Yukawa Bound States and Application to Dark Matter

Yue Zhang
Caltech

Workshop on Collider and Dark Matter Physics
TAMU, 2015

Based on:

- Stable Bound States of Asymmetric Dark Matter
  M.B.Wise, **Y.Z.**, 1407.4121

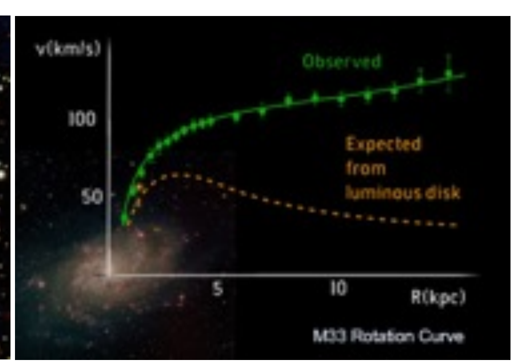
- Yukawa Bound States of a Large Number of Fermions
  M.B.Wise, **Y.Z.**, 1411.1772

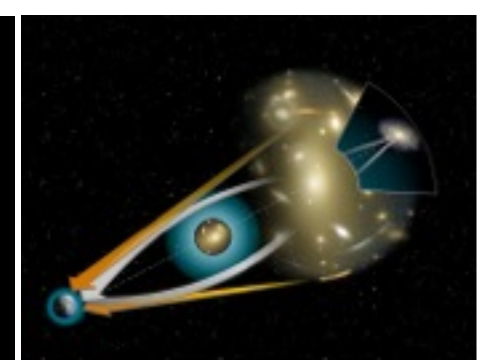
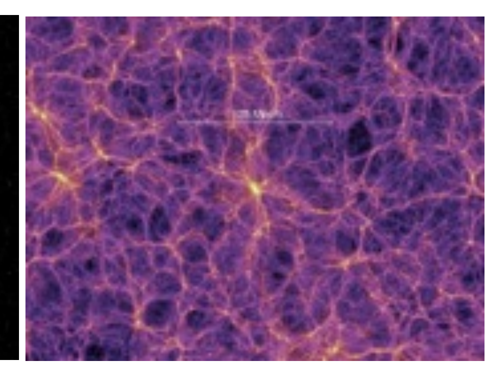
Dark Matter exists

Compelling gravitational evidence

A key member of the universe

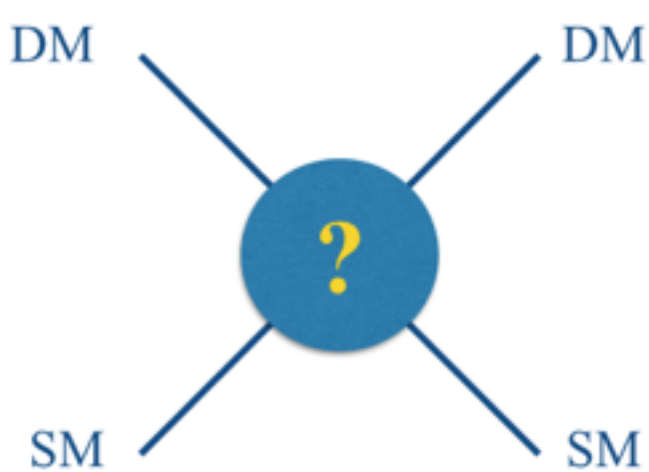
- ~25% of the total energy density
- live long enough
- move slowly enough
- interacting with us weakly enough

Particle physics connection

Rediscover DM using beyond gravity interactions.



- direct detection
- indirection
- produce SM in Labs (*e.g.* colliders)

Need a theory of DM — beyond the Standard Model content.

- From effective operators to simple models to SUSY, GUT…

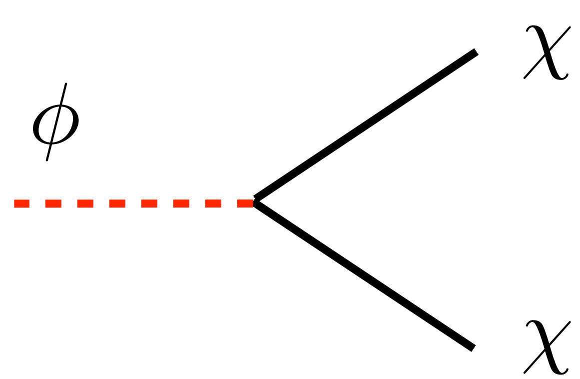
the focus of this talk

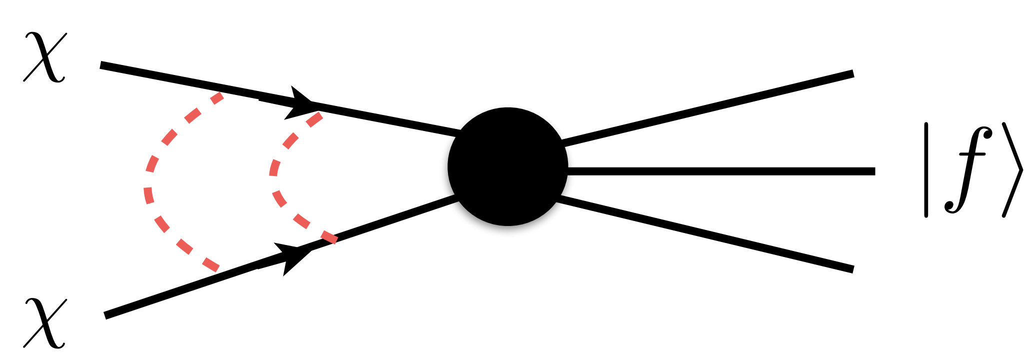
Light mediator to dark matter

Seems favorable for several phenomena in astroparticle physics.

- velocity dependent annihilation (PAMELA).
- velocity dependent scattering (dwarf galaxy).
- relic density for light dark matter (DAMA).
- relative constraints of (in)direct detections (Hooperon).

$(m_\chi \gg m_\phi)$



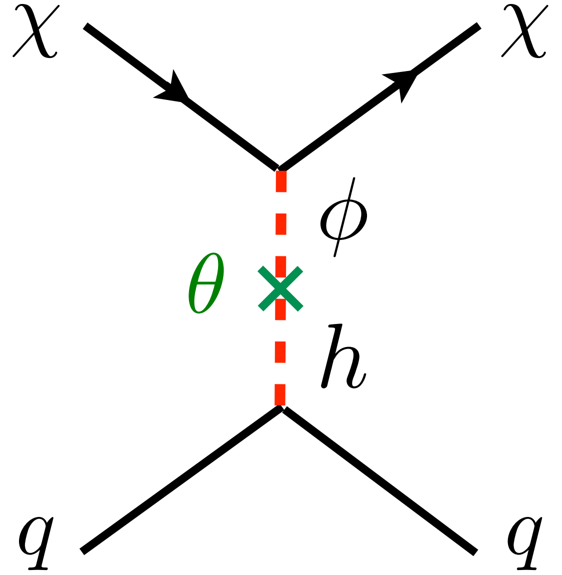


Higgs portal

Higgs boson as the portal to scalar dark force.

Higgs discovery at the LHC gives strong motivation.

$$\mathcal{L}_{\rm dark} \sim m_\chi \bar{\chi}\chi + \frac{1}{2} m_\phi^2 \phi^2 + g_\chi \bar{\chi}\chi\phi + \mu_{\phi h}\phi(H^\dagger H - v^2/2)$$

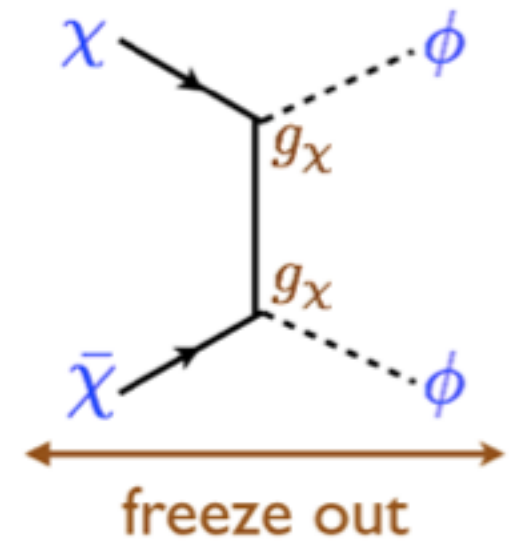


dark matter: χ light mediator: ϕ (SM singlets)

$$\theta \approx \frac{\mu_{\phi h} v}{m_h^2}$$

Such a simple model can already offer very rich dynamics.

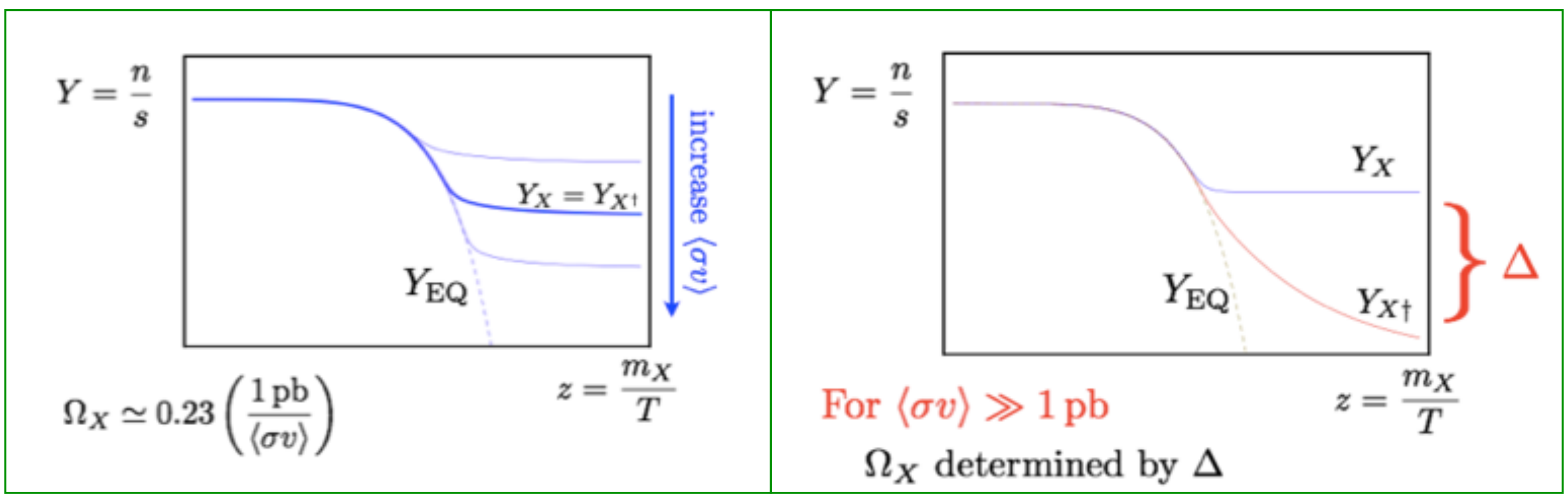
Thermal relic density



WIMP miracle vs Asymmetric DM

Initial conditions:

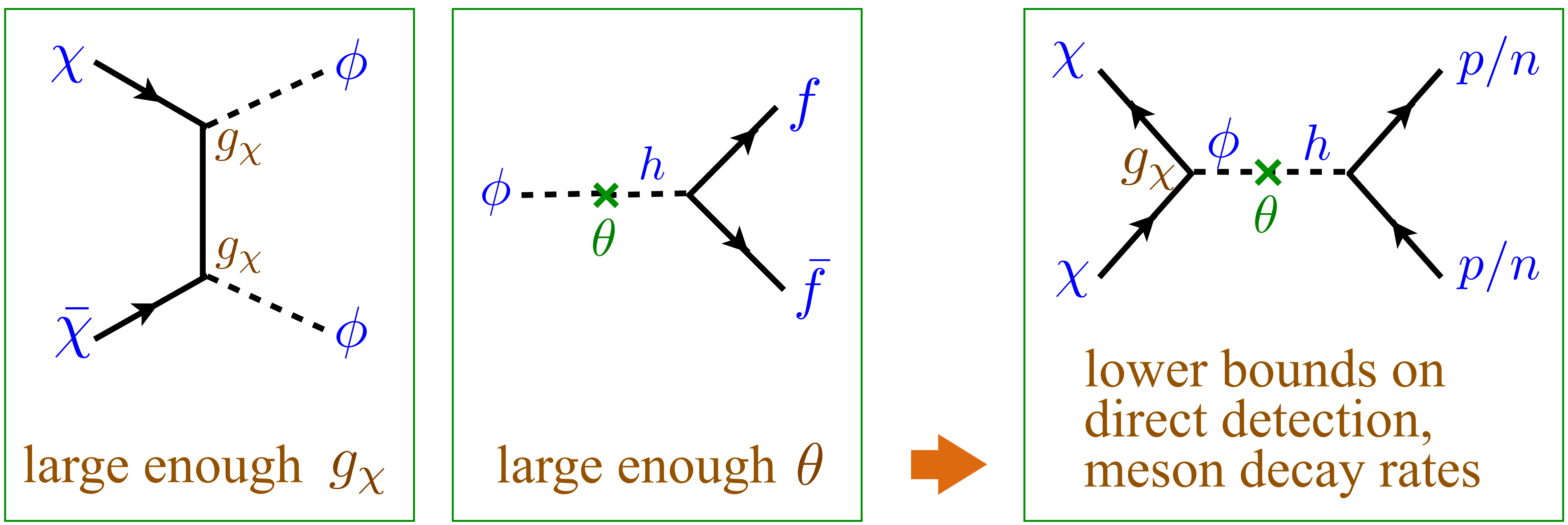
- symmetric DM case: $n_\chi = n_{\bar{\chi}}$
- Asymmetric case: $n_\chi - n_{\bar{\chi}} = \Delta$



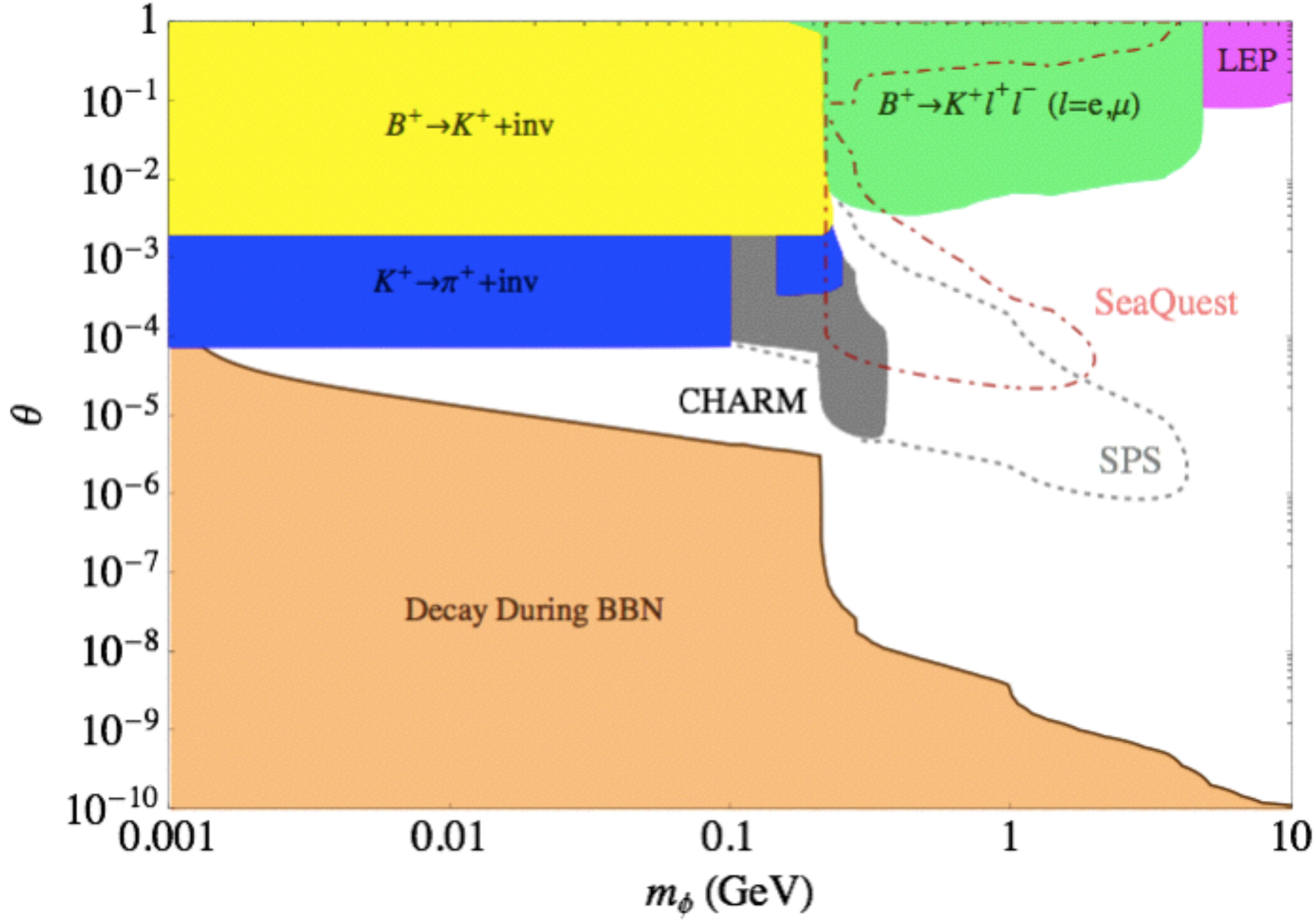
Mediator decay

If mediator gets thermalized and has mass >MeV, better decay before BBN.

In this simple model, decays into SM particles via Higgs.

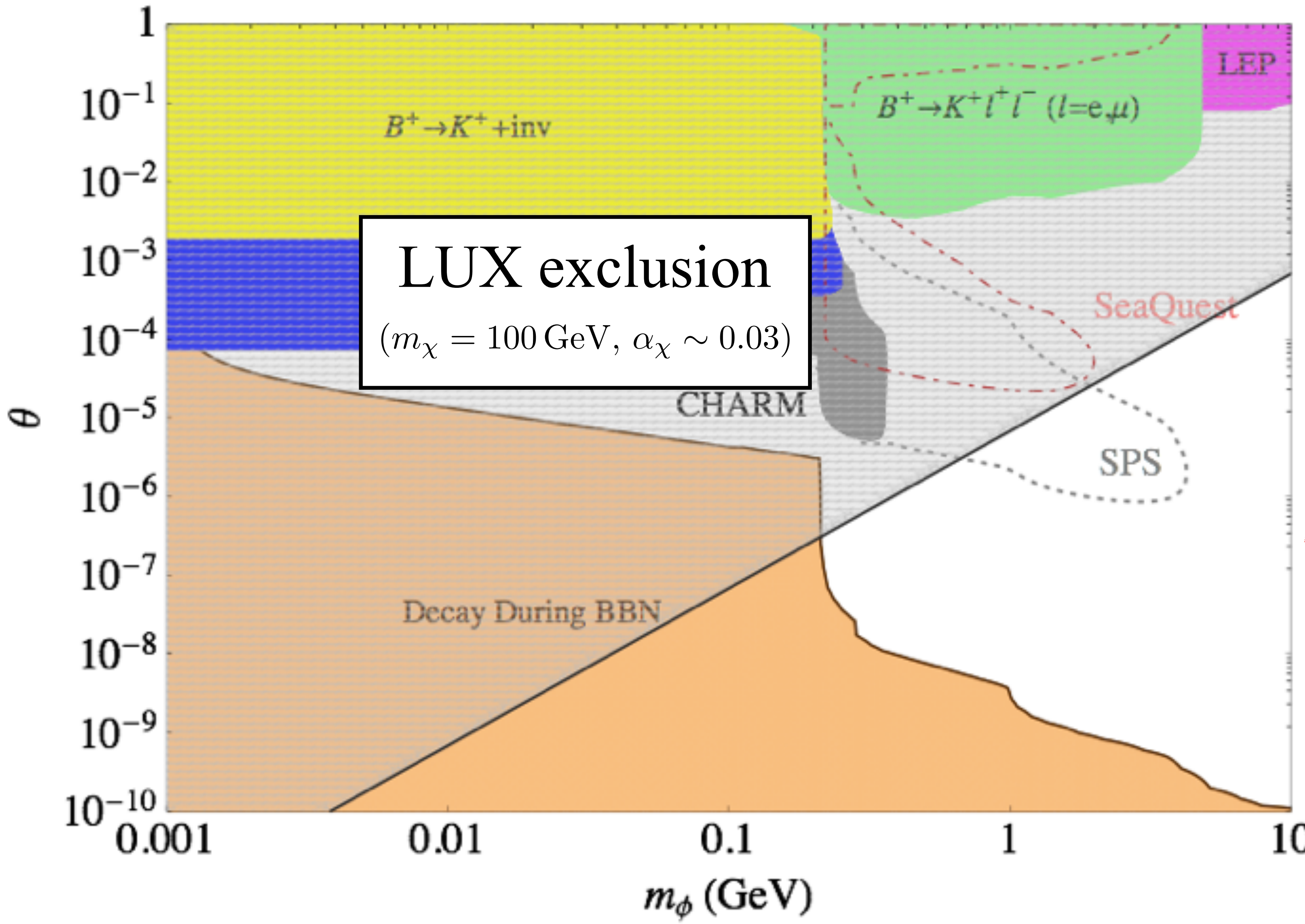


Constraints



Lower bound on the mediator mass.

Constraints



fix $\theta \sim 10^{-7}$ hereafter

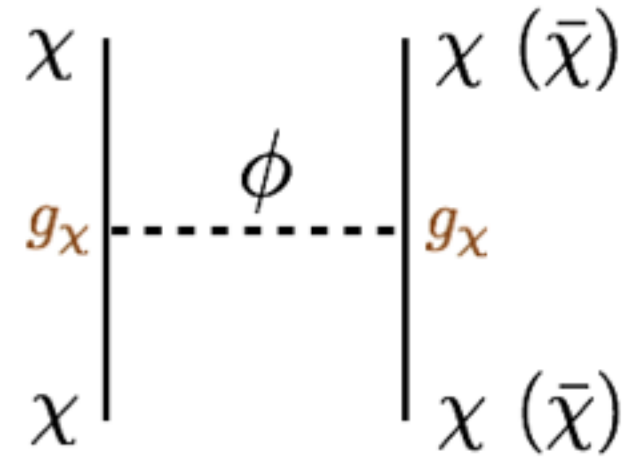
Lower bound on the mediator mass.

Bound states of dark matter

In our world, SM makes many kinds of bound states.

The simple dark sector here can already offer the existence of dark matter bound states.

bound state condition: $$\frac{1}{\alpha_\chi m_\chi} \lesssim \frac{1}{m_\phi}$$



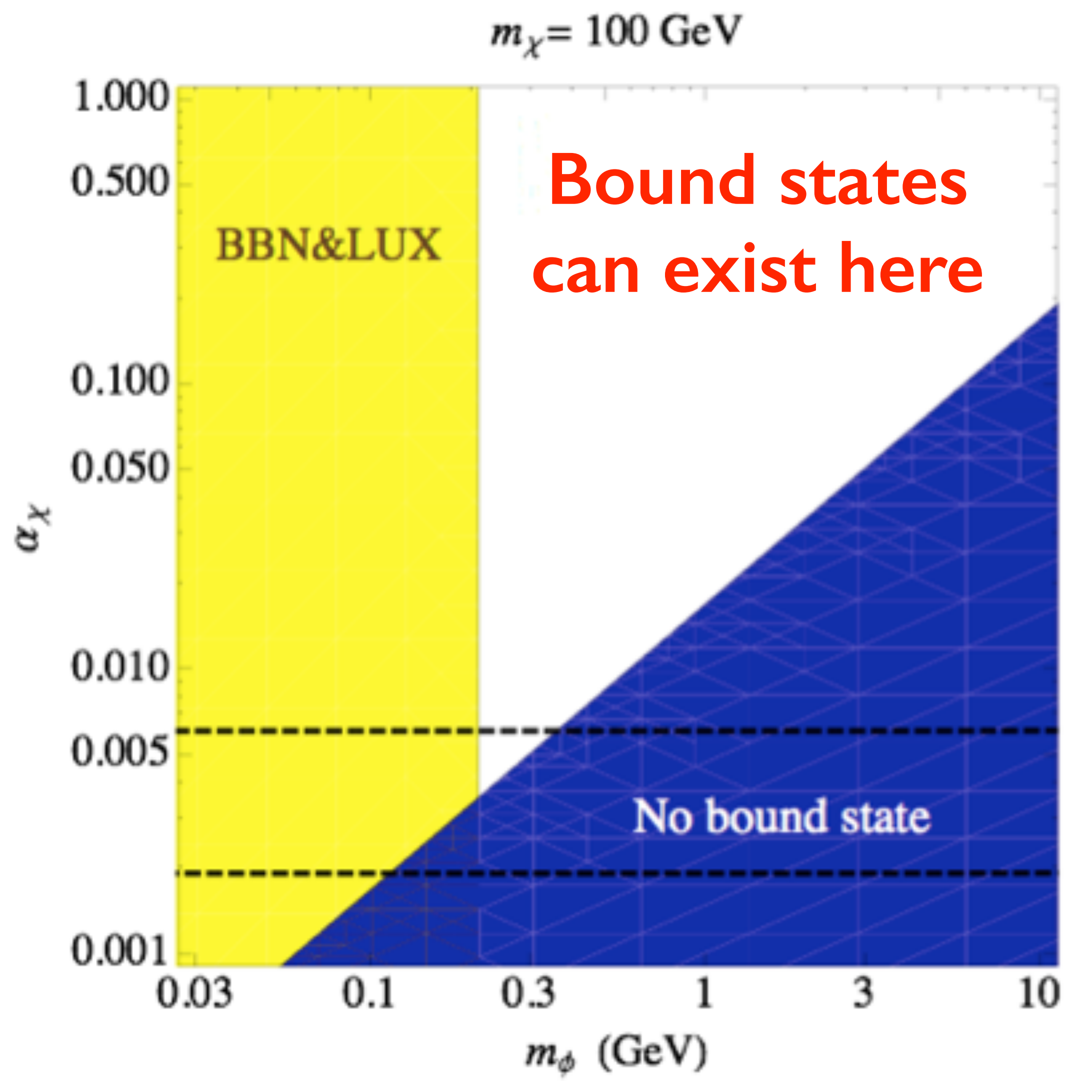
Bohr radius < screening length

Unlike *U(1)*, Yukawa coupling from ϕ exchange is always attractive, and does not neutralize.

$\Rightarrow$ many body bound states

Wise, **Y.Z.**, arXiv:1407.4121

Stable bound states



Bound states can widely exist in parameter space

$(\chi\chi)$ cosmologically stable.

mostly formed if only χ is around

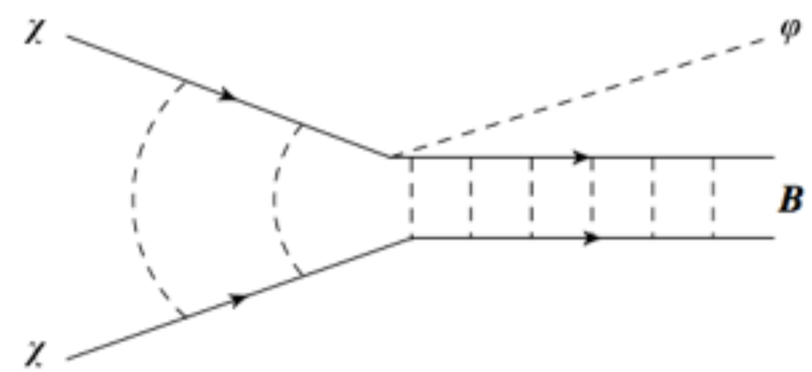
$(\chi\bar{\chi})$ unstable.

Also unlike *U(1)* case (atomic DM), stable Yukawa bound state does not need two species of asymmetric DM.

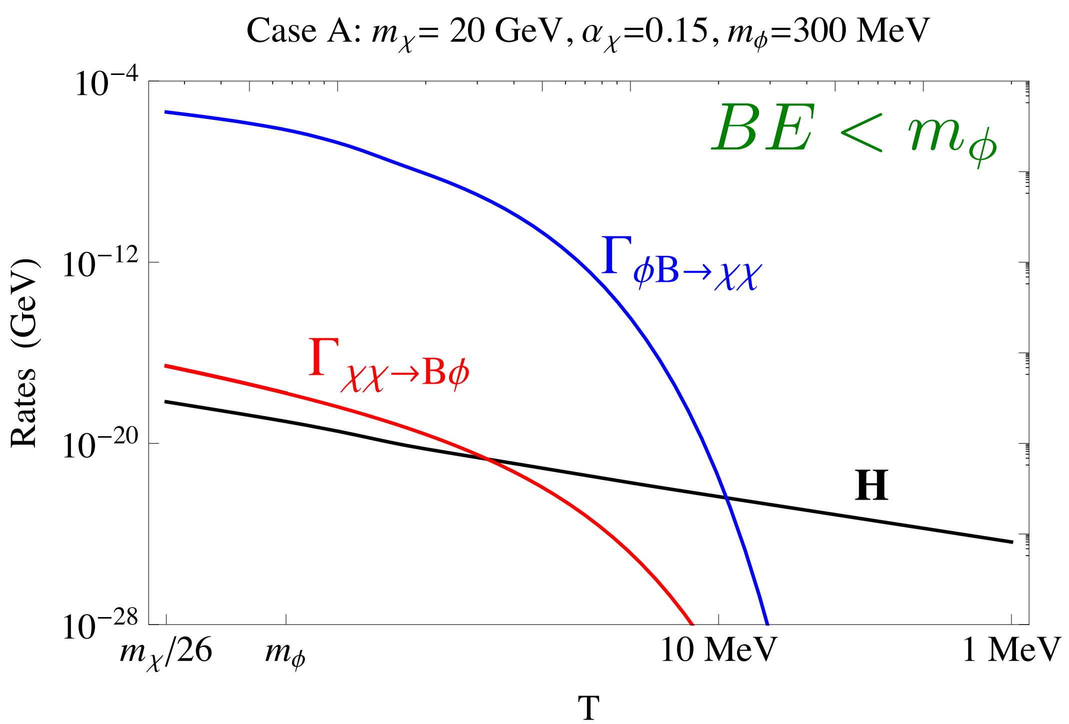
Wise, **Y.Z.**, arXiv:1407.4121

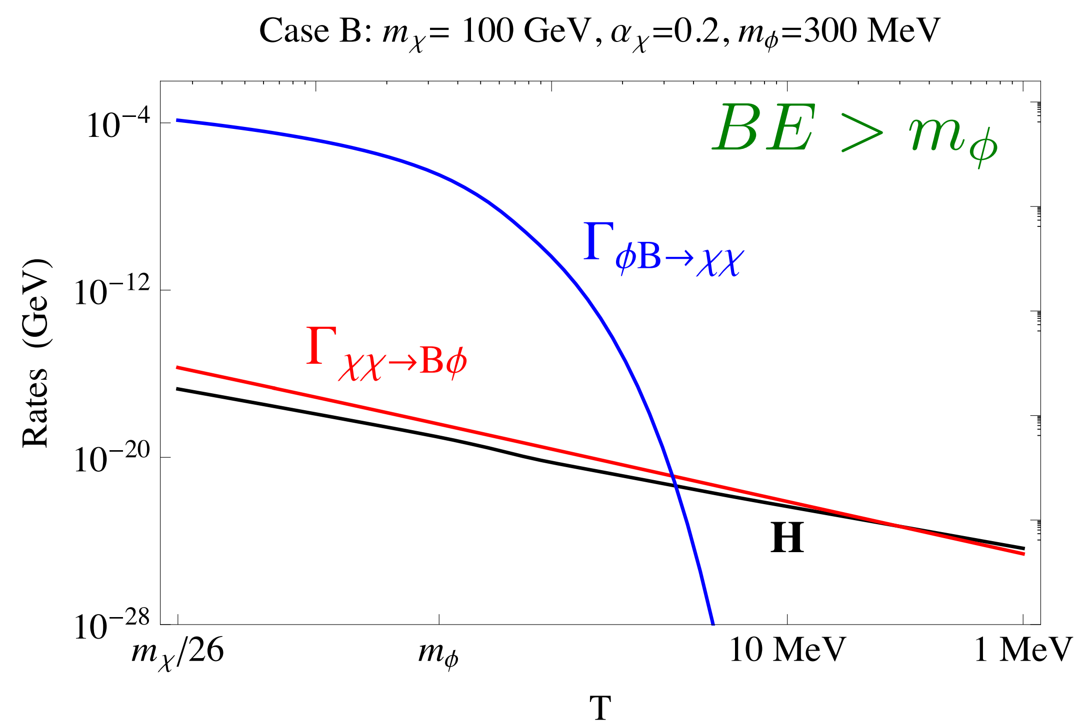
Formation in early universe

Shortly after thermal freeze out if an asymmetry in χ number is left over.



Two scenarios:





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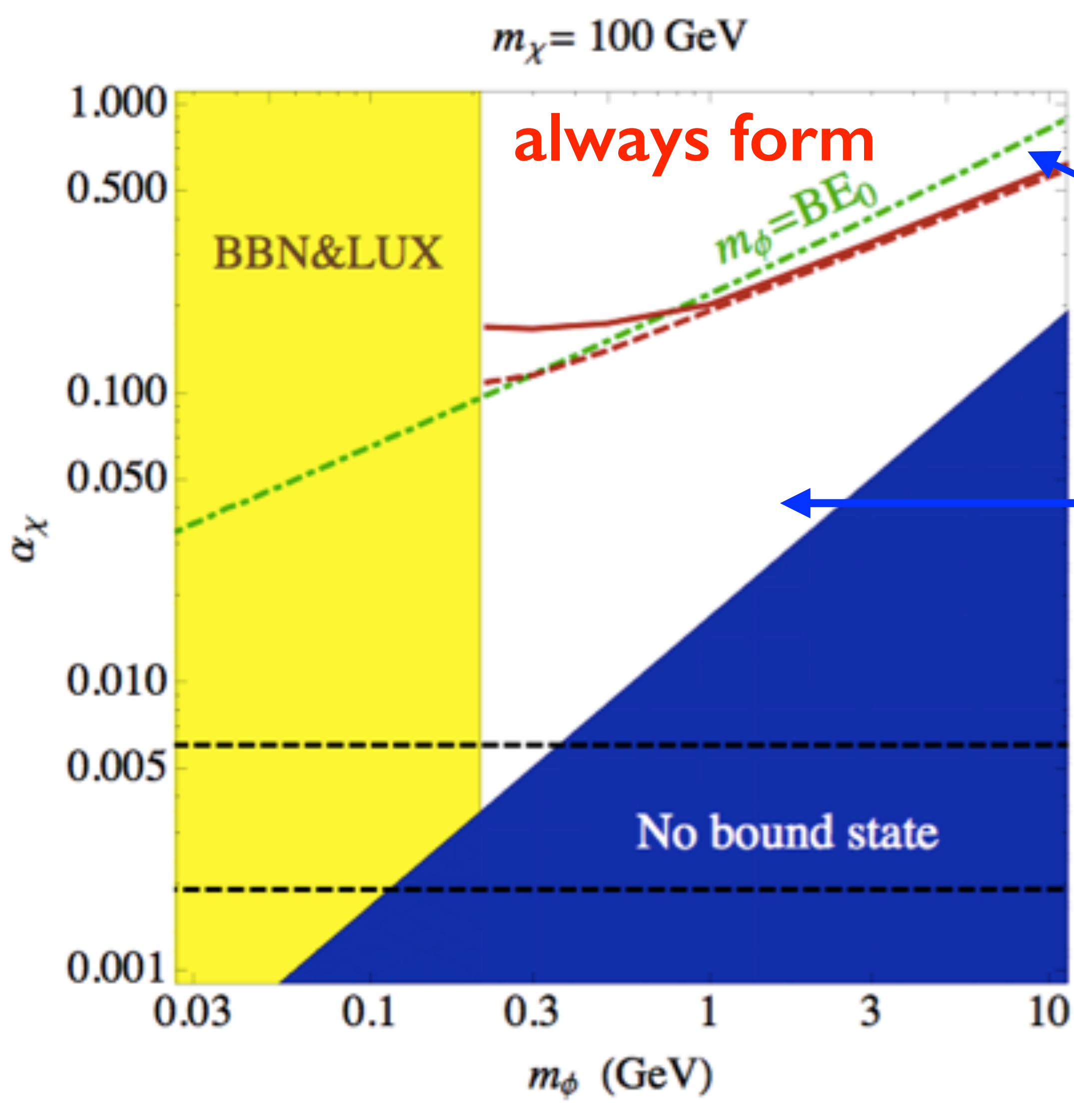
Formation in early universe



form at high T with kinetic energy

cannot form in early universe

but could with high local densities, in galactic center, inside neutrons stars.

— observable signatures today.

(based on calculation of two body bound state formation)

Wise, **Y.Z.**, arXiv:1407.4121

N-body bound states

Interaction through scalar exchange always attractive.

Basic properties of states with *N>>2* — use statistical mechanics.
(nuggets)

We consider a degenerate Fermi gas picture (fixed *N*)

Treat χ particles inside nugget as classical point sources

Effective classical Lagrangian

$$L = -\sum_i (m_\chi + g\phi(\mathbf{x}_i))\sqrt{1-\dot{\mathbf{x}}_i^2} - \frac{1}{2}\int d^3x \nabla\phi\nabla\phi$$

Wise, **Y.Z.**, arXiv:1411.1772

Hydrostatic equilibrium

Forces acting on a χ particle inside nugget

- Attraction due to ϕ exchange
- Repulsion due to degeneracy pressure.

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Hydrostatic equation for $p_F(r)$

$$\left(\frac{r^2}{3\pi^2}\right) p'_F(r) \frac{p_F(r)^4}{\sqrt{m(r)^2 + p_F(r)^2}} = -\frac{g_\chi}{\pi^2} \nabla^2 \phi(r) \int_0^r dr' r'^2 m(r')^3 i(p_F(r')/m(r'))$$

coupled to the Laplacian equation for ϕ field.

$$\nabla^2 \phi(\mathbf{x}) = g_\chi \sum_i \delta^3(\mathbf{x} - \mathbf{x}_i) \frac{m(\mathbf{x}_i)}{\sqrt{\mathbf{p}_i^2 + m(\mathbf{x}_i)^2}}$$

In practice we take ansatz of $p_F(r)$ and minimize $E(R)$.

Wise, **Y.Z.**, arXiv:1411.1772

Generic features

Interesting behaviors of N dependence in R:

- when $N < \alpha_\chi^{-3/2}$, non-relativistic regime (c.f. degenerate star)

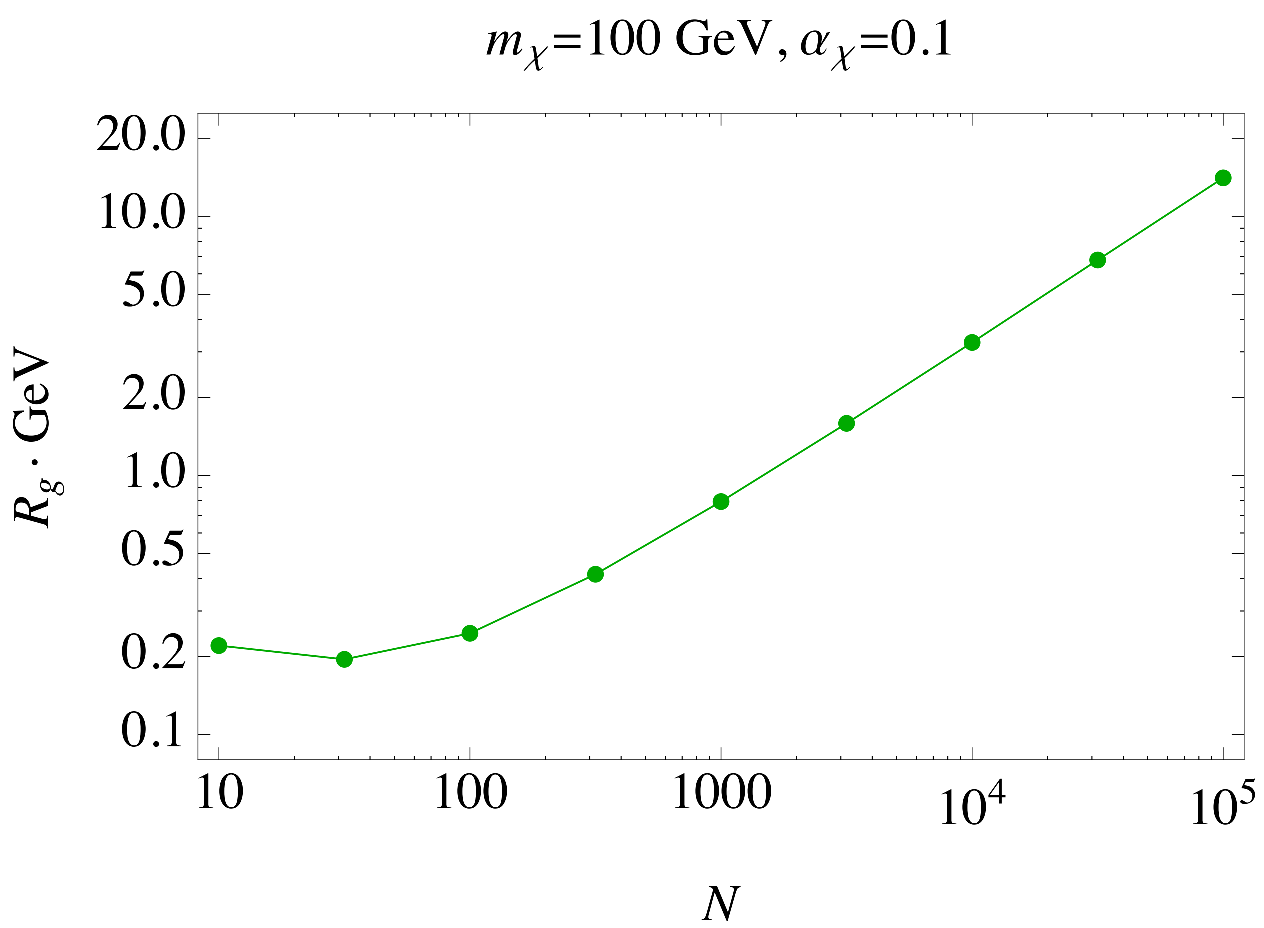
$$\Rightarrow R \sim \frac{1}{\alpha_\chi m_\chi N^{1/3}}$$

- Yukawa force gets weaker for relativistic particles

$$y_\chi \bar{\chi}\chi\phi \sim y_\chi \frac{m}{E} \chi^\dagger \chi \phi \qquad \Rightarrow R \sim \frac{\alpha_\chi N}{m_\chi}$$

Wise, **Y.Z.**, arXiv:1411.1772

Nugget properties



Example of supermassive DM with thermal freeze out history.

General behavior of bound states from Yukawa theory — may have applications other than dark matter.

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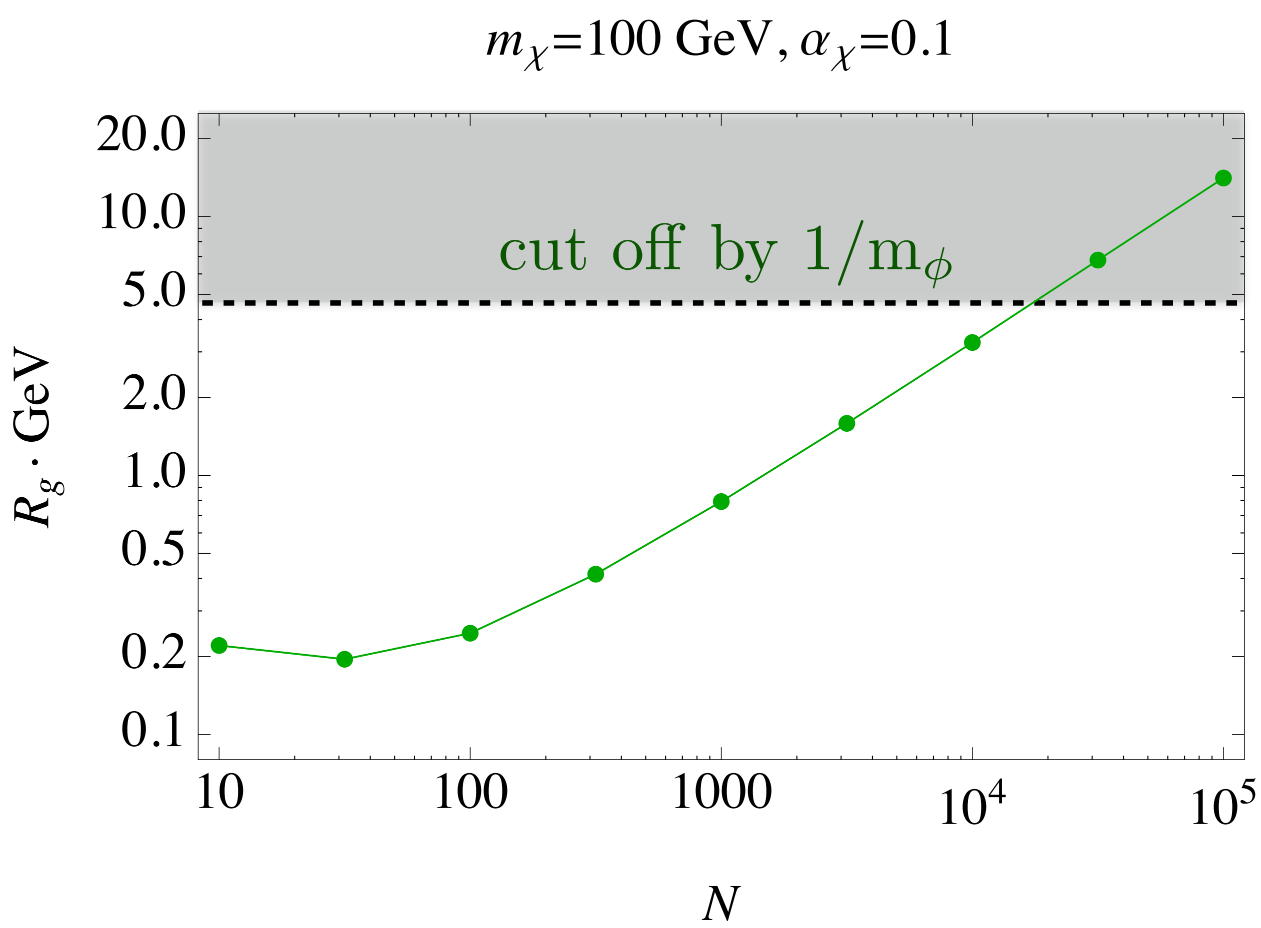
Nugget properties



very heavy bound states allowed

Example of supermassive DM with thermal freeze out history.

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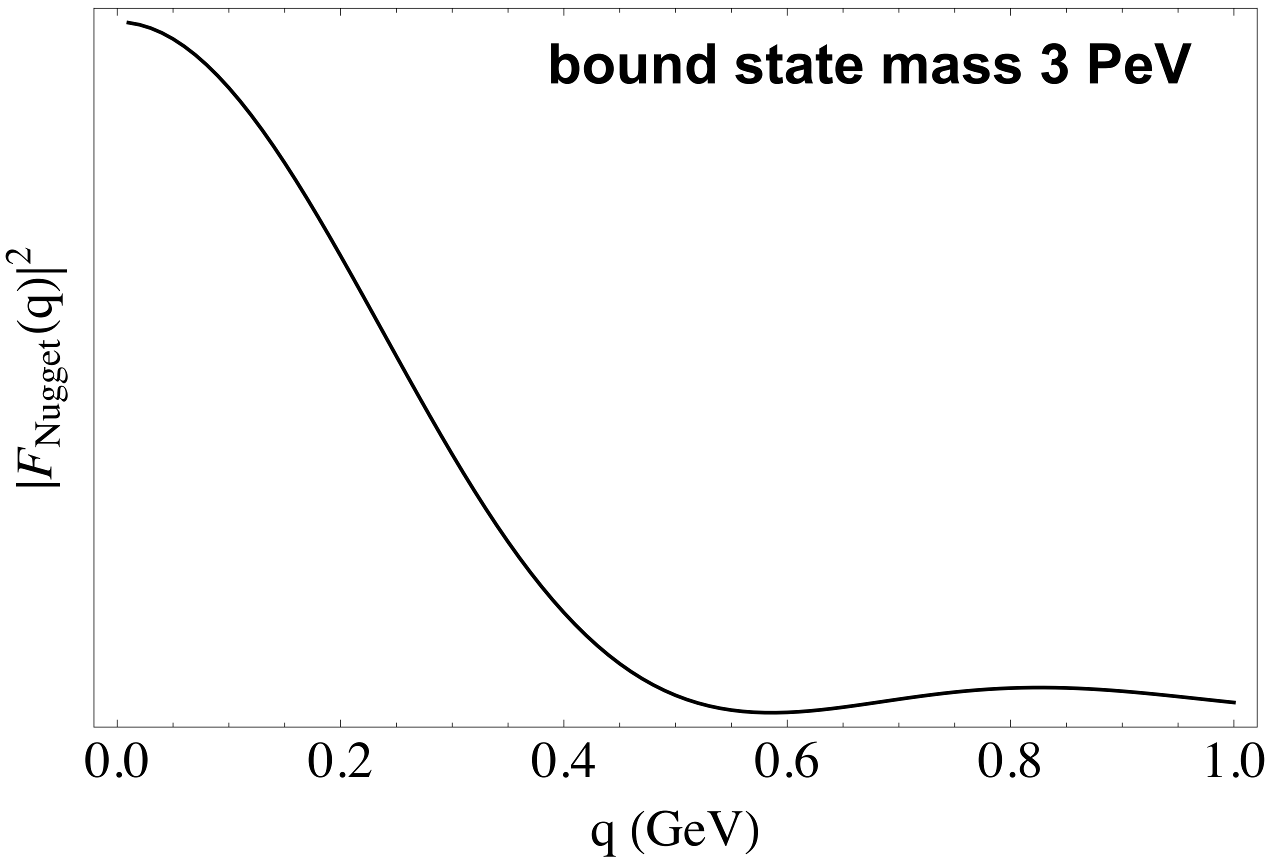
Possible signals

Direct detection rate:

$$n\sigma v \sim \frac{1}{N_\chi}\left[N_{Xe}F_{Xe}(q^2)\right]^2 \boxed{\left[N_\chi F_{Nugget}(q^2)\right]^2}$$

1 for usual elementary DM

α_χ=0.1, m_χ=100 GeV, N=3×10^4, R=6.8/GeV



- coherence enhancement
- additional q-dependence
- many species (N)

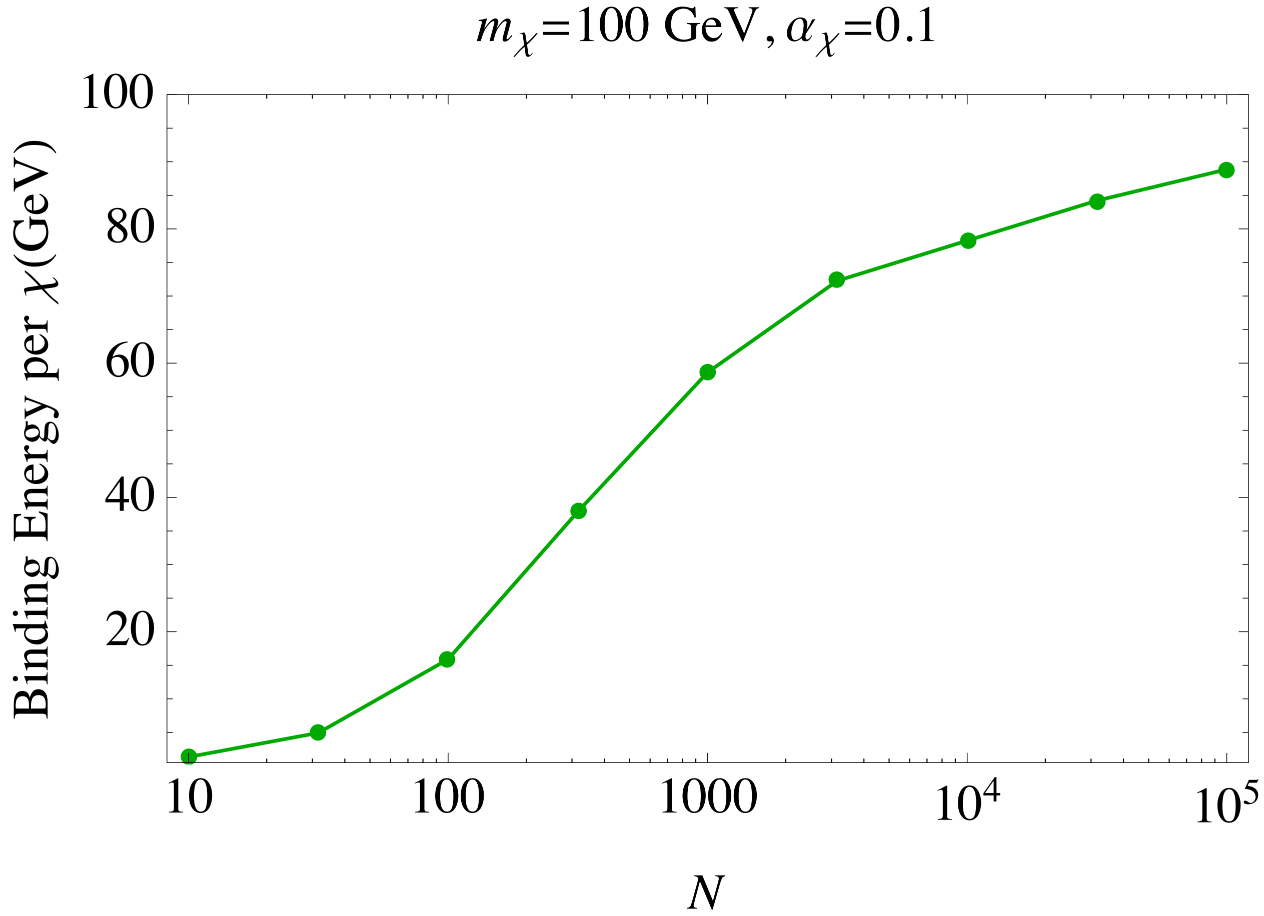
Wise, **Y.Z.**, arXiv:1411.1772

Possible signals

Indirect detection:

Release binding energy when Nuggets meet and merge.

$$(N_1) + (N_2) \to (N_1 + N_2) + \text{many } \phi' s$$



Expect:

- $e^+, \nu, \gamma' s$ from *e.g.*, galactic center, the Sun.
- Inside neutron star, affect cooling.

Wise, **Y.Z.**, arXiv:1411.1772

Possible signals

Dark nucleosynthesis:

To know the distribution *n(N)*, solve ~10^4 BBN equations.

An attempt: Hardy, Lasenby, March-Russell, West, 1411.3739

Impact on structure formations:

Warm DM: recoil with binding energy release when Nuggets merge.

Clumping: largest bound state could stick together via surface force.

Core/cusp problem etc.: must be solved with bound states.

Take home messages

- New scalar dark force offers rich phenomenology.
- Yukawa bound states of dark matter are the natural consequence of this simple setup.
- If they do exist in Nature, offer rich and new phenomena, those not expected for elementary dark matter.
- Current and future experiments also explore the mixing of scalar mediator with the Higgs boson.

Thank you!