Title: Cosmology and Astrophysics of the Twin Higgs

Date: Nov 27, 2018 01:00 PM

URL: http://pirsa.org/18110041

Abstract: <p>The Twin Higgs model is an attractive solution to the little Hierarchy problem with top partners that are neutral under SM gauge charges. The framework is consistent with the null result of LHC colored top partner searches while offering many alternative discovery channels. Depending on model details, the phenomenology looks very different: either spectacular long-lived particle signals at colliders, or a plethora of unusual cosmological and astrophysical signatures via the existence of a predictive hidden sector. I will examine the latter possibility, and describe how the asymmetrically reheated Mirror Twin Higgs provides a predictive framework for a highly motivated and highly non-trivial interacting dark sector, with correlated signals in the CMB, Large Scale Structure, and direct detection searches, as well as higgs precision measurements at colliders. This provides a vivid example of the collider-cosmology complementarity, and motivates a variety of new astrophysical searches that are motivated by the hierarchy problem.</p>

Cosmology and Astrophysics of the Twin Higgs

High Energy Theory Seminar
Perimeter Institute

27 November 2018

David Curtin

UNIVERSITY OF TORONTO

Based on 1803.03263, 1812.xxxxx Chacko, DC, Geller, Tsai
& ongoing work with Jack Setford, Shayne Gryba, …

There has to be new physics…

The usual fundamental mysteries (Hierarchy Problem, DM, Baryogenesis, Neutrinos, …) aren't going anywhere.

Higgs discoveries and DM astro measurements sharpen these questions!

Canonical solutions (SUSY, WIMP DM, …) generally involve IR-minimal models, where the new degree of freedom which solves the mystery has sizable direct coupling to the SM.

This leads to irreducible signatures that haven't shown up so far.

… where is it?

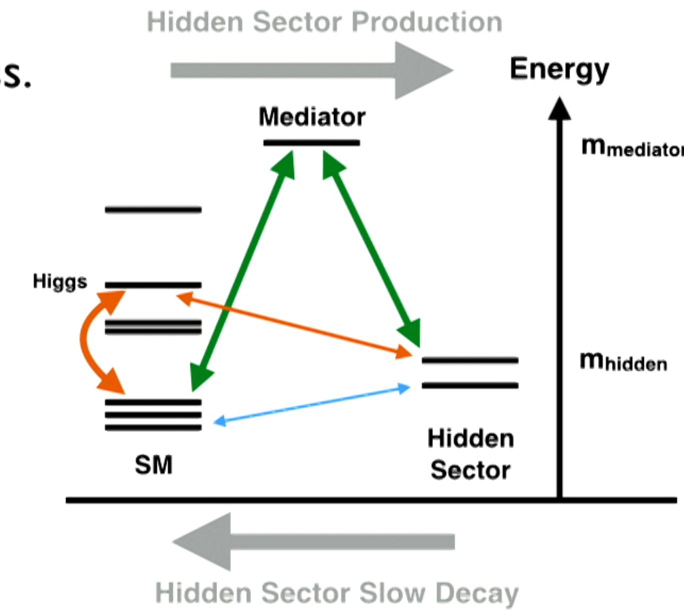
Hidden Sectors

Particles & forces hidden from us due to small coupling, not high mass.

Generically arise due to the grammar of QFT.

Confirmed examples: ν's, DM

Give non-minimal IR spectra from minimal theory input
(e.g. QCD cousins like Hidden Valleys)



Can couple to SM via small portal couplings, e.g.
Heavy Mediators **Higgs Portal** **Photon Portal**

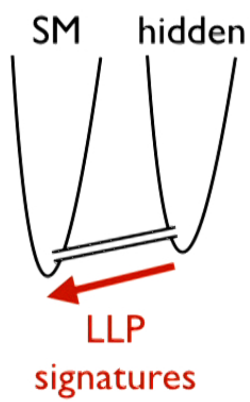
1. Exotic Higgs Decays as probes

LHC can probe tiny exotic branching ratios if decays spectacular.
Sizable Higgs Portal couplings to new physics are generic.

2. Long Lived Particles (LLPs) are generic

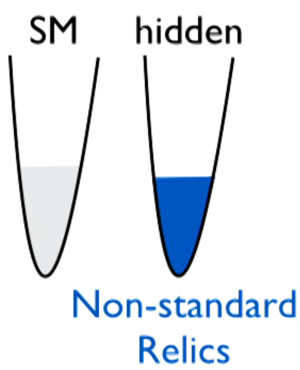
Once produced, Hidden Sector states can only decay back to SM via small portal couplings, generically leading to long lifetimes.
The LLP lifetime is (almost…) a free parameter!

3. Complementarity between Cosmology and Colliders



Models which avoid signatures in one will often show up in the other

(e.g. dark radiation,
DM with structure, etc.)



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LHC can probe tiny ex
Sizable Higgs Portal co

2. Long Lived Particle

Once produced, Hidde
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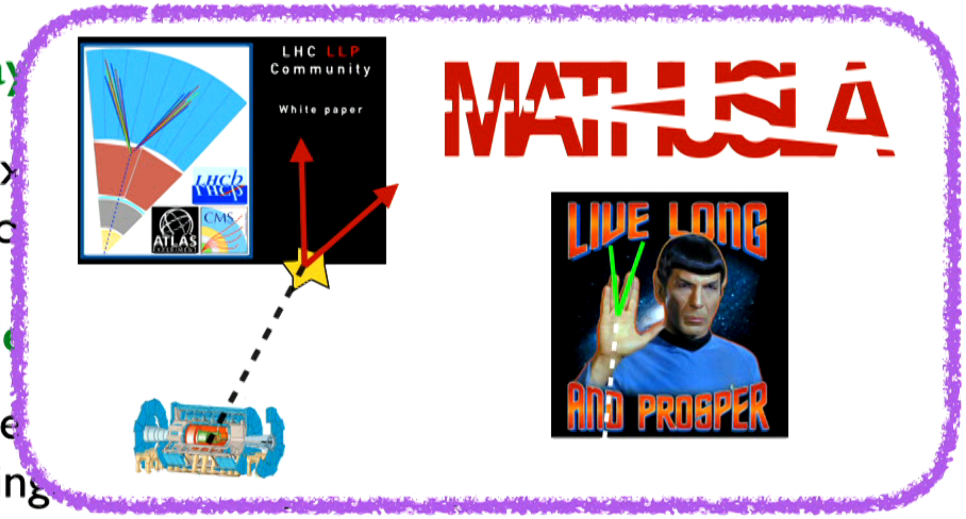

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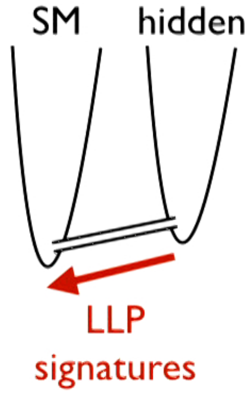

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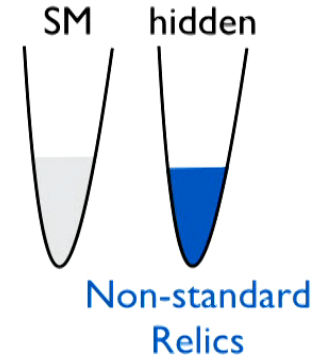


Hidden sectors can give rise to
"arbitrarily" rich cosmology and astrophysics.

Can we make this predictive?

Yes: make the hidden sector solve some of these fundamental mysteries.

→ "signature generator" of
complex hidden sector phenomena

Neutral Naturalness

Neutral Naturalness

Solves the (little) Hierarchy Problem without colored top partners to explain LHC null results.

Example of a particularly motivated hidden sector.

Solution to the hierarchy problem that is discoverable via non-standard searches and demonstrates collider-cosmo complementarity: either get

LLP signals

or

very rich cosmology and astrophysics

hep-ph/0609152 Burdman, Chacko, Goh, Harnik

hep-ph/0506256 Chacko, Goh, Harnik

Minimal Twin Higgs (MTH)

SM_A x SM_B (mirror sector) particle content with Z_2 symmetry

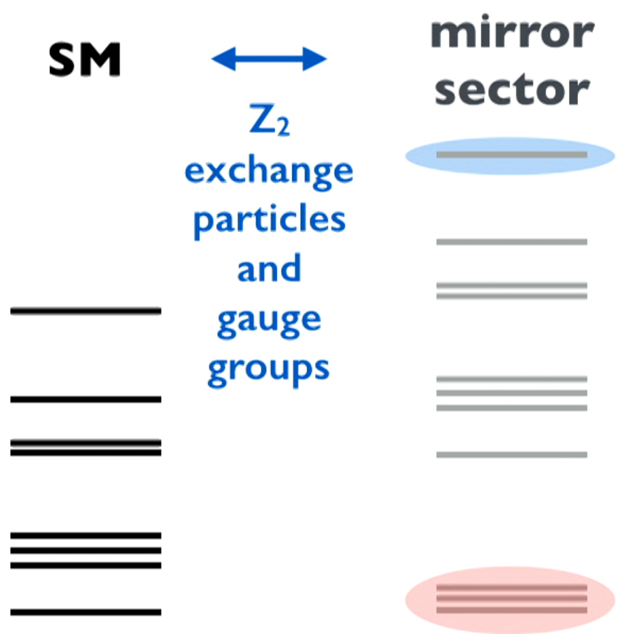
Higgs sector: SU(4), broken by Gauge + Yukawa interactions to $SU(2)_A$ x $SU(2)_B$ x Z_2, which generate mass for goldstone boson.

$$\Delta V = \frac{3}{8\pi^2}\Lambda^2\left(\lambda_A^2 H_A^\dagger H_A + \lambda_B^2 H_B^\dagger H_B\right) \xrightarrow{\lambda_A = \lambda_B \equiv \lambda:} \Delta V = \frac{3\lambda^2}{8\pi^2}\Lambda^2\left(H_A^\dagger H_A + H_B^\dagger H_B\right) = \frac{3\lambda^2}{8\pi^2}\Lambda^2 H^\dagger H$$

Z_2 symmetry of quadratically divergent contributions mimics full SU(4) symmetry, *protects pNGB Higgs mass @ 1-loop.*

This is an IR model up to few TeV.
Have to UV complete.
O(dozen) examples in literature

hep-ph/0506256 Chacko, Goh, Harnik
1411.3310 Burdman, Chacko, Harnik, de Lima, Verhaaren



Z_2 symmetry → hidden sector copy of SM [a complicated hidden valley!]

Strassler, Zurek 2006

Soft Z_2 breaking to make hidden higgs vev higher than SM to avoid Higgs bounds: $v_B/v_A > \sim 3$

This requires tuning $\sim (v_B/v_A)^2 \sim$ Br(h→mirror)

Uncolored top partners.

Massless degrees of freedom: (twin photon, neutrinos)

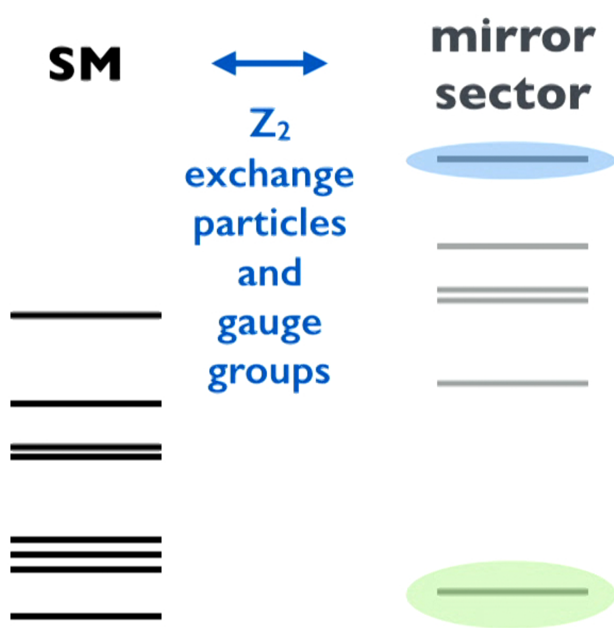
$\Rightarrow \Delta N_{eff} \sim 5$

Minimal model incompatible with cosmology.

Fix 1: *Hard* Z_2 breakings
e.g. Fraternal Twin Higgs

Craig, Katz, Strassler, Sundrum 1501.05310

→ mirror QCD
gives rise to light LLPs
produced via Higgs portal



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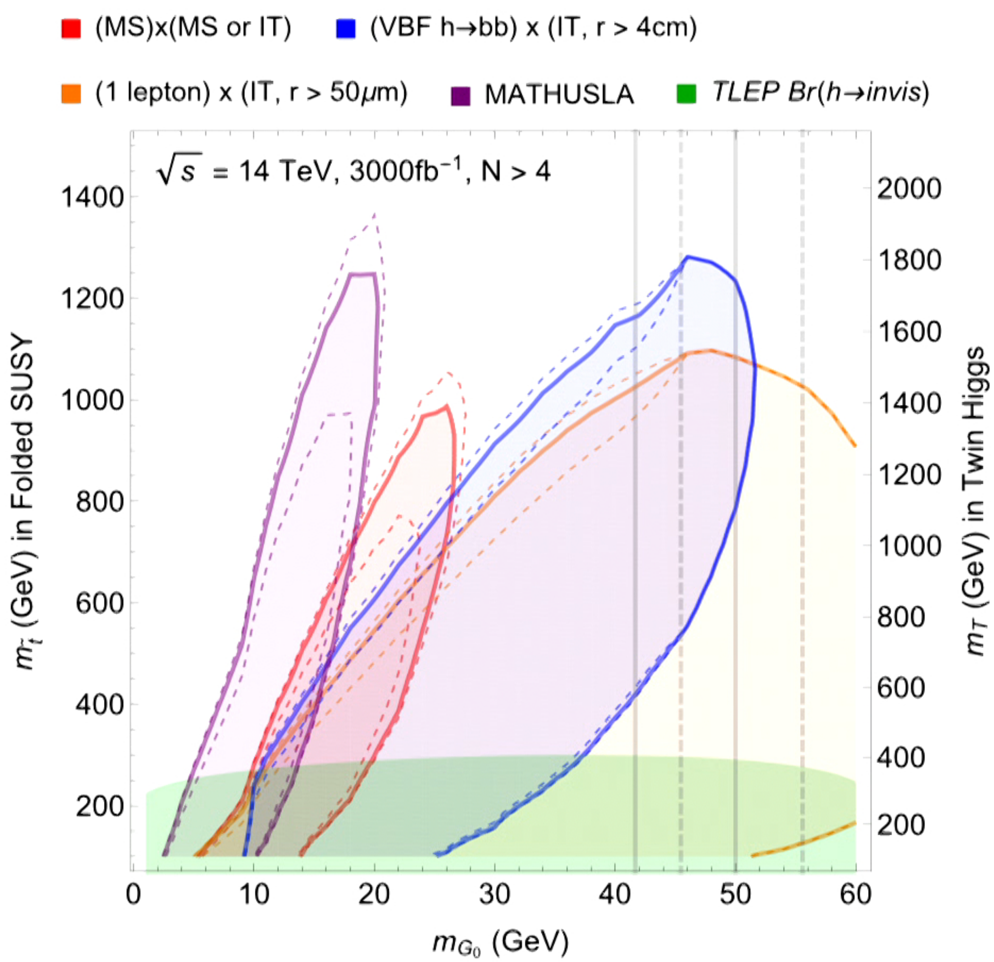
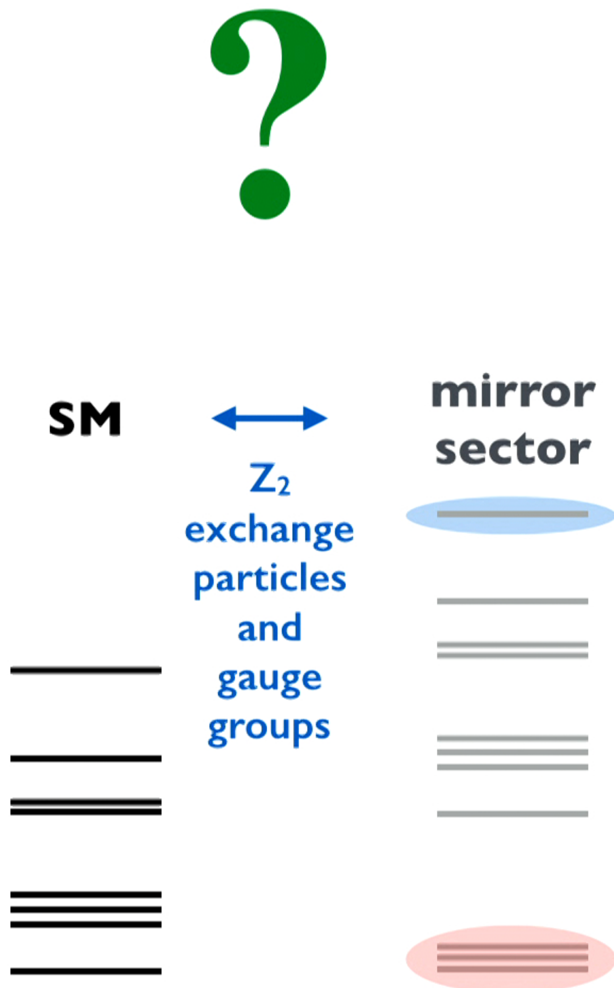


DC, Verhaaren 1506.06141

MATHUSLA Physics Case White Paper 1806.07396



Z_2 symmetry → hidden sector copy of SM [a complicated hidden valley!]

Strassler, Zurek 2006

Soft Z_2 breaking to make hidden higgs vev higher than SM to avoid Higgs bounds: v_B/v_A > ~ 3

This requires tuning ~ $(v_B/v_A)^2$ ~ Br(h→mirror)

Uncolored top partners.

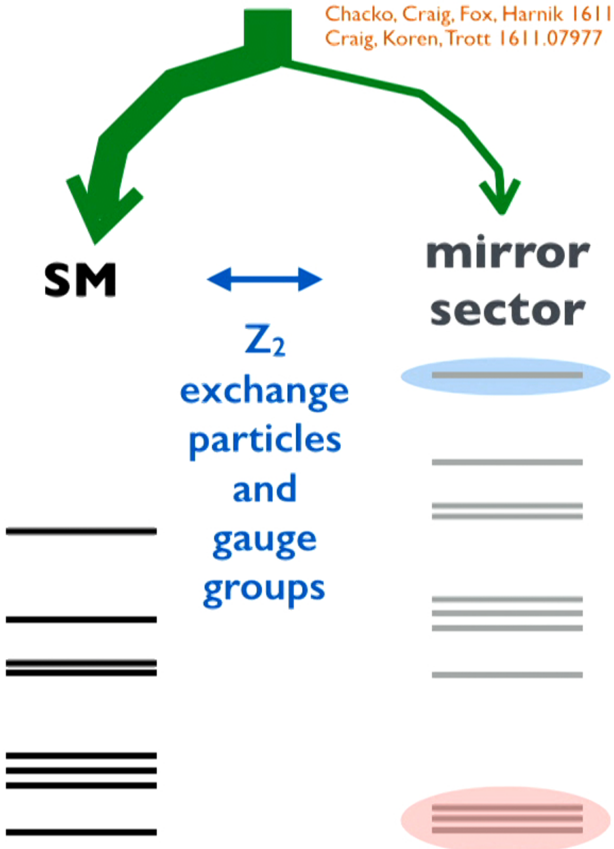
Massless degrees of freedom: (twin photon, neutrinos)

⇒ ΔN_{eff} ~ 5

Minimal model incompatible with cosmology.

Fix 2: dilute mirror sector cosmological abundance: **Asymmetric Reheating!**

Chacko, Craig, Fox, Harnik 1611.07975
Craig, Koren, Trott 1611.07977



Z_2 symmetry → hidden sector copy of SM [a complicated hidden valley!]

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Uncolored top partners.

Massless degrees of freedom: (twin photon, neutrinos)
⇒ ΔN_{eff} ~ 5

Minimal model incompatible with cosmology.

Asymmetrically Reheated Mirror Twin Higgs

Chacko, Craig, Fox, Harnik
1611.07975

Example: νMTH

Let's also solve the Neutrino Mass problem: add RH neutrinos to MTH and implement type-1 See-saw

Toy model with 1 RH neutrino **without Z_2 breaking**
(can extend to 3 & various realistic flavor models):

$$\mathcal{L} \supset -y\left(L_A H_A N_A + L_B H_B N_B\right) - \frac{1}{2} M_N \left(N_A^2 + N_B^2\right) - M_{AB} N_A N_B + \text{h.c.}$$

RH-neutrino mass eigenstates live in both sectors:

$$\begin{aligned} N_+ &= \frac{1}{\sqrt{2}}\left(N_A + N_B\right) \\ N_- &= \frac{1}{\sqrt{2}}\left(N_A - N_B\right) \end{aligned}$$

Chacko, Craig, Fox, Harnik
1611.07975

Example: νMTH

Only source of Z_2 breaking is larger mirror Higgs vev, but this causes lightest RH neutrino to decay preferentially to SM (heavier mirror W boson):

$$\epsilon = \frac{\Gamma_{N \to B}}{\Gamma_N} \approx \frac{v^2}{f^2}$$

If the Neutrinos have mass at GeV scale, decay out of equilibrium AFTER the higgs portal freezes out (mirror & visible sector decoupled). → **Dilute mirror sector!**

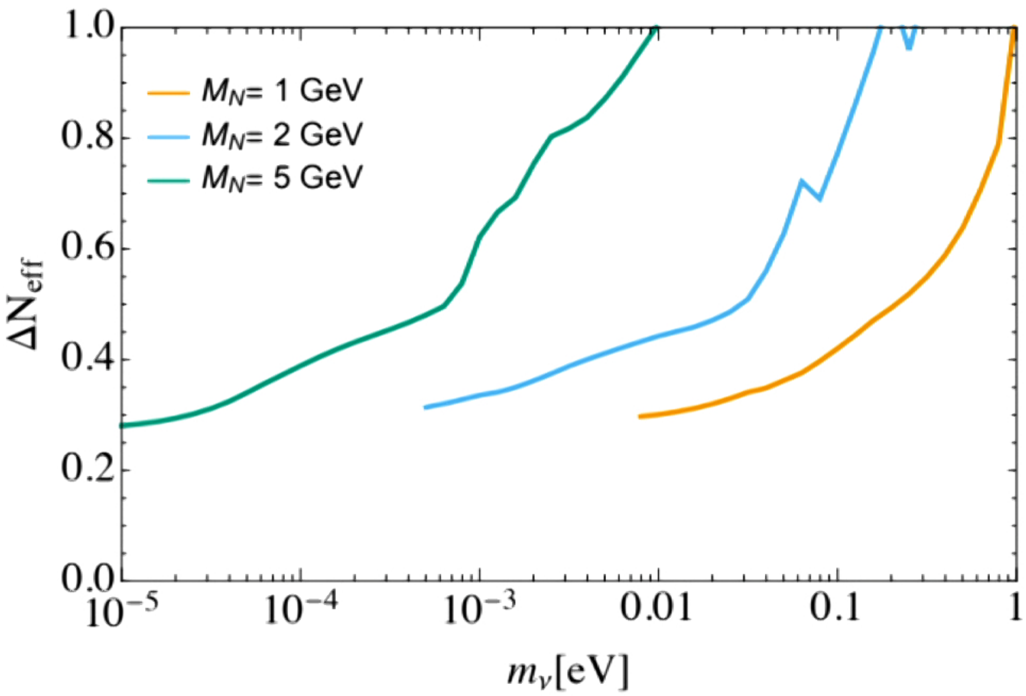
$$M_N < 1 \text{ GeV} \left(\frac{0.01 \text{ eV}}{m_\nu} \right)^{1/2}$$

$\Delta N_{eff} \sim 5\,\epsilon = 5\,(v/f)^2$

Chacko, Craig, Fox, Harnik
1611.07975

Example: νMTH

More realistic three-flavor Z_2-respecting model with v/f ~ 4:



Phenomenology

In the νMTH, the dilution is dictated by $(v_A/v_B)^2$, which is the tuning of the model and also **measurable at colliders via Br(h→invis)**.

Long-lived RH neutrino might also be detectable.

But let's focus on cosmology and astrophysics.

Choose a general parameterization of the Asymmetric Reheating mechanism within the MTH framework:

$$\Delta N_{eff}, \qquad v_B/v_A, \qquad r_{\text{all}} = \Omega_{\text{all mirror baryons}}/\Omega_{\text{DM}}.$$

model like νMTH connects these two

any mirror-baryogenesis mechanism will give some asymmetric mirror relic abundance

1803.03263 Chacko, DC, Geller, Tsai

Three parameters determine a rich hidden sector dictated by the hierarchy problem.

$$\Delta N_{eff}, \qquad v_B/v_A, \qquad r_{\rm all} = \Omega_{\rm all\ mirror\ baryons}/\Omega_{\rm DM}.^{*}$$

What does the cosmology and astrophysics look like?

We have to recalculate all of cosmological history…

**For now, no assumptions on what the majority of DM is made of… [work in progress with Shayne Gryba]*

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Asymmetrically Reheated MTH:

Big Bang Nucleosynthesis

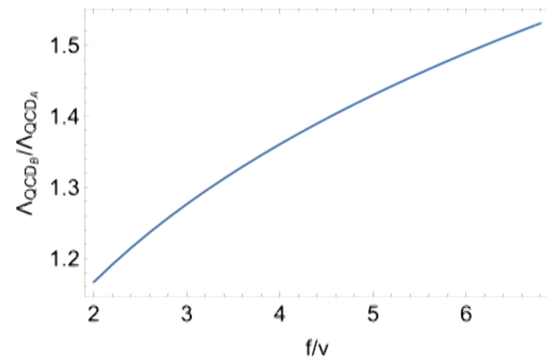
1803.03263 Chacko, DC, Geller, Tsai

Mirror Nuclear Physics

Only difference to SM is v_B/v_A

proton mass: ~30-50% higher than SM

$$\frac{m_{\hat{p}}}{m_p} \approx \frac{m_{\hat{n}}}{m_n} \approx \frac{\Lambda_{QCD_B}}{\Lambda_{QCD_A}} \approx 0.68 + 0.41 \log(1.32 + v_B/v_A)$$

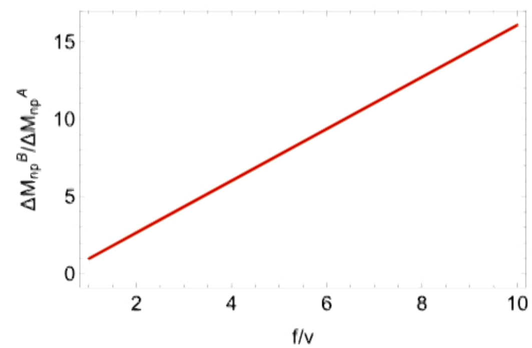


proton-neutron mass difference: ~5x SM

$$\Delta M_{np} \approx C(m_d - m_u) - D\alpha_{EM}\Lambda_{QCD}.$$

get coeffs from lattice 1406.4088 & rescale by $\Lambda_{QCD\,B}$

$$\frac{\Delta M_{\hat{n}\hat{p}}}{\Delta M_{np}} \approx 1.68 v_B/v_A - 0.68, \qquad \Delta M_{np} = 1.29\,\mathrm{MeV}.$$

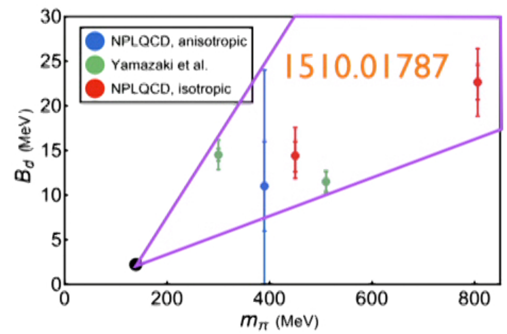


Mirror Deuteron Binding Energy

Deuteron binding energy is important for BBN.
SM Deuteron is "unnaturally" unstable (small binding energy B_D) due to "accidental" cancellation of pion vs 4-fermi term

Lattice: Deuteron remains stable at heavier pion masses!

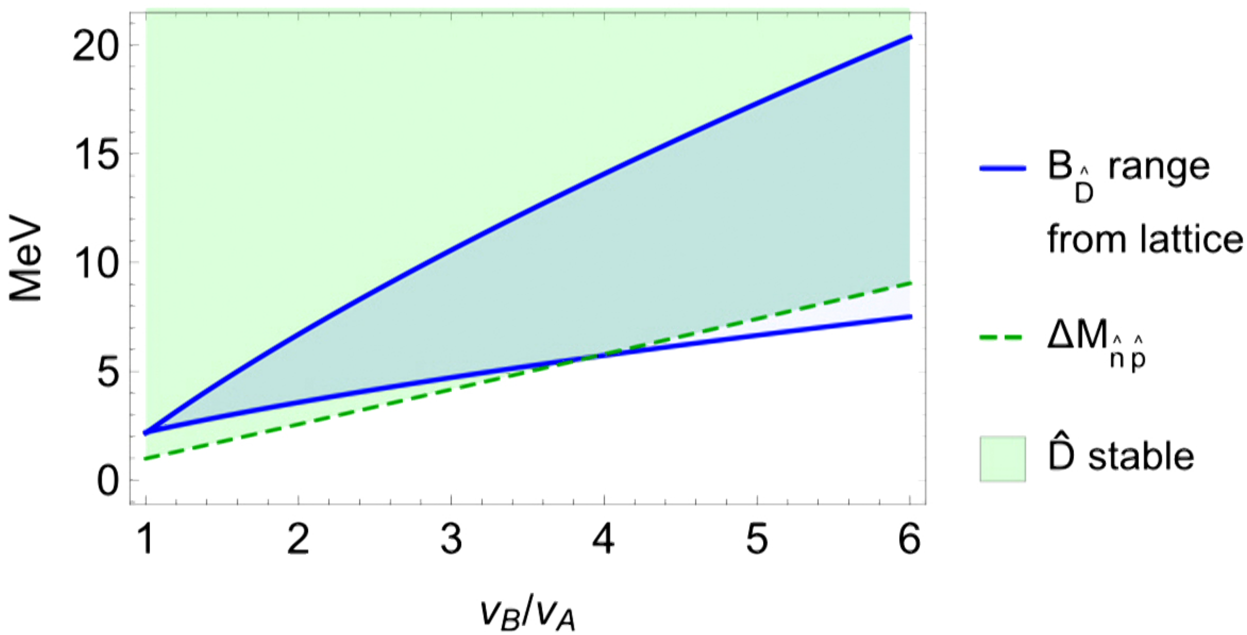
$$B_D^{\text{min}} = -(0.66\ \text{MeV}) + 0.021\, m_\pi\ ,$$
$$B_D^{\text{max}} = -(9.2\ \text{MeV}) + 0.084\, m_\pi\ ,$$



Rescaling by mirror pion mass and Λ_{QCD}, we can estimate mirror Deuteron binding energy!

$$m_{\hat{\pi}} = \sqrt{\frac{\hat{\Lambda}_{\text{QCD}}}{\Lambda_{\text{QCD}}} \frac{v_B}{v_A}}\, m_\pi \approx \sqrt{[0.68 + 0.41\log(1.32 + v_B/v_A)]\, \frac{v_B}{v_A}}\, m_\pi$$

Mirror Deuteron Binding Energy



Accidental Aside: disproves "atomic principle"?

(Agrawal, Barr, Donoghue, Seckel hep-ph/9707380)

Come back to this

BBN in the SM

Want to compute n/p ratio. This determines Helium Fraction.

$$X_n \equiv n_n/(n_n + n_p)$$

Neutron-Proton weak conversion freezes out at 0.2 MeV (t ~ 20s)

$$X_n^{\rm FO} = 0.15 \qquad\qquad T = T_n^{\rm FO} \approx 0.2 \text{ MeV}$$

Deuterium bottleneck:
Helium doesn't form until T < ~ 0.1 MeV around $t = t_{ns}$ = 180s.
This causes some neutrons to decay (τ_n = 880s):

$$X_n(t_{\rm ns}) \approx X_n^{\rm FO} e^{-t_{\rm ns}/\tau_n} \approx 0.122 \quad \Rightarrow \quad Y_p(\text{He}) = \frac{\rho_{\rm He}}{\rho_{\rm H} + \rho_{\rm He}} \approx 0.24$$

BBN in the mirror sector

Mirror sector temperature colder as dictated by ΔNeff,

$$\frac{\hat{T}}{T} = \left(\frac{g_{\star A}}{g_{\star B}}\right)^{1/3} \left(\frac{\Delta N_{\rm eff}}{7.4}\right)^{1/4} < 1$$

Neutron-proton freeze-out modified due to heavier W-mass and larger mass difference: $\Gamma_{\hat{n}} = \Gamma_n \left(\Delta M_{\hat{n}\hat{p}}/\Delta M_{np}\right)^5 \left(v_B/v_A\right)^{-4}$

⇒ obtain prediction for $X_{\hat{n}}^{\rm FO}$

Deuteron bottleneck **is less severe in mirror sector!**

Assuming the ratio of *mirror temperature / mirror Deuteron binding energy* is the same when mirror Deuteron bottleneck resolves, neutron decay only reduces FO abundance by ~10%, can ignore it here.

BBN in the SM

Want to compute n/p ratio. This determines Helium Fraction.

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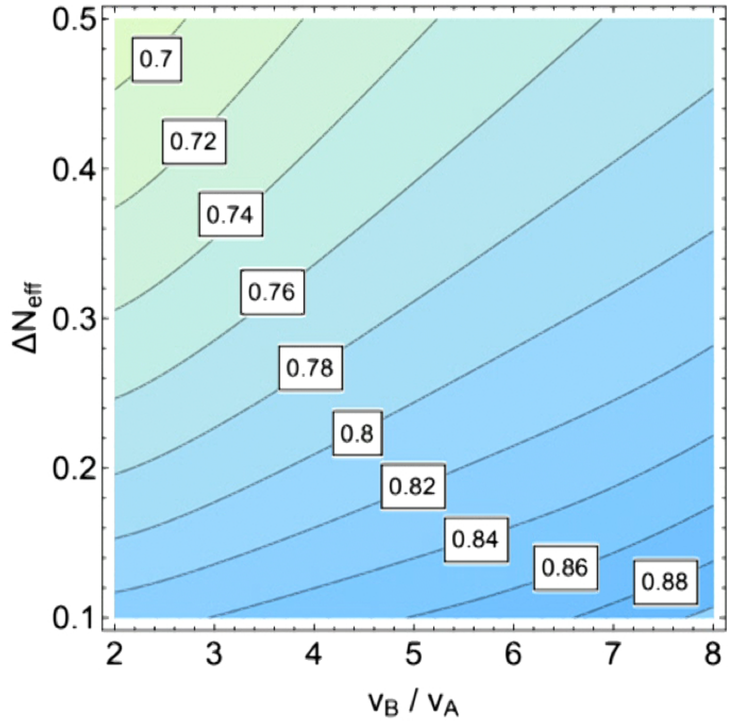
$\hat{Y}_p(^4\hat{\mathrm{He}}) = \rho_{\hat{\mathrm{He}}} / (\rho_{\hat{\mathrm{He}}} + \rho_{\hat{\mathrm{H}}})$



(SM: 0.245)

MTH BBN Prediction:

~75% Mirror Helium Mass Fraction

Asymmetrically Reheated MTH:

Large Scale Structure

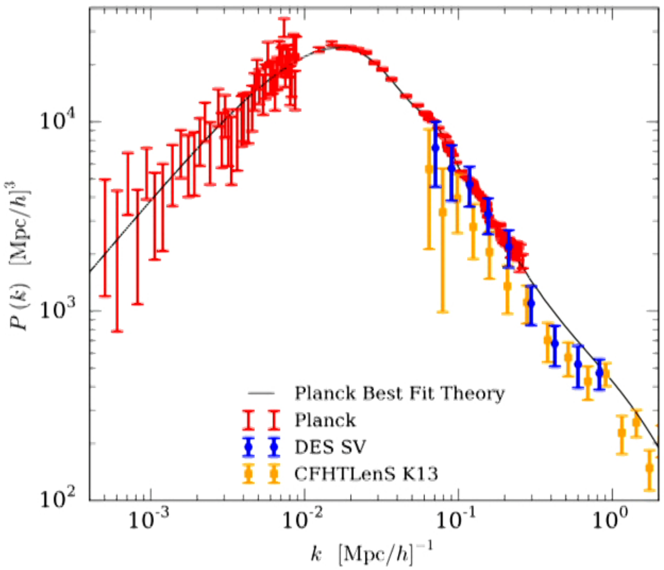
(Slides by Yuhsin Tsai)

1803.03263 Chacko, DC, Geller, Tsai

Large Scale Structure of the Universe

(Slides by Yuhsin Tsai)

$$P(k)_s \propto k^{-3}\langle \delta_s(k,a)^2 \rangle$$



DES: 1507.05552

Density Perturbation

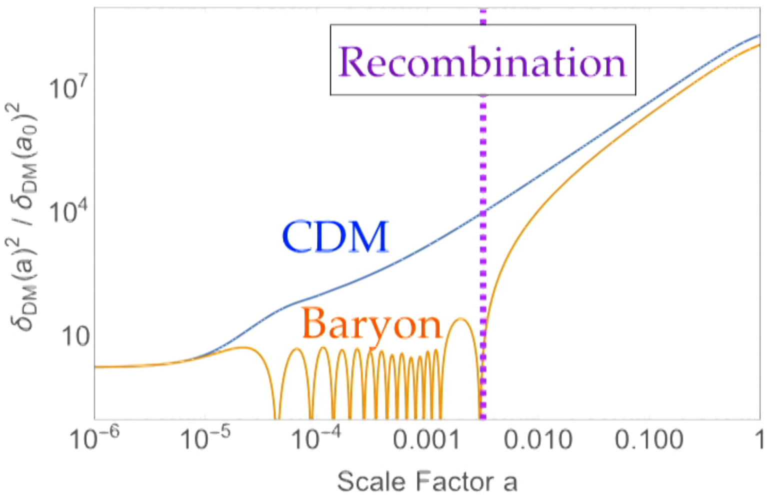
$$\delta_i \equiv \frac{\delta\rho_i}{\bar{\rho}_i} \quad i = \mathrm{DM},\ \gamma,\ b,\ \nu$$

Fourier transform into frequency modes

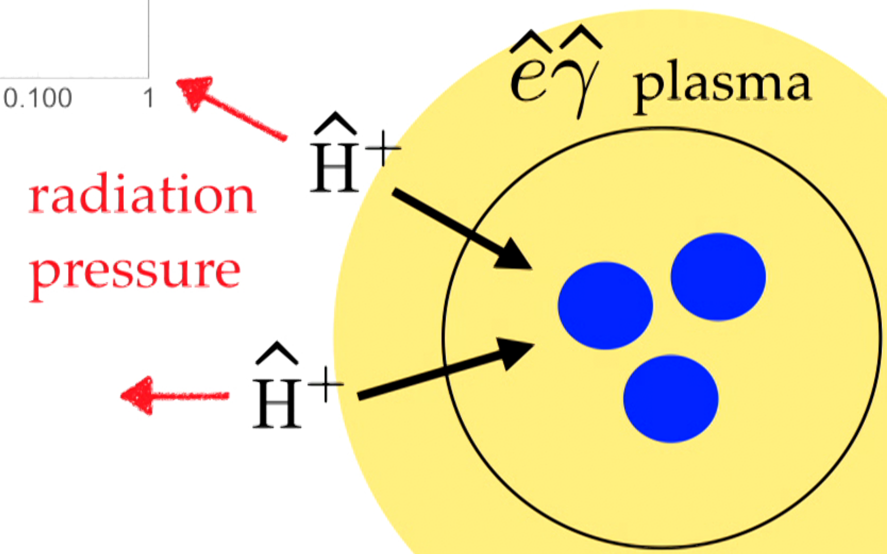
$$\delta_i(x,a) \rightarrow \delta_i(k,a)$$

Mirror Baryon Acoustic Oscillation (BAO)

(Slides by Yuhsin Tsai)



The scattering forbids mirror baryons to form structure

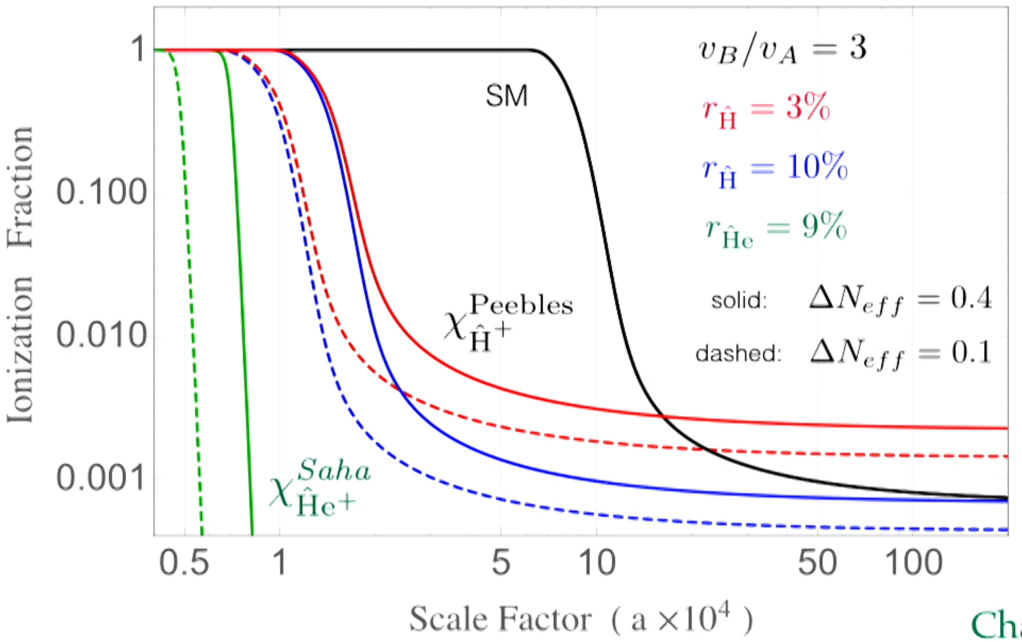


Oscillation stops after recombination

(Slides by Yuhsin Tsai)

$$H^+ + e^- \to H^0 + \gamma + (\gamma) \qquad \frac{n_{H^+} n_{e^-}}{n_{H^0}} \sim \left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-\frac{13.6\,\mathrm{eV}}{T}}$$

Saha's eq



taking more precise energy transitions into account (Peebles)

Chacko, Curtin, Geller, YT ('18)

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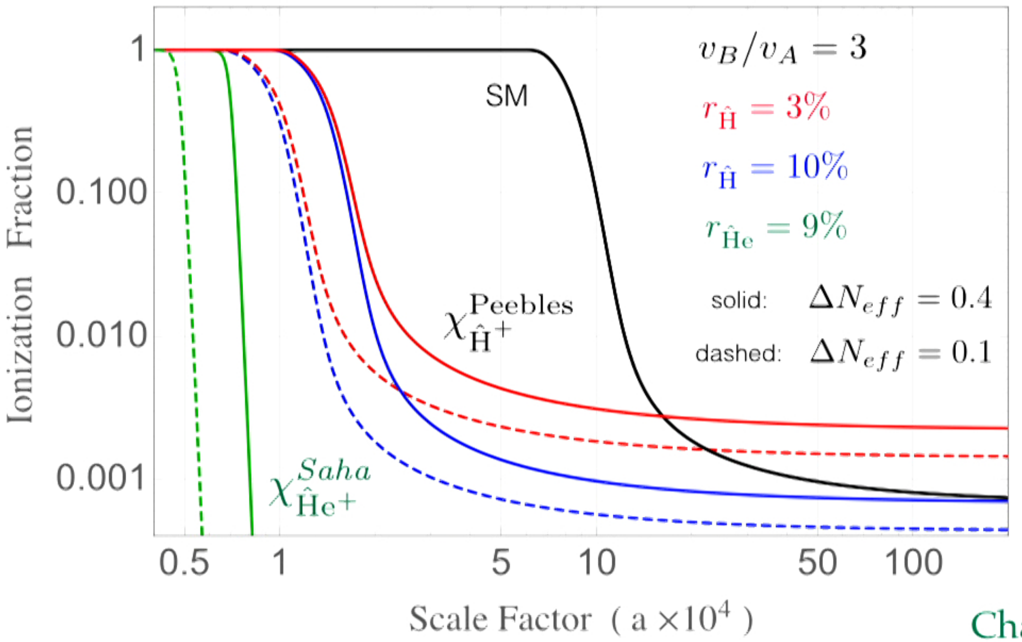


taking more precise energy transitions into account (Peebles)

Chacko, Curtin, Geller, YT ('18)

Quantify the suppression of matter structure

(Slides by Yuhsin Tsai)

$$\delta_{tot}(k) = \sum_{i=\chi,\hat{b},p} (\Omega_i/\Omega_m)\,\delta_i(k),$$

With mirror oscillations

$$\text{P.S. Ratio}(k) \equiv \frac{\delta^2_{tot}(k)\Big|_{\Lambda\text{CDM+MTH}}}{\delta^2_{tot}(k)\Big|_{\Lambda\text{CDM+DR}}}$$

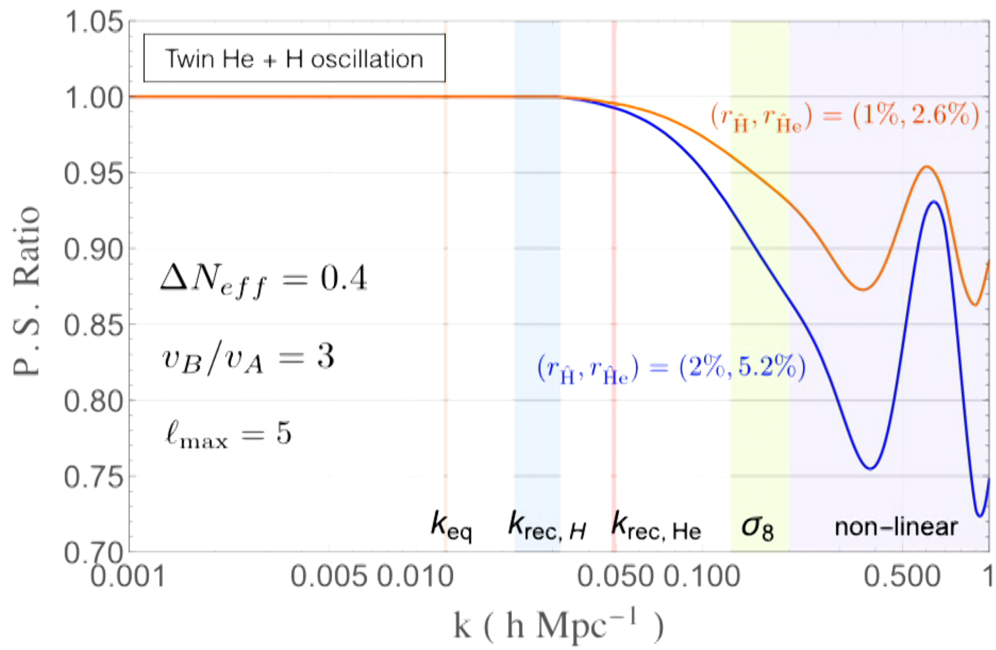
Without mirror oscillations

Twin acoustic oscillations → P.S. Ratio < 1

Can LSS Measurements give a constraint on the mirror DM fraction r_{all}?

Suppression of the Large Scale Structure

(Slides by Yuhsin Tsai)



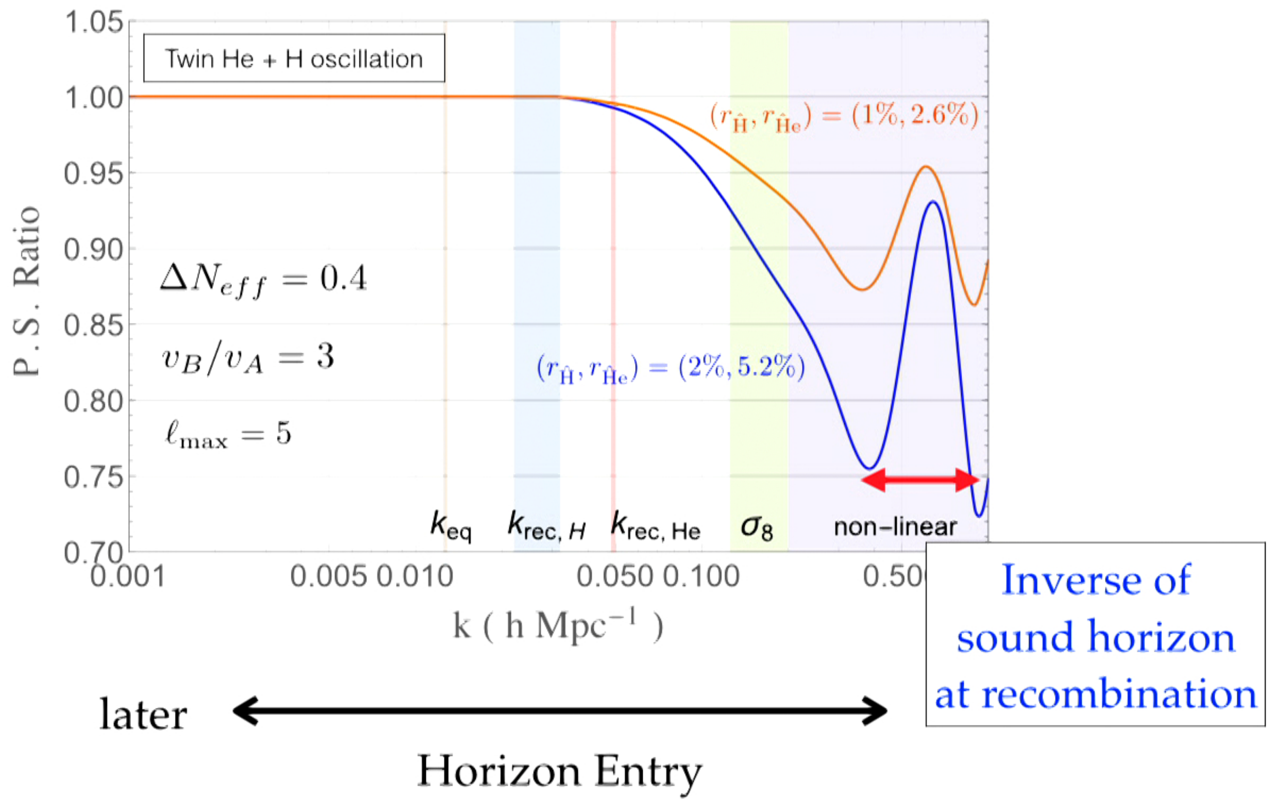
Suppression due to mirror oscillations

later ⟵⟶ earlier

Horizon Entry

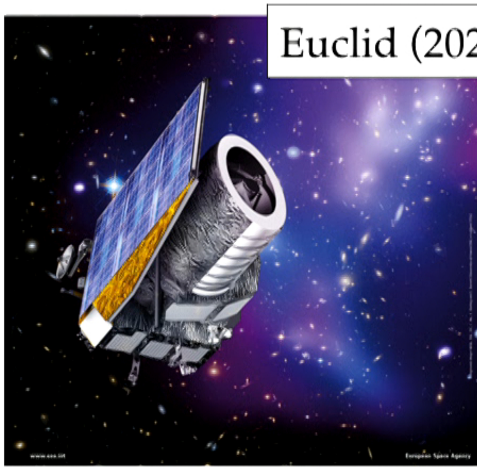
Oscillation pattern

(Slides by Yuhsin Tsai)

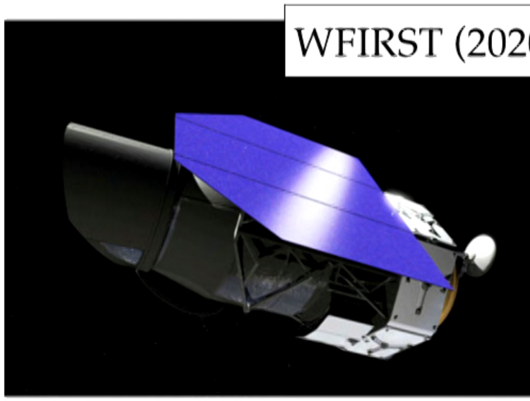


Precision measurement of the LSS

(Slides by Yuhsin Tsai)

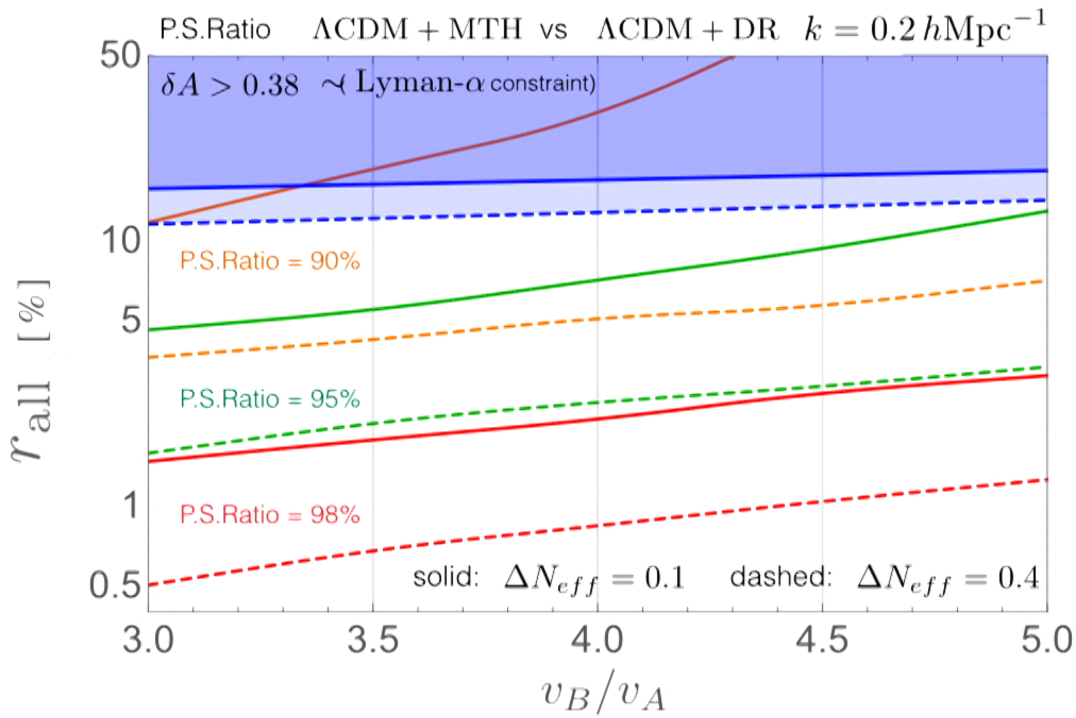


Precent level precision
in ~ 10 years



LSS constraint on mirror particle density

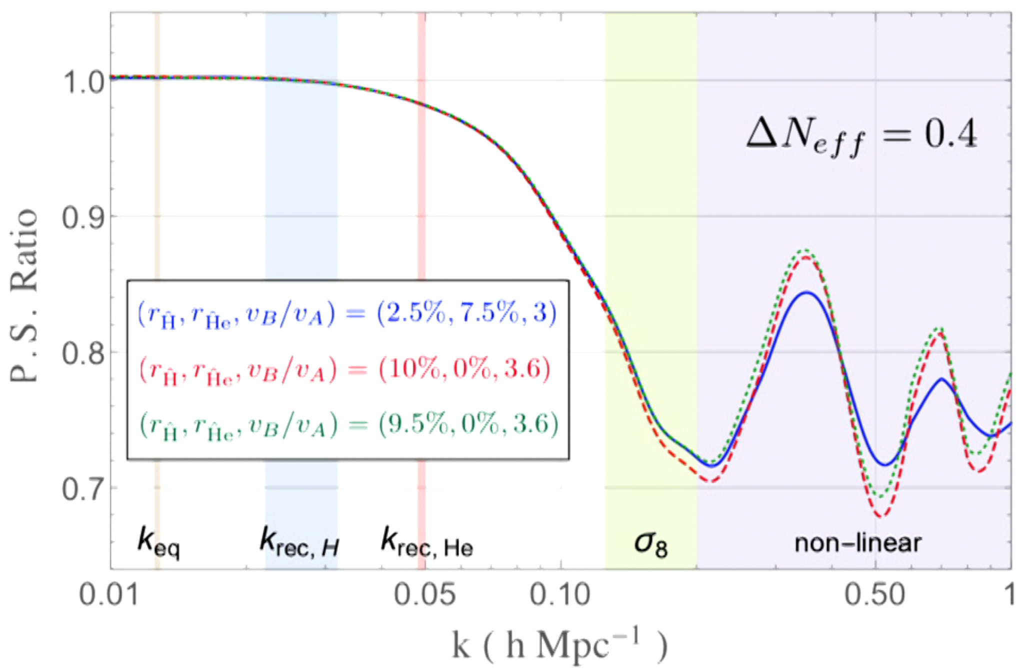
(Slides by Yuhsin Tsai)



Current bound $\Omega_{\hat{\mathrm{H}}+\hat{\mathrm{He}}}/\Omega_{\mathrm{DM}} < 10\%$ Future bound, $< 1\ \%$

Large Scale Structure as dark atom spectroscopy

(Slides by Yuhsin Tsai)



later ⟷ earlier

Horizon entry

Would need additional data (collider, direct detection, …) to break degeneracy of precise atomic composition

Asymmetrically Reheated MTH:

CMB Signals

1803.03263 Chacko, DC, Geller, Tsai

CMB Signals

1. ΔN_{eff} is reduced by asymmetric reheating. Precise dilution is model-dependent and can be correlated with collider measurements, e.g. νMTH: dilution ~ $(v_A/v_B)^2$ ~ Br(h→invis)

2. Irreducible signature of unbroken Z_2:
   free-streaming vs scattering ratio of additional radiation has SM-like ratio:

$$\frac{\Delta N_{eff}^{\hat{\nu}}}{\Delta N_{eff}^{\hat{\gamma}}} = \frac{3}{4.4}$$

MTH Smoking Gun accessible with CMB Stage-IV!

Asymmetrically Reheated MTH:

Mirror Baryons in our Galaxy

1812.xxxxx Chacko, DC, Geller, Tsai

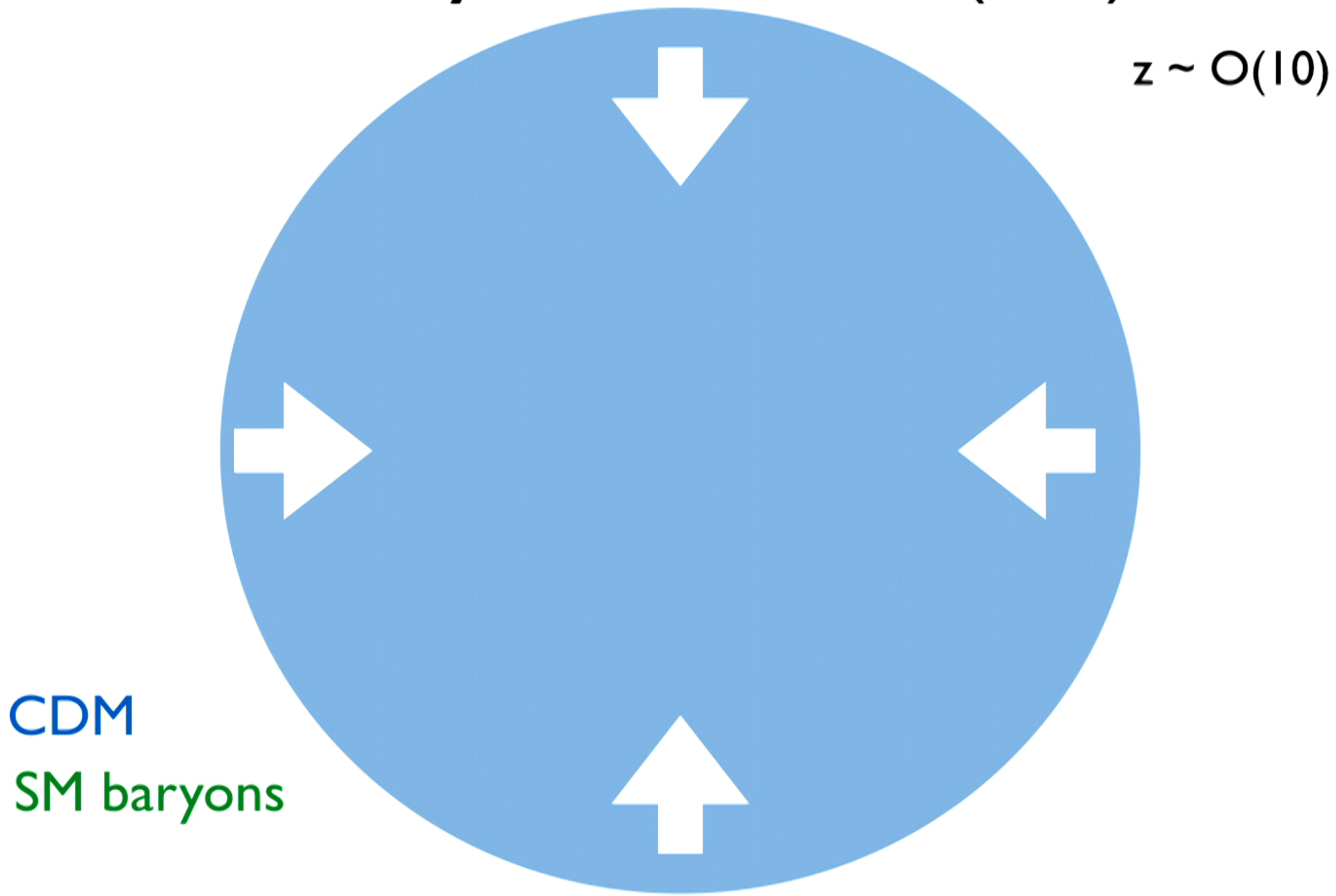
Where are the mirror baryons today?

Can we detect them in DM direct detection experiments?

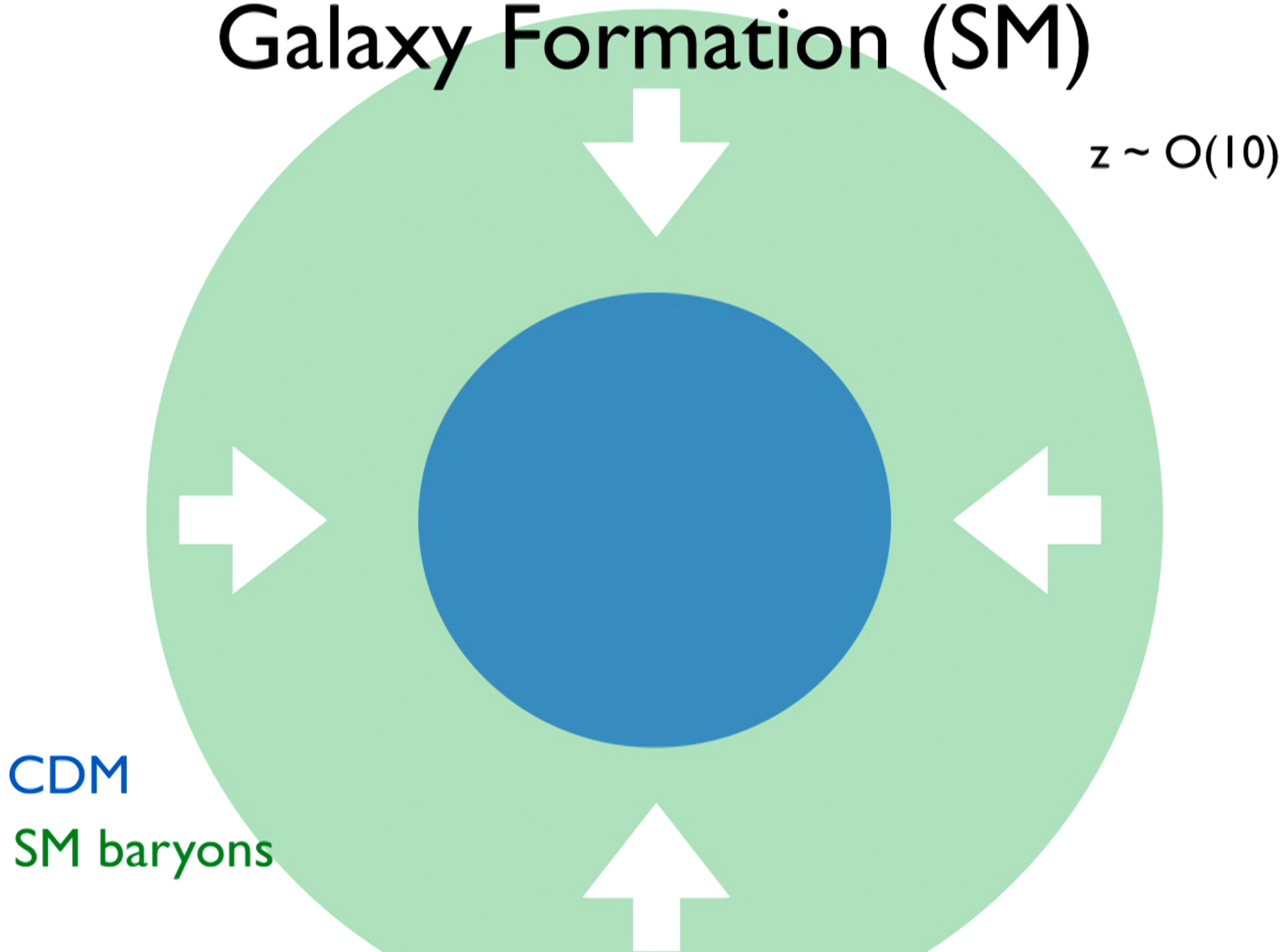
Could they give rise to novel astrophysical phenomena?

see also "Double Disk DM" (Fan, Katz, Randall, Reece 1303.1521), but we solve for distribution of dissipative DM component and have to worry about nuclear physics

Galaxy Formation (SM)

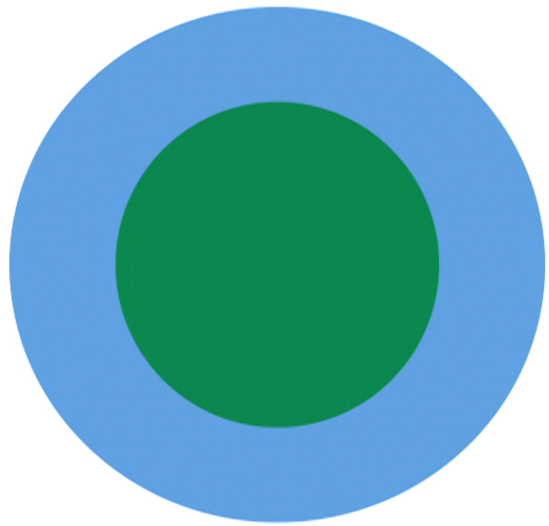


Galaxy Formation (SM)



Galaxy Formation (SM)

z ~ O(10)



SM baryons
get shock-heated
& ionized.

CDM

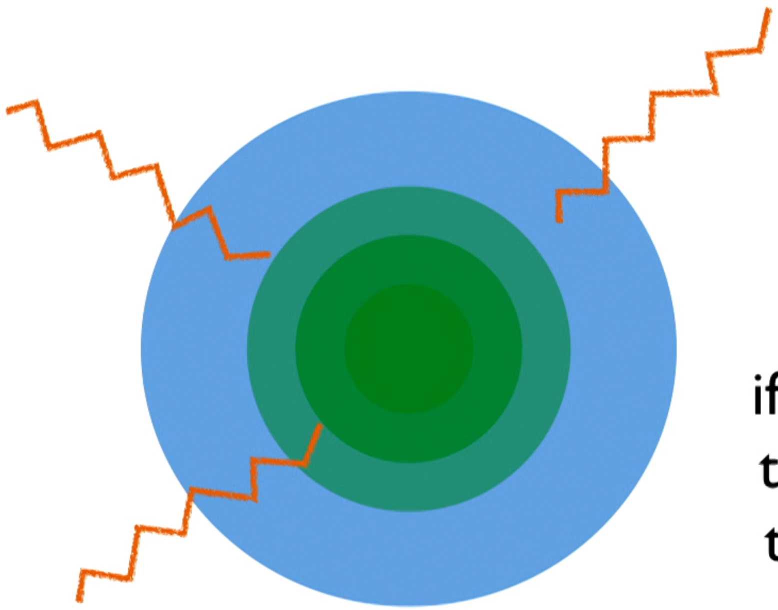
SM baryons

$T \sim T_{vir}$

Galaxy Formation (SM)

SM baryons settle into hydrostatic equilibrium and start COOLING

z ~ O(10)



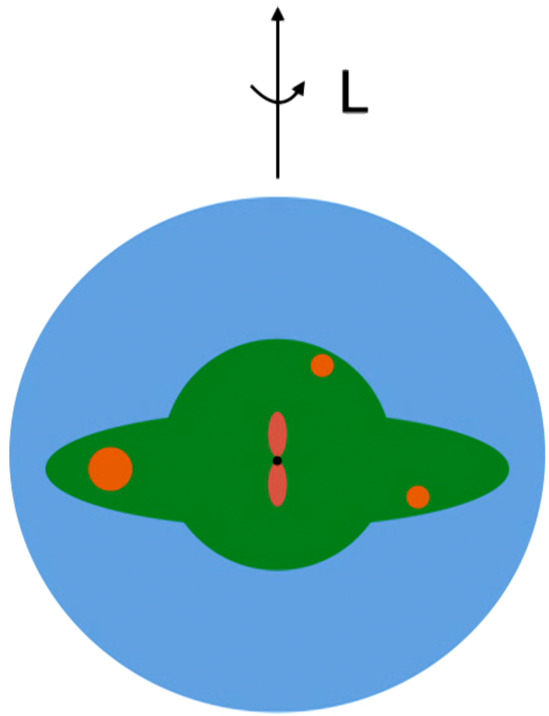
if cooling faster than dynamical timescale, lose pressure support and collapse

CDM

SM baryons

Galaxy Formation (SM)

If halo has sufficient angular momentum and is not disrupted, can form a **disk**



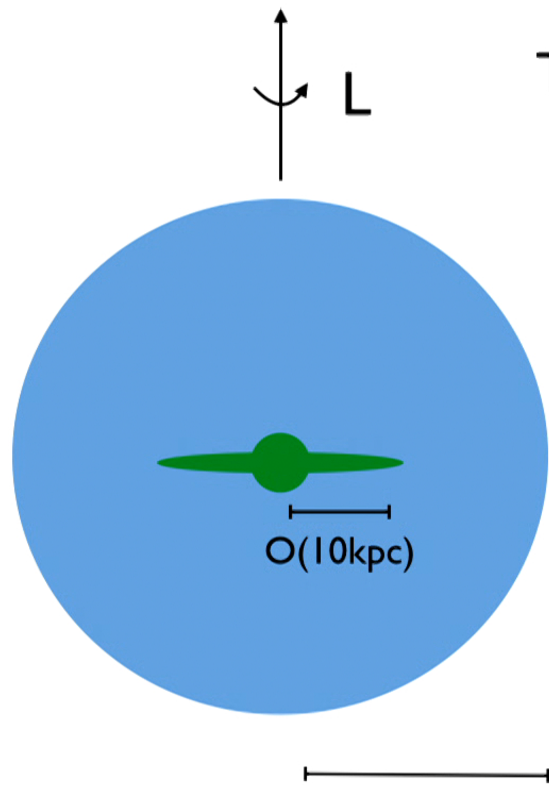
z ~ O(10)

Feedback from star formation, Supernovae and central black hole drastically slows cooling, moves around material, etc

CDM

SM baryons

Galaxy Formation (SM)



CDM Halo R_{vir} ~ 200kpc

Today, our milky way has a visible disk.

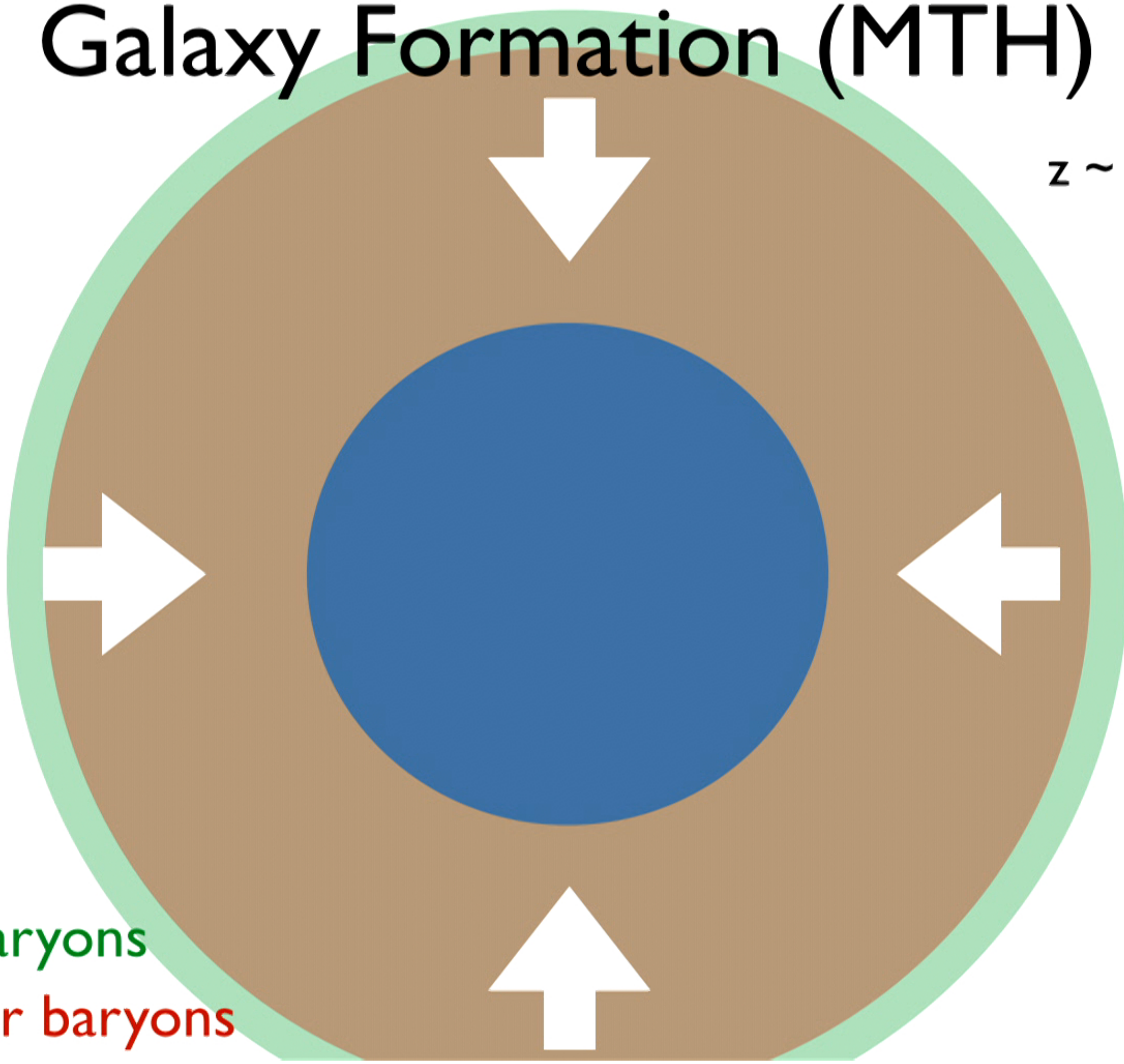
Complex MHD N-body simulations can reproduce this with *parameterized* feedback

CDM

SM baryons

Galaxy Formation (MTH)

z ~ O(10)



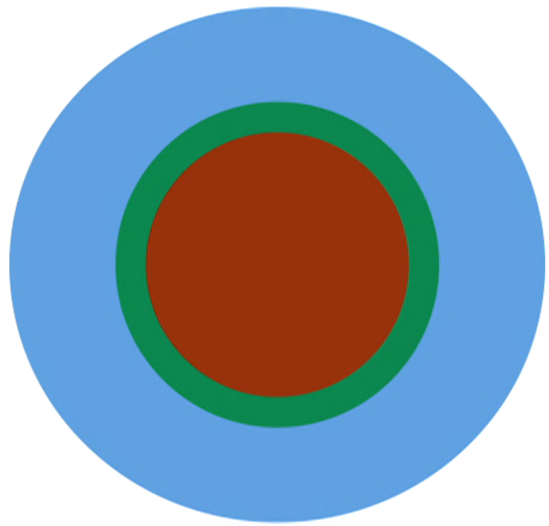
CDM

SM baryons

mirror baryons

Galaxy Formation (MTH)

$z \sim O(10)$

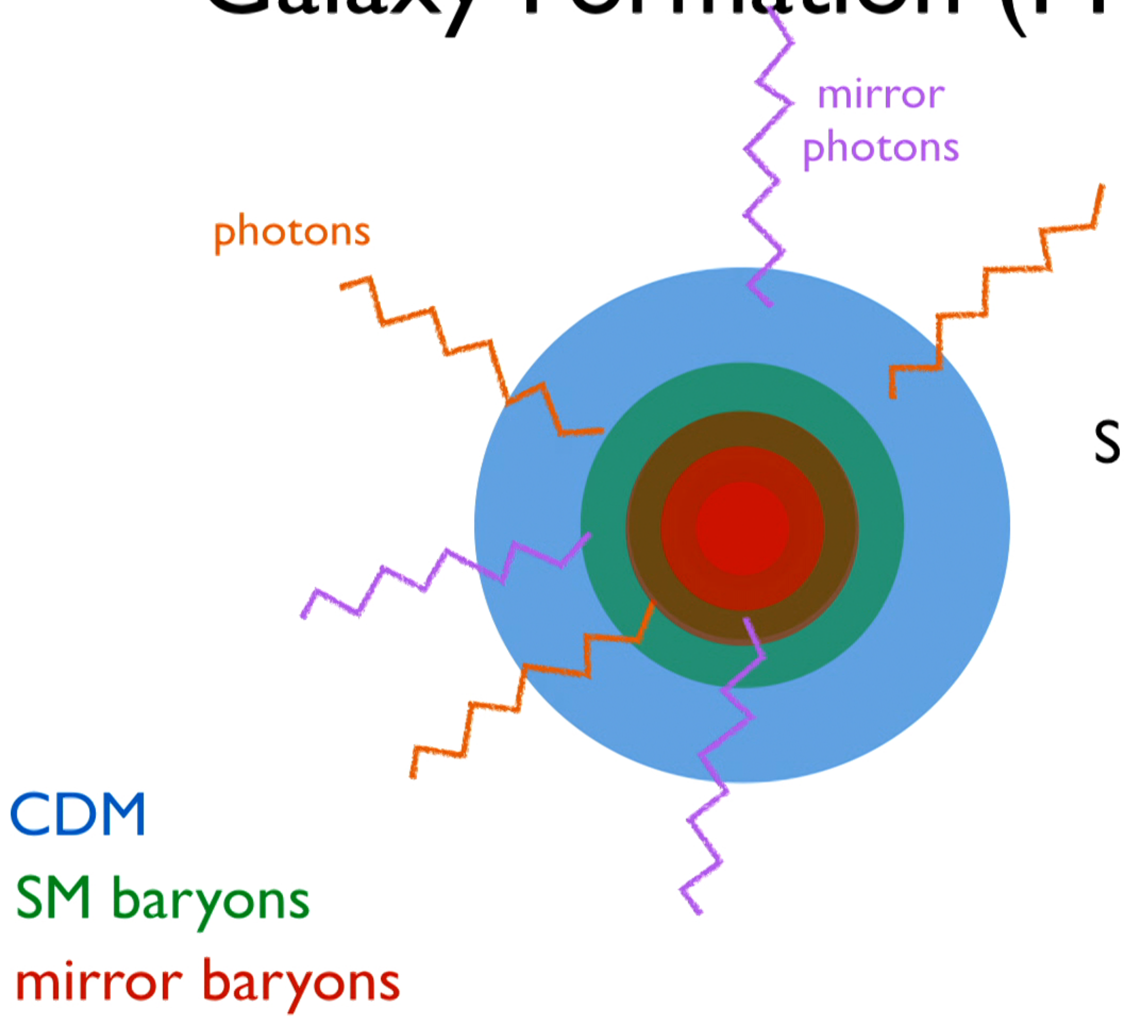


SM and mirror baryons get shock-heated & ionized.

$T \sim T_{vir}$

CDM
SM baryons
mirror baryons

Galaxy Formation (MTH)



z ~ O(10)

SM and mirror baryons settle into hydrostatic equilibrium and start COOLING

Hydrostatic Equilibrium

Assume CDM Background (NFW or Burkert Profile).

$$\frac{dP}{dr} = -\frac{GM_{\rm CDM}(r)\rho(r)}{r^2} \qquad \bar{m}P(r) = \rho(r)T(r)$$

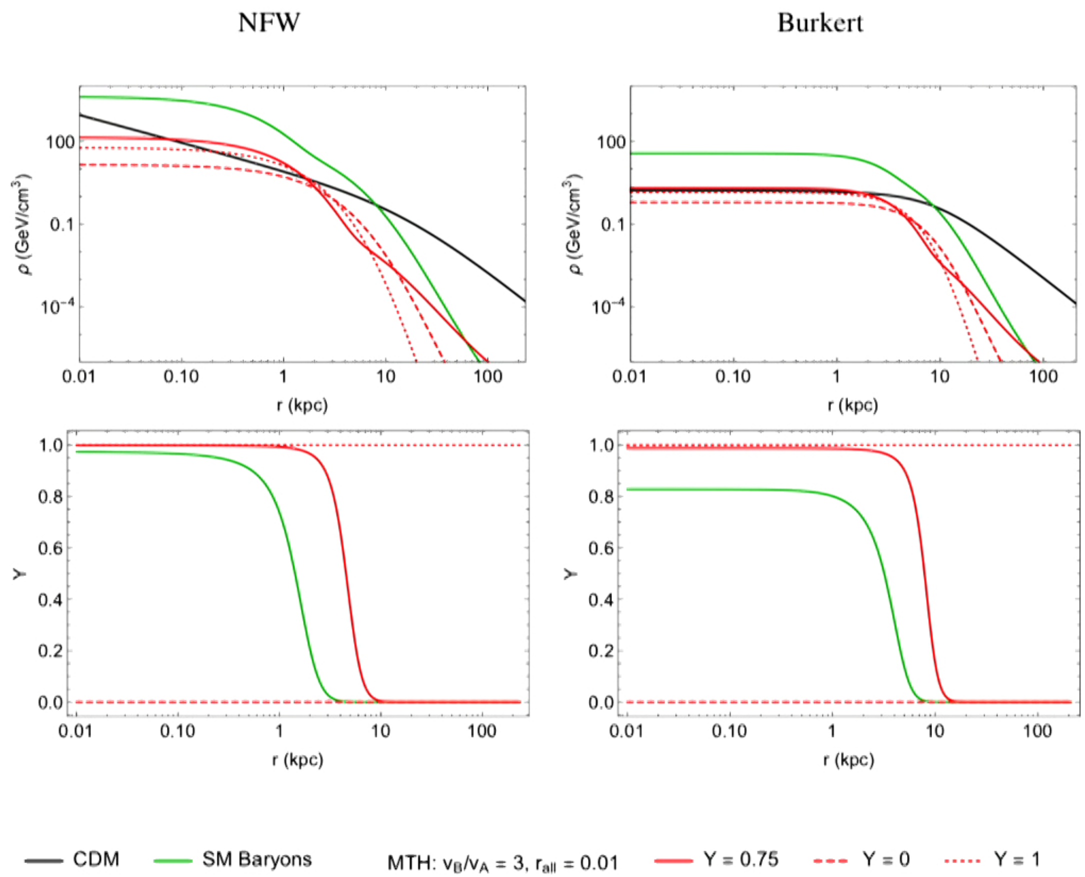
HS EQ ideal gas law

CDM halo sets $T_{gal} = T_{vir}$.

Assuming given ionization to set $\bar{m}$ (solve iteratively for consistent solution) we can solve for numerically for **isothermal** mirror baryon profiles.

Do same for SM baryons.
What can we learn from the **comparison?**

Mirror & SM Baryon Profiles



Mirror & SM Baryon Profiles

Scenario (NFW)	$\frac{T}{\text{eV}}$	$\frac{v_0}{\text{km/s}}$	$(\chi_{H^+}, \chi_{He^+}, \chi_{He^{++}})$	$\frac{\rho_{CDM}}{\text{GeV/cm}^3}$	$\frac{\rho_{mirror}}{\text{GeV/cm}^3}$	$\frac{1}{r_{all}} \frac{\rho_{mirror}}{\rho_{CDM}}$	$Y(R_{sun})$
SM Baryons	76.7	190.6	$(1, 7 \times 10^{-7}, 1)$	0.5	0.51	5.05	3×10^{-6}
$\frac{v_B}{v_A} = 3, r_{all} = 0.01, Y = 0.75$	152.2	190.6	$(1, 2 \times 10^{-6}, 1)$	0.5	0.0075	1.5	2×10^{-2}
$\frac{v_B}{v_A} = 3, r_{all} = 0.01, Y = 0$	80.8	190.6	$(1, -, -)$	0.5	0.024	4.7	0
$\frac{v_B}{v_A} = 3, r_{all} = 0.01, Y = 1$	215.3	190.6	$(-, 8 \times 10^{-7}, 1)$	0.5	0.0040	0.79	1

Scenario (Burkert)	$\frac{T}{\text{eV}}$	$\frac{v_0}{\text{km/s}}$	$(\chi_{H^+}, \chi_{He^+}, \chi_{He^{++}})$	$\frac{\rho_{CDM}}{\text{GeV/cm}^3}$	$\frac{\rho_{mirror}}{\text{GeV/cm}^3}$	$\frac{1}{r_{all}} \frac{\rho_{mirror}}{\rho_{CDM}}$	$Y(R_{sun})$
SM Baryons	68.6	180.3	$(1, 9 \times 10^{-7}, 1)$	0.5	0.59	5.9	4×10^{-3}
$\frac{v_B}{v_A} = 3, r_{all} = 0.01, Y = 0.75$	136.2	180.3	$(1, 2 \times 10^{-6}, 1)$	0.5	0.011	2.2	5×10^{-1}
$\frac{v_B}{v_A} = 3, r_{all} = 0.01, Y = 0$	72.3	180.3	$(1, -, -)$	0.5	0.037	7.5	0
$\frac{v_B}{v_A} = 3, r_{all} = 0.01, Y = 1$	192.7	180.3	$(-, 1 \times 10^{-6}, 1)$	0.5	0.021	4.2	1

at $R = R_{sun} = 8\text{kpc}$

Cooling Processes

A variety of cooling processes are active in the mirror (& SM) plasma.

Most important: bremsstrahlung cooling

$$\hat{e}\hat{X}_i \rightarrow \hat{e}\hat{X}_i\hat{\gamma}, \text{ where } \hat{X}_i = (\hat{\mathrm{H}}^+, \hat{\mathrm{He}}^+, \hat{\mathrm{He}}^{++})$$

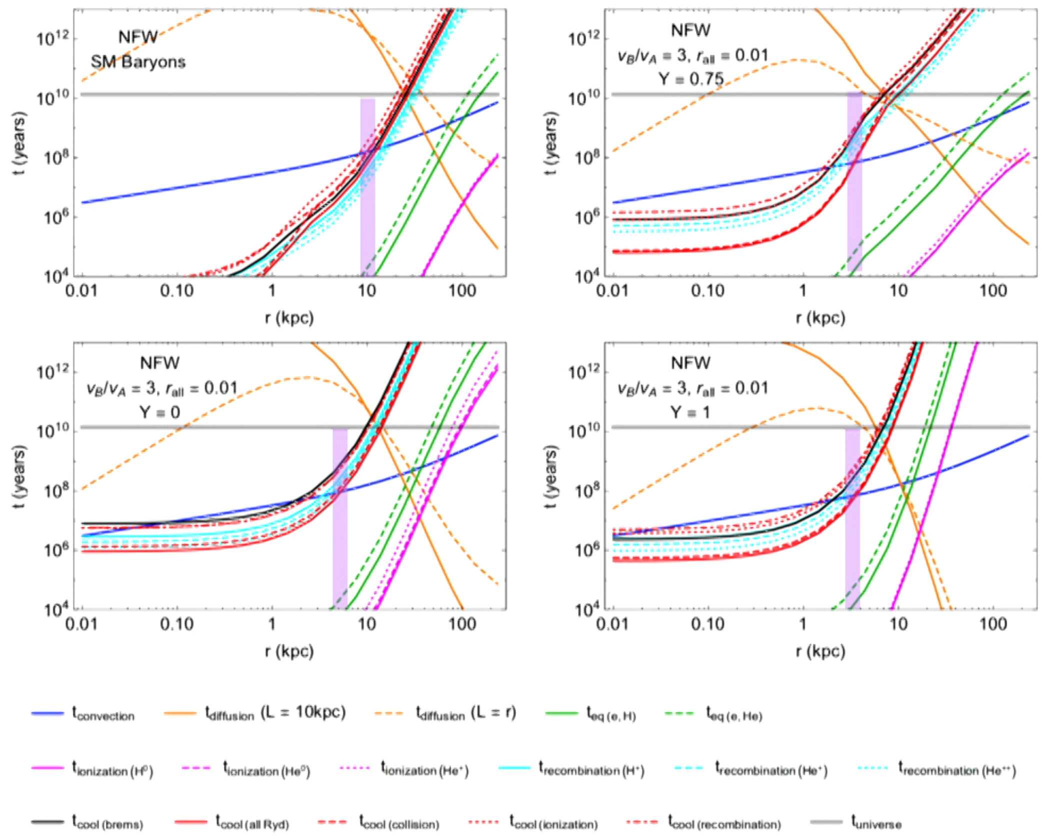
and collisional excitation

$$\hat{e}^- + \ddot{X}_i \rightarrow \hat{e}^- + \ddot{X}_i^* \rightarrow \hat{e}^- + \ddot{X}_i + \hat{\gamma}$$

Can get cross sections and rates by rescaling SM quantities by larger mirror electron mass.

Lots of helpful dissipative DM xsecs: Rosenberg, Fan 1705.10341

Timescales



mirror/SM baryons lose pressure support if $t_{cool} \sim t_{dyn}$

What can we learn?

Mirror sector $t_{cool} \sim 1/r_{all}$

For $r_{all} \sim$ % or less, mirror sector baryons cool LESS EFFICIENTLY than visible sector baryons.

If $r_{all} > 10^{-6}$, *maybe* mirror baryons form a dark disk?

(for such low abundances, mirror helium formation might not be efficient, so Y could be lower than 0.75)

If so, mirror disk might be a bit smaller than visible disk? (mirror halo loses pressure support at smaller r)

If there was no nuclear physics in our mirror sector, we could try and solve for final distribution after cooling.

However, because we have nuclear physics, there will be **mirror stars** and hence **feedback**.

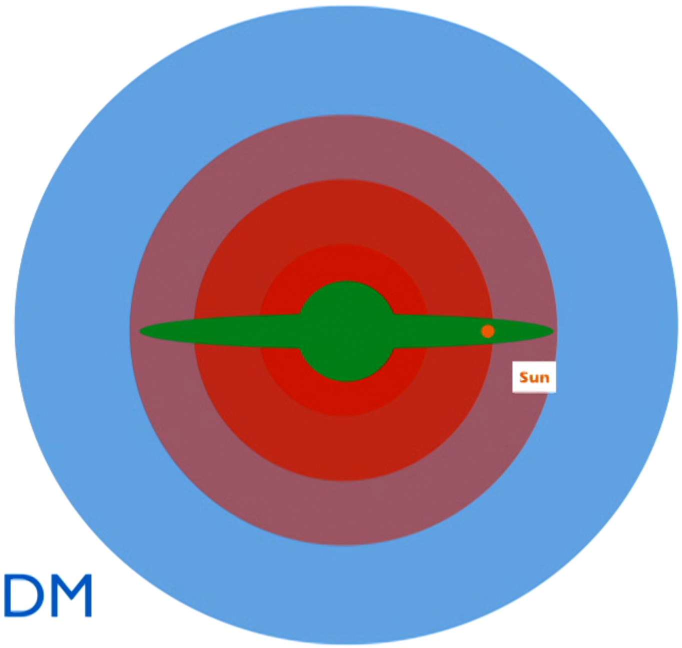
Qualitatively similar to SM but **very different in its details (which are ~ unknowable!)**

Simulations hardly make contact with "microphysics" on stellar astrophysics level, let alone fundamental physics.

No fundamental understanding of feedback $\longleftrightarrow$ cannot predict mirror baryon distribution in detail for r_{all} ~ %

Today?

Local Mirror Baryon Distribution could be ***halo-like***



If there is no collapse due to slow cooling or strong feedback..

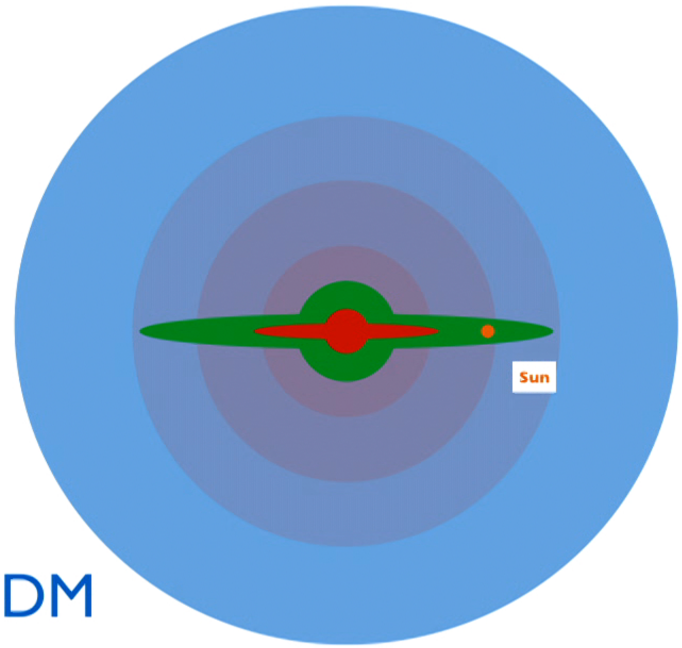
CDM

SM baryons

mirror baryons

Today?

Local Mirror Baryon Distribution could be ***halo-like***



CDM

SM baryons

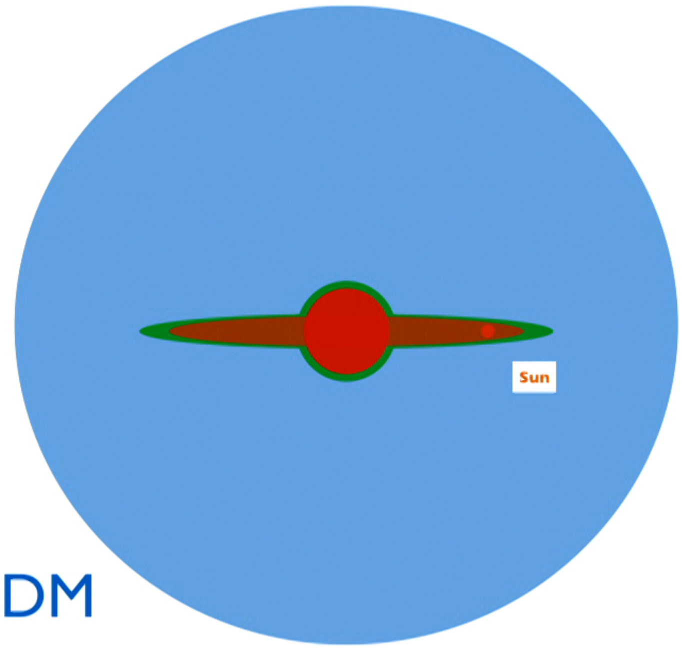
mirror baryons

If mirror disk radius is < R_{sun} and mirror baryons in "outskirts" are still arranged in halo distribution
(could be similar in SM)

Either way, we can assume a local CDM-like distribution with v_0 ~ 220km/s as an optimistic scenario for direct detection

Today?

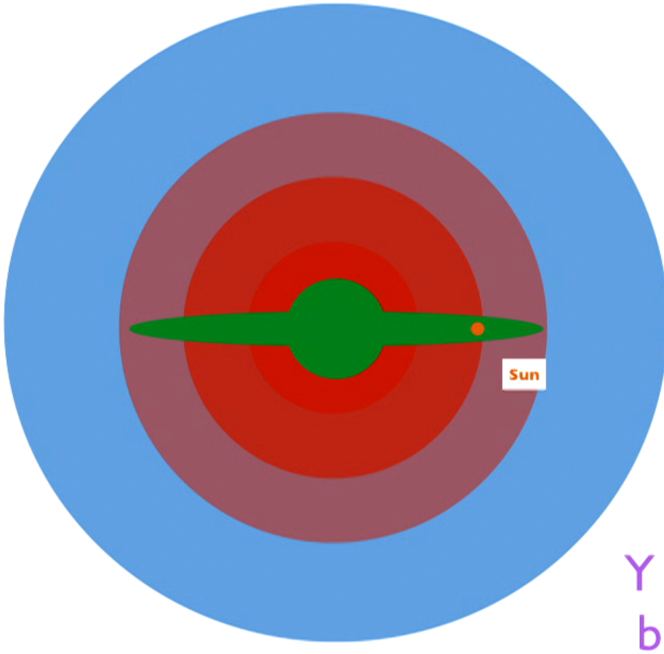
Local Mirror Baryon Distribution could be ***disk-like***

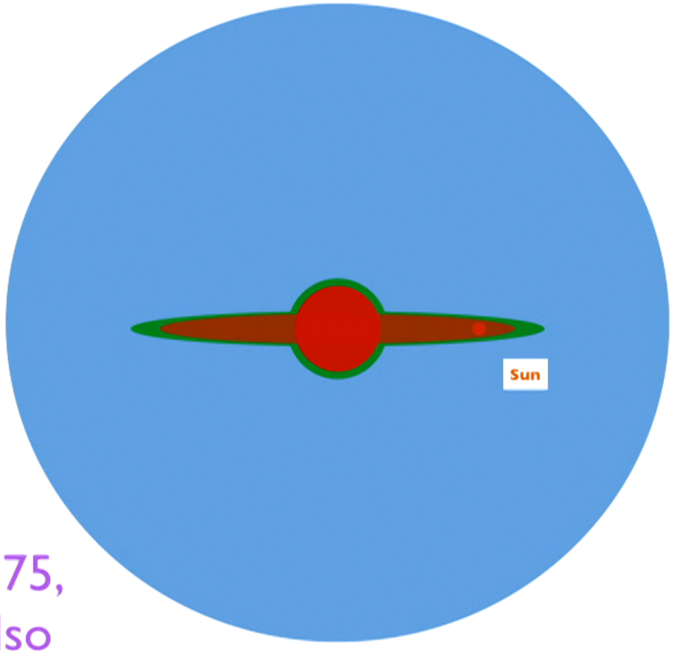


In that case, a pessimistic assumption for direct detection is v_0 ~ local stellar velocity dispersion ~ 20km/s,

and only relative velocity of earth comes from motion around sun ~ 30km/s

CDM
SM baryons
mirror baryons





$v_0 \sim$ 220km/s
v_e = 233 km/s

Y = 0.75,
but also
pure H &
pure He

$v_0 \sim$ 20 km/s
v_e = 30km/s

Probably ionized,
but also consider neutral

Could be ionized
or neutral

Local mirror DM fraction distinct from cosmic average r_{all},
but probably within same order of magnitude.

Asymmetrically Reheated MTH:

Mirror Baryon
DM Direct Detection

1812.xxxxx Chacko, DC, Geller, Tsai

Direct Detection

Higgs Portal:

- guaranteed to be there in MTH model
- too small for direct detection rate above neutrino floor

Photon Portal

- generically expected to be generated at loop level by MTH UV completion

$$\frac{\epsilon}{2\cos\theta_W} B_{\mu\nu} B'^{\mu\nu}$$

- $\epsilon \lesssim 10^{-9}$ to avoid mirror and visible sector equilibrating after dilution → **nano-charged GeV-scale DM**
- in the MTH model, accidental symmetries prevent ϵ from being generated at 3-loop order, so could be right size naturally

Nuclear Recoil

Massless dark photon mediator: collisions have lower recoil than equivalent collision via contact term

$$\frac{d\sigma_p}{dE_r} = \frac{2\pi\alpha_{em}^2\epsilon^2 Q_X^2}{m_p v_X^2 E_r^2} . \qquad E_r^{max} = \frac{2m_p m_X^2 v_X^2}{(m_p + m_X)^2}$$

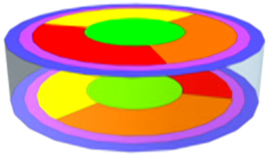
To detect nano-charged GeV-scale DM, need very low nuclear recoil thresholds < ~ 0.1 keV.

⇒ SuperCDMS SNOLAB

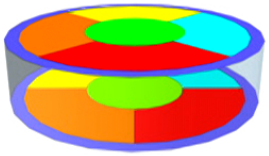
Detector	$7\sigma_{Ph}$ (eV)	$e\Delta V$ (eV)	Analysis threshold (eV) E_{Ph}	Analysis threshold (eV) E_{nr}
Si HV	35	100	100	78
Ge HV	70	100	100	40
Si iZIP	175	8	175	166
Ge iZIP	350	6	350	272

	iZIP Ge	iZIP Si	HV Ge	HV Si
Number of detectors	10	2	8	4
Total exposure (kg·yr)	56	4.8	44	9.6
Phonon resolution (eV)	50	25	10	5
Ionization resolution (eV)	100	110	–	–
Voltage Bias (V)	6	8	100	100

HV:



iZIP:



1610.00006

Electron Recoil

Very different kinematics since SM electron is *bound* in the atom and is the lightest and fastest particle in the collision. Details depend on complicated form factors.

$v_e \sim 1/\alpha_{em} > v_{DM}$

$$\Delta E_e = \vec{q} \cdot \vec{v}_X - \frac{q^2}{2\mu_{XN}}$$

$$q_{\rm typ} \sim \mu_{Xe} v_{\rm rel} \sim m_e v_e \sim \mathcal{O}(\text{few} - 10\,\text{keV})$$

Mirror H, He : $E_e \sim$ few eV.

Mirror e: $E_e \sim 0.1$ eV

How to detect such small recoils?

- ionization in noble gases: Xenon10. threshold 12.4 eV
- ionization in semiconductors: SENSEI (Si) $Q_{th} = 2$. $E_e > 4.7$ eV
- Superconductors: disrupt cooper pairs, create quasi-particle excitations. $E_e > \sim 10^{-3}$ eV! (more futuristic)

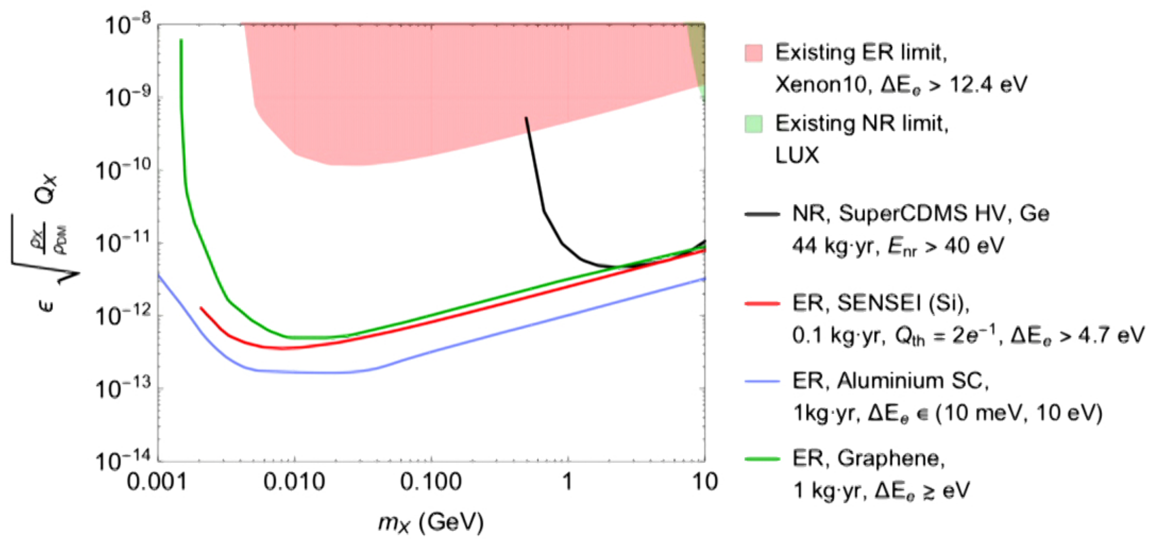
1703.00910 Essig, Volansky Yu

1509.01598 Essig, Fernandez-Serra, Mardon, Soto, Volansky, Yu

1512.04533 Hochberg, Pyle, Zhao, Zurek

Comparison

For comparison, here are sensitivities to standard CDM with single particle X with v_0 = 220 km/s. (NOT MTH)



NR is comparable in GeV range but ER is only choice at MeV

Mirror Baryons: Now

Consider our halo- and disk-like benchmark distributions.

Consider Y = 0.75 MTH prediction but also Y = 0, 1.

Consider both ionized and not ionized.

Xenon10 supplies current constraints:

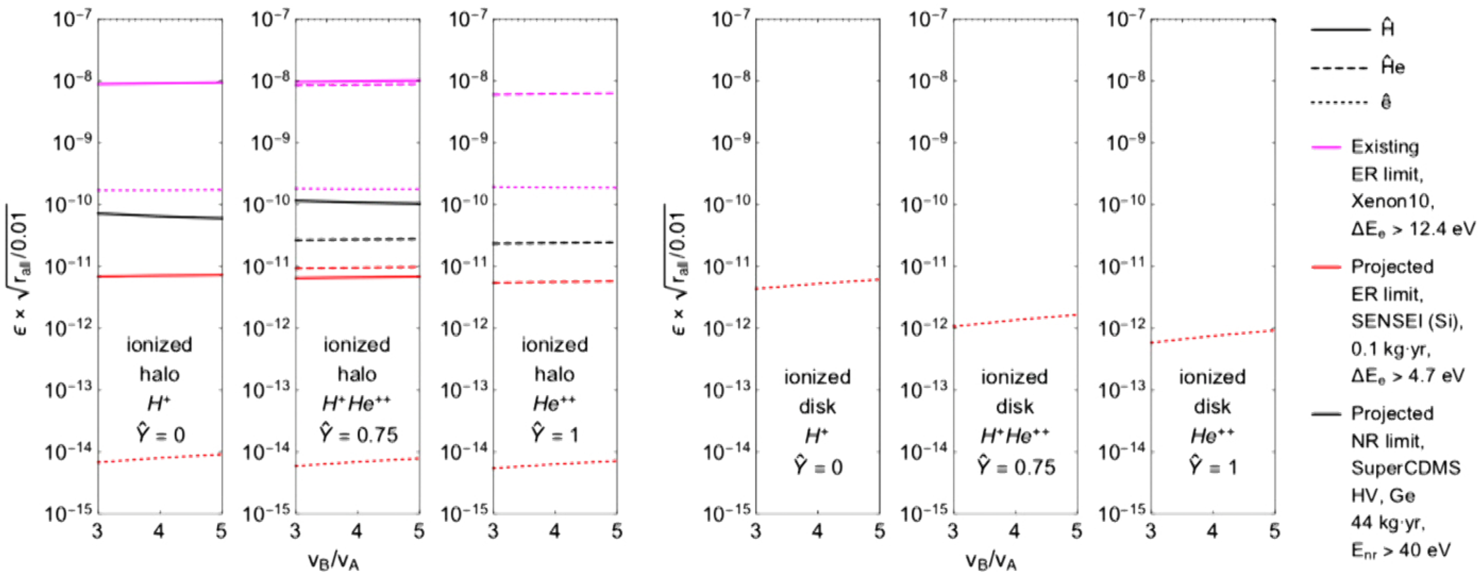
assuming local r_{all} ~ %:

	ionized halo	ionized disk	atomic halo	atomic disk
ER $\hat{H}$, $\hat{H}e$	$\epsilon \sim 10^{-8}$	no signal	AFF: $\epsilon \sim 10^{-7}$	no signal
ER $\hat{e}$	$\epsilon \sim 10^{-10}$	no signal	no signal	no signal

nano-charged regime is barely probed.

Mirror Baryons: Future

SuperCDMS is taking data, SENSEI is approved.



Any ionization: fast mirror electrons provide excellent discovery channel!

Non-ionized case: NR unchanged, ER only on mirror H,He with ~1/10 sensitivity due to form factors.

Probing the mirror baryon distribution

Each mirror baryon distribution gives unique correlated signals in different detectors.

For $r_{all} \sim \%$:

	ionized halo	ionized disk	atomic halo	atomic disk
NR $\hat{\text{H}}$, $\hat{\text{H}}\text{e}$	$\epsilon \sim 10^{-11}$	RR: no signal	$\epsilon \sim 10^{-11}$	RR: no signal
ER $\hat{\text{H}}$, $\hat{\text{H}}\text{e}$	$\epsilon \sim 10^{-11}$	RR: SC only?	AFF: $\epsilon \sim 10^{-10}$	RR and AFF: SC only?
ER $\hat{e}$	$\epsilon \sim 10^{-14}$	$\epsilon \sim 10^{-12}$	no signal	no signal

RR = reduced recoil. AFF = atomic form factor

Probing hidden sector composition

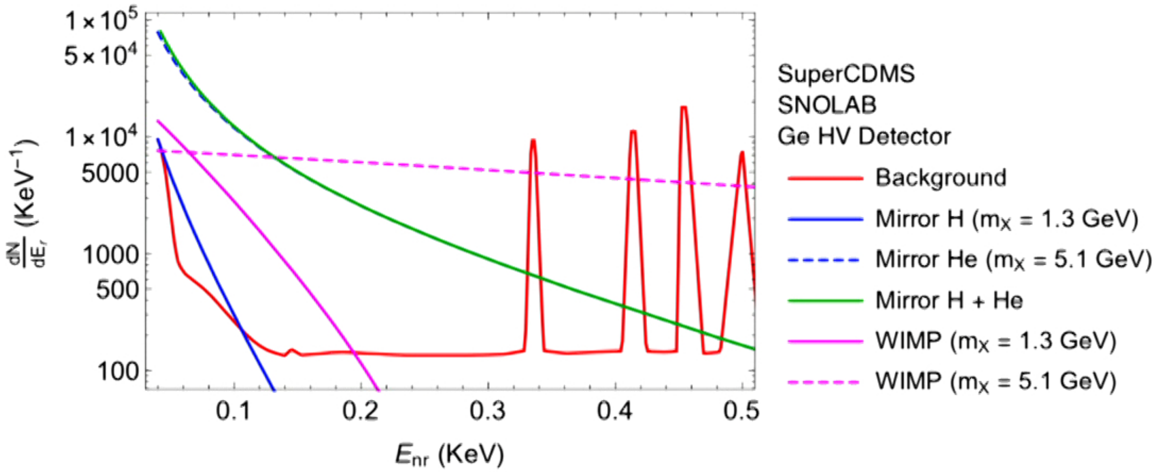


Figure 7. Recoil spectrum in the SuperCDMS SNOLAB Ge HV detector assuming ionized halo dark matter distribution. For mirror H and He, assume $r_{\rm all} = 0.01$, $v_B/v_A = 4$, $\rho_{\hat{\rm He}}/\rho_{\hat{\rm H}} = 0.75$, and $\epsilon = 3 \times 10^{-10}$. For WIMP with $m_X = 1.3(5.1)$ GeV, $\sigma_{nX} = 0.6(1.1) \times 10^{-42}{\rm cm}^{-2}$.

Detailed analysis of recoils will probe multi-component nature of this hidden sector

More probes
of the hidden sector

More things

What about the rest of the DM?
(DC, Shayne Gryba)

What do mirror stars look like, and could we see them?
(DC, Jack Setford)

What does modern lattice data teach us about mirror nuclear physics?
Aside: consequences for anthropics?
(DC, Josh Rudermann, Jack Setford, …)

Concrete example of complicated but highly motivated hidden sector lets us ask very detailed questions and think of new searches!

Conclusions

Hidden sectors are motivated from bottom-up and top-down.

Collider (LLP) vs Cosmology (stable)

Top-down formulations give complicated *predictive* hidden sectors with rich cosmo + astro that you can interrogate in detail.

Asymmetrically reheated MTH:
- solves the little hierarchy problem
- if no LLP signatures, can still measure $Br(h \to invis) \sim v_B/v_A$
- this parameter is correlated with many cosmo+astro observables (ΔN_{eff}, LSS deviations, direct detection, …???) that could provide smoking gun of these hidden sectors.