Light Mediator and Dark Matter Bound States: models and signatures

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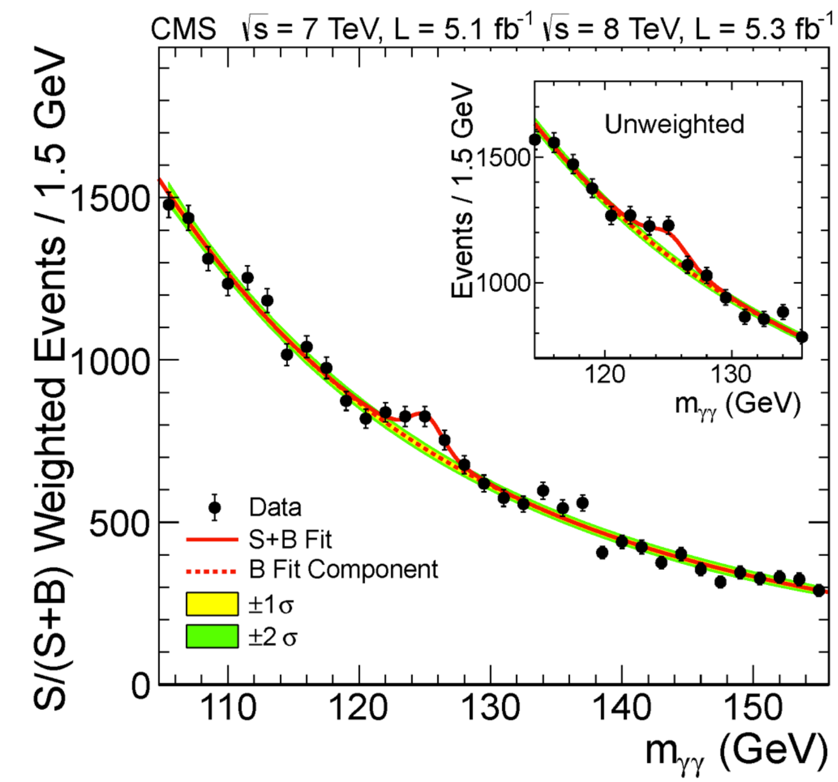
Theory seminar at LANL, 18 March 2015

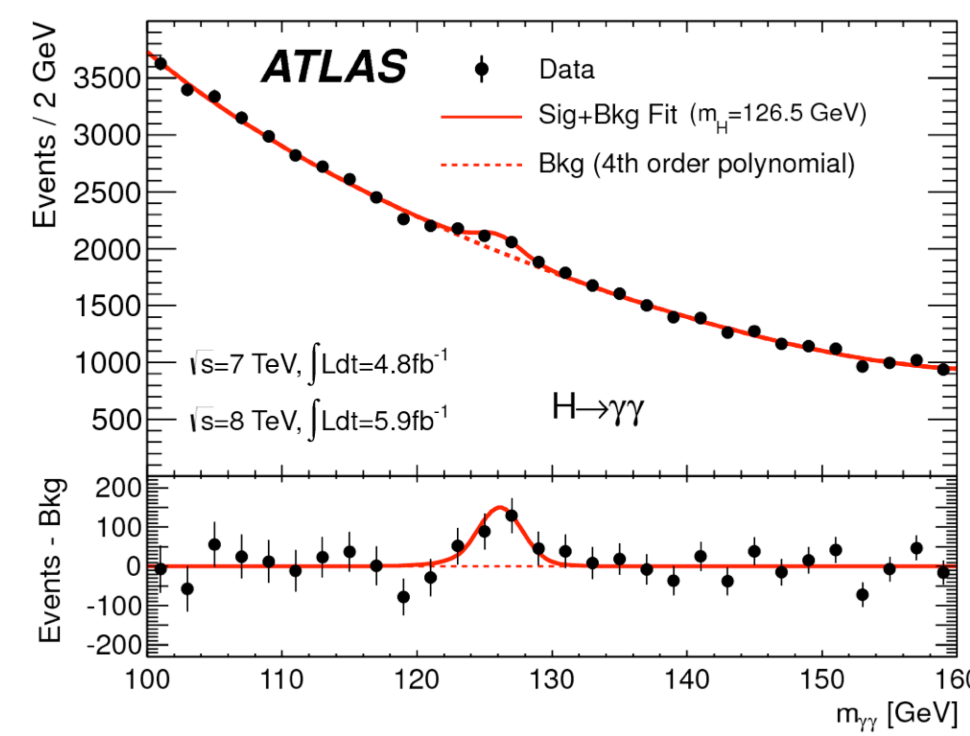
M.B.Wise, Y.Z., 1407.4121
M.B.Wise, Y.Z., 1411.1772
Y.Z., 1502.06983

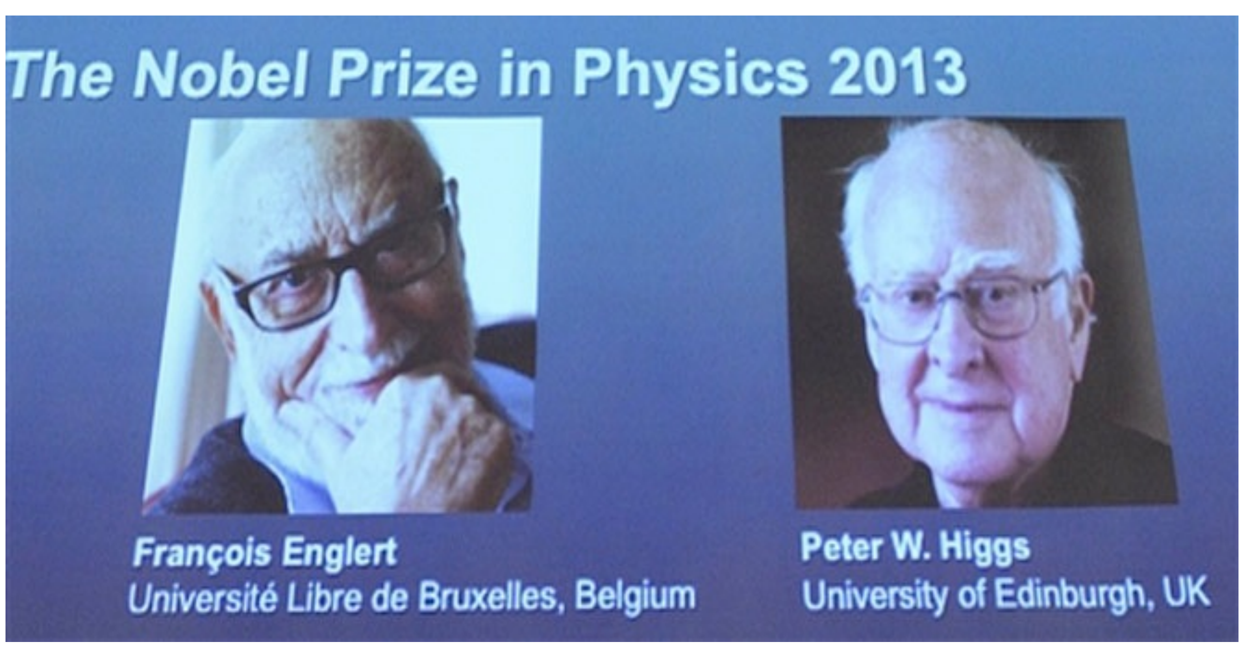
Discovery of a boson

- LHC found a spin-0 particle with mass 125-126 GeV.
- Look like SM Higgs boson.

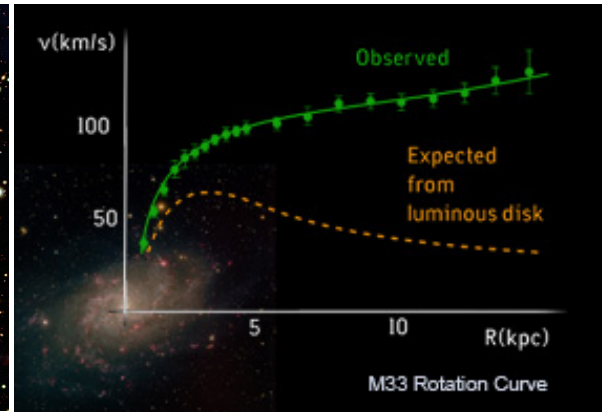


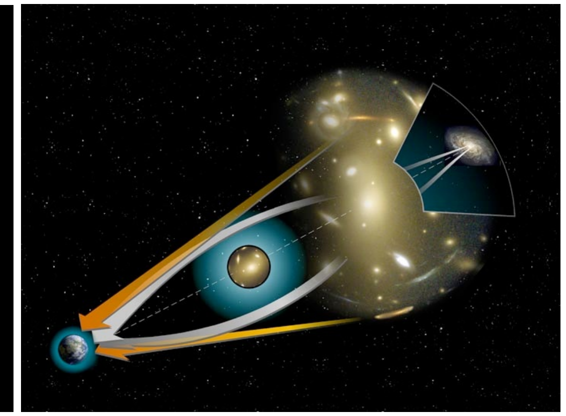
Milestone in particle physics

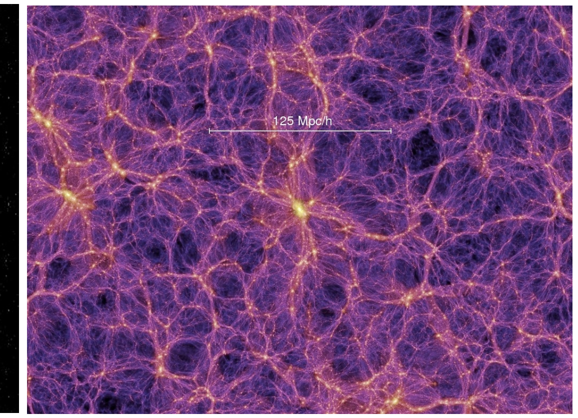




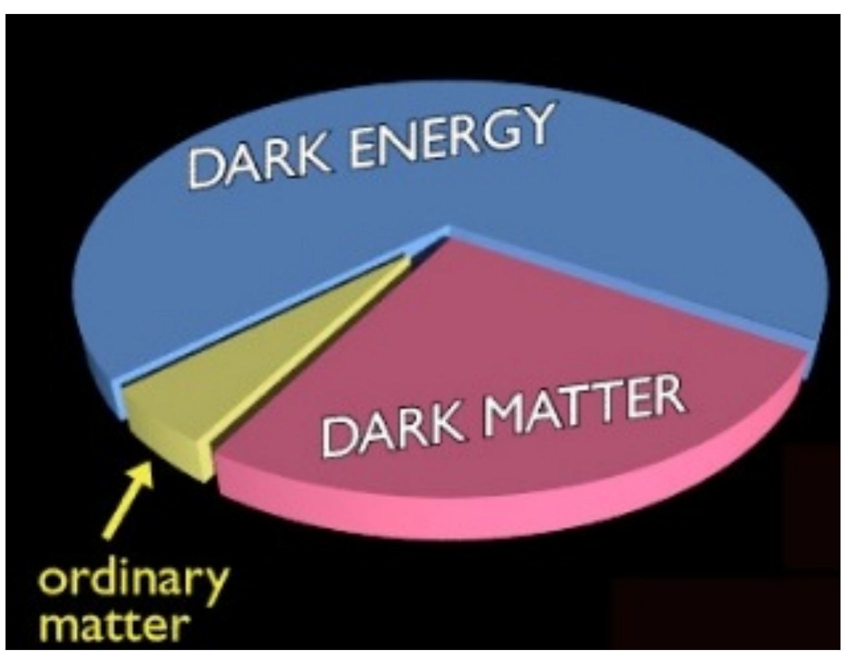
Dark Matter







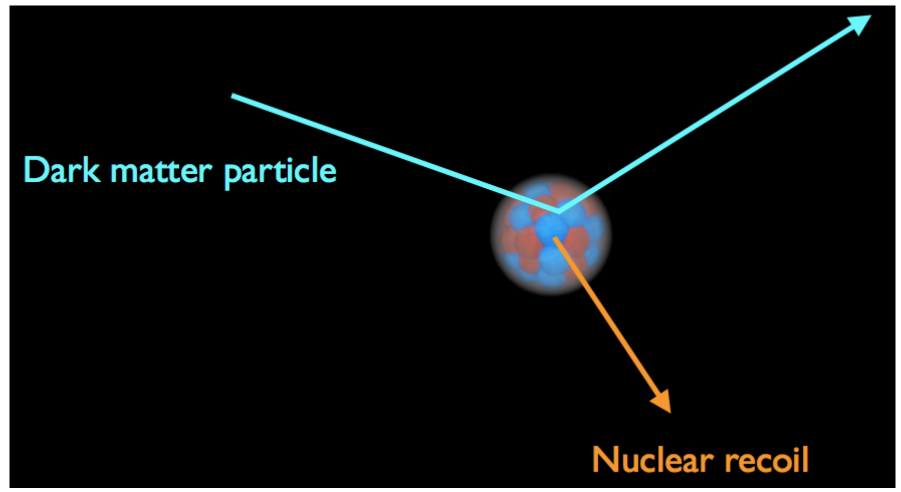
- Compelling evidence for its existence.
- DM contributes 23% of the total energy budget.



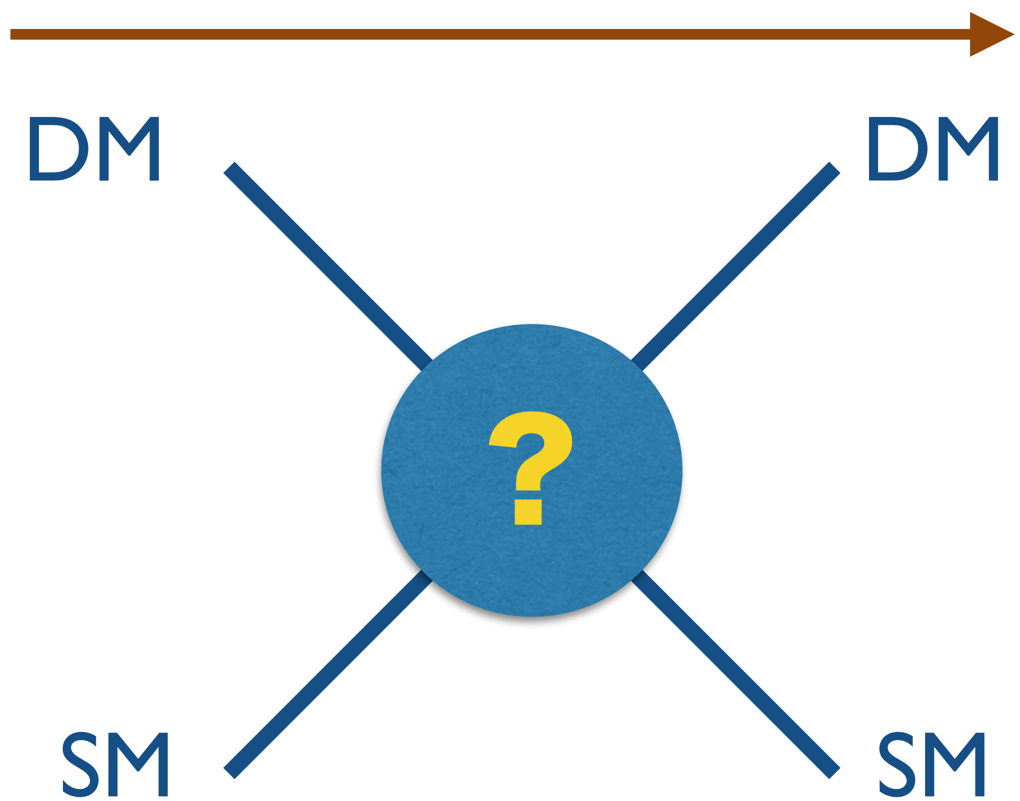
- Cosmologically long lived.
- Non-relativistic.
- (less than) weakly interacting.

Particle physics Standard Model contains no DM candidate.

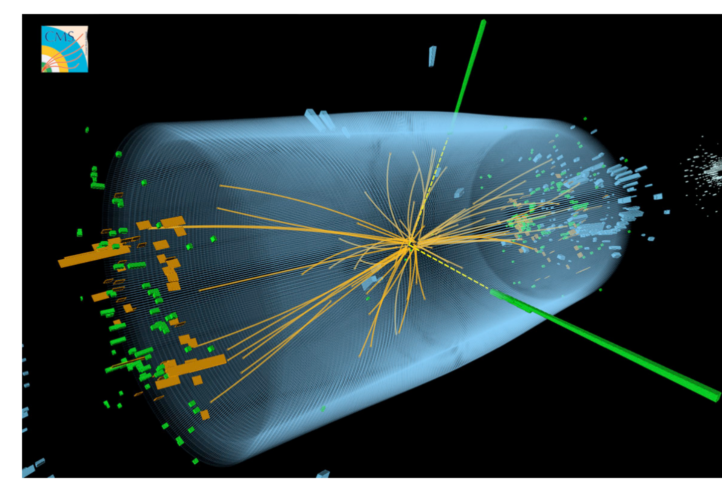
Searches for dark matter

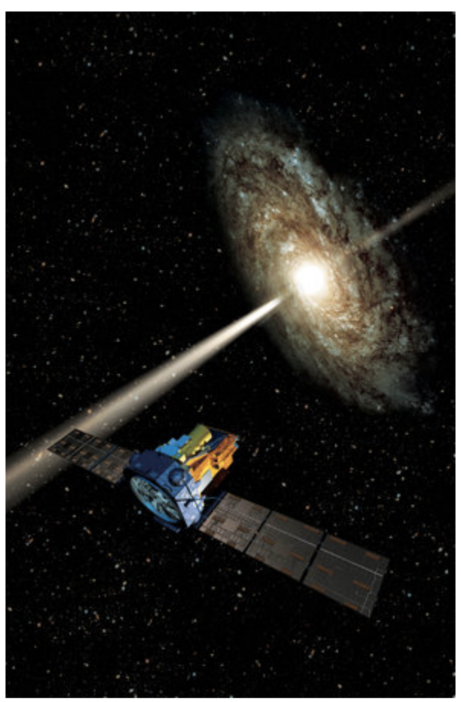


Direct detections



Colliders





Indirect detections

Probe beyond gravitational effects

Theories of dark matter

complexity ↑

SUSY

- solves hierarchy problem
- natural DM candidate
- renormalizable

Simple models

- have their own motivations
- still renormalizable
- enough to offers rich physics

Effective operators

- pure phenomenological approach
- higher dimensional operators

We haven't discovered dark matter yet, be open minded.

DM models with a mediator

Dark Sector $$\mathcal{L}_D = \begin{cases} g_\chi \bar{\chi}\chi\phi \\ g_\chi \bar{\chi}\gamma^\mu \chi V_\mu \end{cases}$$

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

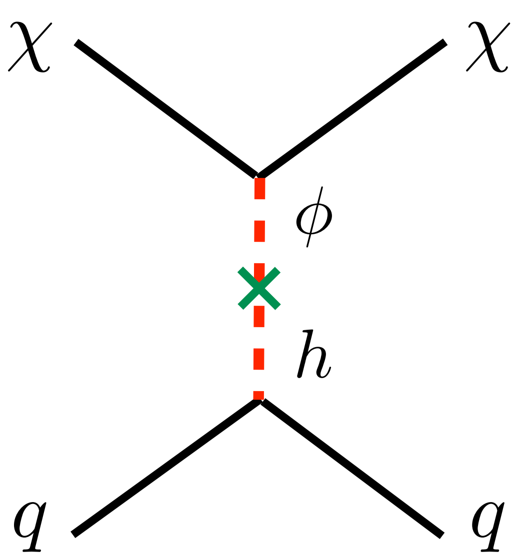
Light mediator as the portal to SM sector

$$\mathcal{L}_{\text{portal}} = \begin{cases} (\mu_{\phi h}\phi + \lambda_{\phi h}\phi^2) H^\dagger H \\ \varepsilon F_{\mu\nu} V^{\mu\nu} \end{cases}$$

mediator to SM decay rate
controlled by an independent parameter

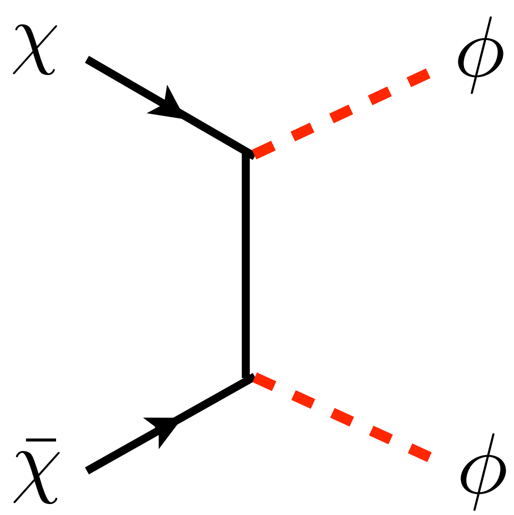
Motivations

Various reasons for considering such a setup



- Higgs portal to fermion DM is well motivated, the only discovered fundamental scalar in nature.
- Give correct relic density to very light DM.
- Secluded dark matter scenario.

Pospelov, Ritz, Voloshin, arXiv:0711.4866



- Velocity dependent DM annihilation, Sommerfeld effect in indirect detection signals.

Arkani-Hame, Finkbeiner, Slatyer, Weiner, arXiv:0810.0713

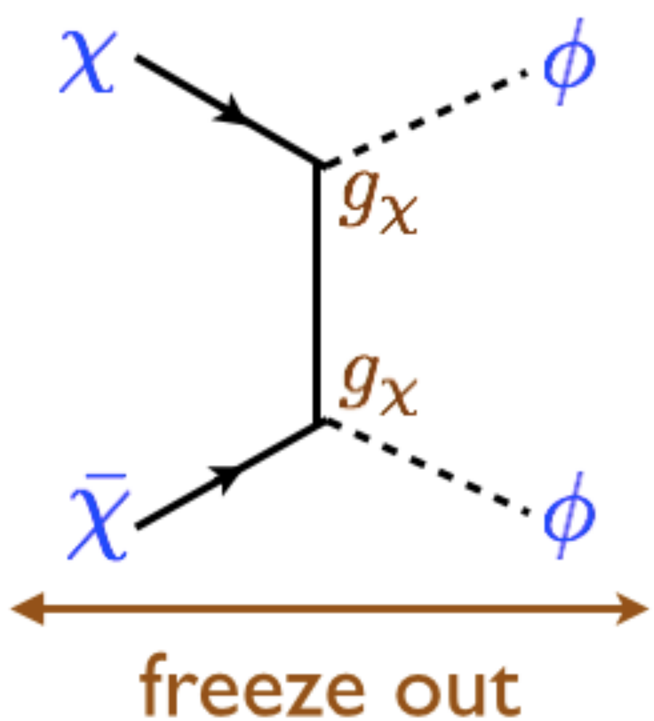
- Velocity dependent DM elastic scattering.

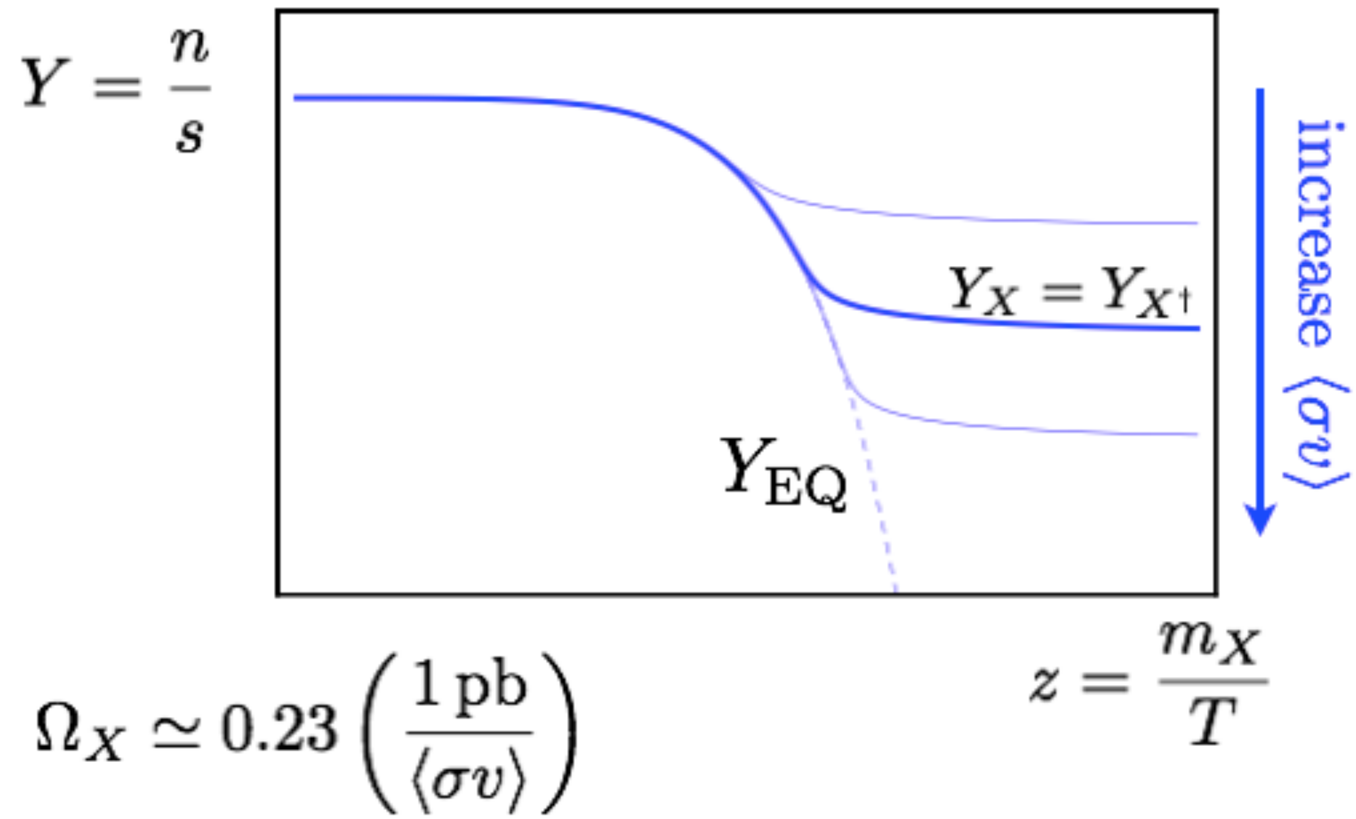
Light mediator scenario

Light mediator: $m_\chi \gg m_\phi$

DM relic density controlled by dark interactions

The WIMP miracle: initial condition $n_X = n_{X^\dagger}$



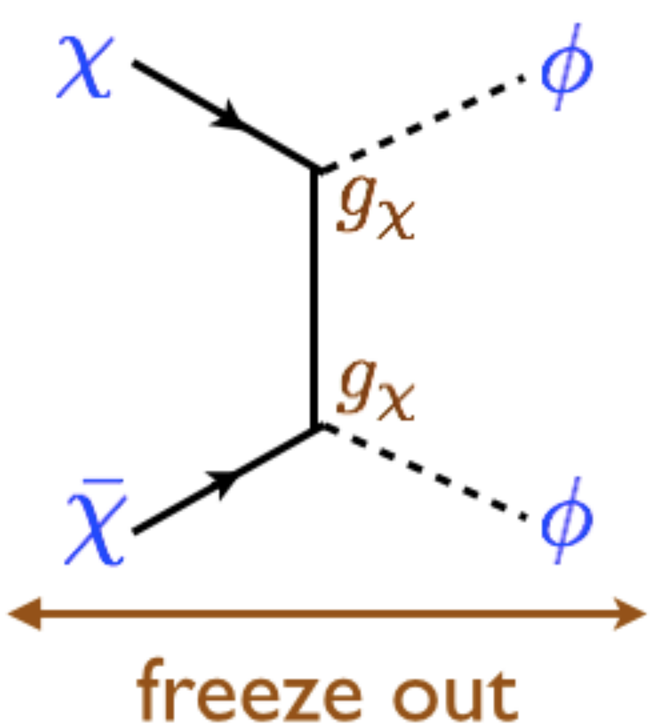


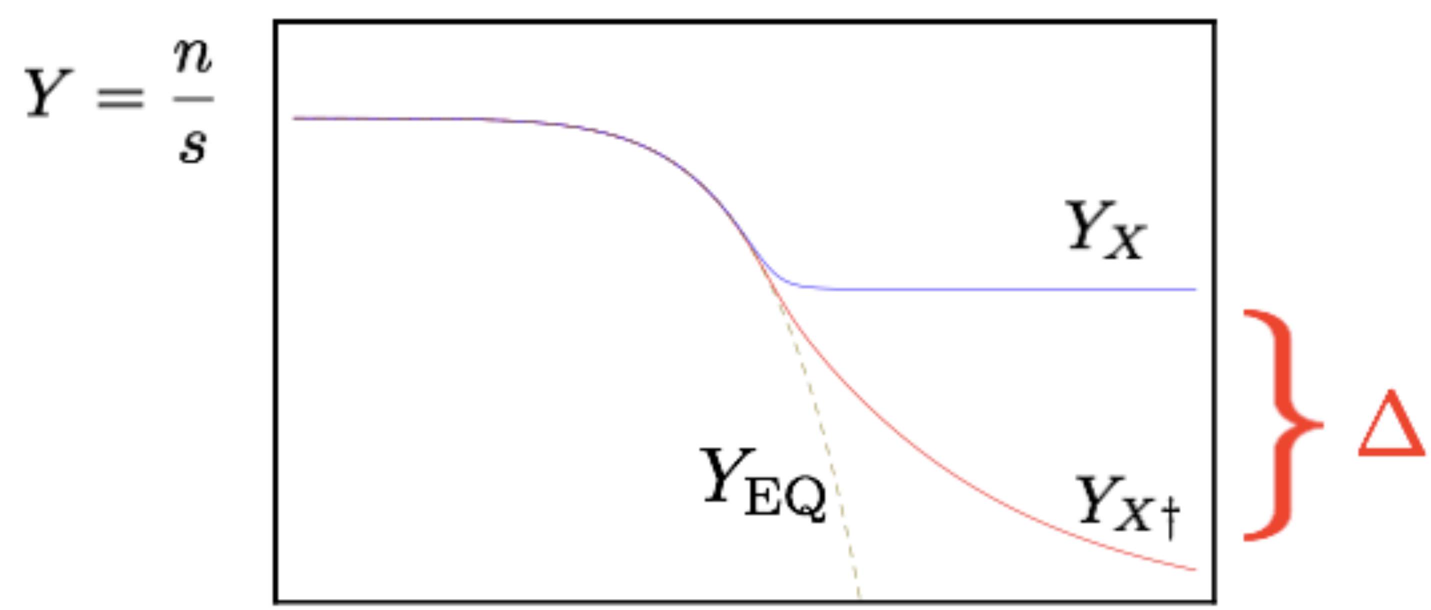
Light mediator scenario

Light mediator: $m_\chi \gg m_\phi$

DM relic density controlled by dark interactions

Asymmetric dark matter: $n_X = n_{X^\dagger} + \Delta$





$z = \frac{m_X}{T}$

For $\langle \sigma v \rangle \gg 1\,\mathrm{pb}$

Ω_X determined by Δ

Decay of the mediator

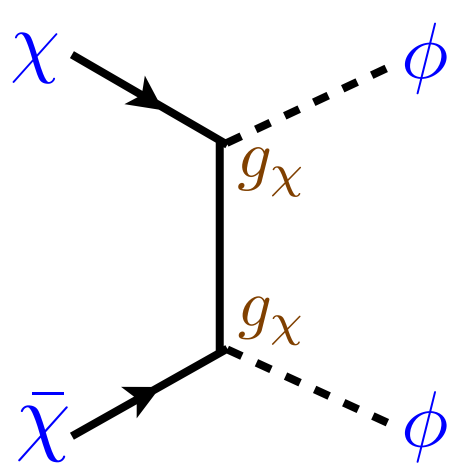
After DM annihilation, mediator has to decay before BBN.

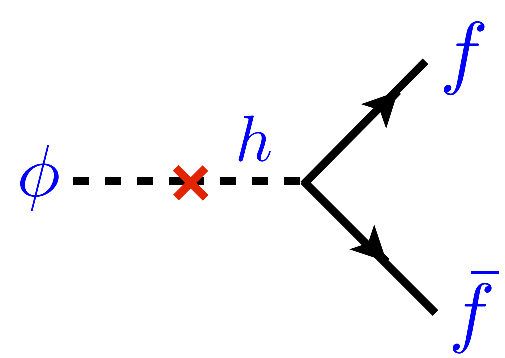
- If mediator is as populated as photons & has mass > MeV.

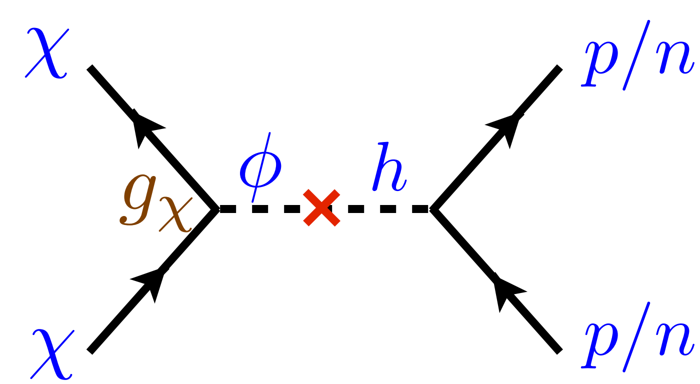
In the simple model discussed here,

- mediator decays into SM particles.

If Higgs portal, mainly decay into heaviest possible particle.

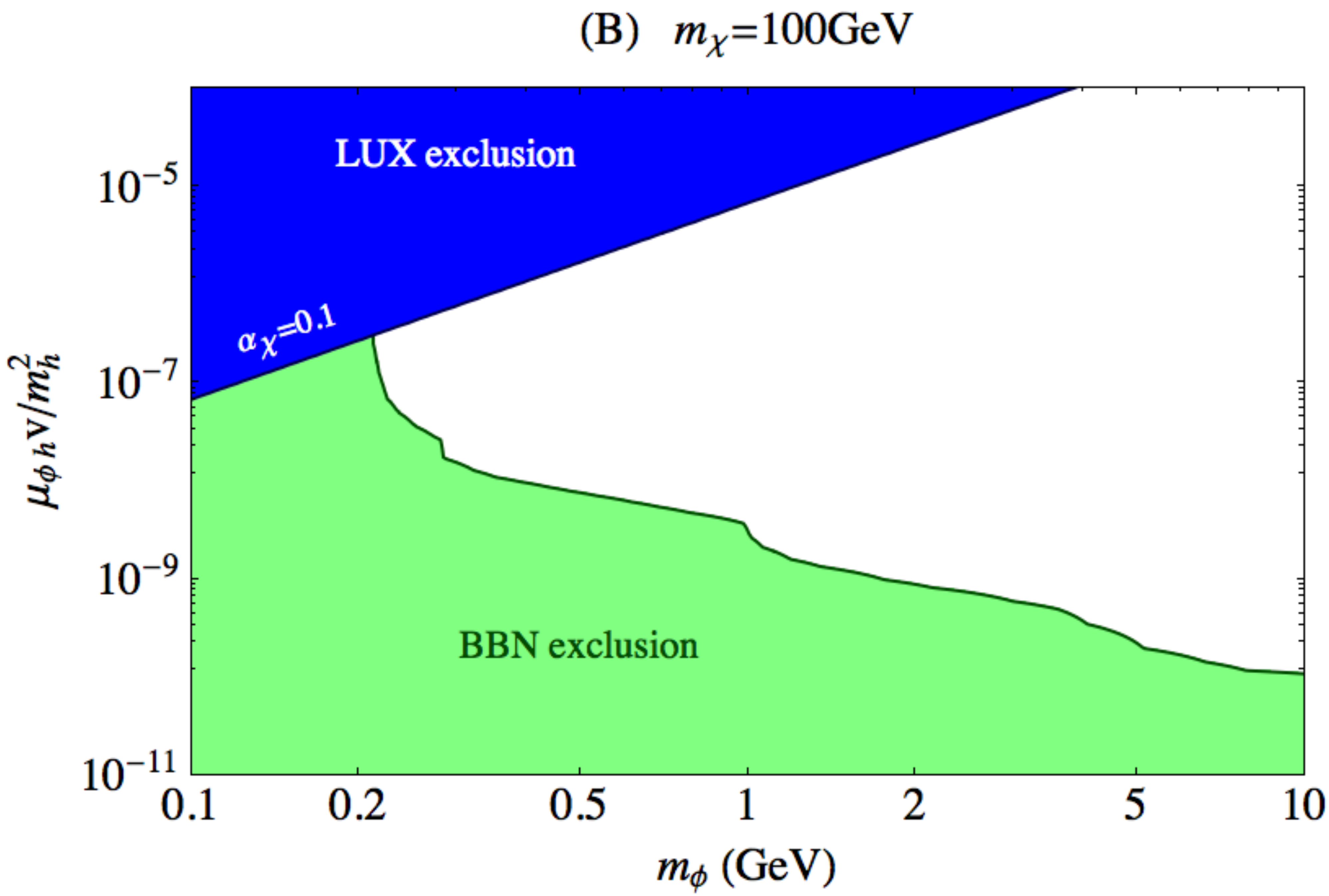




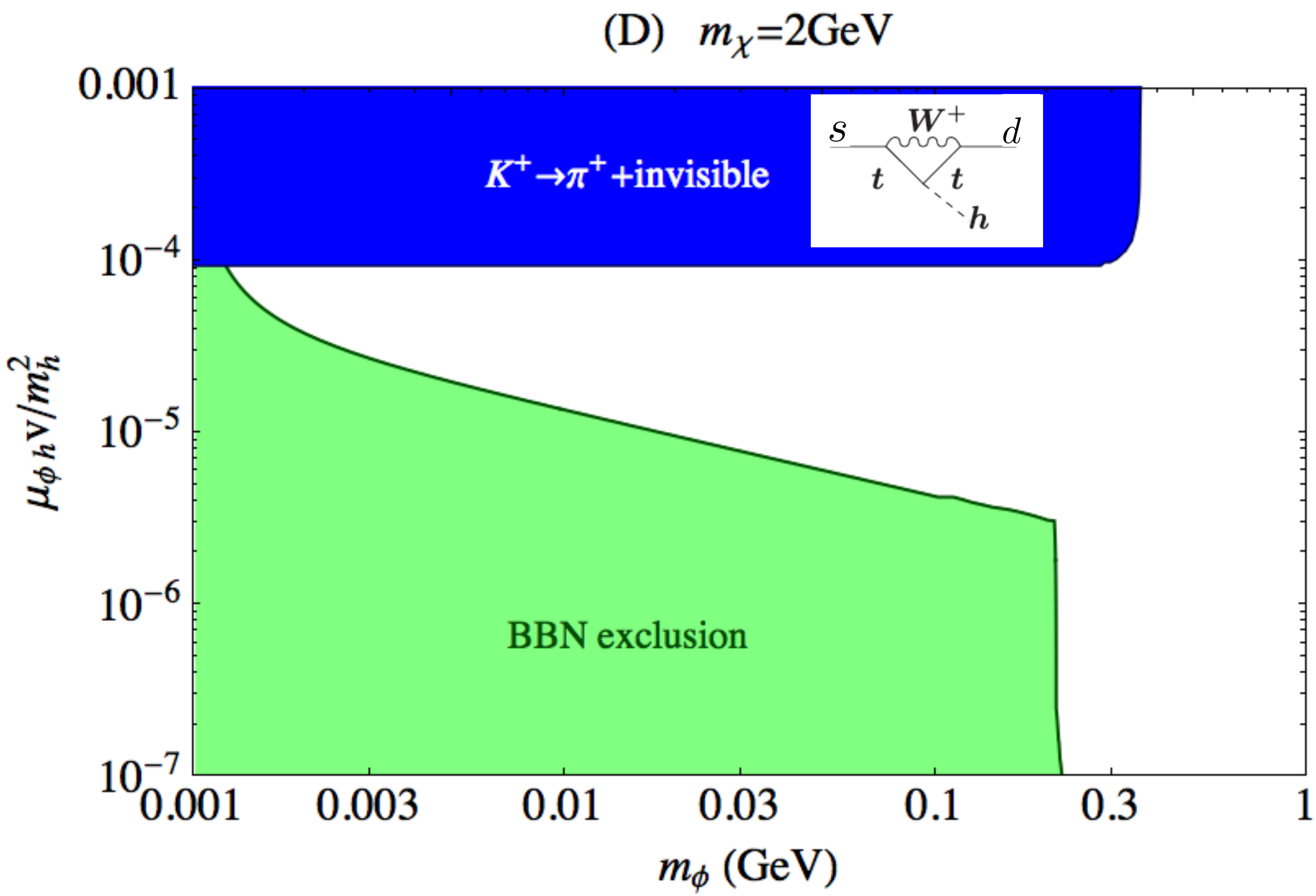


large enough g_χ | decay before BBN → lower bounds on direct detection, etc.

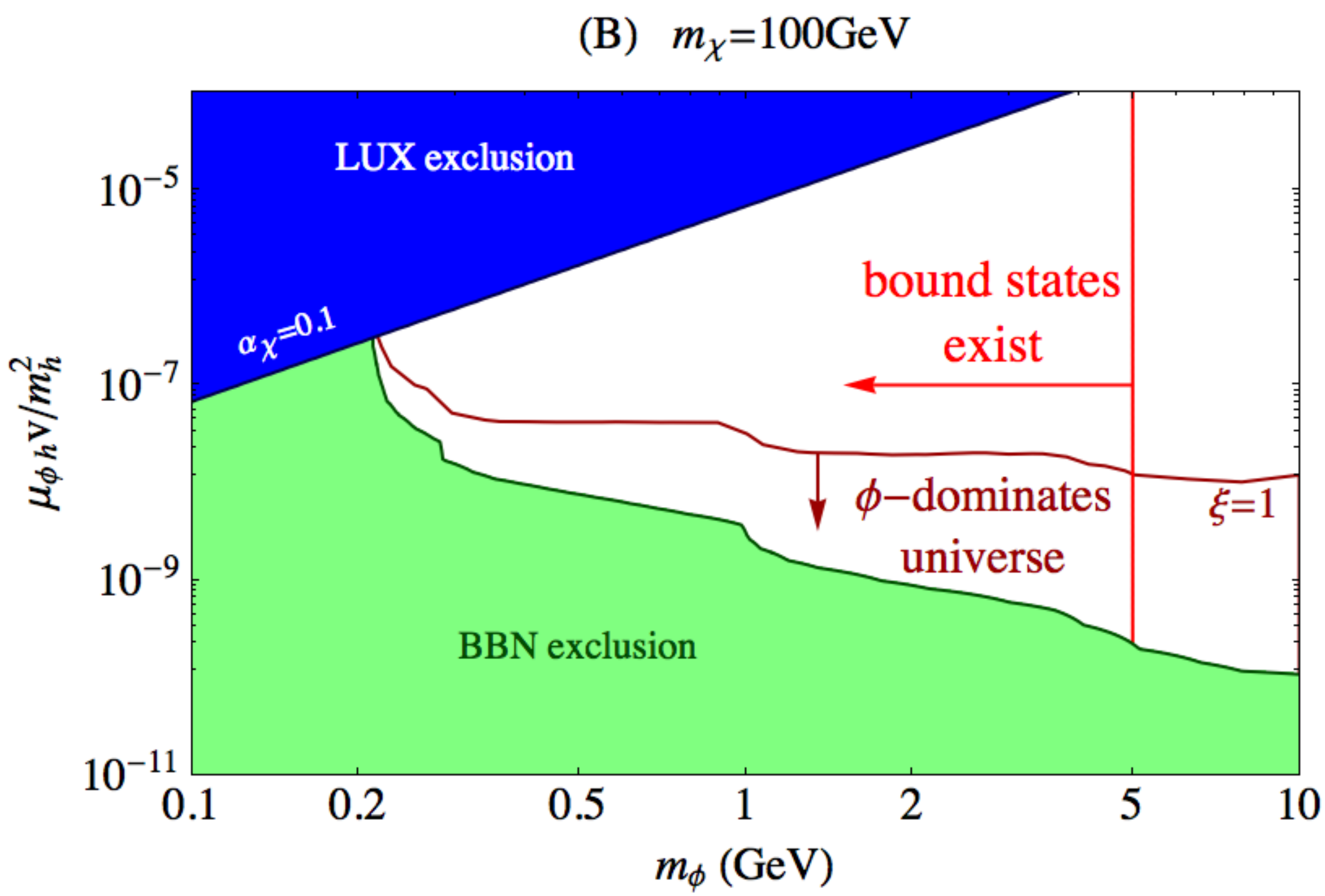
Constraints on scalar case



Constraints on scalar case



Two aspects will be discussed



if m_ϕ small enough

DM could form bound states

- Dark matter bound states via scalar light mediator.
- What if the light mediator temporarily dominates the energy of the universe.

Dark matter bound states

The visible sector has many bound states — rich dynamics due to the Standard Model structure.

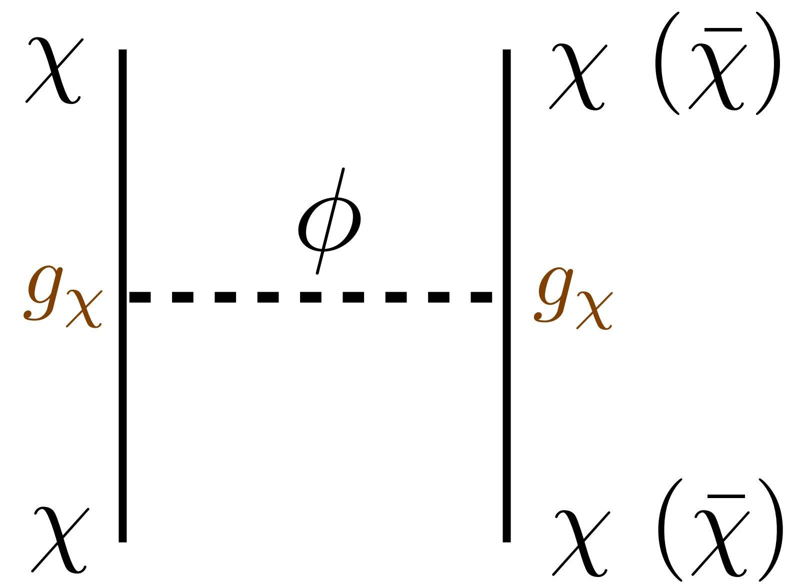
Natural to examine this idea in dark sector — even in simple models — we find dark matter bound states already exist.

Simple model can have rich dynamics:

ϕ exchange is attractive

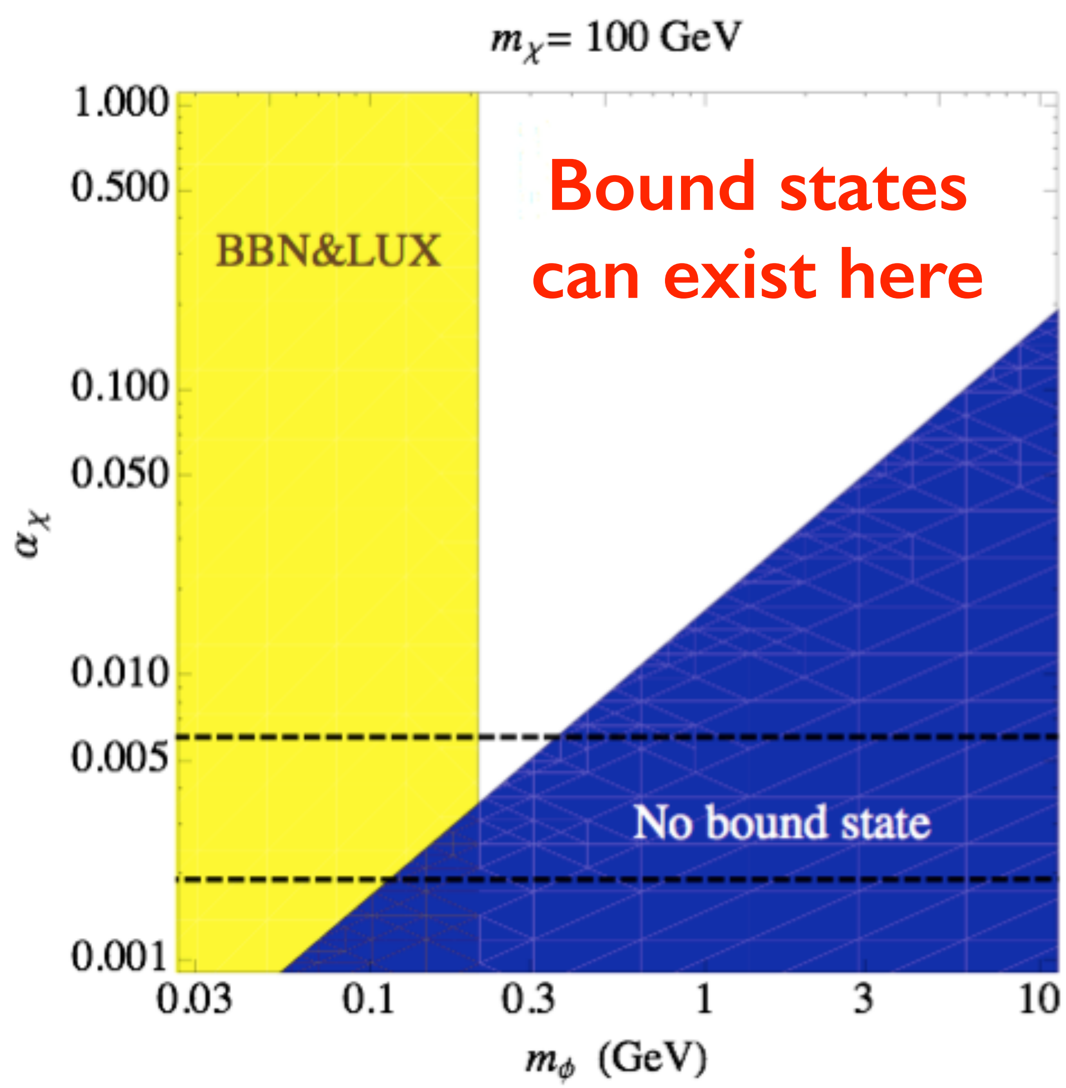
bound state condition: $$\frac{1}{\alpha_\chi m_\chi} \lesssim \frac{1}{m_\phi}$$

Bohr radius < screening length



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

Stable bound states



Bound state can exist in very wide parameter space

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

$(\chi\chi)$ cosmologically stable.

mostly formed if only χ is around

Main difference from dark *U(1)* case:

$(\chi\chi)$ attractive for scalar exchange

repulsive for vector exchange

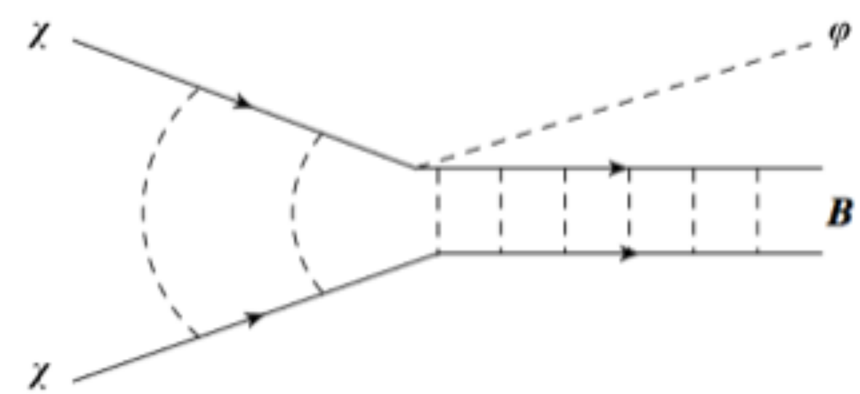
Do NOT need two species of asymmetric DM

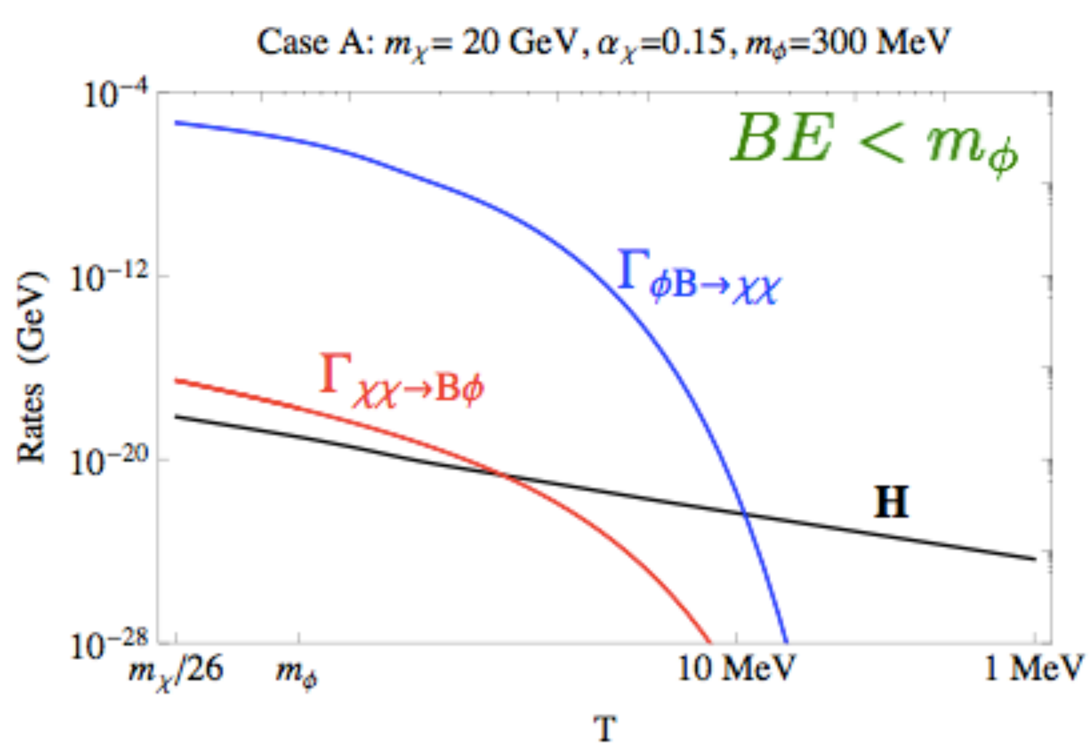
Wise, **Y.Z.**, arXiv:1407.4121, PRD

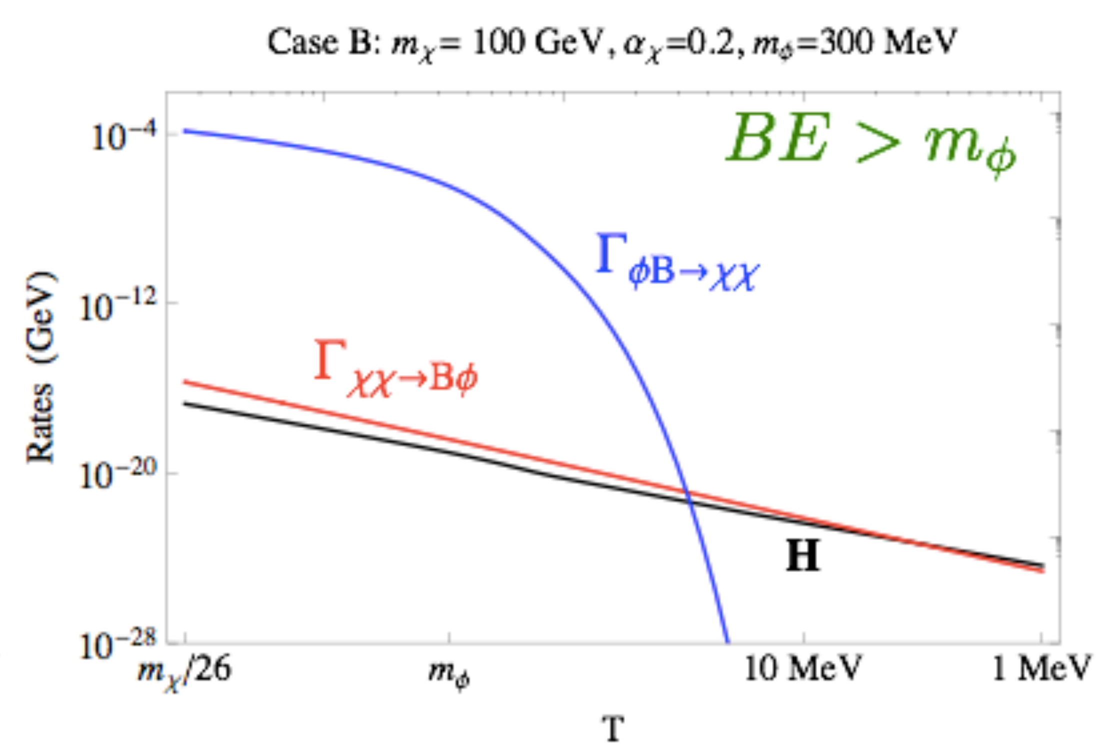
Production in early universe

Bound state formation can happen

- shortly after freeze out if an asymmetry in χ number is left over.

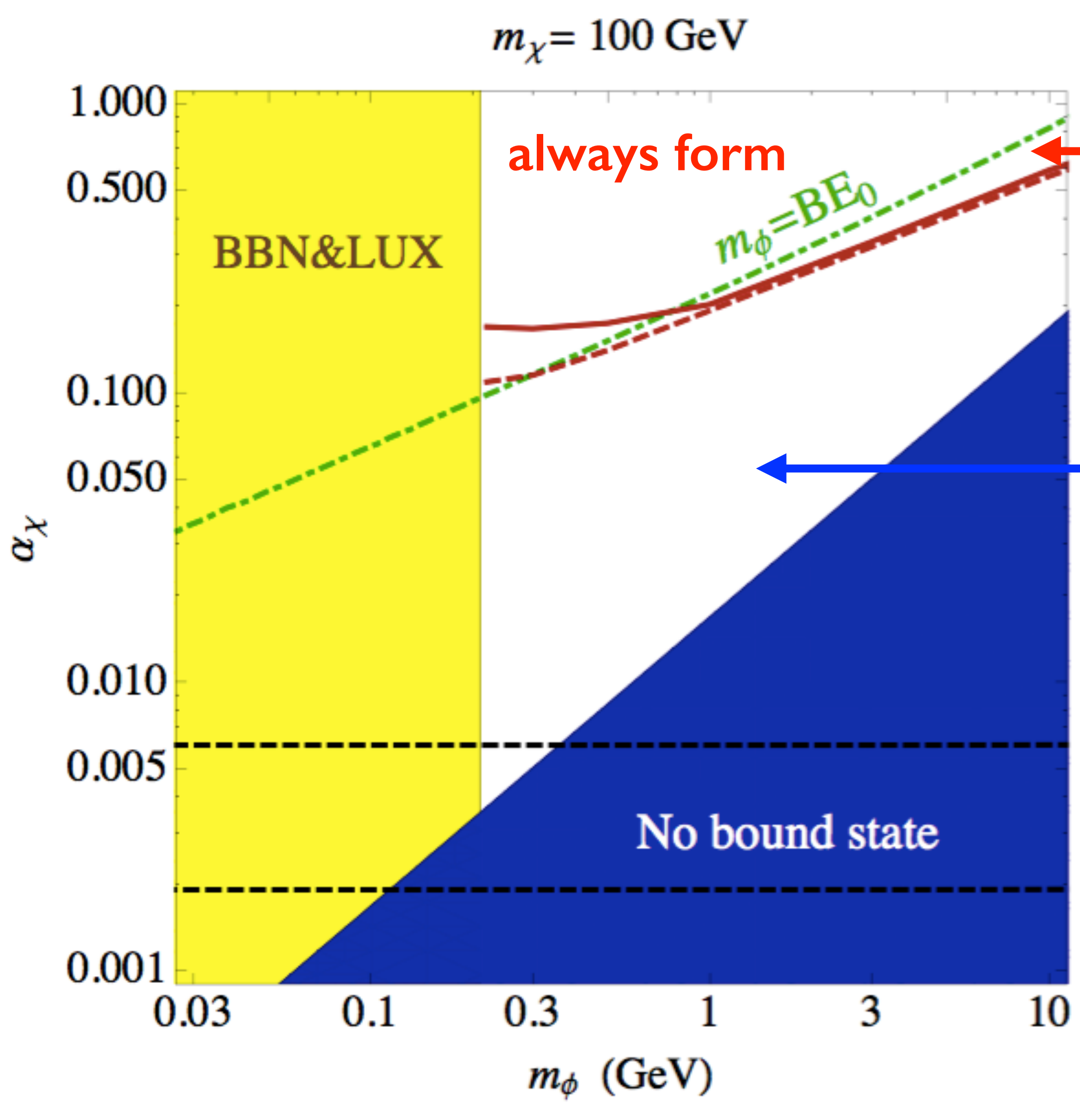






Wise, **Y.Z.**, arXiv:1407.4121, PRD

Production in early universe



form with thermal kinetic energy

cannot form in early universe

but could with high local densities,
— observable signatures today,

in neutron stars/galactic center

More bound states may also form during the non-linear structure growth.

Wise, **Y.Z.**, arXiv:1407.4121, PRD, and in progress

N-particle Bound states

Interaction through scalar exchange always attractive.

Explore properties of states with $N >> 2$ (nuggets).

We consider a degenerate Fermi gas picture

Treat χ particles inside nugget as classical point sources

Effective classical Lagrangian

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

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.

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.

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

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

Generic features

In practice we take ansatz of $p_F(r)$ and minimize the total energy wrt the radius R.

Interesting behaviors of N dependence in R:

When $N < \alpha_\chi^{-3/2}$, non-relativistic regime

(similar to degenerate star)

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

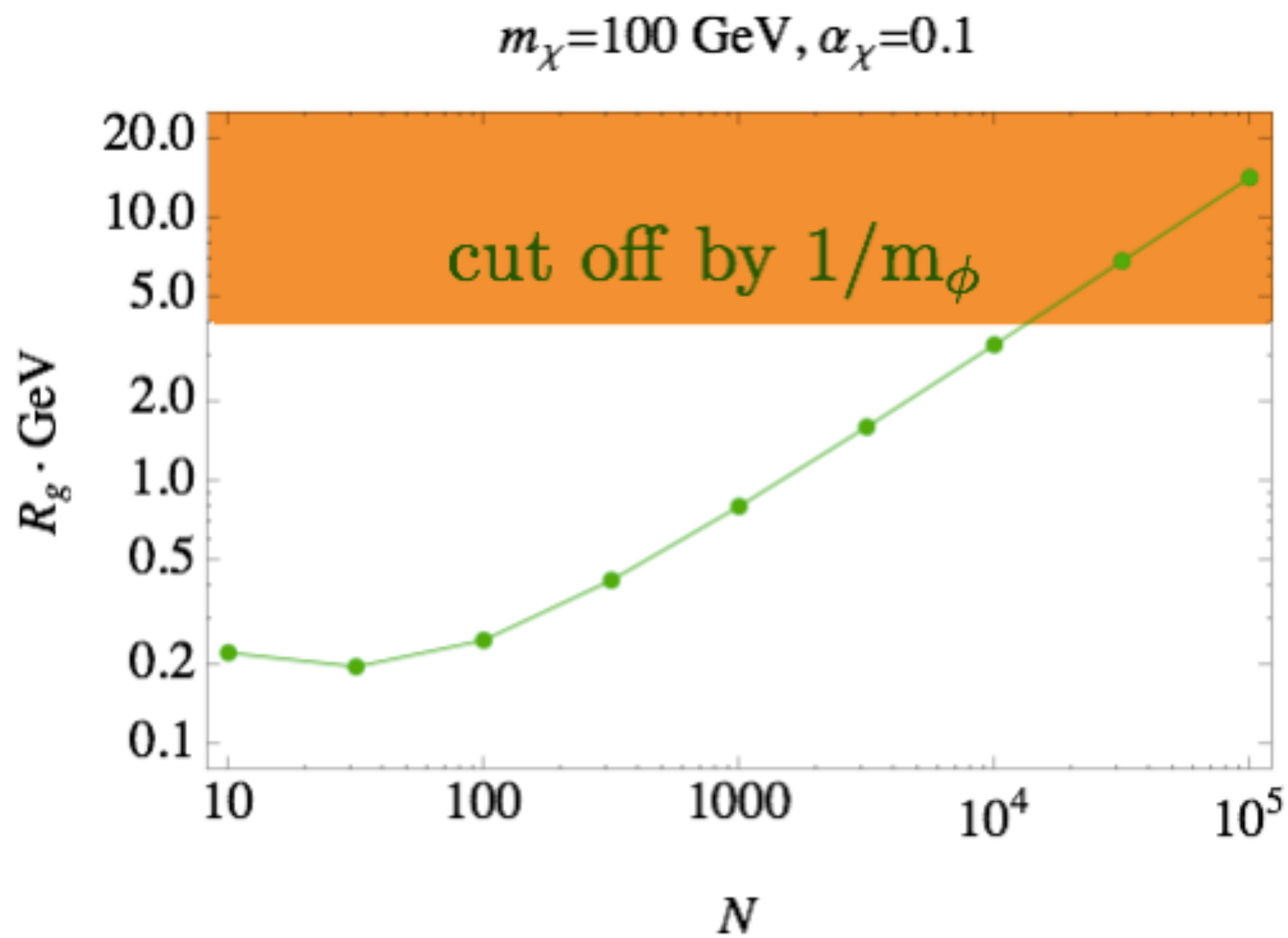
Yukawa force gets weaker when relativistic

$$\bar{\chi}\chi\phi \sim \frac{m}{E}\chi^\dagger\chi\phi$$

$$\Rightarrow R \sim \frac{\alpha_\chi N}{m_\chi}$$

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

Nugget properties



very heavy bound states allowed

Example of supermassive DM with thermal freeze out history.

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

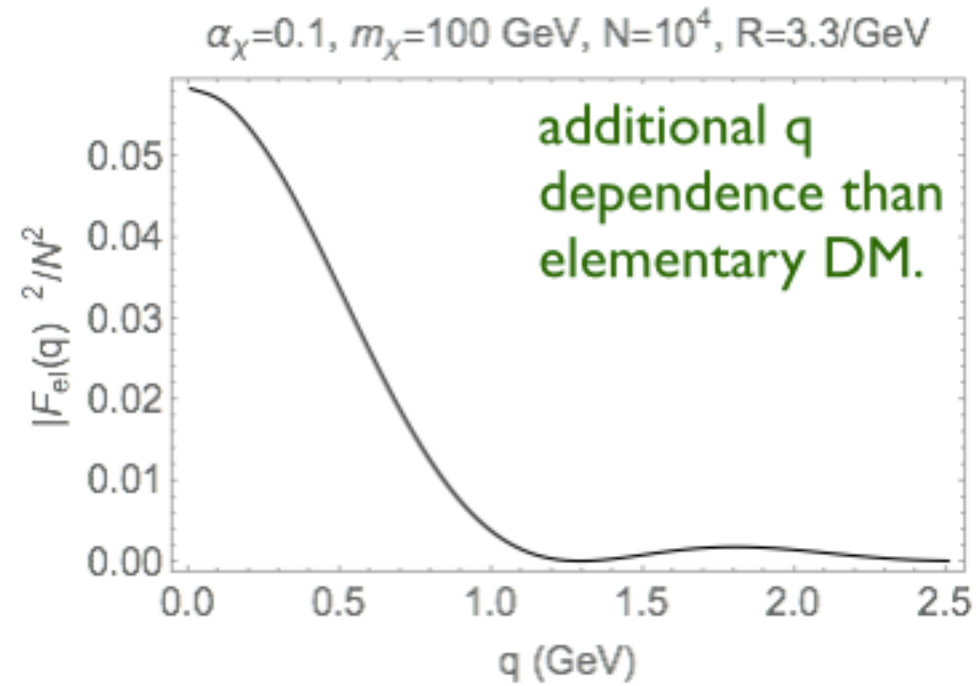
Wise, **Y.Z.**, arxiv:1411.1772

DM phenomenology

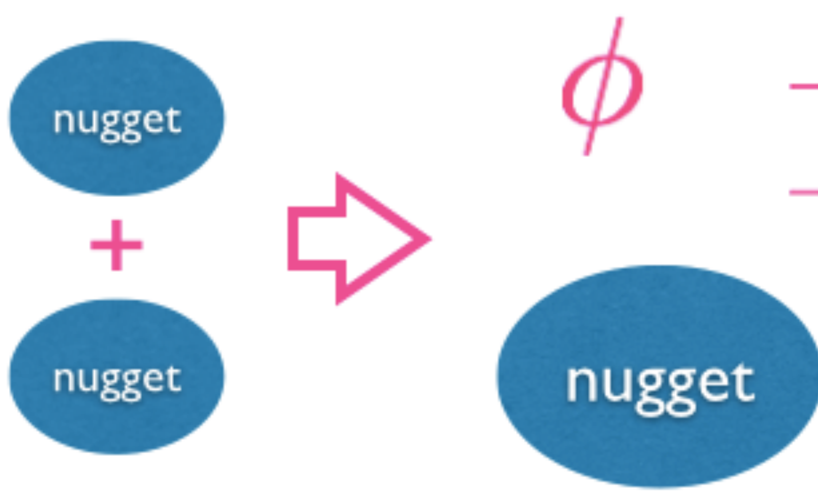
Direct detection:

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

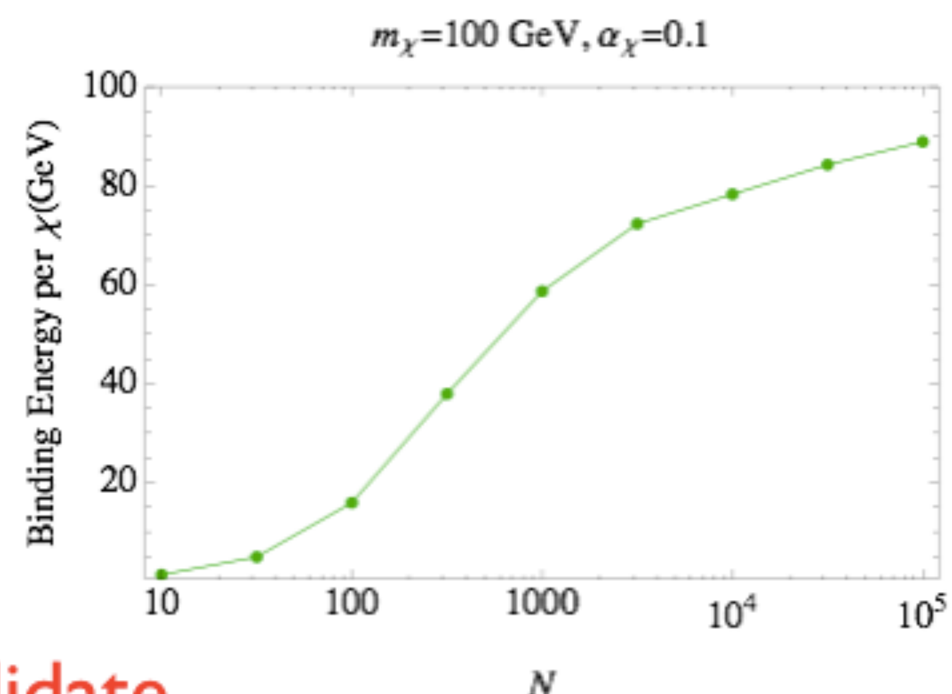
1 for usual elementary DM



Indirect detection of cosmic rays:



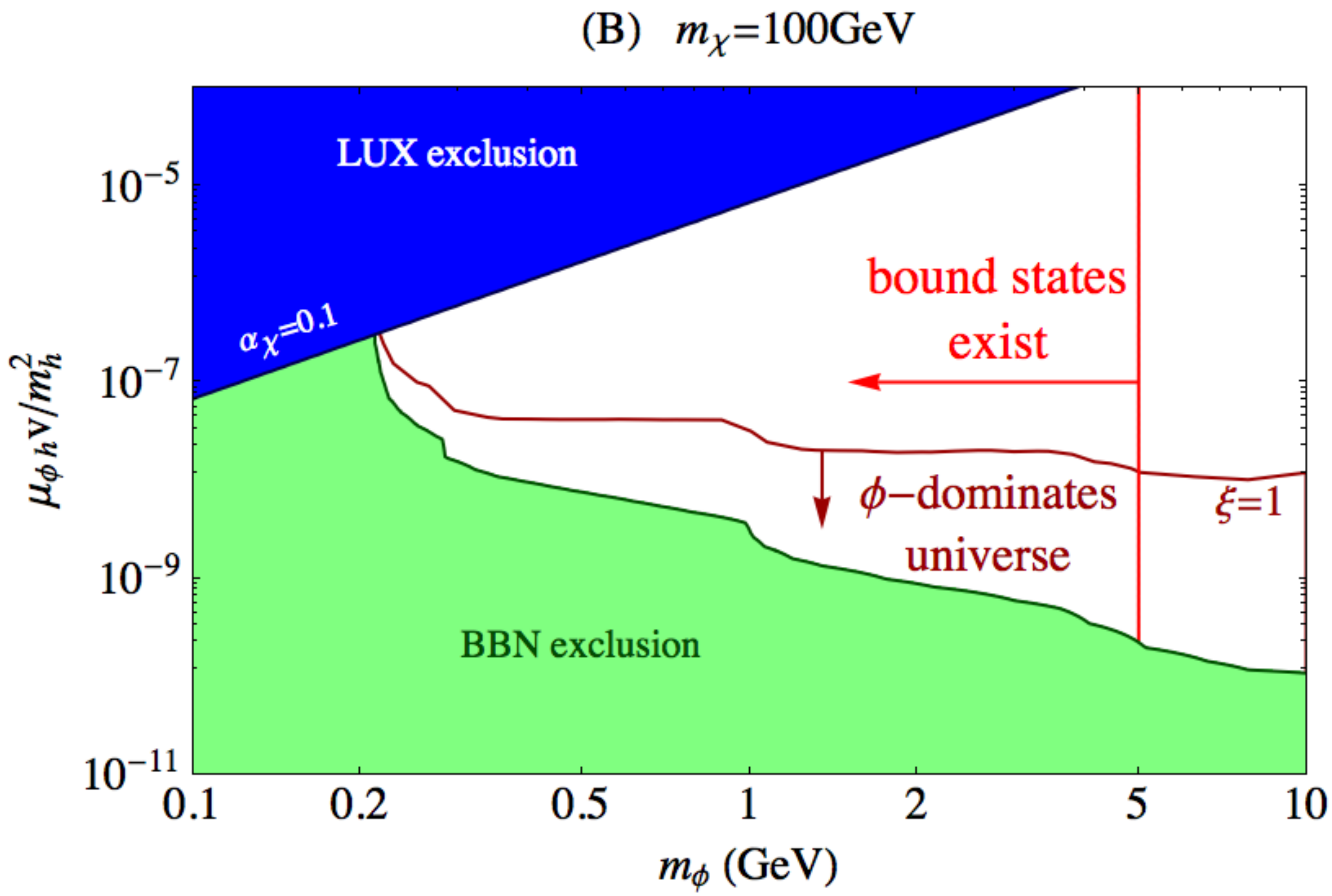
$$\rightarrow \pi^+\pi^- \rightarrow \nu's$$
$$\rightarrow \mu^+\mu^-, \cdots$$



Dark nucleosynthesis: warm DM candidate.

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

Two aspects I want to discuss

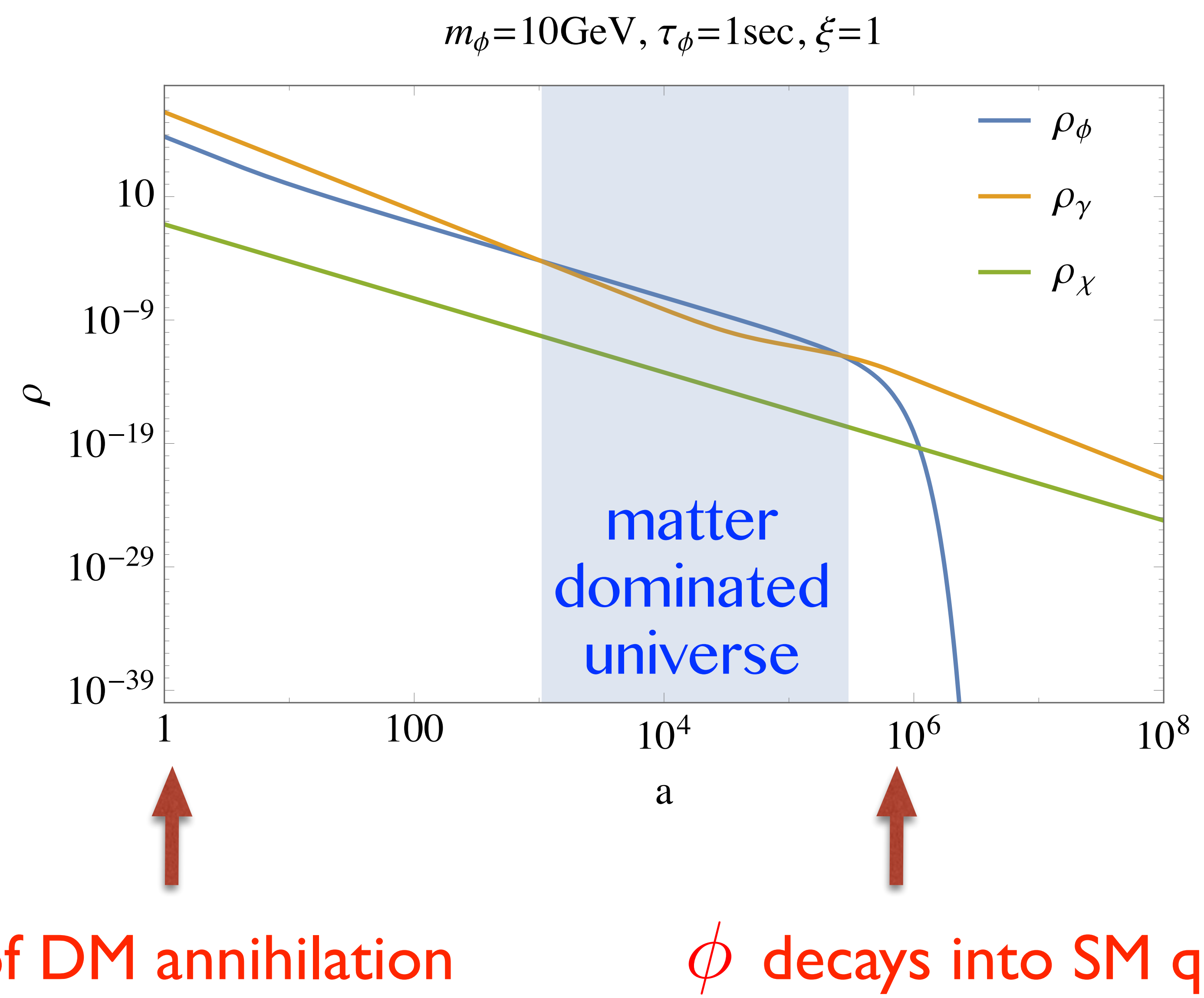


if $\mu_{\phi h} v/m_h^2 \lesssim 10^{-7}$

two sectors never in equilibrium

- Dark matter bound states via scalar light mediator.
- What if the light mediator temporarily dominates the energy of the universe.

Energy density evolutions

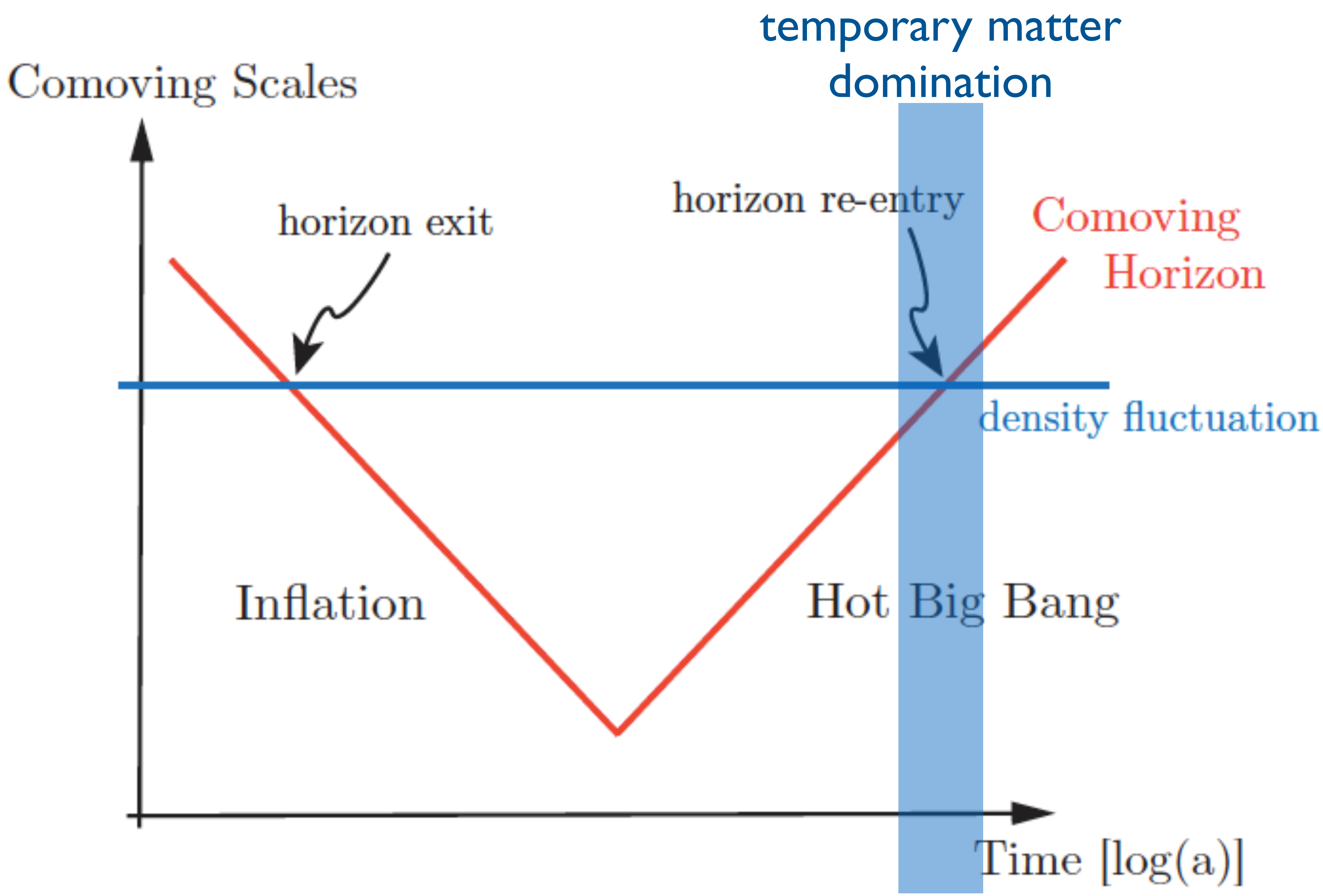


Entropy production, $\mathcal{S} \approx 60$ (assuming $T_D/T = 1$)

Need to overproduce DM from freeze out by this factor.

Y.Z., arxiv:1502.06983

Primordial perturbations



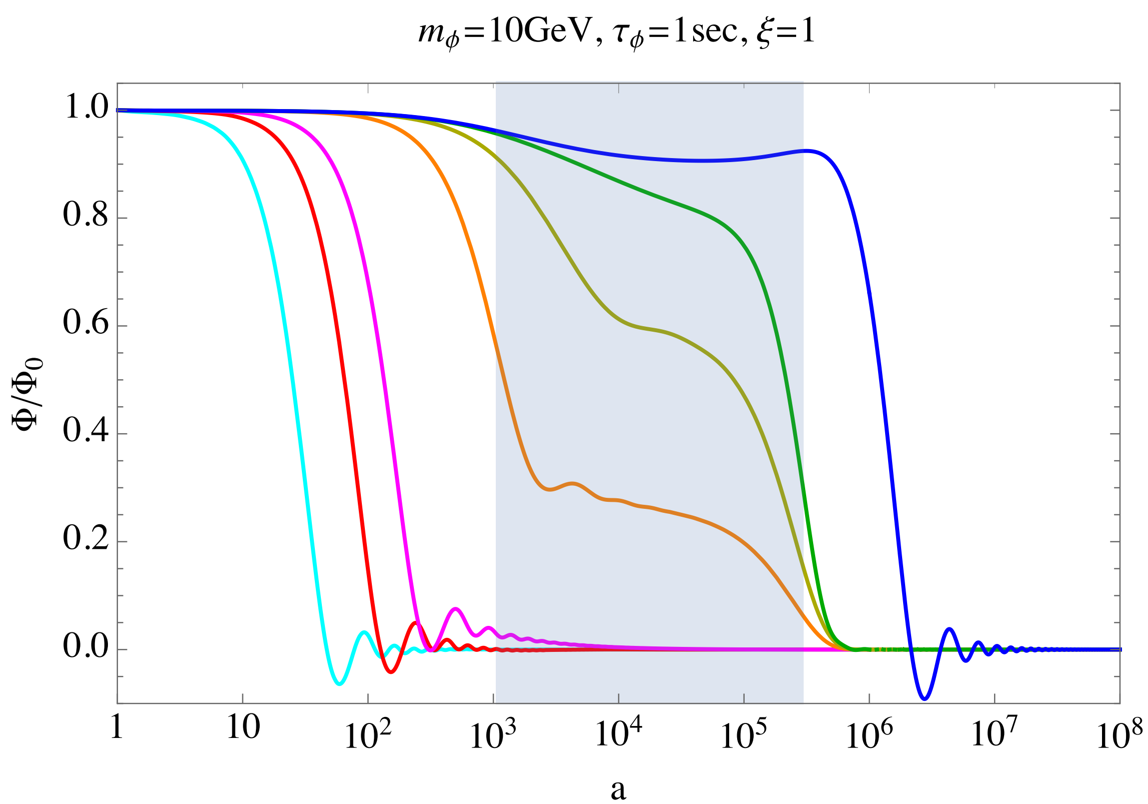
D.Baumann, TASI 2009 Lecture

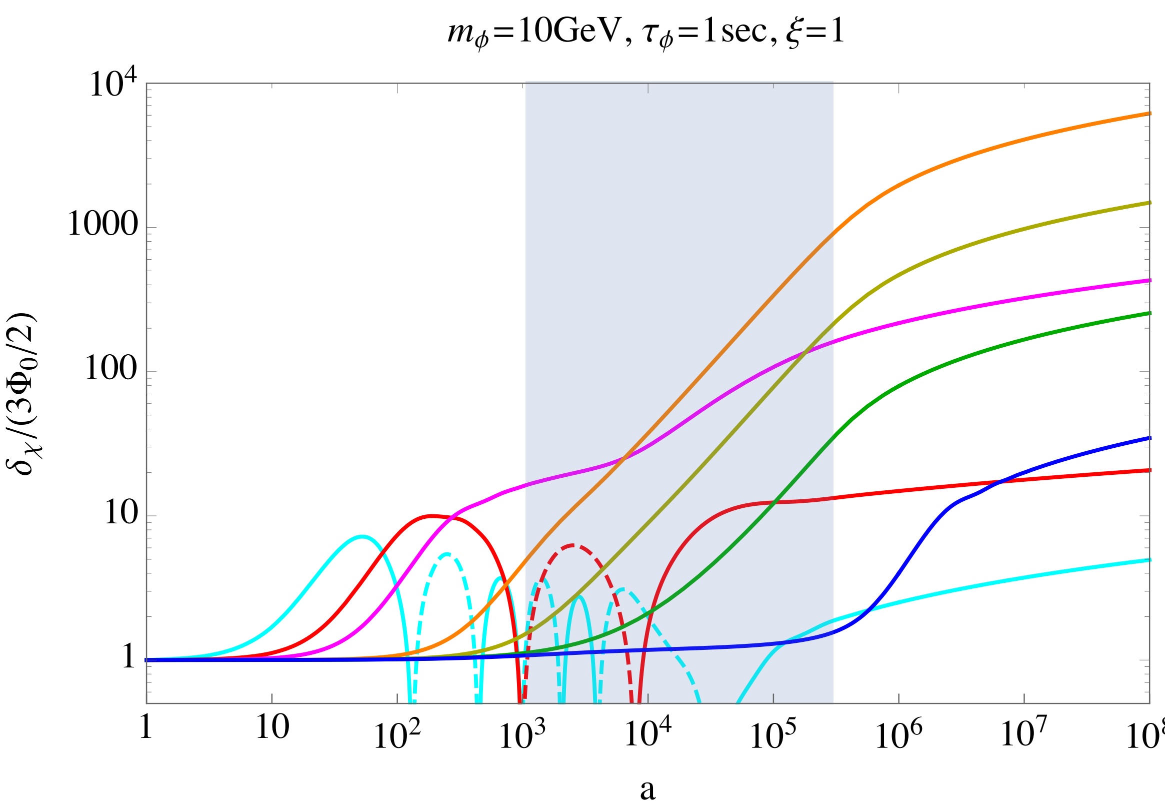
Evolution of perturbations

Impact on dark matter density perturbation

- Radiation domination: logarithmically growth
- Matter domination: linear growth

Affects all modes entering horizon before/during MD.





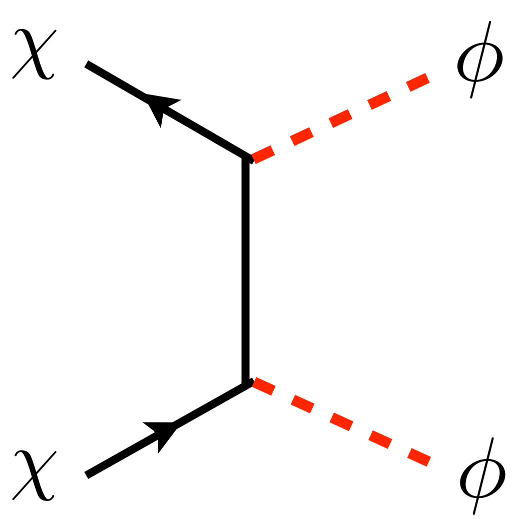
Y.Z., arxiv:1502.06983

Collisional damping effects

ϕ turns into matter only at $T \ll m_\phi$

In the beginning, ϕ is still relativistic, and tightly couples to dark matter χ,

$$\sigma_{\chi\phi} = \frac{4\pi\alpha_\chi^2}{3m_\chi^2}$$



The $\chi - \phi$ plasma had a large sound speed,

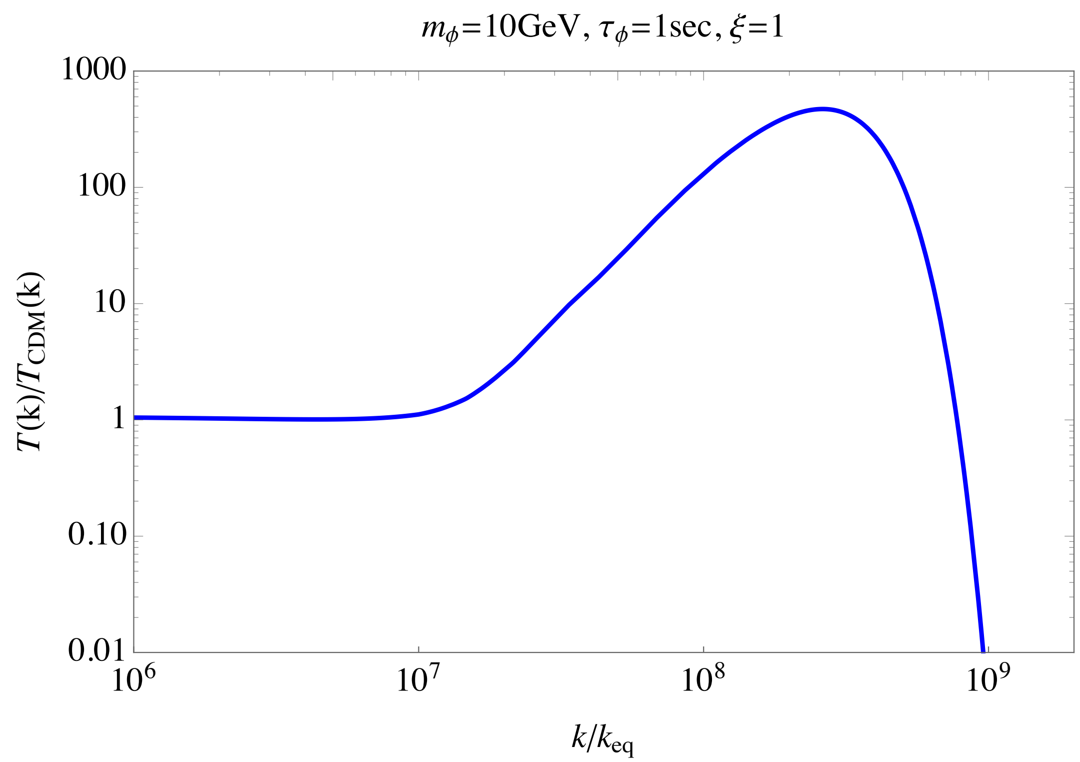
$$c_s^2 \sim T/m_\phi$$

Dark sector acoustic oscillation — Suppresses all modes that enters the horizon very early.

Until matter light mediator domination era begins.

Y.Z., arxiv:1502.06983

A peak in transfer function



In the end will give a peak in the DM power spectrum

Peak: population of structures at this scale will be enhanced.

Properties of the mini halo:

$R \sim 10^{-4}\,\mathrm{pc}(\sim \text{solar system size})$

$M \sim M_\oplus(\sim \text{earthmass})$

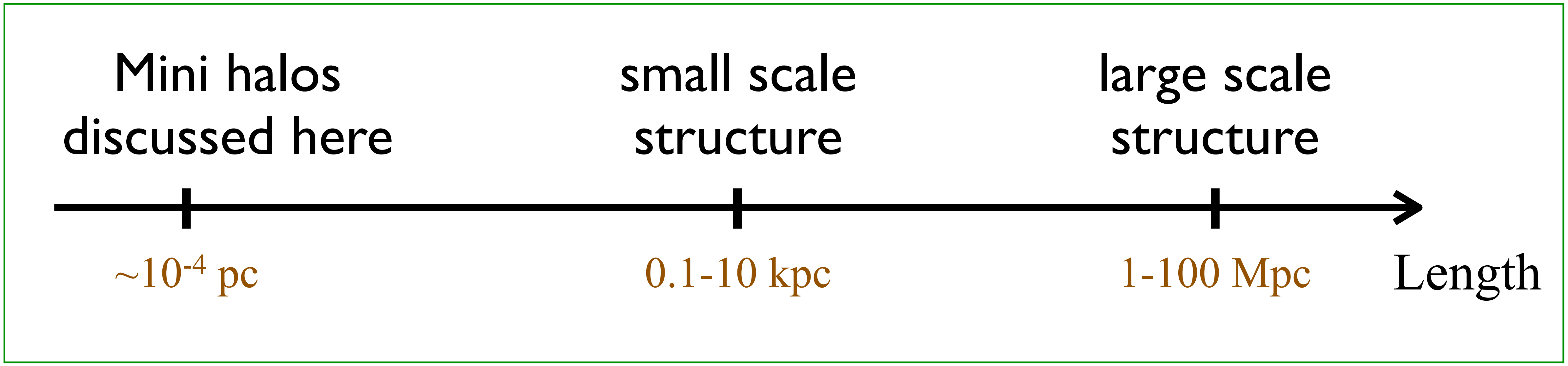
$\Rightarrow 10^9$ of local DM density

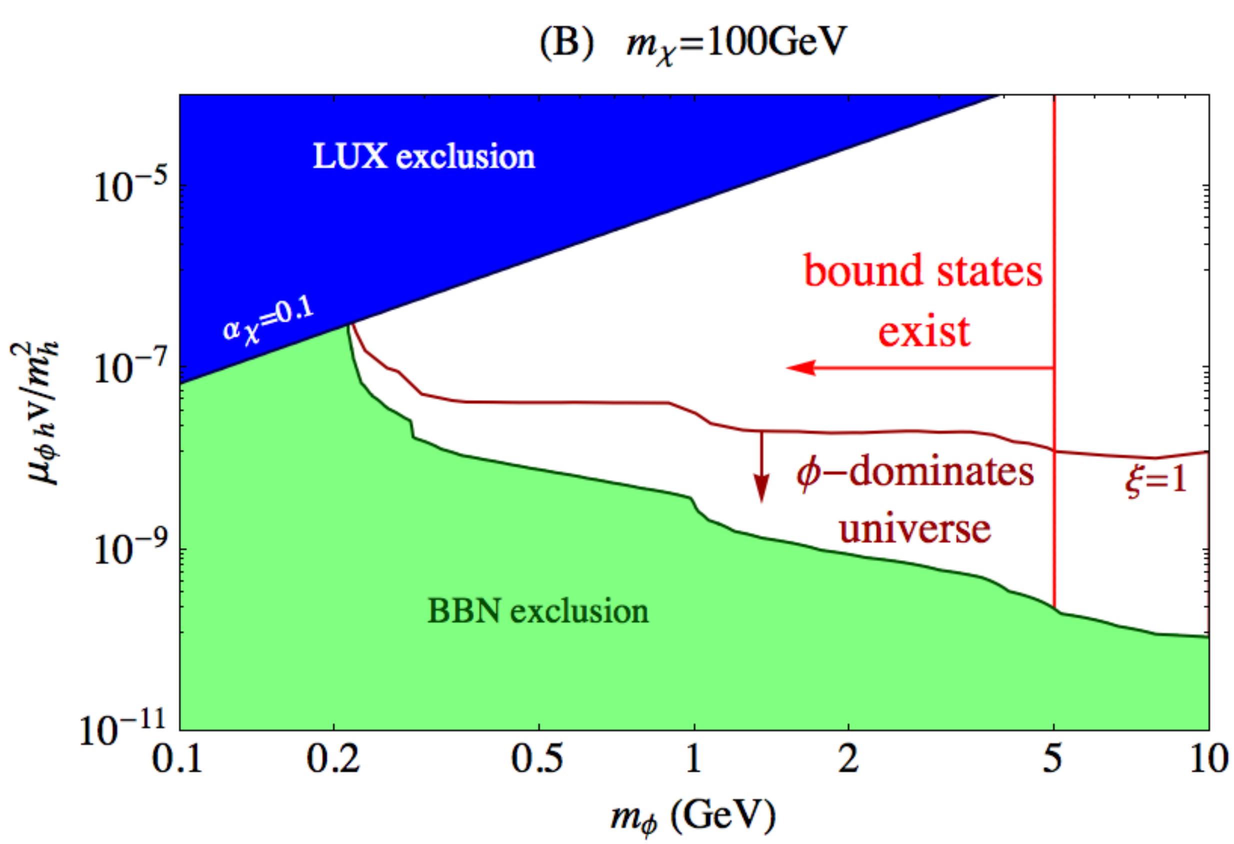
If these mini halos takes *O(1)* fraction of Milky Way mass:

encounter one every ~50 years

Y.Z., arxiv:1502.06983

Summarize the scales





Simple DM model can have rich dynamics in both particle physics and cosmology.

Will be interesting to look at the overlap of two regimes.

Y.Z., arxiv:1502.06983

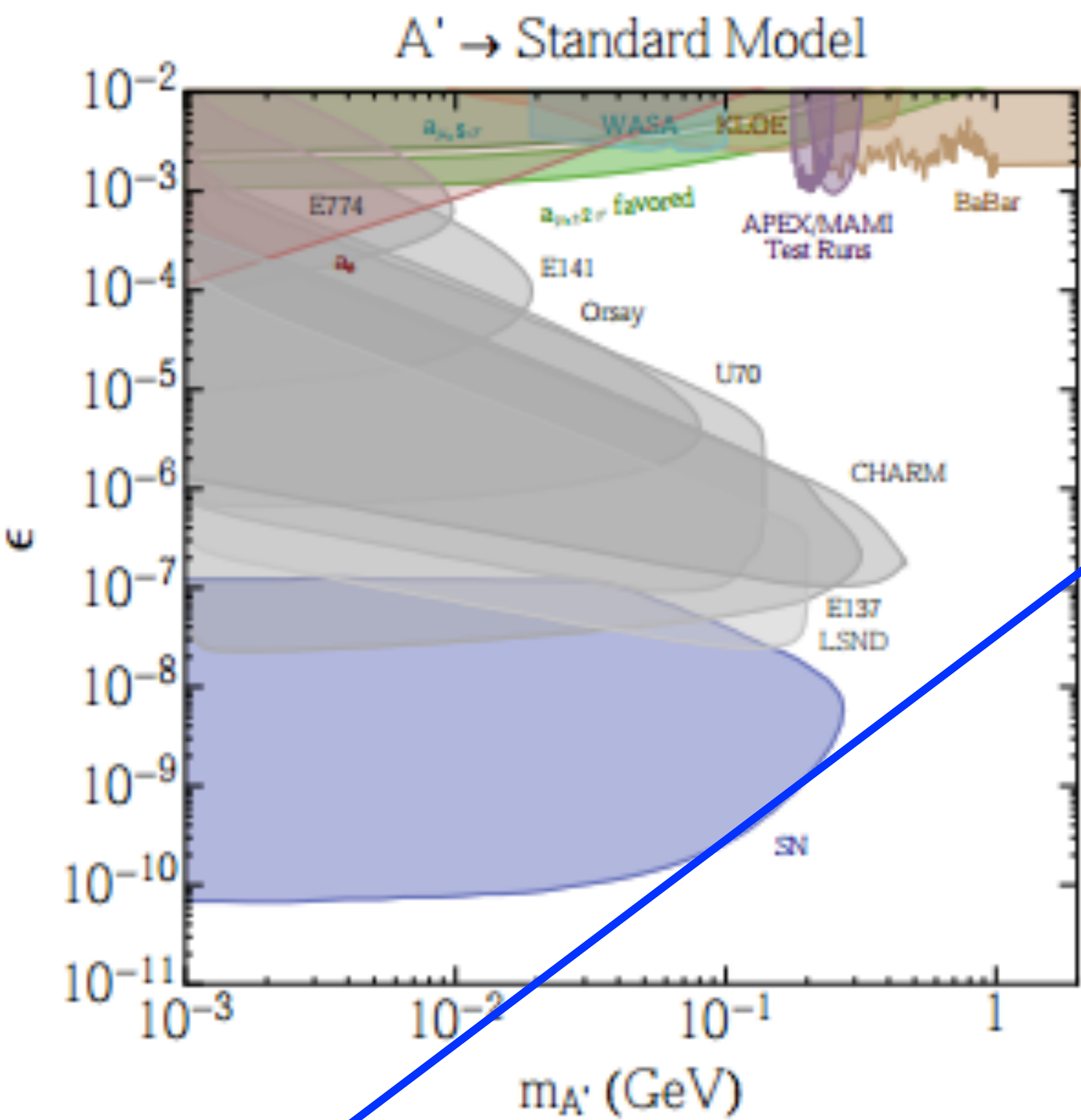
Conclusion

- It is worth exploring simple dark matter models.
- In this talk I discussed a class of models with a light mediator connected to the SM sector.
  - DM bound states properties and its particle cosmology.
  - Light mediator dominated universe offers new structures.
- Opens plenty of new possibilities, and experimentally testable effects.
- This is an exciting direction.

Thank you!

Backup slides

Vector mediator case



direct detection constraint on weak scale dark matter