Asymmetric dark matter with a spontaneously broken $U(1)'$: Self-interaction and Nano-Hertz gravitational waves

第四届粒子物理前沿研讨会-The 4th workshop on frontiers of particle physics

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太原/晋祠宾馆

Based on: *Phys.Rev.D 107 (2023) 9, 095072* Zien Chen, Kairui Ye, MZ
2306.16966 Chengcheng Han, Jin Min Yang, Ke-Pan Xie, MZ

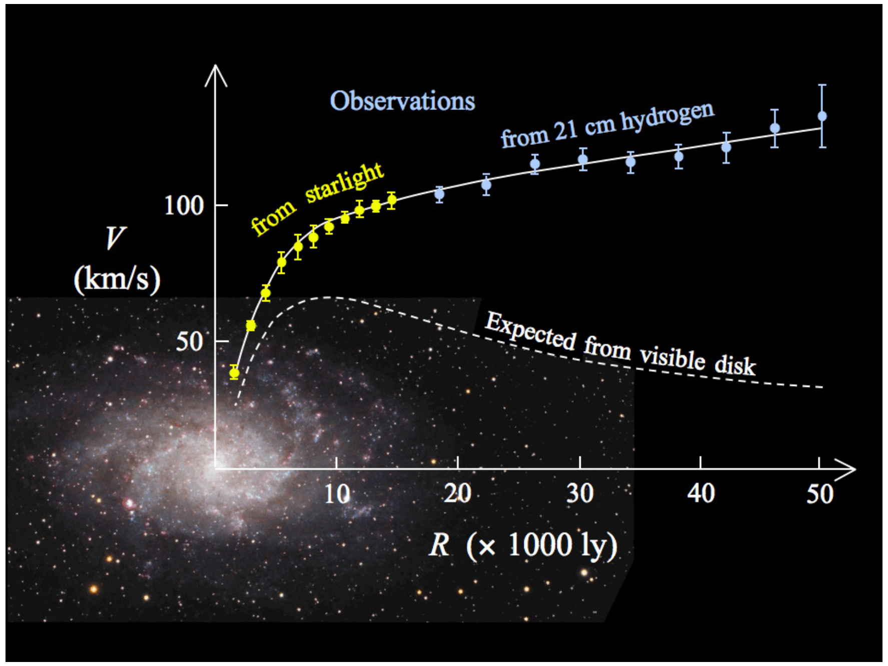
Outline

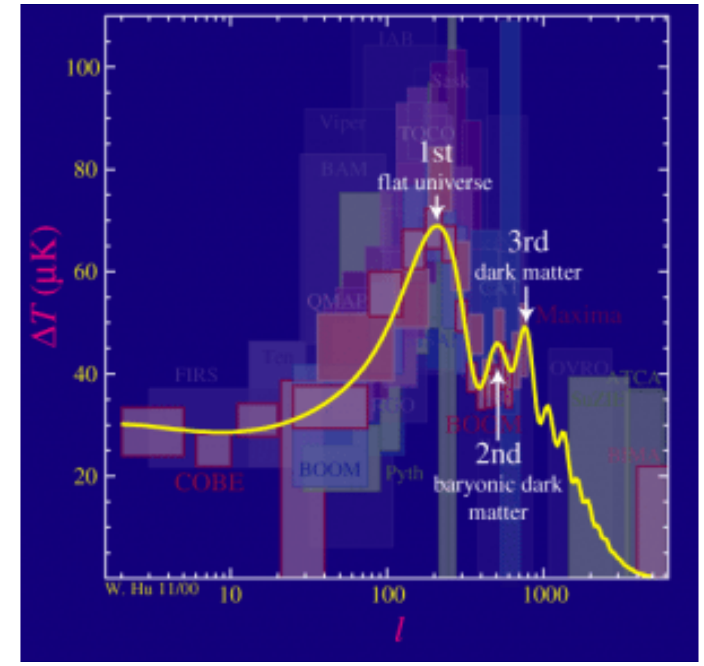
1.Motivation: why self-interacting? why asymmetric?

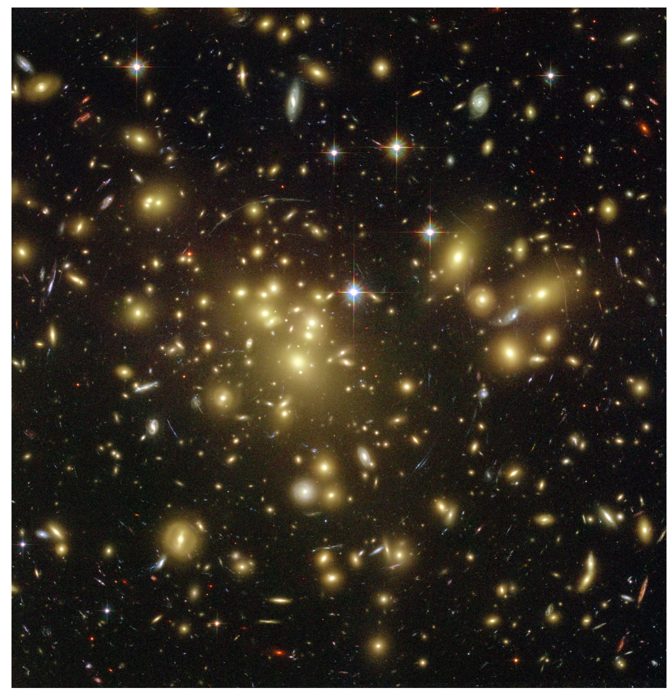
2.Model & Bound & Signal
  a) Scenario I: Isolated Dark Sector (can't explain PTA data)
  b) Scenario II: Decayed Dark Sector (can explain PTA data)

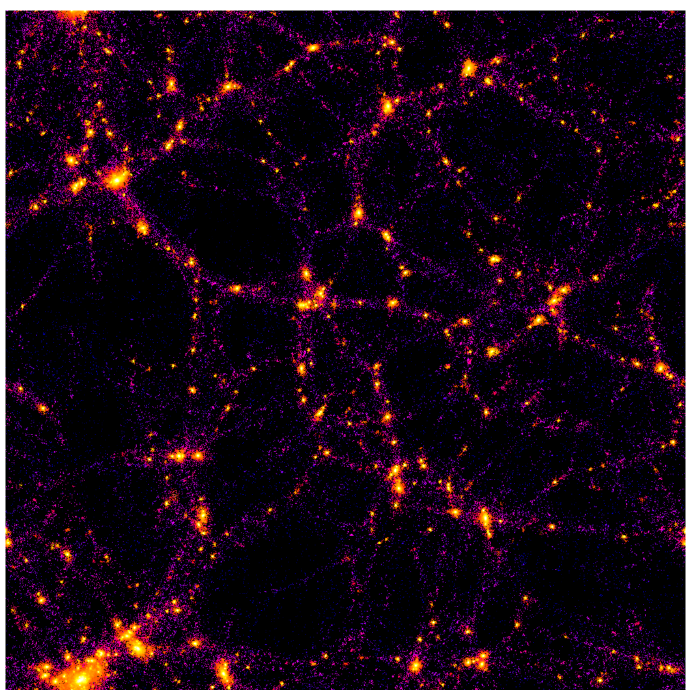
3.Conclusion

Motivation: why self-interacting? why asymmetric?



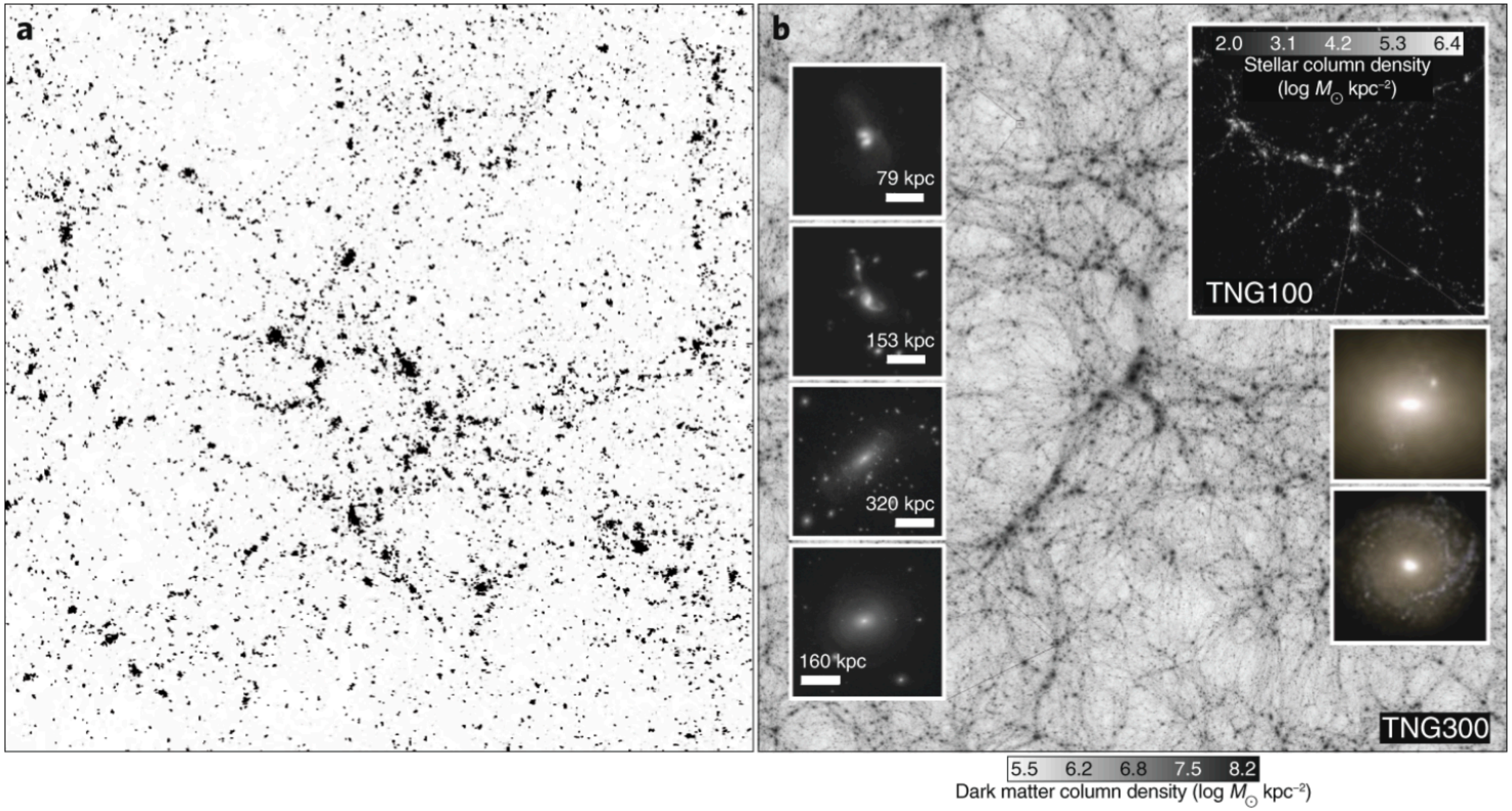






Plenty evidences for the existence of DM!

Motivation: why self-interacting? why asymmetric?



DM relic density is fixed by CMB.
In addition to relic density, we also know DM should be cold.
We also assume DM to be collisionless (only via gravity) in large scale simulation.
"Cold + Collisionless" : consistent with observation at large scale!

Motivation: why self-interacting? why asymmetric?

But at small scale ($\lesssim$ Mpc), collisonless faces some challenge.

CDM small-scale problems:

core-cusp problem(the core of DM halo is not cuspy)

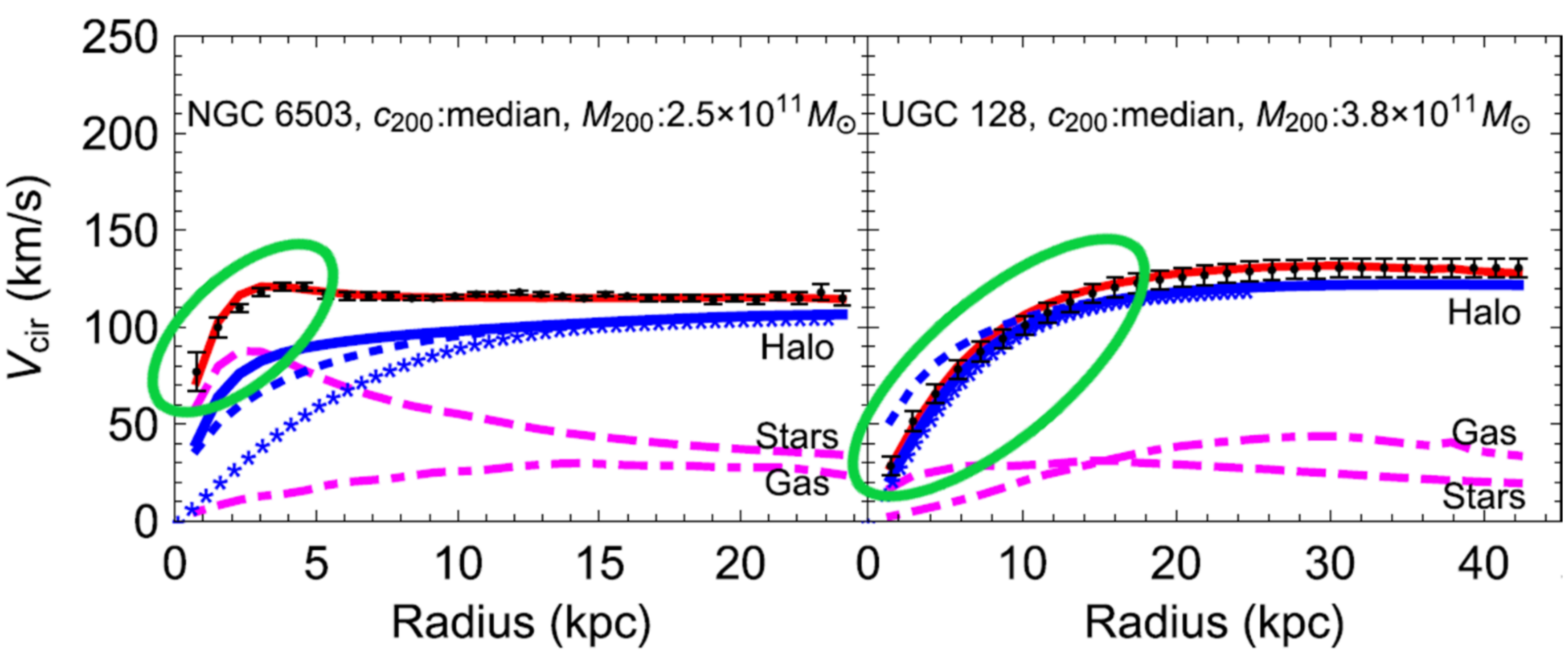
(can partly be fixed by baryon effects)

diversity problem(rotation curves are very different)

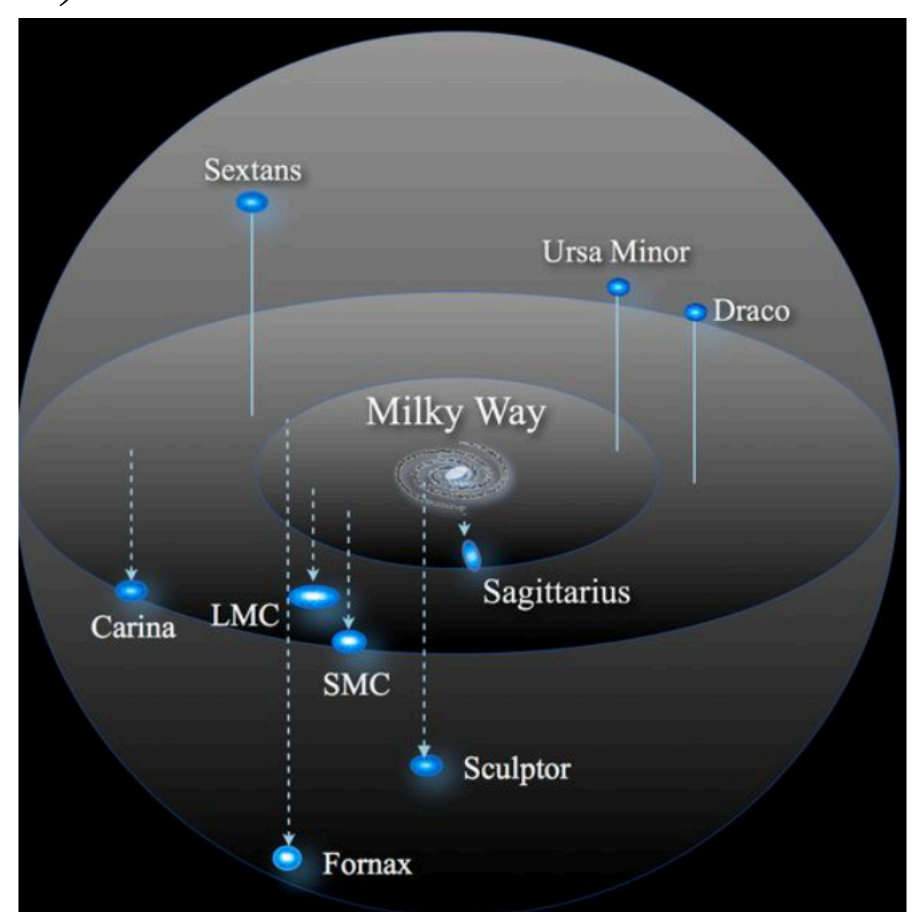
missing satellites(we didn't see many dwarf satellite galaxies inside MW)

(can be fixed by baryon effects)

too-big-to-fail(why the massive sub-halos are so dark?)



Kamada, Kaplinghat, Pace, and Yu (2017)



Motivation: why self-interacting? why asymmetric?

To solve those small-scale problems, we need to give up the assumption collisionless and assume collision between DMs.

For example, if we assume a elastic cross-section between DMs, $\sigma/m_{DM} \simeq 1\ \mathrm{cm}^2\ \mathrm{g}^{-1}$, then the core-cusp problem can be solved:

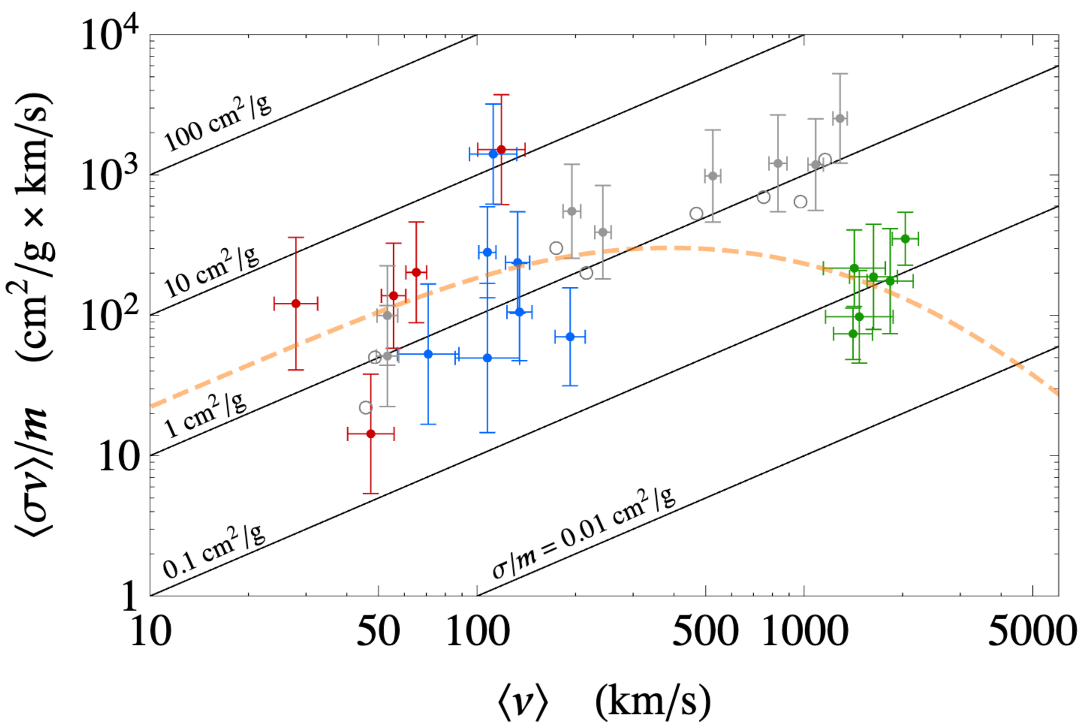
Rocha M, Peter A H G, Bullock J S, et al. Monthly Notices of the Royal Astronomical Society, (2013)

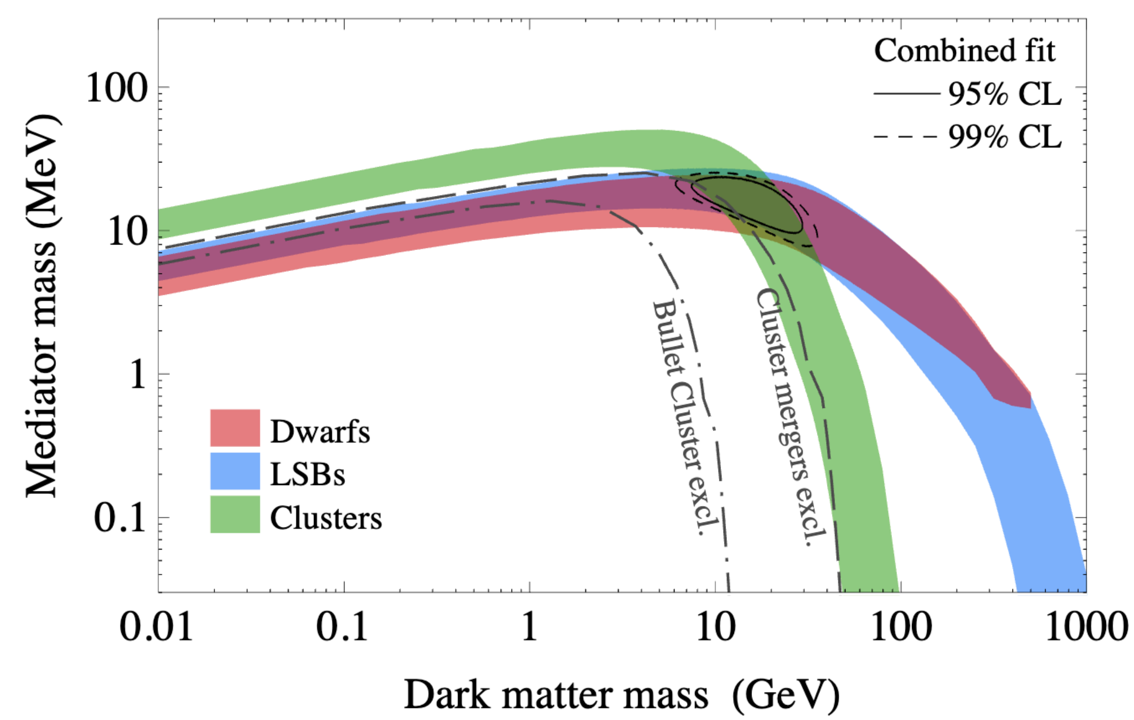
Elastic scattering between DMs thermalize the core, and thus erase the cusp.

Motivation: why self-interacting? why asymmetric?

Later studies show that a constant cross-section is not enough, we need a velocity-dependent cross-section.

If this velocity-dependent cross-section is induced by a dark mediator, then it is possible to fix the masses of DM and dark mediator by small-scale structure data.





Manoj Kaplinghat, Sean Tulin, and Hai-Bo Yu, PRL (2016)

Small-scale data fitting → DM mass ~ 10 GeV - 100 GeV

Mediator mass ~ 1 MeV - 10 MeV

Motivation: why self-interacting? why asymmetric?

Now, we explain the 1st Question: why self-interacting.

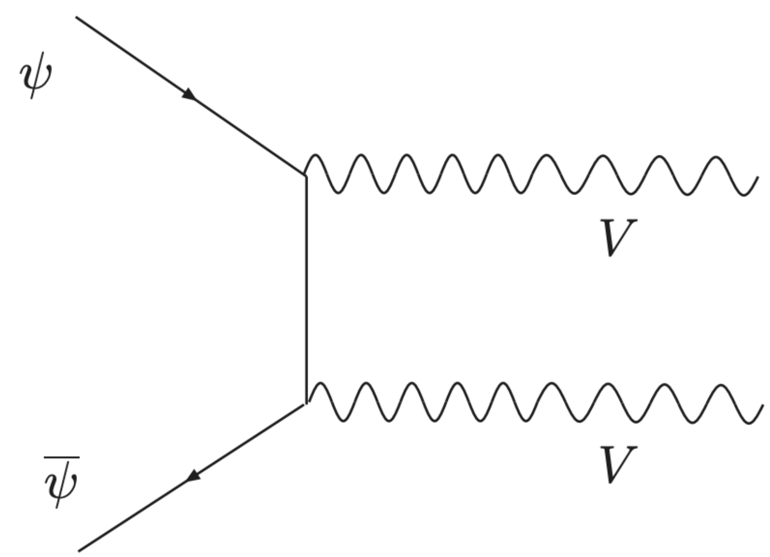
The 2nd Question, i.e. Why Asymmetric, comes from Sommerfeld effect.

Now, we have DM and mediator with mass hierarchy.

DM mass ~ 10 GeV - 100 GeV

Mediator mass ~ 1 MeV - 10 MeV

Let's assume DM is produced by thermal freeze-out:



M. Pospelov, A. Ritz, and M. Voloshin, PLB (2007)

"Secluded freeze-out" : DM $\psi\bar{\psi}$ annihilate to mediator pair VV.

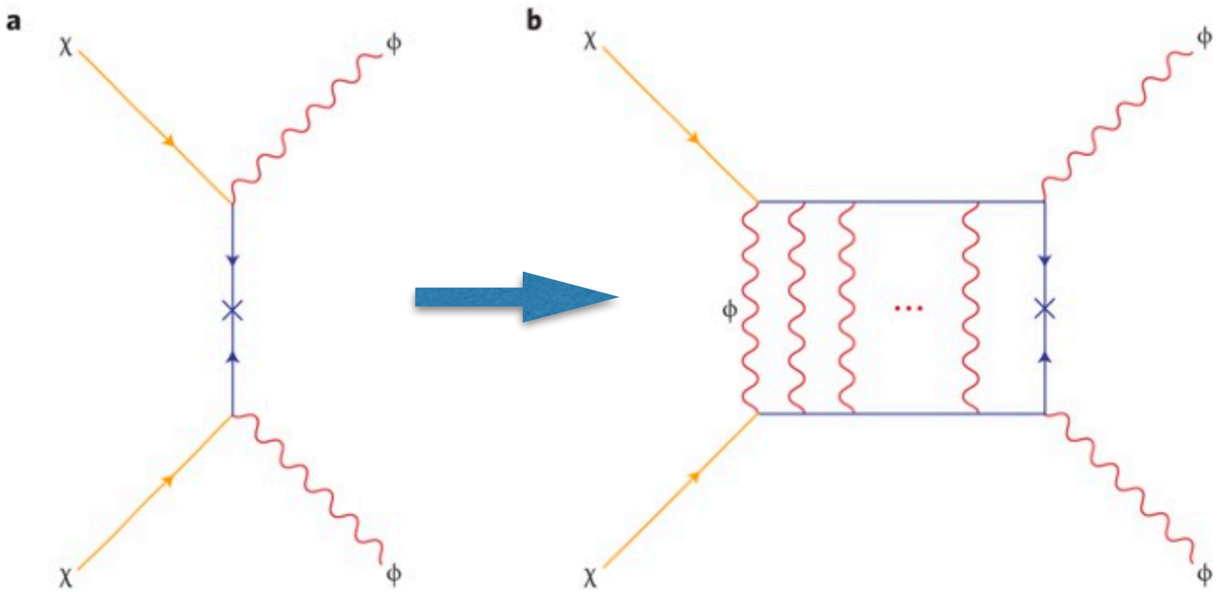
Easy to get relic density and escape DM search bounds. But……

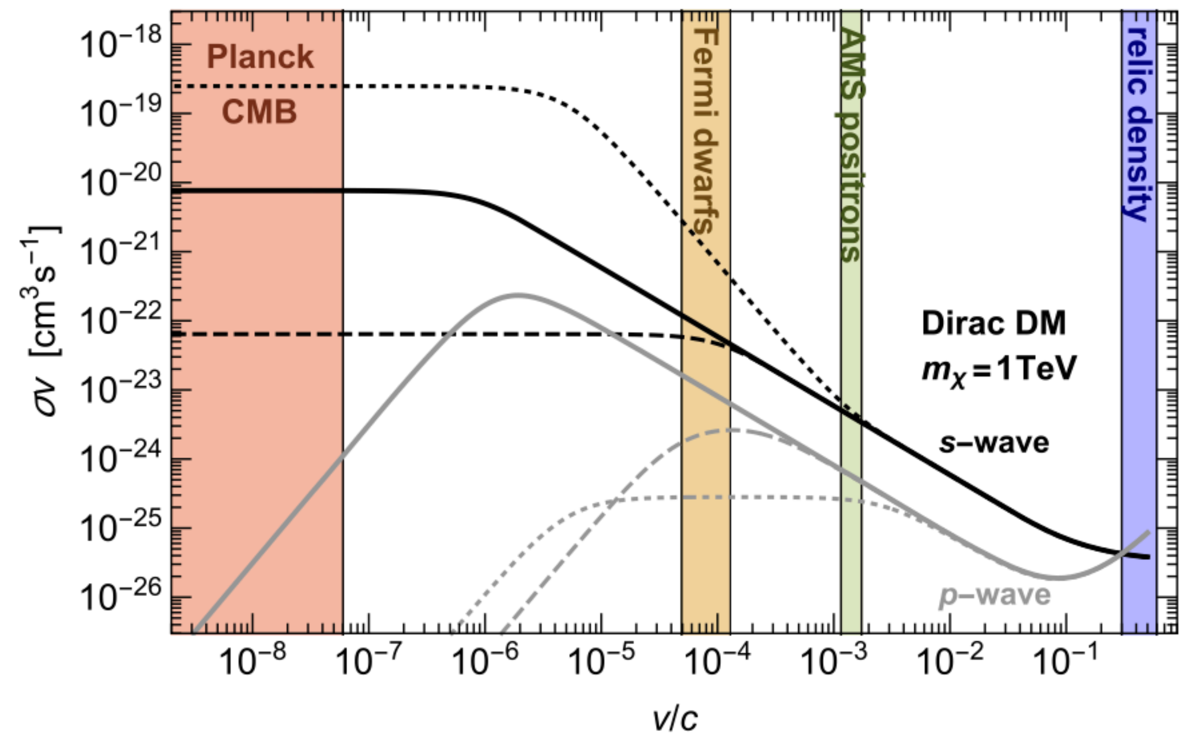
Motivation: why self-interacting? why asymmetric?

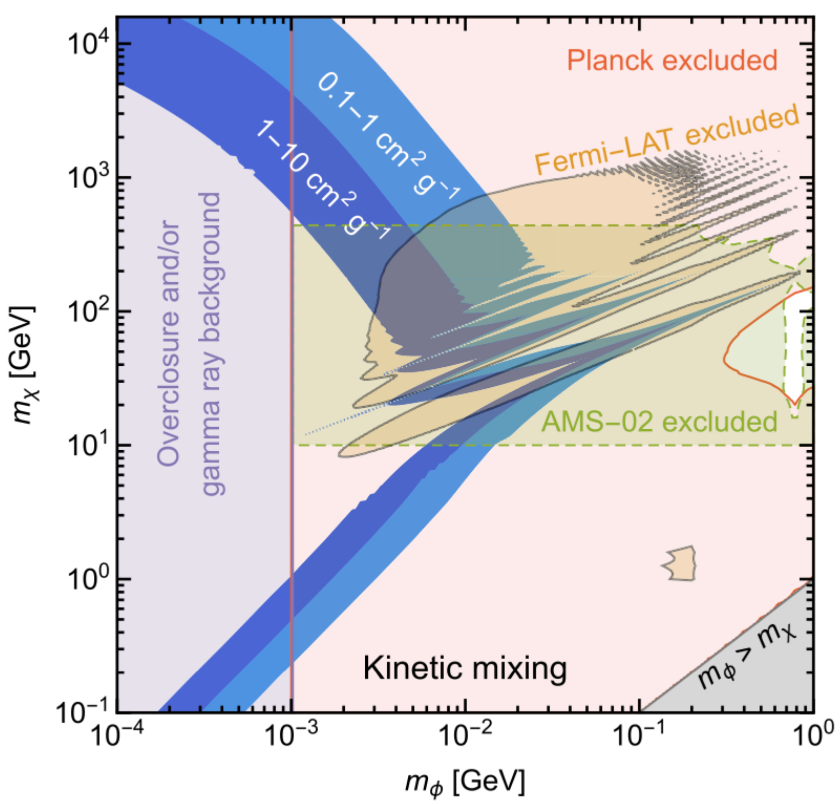
But, with the velocity of DM become slower and slower, Sommerfeld effect starts to work. Because of the mass hierarchy.

DM mass ~ 10 GeV - 100 GeV

Mediator mass ~ 1 MeV - 10 MeV







Result: energy injection from DM annihilation during CMB period is too strong! CMB data have excluded this scenario, completely!

Motivation: why self-interacting? why asymmetric?

How can we escape the strong bound from CMB (and also the indirect search)?

All we need to do, is the reduce the energy injection, right?

If DM is charged (and so we have DM and anti-DM), and anti-DM is almost disappeared in the later universe. Then energy injection will also be suppressed.

Suppression factor: $\dfrac{2r}{(1+r^2)}$.

r is the ratio between anti-DM abundance and DM abundance: $r = \dfrac{Y_{\bar{\chi}}}{Y_\chi}$.

If r is small enough, then we are free from CMB and indirect search!

This is why we need asymmetric DM.

The Minimal Self-Interacting ADM Model

Let’s summarize what we need:

Stable DM with mass ~ 10 GeV - 100 GeV

Light mediator with mass ~ 1 MeV - 10 MeV

Asymmetry between DM and anti-DM

Try to build a model to comprise all these ingredients !

We can introduce a $U(1)'$ to gauge the dark sector, so DM and anti-DM have inverse $U(1)'$ charge.

We also need to break the $U(1)'$ to make mediator massive: Higgs mechanism in the dark sector.

Finally, asymmetry can be produced by many method, let’s choose the leptogenesis-like mechanism for simplicity.

The Minimal Self-Interacting ADM Model

The minimal model with $U(1)'$ is following:

$$\mathscr{L}_{\text{Dark}} = \bar{\chi}(i\not{D} - m_\chi)\chi - (D_\mu S)^\dagger D^\mu S - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - V(S)$$

$$+\frac{1}{2}\sum_{i=1,2}\bar{N}_i(i\not{\partial} - M_{N_i})N_i^C - \sum_{i=1,2} y'_i \bar{N}_i \chi S^\dagger + h.c.$$

χ : DM , $\bar{\chi}$: anti-DM , $A'(\gamma')$: dark photon as the mediator

S : dark Higgs used to break $U(1)'$, and join the dark leptogenesis

N_1, N_2 : dark asymmetry generator

But this model has a serious problem! After SSB of $U(1)'$, S obtain vev.

Integrating out the heavy N_1, there will be a Majorana mass for DM:

$$\frac{(y'\langle S\rangle)^2}{M_{N_1}}$$

This Majorana mass cause DM oscillate to anti-DM, but we don't want the anti-DM back!

The Minimal Self-Interacting ADM Model

So, you have to introduce 2 dark Higgs in the minimal model:

$$\mathscr{L}_{\text{Dark}} = \bar{\chi}(i\not{D} - m_\chi)\chi - (D_\mu S_1)^\dagger D^\mu S_1 - (D_\mu S_2)^\dagger D^\mu S_2 - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - V(S_1, S_2)$$
$$+\frac{1}{2}\sum_{i=1,2}\bar{N}_i(i\not{\partial} - M_{N_i})N_i^C - \sum_{i=1,2} y'_i \bar{N}_i \chi S_1^\dagger + h.c.$$

χ : DM , $\bar{\chi}$: anti-DM , $A'(\gamma')$: dark photon as the mediator

S_1 : join the dark leptogenesis

S_2 : dark Higgs used to break $U(1)'$

N_1, N_2 : dark asymmetry generator

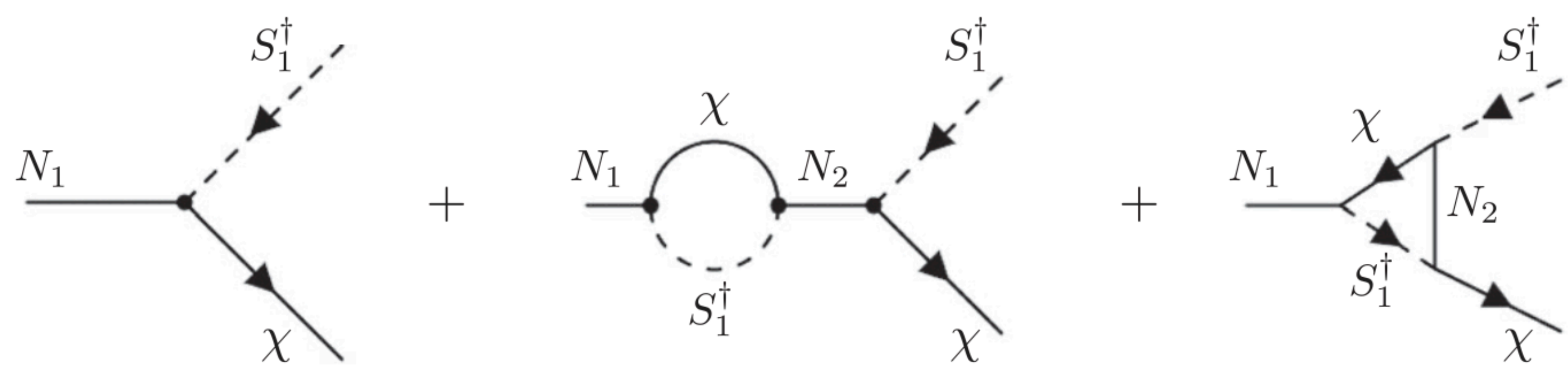
Then this model works~

Let's see how the asymmetry helps to escape limits from CMB.

The Minimal Self-Interacting ADM Model

(We assume the dark sector is thermalized by reheating)

Firstly, asymmetry is generated by the CP violated and out-of-equilibrium decay of N_1:



$$\epsilon \equiv \frac{\Gamma(N_1 \to \chi S_1^\dagger) - \Gamma(N_1 \to \bar{\chi} S_1)}{\Gamma(N_1 \to \chi S_1^\dagger) + \Gamma(N_1 \to \bar{\chi} S_1)} \simeq -\frac{1}{16\pi}\frac{M_{N_1}}{M_{N_2}}\frac{\mathrm{Im}[(y_2'^* y_1')^2]}{|y_1'|^2}$$

Then we need to estimate abundance ratio $r = \dfrac{Y_{\bar{\chi}}}{Y_\chi}$ at CMB period (labeled as r_∞).

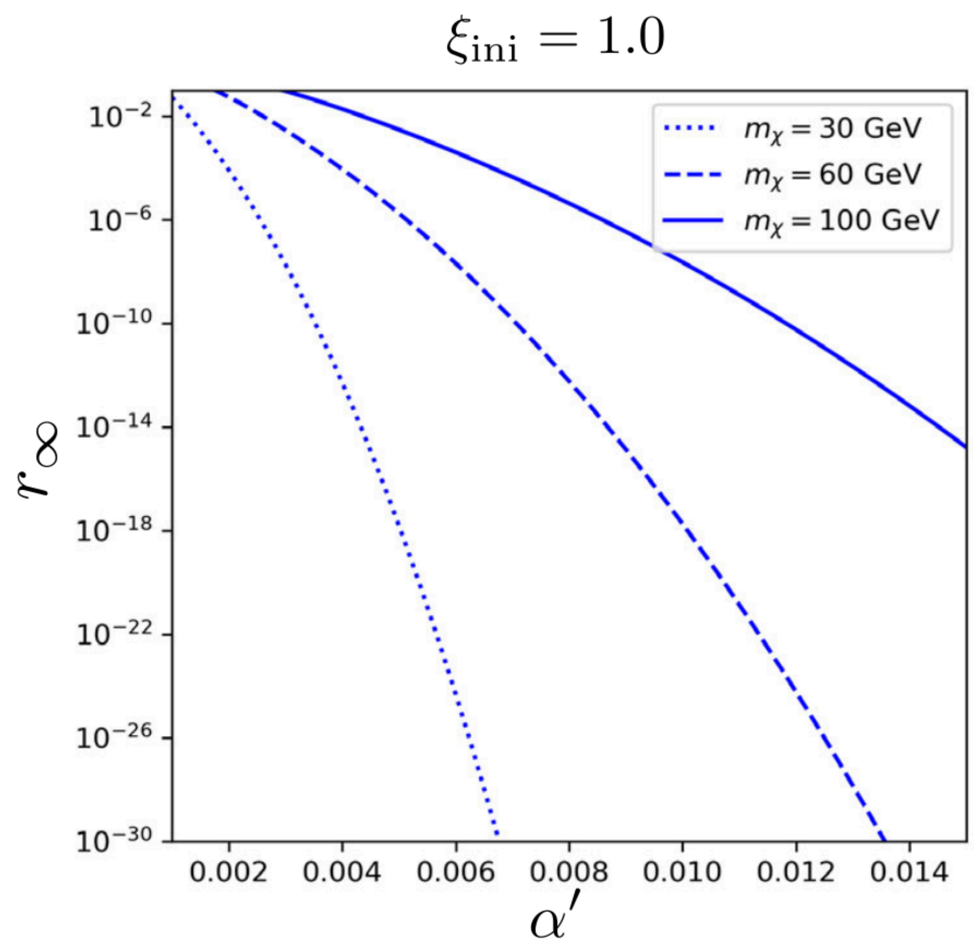
Boltzmann equations:

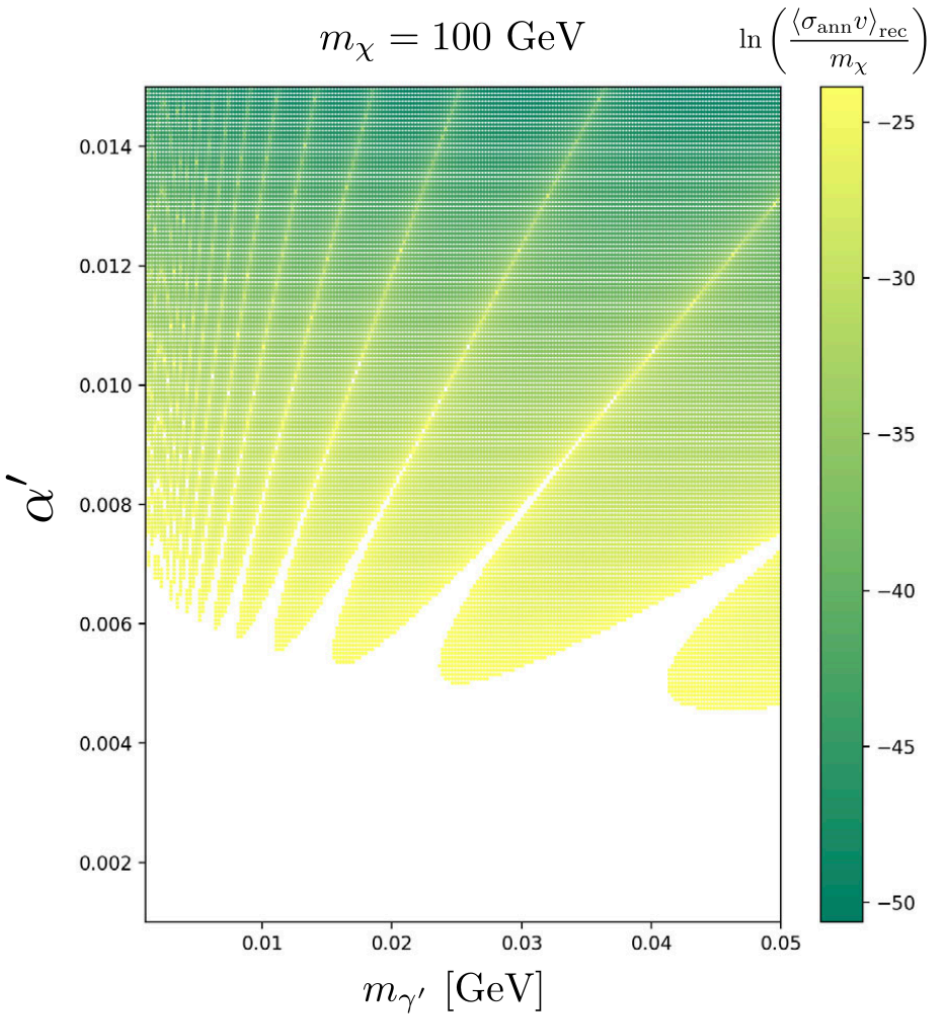
$$\frac{dY_{\chi,\bar{\chi}}}{dx} = -\frac{m_\chi M_{\rm Pl}}{x^2}\sqrt{\frac{\pi g_*}{45}}\langle\sigma_{\rm ann} v\rangle (Y_\chi Y_{\bar{\chi}} - Y_{\rm eq}^{\rm sym} Y_{\rm eq}^{\rm sym})$$

$$\longrightarrow \quad \frac{dr}{dx} \simeq -\frac{m_\chi M_{\rm Pl}}{x^2}\sqrt{\frac{\pi g_*}{45}}\langle\sigma_{\rm ann} v\rangle Y_{\Delta\chi} r.$$

The Minimal Self-Interacting ADM Model

The final ratio is a function of DM mass and coupling strength α'. r_∞ decrease rapidly as α' getting large:





Thus the energy injection during CMB period is very suppressed! There is a large survival region!

Scenario I: Isolated Dark Sector

However, MeV mediator is limited by BBN, CMB, supernova, beam-dump, direct search ……

We don't want to discuss all these limits in one paper. So, to make things easier, we turn off all the portals (Higgs portal, Neutrino portal, kinetic mixing) and make the dark sector isolated from visible sector.

So, the entropy in the dark sector is by itself conserved, if there is no massless dark particles…… overclosure!

To evade overclosure, we need "dark radiation"(DR) in the dark sector. But which can be DR?

χ : DM , $\bar{\chi}$: anti-DM , $A'(\gamma')$: dark photon as the mediator

S_1 : join the dark leptogenesis S_2 : dark Higgs used to break $U(1)'$

N_1, N_2 : dark asymmetry generator

It seems like we have 2 choices: S_1 or S_2. But, S_2 can not be too light (Weinberg bound), so we can only choose S_1 as DR.

Scenario I: Isolated Dark Sector

χ : DM , $\bar{\chi}$: anti-DM , $A'(\gamma')$: dark photon as the mediator

S_1 : join the dark leptogenesis, serve as DR

S_2 : dark Higgs used to break $U(1)'$

N_1, N_2 : dark asymmetry generator

This is the simplified scenario we will study:

Name	Mass range	Role
χ	10 GeV–100 GeV	Dark matter
γ'	1 MeV–100 MeV	Mediator between DMs
N_1, N_2	$M_{N_i} \gg m_\chi$, $M_{N_2} > M_{N_1}$	Generate DM-anti-DM asymmetry
S_2	$m_{s_2} < m_{\gamma'}$	Break $U(1)'$ symmetry
S_1	$m_{S_1} \ll 1$ eV	Dark radiation

Scenario I: Isolated Dark Sector

What is the bound on this isolated "ADM + mediator + DR" scenario?

There are 2 bounds you need to consider:

(1) DR as massless d.o.f. contributes to observed $N_{\rm eff}$.

(2) DM + DR will cause the "dark acoustic oscillations" that might leave its imprint on CMB or LSS.

$N_{\rm eff}$ bound is quite simple:

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad (95\%).$$

$$N_{\rm eff}^{\rm SM} = 3.045.$$

$$\Delta N_{\rm eff} = \frac{8}{7}\left(\frac{T_\nu}{T_\gamma}\right)^{-4}\frac{\rho_{\rm DR}}{\rho_\gamma} = \frac{8}{7}\left(\frac{4}{11}\right)^{-4/3}\left(\frac{2}{2}\right)\left(\frac{T'}{T_\gamma}\right)^4$$

$\rightarrow$

$$\frac{T'}{T_\gamma} < 0.86$$

Dark sector can not be too hot!

Scenario I: Isolated Dark Sector

Dark acoustic oscillations bound is very complicated, but this bound can be replaced by the DM-DR scattering cross-section at kinetic decoupling temperature.

Kinetic decoupling temperature is given by:

$$n_{\gamma'} \langle \sigma v \rangle_{\text{DM-DR}} v_{\text{DM}}^2 \approx H(T'_{\text{dec}})$$

$$n_{\gamma'} \langle \sigma v \rangle_{\text{DM-DR}} v_{\text{DM}}^2 \approx \frac{2.4}{\pi^2} (T'_{\text{dec}})^3 \times \pi \frac{\alpha'^2 (T'_{\text{dec}})^2}{m_{\gamma'}^4} \times \frac{T'_{\text{dec}}}{m_\chi}$$

Then you can obtain a final bound on masses and coupling strength:

$$\frac{\alpha'}{m_{\gamma'}^2 \sqrt{m_\chi M_{\text{Pl}}}} \lesssim 4.7 \times 10^{-3} \ \text{GeV}^{-3}$$

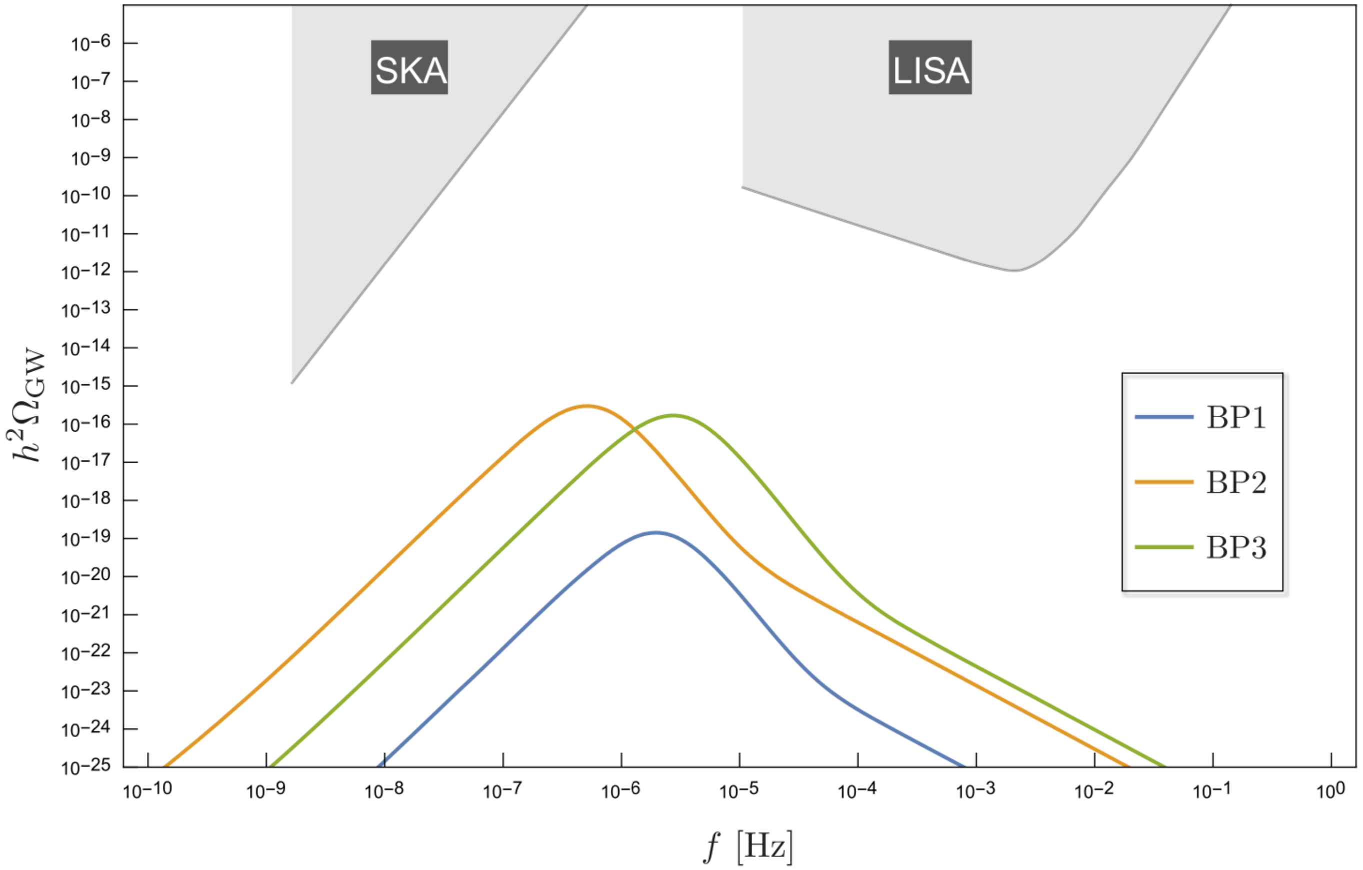
This bound is actually very weak. But why? Because in our model, DM-DR scattering is not Compton-scattering!

Scenario I: Isolated Dark Sector

And, how to detect this scenario?

There is a spontaneous $U(1)'$ symmetry breaking. So, if this SSB is 1st phase transition, then there will be PTGWs.

We choose 3 benchmark points, and do some calculation. But unluckily:



These 3 points give mild super-cooling, so the PTGWs signals are too weak. Certainly we can consider points with strong super-cooling. But in this case, we need to reconsider the $N_{\rm eff}$ bound. (working with Kepan)

Scenario II: Decayed Dark Sector

If the lightest dark particle is unstable (i.e. open the portal), then we don't need DR anymore (S_1 can be heavy and thus be irrelevant).

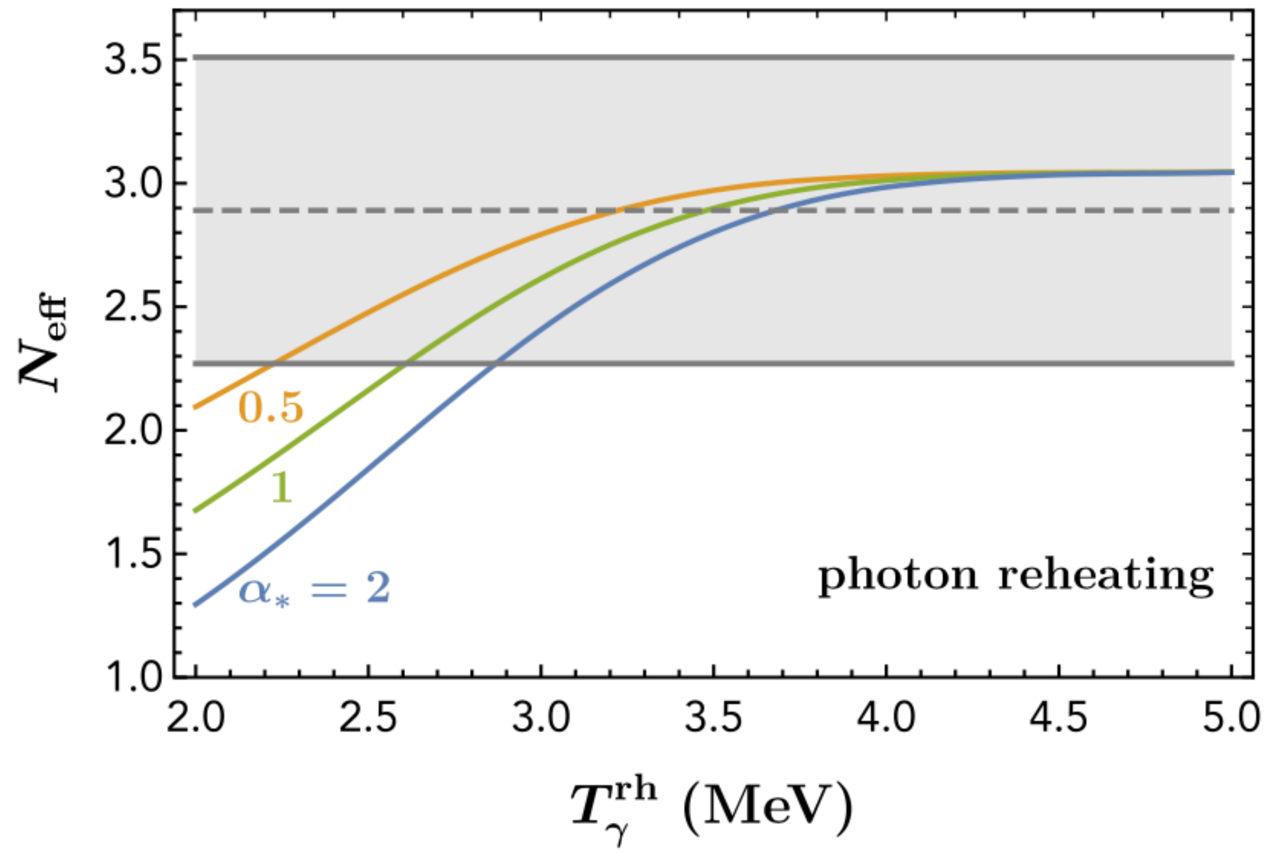
Benefit: the dark $U(1)'$ phase transition can be strong enough to explain recent PTA data (PT strength > 0.1).

Be careful: strong limits from BBN, $N_{\rm eff}$, and DM direct detection.

Scenario II: Decayed Dark Sector

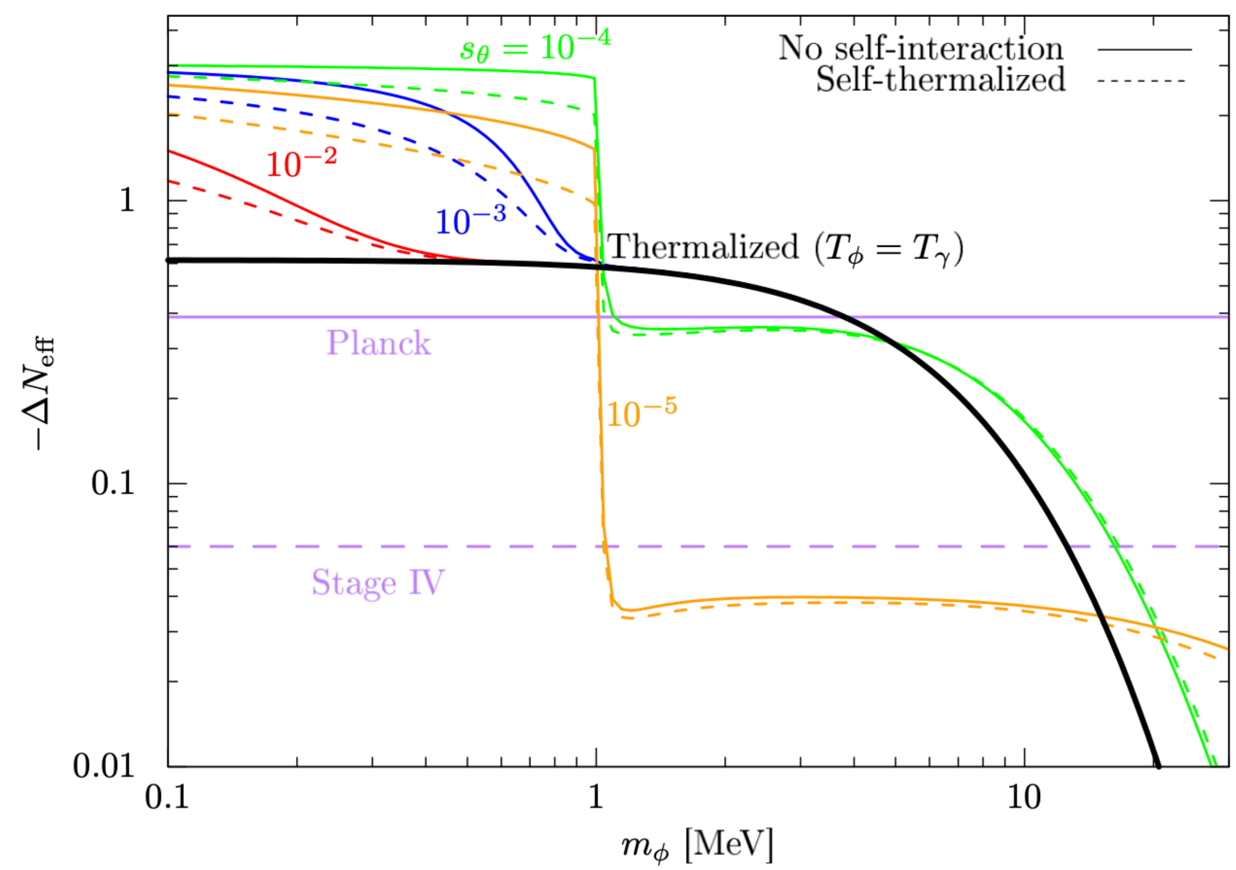
Bound 1: dark $U(1)'$ phase transition should happen before neutrino decoupling

PRD (2022) Y. Bai, M. Korwar



Bound 2: Lightest dark particle should be heavier than 3.8 MeV

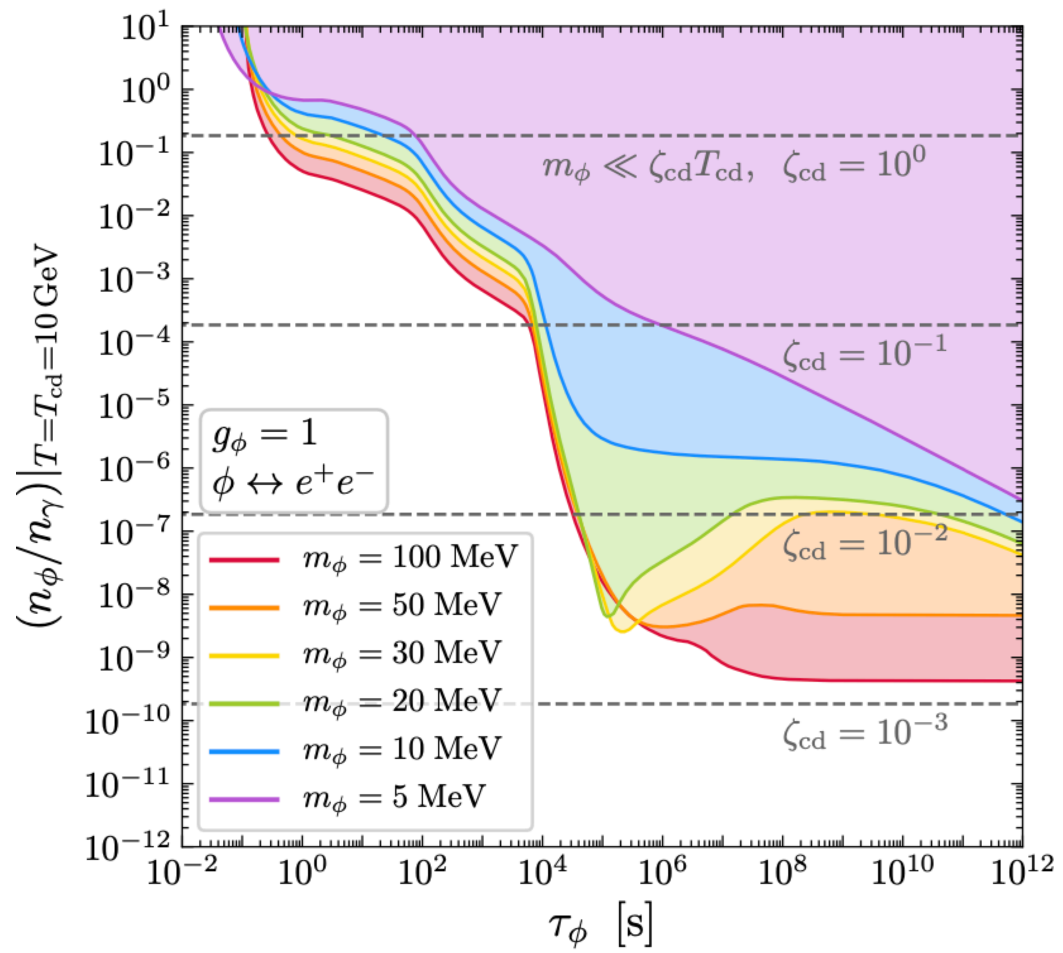
JHEP (2022) M. Ibe, S. Kobayashi, Y. Nakayama, S. Shirai



Scenario II: Decayed Dark Sector

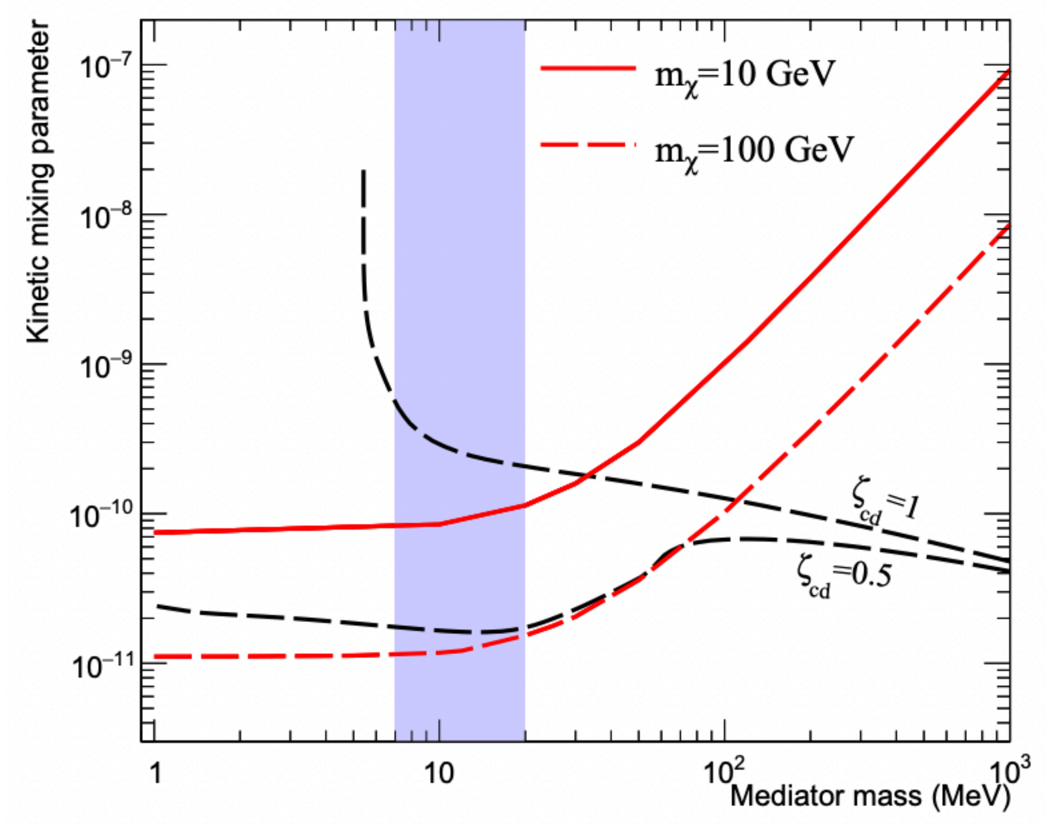
Bound 3: Lightest dark particle should decay before BBN

2011.06519 P. F. Depta, M. Hufnagel, K. Schmidt-Hoberg



Bound 4: Kinetic mixing should be small enough

2104.14724 PandaX-II



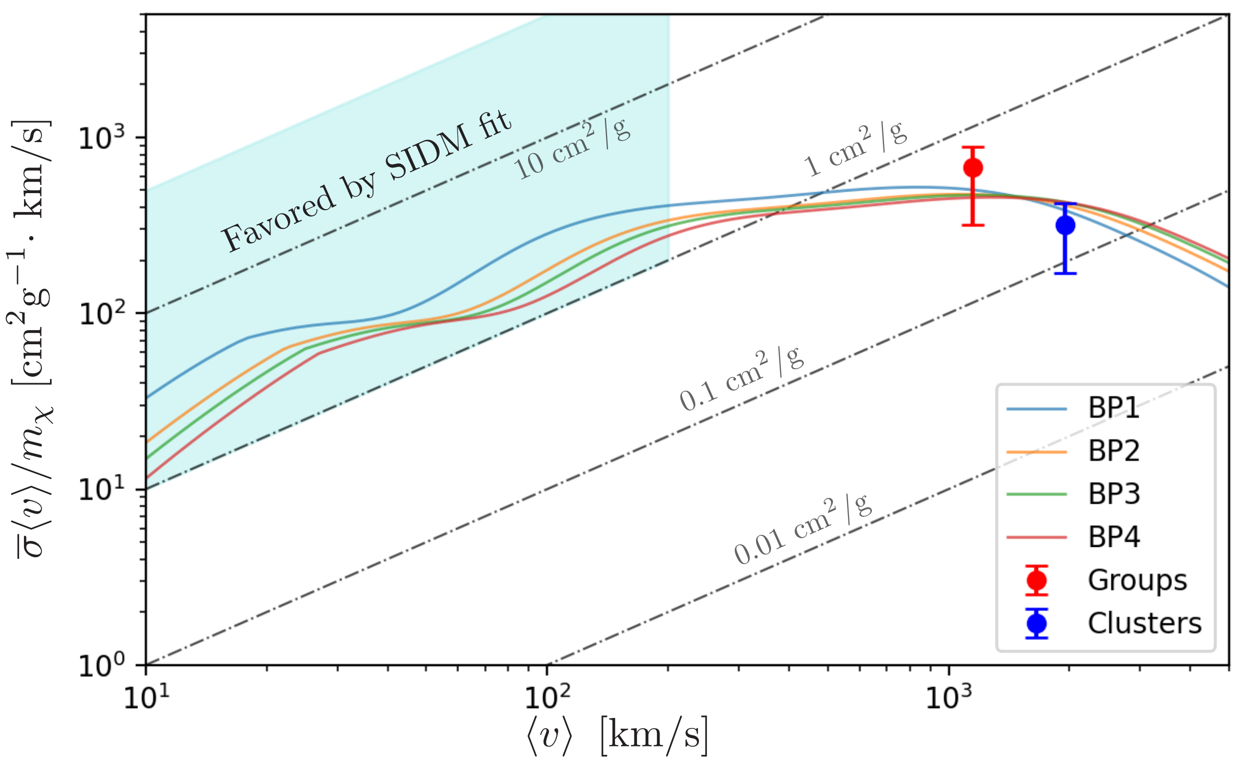
Scenario II: Decayed Dark Sector

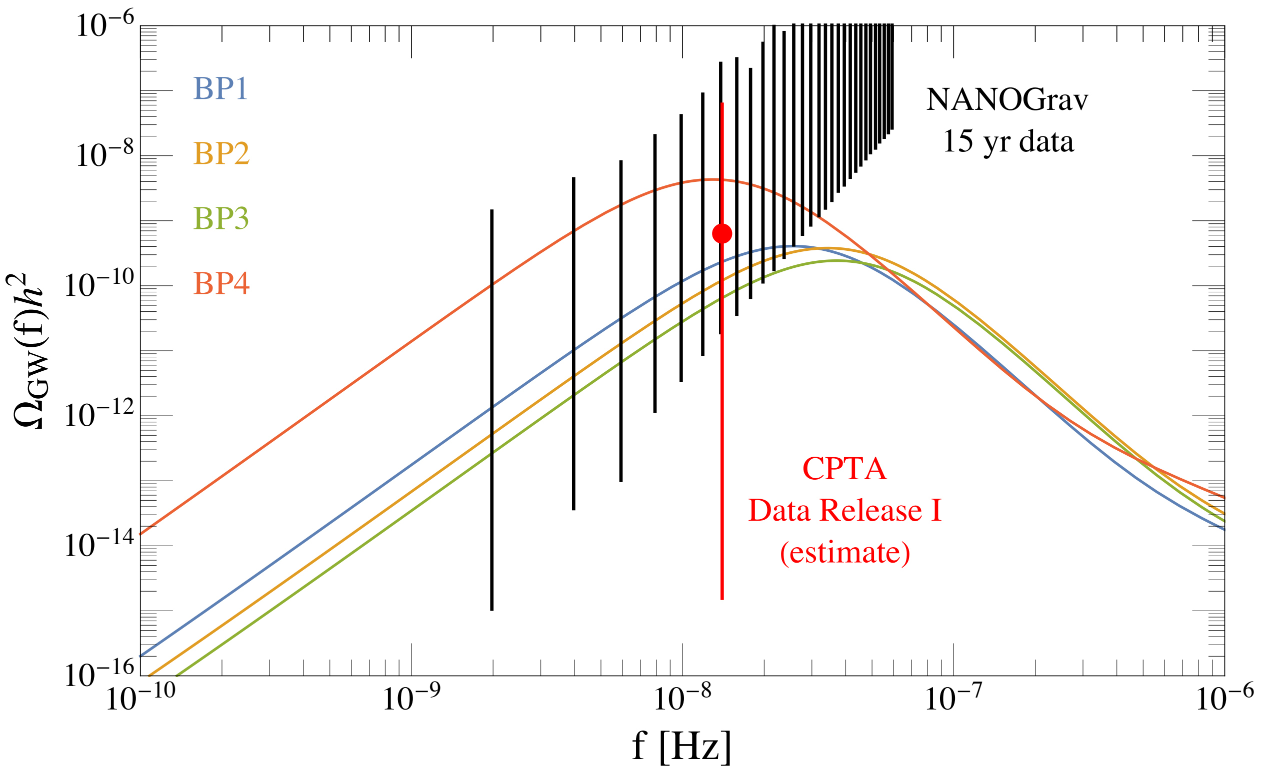
We found some benchmark points that are:

(1) consistent with current bound

(2) can solve small structure problems

(3) can explain recent PTA data





Conclusion:
Self-Interacting ADM — a natural & beautiful model