Hidden Sectors:

From Long-Lived Particles to Cosmology and Astrophysics

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Aachen, Germany

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Why explore hidden sectors?

(a particle theorists's perspective)

There has to be new physics…

The fundamental mysteries of the Standard Model (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 (LHC, DM direct detection, …) that haven't shown up so far.

… where is it?

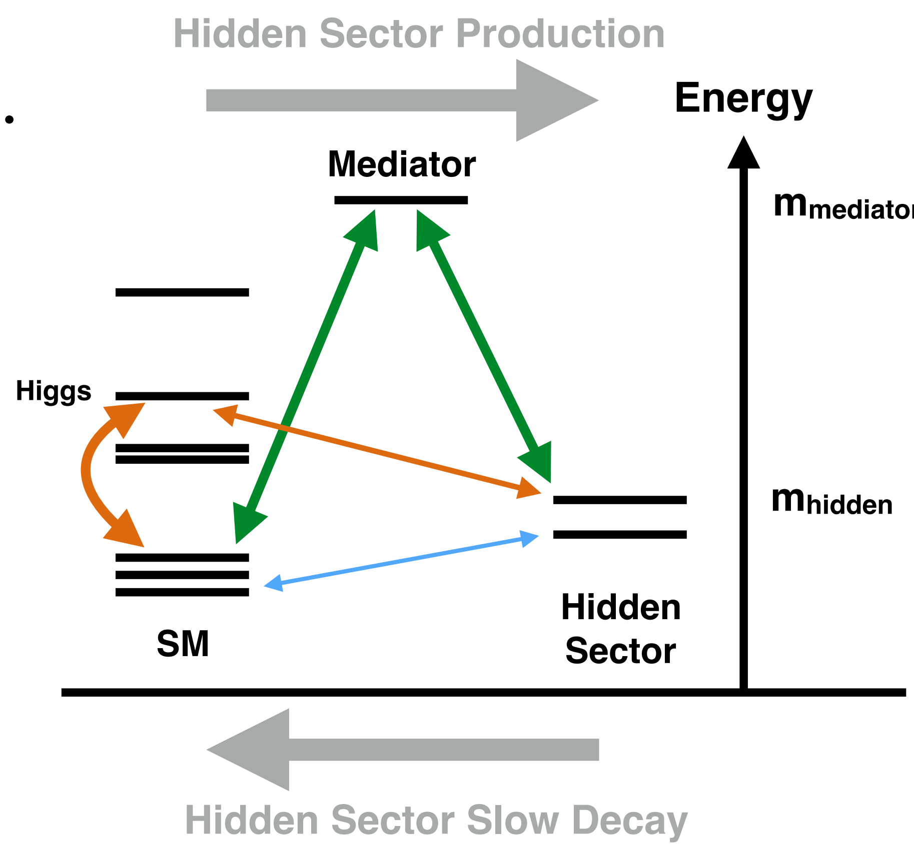
Hidden Sectors

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**

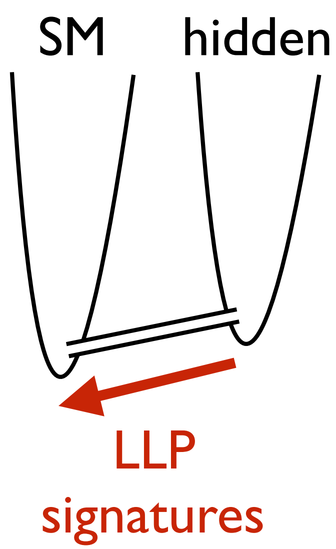
1. LHC: Exotic Higgs Decays as probes

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

2. LHC/Cosmo: Long Lived Particles (LLPs) are generic

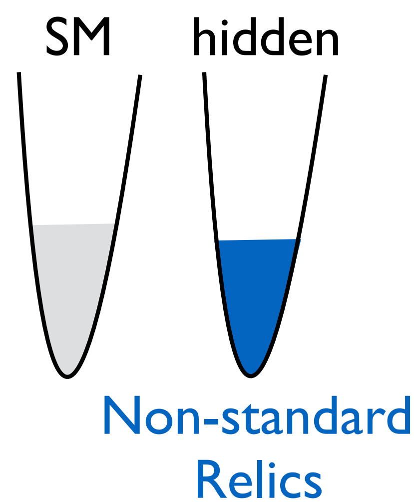
Once produced, Hidden Sector states can only decay back to SM via small portal couplings, generically leading to long lifetimes.
The LLP lifetime is (almost…) a free parameter!

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.)



Hidden Sectors

Long-Lived Particle (LLP) Signatures

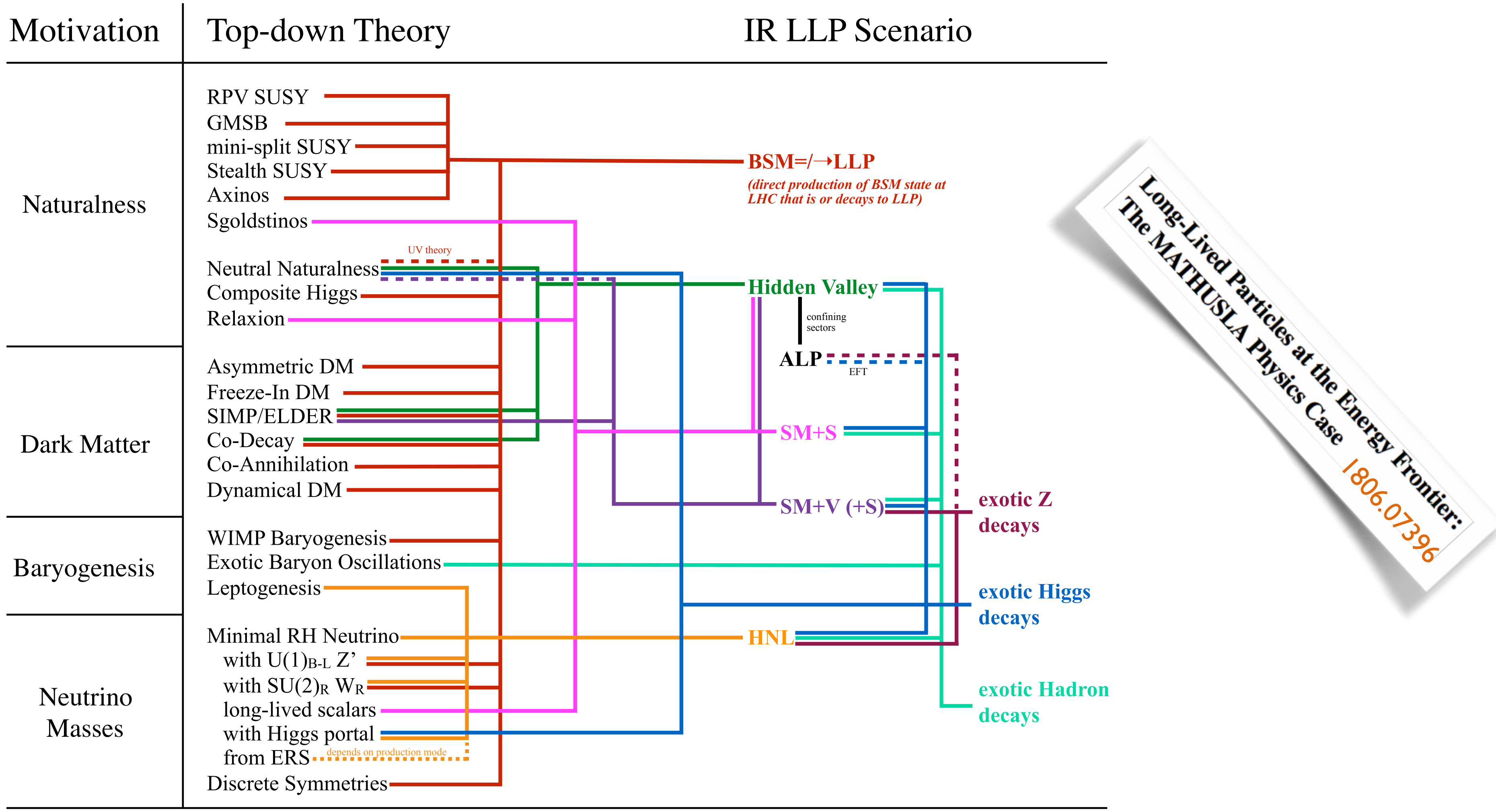
Cosmology/ Astrophysics

Hidden Sectors

Long-Lived Particle (LLP) Signatures

Cosmology/ Astrophysics

Hidden Sectors are a "bottom-up" LLP motivation. Plenty of "top-down" hep theory motivations too:

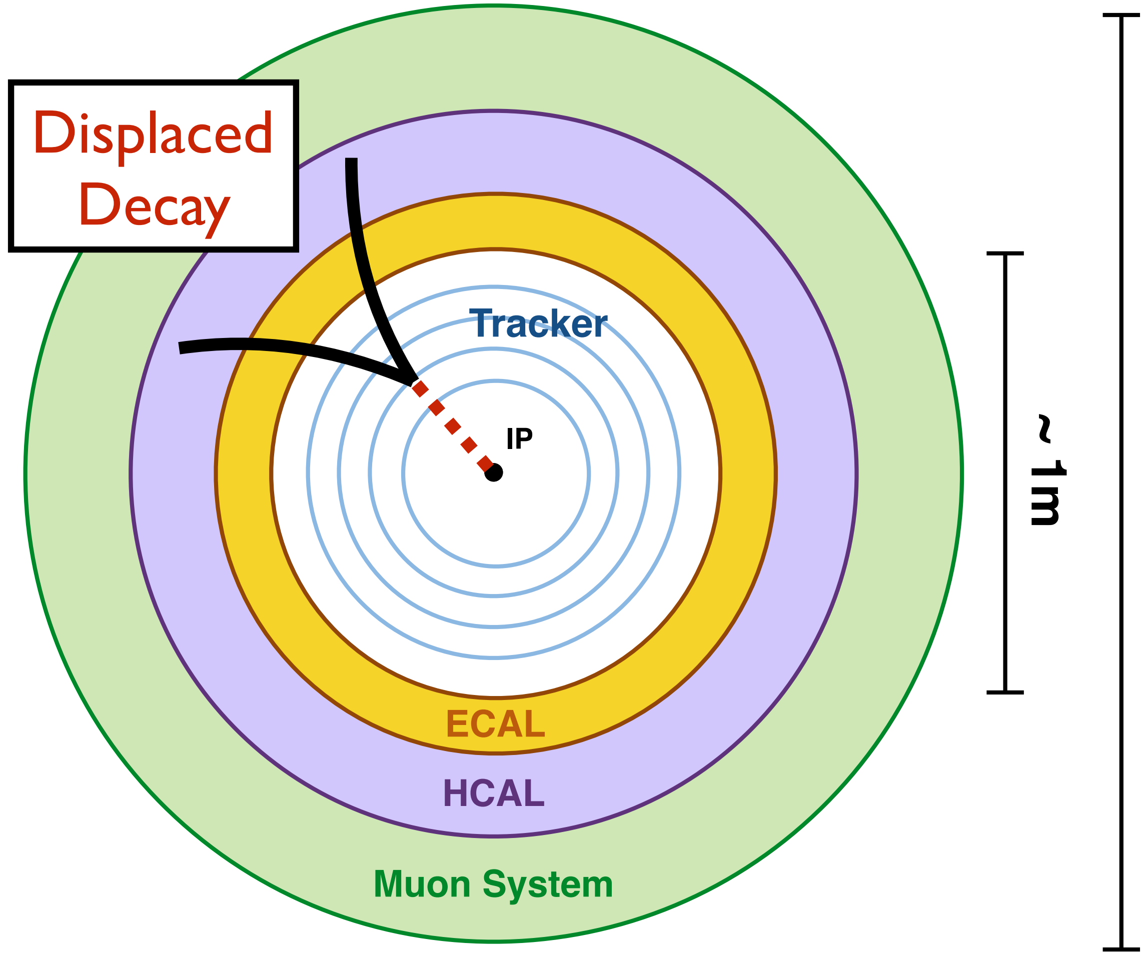


Most of these scenarios are still very poorly constrained at the LHC!

LLPs at the LHC

Neutral LLPs that decay in the detector are *spectacular* signatures that are missed by most standard searches, since trigger & detector are designed for *prompt* signals.

Comprehensive search program has been ramping up last few years.



A Coordinated LLP Search Program

Searching for long-lived particles beyond the Standard Model at the Large Hadron Collider

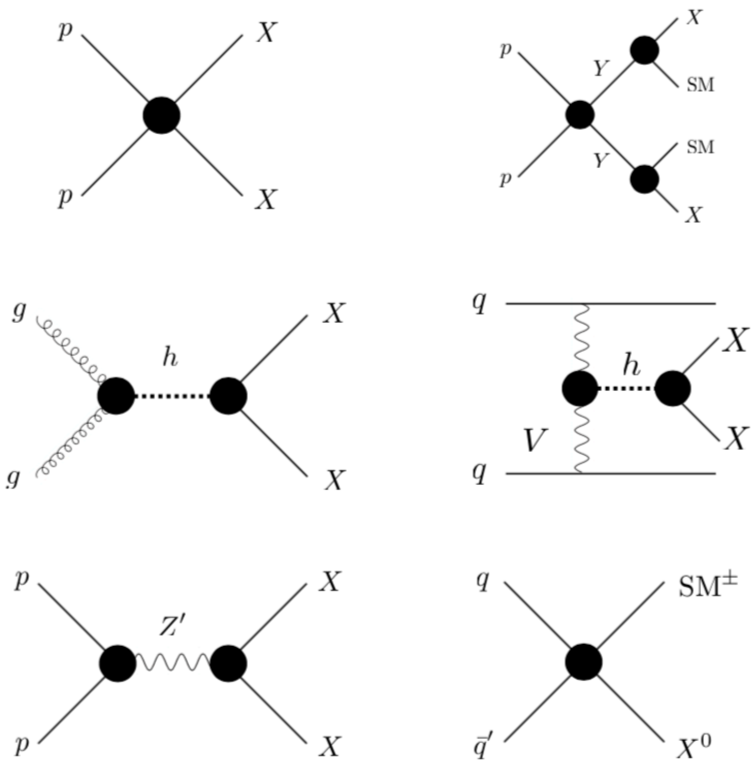
March 6, 2019

1903.04497

Particles beyond the Standard Model (SM) can generically have lifetimes that are long compared to SM particles at the weak scale. When produced at experiments such as the Large Hadron Collider (LHC) at CERN, these long-lived particles (LLPs) can decay far from the interaction vertex of the primary proton-proton collision. Such LLP signatures are distinct from those of promptly

LHC LLP Community

Simplified Model Roadmap of LLP Signature Space:

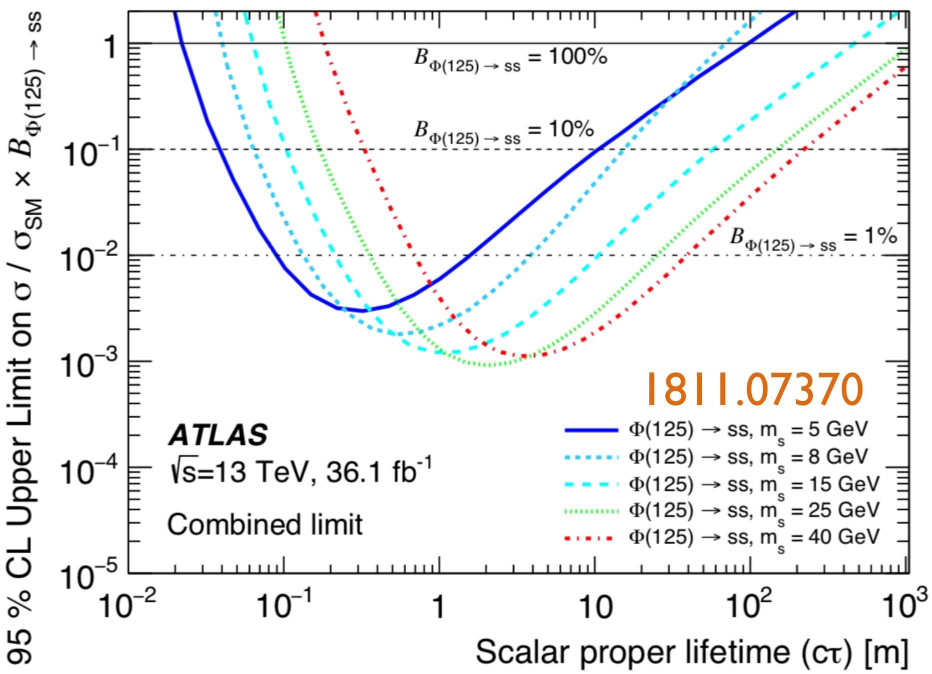


Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair or neutralino pair	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$	†	SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*	†	Higgs, DM*	RHν	Higgs, DM* RHν*	RHν*
HIG: $h \to X + \text{inv.}$	DM*, RHν	†	DM*	RHν	DM*	†
RES: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*	†	Z', DM*	RHν	Z', DM*	†
RES: $Z(Z') \to X + \text{inv.}$	DM	†	DM	RHν	DM	†
CC: $W(W') \to \ell X$	†	†	RHν*	RHν	RHν*	RHν*

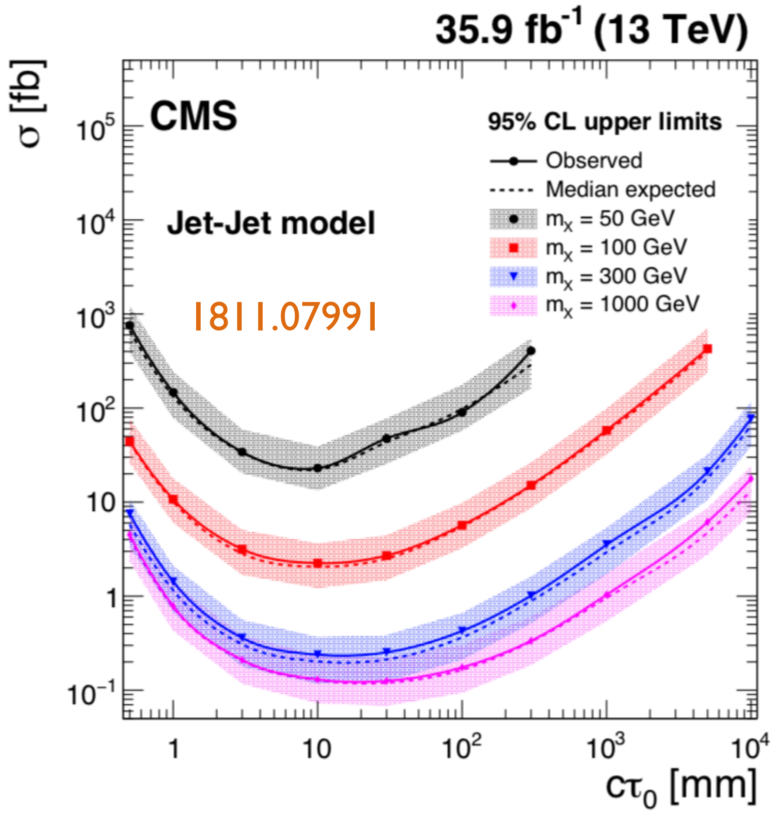
Lots of progress in past few years.

Searches are extremely labor-intensive due to customized event reconstruction, special triggers, small but complicated backgrounds.

Higgs→LLPs in ATLAS Muon System



Displaced Jets in CMS tracker



First searches for "low-lying fruit" LLPs are underway or finishing!

The problem of long lifetimes:

The LHC could be making LLPs that are invisible to its detectors!

Any LLP can have lifetime up to BBN limit ~ 0.1s.

If the LLP has lifetime >> detector size, most LLPs escape detector

Tiny rate of decays in detector → searches at ATLAS/CMS become very vulnerable to even small backgrounds.

Background free environment is critical!

MATHUSLA

MAssive Timing Hodoscope
for Ultra-Stable NeutraL PArticles

Chou, DC, Lubatti 1606.06298
DC, Peskin 1705.06327
Physics Case White Paper 1806.07396
Letter of Intent: CERN-LHCC-2018-025
European Strategy submission: 1901.04040 & 1901.09966
…

mathusla.web.cern.ch

Easy reading:

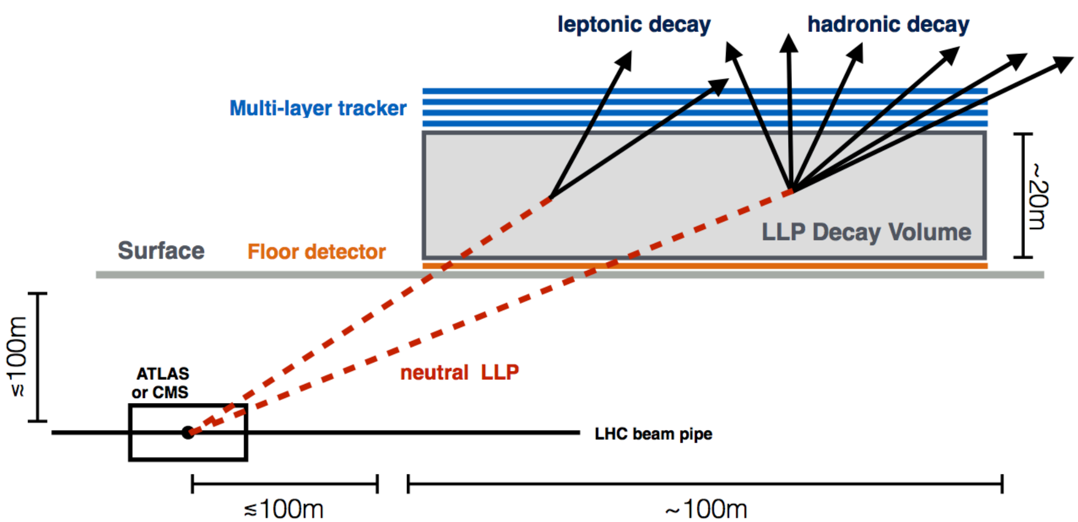
Physics Today article about LLPs and hidden sectors (DC, Raman Sundrum, June 2017)
http://physicstoday.scitation.org/doi/10.1063/PT.3.3594

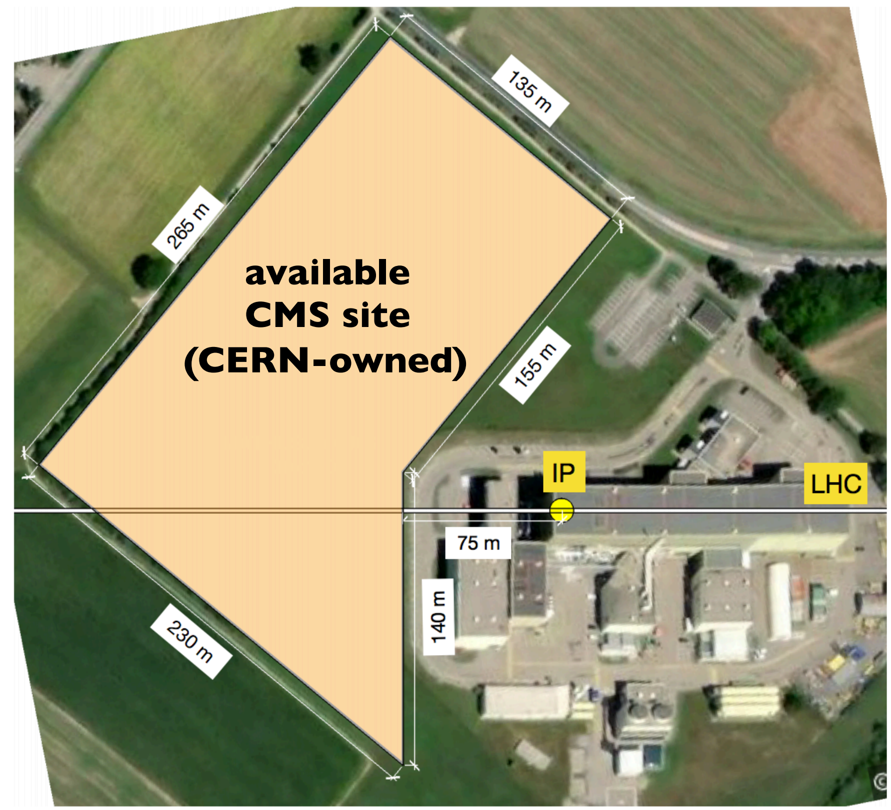
In-depth feature article in Quanta and Wired magazine, September 2018
https://www.quantamagazine.org/how-the-hidden-higgs-could-reveal-our-universes-dark-sector-20170926/ https://www.wired.com/story/hidden-higgs-dark-sector/

"Nuclear Detectives Hunt Invisible Particles That Escaped the World's Largest Atom Smasher", Live Science, May 2018 https://www.livescience.com/62633-lhc-stray-particles-mathusla-detection.html

PHYSICS TODAY
Quanta
WIRED
LIVESCIENCE

An external LLP detector for the HL-LHC



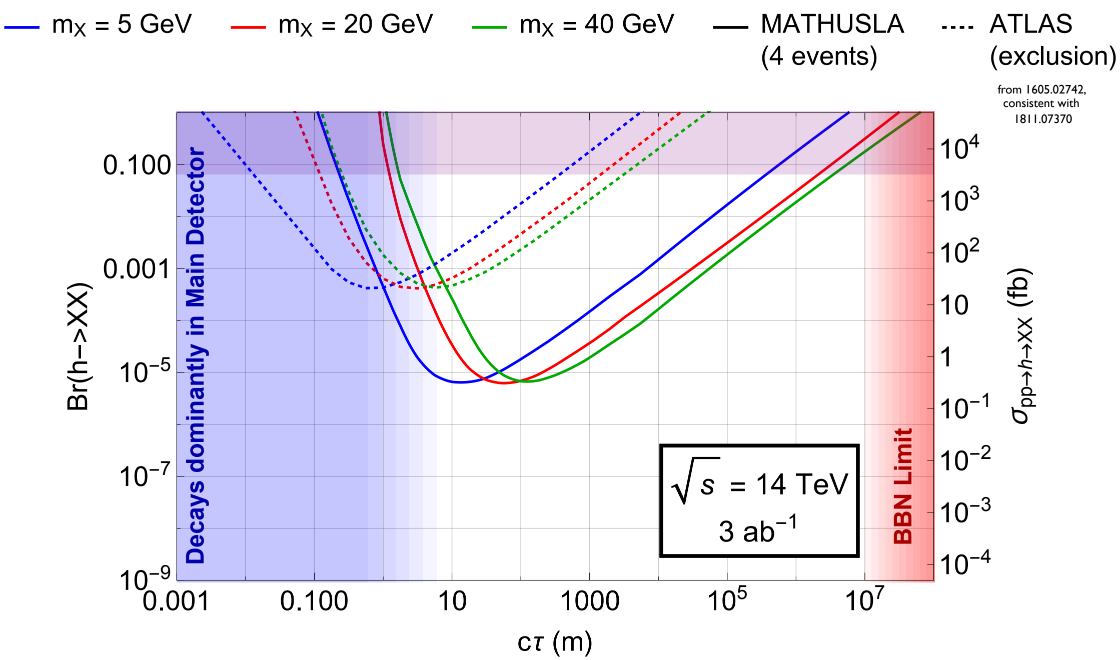


… searches for LLPs by reconstructing displaced vertices in air-filled decay volume, removed from LHC collision backgrounds.

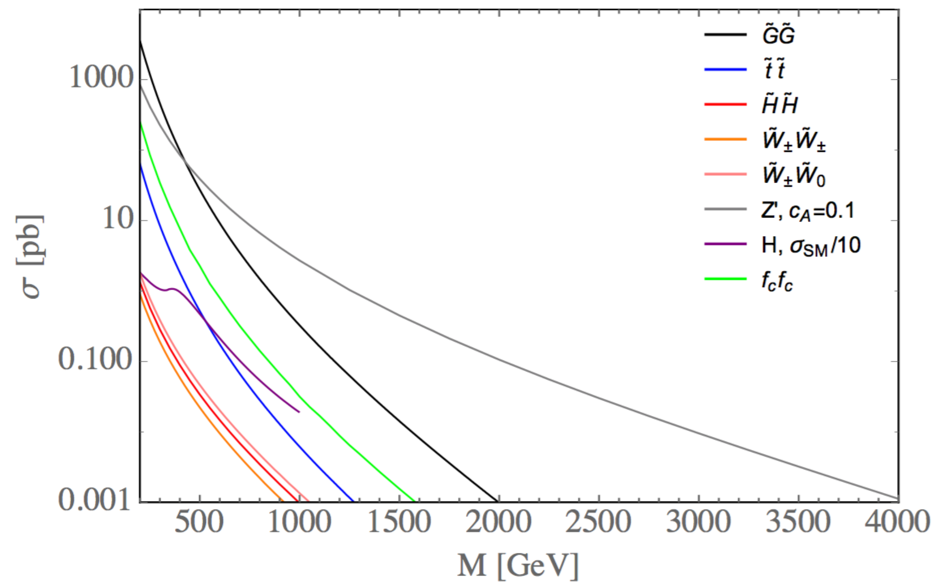
Sensitivity

Physics Case White Paper 1806.07396

LLP cross section reach (exotic Higgs decay example)



Any LLP production process with σ > fb can give signal.



Up to 1000x better sensitivity than main detectors

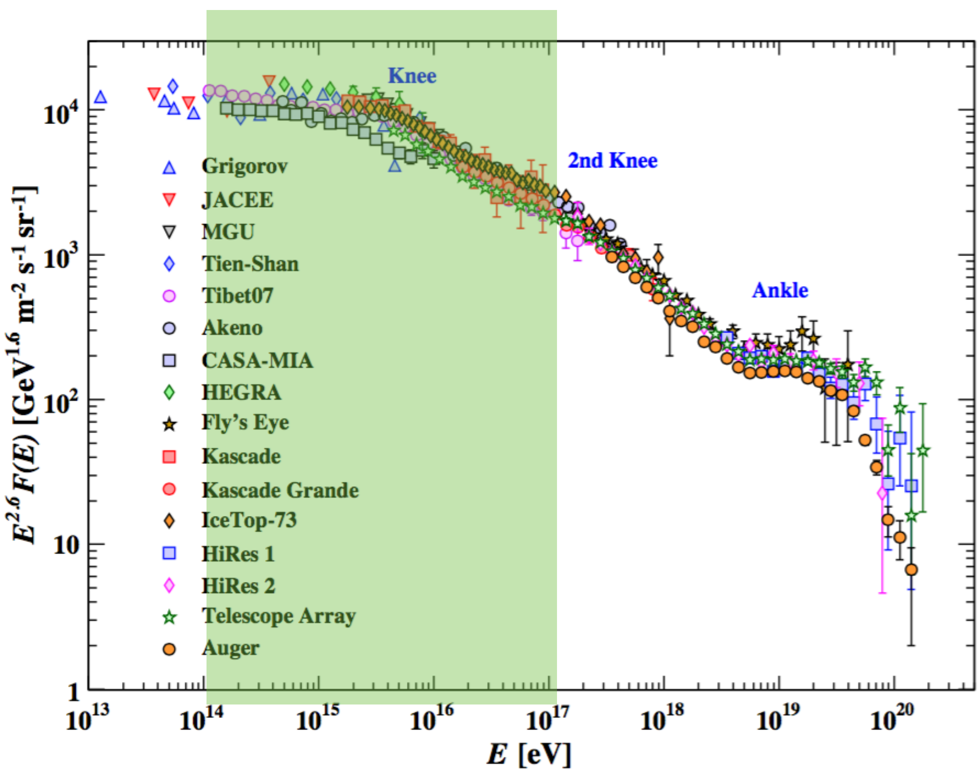
Probe TeV+ scales!

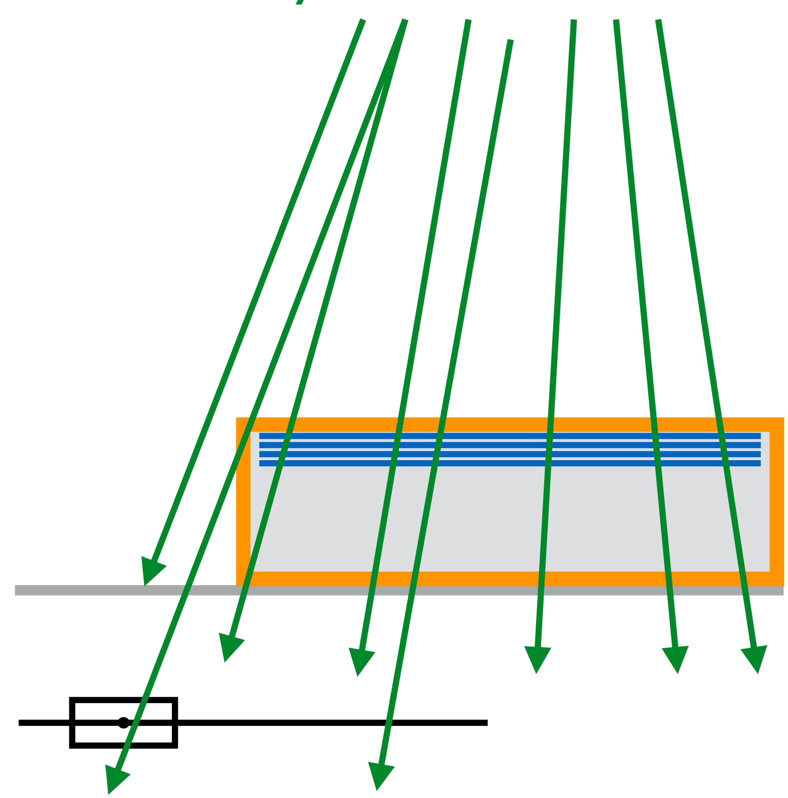
Sensitivity of the original 200m x 200m x 20m physics sensitivity benchmark can be reached by realistic 100m x 100m x 25m detector geometry at CMS site.

Guaranteed Physics Return

MATHUSLA is an excellent Cosmic Ray Telescope!

Has unique abilities in CR experimental ecosystem
(precise resolution, directionality, full coverage of its area)





MATHUSLA collaboration

A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

1811.00927

Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p]
é Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio
na Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo
essie Shelton,[t] Brian Shuve,[s] Martin A. Subieta
rt de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo
ez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d]
Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles

2018 Test Stand
above ATLAS

MATHUSLA

1901.04040

MATHUSLA:
A Detector Proposal to Explore
the Lifetime Frontier at the HL-LHC

Input to the update process of the European Strategy for Particle Physics
18. December 2018

Henry Lubatti (Corresponding Author),[1,*] Cristiano Alpigiani,[1] Juan Carlos Arteaga-Velázquez,[2] Austin Ball,[3] Liron Barak,[4] James Beacham,[5] Yan Benhammo,[4] Karen Salomé Caballero-Mora,[6] Paolo Camarri,[7] Tingting Cao,[4] Roberto Cardarelli,[7] John Paul Chou,[8] David Curtin,[9] Albert de Roeck,[3] Giuseppe Di Sciascio,[7] Miriam Diamond,[9] Marco Drewes,[10] Sarah C. Eno,[11] Rouven Essig,[12] Jared Evans,[13] Erez Etzion,[4] Arturo Fernández Téllez,[14] Oliver Fischer,[15] Jim Freeman,[16] Stefano Giagu,[17] Brandon Gomes,[8] Andy Haas,[18] Yuekun Heng,[19] Giuseppe Iaselli,[20] Ken Johns,[21] Muge Karagoz,[11] Audrey Kvam,[1] Dragoslav Lazic,[22] Liang Li,[23] Barbara Liberti,[7] Zhen Liu,[11] Giovanni Marsella,[24] Piter A. Paye Mamani,[25] Mario Iván Martínez Hernández,[14] Matthew McCullough,[3] David McKeen,[26] Patrick Meade,[12] Gilad Mizrachi,[4] David Morrissey,[26] Meny Raviv Moshe,[4] Antonio Policicchio,[17] Mason Proffitt,[1] Marina Reggiani-Guzzo,[27] Mario Rodríguez-Cahuantzi,[14] Joe Rothberg,[1] Rinaldo Santonico,[7] Marco Schioppa,[28] Jessie Shelton,[29] Brian Shuve,[30] Yiftah Silver,[4] Daniel Stolarski,[31] Martin A. Subieta Vasquez,[25] Guillermo Tejeda Muñoz,[14] Steffie Ann Thayil,[8] Yuhsin Tsai,[11] Emma Torro,[1] Gordon Watts,[1] Charles Young,[32] and Jose Zurita[33]

Now trying to secure O(million USD) funding for
detector R&D, larger-scale prototype, preparing TDR
in next few years

Interested? Join us!

LLP search program at CERN is bound to become exciting in next few years:

- MATHUSLA
- FASER (approved!)
- Codex-B
- SHiP

- main detector upgrades (granulated calorimeters, timing layers, …)

Hidden Sectors

Long-Lived Particle (LLP) Signatures

Cosmology/ Astrophysics

out-of-equilibrium decay, BBN, …

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

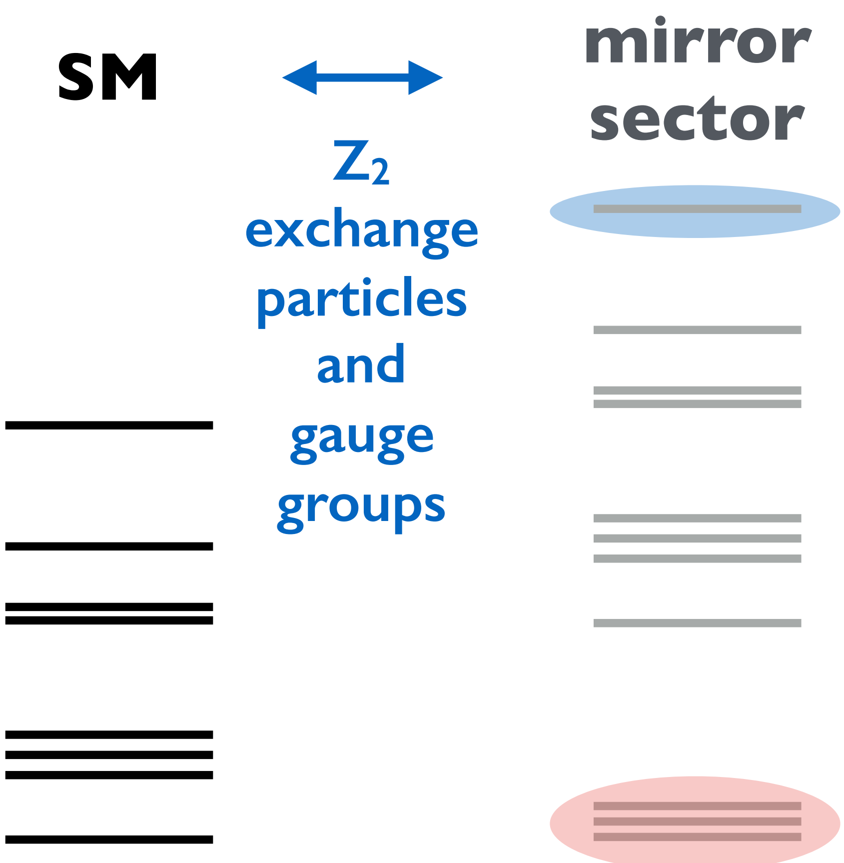
Higgs sector: SU(4), broken by Gauge + Yukawa interactions to $SU(2)_A$ x $SU(2)_B$ x Z_2, which generate mass for goldstone boson.

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

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: $v_B/v_A > \sim 3$

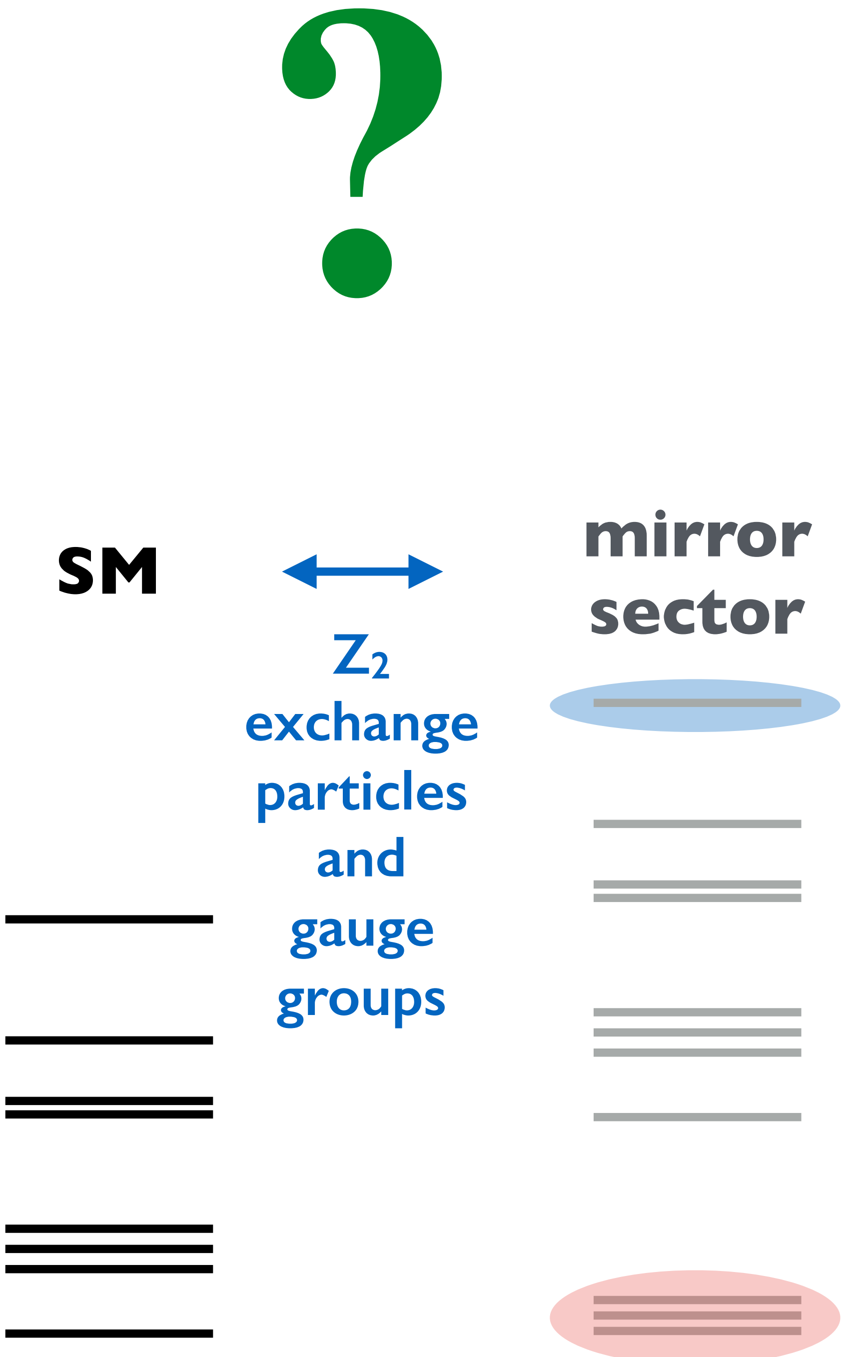
This requires tuning ~ $(v_B/v_A)^2$ ~ Br(h→mirror)

Uncolored top partners.

Massless degrees of freedom: (twin photon, neutrinos)

⇒ $\Delta N_{eff} \sim 5$

Minimal model incompatible with cosmology.



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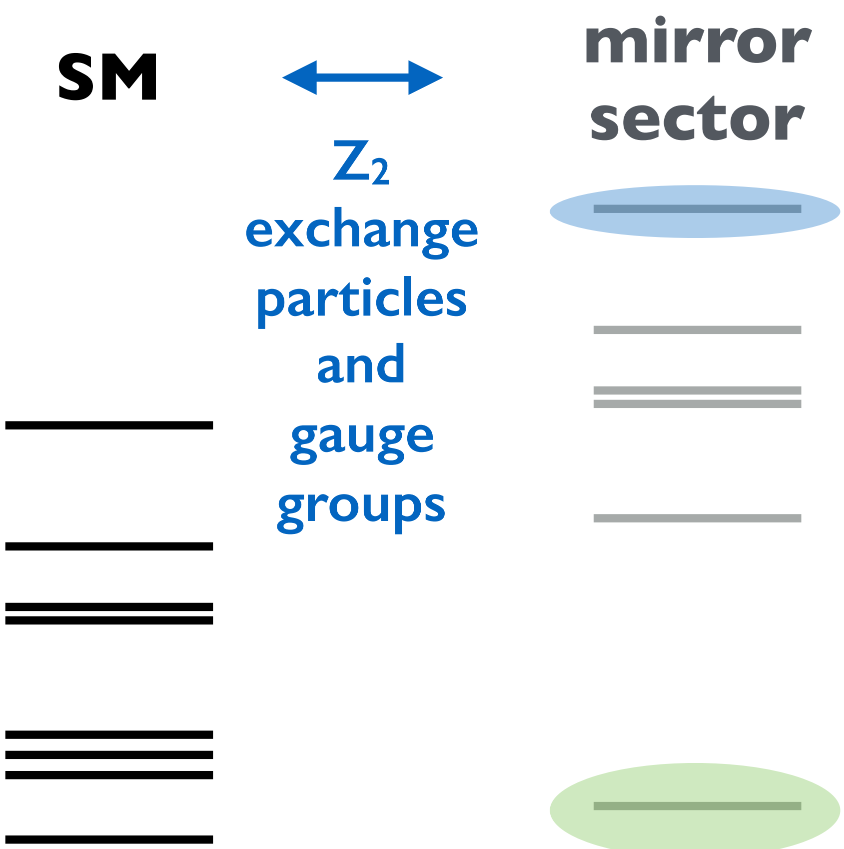
Minimal model incompatible with cosmology.

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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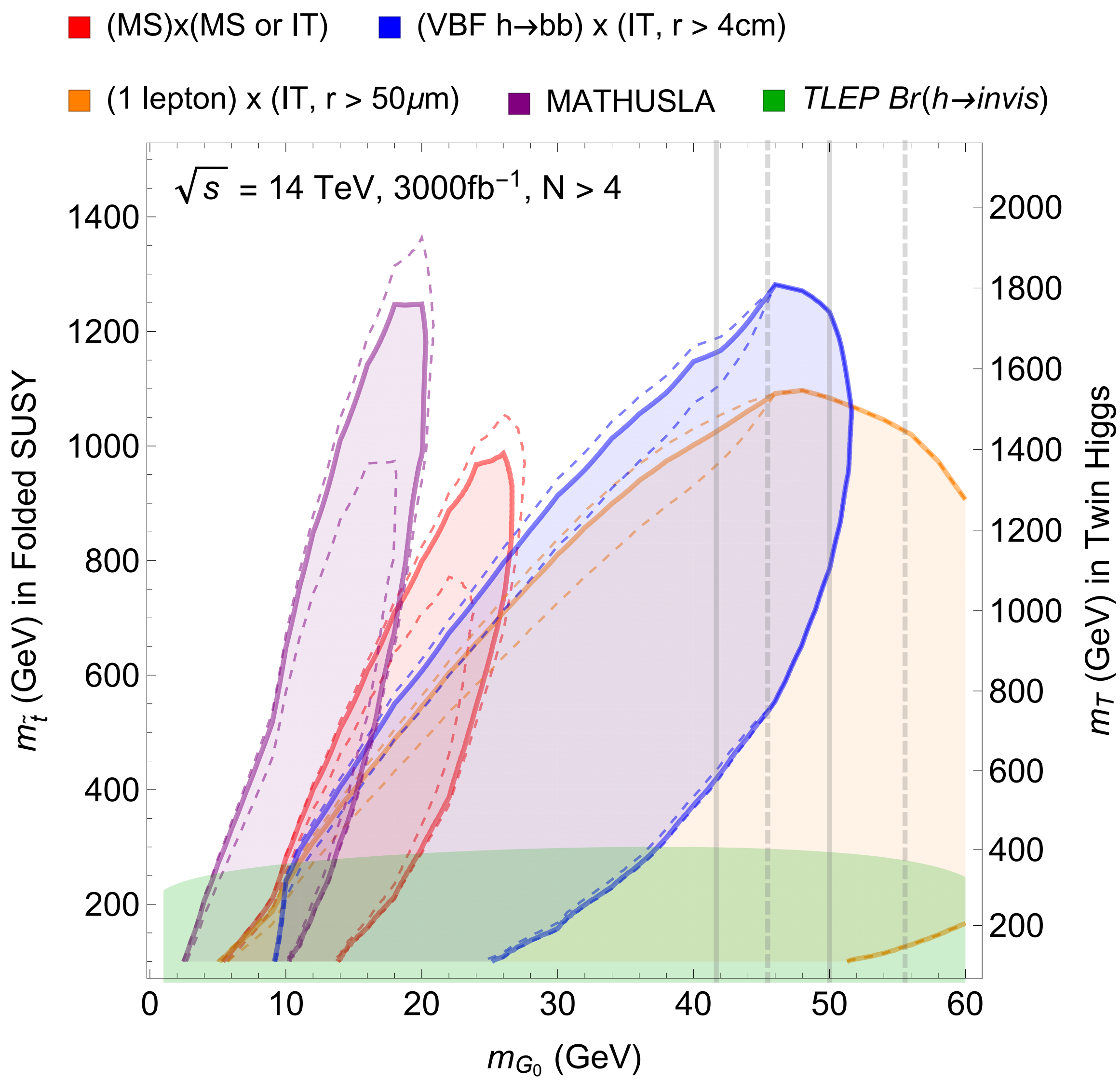
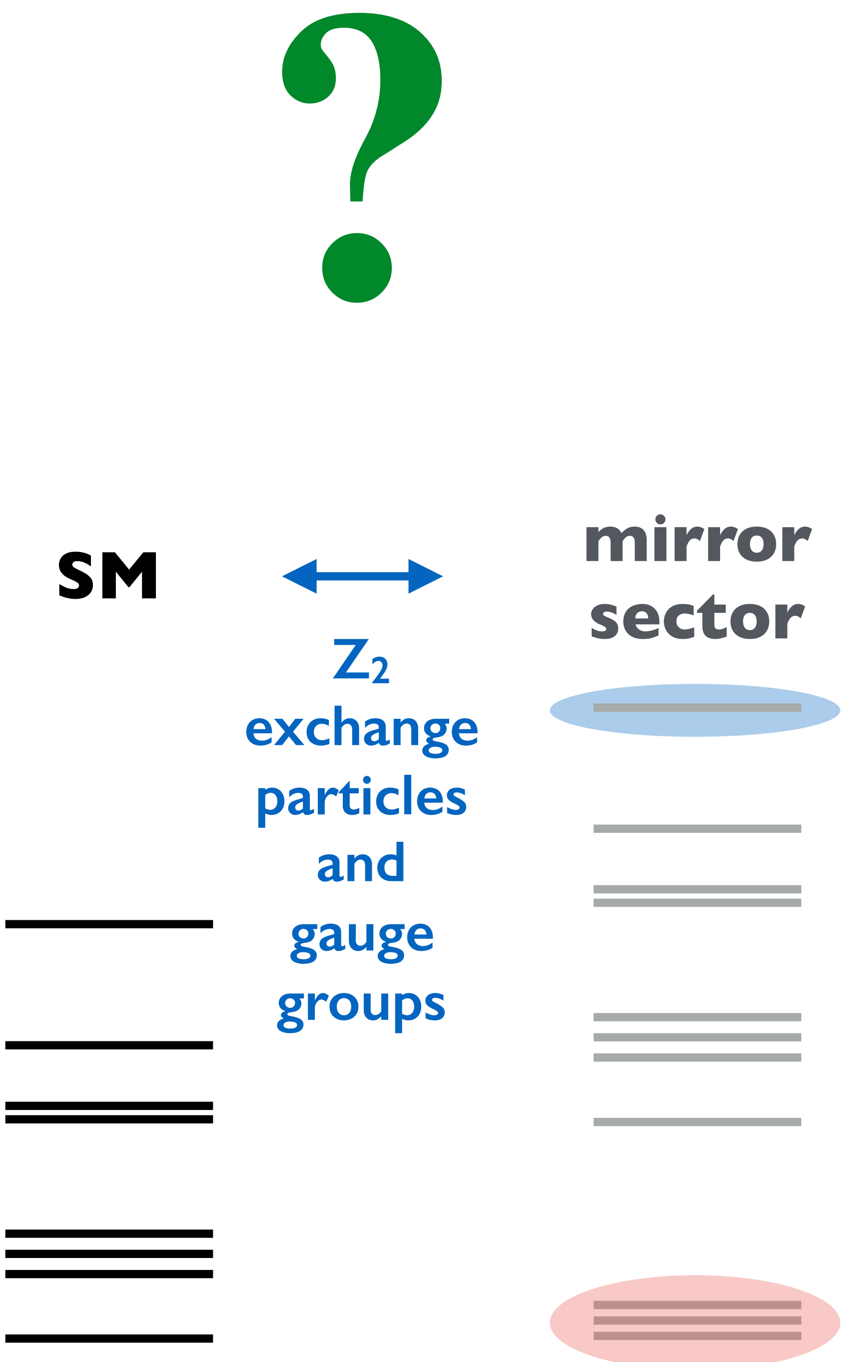
LLPs @ LHC!



DC, Verhaaren 1506.06141

MATHUSLA Physics Case White Paper 1806.07396



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Uncolored top partners.

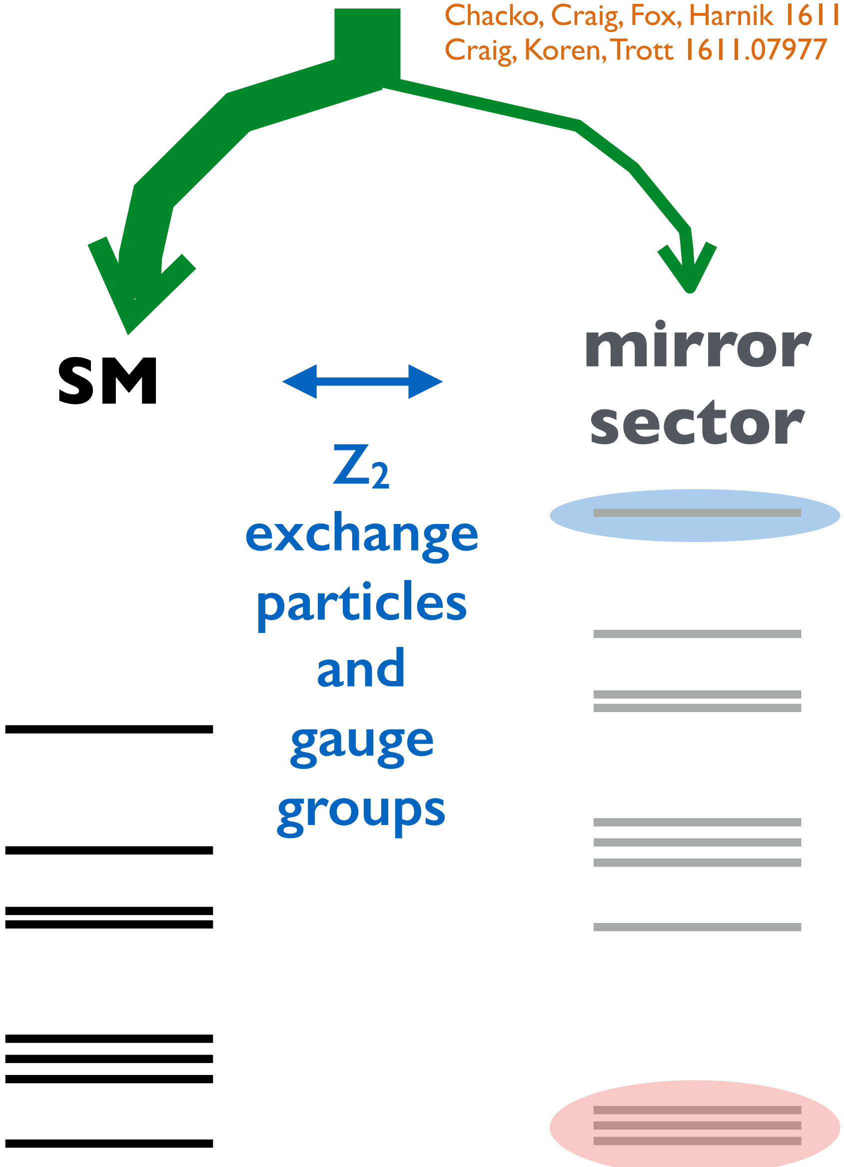
Massless degrees of freedom: (twin photon, neutrinos)

⇒ $\Delta N_{eff} \sim 5$

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



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

Uncolored top partners.

Massless degrees of freedom: (twin photon, neutrinos)
$\Rightarrow$ **$\Delta N_{eff} \sim 5$**

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:

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

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):

$$\Gamma_{N\to i} \propto \frac{m_{\nu_i}^2}{m_{W_i}^4} \longrightarrow \boxed{\epsilon = \frac{\Gamma_{N\to B}}{\Gamma_N} \approx \frac{v^2}{f^2}}$$

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!**

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

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

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

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

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

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]*

1803.03263 Chacko, DC, Geller, Tsai

Asymmetric MTH Cosmology

- mirror-BBN: predicts ~ 75% mirror Helium mass fraction in mirror sector (compare to 25% SM).

- Mirror-baryo-acoustic oscillations modify matter power spectrum, shows up in CMB & LSS:
  Current Ly-α constrains r_{all} < ~ 10%
  CMB Stage IV will probe r_{all} ~ 1%

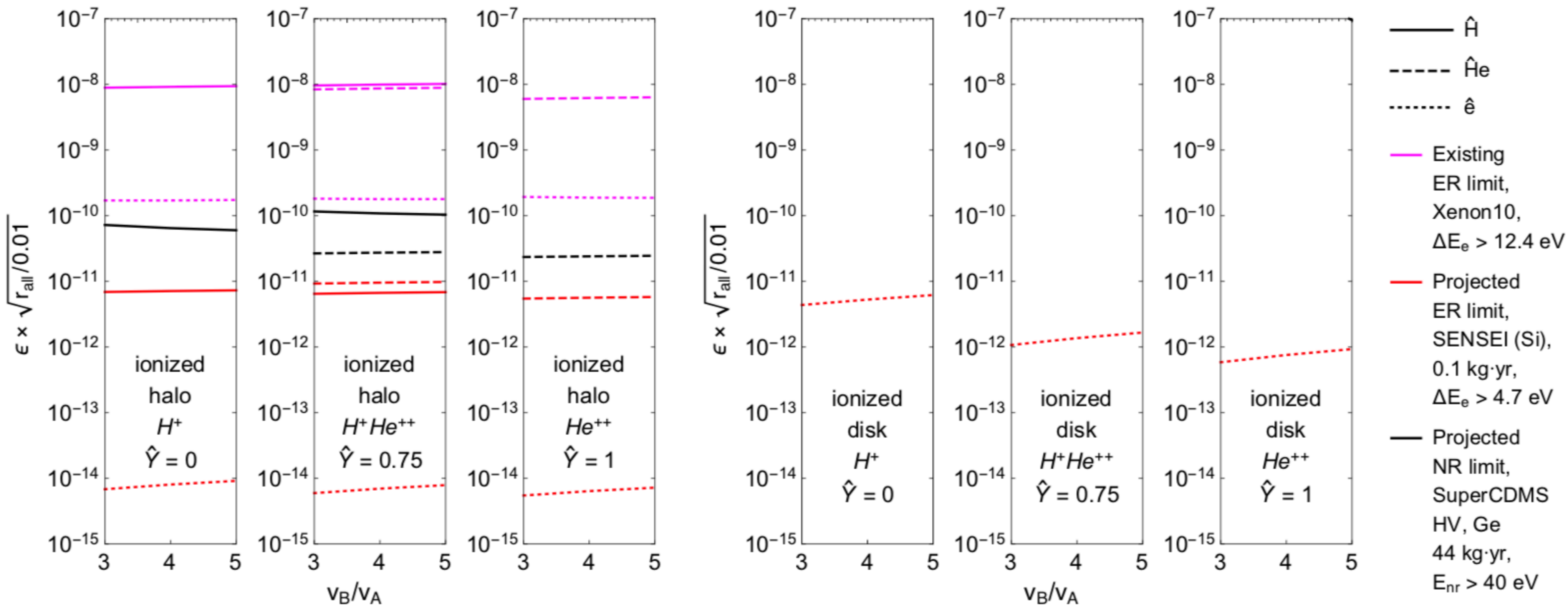
- ΔN_{eff} ~ 0.few
  same free-streaming vs scattering fraction as SM

- Mirror baryons part of our galaxy, but cool slower than SM baryons. **Feedback is complicated**.
  Distribution may be disk-like or halo-like.

1803.03263, 1907.XXXX Chacko, DC, Geller, Tsai

Mirror Baryons Direct Detection

SuperCDMS (nuclear recoil) taking data, SENSEI (electron recoil) is approved.



If there is *any* ambient mirror ionization, fast mirror electrons provide excellent discovery channel!

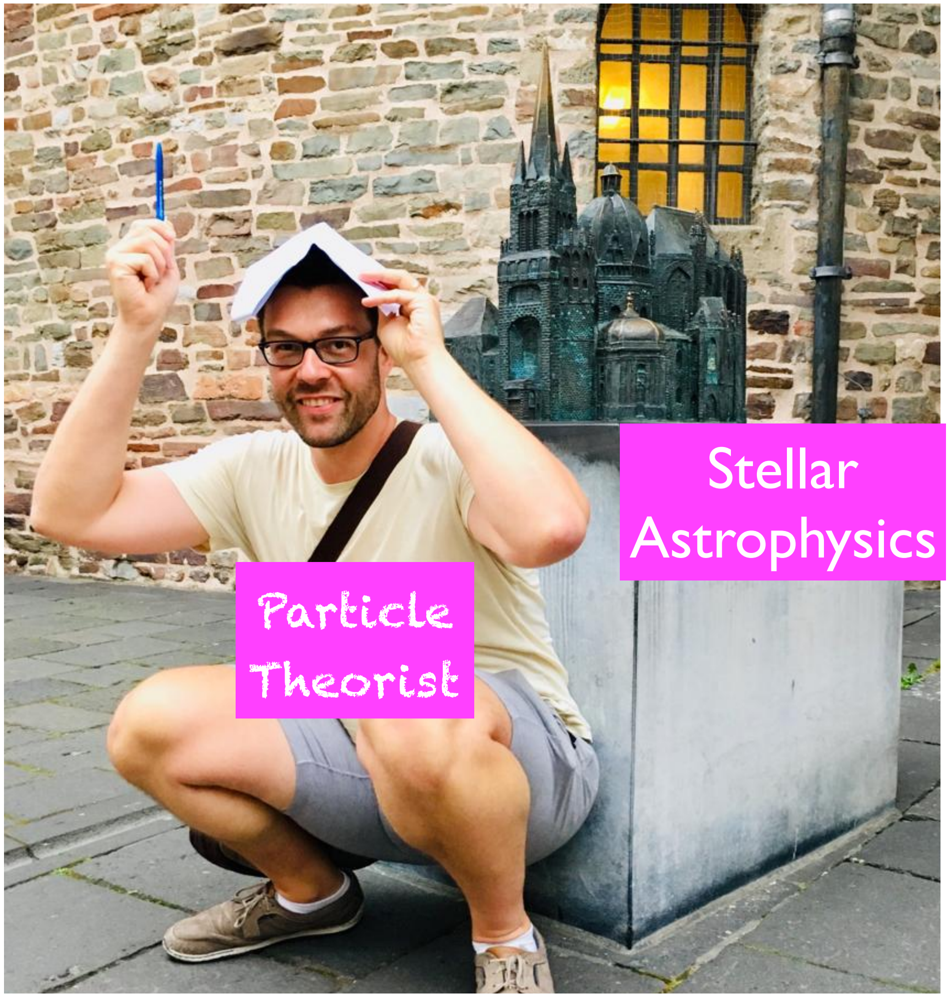
(Detection possible in other cases too)

1803.03263, 1909.XXXX Chacko, DC, Geller, Tsai

But complex mirror sectors can give rise to MUCH weirder astrophysical phenomena…

*This is exciting since we want to know if there are any *new searches* we could do to detect them*

Mirror Stars



1909.xxxxx , 1909.xxxxx DC, Jack Setford

Hierarchy Problem → Mirror Stars?

Mirror DM (perfect SM copy) is an old idea.

Foot, Ignatiev, Volkas astro-ph/0011156 and more

Mirror star signatures never really studied.

Neutral Naturalness motivates *family* of mirror sectors that are *fundamentally* motivated and allow for mirror stars.

Similar to SM, but different enough to change detailed stellar astrophysics.
(heavier mirror electron, different mirror nuclear binding energies)

Want to consider mirror stars as a *general* class of hidden sector signatures!

Factorize the Question

Mirror Stars

1. What do they look like in the sky?

2. Hidden Sector Model → Mirror Star Characteristics?

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Figure this out first for "general" mirror star

1909.xxxxx , 1909.xxxxx DC, Jack Setford

Factorize the Question

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Figure this out first for “general” mirror star

1909.xxxxx , 1909.xxxxx DC, Jack Setford

Neutral Naturalness is a great signature generator!

working on it…

How to discover Mirror Stars?

Source of signal: mirror photon mixing!

$$\epsilon F_{\mu\nu} F'^{\mu\nu}$$

($0 < \epsilon < 10^{-9}$ is theoretically motivated)

Use

SM stars

as

benchmark

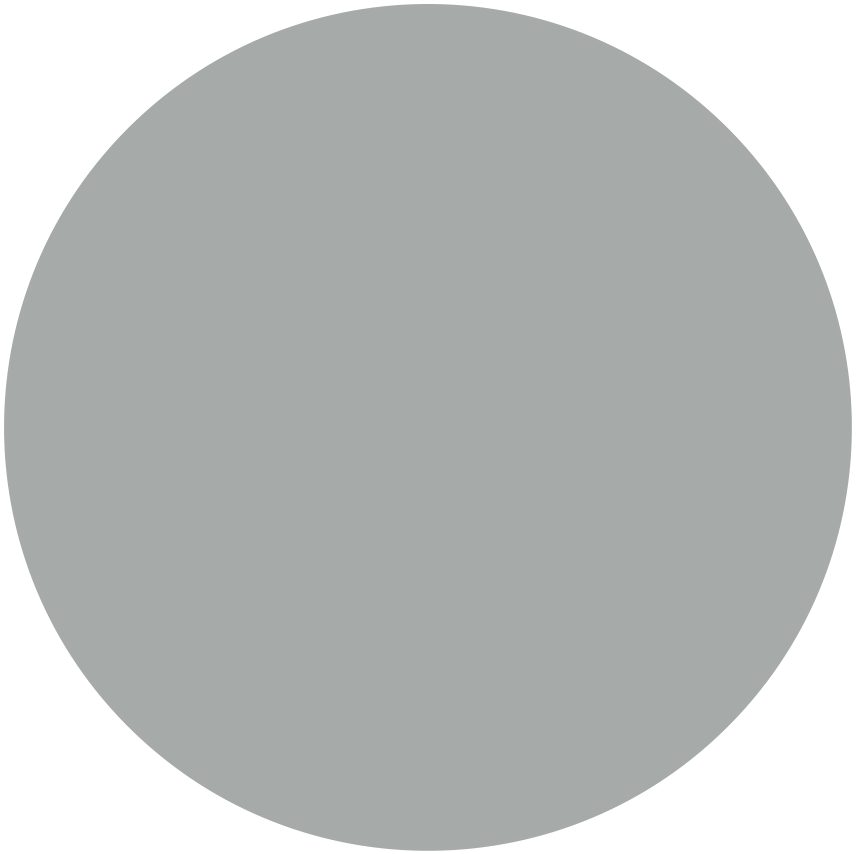
"mirror stars"

to study signature in detail.

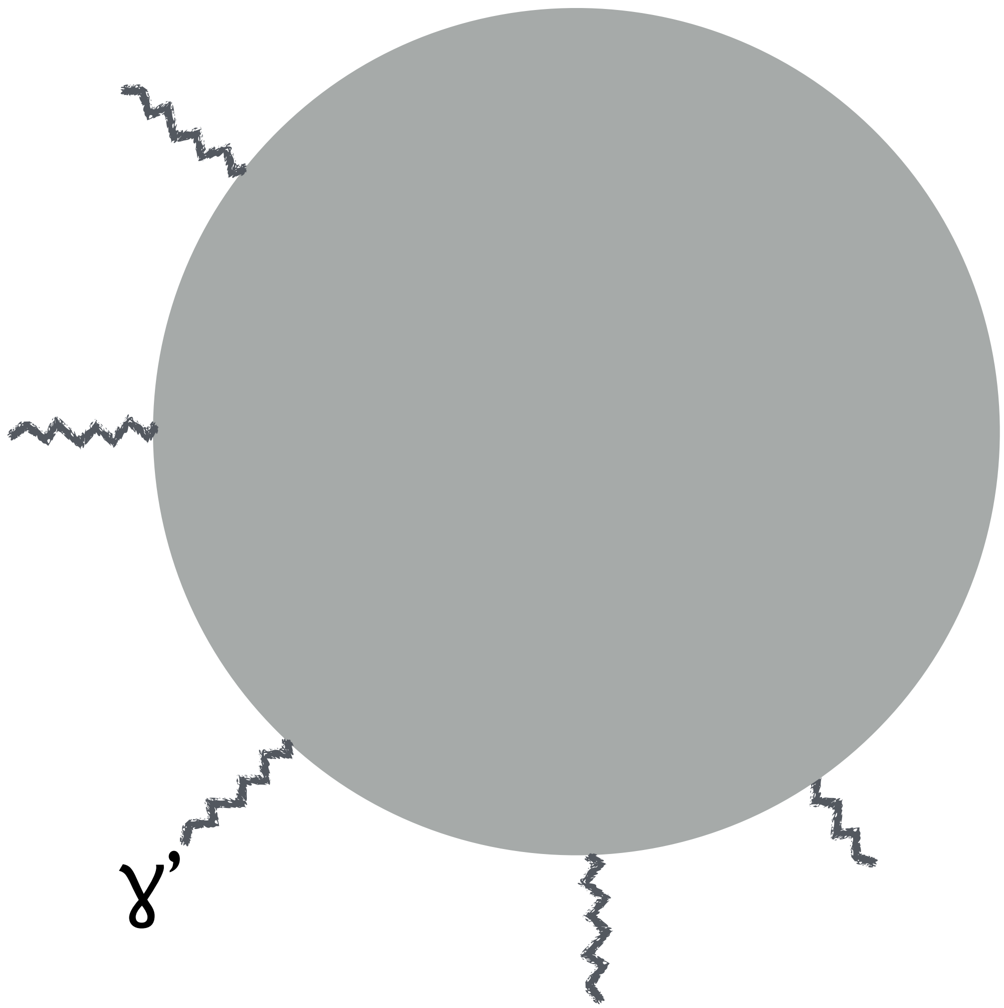
M / M_{sun}	1	5	50
He / H	0.24	0.24	0.24
R / R_{sun}	1	3.80	16.1
T_{core} / 10^7 K	1.54	2.83	4.13
L / L_{sun}	0.96	721	5.18×10^5
τ_{star} / years	4.3×10^9	5.6×10^7	2.3×10^6
n_{core} / cm^{-3}	4.5×10^{25}	6.2×10^{24}	7.4×10^{23}
ϵ_{crit}^{mirror}	2.6×10^{-9}	5.9×10^{-9}	1.3×10^{-8}
ϵ_{crit}^{self}	2.5×10^{-16}	3.0×10^{-15}	8.2×10^{-14}

can compute properties with MESA

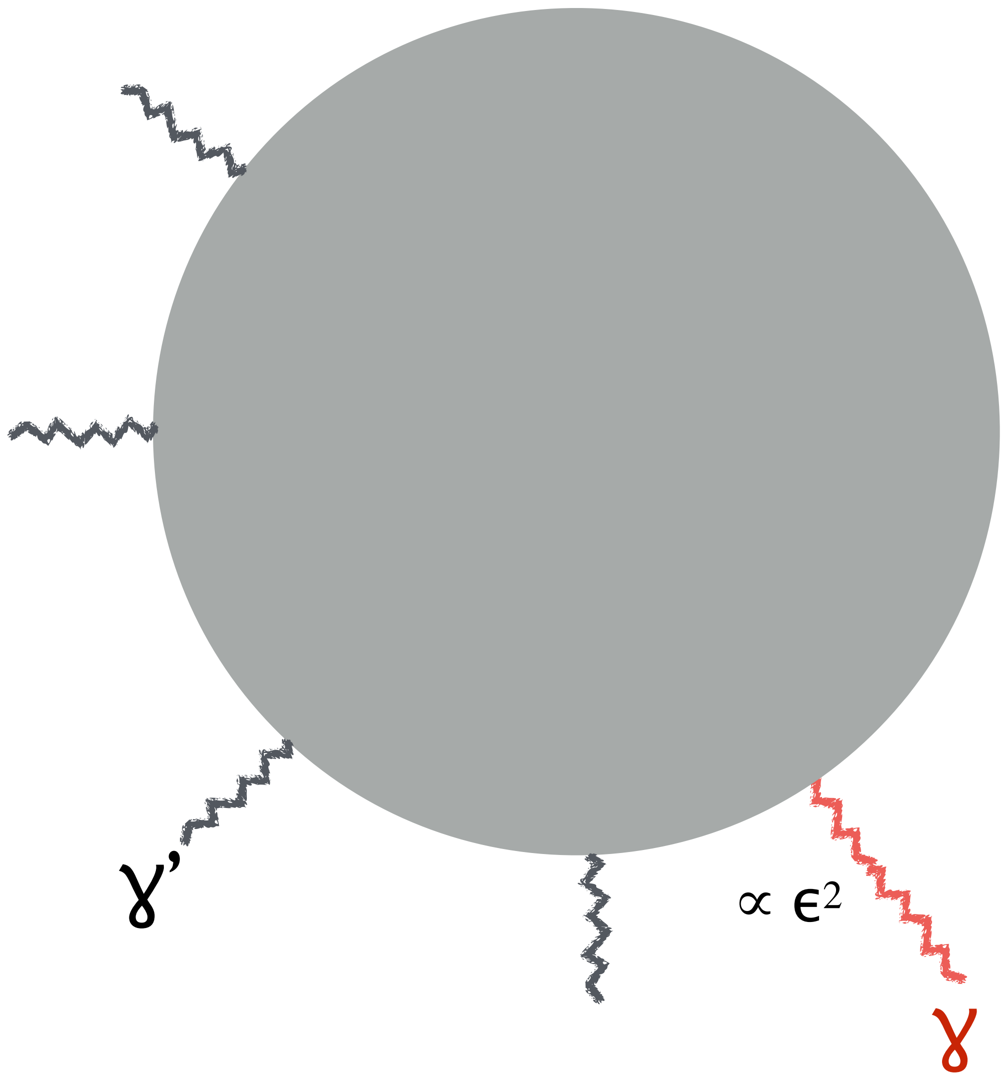
Mirror Star Signals



Mirror Star Signals

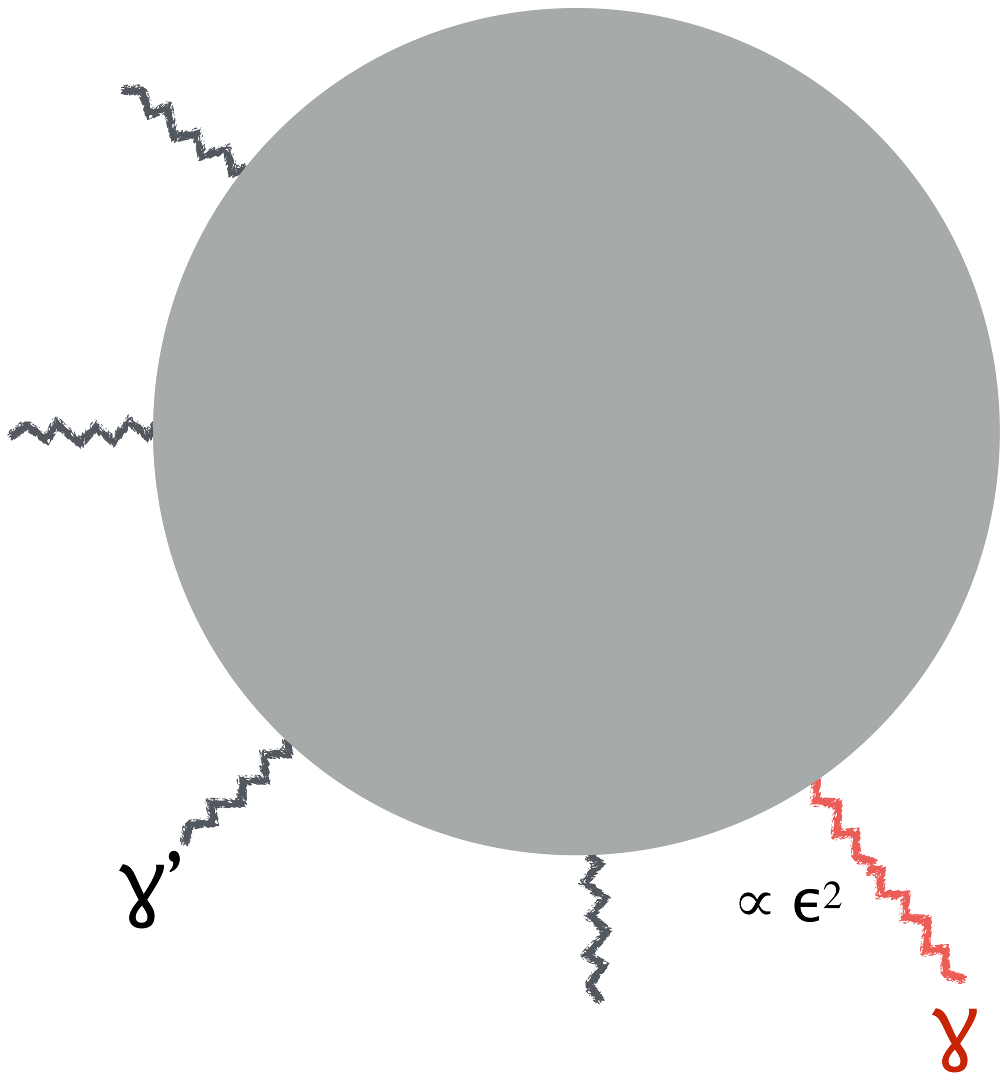


Mirror Star Signals



1) Photons from surface ~ ϵ^2

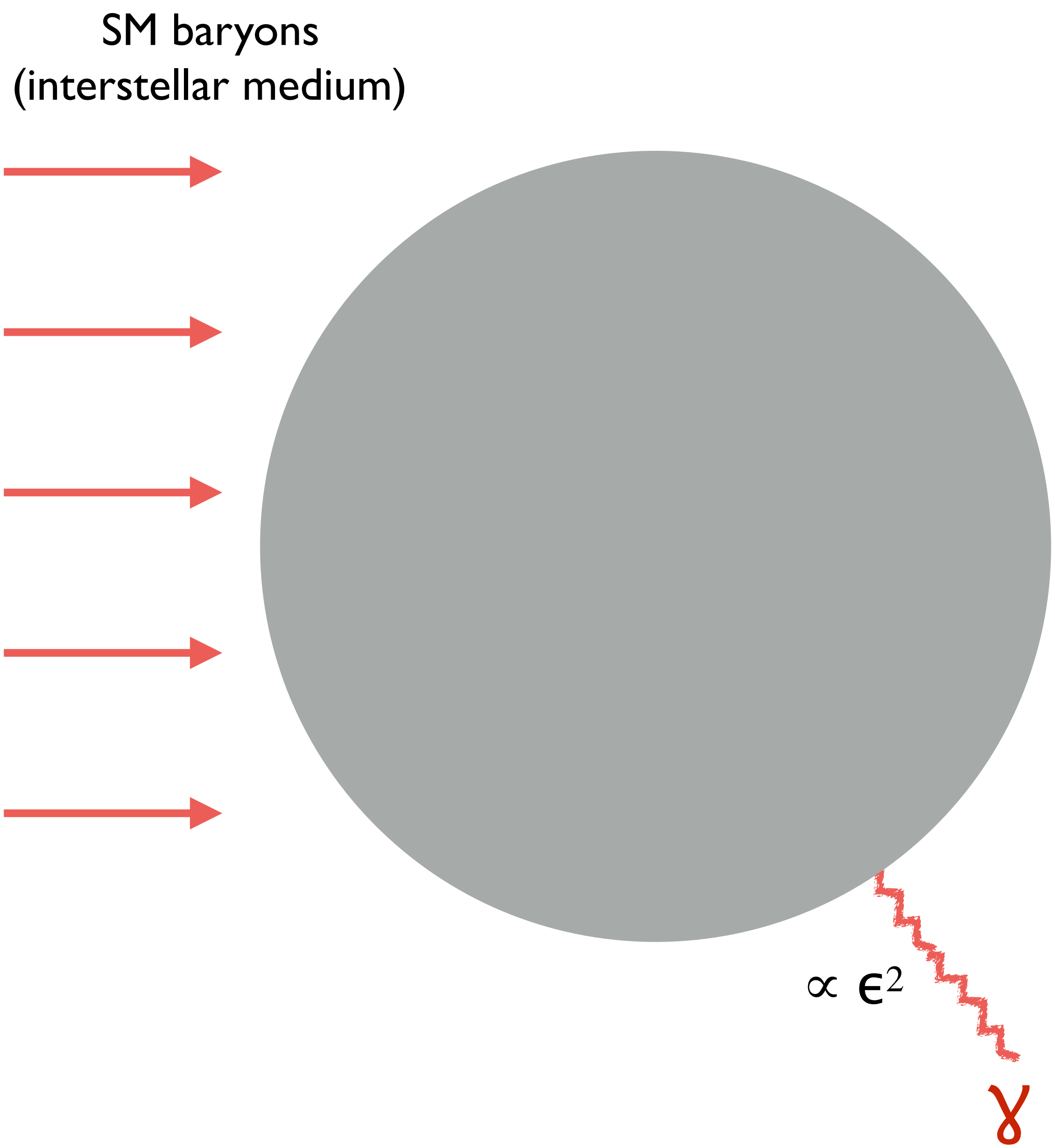
Mirror Star Signals



1) Photons from surface ~ ϵ^2

Also straight from core? NO!

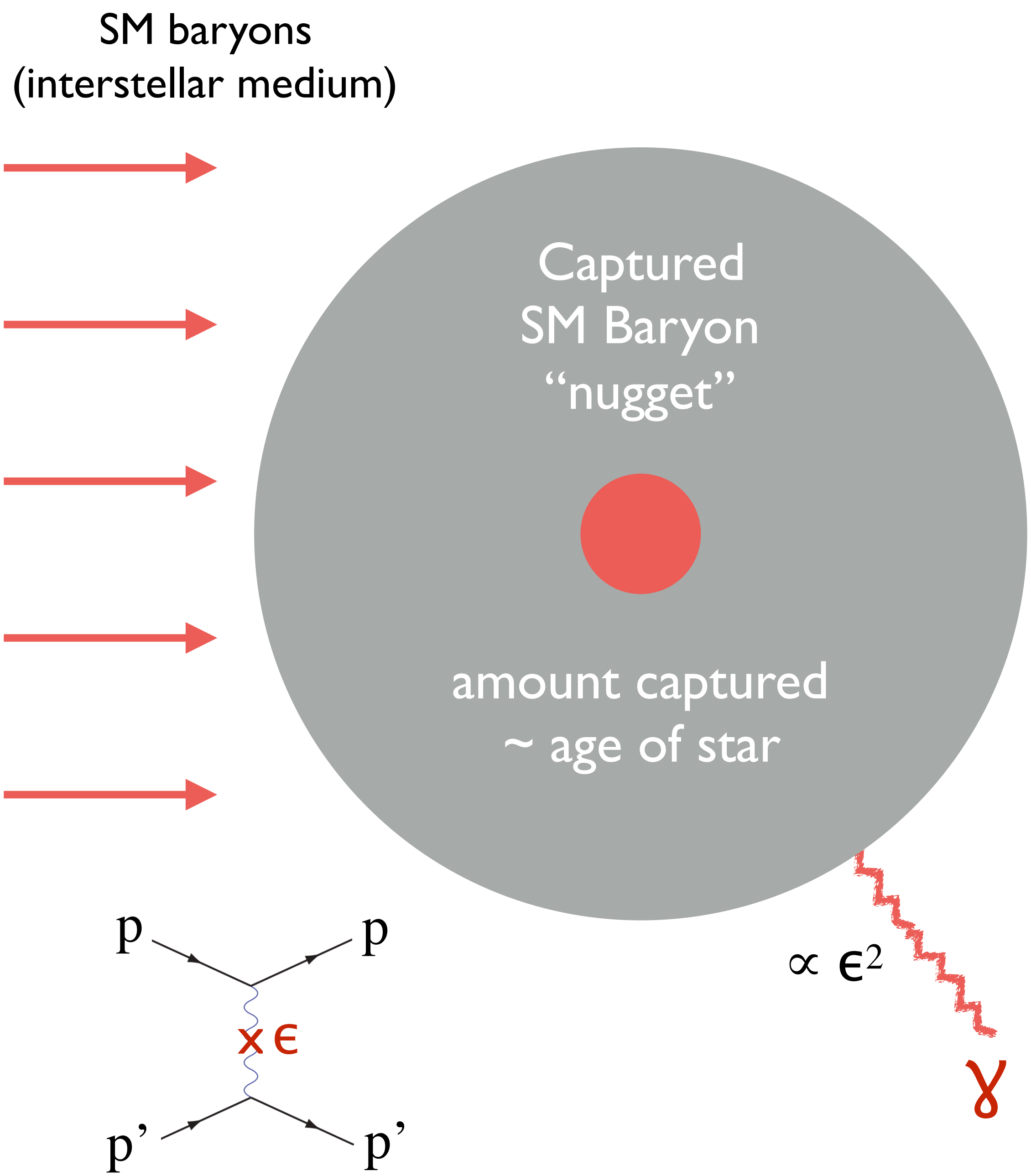
Mirror Star Signals



1) Photons from surface ~ ϵ^2

Also straight from core? NO!

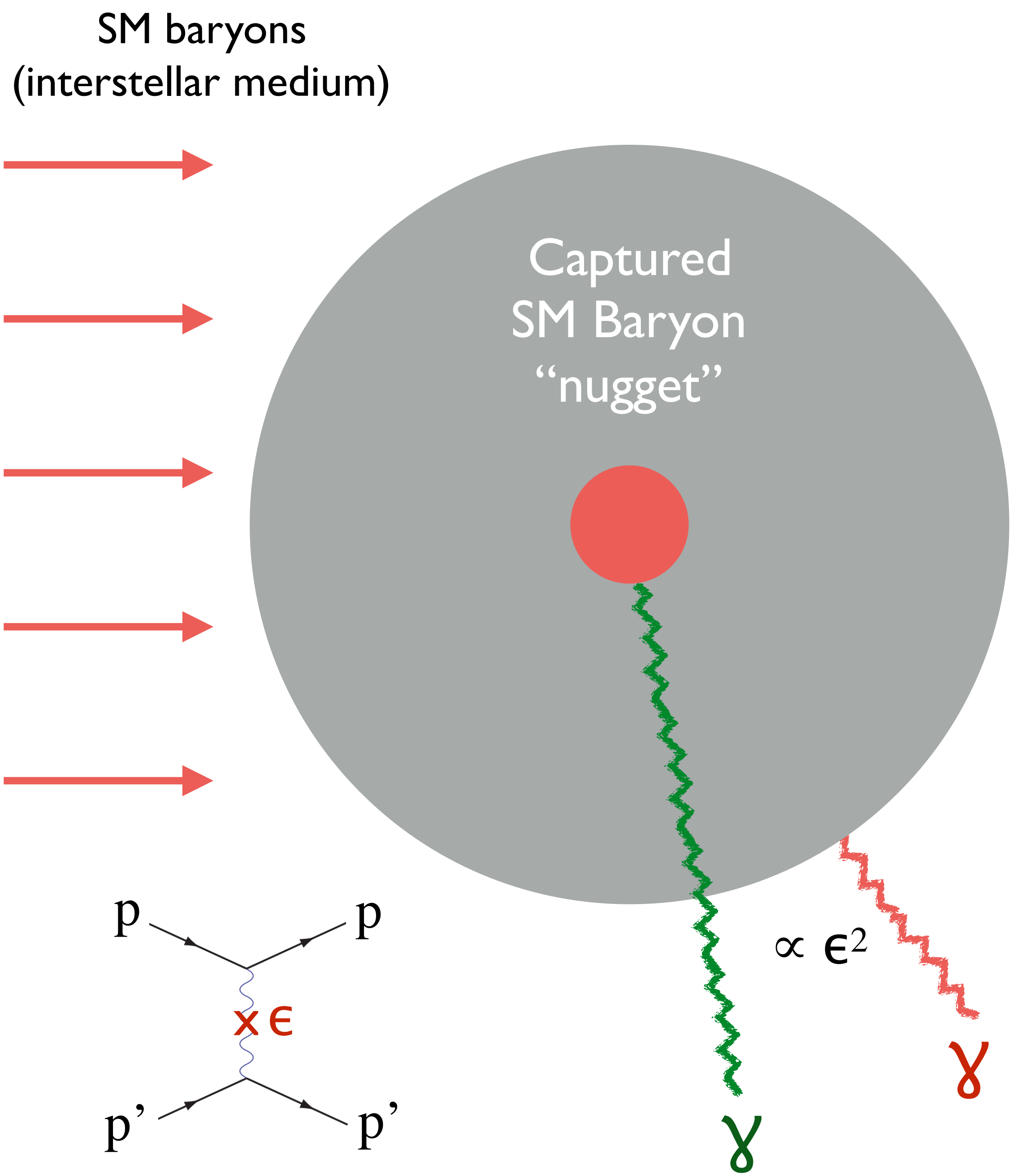
Mirror Star Signals



1) Photons from surface ~ ϵ^2

Also straight from core? NO!

Mirror Star Signals

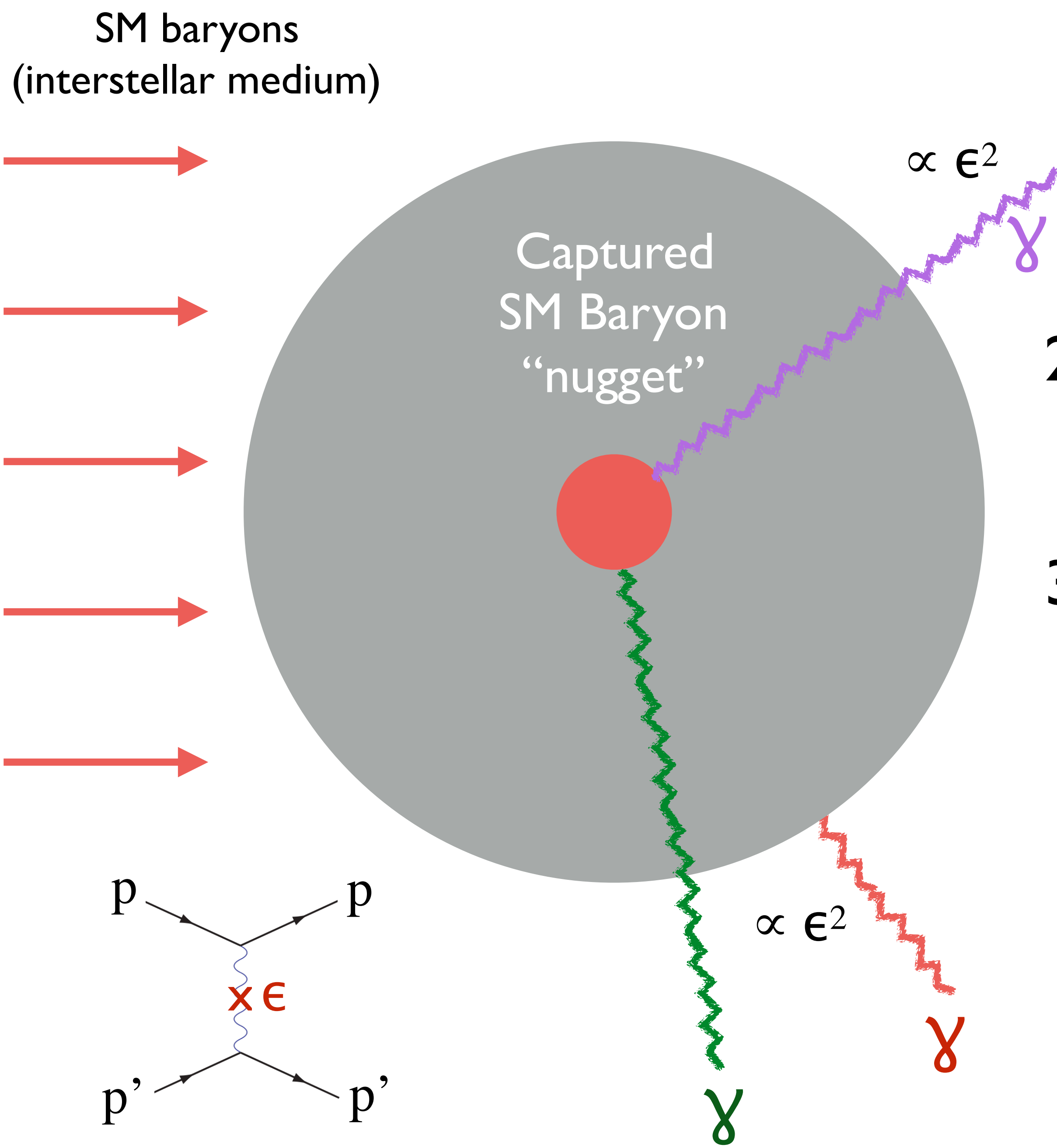


1) Photons from surface ~ ϵ^2

Also straight from core? NO!

2) Thermal emission from SM nugget: **Optical!**

Mirror Star Signals

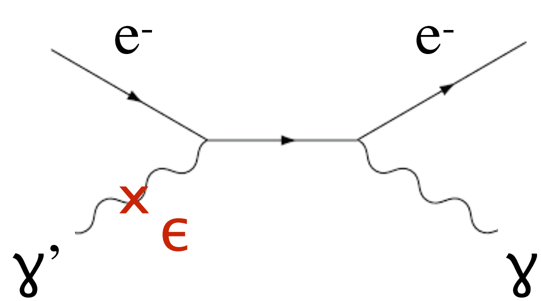


1) Photons from surface ~ ϵ^2

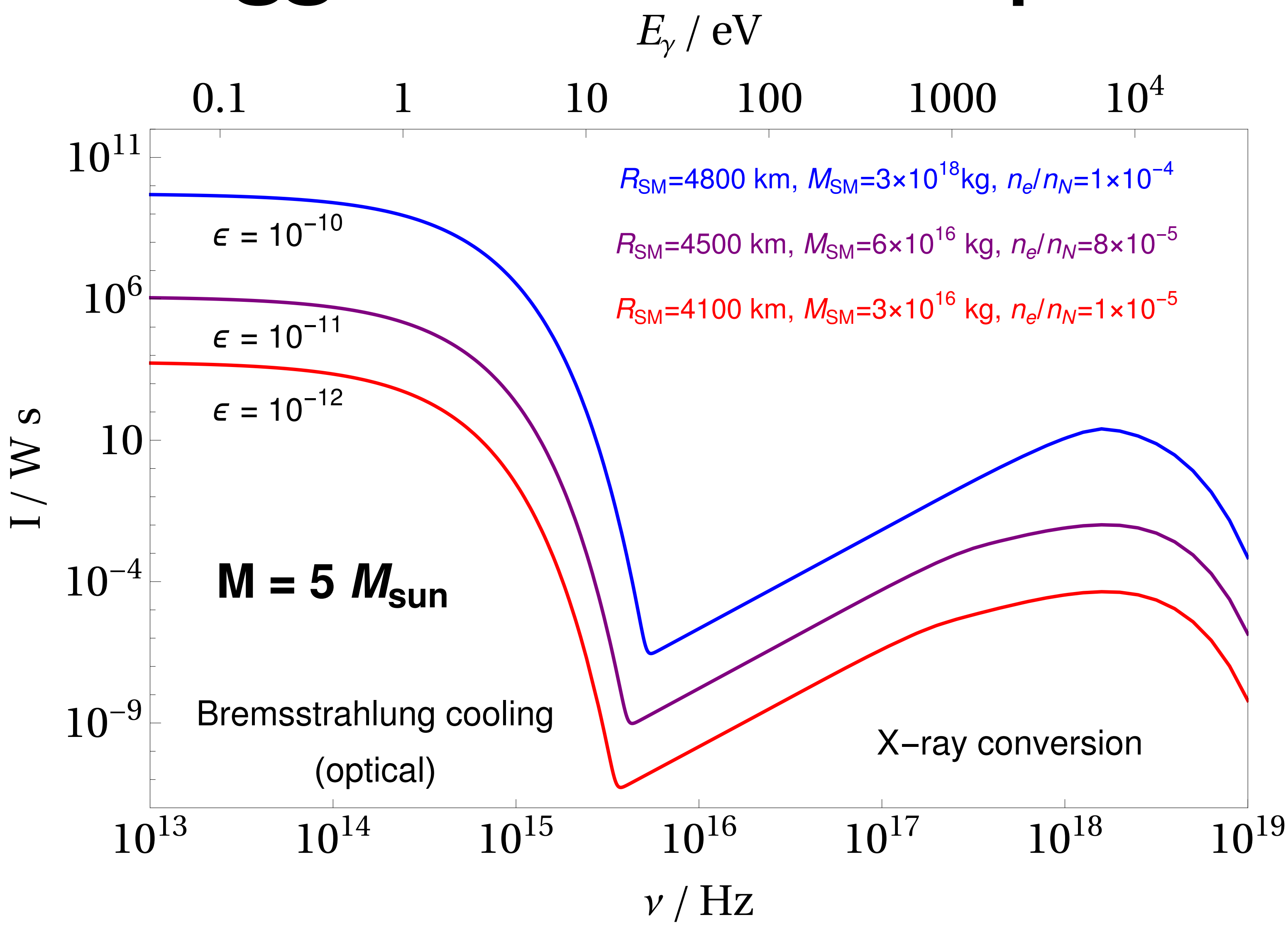
Also straight from core? NO!

2) Thermal emission from SM nugget: **Optical!**

3) Mirror Thomson Conversion: **X-rays**



SM "Nugget" Emission Spectrum



Optical cooling signal
given low lumi, MUCH too hot ~ 10^4K
to be standard astrophysical object

X-rays
straight from
the mirror star core!

Mirror Star Signature

Mirror stars have a *highly distinctive* double-signal:

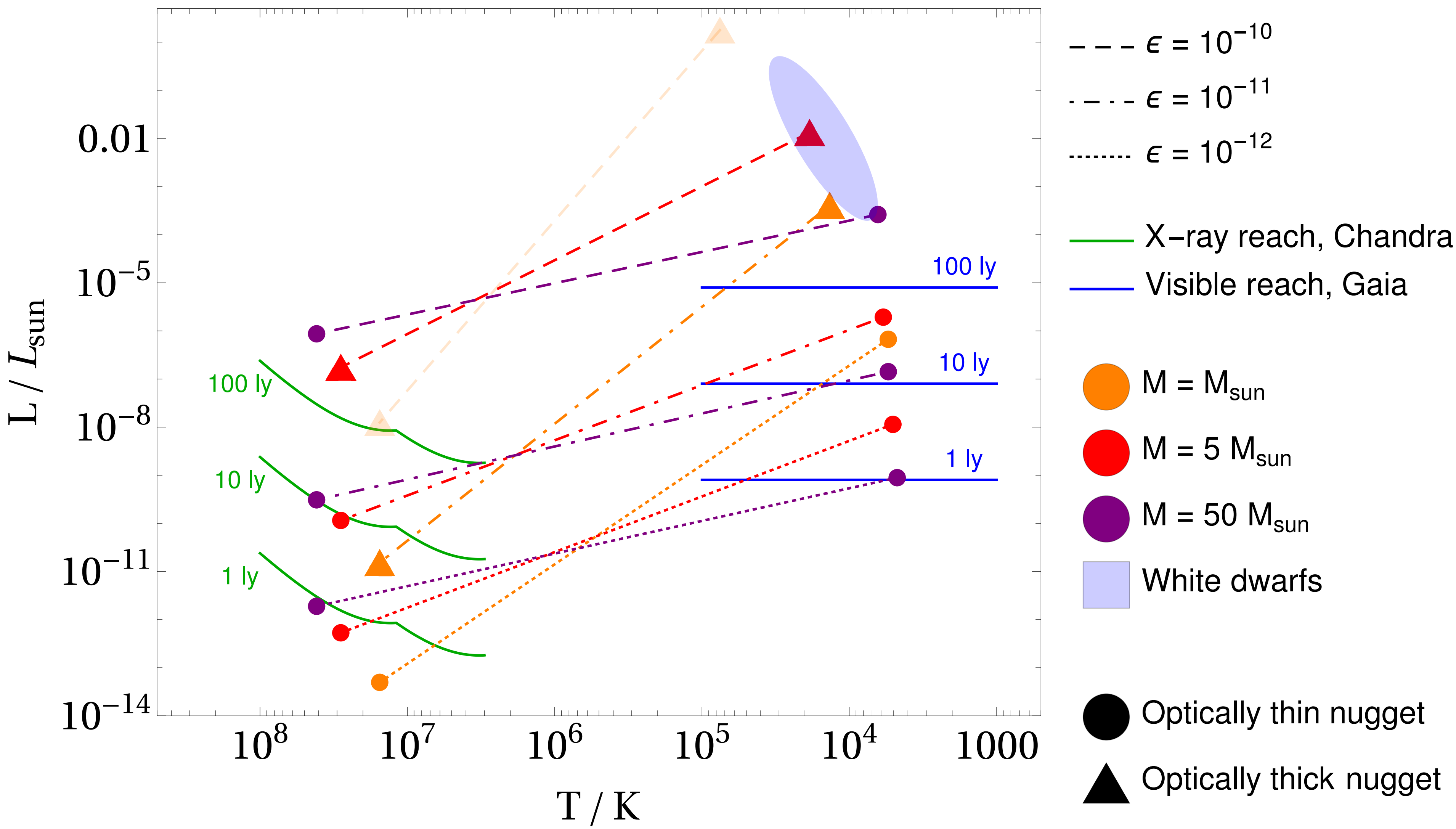
Hot! Thermal optical spectrum at ~10,000K, superficially similar to white dwarfs. But…

X-rays from the Mirror Star core reveal **core temperature** and **details of dark nuclear physics**

Only visible if close → parallax → get absolute lumi → **Faint!**

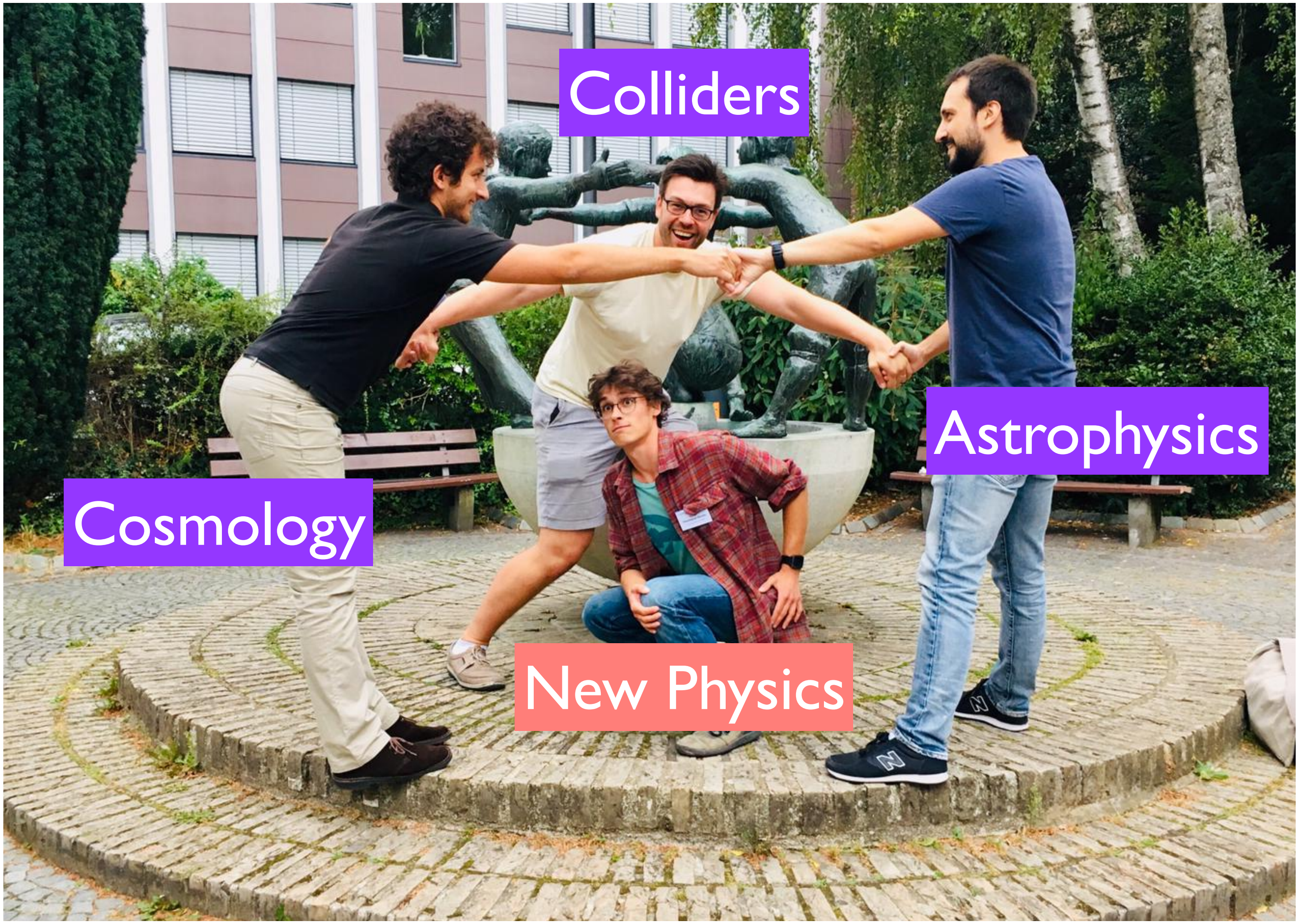
Upon detailed examination, this will look nothing like anything from SM astrophysics!

Mirror Stars in HR Diagram



Next: will look for this in GAIA data and X-ray catalogues

Conclusions



Conclusions

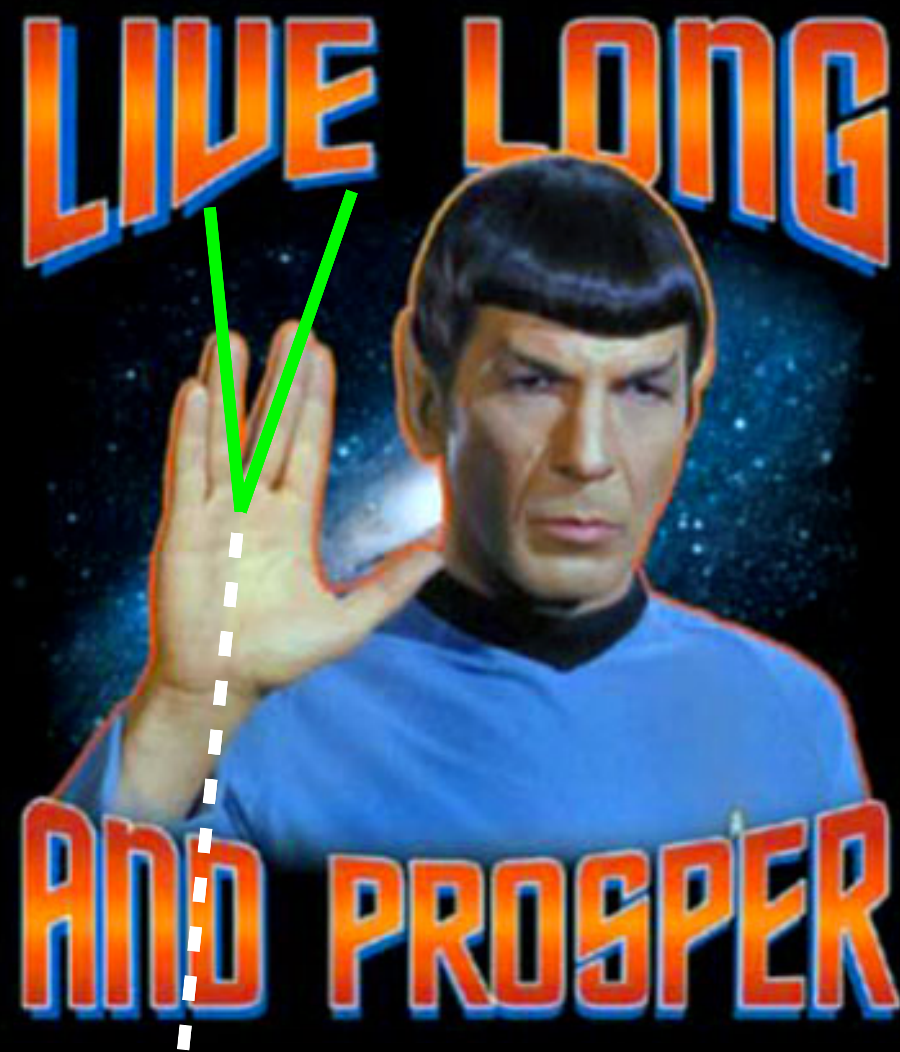
Hidden sectors are motivated from bottom-up and top-down.
Observe at **Colliders** (LLP) or in **Cosmology/Astrophysics** (stable)

LHC LLP program ramping up. We need to build MATHUSLA!

Top-down formulations give ***rich, predictive hidden sectors*** with rich cosmology and astrophysics that you can interrogate in detail.

Asymmetrically reheated MTH:
- solves the little hierarchy problem
- **if** no LLP signatures, can still measure **Br(h→invis) ~ v_B^2/v_A^2**
- this parameter is correlated with many many cosmo + astro observables: **ΔN_{eff}, LSS deviations, direct detection, mirror stars**

MIRROR STARS can a rise in many hidden sectors.
We found they produce a highly robust and distinctive signal!



— Thank you —

BACKUP

1. Theory and Motivation for the Lifetime Frontier

Looking for LLPs: Rules of the game

LLPs are spectacular signatures:

- if they are charged/colored, very conspicuous
- **invisible if neutral, but their <u>decay is spectacular</u>, usually reconstructed as a "displaced vertex" (DV)**

harder, focus here

Neutral LLPs: geometrical nature can be **difficult to trigger** on at L1. **Backgrounds low but hard to predict**, so often try to eliminate BG completely.
(MET searches are usually insensitive due to small xsecs.)

Most searches today & near future try to solve these problems via **"LLP + X"** strategy. Require:
- *geometric nature* of LLP decay ("LLP")
- something else ("X") to *eliminate background* (X could be a second LLP) and *help triggering* (high HT, lepton, …)

Recent Analyses

These analyses are difficult and take a long time.

Significant experimental progress in recent years!

For Neutral LLPs, *most* current cutting edge searches could be classified as:

- standard prompt trigger + offline DV search (e.g. prompt lepton + DVs from VH, H->LLPs)
- ATLAS Muon System: L1 trigger, look for any DV inside MS, muon DVs anywhere
- CMS displaced jet HLT triggers: lower L1 HT cut than prompt, displaced search at HLT

(there are also searches in Calorimeter, e.g. ATLAS 1902.03094, disappearing track searches, etc…)

H → 2a → 4b (ATLAS)

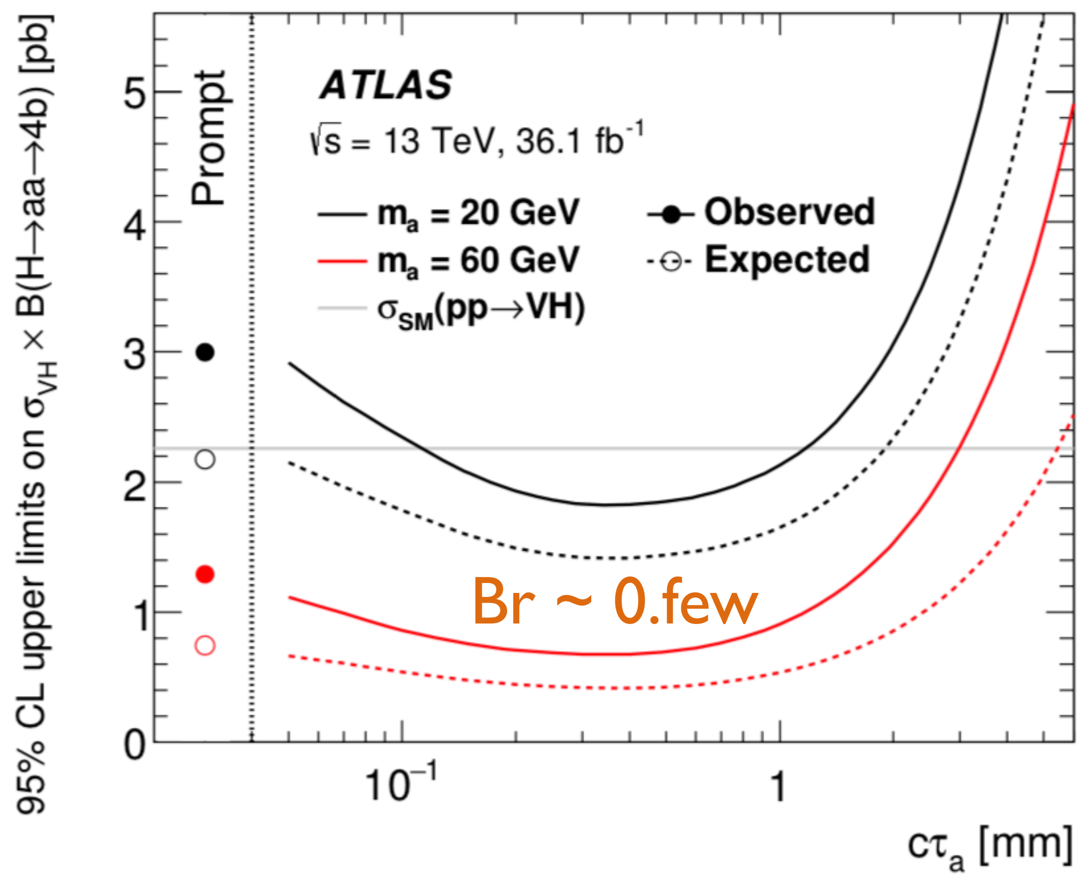
Searches for VH production, H → 2a → 4b.

1806.07355

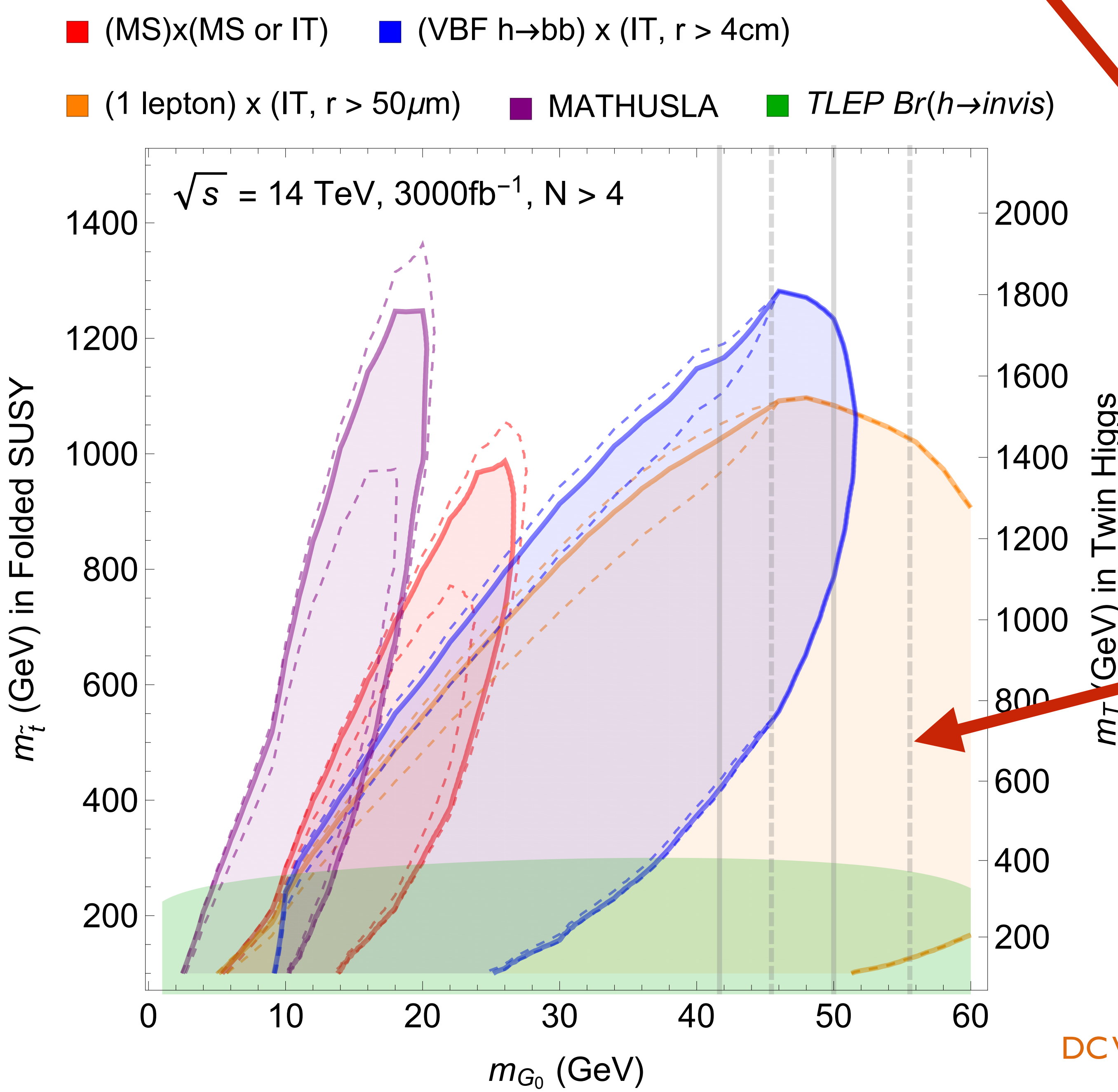
TRIGGER: relies on lepton from V. **Exactly what we want** for inclusive LLP searches from exotic Higgs decays, since LLP in this mass range is difficult to trigger on.

HOWEVER, this is a **PROMPT** search where they compute sensitivities to macroscopic lifetimes as well.
(Important new way of presenting prompt results!)

Hopefully dedicated LLP analyses with this trigger coming in the near future.



We need this channel for Neutral Naturalness!!



1806.07396
DC Verhaaren 1506.06141

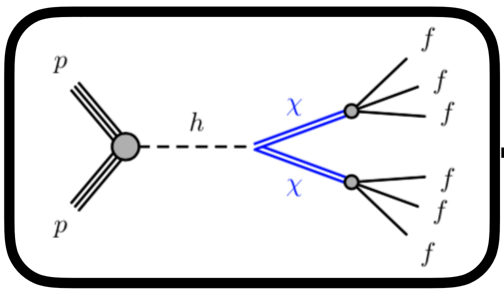
1 or 2 jj DVs *inside* ATLAS Muon System

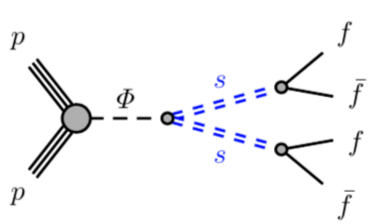
ATLAS MS can trigger on hadronic LLP decay at L1!

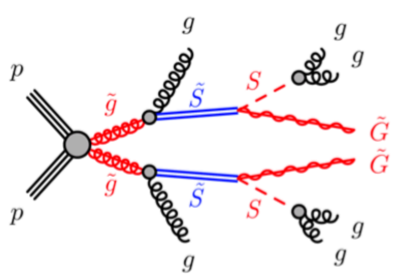
based on 1605.02742 Coccaro, DC, Lubatti, Russell, Shelton

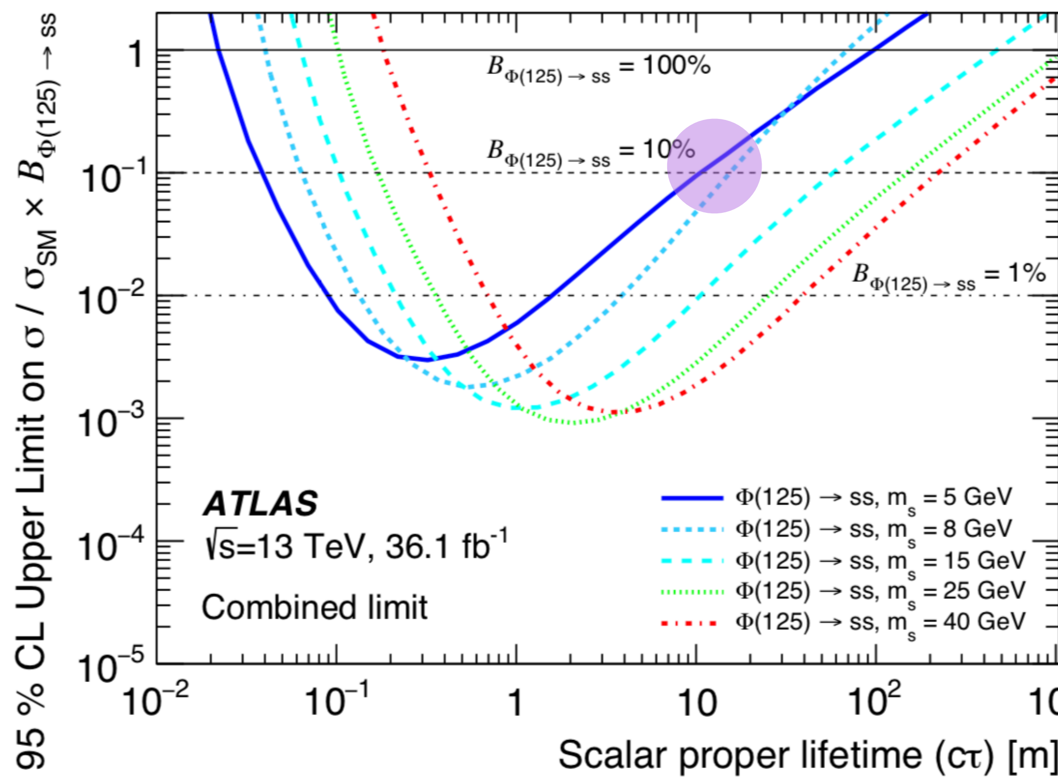
Require either 2DVs, or
1DV + (MET > 30 GeV), or 1DV + (pTJJ > 150 GeV)

1DV search has significant background, but extends long-lifetime reach!









1811.07370

1 μμ DV anywhere with ATLAS MS

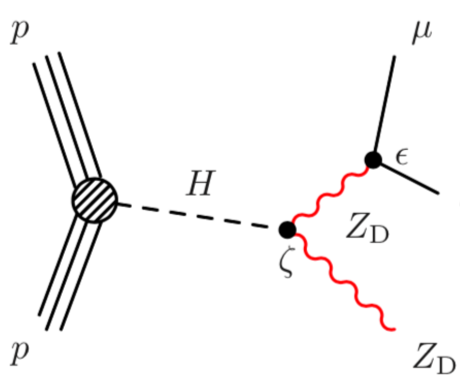
ATLAS MS can trigger on L1. Very inclusive search for single LLP → μμ anywhere within 4m of beam

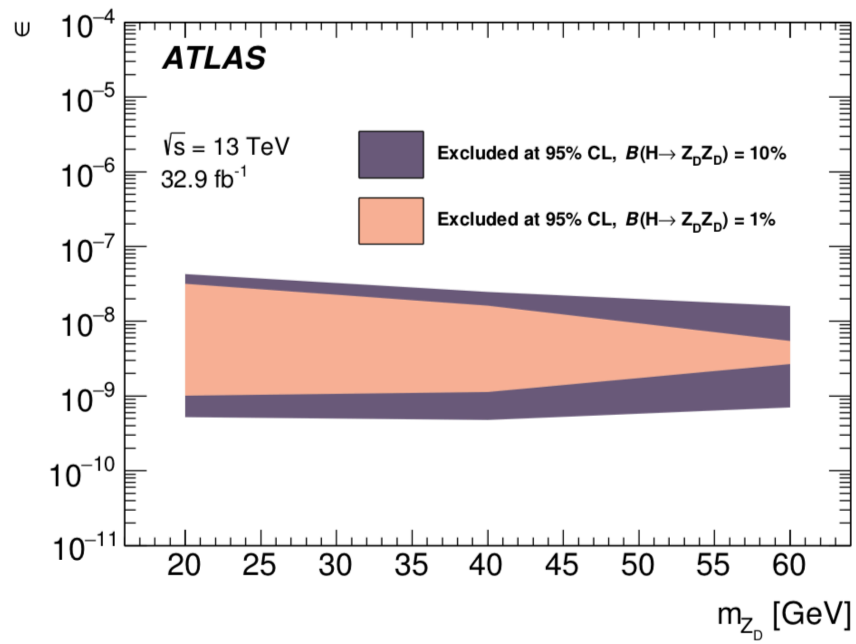
Low-mass SR: fully inclusive.

N_{BG} ~ 10 , equiv to σ_{BG} ~ 0.3fb. **Not zero BG! (surprise?)**

High-mass SR: MET > 110 GeV.

N_{BG} ~ 0



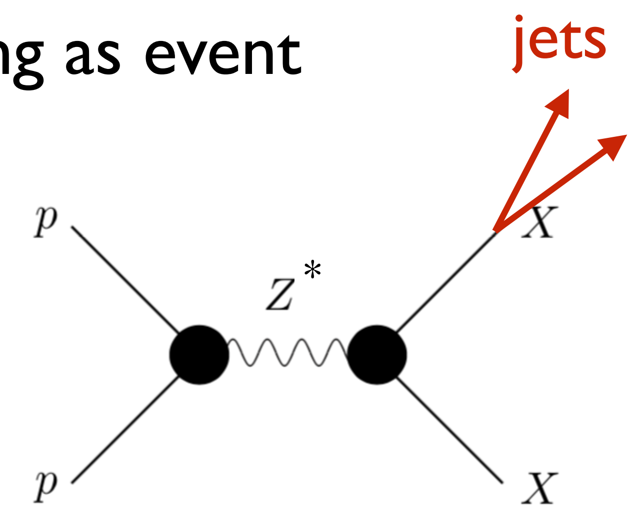


1808.03057

CMS Displaced Jets

1811.07991

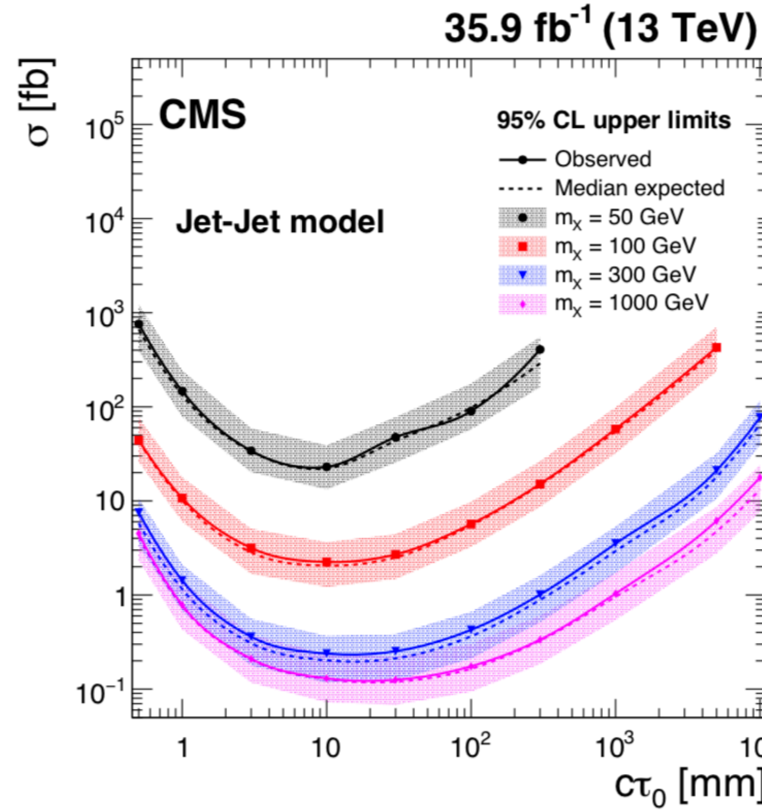
CMS can trigger on displaced jets at HLT as long as event passes L1 HT seed → **HT > 400 GeV**



Benchmark model of LLP X pair production via Z* mediator. X -> jets.

Very efficient for heavy LLPs.
Stringent HT cut eliminates BG.

Surprising: also get significant limits for mX = 50 GeV!

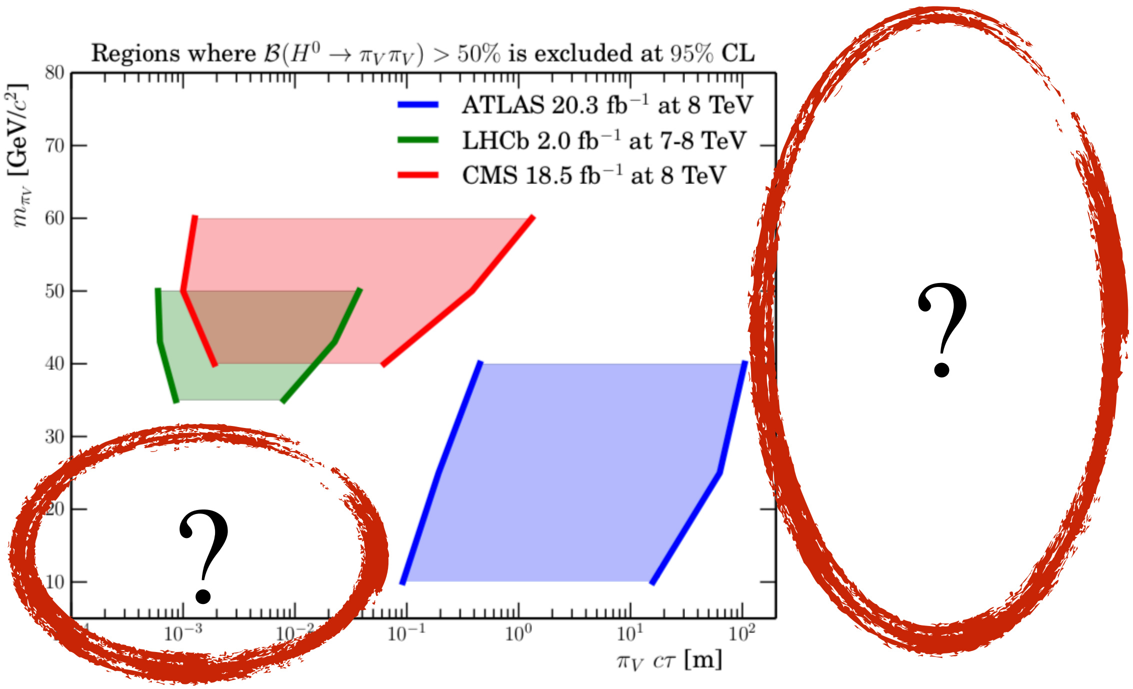


Why not use this to get limits on exotic Higgs decays? (Naively expect <~ 1% efficiency from boosted fraction p_{TH} > 200 GeV → Br limit 0.few?)

A Coordinated LLP Search Program

Identify and Target Gaps in Coverage:

e.g. for exotic Higgs decays with relatively high rate (Br = 0.5)



e.g. Dark Showers

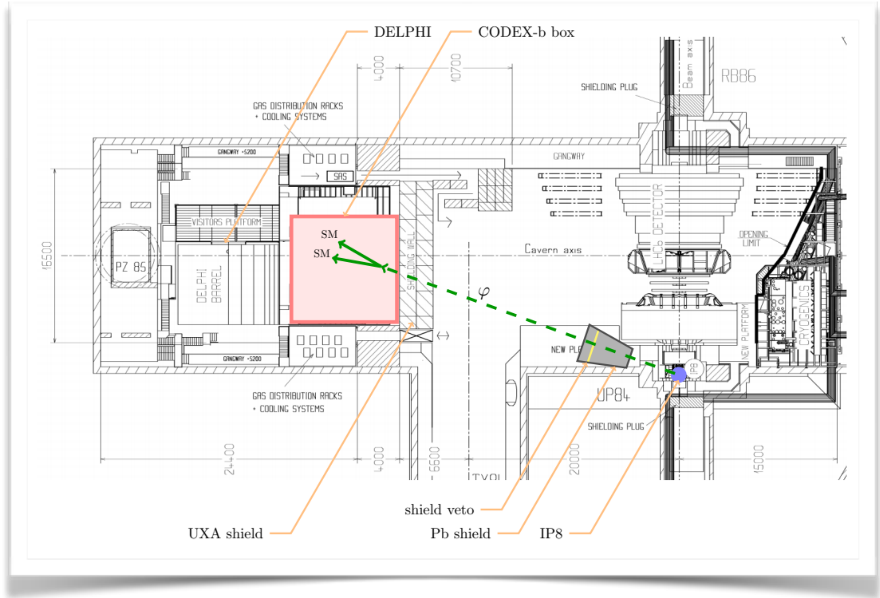
hidden valley can give rise to high-multiplicity soft final states (soft unclustered energy patterns SUEPs). Soft Multi-Muon Searches?

... and more

Other Proposed External LLP Detectors for the LHC (for light LLPs)

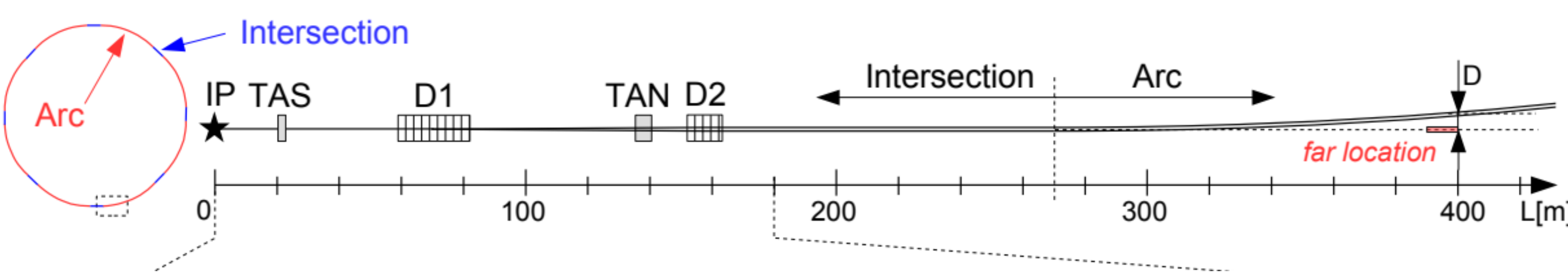
CODEX-b:
"mini-MATHUSLA" near LHCb

Gligorov, Knapen, Papucci, Robinson, 1708.09395



See Jonathan Feng's talk

FASER: tracker telescope staring along beam axis into ATLAS collision



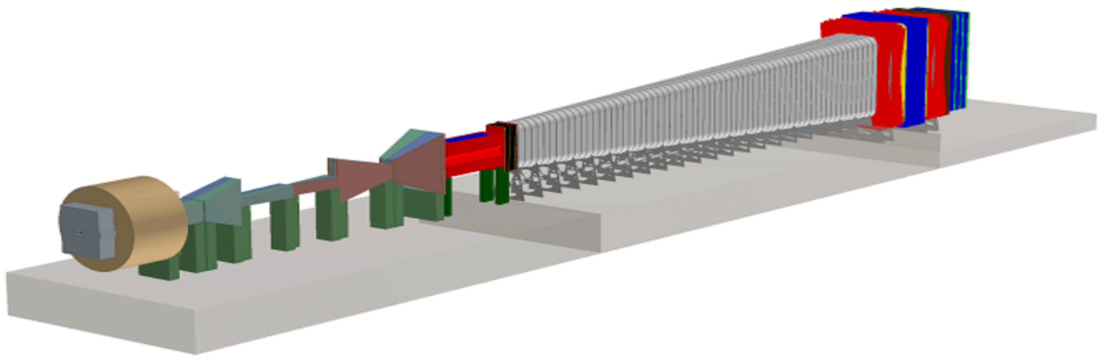
Relatively Cheap & <u>FUNDED</u>!!!

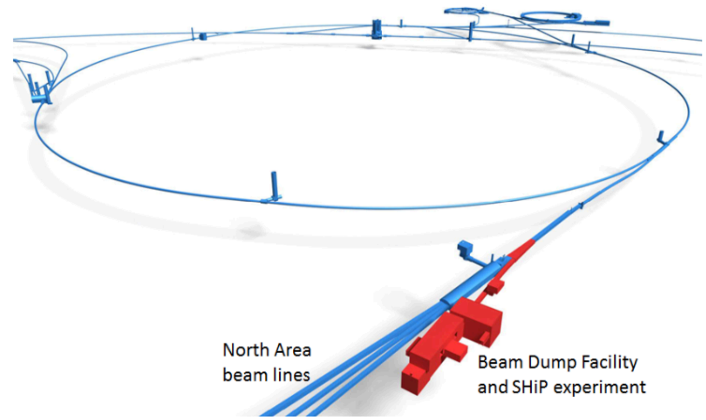
Feng, Galon, Kling, Trojanowski 1710.09387

SHiP

ship.web.cern.ch

$\sqrt{s}$ = 38 GeV fixed target facility proposed for SPS, specifically for low-mass hidden sectors via LLP searches.





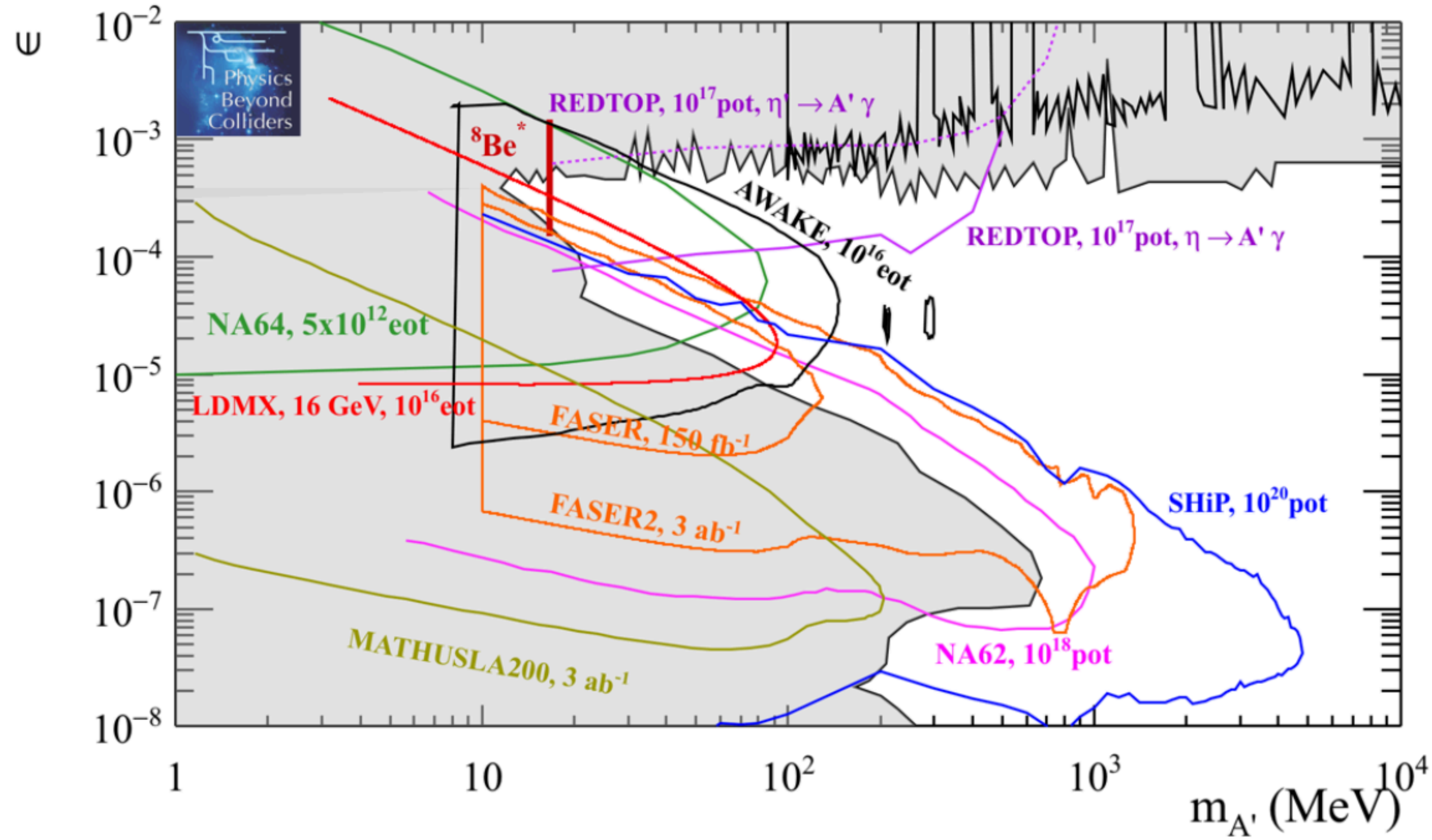
Physics case for SHiP examined by Physics Beyond Colliders (PBC) working group at CERN.

PBC compared SHiP reach for low-mass LLP simplified models to MATHUSLA, CODEX, Faser. (This does not examine full physics case for MATHUSLA & CODEX, which can probe higher masses.)

Compare reach for

low-mass LLP scenarios

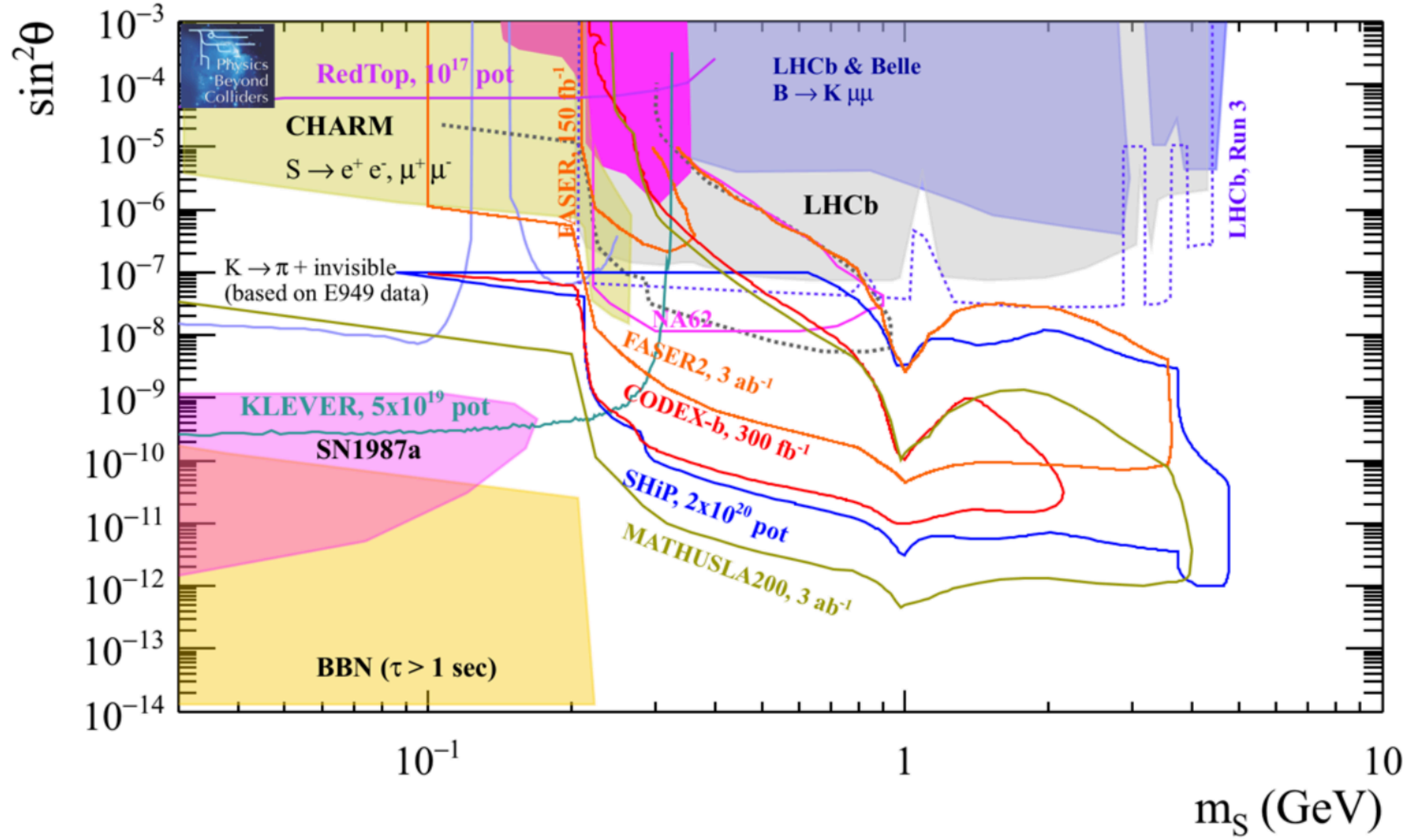
Dark Photon only



For < ~GeV dark photon + invisible or milli-charged states, need LDMX, milliQan

PBC BSM working group report 1901.09966

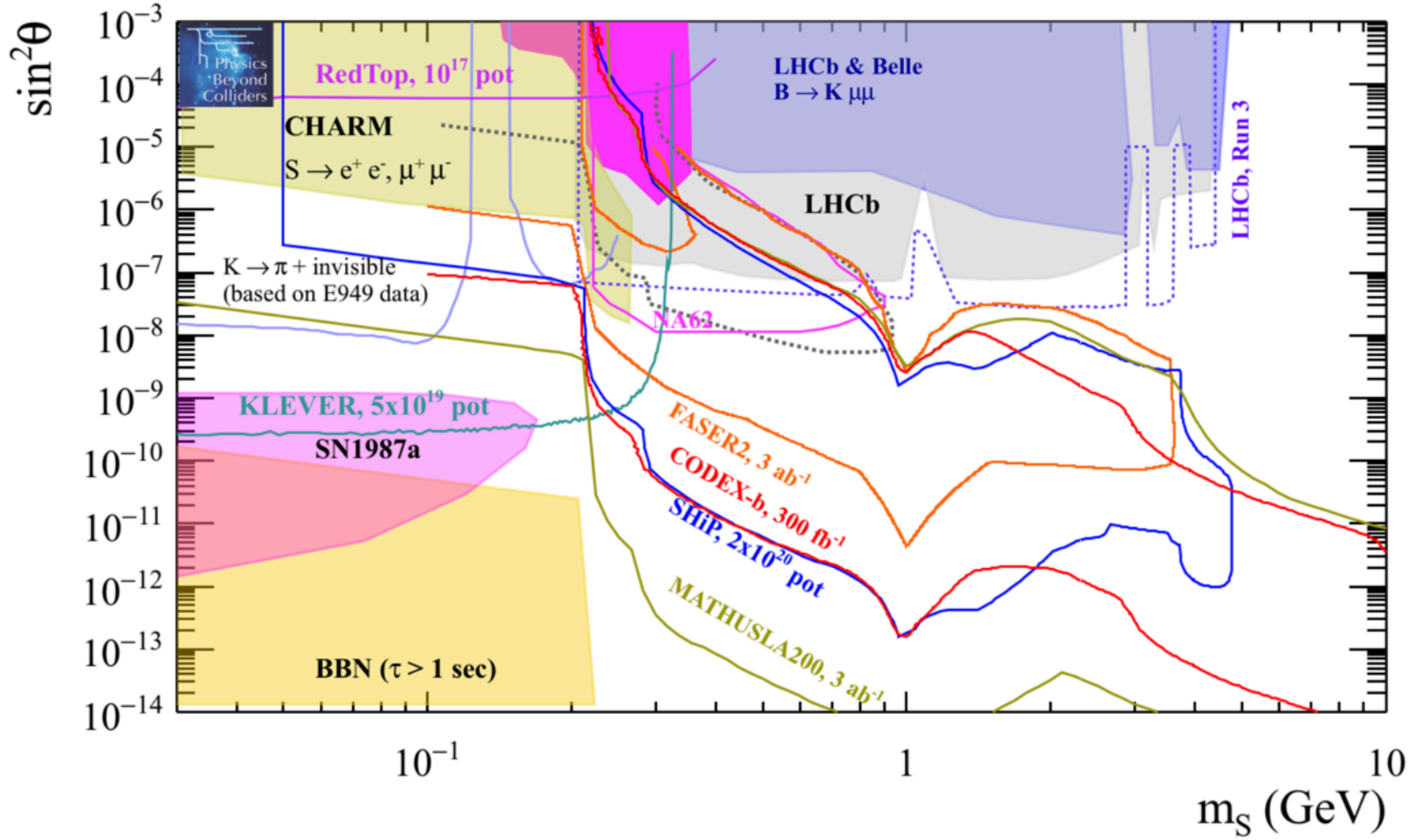
Dark Scalar only



very complementary coverage… MATHUSLA, SHiP and FASER cover longer, intermediate and shorter lifetimes.

PBC BSM working group report 1901.09966

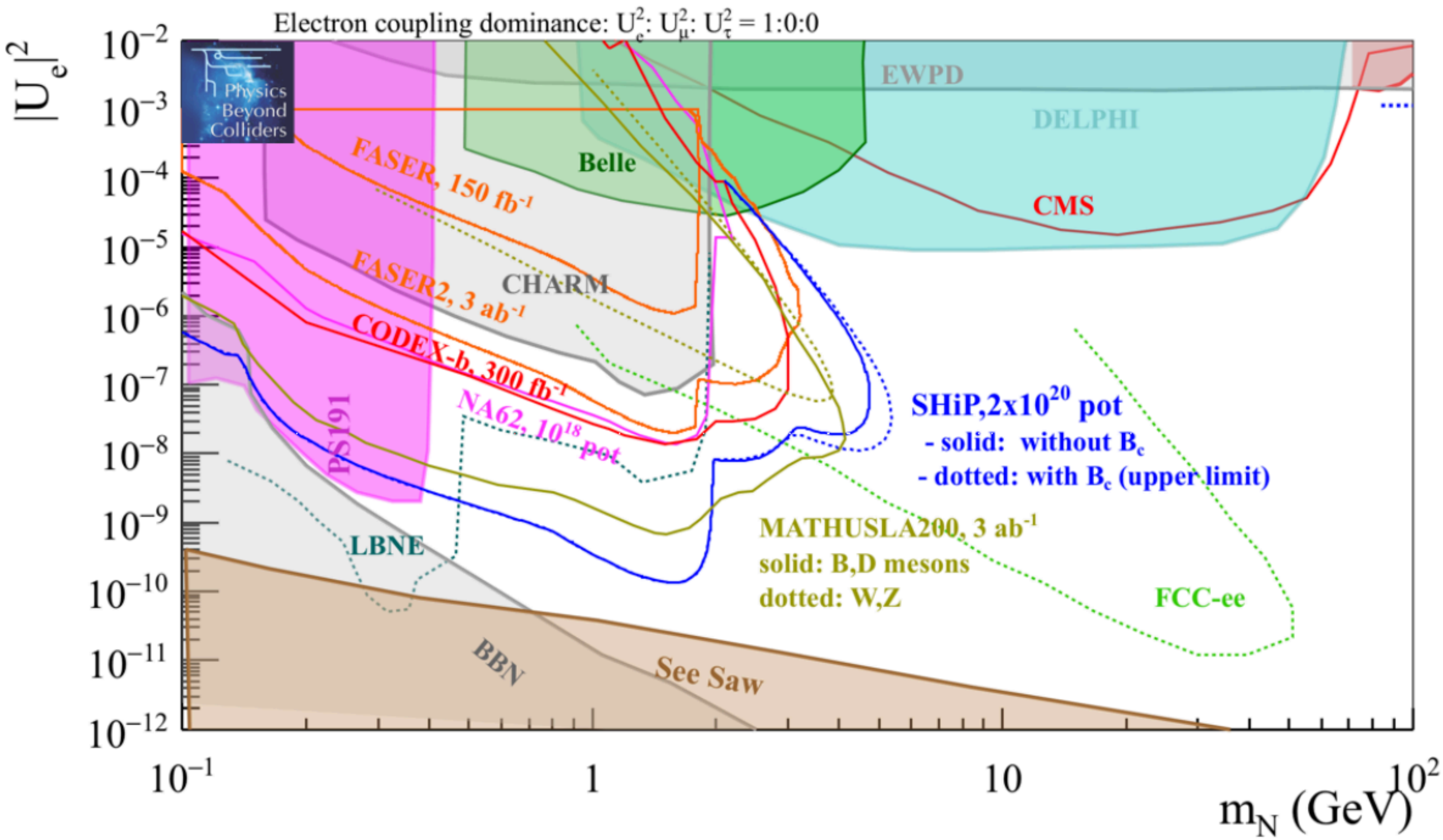
Dark Scalar with exotic higgs decays



LHC external detectors probe higher masses

PBC BSM working group report 1901.09966

Sterile RH Neutrinos

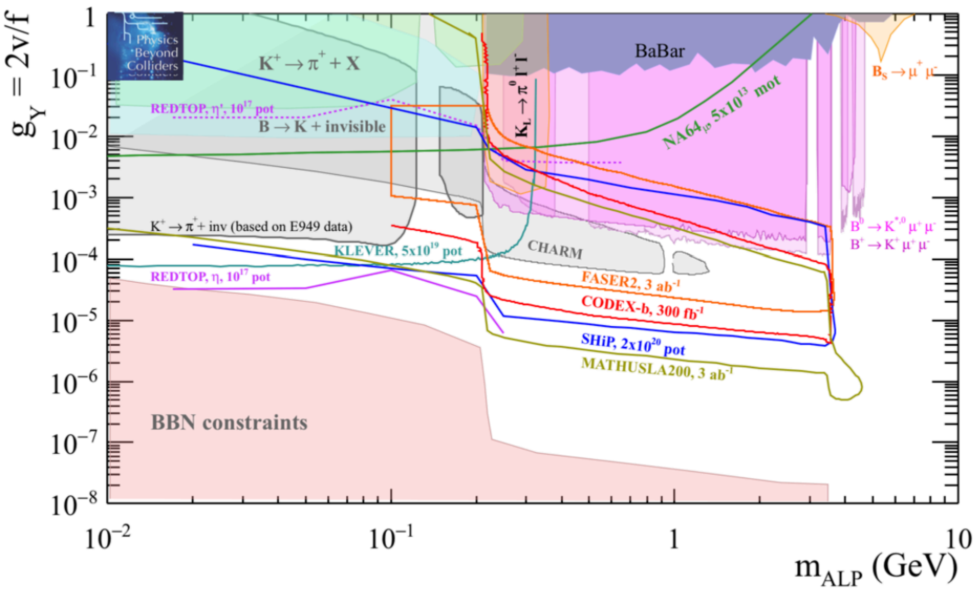


very complementary coverage…

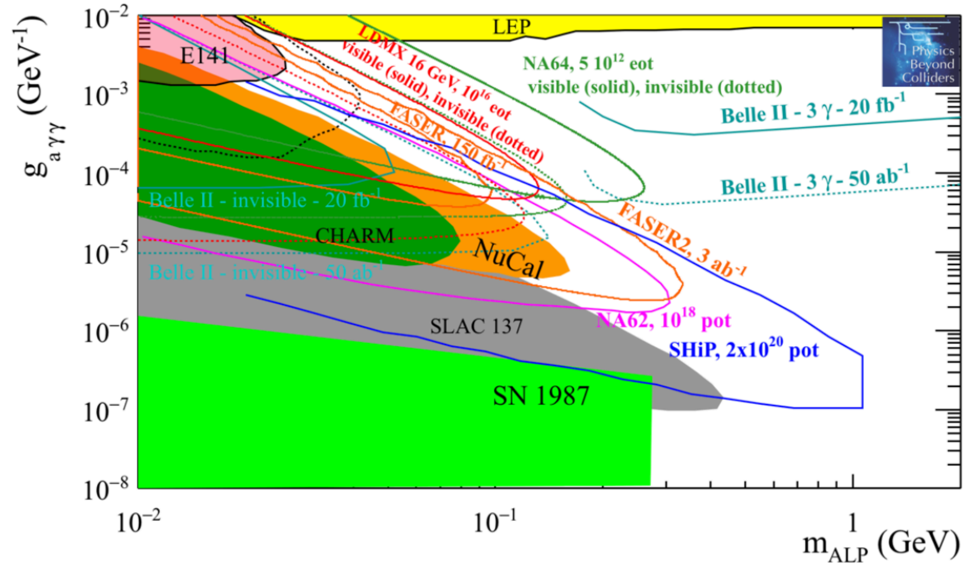
PBC BSM working group report 1901.09966

Axion-like Particles

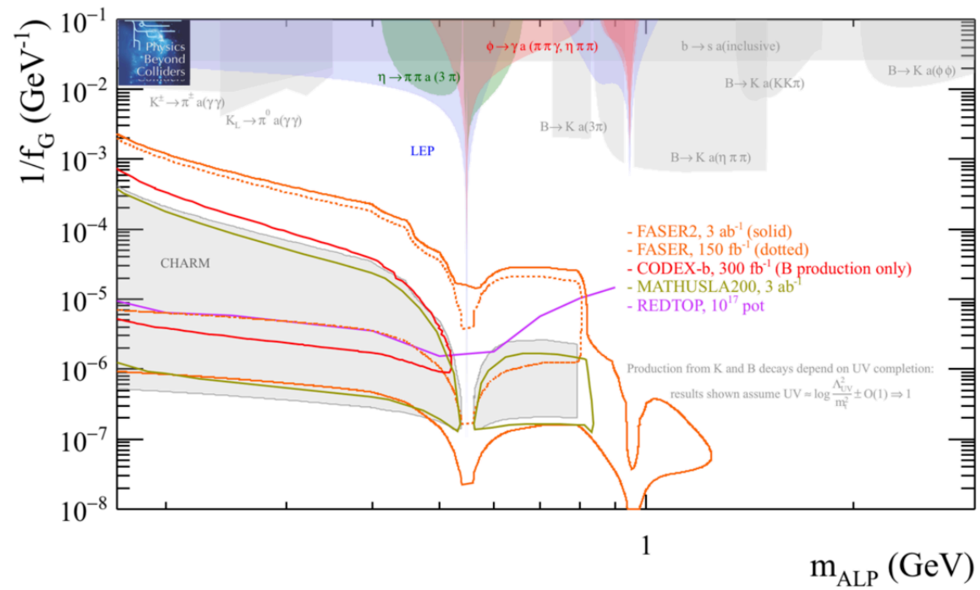
pure fermion coupling



pure photon coupling



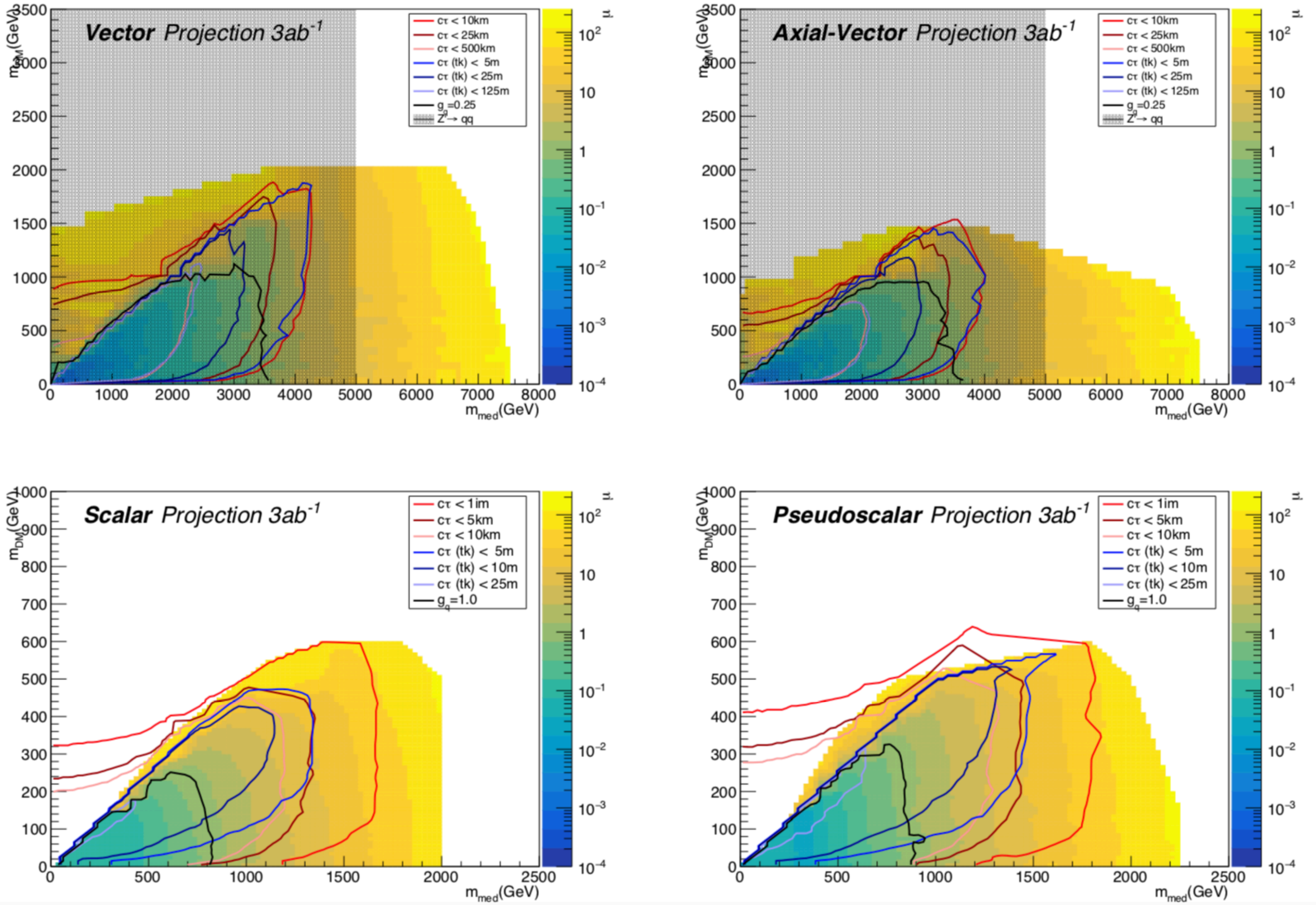
pure gluon coupling



Theory predictions still very uncertain for pure gluon coupling scenario

PBC BSM working group report 1901.09966

LLP searches: MET vs DV



1806.07396

Asymmetrically Reheated MTH:

Big Bang Nucleosynthesis

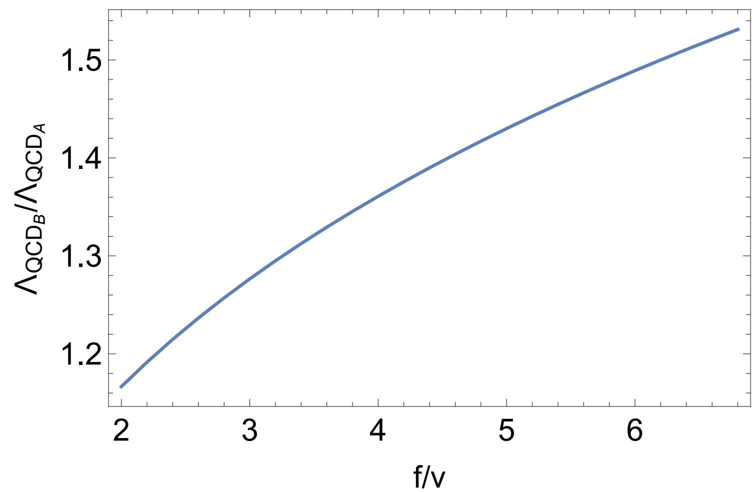
1803.03263 Chacko, DC, Geller, Tsai

Mirror Nuclear Physics

Only difference to SM is v_B/v_A

proton mass: ~30-50% higher than SM

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

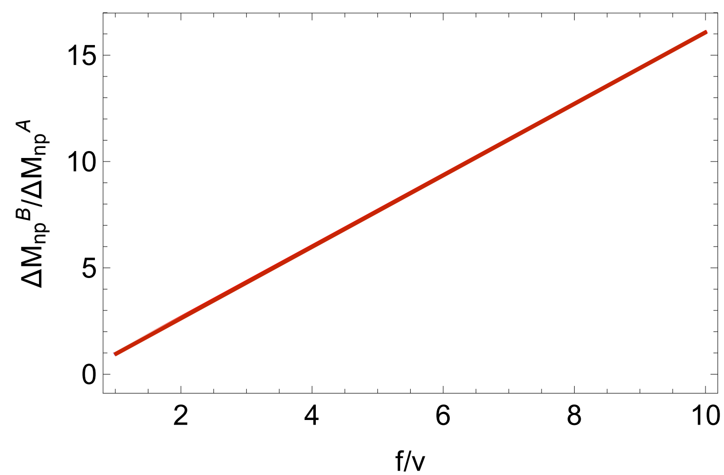


proton-neutron mass difference: ~5x SM

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

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

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

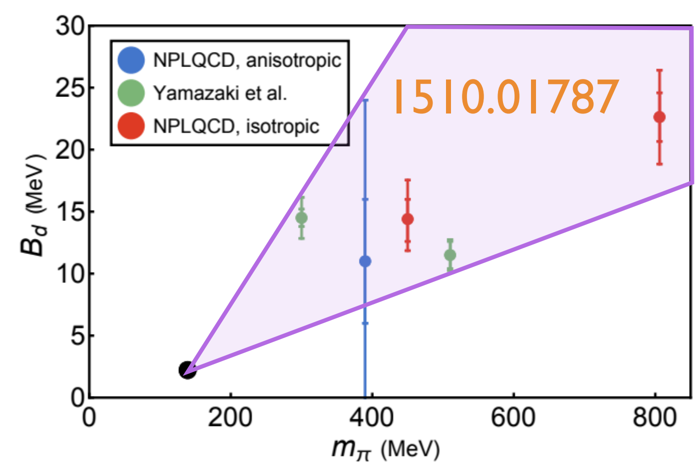


Mirror Deuteron Binding Energy

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!

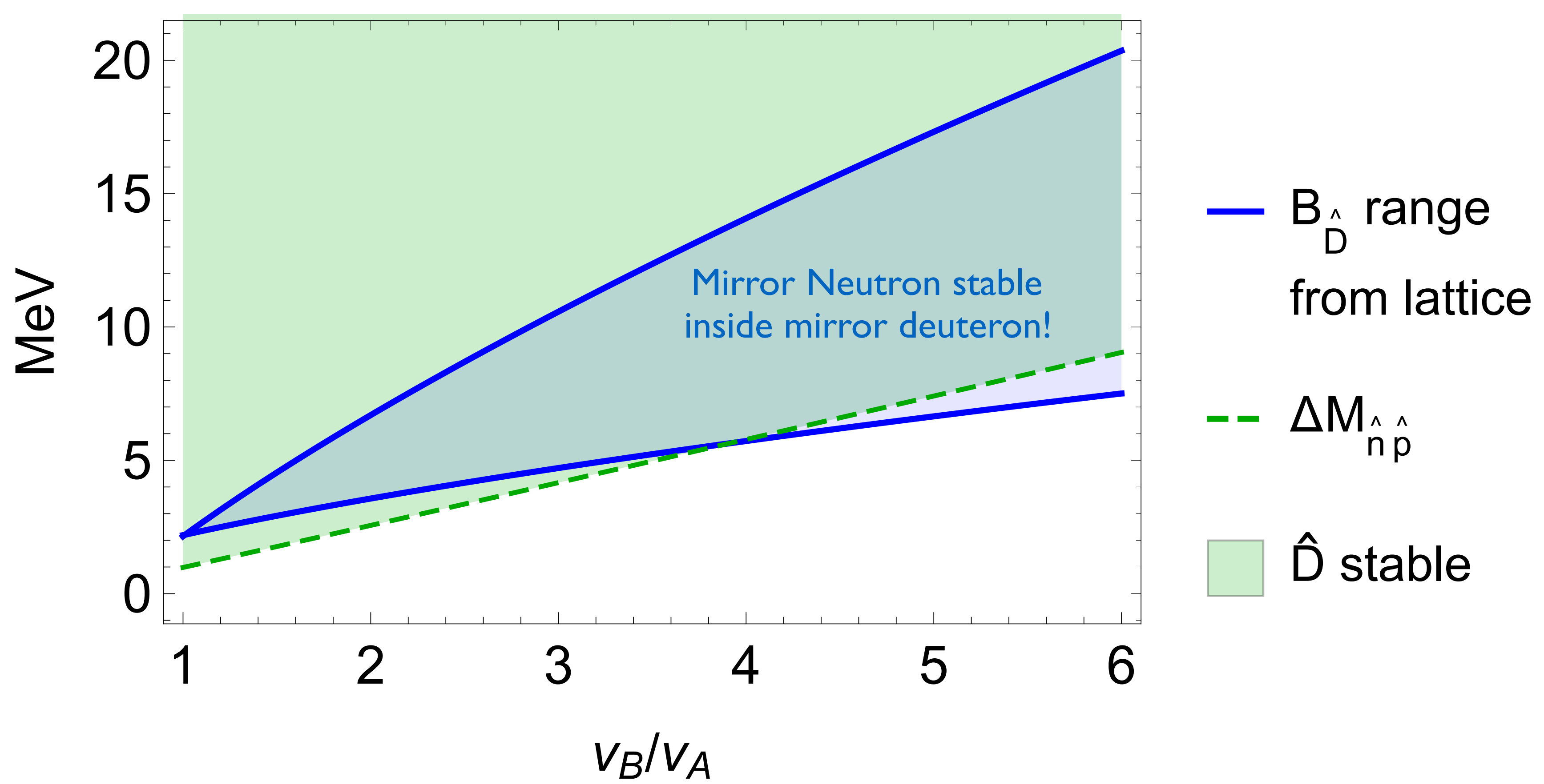
$$B_D^{\min} = -(0.66\ \mathrm{MeV}) + 0.021\, m_\pi\ ,$$
$$B_D^{\max} = -(9.2\ \mathrm{MeV}) + 0.084\, m_\pi\ ,$$



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

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

Mirror Deuteron Binding Energy



Accidental Aside: disproves "atomic principle"?

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

fun side question:
anthropics vs lattice?

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)

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

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):

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

BBN in the mirror sector

Mirror sector temperature colder as dictated by ΔNeff,

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

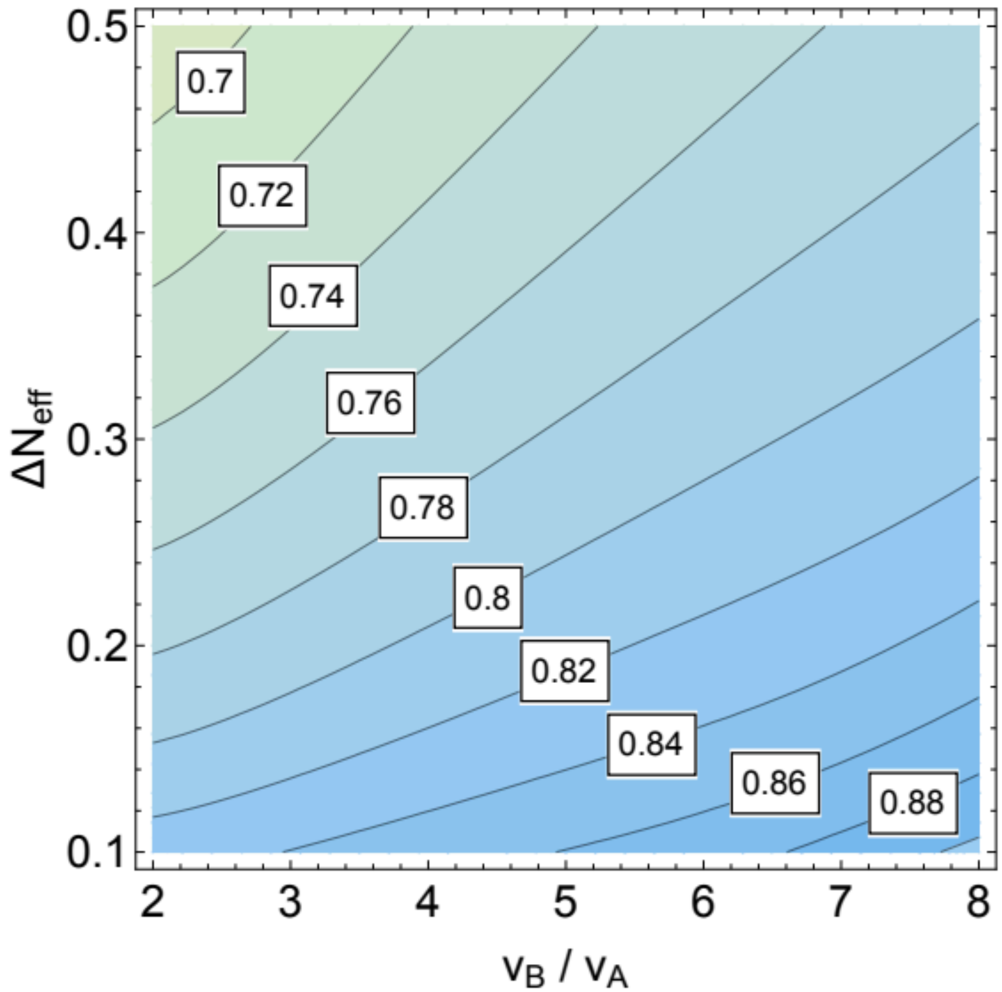
Neutron-proton freeze-out modified due to heavier W-mass and larger mass difference:
$$\Gamma_{\hat{n}} = \Gamma_n \left(\Delta M_{\hat{n}\hat{p}} / \Delta M_{np}\right)^5 \left(v_B / v_A\right)^{-4}$$

⇒ 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.

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



(SM: 0.245)

MTH BBN Prediction:

~75% Mirror Helium Mass Fraction

Asymmetrically Reheated MTH:

Large Scale Structure

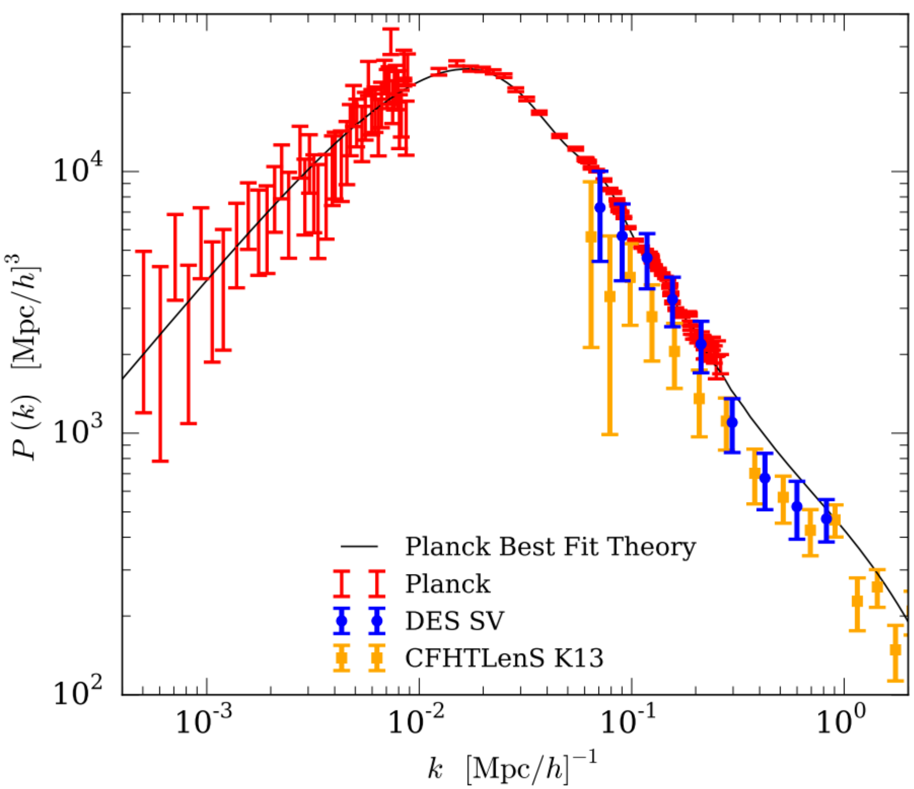
(Slides by Yuhsin Tsai)

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

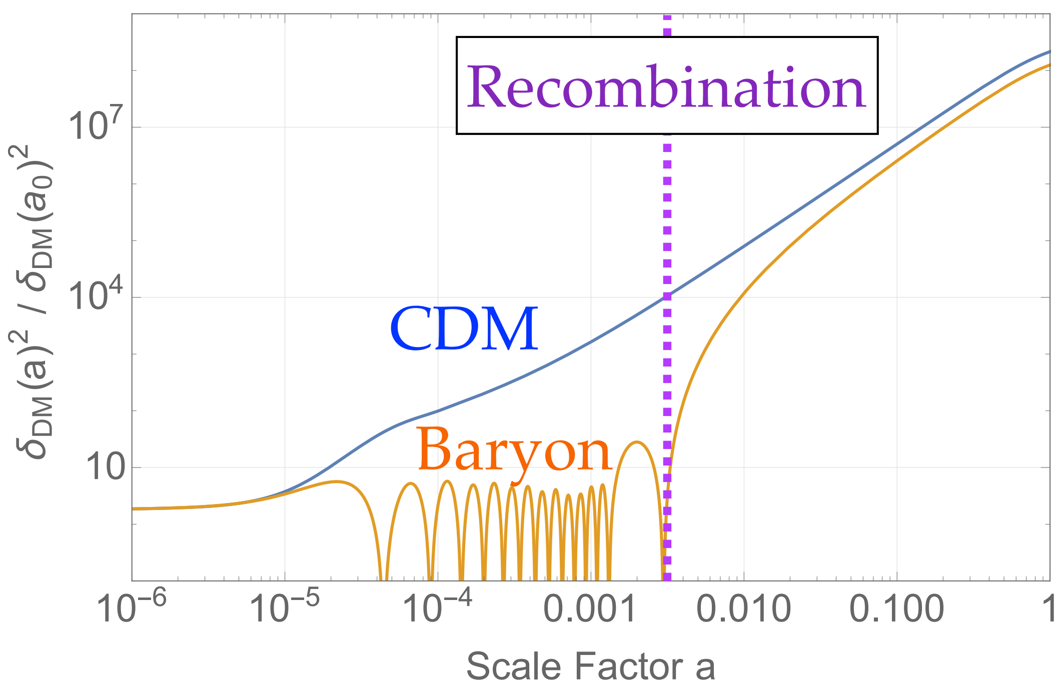
$$\delta_i \equiv \frac{\delta\rho_i}{\bar{\rho}_i} \quad i = \mathrm{DM},\ \gamma,\ b,\ \nu$$

Fourier transform into frequency modes

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

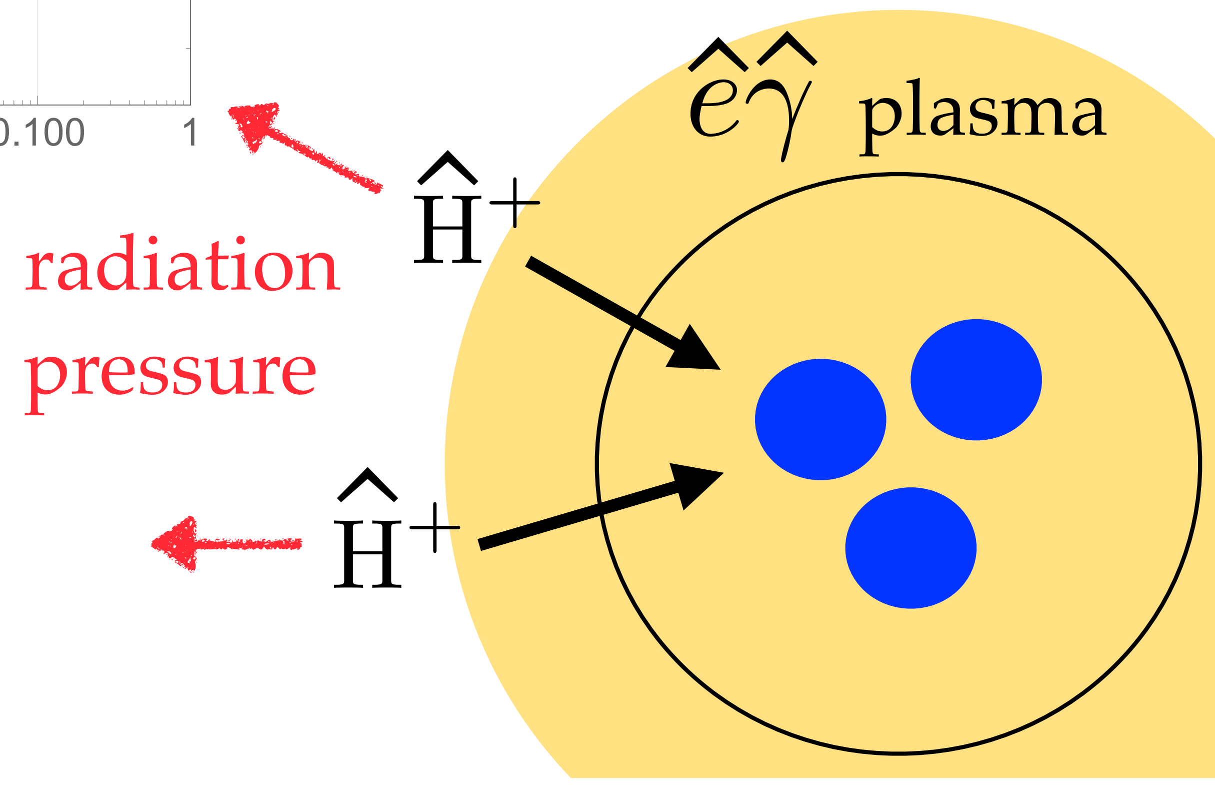
Mirror Baryon Acoustic Oscillation (BAO)

(Slides by Yuhsin Tsai)



The scattering forbids mirror baryons to form structure

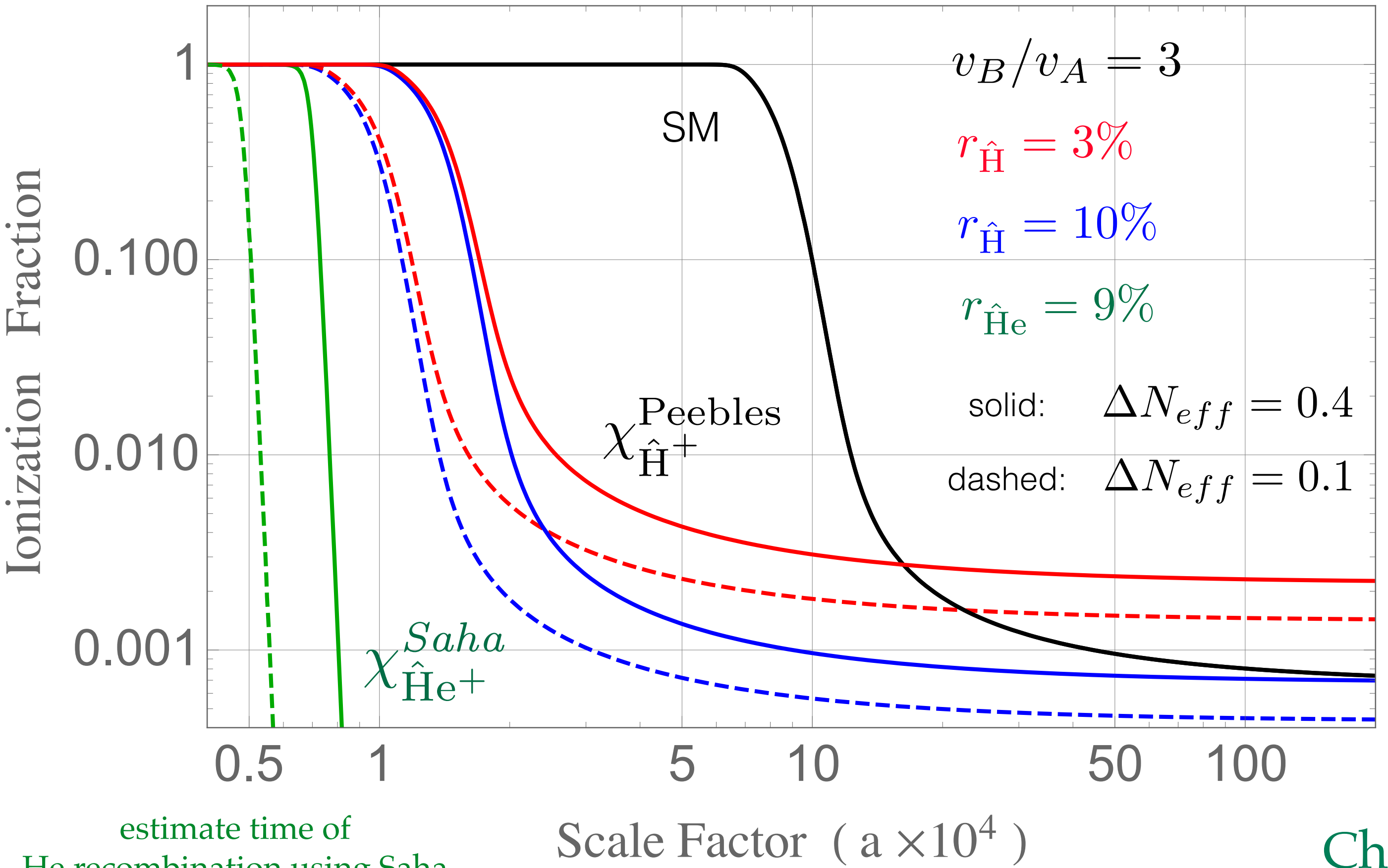
DM structure growth on scales that enter horizon prior to twin recombination is suppressed



Oscillation stops after recombination

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

Saha's eq



estimate time of
He recombination using Saha

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

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

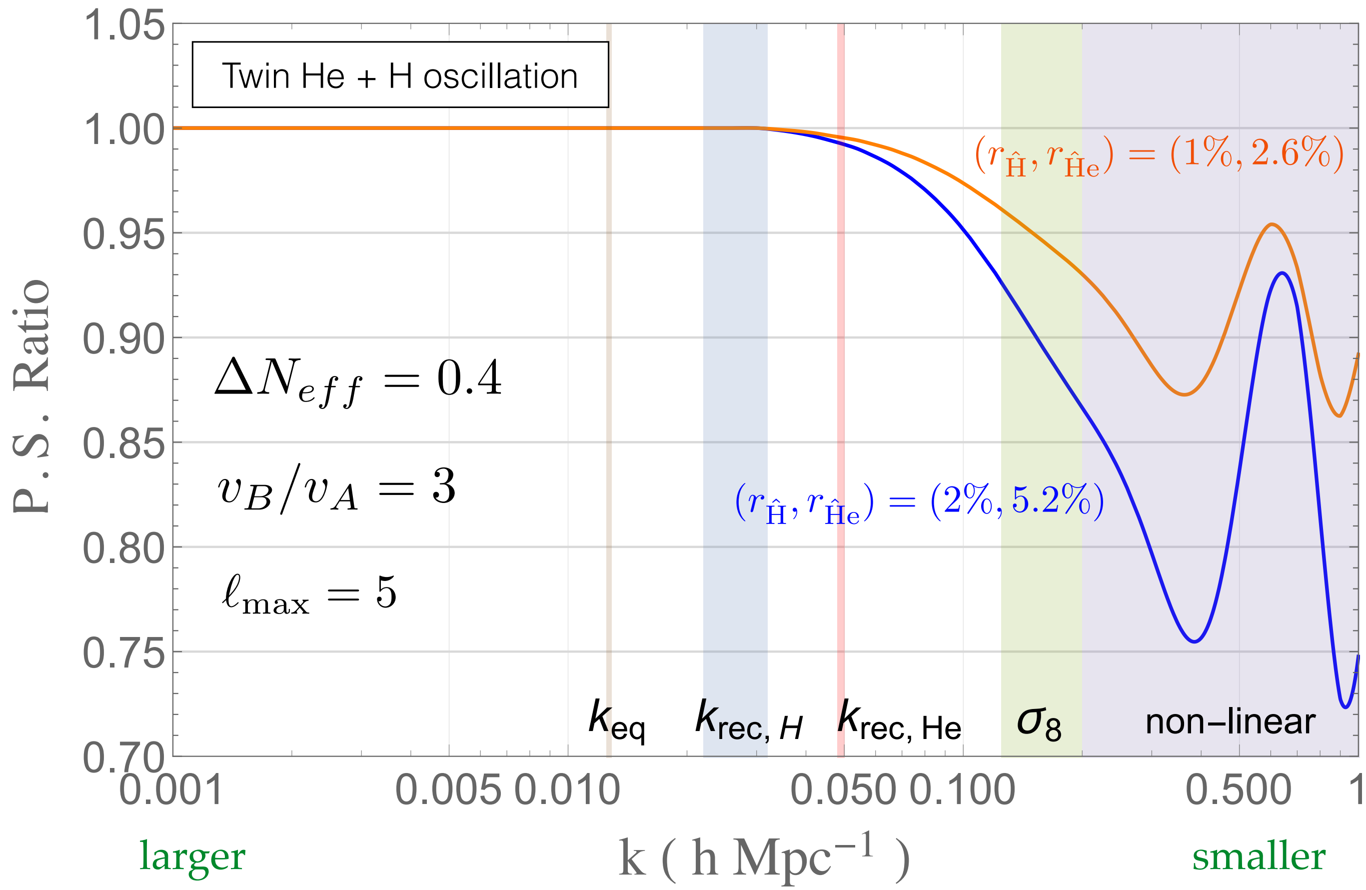
Without mirror oscillations
(keep ΔN_{eff} same by adding DR)

Twin acoustic oscillations $\longrightarrow$ P.S. Ratio < 1

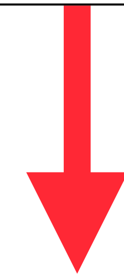
Can LSS Measurements give a constraint on the mirror DM fraction r_{all}?

(Slides by Yuhsin Tsai)

Suppression of the Large Scale Structure



Suppression due to mirror oscillations

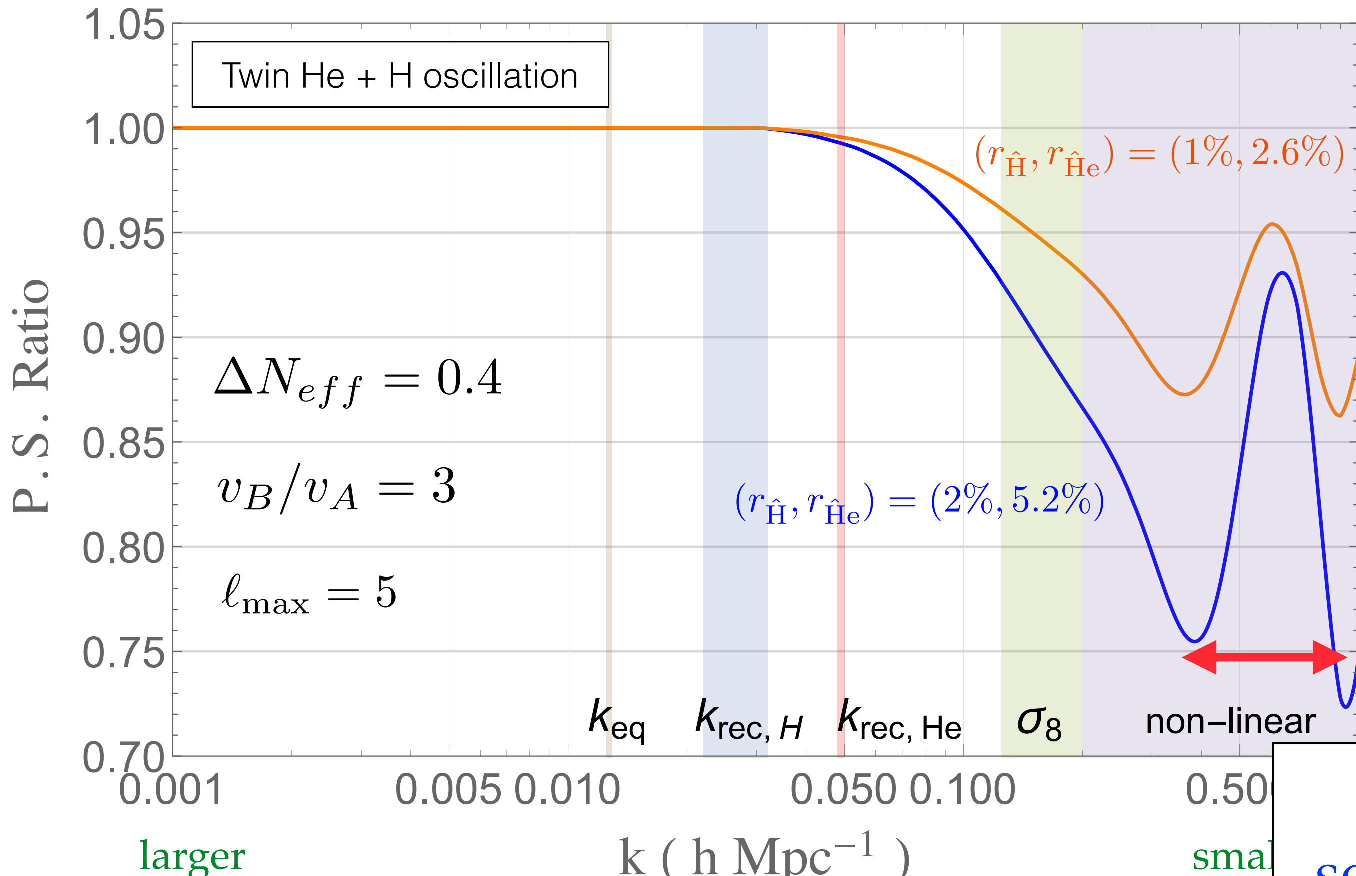


later ⟷ earlier

Horizon Entry

(Slides by Yuhsin Tsai)

Oscillation pattern



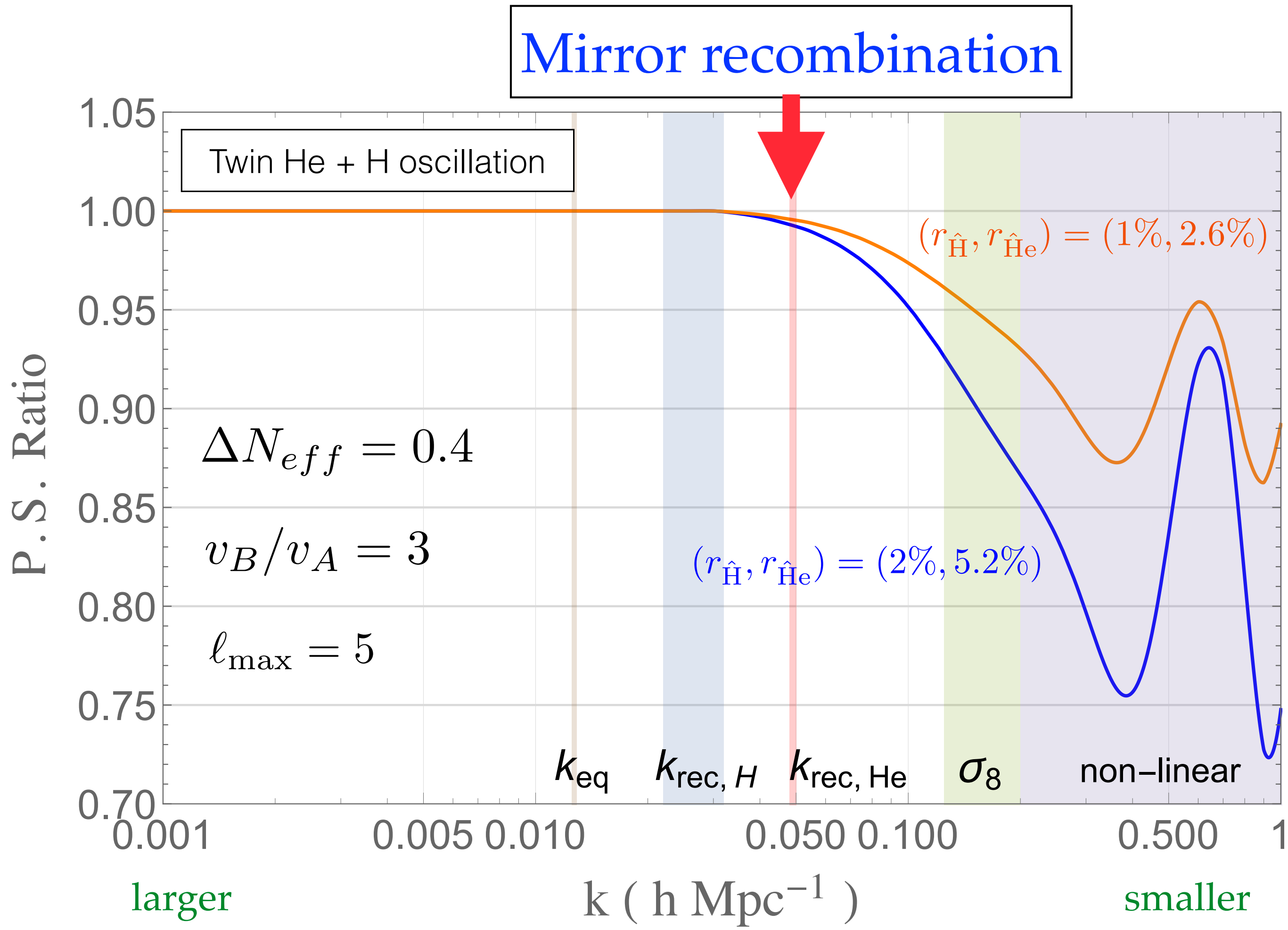
Inverse of sound horizon at recombination

later

Horizon Entry

(Slides by Yuhsin Tsai)

Behave as Cold DM after recombination



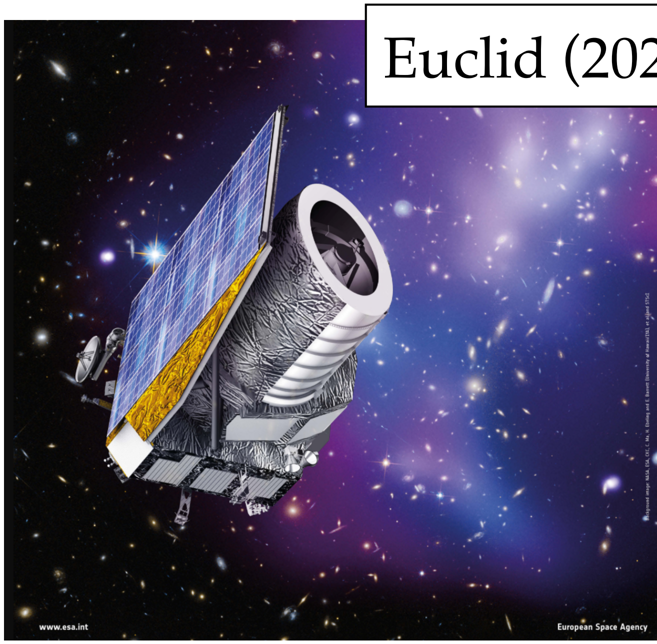
later earlier

Horizon Entry

Precision measurement of the LSS

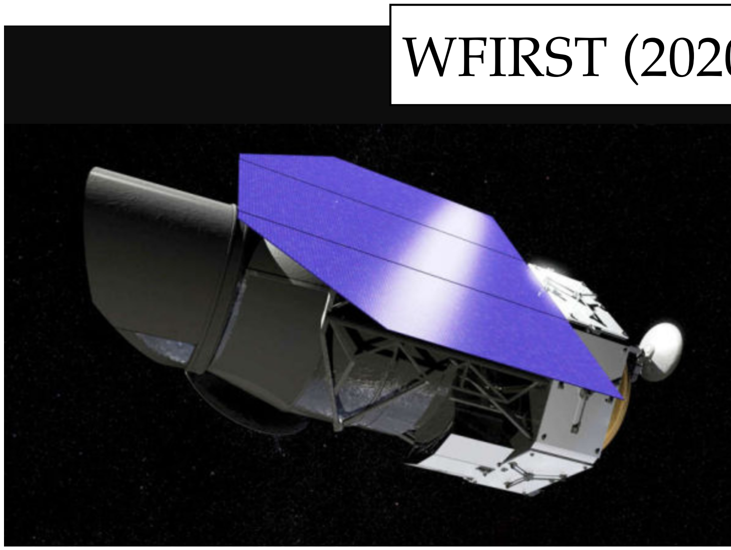
(Slides by Yuhsin Tsai)

Euclid (2020')



Precent level precision
in ~ 10 years

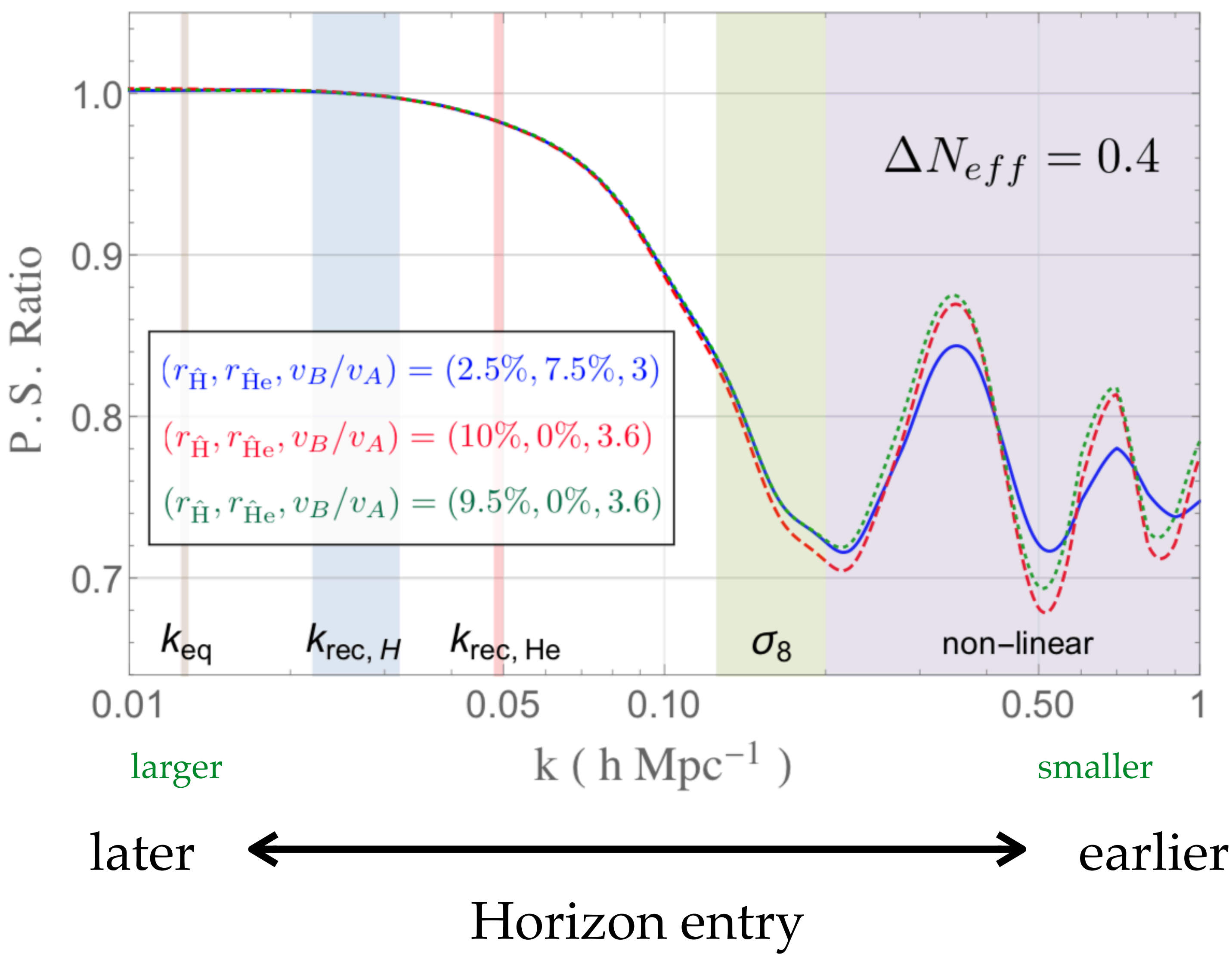
WFIRST (2020')



LSST (2019')

Large Scale Structure as dark atom spectroscopy

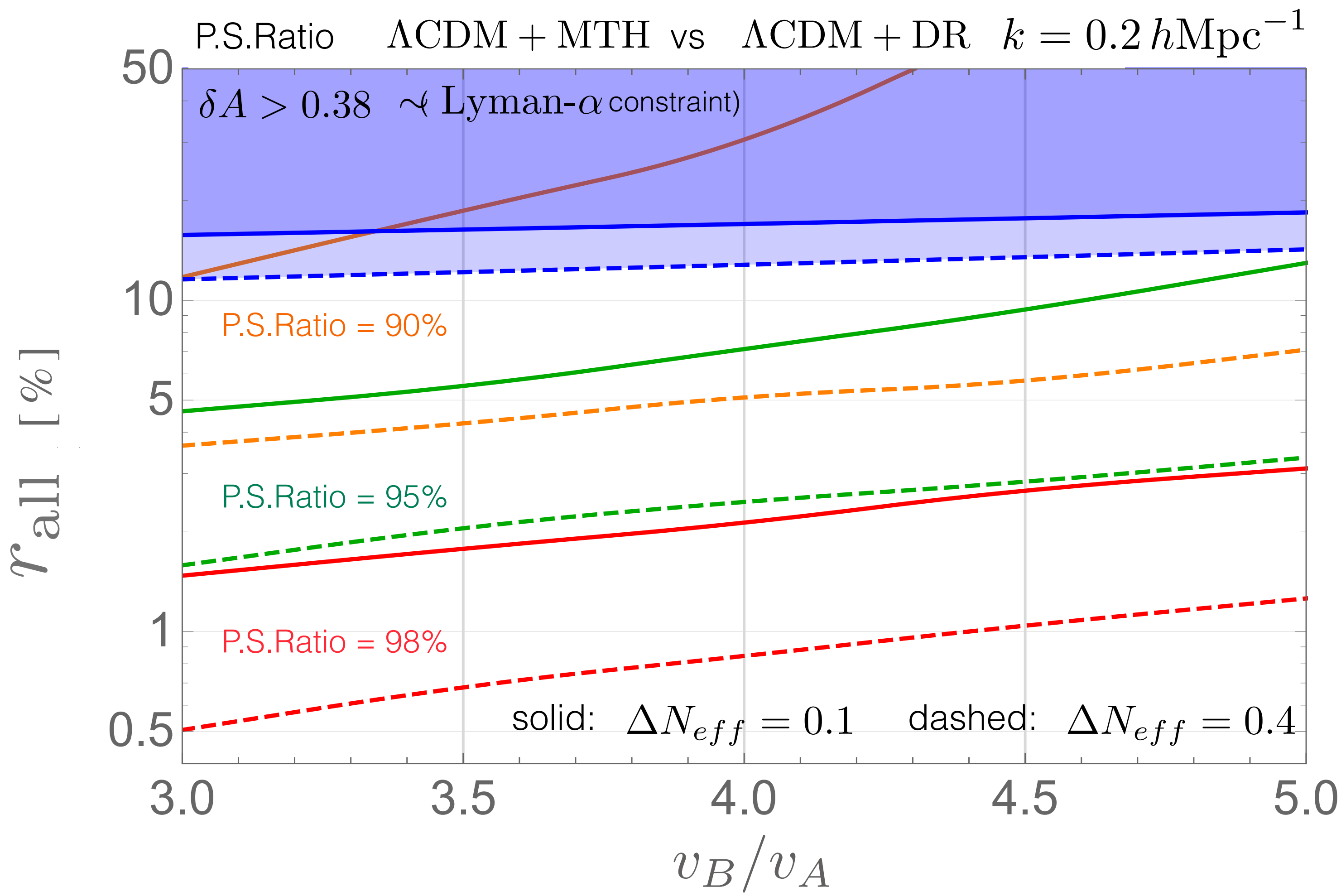
(Slides by Yuhsin Tsai)



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

LSS constraint on mirror particle density

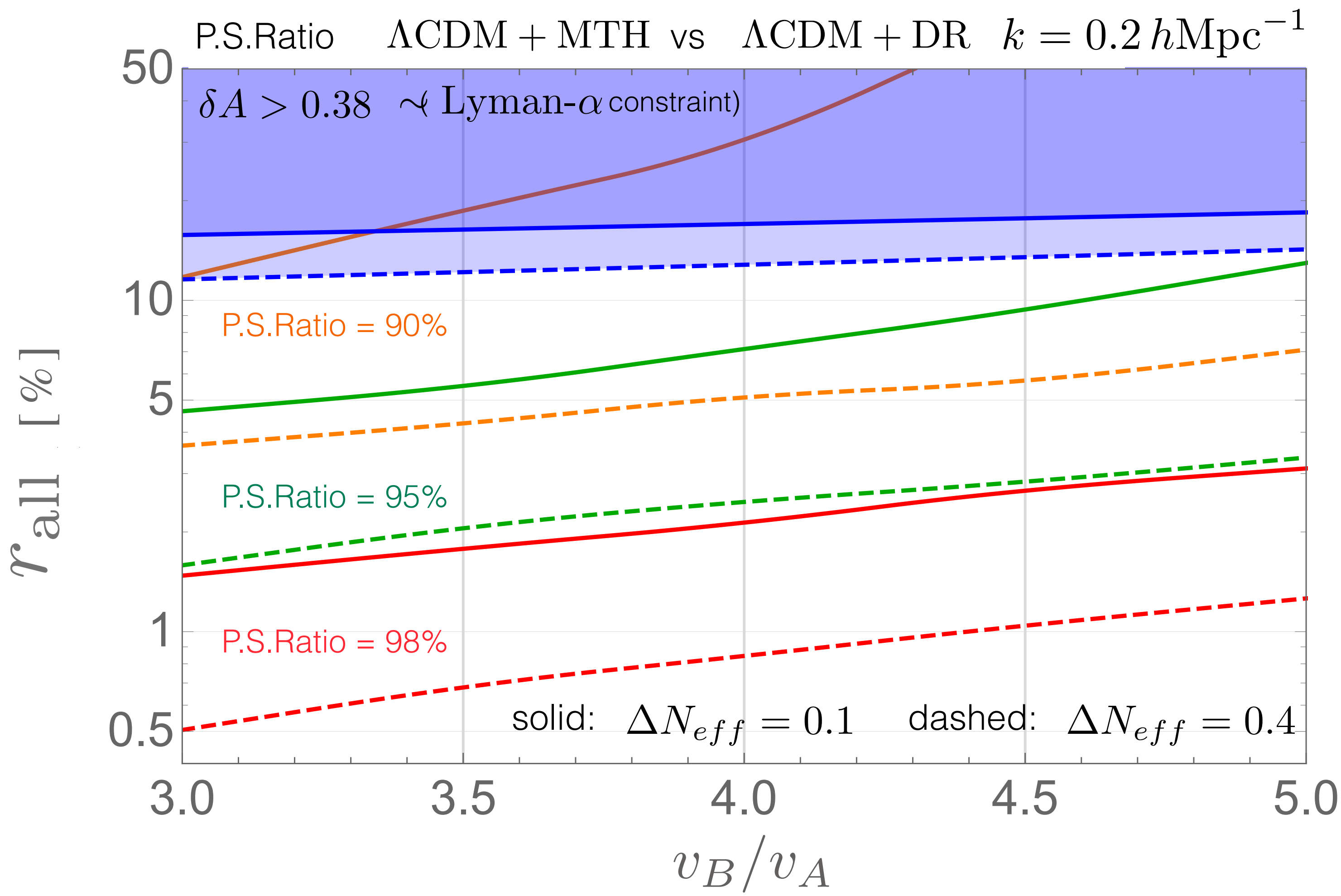
(Slides by Yuhsin Tsai)



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

Possible solution to LSS puzzles

(Slides by Yuhsin Tsai)



$\Omega_{\hat{\mathrm{H}}+\hat{\mathrm{He}}}/\Omega_{\mathrm{DM}} \simeq 5\%$ may solve the $(\sigma_8,\ H_0)$ puzzles

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($h \rightarrow$ 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

1905.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 have dissipation AND nuclear physics in the mirror sector

Mirror Baryon Distribution Today

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

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 ⟷ cannot predict mirror baryon distribution in detail for r_{all} ~ %

(See backup slides for more details)

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.

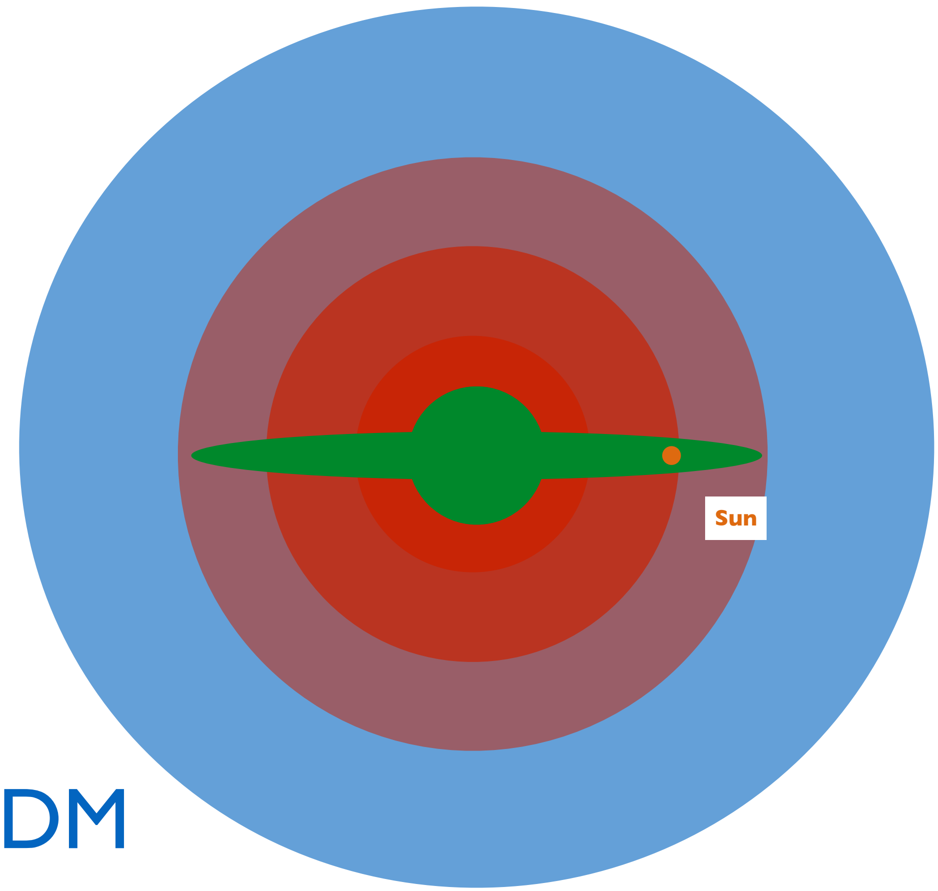
If $r_{all} > 10^{-6}$, *maybe* mirror baryons form a dark disk?

(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)

Today?

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



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

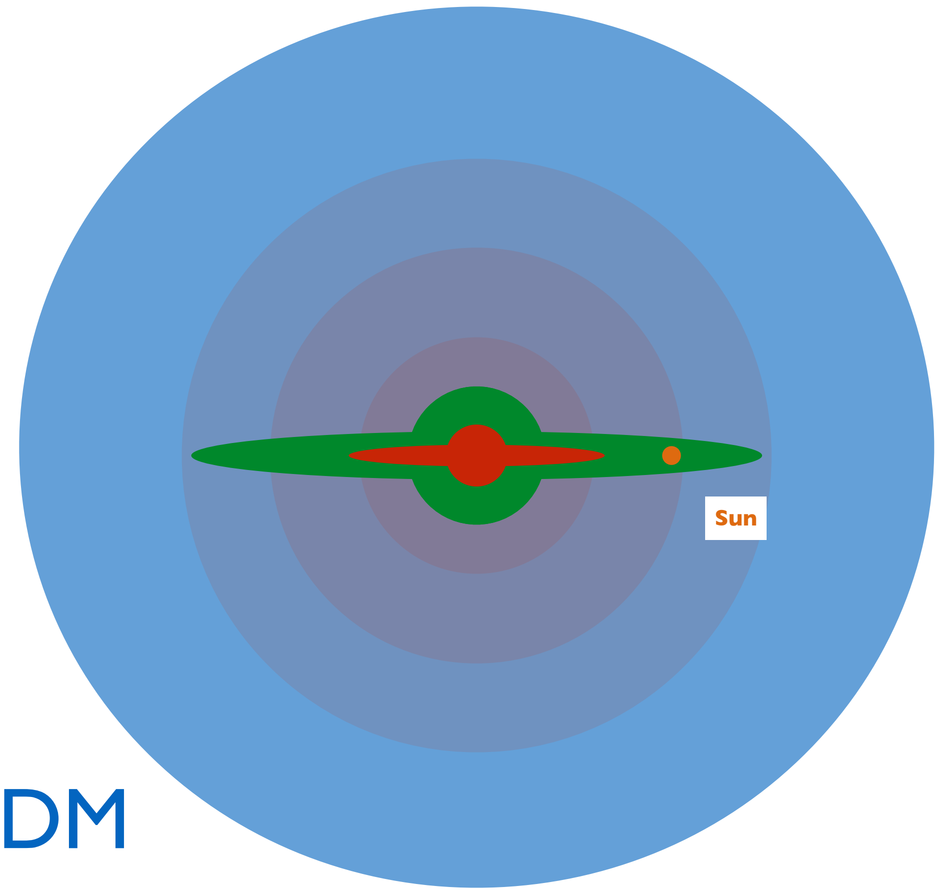
CDM

SM baryons

mirror baryons

Today?

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



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

CDM

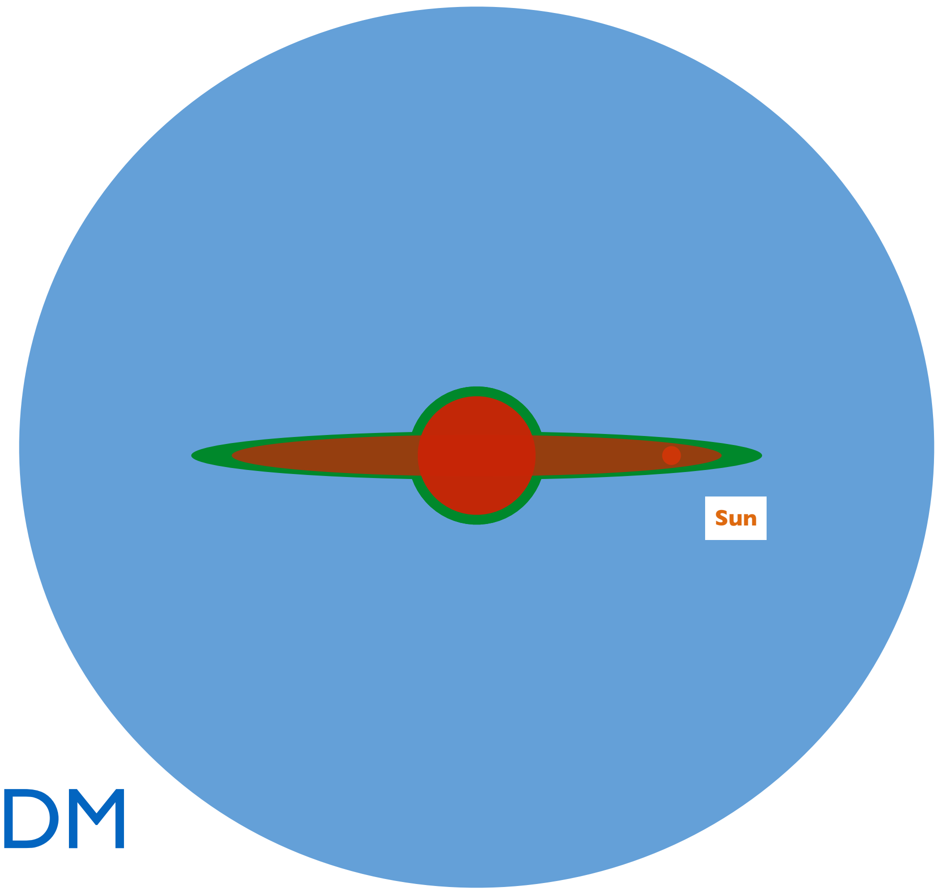
SM baryons

mirror baryons

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

Today?

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



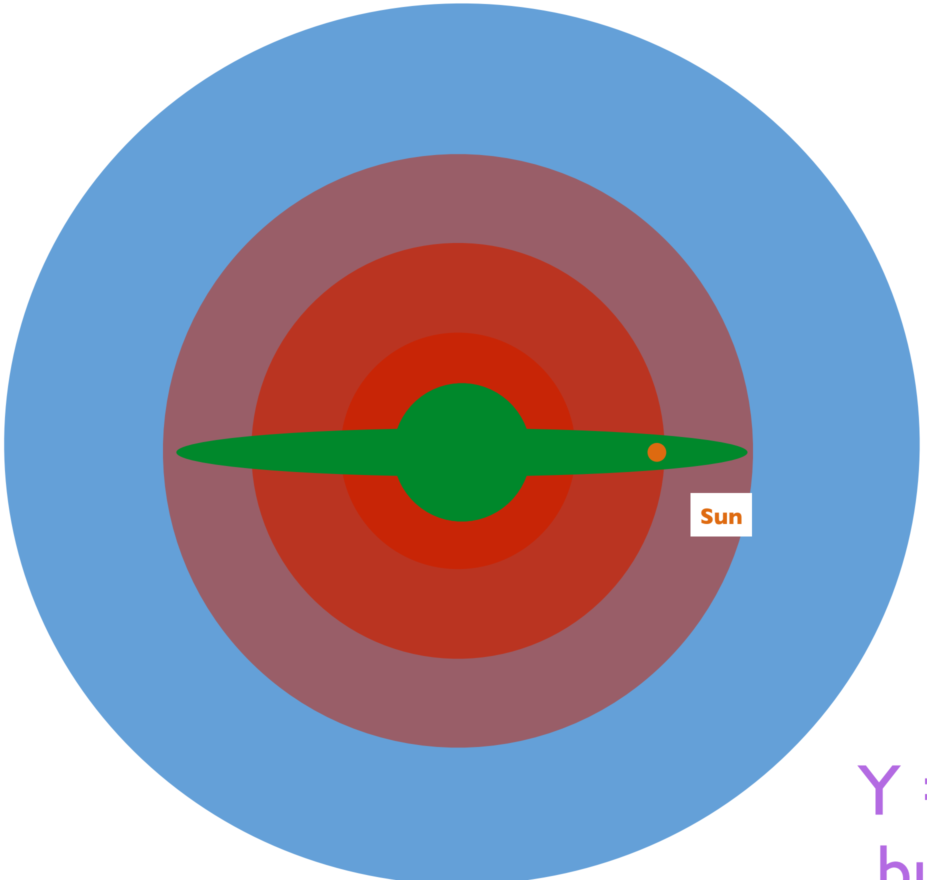
In that case, a pessimistic assumption for direct detection is v_0 ~ local stellar velocity dispersion ~ 20km/s,

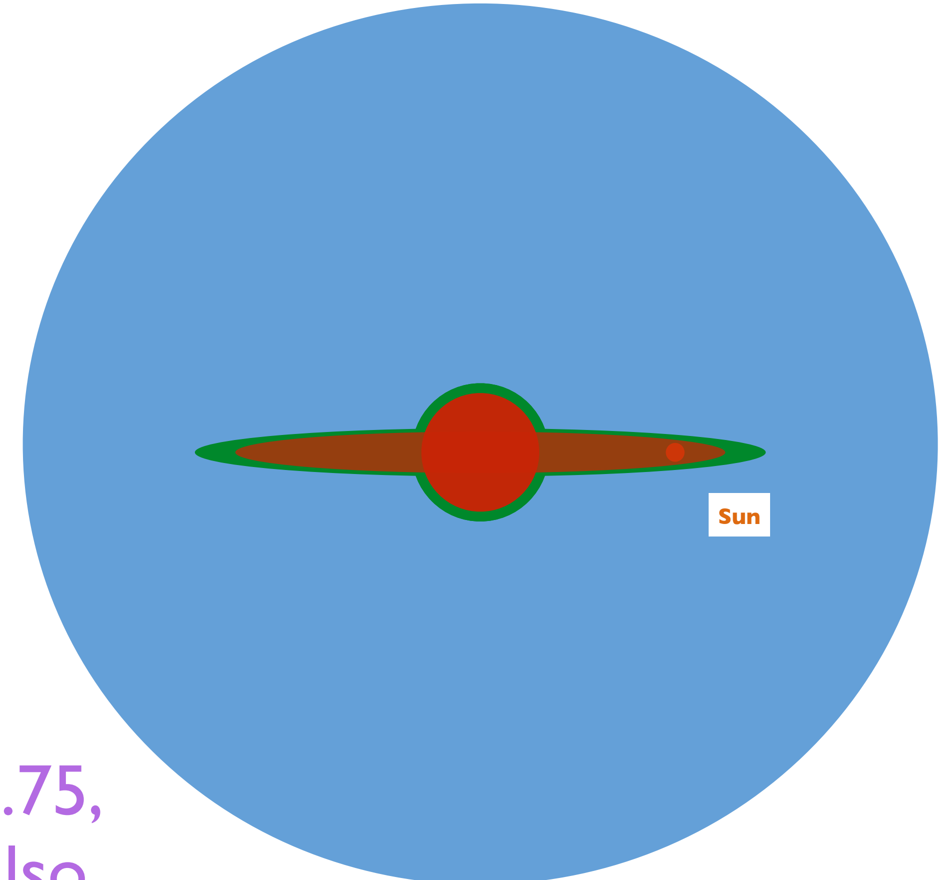
and only relative velocity of earth comes from motion around sun ~ 30km/s

CDM

SM baryons

mirror baryons





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

Probably ionized,
but also consider neutral

$Y = 0.75$,
but also
pure H &
pure He

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

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

1905.xxxxx Chacko, DC, Geller, Tsai

Where are the mirror baryons today?

A: Probably around us.

Can we detect them in DM direct detection experiments?

Could they give rise to novel astrophysical phenomena?

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

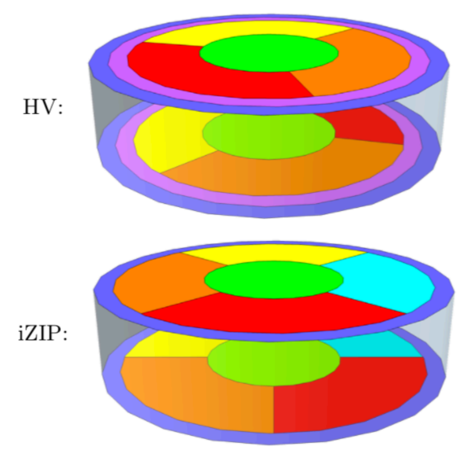
$$\frac{d\sigma_p}{dE_r} = \frac{2\pi\alpha_{em}^2\epsilon^2 Q_X^2}{m_p v_X^2 E_r^2} \,. \qquad E_r^{max} = \frac{2 m_p m_X^2 v_X^2}{(m_p + m_X)^2}$$

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}	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



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.

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

$$\Delta E_e = \vec{q} \cdot \vec{v}_X - \frac{q^2}{2\mu_{XN}} \qquad q_{\rm typ} \sim \mu_{Xe} v_{\rm rel} \sim m_e v_e \sim \mathcal{O}(\text{few} - 10\,\text{keV})$$

Mirror H, He : $E_e \sim$ few eV. Mirror e: $E_e \sim 0.1$ eV

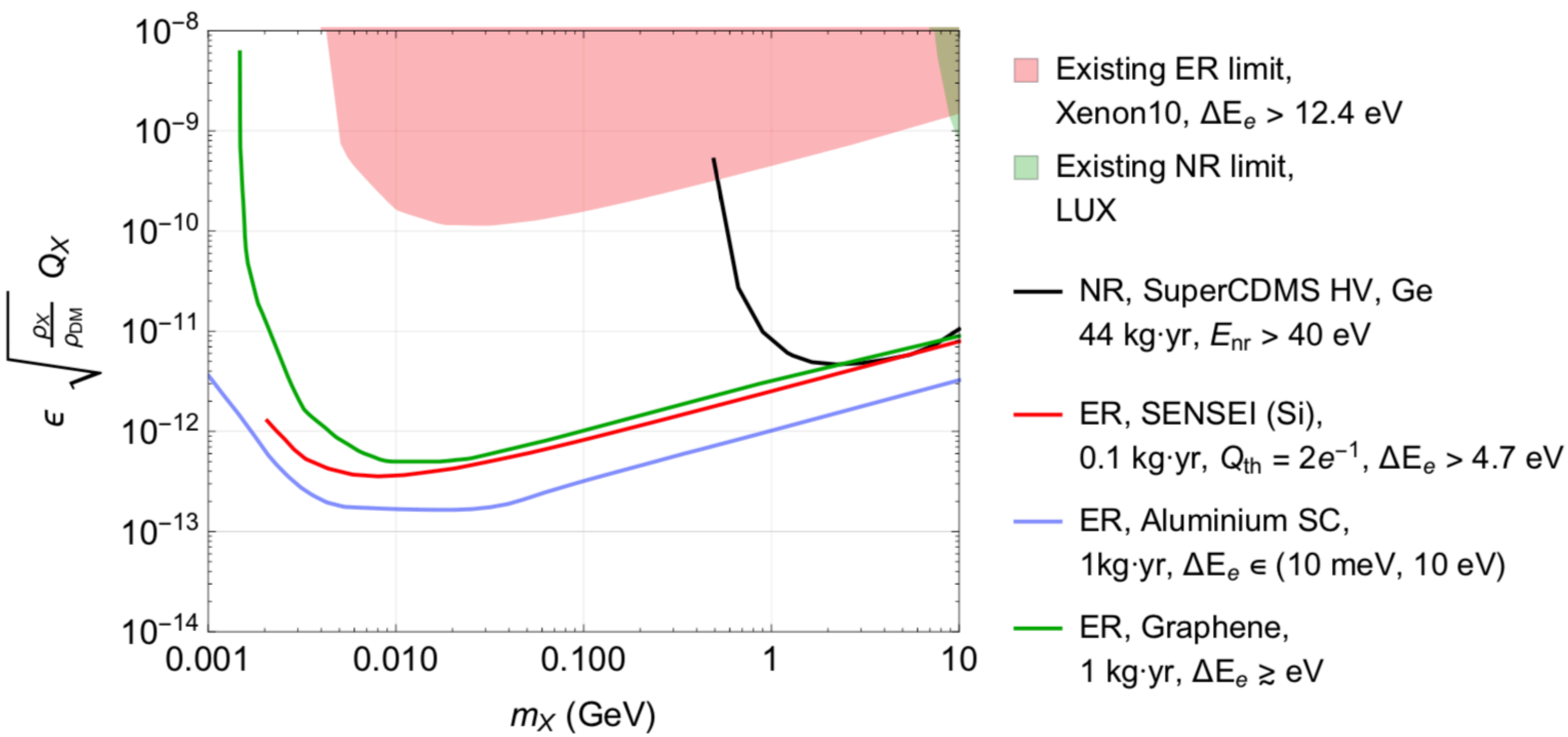
How to detect such small recoils?

- 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:

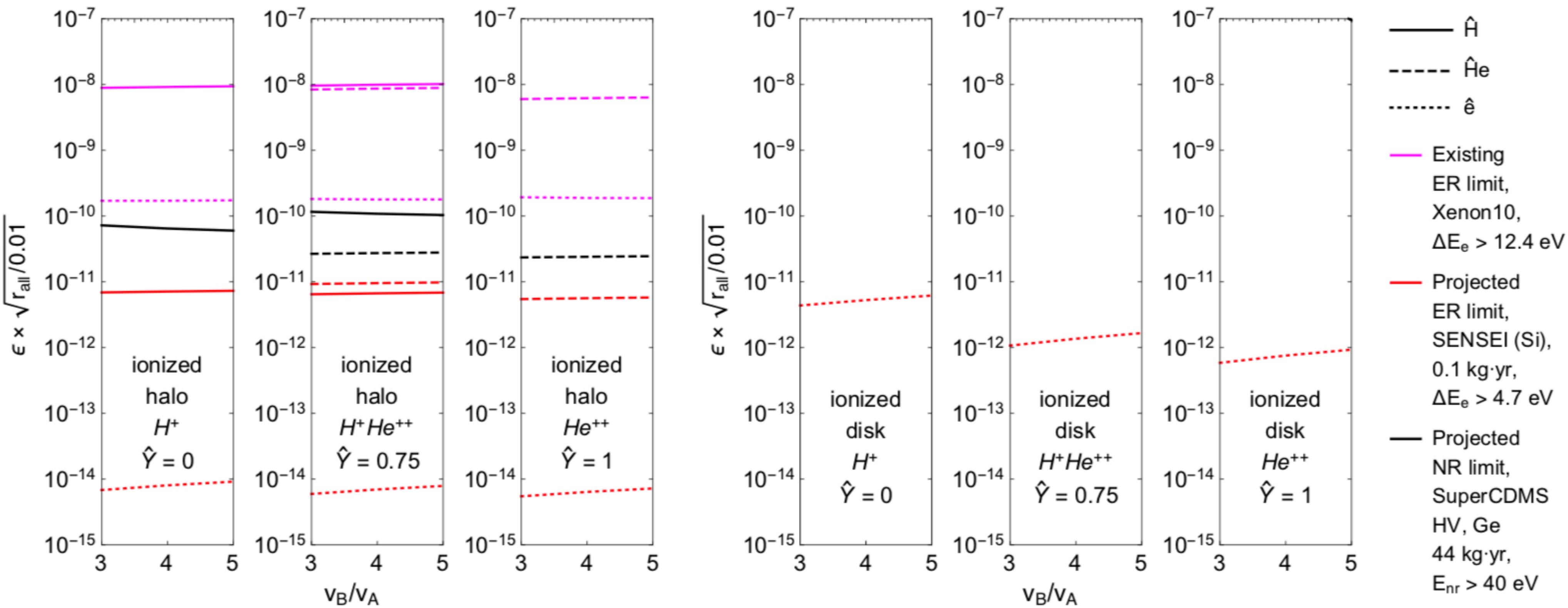
assuming local r_{all} ~ %:

	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 $\hat{\mathrm{H}}$, $\hat{\mathrm{He}}$	$\epsilon \sim 10^{-11}$	RR: no signal	$\epsilon \sim 10^{-11}$	RR: no signal
ER $\hat{\mathrm{H}}$, $\hat{\mathrm{He}}$	$\epsilon \sim 10^{-11}$	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

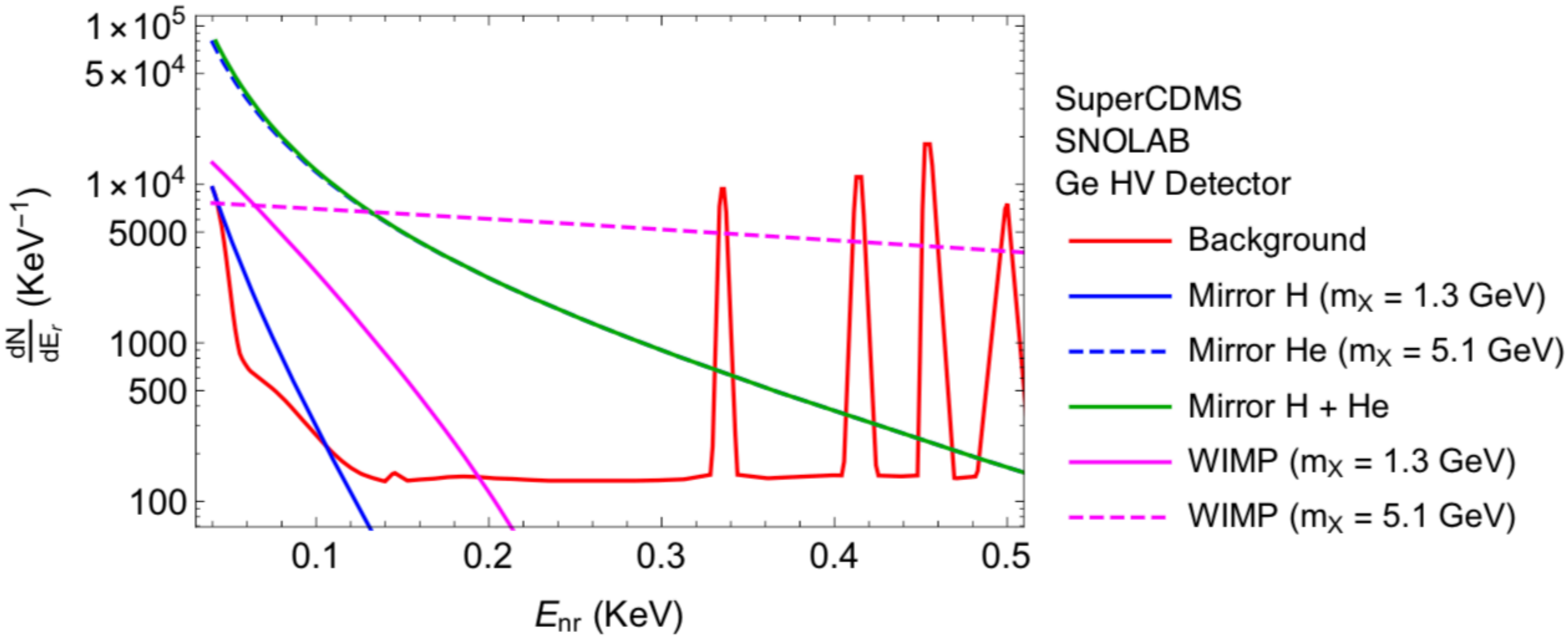


Figure 7. Recoil spectrum in the SuperCDMS SNOLAB Ge HV detector assuming ionized halo dark matter distribution. For mirror H and He, assume $r_{\rm all} = 0.01$, $v_B/v_A = 4$, $\rho_{\hat{\rm He}}/\rho_{\hat{\rm H}} = 0.75$, and $\epsilon = 3 \times 10^{-10}$. For WIMP with $m_X = 1.3(5.1)$ GeV, $\sigma_{nX}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

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