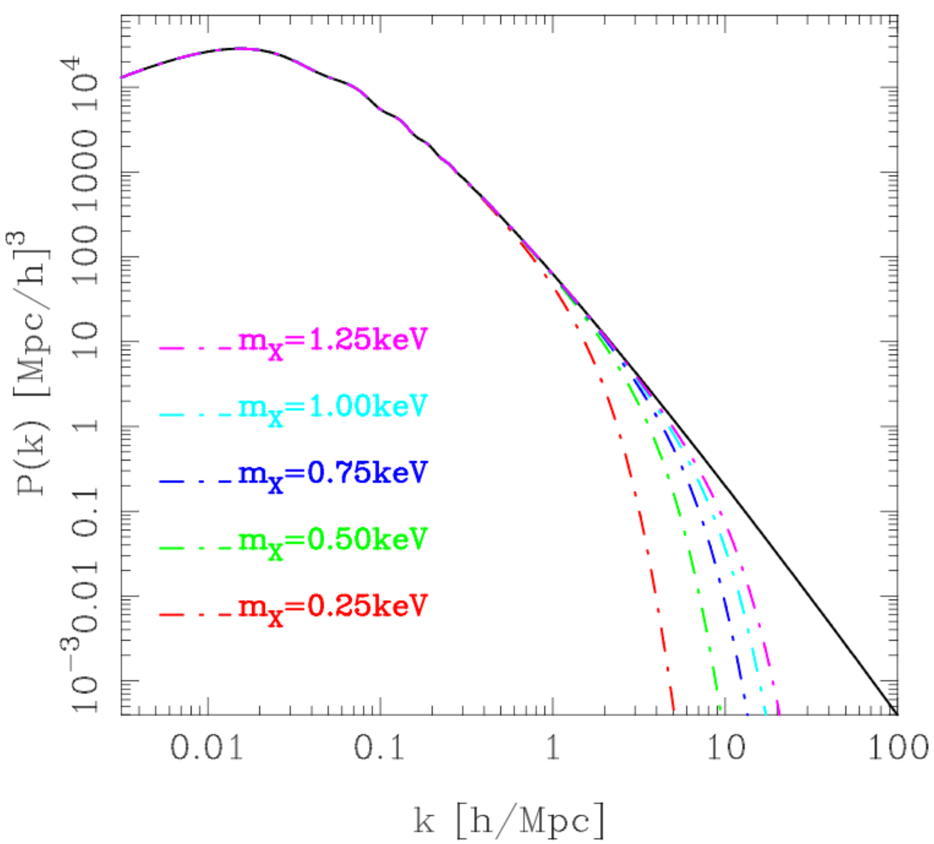
e.g. for a *thermal* sterile neutrino DM

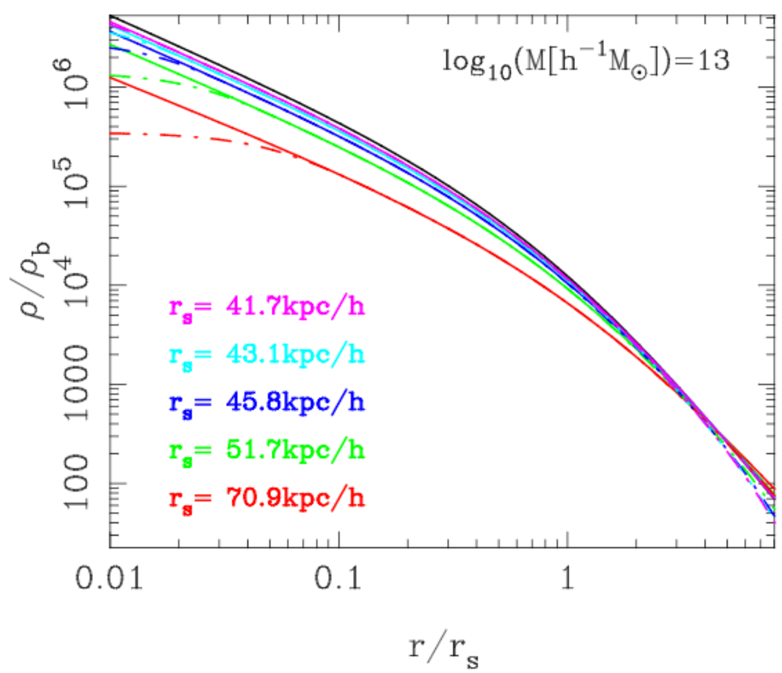
$$T(k) \equiv \sqrt{\frac{P(k)}{P_{\Lambda CDM}}} \propto \left[1 + \left(\frac{k}{k_c}\right)^2\right]^{-5} \qquad k_c \simeq 20 \frac{m}{\rm keV}\, h\, {\rm Mpc}^{-1}$$

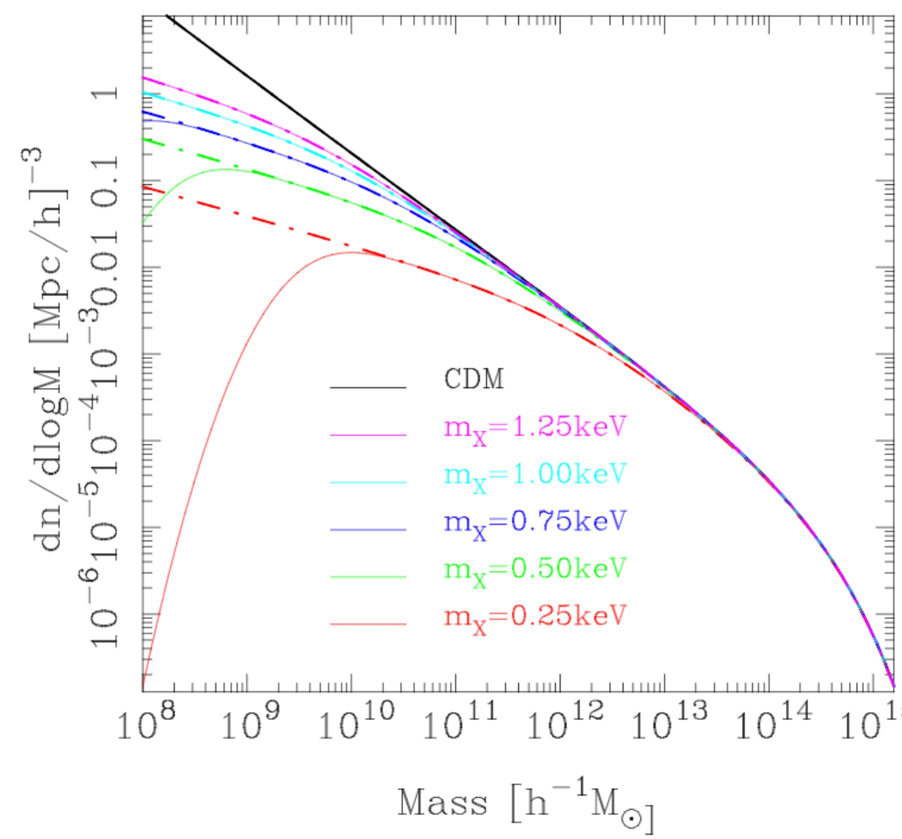
1) Probing the free-streaming length

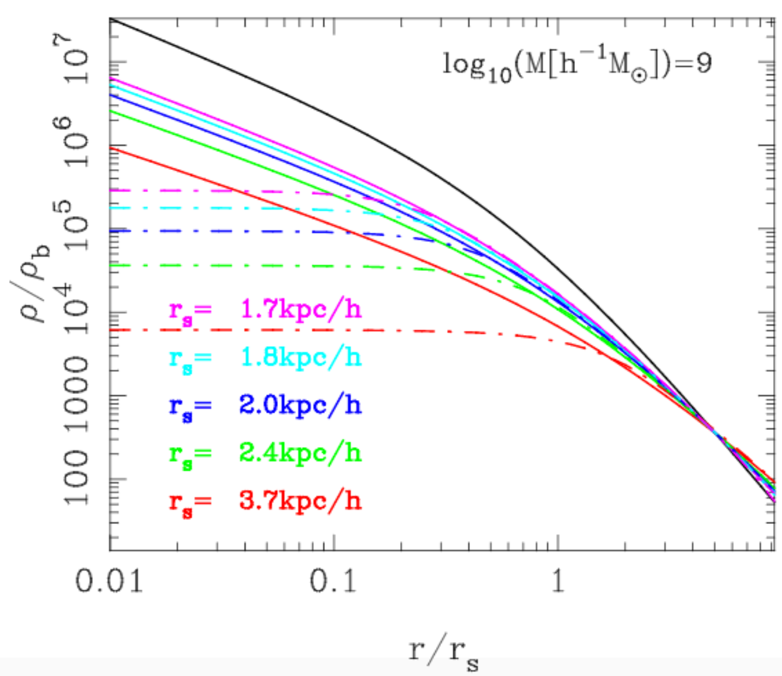
Probed via weakly (?) non-linear scales in power spectrum (e.g. Ly-α), halo mass function, or halo profile

traditionally studied also with semi-analytical models (today mostly inadequate, notably for halo profile)









R. E. Smith & K. Markovic, "Testing the Warm DM paradigm with large-scale structures," PRD 84, 063507 (2011)[1103.2134]

Forecast m>2.6 keV

current bounds discussed earlier this afternoon

we will encounter these probes again later on…

2) Interlude on freeze-in, I

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, $Y(x<<1)=Y_{eq}$

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

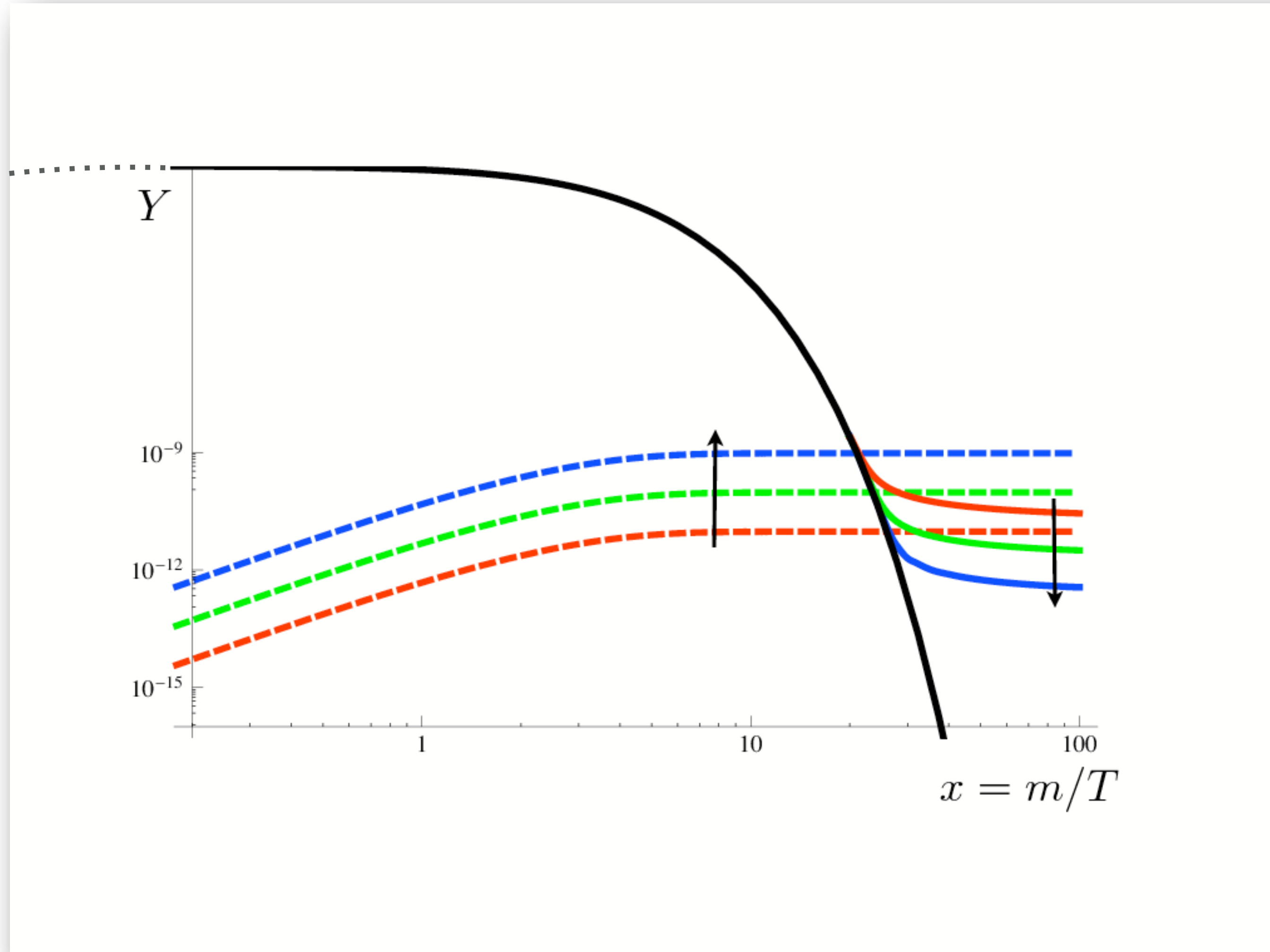
This is unnecessary: had we started with $Y(x_0<<1)=0$, provided that $\Gamma_{eq}/H=K>>1$ the equation

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

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!

2) Interlude on freeze-in, II

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



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

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]

2) Some properties of freeze-in

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

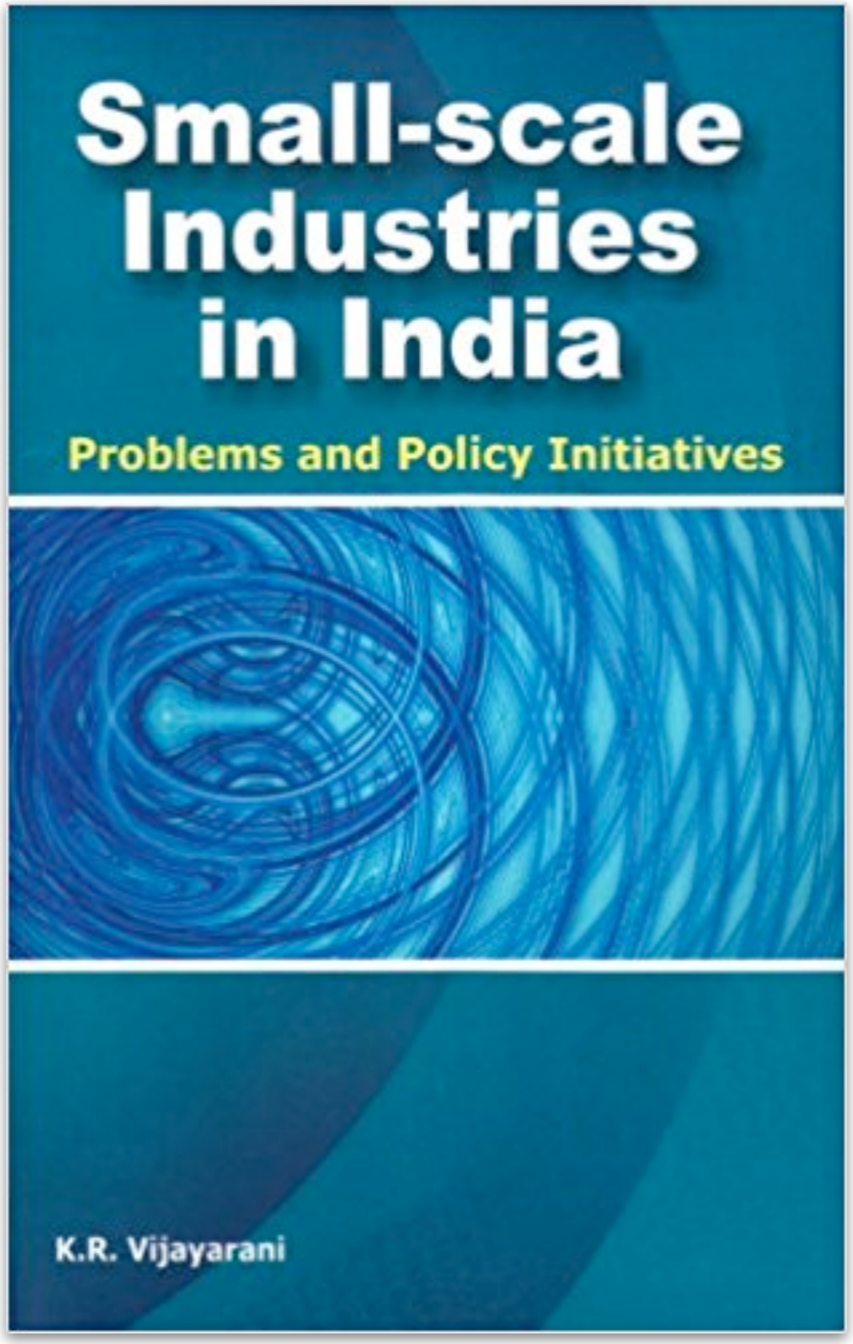
$$Y_\infty \simeq \int_{x_0}^{\infty} dx' \frac{x'\, s\,\langle\sigma v\rangle}{H(m)} Y_{\rm eq}^2$$

- 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…)

Part II: Problems at small scales? (and related industry)



very quickly, previously covered

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.

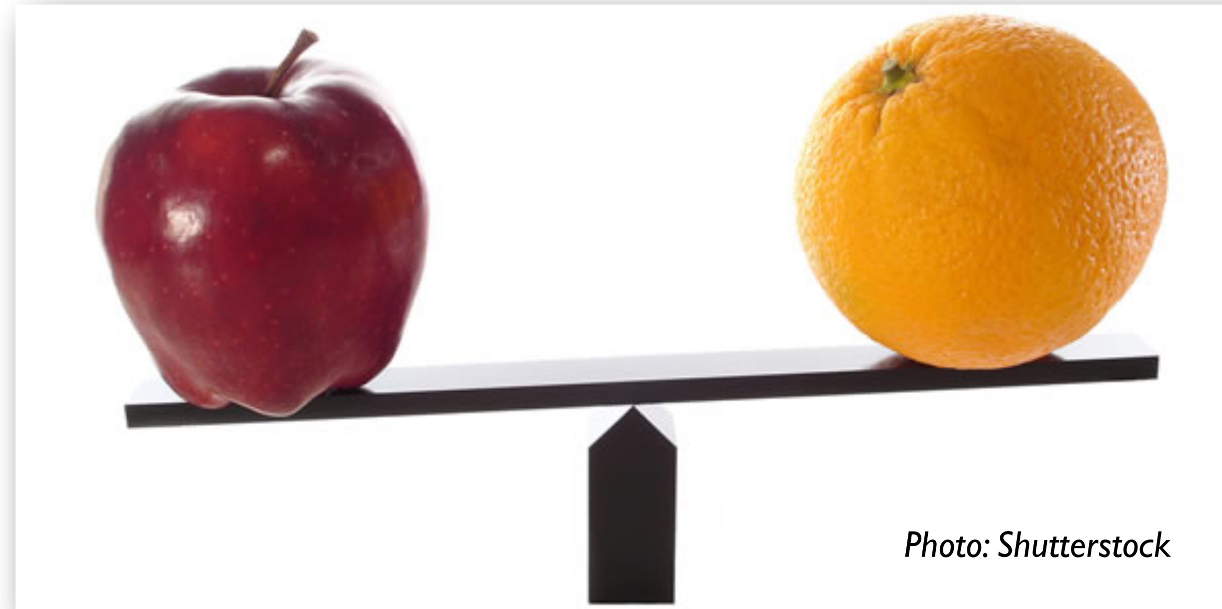
Within these limitations, some "expectations" obtained, for instance

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

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?

Problems

After a couple of decades of conferences, debates, & heated exchanges,
Big Surprise (?): naive comparison data vs DM simulation shows disagreements!



(In?)complete list of 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

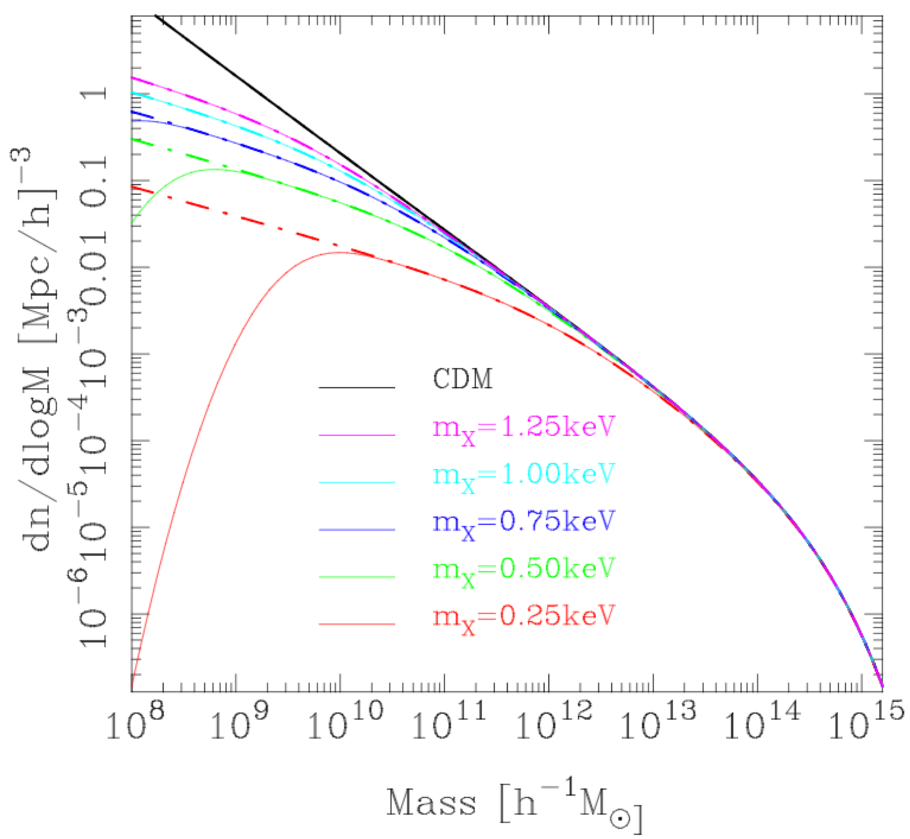
Option nr. 1
Baryons act non-trivially (+observations → interpretation issues)

Option nr. 2
Exotics: anything from "DM is a flawed idea" (*won't deal with it here*) to "special DM properties".

Option II: Could it be due to DM microphysics?

CAVEAT: what happens to baryonic effects in this context? They can't just disappear…

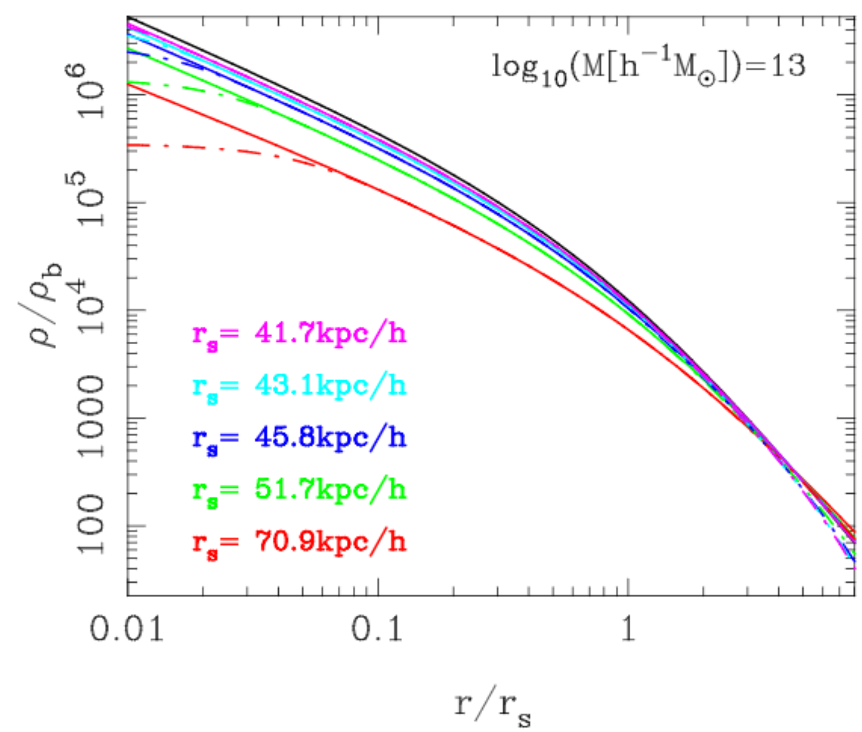
People tried with "warm thermal DM", of course!



remember the plots from

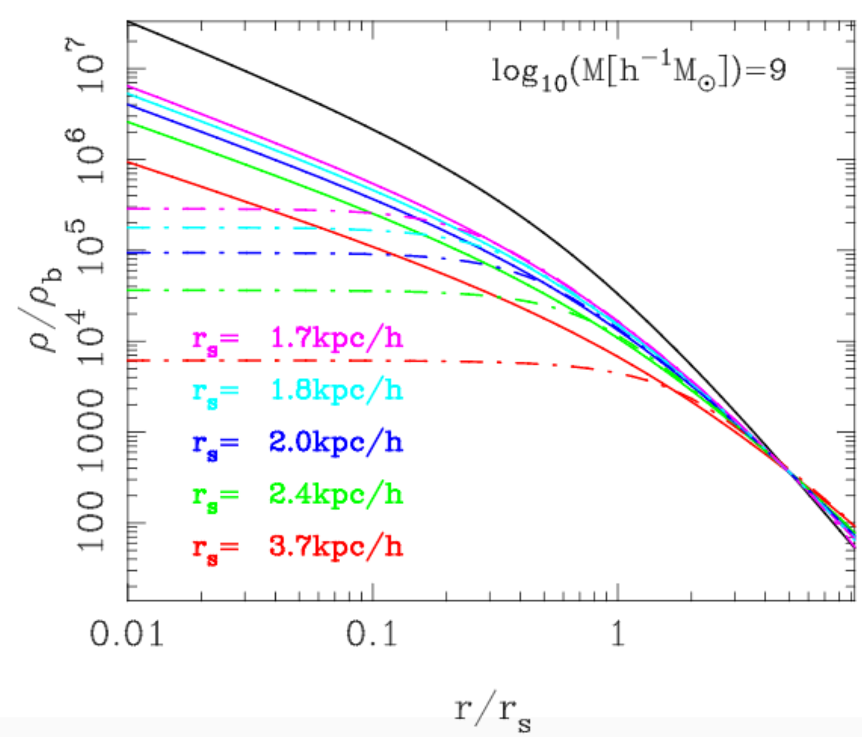
R. E. Smith & K. Markovic, PRD 84, 063507 (2011)[1103.2134]

that I showed you previously



It turns out that values of P(k) suppression having sizable impact on halo profiles (i.e. produce cores) would be in disagreement with the halo mass function well above the low-mass cutoff *e.g. Di Maccio et al. 2013*

Halo mass function tells you that **DM can't bee too warm!**



Usually you can solve or two problems but need to invoke something else to address the other(s)

(covered earlier this afternoon)

Lately… the Dark (Matter) Force awakens?

In particular, phenomena could be linked to strong DM-DM elastic scattering* (**$\sigma/m \sim 1$ cm²/g=1.8 b/GeV**)
(*some alternative proposal at the end…)

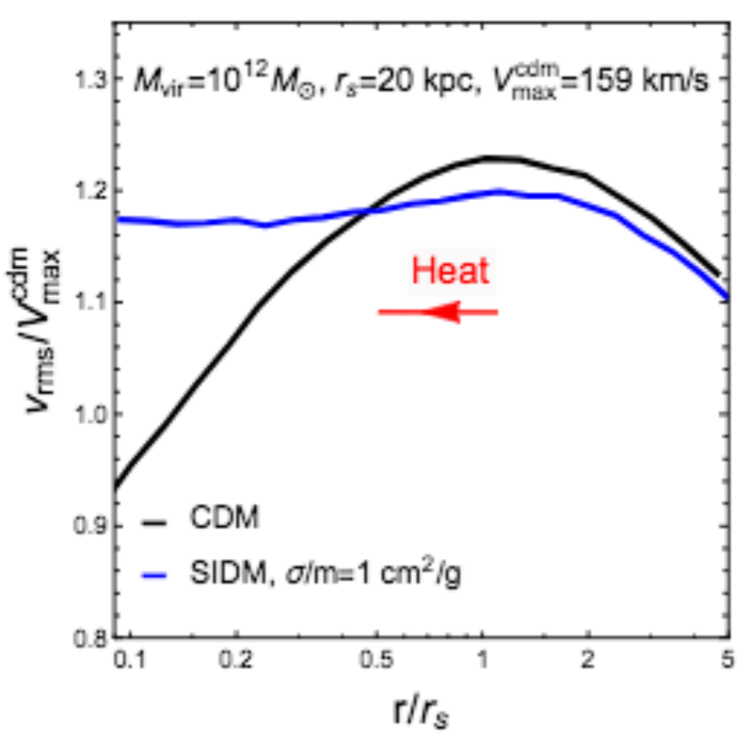
Idea of **Self-Interacting DM** goes back to:

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

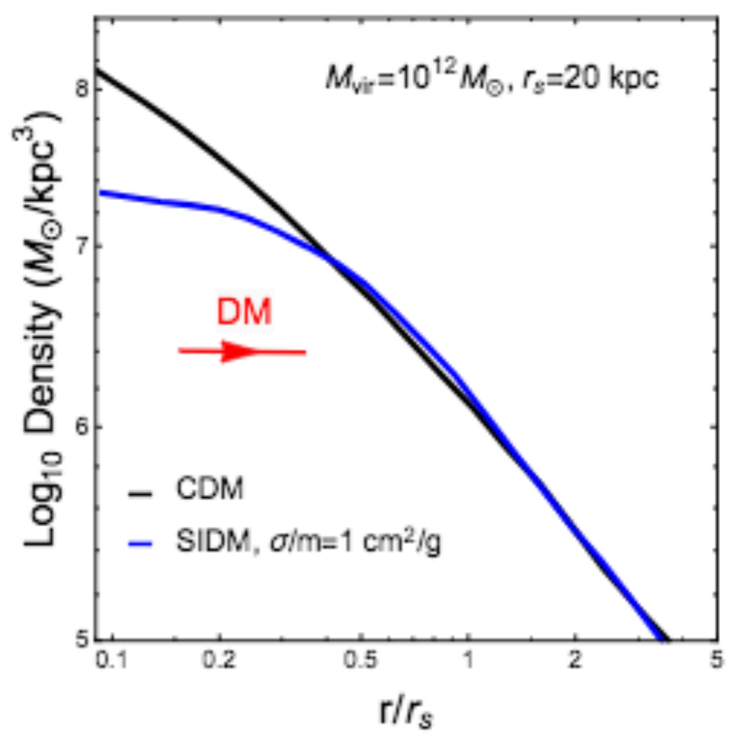
Major revival (talking about sequels) in recent years, for a review & refs.

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

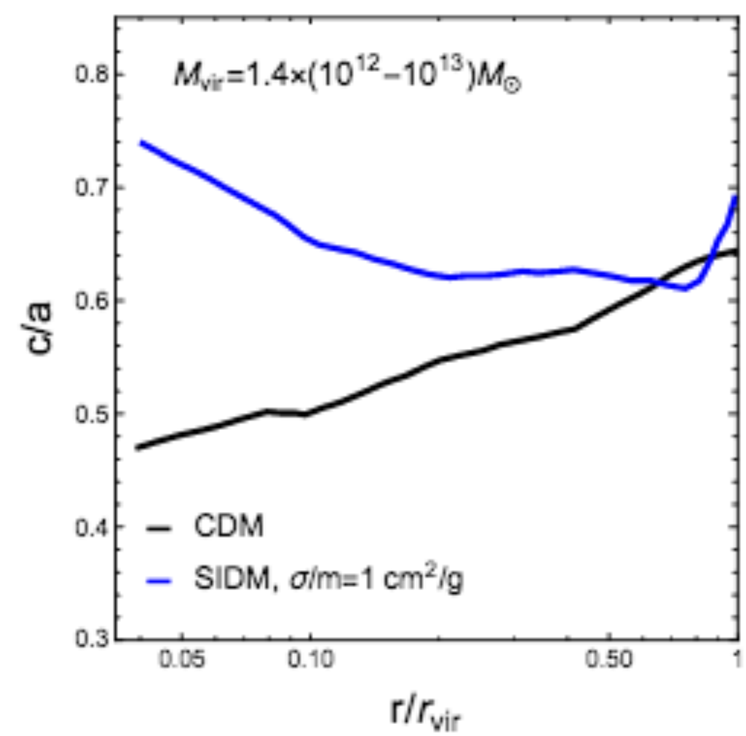
In inner halos, scatterings lead to DM "thermalization"



more uniform & isotropic v-dispersion



cored profiles & suppressed DM density



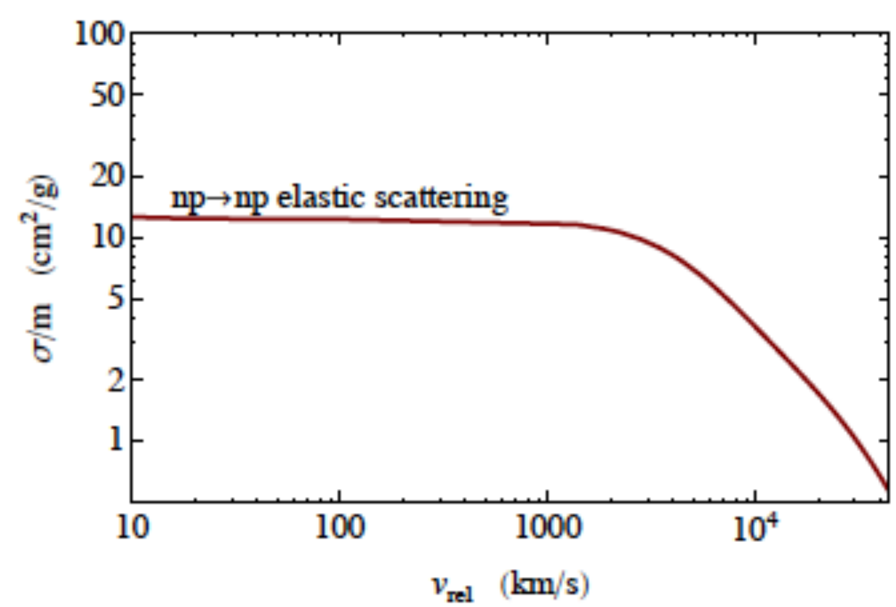
more spherical inner halos

Observational constraints require $\sigma=\sigma(\mathbf{v})$

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

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

One can in principle get large xsec 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*

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

but then problems start, both model-ind. and model-dependent ones:

i) No velocity dependence (either excluded by clusters, or no effects on cores…)

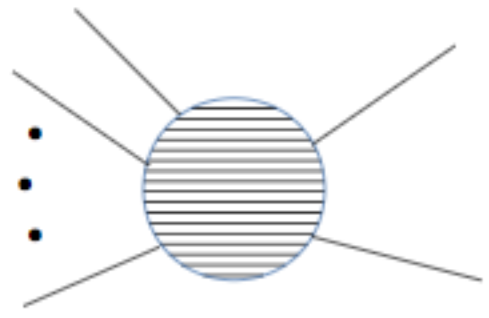
Can be embedded e.g. in a singlet scalar DM with Z_2 symmetry

$$V = \mu_S^2\, S^2 + \lambda_S\, S^4 + \lambda_{HS}\, |H|^2\, S^2$$

ii) Cannot be produced as WIMP (*must annihilate into fermions via Higgs portal, the invisible Higgs b.r. bound implies way too low annihilation rates → overclosure*)

Fixing ii) with alternative production mechanism: *cannibalism*

N→2 processes among DM dominate



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]*

But requires delicate balance:
chemical freeze-out via 3→2 requires 2→2 towards SM suppressed

but must be in *kinetic* equil. with SM (otherwise "hot" DM); achieved via portal operator with *different* scale

Concrete realizations within strongly interacting theories
(Pion-like DM from non-Abelian theory, e.g. Sp(Nc), Nf≧2)

Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky, J. G. Wacker, PRL115, 021301 (2015) [1411.3727]

The operator responsible for cannibalism is the analogous of the Wess-Zumino-Witten term in QCD

But no v-dependence, yet! Problem i) not touched

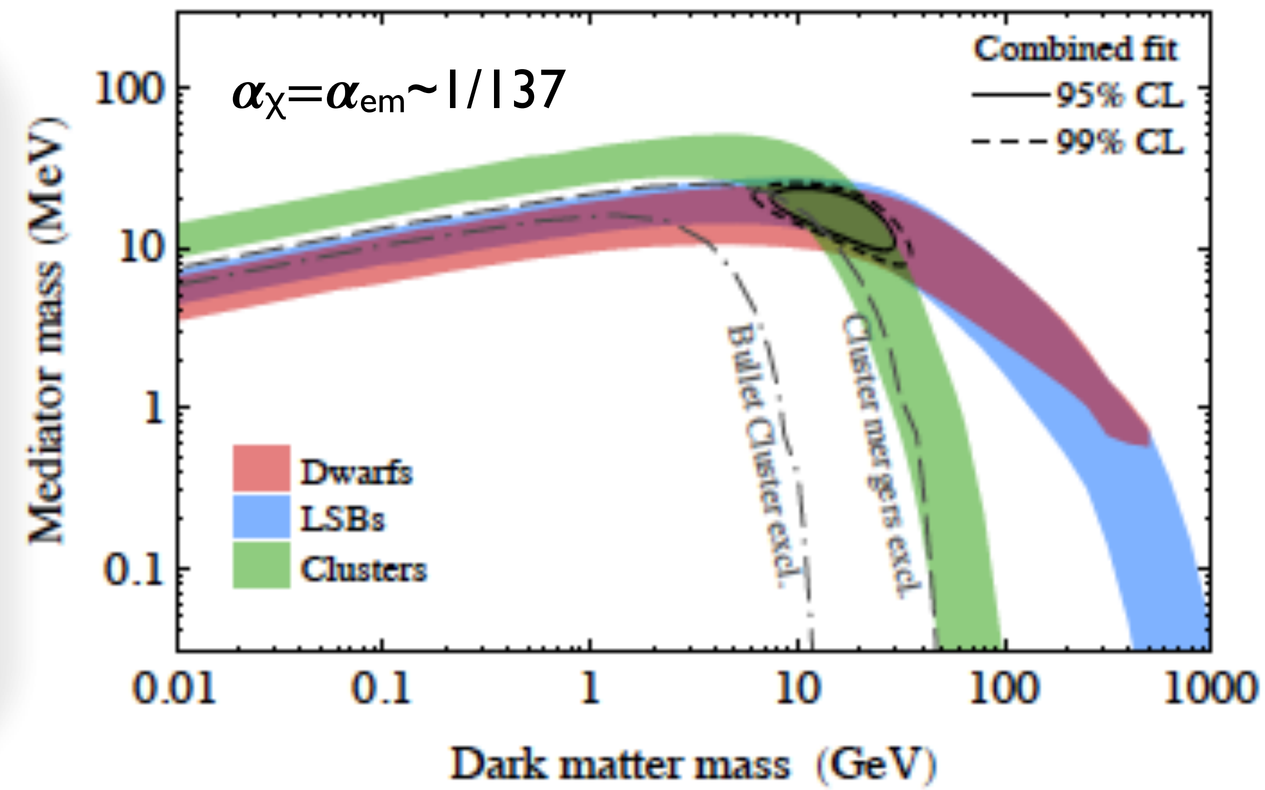
v-dependence require at least 2 dofs/scales!

E.g. scalar interaction with a light mediator ϕ

$$\mathcal{L}_{\rm int} = g_\chi \bar{\chi}\chi\phi \qquad \alpha_\chi \equiv \frac{g_\chi^2}{4\pi}$$

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

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

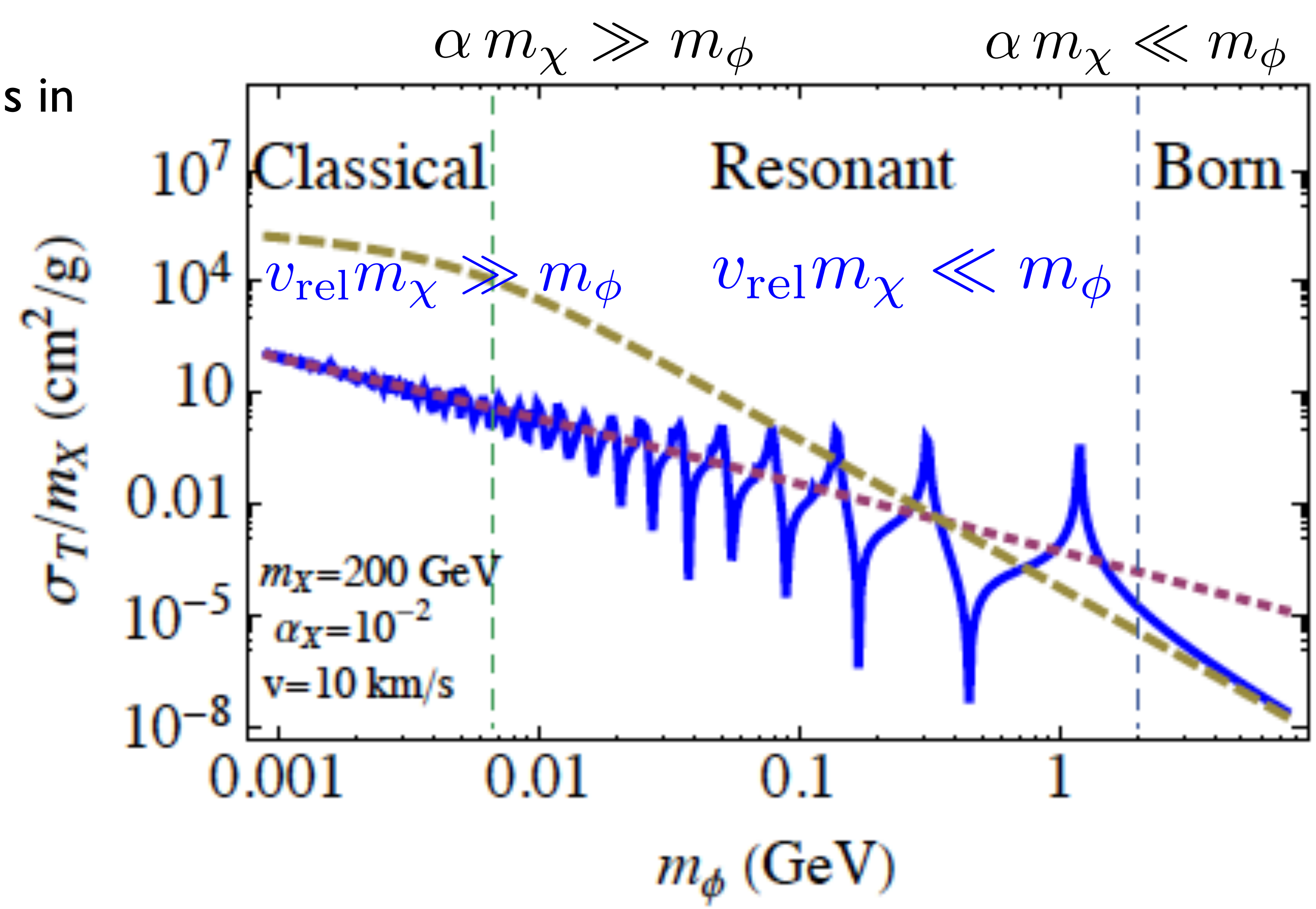


more general approach on type of eff. potentials in

B. Bellazzini, M. Cliche and P. Tanedo, "Effective theory of self-interacting dark matter," PRD 88, 083506 (2013)[1307.1129]

Systematic exploration of regimes for light mediators

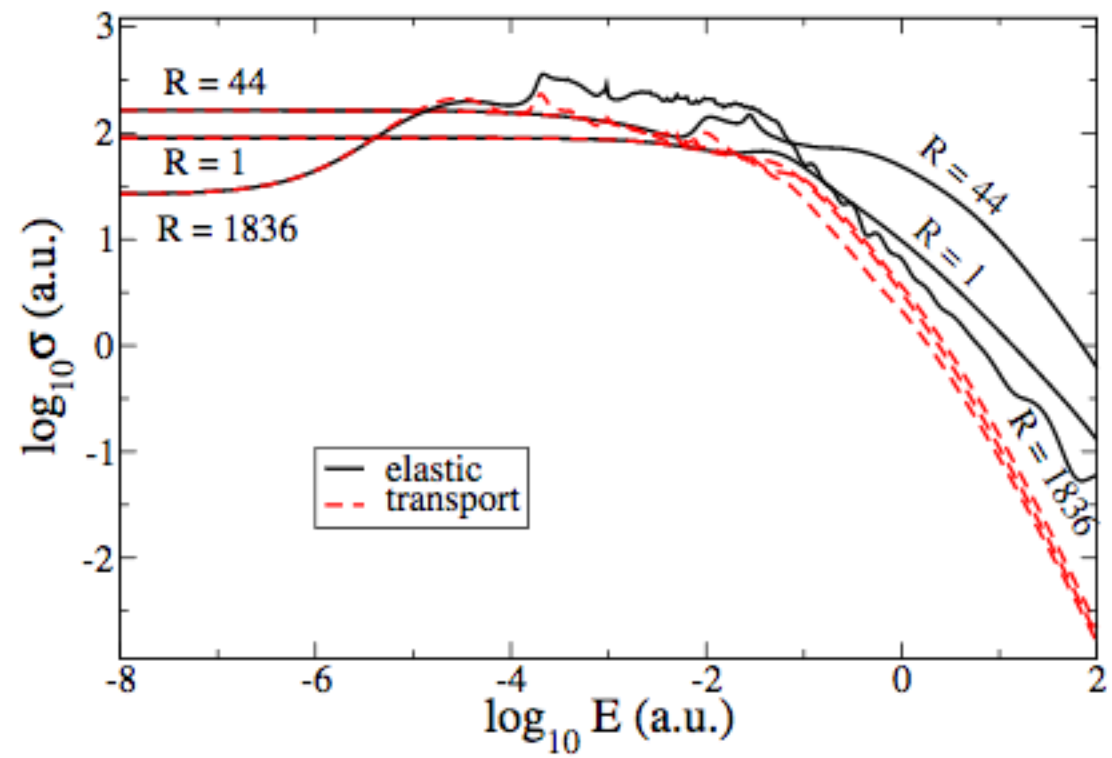
S. Tulin, H. B. Yu and K. M. Zurek, PRD 87, 115007 (2013)[1302.3898]



Detour: (Quasi-)massless mediators?

Naively: too steep xsec dependence (Rutherford) $\sim v^{-4}$

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

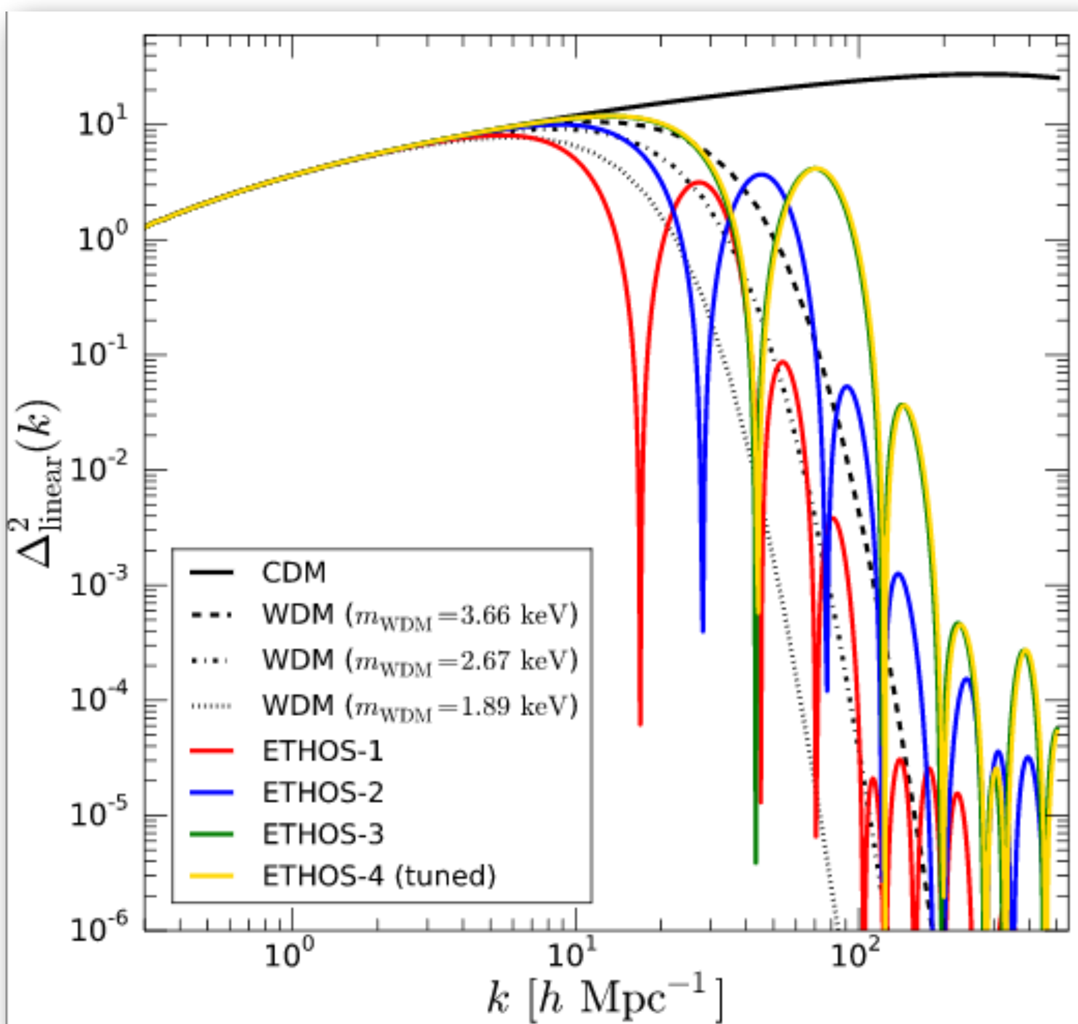
Dark Oscillations

The fraction of DM coupling to new BSM relativistic particles:

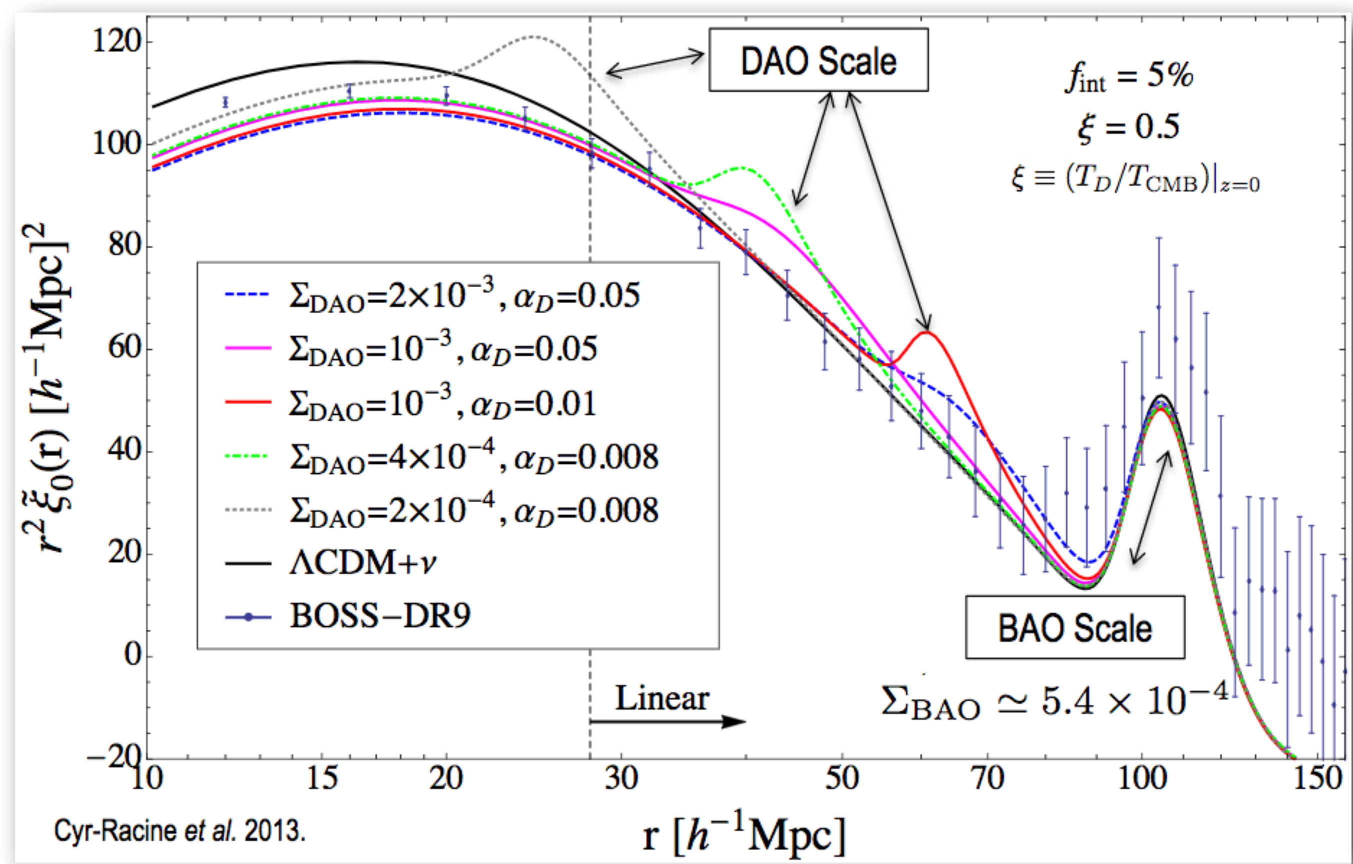
i) leads to non-vanishing sound speed & provides pressure support against gravitational collapse
ii) Has a relatively late epoch of kinematic decoupling

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

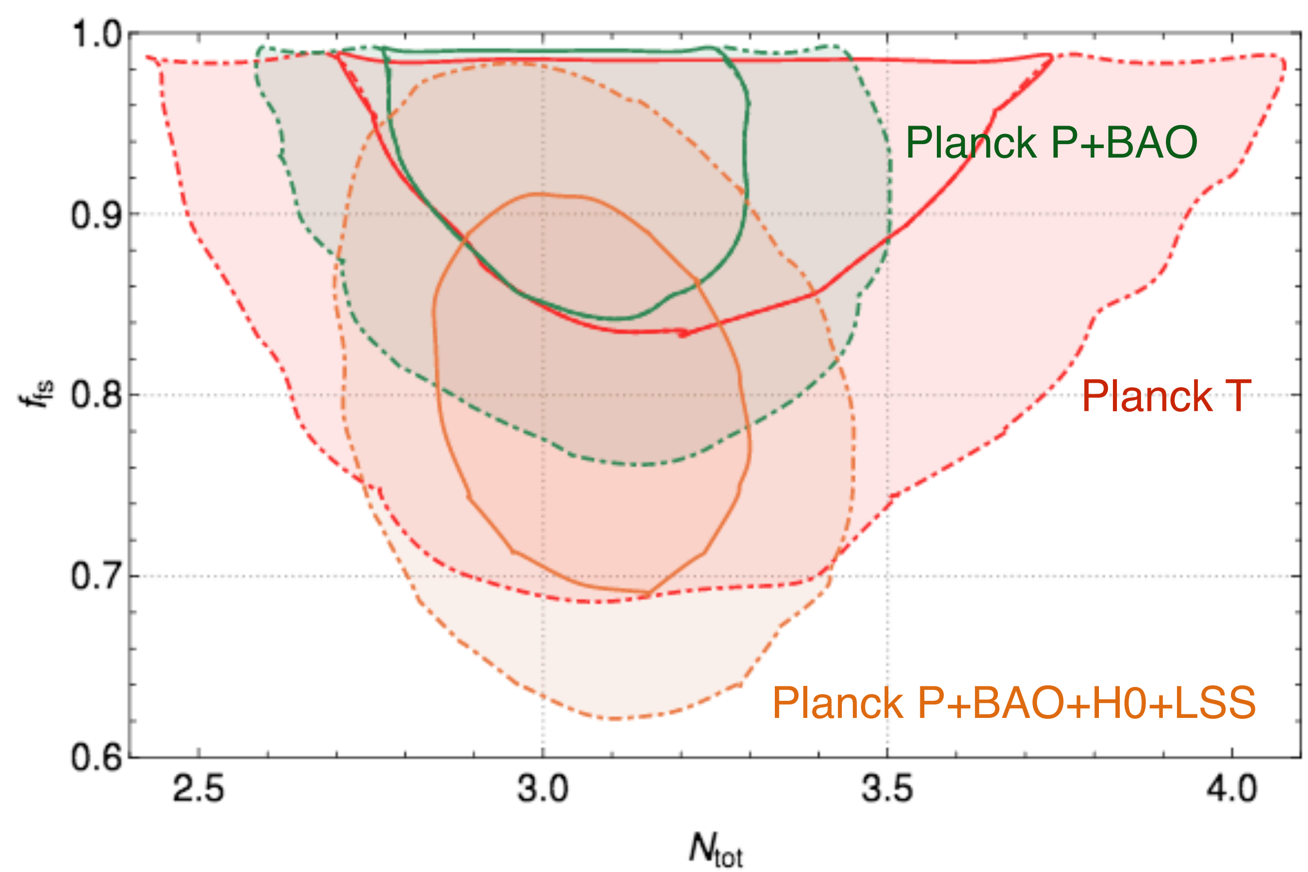
The light/massless mediator is typically stable or very long-lived, contributing to the amount of relativistic degrees of freedom (Dark Radiation) in the early Universe, and is subject to constraints from Big Bang Nucleosynthesis (BBN) and CMB

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…)

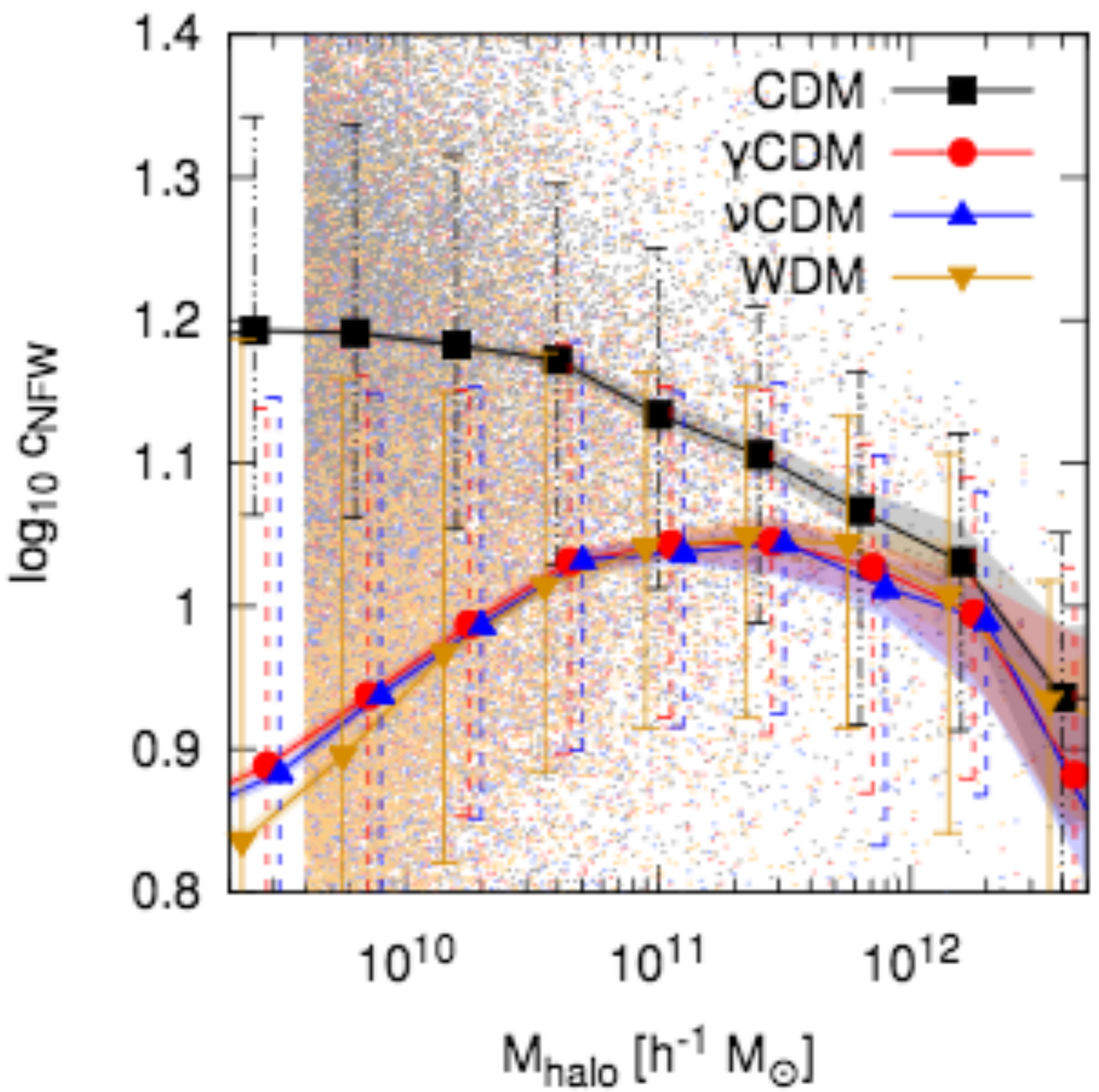


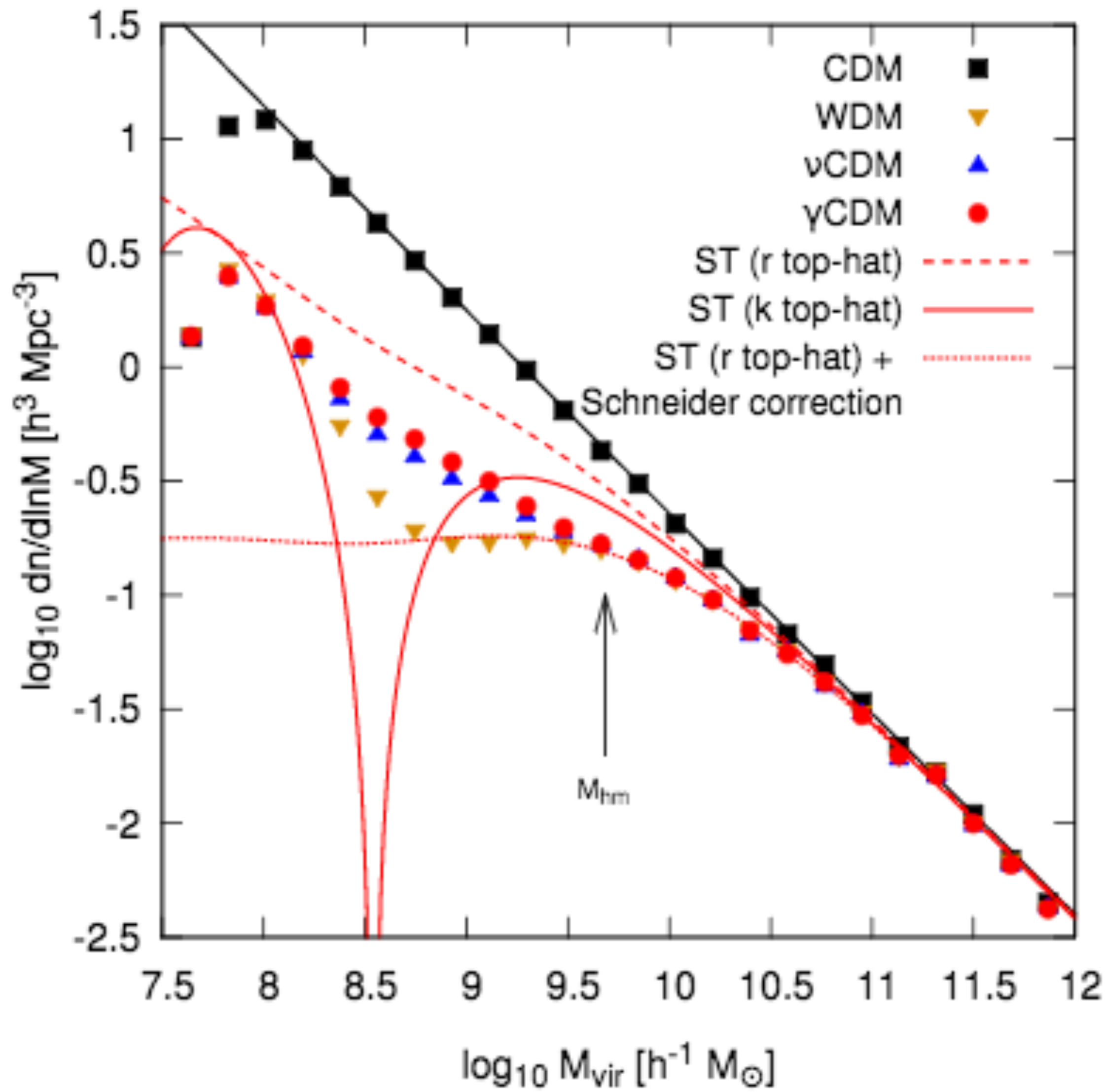
Or… DM coupled to SM "radiation"!?!

The relativistic particles DM couples to could be SM radiation, either photons or neutrinos:

C. Boehm et al, 1309.7588 (γ) 1401.7597 (ν) 1404.7012, 1412.4905 (simulations)

1) Cosmology provides best bounds; 2) there might be small-scale signatures





single halo properties only moderately different from CDM, e.g. slightly (~10%) reduced concentrations at low masses, essentially due to delayed formation

the halo mass function is significantly suppressed at small masses, and to some extent different from the WDM scenario

Alternative to light mediators? Strong interactions

strongly interacting analogues of atomic dark matter, e.g.: *K. Boddy, J. Feng, M. Kaplinghat, T. Tait, "Self-Interacting Dark Matter from a Non-Abelian Hidden Sector," PRD 89, 115017 (2014)[1402.3629]*

For another study see *J. Cline, Z. Liu, G. Moore, W. Xue, "Composite strongly interacting dark matter," PRD 90, 015023 (2014)[1312.3325]*

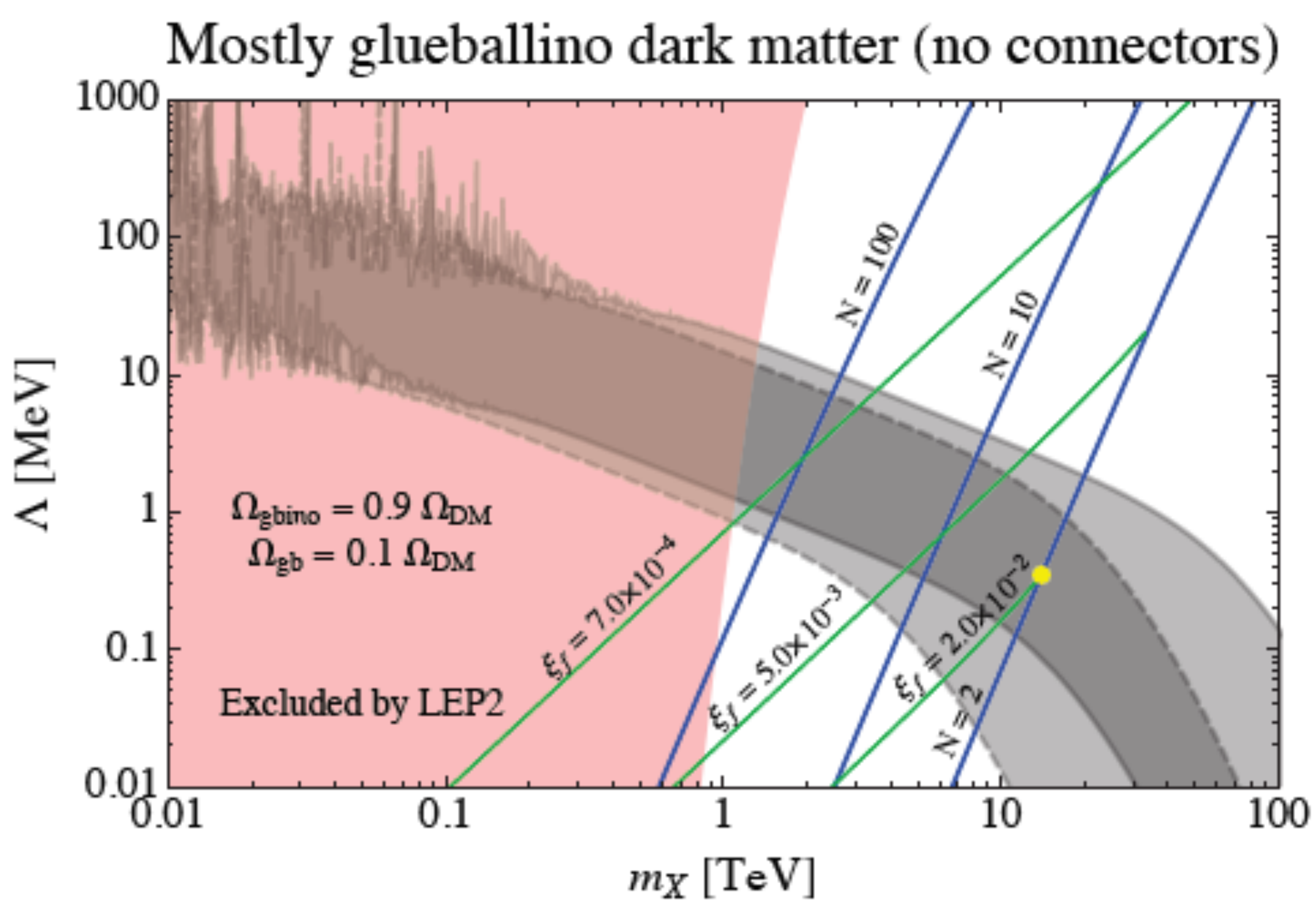
a) Pure non-Abelian gauge theory, confinement scale Λ~0.1-0.3 GeV. below Λ, DM are "glueballs" of mass ~Λ , with right scale for scattering

$$\sigma \simeq 4\pi/\Lambda^2$$

b) Add massive (>> Λ) gauge adjoint Majorana fermion.
Two types of composite particles:

- bosonic glueballs with mass ~Λ
- fermionic states with mass >> Λ, e.g. 10 TeV

Can be realized in a dark supersymmetric setup using anomaly-mediated SB & WIMPless miracle DM is mostly "glueballinos" interacting via "glueballs"



Notes

1. v-dependence obtained via the two scales
2. depends on a free parameter $\xi = T_{dark}/T_{visible}$
3. careful not to screw up BBN (e.g. extra radiation)!
4. glueball fraction interacts **very** strongly! Implications?
5. if another scale connecting with SM, im(com)plications

This path more **contrived & harder to study**. Quantitative statements may require lattice studies, see e.g.

G. Kribs & E. Neil, "Review of strongly-coupled composite dark matter models and lattice simulations," 1604.04627

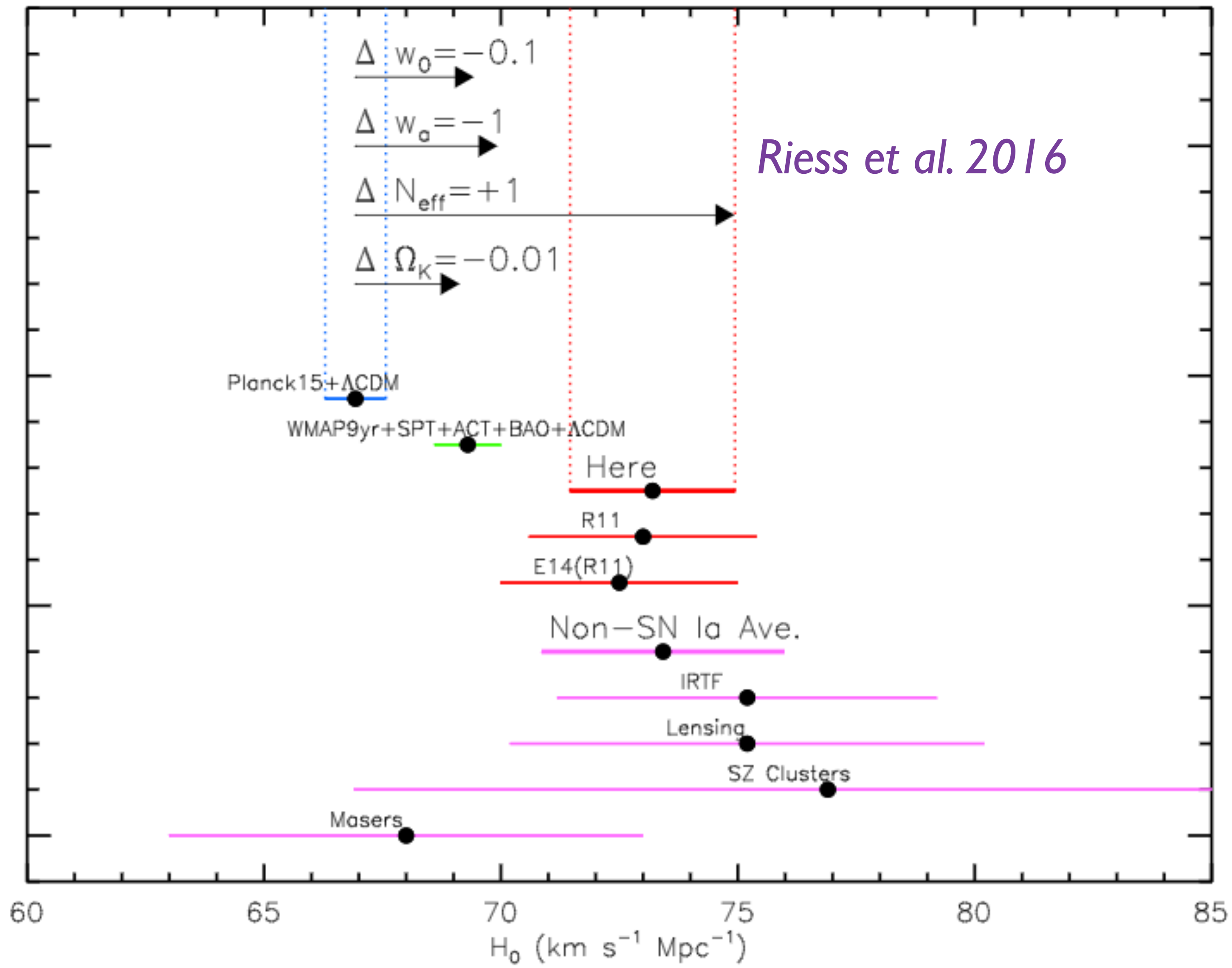
SIDM… for large scale anomalies?

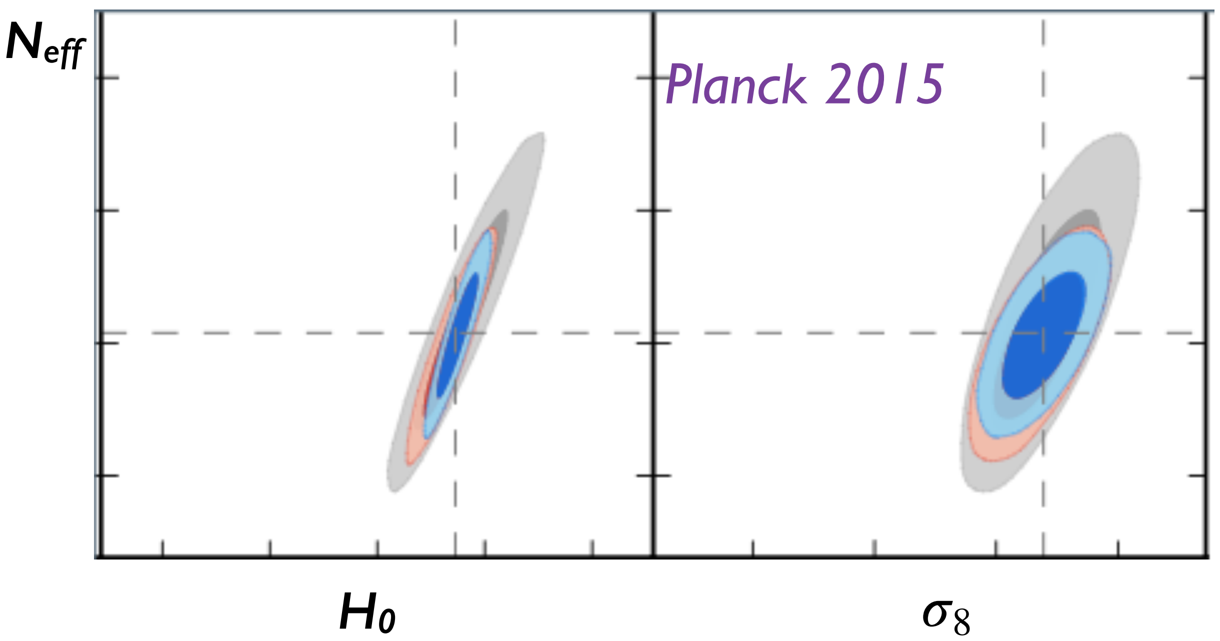
An issue with Hubble expansion rate? *(Again?!)*

Well-known tension between local (distance-ladder type, SN Ia) determinations of H_0 and cosmologically inferred ones, notably Planck.

one of the hottest topics in observational cosmology

Although some 1-parameter extension of ΛCDM might look superficially good (e.g. N_{eff}), it turns out that they screw up some other observable, e.g. σ_8 (correlations!)





even finding 2-parameter extensions that work is a non-trivial task!

e.g. we tried w decaying DM fraction (& failed) in *V. Poulin, PS, J. Lesgourgues, JCAP 1608, 036 (2016) [1606.02073]*

DM+DR rescuing Hubble?

Adding not only DR, but also a "drag" due to its coupling to DM, can solve the discrepancy!

Lower σ_8 without requiring lower H_0 or higher Ω_m : on the contrary compatible with higher H_0

J. Lesgourgues, G. Marques-Tavares and M. Schmaltz, "Evidence for dark matter interactions in cosmological precision data?," JCAP 1602, 037 (2016) [1507.04351]

Effective parameters:
drag rate $\Gamma=\Gamma_0(T/T^0_{cmb})^2$
extra rel. dof ΔN_{eff}

$$\begin{aligned}
\dot{\delta}_{\rm dm} &= -\theta_{\rm dm} + 3\dot{\phi} \\
\dot{\theta}_{\rm dm} &= -\frac{\dot{a}}{a}\theta_{\rm dm} + a\Gamma(\theta_{\rm dr} - \theta_{\rm dm}) + k^2\psi \\
\dot{\delta}_{\rm dr} &= -\frac{4}{3}\theta_{\rm dr} + 4\dot{\phi} \\
\dot{\theta}_{\rm dr} &= k^2\frac{\delta_{\rm dr}}{4} + k^2\psi + \frac{3}{4}\frac{\rho_{\rm dm}}{\rho_{\rm dr}}a\Gamma(\theta_{\rm dm} - \theta_{\rm dr})
\end{aligned}$$

Specific models e.g. *M.A. Buen-Abad, G. Marques-Tavares and M. Schmaltz, PRD 92, 023531 (2015) [1505.03542]*
DM= Dirac fermion, neutral component of $SU(2)_{weak}$ triplet ("Wino-like" DM, WIMP) transforms in the fundamental rep. of dark SU(N) gauge group, whose "gluons" constitute the DR
(dark gauge coupling is so small that SU(N) confines at scales much larger than size of the visible universe)

$$\Delta N_{\rm eff} \simeq 0.07(N^2 - 1)$$

$$\Gamma_0 \simeq 1.9 \times 10^{-7}{\rm Mpc}^{-1}\left[\frac{N^2-1}{3}\right]\left[\frac{\alpha_\chi^2 \log\alpha_\chi}{2\times 10^{-16}}\right]\left[\frac{1.2\,{\rm TeV}}{M_\chi}\right]$$

***Note:* couplings much smaller than what needed to address small scale problems**

Final comments

“Mass (Colder Darker Matter)”
Cornelia Parker 1997

Alternative small-scale fix: Quantum DM effects

Fuzzy Dark Matter: extremely light bosons ($m \sim 10^{-22}$ 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

More and more refined studies appearing, e.g. simulations inclusion of baryonic effects in *J. Chan et al. 1712.01947*

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 cm^2/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 *(at what price?)*

- 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 DE?

Beyond gravitational signatures

It is possible that the DM sector is not completely secluded from the SM
(coverage of implications would require at least another talk!)

1) For phenomenological reasons: to get viable cannibal models "with portals", to gain extra signatures…

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]

BBN, CMB spectral & angular distortions, X-ray/gamma-ray put most severe constraints to these scenarios. Beware of the risk of too large Higgs $\to$ invisible (notably if kinetic eq. with SM required)

Main drawback: even when they work, "extra scale(s)" put by hand.

2) For theoretical desiderata, e.g. "co-genesis" mechanisms for DM and baryon production via "asymmetry"

K. Zurek "Asymmetric Dark Matter: Theories, Signatures, and Constraints," Phys. Rept. 537 91 (2014) 1308.0338

Must make sure that the symmetric part of relic abundance is annihilated away! Requires large couplings and/or with light dark particles, hence the characteristic link of these models with **"strongly interacting"** DM and/or **"dark radiation/dark forces"**.

A specific scenario linked with leptogenesis: *A. Falkowski, J.T. Ruderman and T. Volansky, JHEP 1105, 106 (2011) [1101.4936]* See also *A. Falkowski et al. 1712.07652* for a case where annihilation $\sigma_{\rm ann}$ is not large enough

(Personal) Overview & Conclusions

From the particle physics point of view

Cosmology is sensitive to DM aspects particles colliders & direct detection are not very sensitive to, e.g.

- long-lived (BBN, CMBspectr., CMB anis., LSS)
- light (warm DM, dark radiation…)
- feebly interacting with SM (via non-thermal produc.)
- strongly self-interacting (even secluded from SM)
- DM quantum effects (fuzzy, BEC…)

From the cosmology point of view, these non-standard DM can be linked to

- ➡ altered initial power spectrum (e.g. Primordial Black Holes, not covered here)
- ➡ altered transfer function (e.g. warm DM, superwimps)
- ➡ altered structure formation process (e.g. "new forces" in the dark sector…)

Currently

Perhaps **intriguing hints** from small-scale anomalies, but extremely hard to get convincing arguments (need to understand-thus anyway include-baryonic effects; hard to disentangle!)

Would be important to get "perturbative" evidence (such as dark oscillations, extra dof…) or more direct "anomalies" (e.g. from lensing? Searches for baryon-less halos…)