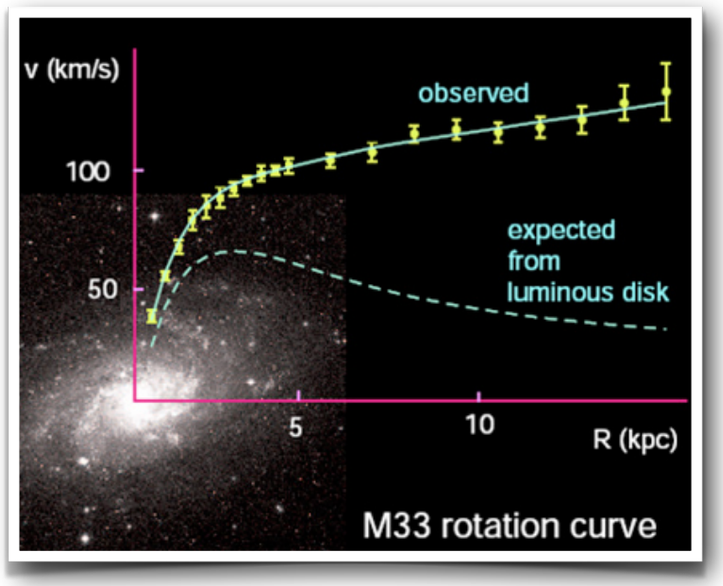
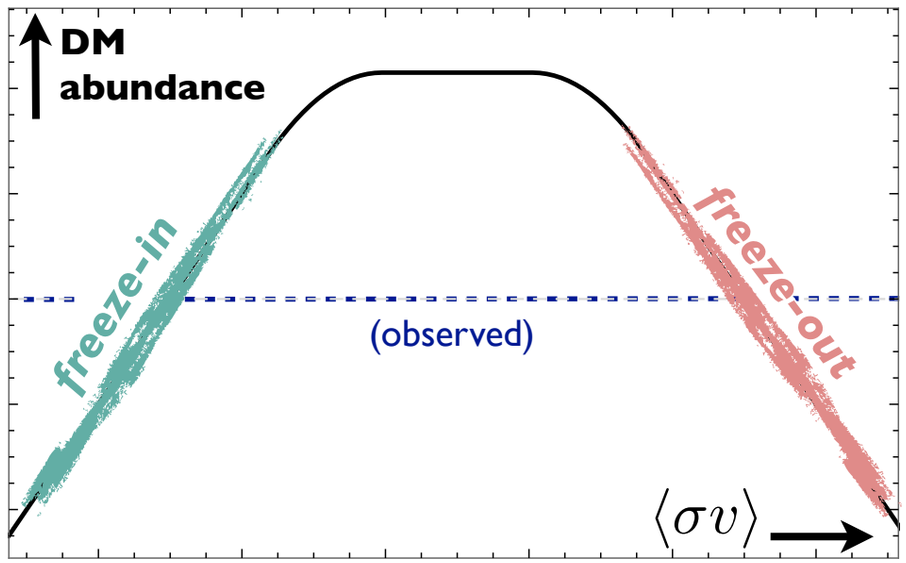
Theory seminar, Oslo, 22 August 2022

Thermal production of dark matter in the early universe

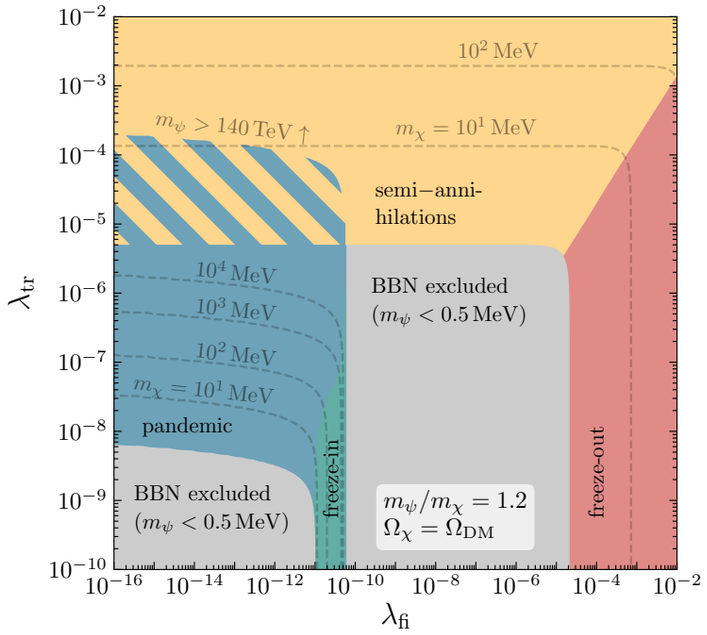
Torsten Bringmann



evidence

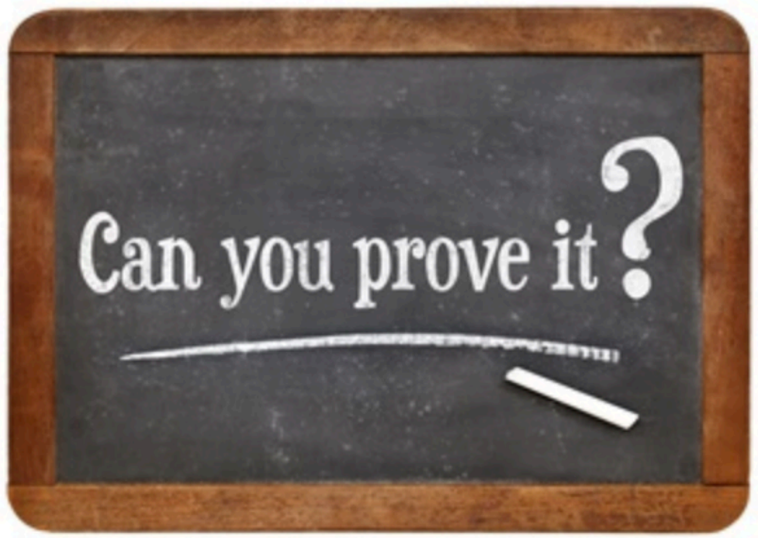


standard production mechanisms

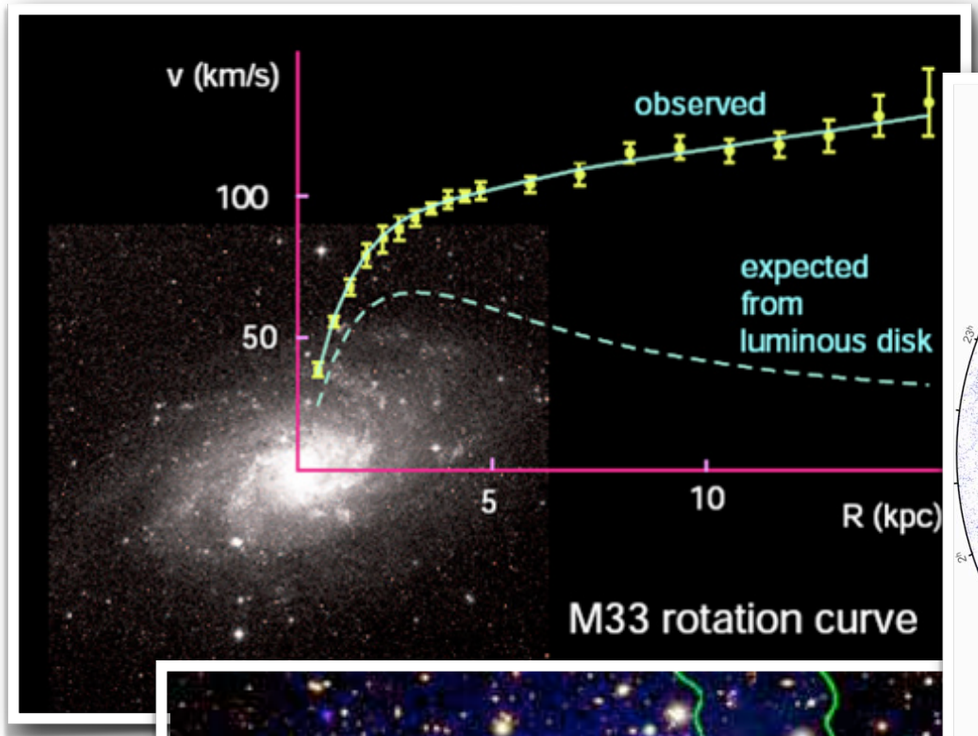


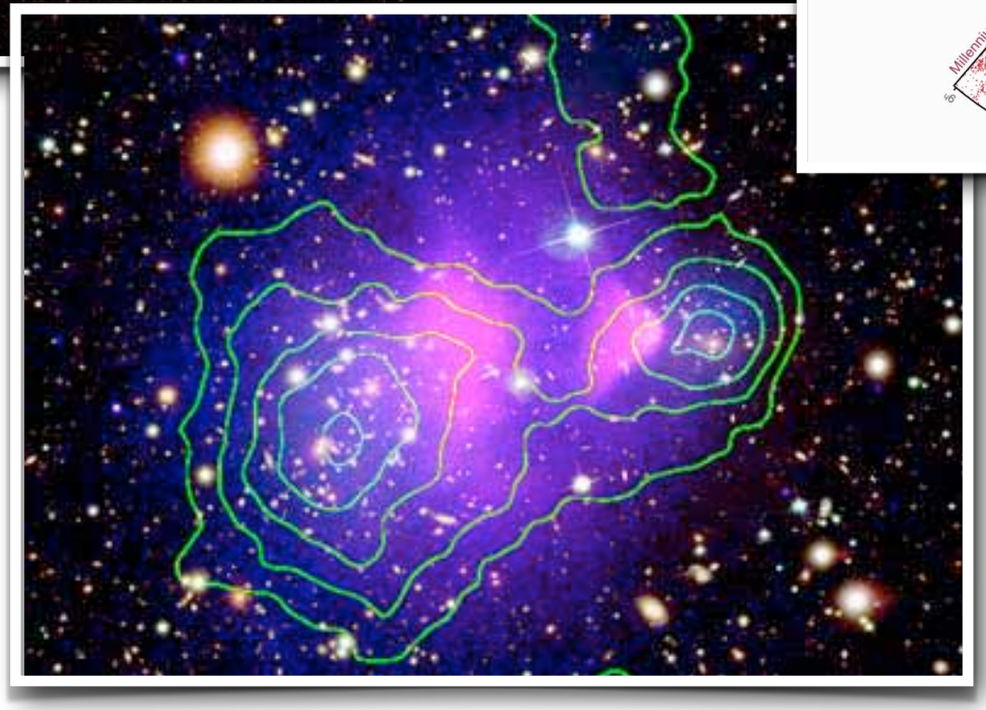
'pandemic' production

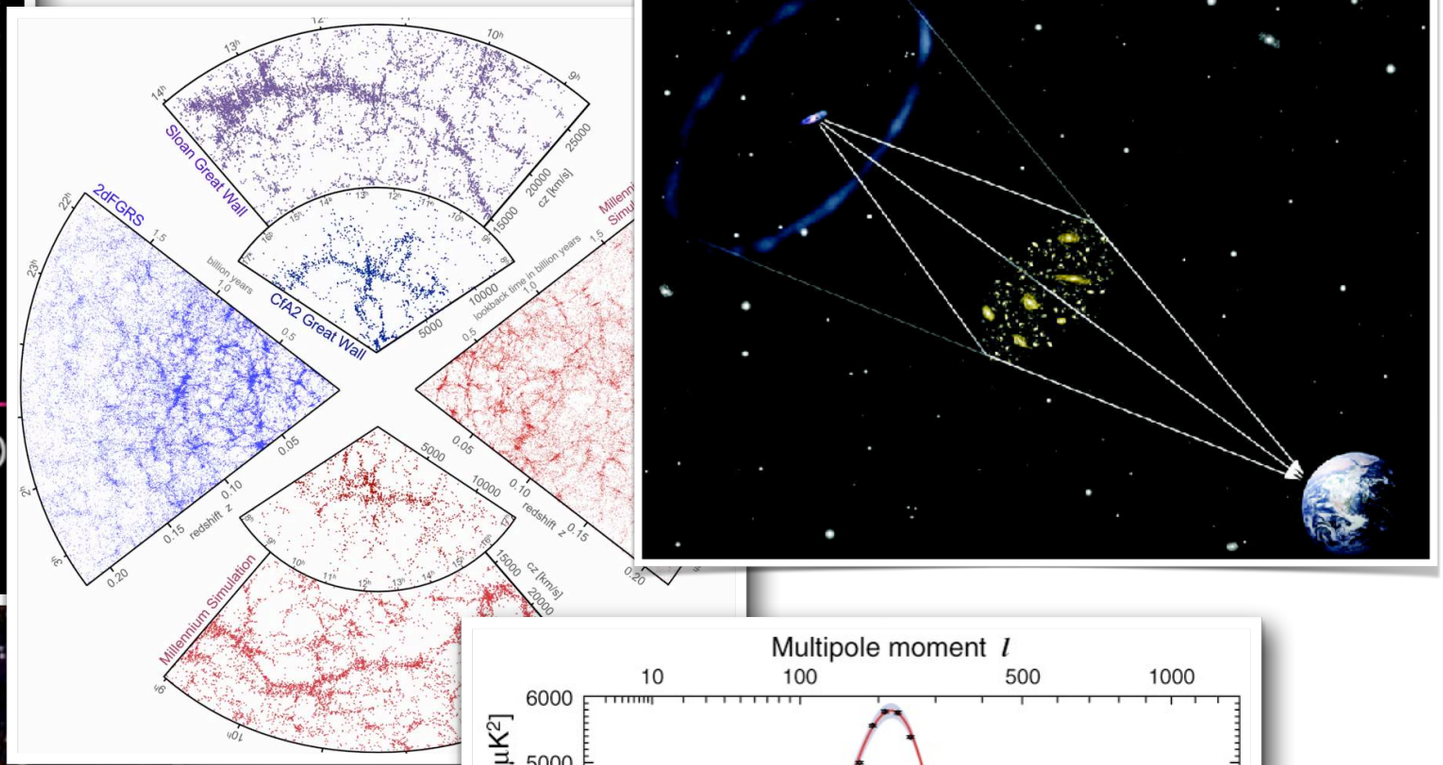
Part I

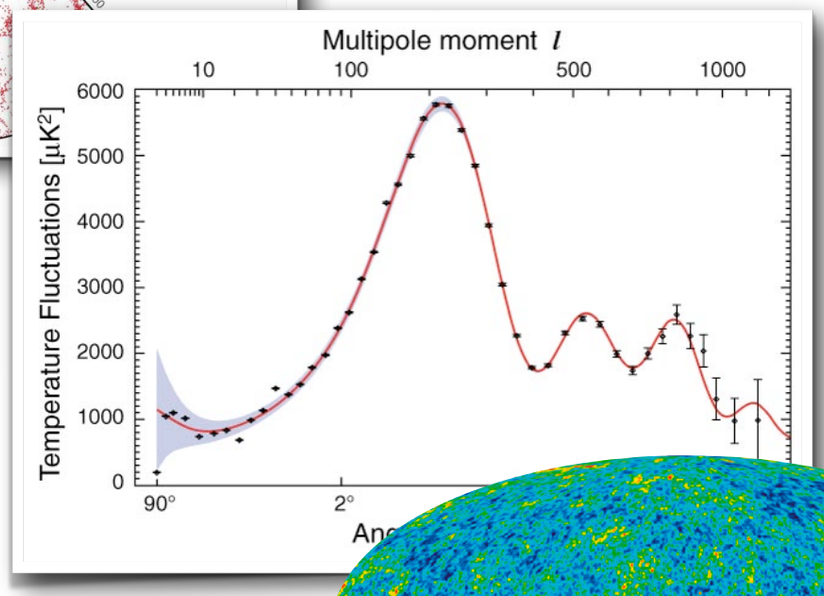


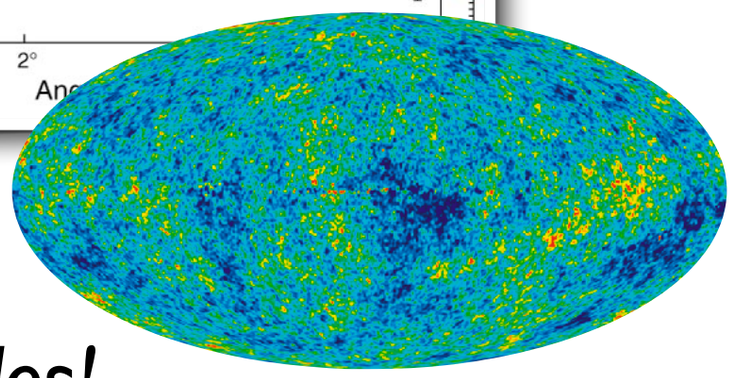
Dark matter all around









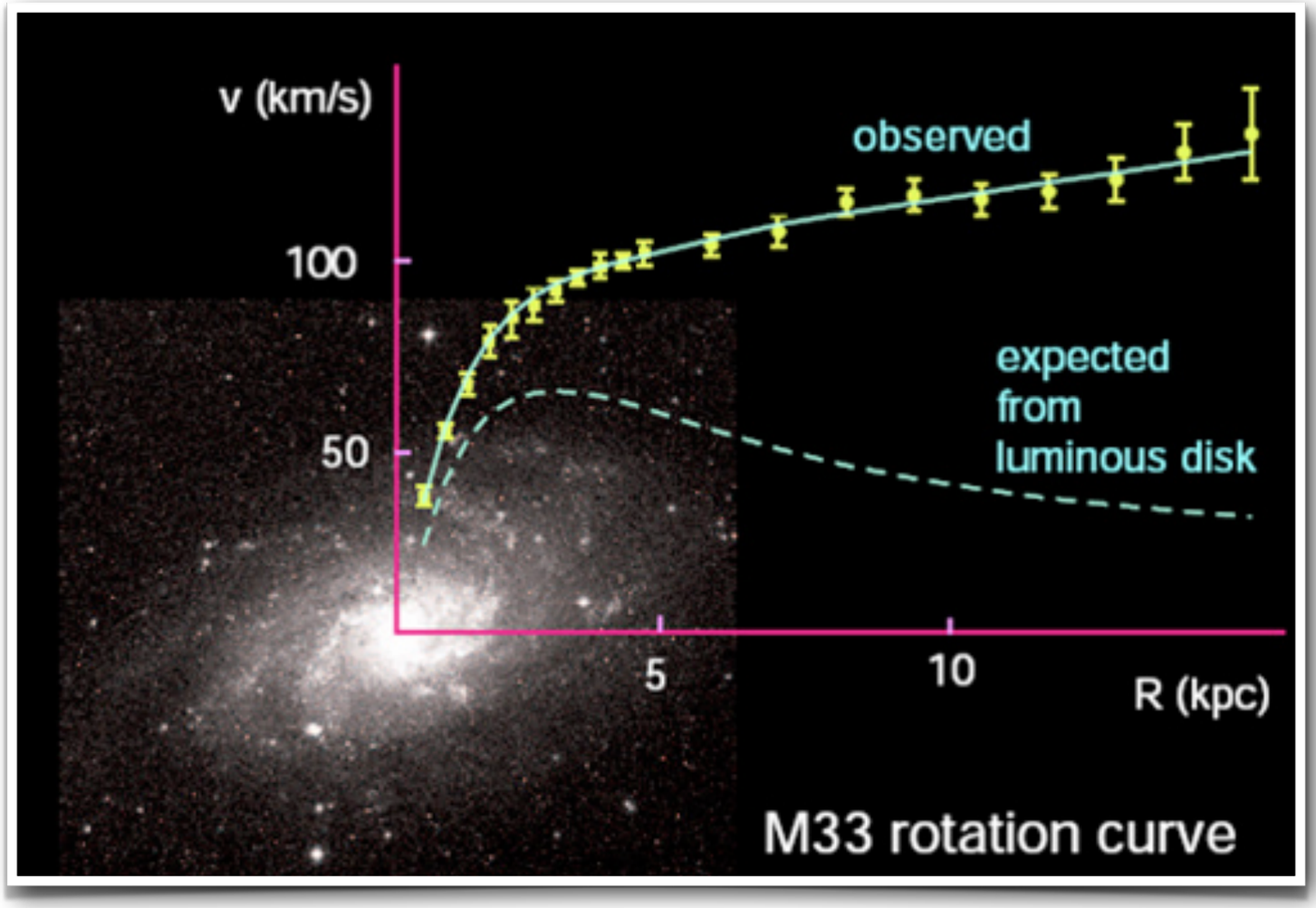


➡ *overwhelming evidence on <u>all</u> scales!*

Galactic scales

Newton:

$$G_N m_\odot \frac{M(r<R)}{R^2} = m_\odot \frac{v^2}{R}$$



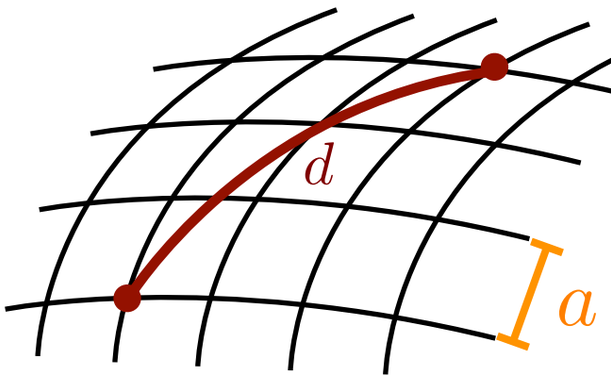
'missing' mass

- Rotation curves no longer main argument for *existence* of dark matter !!!
  - observed rotation curves rather diverse
  - other potential explanations (for this particular discrepancy)

Cosmological scales

Image credit: Jimmy Harris





homogeneity + isotropy

add tiny initial **perturbations** to background evolution

- Friedman equations fix $a(t)$:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$$

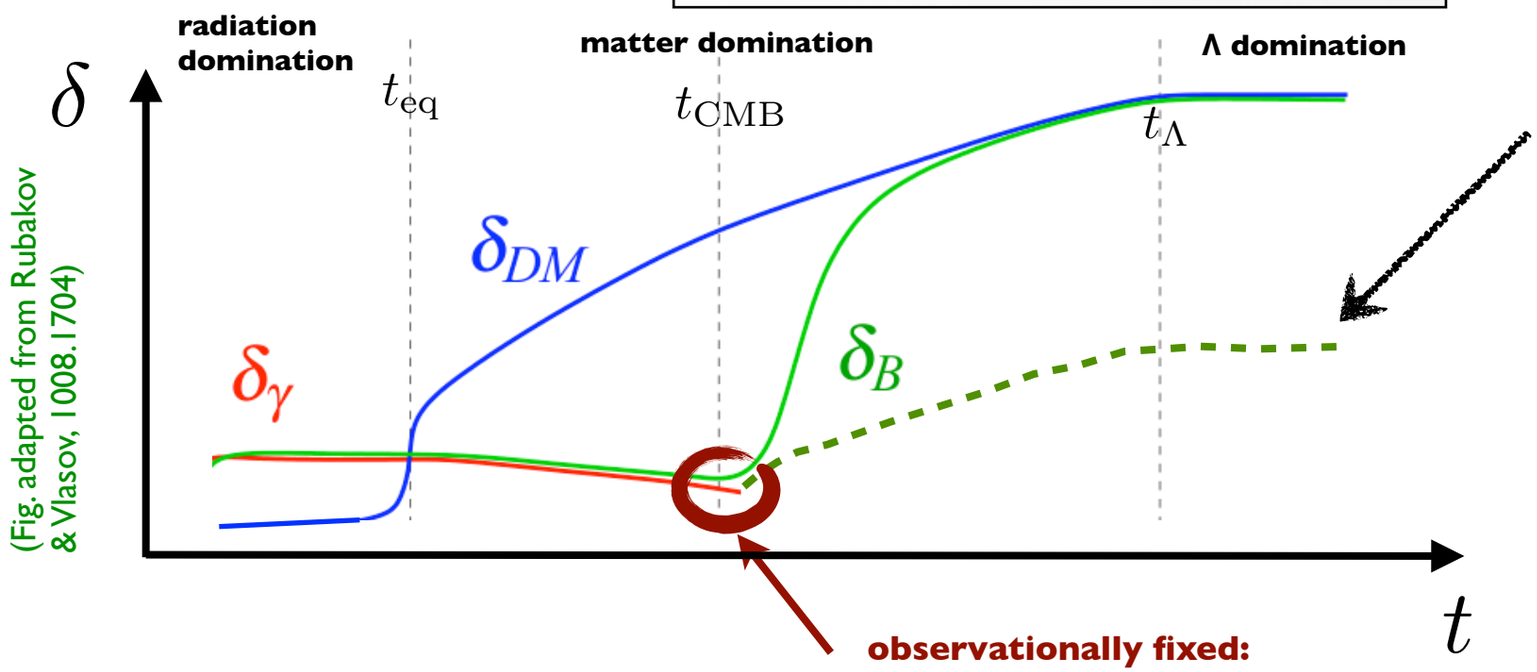
➡ *background evolution*

- Gravitational clustering (in linear regime) and collapse (non-linear)

➡ *Strong impact of dark matter*

Cosmological scales

- Linear gravity $\rho(t, \mathbf{x}) = \bar{\rho}(t)[1 + \delta(t, \mathbf{x})]$

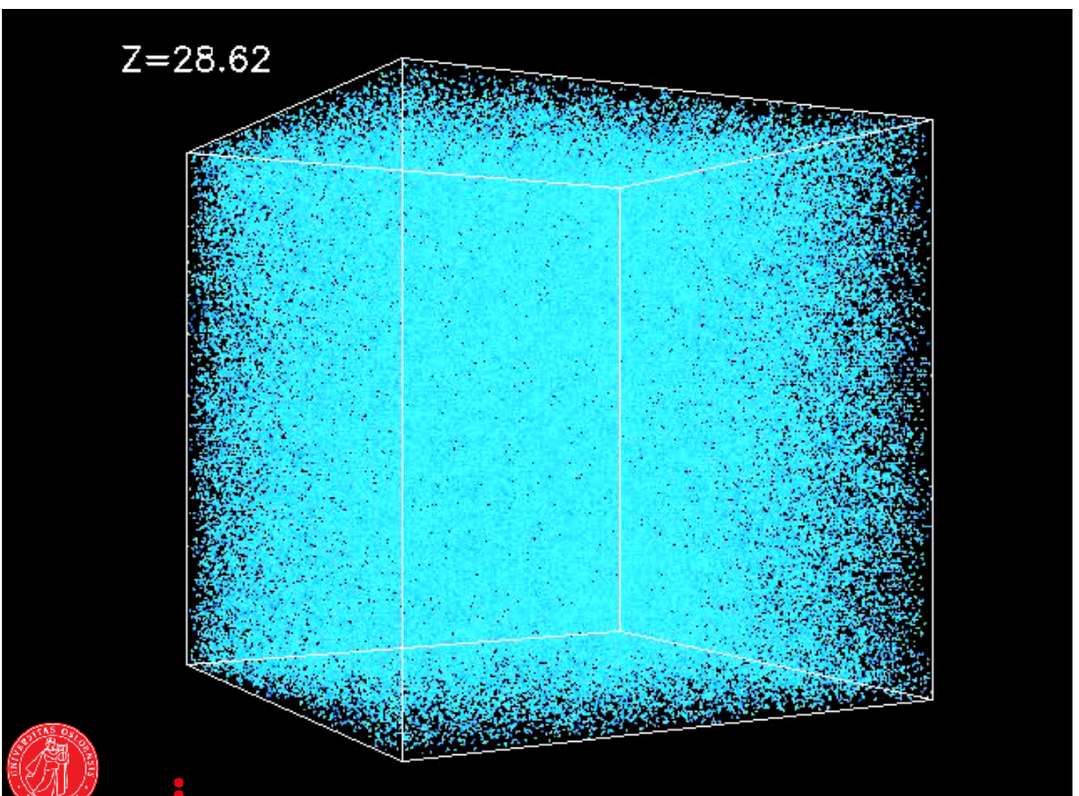


(Fig. adapted from Rubakov & Vlasov, 1008.1704)

$\sim 10^3$

assuming no DM: $\delta_b^{\rm today} \simeq \delta_\gamma^{\rm CMB}\,(1 + z^{\rm CMB}) \sim 10^{-2}$

➡ Without DM, we'd still be in the *linear* regime: no galaxies, stars, planets, …!



- Non-linear evolution
  - Need simulations
  - Dark matter required to reach ~perfect agreement with observations (at large scales)

From evidence to precision

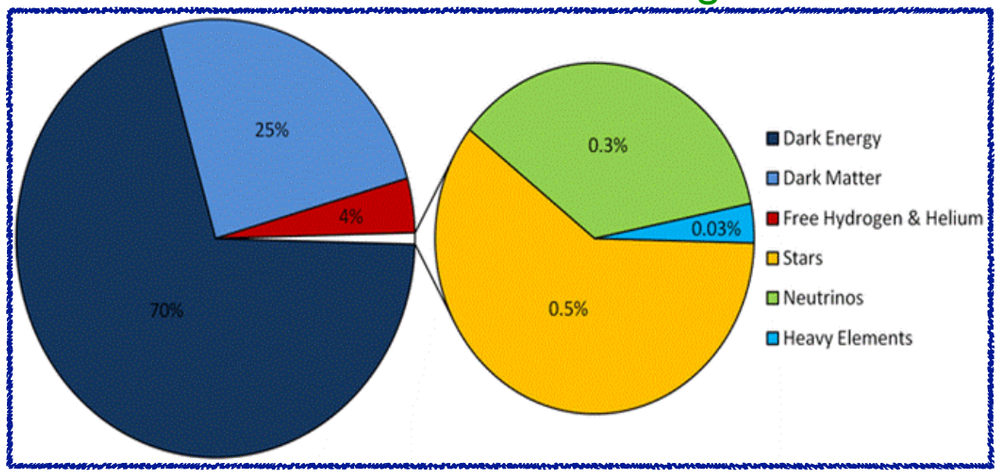
- DM is a crucial ingredient of cosmological SM!
  - constant co-moving energy density
  - only gravitational interactions
  - cold + dissipation-less

$$\Omega_{\rm CDM} h^2 = 0.1188 \pm 0.0010$$

Ade+ [Planck Coll.], A&A '16

Percent-level measurements of a single parameter!

Image credit: KIAS



- DM conversion into (in)visible energy?
  - E.g. decays, late-time annihilation, coalescing PBHs, …

$\Omega_{\rm CDM}$ decrease of up to 10% possible during matter domination!

***(model-independent*; NB: much more allowed during RD)** TB, Kahlhoefer, Schmidt-Hoberg & Walia, PRD '18

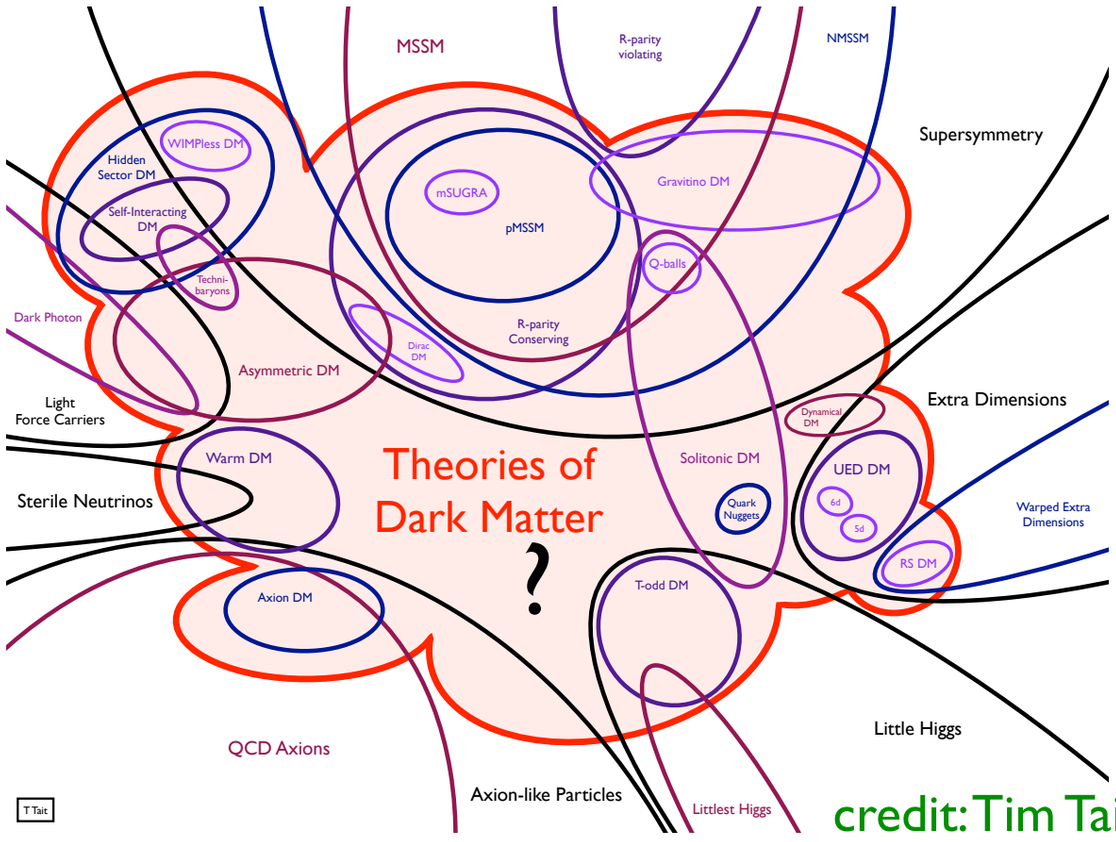
- Q: Can't we explain *all* this also by modified gravity?
  - A: **No!** [though definitely yes for *selected* observations]



Candidates

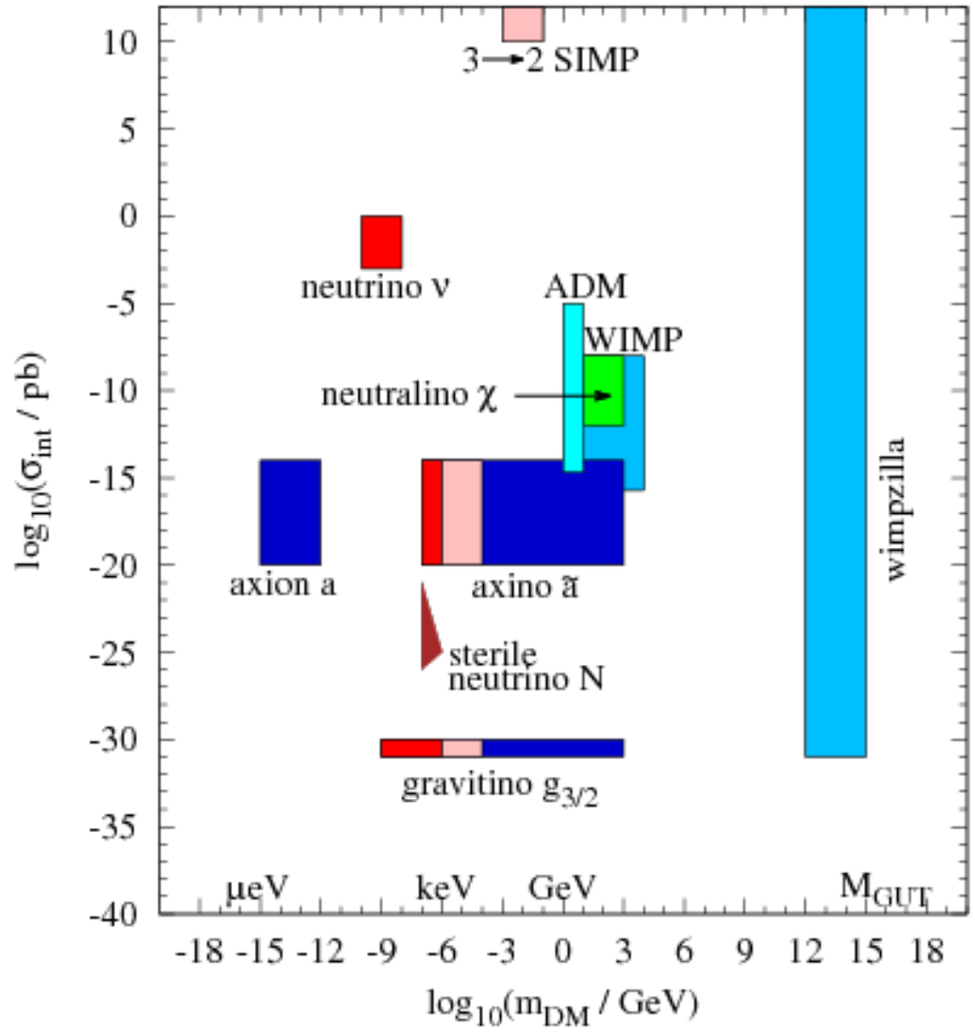
- Existence of (particle) DM = evidence for BSM physics!
  - + rather good handle on what it is ***not***

- Unfortunately, this still leaves too many options…



credit: Tim Tait

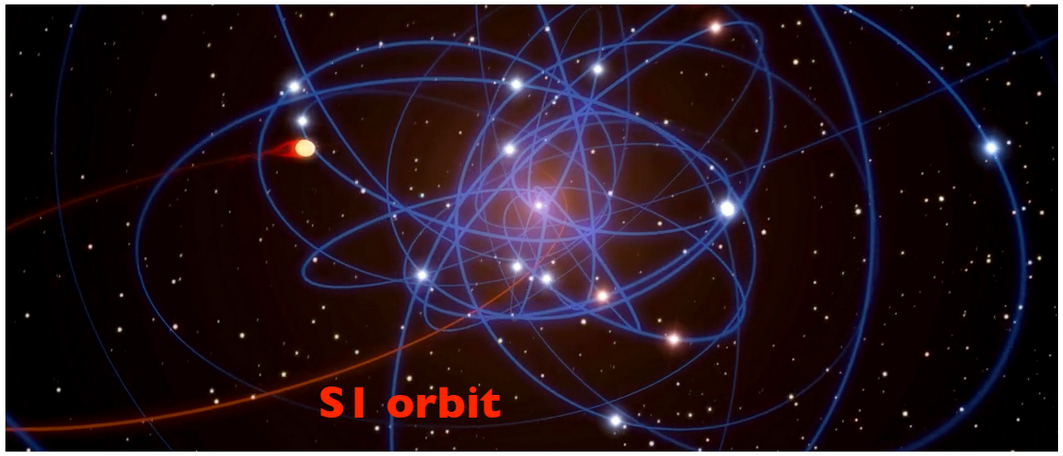
Baer+, Phys.Rep.'15



Black holes (I)

- Wouldn't (super-)solar mass black holes be an "obvious" / "conventional" candidate?

  [# 2017, 2020]



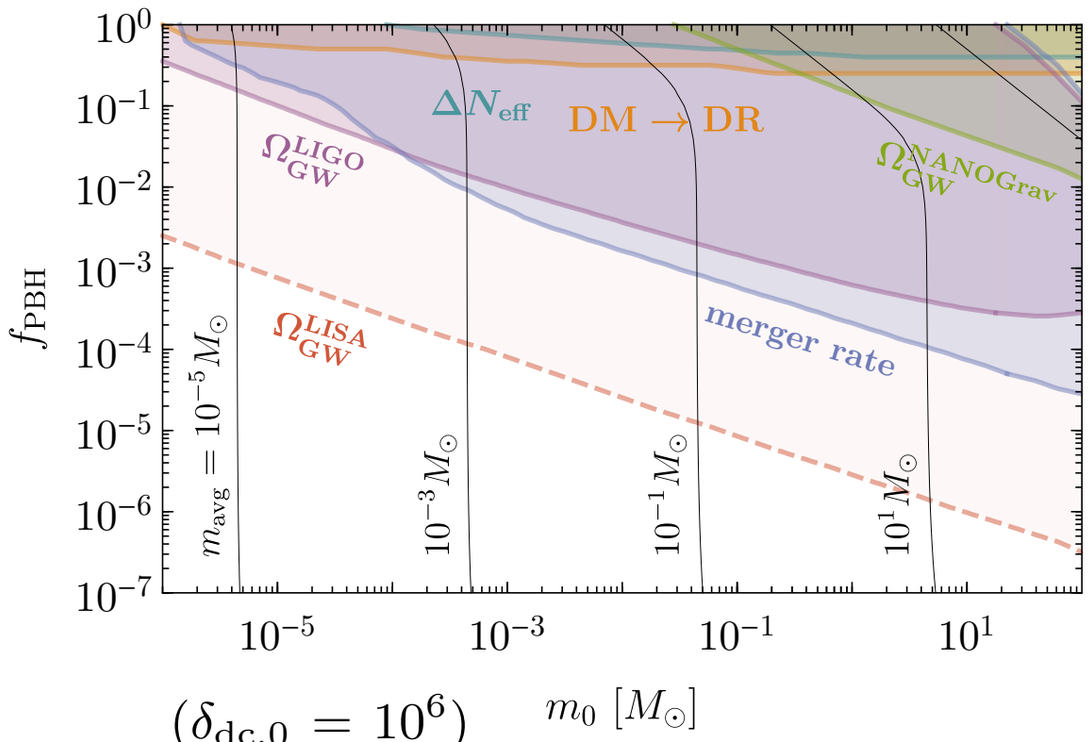
- Strongly constrained by micro-lensing and CMB!

  ➡ Black holes can only be a sub-dominant DM component

overview:
Carr, Kohri, Sendouda & Yokoyama, 2002.12778

- Conclusion does not change for large black hole clustering…

c.f. García-Bellido & Clesse, PDU '18
…



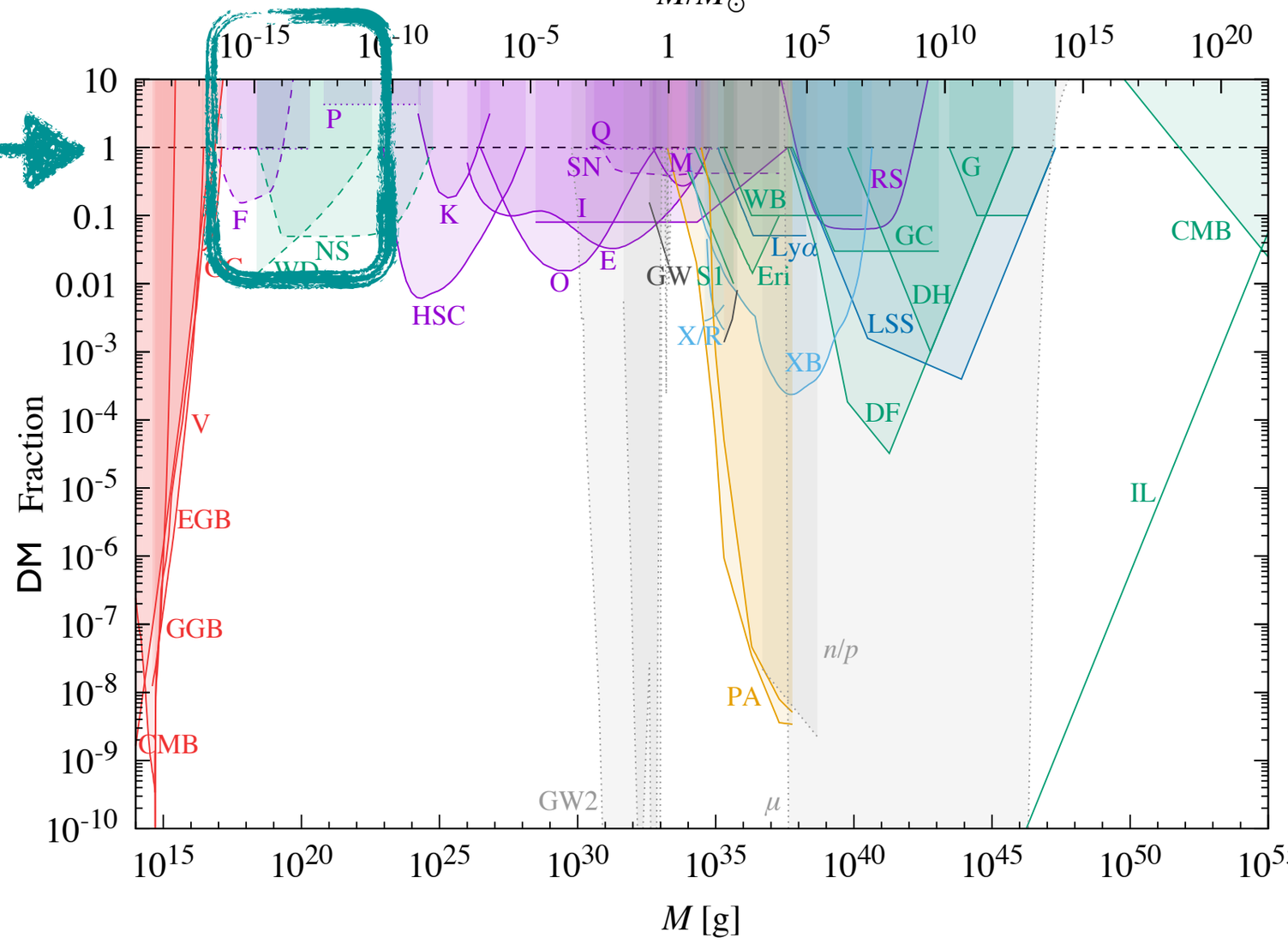
$(\delta_{\rm dc,0} = 10^6)$

TB, Depta, Hufnagel & Schmidt-Hoberg, PRD '19

Black holes (II)

- Primordial black holes can be much smaller

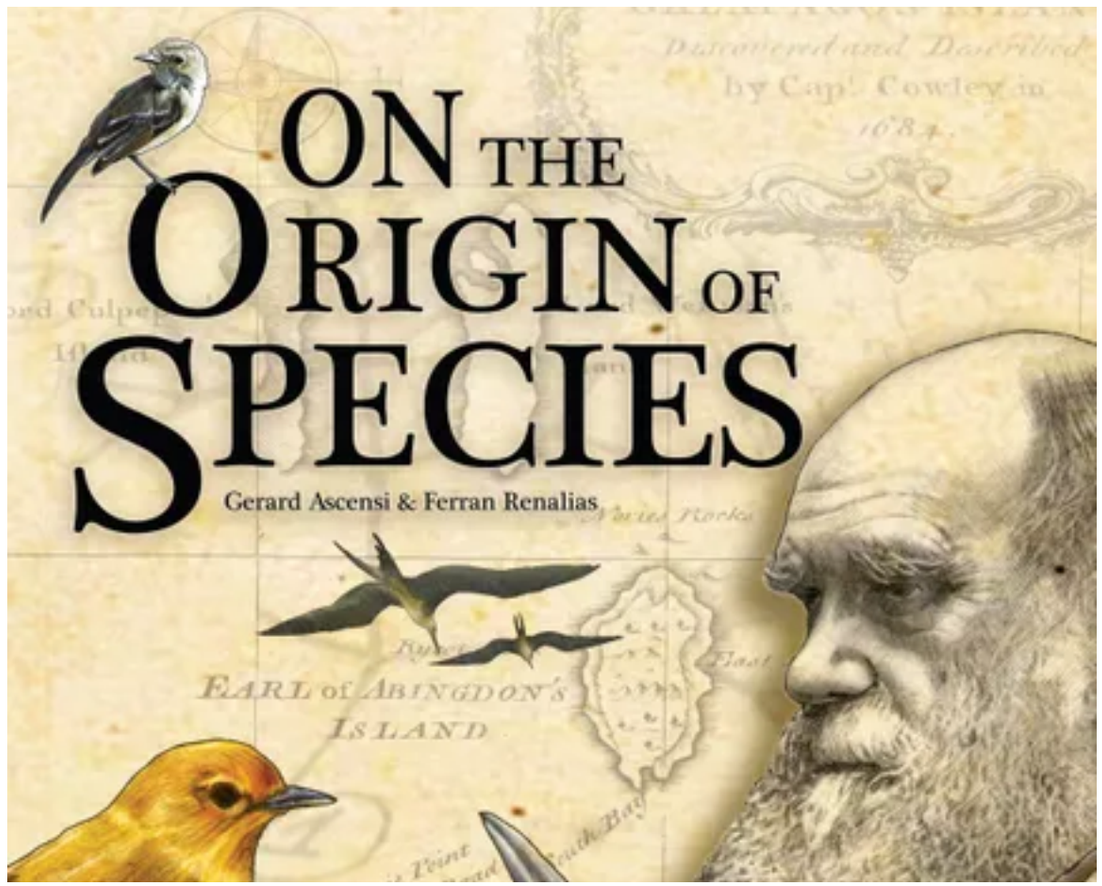
  ➡ open mass window for $f_{\rm PBH} \sim 1$! Katz, Kopp & Sibiryakov, JCAP '18



Carr, Kohri, Sendouda & Yokoyama, 2002.12778

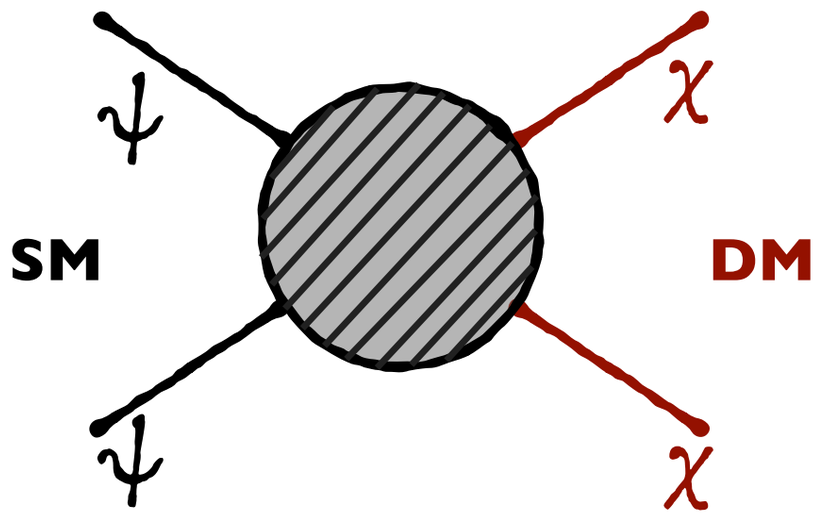
- But this would also not be "SM physics" … !
  - *formation* (+ requirement of $f_{\rm PBH} \sim 1$) requires BSM physics

Part II


ON THE
ORIGIN OF
SPECIES
Gerard Ascensi & Ferran Renalias
EARL of ABINGDON's
ISLAND

The origin of dark matter

- Existence of (particle) DM = evidence for BSM physics
- Any convincing model for dark matter must include a production mechanism that can explain the observed abundance!
- Let's postulate some interaction with the primordial heat bath:
  - [Z_2 symmetry not strictly necessary, but automatically guarantees stability of DM]



Boltzmann equation

- Evolution of DM phase-space density:

$$L[f_\chi] = C[f_\chi]$$

$$\text{“}= \frac{\mathrm{d}f_\chi}{\mathrm{d}t}\text{”} = E\left(\partial_t - H\mathbf{p}\cdot\nabla_\mathbf{p}\right) f_\chi \quad \textbf{for FRW metric}$$

- Collision term:

$$C[f_\chi] = \frac{1}{2g_\chi}\int\frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}(2\pi)^4\delta^{(4)}(\tilde{p}+p-\tilde{k}-k)$$

$$\times\left[|\mathcal{M}|^2_{\bar{\chi}\chi\leftarrow\bar{f}f}\, f_\psi(\omega)f_\psi(\tilde{\omega}) - |\mathcal{M}|^2_{\bar{\chi}\chi\rightarrow\bar{f}f}\, f_\chi(E)f_\chi(\tilde{E})\left\{1\pm f_\psi(\omega)\right\}\left\{1\pm f_\psi(\tilde{\omega})\right\}\right]$$

‘production’ ‘annihilation’

- Detailed balance: ‘production’ = ‘annihilation’ *in equilibrium*

  ⇝ allows to re-write everything in terms of a *would-be* equilibrium population of DM

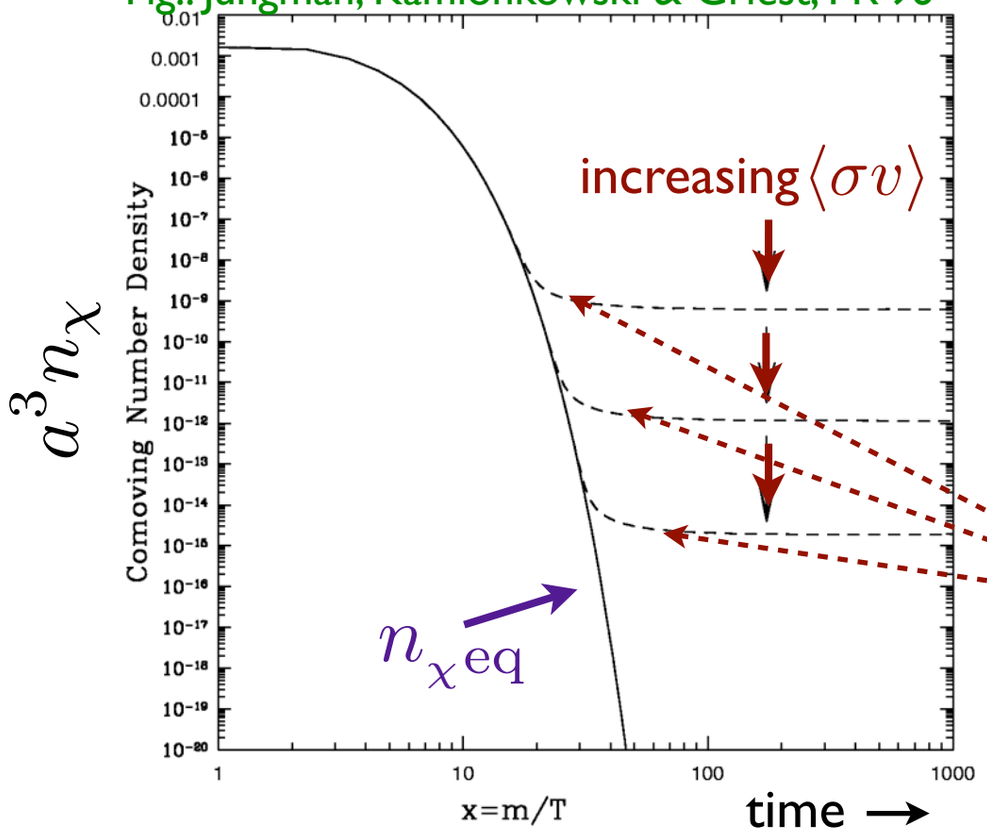
- Pauli suppression / Bose enhancement

  ⇝ not relevant for production of non-relativistic ***DM*** [energy conservation!]

Weakly Interacting Massive Particles

- well-motivated from particle physics [SUSY, EDs, …]
- thermal production in early universe:

Fig.: Jungman, Kamionkowski & Griest, PR'96



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma v\rangle\left(n_\chi^2 - n_{\chi\,\mathrm{eq}}^2\right)$$

$\langle\sigma v\rangle$: $\chi\chi \to \mathrm{SM\ SM}$ (thermal average)

"Freeze-out" when annihilation rate falls behind expansion rate

Relic density (today): $\Omega_\chi h^2 \sim \dfrac{3\cdot 10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma v\rangle} \sim \mathcal{O}(0.1)$

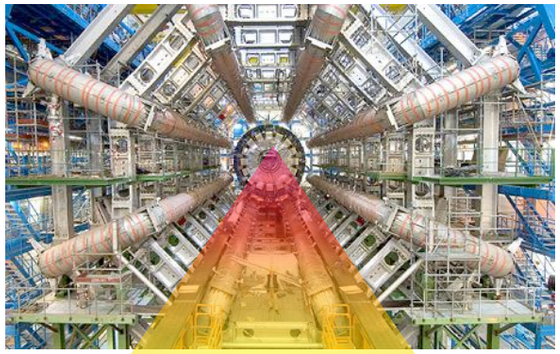
for weak-scale interactions!

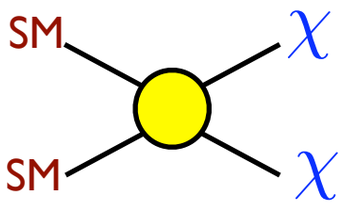
= a 'miracle' ?

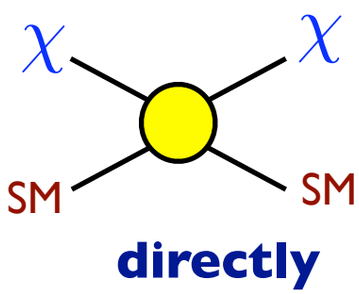
WIMP DM is a *predictive* scenario

- Same interaction can be probed today, in multiple ways:

at colliders

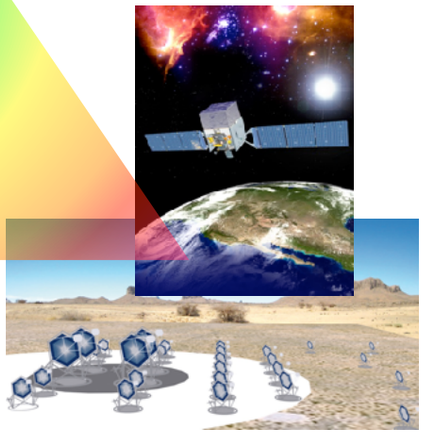






directly







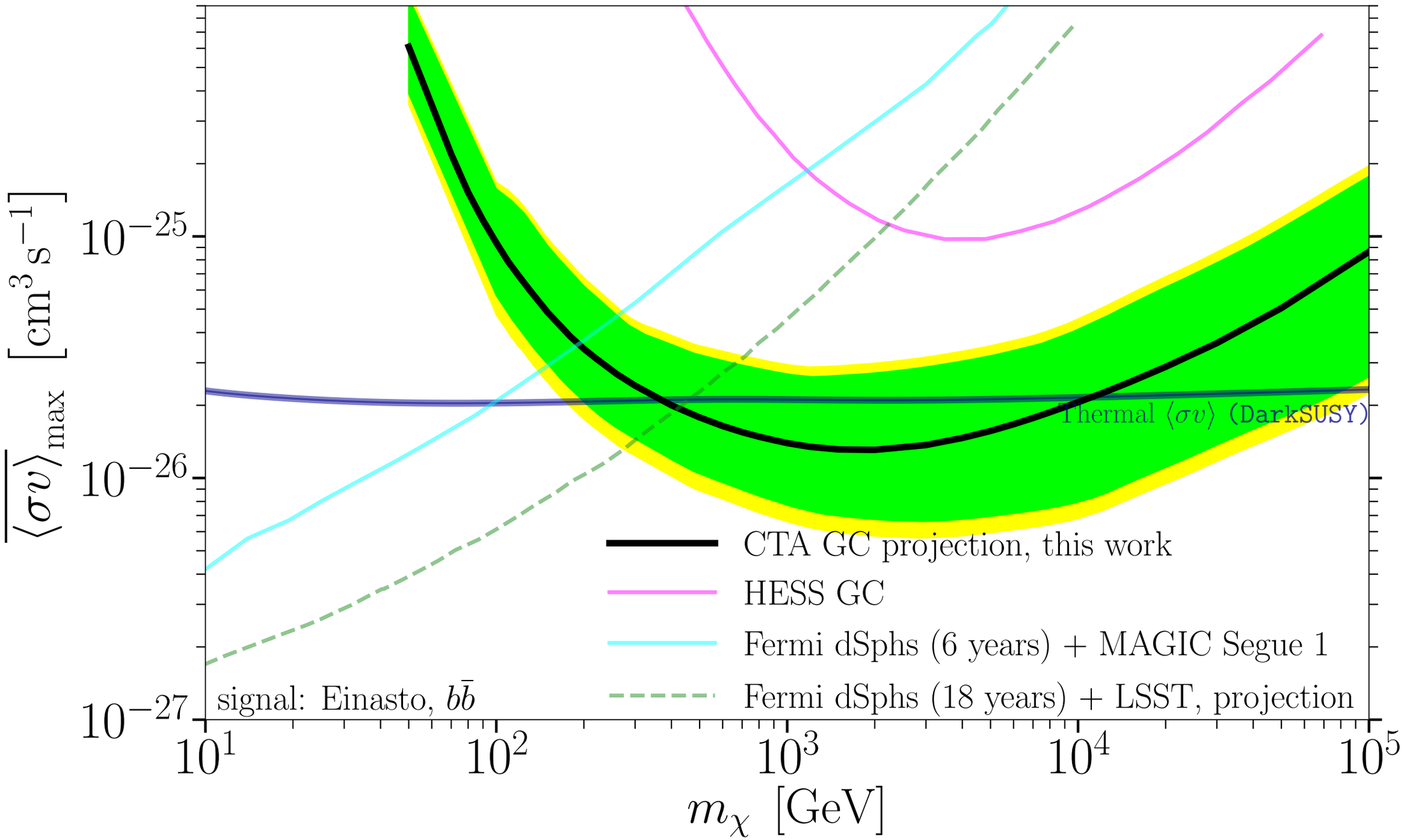
indirectly

- WIMP DM is seriously pressured, but certainly not (yet) 'dead' !

Arcadi+, EPJC '18
Athron+, 2106.02056
(+ many more)

Example: indirect detection constraints

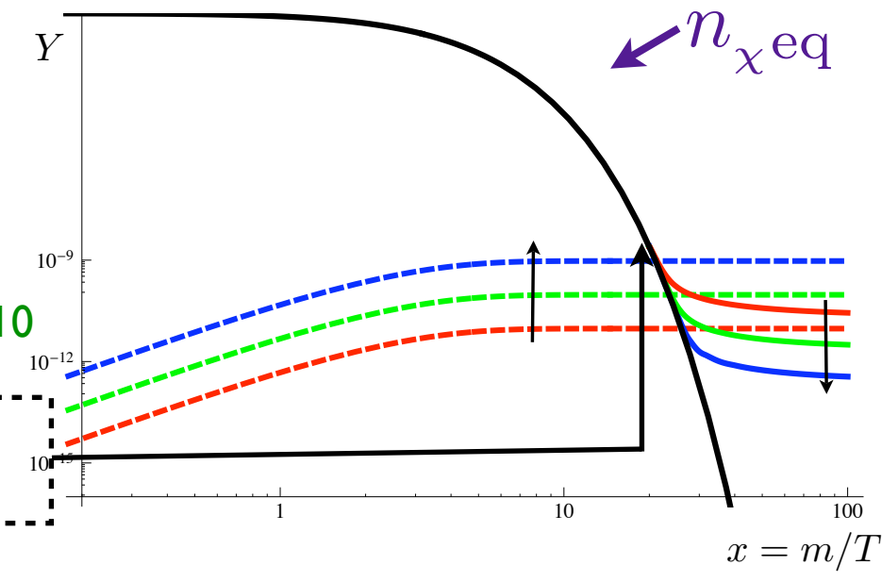
Acharyya+, JCAP '21



Feably Interacting Massive Particles

- alternative production from thermal bath with much smaller interactions
  - DM never equilibrates in this case

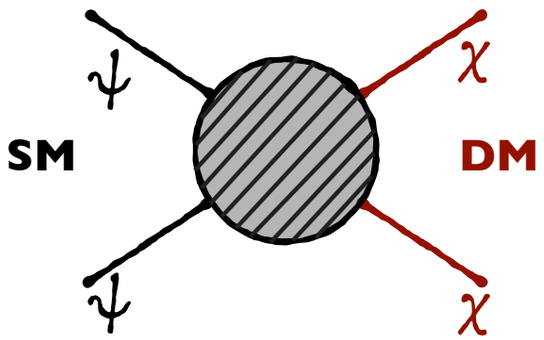
Hall+, JHEP '10



***Increasing* interaction rate for freeze-in**

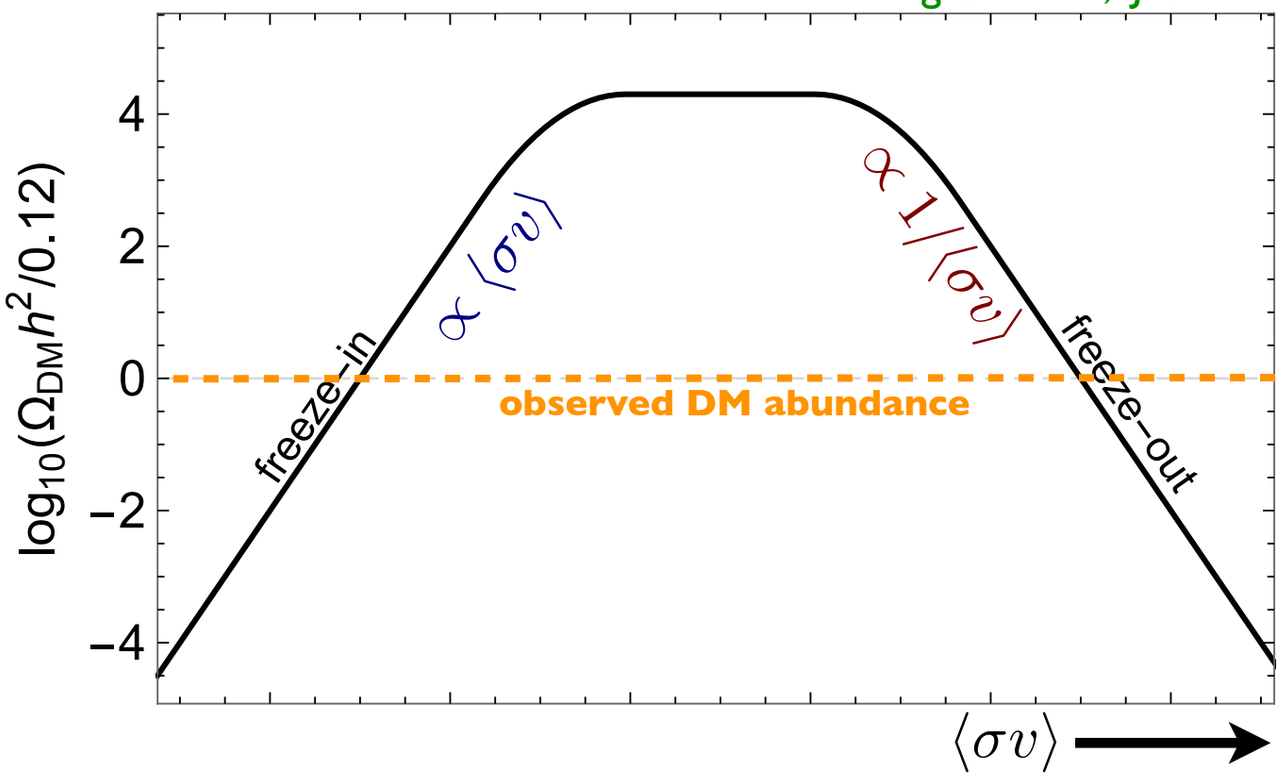
- Smooth transition between two regimes:

freeze-in

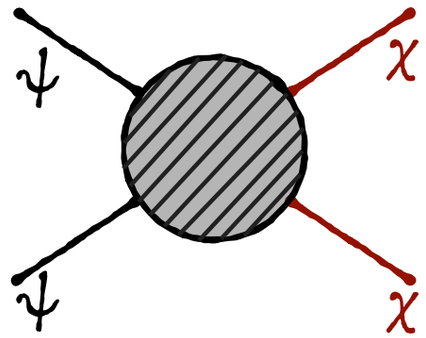


depends on initial conditions

Fig: Bernal+, IJMP '17



freeze-out



insensitive to initial conditions

Collision term for FIMPs

$$C[f_\chi] = \frac{1}{2g_\chi}\int\frac{d^3\tilde{p}}{(2\pi)^3 2\tilde{E}}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}(2\pi)^4\delta^{(4)}(\tilde{p}+p-\tilde{k}-k)$$
$$\times\left[|\mathcal{M}|^2_{\bar{\chi}\chi\leftarrow\bar{\psi}\psi}\, f_\psi(\omega) f_\psi(\tilde{\omega}) - |\mathcal{M}|^2_{\bar{\chi}\chi\to\bar{\psi}\psi}\, f_\chi(E) f_{\bar{\chi}}(\tilde{E})\{1\pm f_\psi(\omega)\}\{1\pm f_\psi(\tilde{\omega})\}\right]$$

'production' 'annihilation'

$$\Rightarrow \boxed{C[f_\chi] = \langle\sigma v\rangle_{\chi\chi\to\psi\psi}\left(n_\chi^{\rm MB}\right)^2}$$

annihilation of ***would-be*** MB population → ***actual*** (in eq)

- Only 2 integrals after exploiting spherical symmetry:
  [γ : Lorenz boost to CMS; $\tilde{s} = s/(4m_\chi^2)$]

$$\langle\sigma v\rangle_{\chi\chi\to\psi\psi} = \frac{8x^2}{{K_2}^2(x)}\int_1^\infty d\tilde{s}\,\tilde{s}\,(\tilde{s}-1)\int_1^\infty d\gamma\,\sqrt{\gamma^2-1}e^{-2\sqrt{\tilde{s}}x\gamma}\sigma_{\chi\chi\to\psi\psi}(s,\gamma)$$

→ $K_1(2\sqrt{\tilde{s}}x)/(2\sqrt{\tilde{s}}x)$ ✔

TB, Heeba, Kahlhoefer & Vangsnes, JHEP '22
(see also Lebedev & Toma, PLB '19
Arcadi+, JHEP '19)

$$\sigma_{\chi\chi\to\psi\psi}(p,\tilde{p}) = \frac{(2\pi)^4}{4N_\psi E\tilde{E}\,v_{\rm Møl}}\int\frac{d^3k}{(2\pi)^3 2\omega}\int\frac{d^3\tilde{k}}{(2\pi)^3 2\tilde{\omega}}\,\delta^{(4)}(\tilde{p}+p-\tilde{k}-k)\,\left|\overline{\mathcal{M}}\right|^2\{1\pm f_\psi(\omega)\}\{1\pm f_\psi(\tilde{\omega})\}$$

→ 1

- In *this* formulation, direct analogy with WIMP case!
  - Can recycle sophisticated numerical tools for thermal averages
  - Easier to estimate higher-order corrections



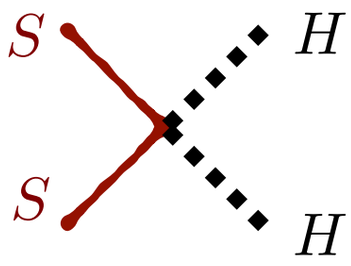
Case study

- **Scalar Singlet DM**

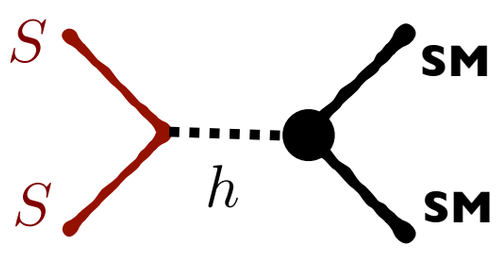
$$\mathcal{L} = \frac{1}{2}\partial_\mu S \partial^\mu S + \frac{1}{2}\mu_S^2 S^2 + \frac{1}{2}\lambda_{hs} S^2 |H|^2 + \frac{1}{4}\lambda_s S^4$$

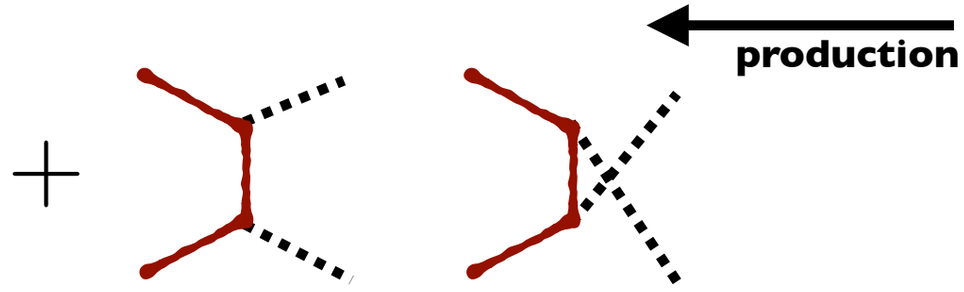
Silveira & Zee, PLB '85

- before EWSB:



- after EWSB:

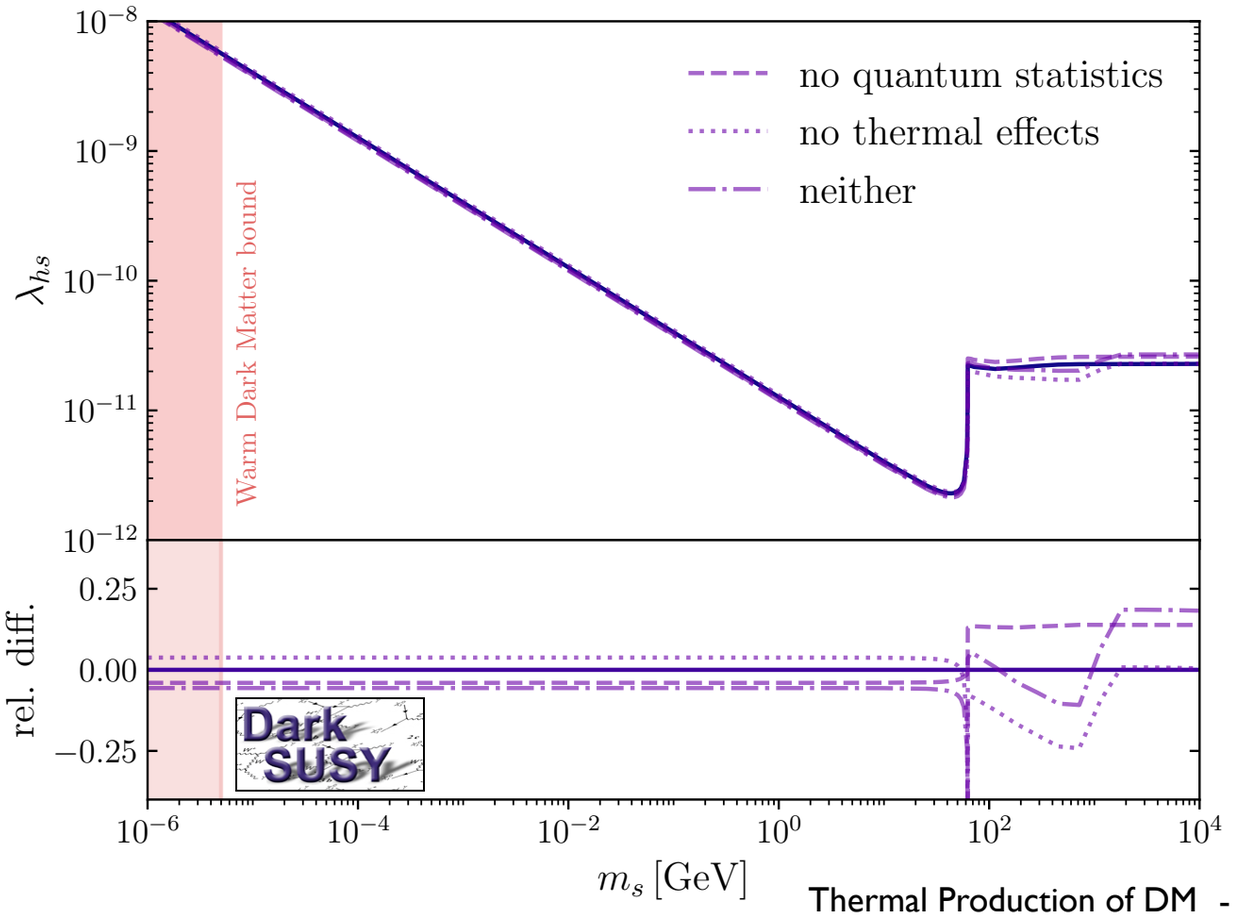




- Freeze-in coupling required for correct relic density

TB, Heeba, Kahlhoefer & Vangsnes, JHEP '22

- unlike for (non-rel.) freeze-out, quantum statistics do affect final result [@ $\mathcal{O}(10\%)$] !



DarkSUSY

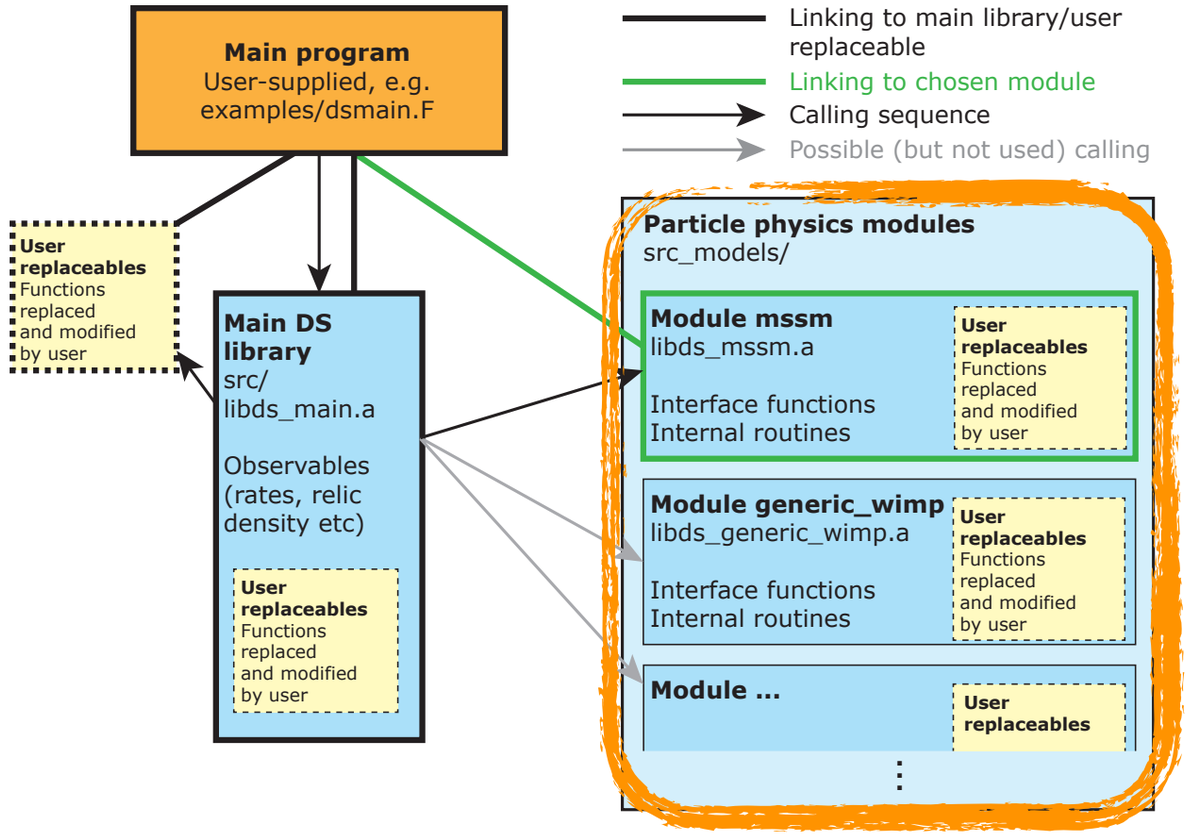


TB, Edsjö, Gondolo, Ullio & Bergström, JCAP '18

http://darksusy.hepforge.org

Since version 6: no longer restricted to supersymmetric DM !

- Numerical package to calculate 'all' DM related quantities:
  - *relic density + kinetic decoupling* **(also for $T_{\rm dark} \neq T_{\rm photon}$)**
  - *generic SUSY models + laboratory constraints implemented*
  - *cosmic ray propagation*
  - particle yields for generic DM annihilation or decay
  - *indirect detection rates: gammas, positrons, antiprotons, neutrinos*
  - *direct detection rates*
  - …

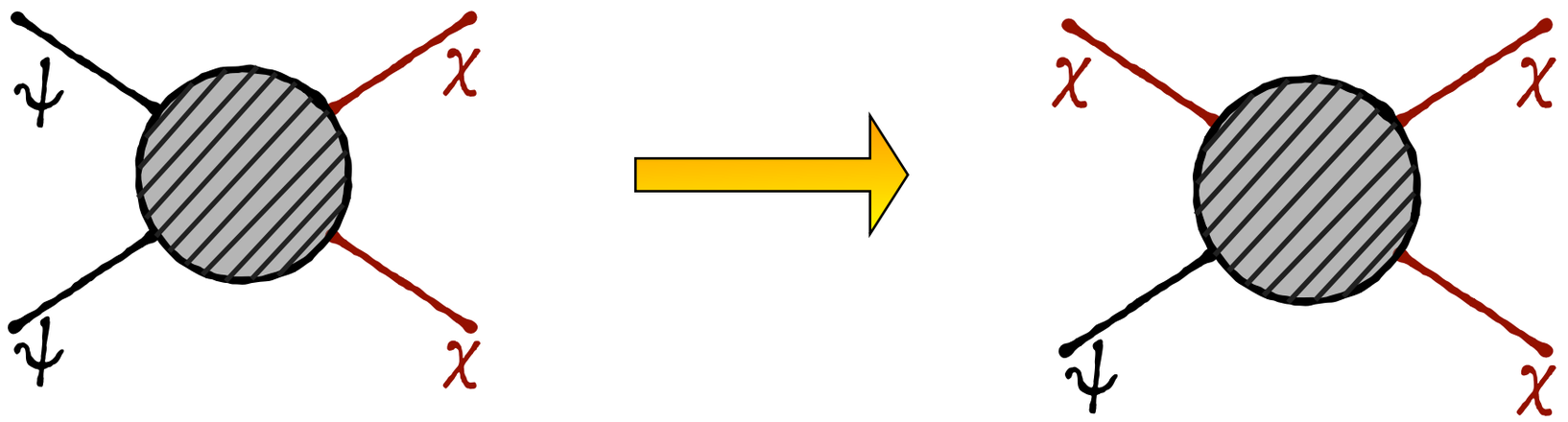


since 6.1: DM self-interactions

since 6.2: 'reverse' direct detection
(also Q^2 -dependent scattering!)

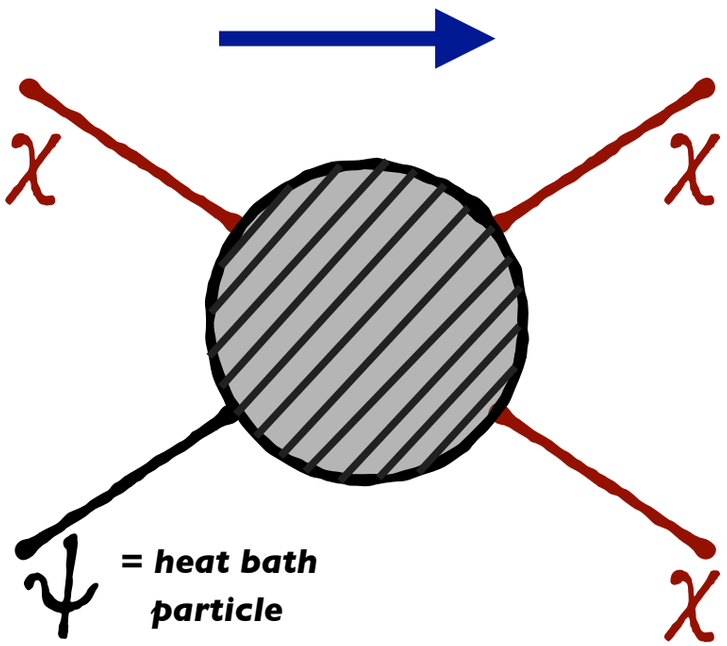
since 6.3: freeze-in

Part III



A new production mechanism

- ‘Pandemic’ dark matter



TB, Depta, Hufnagel, Rudermann & Schmidt-Hoberg, 2103.16572

Hryczuk & Laletin, 2104.05684

$$\dot{n_\chi} + 3Hn_\chi = n_\chi n_\psi^{\rm eq} \langle\sigma v\rangle$$

[for $n_\chi \ll n_\psi^{\rm eq}$]

- The ‘SIR’ compartmental model

A Contribution to the Mathematical Theory of Epidemics.

By W. O. Kermack and A. G. McKendrick.

(Communicated by Sir Gilbert Walker, F.R.S.—Received May 13, 1927.)

S ***# susceptible individuals***

I ***# infected individuals***

recovered $(R = \text{tot} - S - I)$

β ***infection rate***

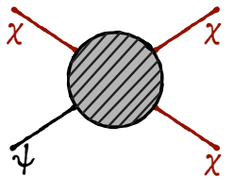
γ ***recovery rate***

$$\dot{I} = \beta S I - \gamma I$$

➡ *reproduction number, or ‘R-value’:* $R \equiv \frac{\beta S}{\gamma} = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle}{3H}$

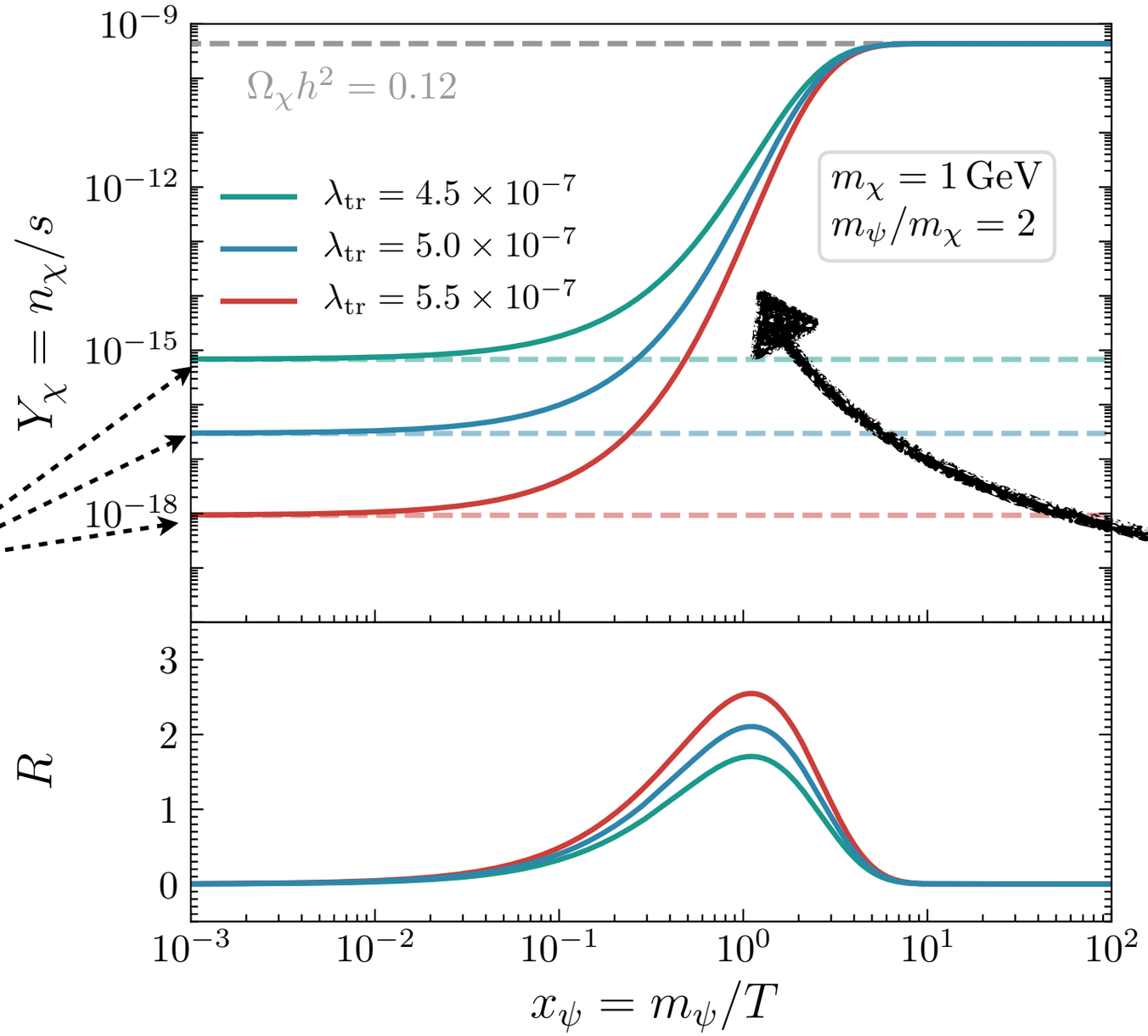
Exponential DM production

$\mathcal{L} \supset (\lambda_{\rm tr}/3!)\psi\chi^3$



$= -i\,\lambda_{\rm tr}$

toy model



Tiny initial DM abundance

exponential growth

$R \gtrsim 1$

large H

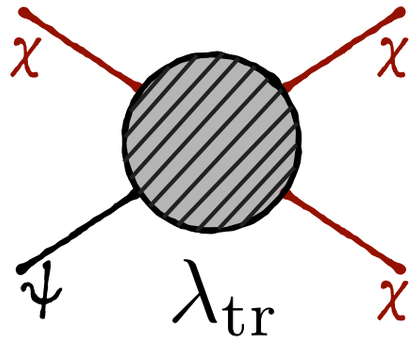
small $n_\psi^{\rm eq}$

$$R \equiv \frac{\beta S}{\gamma} = \frac{n_\psi^{\rm eq}\langle\sigma v\rangle}{3H}$$

Adding freeze-in production

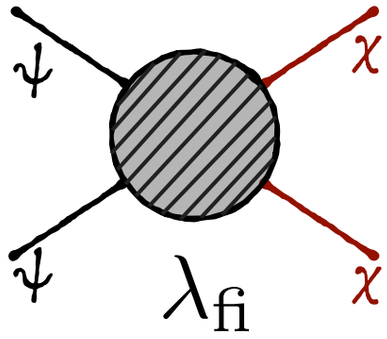
TB, Depta, Hufnagel, Rudermann & Schmidt-Hoberg, PRL '22

'transmission'

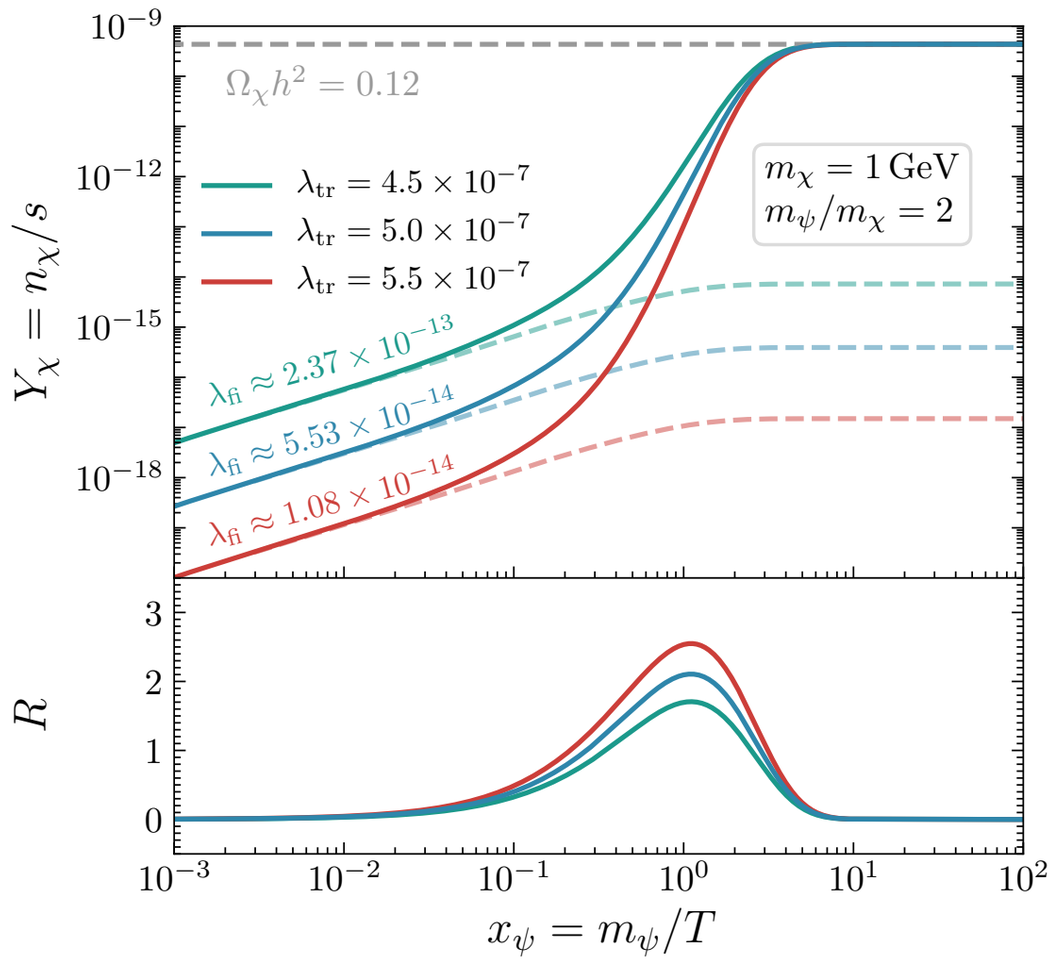


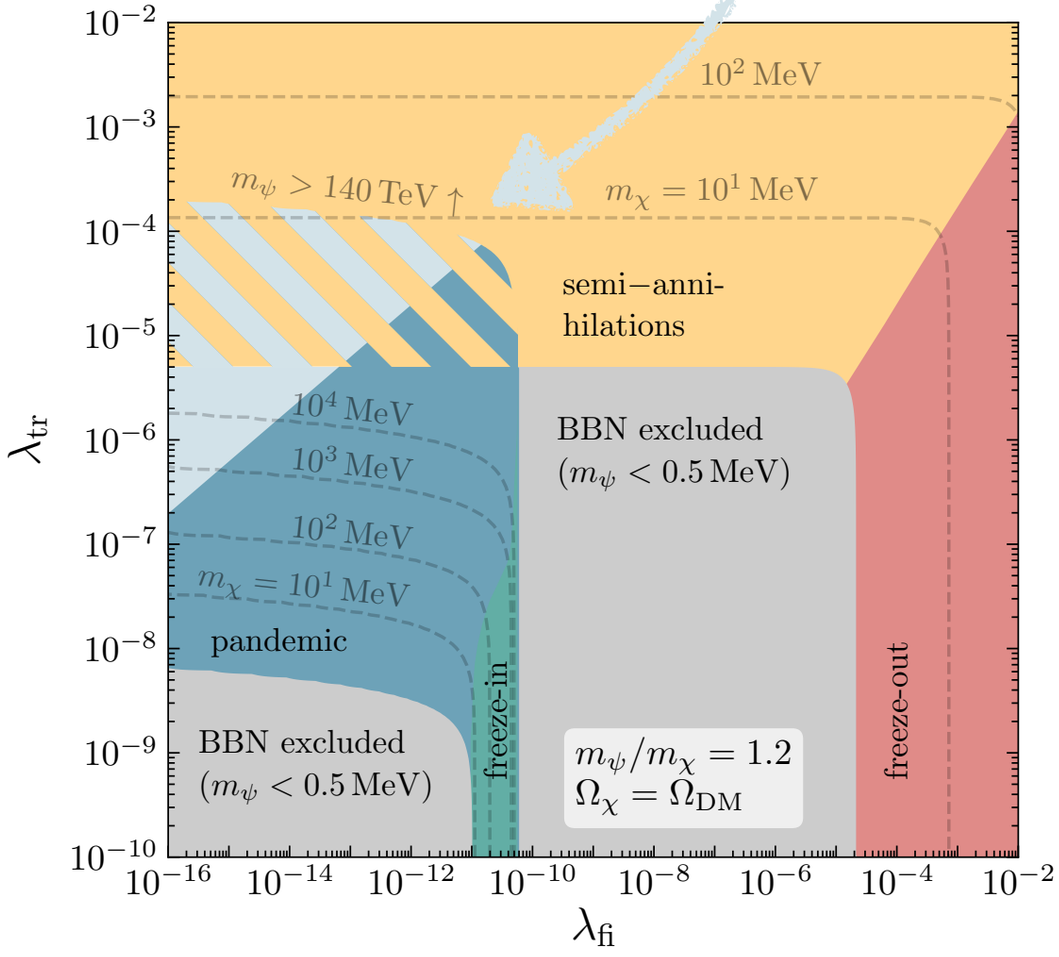
+

'freeze-in'



2→4 freeze-in dominates



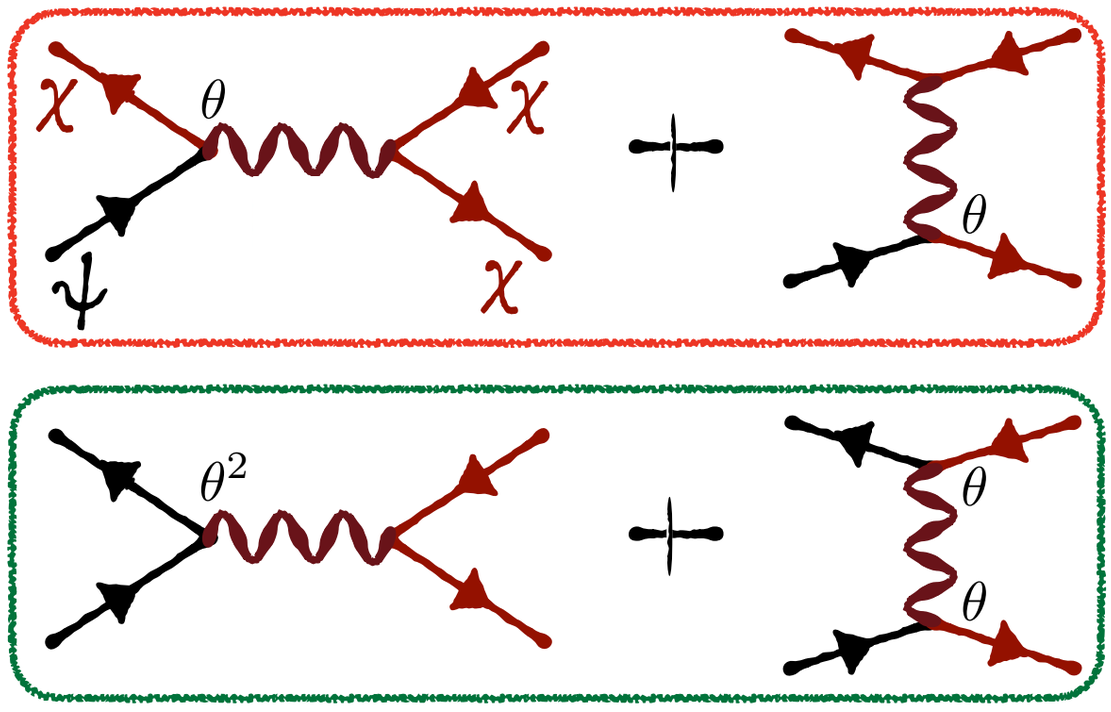


➡ *'Pandemic' production is a very generic mechanism for the genesis of DM!*

Signals ?

- Necessarily model-dependent
  - 'Pandemic DM' describes a class of models, just like 'WIMP' does
- Q: Is there a *generic* way to realize $\langle \sigma v \rangle_{\rm fi} \ll \langle \sigma v \rangle_{\rm tr}$?
- A: yes — just add a dark sector mediator and mass mixing!

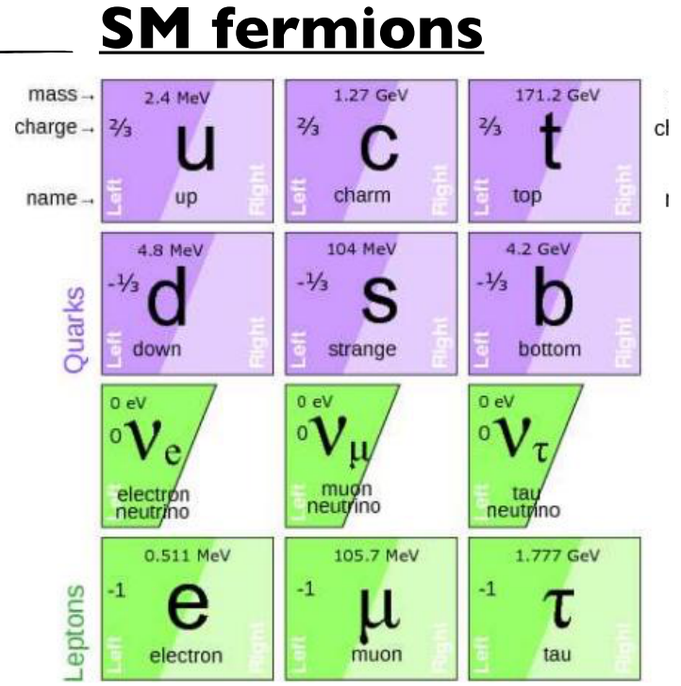
$$\mathcal{L} \supset -\delta m \left(\bar{\psi}\chi + \bar{\chi}\psi\right) - g\bar{\chi}\not{V}\chi \quad \Rightarrow \quad \mathcal{L} \supset -g\left[\bar{\chi}\not{V}\chi + \theta\left(\bar{\psi}\not{V}\chi + \bar{\chi}\not{V}\psi\right) + \theta^2\bar{\psi}\not{V}\psi\right]$$



transmission $\propto \theta$

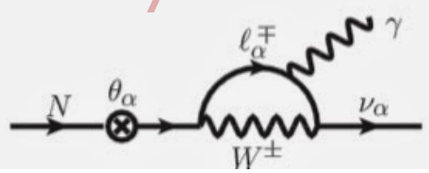
freeze-in $\propto \theta^2$

Sterile neutrinos



- A right-handed neutrino would be neutral under *all* SM gauge forces
- An excellent, well-motivated dark matter candidate
- Production by SM processes: oscillations with active neutrinos, combined with NC and CC scatterings — Dodelson & Widrow, PRL '94
- Unfortunately, this scenario is ruled out by observations…

X-ray lines



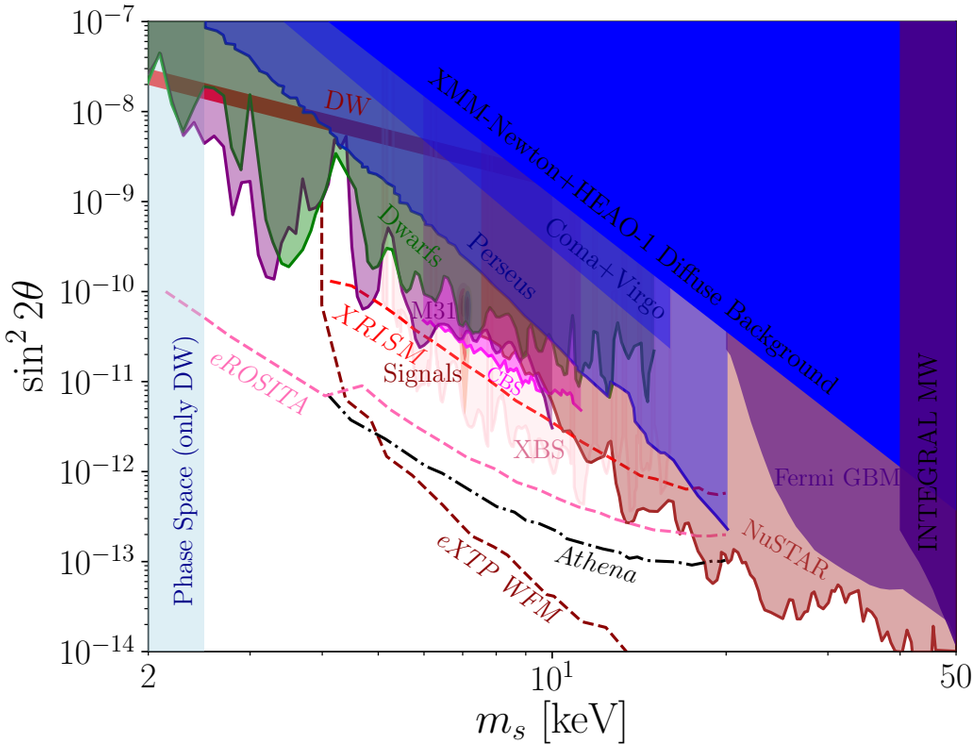


Fig.: Abazajian+, 2203.7377

Interacting sterile neutrinos

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, arXiv:2206.10630

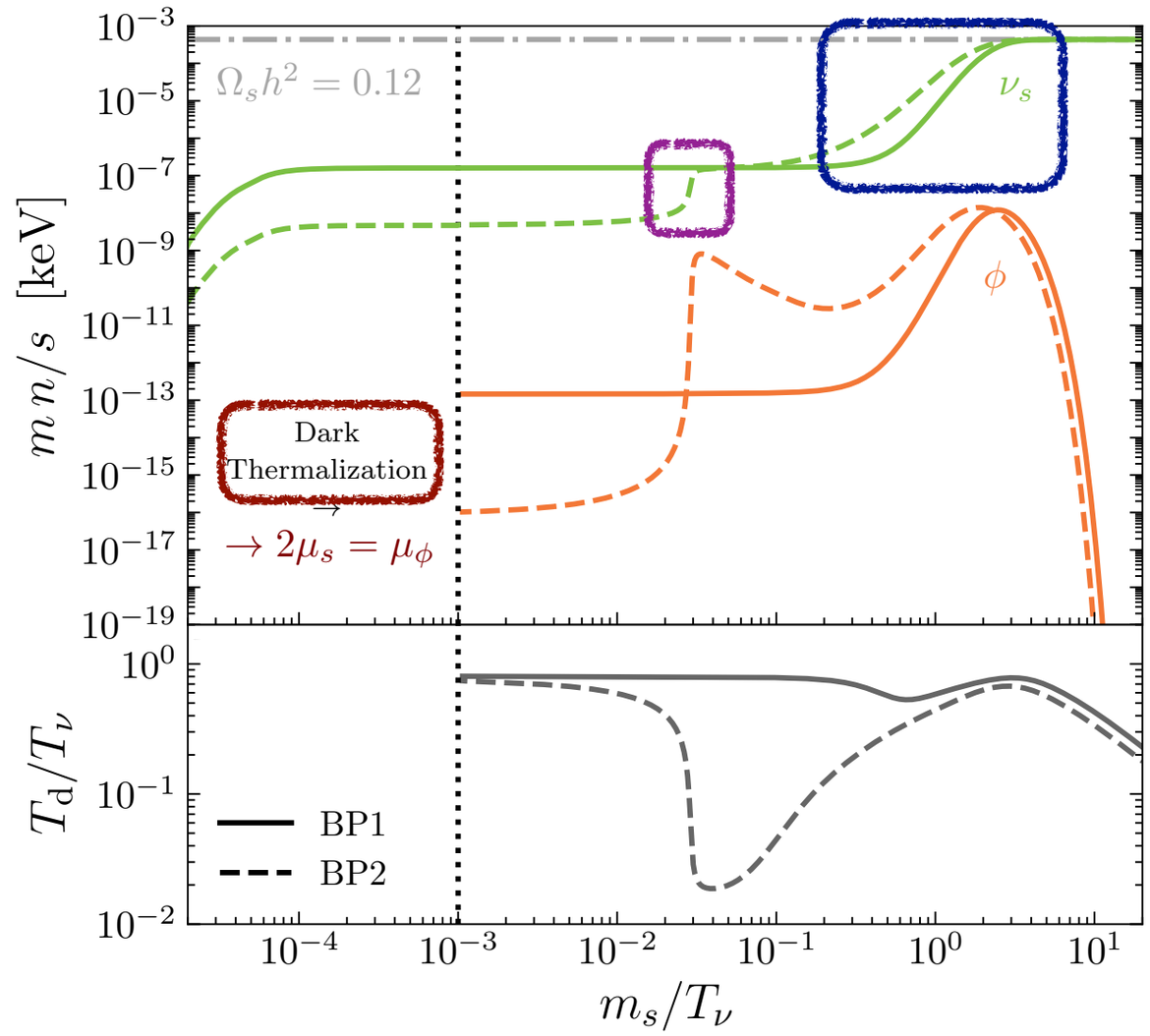
- Let's add a scalar ϕ that only couples to the sterile neutrinos

$$\mathscr{L} \supset \frac{y}{2}\phi\bar{\nu}_s\nu_s \quad \Rightarrow \quad \frac{y}{2}\phi[\sin^2\theta\bar{\nu}_\alpha\nu_\alpha - \sin\theta\cos\theta(\bar{\nu}_\alpha\nu_s + \bar{\nu}_s\nu_\alpha) + \cos^2\theta\bar{\nu}_s\nu_s] \qquad m_\phi > 2m_s$$

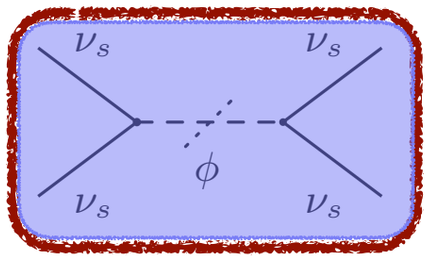
- Early times (~QCD PT): standard DW production

- Evolution afterwards:

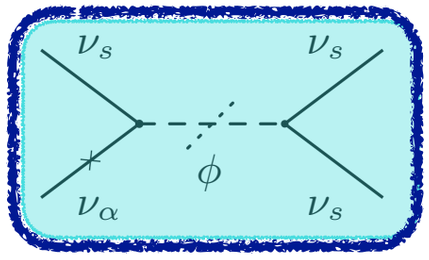
solid: benchmark point with large θ, small y
dashed: benchmark point with small θ, large y



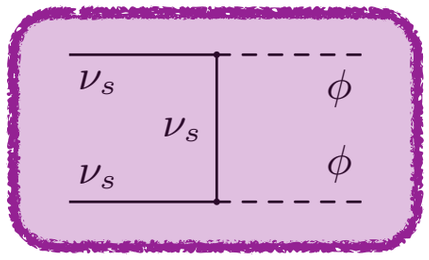
- Thermalization in dark sector



- Exponential growth



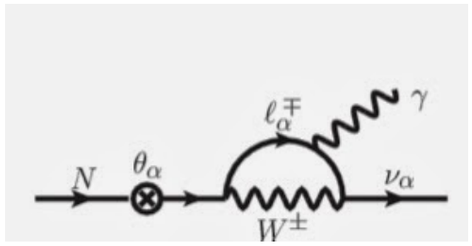
- Reproductive freeze-in



Sterile neutrinos… revived !

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, arXiv:2206.10630

- Observational constraints
  - (Standard) X-ray lines



  - ν_s self-interactions

$$\sigma_T/m_s \lesssim 1\,\mathrm{cm}^2/\mathrm{g}$$

cf. Tulin & Yu, PR '18

maybe 0.1 possible… (?)

  - Lyman-α

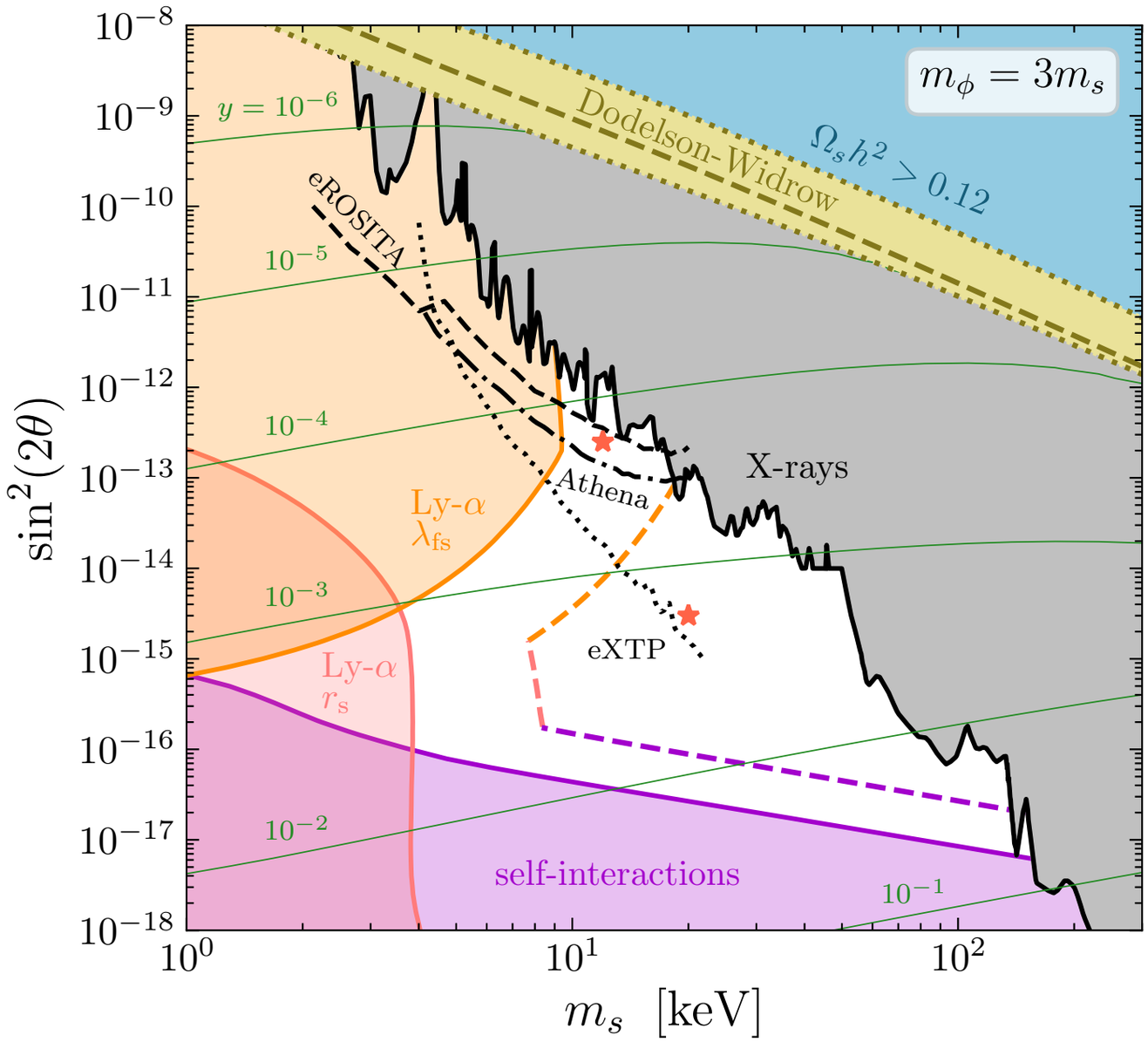
recast $m_{\rm WDM} > 1.9\,\mathrm{keV}$ to

Garzilli+, MNRAS '21

$$\lambda_{\rm FS} < 0.24\,\mathrm{Mpc}$$
$$r_{\rm s} < 0.36\,\mathrm{Mpc}$$

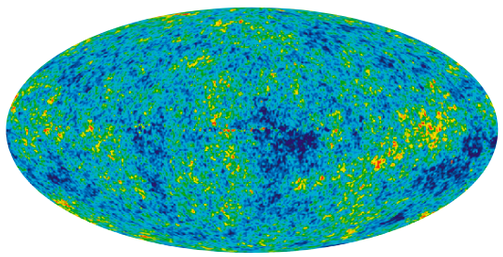
maybe $m_{\rm WDM} > 5.3\,\mathrm{keV}$ possible… (?)

Palanque-Delabrouille+, JCAP '20



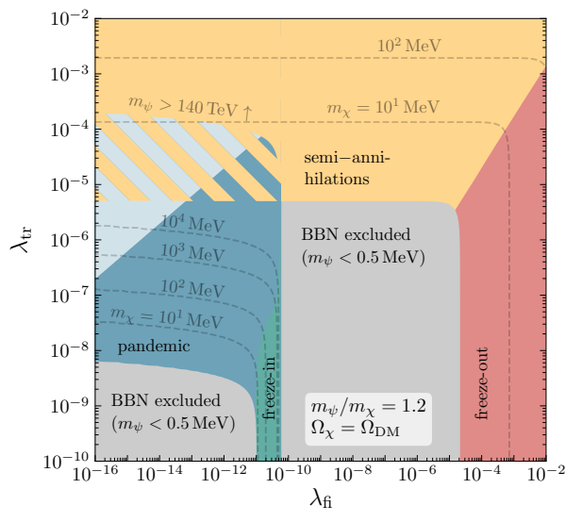
- New parameter space
  - Bounded from above *and* below
  - Significant parts in observational reach

Conclusions



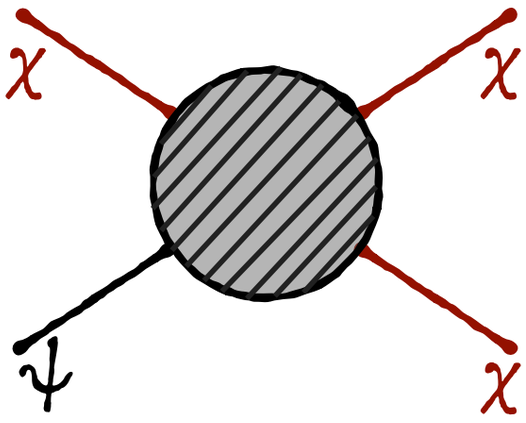
- Dark matter = evidence for BSM physics

- There are a handful of generic ways of DM genesis from primordial heat bath



- Pandemic dark matter is a novel such mechanism. Mathematical analogy to spread of diseases works almost scarily well

[see *arXiv v1 for exploiting most of it* 😉]



Thanks for your attention!