DARK MATTER THROUGH THE HIGGS PORTAL

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COST Advanced School on Physics of Dark Matter and Hidden Sectors: from Theory to Experiment

OUTLINE

1. Intro to DM

2. (Thermo)dynamics of early universe and production of DM abundance

3. Dark sectors and their portals, examples of models and constraints

4. Conclusions

1. INTRODUCTION: DARK MATTER

The Dark Universe

Summary:

Observations over vastly different distance (and time) scales

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Observable universe,

Galaxy clusters,

Galaxies,
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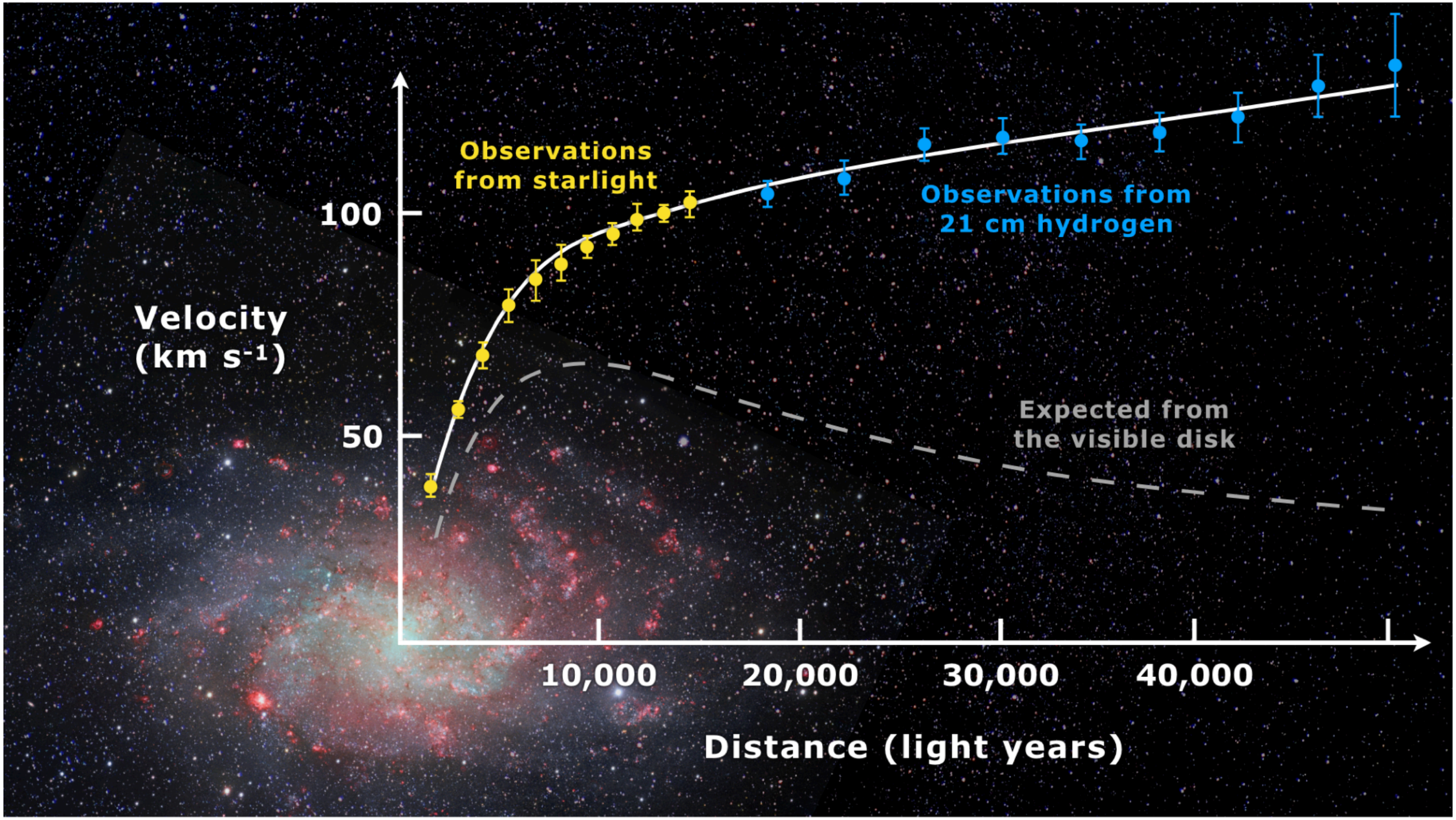
All explained by a dominant cold dark matter component

Galactic rotation curves

size: 10-100 kpc, time: now

(image: wikipedia)



Newtonian dynamics:

$$F = \frac{mv^2}{r} = G_N \frac{mM}{r^2} \quad \Rightarrow \quad v \sim r^{-1/2}$$

Assuming a dark matter halo:

$M(r) \propto r \qquad \rho(r) \propto r^{-2}$

compatible with observations.

Galaxy clusters

scale: 10 Mpc

- e.g. Coma: $\mathcal{O}(1000)$ galaxies, bound by gravity.
- 1933 Fritz Zwicky measured their velocities
- From these, he inferred the mass of the cluster.

Wide field image of the Coma Cluster taken at the Mount Lemmon SkyCenter using the 0.8m Schulman Telescope. (Image from Wikipedia)

Application of the virial theorem:

$$2\langle T \rangle = -\langle V \rangle$$

Measure the velocities of galaxies…

… to obtain estimate of the total mass of the cluster.

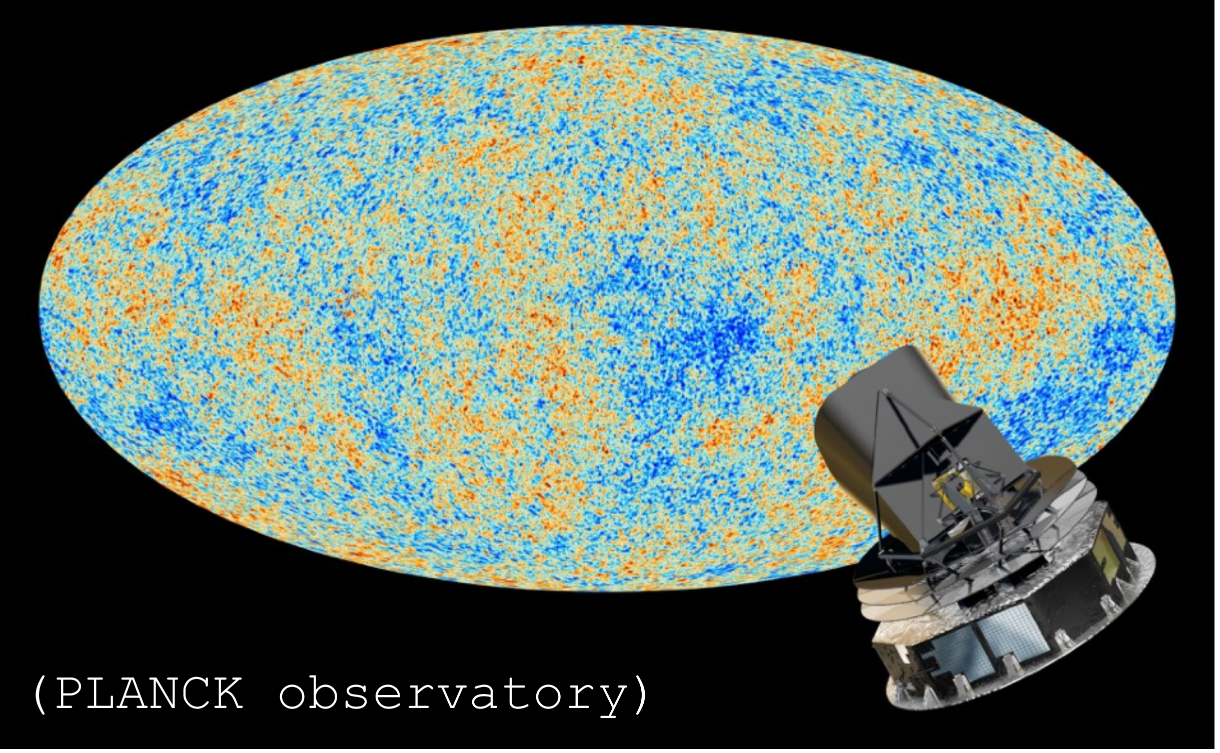
Resulting mass is much more than the mass of the luminous galaxies in the cluster!

$$\mathcal{M} > 9 \times 10^{46}\,\mathrm{gr}\,. \tag{35}$$

The Coma cluster contains about one thousand nebulae. The average mass of one of these nebulae is therefore

$$\overline{M} > 9 \times 10^{43}\ \mathrm{gr} = 4.5 \times 10^{10}\ M_{\odot}\,. \tag{36}$$

the average mass of nebulae in the Coma cluster. This result is somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^{7} suns. According

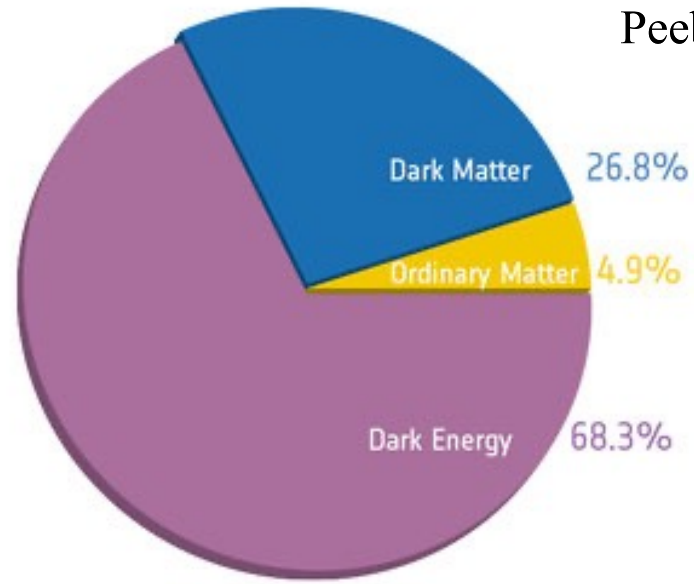


(PLANCK observatory)

Temperature fluctuations in CMB

(scale: Gpc)

Peebles & Yu (1970)



80% of all matter
is
non-baryonic & 'dark'

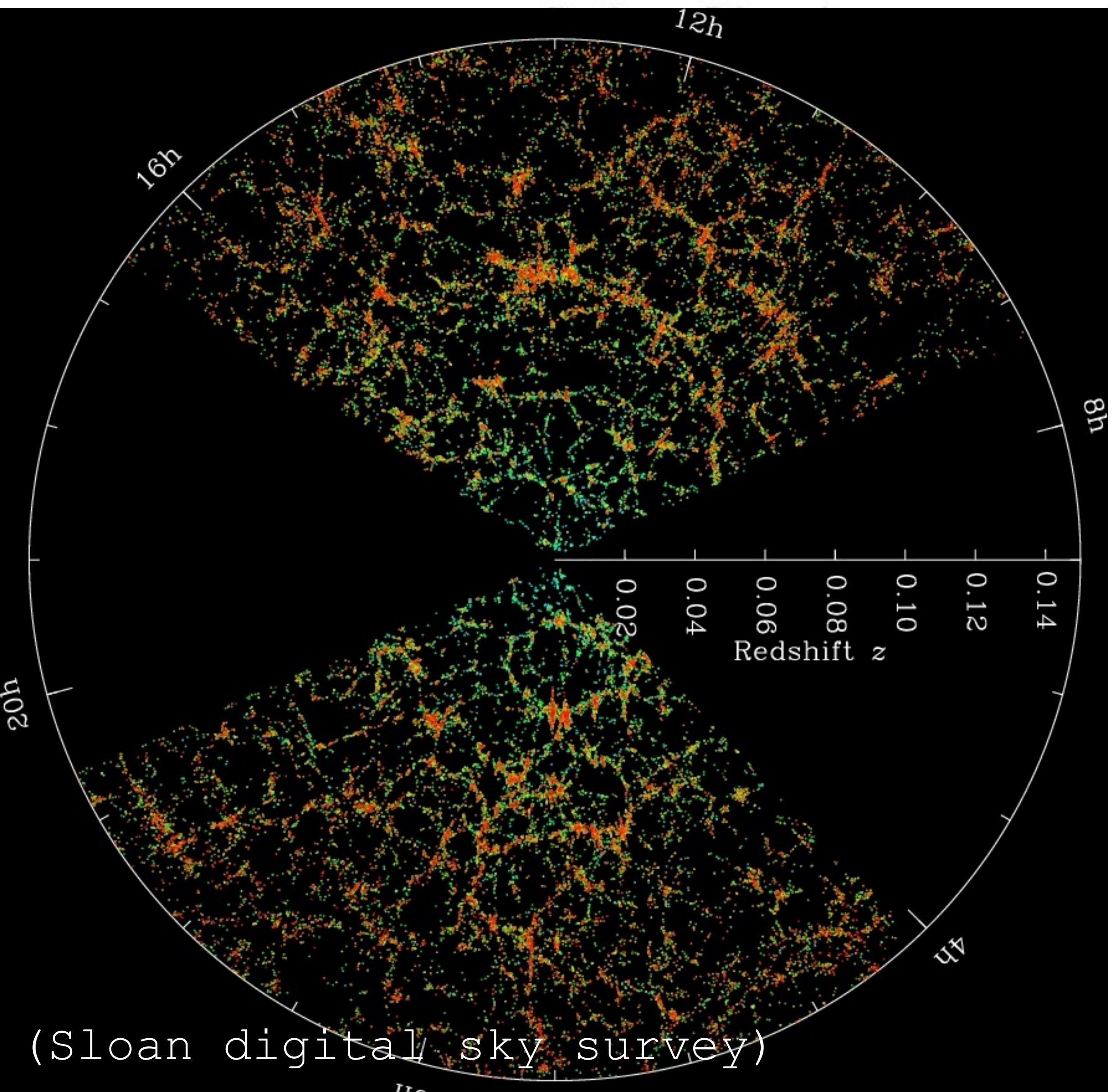
$$\Omega_i = \rho_i/\rho_{\text{crit}} \approx \rho_i/\rho_{\text{tot.}}$$

$$\Omega_b \approx 0.049, \qquad \Omega_{\text{CDM}} \approx 0.268, \qquad \Omega_\Lambda \approx 0.683$$

equivalently

$$\Omega_b h^2 = 0.022, \qquad \Omega_{\text{CDM}} h^2 = 0.12, \qquad \Omega_\Lambda h^2 = 0.31$$

$$H_0 = 100h\text{km/s/Mpc}$$



(Sloan digital sky survey)

At large scales ordinary matter forms stars, galaxies, galaxy clusters,…

These grow out of the initial fluctuations.

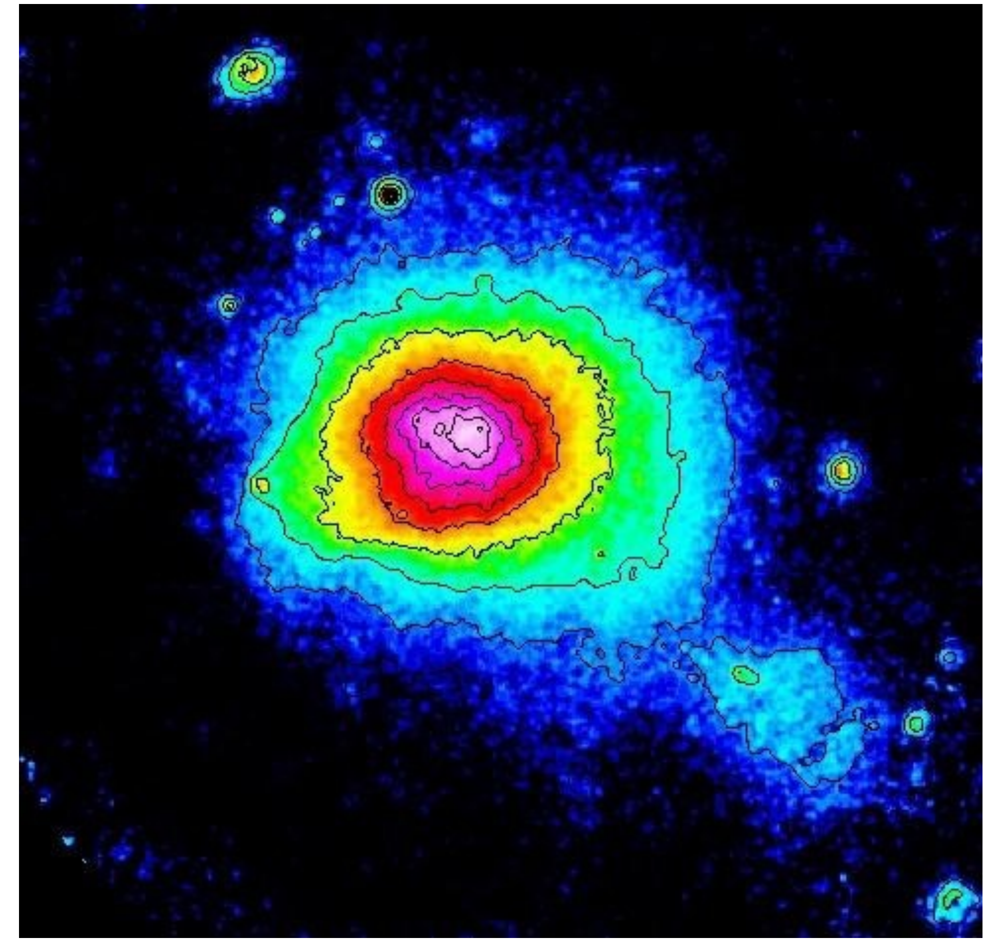
Possible, because of **cold** dark matter!

Peebles (1984)

ΛCDM - paradigm

optical image of Coma

X-ray image of Coma



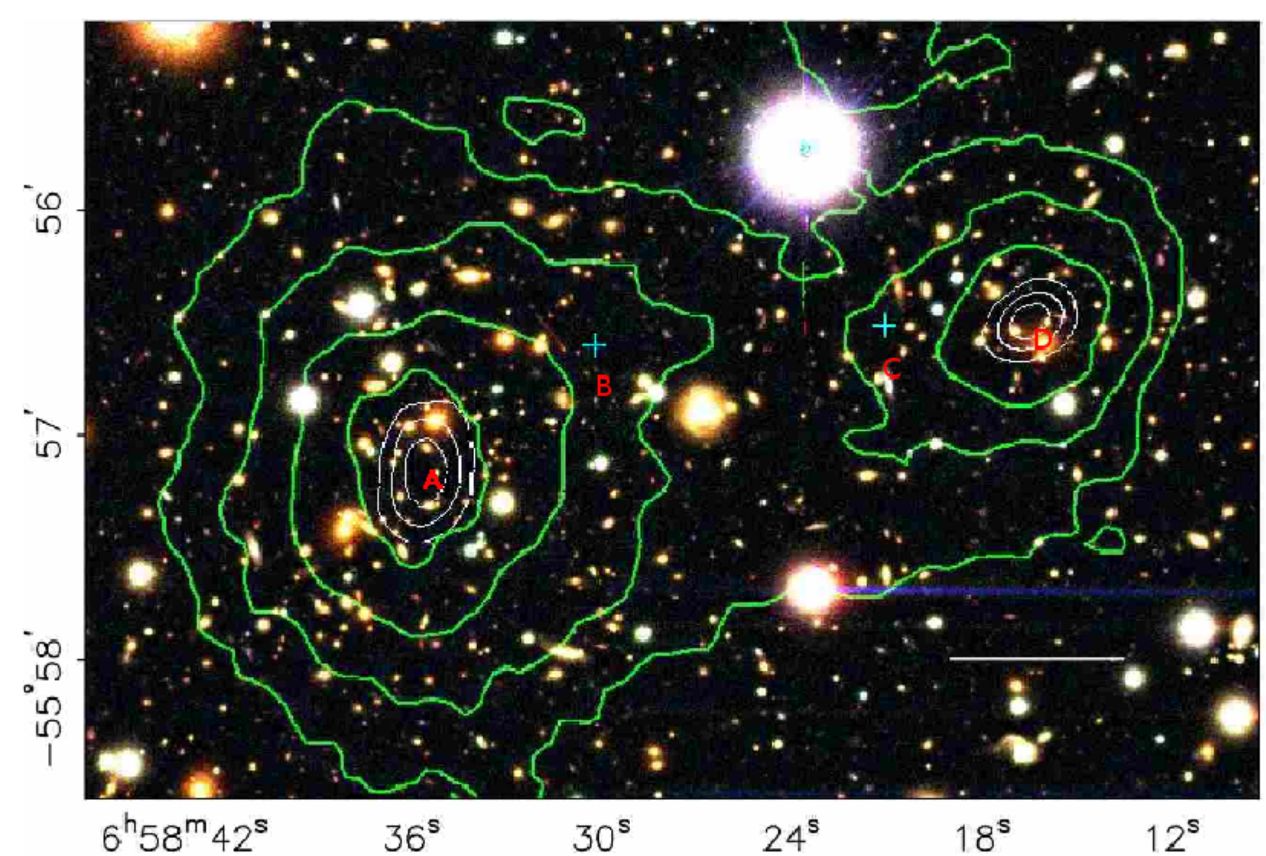
Most of visible matter: intracluster plasma.

To make a case for dark matter, we try to separate visible matter from centres of gravity.

The bullet cluster: a cosmic collider

intracluster plasma (red) slowed down by the collision.

centers of gravity (blue) unaffected by the collision.



Equipotential lines of gravity from gravitational lensing

D. Clowe *et al*. (2006)

Solar neighbourhood:

Local density $\rho_{\mathrm{CDM}} \simeq 0.3\,\mathrm{GeV/cm^3}$

Velocity distribution: Standard Halo Model

$$f_G(\boldsymbol{v}) = \frac{1}{N(v_0)} \exp\left(-\frac{\boldsymbol{v}^2}{v_0^2}\right) \theta(v_{\mathrm{esc}} - |\boldsymbol{v}|)$$

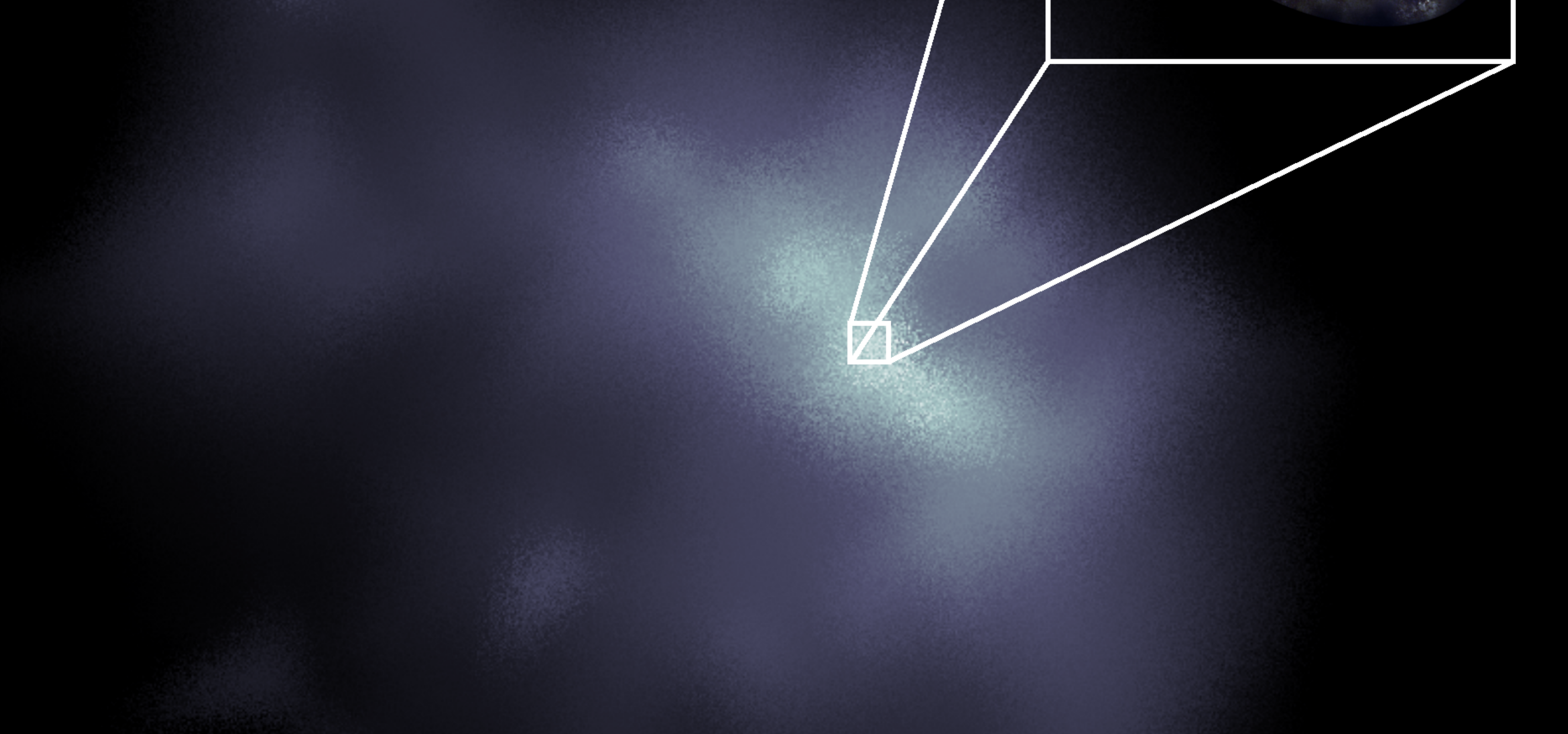


Image credit: Cosmological Physics and Advanced Computing Group, Argonne National Laboratory

But what is it: Dark Matter candidates

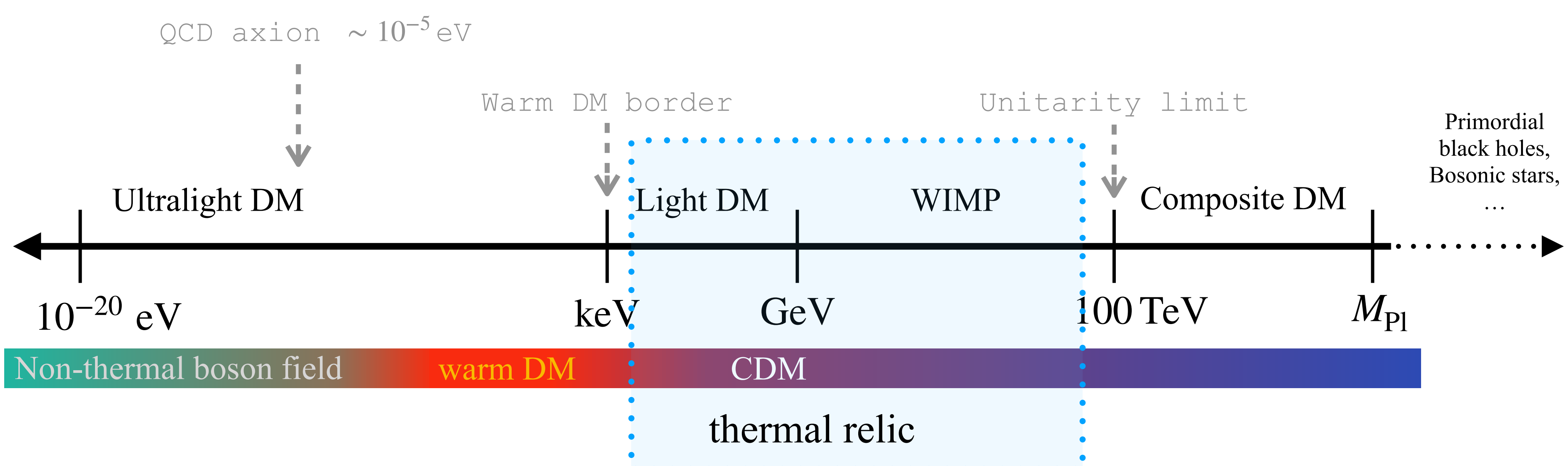
MACHOs (MAssive Compact Halo Objects), e.g.
low luminosity stars, planets, black holes

Primordial black holes ?

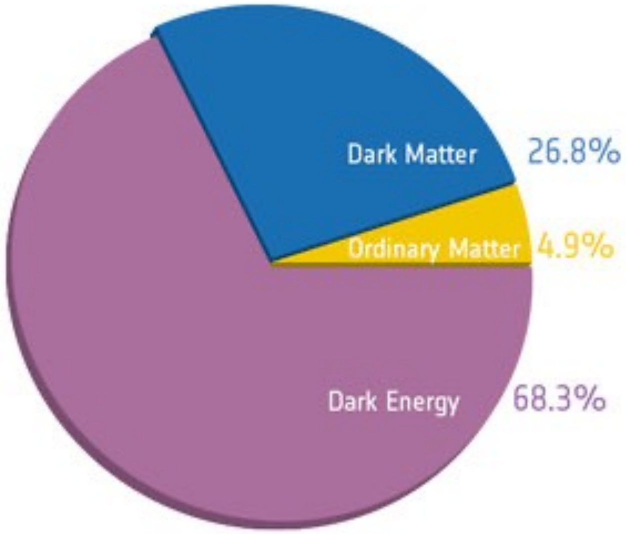
New elementary particle(s) from Beyond SM physics:

Weakly Interacting Massive Particle = WIMP

`Cold, Stable, Neutral, Not ordinary matter, Weakly interacting`



2. (THERMO)DYNAMICS OF THE UNIVERSE AND ABUNDANCE OF DM



Expanding background and thermal evolution of the universe

Friedmann equations: ($k = 0$, flat universe)

$$\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = \frac{8\pi G_N}{3}\rho \qquad H \equiv \frac{\dot{a}}{a}, \qquad G_N = \frac{1}{M_{\rm Pl}}$$

$$\dot{\rho} = -3(\rho + P)\frac{\dot{a}}{a}$$

Thermodynamics:

$$\rho = Ts - P, \qquad d\rho = Tds, \qquad dP = sdT$$

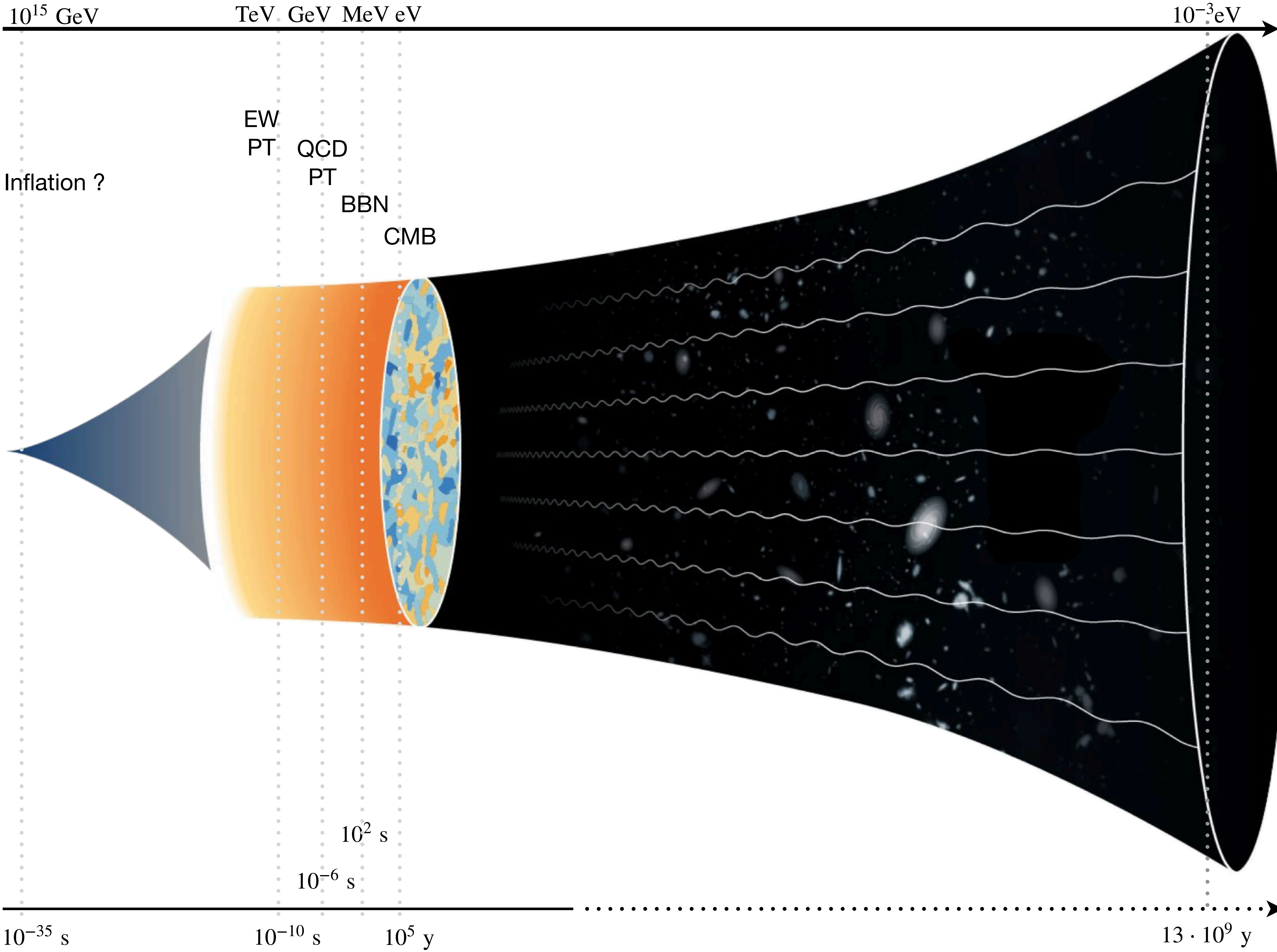
$$\Rightarrow \qquad \frac{d}{dt}\left(sa^3\right) = 0 \qquad \text{(entropy conservation)}$$

and $$t = \sqrt{\frac{45}{16 g_* \pi^3}}\frac{M_{\rm Pl}}{T^2} \qquad \text{(time vs. temperature)}$$

$$\rho = g_* \frac{\pi^2 T^4}{30} = \left(\sum_B g_i + \frac{7}{8}\sum_F g_i\right)\frac{\pi^2 T^4}{30}$$

e.g.

$$\frac{t}{\rm s} \simeq \left(\frac{\rm MeV}{T}\right)^2 \qquad (g_* = 10.75)$$



10^{15} GeV
TeV
GeV
MeV
eV
10^{-3}eV
Inflation ?
EW PT
QCD PT
BBN
CMB
10^{2} s
10^{-6} s
10^{-35} s
10^{-10} s
10^{5} y
$13 \cdot 10^{9}$ y

Evolution of particle distributions

(interaction rate)

$$\dot{f} = -\Gamma(k)\left(f - f_{\rm eq}\right) + \mathcal{O}(f - f_{\rm eq})^2$$

(linear response near equilibrium)

In expanding background

$$\partial_t f(t,k) - Hk\partial_k f(t,k) = -\Gamma(k)(f - f_{\rm eq})$$

Switching to $k_t = k(t_0)\dfrac{a(t_0)}{a(t)}$ removes the expansion term.

Furthermore, $x \equiv \ln(T_{\rm max}/T)$, with Jacobian $\mathcal{J} \simeq H$ leads to

$$\frac{f(x, k_T)}{dt} = -\tilde{\Gamma}(k_T)(f - f_{\rm eq}), \qquad \text{where } \tilde{\Gamma} \equiv \frac{\Gamma}{\mathcal{J}} \simeq \frac{\Gamma}{H}$$

Departure from equilibrium is controlled by the ratio of the interaction rate and the expansion rate

For example, neutrinos: $\Gamma \sim G_F^2 T^5 \quad \Rightarrow \quad \tilde{\Gamma} \sim M_{\rm Pl} G_F^2 T^3$

$$\tilde{\Gamma} \sim 1 \quad \Rightarrow \quad T \sim \left(\frac{1}{M_{\rm Pl} G_F^2}\right)^{1/3} \sim 10^{-3}\,{\rm GeV}$$

Consider DM as a thermal relic. Start from the rate equation:

$$\frac{f(x,k_T)}{dt} = -\tilde{\Gamma}(k_T)(f - f_{\rm eq}),$$

Assume kinetic equilibrium $\quad f = f_{\rm eq}\frac{n}{n_{\rm eq}} \qquad n_{\rm eq} = \int_{k_T} f_{\rm eq}$

Insert into rate equation and integrate over k_T. Also, define yield as $Y(x) = n(x)/s(T)$

$$Y'(x) = -\langle\tilde{\Gamma}\rangle\Big(Y(x) - Y_{\rm eq}(x)\Big) \qquad Y_{\rm eq} = n_{\rm eq}(x)/s(T)$$

$$\langle\tilde{\Gamma}\rangle \equiv \frac{\int_{k_T}\tilde{\Gamma}(k_T)f_{\rm eq}}{\int_{k_T} f_{\rm eq}}$$

DM has some symmetry guaranteeing its stability.
The RHS must be quadratically dependent on Y.

$$Y^2 - Y_{\rm eq}^2 = (Y - Y_{\rm eq})(Y - Y_{\rm eq} + 2Y_{\rm eq}) = 2Y_{\rm eq}(Y - Y_{\rm eq}) + \mathcal{O}(Y - Y_{\rm eq})^2 \qquad \frac{\langle\Gamma\rangle}{2n_{\rm eq}} \equiv \langle\sigma v\rangle$$

$$\Rightarrow \boxed{Y'(x) = -\frac{\langle\tilde{\Gamma}\rangle}{2Y_{\rm eq}}\Big(Y^2(x) - Y_{\rm eq}^2(x)\Big)} \Leftrightarrow \qquad \dot{n} + 3Hn = -\langle\sigma v\rangle(n^2 + n_{\rm eq}^2)$$

(ZOPLW equation)

Zel'dovich, Okun, Pikelner (1966),
Lee, Weinberg (1977)

To investigate how this operates, let's again consider when $\langle\tilde{\Gamma}\rangle \sim 1$ i.e. $\langle\Gamma\rangle = 2n_{\rm eq}\langle\sigma v\rangle \sim H$

Parametrise: $\langle\sigma v\rangle = \dfrac{\alpha^2}{M^2}$

$$H \simeq \frac{T^2}{M_{\rm Pl}}$$

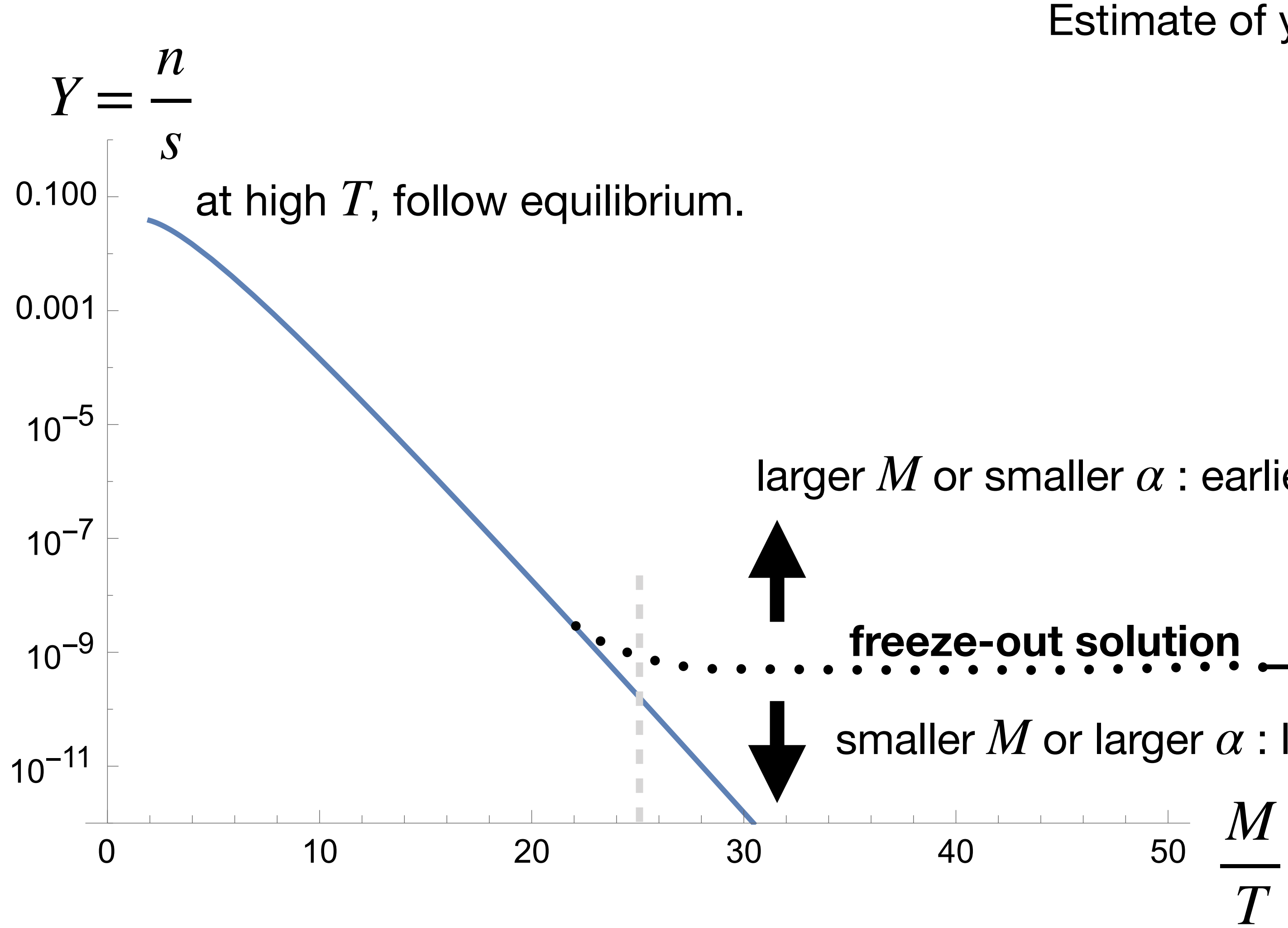
$$\Rightarrow \quad \frac{M}{T} \simeq \ln\left(\frac{\alpha^2}{(2\pi)^{3/2}}\frac{M_{\rm Pl}}{(MT)^{1/2}}\right) \sim 25$$

Take $\alpha = 0.01$, $M \sim T \sim 1\,\mathrm{TeV}$ inside log.

Nonrelativistic: $n_{\rm eq} \simeq \left(\dfrac{MT}{2\pi}\right)^{3/2} e^{-M/T}$

Decoupling at $T \sim M/25 \ll M$

Estimate of yield: $Y \sim \dfrac{n_{\rm eq}}{s} \sim \dfrac{1}{g_*}\left(\dfrac{M}{T}\right)^{3/2} e^{-M/T} \sim 10^{-10}$



Observations: $Y_0 M \approx 4.4 \cdot 10^{-13}\,\mathrm{TeV}$

$(\Omega_{\rm CDM} = 0.268)$

So our result from decoupling is too big if $M \sim 1\,\mathrm{TeV}$:

These estimates also imply that correct abundance can be produced by

$$\alpha \sim 0.01, \qquad M \sim 100\,\mathrm{GeV}$$

$$\text{i.e. } \langle \sigma v \rangle \sim 10^{-8}\,\mathrm{GeV}^{-2} = 3 \cdot 10^{-26} \frac{\mathrm{cm}^3}{s}\,.$$

This is known as the 'WIMP miracle'.

But note that $\sigma \sim \dfrac{\alpha^2}{M^2} \sim 10^{-8}\,\mathrm{GeV}^{-2}$ only implies that $\alpha \sim \dfrac{M^2}{10\,\mathrm{TeV}}$.

The relic density can be parametrically estimated as $\left(\dfrac{\Omega_{\mathrm{CDM}}}{0.2}\right) \simeq \dfrac{x_{\mathrm{f.o.}}}{20} \left(\dfrac{10^{-8}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle}\right)$

$x \equiv M/T$

The unitarity limit: $\sigma \leq \dfrac{(4\pi)^2}{M^2}$ implies $\left(\dfrac{\Omega_{\mathrm{CDM}}}{0.2}\right) \geq \dfrac{M^2}{(4\pi)^2 \cdot 10^8\,\mathrm{GeV}^2}$ $\Rightarrow M \leq 120\,\mathrm{TeV}$

Alternative mechanism: freeze-in

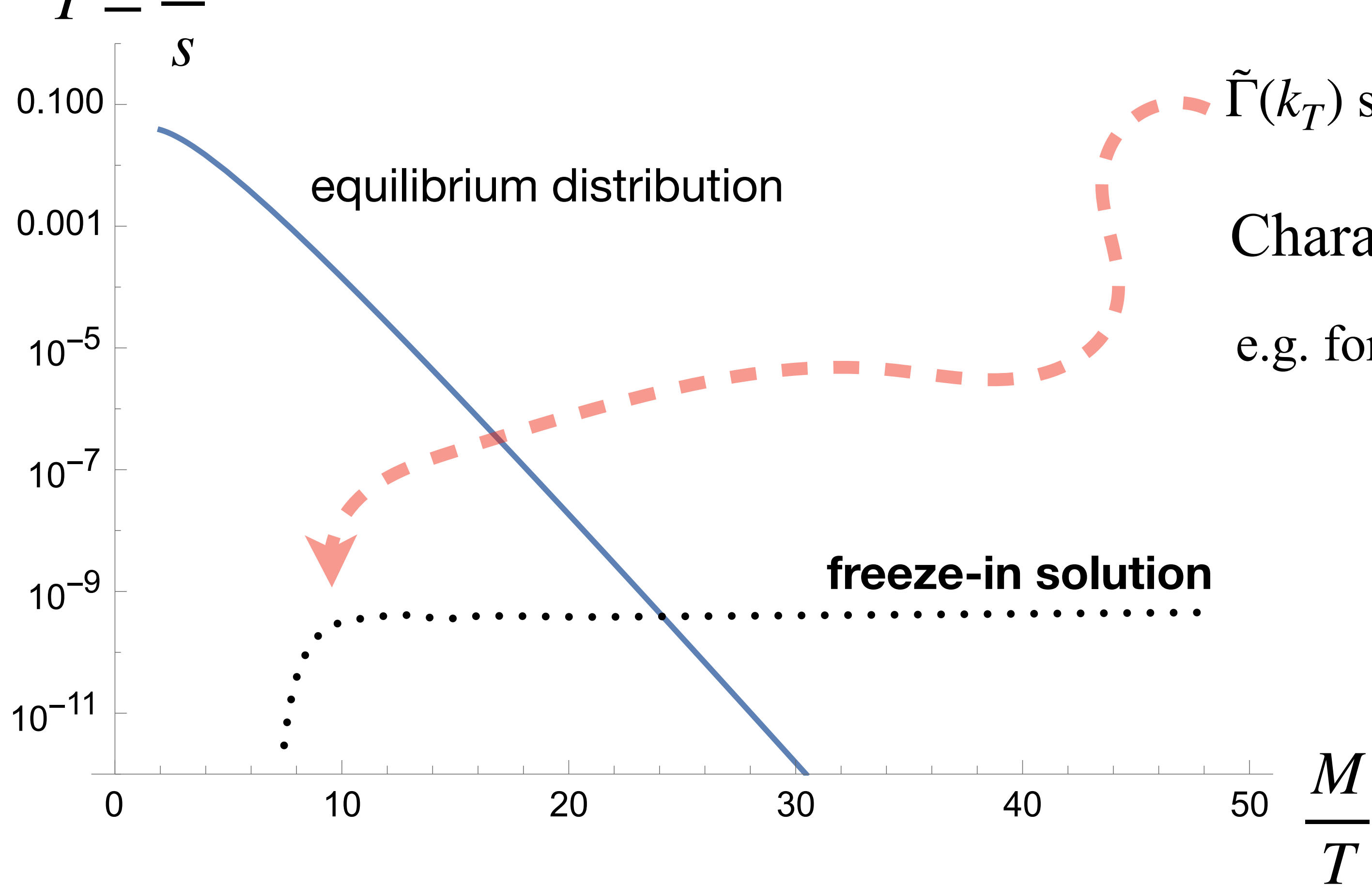
$$\frac{f(x, k_T)}{dt} = -\,\tilde{\Gamma}(k_T)(f - f_{\rm eq}),$$

Now assume that $\tilde{\Gamma} \ll 1$ and initially $f(0,k_T) = 0$.

Then we can neglect f in comparison to $f_{\rm eq}$

$$\frac{f(x, k_T)}{dt} = \tilde{\Gamma}(k_T) f_{\rm eq}$$

$Y = \frac{n}{s}$



$\tilde{\Gamma}(k_T)$ significant only in some range $T_{\min} \leq T \leq T_{\max}$

Characterised by 'feeble' coupling: $\sim 10^{-10}$

e.g. for $h \to$ DM + DM

$$y \sim 10^{-12} \left(\frac{\Omega_{\rm CDM} h^2}{0.12}\right)^{1/2} \left(\frac{g_*}{100}\right)^{3/4} \left(\frac{m_h}{m_{\rm DM}}\right)^{1/2}$$

J. McDonald (2002)
L.J. Hall et al. (2010)
N. Bernal et al. (2017)

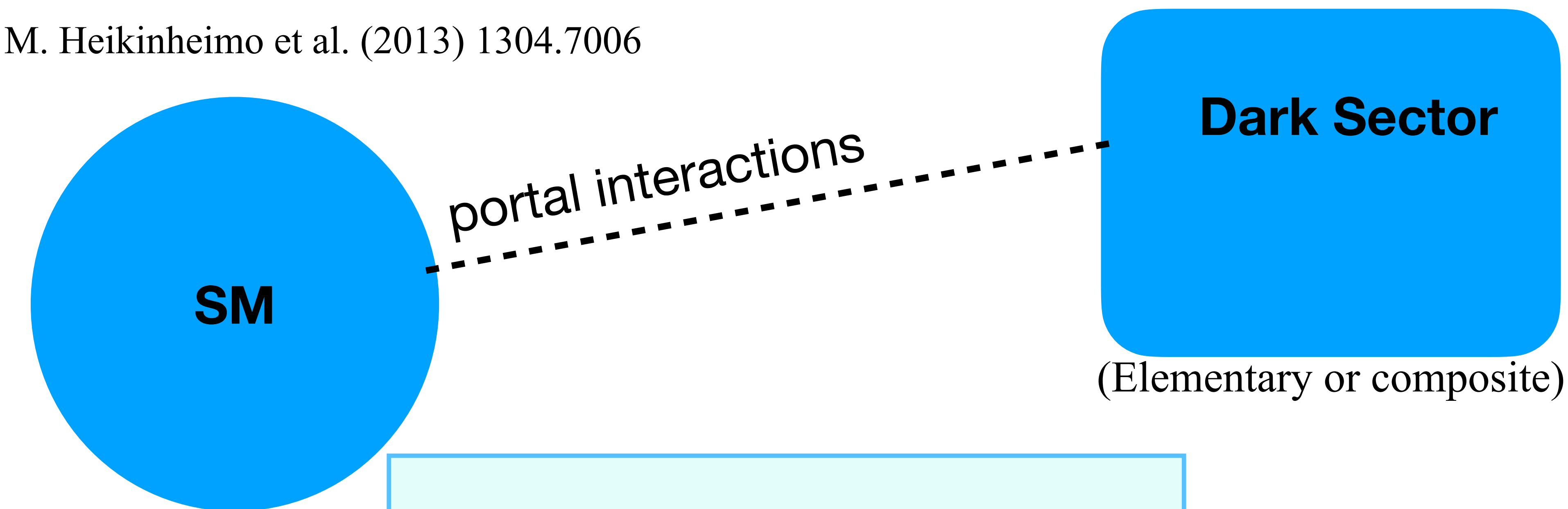
3. DARK SECTORS AND THEIR PORTALS. MODELS & CONSTRAINTS

Before discovery of the Higgs boson, BSM model building driven by theory aesthetics:
Naturality, fine-tuning, …

Dark matter appeared as part of the new spectrum of states required to ’stabilize’ the electroweak scale.

No new spectrum has been observed.
Led to a paradigm shift, putting DM more into spotlight as motivation for BSM building.

M. Heikinheimo et al. (2013) 1304.7006



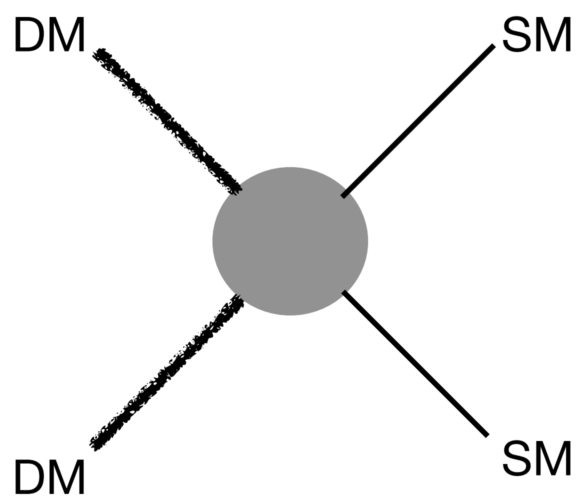
The Higgs portal $\lambda |H|^2 \mathcal{O}_{\mathrm{DS}}$

If DS contains U(1) gauge field, vector portal: $\epsilon F'_{\mu\nu}F^{\mu\nu}$

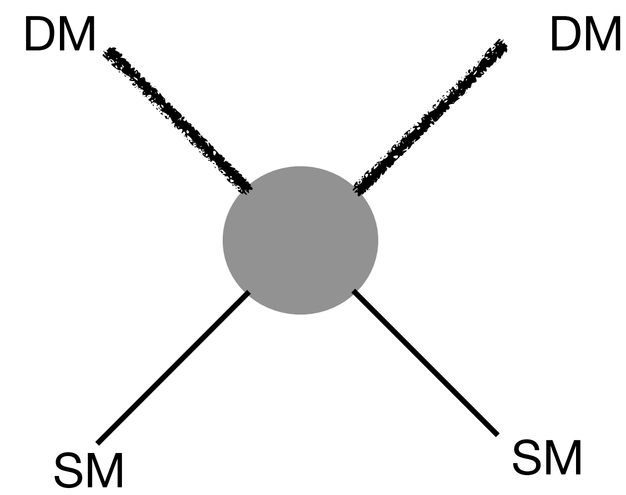
Sterile neutrino can have interaction $y_{ij}\overline{L}_i H N_j$

Axion-like particles in DS couple via $\dfrac{1}{F_a} a \left(F_{\mu\nu}\tilde{F}^{\mu\nu} + G^c_{\mu\nu}\tilde{G}^{c\mu\nu} \right) + \dfrac{1}{F_a}\partial_\mu a \bar{f}\gamma^\mu\gamma^5 f$

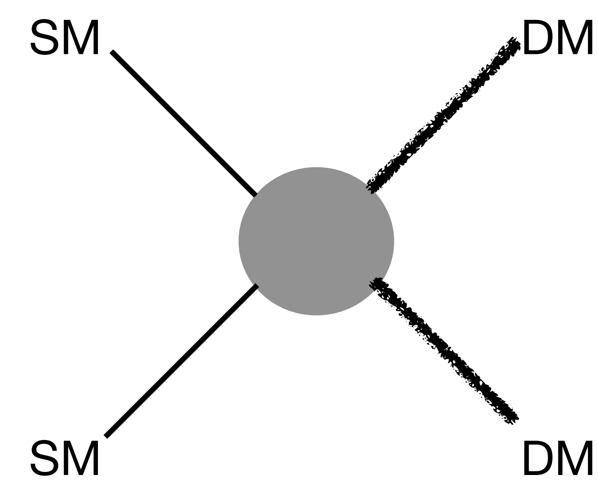
Constraints:



indirect detection:
from galactic centres



direct detection:
underground on Earth



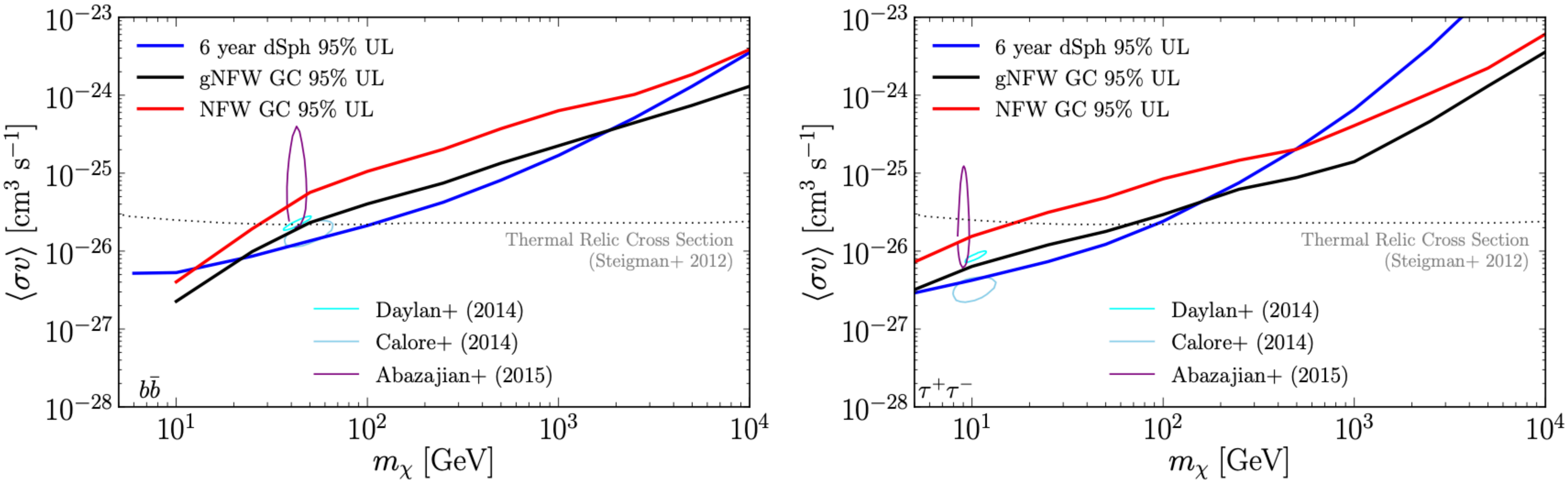
production:
missing energy in colliders

Most relevant for thermal relic DM (freeze-out):

- Correct relic abundance needs large enough cross section.
- This may make DM visible in above search channels.

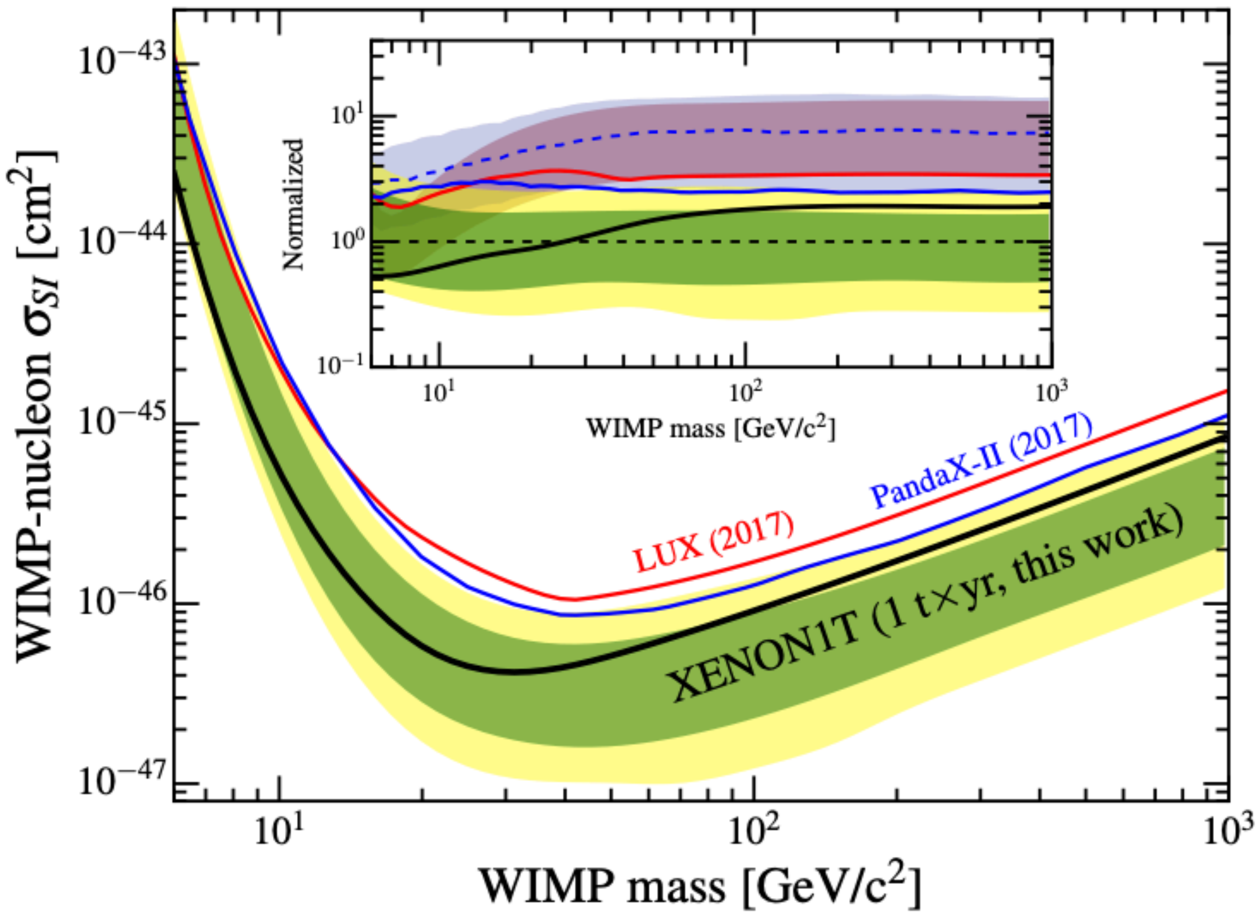
DM annihilation at galactic centres:

Constraints from indirect detection (Fermi-LAT collaboration, 1704.03910)



DM scattering on nuclei

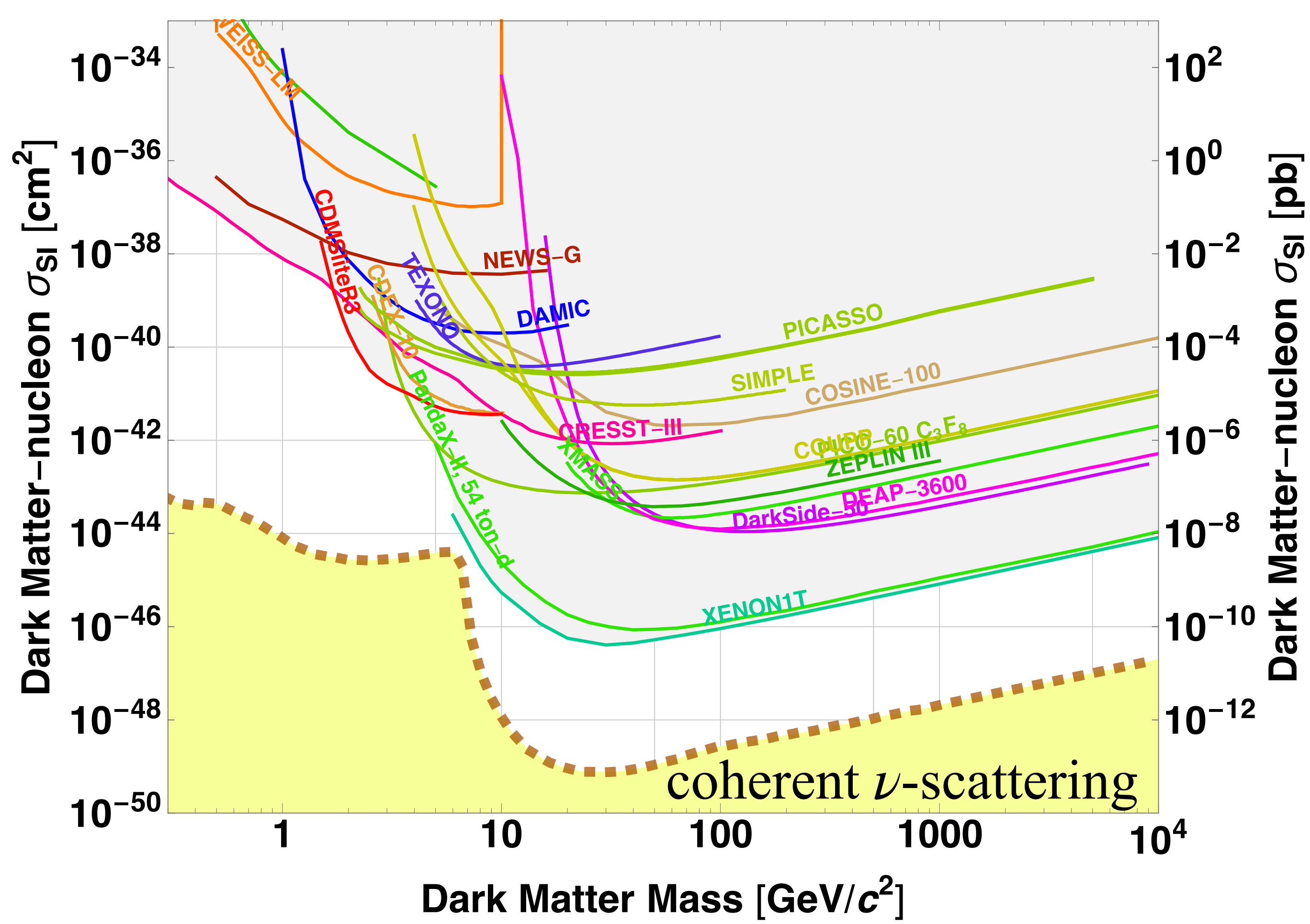
Spin-independent cross section: (Xenon1T 1805.12562)



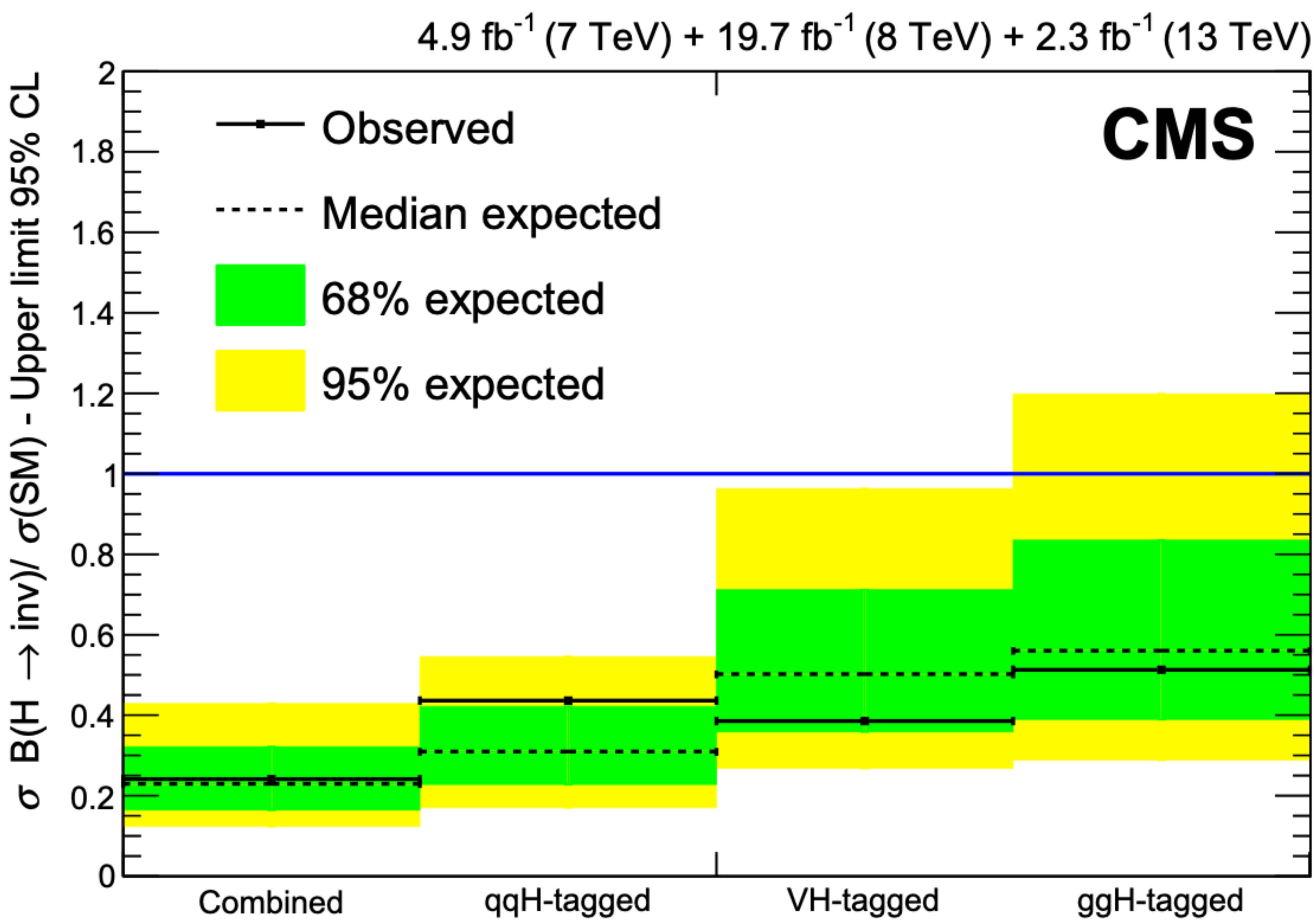
Scattering cross section

$$\frac{dR}{dE_R} = N_T n_{\rm CDM} \int \frac{d\sigma}{dE_R} \underbrace{v f(\boldsymbol{v})} d^3\boldsymbol{v}$$

DM velocity distribution
”Standard Halo Model”



Higgs invisible width: (CMS collaboration, 1610.09218)



Example: $$\mathscr{L}_{\rm DS} + \mathscr{L}_{\rm portal} = \frac{1}{2}\partial_\mu S \partial^\mu S - \mu_S^2 S^2 - \frac{\lambda_S}{4} S^4 - \frac{\lambda_{hs}}{2} S^2 |H|^2$$

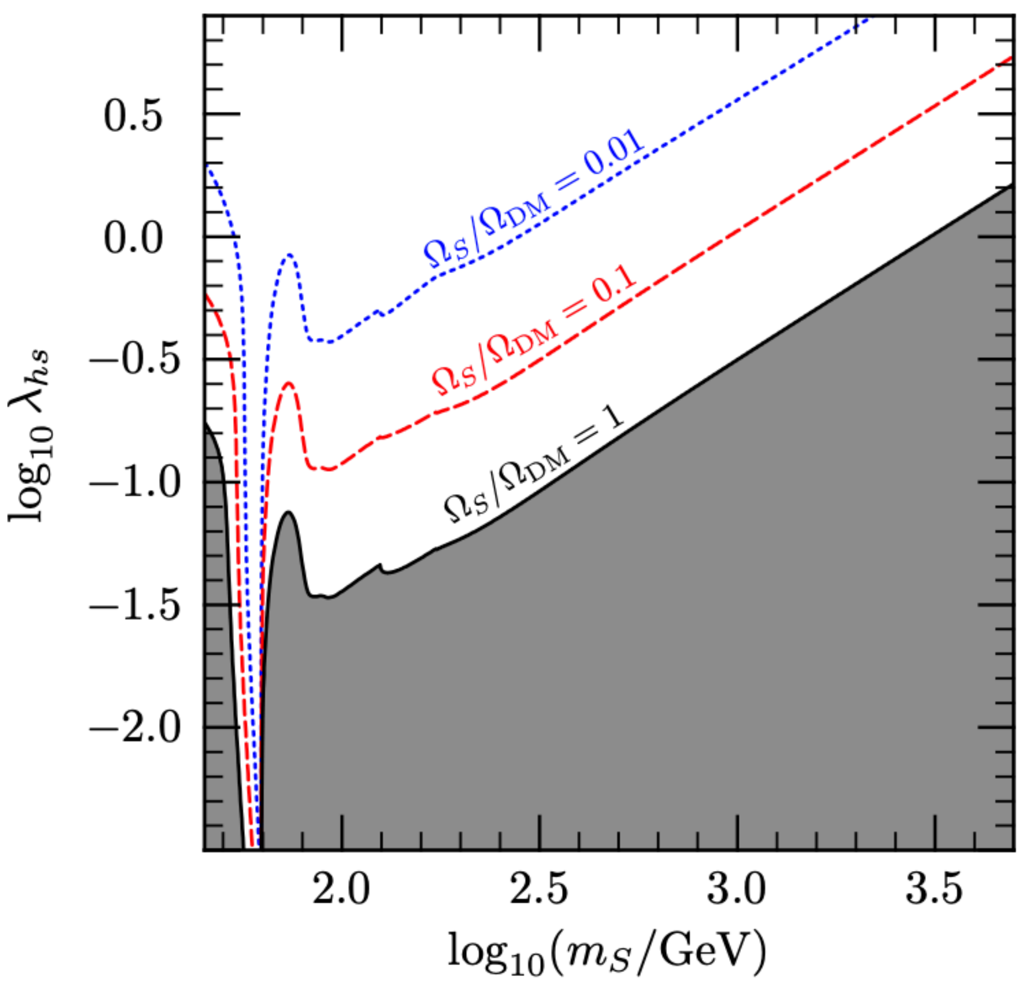
S is the DM candidate, Z_2-symmetry, $\langle S \rangle = 0$

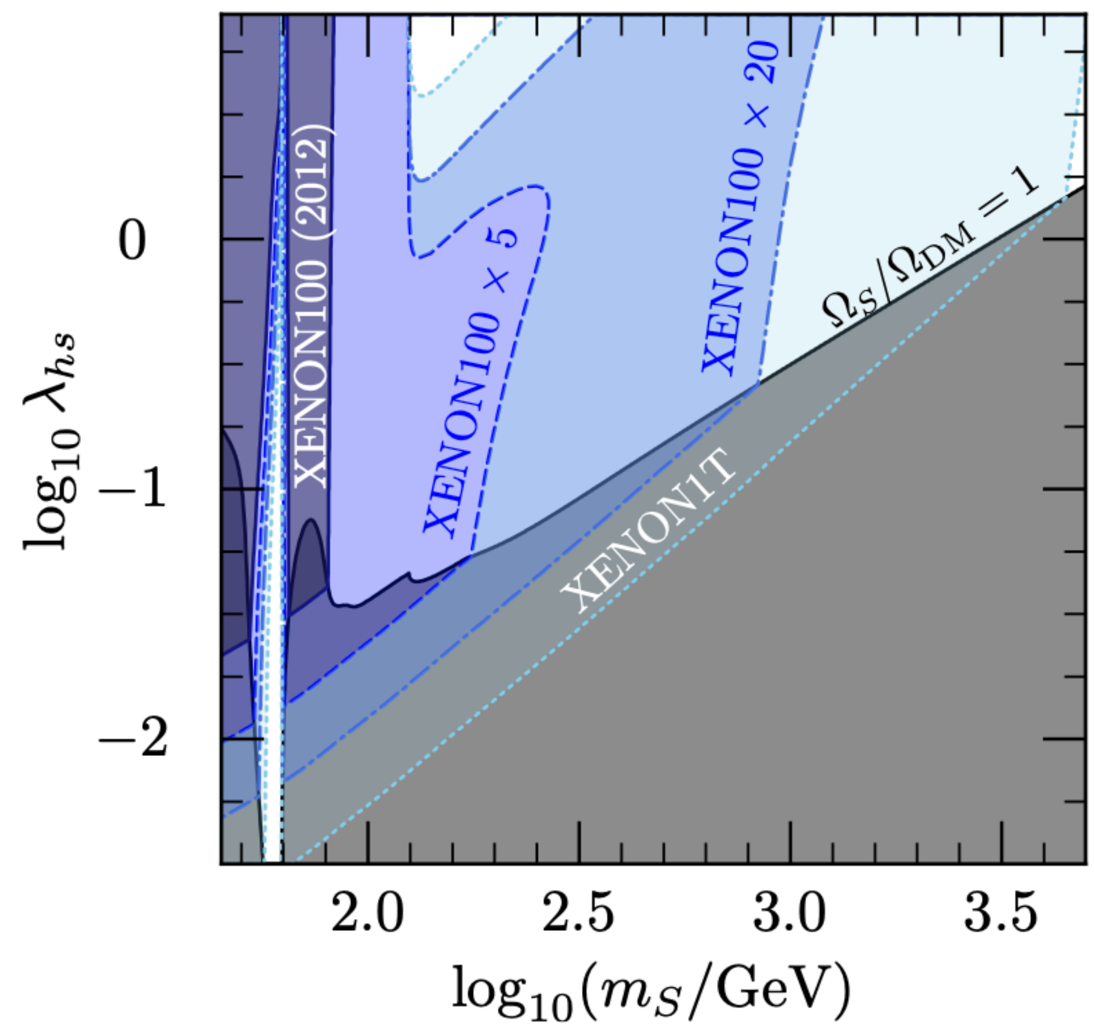
(S = real singlet scalar)

Freeze-out:

Annihilations: $SS \to \bar{f}f, \qquad SS \to WW, ZZ, \qquad SS \to hh$

(1306.4710)





This tension can be released in models with more dofs:

Sommerfeld enhancement, composite states, momentum dependent couplings.

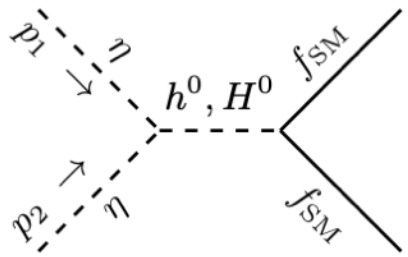
Example: $$\mathscr{L}_{\rm DS} + \mathscr{L}_{\rm portal} = \partial_\mu S^\dagger \partial^\mu S - \mu_S^2 |S|^2 - \frac{\lambda_S}{4}|S|^4 - \frac{\lambda_{HS}}{2}|S|^2|H|^2 - m_\eta \eta^2$$

η is the DM candidate, 2 CP even mass eigenstates

($S = \sigma + i\eta$, complex singlet scalar)

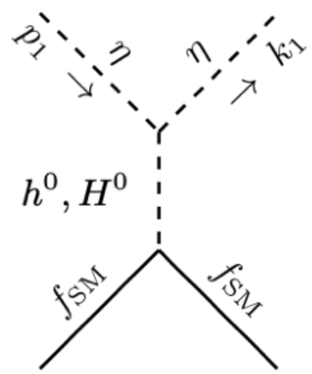
(T. Alanne et al. 1812.05996)

Relic abundance:



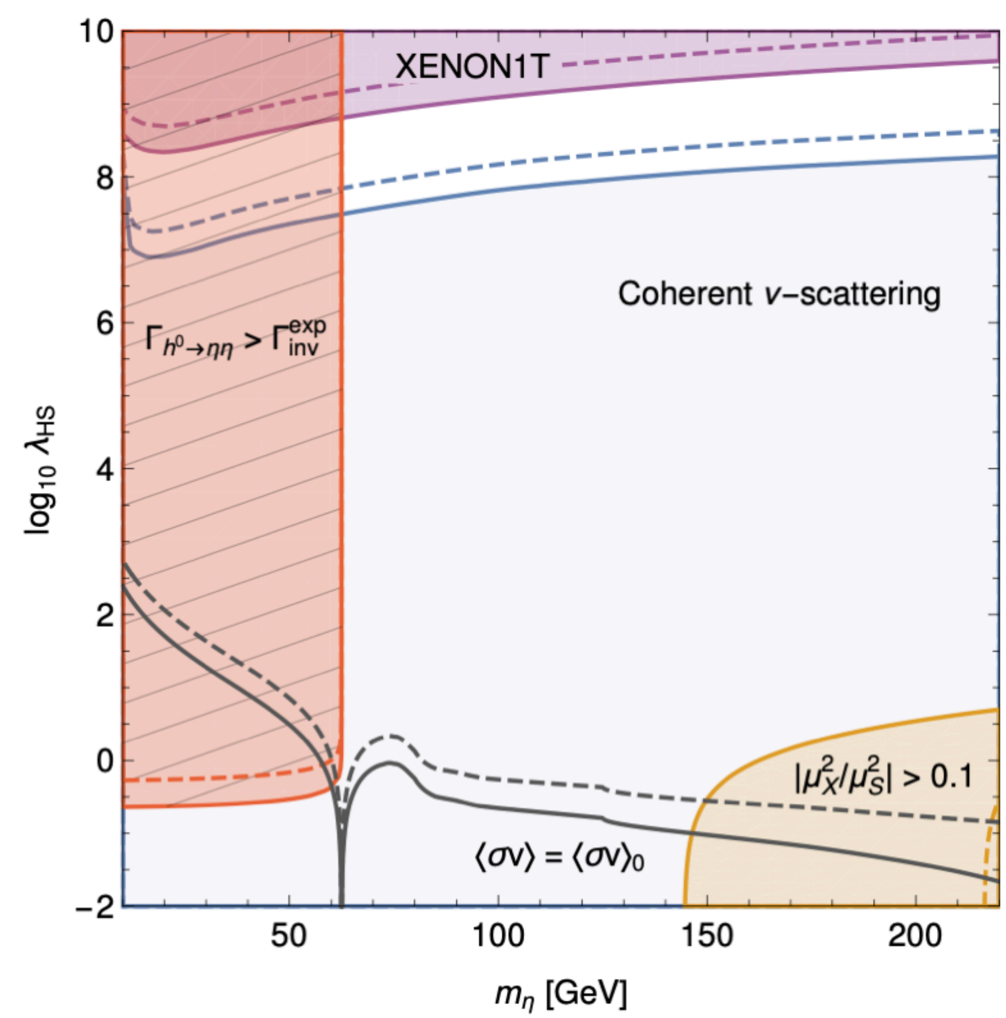
$$\Rightarrow \langle \sigma v \rangle \simeq 3 \cdot 10^{-26}\, {\rm cm}^3/{\rm s}$$

Direct detection:

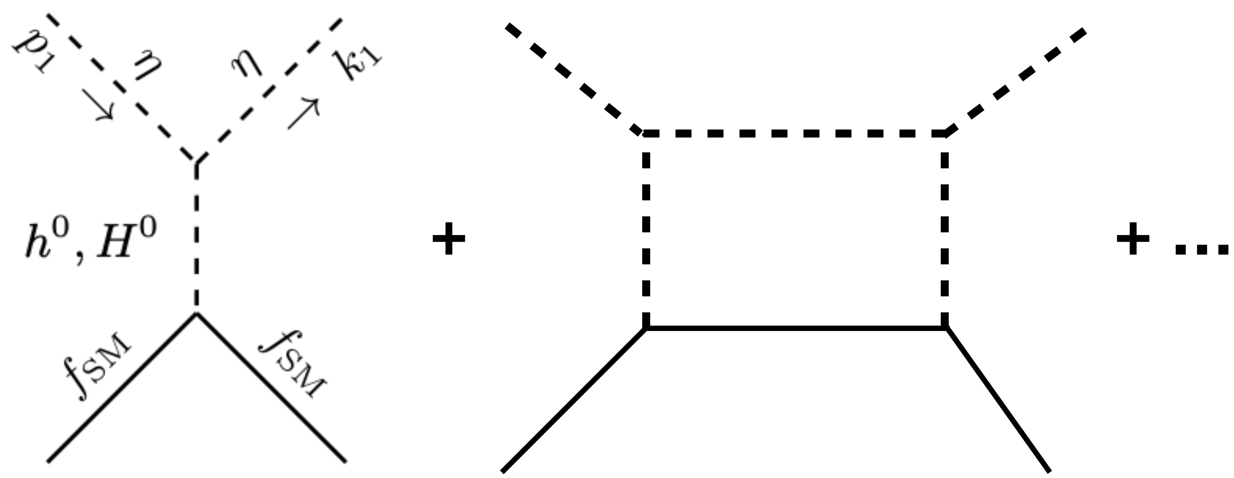


$$\frac{d\sigma_{\rm SI}}{d\cos\theta} \sim \frac{\lambda_{HS} f_N^2 m_N^2}{(m_h^2 - t)^2 (m_H^2 - t)^2} t^2 \longrightarrow 0 \quad \text{as } t \to 0$$

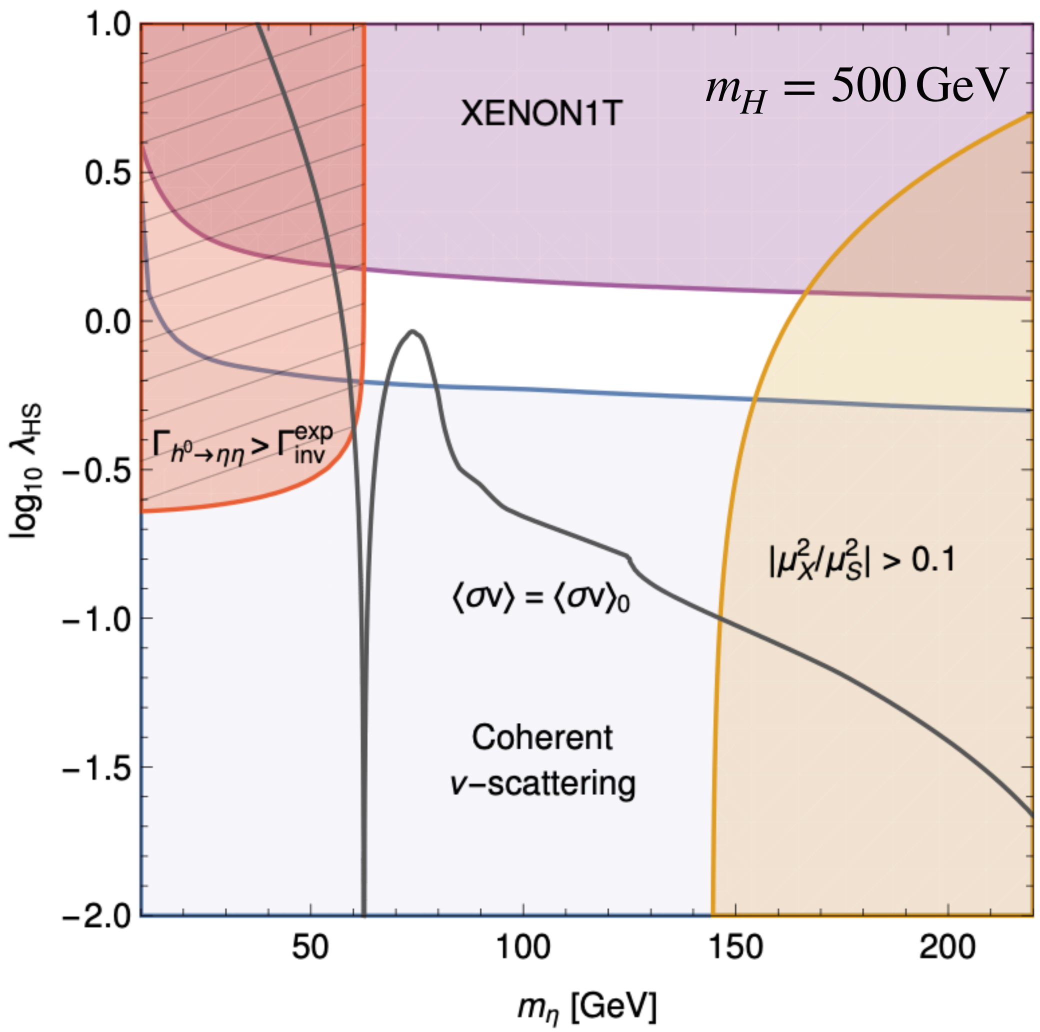
(1812.05996)



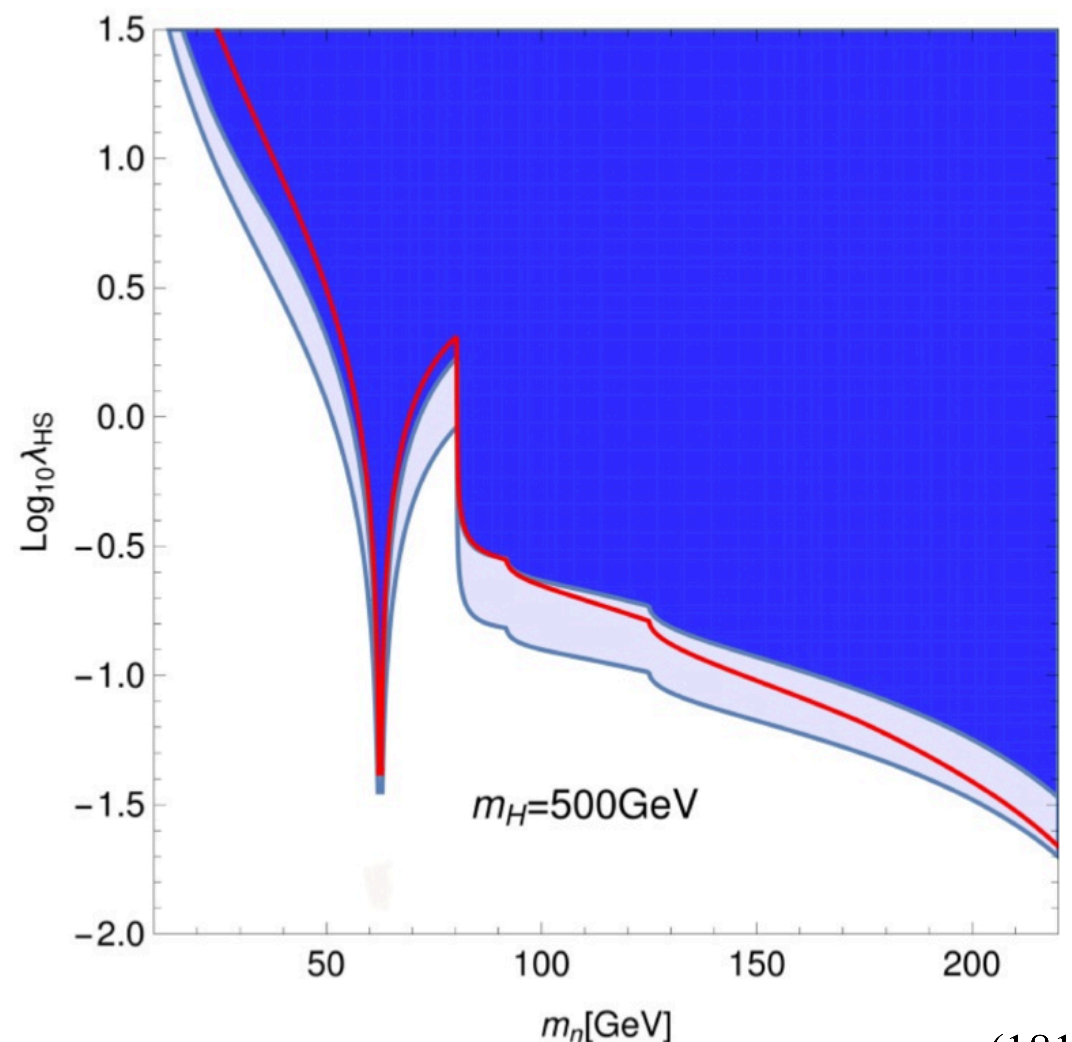
But this is a bit too naive. Loop corrections $\sim t^0$, will dominate.



D. Azevedo et al (2018) 1810.06105



indirect detection not suppressed



(1812.05996)

Possibilities of phase transitions in hidden sector & gravitational waves (Alanne et al. 2008.09605)

CONCLUSIONS

Dark sectors and their portals provide simple generic benchmarks for CDM.

CDM abundance may arise as a frozen-out thermal relic or via non-thermal freeze-in.

(In)direct detection provides stringent limits on model building.