

The (un)reasonable elusiveness of dark matter

Torsten Bringmann



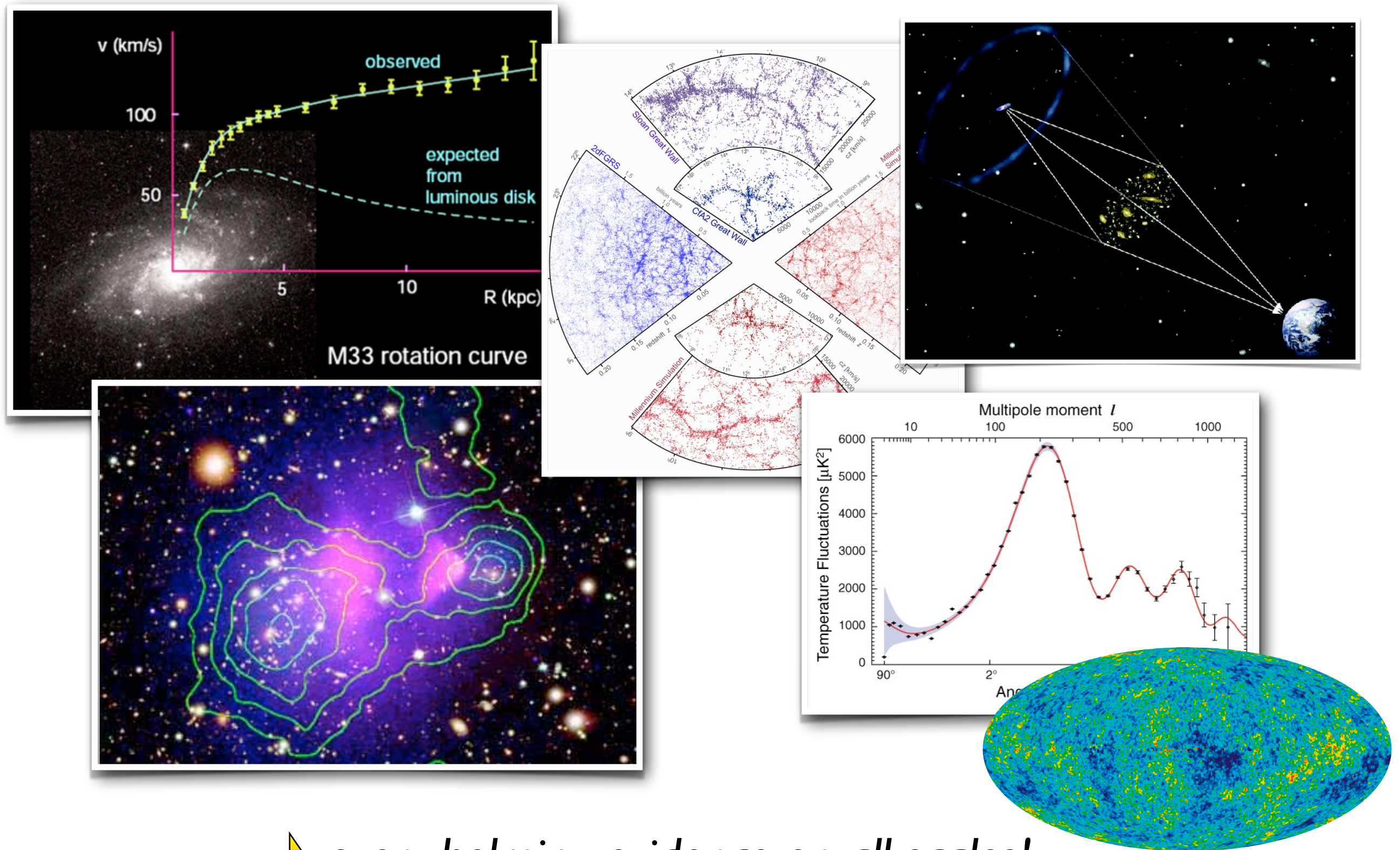
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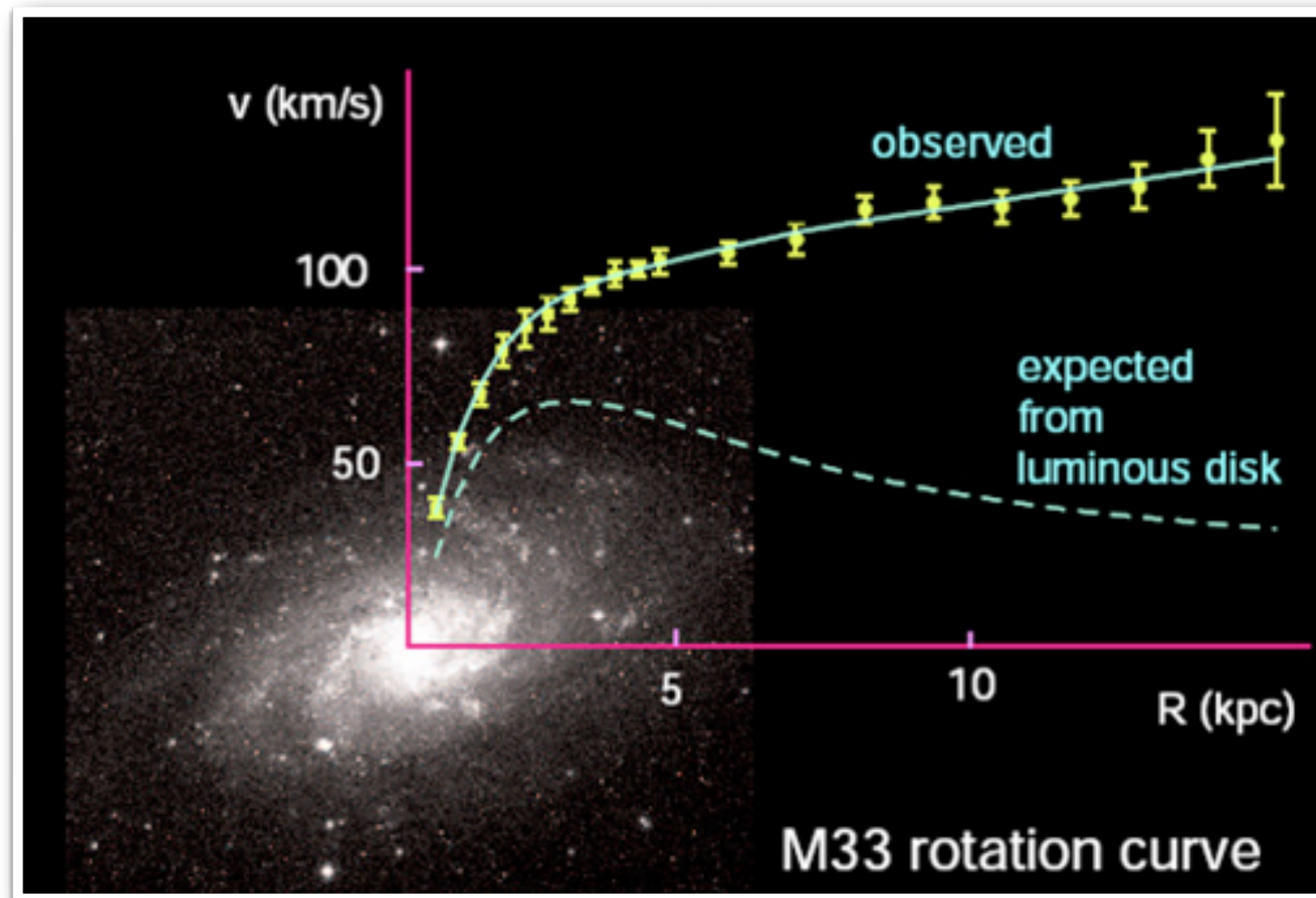
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Dark matter all around



➔ **overwhelming evidence on all scales!**

Galactic scales



Newton:

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

‘missing’ mass



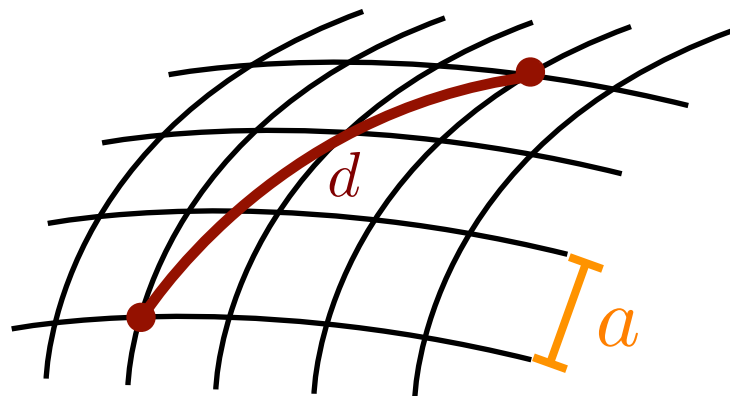
● **Rotation curves** no longer main argument for existence of **dark matter** !

● 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

- Background evolution:
'Friedman equations' fix $a(t)$

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

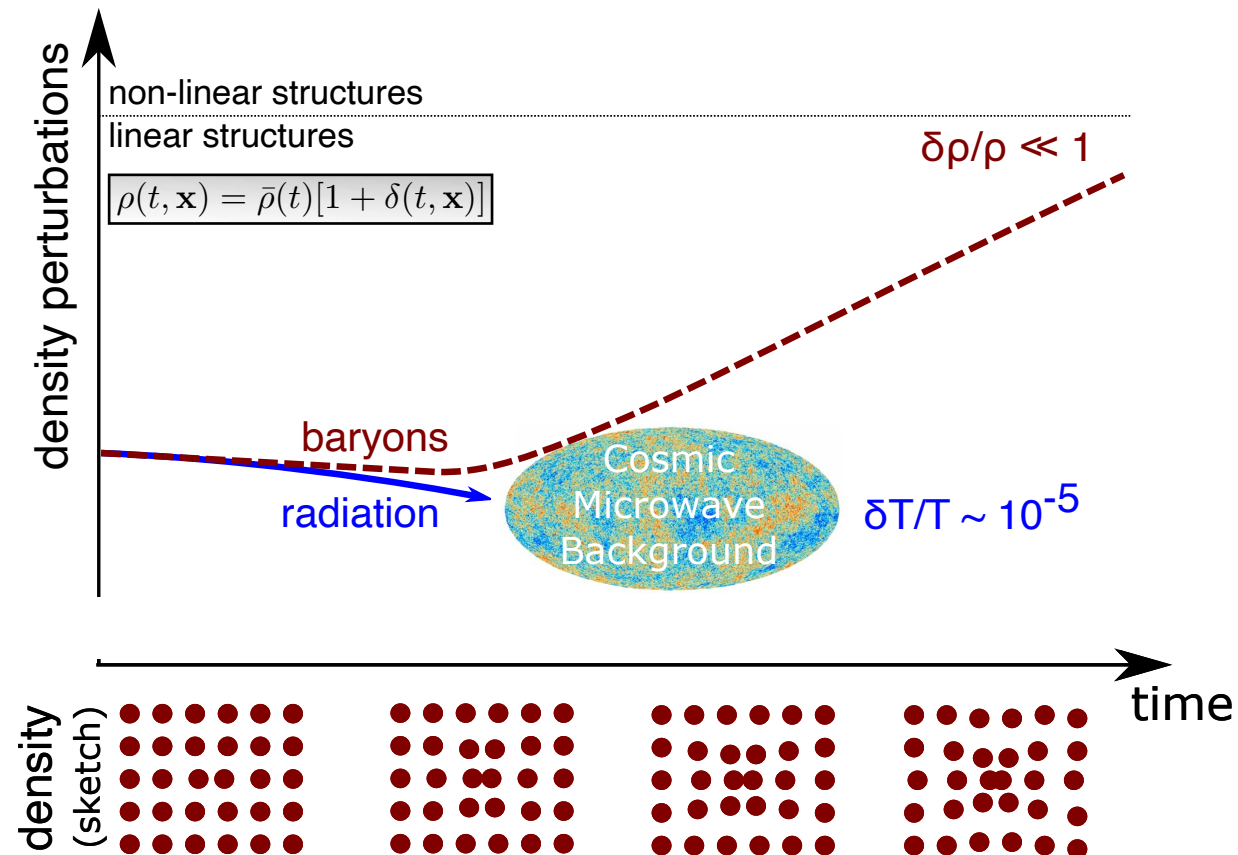
→ *no difference between
dark and visible matter*

→ *Strong impact
of dark matter*

Cosmological scales

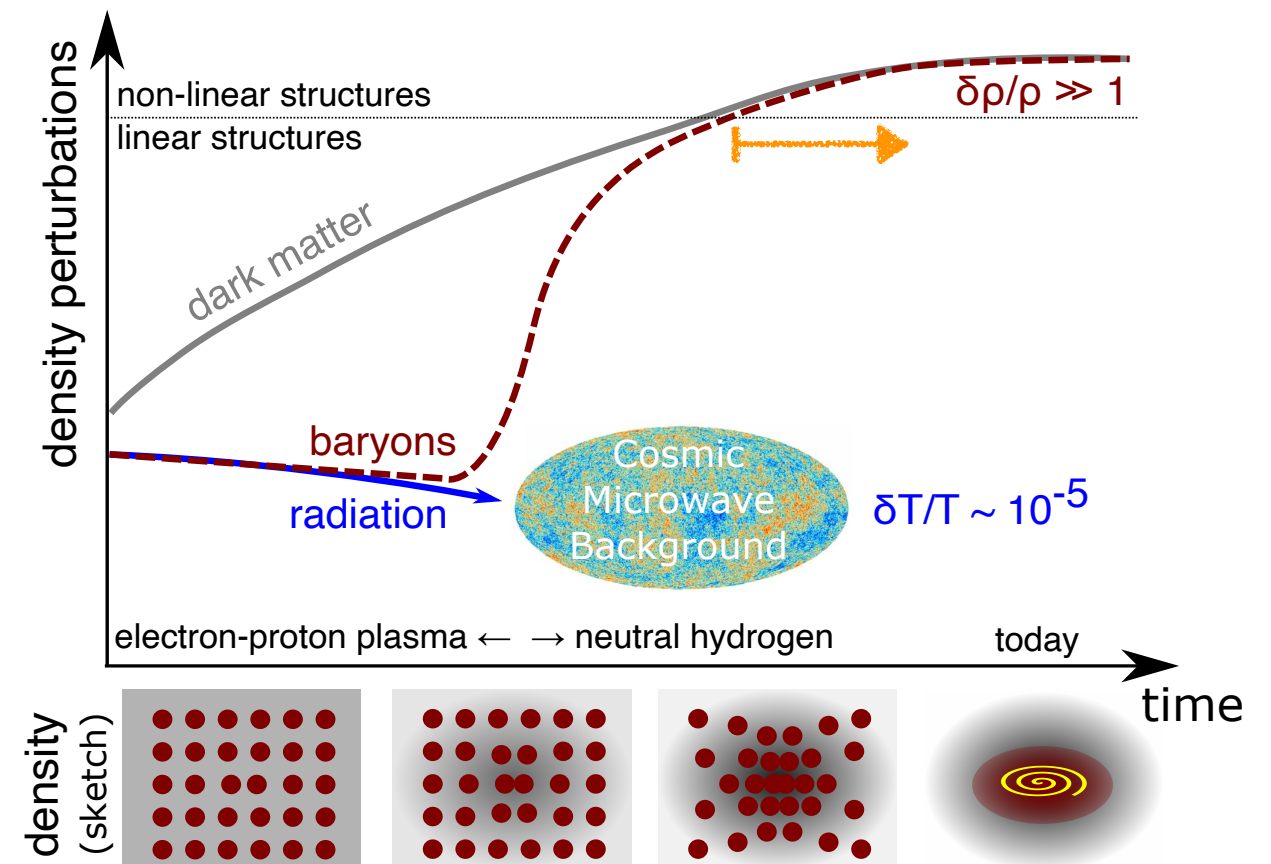
pedagogical DM review:
Balacs, TB, Kahlhoefer & White, 2411.05062

Structure formation without dark matter



- Without dark matter, we would still be in the *linear* regime: **no** galaxies, stars, planets, ...!

Structure formation with dark matter



- With dark matter
 - Need simulations for **non-linear evolution**
 - obtain \sim perfect agreement with observations (at large scales)

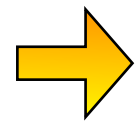
From evidence to precision

- DM is a **crucial ingredient** of cosmological SM!

- constant** co-moving energy **density**

- only gravitational** interactions

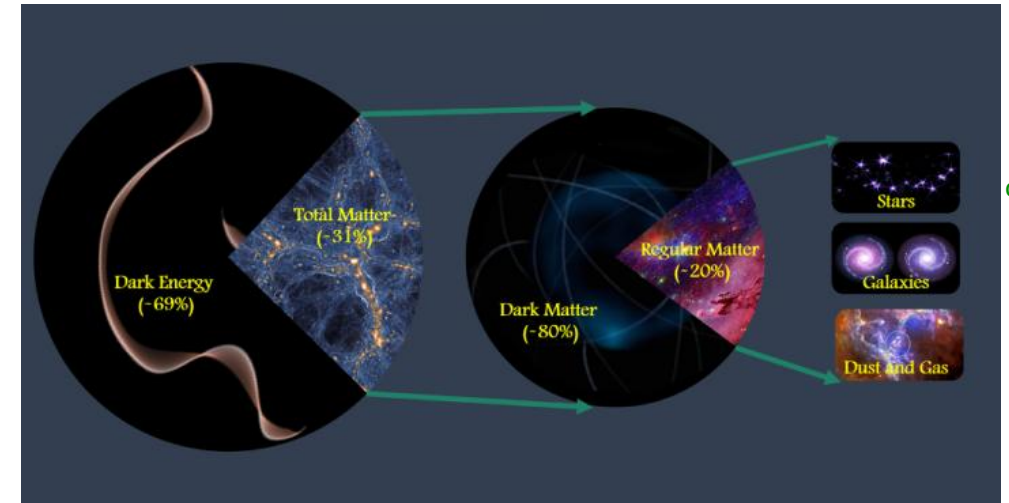
- cold + dissipation-less



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

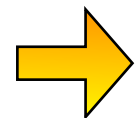
Ade+ [Planck Coll.], A&A '16

**Percent-level
measurements of a
single parameter!**



- Q: Can DM **convert** into (in)visible energy?

- E.g. decays, late-time annihilation, coalescing PBHs, ...



Ω_{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

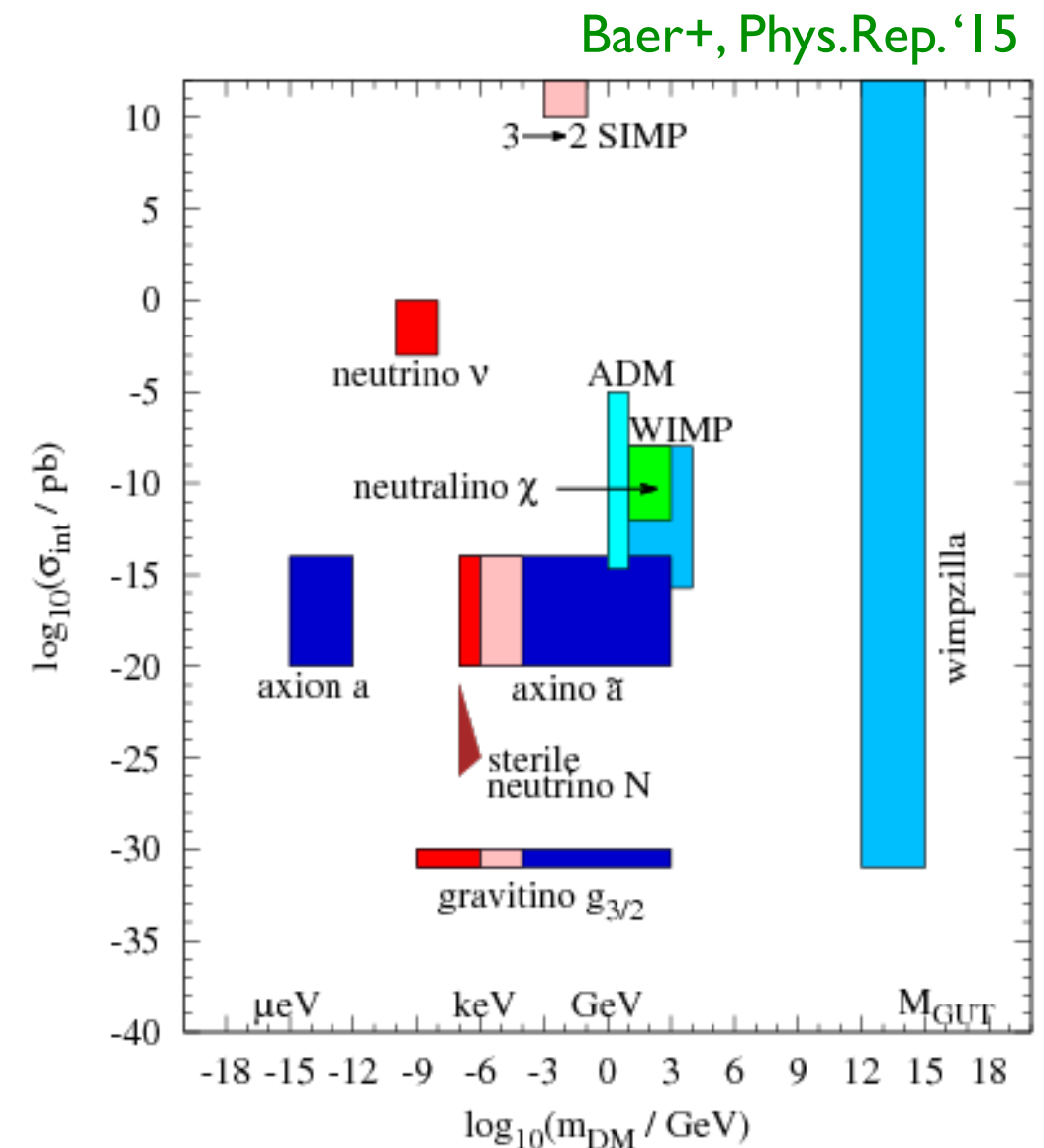
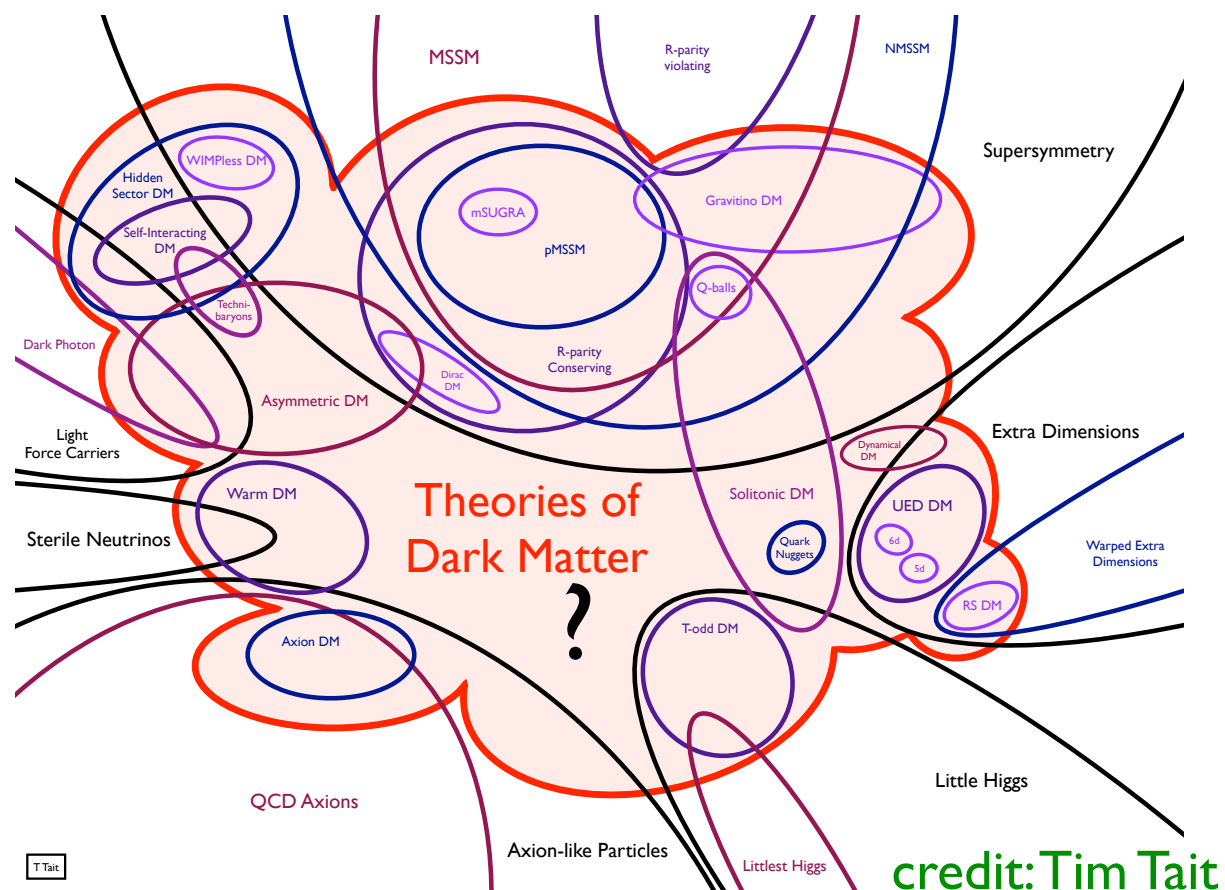
- Q: Can't we explain *all* this also by **modified gravity**?

- A: **No!** [though definitely yes for *selected* observations]



Candidates

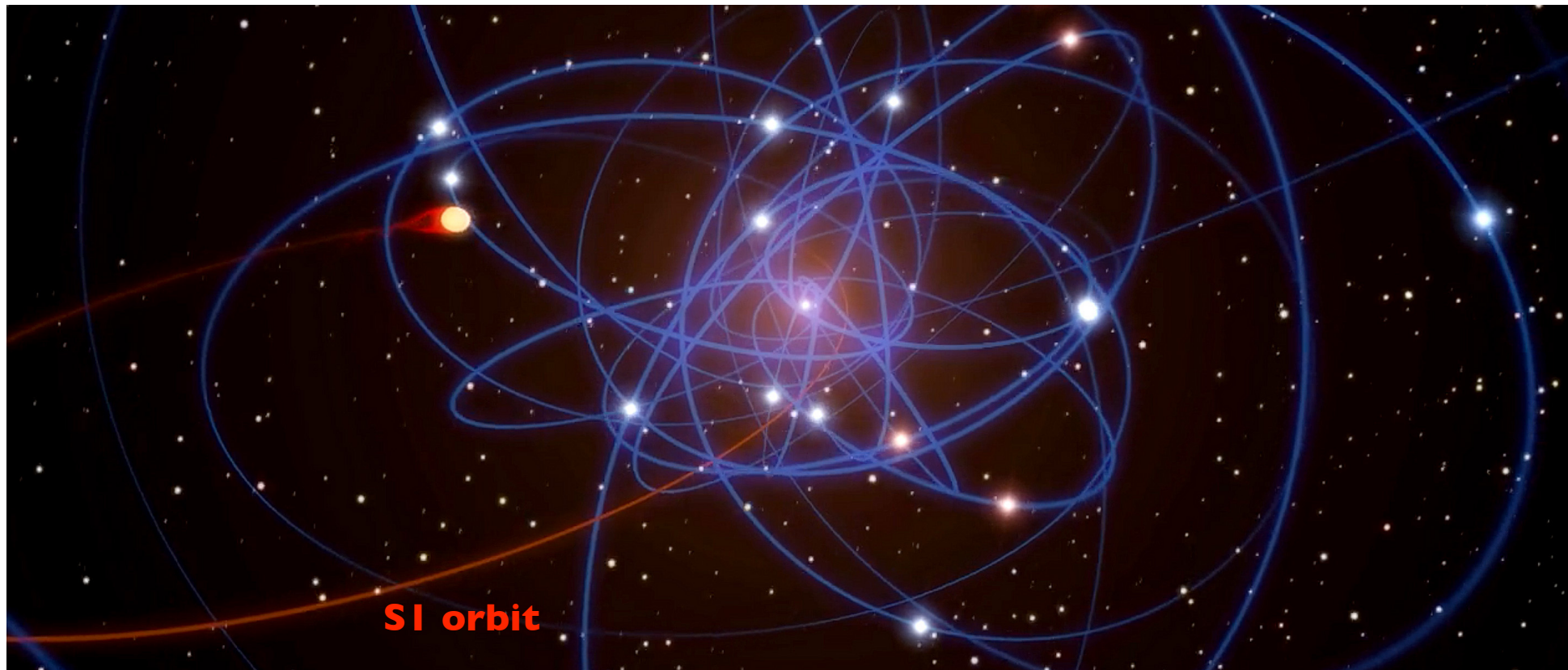
- Existence of (particle) DM = **evidence** for BSM physics!
+ rather good handle on what it is **not**
- Unfortunately, this still leaves quite a few options...



Black holes (I)

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

[#  2017, 2020]

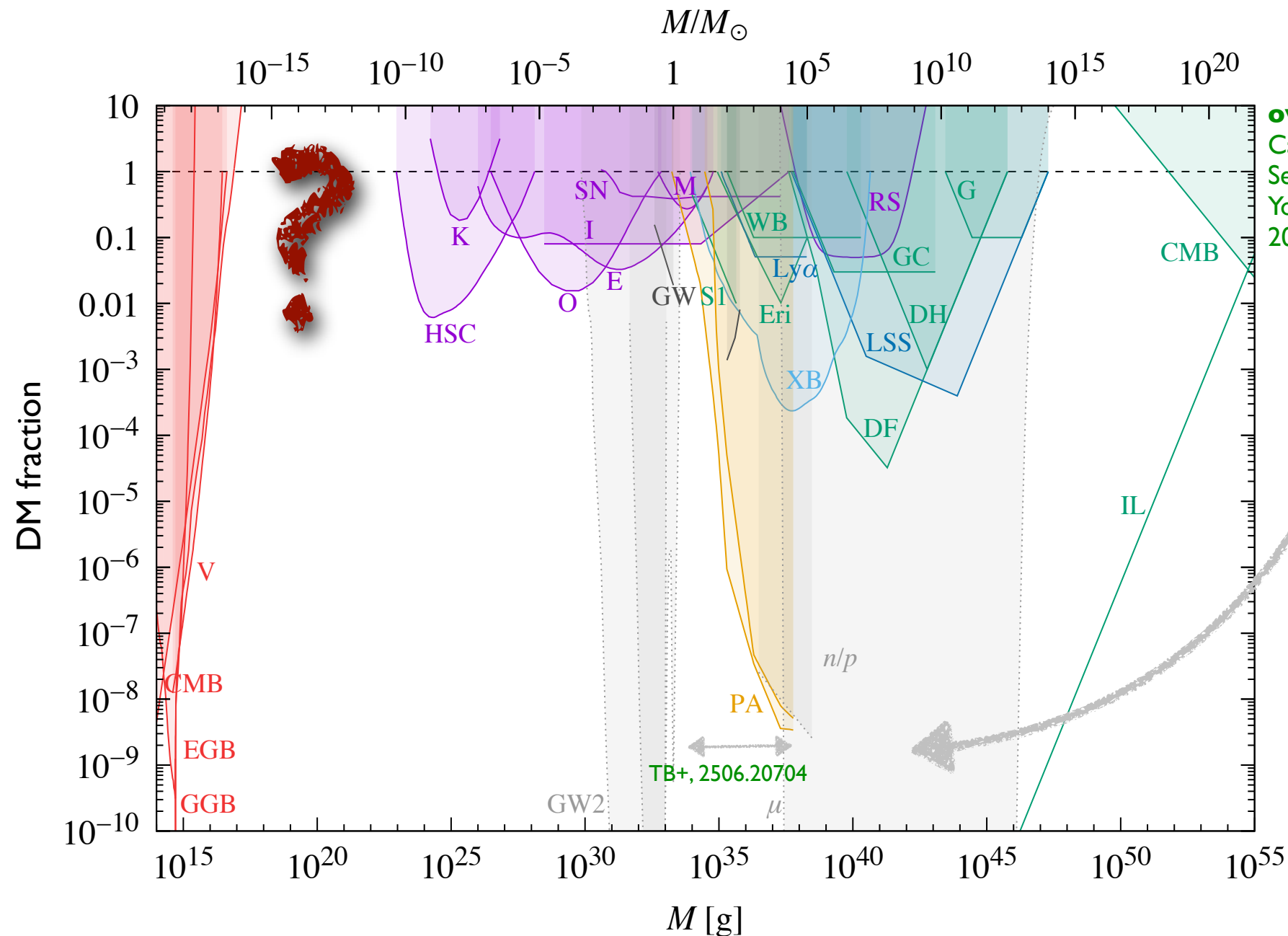


- Strongly constrained by micro-lensing and CMB!
➔ Black holes can only be a sub-dominant DM component

overview:
Carr, Kohri, Sendouda &
Yokoyama, 2002.12778

Black holes (II)

- **Primordial** black holes can be much smaller



overview:
Carr, Kohri,
Sendouda &
Yokoyama,
2002.12778

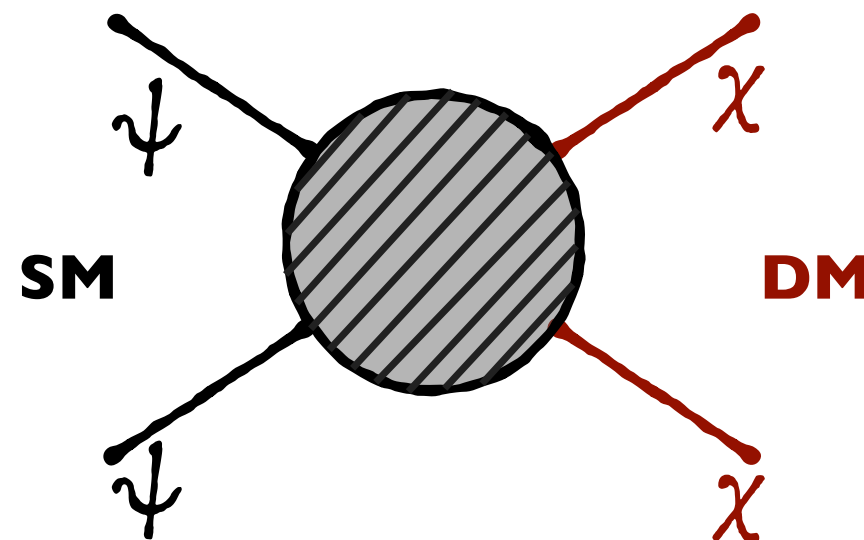
PBHs can hardly form
at all through direct
collapse of primordial
density fluctuations

- But this would also **not** be “**SM physics**” ... !
- *formation* (+ requirement of $f_{\text{PBH}} \sim 1$) requires BSM physics



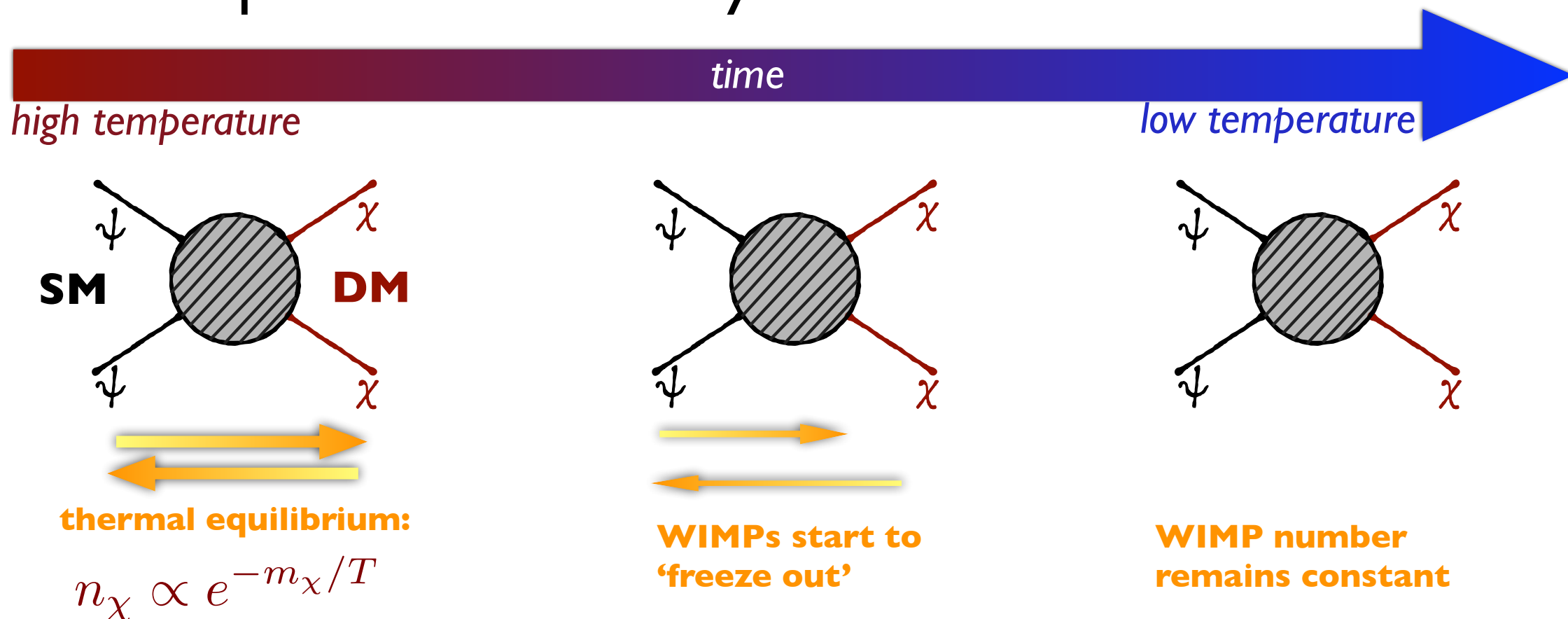
The origin of dark matter

- 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!
- Simplest generic interaction with the primordial heat bath:
 - [Z_2 symmetry not strictly necessary, but automatically guarantees stability of DM]



Weakly Interacting Massive Particles

- well-motivated from particle physics
 - Appear as 'by-products' in attempts to cure fine-tuning problems of **S**tandard **M**odel problems [SUSY, Higgs sector extensions, ...]
- thermal production in early universe:



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

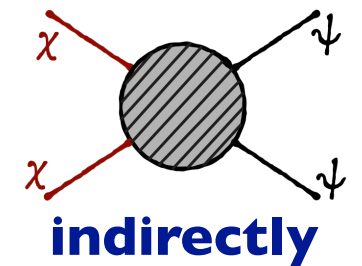
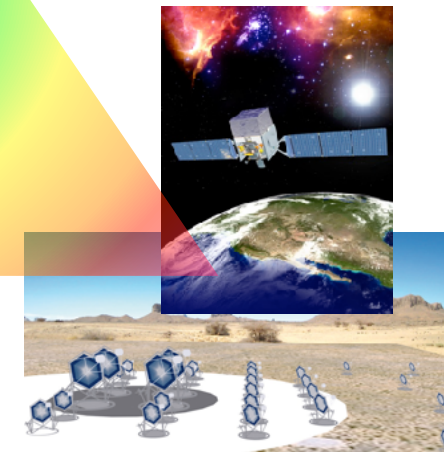
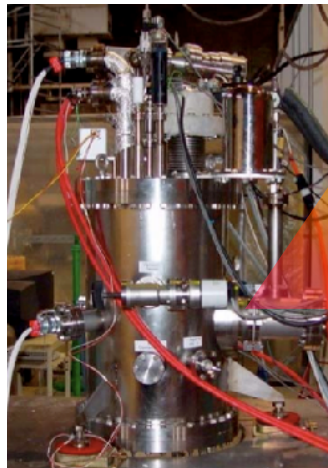
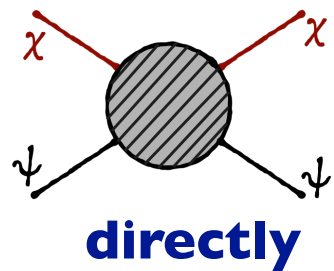
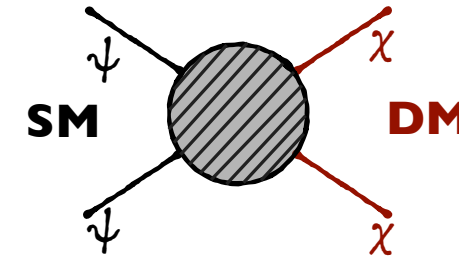
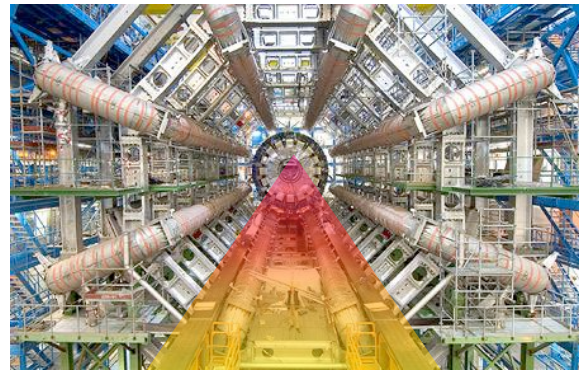
for weak-scale interactions

= a 'miracle' ?

WIMP DM is a *predictive* scenario

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

at colliders



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

Arcadi+, EPJC '18
Athron+, EPJC '21
(+ many more)

Beyond WIMPs

- Why should **dark** matter particles at all interact with **ordinary** matter?

- Very natural scenario: a **secluded dark sector** !

- Only well-known & well-studied concepts familiar from standard model

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Standard Model

- SM particles

$$\text{e.g. } U(1)_X \times \dots$$

Dark Sector

- Dark matter
- Dark radiation, ...
(‘sterile neutrinos’, ‘dark photons’, ...)

- A **nightmare scenario** ?

- Zero signals in traditional dark matter experiments!

Generic dark sector models

Standard Model

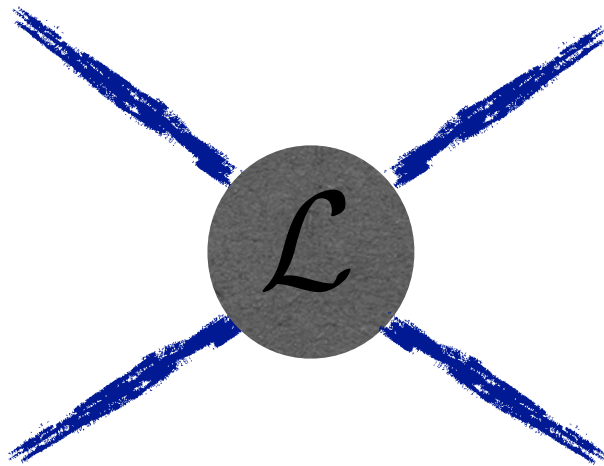
- SM particles

.....
e.g. $\mathcal{L}_{\text{Higgs}} \supset \kappa |\phi|^2 |\Theta|^2$

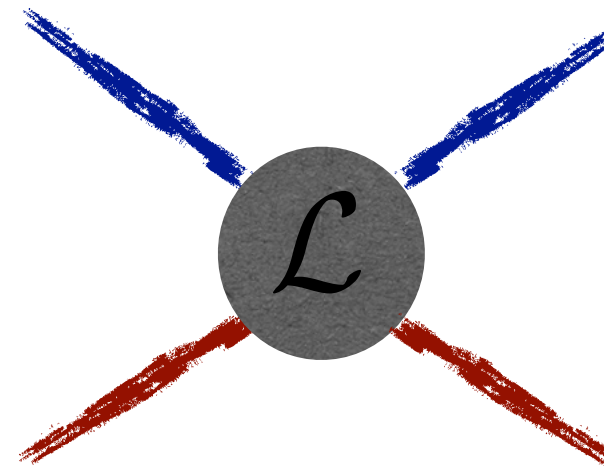
Dark Sector

- Dark matter, dark radiation, ...

- Even ‘invisible interactions’ can affect cosmological observables



- imprints on inner (sub-)halo structure



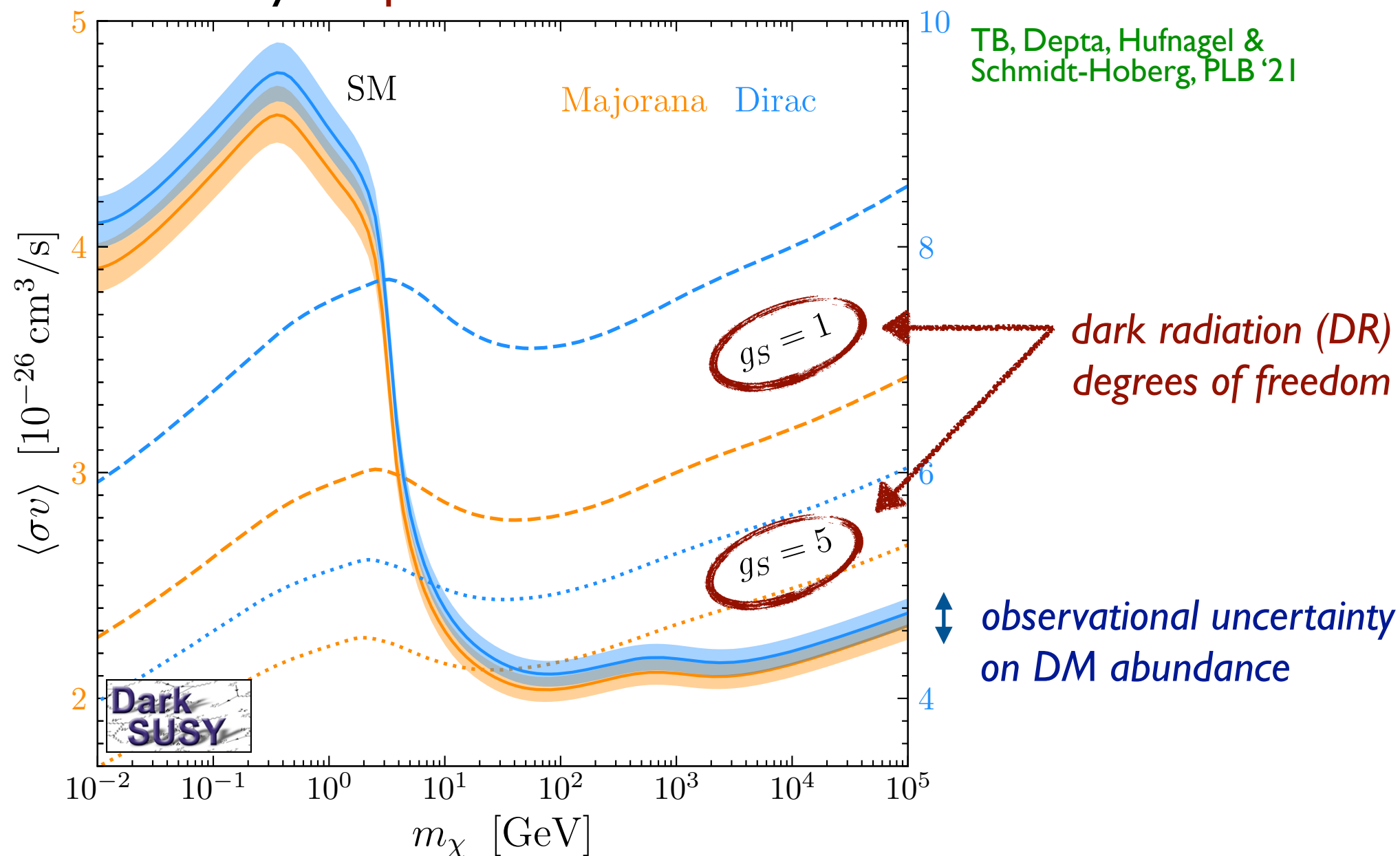
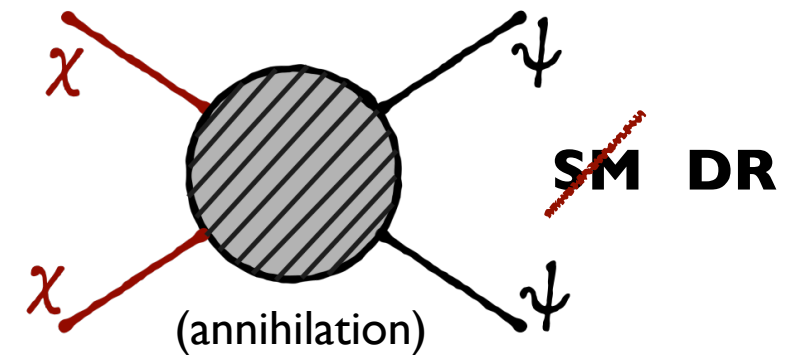
- imprints on power spectrum of matter density fluctuations

- ‘Portal’ couplings expected

- Likely strong enough to thermalize the DS at high temperatures...
- ...but no longer active at lower temperatures \Rightarrow well-defined $T_{\text{photon}} \neq T_{\text{dark}}$

Freeze-out of 'hidden' dark matter

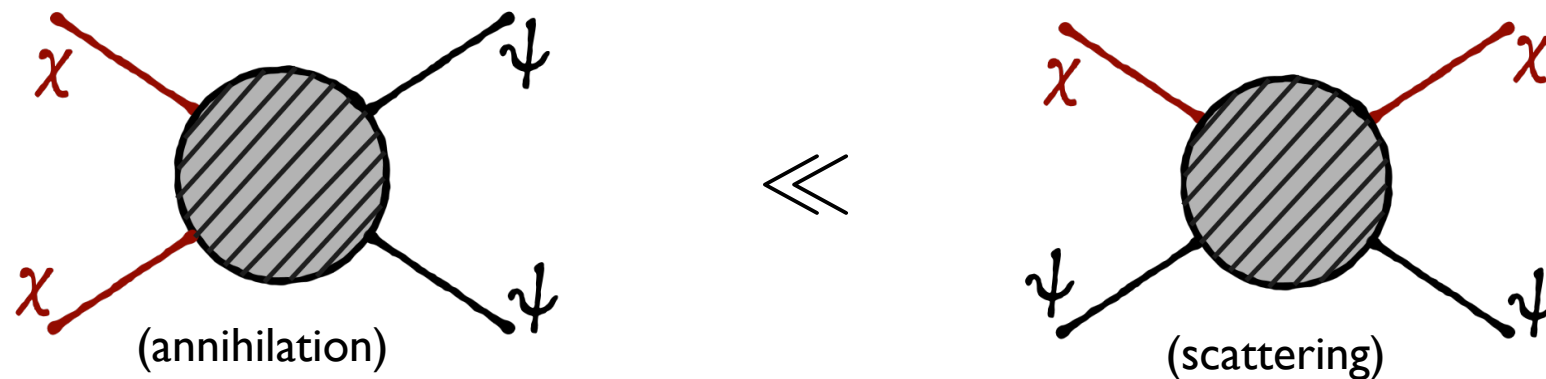
- Thermal production works equally well in fully decoupled dark sector
 - but details need to be implemented correctly for **precision treatment**



Freeze-out \neq decoupling !

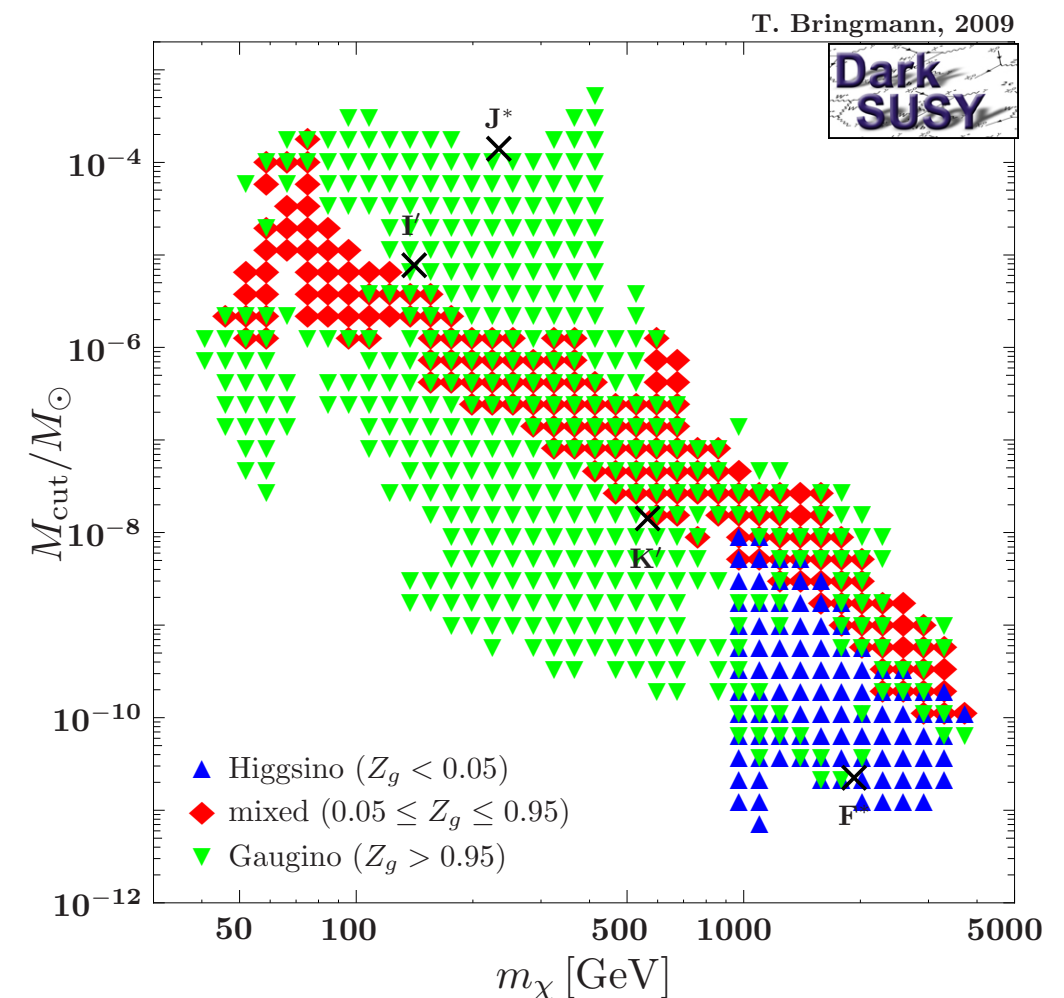
- Expect WIMPs (and similar DM particles) to stay much longer in **kinetic** than in chemical **equilibrium**:

Review: TB, NJP '09



- Density contrasts & cosmological structures can only grow after kinetic decoupling

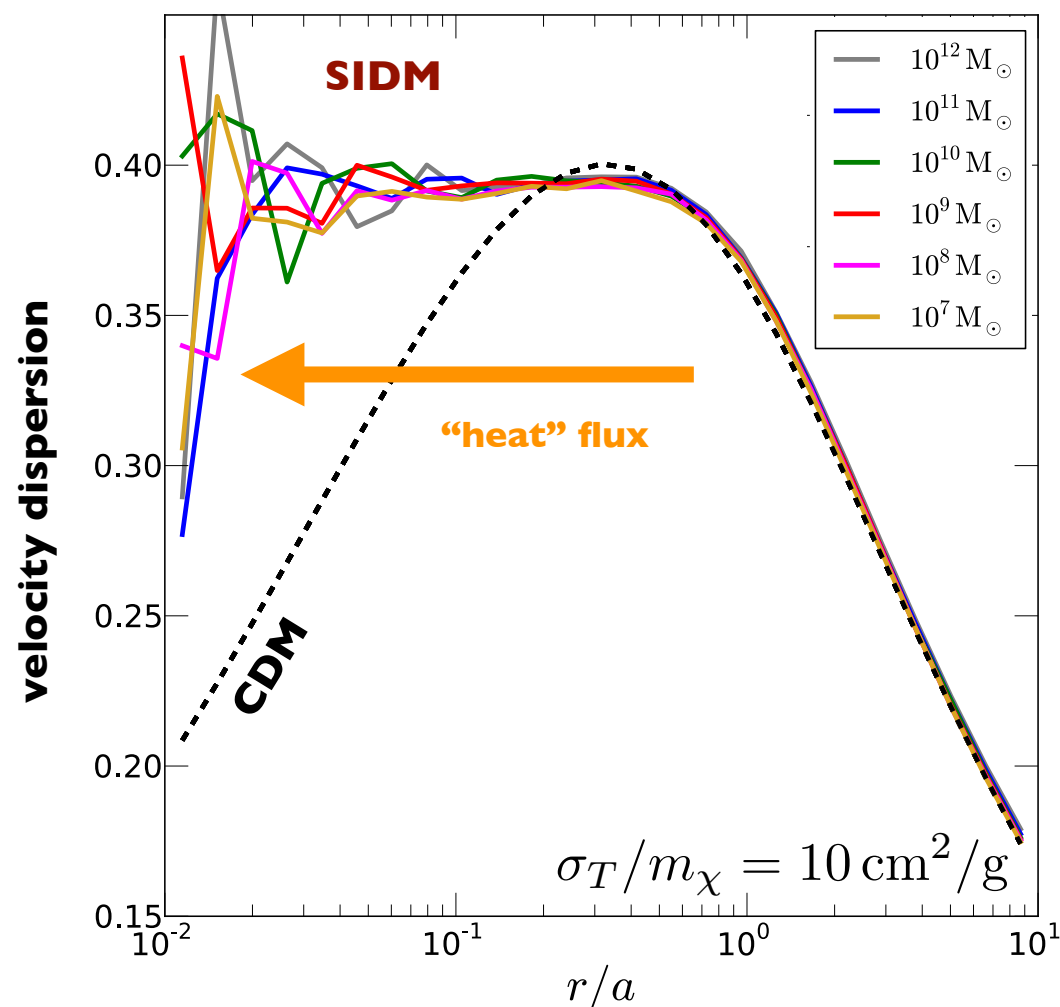
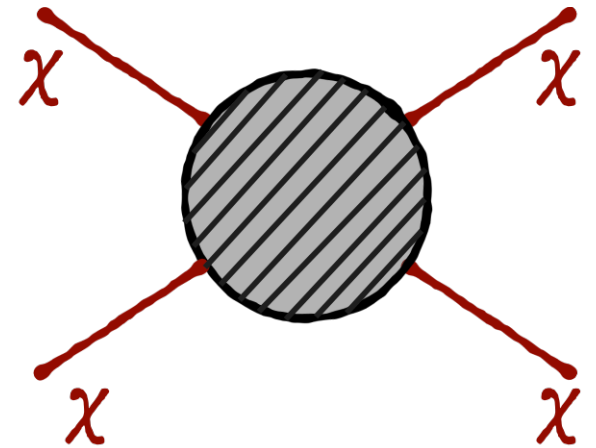
➔ Model-dependent
smallest proto-halo mass



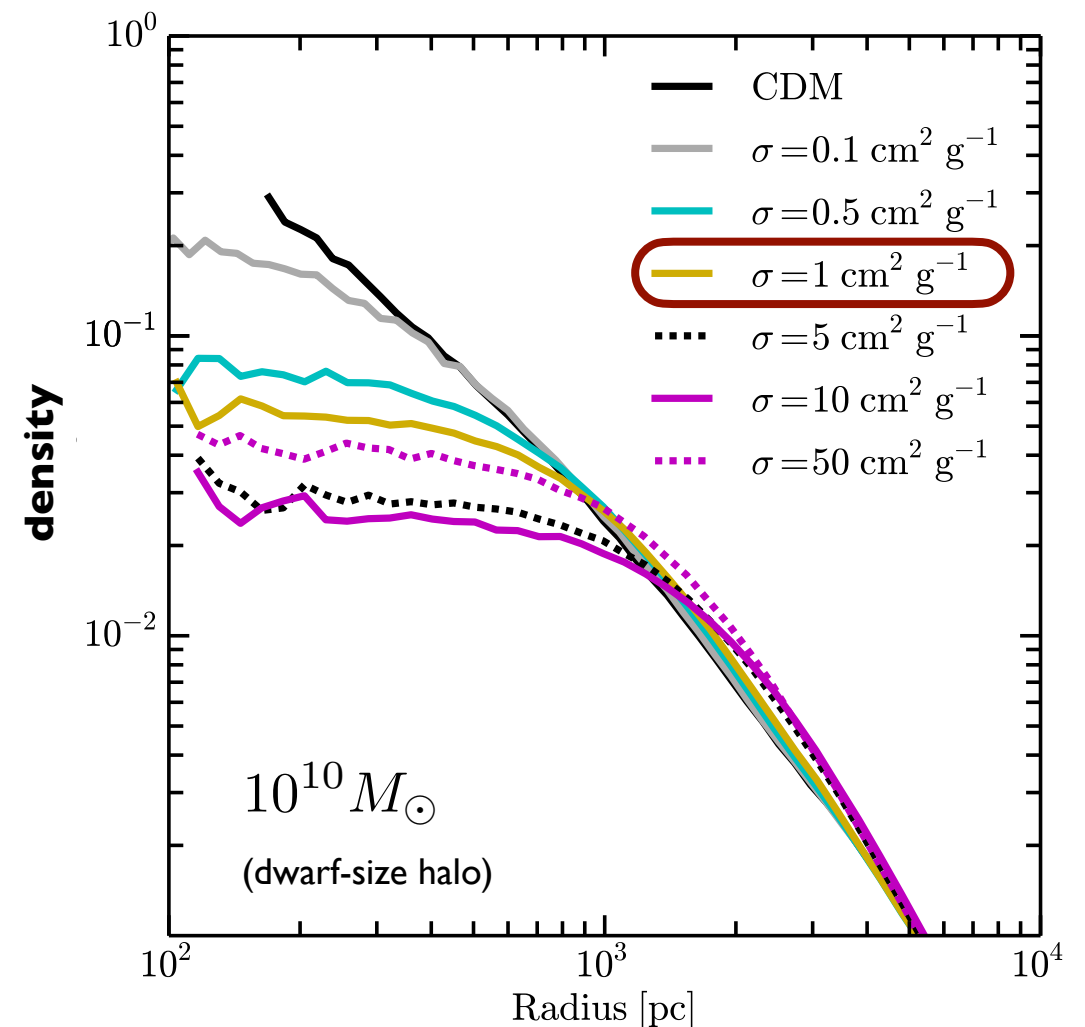
Self-interacting DM (SIDM)

DM-DM scatterings Spergel & Steinhardt, PRL '99

- often do not affect linear perturbations (number densities too small)
 - but **isotropise** DM distribution in inner parts of halo
- **core** formation once $\mathcal{O}(1)$ scatters per dynamical time

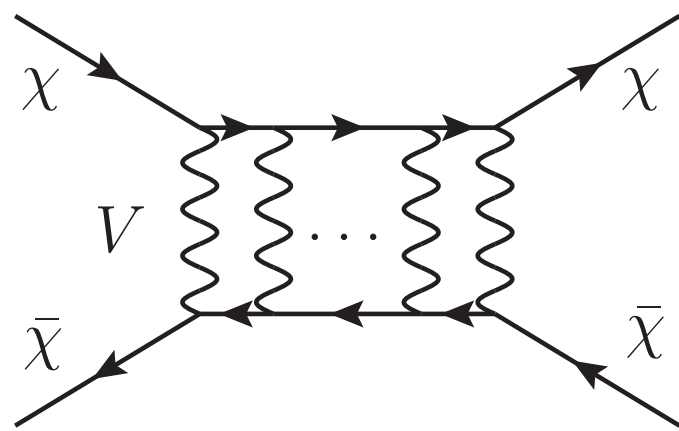


Vogelsberger, Zavala & Loeb, MNRAS '12



Elbert+, MNRAS '15

Effective Theory of Structure Formation



particle model

input:
masses, spins,
coupling constants



cosmological
simulations

input:
consistent initial
conditions, non-
gravitational forces
between “particles”



astrophysical
observables

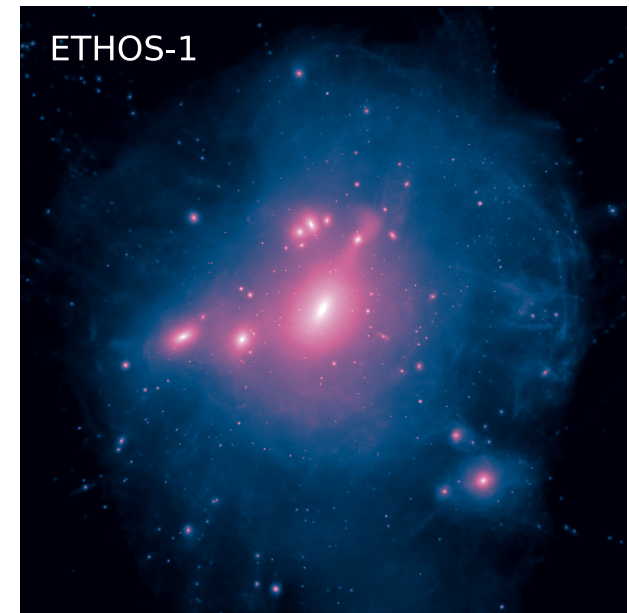
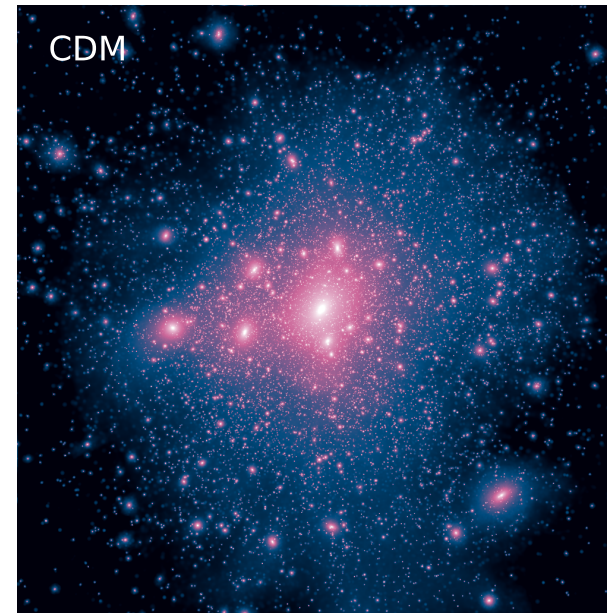
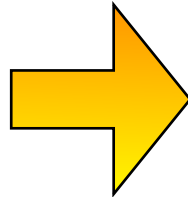
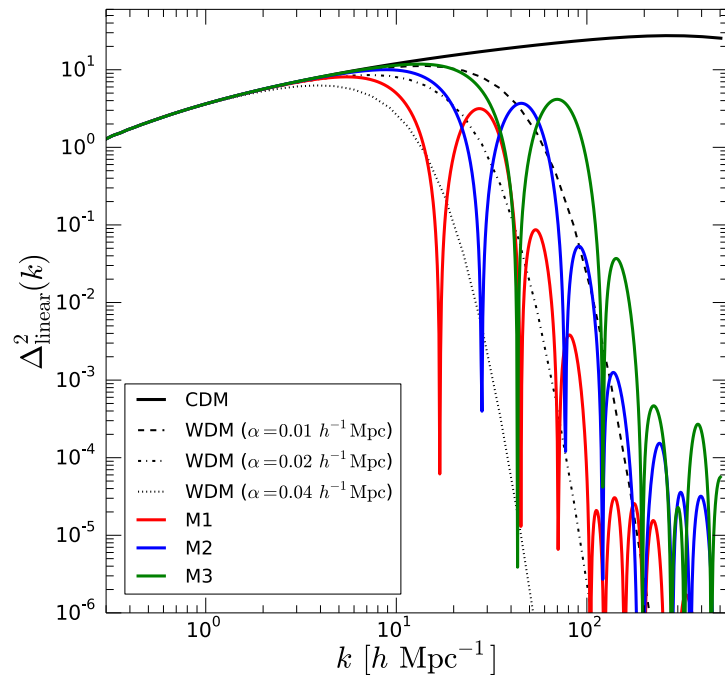
input
(for interpretation of data):
output from
simulations

- The first task can be **demanding**, the second in addition computationally very expensive
- But expect large degeneracies, so **very inefficient**...
- **Idea of ETHOS**: identify **effective parameters** and provide **maps** for each of those steps (\leadsto no need to re-compute each model!)

Cyr-Racine+, PRD'16; Vogelsberger+, MNRAS '16

Late kinetic decoupling

- Four benchmarks examples: Vogelsberger+, MNRAS'16



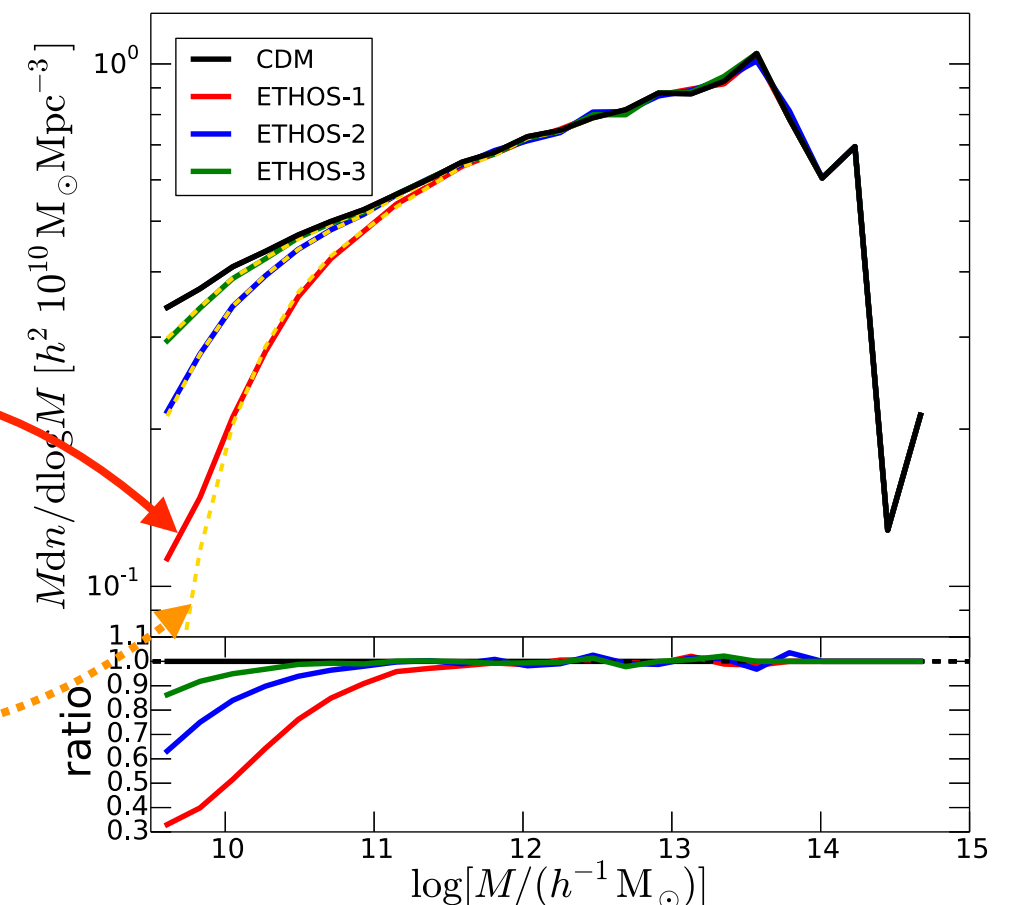
- Almost identical suppression of halo mass function **as for WDM** cosmology:

$$M_{\text{cut,kd}} = 5 \cdot 10^{10} \left(\frac{T_{\text{kd}}}{100 \text{ eV}} \right)^{-3} h^{-1} M_{\odot}$$

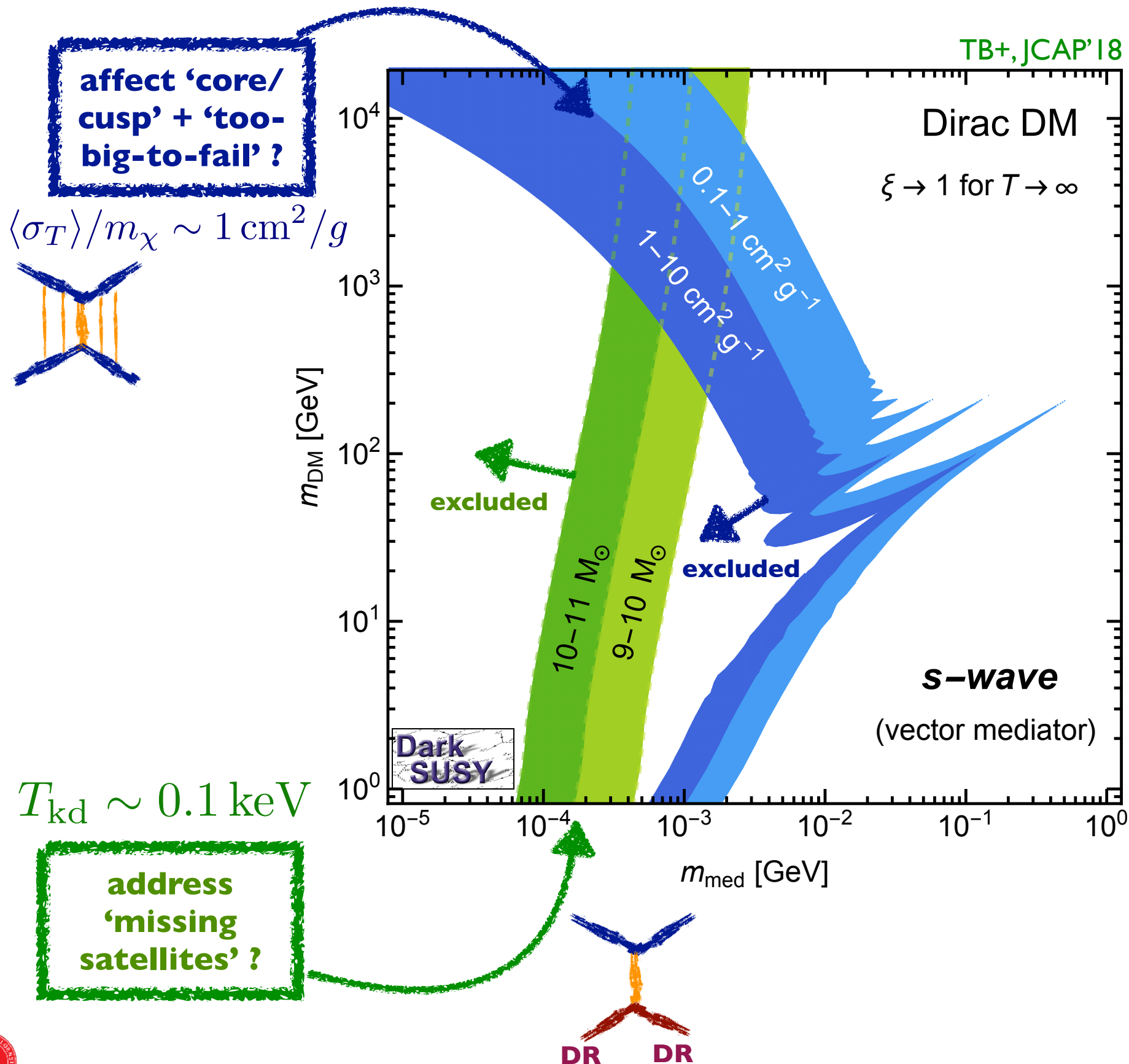
[solid lines; NB: up to factor ~2 same as analytic estimate!]

$$M_{\text{cut,WDM}} = 10^{11} \left(\frac{m_{\text{WDM}}}{\text{keV}} \right)^{-4} h^{-1} M_{\odot}$$

[dashed lines; would-be result from WDM free-streaming]

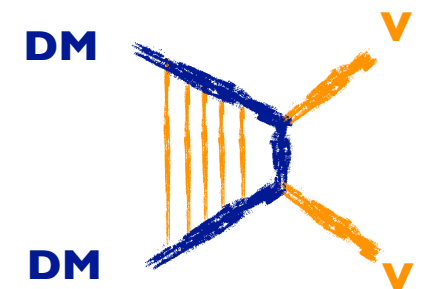


Full parameter scan



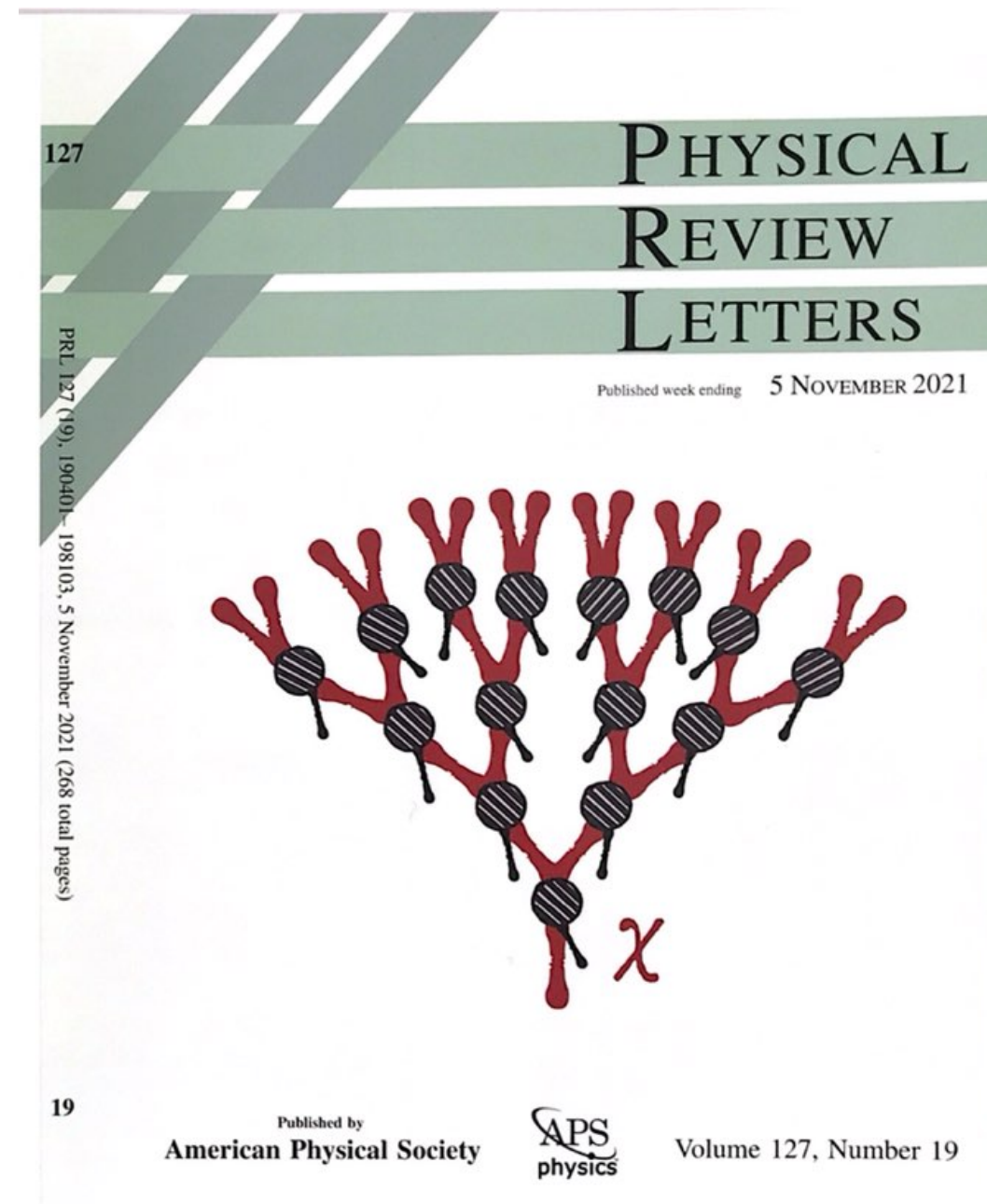
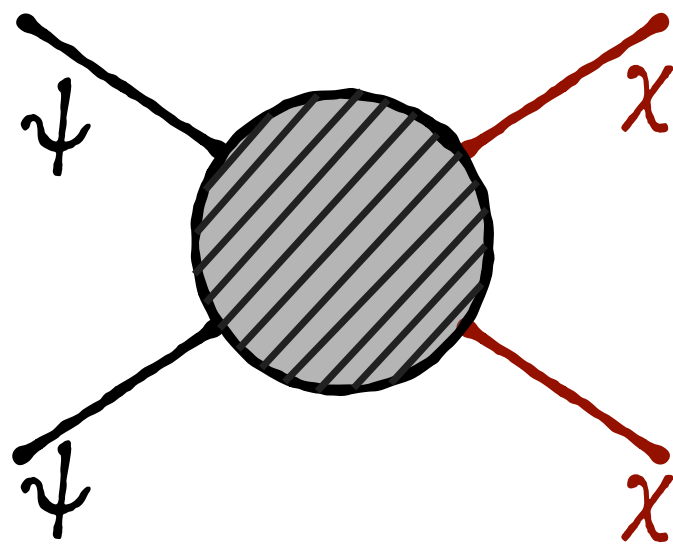
Consider simple dark sector model with massive mediator

coupling fixed by thermal relic density



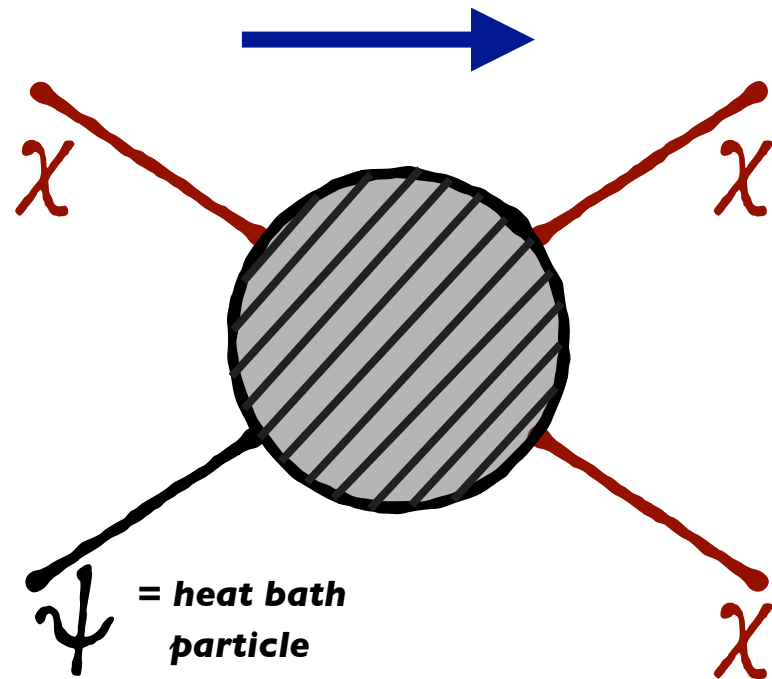
The origin of dark matter

- Any convincing model for dark matter must include a **production mechanism** that can explain the observed abundance!
- Are $2 \rightarrow 2$ interactions the only option to produce the observed dark matter abundance?



A new production mechanism

• ‘Pandemic’ dark matter



TB, Depta, Hufnagel, Rudermann
& Schmidt-Hoberg, PRL '21
Hryczuk & Laletin, JHEP '21

$$\dot{n}_\chi + 3H n_\chi = n_\chi n_\psi^{\text{eq}} \langle \sigma v \rangle$$

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

• 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 = tot - S - I

β **infection rate**

γ **recovery rate**

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

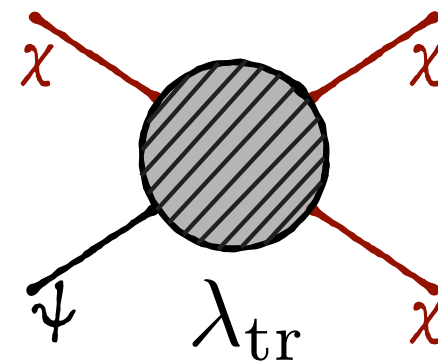
➔ **reproduction number, or ‘R-value’:**

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

Adding freeze-in production

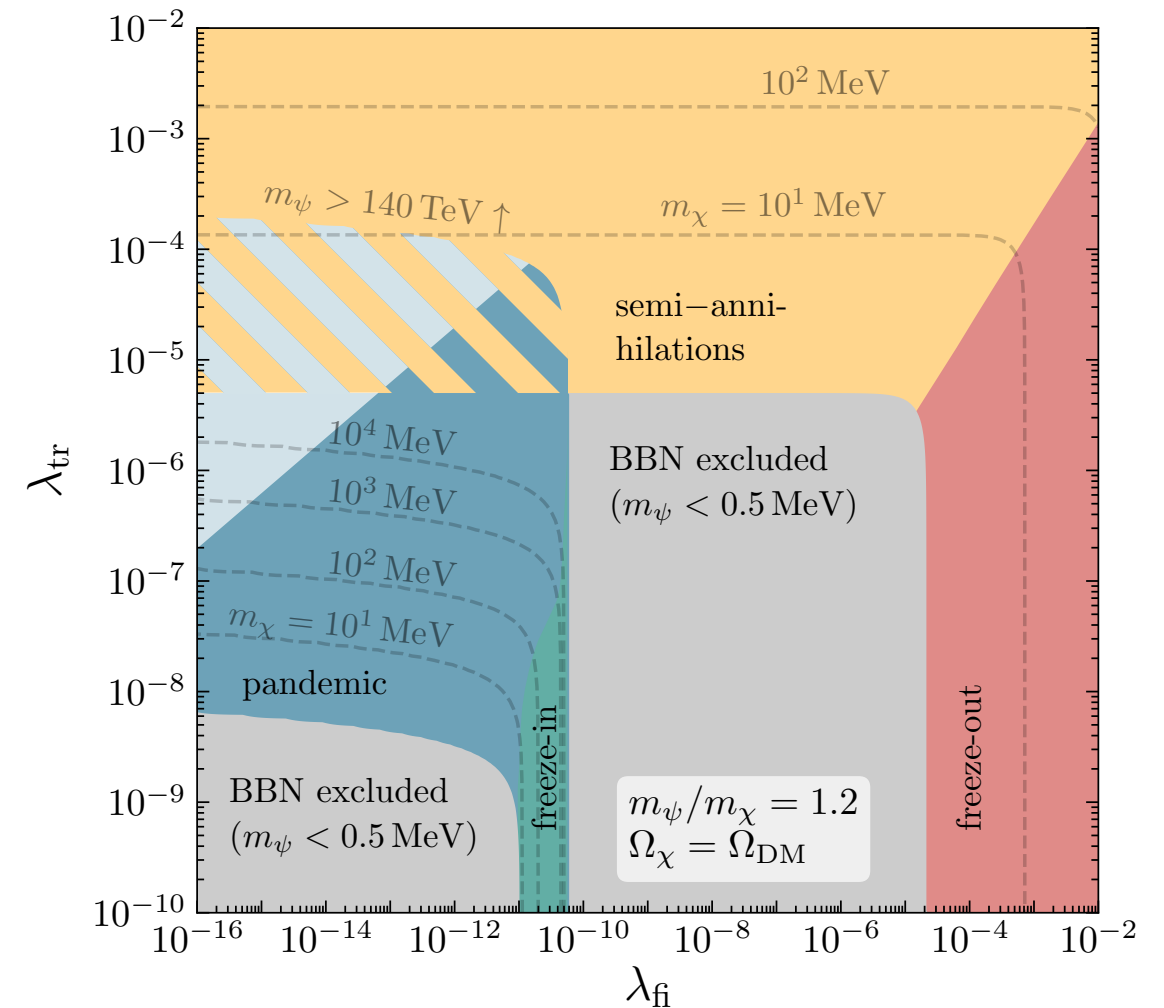
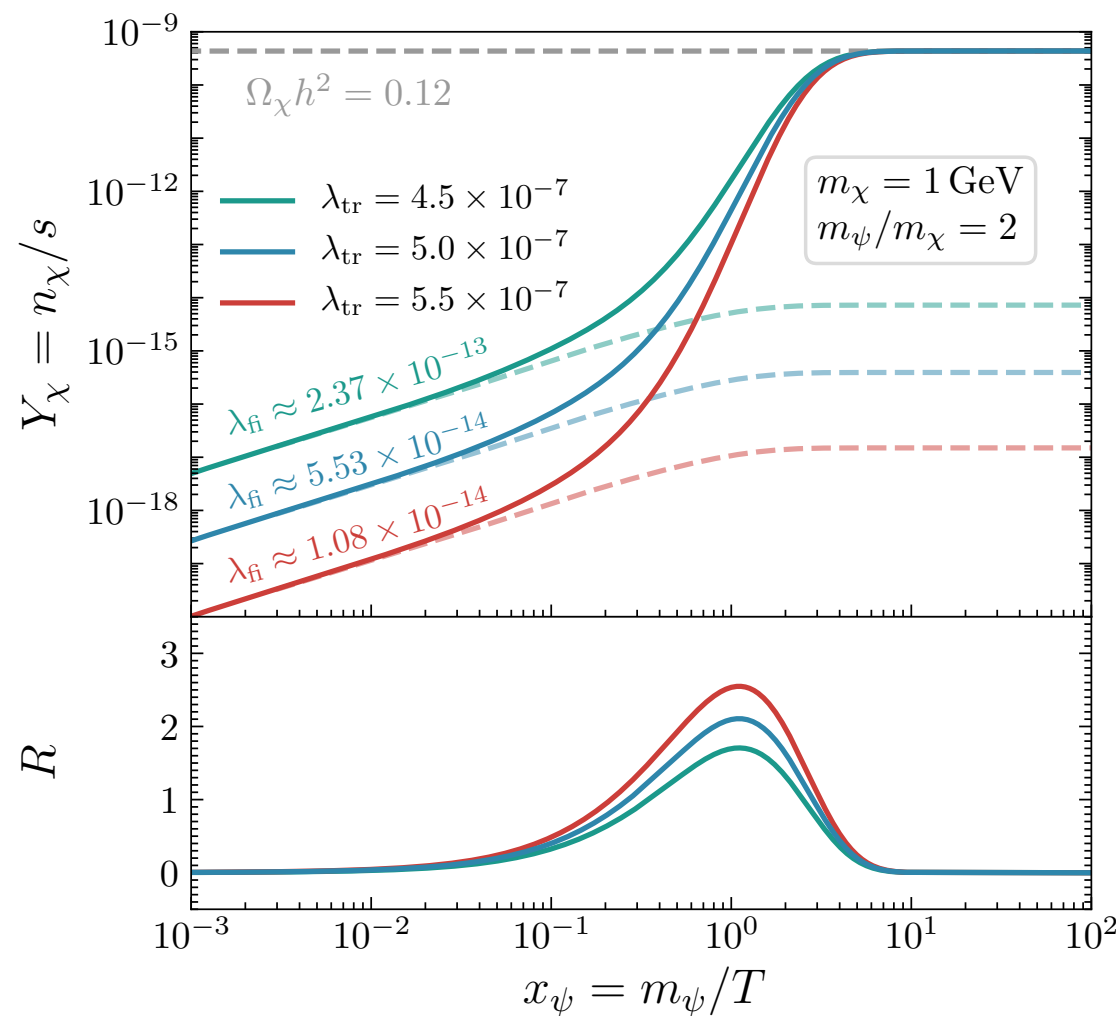
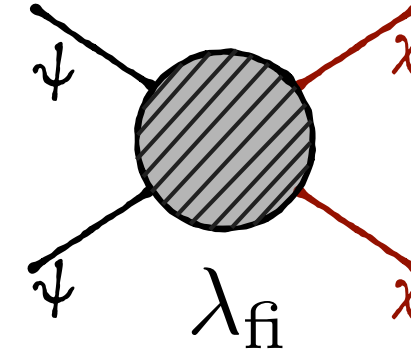
TB, Depta, Hufnagel, Rudermann
& Schmidt-Hoberg, PRL '22

‘transmission’



+

‘standard 2→2’



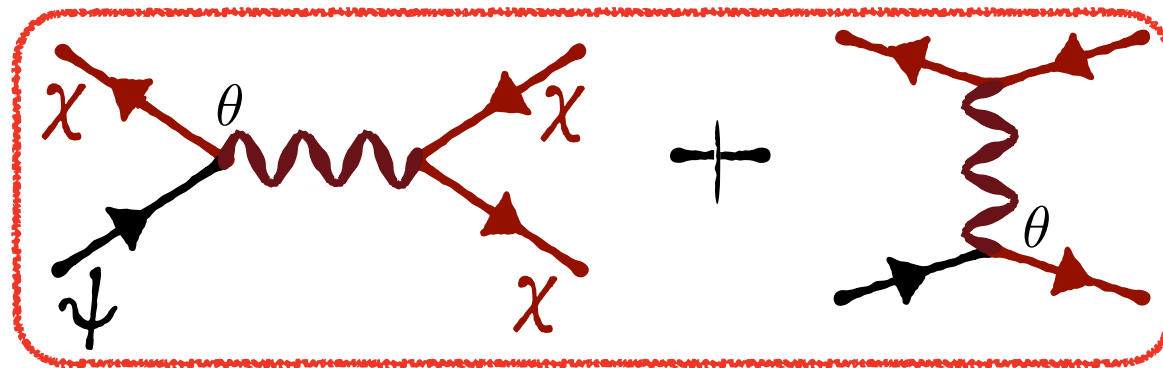
➔ ‘Pandemic’ production is a very **generic mechanism** for the genesis of DM!

Signals ?

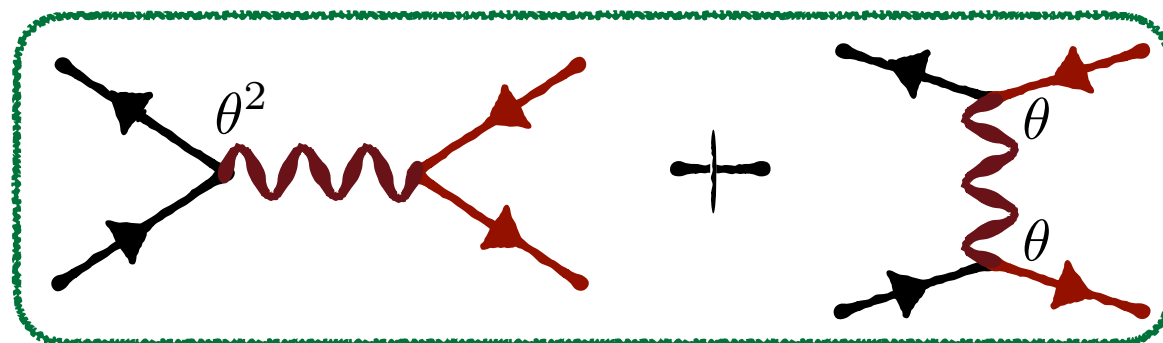
- Necessarily model-dependent
 - ‘**Pandemic DM**’ describes a **class** of models, just like ‘WIMP’ does
- Q: Is there a *generic* way to get larger ‘transmission’ rates than conventional $2 \rightarrow 2$ rates ?
- A: yes — just add a **dark sector mediator** and **mass mixing**!

$$\mathcal{L} \supset -\delta m (\bar{\psi}\chi + \bar{\chi}\psi) - g\bar{\chi}\tilde{V}\chi$$

→ tiny mixing angle θ



transmission $\propto \theta$



standard $2 \rightarrow 2$ $\propto \theta^2$

Sterile neutrinos



- A **right-handed** neutrino would be **neutral** under *all* SM gauge forces

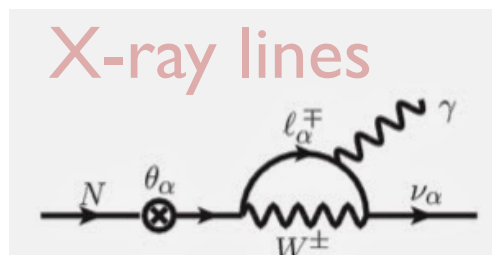
- An **excellent**, well-motivated dark matter **candidate**

- Production by** SM processes

- oscillations with active neutrinos, combined with (electroweak) scatterings

Dodelson & Widrow, PRL '94

- Unfortunately, this scenario is **ruled out** by observations...



SM fermions

mass →	2.4 MeV	1.27 GeV	171.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
name →	u up	c charm	t top
	Left Right	Left Right	Left Right
	4.8 MeV	104 MeV	4.2 GeV
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	d down	s strange	b bottom
	Left Right	Left Right	Left Right
Quarks			
	0 eV	0 eV	0 eV
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	Left Right	Left Right	Left Right
	0.511 MeV	105.7 MeV	1.777 GeV
	-1	-1	-1
	e electron	μ muon	τ tau
	Left Right	Left Right	Left Right
Leptons			

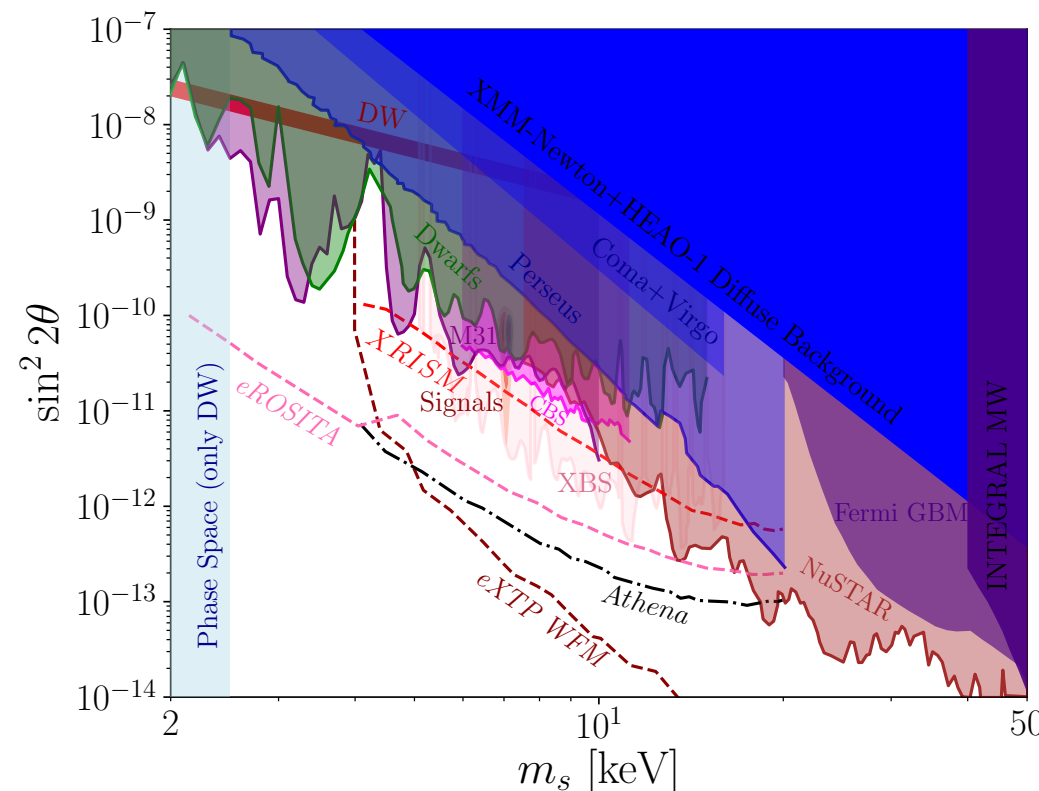


Fig.: Abazajian+, 2203.7377

Interacting sterile neutrinos

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, PRD '23

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

$$\mathcal{L} \supset \frac{y}{2} \phi \bar{\nu}_s \nu_s \quad m_\phi > 2m_s$$

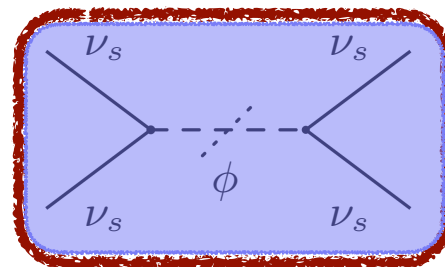
- Early times (\sim QCD PT): standard **DW** production

- Evolution afterwards:

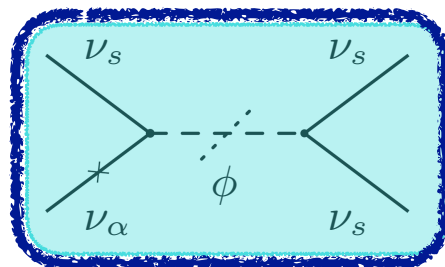
solid: benchmark point with large θ , small y

dashed: benchmark point with small θ , large y

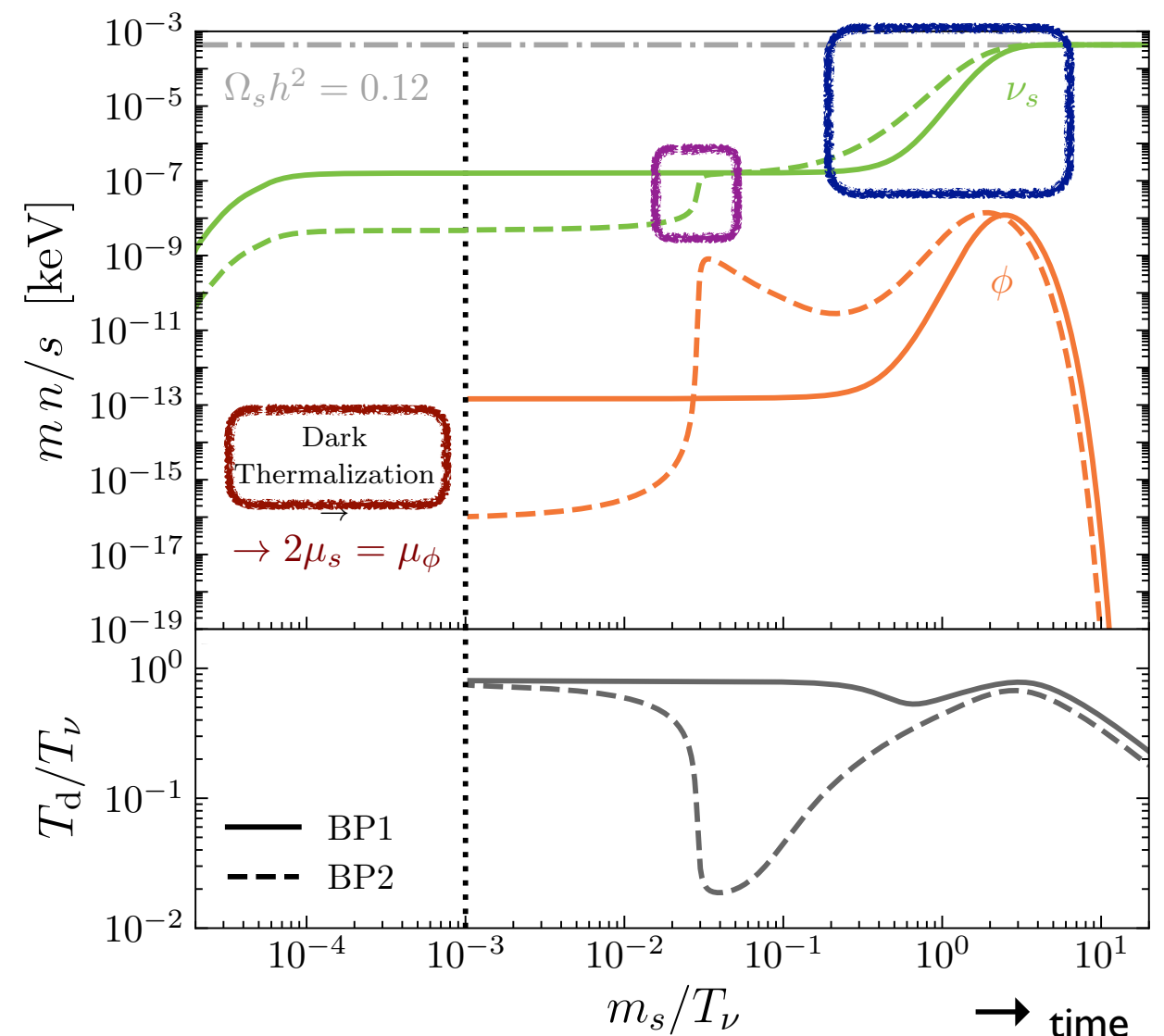
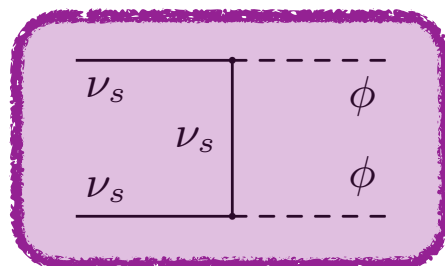
- Thermalization**
in dark sector



- Exponential growth**



- Reproductive freeze-in**

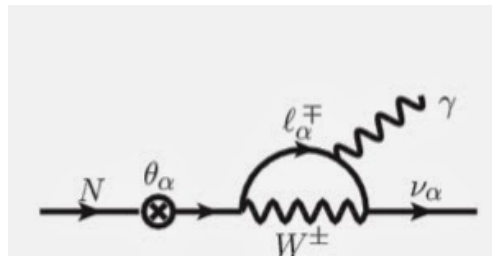


Sterile neutrinos... revived !

TB, Depta, Hufnagel, Kersten, Ruderman & Schmidt-Hoberg, PRD '23

Observational constraints

(Standard) X-ray lines



ν_s self-interactions

$$\sigma_T / m_s \lesssim 1 \text{ cm}^2 / \text{g} \quad \text{cf. Tulin \& Yu, PR '18}$$

maybe 0.1 possible... (?)

Lyman- α (small-scale structure)

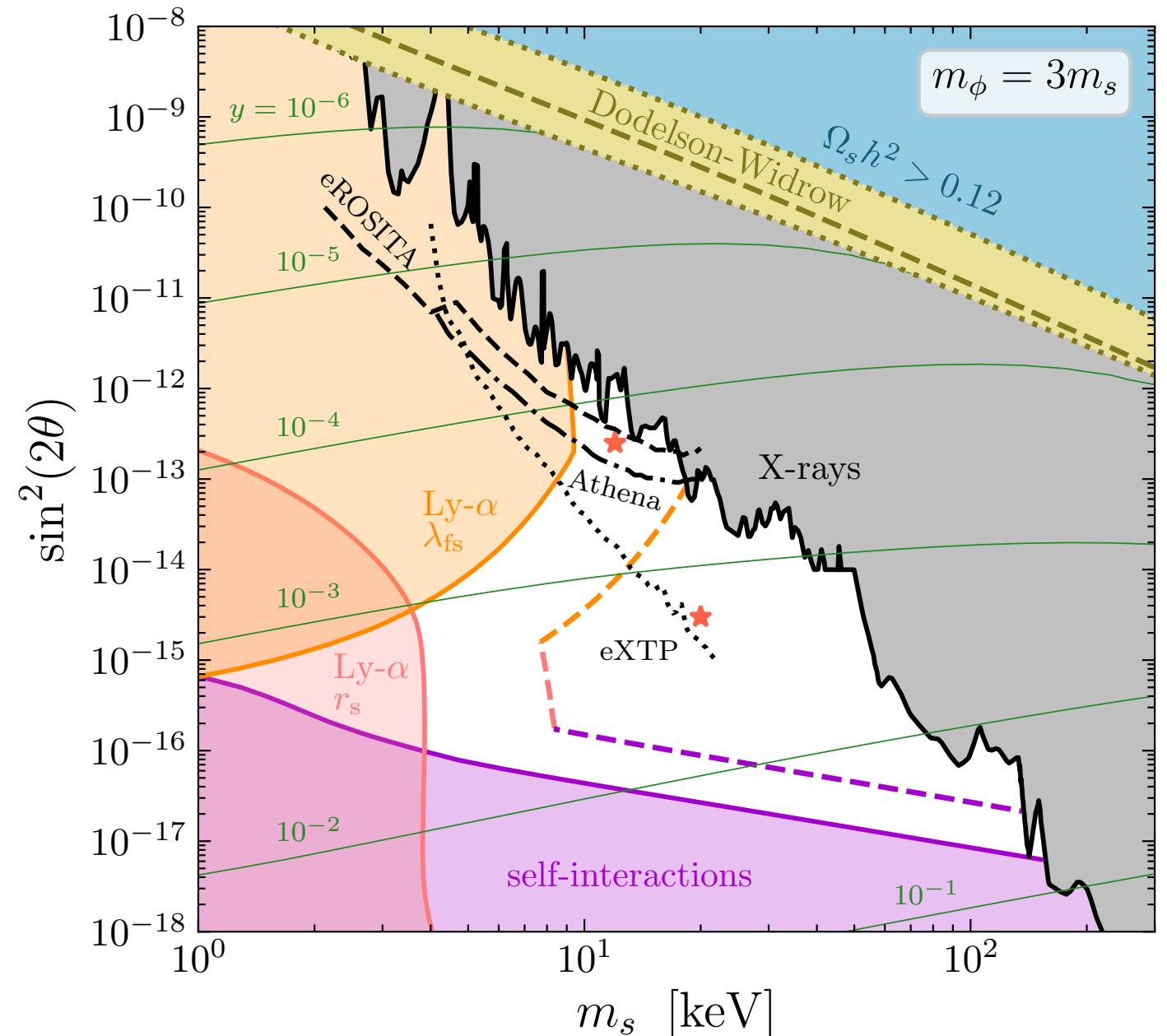
recast $m_{\text{WDM}} > 1.9 \text{ keV}$ to
Garzilli+, MNRAS '21

$$\lambda_{\text{FS}} < 0.24 \text{ Mpc}$$

$$r_s < 0.36 \text{ Mpc}$$

maybe $m_{\text{WDM}} > 5.3 \text{ keV}$ possible... (?)

Palanque-Delabrouille+, JCAP '20



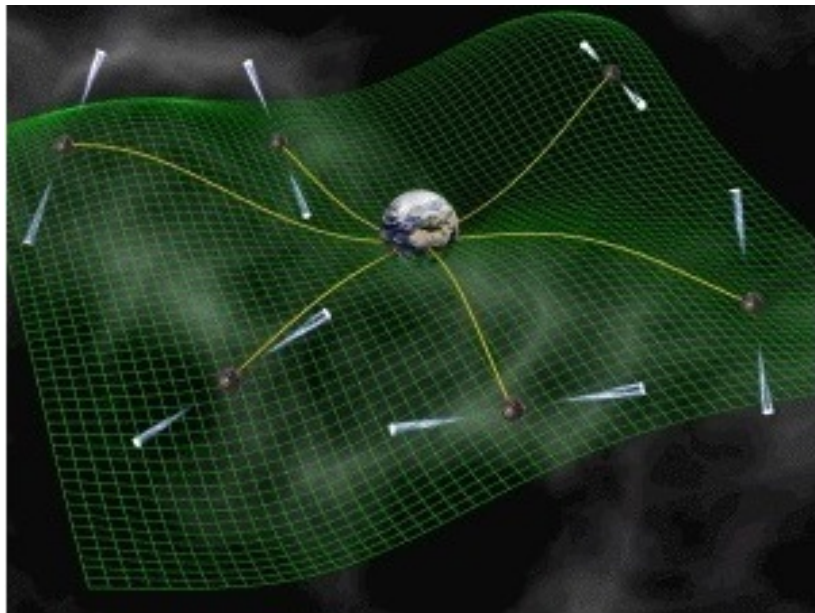
New parameter space

Bounded from above and below

Significant parts in **observational reach**

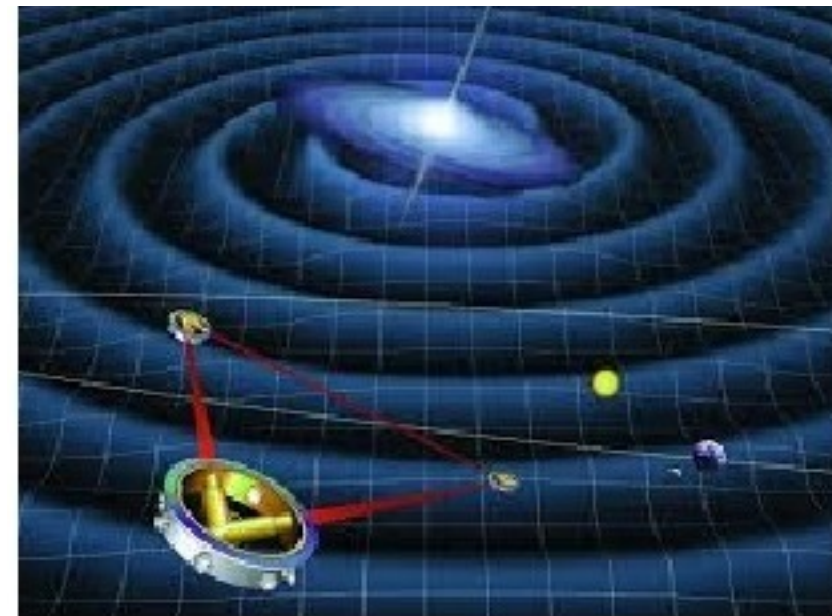
Gravitational wave signals

- Many individual merger events seen by LIGO/Virgo/KAGRA
 - BH/BH, BH/NS, NS/NS
- *Cosmological* signals are just as exciting



Picture: D. Chamion, MPI

- Stochastic GW background at **nHz** frequencies **observed** by pulsar timing arrays



Picture: NASA

- The **LISA** mission is now fully approved, and will target **mHz** frequencies

➔ *Yet another ‘dark’ way of probing new physics!*

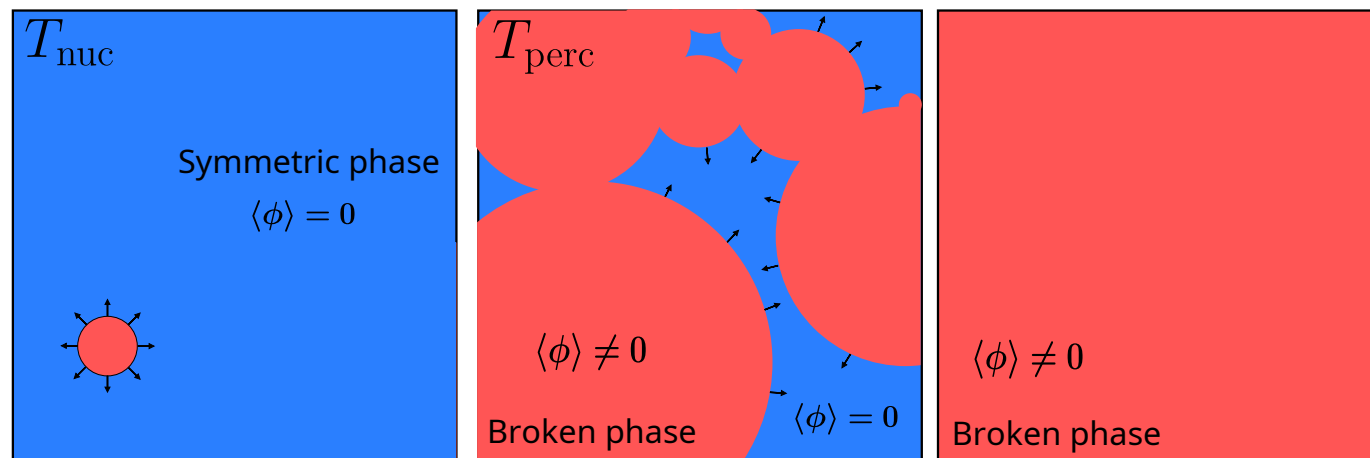
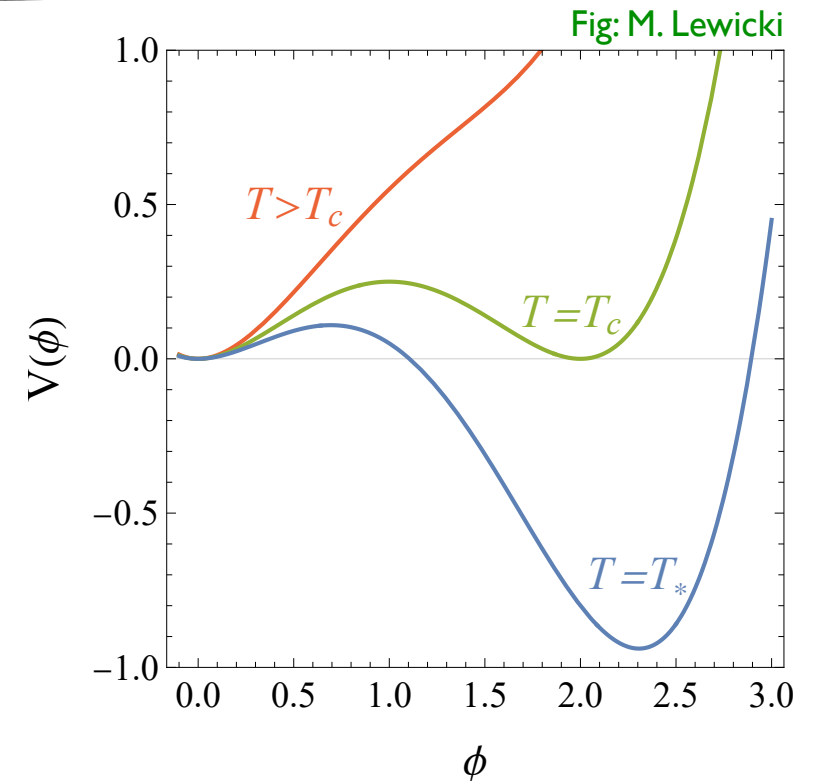
Cosmological phase transitions

- GW signal requires **first-order transition**

- Not in the standard model: new physics... !

- Triggered by temperature corrections to the potential

$$V(\phi, T) = \frac{g_m^2}{24} (T^2 - T_0^2) \phi^2 - \frac{g_m}{12\pi} T \phi^3 + \lambda \phi^4$$



J. Matuszak, '23

- Bubbles of new vacuum phase

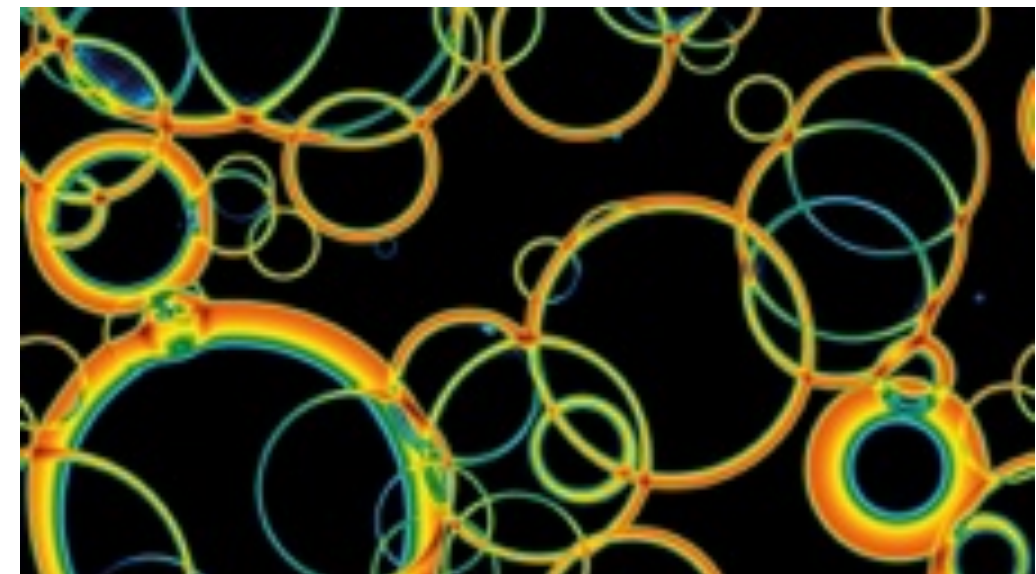
- **nucleate** spontaneously

- quickly expand and **percolate**

- Need **numerical simulations**

- highly non-linear dynamics

- GWs produced through bubble wall collisions, sound waves and plasma turbulence



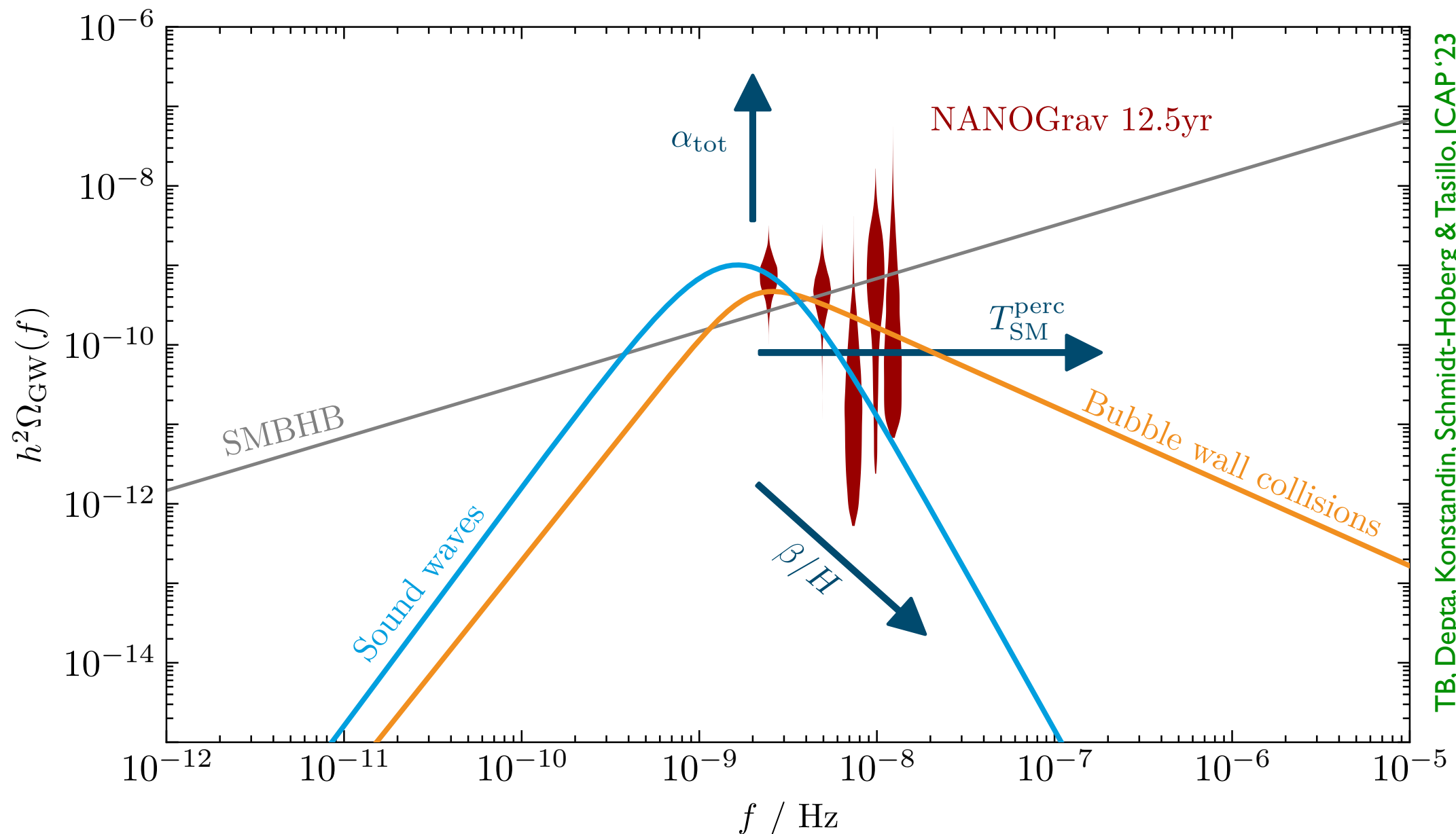
Resulting GW spectrum

Main phenomenological parameters:

- nucleation/percolation temperature T
- PT strength α
- Characteristic scale β (inverse time)

$$\alpha \approx \frac{\Delta V}{\rho_R} \gg 1$$

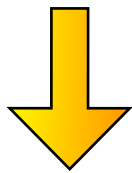
$$\Gamma \propto e^{-\frac{S_3(T)}{T}} = e^{\beta(t-t_0)} \implies \frac{\beta}{H} = T \frac{d}{dT} \left(\frac{S_3(T)}{T} \right) \Big|_{T=T_p}$$



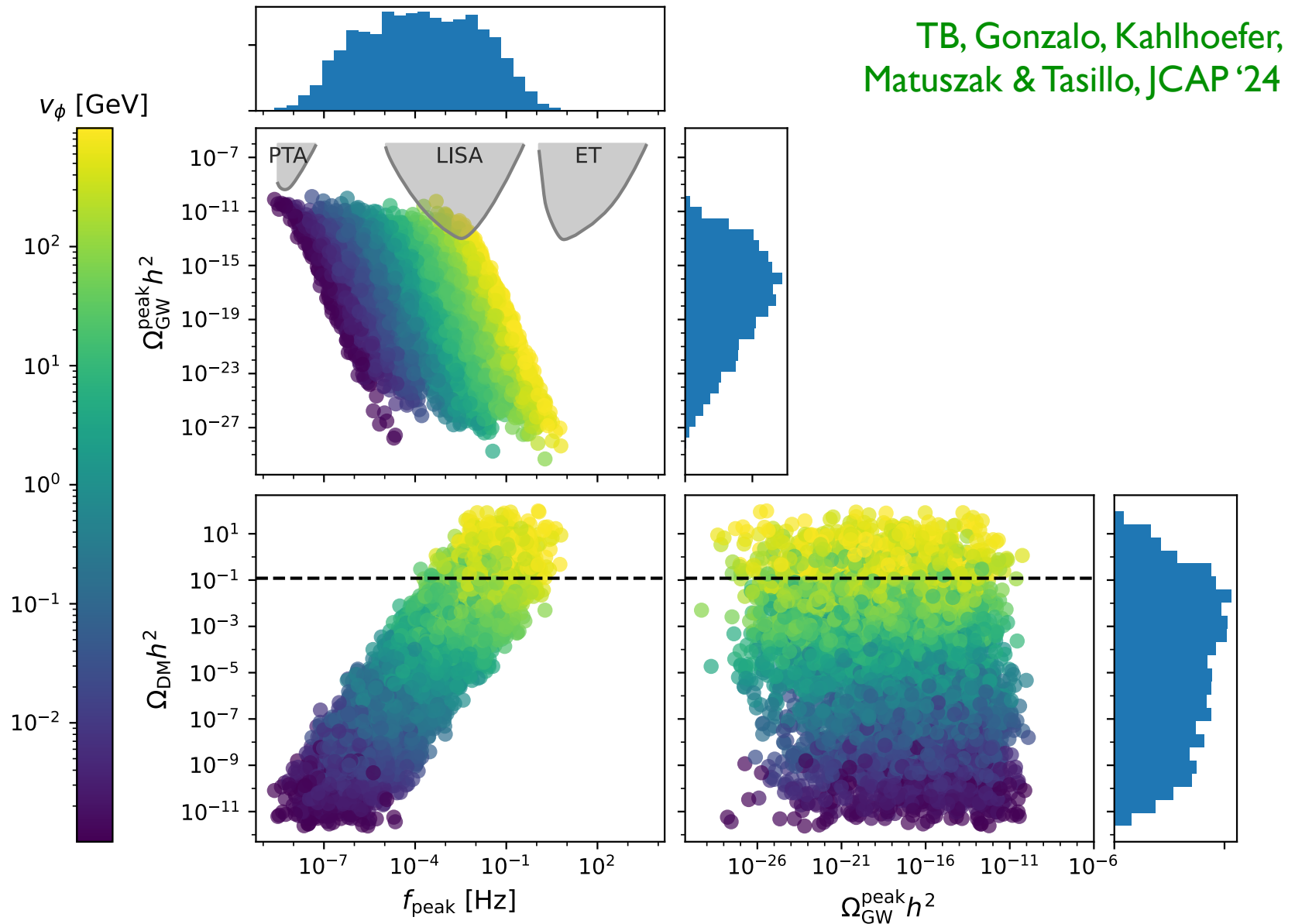
TB, Depta, Konstantin, Schmidt-Hoberg & Tasillo, JCAP '23

A LISA miracle ?

- 🏆 Ordinary matter acquired mass in EW phase transition
 - 🕒 aka Higgs mechanism
- 🏆 What if dark matter acquired mass in dark phase transition ?
 - 🕒 'dark Higgs' mechanism

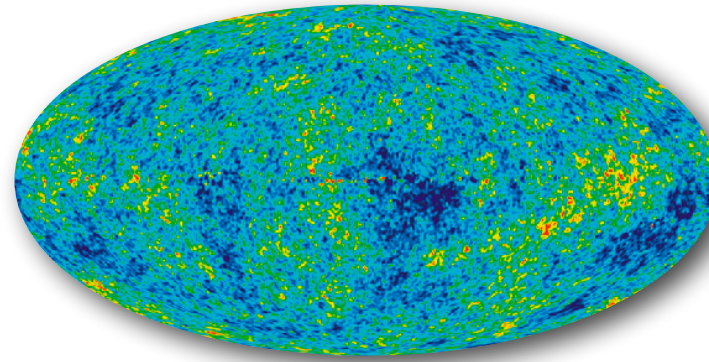
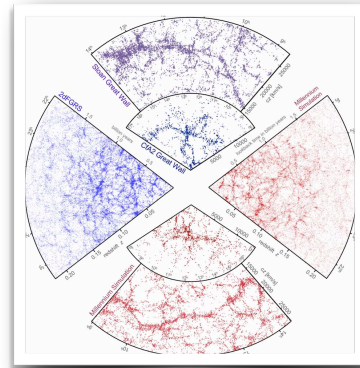
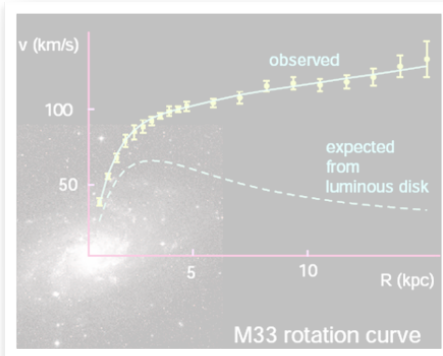


- dark matter can be produced via thermal freeze-out in dark sector
- Striking correlation between GW peak frequency and DM abundance

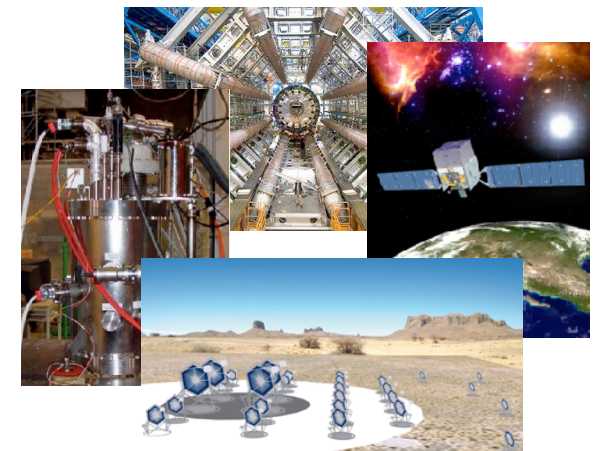
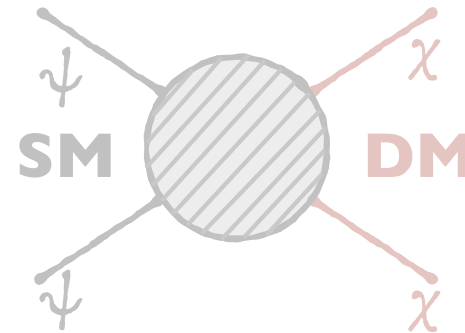


Conclusions

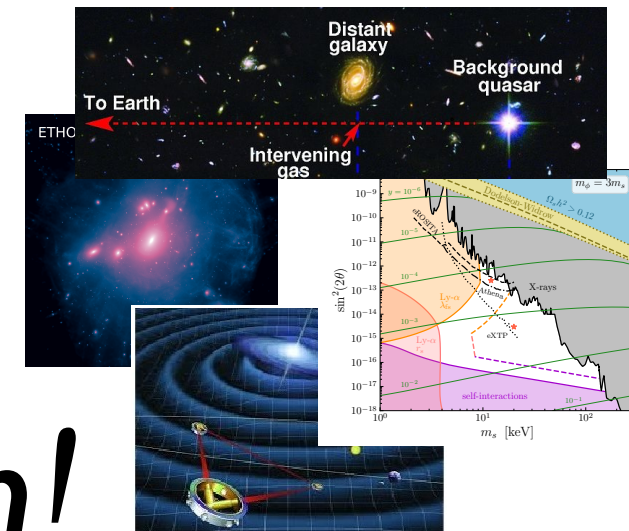
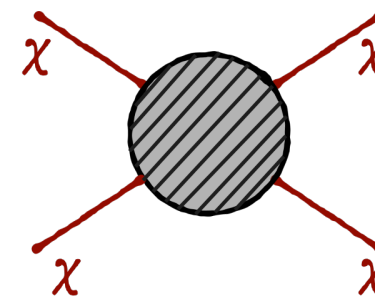
- Dark matter = **evidence** for new physics



- Detection *may* be **impossible** with traditional approaches...



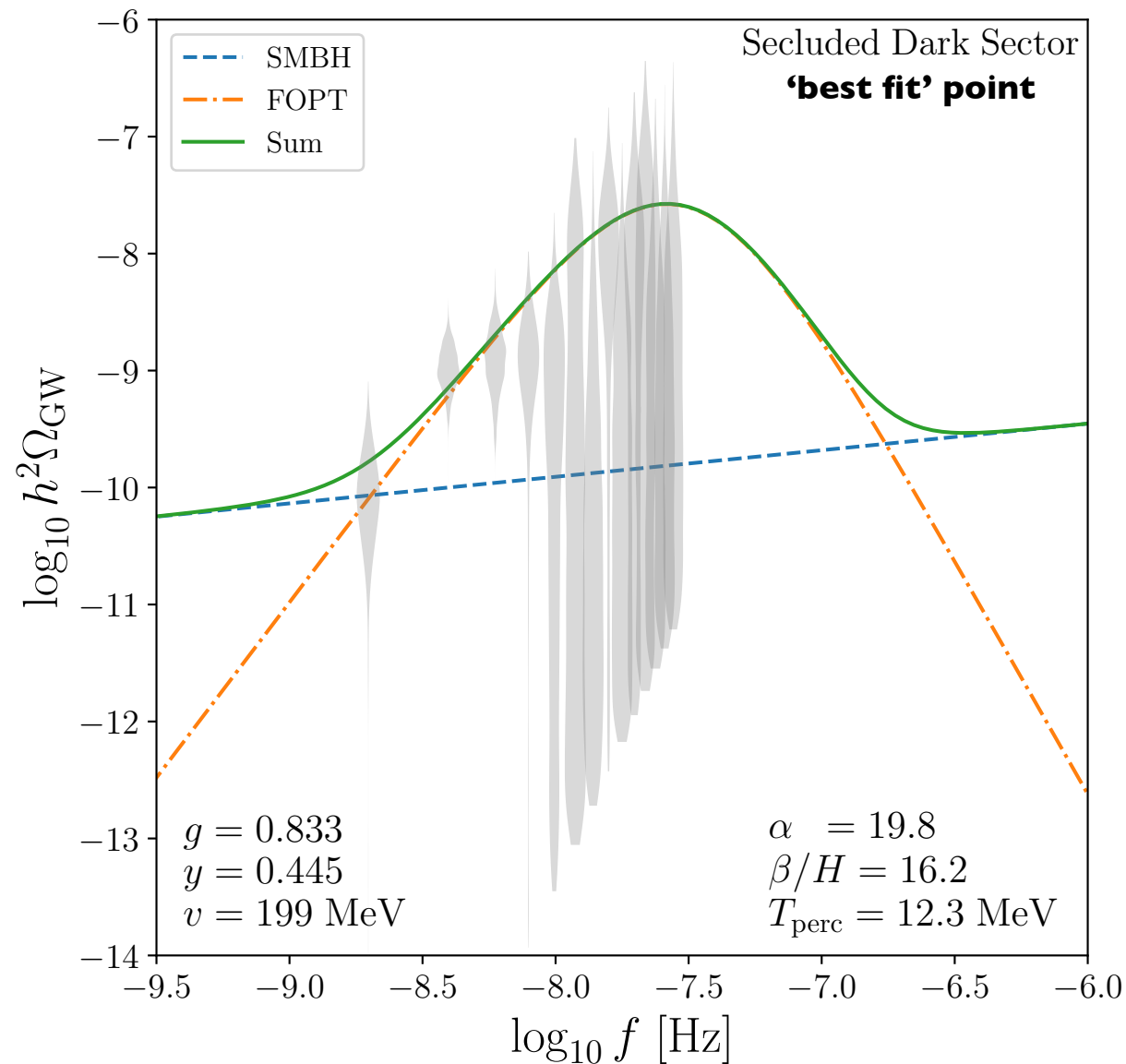
- ...but this is not our only chance
- can use the entire **cosmos as laboratory** to probe truly 'hidden' (and quite reasonable!) models



Thanks for your attention!

Global fit results

Balan, TB, Kahlhoefer, Matuszak & Tasillo, 2502.19478



- **Loud PT** on top of astrophysical SMBH merger signal
 - addresses issues with signal slope and normalization
- **100%** of observed **dark matter**
 - NB: $\langle \sigma v \rangle_{\chi\chi \rightarrow \phi\phi}$ strongly suppressed by $m_\chi < m_\phi$
- Satisfies constraints from BBN, CMB, Bullet cluster, (in)direct searches



- **Testable prediction** for **DMX**:

$$m'_A = 100 - 200 \text{ MeV}$$

$$\kappa \simeq 10^{-4}$$

