Title: Signatures of Mirror Stars

Speakers: Jack Setford

Series: Particle Physics

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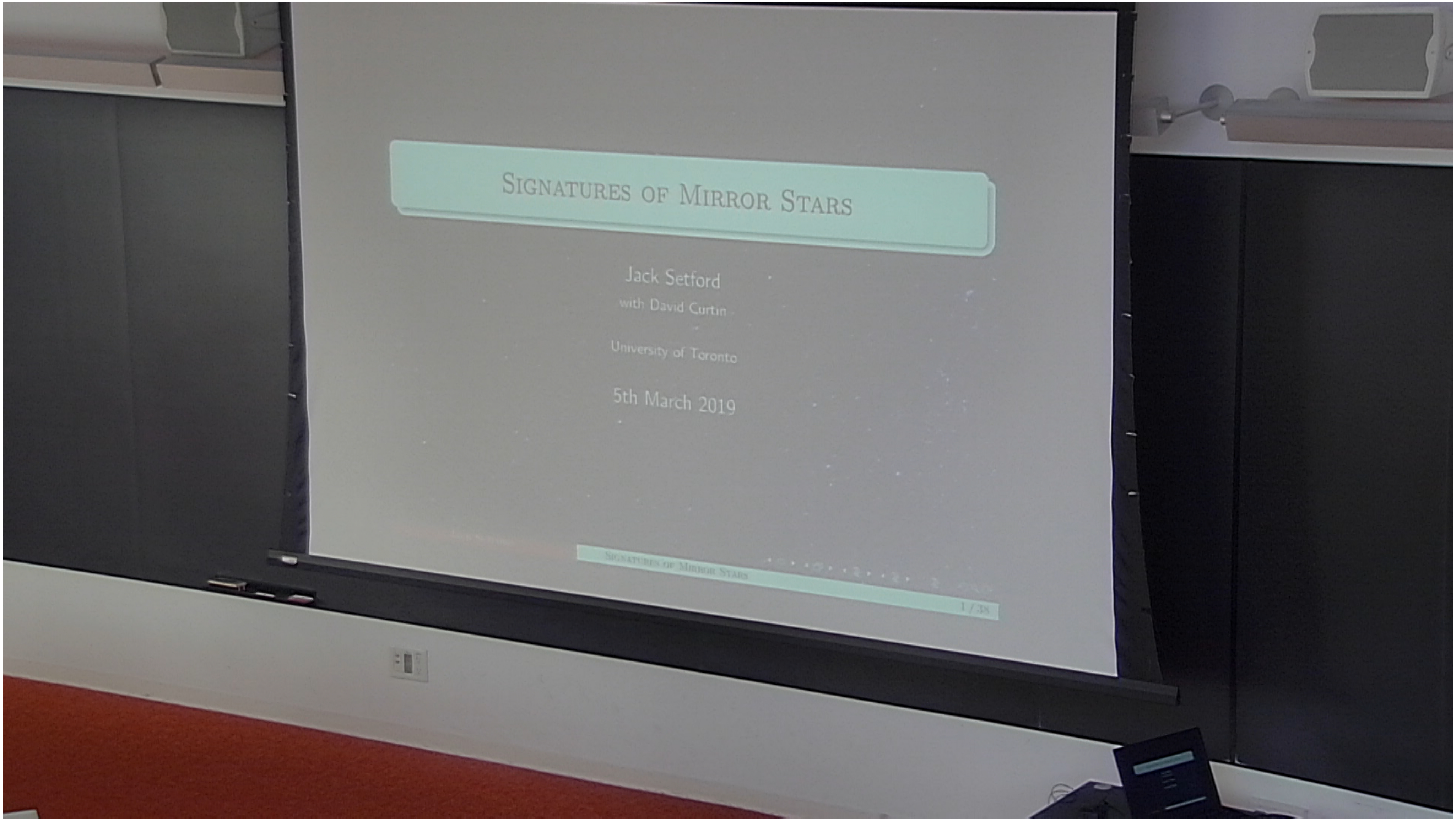
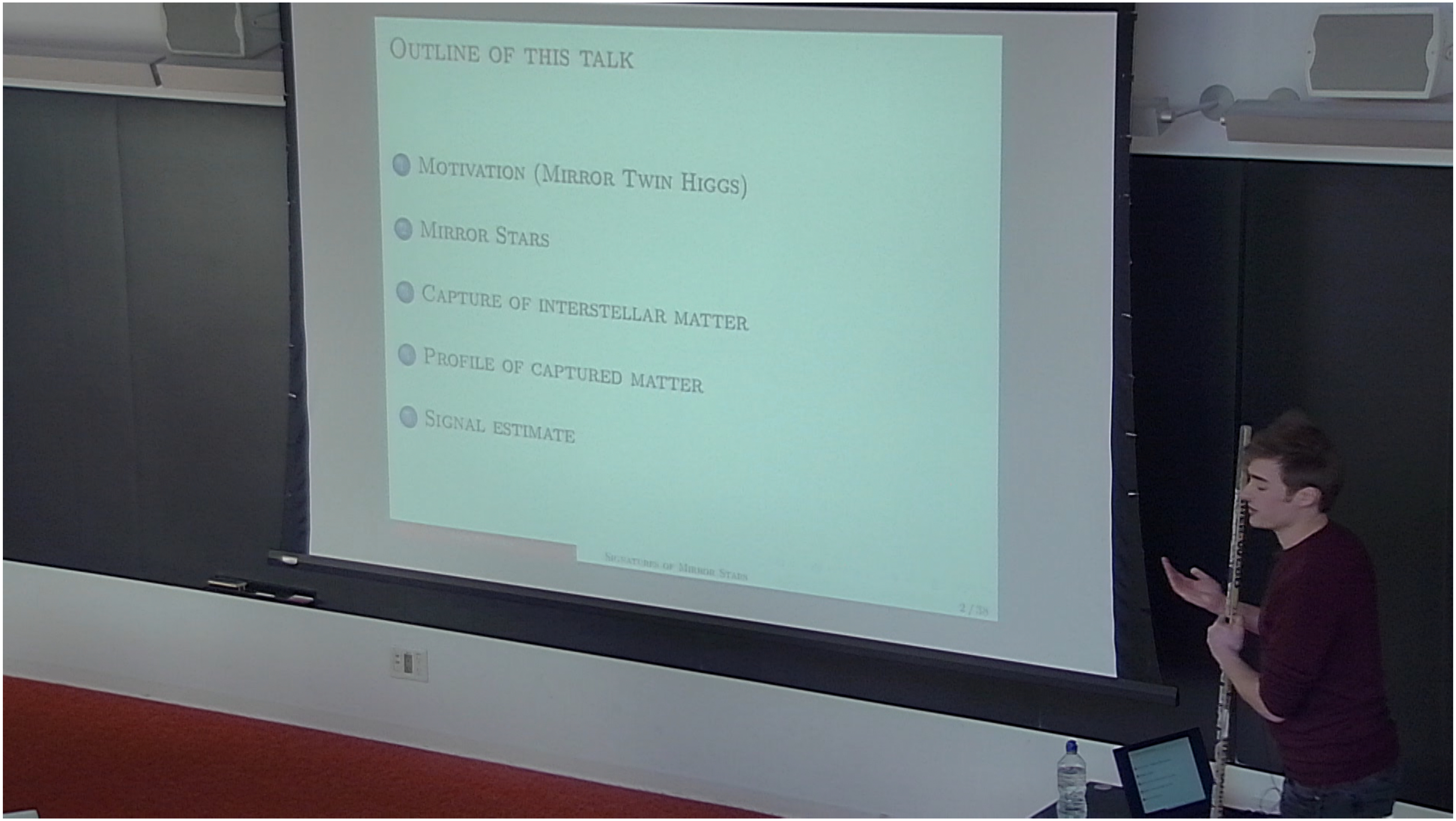
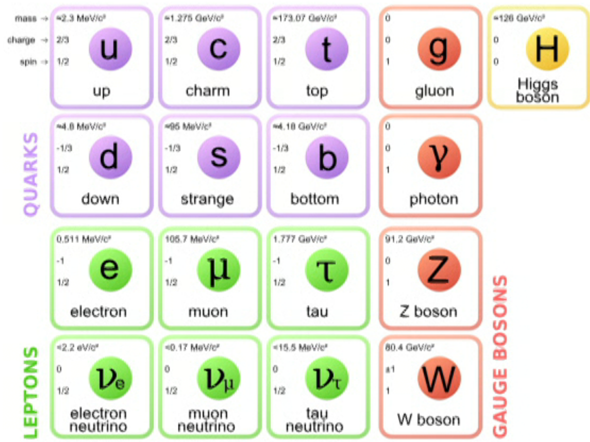
Abstract: Mirror sectors -- hidden sectors that are approximate copies of the Standard Model -- are a generic prediction of many models, notably the Mirror Twin Higgs model. Such models can have a rich cosmology and many interesting detection signatures beyond the realm of colliders. In this talk, I will focus on the possibility that mirror matter can form stars which undergo mirror nuclear fusion in their cores. I will discuss the mechanisms by which these objects can emit Standard Model light and estimate their luminosity and prospects for their detection.


Signatures of Mirror Stars
Jack Setford
with David Curtin
University of Toronto
5th March 2019
Signatures of Mirror Stars
1 / 38


OUTLINE OF THIS TALK
MOTIVATION (MIRROR TWIN HIGGS)
MIRROR STARS
CAPTURE OF INTERSTELLAR MATTER
PROFILE OF CAPTURED MATTER
SIGNAL ESTIMATE
SIGNATURES OF MIRROR STARS

Why mirror sectors?

- Renewed interest in mirror sectors from naturalness-inspired models.
- Mirror Twin Higgs models are neutrally natural (naturally neutral?) and are a well-motivated solution to the hierarchy problem.
- Some versions of the MTH model predict a mirror sector which is an approximate copy of the Standard Model.



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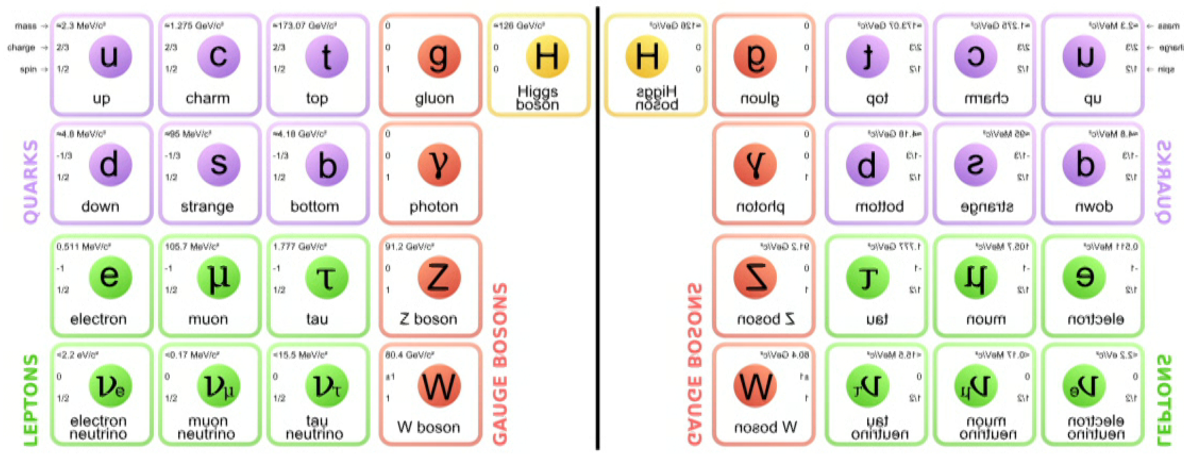


"Approximate copy"?

New Higgs decays to invisibles – need to raise twin Higgs VEV to avoid collider constraints $\rightarrow v_B/v_A \gtrsim 3$.
Cosmological ΔN_{eff} problem. Various ways of getting around this:

- Hard Z_2 breaking in twin Yukawa sector,
- Remove 1st and 2nd generation twin fermions $\rightarrow$ Fraternal Twin Higgs,
- Asymmetric reheating, for instance by adding a $\mathcal{O}(10)$ GeV right-handed neutrino $\rightarrow \Delta N_{eff} \approx 7.4\,(v_A/v_B)^2$.

[Chacko, Craig, Fox, Harnik, arXiv:1611.07975]
[Craig, Koren, Trott, arXiv:1611.07977]

Some basic twin nuclear physics

Proton and neutron masses:

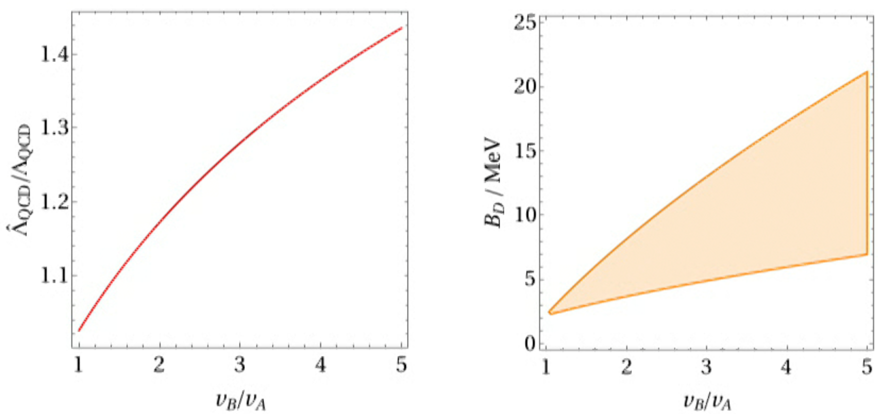
[Chacko, Curtin, Geller, Tsai, arXiv:1803.03263]

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

Deuterium binding energy:

$$B_{\hat{D}}^{min} = -(0.66 \text{ MeV}) + 0.021\, m_{\hat{\pi}} \quad (1)$$

$$B_{\hat{D}}^{max} = -(9.2 \text{ MeV}) + 0.084\, m_{\hat{\pi}} \quad (2)$$



Twin cosmology

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

- Mirror sector cannot account for the total dark matter abundance (large scale structure bounds, self-interaction bounds) – is at most 1-10% of total DM density.
- Input parameters ΔN_{eff}, v_B/v_A, $\Omega_{mirror}/\Omega_{DM}$.
- $\rightarrow$ Mirror helium mass fraction $\approx 75\%$.

Beyond collider signatures

- Null results at colliders.
- Neutral naturalness *by construction* is more difficult to test at the LHC.
- Cosmological / astrophysical signatures are important to investigate.
- Cosmological signatures complementary with long-lived particle signatures.

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.

STARS!

Standard Model stars were a particularly easy scientific discovery.

Mirror photons

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

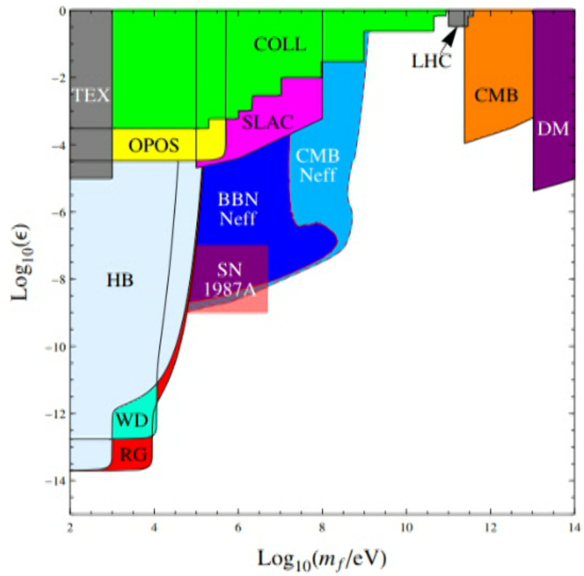
$$\mathcal{L} \supset \frac{\epsilon}{2} F_{\mu\nu} \hat{F}^{\mu\nu}$$

Current bounds on ϵ are

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

In MTH, ϵ is forbidden at 1- and 2-loop, so small value arises naturally.

[Vogel, Redondo, arXiv:1311.2600]

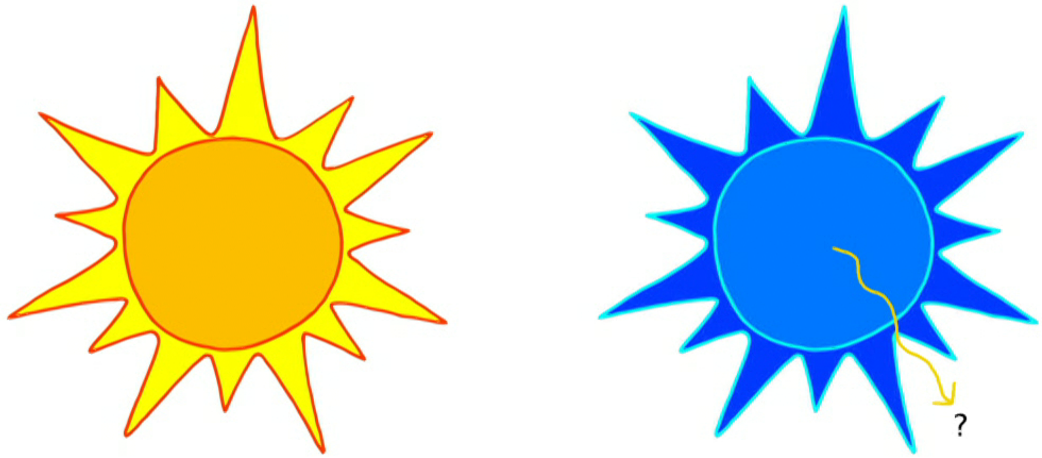


Mirror photons

Basis freedom:

	$U(1)_{SM}$	$U(1)_{mirror}$
SM	1	ϵ
Mirror	0	1

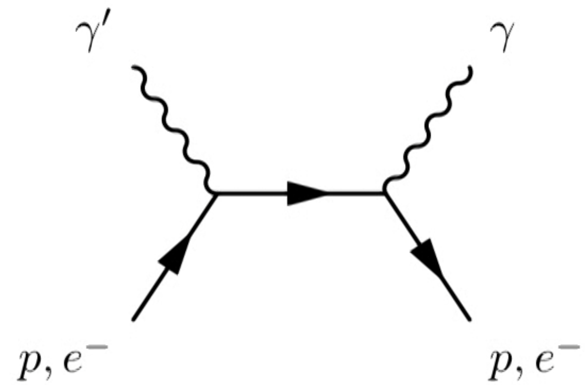
	$U(1)_{SM}$	$U(1)_{mirror}$
SM	1	0
Mirror	ϵ	1

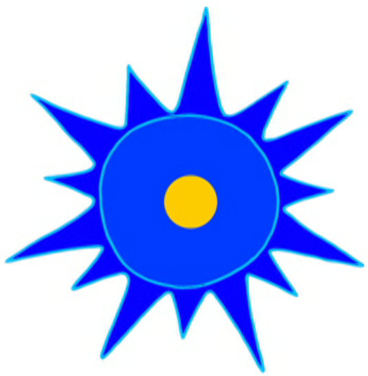


We can see mirror photons from the surface of a mirror star at intensity $\epsilon^2\times$ its mirror intensity.

Interaction with SM matter

If there is any SM matter in the star – especially ionized matter – it will induce mirror photon conversion. If the SM matter density is sufficiently low (optically thin), these photons will immediately escape the star.





Assume some density of captured material ρ_{SM} in the star. Can we estimate the rate of SM photons leaving the star?

Naive estimate

Mirror photon produced in the core travels distance $D = R^2/\lambda_{mirror}$ before it leaves the region of capture. Define some λ_{SM}, mean length to travel before conversion. Approximately a fraction D/λ_{SM} will convert.

$$\frac{L_{SM}}{L_{mirror}} = \frac{D}{\lambda_{SM}} = \frac{R^2}{\lambda_{mirror}\lambda_{SM}} \tag{3}$$

Mean free path $\lambda = 1/(n\sigma)$, and for Thomson scattering we can write $\sigma_{SM} \sim \epsilon^2\sigma$...

$$\frac{L_{SM}}{L_{mirror}} = \frac{R^2}{\lambda_{mirror}^2}\frac{n_{SM}}{n_{mirror}}\epsilon^2. \tag{4}$$

Therefore we want to understand both the *amount* of captured matter and its profile within the star.

Simulating mirror stars

How to simulate a mirror star:

- Starting point, assume star is composed of mirror hydrogen and mirror helium.
- Understand different reaction rates and energy output; weaker weak interaction, higher deuterium binding energy, etc.
- Solve equations of stellar structure:

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2} \qquad \frac{dM}{dr} = 4\pi r^2 \rho(r)$$

$$\frac{dL}{dr} = 4\pi r^2 \rho(r)\epsilon(r) \qquad \frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa(r)\rho(r)}{T(r)^3}\frac{L(r)}{4\pi r^2}$$

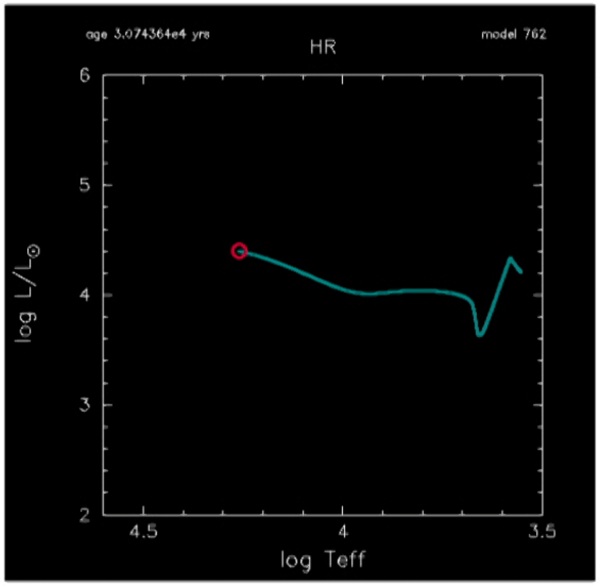
- Understand mirror opacity in terms of fundamental parameters.

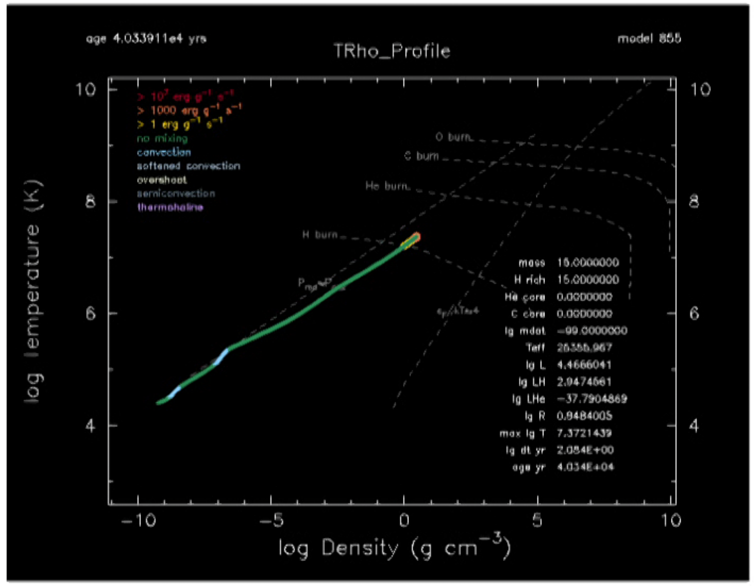
Understanding the signal

- Understanding mirror nuclear and stellar physics is interesting – project in its own right.
- We're interested in a broader class of models that may lead to mirror stars.
- Let's try and better understand the signal – assume for now that the mirror stars are Standard Model like, i.e. same opacity, same reaction rates and energy output.

SM-like mirror stars

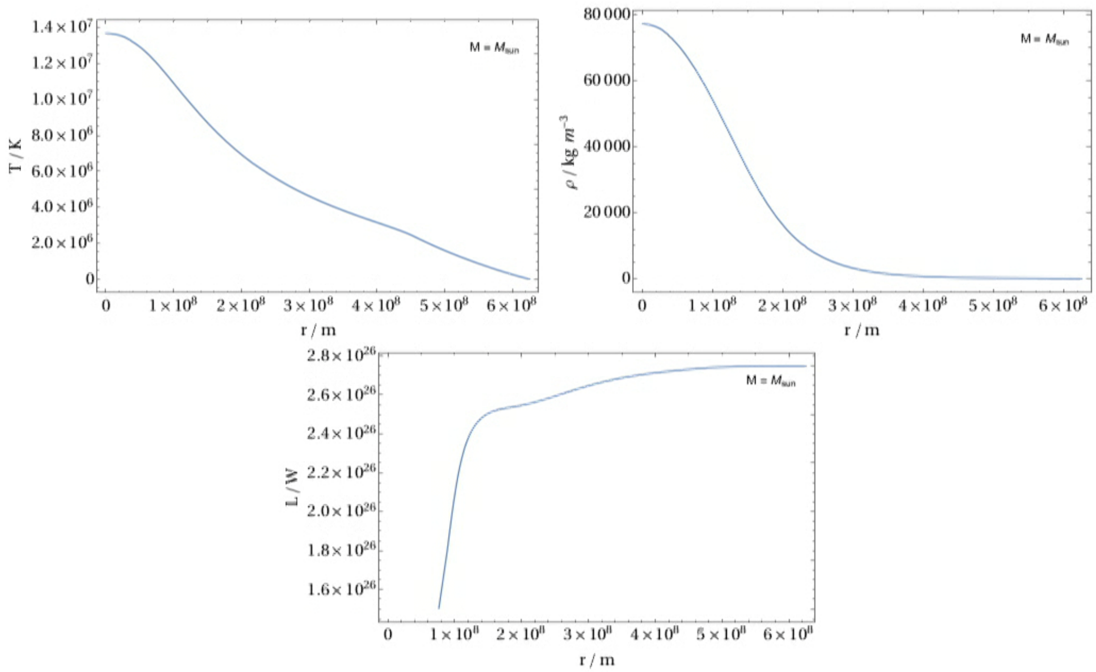
- Mirror stars are SM-like, i.e. same opacity, same reaction rates and energy output.
- Generate stellar profiles using MESA for different masses.





SM-like mirror stars

Benchmark star with $M = M_{sun}$.



Similarly have profiles for pressure, opacity, composition, etc.

Signal calculation

Towards calculating the density of captured matter...

Capture:

- Mirror capture of SM (SM nuclei scattering off mirror stellar matter)
- Self-capture (SM nuclei scattering off captured SM nuclei)

Escape:

- Evaporation (SM ejection via collision with particles in the star, SM or mirror)

Heating:

- Collisional heating (collisions between mirror nuclei and captured SM nuclei / atoms)

Cooling:

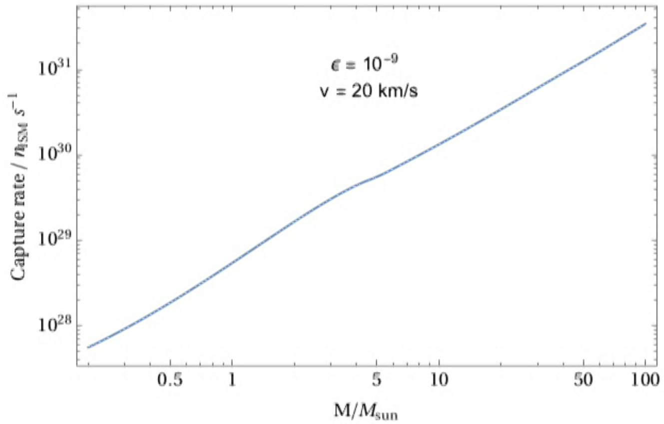
- Bremsstrahlung cooling (energy loss to photons via SM-SM scattering)

Mirror capture of SM

Incoming wind of SM matter (ionized and atomic).
Capture rate for hydrogen (assuming scattering off mirror hydrogen):

$$\Omega(w,r) = n\,w\,\Theta\left(1-\frac{u^2}{w^2}\right)\int_{E_k(u)}^{E_k(w)}\frac{d\sigma}{dE}dE,$$

where $w = \sqrt{u^2 + v_{escape}^2(r)}$.



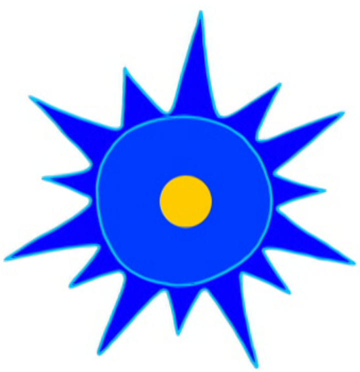
Capture rate scales with ϵ^2.

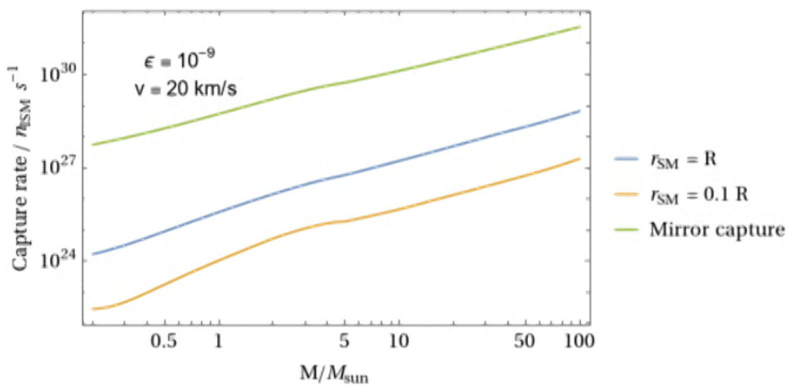
Geometric capture limit

Once density of captured material exceeds $\epsilon^2 n_{mirror}$, incoming matter is more likely to scatter off captured matter than mirror matter.

Capture rate is proportional to amount captured, $\frac{dN_{SM}}{dt} \propto N_{SM}$. Capture grows exponentially, until geometric limit is reached (scales with r_{SM}^2).

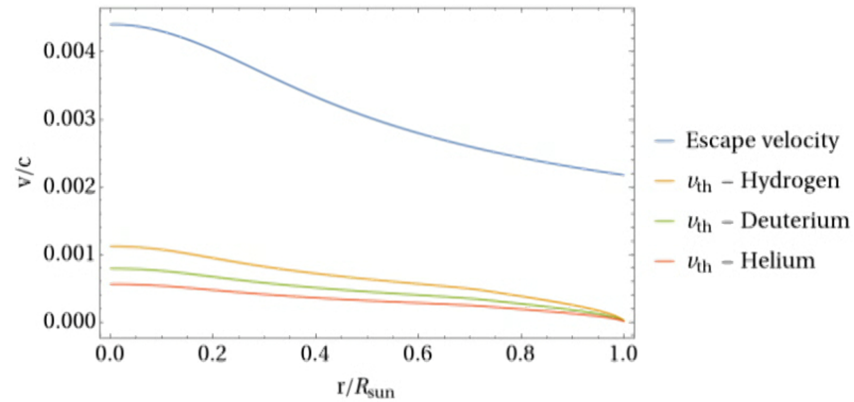
$$\sigma_{capture} \leq \pi r_{SM}^2$$





Evaporation

Thermal velocities are usually not so far below the escape velocity.



Evaporation probability:

$$P_{evaporation} \propto \exp\left(-\frac{mv_{escape}^2}{2kT}\right)$$

Critical mass, above which evaporation is neglibile on stellar lifetime. For the sun $m_{crit} \approx 3.5$ GeV.

$\rightarrow$ Hydrogen efficiently evaporates – most captured material will be helium.

Profile of captured matter

First assume that the captured material is in isothermal hydrostatic equilibrium. Interactions with the mirror matter provide an external pressure source.

$$P_{external} = \epsilon^2 P_{mirror}.$$

Equation for isothermal hydrostatic equilibrium:

$$kT\frac{dn}{dr} + \epsilon^2 \frac{dP_{mirror}}{dr} = -\frac{GM(r)\, m\, n(r)}{r^2}$$

(Ignores captured matter gravitational self-interactions)

Look for a solution, then try and justify isothermal assumption.

Profile solution

$$\frac{dn}{dr} + A(r)\,n = B(r)$$

$$A(r) = \frac{GM(r)m}{kTr^2} \quad B(r) = -\frac{\epsilon^2}{kT}\frac{dP_{mirror}}{dr}$$

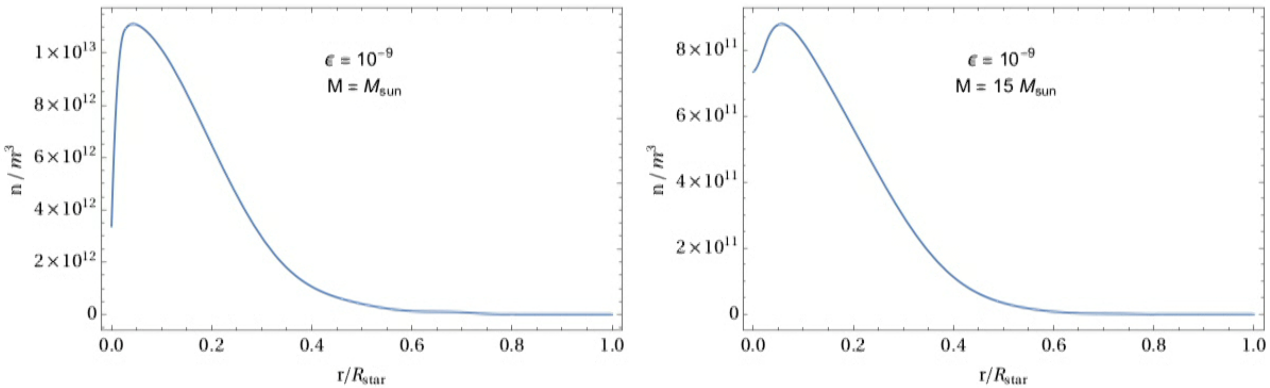
Can solve with an integrating factor.

$$n(r) = e^{-\int A(r)dr}\int B(r)e^{\int A(r)dr}dr + Ce^{-\int A(r)dr}$$

C is a constant of integration, grows as more material is added.

For $\int A(r)dr \gg 1$ first term is well approximated by $B(r)/A(r)$.

Profile solution



Outer profile mostly independent of temperature.

Required amount of material to satisfy solution accumulates very quickly.

Inner solution $\sim e^{-\int A(r)dr}$, characteristic radius from virial theorem:

$$r_{inner} \approx \sqrt{\frac{9kT}{4\pi G \rho_{mirror} m}}$$

Heating

Collisions between captured particles (nuclei and atoms) with mirror nuclei will heat the captured material. If captured material cools sufficiently it will be primarily atomic rather than ionized.

Cross section between atoms and nuclei:

$$\frac{d\sigma}{d\Omega} = \frac{2\pi\epsilon^2\alpha^2 Z_1^2 Z_2^2 \mu^2}{\alpha^2 m_e^2 + q^2}$$

At low q the interaction is a contact interaction – at high q it reduces to Rutherford scattering.
Heating rate per unit volume

$$P_{heat} \sim n_{SM}\, n_{mirror}\, \sigma\, v_{rel}\, k\, T_{mirror}$$

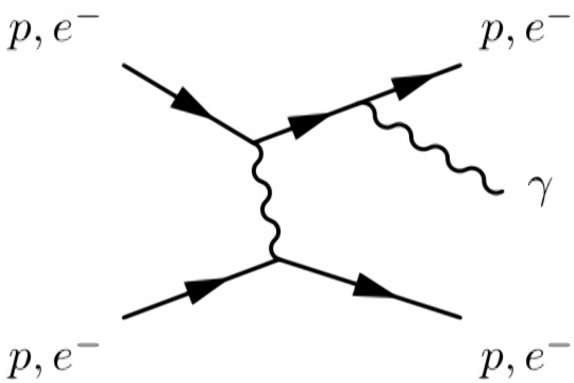
Incoming wind of hydrogen also deposits energy into the captured material.

Cooling

Captured matter eventually becomes dense enough that cooling via bremsstrahlung emission becomes efficient.

Rate of energy loss due to bremsstrahlung:

$$P_{brems} = \frac{16}{3}\sqrt{\frac{2\pi}{3}} n_X n_e \frac{\alpha^3}{m_e^{3/2}} T^{1/2} \bar{g}_{ff}$$



Assumes optically thin – have to check.

Also contributes to SM signal!

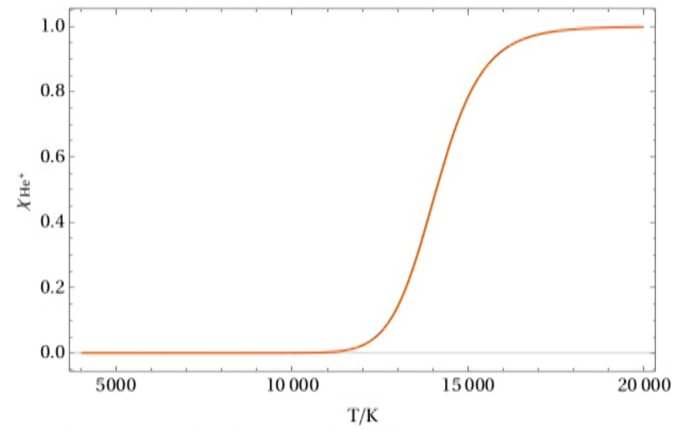
Need to calculate n_X, n_e as a function of T. Saha equation?

Ionized fraction

For optically thin gas, ionization fraction is given by ratios of ionization and recombination cross sections.

For instance, for helium:

$$\chi_{H^+} = \frac{\langle \sigma_{\rm ion} v \rangle}{\langle \sigma_{\rm ion} v \rangle + \langle \sigma_{\rm rec} v \rangle},$$



Cooling depends on ionized fraction – cooling rate for all processes becomes negligible below $\mathcal{O}(1000\ \mathrm{K})$.

Solving for equilibrium temperature

Solve for T in the outer and inner regions – equate collisional heating power with bremsstrahlung power.

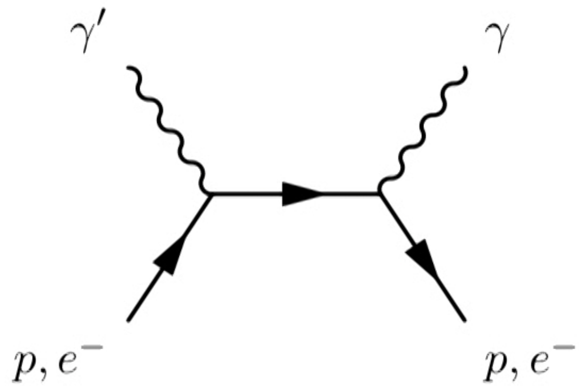
- Outer region, take n as input and solve for T_{outer}.
- Inner region, take number of captured particles as input. Density is a function of virial radius which is a function of temperature $\rightarrow$ solve for T_{inner}.

Results:

- Equilibrium temperatures of around 6000 K (inner region) and 12000 K (outer region).
- Figures do not depend strongly on the mass of the star.
- At these temperatures and densities the gas is optically thin.

Conversion signal

In principle the conversion rate is frequency dependent (similar to the opacity of the stellar material). We will only calculate conversion via Thomson scattering, which is frequency independent.



$$\sigma_{conv} = \frac{8\pi}{3}\frac{\epsilon^2\alpha^2}{m_e^2}.$$

Intensity into SM light:

$$I(\nu)\,d\nu = \int_0^R dr\,4\pi r^2\,\Gamma\,B(T(r),\nu)\,d\nu$$

where Γ is the conversion rate.

Cooling signal

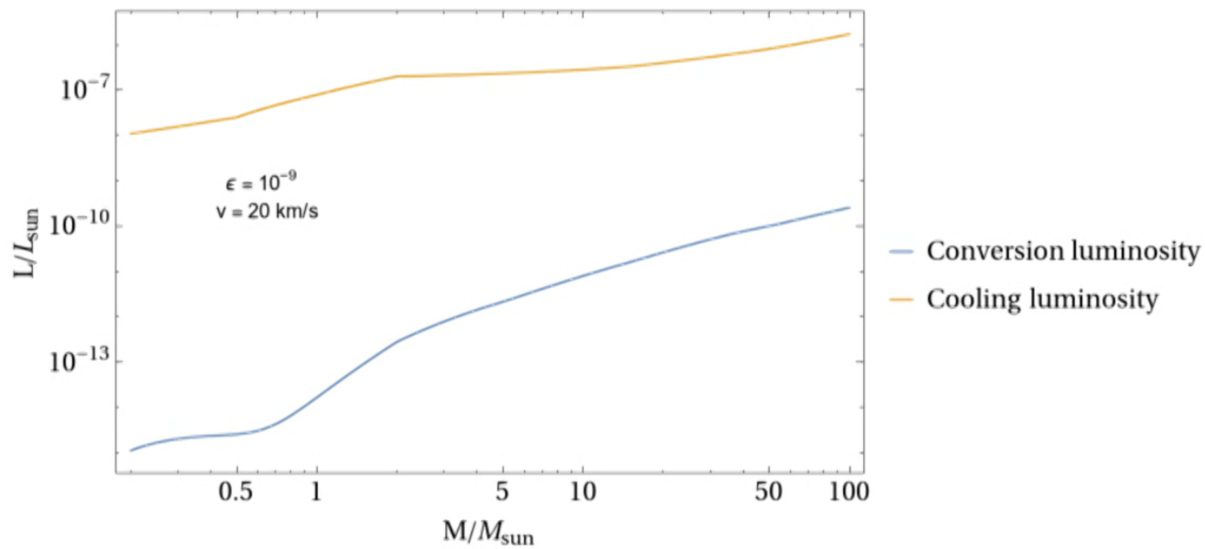
- We can estimate the cooling signal using the heating rate as a function of core density.

$$P_{heat} \sim n_{SM}\, n_{mirror}\, \sigma\, v_{rel}\, k\, T_{mirror}$$

- Visible light signal.
- Potential dual signal, in X-ray and in visible spectrum.

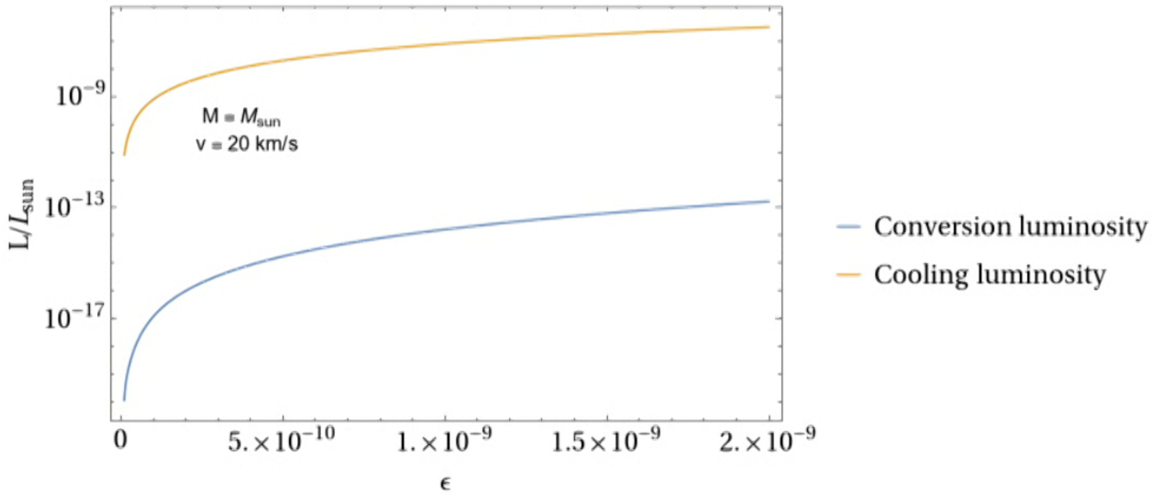
Results

Luminosity as a function of star mass:



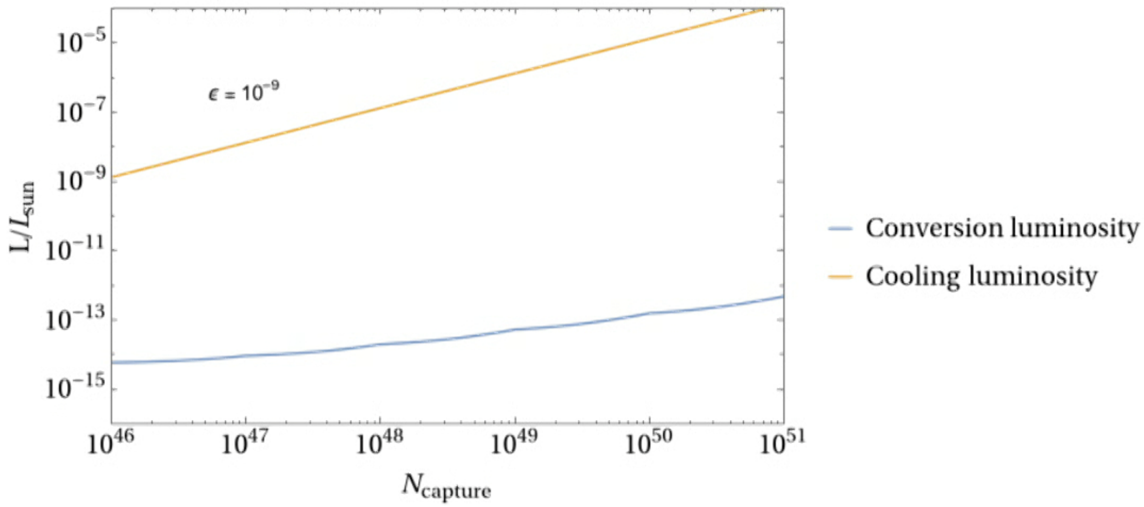
Results

Luminosity as a function of ϵ, for one solar mass star:



Results

Luminosity as a function of amount of captured matter, for one solar mass star:

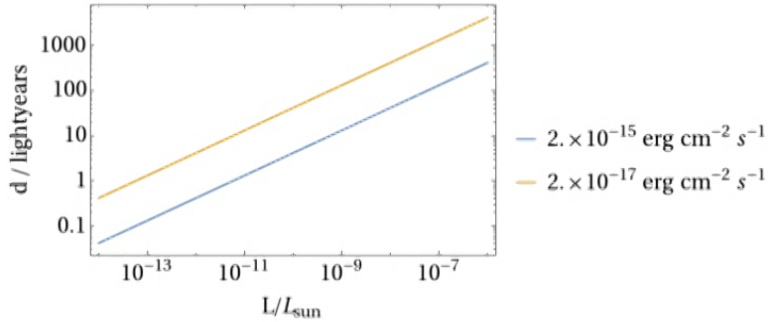


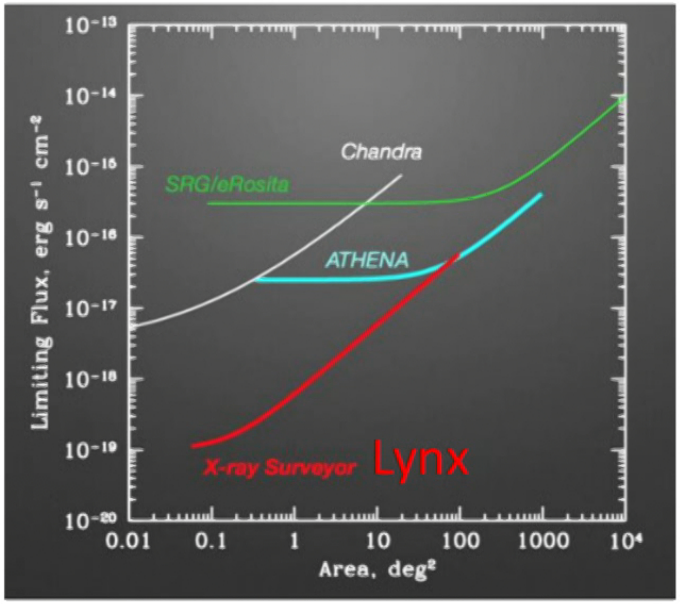
Reasonable values for $N_{capture}$ (for a solar mass mirror star) are around $10^{47} - 10^{48}$.

So could we see Mirror Stars?

$\epsilon = 10^{-9}$, $M = M_{sun}$, $d = 1$ ly:
Incident flux in X-ray
$\approx 3 \times 10^{-18}$ erg cm^{-2} s^{-1}

$\epsilon = 10^{-9}$, $M = 15\,M_{sun}$, $d = 1$ ly:
Incident flux in X-ray
$\approx 3 \times 10^{-15}$ erg cm^{-2} s^{-1}





So could we see Mirror Stars?

More promising might be visible light signature.

At 10 light years, our one solar mass benchmark has the same apparent magnitude as Callirrhoe (moon of Jupiter, discovered 2000). $m \approx 21$.

At 100 light years, the same star has the same apparent magnitude as Fenrir (moon of Saturn, discovered 2004). $m \approx 25$.

Same magnitude as if the sun were around 40,000 light years away. For comparison, Gaia aims to catalogue all stars brighter than magnitude 20.

Conclusions

- Mirror sectors theoretically well-motivated.
- Mirror stars can efficiently capture interstellar matter, which enables photon conversion into detectable light, potentially detectable X-ray signal
- Heating and cooling of captured matter also produced a visible spectrum signal.
- Weird signal – faint, nearby, hot object with an X-ray signal. Close $\rightarrow$ parallax.