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DARK MATTER AND THE H_0 TENSION

Andrzej Hryczuk

NARODOWE CENTRUM BADAŃ JĄDROWYCH ŚWIERK

based on:

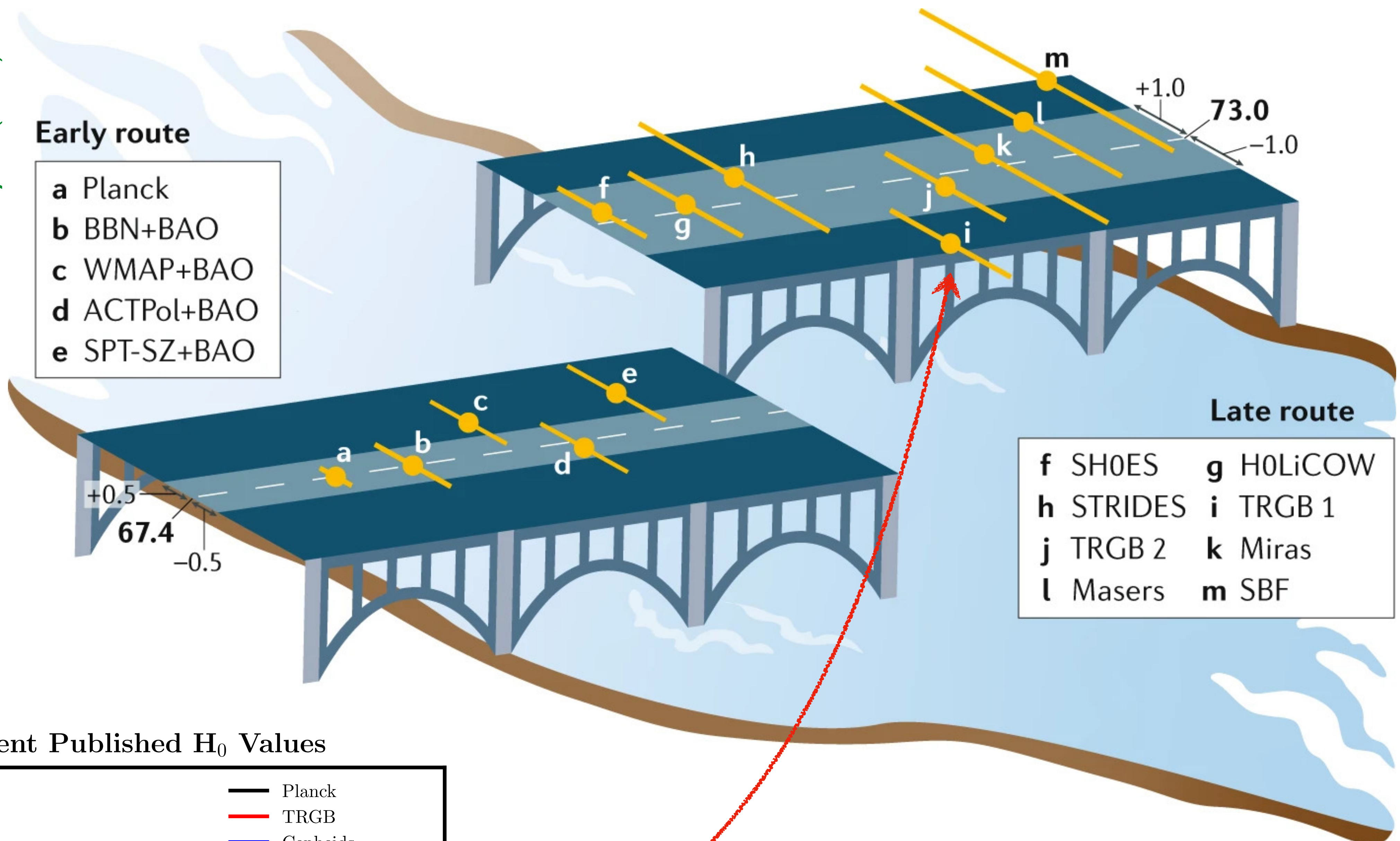
AH, K. Jodłowski 2006.16139

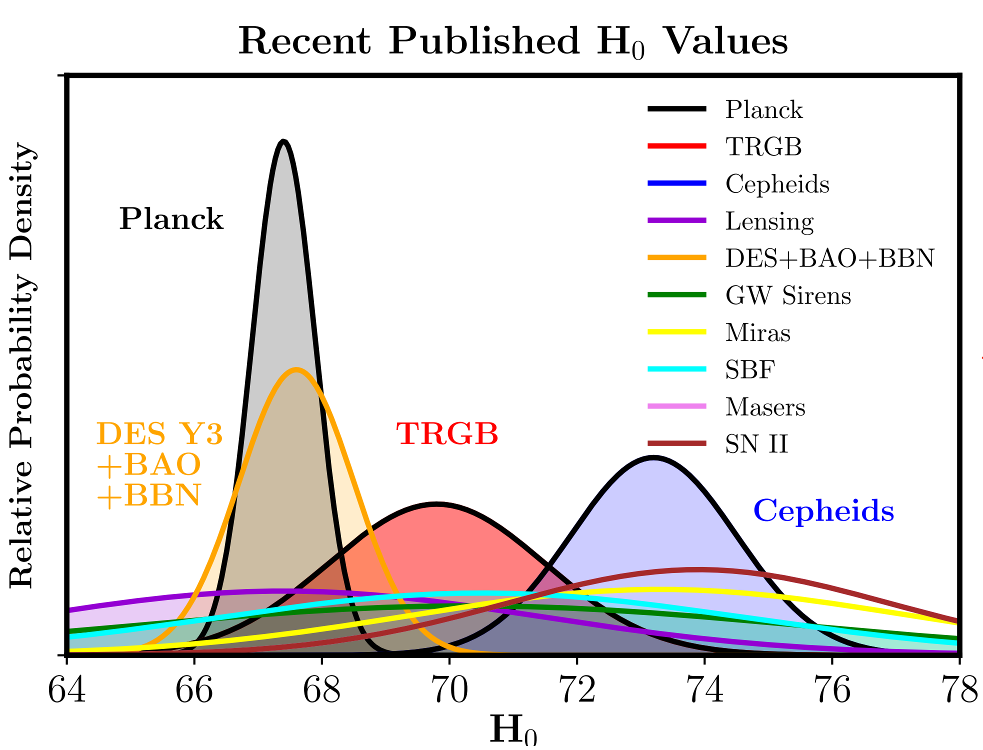
Zjazd Fizyków Polskich 2021

23rd September 2021

Preface: H_0 tension (ca. Sep. 2021)

Riess, Nat. Rev. Phys. 2 (2020) 10





Freedman, 2106.15656

The updated Tip of the Red Giant Branch (TRGB) calibration applied to a distant sample of Type Ia supernovae from the Carnegie Supernova Project

$$H_0 = 69.8 \pm 0.6\ (\text{stat}) \pm 1.6\ (\text{sys})\ \text{km s}^{-1}\ \text{Mpc}^{-1}$$

ΛCDM PROBLEMS

"Early vs. late":

I. H_0 tension

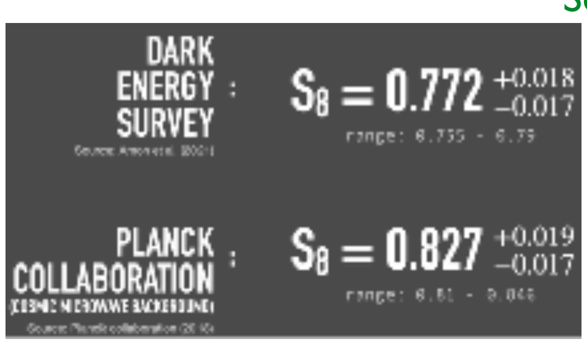
~4 to 6σ

(depending on datasets combination and stat. method)

II. $S_8 - \Omega_m$

strengthened a bit by DES results from May 2021

Secco et al, 2105.13544



but by itself only ~2.3σ

III. BAO z<1 vs. Ly-α

(recently shrunk to below 2σ…)

Small scale:

I. Diversity

in ΛCDM essentially one parameter specifying a halo, while reality much more diverse

II. Too-big-to-fail

most massive sub-haloes are expected to host luminous counterparts, but seem not to

III. Core-cusp

simulations predict more cuspy profiles than typically observed

IV. Missing satellites

simulations predict more more sub-haloes and hence we'd expect more MW satellites

What is the role for DM?

Small scale:

going beyond the collisionless CDM
(e.g. having warm component or including self-interactions) can address
(at least some of the) cosmological problems

quite rich literature on the subject…
…generically velocity-dependent self-interactions are preferred

see e.g. review by Tulin, Yu '17

DM self-interactions due to exchange of a light mediator

"Early vs. late":

in ΛCDM the DM component is extremely simple

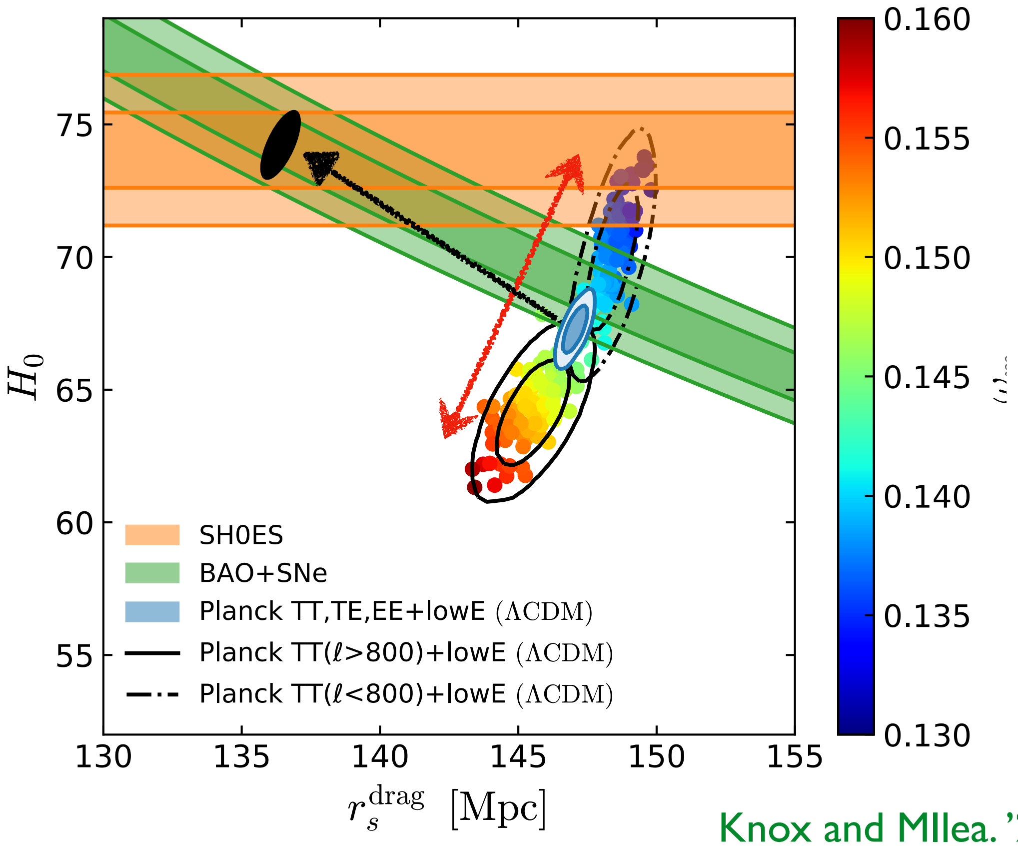
non-interacting, cold, with constant equation of state throughout whole evolution

however, if at late times a fraction of its energy is transferred to radiation (e.g. through decay or annihilation), then this can significantly affect the evolution

… but can it address both at the same time?!

DM AND THE H_0

Simply modifying the amount of matter in ΛCDM changes H_0



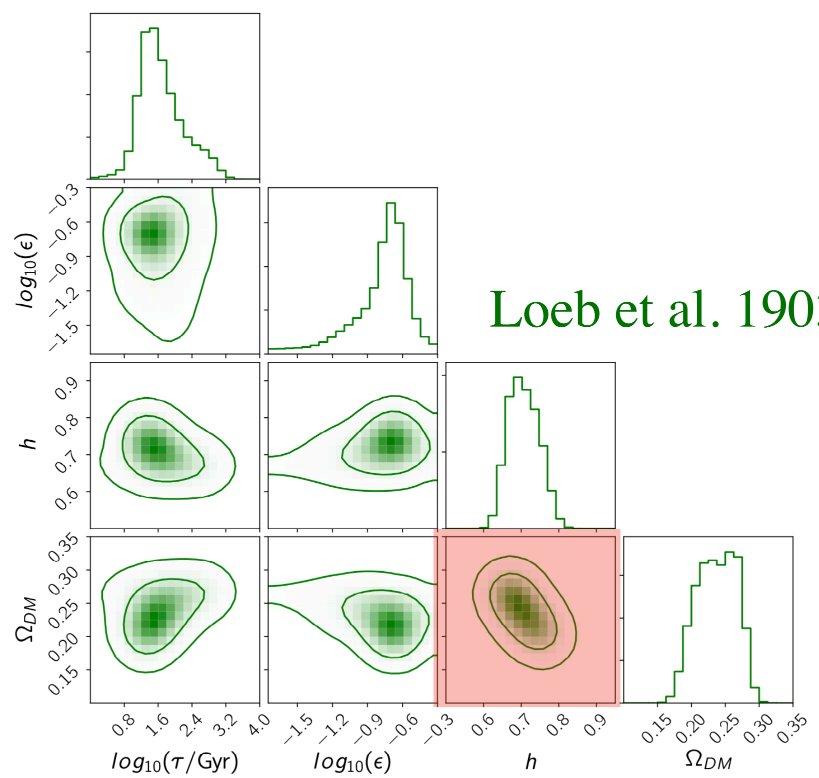
Knox and MIlea. '20

…but in an orthogonal direction to what is needed to also lower the sound horizon at the drag epoch by ~7%

However, if DM evolution changes after recombination

…the ΛCDM fit is unaltered, while as matter is depleted into radiation the matter-dark energy equality is shifted to earlier redshifts, allowing for higher value of H_0 at late times.

E.g., fraction of DM decaying to radiation:



Loeb et al. 1903.06220

see also:

Poulin, Lesgourges, Serpico '16, Haridasu, Viel '20, Clerk et al. '20,…

July 2021: the Olympics

Schoneberg et al. 2107.10291

However, the DM solution (on its own) is not among the preferred ones:

Model	$\Delta N_{\mathrm{param}}$	M_B	Gaussian Tension	Q_{DMAP} Tension		$\Delta\chi^2$	$\Delta\mathrm{AIC}$		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X
ΔN_{ur}	1	-19.395 ± 0.019	3.6σ	3.9σ	X	-4.60	-2.60	X	X
SIDR	1	-19.385 ± 0.024	3.2σ	3.6σ	X	-3.77	-1.77	X	X
DR-DM	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-7.82	-3.82	X	X
mixed DR	2	-19.388 ± 0.026	3.2σ	3.7σ	X	-6.40	-2.40	X	X
SIν+DR	3	-19.440 ± 0.038	3.7σ	3.9σ	X	-3.56	2.44	X	X
Majoron	3	-19.380 ± 0.027	3.0σ	2.9σ	✓	-13.74	-7.74	✓	✓ 2
primordial B	1	-19.390 ± 0.018	3.5σ	3.5σ	X	-10.83	-8.83	✓	✓ 3
varying m_e	1	-19.391 ± 0.034	2.9σ	3.2σ	X	-9.87	-7.87	✓	✓ 3
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.7σ	✓	-16.11	-12.11	✓	✓ 1
EDE	3	-19.390 ± 0.016	3.6σ	1.6σ	✓	-20.80	-14.80	✓	✓ 2
NEDE	3	-19.380 ± 0.021	3.2σ	2.0σ	✓	-17.70	-11.70	✓	✓ 2
CPL	2	-19.400 ± 0.016	3.9σ	4.1σ	X	-4.23	-0.23	X	X
PEDE	0	-19.349 ± 0.013	2.7σ	2.0σ	✓	4.76	4.76	X	X
MPEDE	1	-19.400 ± 0.022	3.6σ	4.0σ	X	-2.21	-0.21	X	X
DM $\to$ DR+WDM	2	-19.410 ± 0.013	4.2σ	4.4σ	X	-4.18	-0.18	X	X
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.2σ	X	0.11	4.11	X	X

[Although, to be fair, it seems like none of the proposed ideas does the job well…]

SOME MORE ISSUES…

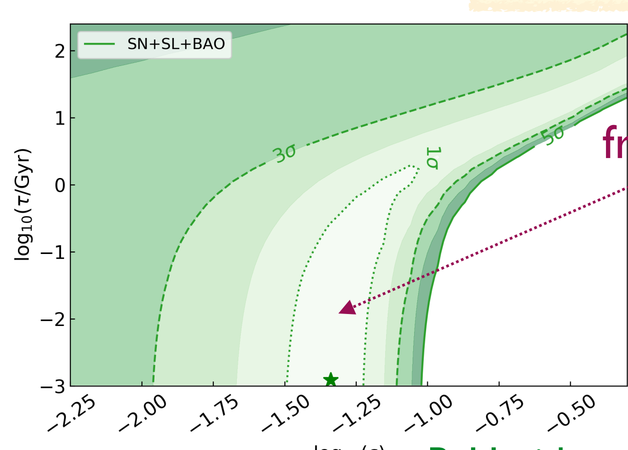
Energy transfer to radiation needs to happen very late
(often after recombination)

if through annihilation
enormous rates are needed
[but see T. Bringmann et al. '18; T. Binder et al. '18 for models of this type]

if through decay

the rate of change of eq. of state not ideal for the fit

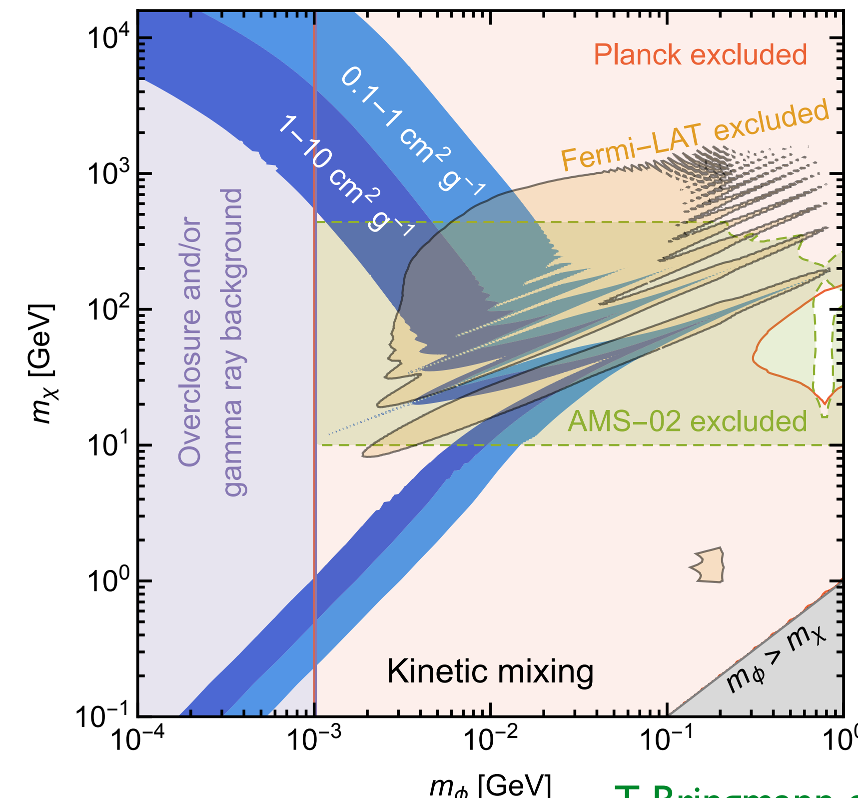
one needs to ensure only a small fraction of DM decayed
(extremely long lifetime or multi-component)



fraction of ~8%

B. Haridasu, M. Viel '20

Simple models with thermally produced DM very strongly constrained



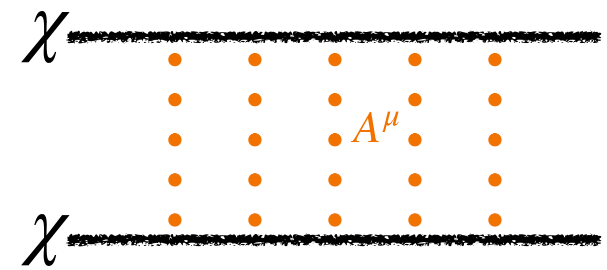
T. Bringmann et al. '16

with many of the constraints quite severe even in more general models

light mediator (if coupled to SM) affects CMB, indirect detection, colliders…

The Idea

Dark matter self-interacting through light mediator



to avoid limits from CMB and indirect detection

make the mediator stable…

typically overcloses the Universe

…but never in equilibrium
(with negligible initial population)

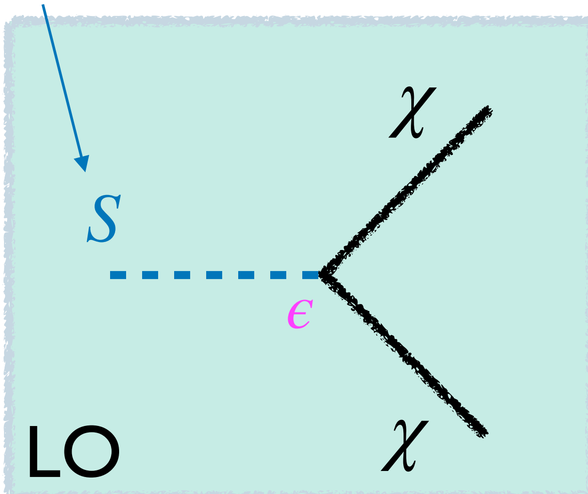
freeze-in like

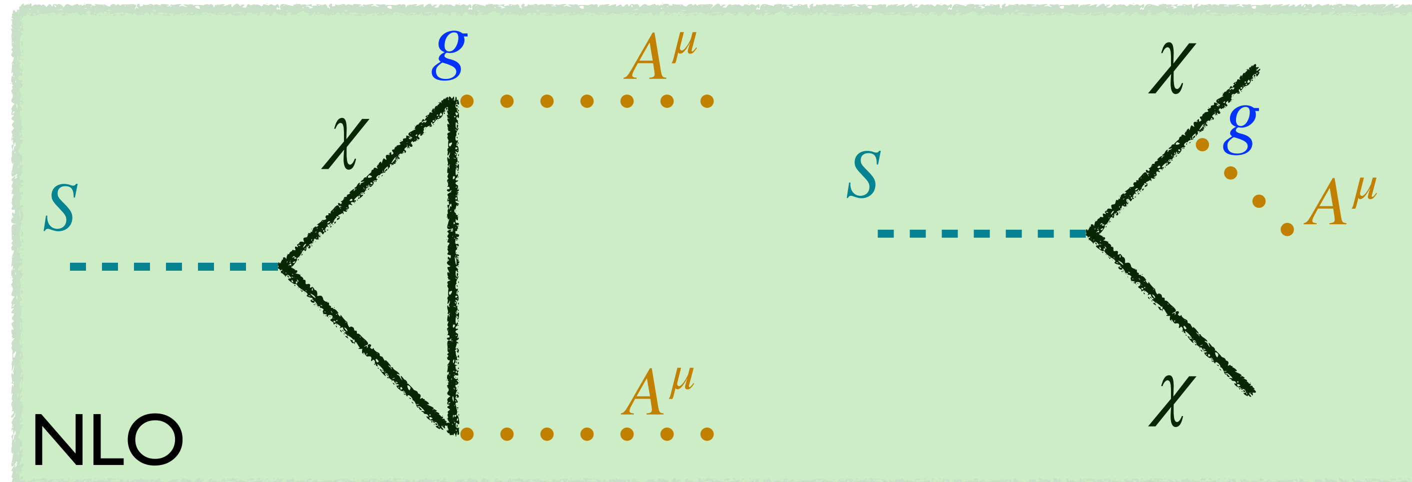
superWIMP like

both give viable, though not that unexpected mechanisms for self-interacting DM production, but superWIMP has an **intriguing feature**…

The Idea

WIMP-like connector state





$\Gamma_{S\to\chi\chi} \propto \epsilon^2$ $\Gamma_{S\to AA} \propto \epsilon^2 g^4$ $\Gamma_{S\to\chi\chi A} \propto \epsilon^2 g^2$

therefore, parametrically:
$$BR(S \to AA) \propto g^4$$
$$BR(S \to \chi\chi A) \propto g^2$$
$\sim (1-10)\,\%$

(with different phase space factors and energy of the mediator)

if $\boxed{\delta = 1 - \dfrac{2m_\chi}{m_S} \ll 1}$ $\Rightarrow$ S decays mostly to matter χ
with small fraction to radiation A

Property needed to modify expansion rate here present in an automatic way!

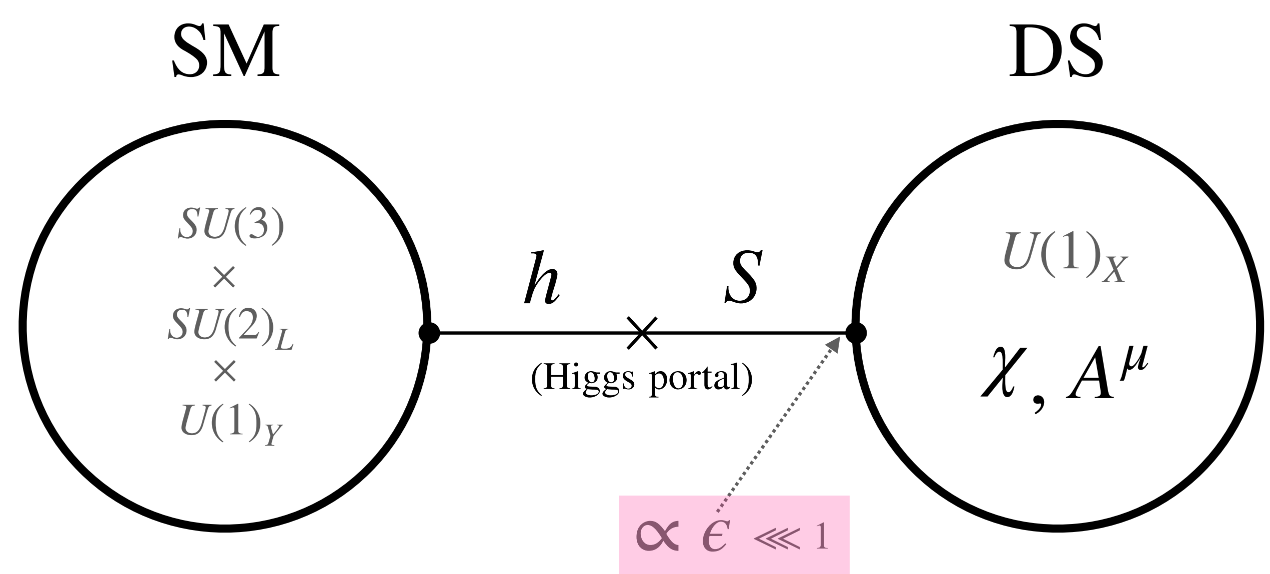
Example Model

SM and dark sector connected through a very weak Higgs portal:

Assume WIMP-like symmetry

$$Z_2 : S \to -S$$

that is broken* (explicitly or spontaneously) with breaking parametrized by ϵ



Relevant interaction terms:

$$\mathscr{L}^{\mathrm{DS}} \supset \lambda_{HS} S^2 H^\dagger H + \epsilon S \bar{\chi}\chi + \epsilon \mu_{HS} \cancel{S H^\dagger H} + ig A^\mu \bar{\chi}\gamma_\mu \chi$$

leads to freeze-out of S

decay

$\epsilon \lll 1$

↓

very long life-time of S

subdominant

self-interactions

g not tied to DM production

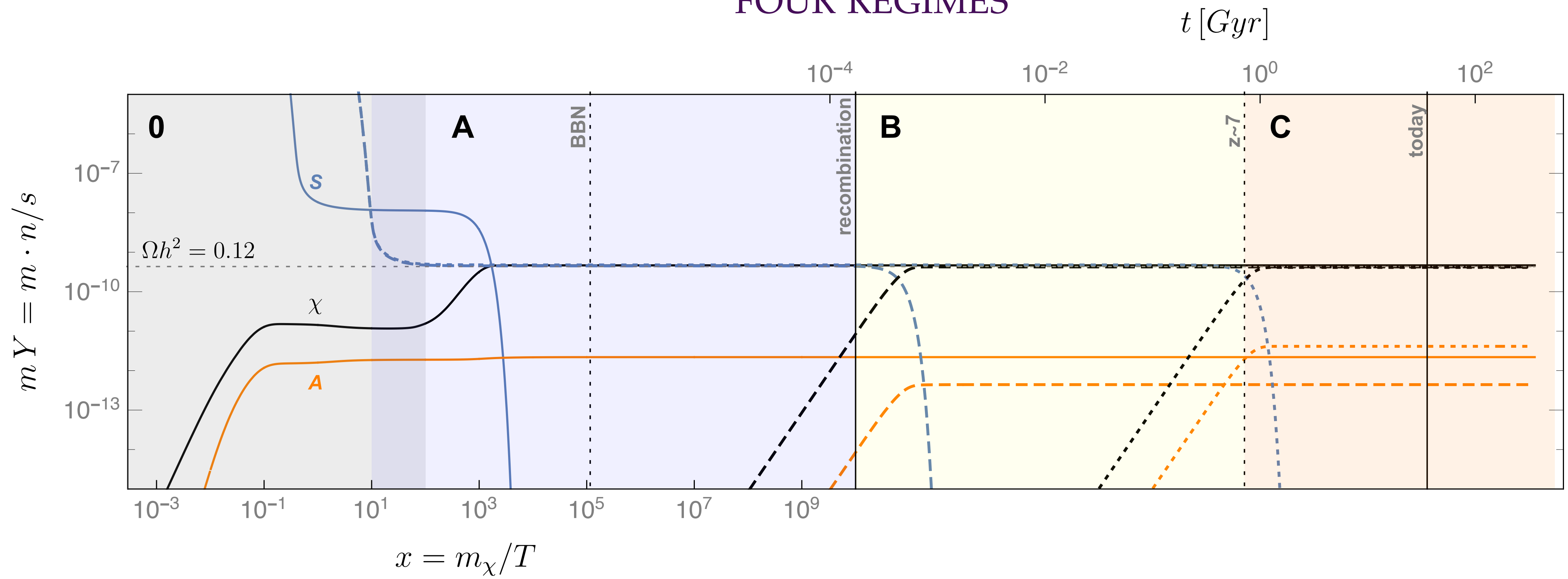
↓

can be large

* at some high scale, e.g GUT or even Planck scale

HISTORY

FOUR REGIMES



~~0) weak $\lesssim$ ϵ~~

~~DS thermalizes, usual thermal self-interacting DM model~~

A) very weak $\lesssim \epsilon \lesssim$ weak

superWIMP production, viable model but no impact on H_0 tension

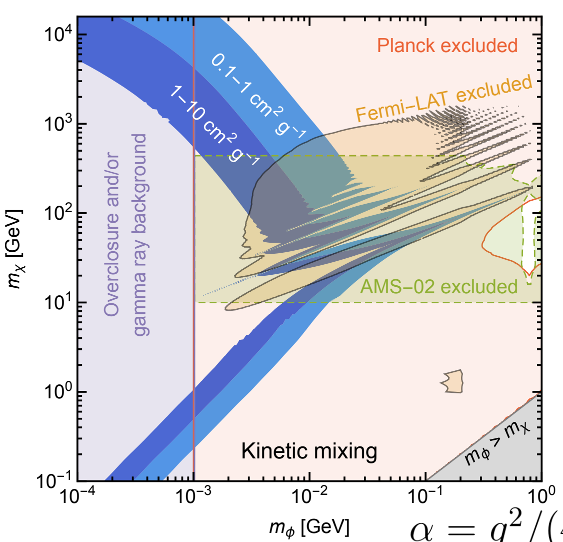
B) ultra weak $\lesssim \epsilon \lesssim$ very weak

life-time on cosmological scales changing the expansion rate - chance to impact the H_0 tension

C) $\epsilon \lesssim$ ultra weak

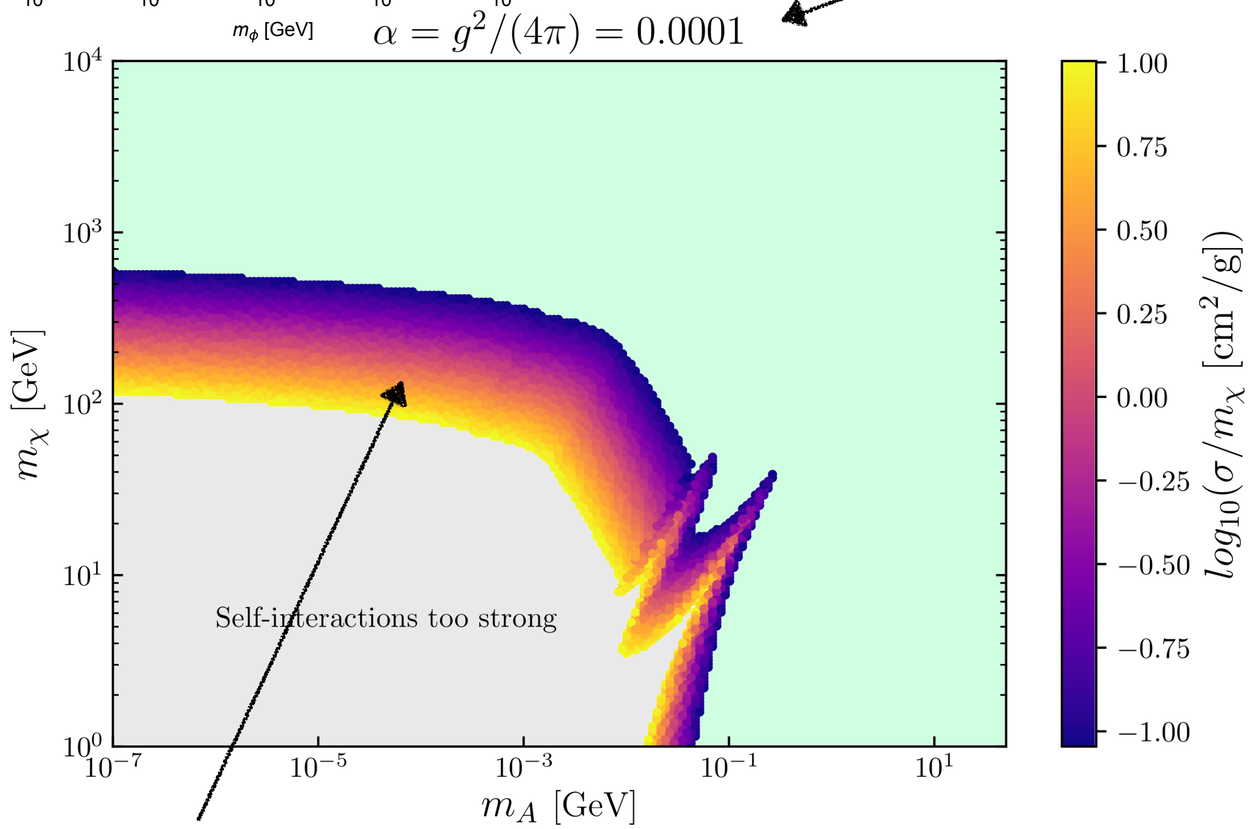
two-component DM (S and χ), where only one is self-interacting (in this case perhaps even ultra-strongly)

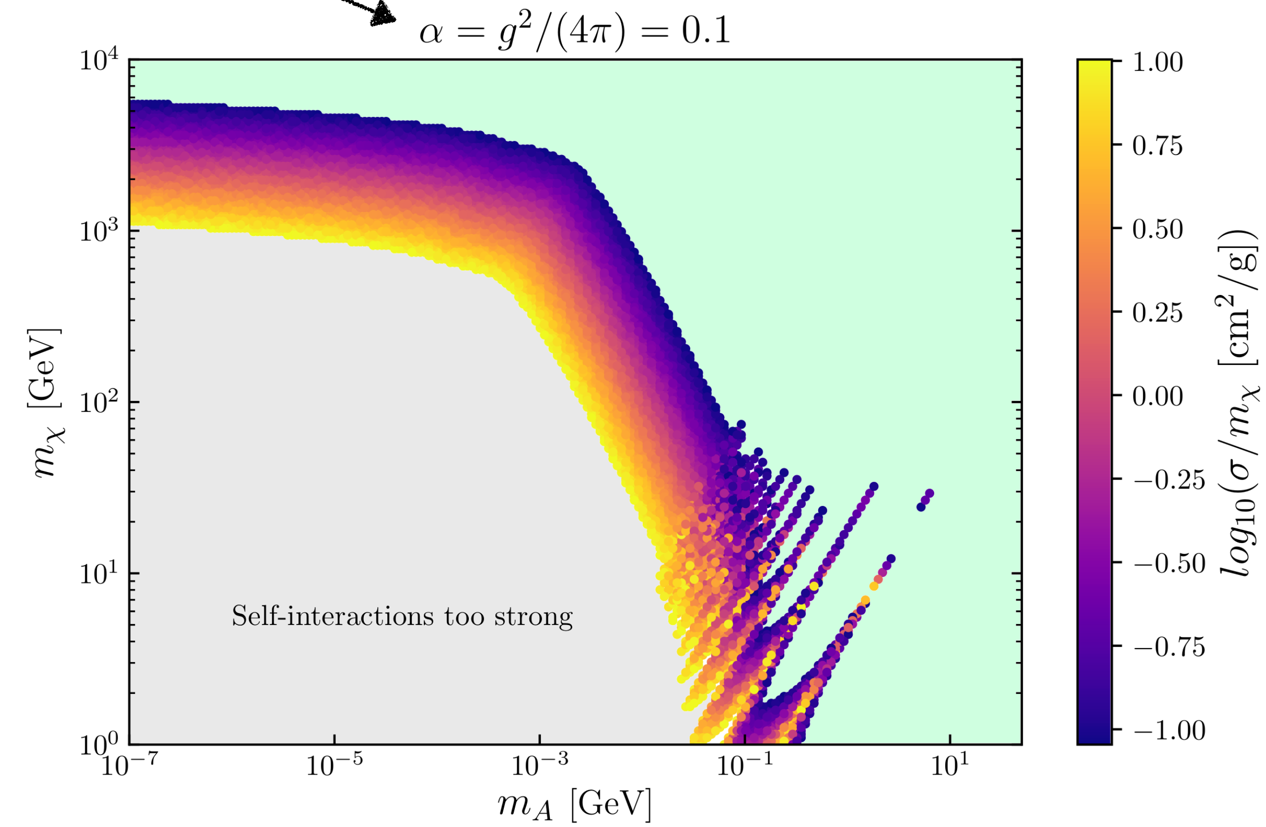
[The model can be viewed also as an extension of the usual Higgs portal DM to weaker couplings]



Regime A: only SIDM

not fixed by relic density; can be varied independently





preferred regime for small scale problems

In this regime DM is produced from out of equilibrium decay and never thermalizes

more extended parameter space giving large self-interactions than in thermal models

the mediator is not in the plasma and therefore can be absolutely stable

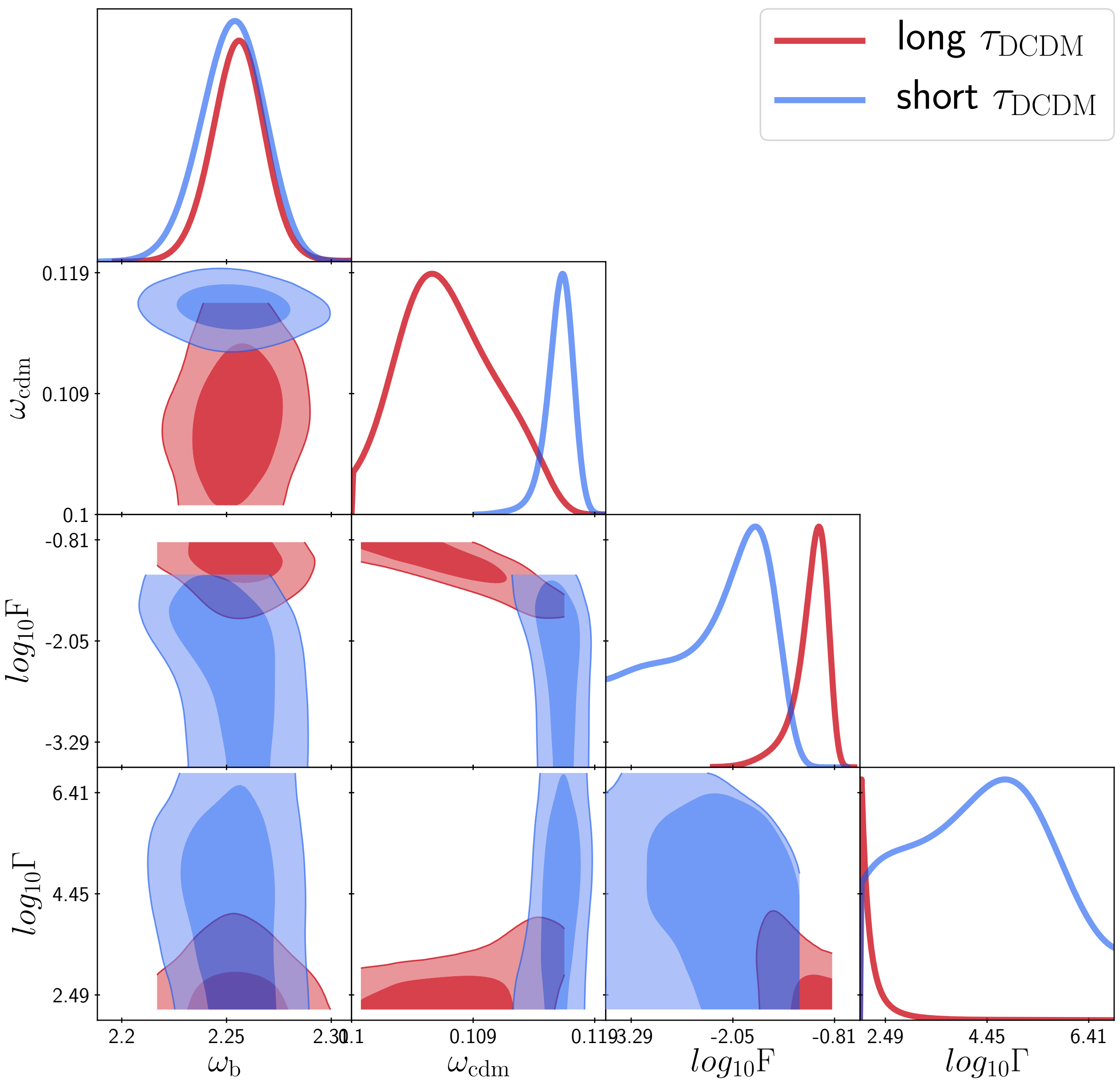
DCDM MODEL

It has been noted that the Decaying DM model (DCDM) with two parameters:

Γ — decay width $\qquad F$ — fraction of the decaying component

can improve the fit to the Hubble parameter over the CDM

…; S. Aoyama et al. '14; V. Poulin, P. Serpico, J. Lesgourgues '16; K. Enqvist et al. '15; G. Blackadder, S. Koushiappas '18; Y. Gu et al. '20; …



We have performed our fit with MontePython using combined datasets:

- Planck 2018
- BAO data from the BOSS survey
- the galaxy cluster counts from Planck catalogue
- local measurement of the Hubble constant.

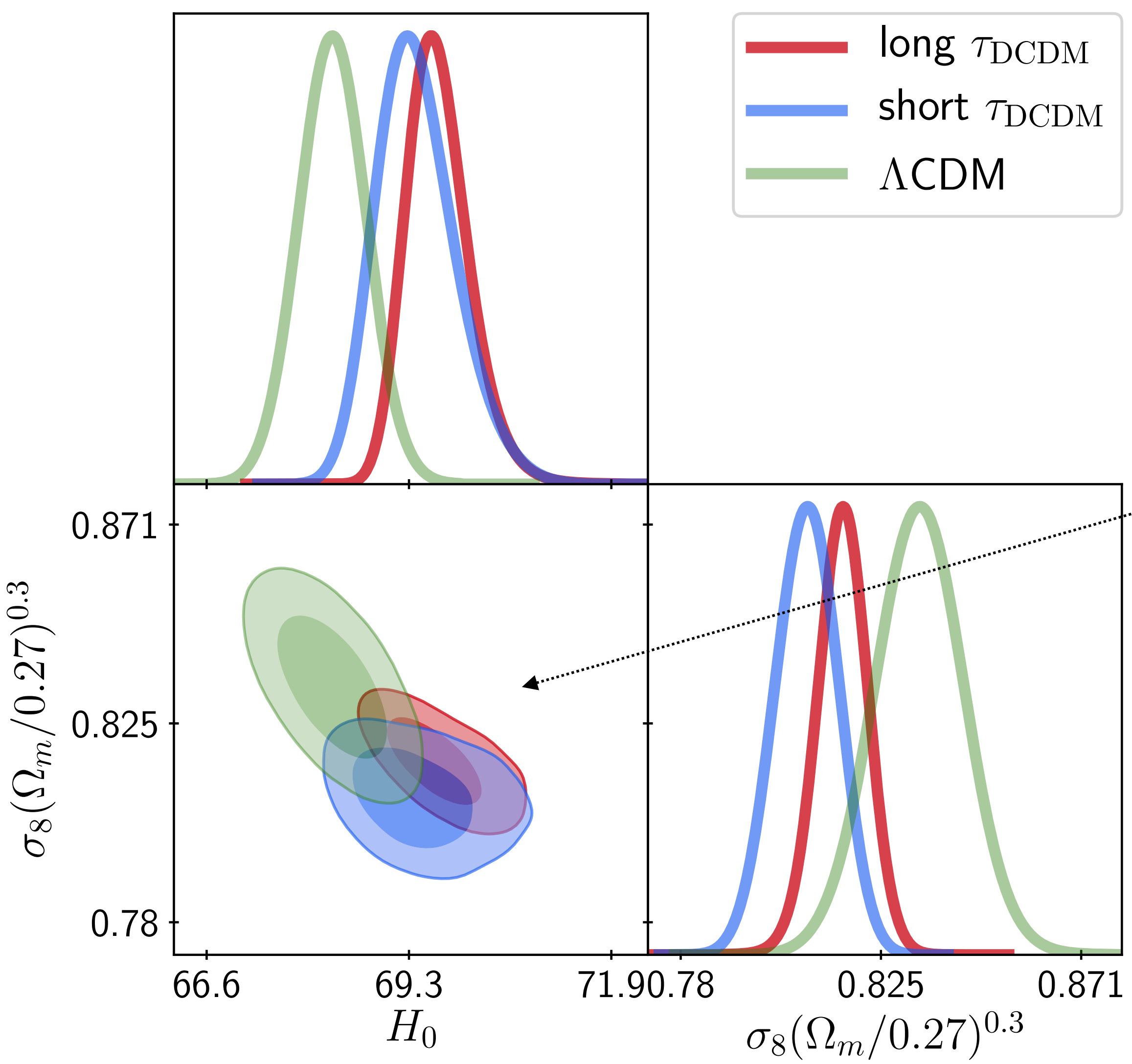
with two different life-time priors: short and long (motivated by previous results)

K. Vattis, S. Koushiappas, A. Loeb '19

DCDM MODEL

The H_0 parameter best fit:

$\log_{10} \mathrm{F}$	$-2.41^{+0.96}_{-0.48}$	$-1.1^{+0.25}_{-0.081}$	-
$\log_{10} \Gamma$	$4.36^{+1.38}_{-1.49}$	$2.33^{+0.13}_{-0.33}$	-
H_0	$69.4^{+0.43}_{-0.60}$	$69.7^{+0.33}_{-0.44}$	$68.28^{+0.45}_{-0.45}$
σ_8	$0.791^{+0.0062}_{-0.0051}$	$0.80^{+0.0030}_{-0.0031}$	$0.8065^{+0.0073}_{-0.0077}$



Two preferred lifetime regimes:

– short (regime B): $\tau \sim$ 4 Myr while fraction of dark radiation is strongly constrained to be below ~ 1%

– long (regime C): $\tau \sim$ 5 Gyr while fraction of dark radiation is allowed to be as big as ~ 10%.

The shift of the H_0 compared to ΛCDM is however rather mild in models of the type as our example

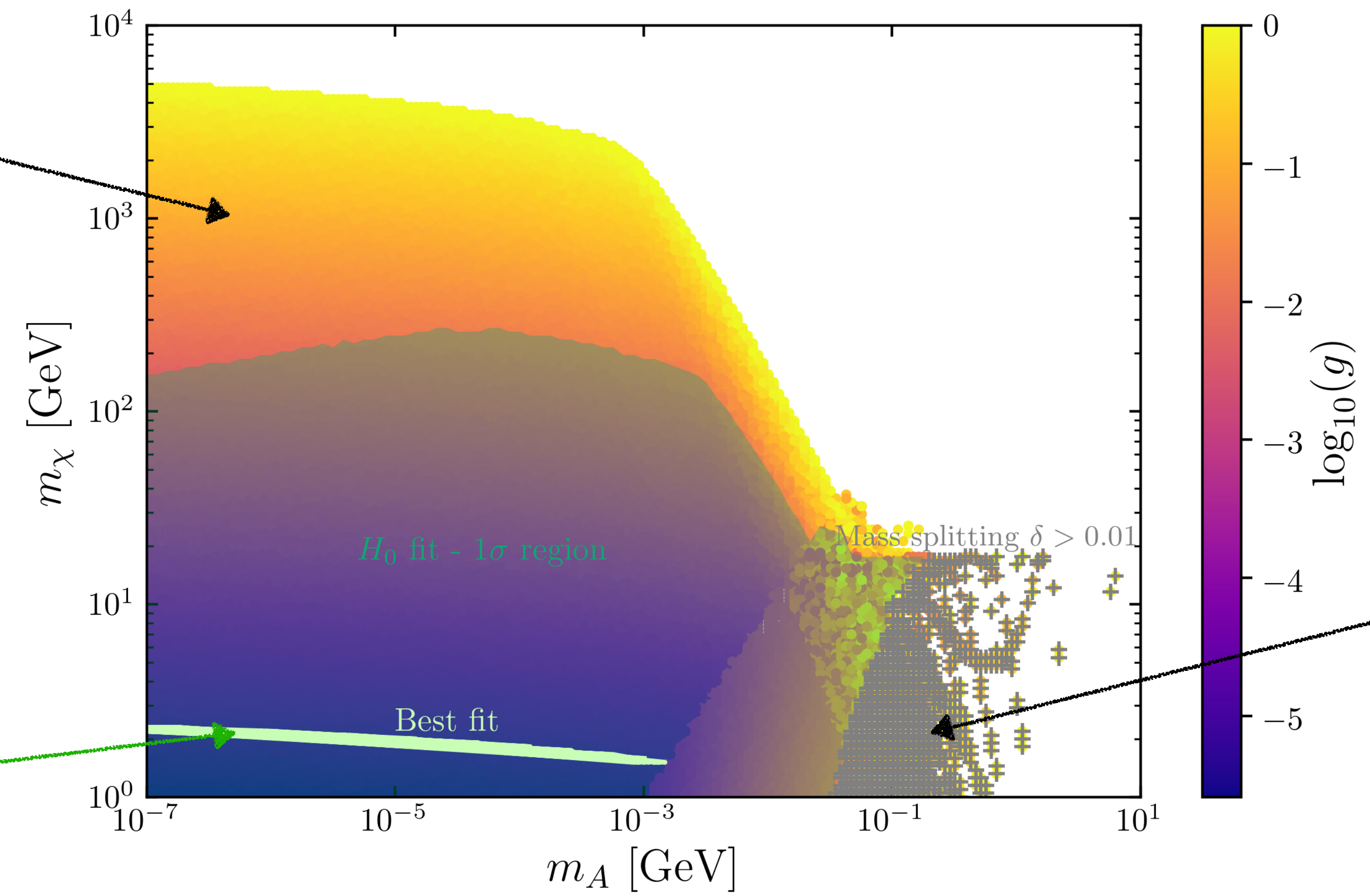
… although this could perhaps be modified with model building, complete solution of the H_0 tension is unlikely

see also S. Clark et al. '20

but DCDM can play its part in the full solution

REGIME B: SIDM FROM LATE DECAYS

now only points with
$\sigma/m_\chi = (1 \pm 10\%)\,\mathrm{cm}^2/\mathrm{g}$



gray points are in tension with structure formation (when DM has too large velocity at production)

best fit region to cosmological data

In this regime life-time on cosmological scales changing the expansion rate - chance to impact the H_0 tension

best fit spans over wide region of mediator mass $\lesssim 1\mathrm{MeV}$ but pretty specific m_χ

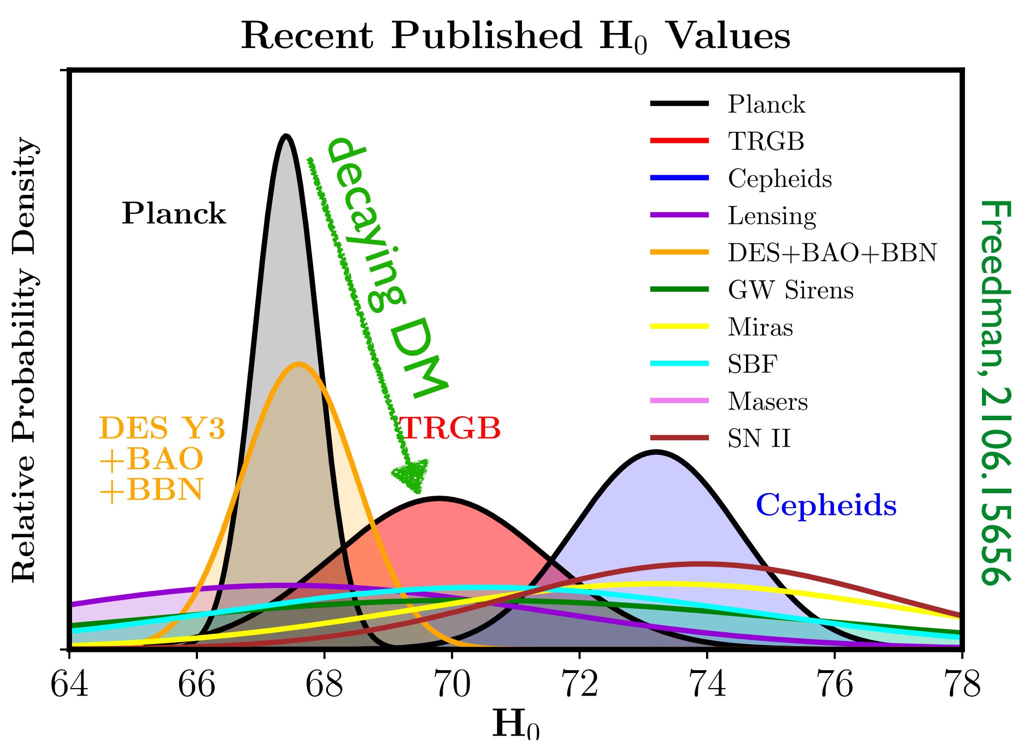
though the change of the H_0 parameter is not large enough to completely solve the tension

DOES THIS MODEL SOLVE THE H_0 TENSION?

NO…

…but:

I.



TRGB: $H_0 = 69.8 \pm 0.6$ (stat) ± 1.6 (sys) km s^{-1} Mpc^{-1}

our best fit: $H_0 = 69.4 + 0.43 - 0.60$ km s^{-1} Mpc^{-1}

II.

There is a growing consensus that a mix of pre- and post-recombination effects are needed to completely solve the tension

(unless systematics is to blame…)

might be a part of the solution!

REGIME C: ULTRA-SIDM

For longer S life-times it won't decay completely even till today

two-component DM (S and χ) combination of CDM and SIDM

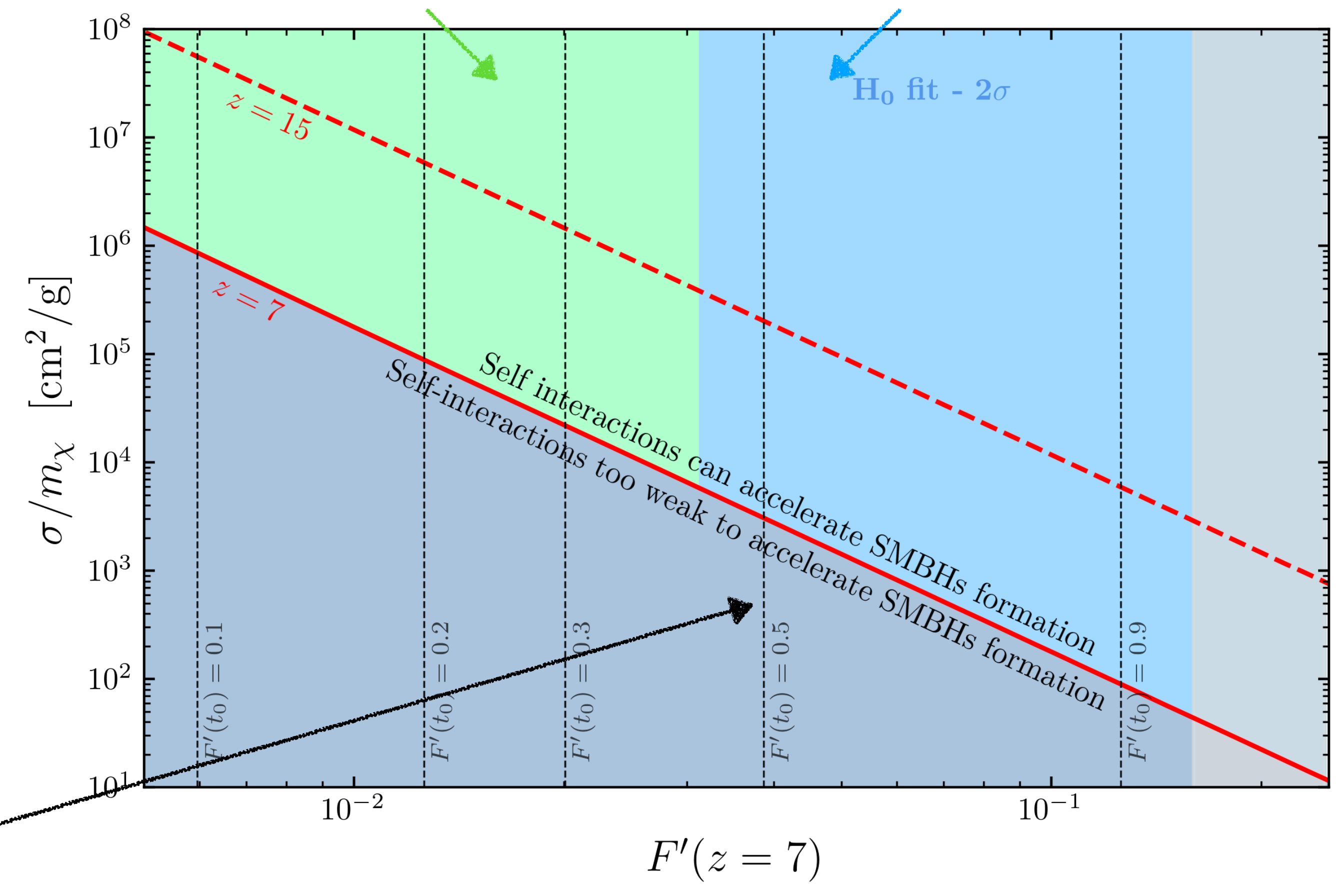
when only fraction of DM is self-interacting it can actually have much larger scattering cross section

to fit the H_0 one needs larger fraction going to radiation (i.e. larger BR to mediator A)

problem: between z~7 and z~0 large fraction of S will manage to decay leading to too large present day population of uSIDM

helps in SMBHs formation

+ improves fit to H_0



uSIDM

J. Pollack, D. Spergel, P. Steinhardt '14

provides a candidate mechanism for seeding the formation of supermassive black holes (SMBHs)

[standard formation theory is challenged by observation of very old, z ~7 SMBHs]

J. Choquette, J. Cline, J. Cornell '19

the model can either improve the fit to H_0 or help with SMBHs formation rate, but not both

BONUS: XENON 1T

Throughout the whole discussion we assumed the mediator is completely stable…

…but it does not need to be

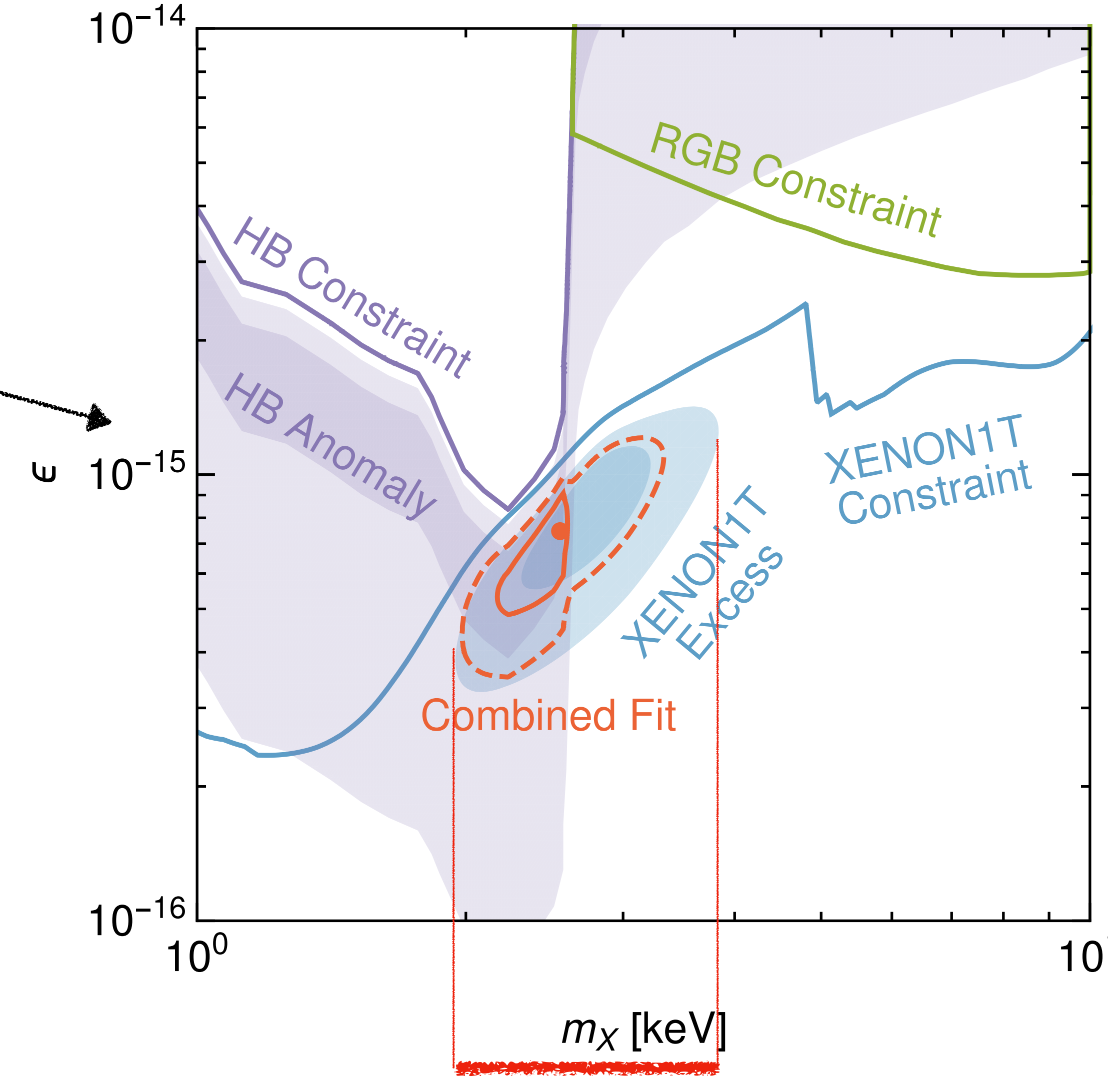
Allowing e.g. some small kinetic mixing with the SM photon does not spoil any of the results above, while can have phenomenological consequences

e.g.

$\Downarrow$

Worth investigating also other potential signals, e.g. the detection of the decay products (especially in regimes B and C)

G. Alonso-Alvarez et al. '20



[mass range perfectly consistent with best fit to self-interaction strength + H_0 in our model]

Conclusions

1. Mechanism of self-interacting DM production from decays of an intermediate state offers a new way of constructing models satisfying the known constraints

2. It provides a natural way of transferring few % of energy density to radiation at late times allowing for slightly alleviating the H_0 tension

[or from a different angle: can be a part of the solution as it's quite likely that true explanation is a combination of few effects]

3. Extensions of the simple model discussed here can offer interesting phenomenology and are worth investigating

4. More data coming: a 5yr observing run by the upgraded LIGO, Virgo, KAGRA and LIGO India detectors should be enough to measure H_0 to 1% by 2030