Neutral Naturalness: From Colliders to Cosmology and Astrophysics

New Physics with LLPs Workshop
15th Recontres du Vietnam 2019
ICISE, Qui Nhơn, Vietnam

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Based on
1803.03263, 1905.xxxxx Chacko, DC, Geller, Tsai
1906.xxxxx DC, Jack Setford
ongoing work with Shayne Gryba

Cảm ơn bạn
to the organizers and the ICISE center

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XV th RENCONTRES DU VIETNAM
Gặp gỡ Việt Nam lần thứ 15

Exploring Hidden Sectors

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?

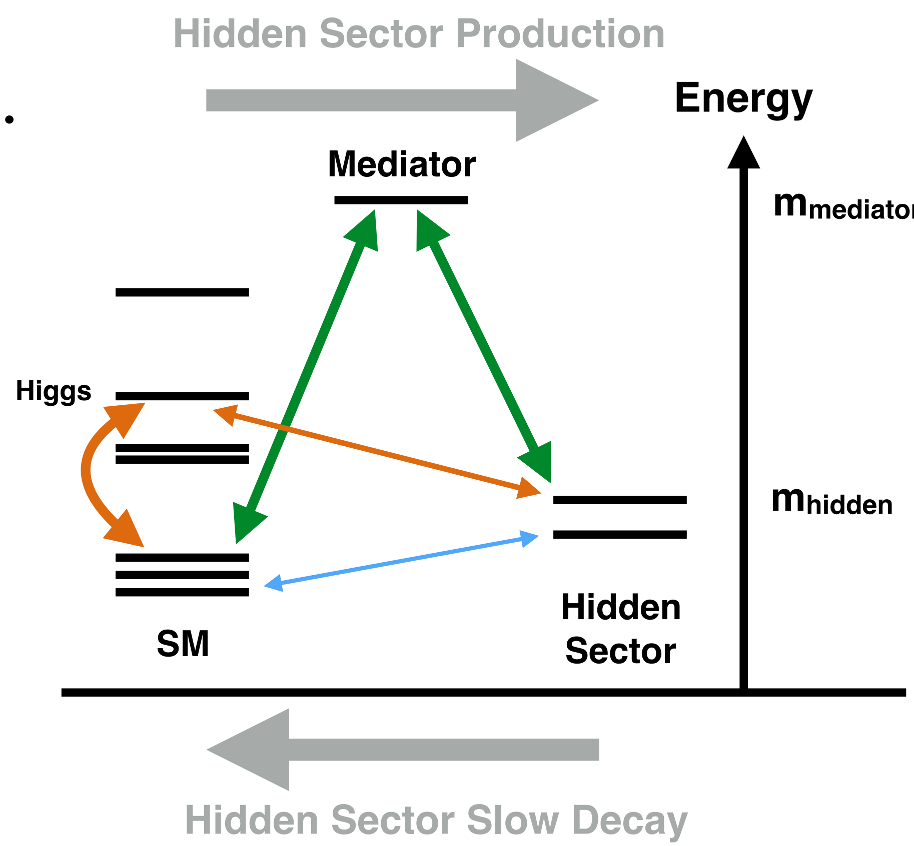
Hidden Sectors

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**

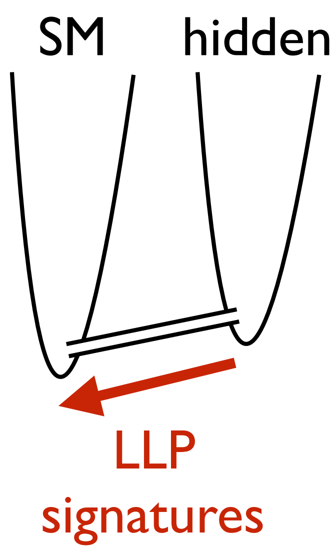
1. Exotic Higgs Decays as probes

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

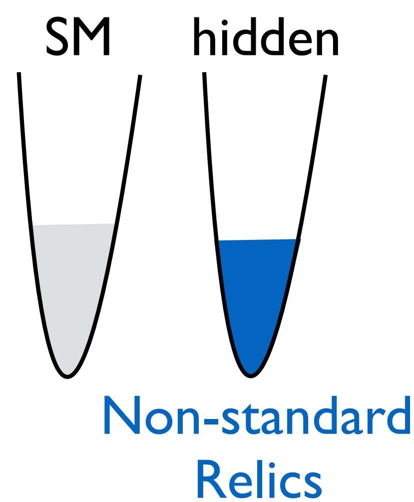
Once produced, Hidden Sector states can only decay back to SM via small portal couplings, generically leading to long lifetimes.
The LLP lifetime is (almost…) a free parameter!

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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Sizable Higgs Portal co

2. Long Lived Particle

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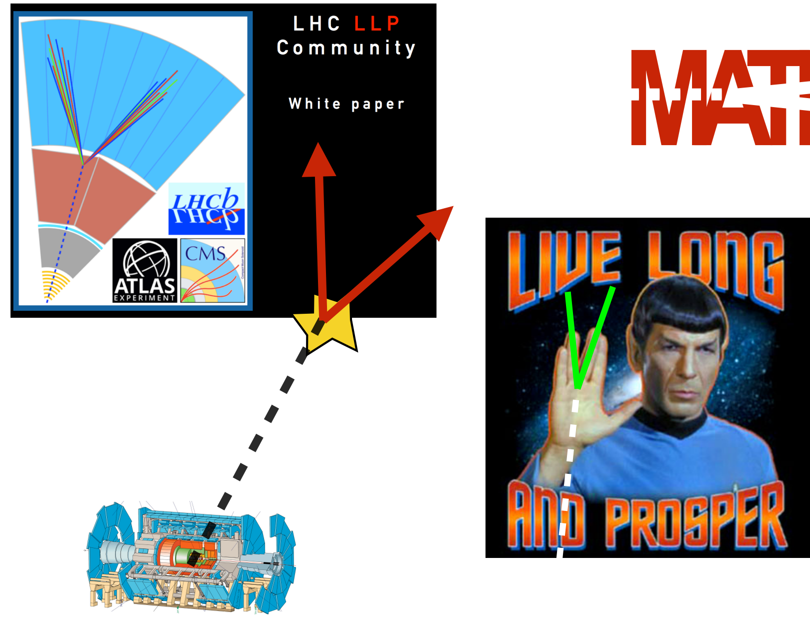

MATHUSLA
FASER
CODEX-b
...

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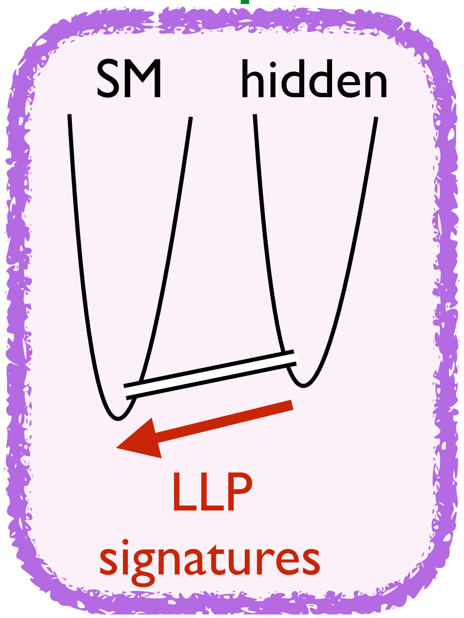

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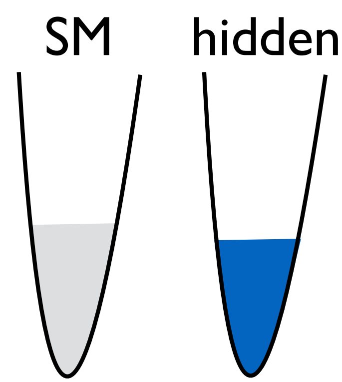

Non-standard
Relics

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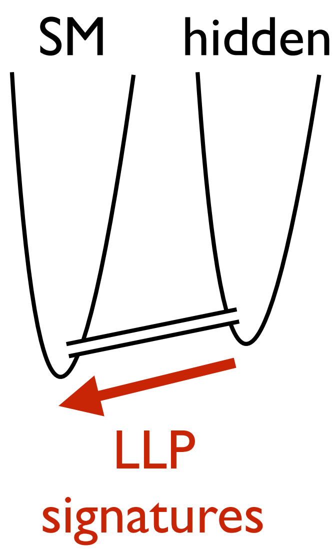

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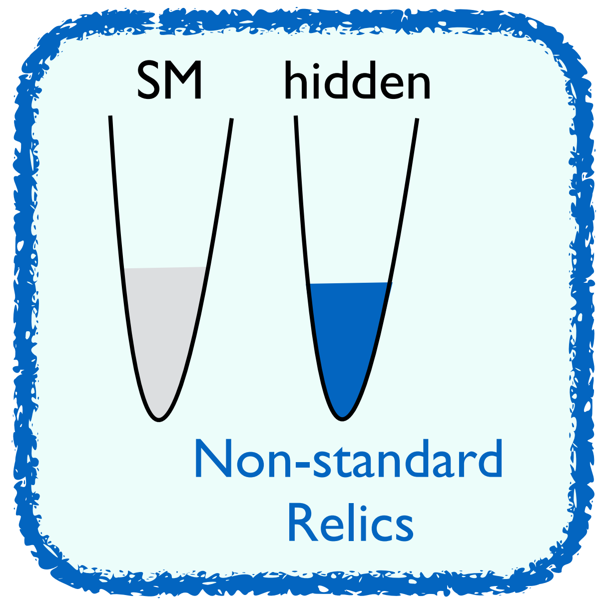


Big Picture I

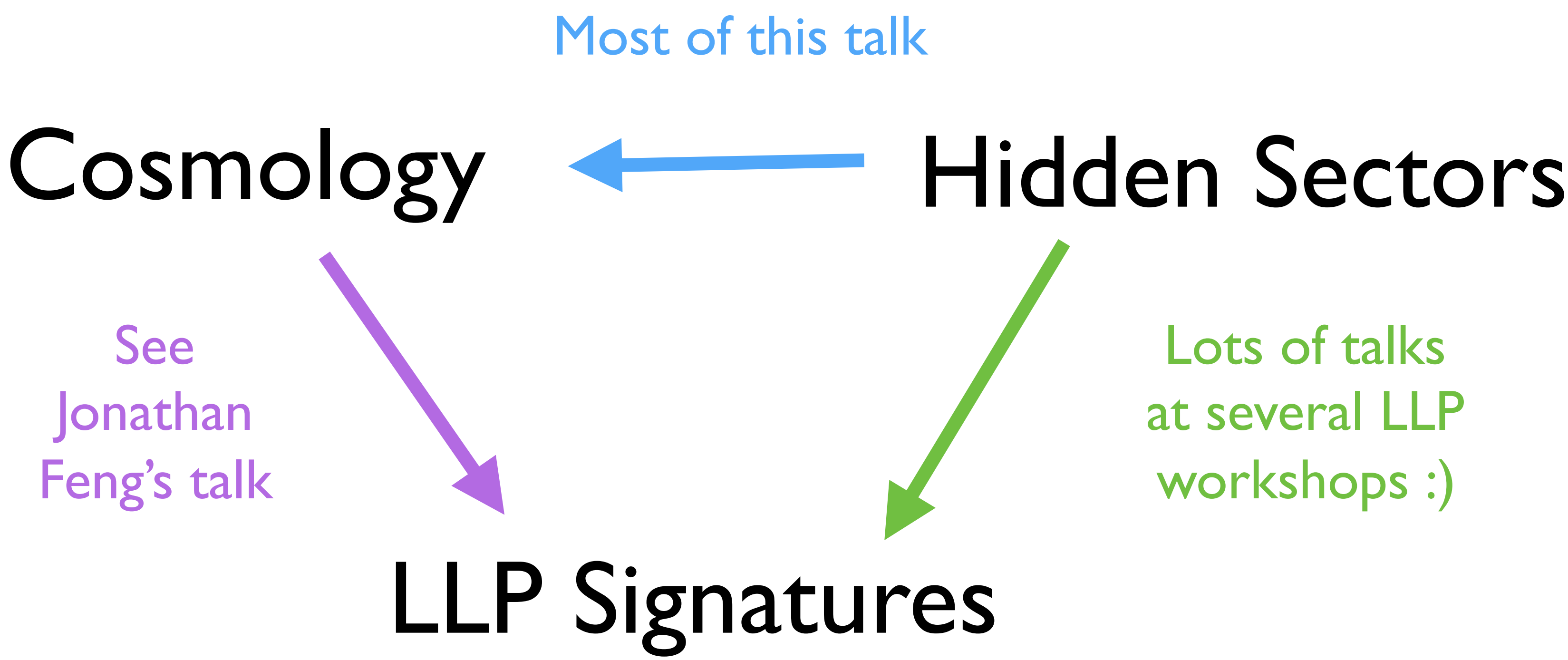
Hidden sectors can give rise to
"arbitrarily" rich cosmology and astrophysics.

Can we make this predictive?

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

→ "signature generator" of
complex hidden sector phenomena

Big Picture II



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

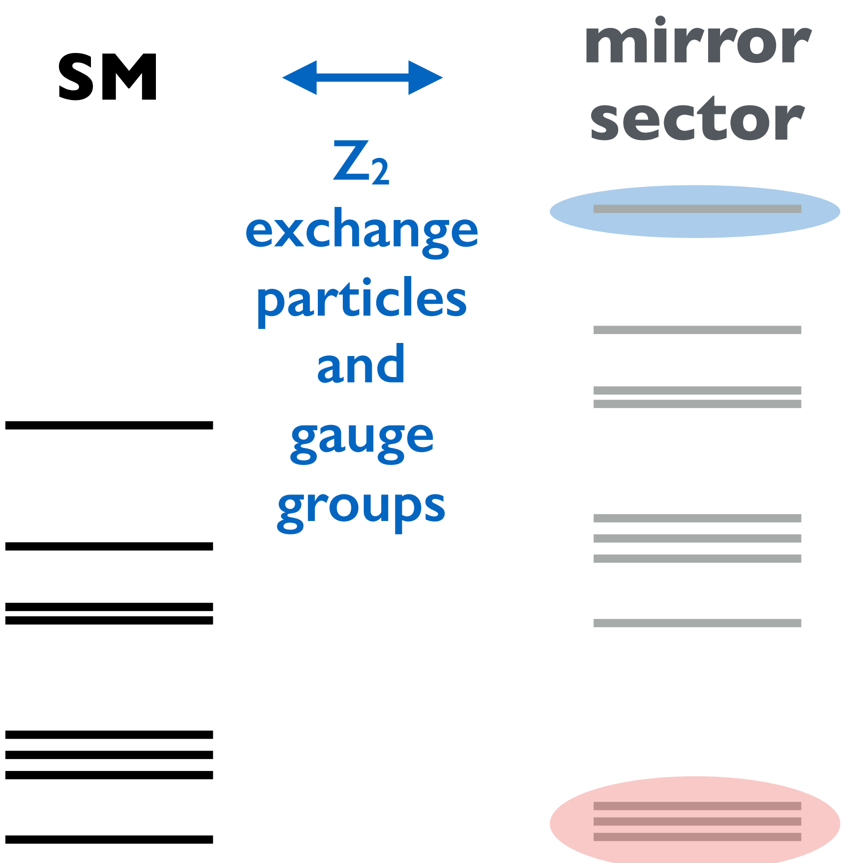
Higgs sector: SU(4), broken by Gauge + Yukawa interactions to $SU(2)_A$ x $SU(2)_B$ x Z_2, which generate mass for goldstone boson.

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

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: $v_B/v_A > \sim 3$

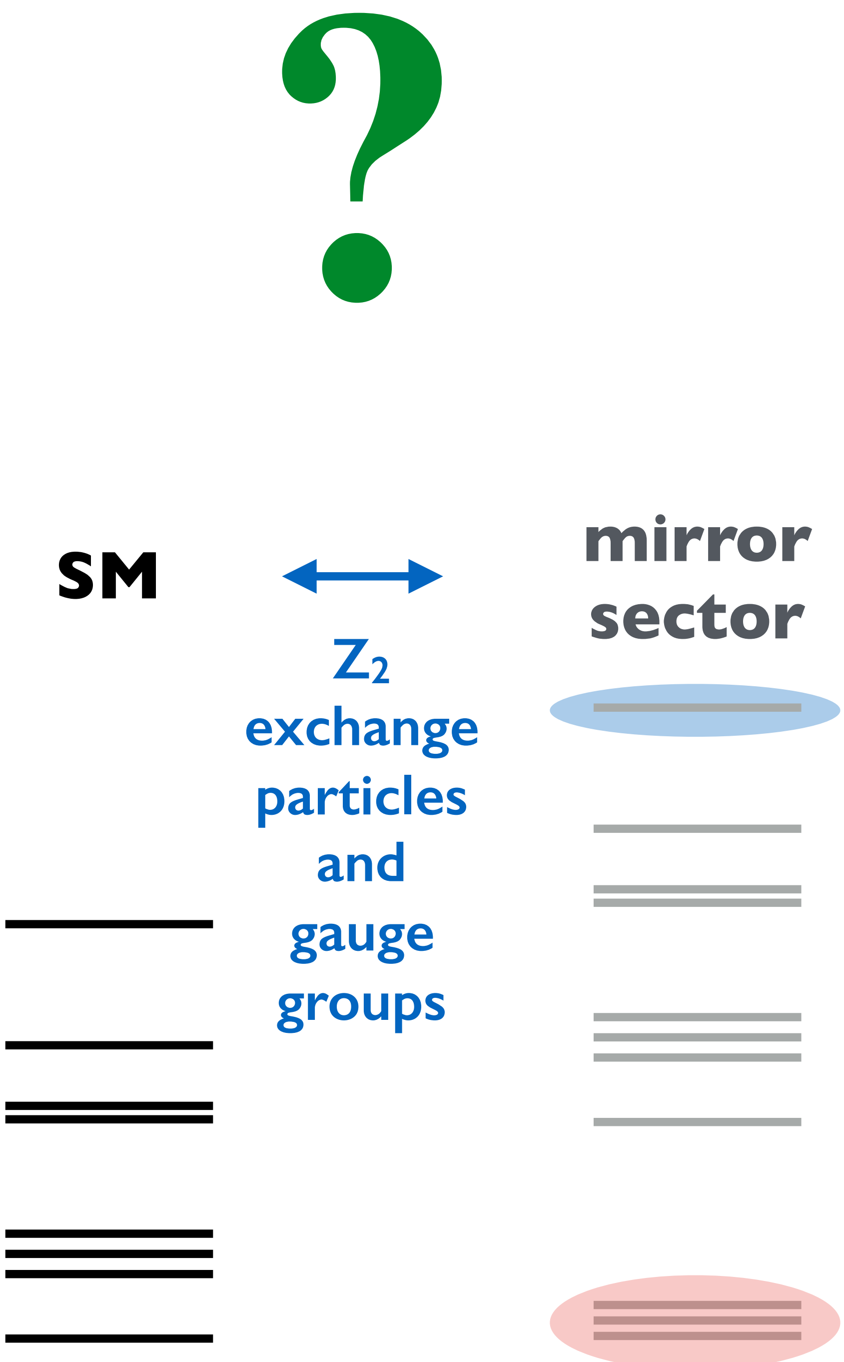
This requires tuning ~ $(v_B/v_A)^2$ ~ Br(h→mirror)

Uncolored top partners.

Massless degrees of freedom: (twin photon, neutrinos)

⇒ ΔN_{eff} ~ 5

Minimal model incompatible with cosmology.



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Uncolored top partners.

Massless degrees of freedom: (twin photon, neutrinos)

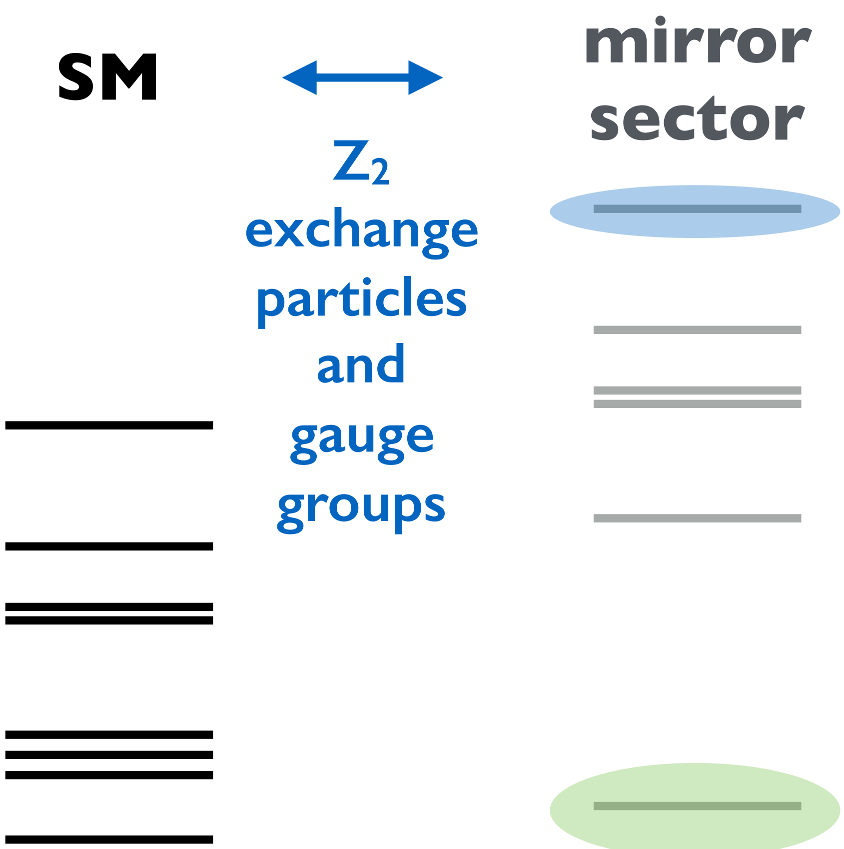
$\Rightarrow \Delta N_{eff} \sim 5$

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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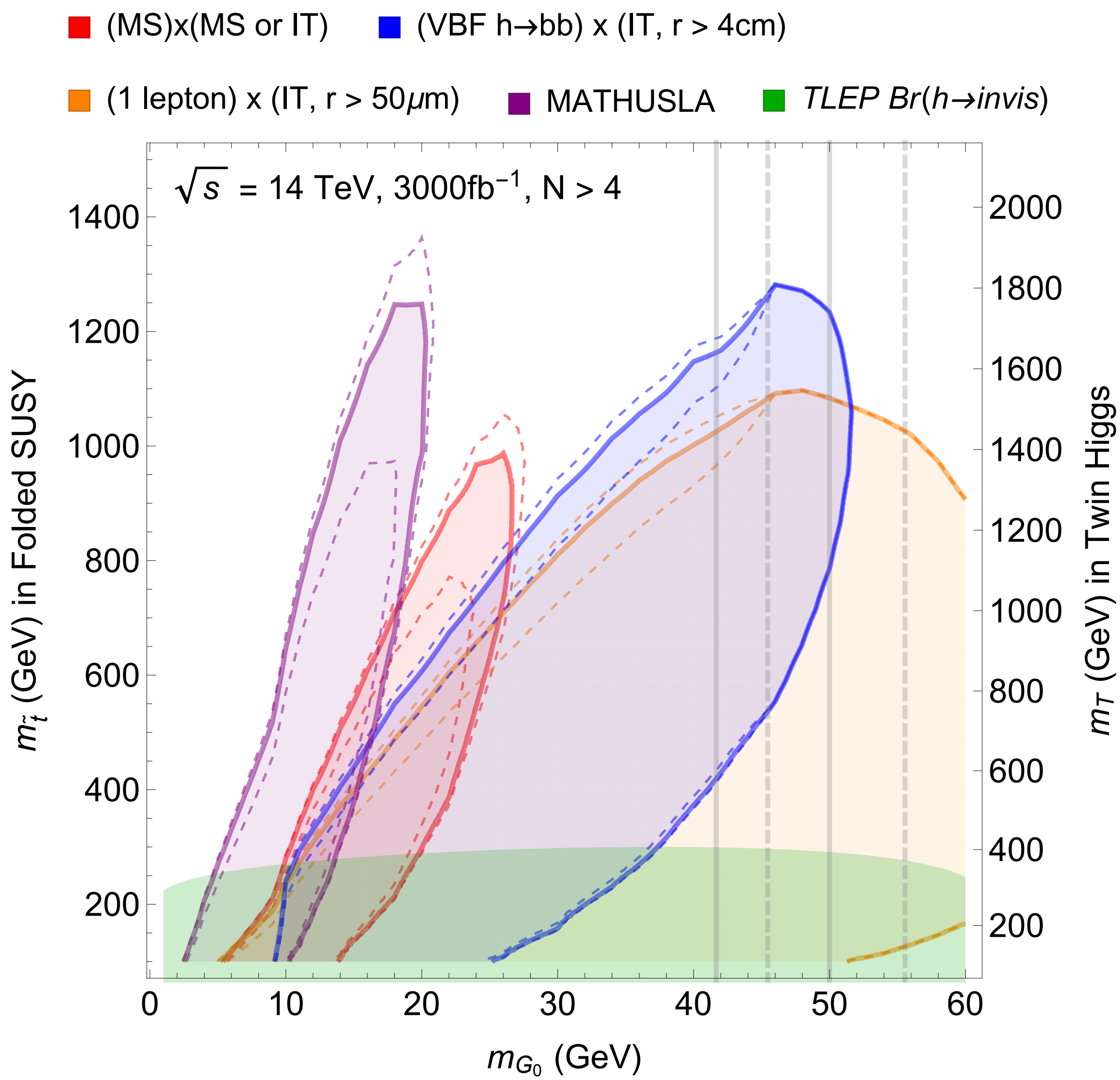
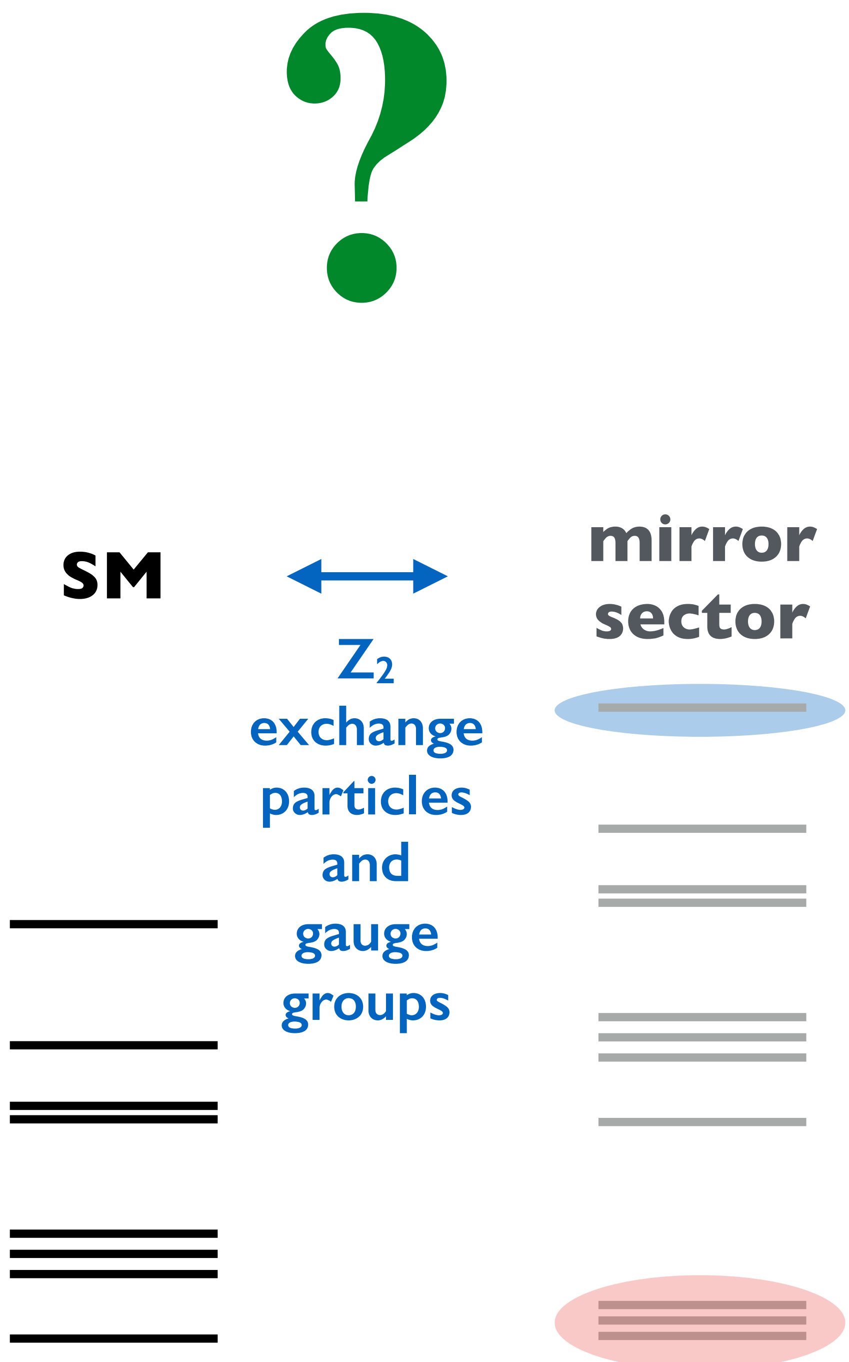
LLPs @ LHC!



DC, Verhaaren 1506.06141

MATHUSLA Physics Case White Paper 1806.07396



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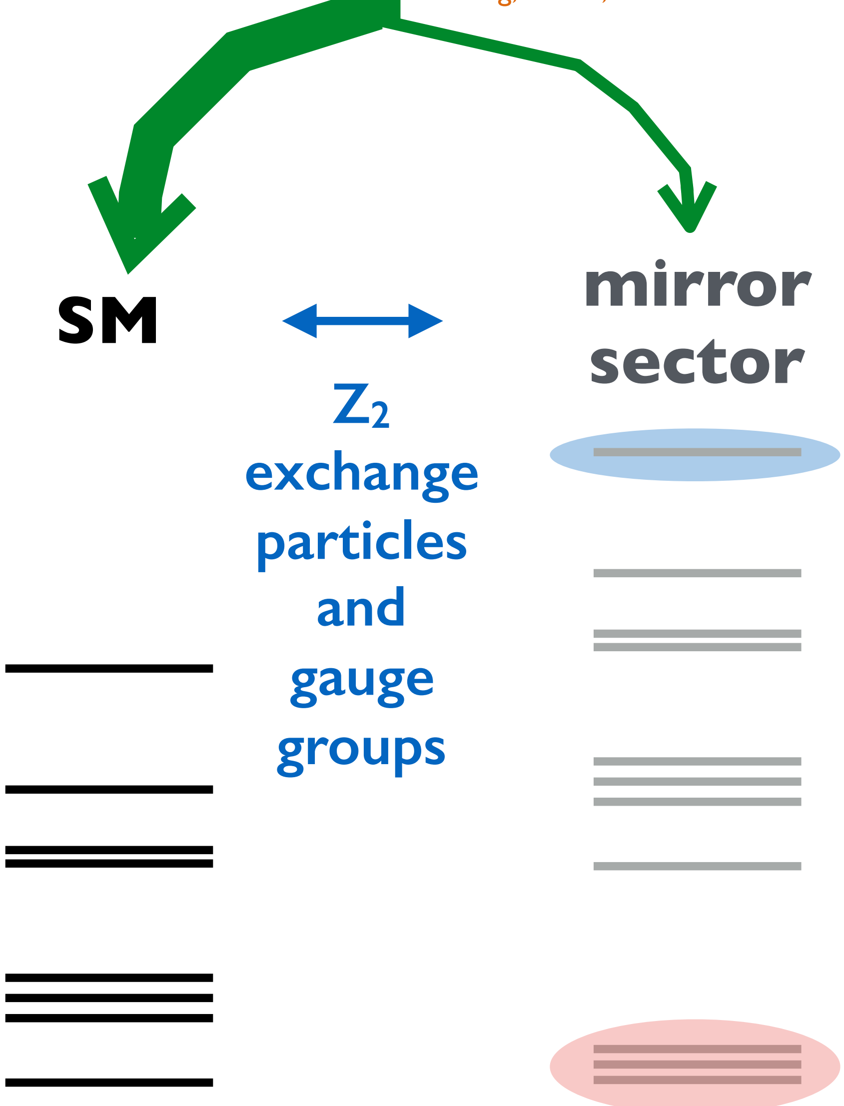
Fix 2: dilute mirror sector cosmological abundance: **Asymmetric Reheating!**

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



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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!**

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

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

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

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

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

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]*

1803.03263 Chacko, DC, Geller, Tsai

Asymmetric MTH Cosmology

- 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%

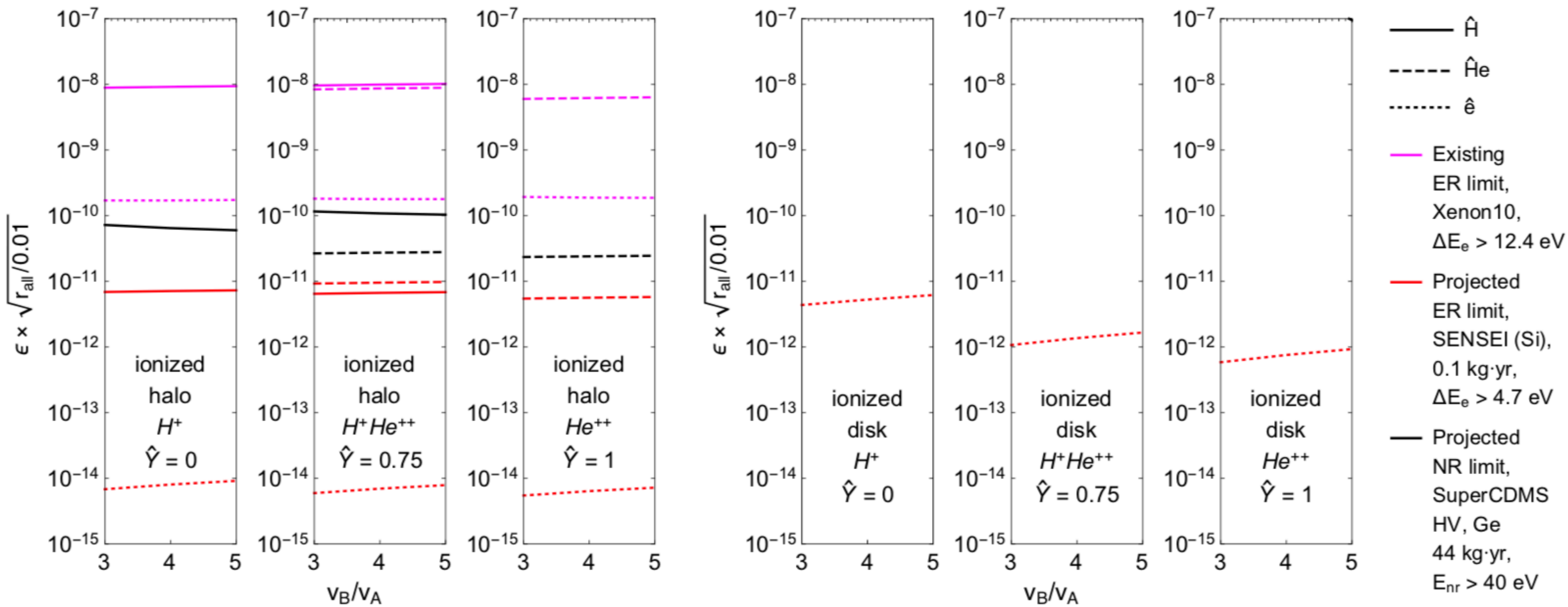
- ΔNeff ~ 0.few
  same free-streaming vs scattering fraction as SM

- 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)

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

Mirror Stars

Hierarchy Problem → Mirror Stars?

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

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

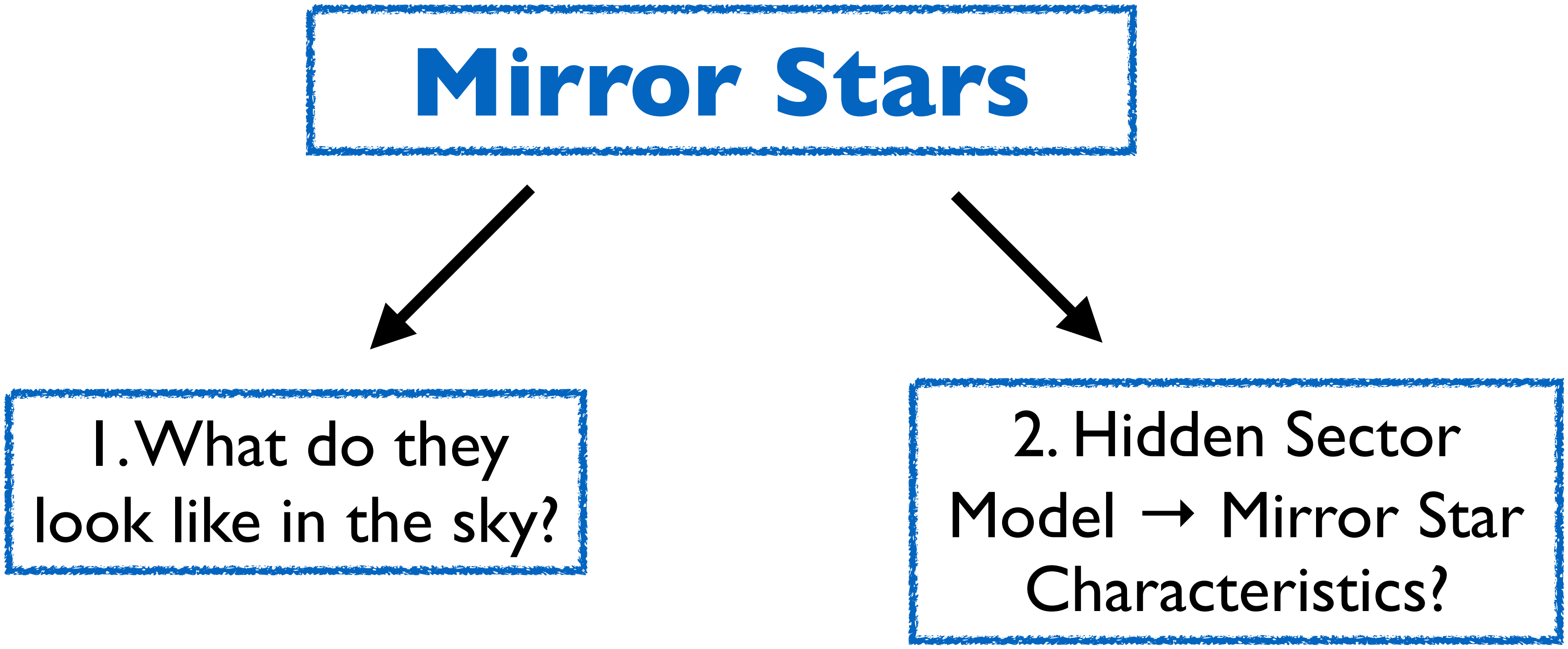
Mirror star signatures never really studied.

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.

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

Factorize the Question



Factorize the Question

Mirror Stars

1. What do they look like in the sky?

2. Hidden Sector Model → Mirror Star Characteristics?

Figure this out first for general mirror star

1907.xxxxx DC, Jack Setford

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Neutral Naturalness is a great signature generator!

next paper

How to discover Mirror Stars?

Use SM stars as benchmark "mirror stars" to study signature in detail.

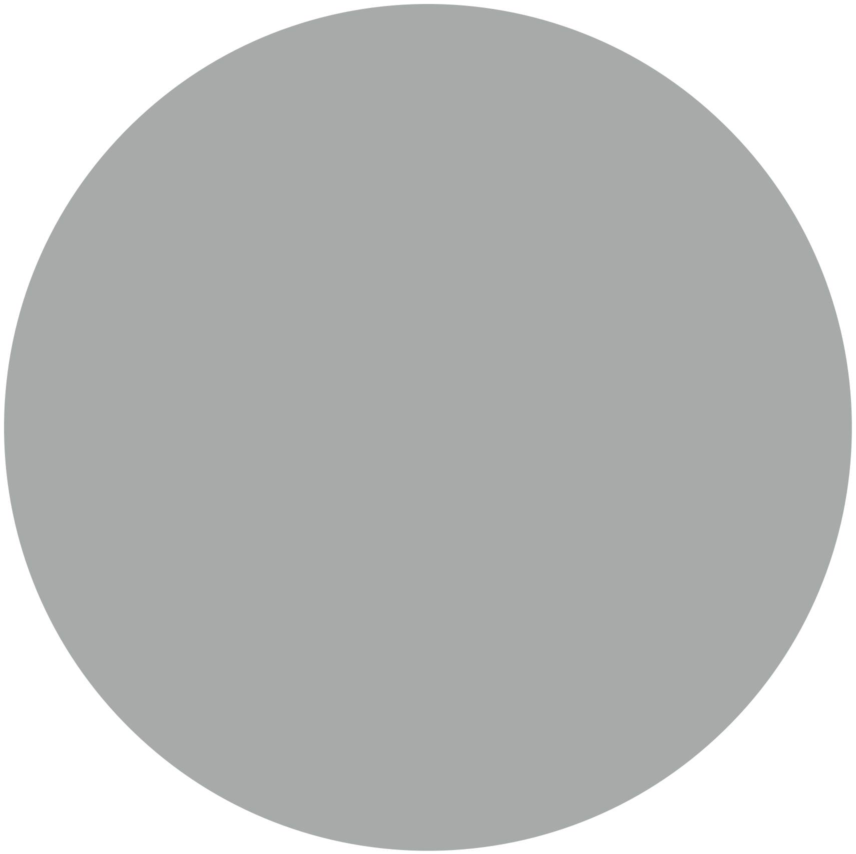
Mass / M_{sun}	He mass fraction	Radius / R_{sun}	T_{core} / 10^7 K	Luminosity / L_{sun}	Lifetime / years
0.2	0.24	0.21	0.68	6.7×10^{-3}	2.5×10^{11}
0.5	0.24	0.45	0.92	0.04	3×10^{10}
1	0.24	0.89	1.37	0.72	1×10^{10}
2	0.24	1.66	2.10	16.5	9×10^{8}
5	0.24	2.71	2.73	578	9×10^{7}
15	0.24	4.95	3.43	1.98×10^{4}	5×10^{6}
50	0.24	9.82	4.05	3.72×10^{5}	3×10^{5}
80	0.24	13.3	4.25	8.94×10^{5}	8×10^{4}
100	0.24	15.7	4.34	1.31×10^{6}	5×10^{4}
1	0.75	1.15	2.35	17.1	?
5	0.75	2.80	3.46	5700	?
15	0.75	5.15	4.13	1.05×10^{5}	?

Table 1: MESA benchmark stars used in the calculations.

Source of signal: mirror photon mixing!

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

Mirror Star Signals



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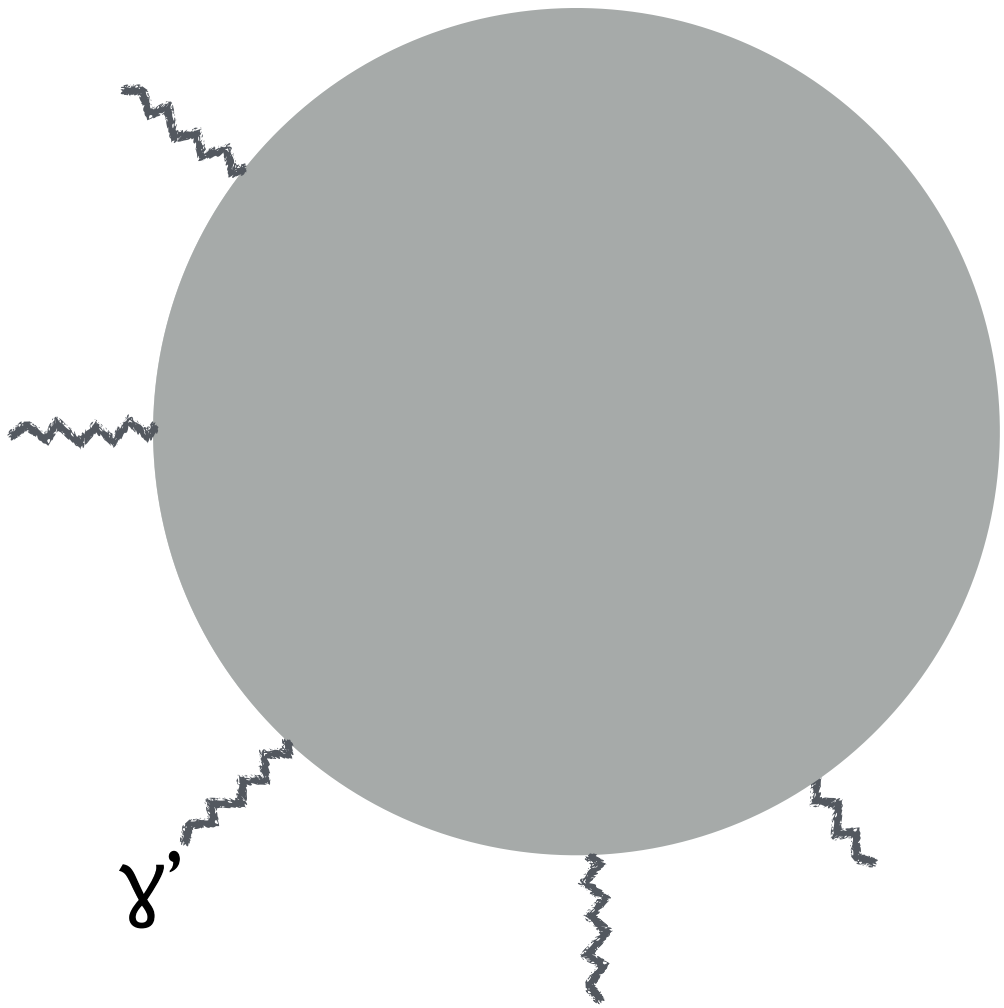

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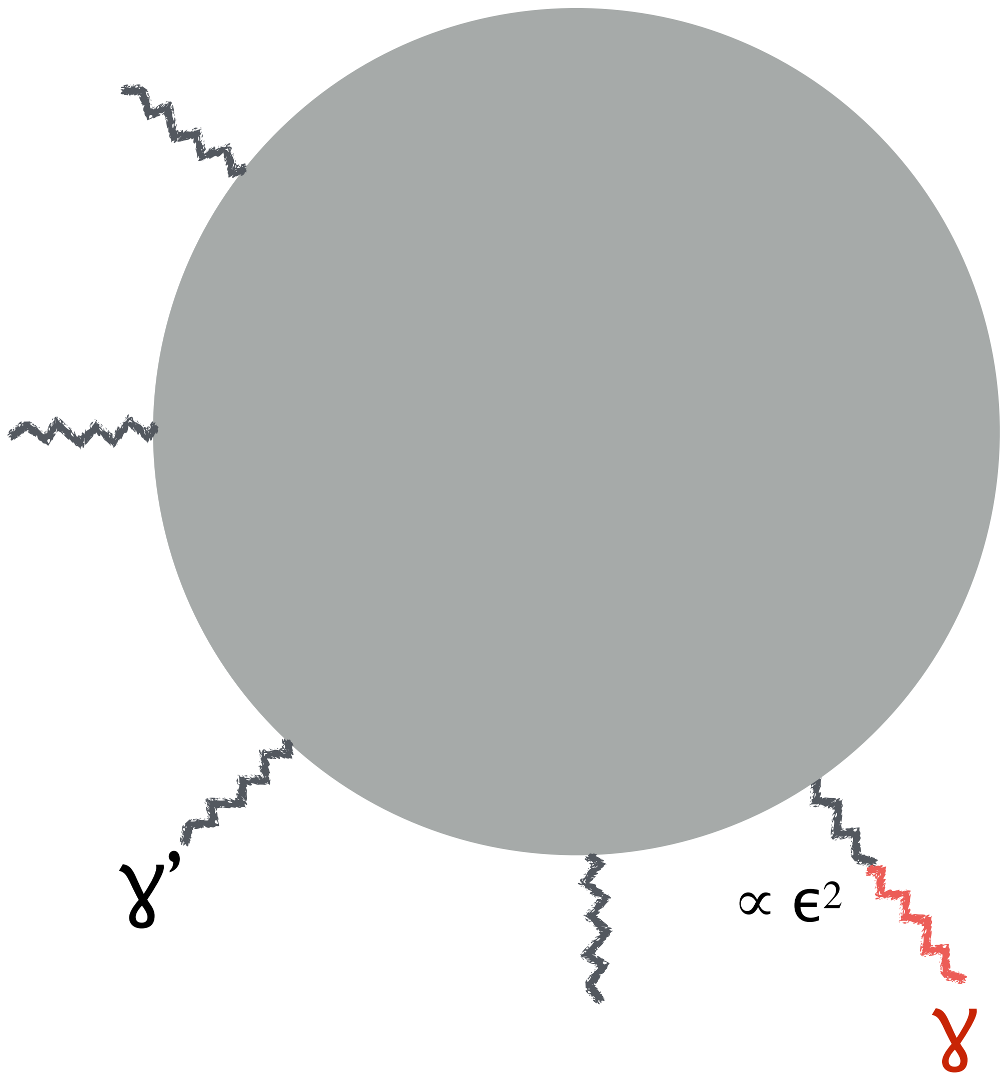
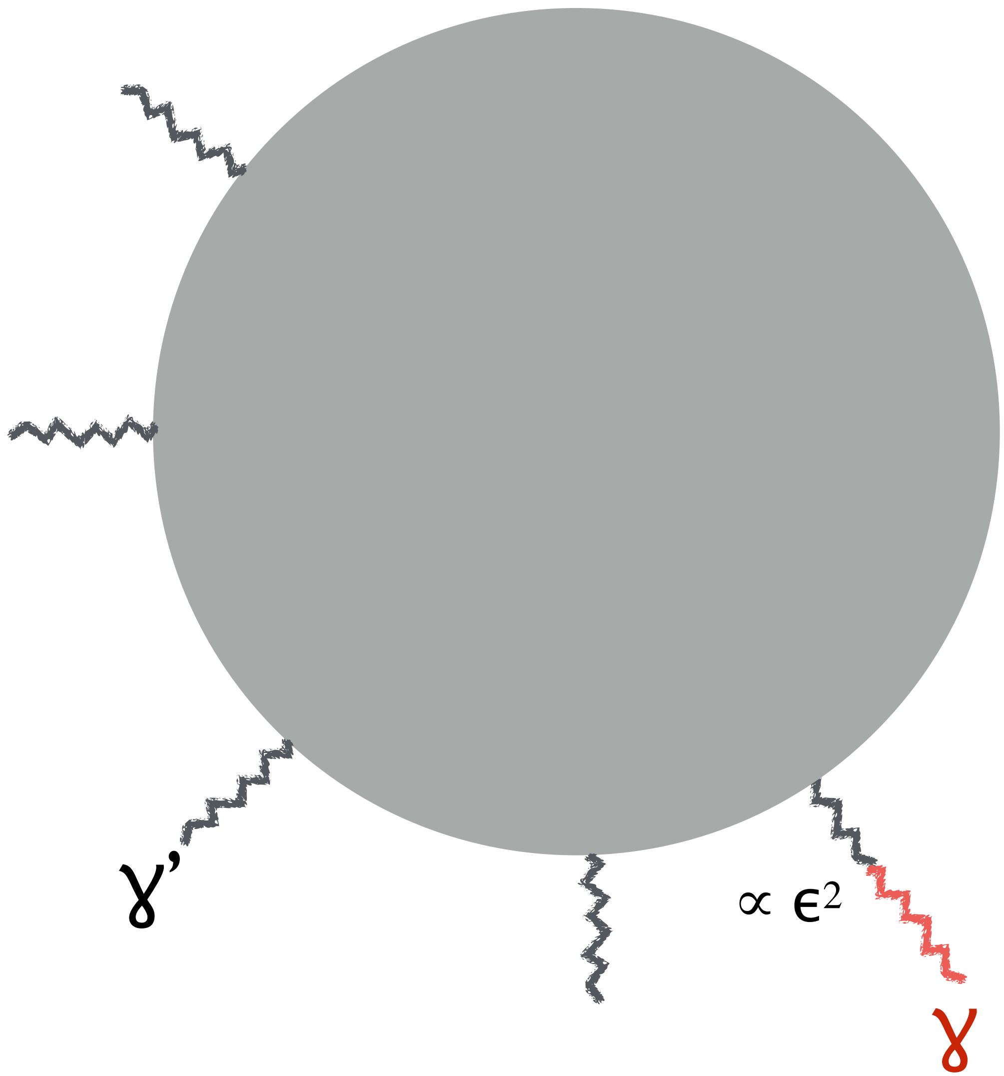


1) Photons from surface ~ ϵ^2

Mirror Star Signals

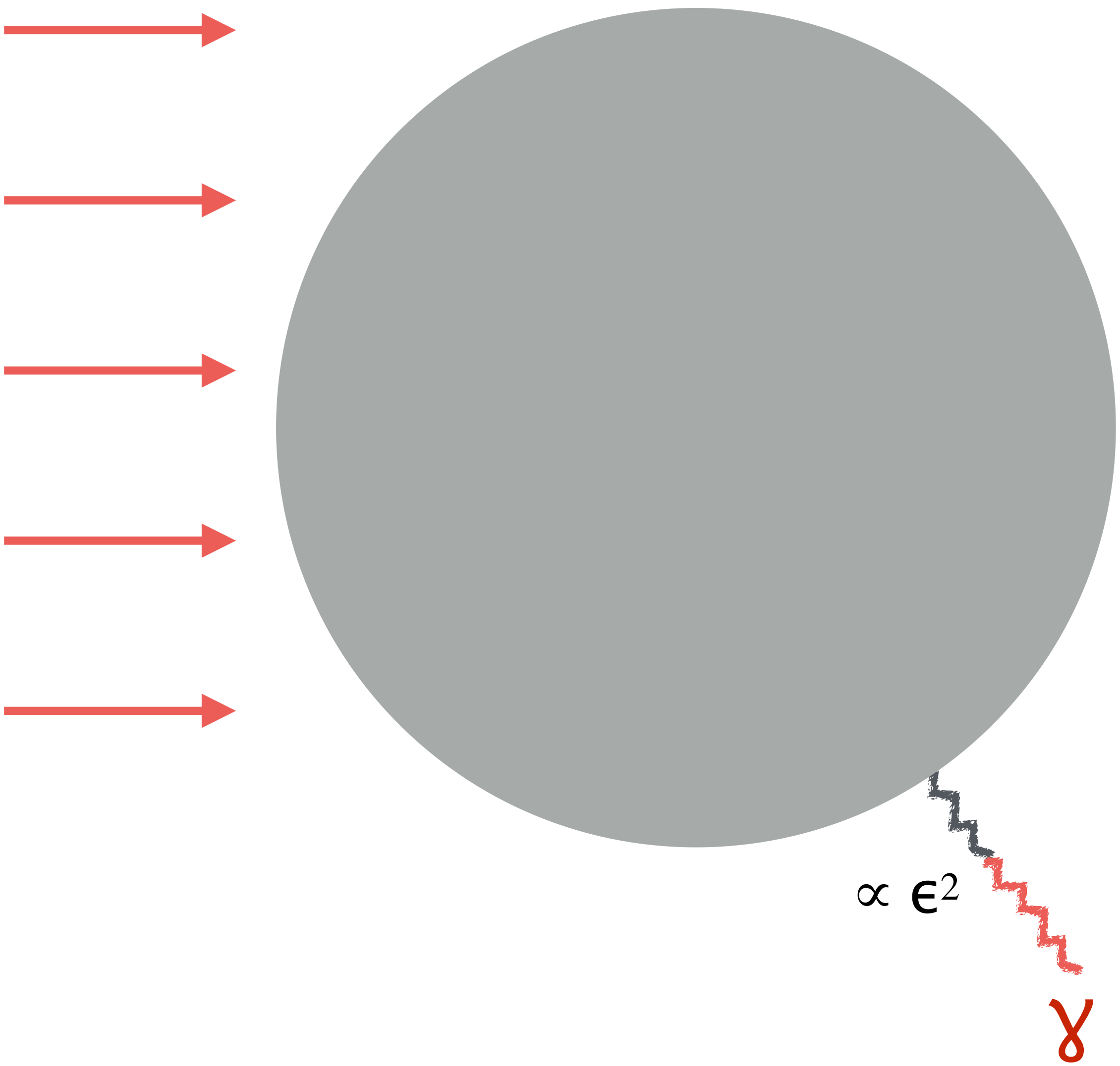


1) Photons from surface ~ ϵ^2

Also straight from core? NO!

Mirror Star Signals

SM baryons
(interstellar medium)

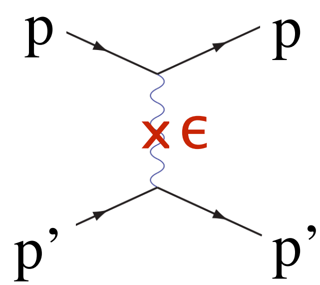


1) Photons from surface $\sim \epsilon^2$

Also straight from core? NO!

SM Baryon Capture in Mirror Star

$$\frac{d\sigma}{dE_R} = \frac{2\pi\epsilon^2\alpha^2 Z_1^2 Z_2^2}{m_T v^2 E_R^2},$$



There is capture due to mirror-SM collisions…

$$\left(\frac{dN_i}{dt}\right)_{mirror} = n_i^{ISM} \sum_j \frac{4\pi N_j \epsilon^2\alpha^2 Z_i^2 Z_j^2}{m_i m_j u^3}$$

SM ISM density

relative velocity

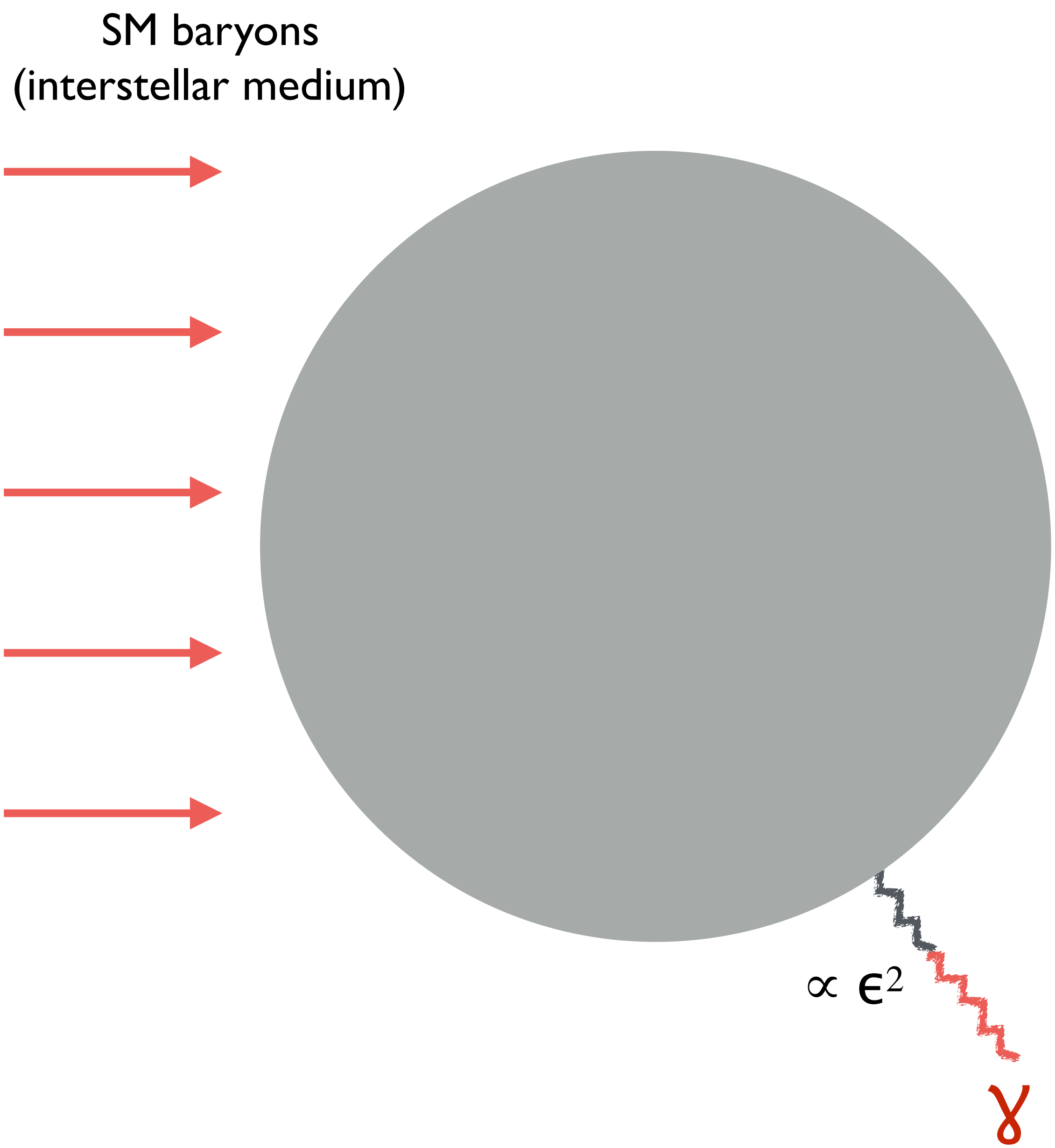
and SM-SM collisions

$$\left(\frac{dN_i}{dt}\right)_{geometric} = n_i^{ISM} \sqrt{\frac{3}{2}} \frac{\overline{v}_{esc}^2}{u} \pi R^2,$$

geometric limit due to unsuppressed interactions

Total amount captured ∝ age of star!

Mirror Star Signals



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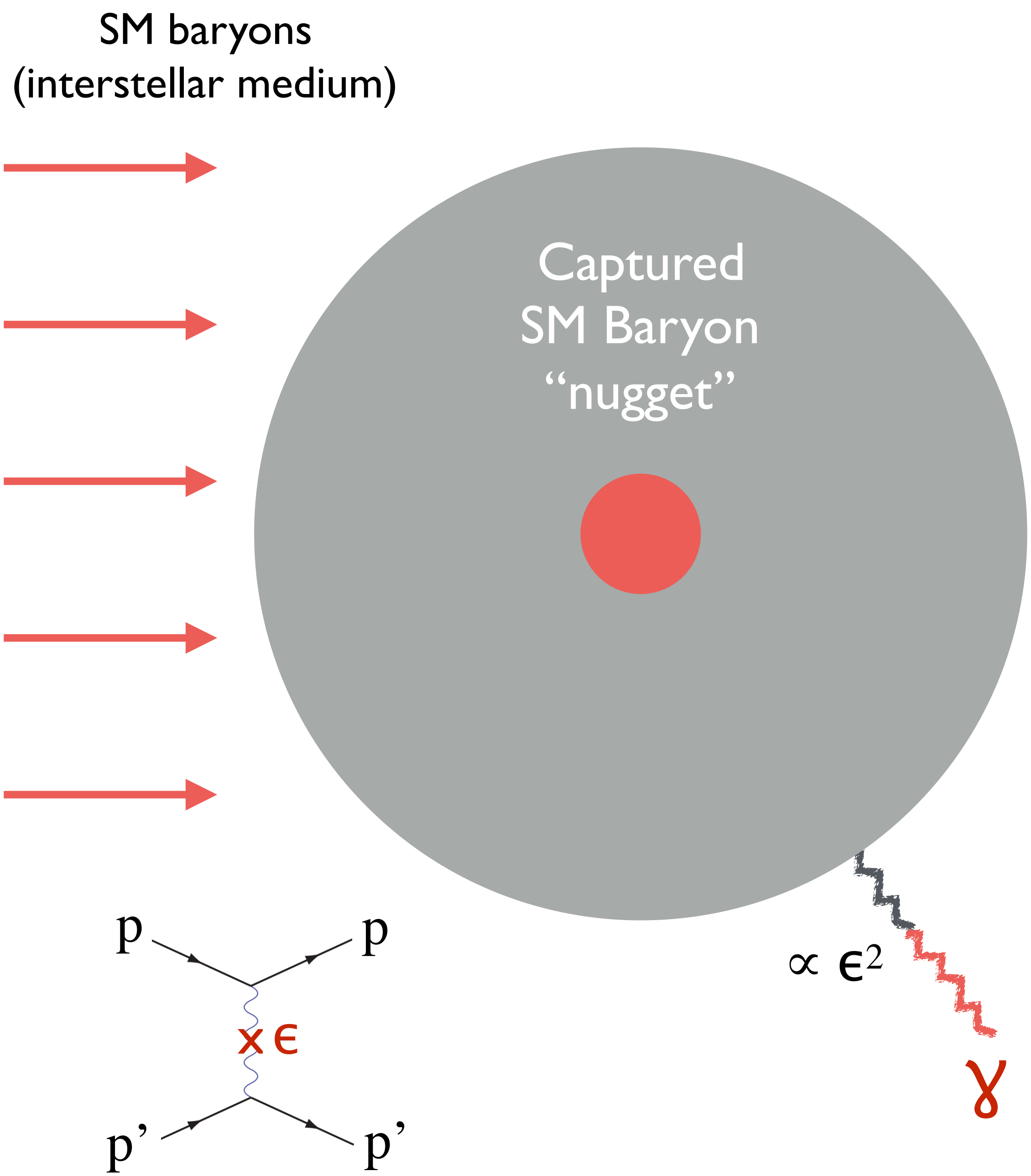

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Captured SM "Nugget"

Captured matter arranges itself in profile with R ~ virial radius given by equilibrium temperature.

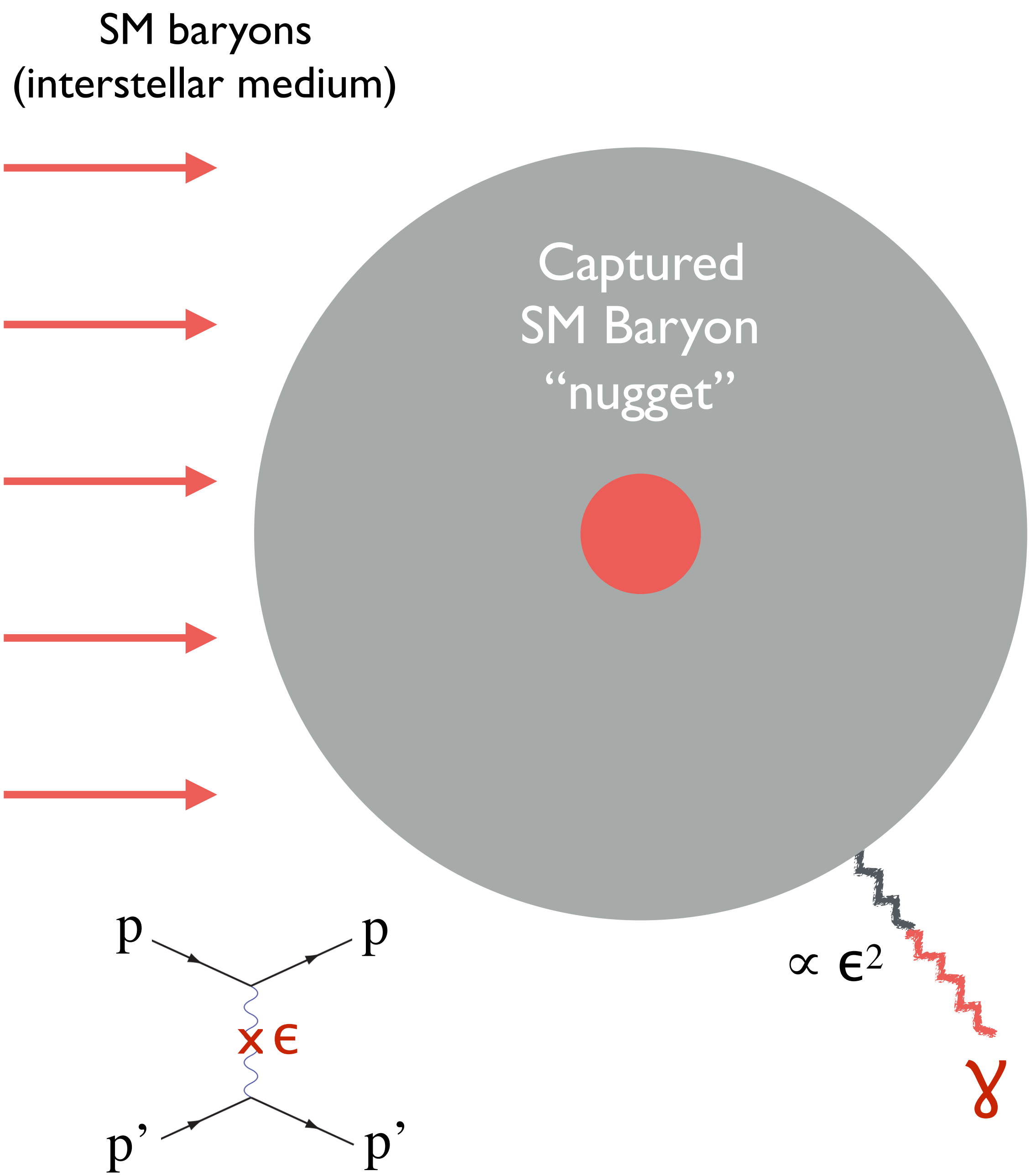
Equilibrium temperature given by SM ionization energy where **bremsstrahlung cooling** becomes efficient.

$T_{eq} \sim 10^4$ K

$r_{SM} \sim 10^{-3} R_{star}$. Nugget is ~ planet size!

Nugget is **optically thin** for optical photons (bremsstrahlung cooling), but **optically thick** for ionization and X-ray photons.

Mirror Star Signals



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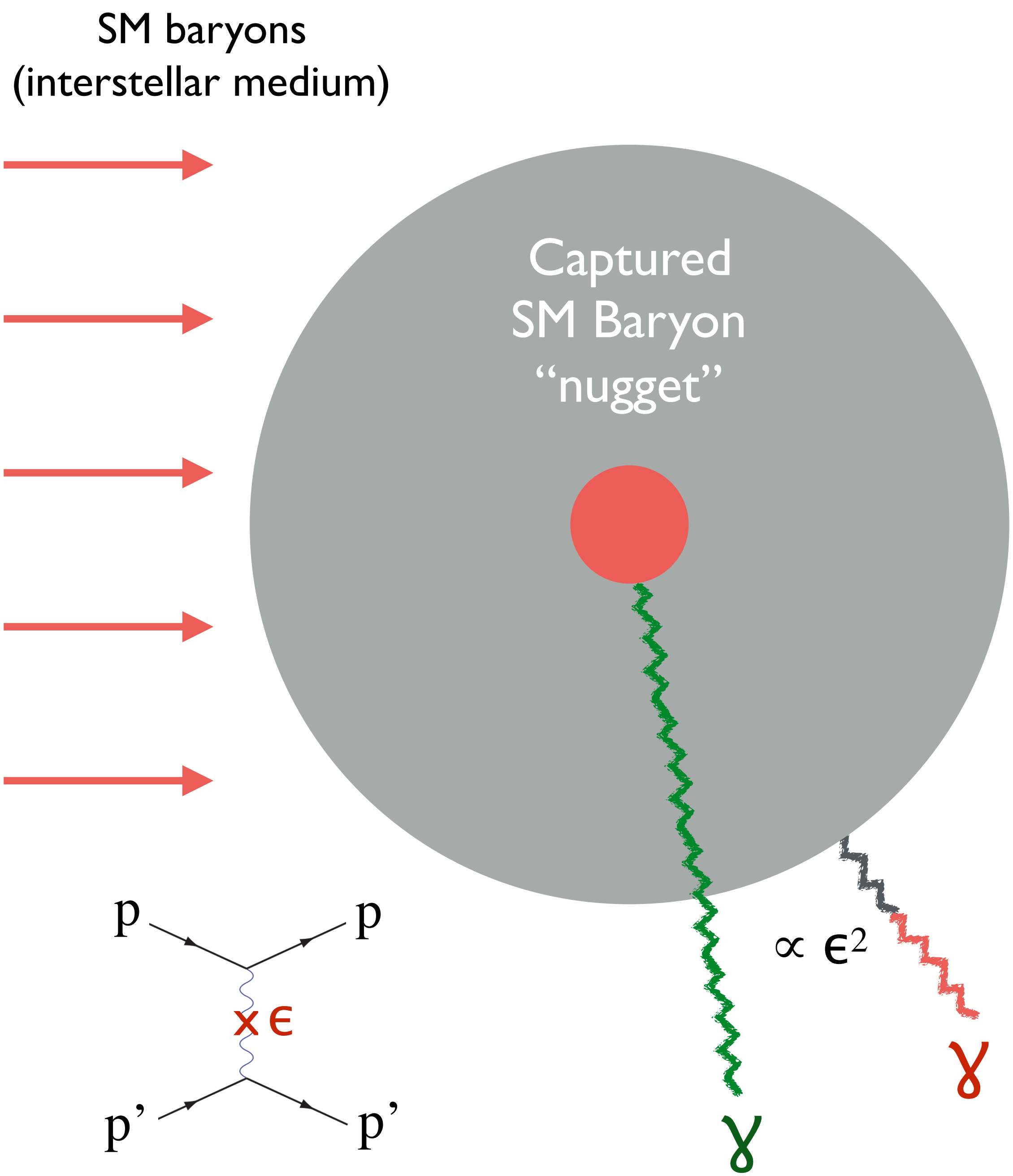
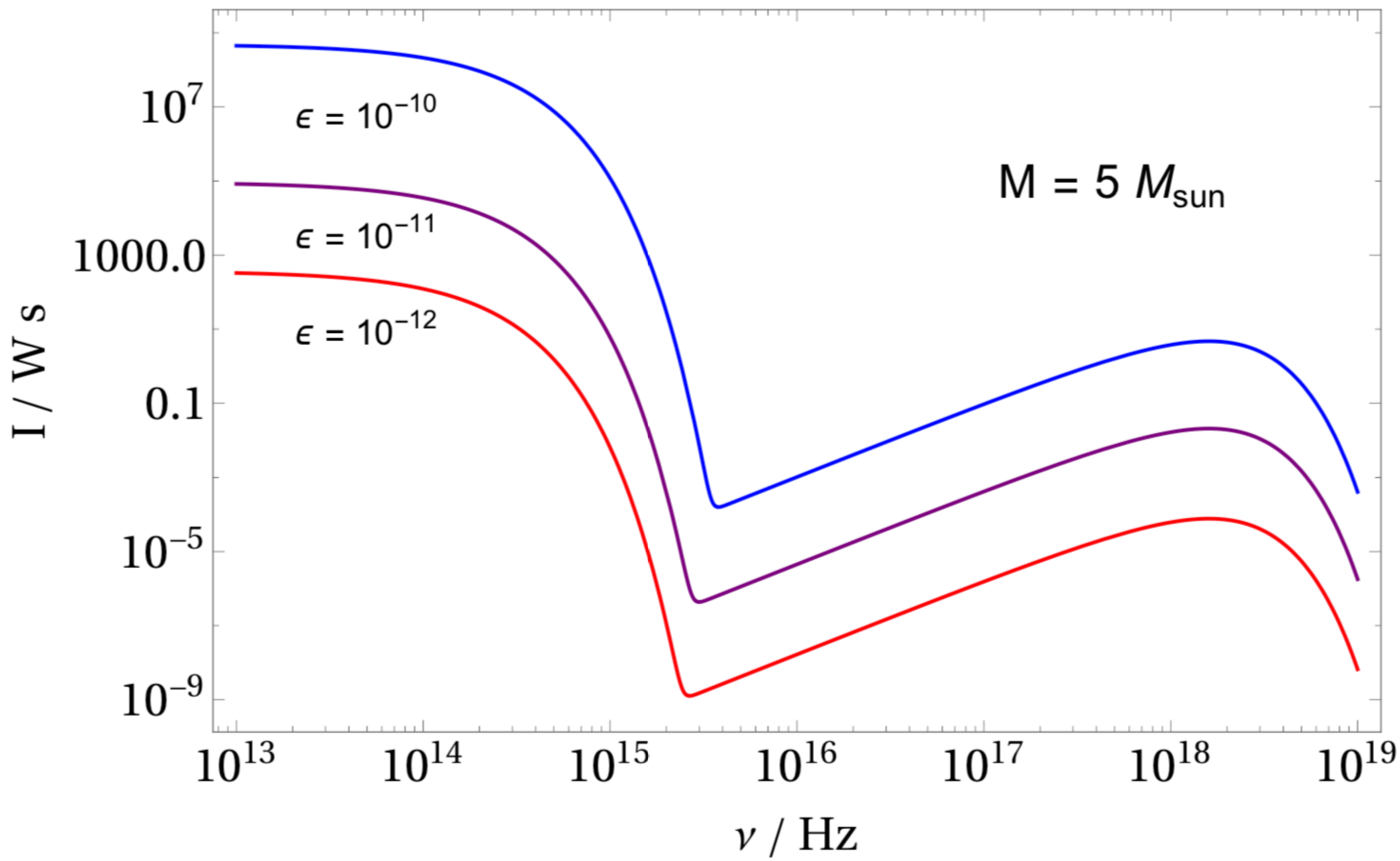


1) Photons from surface ~ ϵ^2

Also straight from core? NO!

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

SM "Nugget" Emission Spectrum



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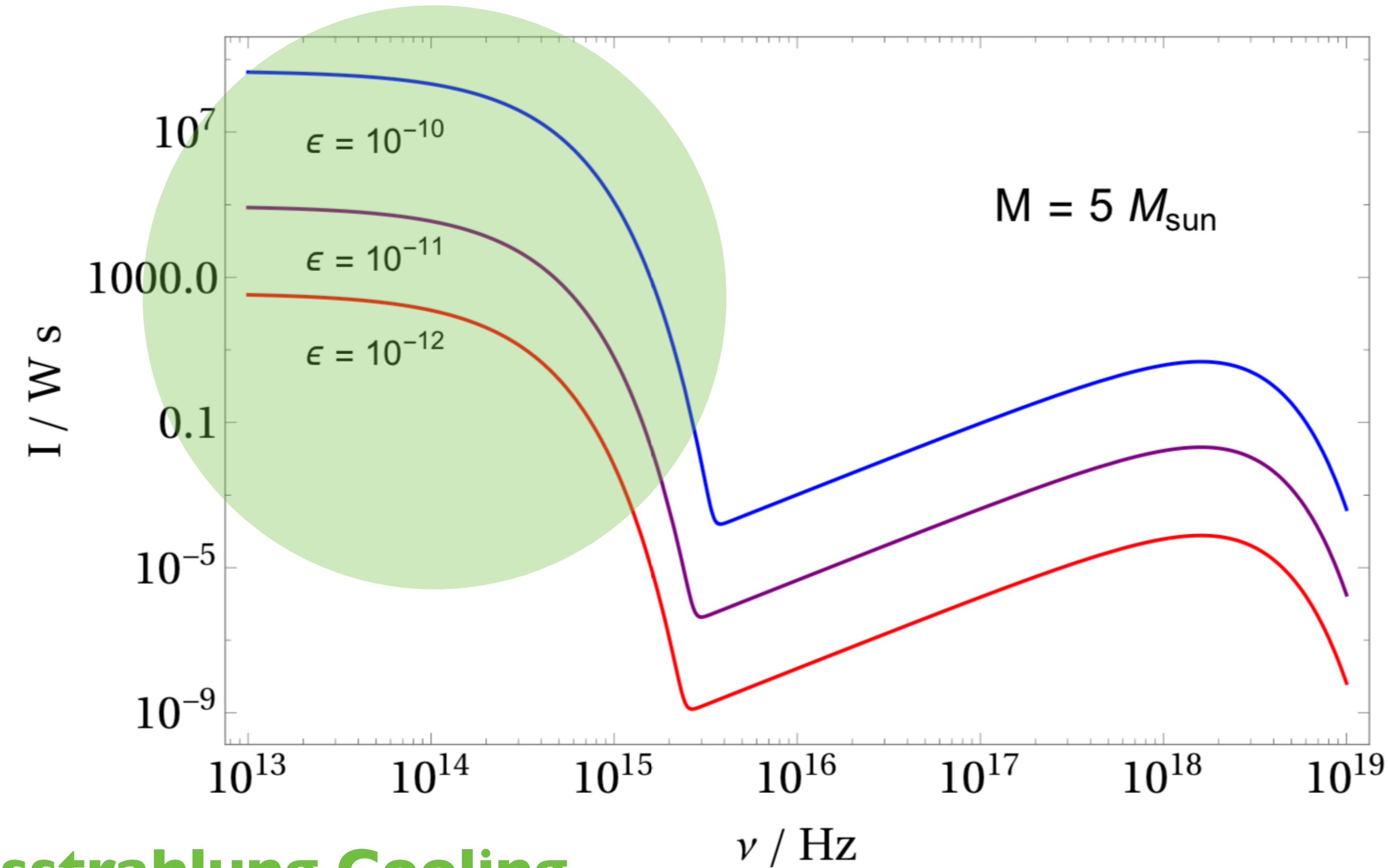

Bremsstrahlung Cooling gives optical signal!

Given its low luminosity, MUCH too hot to be standard astrophysical object

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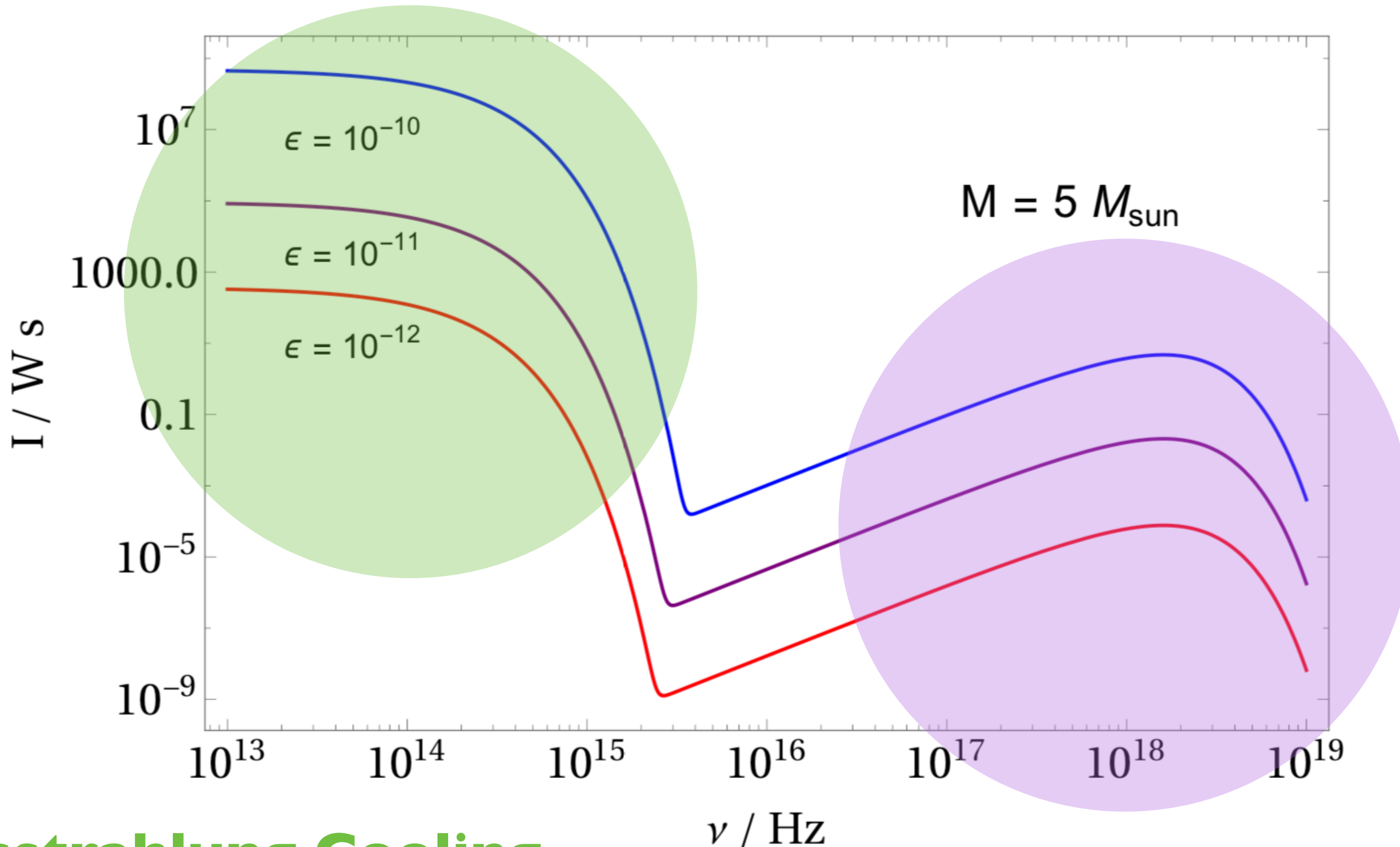

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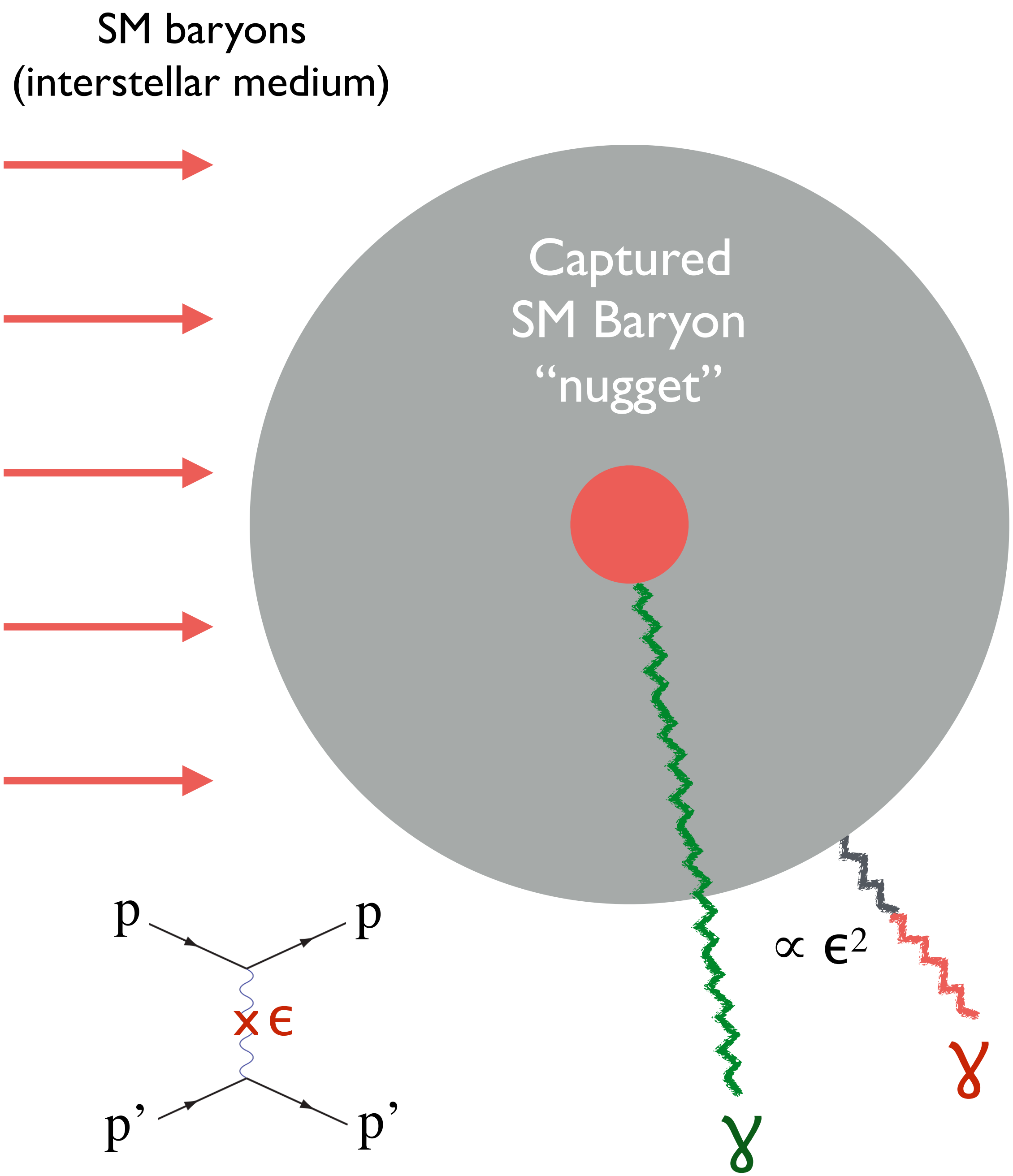
What's this…
X-ray Black Body Signal!?

Mirror Star Signals



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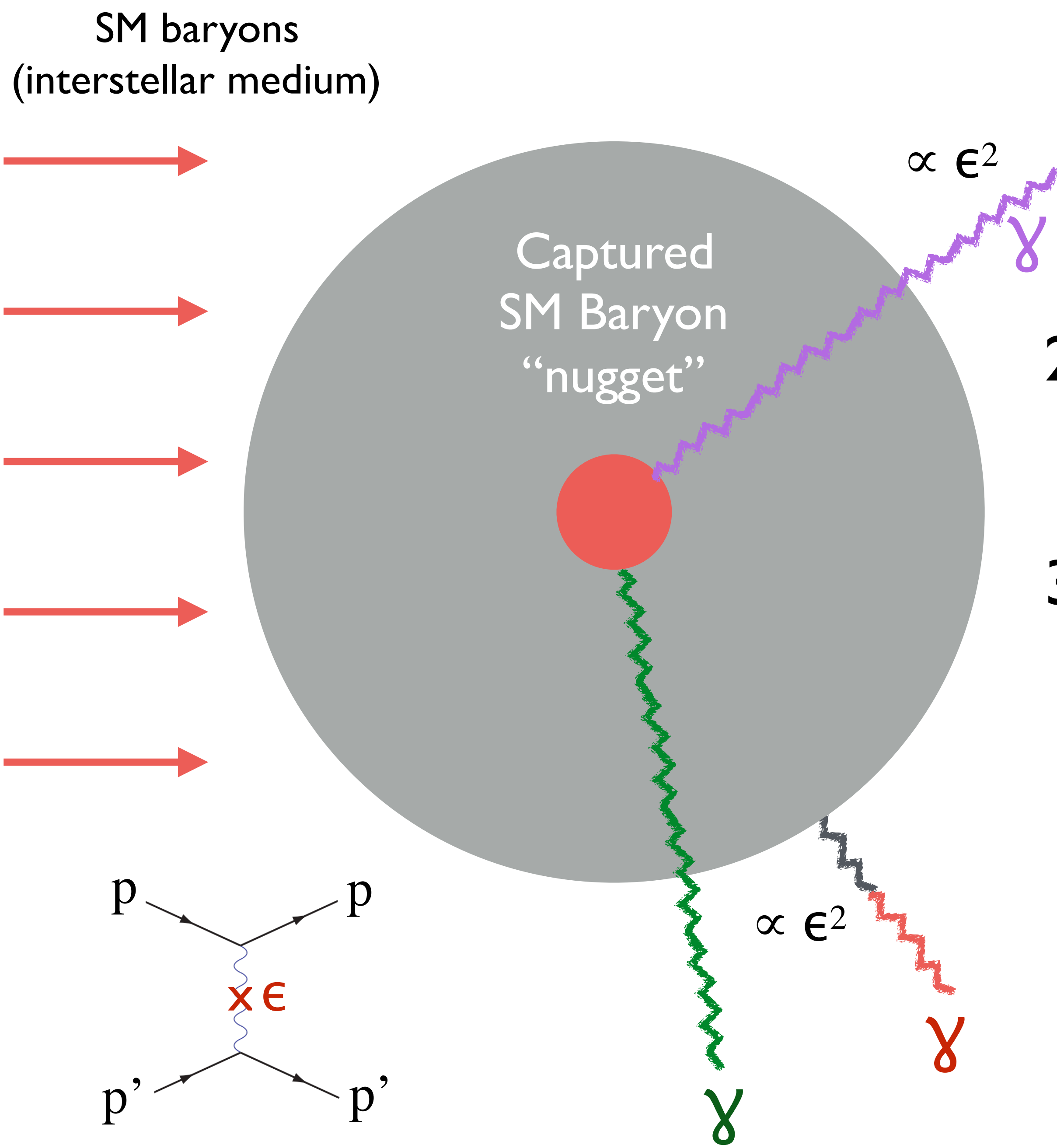

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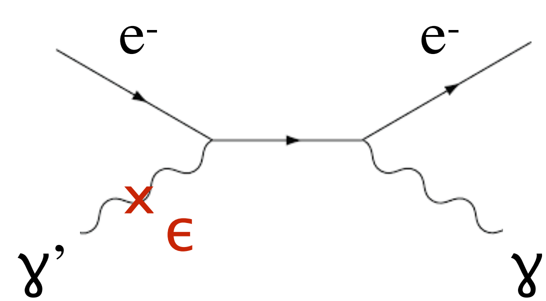
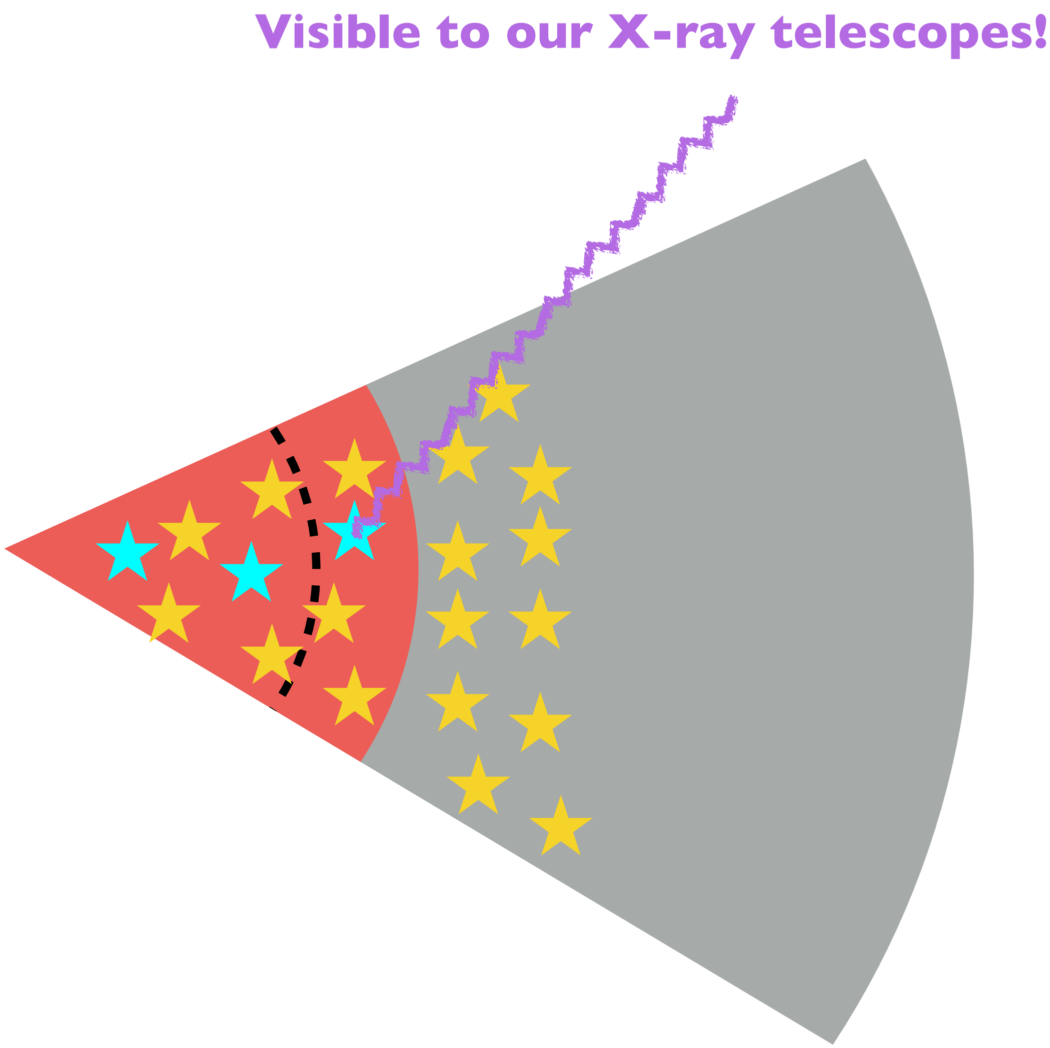
2) Thermal emission from SM nugget: **Optical!**

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



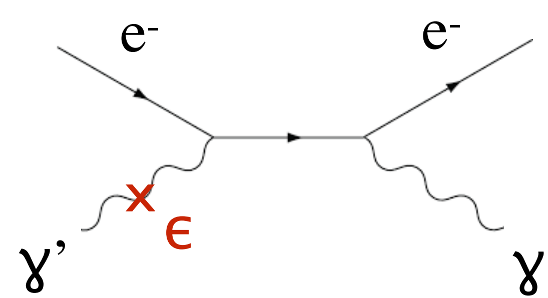
X-Ray Signal



★ = Mirror Fusion

As in regular star,
does not reach surface
directly

★ = Mirror Thomson Conversion



= X-ray photosphere of SM nugget

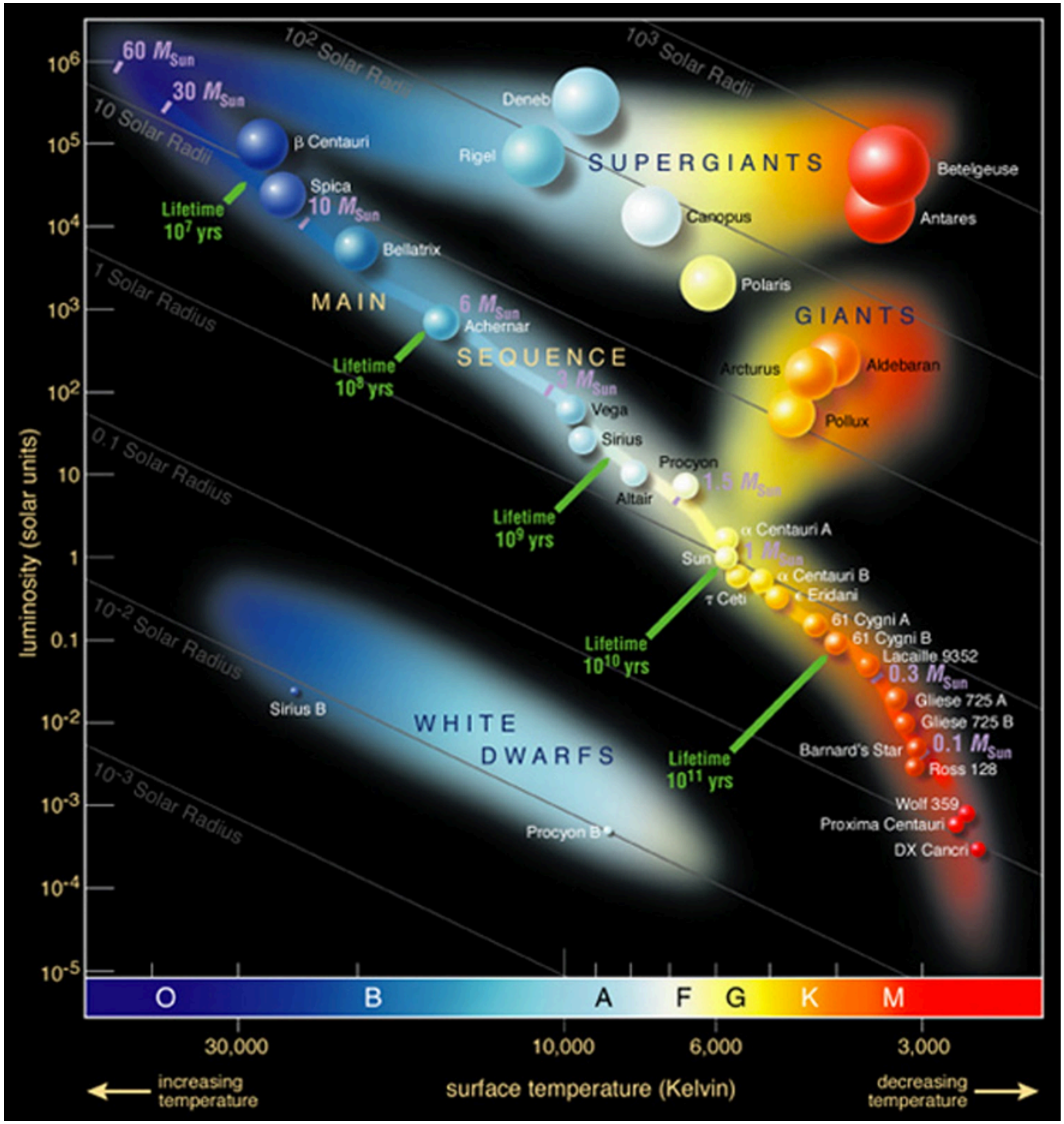
These mirror stars have a very bizarre double-signal:

optical bremsstrahlung photons from the captured SM matter

and

converted X-ray photons straight from the mirror star core

Mirror Stars in HR Diagram



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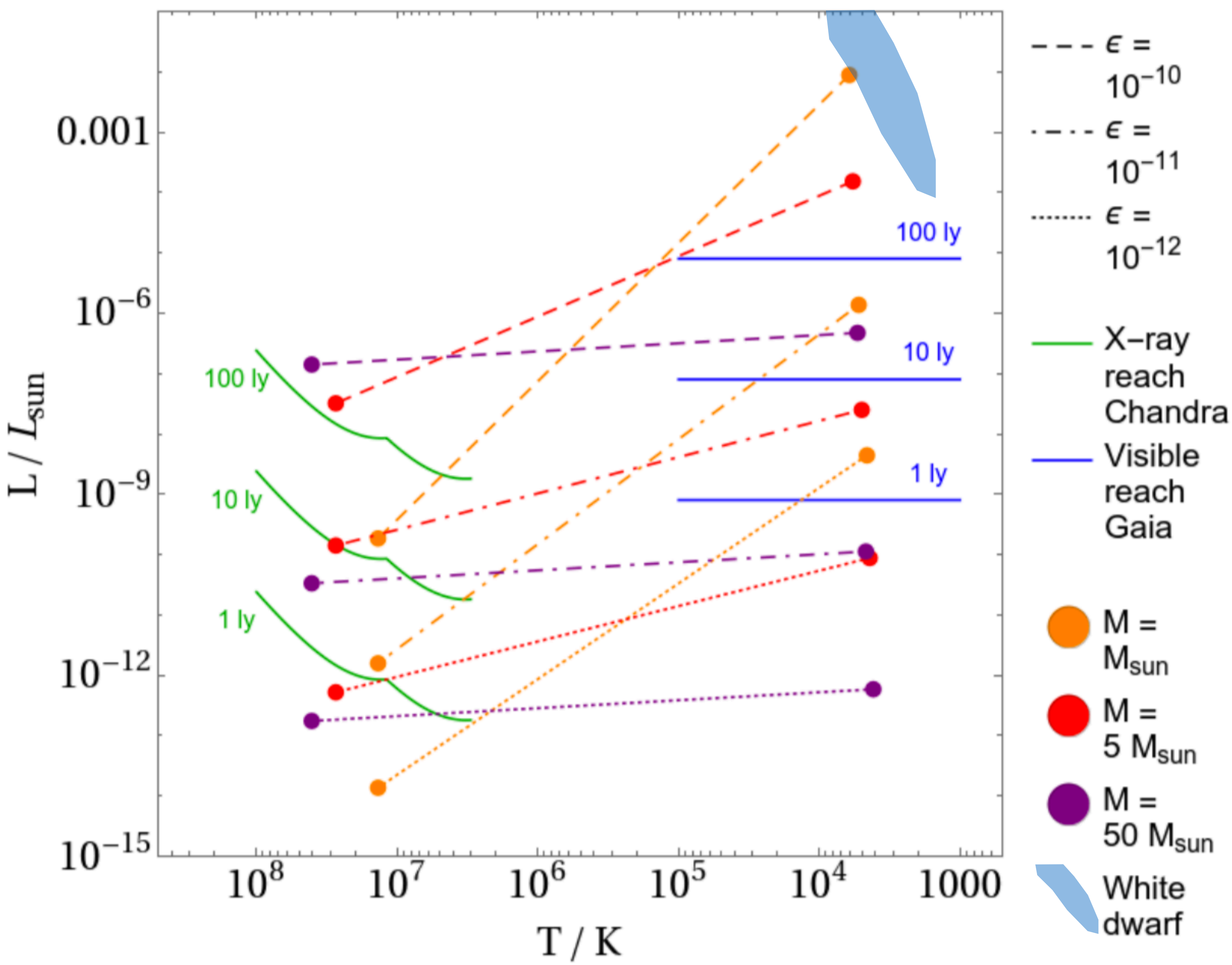
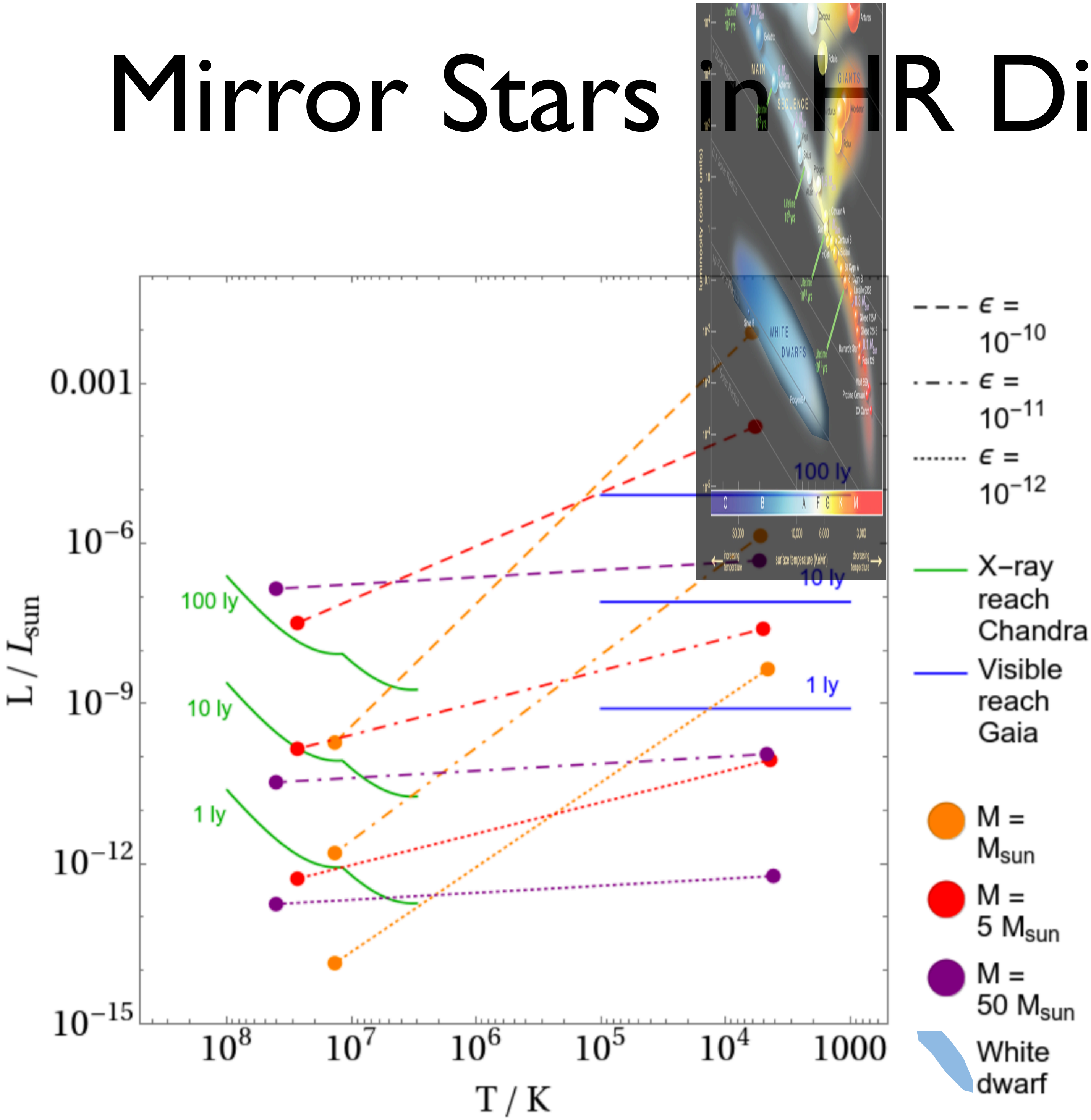


Some of these mirror stars could show up in GAIA data.

Requires closer analysis.

Could then diagnose mirror star with X-ray observations

Mirror Stars in HR Diagram



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Upshot

Mirror stars have a *robust* and *highly distinctive* signal.

Hot! (~10,000K)

X-rays = Mirror Star Core Temperature!

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

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

Conclusions

Conclusions

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

Collider (LLP) vs **Cosmology** (stable)

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 **$Br(h \rightarrow invis) \sim v_B^2/v_A^2$**
- 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!