# DARK MATTER IDENTIFICATION: INTERDISCIPLINARY CHALLENGES

- What do we mean by DM & why do particle physicists care
- Stategies towards DM identification: A bottom-up option?
- “The small-scale disagreements” as example of interdisciplinary approach
- Comments and perspectives

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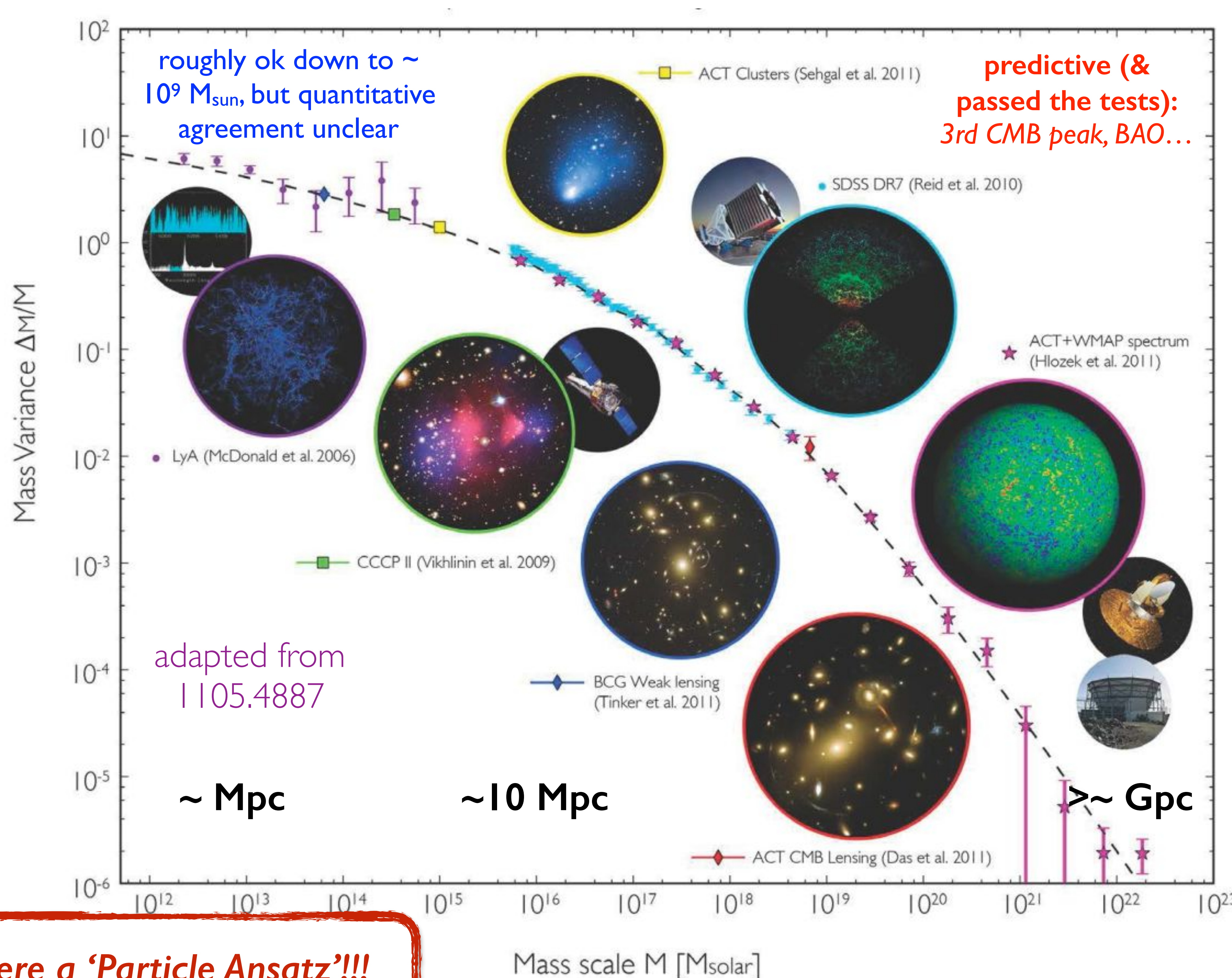
Atélier Théorie, IN2P3 - June 7, 2021

DM = **simple** effective description of cosmo/astro data on many scales/at different epochs




***Nowhere a 'Particle Ansatz'!!!***

$$G_{\mu\nu} + \Lambda\, g_{\mu\nu} = 8\pi G \left( T_{\mu\nu}^{\text{known}} + T_{\mu\nu}^{\text{DM}} \right) \qquad T_{\mu\nu}^{\text{DM}} = \rho^{\text{DM}} U_\mu U_\nu$$

# Among particle theorists, DM excitement not due to "rotation curves"!

*(Causes many misunderstandings between astro and particle communities)*

## Crucial role of cosmological evidence

**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) DM is non-baryonic, rather than brown dwarf stars, planets, unseen gas, etc.**

Also lead to basic properties/constraints

- **Mass density** (unless we move too deep into potential wells)
- **Lifetime** (longer than O(10) times the lifetime of the Universe)
- **Non-relativistic** (sufficiently 'cold')
- **Not collisional** (compared to 'baryonic gas')
- **Not dissipative** (compared to 'baryonic gas')
- **Has** (very???) **weak interactions with ordinary matter and radiation (dark !)**
- **Mass between ~$10^{-21}$ eV/$c^2$ and ~ 10 solar masses** (precision cosmology!)

The <u>identification</u> of DM nature requires however some breakthrough

# Possible strategies

I. **<u>"Theory-driven"</u>**
**DM makes sense in a more encompassing theory of particle physics and/or gravity. Test the consequences…**

*We have been trying so far, unsuccessfully*

II. **<u>"Observation-driven"</u>**
***Convincingly* prove that the (effective!) CDM part of the *cosmo model* breaks down in some regime, then try to reconstruct the theory.**

*Analogy in alternative history:*
*Imagine we had precise cosmo measurements before discovering neutrinos , we would have inferred the presence of 'dark radiation', eventually explained via SM (in fact the first indications for only 3 "light" generations came from cosmo!)*

*Challenge:*
*The model suggests itself that its predictions are less and less reliable at small scales and when baryons involved. (Analogy: non-perturbative QCD regime)*
*Sure, we have semi-empirical rules for hadronic masses, but nobody would use them to show that QCD is broken!*
*Key: Identify observables usable for diagnostics (in the analogy: if you want to test and break QCD, look at perturbative QCD or reliable lattice observables)*

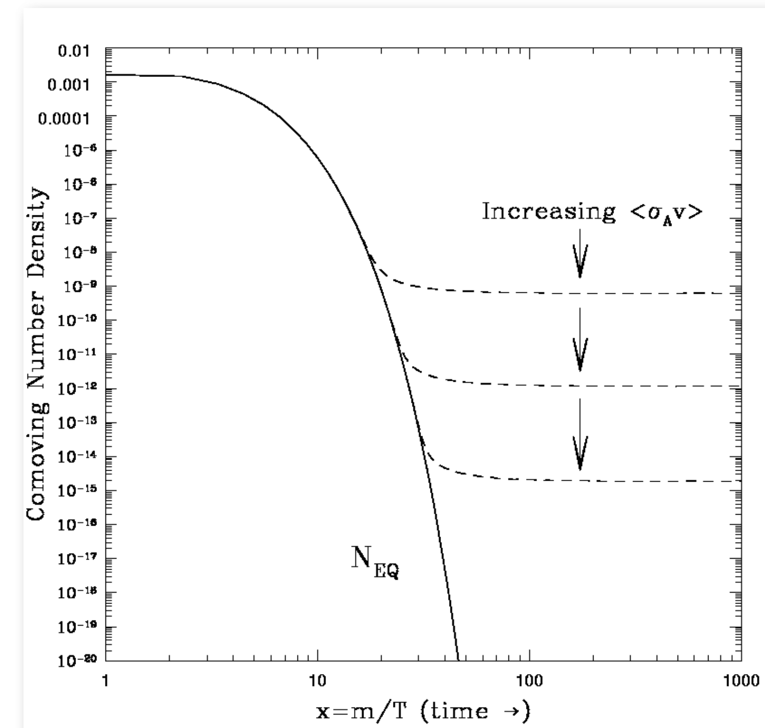
# Ex. I. Standard Bet: Weakly Interacting Massive Particle

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

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

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...



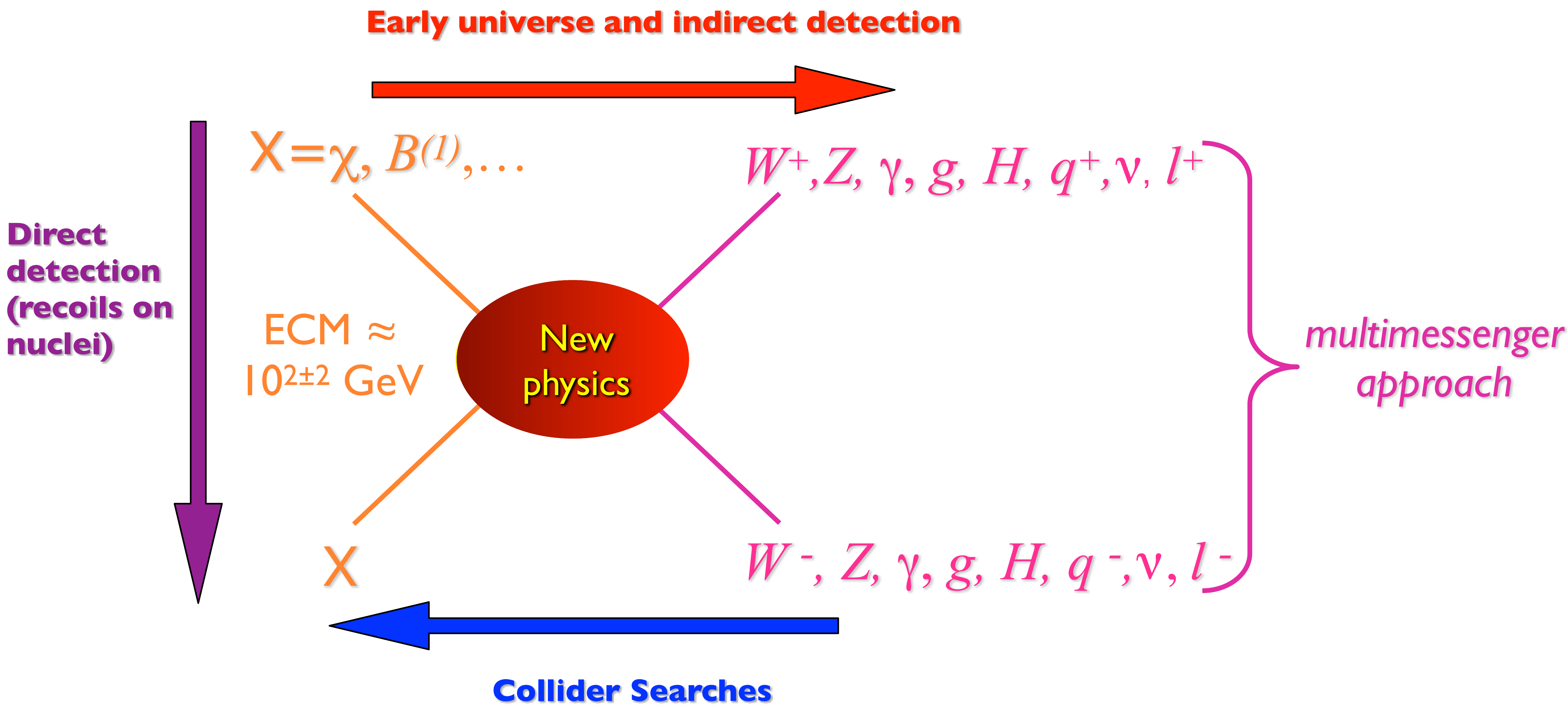

Textbook calculation yields the current average cosmological energy density

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

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

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

# 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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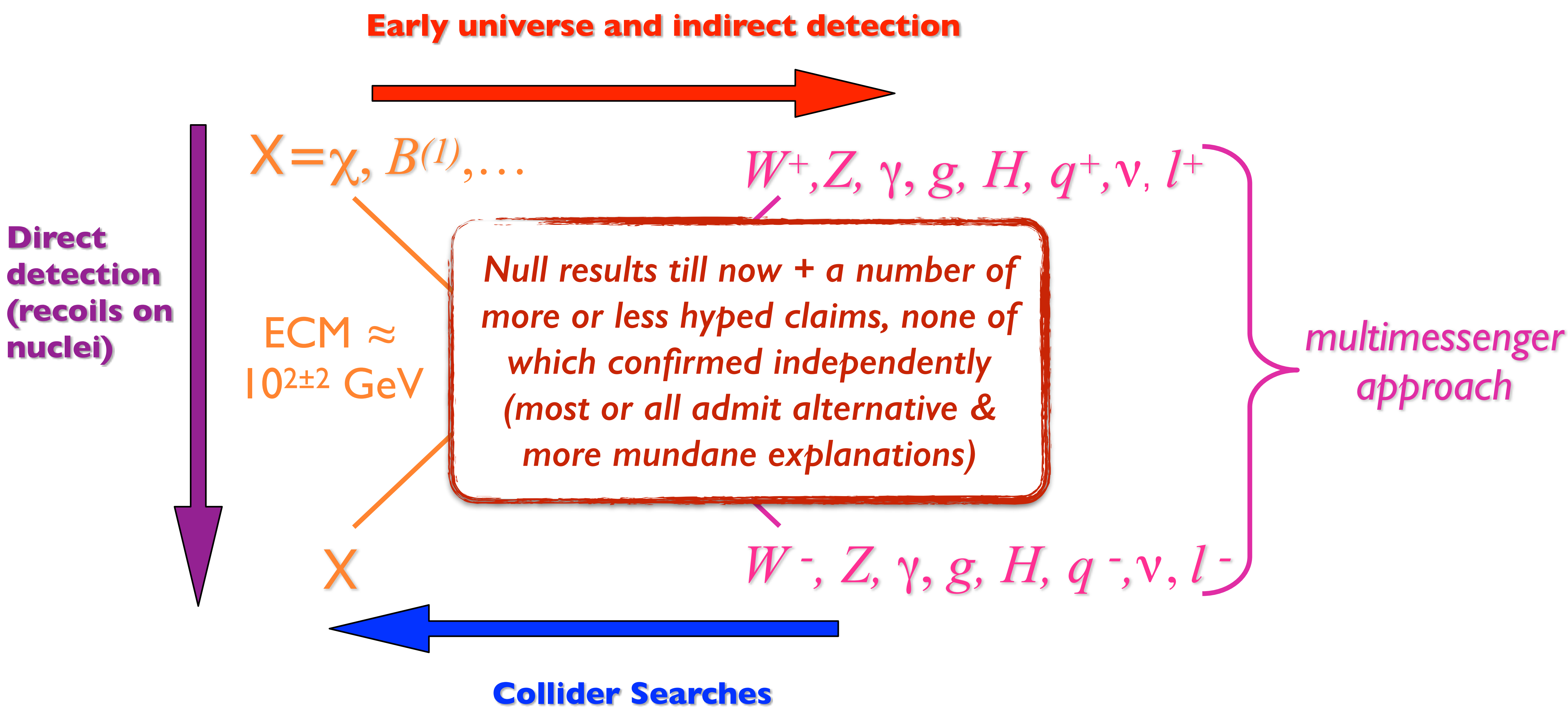


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# Ex. II: Gravitational probes of DM at small scales

- 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.

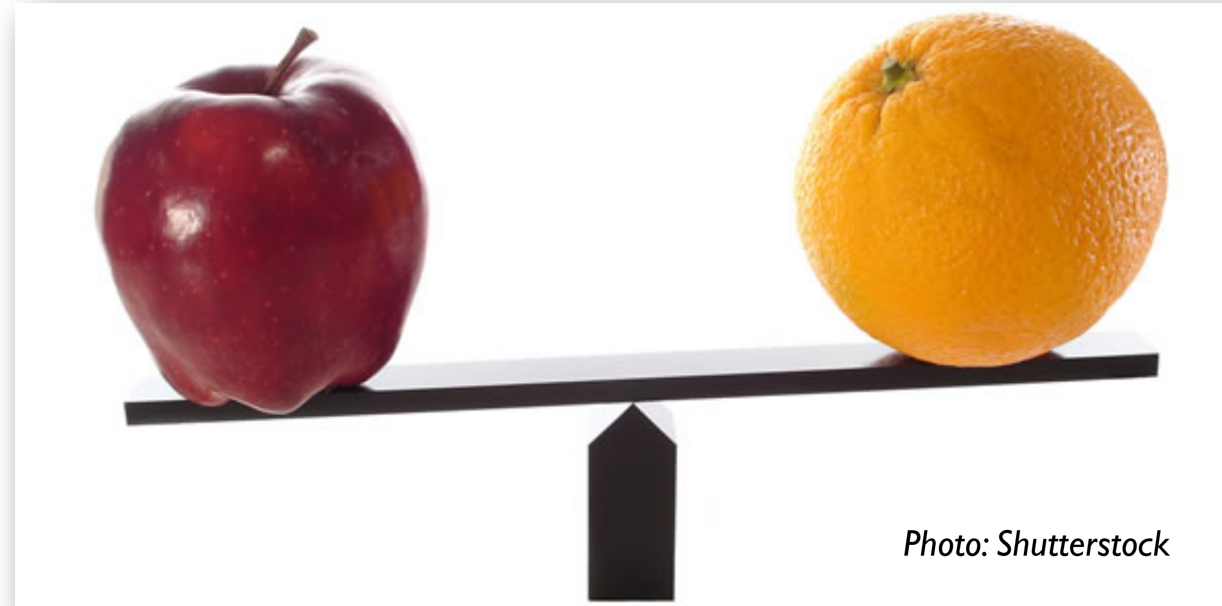
**Within these limitations, some "expectations" obtained, for instance**

- 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 $dn/dM \sim M^{-1.95}$

**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 cuspy 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)

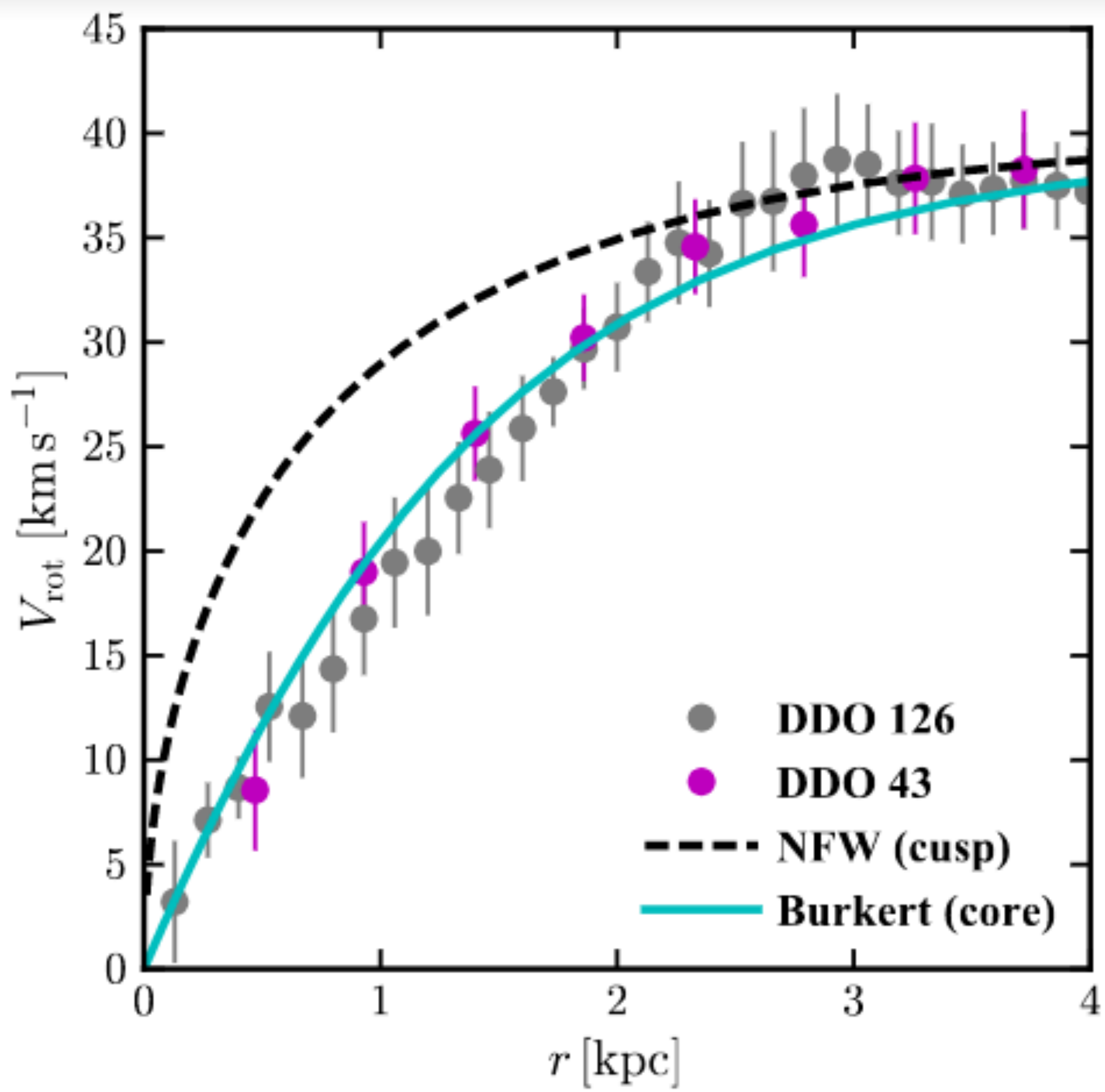
**Option nr. 2**
**Exotics**: anything from "DM is a flawed idea" to "that may help identify nature of DM"

# A 27 yr-old classic: Cusp/core problem

*B. Moore, "Evidence against dissipationless dark matter from observations of galaxy haloes," Nature 370, 629 (1994)*
*R.A. Flores & J.R. Primack, "Observational and theoretical constraints on singular dark matter halos," ApJ. 427, L1 (1994)*

***Central regions*** of DM dominated galaxies as inferred from rotation curves tend to be both ***less dense*** (in normalization) ***and less cuspy*** (in inferred density profile slope) ***than predicted*** for CDM halos.

The issue is most prevalent for dwarf and low surface bright-ness (LSB) galaxies



# Could it be due to DM microphysics?

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

# Incomplete list of models claimed to be responsible

- **Warm DM**
- **Fuzzy DM**
- **Strongly self-interacting DM (perhaps in cannibal form…)**
- **"Dissipative" DM / Dark Radiation**
- **…**

*Interestingly, they are related to different production mechanisms, often beyond the thermal one, providing an alternative criterion of DM classification*

**Cannot cover all, but let me illustrate how relying on this path can lead…**

**[?] …to 'constructive' speculations (model-building and observational search programs)**
**[?] …us astray (even more)**

*(Time will tell which one)*

# What if the Dark (Matter) Force awakens?

Phenomena could be linked to strong
DM-DM elastic scattering (**$\sigma/m \sim 1\ \mathrm{cm^2/g} = 1.8\ \mathrm{b/GeV}$**)

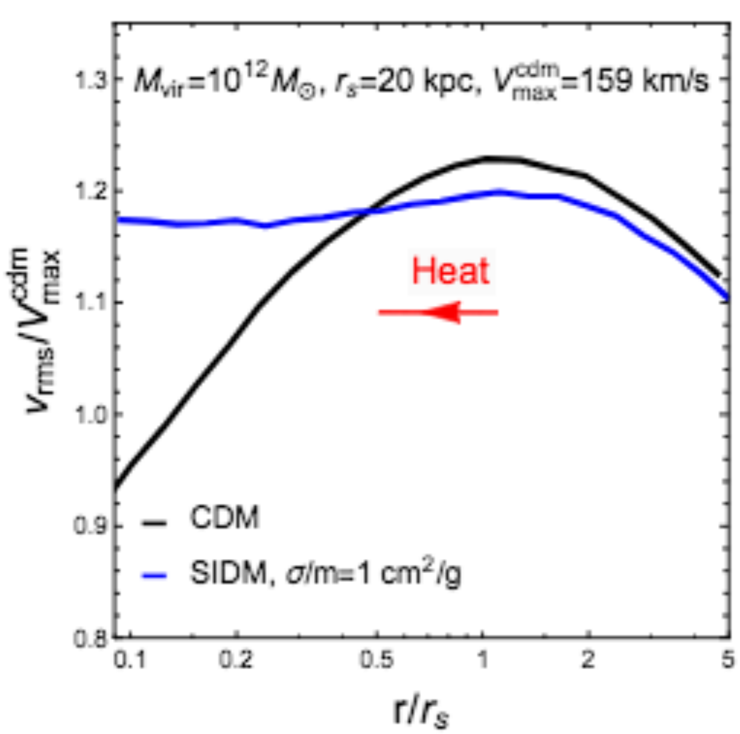
Idea of **Self-Interacting DM** goes back to:

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

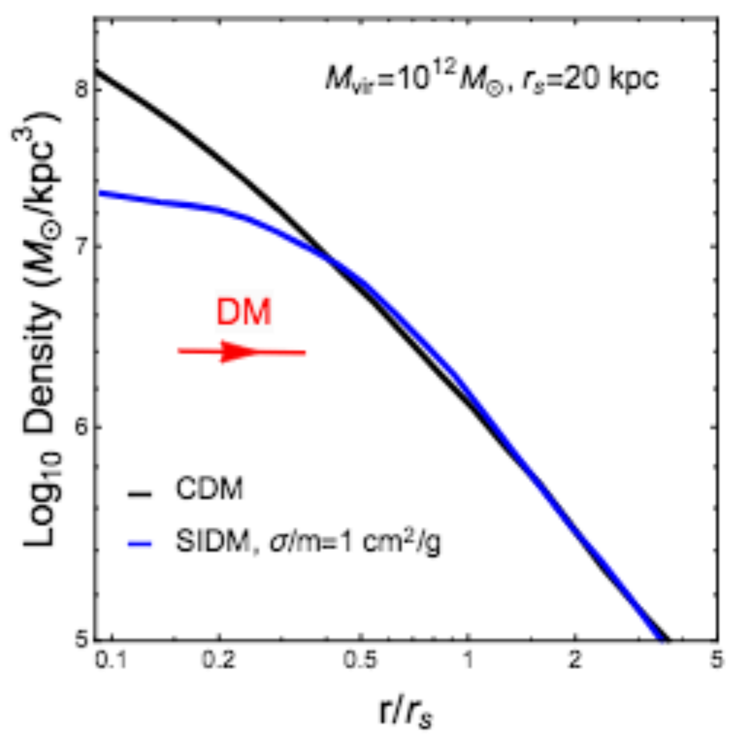
Major revival (talking about sequels!) in recent years, for a review & refs.

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

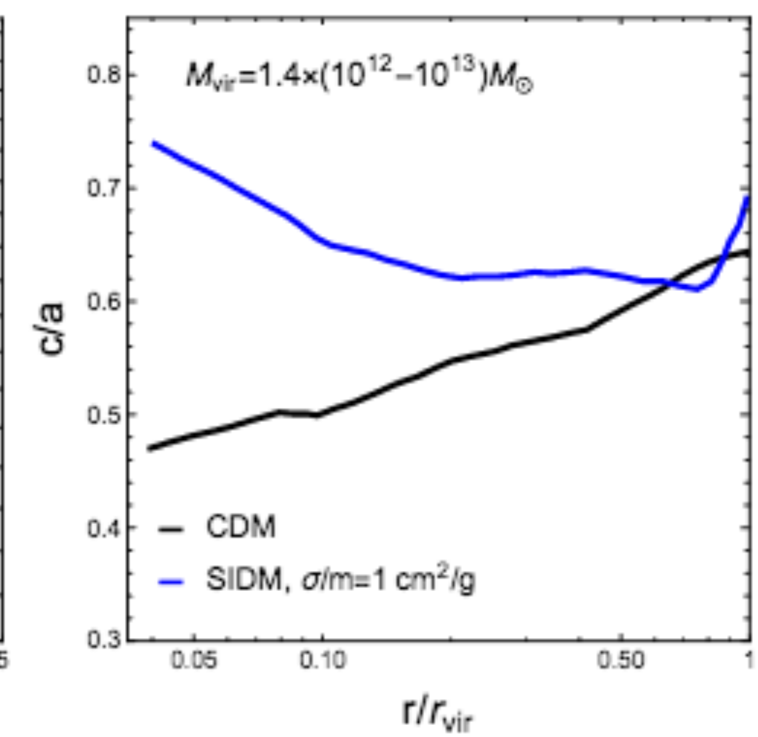
**In inner halos, scatterings lead to DM "thermalization"**




more uniform & isotropic v-dispersion




cored profiles & suppressed DM density



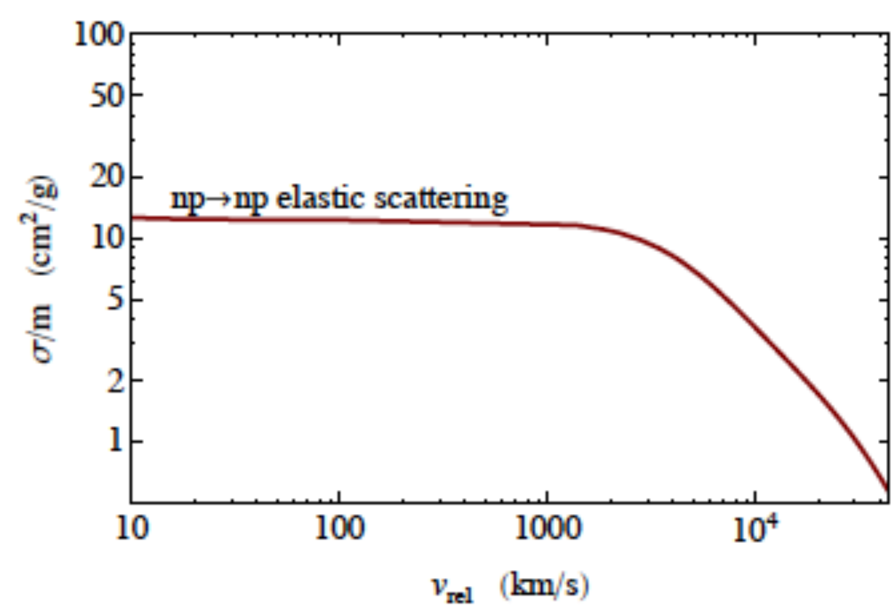

more spherical inner halos

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

| **Positive observations** | $\sigma/m$ | $v_{rel}$ | 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 | $\lesssim$ 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!

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

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]*

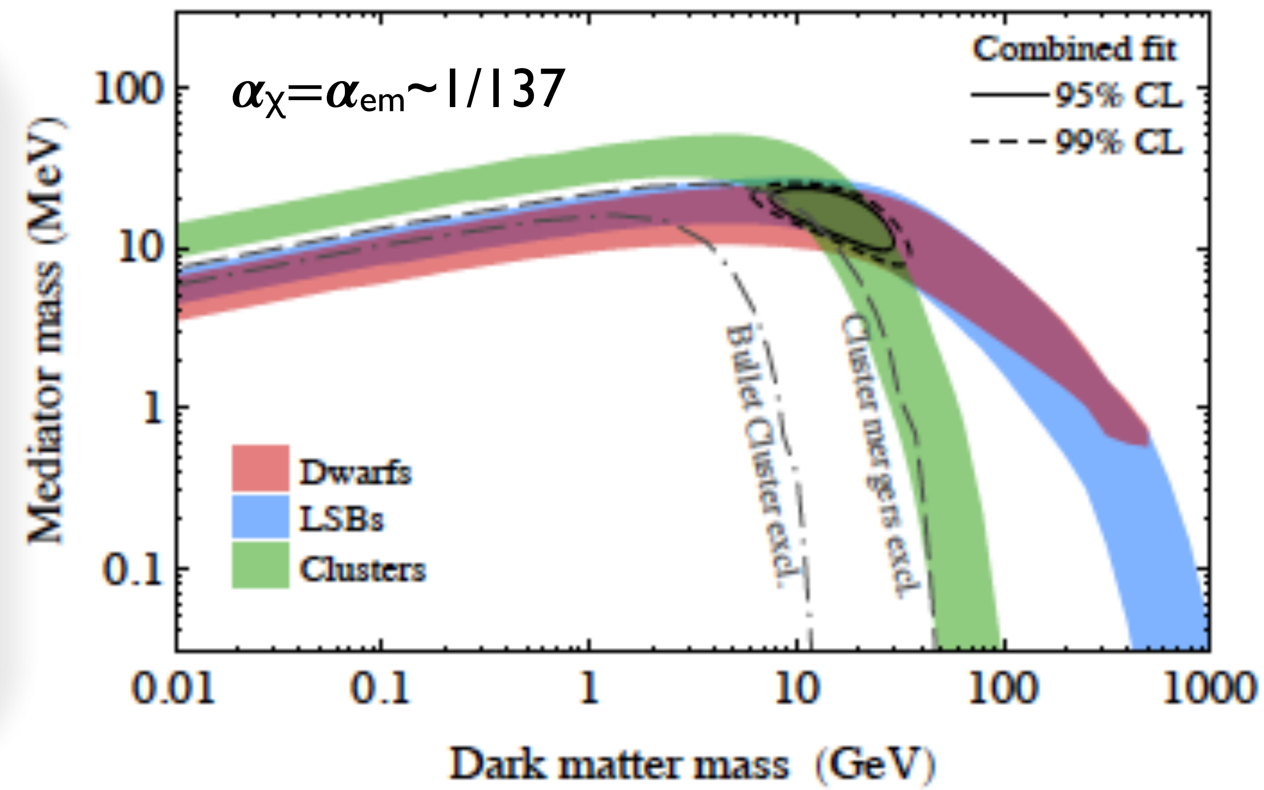
# v-dependence require at least 2 dofs/scales!

**E.g. scalar interaction with a light mediator $\phi$**

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

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

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

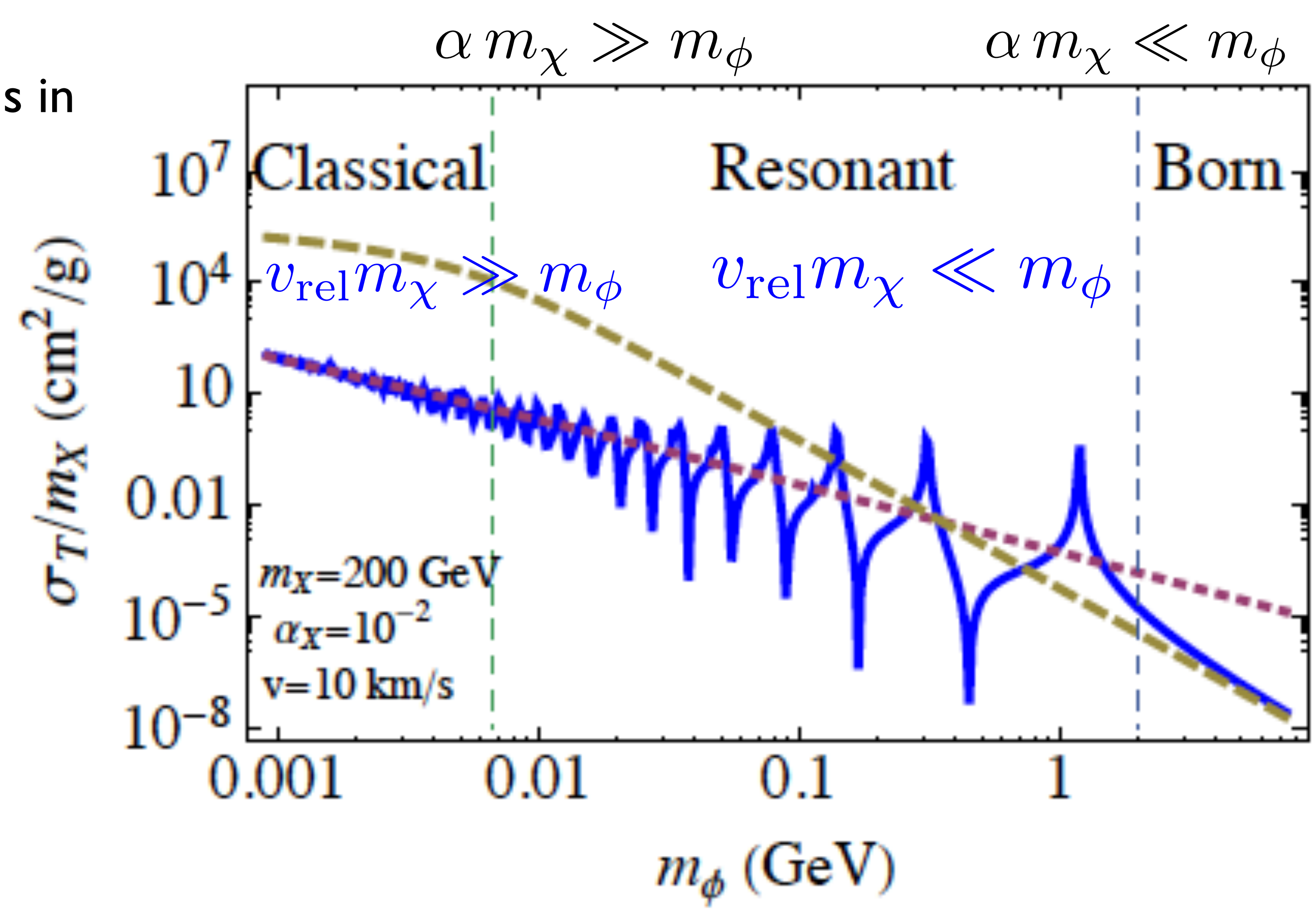



more general approach on type of eff. potentials in

*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]*



# Dark Oscillations

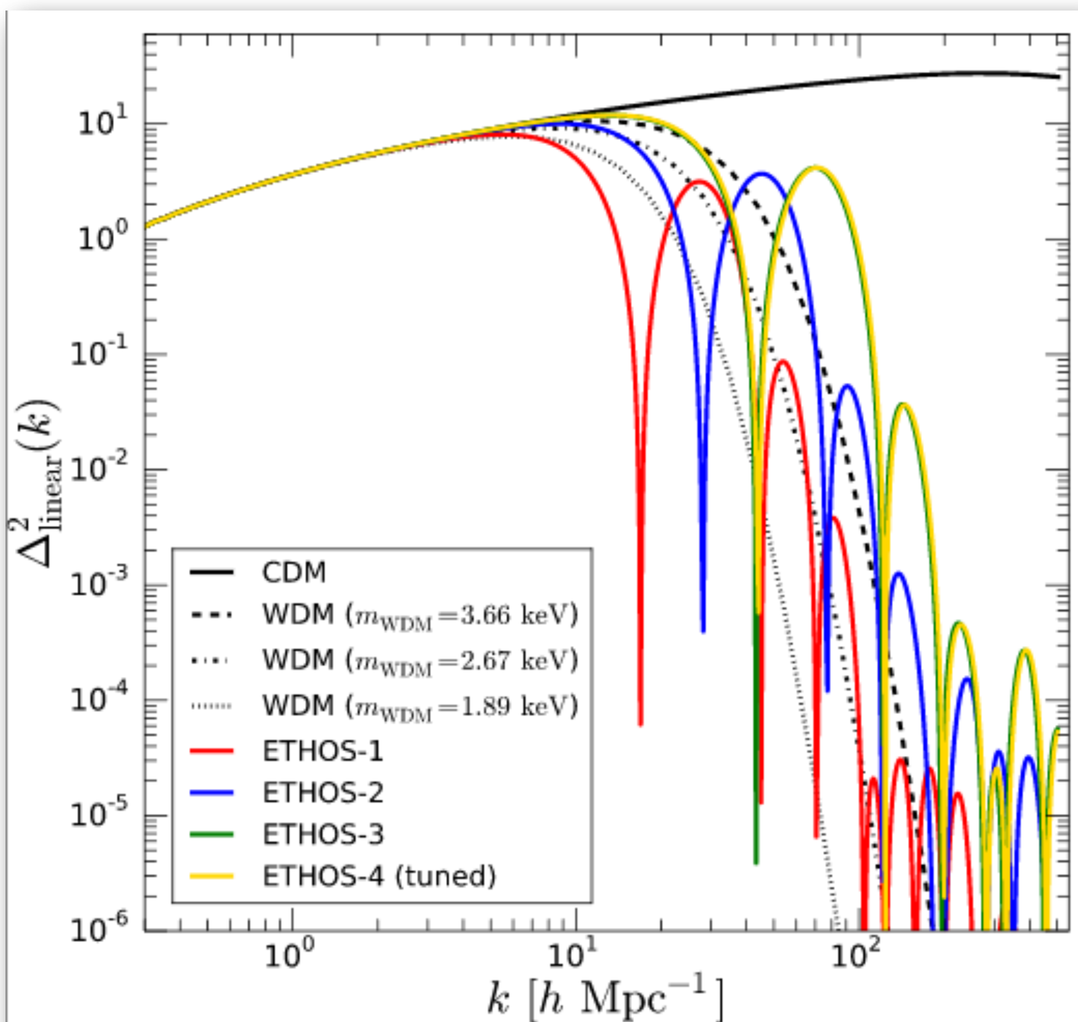
The fraction of DM coupling to new BSM relativistic particles:

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

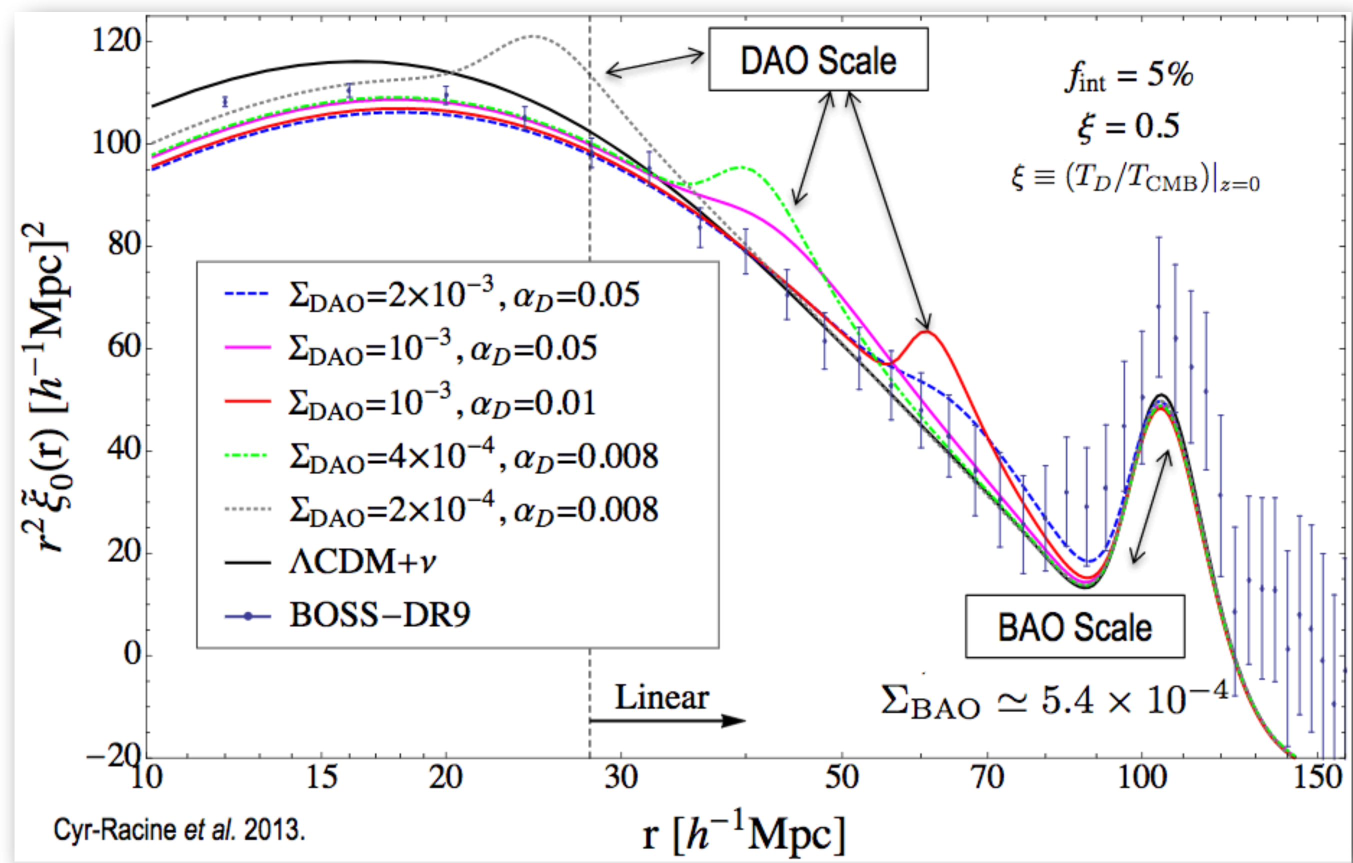
ii) Has a relatively late epoch of kinematic decoupling

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

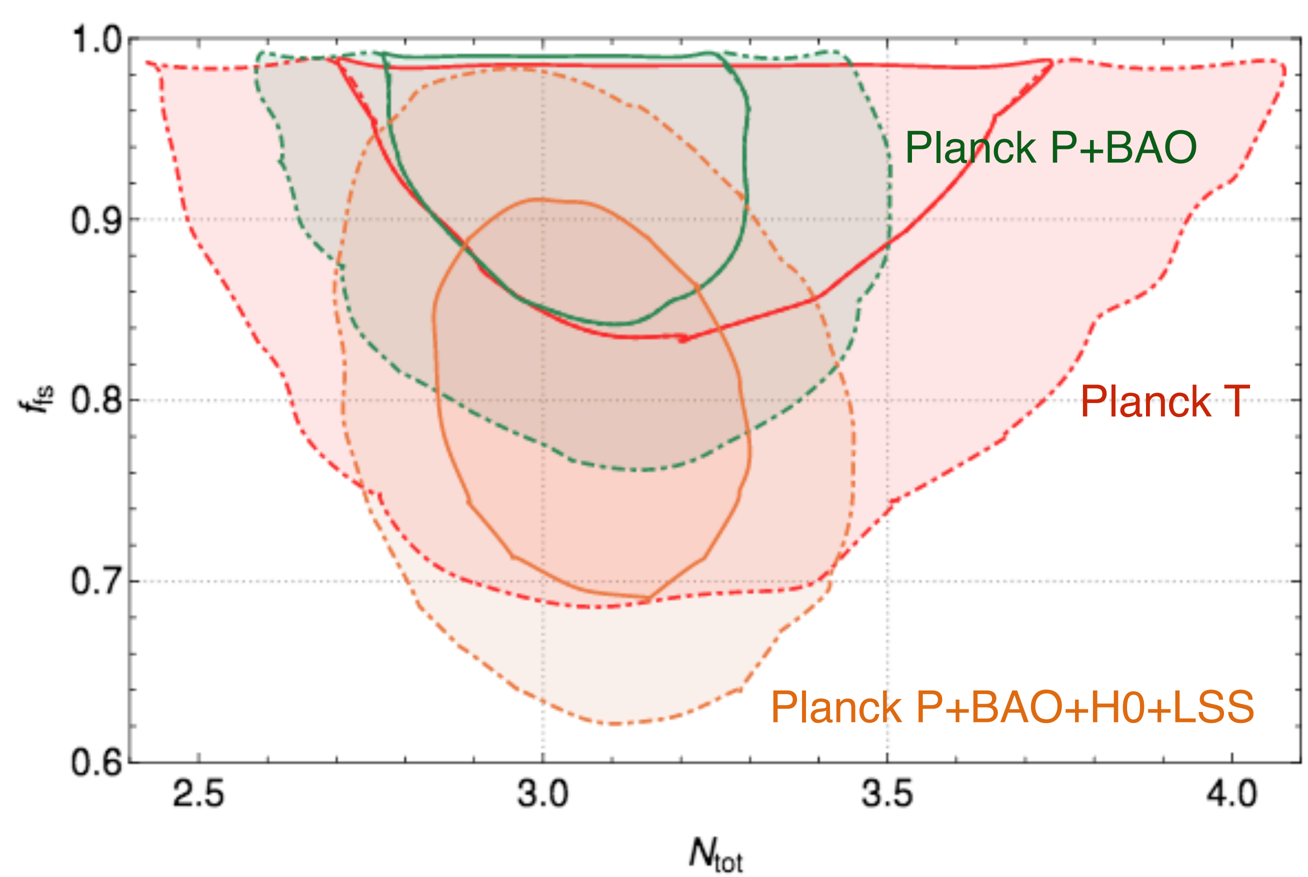
The light/massless mediator is typically stable or very long-lived, contributing to the amount of relativistic degrees of freedom (Dark Radiation) in the early Universe, and is subject to constraints from Big Bang Nucleosynthesis (BBN) and CMB

BBN *alone* gives $\Delta N_{eff}<1$ at about 3 $\sigma$ with standard assumptions (*R. H. Cyburt, et al. Rev. Mod. Phys. 88, 015004 (2016) [1505.01076]*) or at about 2 $\sigma$ 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…)



# More in general: Complementarities and challenges

**From the particle physics point of view**

Cosmo & astro 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, high-z ones…) or more "direct" anomalies (e.g. from lensing? Searches for baryon-less halos…)

# Some considerations: Food for thought

- While eagerly waiting for discoveries breaking the SM or new fruitful guiding principle for BSM theory-building, we should also investigate 'observational anomalies': Can arise either via 'increased precision' (e.g. $H_0$) or opening of new windows (e.g. EDGES)

  *Pursuing both is important, like intensity and energy frontiers at colliders!*

- Astro/cosmo probes, notably at small scales and poorly explored intermediate redshifts can test cosmology in new regimes, perhaps shedding light on DM properties.

- To be useful in understanding the DM phenomenon, must make sure that 'nuisance' effects (role of baryons, non-linearities…) are small and/or under control.

*Effort for different approaches to simulations, comparisons, extension to non-standard theories, etc.*

- We need a cross-talk among different communities, making sure that we are on the same page on "what do we want to explain". Most phenomena in nature are emergent and not easily linked to underlying physics: building 'theories' to explain each empirical relation unlikely to succeed, need predictive power in a different domain!

- In order to test a broad spectrum of theories and phenomena, broad spectrum of tools and competences needed. Break barriers beyond traditional divisions among particle theorists, cosmologists, researchers on gravity, experimentalists…

*Exchange 'forum' among different communities needed if we want to overcome misunderstandings, produce innovative thinking and suggest new research programs. Needed diversity present in France, but scattered across IN2P3, INP, INSU, CEA, etc.*

# (Non?)exhaustive list of interested actors in France

Institutes by subjects

**Particle model building & collider pheno:** IN2P3, INP, CEA
**Primordial black holes:** IN2P3, INP, INSU
**Modified gravity (DM context):** INSU, CEA

**Structure formation:** INSU, CEA, (1 IN2P3)

**Indirect/astro/cosmo searches:** INP, IN2P3, CEA
**Direct searches** (WIMPs & axions): INP, IN2P3, CEA
**Gravitational/dynamical searches** (lensing + kinematics): INSU, IN2P3

Labs within Institutes

**IN2P3:** APC, IJCLab, IPNL, LPC-Clermont, LPNHE, LPSC, LUPM
**INP:** LAPTh, L2C, LPT-ENS, LPTHE, CPT
**INSU:** CRAL, IAP, LAM, ObAS, ObPM, OCA
**CEA:** IPhT, IRFU

extremely diverse communities
# No common place or structure for interaction / discussion at the national level
=> Need remedy to improve efficiency / impact potential / circulation of ideas and students
=> A *common permanent discussion platform? GDR? Annual workshop?*
(should involve all institutes but not multiply bureaucracy x *N*… or even worse, non-linearly!)