Signatures of Mirror Stars

Jack Setford
with David Curtin

University of Toronto

arXiv:1909.04071 & arXiv:1909.04072

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Motivation

Dark Complexity:

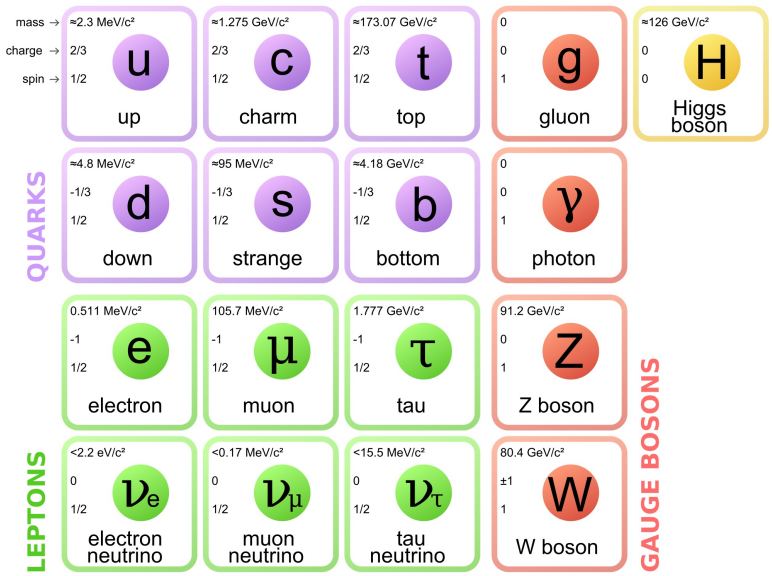
- Non-minimal hidden / dark sectors are interesting.
- Where to start? Dark sectors related to SM by symmetry.

Hierarchy problem:

- Neutral naturalness suggests a family of non-minimal hidden sector models.
- Mirror Twin Higgs – mirror sector with Z_2 symmetry.

Mirror Twin Higgs

- New states protect Higgs mass up to ~ 10 TeV cutoff, assuming Z_2 symmetric Yukawas and gauge couplings.
- Can solve cosmological issues in Z_2 symmetric case with *asymmetric* reheating.



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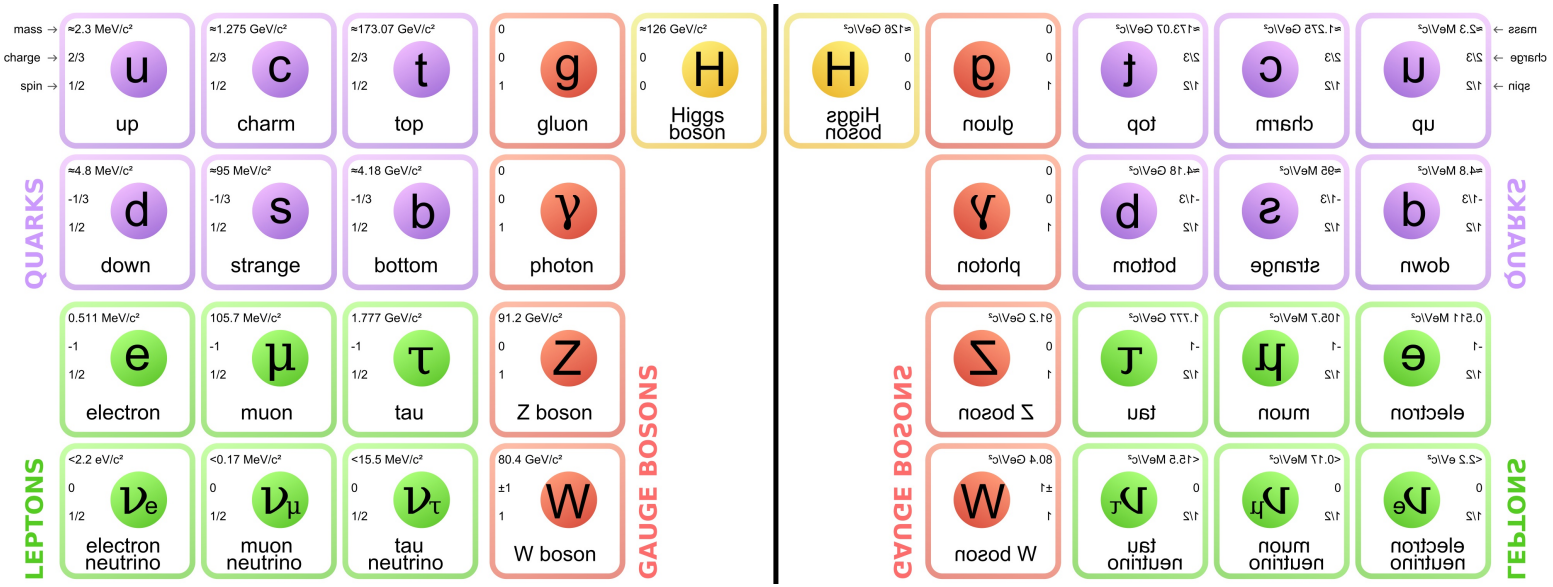
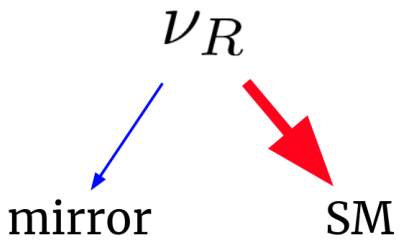


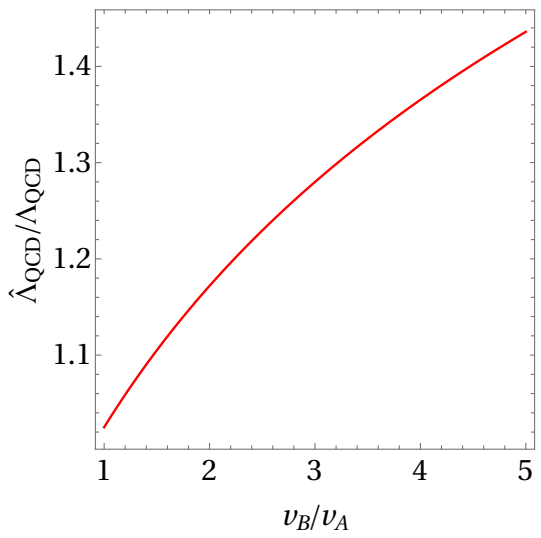
Mirror Twin Higgs

Mirror sector mass scale $\sim v_B$

- Collider searches $\rightarrow v_B/v_A > 3$
- ΔN_{eff}, asymmetric reheating $\rightarrow v_B/v_A > 5$.



Mirror nuclear physics can be *similar* to SM nuclear physics.



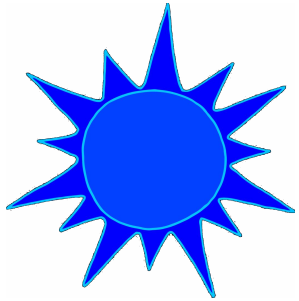
Mirror sector is at most 10% of total dark matter density (self interaction and large scale structure bounds.)

Predictive framework for cosmology, e.g. Helium mass fraction $\rightarrow$ 75% (25% in SM).

[Chacko, Curtin, Geller, Tsai, arXiv:1803.03263]

Mirror Stars

- If physics of the mirror sector is similar enough to SM physics, it's reasonable to suppose mirror stars might form.
- Mirror stars of an exact mirror sector have been discussed before.
  [Foot, Ignatiev, Volkas, arXiv:astro-ph/9902065, arXiv:astro-ph/0011156]
- But no estimate of expected signal.
- We're interested in a broad class of models with mirror nuclear physics – MTH model is a good benchmark.



Mirror photons

As usual in models with a second $U(1)$ gauge boson we expect a kinetic mixing term:

$$\mathscr{L} \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

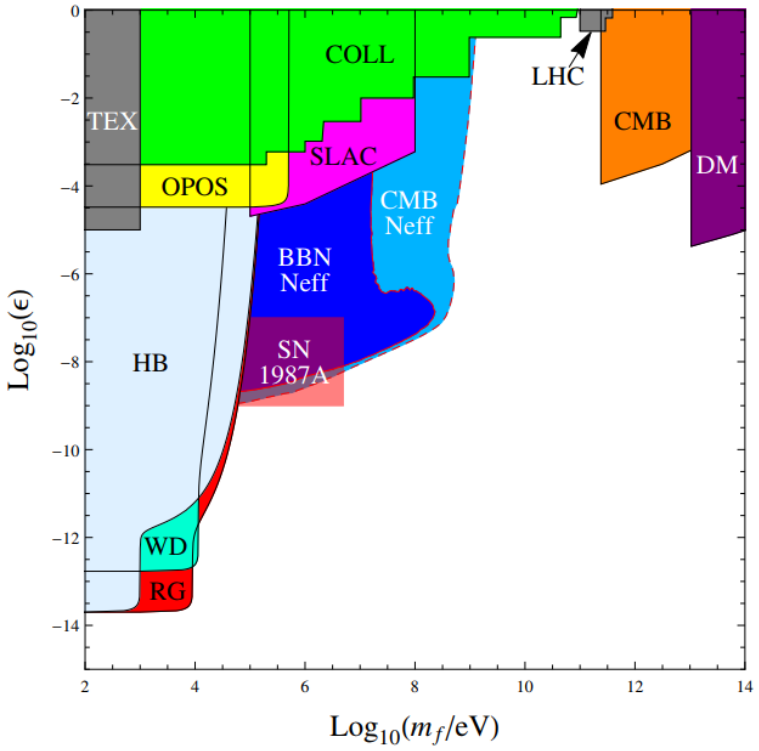
Current bounds on ϵ are

$$\epsilon \lesssim 10^{-9}.$$

In MTH, ϵ is not generated at up to 3-loop, so small value arises naturally.

We consider values in the range $\epsilon = 10^{-10} - 10^{-13}$.

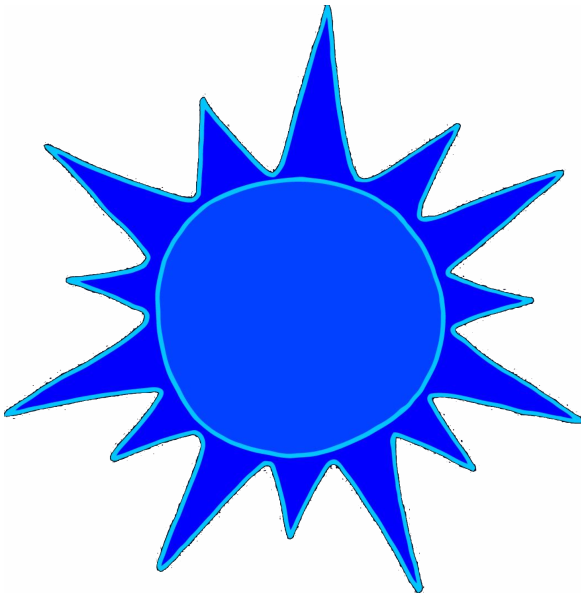
[Vogel, Redondo, arXiv:1311.2600]



Signals from a Mirror Star

How can we see a mirror star?

$\epsilon^2 L_{star}$ surface brightness:



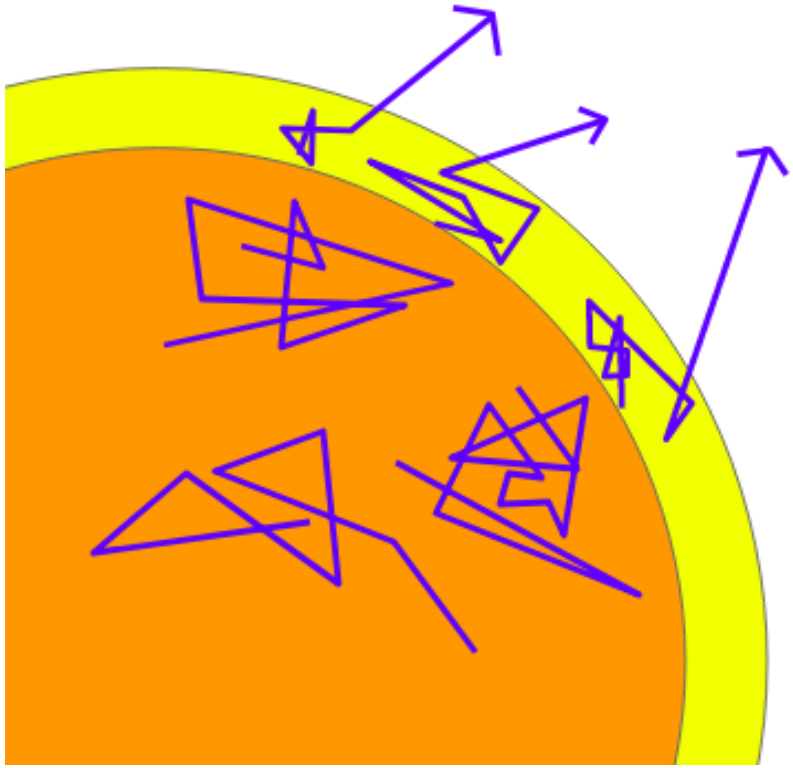
$\times \epsilon^2$

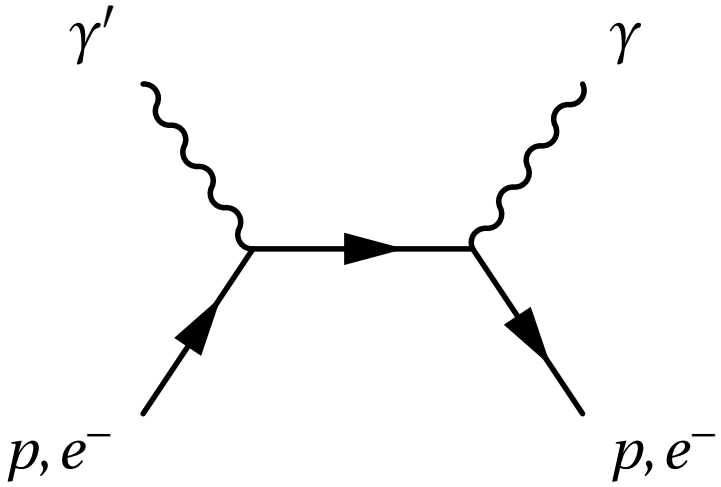
Captured SM matter:

Captured SM matter is heated via ϵ^2-suppressed processes: collisions with mirror nuclei, and photon conversion.

Photon conversion, X-ray signature

SM matter *catalyzes* mirror photon conversion:





Converted photons can heat up the captured material.
There is an X-ray photosphere from which converted X-ray escape
→ potential signature.

Calculation program

MODEL STARS

↓

CAPTURE

↓ ↑

PROPERTIES OF NUGGET (temperature, optical depth)

↓

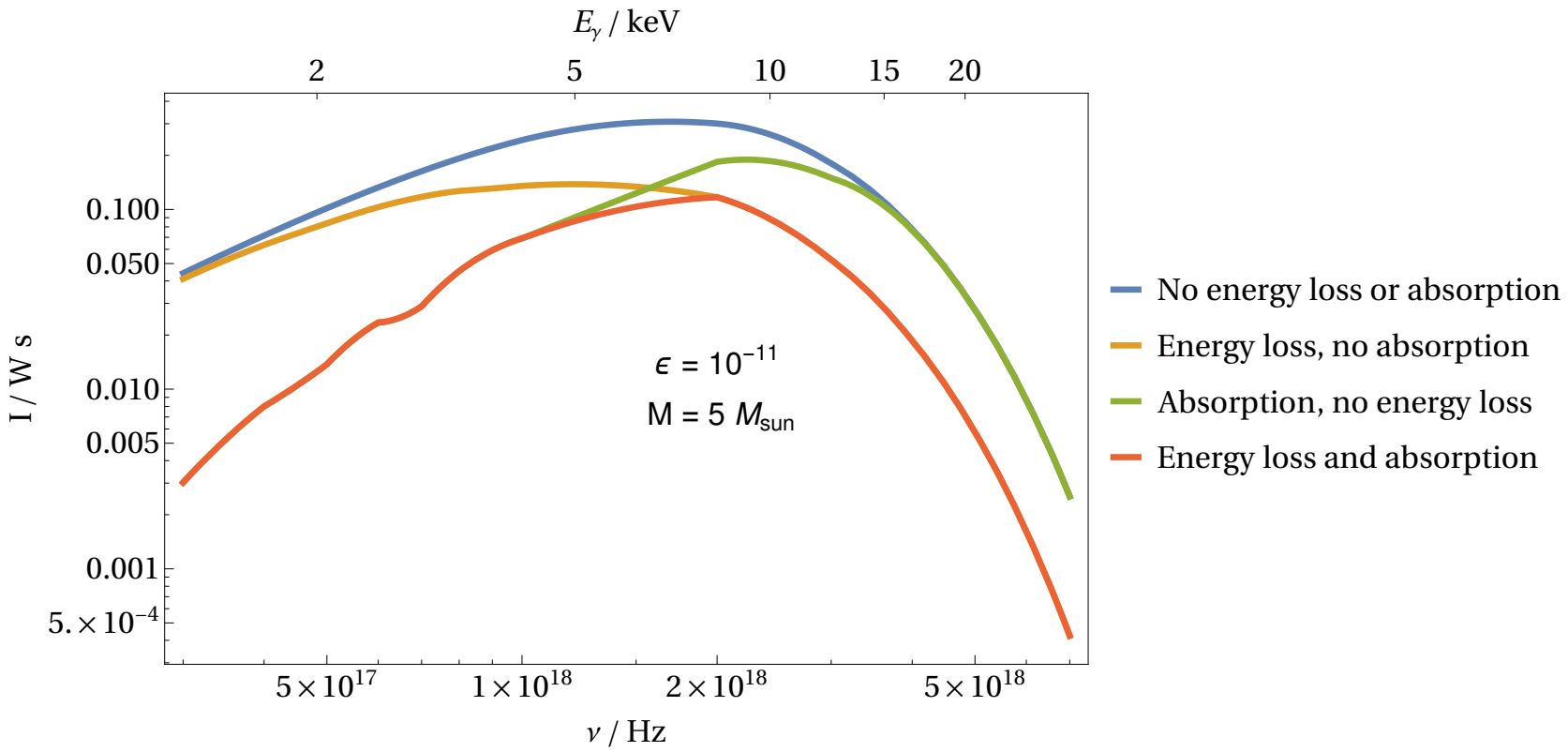
SIGNAL

Optical depth of nugget

	Optically thin	Optically thick
Thermal photons	Nugget cools via collisional processes e.g. bremsstrahlung	Nugget cools as blackbody with effective surface temperature
Converted X-rays	All X-rays escape	Most X-rays deposit energy as heating, while conversions in photosphere can escape.

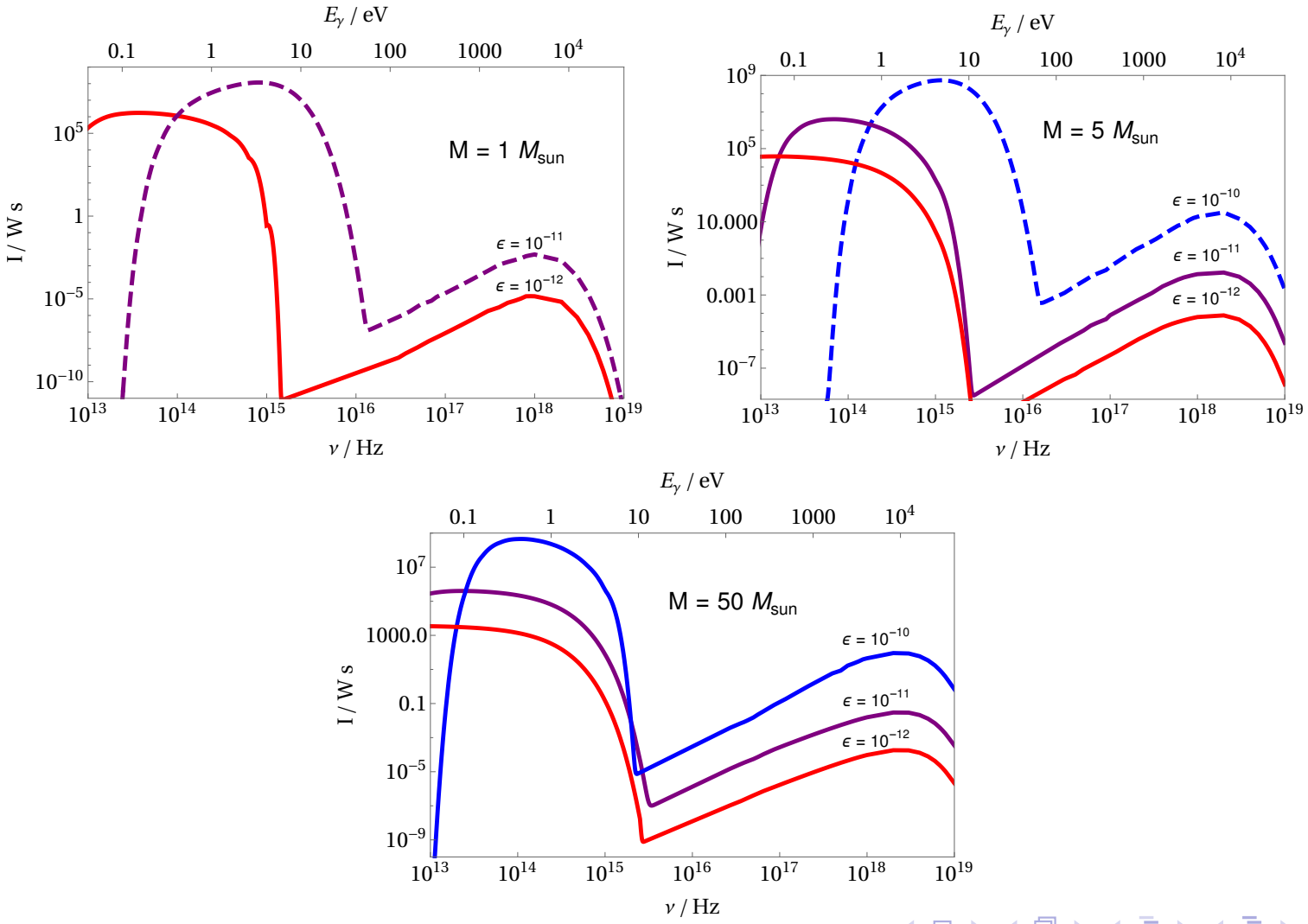
X-rays: absorption and energy loss

X-rays that convert within the nugget will scatter until absorbed via photoionization.



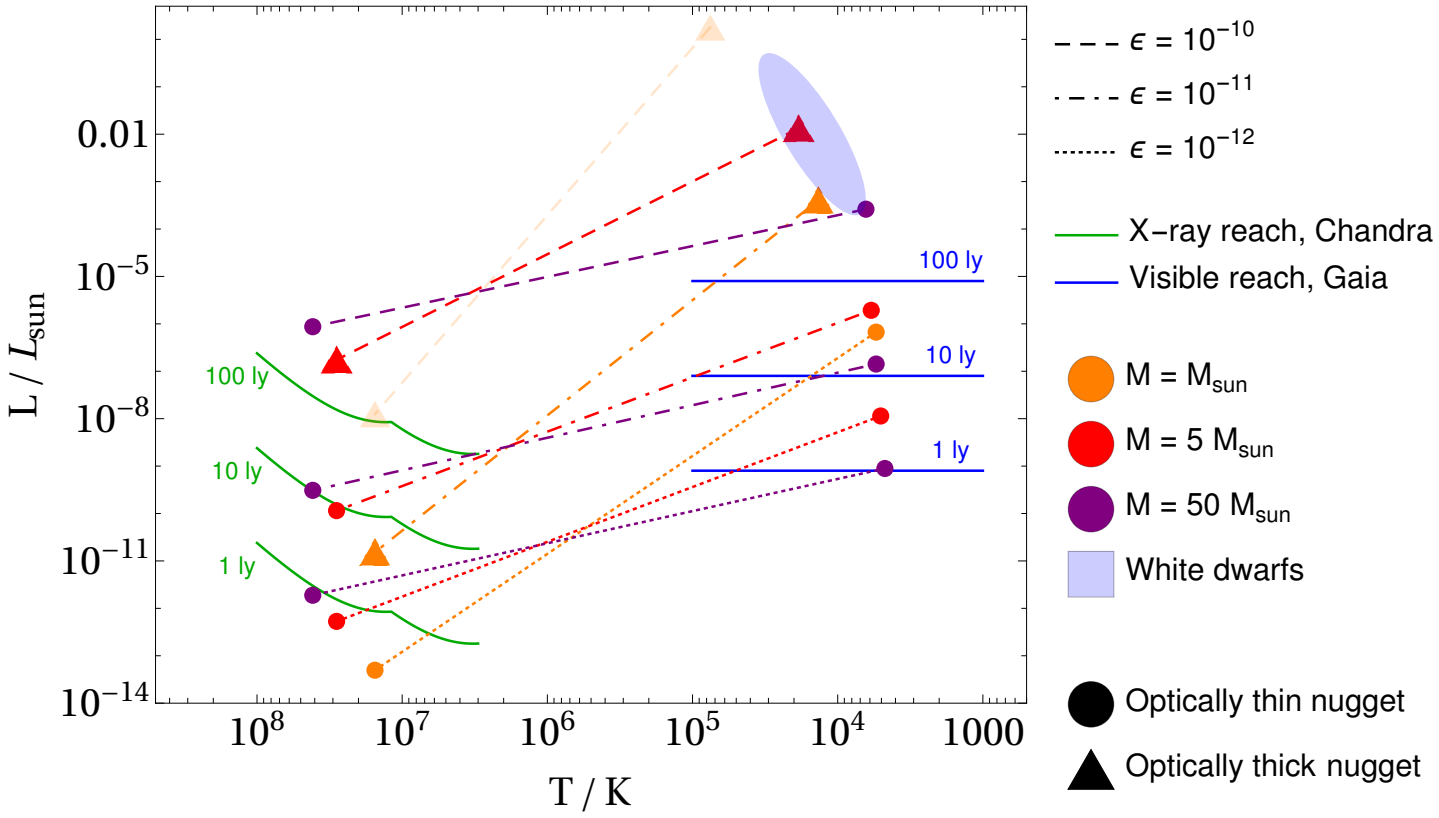
Results: Spectrum

Shape of spectrum depends on optical depth: black body / bremsstrahlung emission. For higher ϵ there is attenuation due to absorption by mirror star matter.



Results: Luminosities

Two distinct thermal spectra – can plot separately on a Hertzsprung-Russell diagram:



Conclusions

- Mirror sectors theoretically well-motivated.
- Mirror stars can efficiently capture interstellar matter, which leads to a signal in SM photons.
- Two thermal signatures: the temperature of the nugget and the temperature of the mirror star core.
- Weird signal – faint, nearby, hot object with an X-ray signal. Close → parallax.

Back-up slides

Profile of captured matter

Assume that the captured material is in isothermal hydrostatic equilibrium, in an *external* gravitational well.
Simplifying assumption, isothermal profile.

$$kT_{nugget}\frac{dn}{dr} = -\frac{GM_{mirror}(r)\, m_{SM}\, n(r)}{r^2}$$

(Ignores captured matter gravitational self-interactions)

Solution given by

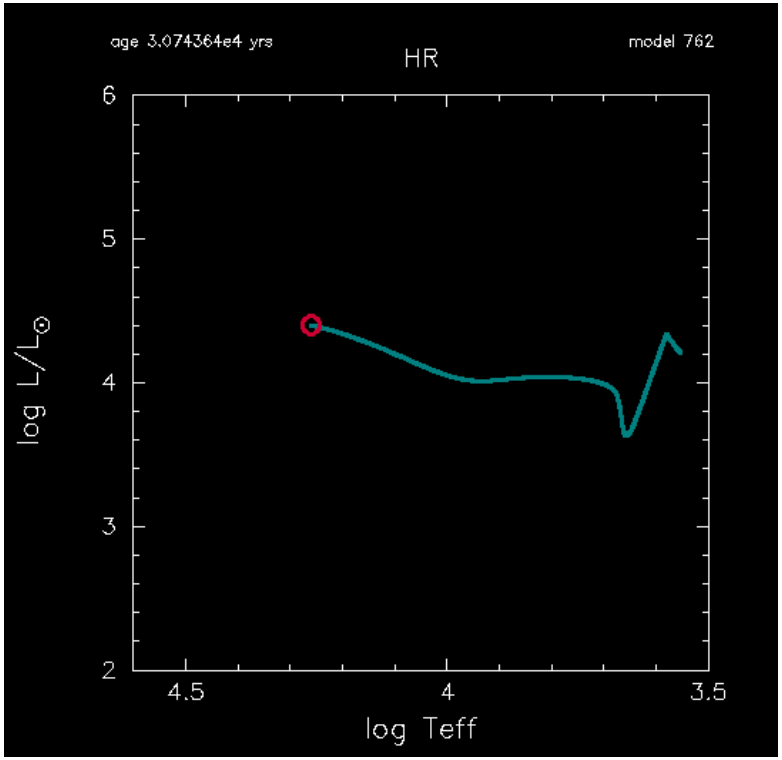
$$n(r) = Ce^{-\int A(r)dr}, \quad A(r) = \frac{GM_{mirror}(r)\, m_{SM}}{kT_{nugget}\, r^2} \tag{1}$$

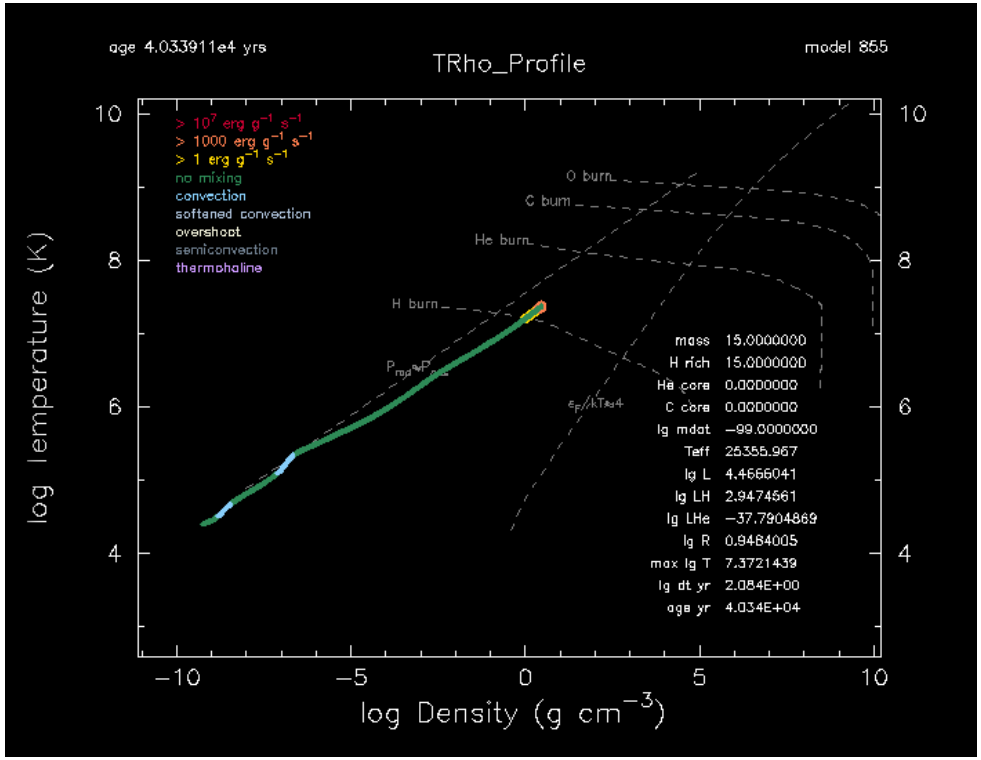
Virial theorem, characteristic radius:

$$r_{capture} = \sqrt{\frac{9kT_{mirror}}{4\pi G\rho_{mirror}\, m_{SM}}} \tag{2}$$

SM-LIKE MIRROR STARS

- Mirror stars are SM-like, i.e. same opacity, same reaction rates and energy output.
- Generate stellar profiles using MESA for different masses.





Calculating X-ray spectrum

$$\frac{dP_{x\text{-}ray}}{d\nu_{obs}} = \int_0^{R_{nugget}} dr 4\pi r^2 \int_0^{\infty} d\nu_i \frac{\nu_f}{\nu_i} \frac{dP_{conv}}{dV\, d\nu_i} \times \Theta\big(\lambda_{abs}(\nu_f) - N_{scat}(r)\lambda_{scatter}\big)\delta\big(\nu_{obs} - \nu_f(\nu_i, r)\big) \quad (3)$$

Heaviside function accounts for absorption, delta function forces observed frequency to be equal to the final frequency $\nu_f(\nu_i, r)$ after the X-ray has scattered to the surface of the nugget.

$$\frac{d^2 P_{conv}}{dV d\nu} = \epsilon^2\, n_{SM} \sigma_{thoms} 4\pi B_\nu(\nu, T) \quad (4)$$