Spectral distortions as a window beyond the WIMP paradigm

Pasquale Dario Serpico
(LAPTh - Annecy, France)

"Probing fundamental physics with CMB spectral distortions"

CERN, March 14th, 2018 *(Happy π day!)*

Outline of my talk

WIMPs

Why perspectives within the WIMP paradigm do not look good…

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Why perspectives within the WIMP paradigm do not look good…

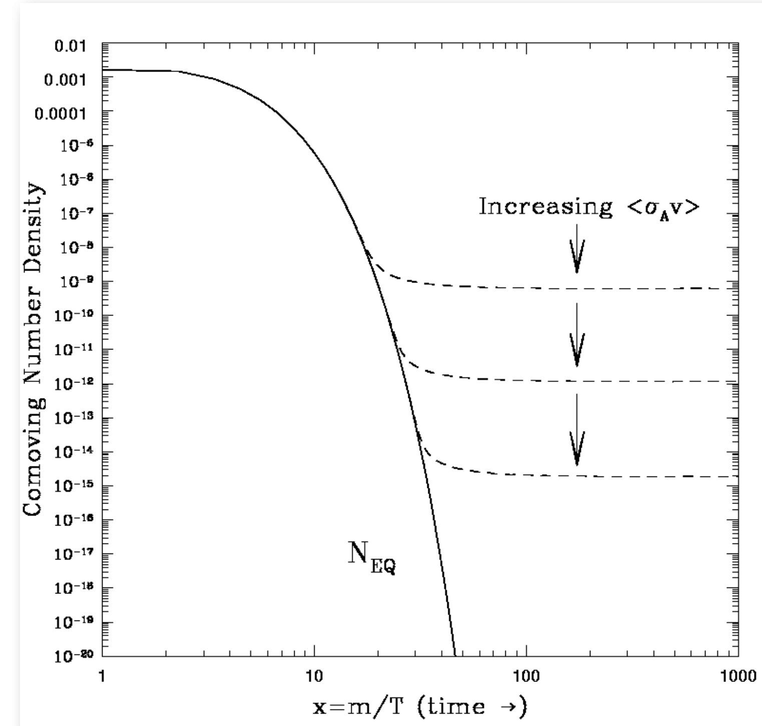
Part I: The Bad?

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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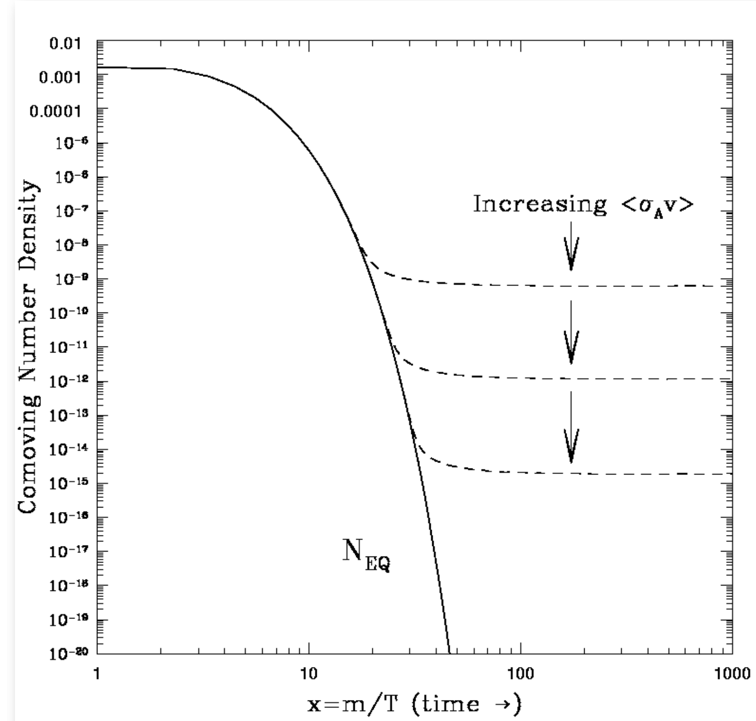


Textbook calculation yields the current average cosmological energy density

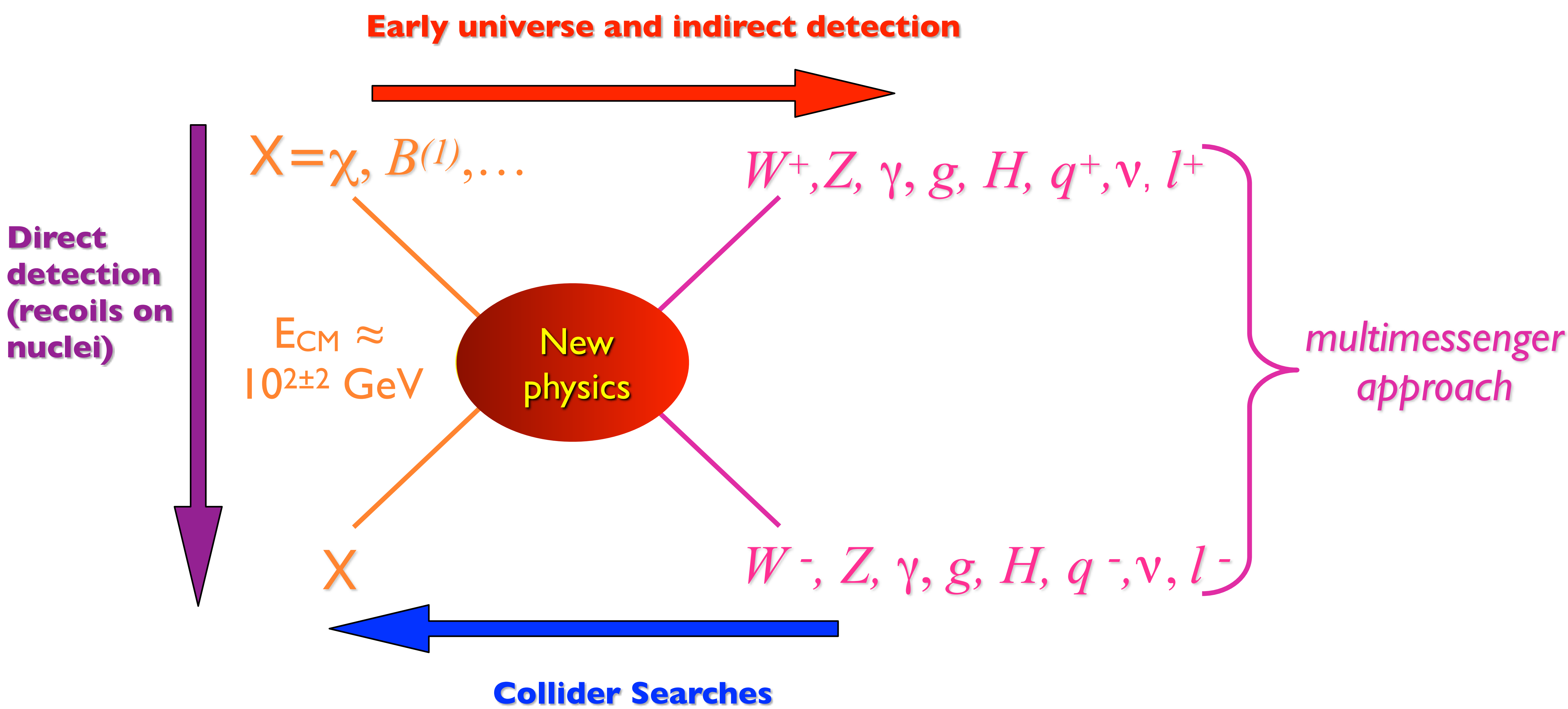
$$\Omega_X h^2 \simeq \frac{0.1\,\mathrm{pb}}{\langle \sigma v \rangle}$$

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 (and henceforth), 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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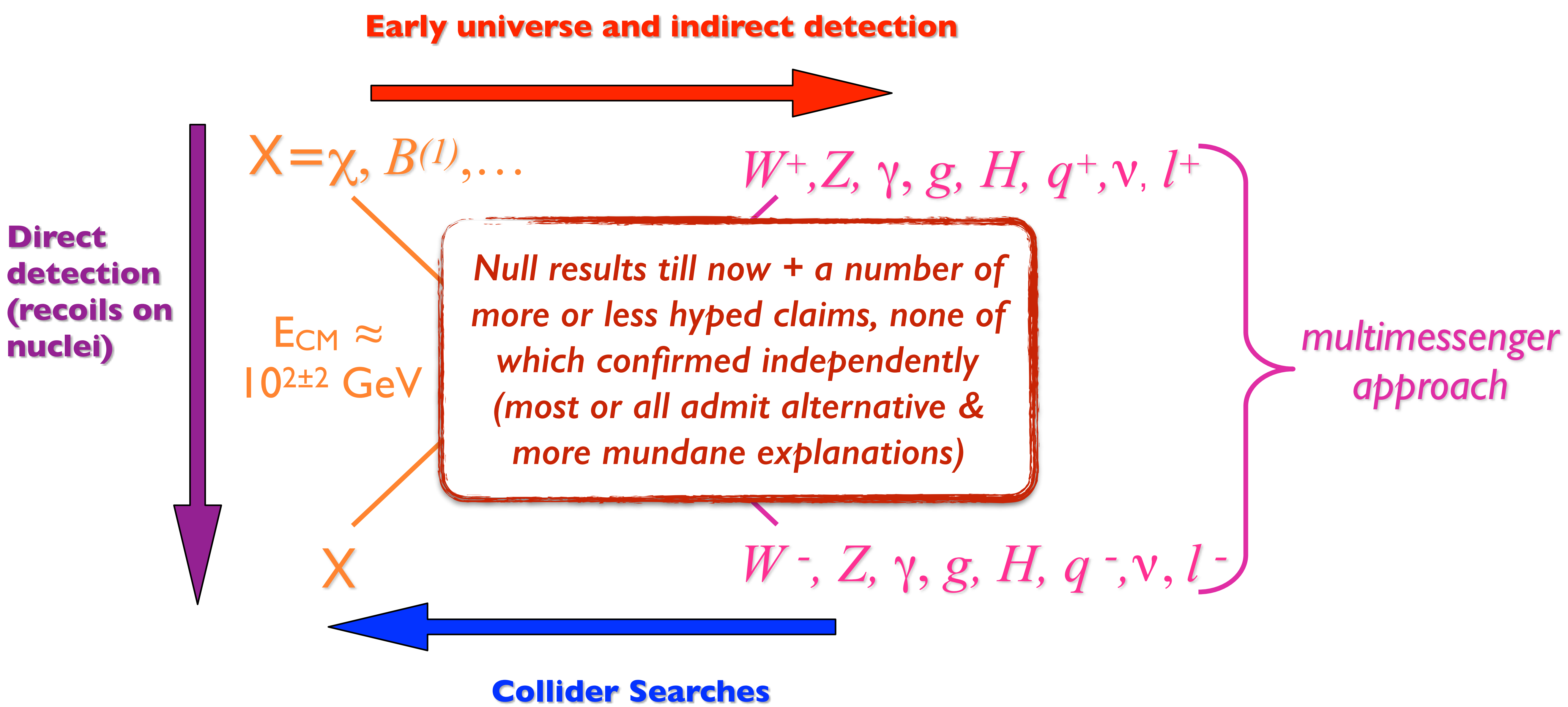

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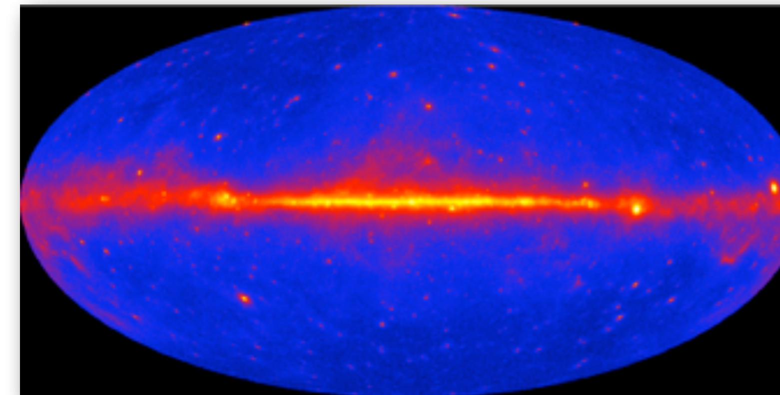
INDIRECT DM SEARCHES: MANY CHANNELS

each with advantages and problems: won't discuss details but for 1 case

- **Gamma rays**

☺ Retain directionality
☺ Relatively easy to detect
☹ A lot of backgrounds (known and unknown)
☹ Signal strongly depends on poorly known DM distribution

$$\Phi_\gamma(E_\gamma, \hat{\mathbf{n}}) = \left[\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma)\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right]\int_{\mathrm{los}} \rho^2(\ell, \hat{\mathbf{n}})d\ell$$



- **Neutrinos**

☺ Do not suffer significant absorptions
☺ Little (known) backgrounds
☺ Can probe spin-dependent ***capture*** cross-section: signal from Sun core!
☹ "Little" problem: hard to detect!

- **Charged cosmic rays**

☺ Different species: different sensitivity to signal & background

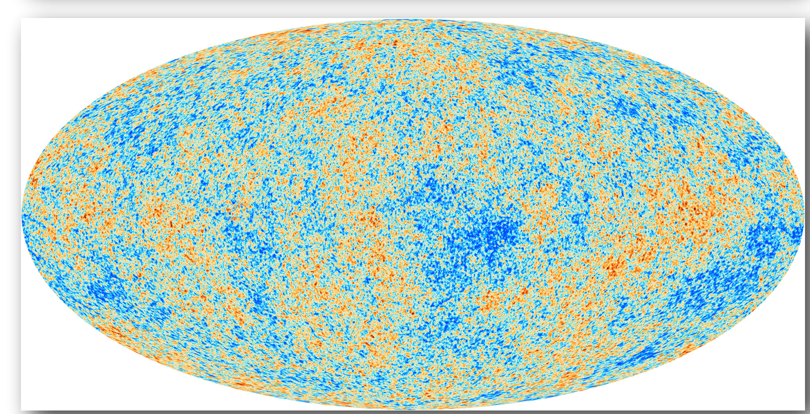
$$\Phi_a(E_a) = \left[\frac{dN_a}{dE_a}(E_a)\frac{\langle\sigma v\rangle}{8\pi m_X^2}\right]\mathcal{F}_a(E_a, \ldots)$$

☹ "Indirect" calculation: **Functional** of dN/dE, DM distribution & astrophysics!
☹ Current data precision not matched by a "standard CR model"
☹ No/Little directionality

- **CMB**

☺ ~independent of astrophysical uncertainties
☹ "Only" calorimetric…
☹ Close to saturation

$$p_{\mathrm{ann}} = \frac{\langle\sigma v\rangle}{8\pi m_X^2}[4\pi][2m_X]f(z)$$



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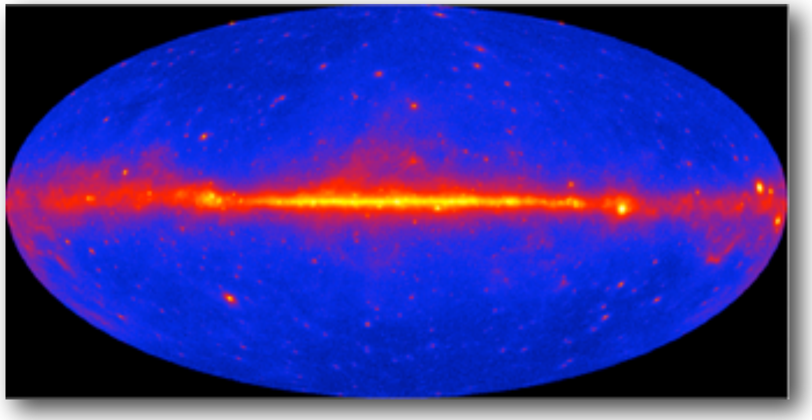

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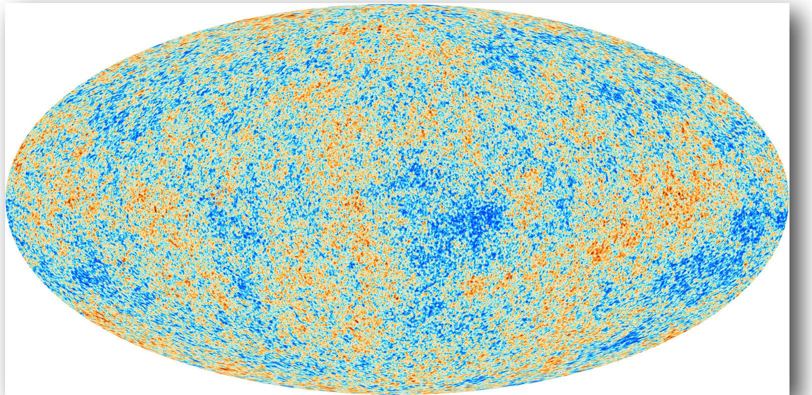


…

What do WIMPs do on CMB?

Via annihilation byproducts, they inject energy in the medium

$$\frac{dE}{dV\,dt} = \rho_c^2(1+z)^6\Omega_{\rm DM}^2\, p_{\rm ann}$$

key-parameter linked to particle physics

$$p_{\rm ann} = \frac{\langle\sigma v\rangle}{8\pi m_X^2}[4\pi][2m_X]f(z) = f(z)\frac{\langle\sigma v\rangle}{m_X}$$

To *some extent* injected energy can be used to **heat the medium** (**& excite/ionize** it, after recombination)

$$\left.\frac{dE}{dV\,dt}\right|_{{\rm dep},c} = \boxed{f_c^{(P)}(z,x_e)}\left.\frac{dE}{dV\,dt}\right|_{\rm inj}$$

CMB is sensitive to:

$x_e(z)$ & notably the overall optical depth experienced by photons: WIMPs can alter recombination & reionization

T_M & the heating: at early times via spectral distortions, at late times subleading (via feedback on $x_e(z)$, to which it is coupled)

Qualitatively, decaying or annihilating particles can have similar effects, but:

CMB spectral distortions & CMB anisotropies expected for WIMP DM annihilation are **linked**, since recombination & reionization effects directly related to heating & no "tunable" timescales available

Some seminal papers on this subject (pre-2008)

J.A. Adams, S. Sarkar, D.W. Sciama,
"CMB anisotropy in the decaying neutrino cosmology" MNRAS 301, 210 (1998) [astro-ph/9805108]

X. L. Chen and M. Kamionkowski,
"Particle decays during the cosmic dark ages," Phys. Rev. D 70, 043502 (2004) [astro-ph/0310473].

L. Zhang, X. Chen, M. Kamionkowski, Z. G. Si and Z. Zheng,
"Constraints on radiative dark-matter decay from the cosmic microwave background," Phys. Rev. D 76, 061301 (2007) [0704.2444]

P. J. E. Peebles, S. Seager and W. Hu, "Delayed recombination," Astrophys. J. 539, L1 (2000)

R. Bean, A. Melchiorri and J. Silk,
"Recombining WMAP: Constraints on ionizing and resonance radiation at recombination," Phys. Rev. D 68, 083501 (2003) [astro-ph/0306357] "Cosmological constraints in the presence of ionizing and resonance radiation at recombination," Phys. Rev. D 75, 063505 (2007) [astro-ph/0701224]

N.Padmanabhan and D. P. Finkbeiner,
"Detecting dark matter annihilation with CMB polarization: Signatures and experimental prospects," Phys. Rev. D 72, 023508 (2005) [astro-ph/0503486].

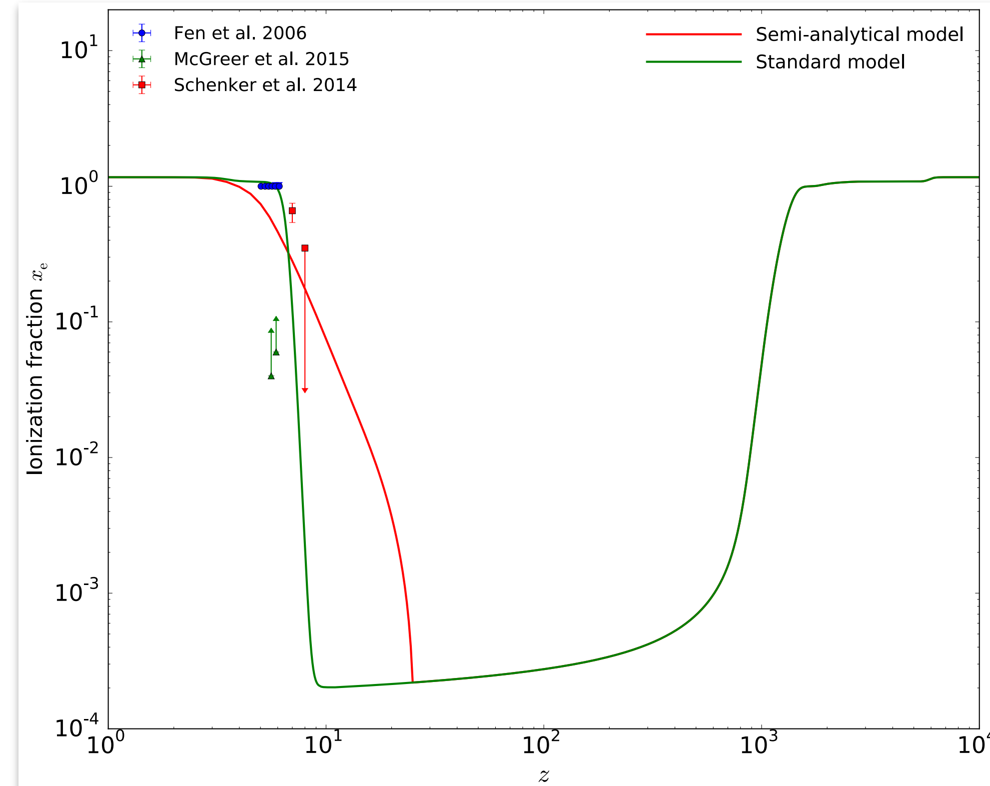
M. Mapelli, A. Ferrara and E. Pierpaoli,
"Impact of dark matter decays and annihilations on reionzation," MNRAS 369, 1719 (2006) [astro-ph/0603237]

L. Zhang, X. L. Chen, Y. A. Lei and Z. G. Si,
"The impacts of dark matter particle annihilation on recombination and the anisotropies of the cosmic microwave background," Phys. Rev. D 74, 103519 (2006) [astro-ph/0603425].

Dozens of relevant papers, in the last decade…

Why are CMB anisotropies such a sensitive probe?

Have a look at the standard ionization and gas temperature evolution



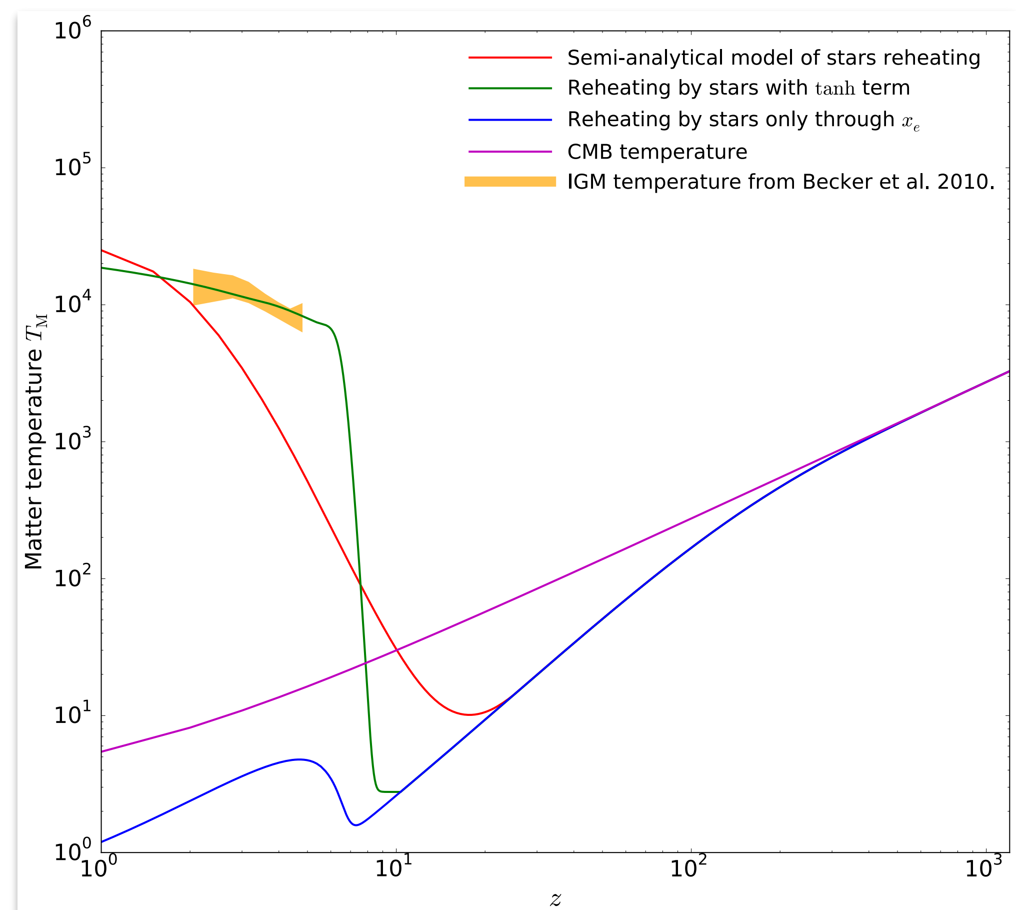
Note:

few tens of eV/baryons are in principle sufficient to ionize all atoms!

In the DM, in principle ~5 GeV/baryon "stored"

The reionization fraction in the standard expectation drops to ~ 5 10^{-3}

converting O(10^{-11}) of the energy stored into DM mass into visible form may be sufficient to induce major alterations in x_e or T_M!

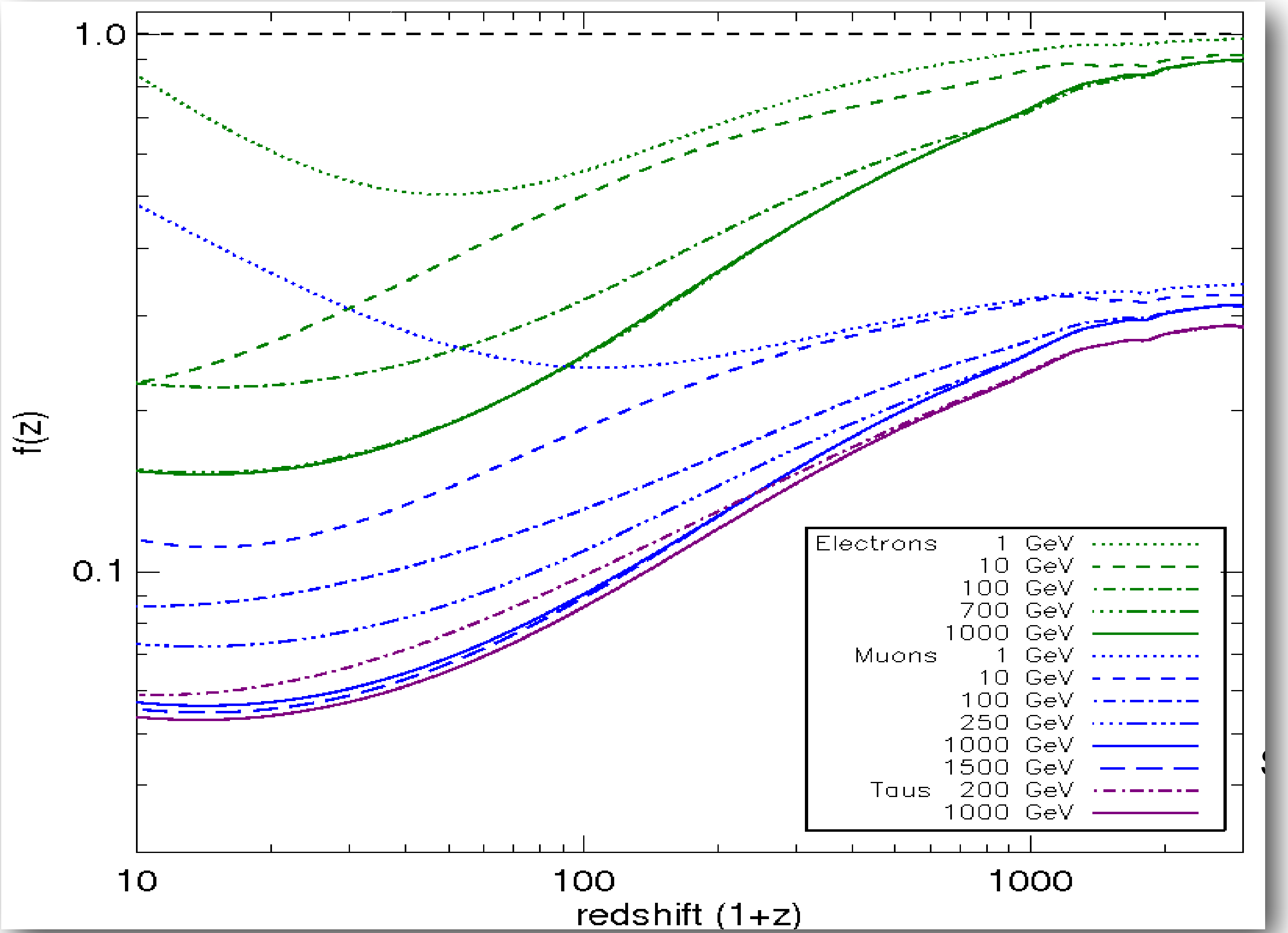


this maximal sensitivity is actually achieved, if energy is injected at/just after recombination

A crucial ingredient

energy deposition functions f_c depend on *cascade* (=*energy degradation/particle multiplication*) processes in the plasma/gas.
They vary with the process (ionization, heating…) and particle species.
Currently computed at O(10%)

Typically one finds $f_c(z)$~ few x 0.1

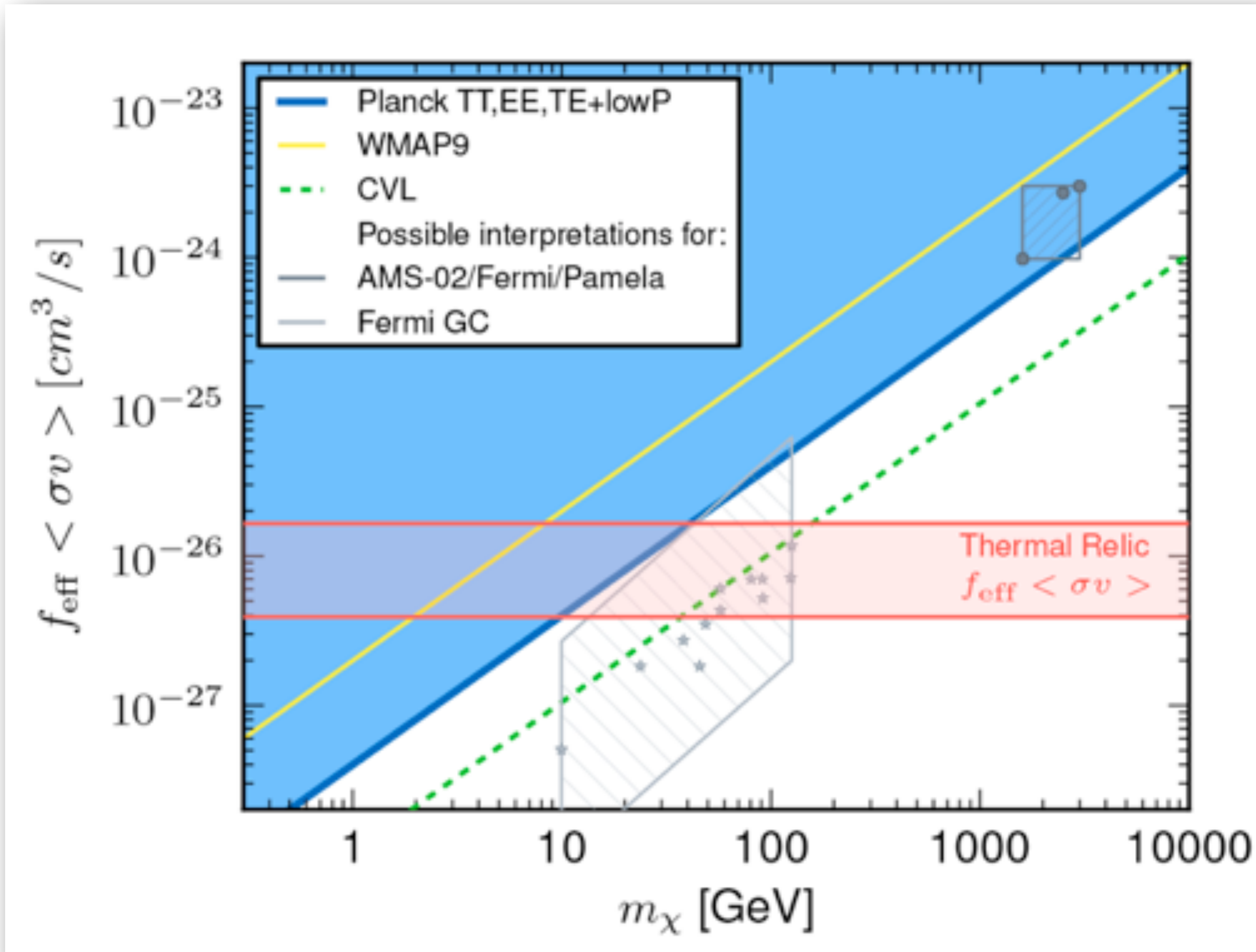


e.g. Slatyer et al. 2009

CMB anisotropy constraints on WIMPs

$$p_{\rm ann} \lesssim 4 \times 10^{-28} \frac{\rm cm^3}{\rm s\,GeV}$$

(Planck XIII, 2015)

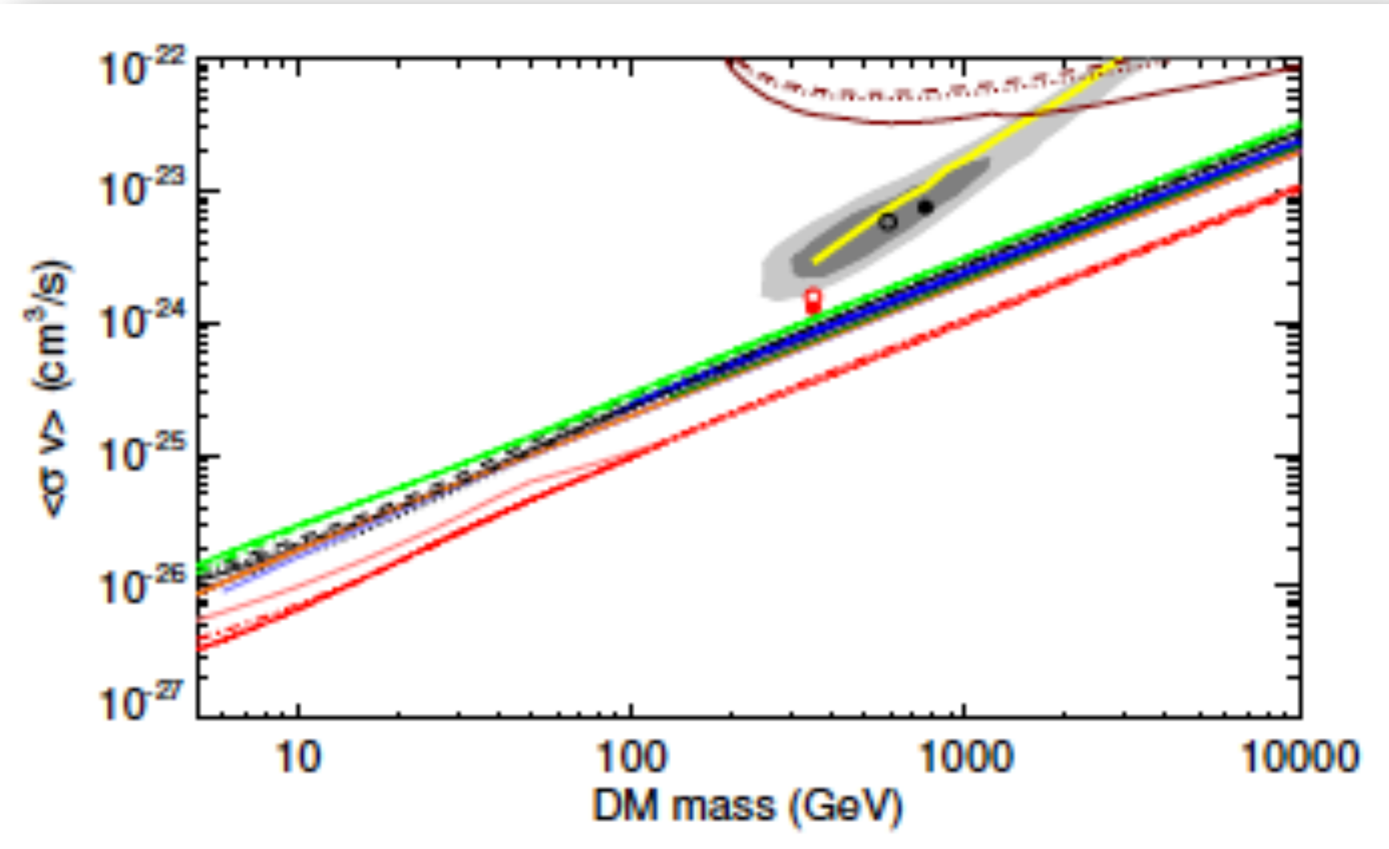


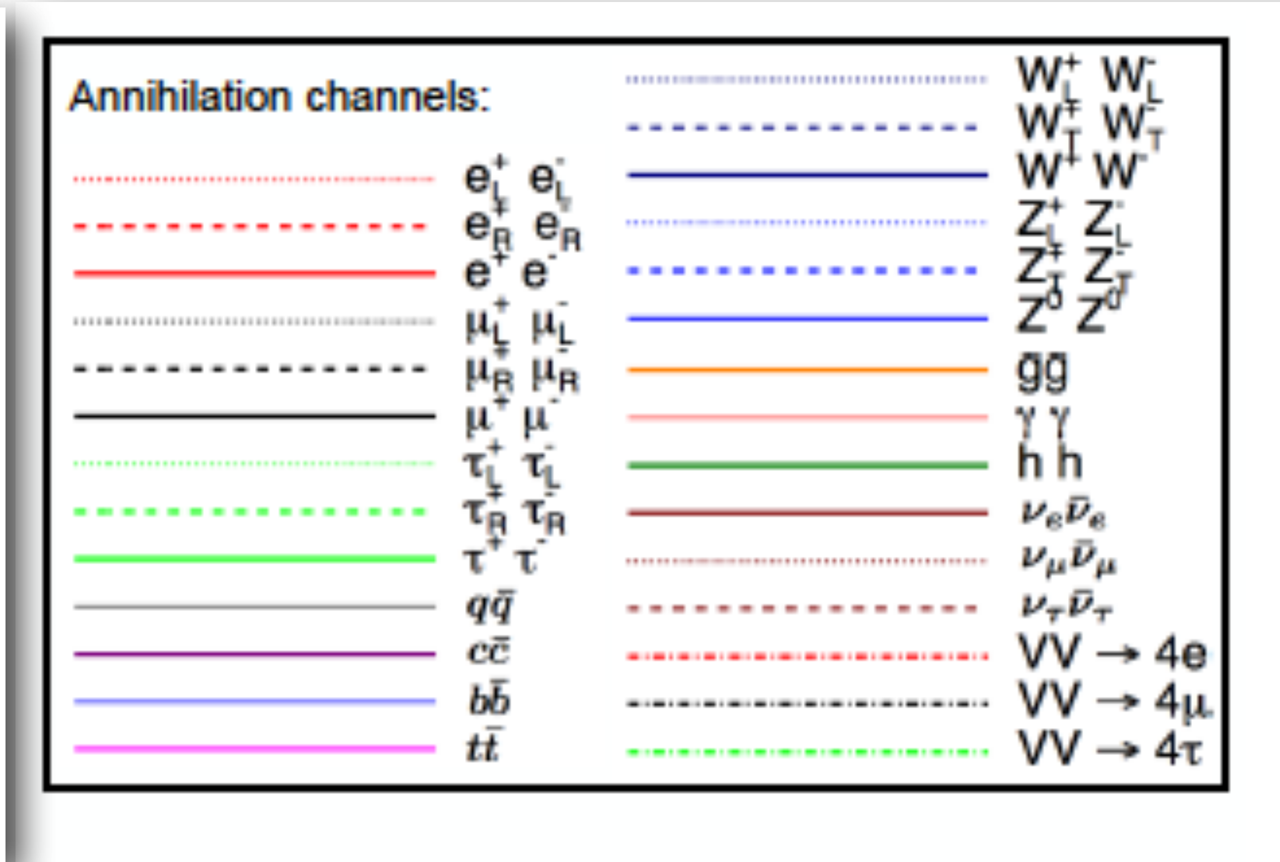
Same ballpark of "low-z", astrophysical constraints (~better for light leptonic final states, worse for baryonic ones)

among "key Planck results" announced on 01/12/2014 by S. Galli

It is *calorimetric* and quite robust, independent of astro details

More recent updates





In dedicated, consistent calculations, for dozens of models, even alone, CMB rules out annihilating DM as explanation of "PAMELA/AMS" positron excess!
(even neglecting other astrophysical constraints)

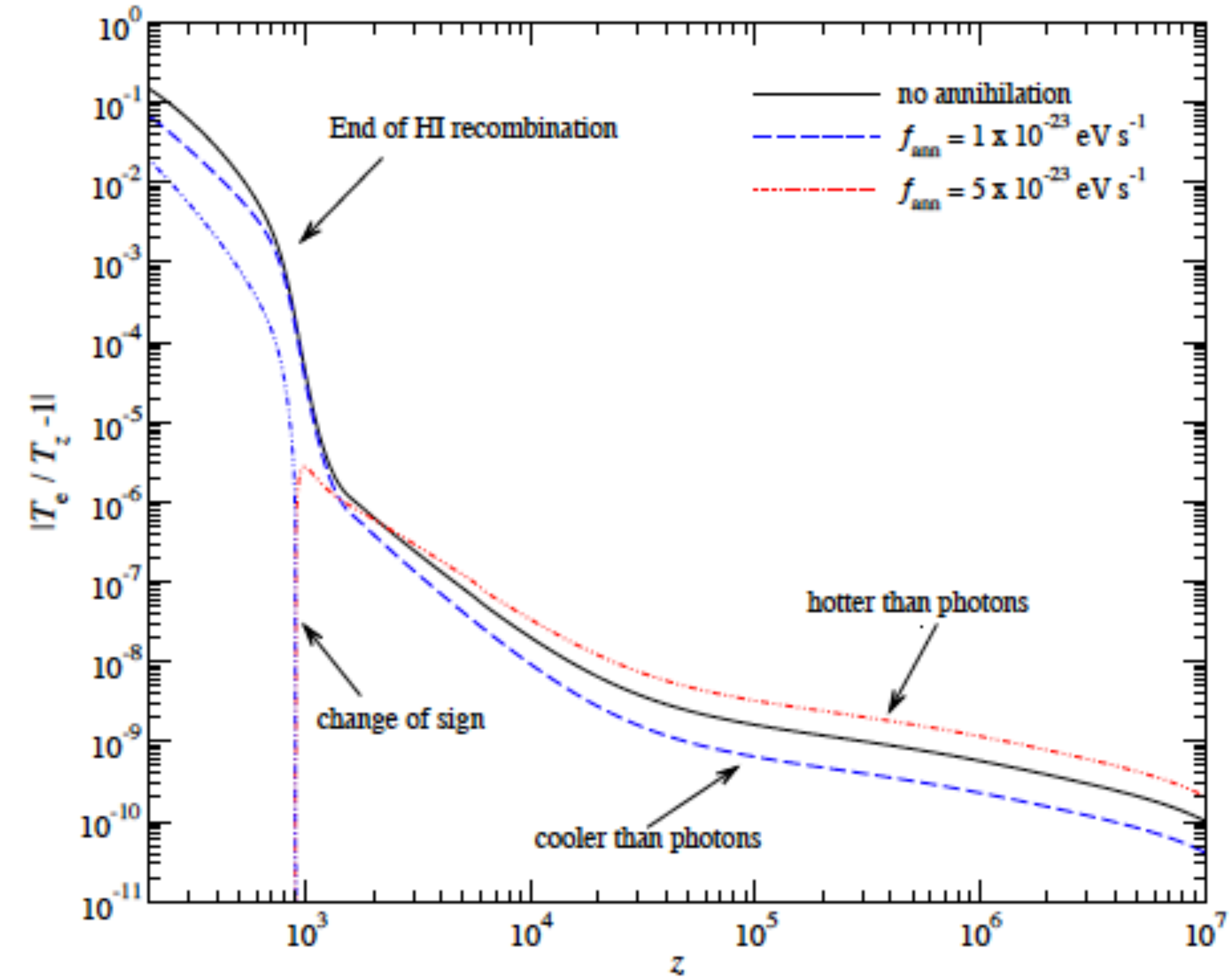
T.R. Slatyer, "Indirect dark matter signatures in the cosmic dark ages. I. Generalizing the bound on s-wave dark matter annihilation from Planck results," Phys. Rev. D 93, 023527 (2016) [1506.03811]

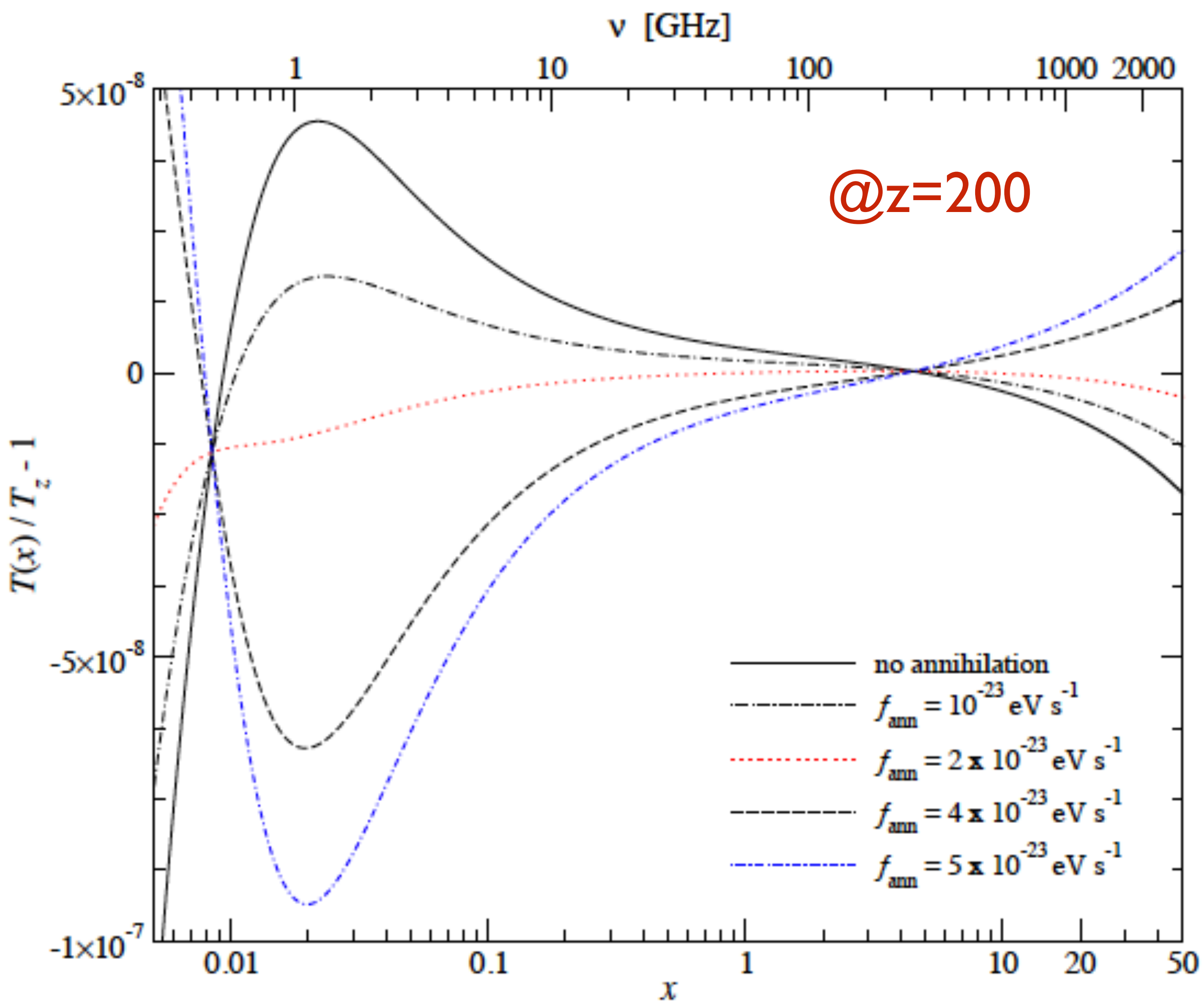
Spectral distortions: how do they compare?

In principle, both "μ-y" and "recombination" epochs are affected

The effect in the early universe

At large/excluded values of the annihilation cross-section, heating from annihilations pushes electron temperature above the photon one: photons get upscattered:
μ-type distortions, μ>0





At values comparable to current bounds, this never happens. The "standard" μ<0 distortions by adiabatically cooling electrons dominate. Detection of specific signatures of DM annihilation appears hopeless.

e.g. J. Chluba and R.A. Sunyaev, "The evolution of CMB spectral distortions in the early Universe," MNRAS 419, 1294 (2012) [1109.6552]

Spectral distortions: how do they compare?

In principle, both "μ-y" and "recombination" epochs are affected

These effects appear to be small

Primordial distortions of the order $\mu \approx 3\times 10^{-10}\, f_{\rm d,lim}\left[\frac{M_\chi c^2}{100\,{\rm GeV}}\right]^{-1}\left[\frac{\Omega_\chi h^2}{0.13}\right]^{2}\left[\frac{\langle\sigma v\rangle}{3\times 10^{-26}\,{\rm cm^3/s}}\right]$

P. McDonald, R. J. Scherrer and T. P. Walker, "Cosmic microwave background constraint on residual annihilations of relic particles," Phys. Rev. D 63, 023001 (2001) [astro-ph/0008134]

So, *naively* one can only hope to improve over ***current*** bounds if sensitivity to distortions attains at least the 10^{-10} level *(two generations of detectors away?)*

Alterations to the (yet undetected) recombination spectrum @ (sub)percent level

J. Chluba, "Could the Cosmological Recombination Spectrum Help Us Understand Annihilating Dark Matter?," MNRAS 402, 1195 (2010) [0910.3663]

As you might guess, there are loopholes to this conclusion, otherwise my talk is over

On how to avoid bounds

… and restore some hope

On how to avoid bounds

… and restore some hope

Part II: The Ugly?

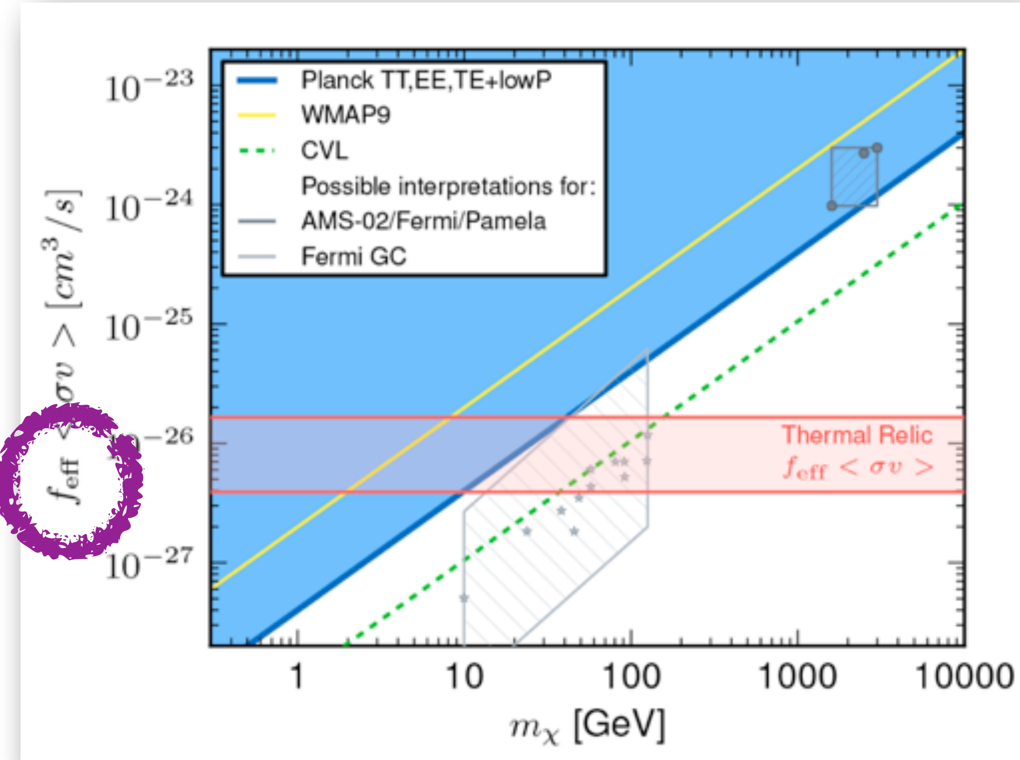
First loophole: z-dependence of annihilation rate

Computations quoted refer to s-wave annihilating WIMPs

$$f_{\rm eff} = f(z = 600)$$

epoch of maximal CMB anisotropy sensitivity

Not a big deal if $<\sigma v>$~const. (s-wave), implicit in all what I presented



Things are different for $<\sigma v>=<\sigma v>(z)$ e.g. p-wave annihilations

In this case, further factor of $v^2 \sim (1+z)^2$ with respect to previous estimates: make SD probe much more powerful relatively to "late time" CMB anisotropies.

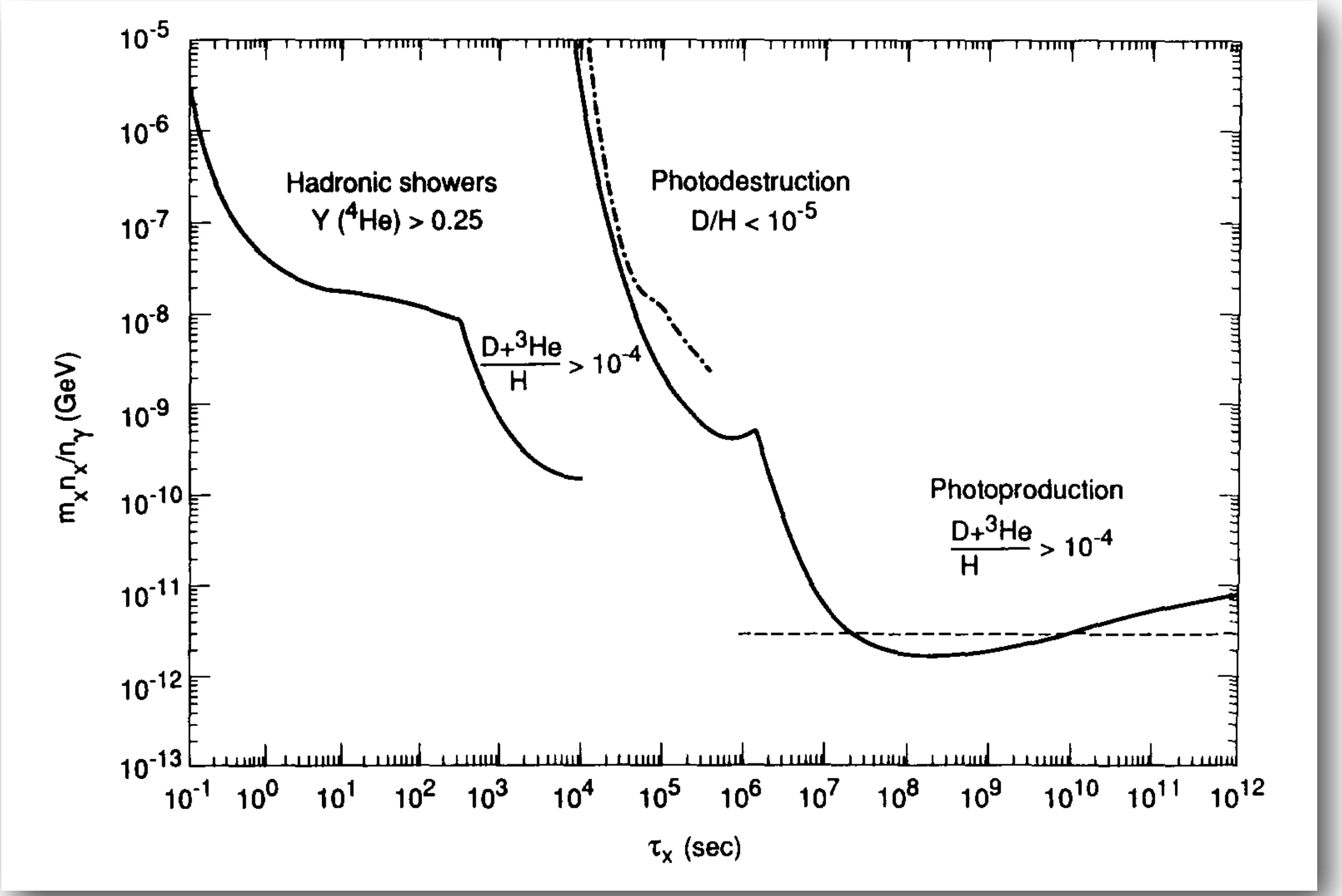
J. Chluba, "Distinguishing different scenarios of early energy release with spectral distortions of the cosmic microwave background," MNRAS 436, 2232 (2013) [1304.6121]

But what about earlier times? BBN, for instance?

on cascade BBN (using decaying proxy…)

BBN is extremely sensitive to injection of hadronic energy at early times…
The corresponding bound can be avoided for e,μ, γ final states.
But then photo-disintegration bounds kick-in (at later time, due to "e^+e^- *wall*")!

e.g. J.R. Ellis, D.V. Nanopoulos and S. Sarkar, "The Cosmology of Decaying Gravitinos," NPB 259, 175 (1985)



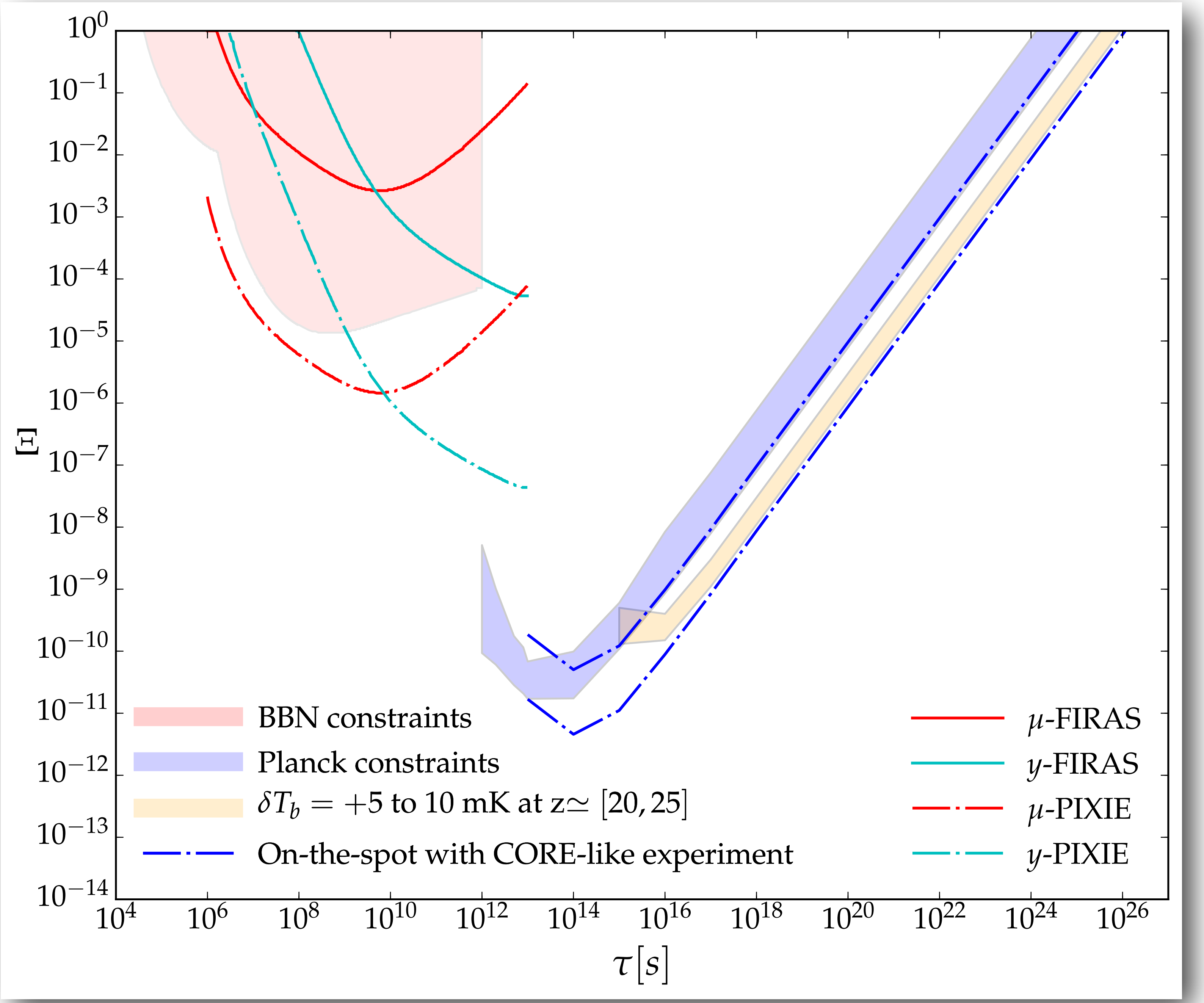
J. R. Ellis, G. B. Gelmini, J. L. Lopez, D.V. Nanopoulos and S. Sarkar,
"Astrophysical constraints on massive unstable neutral relic particles," Nucl. Phys. B 373, 399 (1992)

Synopsis (shown for decaying DM!)

Bounds at z~10⁶ can be 10⁶ times stronger than at z~10³ for p-wave: PIXIE-like sensitivity better even than CORE+…

…but BBN would have an even larger comparative improvement unless…

…only photons of MeV energy or less are injected!



V. Poulin, J. Lesgourgues, PS, JCAP 1703, 043 (2017) [1610.10051]

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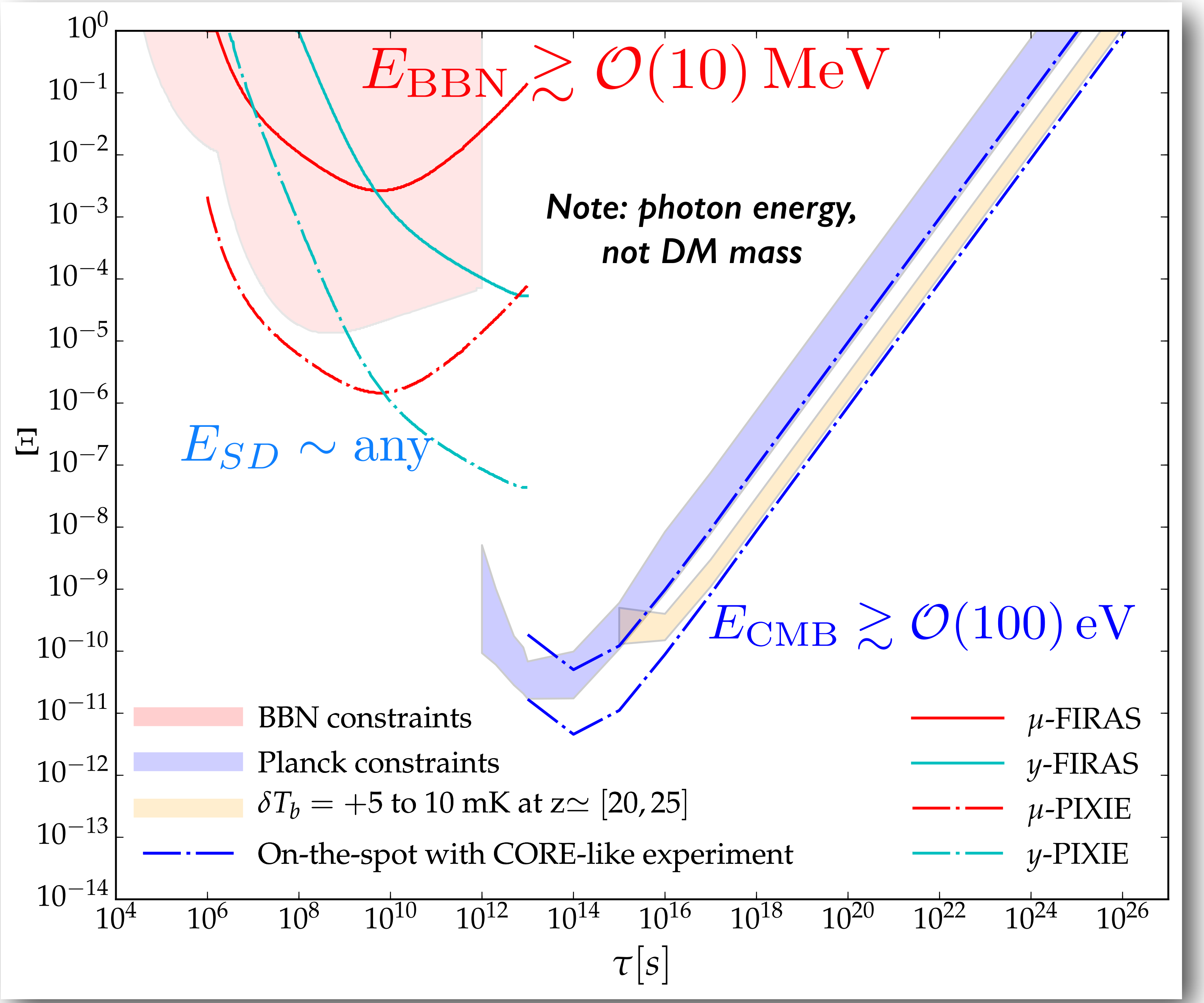
…What the plot does not show is the complementarity in E-space!



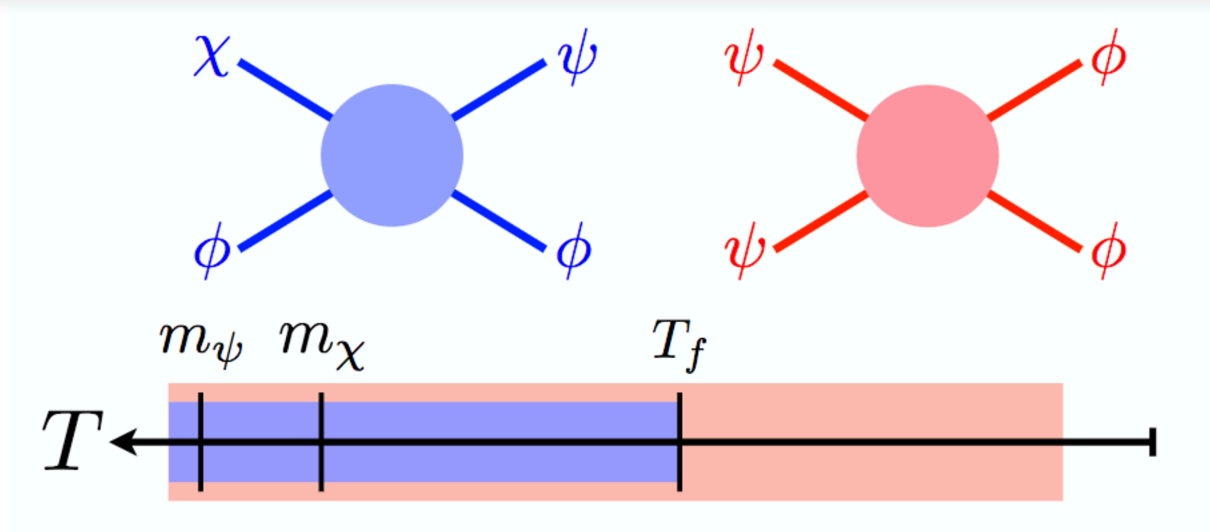
Light (m≲100 MeV) DM particles annihilating via p-wave are potentially searchable via SD signature.

V. Poulin, J. Lesgourgues, PS, JCAP 1703, 043 (2017) [1610.10051]

Their lightness makes them evade BBN hadronic bounds, and at the same time may soften or evade the BBN leptonic bounds, too!

A 2nd exception (via the 4th one): freeze-out via "coscattering"

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]



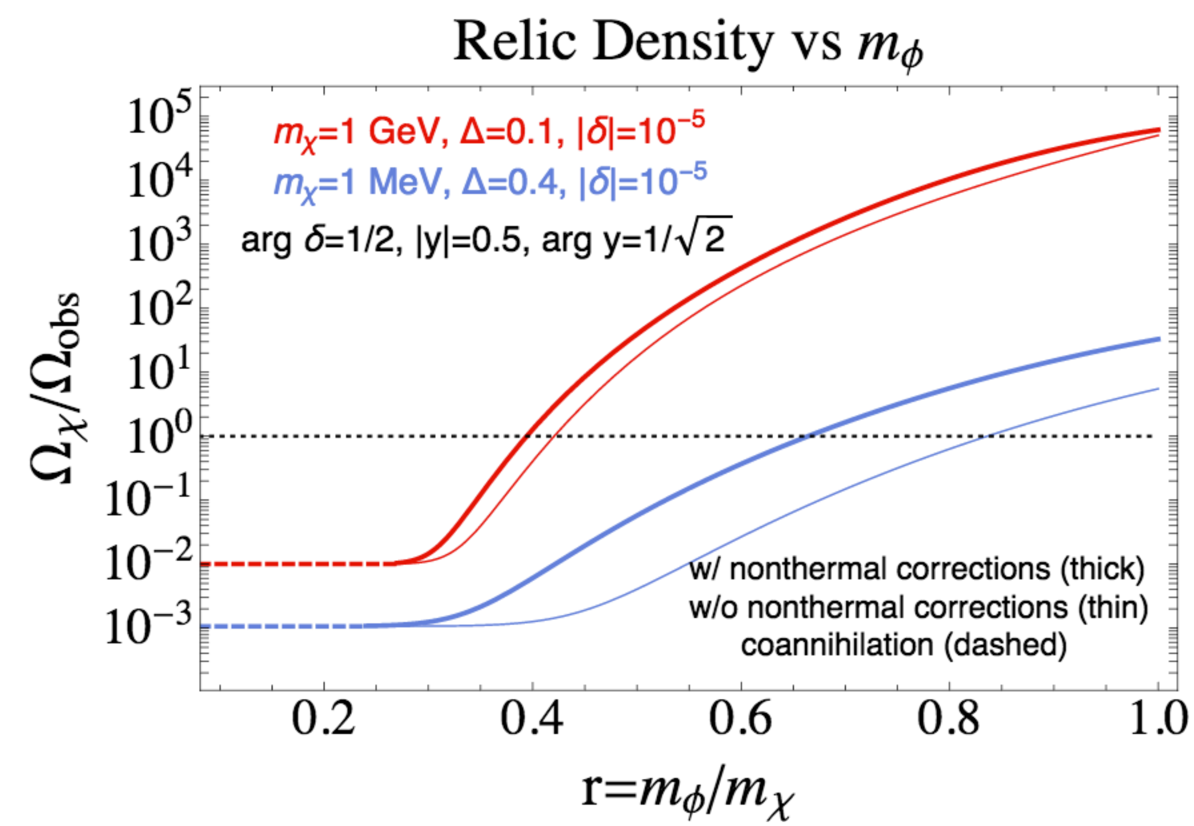
freeze-out of DM χ via inel. scatter from a comparable mass particle ψ, whose abundance is controlled by annihilation freeze-out into φ (in thermal bath)

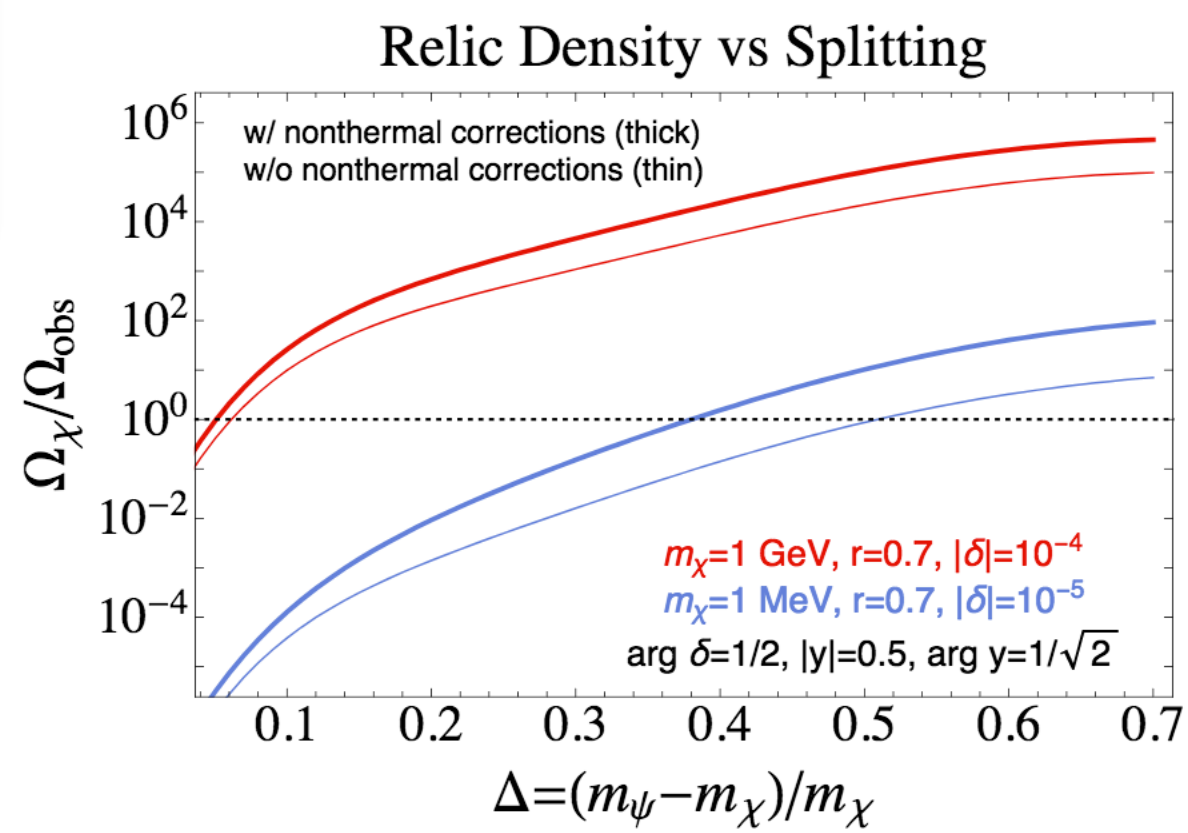
$$\frac{\Omega_\chi}{\Omega_{DM}} \approx \frac{0.6\ \text{pb}}{\sigma_{\text{inv}}} \frac{p\, x_f e^{x_f(r+\Delta-1)}}{\sqrt{g_*} r^{3/2}(1+\Delta)^{3/2}}. \qquad \sigma_{\text{inv}} \equiv \langle \sigma_{\psi\to\chi} v\rangle$$

ψ eventually decays via soft channel $\psi \to \chi\, e^+e^-$

& produce SD (detectable e.g. by PIXIE)

$$\tau_\psi \approx 1.2\times 10^8\ \text{s}\left(\frac{10\ \text{GeV}}{m_\psi}\right)\left(\frac{10^{-12}}{y_{e\phi}\delta}\right)^2\left(\frac{0.01}{\Delta}\right)^3 r^4$$





Third loophole: LKD via DM-baryon scattering

If **DM is in kinetic equilibrium with baryons down to z<2x10⁶**
(an example of late kinetic decoupling, *LKD*)

$$\dot{T}_\chi = -2H\,T_\chi + \Gamma_{\chi\,b}(T_b - T_\chi)$$

$$\dot{T}_b = -2H\,T_b + \Gamma_{\rm Com}(T_\gamma - T_b) - \frac{N_\chi}{N_b}\Gamma_{\chi\,b}(T_b - T_\chi)$$

this drains energy from CMB and induces ("negative") distortions

$$\rho_\gamma \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\Delta\rho_\gamma}{\rho_\gamma}\right) = -\frac{3}{2}N_b\Gamma_{\rm Com}(T_\gamma - T_b)$$

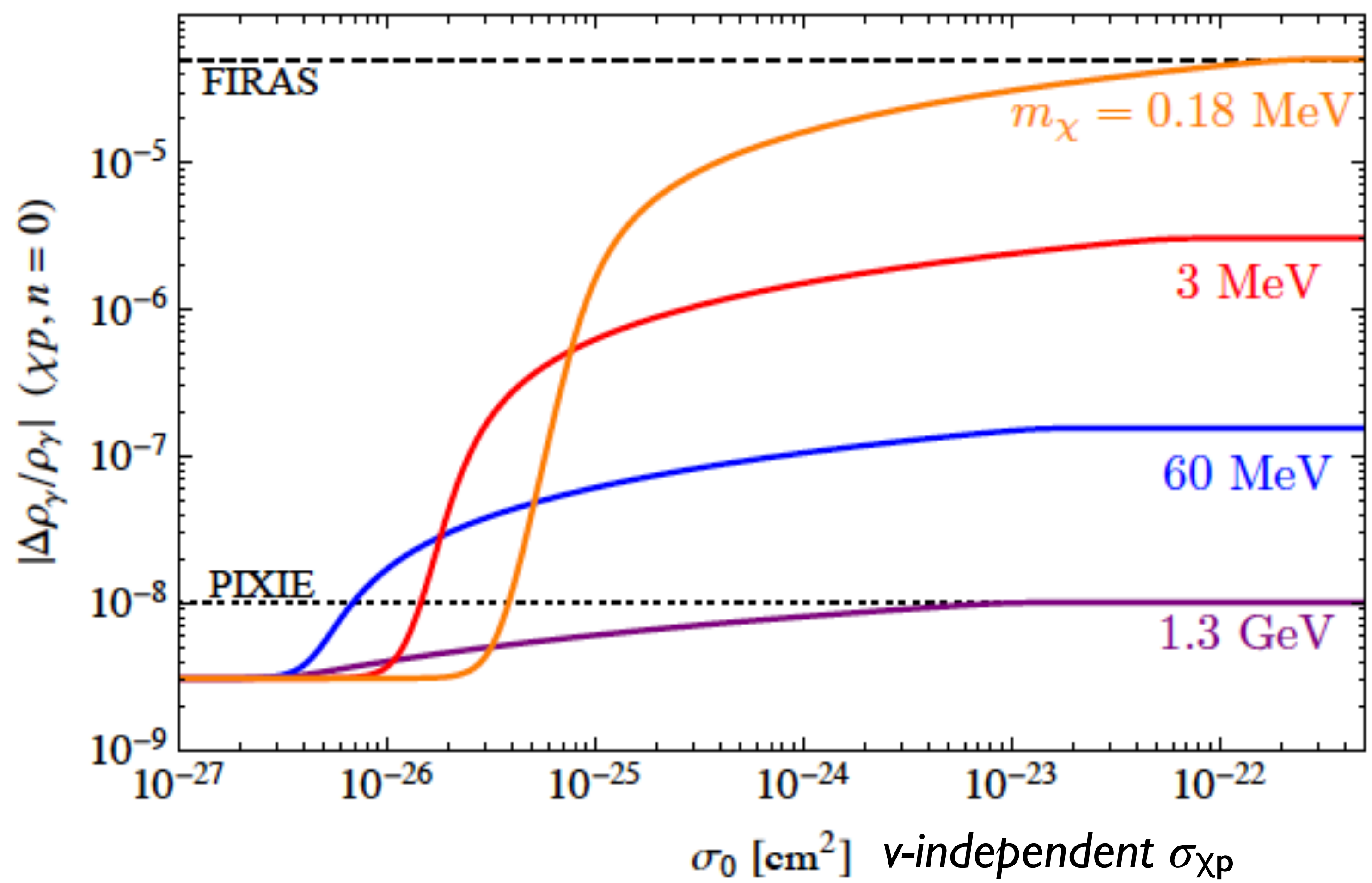
Only energies of the order of the thermal bath involved, no problems with BBN!

"*The best you can do*" is to thermalize all of the DM, →SD ∝ n_χ/n_γ, so

$-\mu \sim O(10^{-9})\, m_\chi/m_b$

hence FIRAS bounds only apply below ~180 keV, but PIXIE could reach GeV's

Y. Ali-Haïmoud, J. Chluba & M. Kamionkowski, Phys. Rev. Lett. 115, 071304 (2015) [1506.04745]



v-independent $\sigma_{\chi p}$

Effects of DM-baryon scattering @ inhomogeneous level

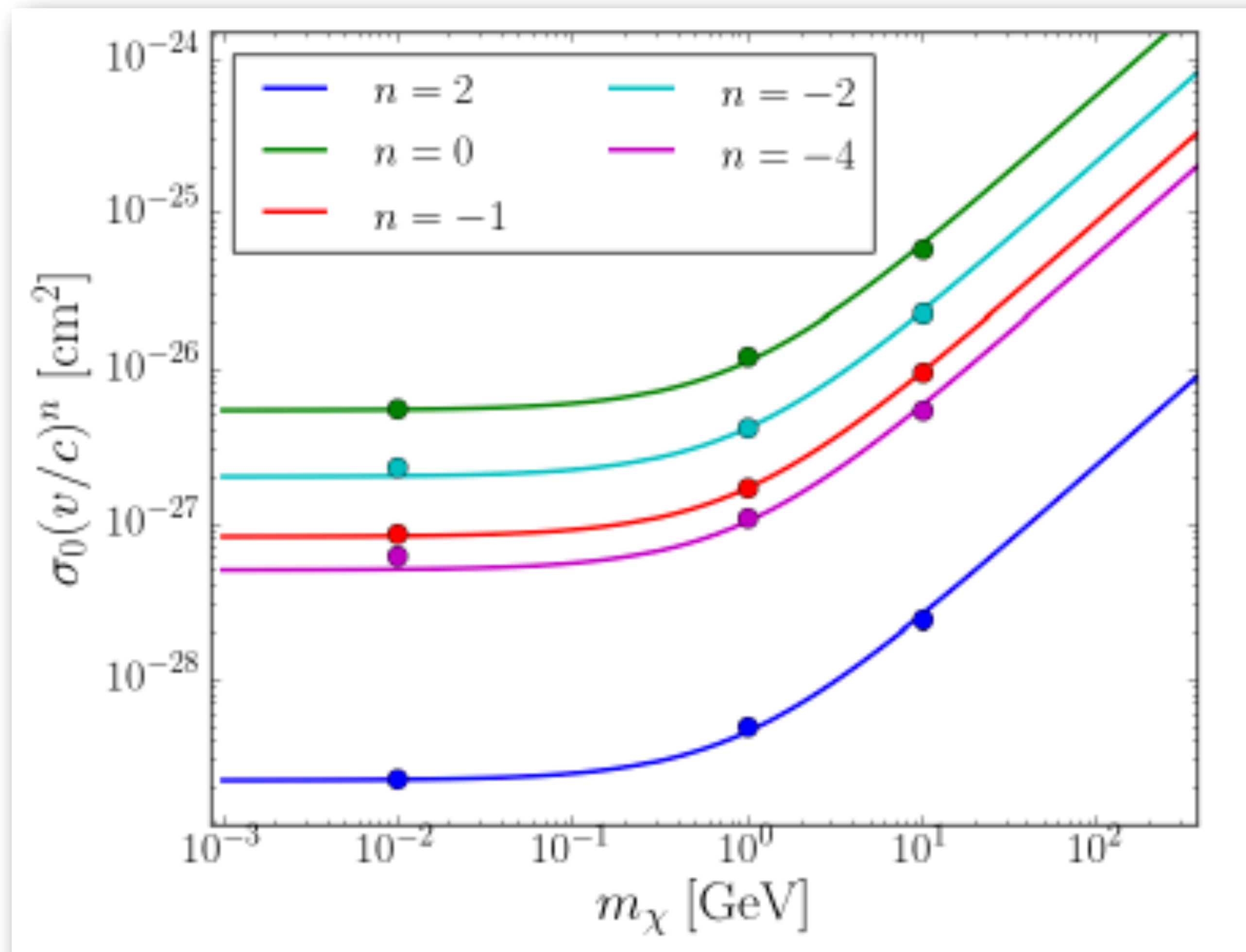
But a DM-baryon momentum-exchange with rate R_χ, depending on $\sigma=\sigma_0 v^n$,
dampens the growth of fluctuations in DM, modifies baryon relative velocity
$\rightarrow$ P(k) suppression @ small scale & shifts CMB peaks, impacts Ly α…

First investigations going back to *X. I. Chen, S. Hannestad & R. J. Scherrer, Phys. Rev. D 65, 123515 (2002) [astro-ph/0202496]*

More modern & parametric treatment in *C. Dvorkin, K. Blum & M. Kamionkowski, Phys. Rev. D 89, 023519 (2014) [1311.2937]*

effect enters via modified 1st and 2nd moment equations for perturbations

$$\dot{\delta}_\chi = -\theta_\chi - \frac{\dot{h}}{2},$$
$$\dot{\delta}_b = -\theta_b - \frac{\dot{h}}{2},$$
$$\dot{\theta}_\chi = -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi(\theta_b - \theta_\chi),$$
$$\dot{\theta}_b = -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma(\theta_\gamma - \theta_b) + \frac{\rho_\chi}{\rho_b} R_\chi(\theta_\chi - \theta_b),$$



😥 *Most recent bounds (CMB anisotropies, Ly α) from W. L. Xu, C. Dvorkin and A. Chael, 1802.06788 ~10 times stronger than SD from FIRAS*

Fourth loophole: LKD via DM-photon scattering

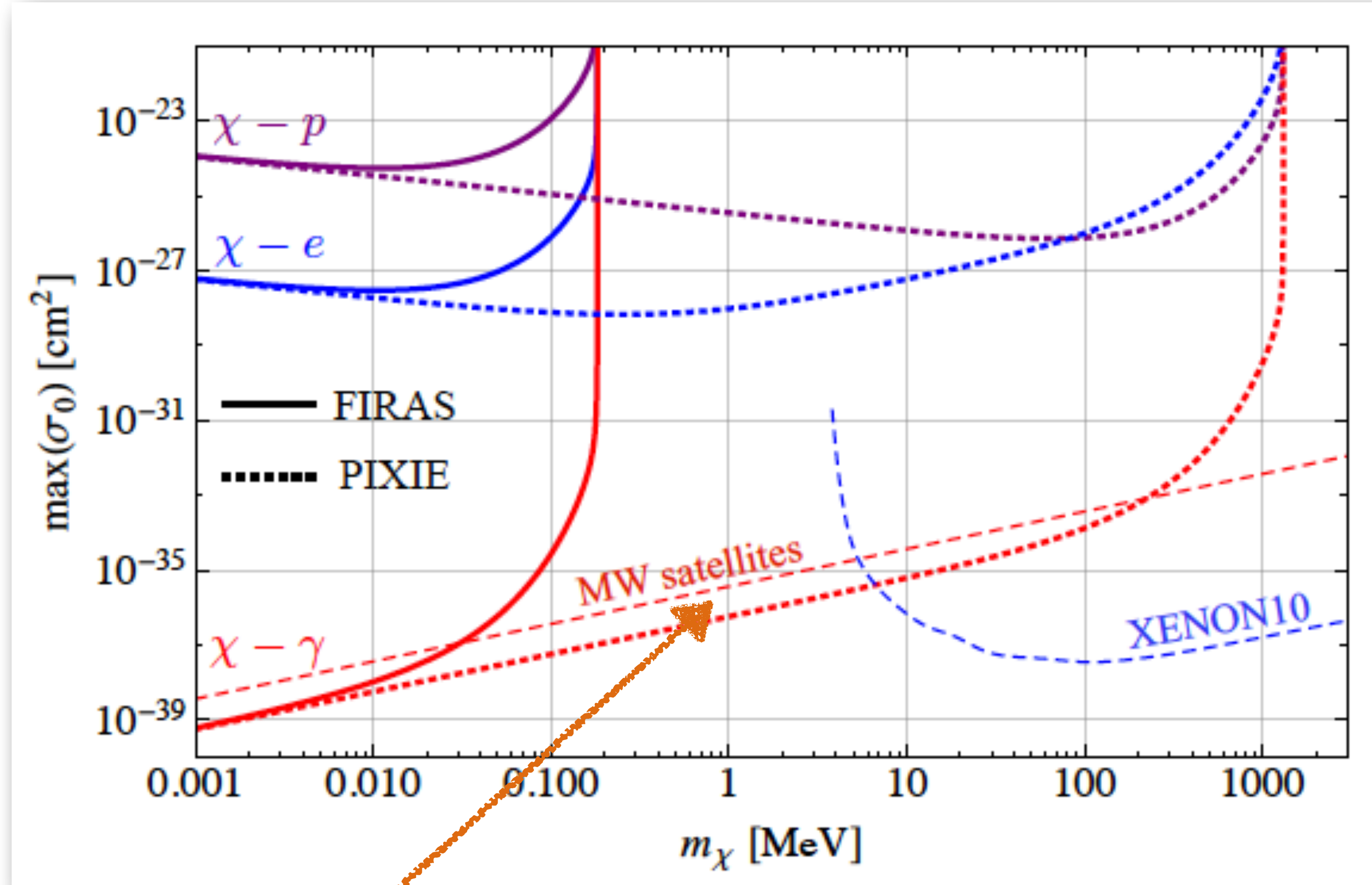
much more effective if coupling directly to photons!

$$\dot{T}_\chi = \Gamma_{\chi\gamma}(T_\gamma - T_\chi)$$

$$\rho_\gamma \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\Delta\rho_\gamma}{\rho_\gamma}\right)_{\chi\gamma} = -\frac{3}{2} N_\chi \Gamma_{\chi\gamma}(T_\gamma - T_\chi)$$

given the high-entropy, big improvement not surprising!

Note 1: *in a concrete model of interactions with baryons, interactions with photons even if loop-suppressed might improve previous bounds on* $\sigma_{\chi p}$ …



Y. Ali-Haïmoud, J. Chluba & M. Kamionkowski, Phys. Rev. Lett. 115, 071304 (2015) [1506.04745]

Note 2: once again, these bounds must compete with other bounds depending on the impact of such couplings at the inhomogeneity level, like the requirement that the number of satellites of the MW is not depleted below the observed one, derived in

C. Boehm et al. MNRAS 445, L31 (2014) [1404.7012]

Already FIRAS bounds extremely competitive at small masses! But there is more…

SD Effects @ inhomogeneous level in the standard ΛCDM

J. Chluba, "Which spectral distortions does LCDM actually predict?," MNRAS 460, 227 (2016) [1603.02496]

dissipation of small-scale modes causes μ-type distortions at the 1.7 x 10^{-8} level

effective heating rate
(radiation era, tight coupling)

$$\frac{\mathrm{d}\,(Q/\rho_\gamma)}{\mathrm{d}z} \simeq \frac{4a}{\mathcal{H}\dot{\kappa}} \int \frac{\mathrm{d}k}{2\pi^2} k^4 P_{\mathcal{R}}(k) \frac{16}{15} \Theta_1^2.$$

Or, in terms of the diffusion damping scale, k_D (and neglecting baryon load)

$$\partial_z k_D^{-2} = -\frac{c_s^2 a}{2\mathcal{H}\dot{\kappa}} \left(\frac{16}{15} + \frac{R^2}{1+R} \right)$$

$$\frac{\mathrm{d}\,(Q/\rho_\gamma)}{\mathrm{d}z} \simeq -4A^2 \int \frac{k^2 \mathrm{d}k}{2\pi^2} P_{\mathcal{R}}(k)\, k^2 \,\left[\partial_z k_D^{-2}\right]\, \mathrm{e}^{-2k^2/k_D^2(k)}$$

Although dissipation happens "late" in the radiation era, k-modes concerned pretty high

μ-type distortions **$3\mathrm{x}10^5 \lesssim z \lesssim 2\mathrm{x}10^6$** selects relevant modes **330 Mpc$^{-1} \lesssim k \lesssim$ 5700 Mpc^{-1}** in the above integral, in turn entering the horizon at **$10^8 \lesssim z \lesssim 10^9$**

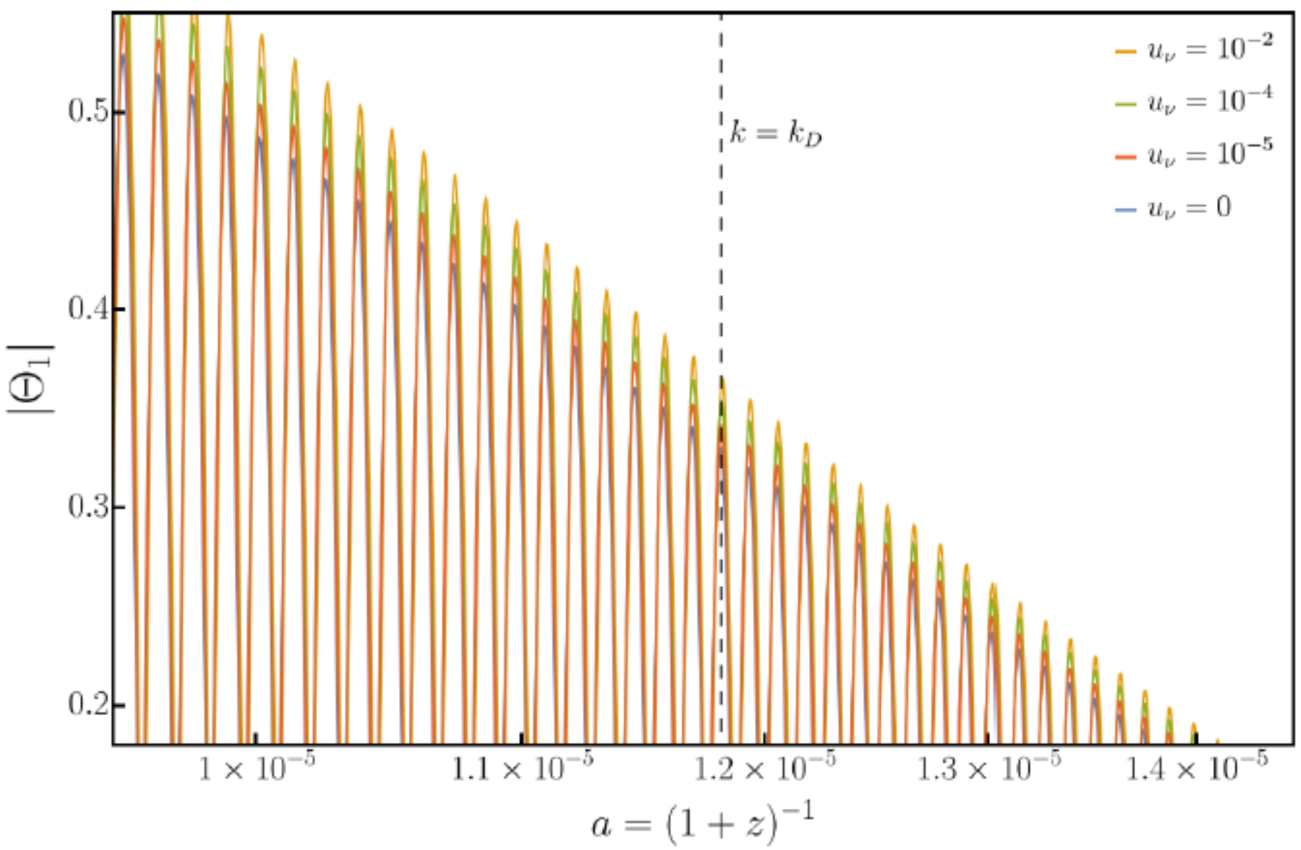
SD Effects of DM-neutrino scattering @ inhomogeneous level

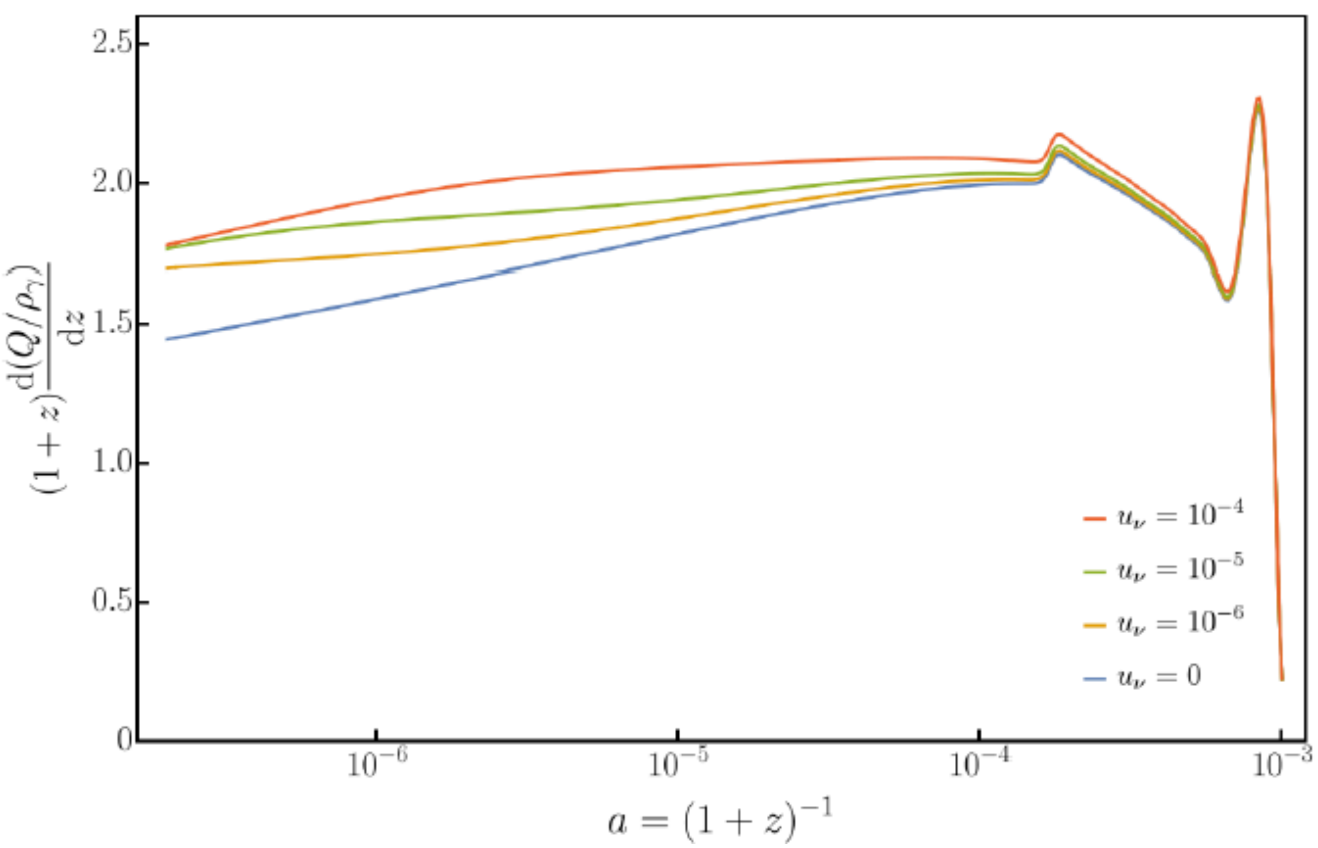
In LKD scenarios, the coupling with relativistic species (notably neutrinos) cause quantitative alterations to those expectations

J.A.D. Diacoumis and Y.Y.Y. Wong, JCAP 1709, 011 (2017) [1707.07050]

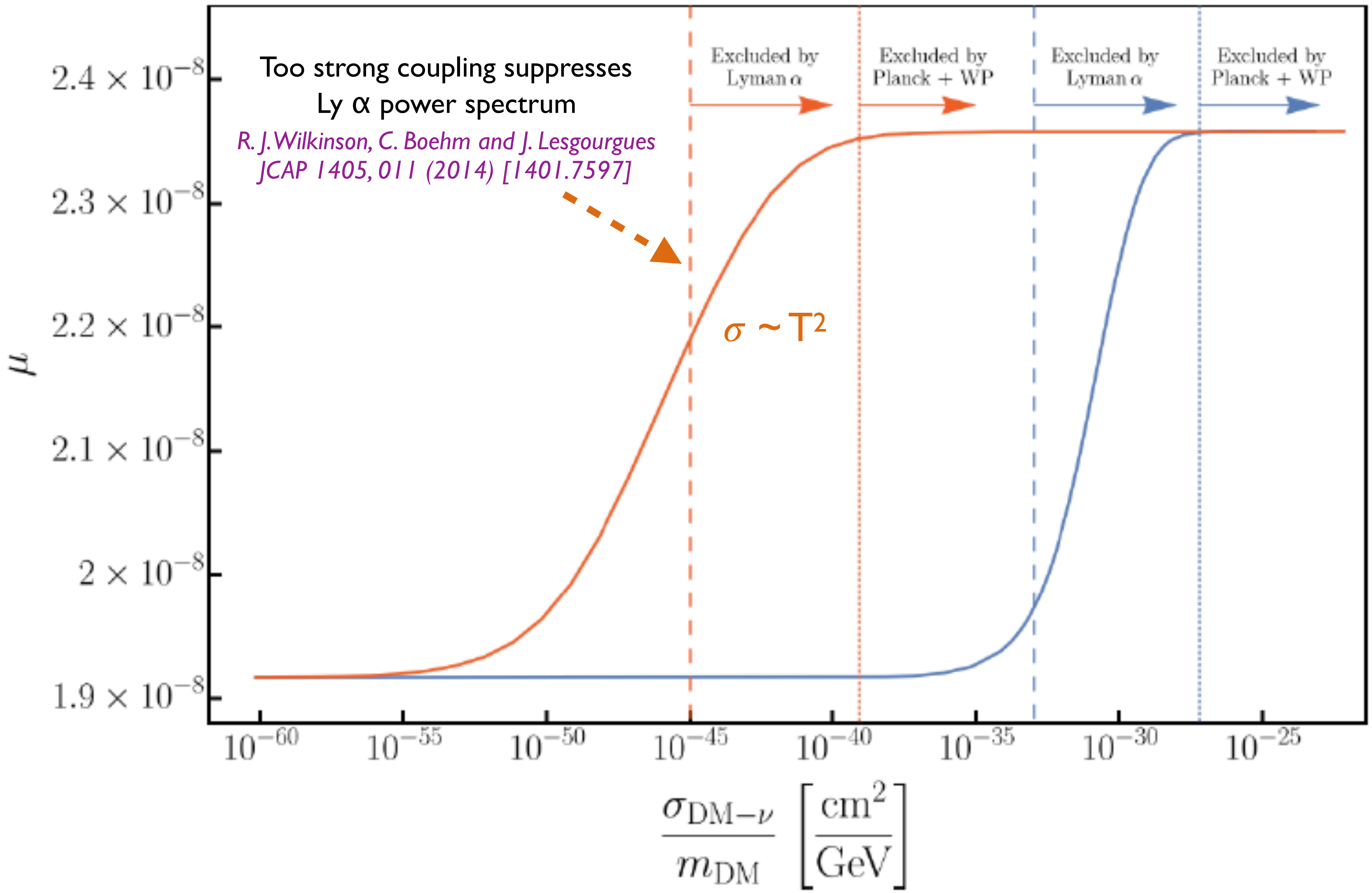
More details in James Diacoumis' talk on Friday!

$$u_\nu \equiv \frac{\sigma_{\chi\,\nu}}{\sigma_T}\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)$$





DM interacting with neutrinos



a 10^{-9} sensitivity (à la PRISM) only modest improvements expected for photons (but with linear physics!), yet **constraints for interactions with neutrinos could improve by a factor ~100.**

J.A.D. Diacoumis and Y.Y.Y. Wong, JCAP 1709, 011 (2017) [1707.07050]

Is all this ad hoc?

Maybe it looks so, given the bottom-up way I presented it to you.

But several of the ingredients we found leading to appreciable SD while remaining consistent with other constraints are actually invoked in DM models explaining "small scale anomalies"

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Part III: The Good?

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 $dn/dM \sim M^{-1.9}$

To cut a long story short, none of these seems to be matching detailed observations

for a recent review:

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

Problems

- **Missing satellite** problem: *Many more halos than (satellite) Galaxies*
- **Cusp/core** controversy: *too little DM and not cuspy enough 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" to "special DM properties".

Visual summary of option nr. 1, not covered in this talk

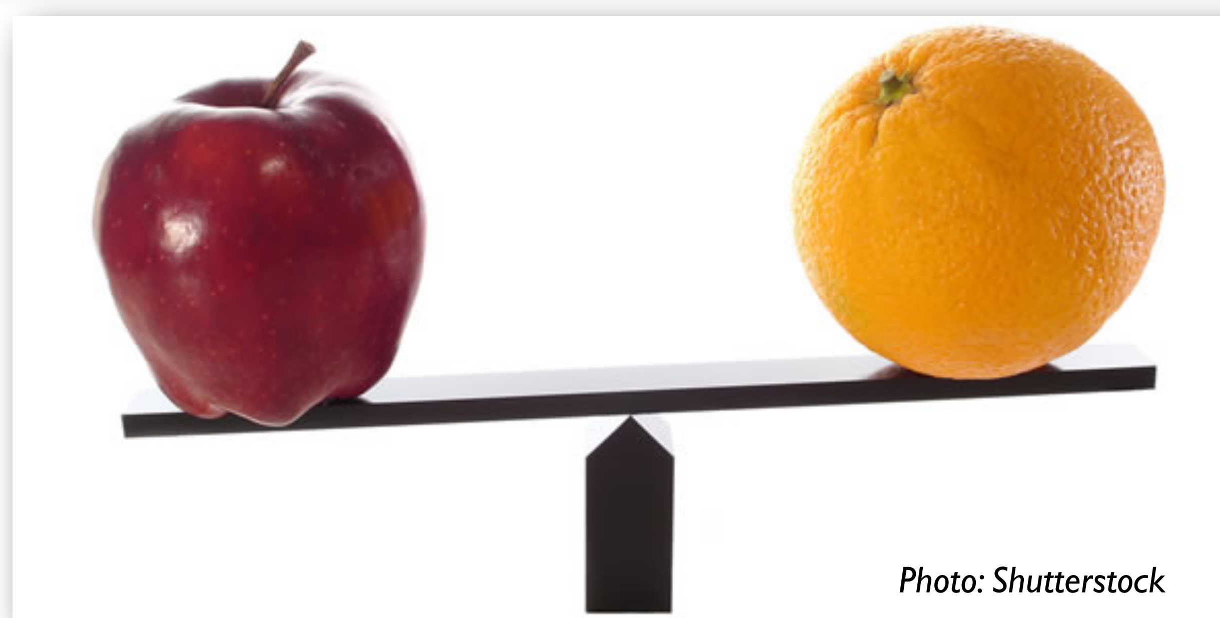
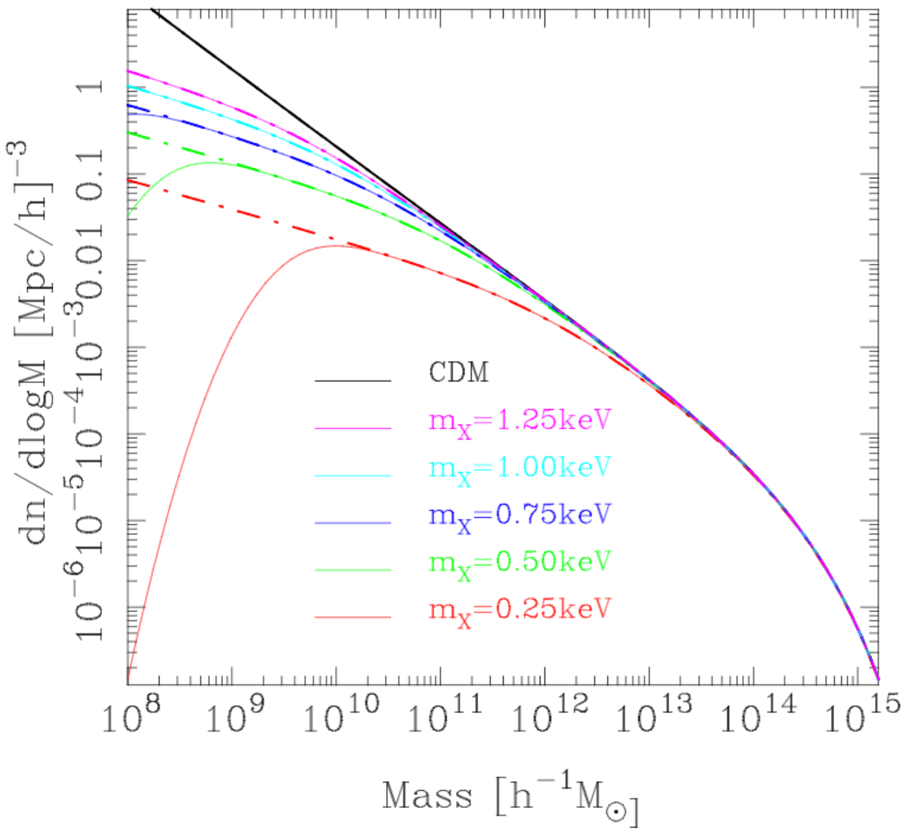


Photo: Shutterstock

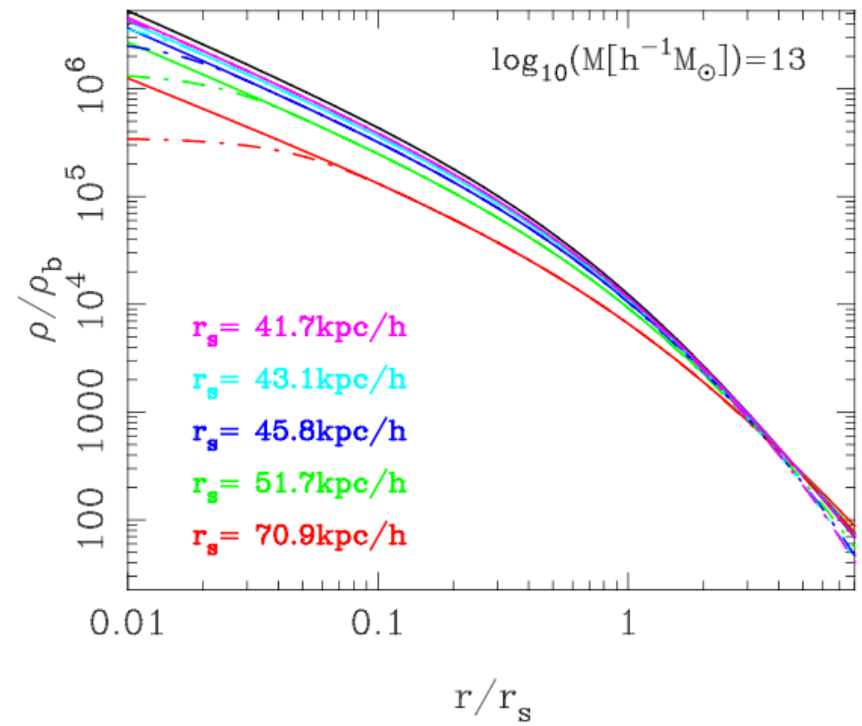
Option II: Could it be due to DM microphysics?

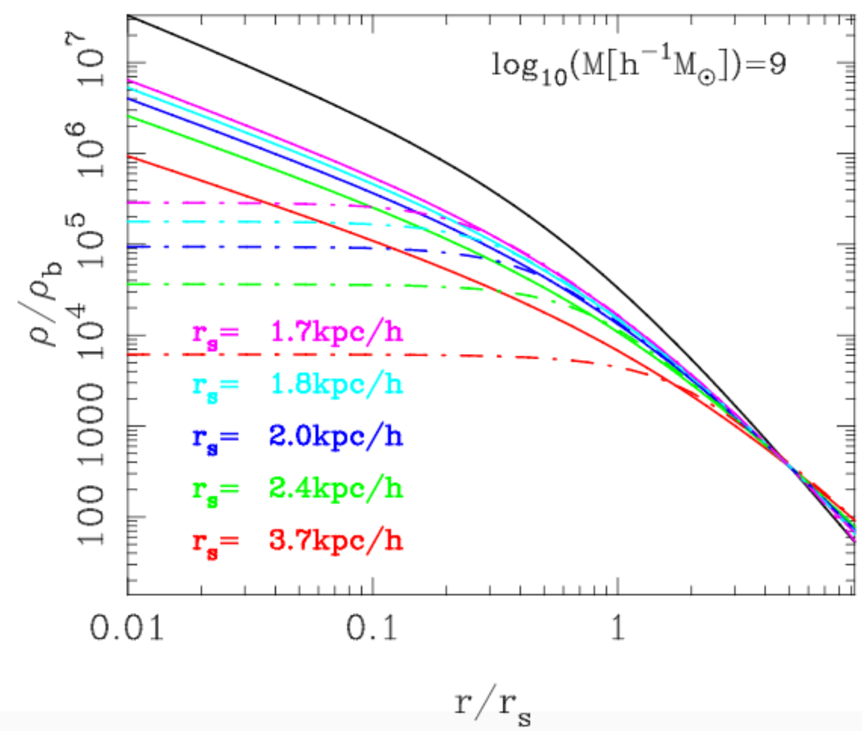
People tried with “warm thermal DM”, of course!



e.g.

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





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

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

Usually difficult to find a simultaneous solution to the “problems”

A New Hope: the Dark (Matter) Force awakens?

In particular, phenomena could be linked to strong DM-DM elastic scattering (**$\sigma/m \sim 1\ cm^2/g = 1.8\ b/GeV$**)

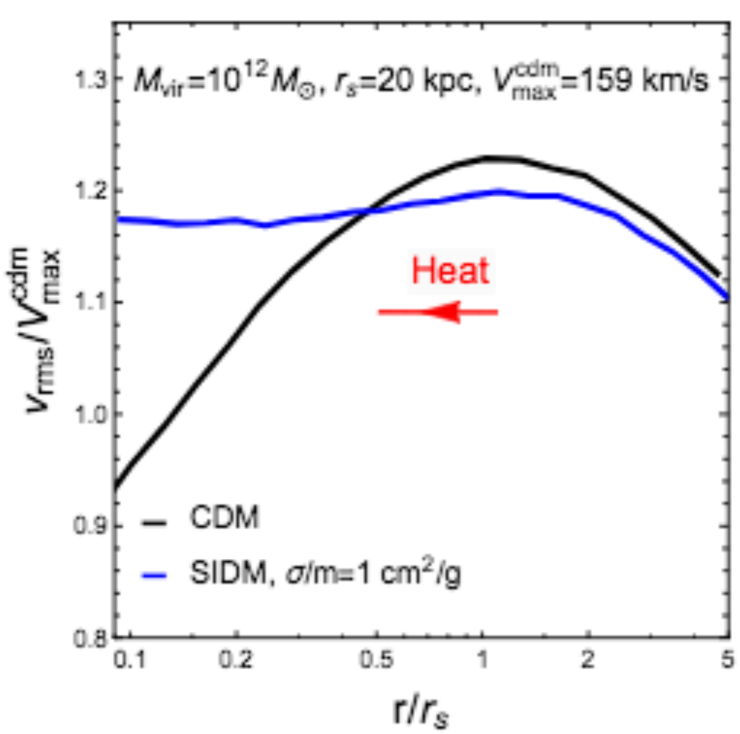
Idea of **Self-Interacting DM** goes back to:

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

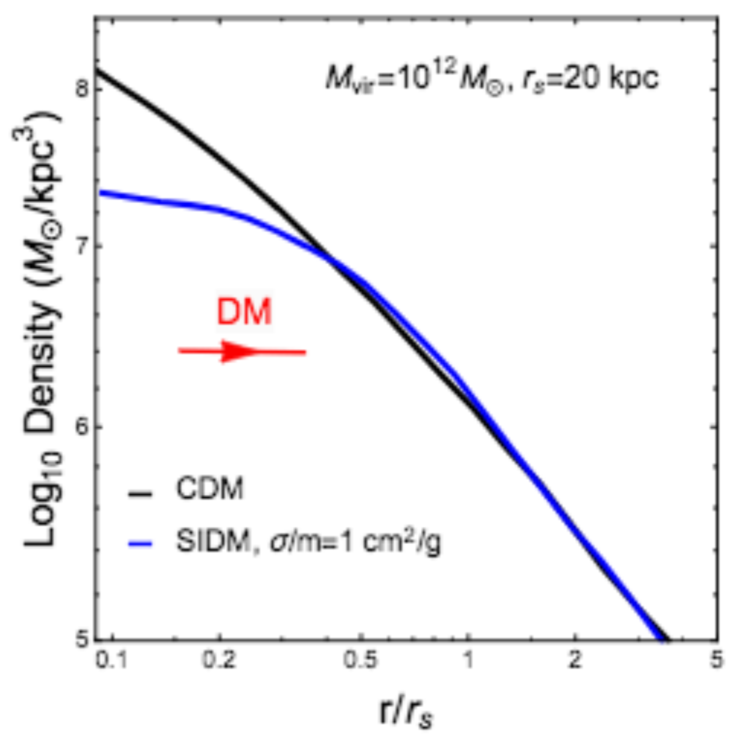
Major revival *(talking about sequels)* in recent years, for a review & refs.

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

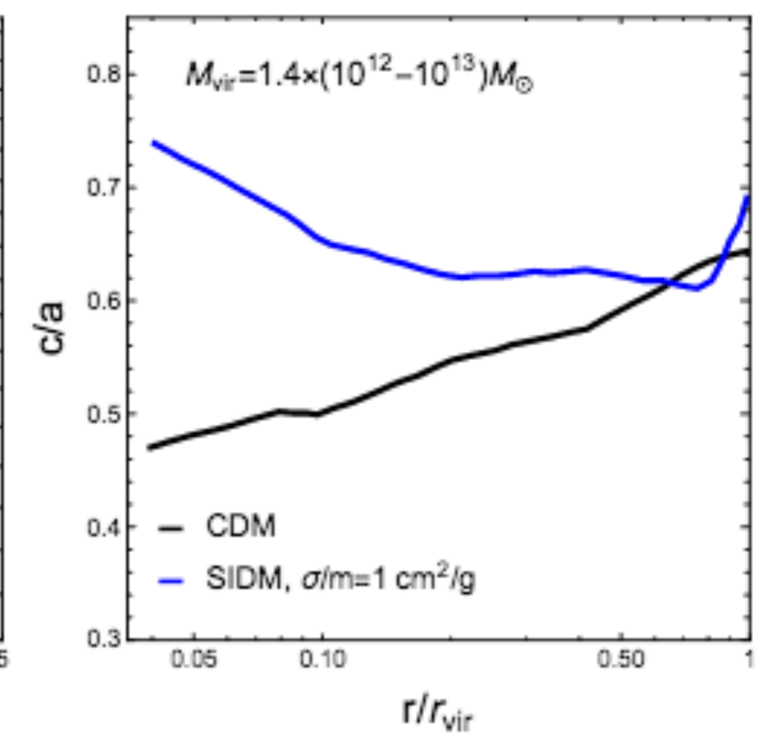
In inner halos, scatterings lead to DM "thermalization"



more uniform & isotropic v-dispersion



cored profiles & suppressed DM density



more spherical inner halos

Pointing towards a low DM mass scale?

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

One can in principle get large σ_{el} with a model as simple as a self-interacting scalar field

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

actual parameters needed closer to ***m~10 MeV*** for ***g~1***

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

A notable class of more theoretically motivated models where some of the desired features arise are "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 (for a review)

E.g. for the symmetric part of relic abundance to be annihilated away, one *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"**.

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

Dark Matter - radiation (dark or visible) coupling

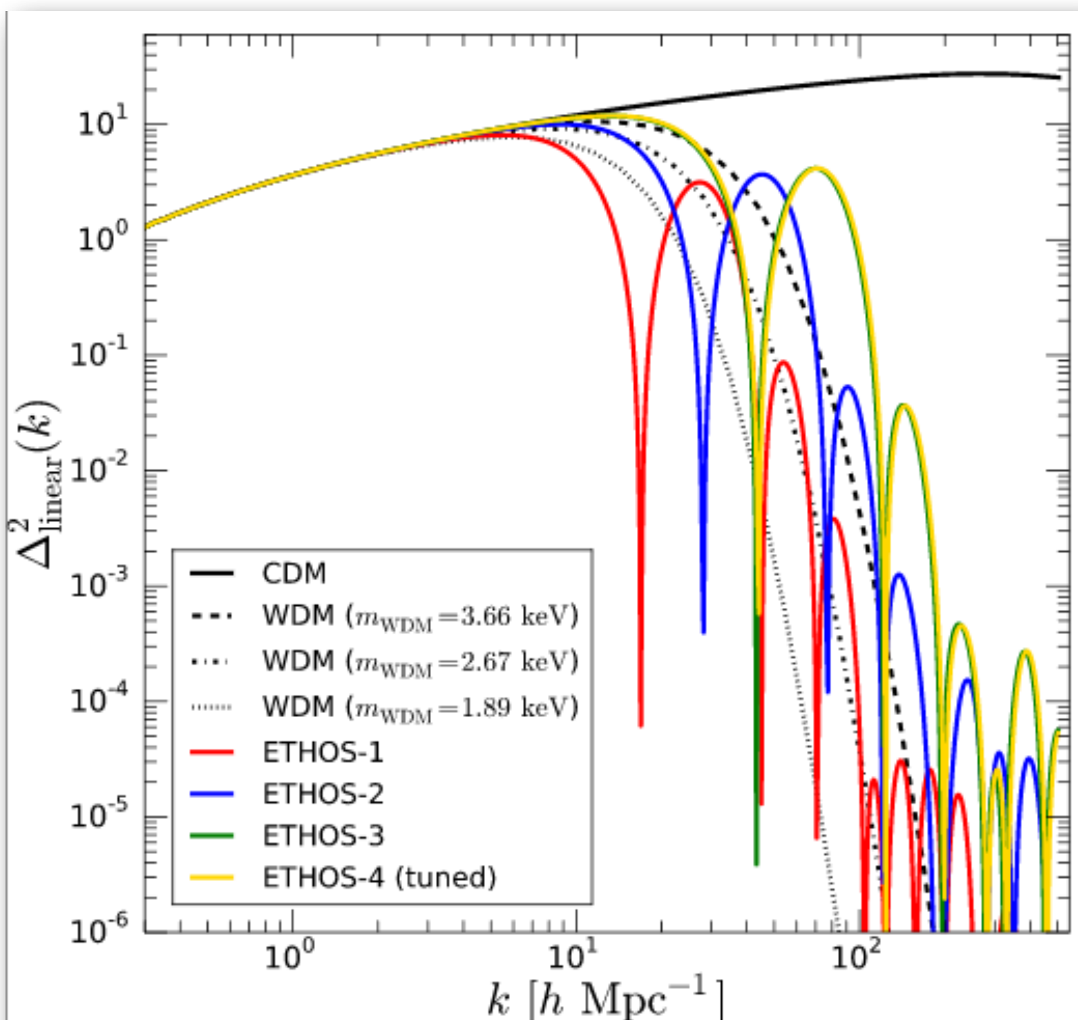
The (fraction of) DM coupling to relativistic particles:

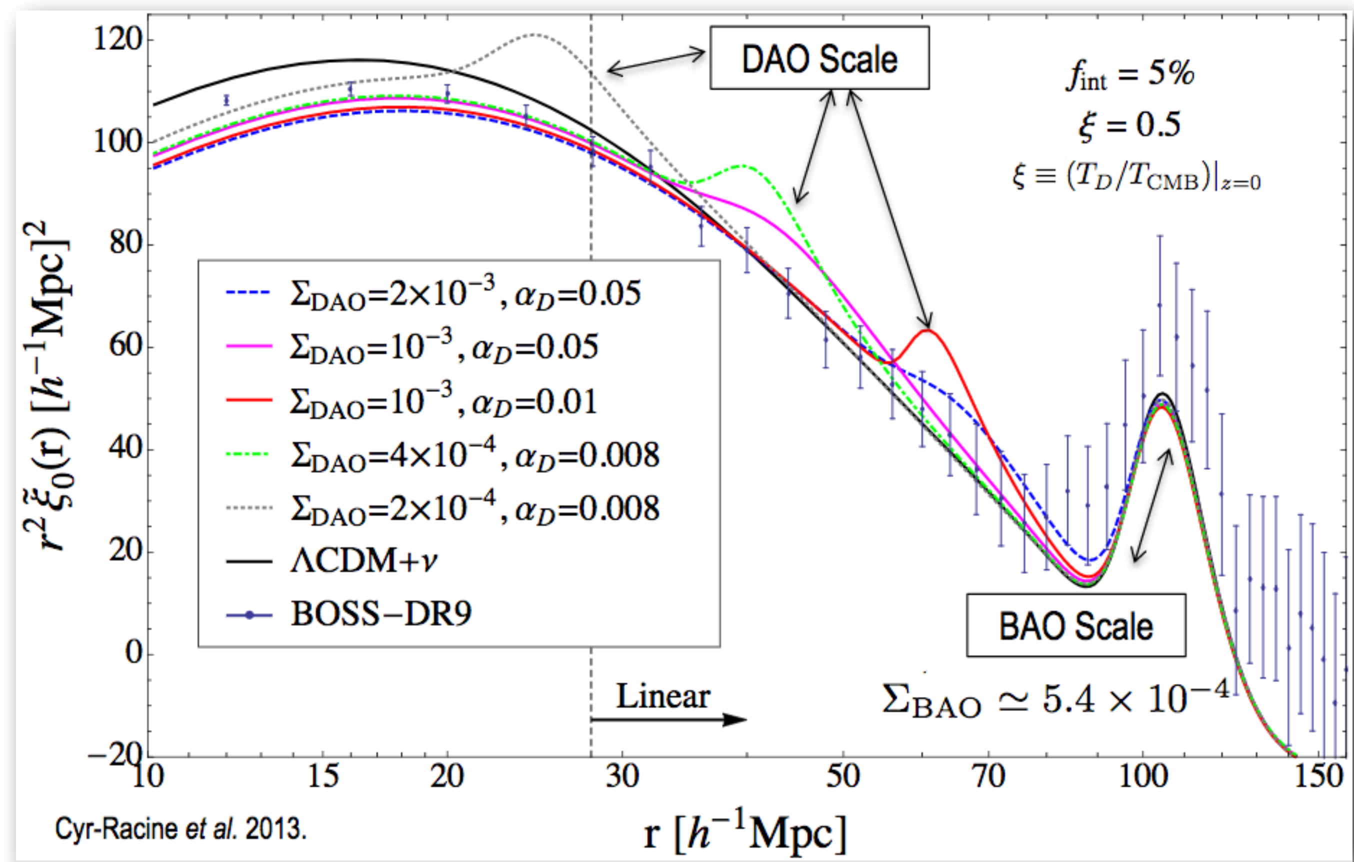
i) leads to non-vanishing sound speed & provides pressure support against gravitational collapse

ii) Has a relatively LKD

Leads to **small-scale damping of DM P(k)** (like WDM, but now collisional rather than due to free-streaming) + "**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]*



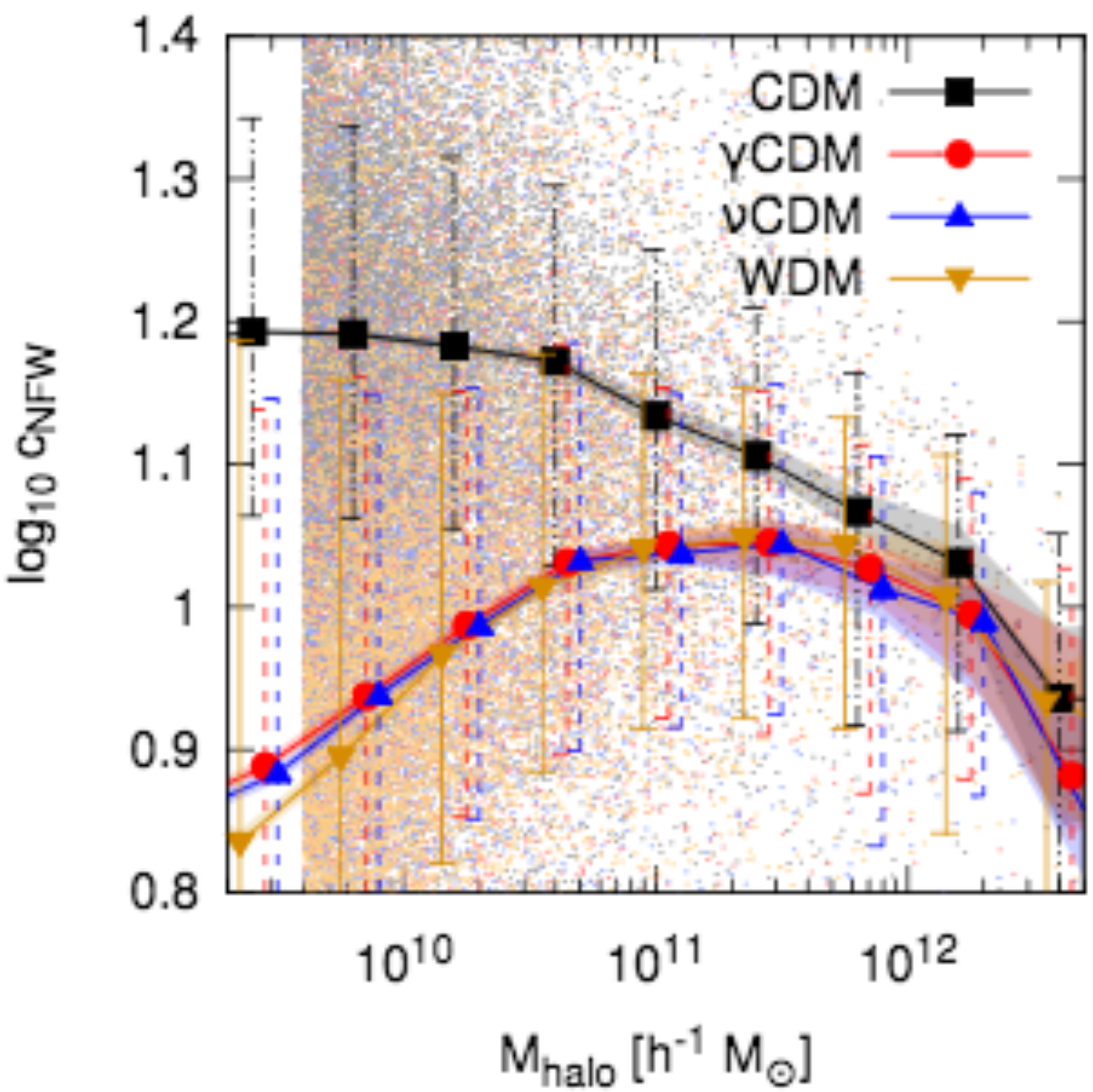


used to constrain "double disk" (or dinosaurs killer) models

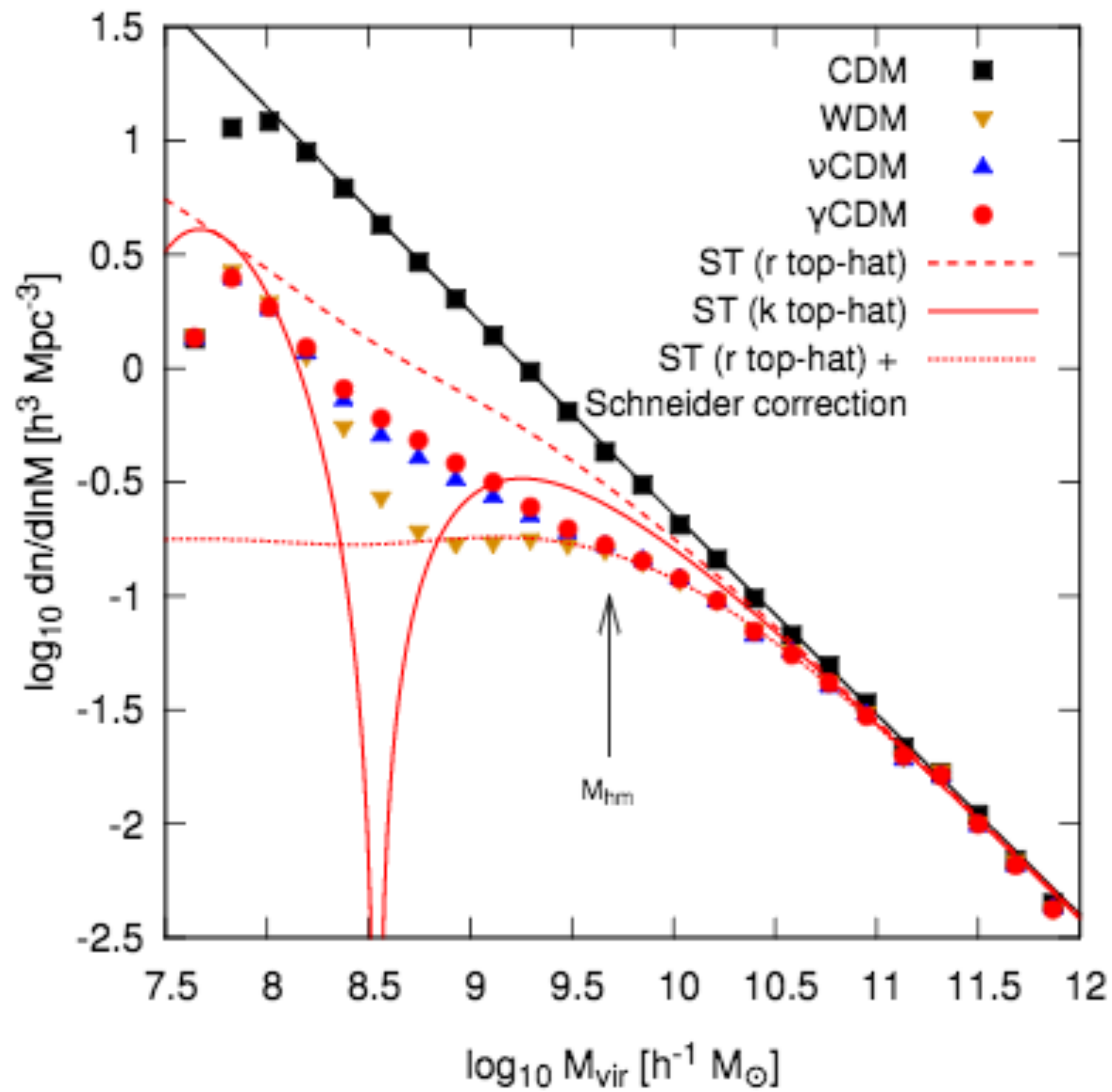
No need for the radiation to be "dark"

The relativistic particles DM couples to could be SM radiation, either photons or neutrinos: The simulations in *C. Boehm et al, 1412.4905* suggest some effects, but difficult diagnostics!

halo profiles moderately different from CDM, e.g. slightly (~10%) reduced concentrations at low-M due to delayed formation, but degenerate with alternatives!



the halo mass function is significantly suppressed at small masses, but only minor differences from the WDM scenario



SD could be only "theoretically robust" way to test these model features in a still **linear** regime

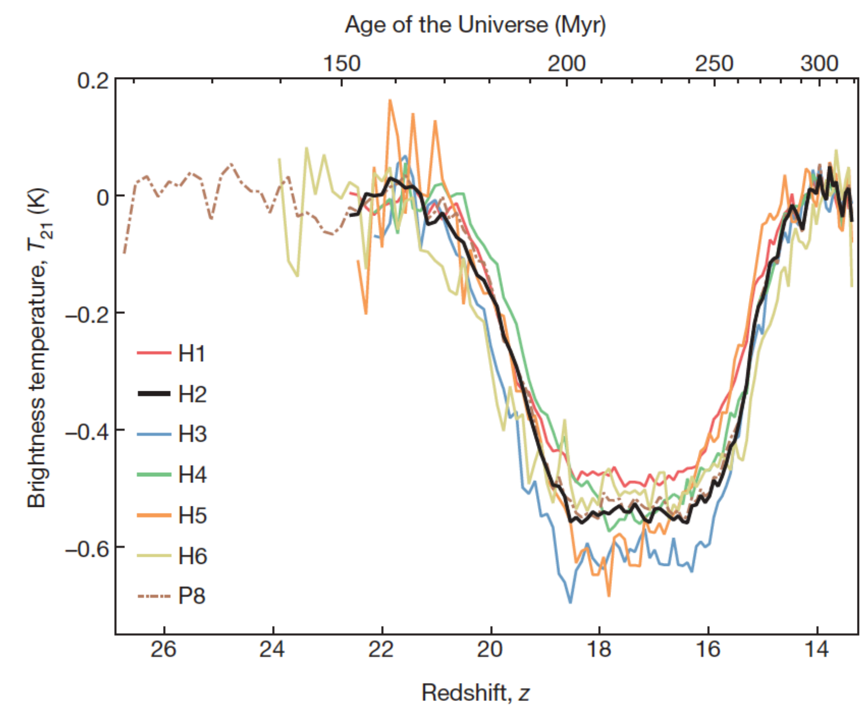
Finally: Too good to be true? Recent 21 cm announcement

LETTER

doi:10.1038/nature25792

An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]



If we are really lucky (but are we?), direct motivation from recent observations…

LETTER

Possible interaction between baryons and dark-matter particles revealed by the first stars

Rennan Barkana[1]

Summary & Conclusions

CMB SD do not appear a promising channel to constrain/detect vanilla WIMPs, notably due to competing constraints from CMB anisotropies (& to some extent BBN)

But:

1) There is no indication for vanilla WIMPs *(obvious, but worth reminding…)*
2) There are a few off-the-beaten-path cases (relatively light particles annihilating via p-wave, coscattering, LKD scenarios) where the SD is known to be much more promising.
3) Some of the features promising for SD also found in models attempting to address the "small-scale tensions" in the CDM paradigm (& maybe recently anomalous EoR observations?)

Then, SD provides one of the few (the only?) "perturbative" channels for diagnostics.

And I did not even enlarge too much the DM theory space, other interesting consequences e.g. for axion models, PBH, macroscopic DM, etc.

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And I did not even enlarge too much the DM theory space, other interesting consequences e.g. for axion models, PBH, macroscopic DM, etc.

Lacking any theory breakthrough, the only major progress I see on the quest for the nature of DM is to obtain some empirical evidence *(again obvious, but worth reminding…)*

Besides sharpening search tools we already have, lack of WIMP signatures & rising interest in alternatives should make us wonder if the answer won't come from searching elsewhere.

The only way to figure it out is to open these new windows on the dark.

Thank you