Hunting for axions in the solar basin

W. DeRocco,[1] J. Huang,[2] K. Van Tilburg,[3, 4] S. Wegsman[3]

[1]*Stanford University*

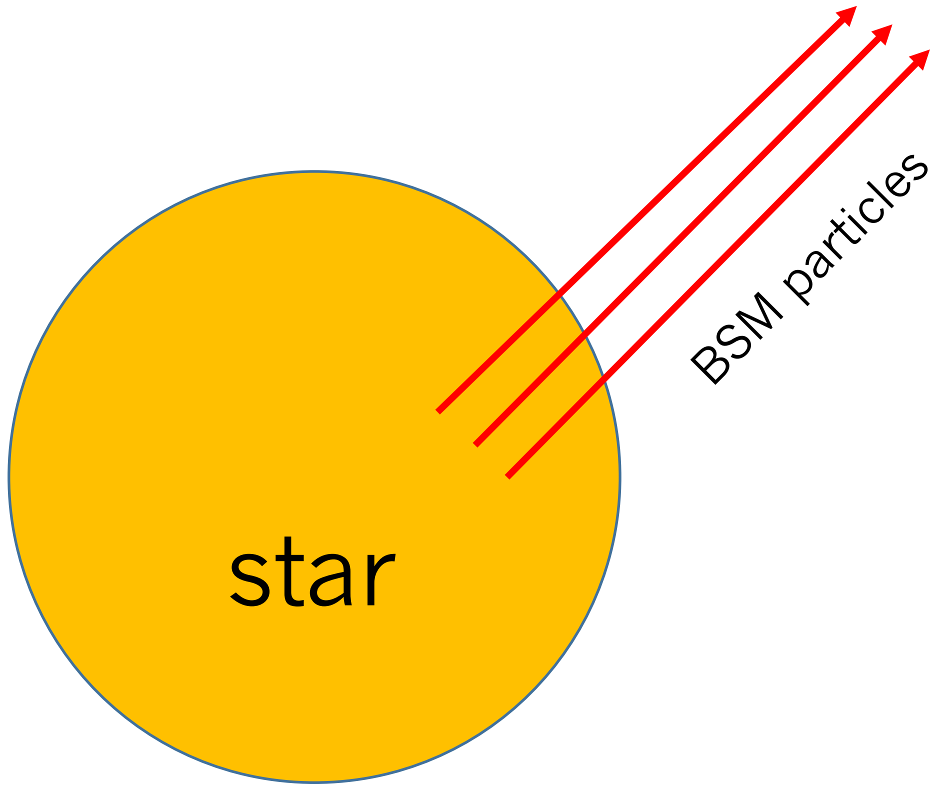
[2]*Perimeter Institute*

[3]*New York University*

[4]*Flatiron Institute*

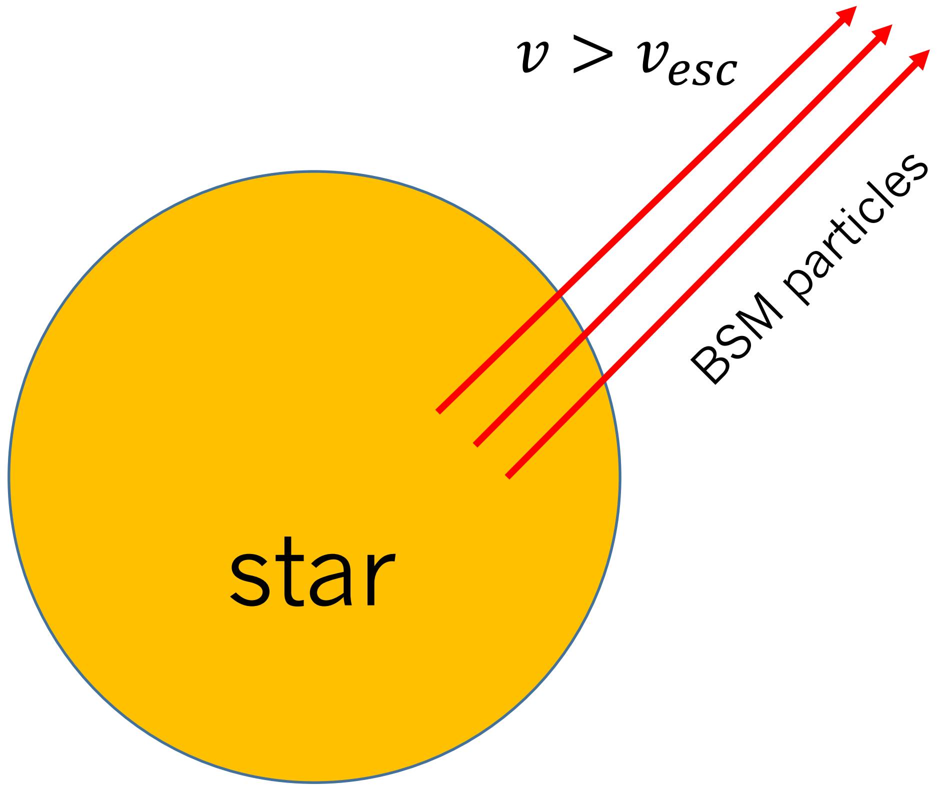
Motivation

- Stars are well-known to be excellent sources of new particles



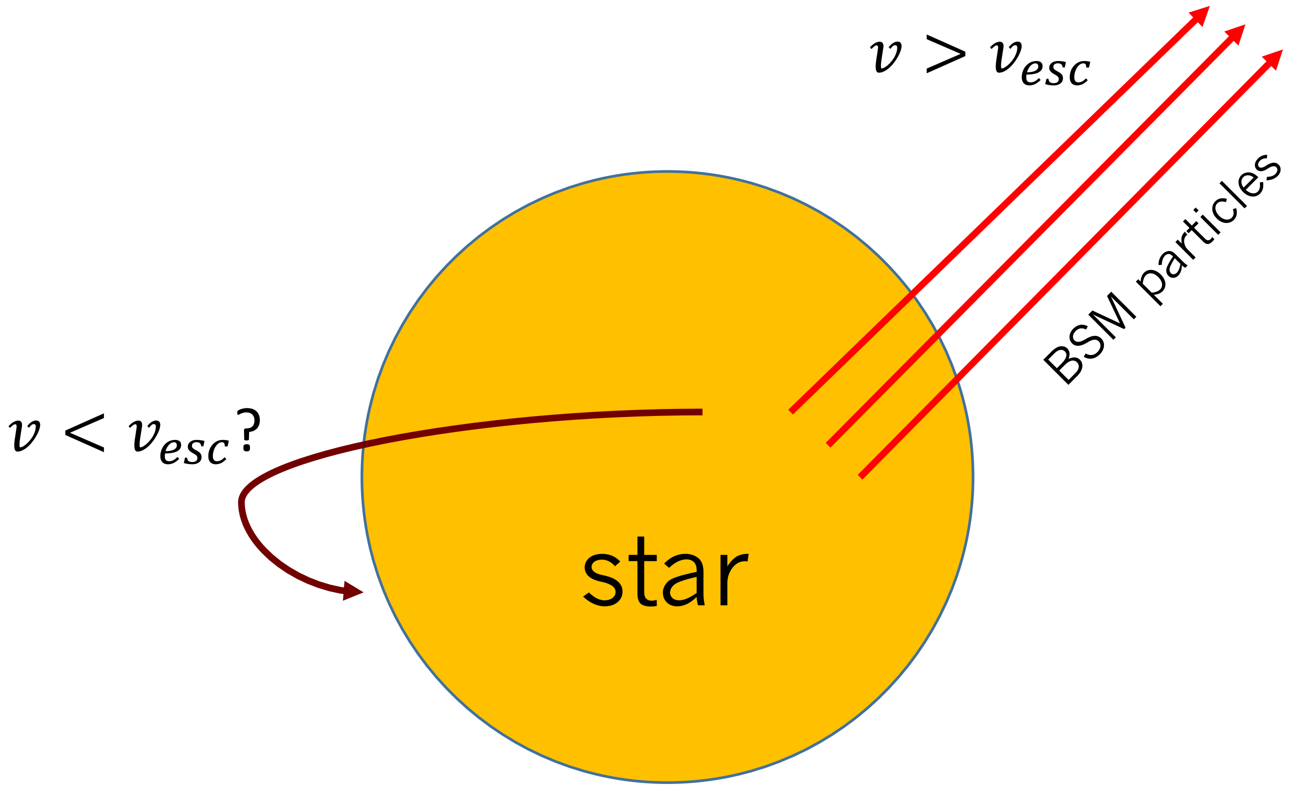
Motivation

- Stars are well-known to be excellent sources of new particles
- Most analyses focus on escaping flux



Motivation

- Stars are well-known to be excellent sources of new particles
- Most analyses focus on escaping flux
- What about the low-velocity tail?



Outline

- **Part I:** Stellar basins are a generic phenomenon
- **Part II:** Existing observations of the Sun may shed new light on axions

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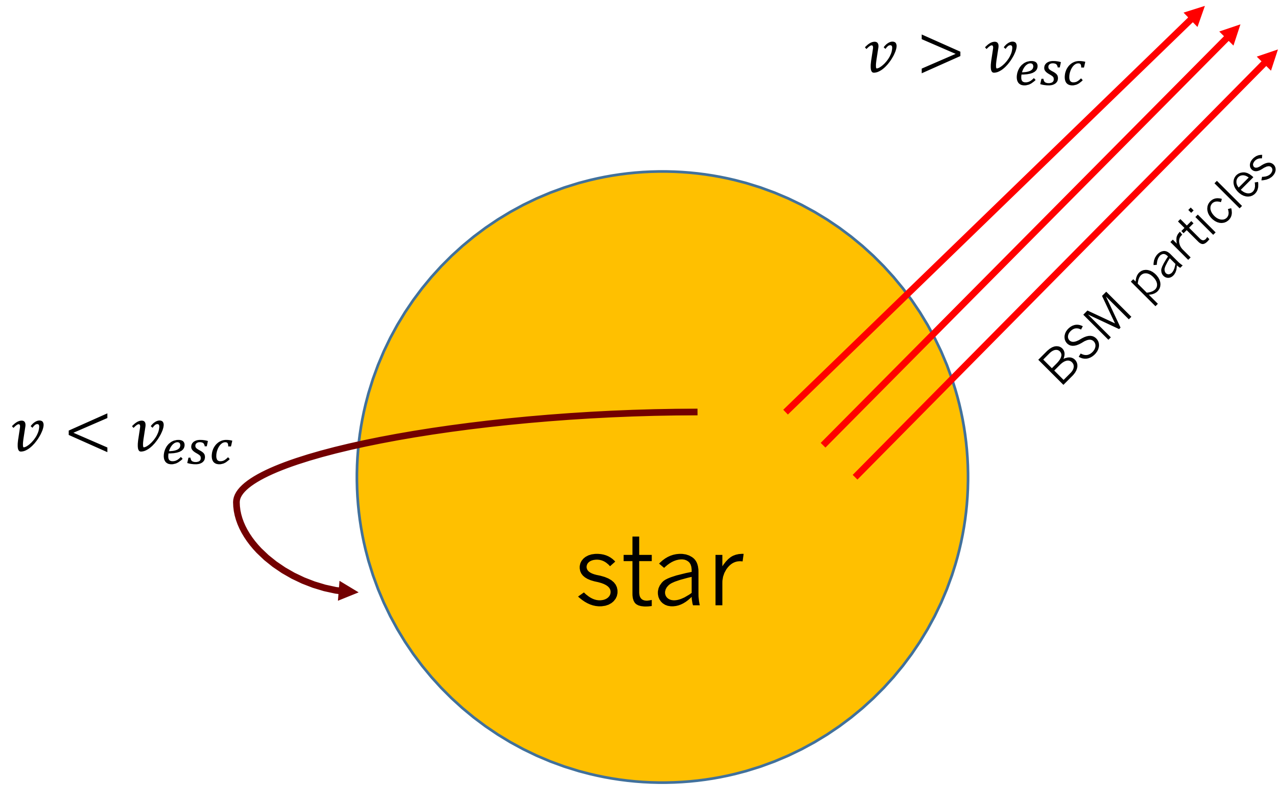
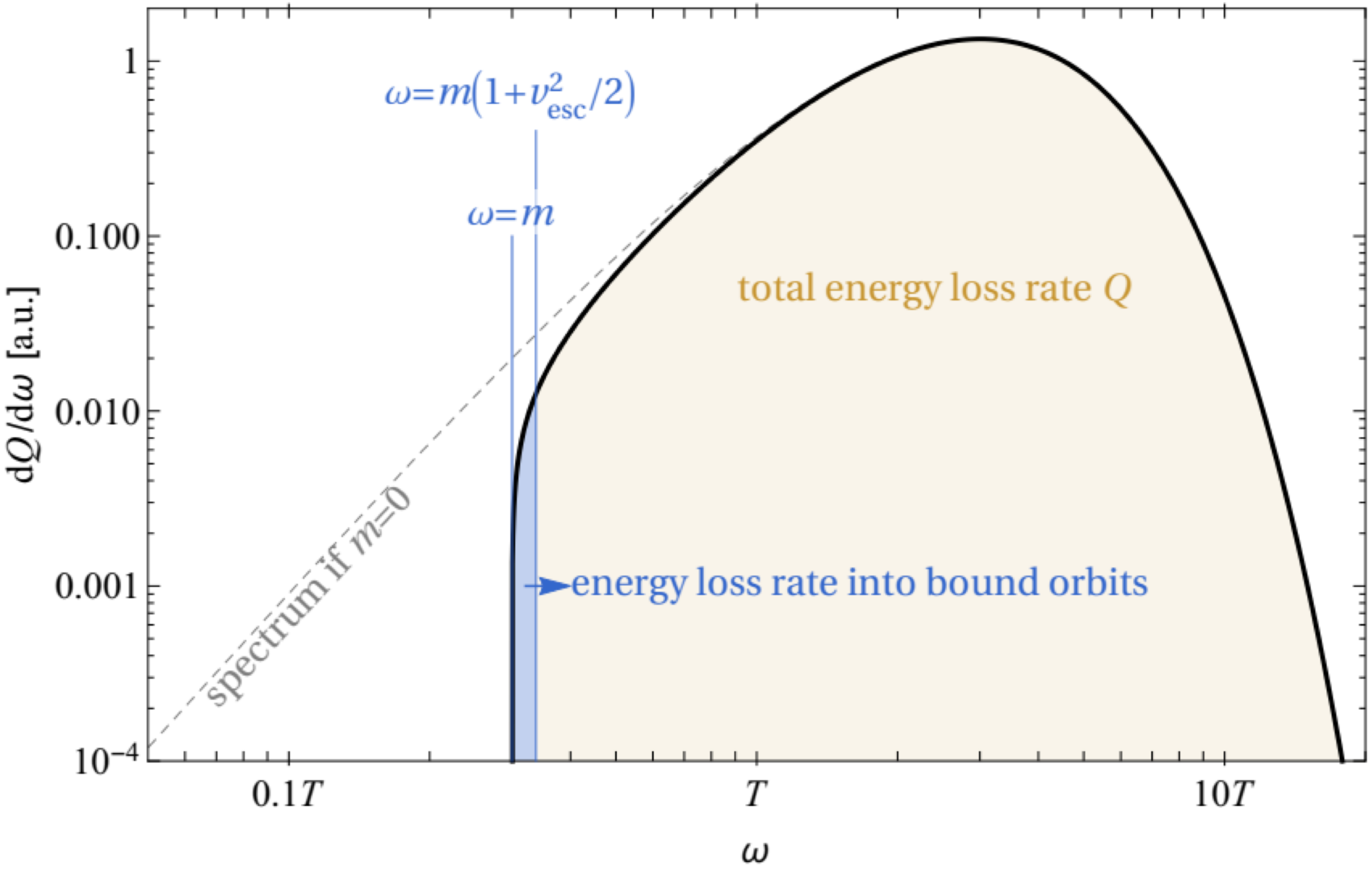
Gravitational trapping

- Low-velocity particles cannot escape gravitational well



Low-velocity tail

- Low-velocity particles cannot escape gravitational well
- Small fraction of spectrum



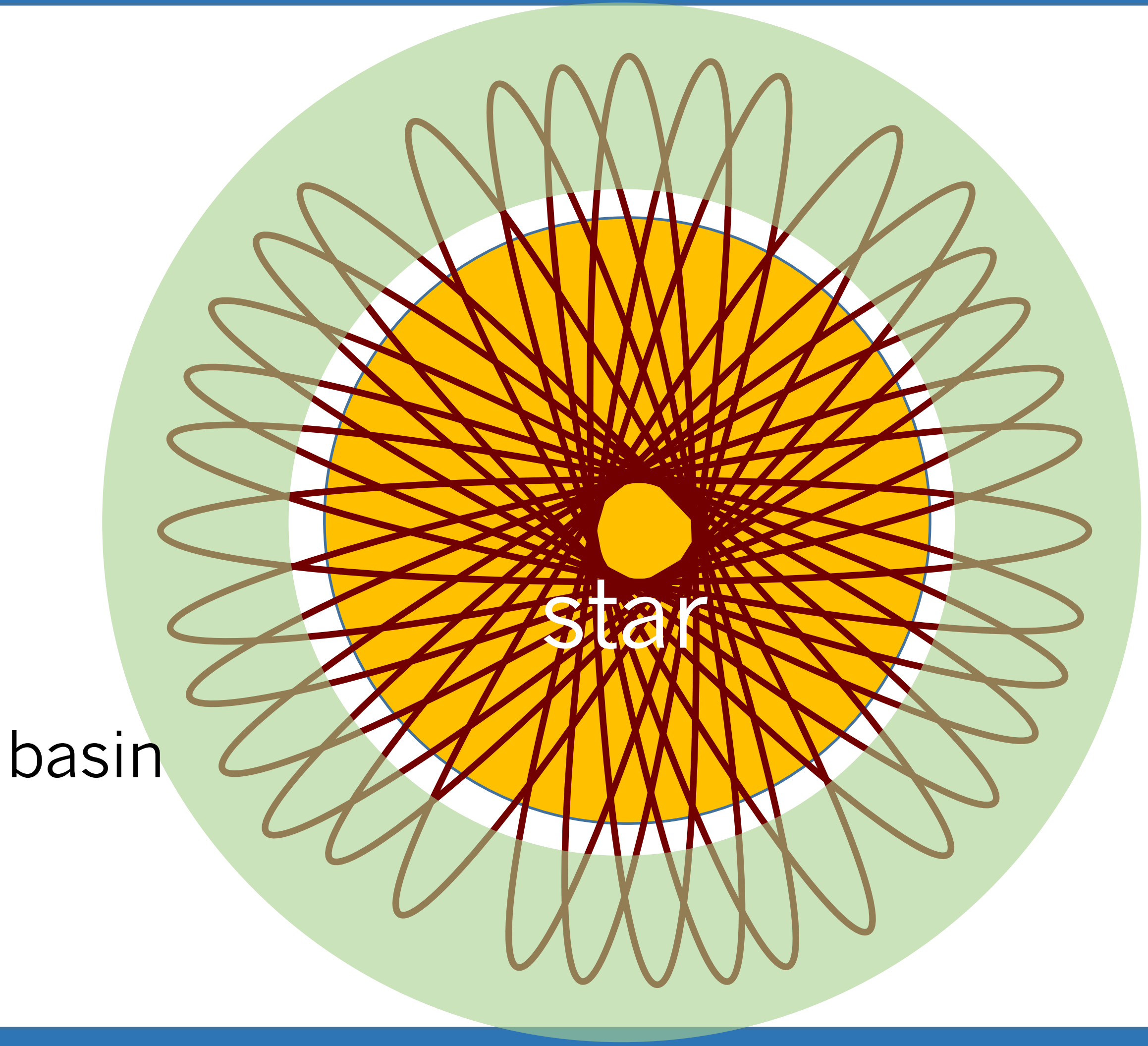
https://arxiv.org/pdf/2006.12431.pdf

Stellar basin

- Low-velocity particles cannot escape gravitational well
- Small fraction of spectrum
- Long accumulation time!

$$\rho(r) \sim \dot{\rho}(r)\tau$$

- Particles accumulate to form "**stellar basin**"

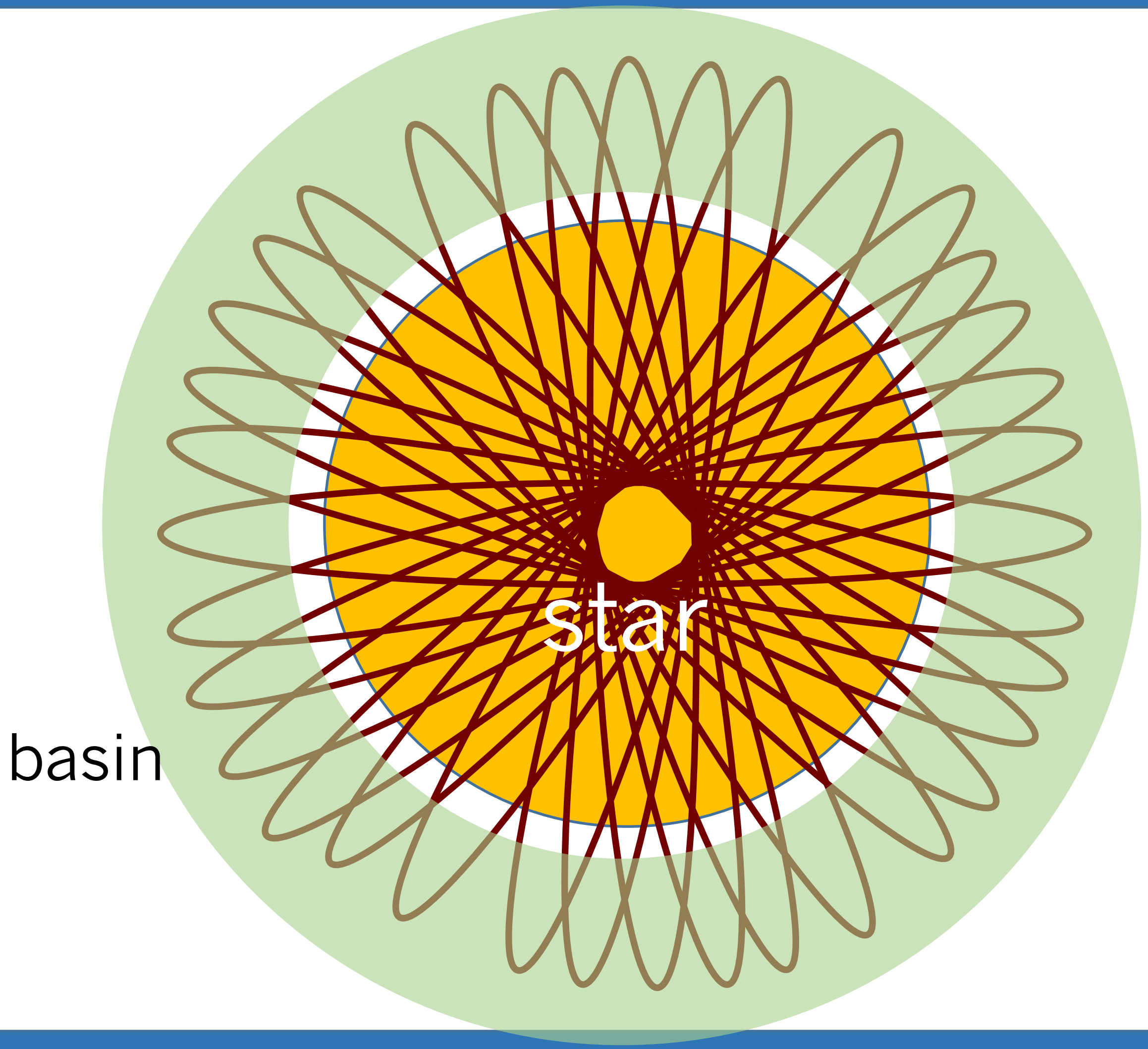


Stellar basin

- Low-velocity particles cannot escape gravitational well
- Small fraction of spectrum
- Long accumulation time!

$$\rho_b(r) \sim \dot{\rho_b}(r)\tau$$
$$\Rightarrow \rho_b\ (r) \gg \rho_{DM}$$

- High abundance leads to new signatures!



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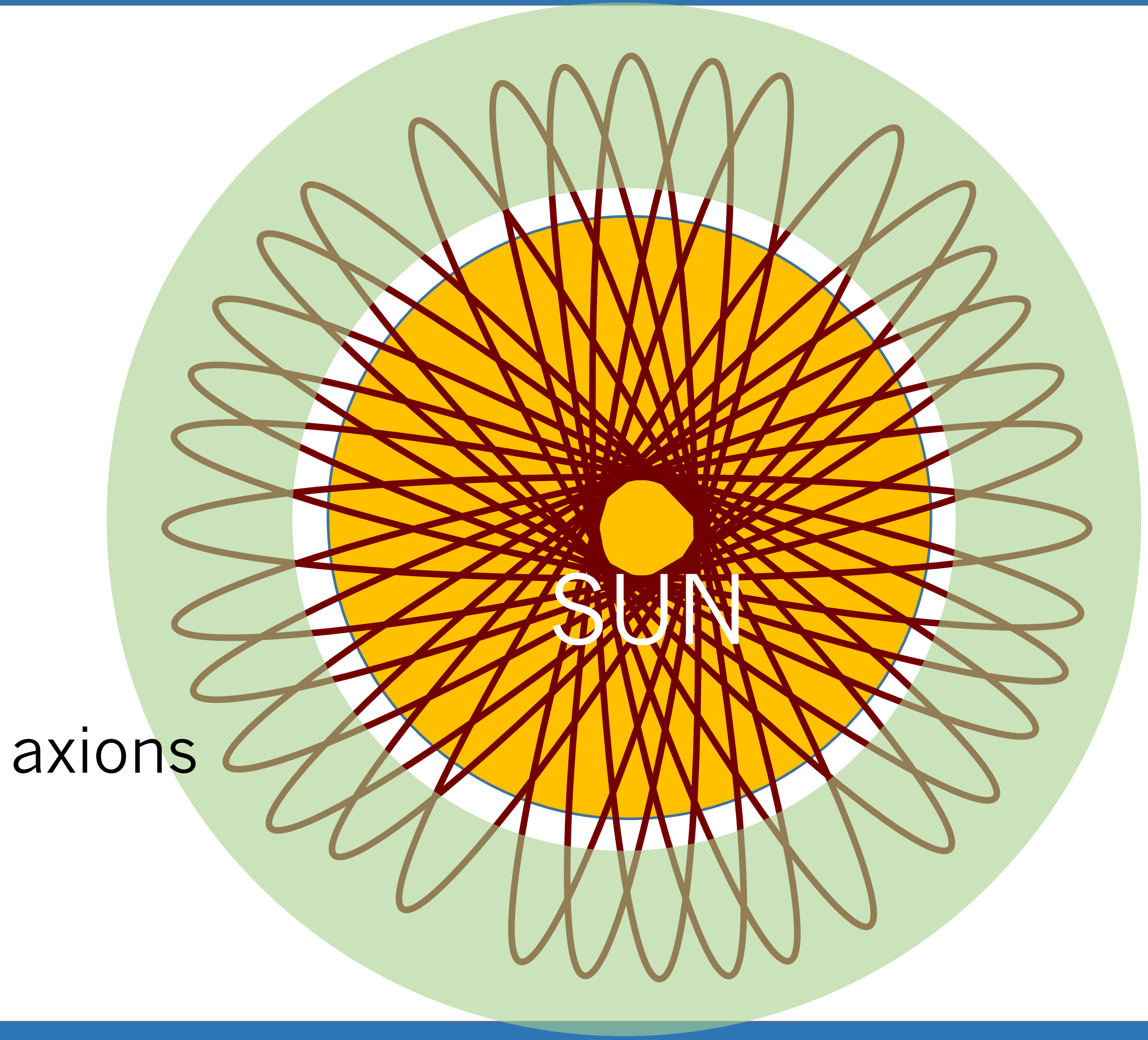
Solar basin

- Low-velocity particles cannot escape gravitational well
- Particles accumulate to form "**stellar basin**"
- What can we see in our very own solar basin?
  - **Axions!**



Model

$$\mathcal{L} \subset -\frac{1}{2}m_a^2 a^2 + \frac{g_{aee}}{2m_e}(\partial_\mu a)\bar{\psi}_e \gamma^\mu \gamma^5 \psi_e - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$$

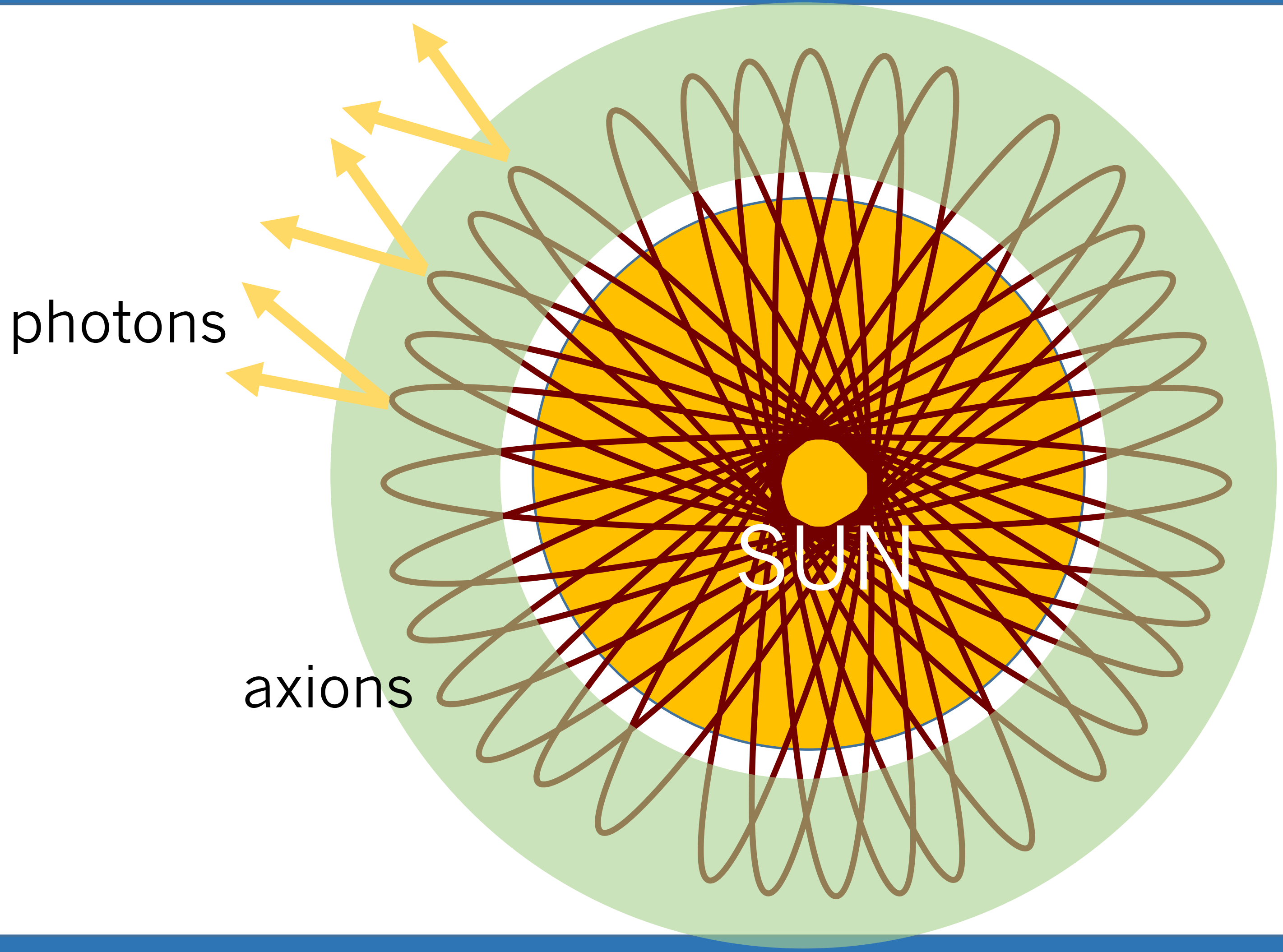
Mass near temperature of solar core

Production by electrons in solar core

Decay to two photons/ Primakoff production

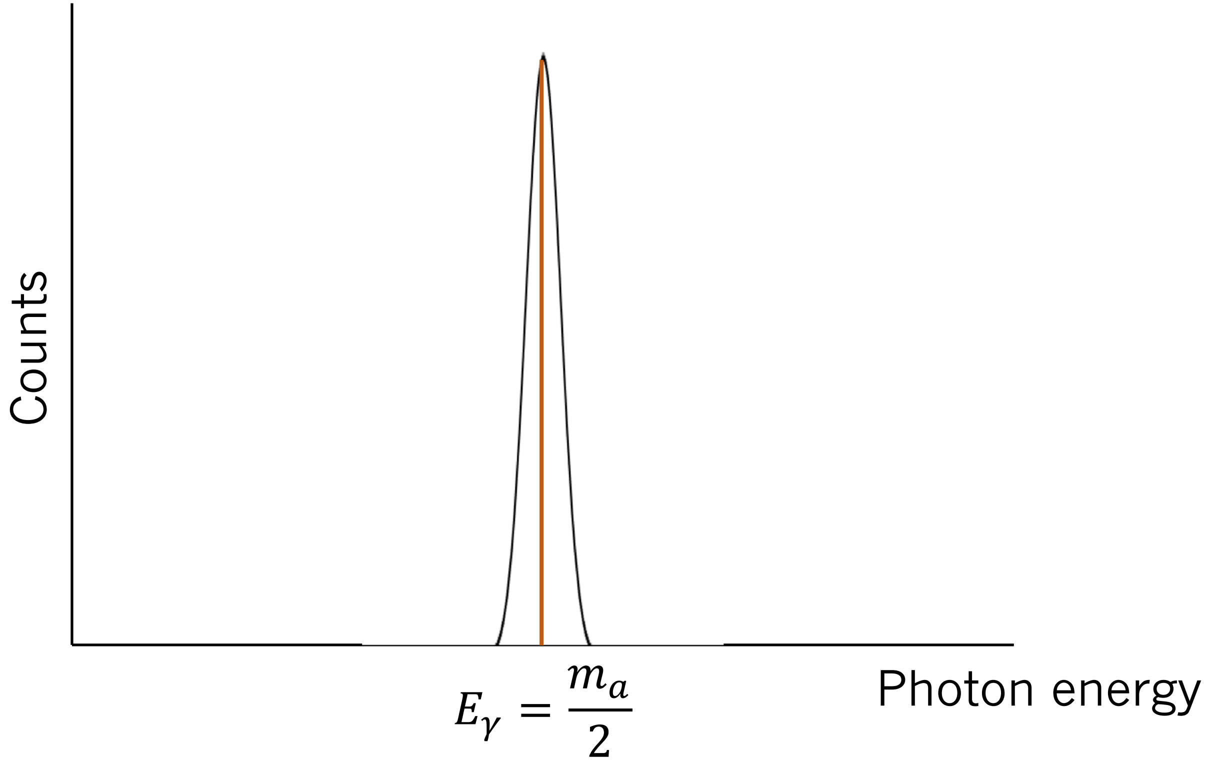
Observable signatures

- Low-velocity particles cannot escape gravitational well
- Particles accumulate to form "**stellar basin**"
- Axions produced in solar core accumulate around the Sun for $\tau \sim \frac{1}{\Gamma}$
- Decay to two photons is observable



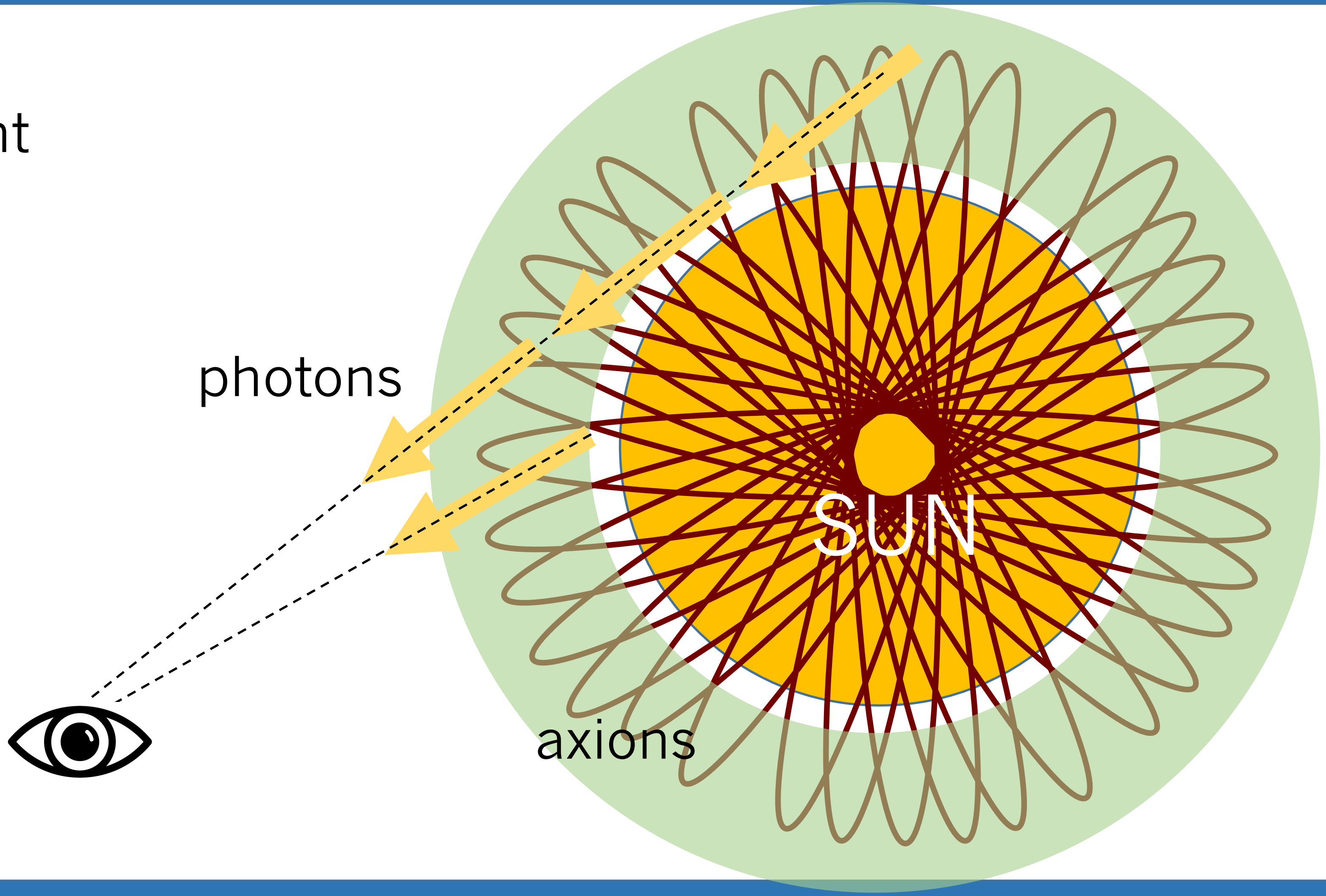
Decay signatures: energy spectrum

- Signal maximized at $m_a \approx T_{sun}(0)$
- Axions decay near rest
- **X-ray line at ~ keV energy**



Decay signatures: spatial template

- Integrated line of sight doubles at solar limb

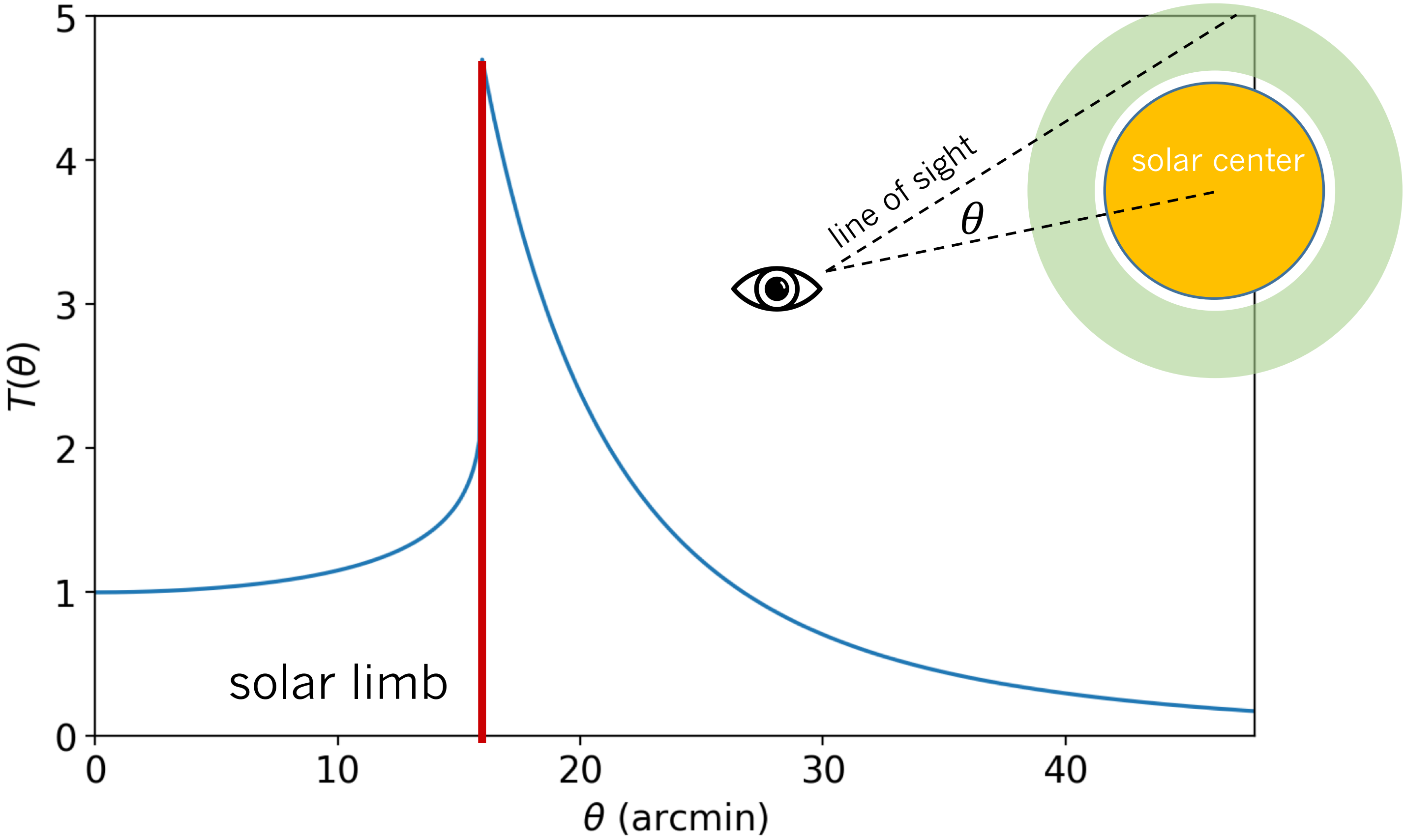


Decay signatures: spatial template

- Integrated line of sight doubles at solar limb
- Signal falls off with

$$T(\theta) \propto \int dl\, R^{-4} \propto \theta^{-3}$$

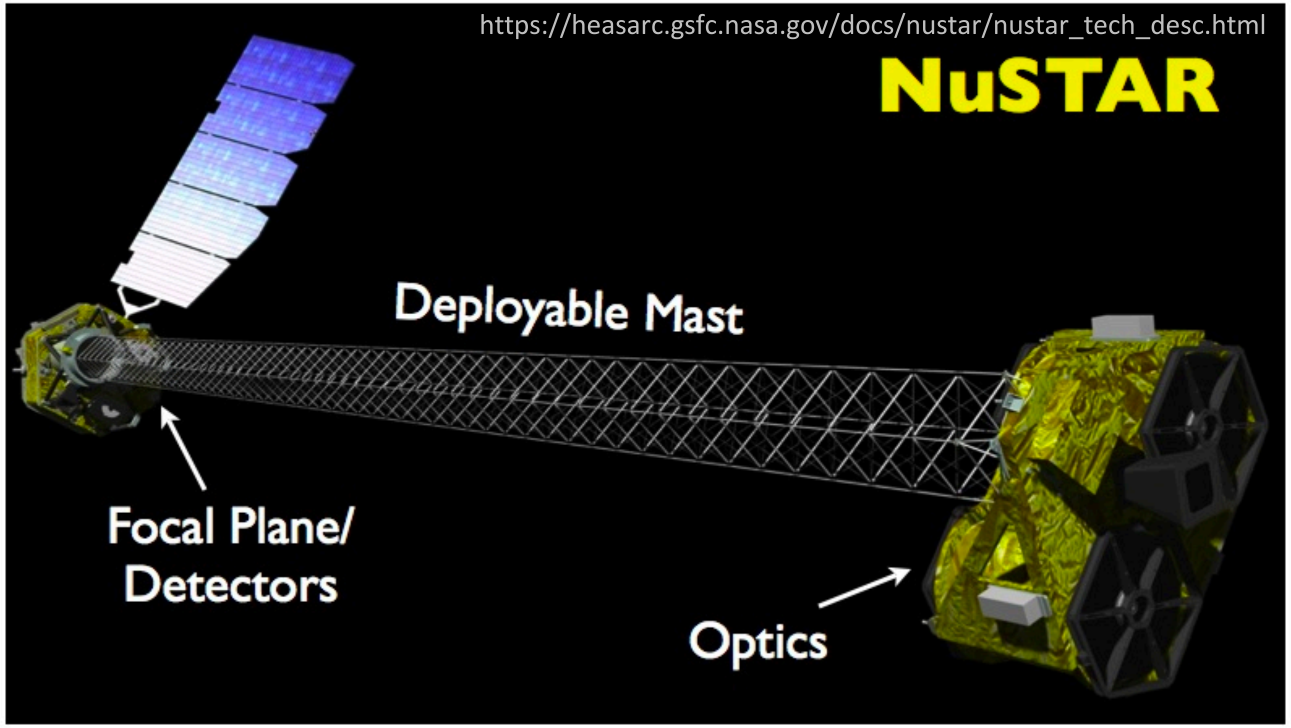
- **Profile with ~ arcmin-scale features**



$\theta \equiv$ angle from solar center

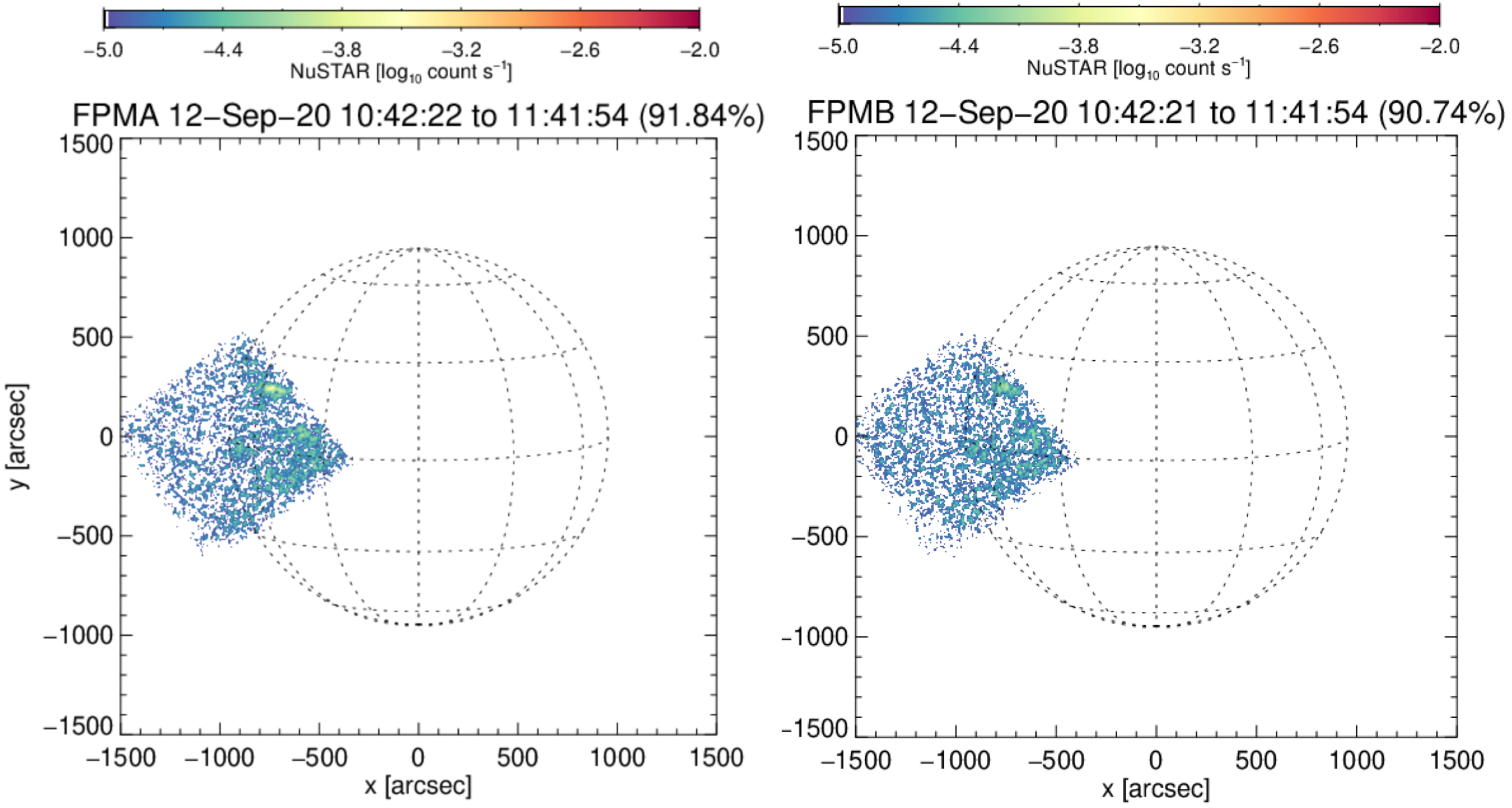
NuSTAR

- Orbital X-ray telescope
- Two identical detectors (FPMA and FPMB)
- Energy range: 3 - 78 keV; 40 eV bins
- Angular resolution ~ 0.3 arcmin



New data

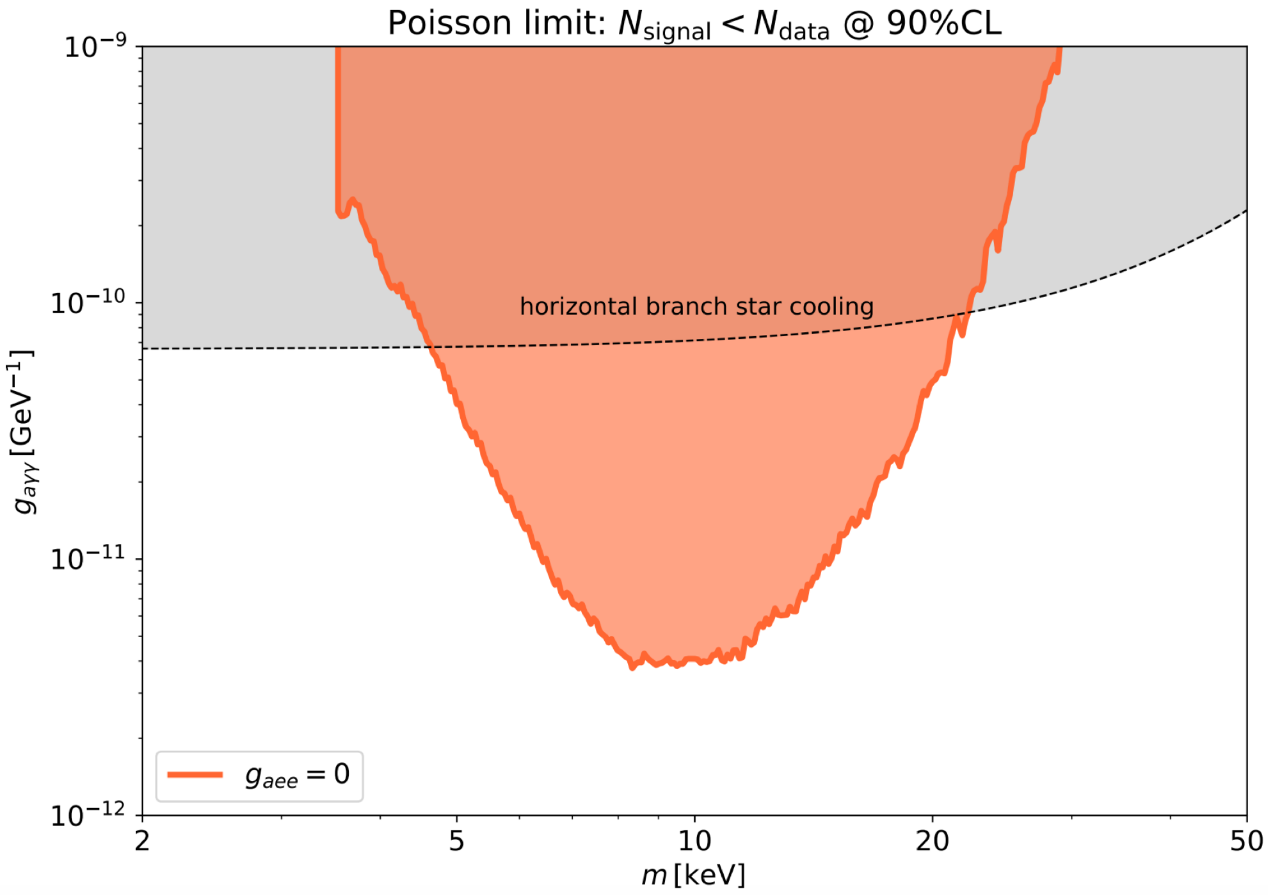
- Recent quiescent limb dwells (September 2020)
- Very clean dataset with discovery potential!



https://github.com/ianan/nsigh_all/blob/master/maps/maps_20200912/maps_20200912_104222_nu80610202001_FPMA.png

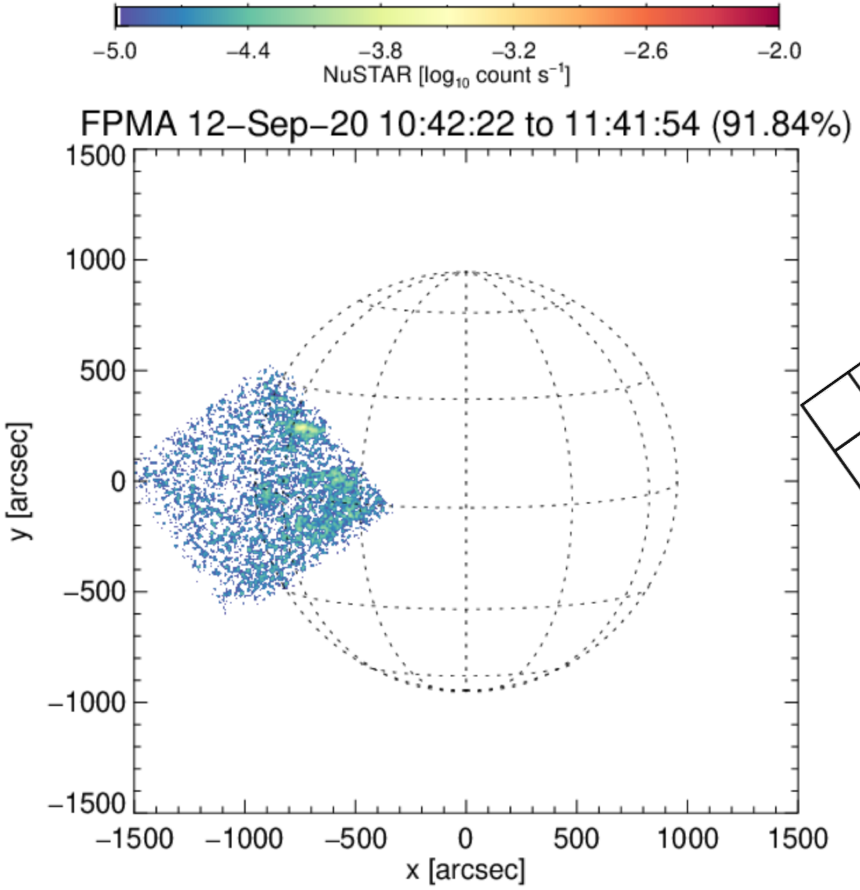
Initial constraints

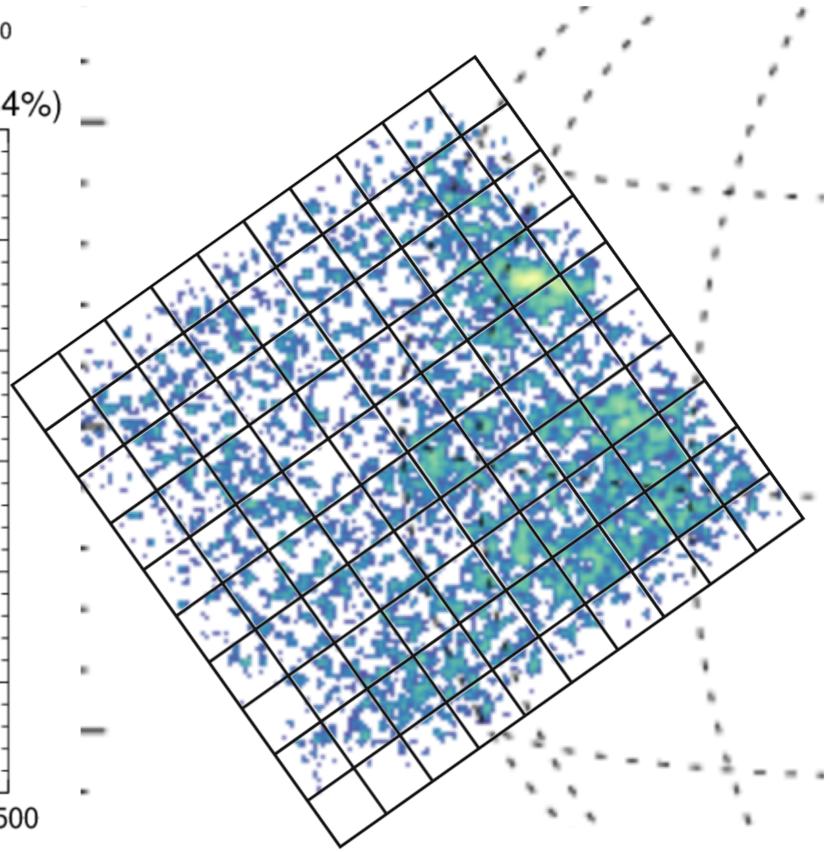
- Naive Poisson limit
- **Improves constraints by over an order of magnitude**
- But this can only improve…



Future work

- Grid FOV into 13 x 13 $arcmin^2$ regions for both detectors
- Fit with spatial template
- Compute log-likelihood ratio for signal at particular mass





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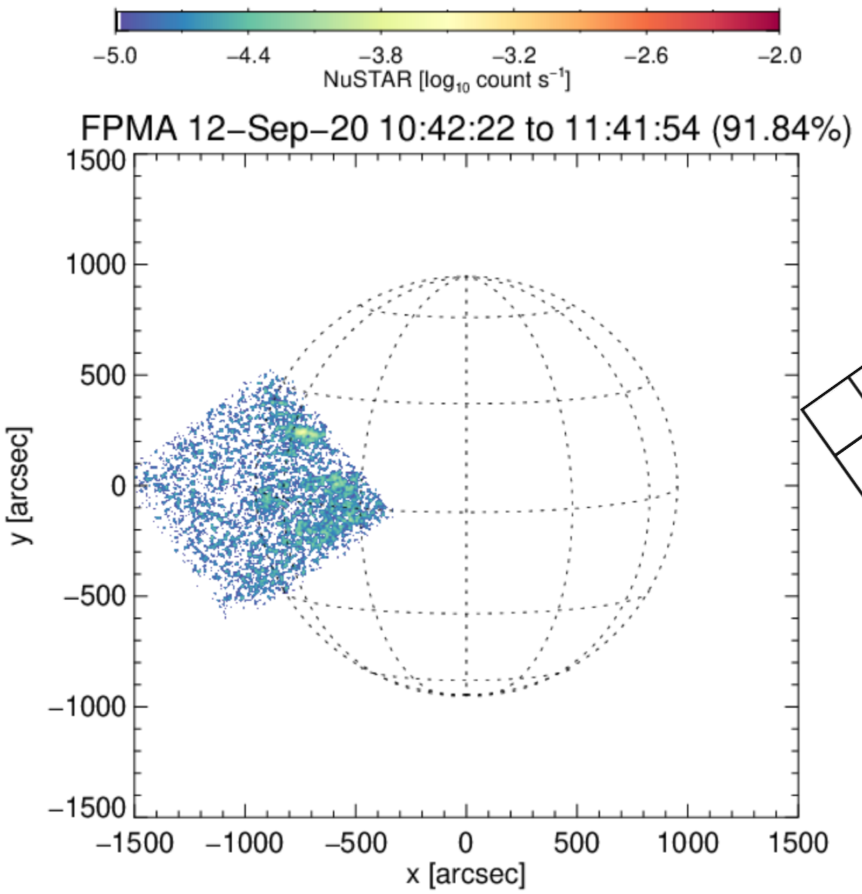
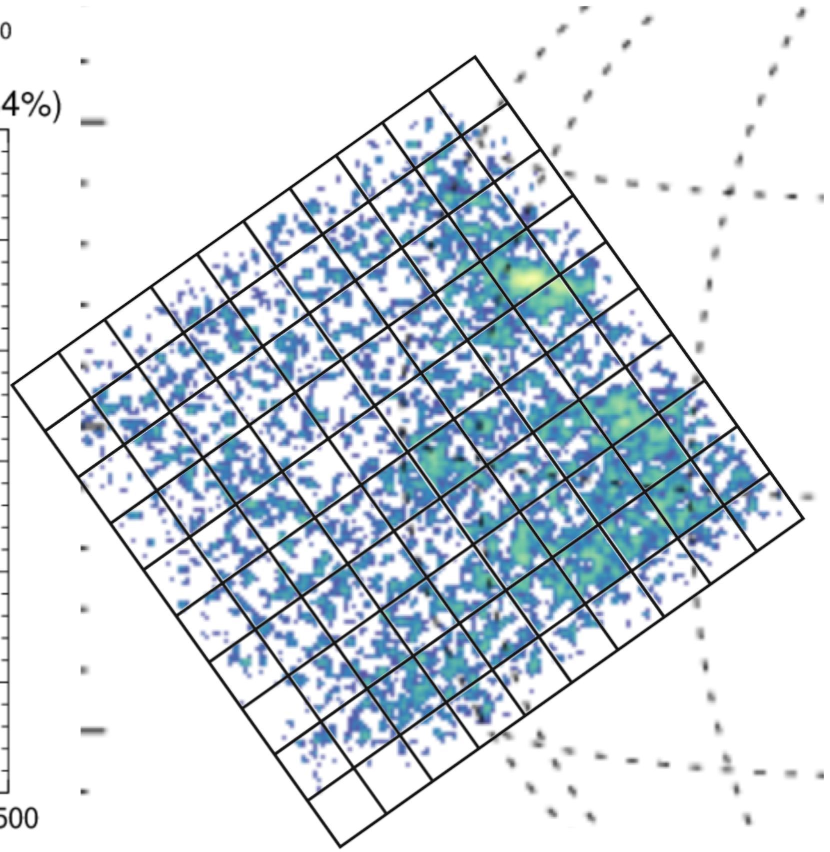
- Stay tuned!





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Takeaways

- **Part I:** Stellar basins are a generic phenomenon
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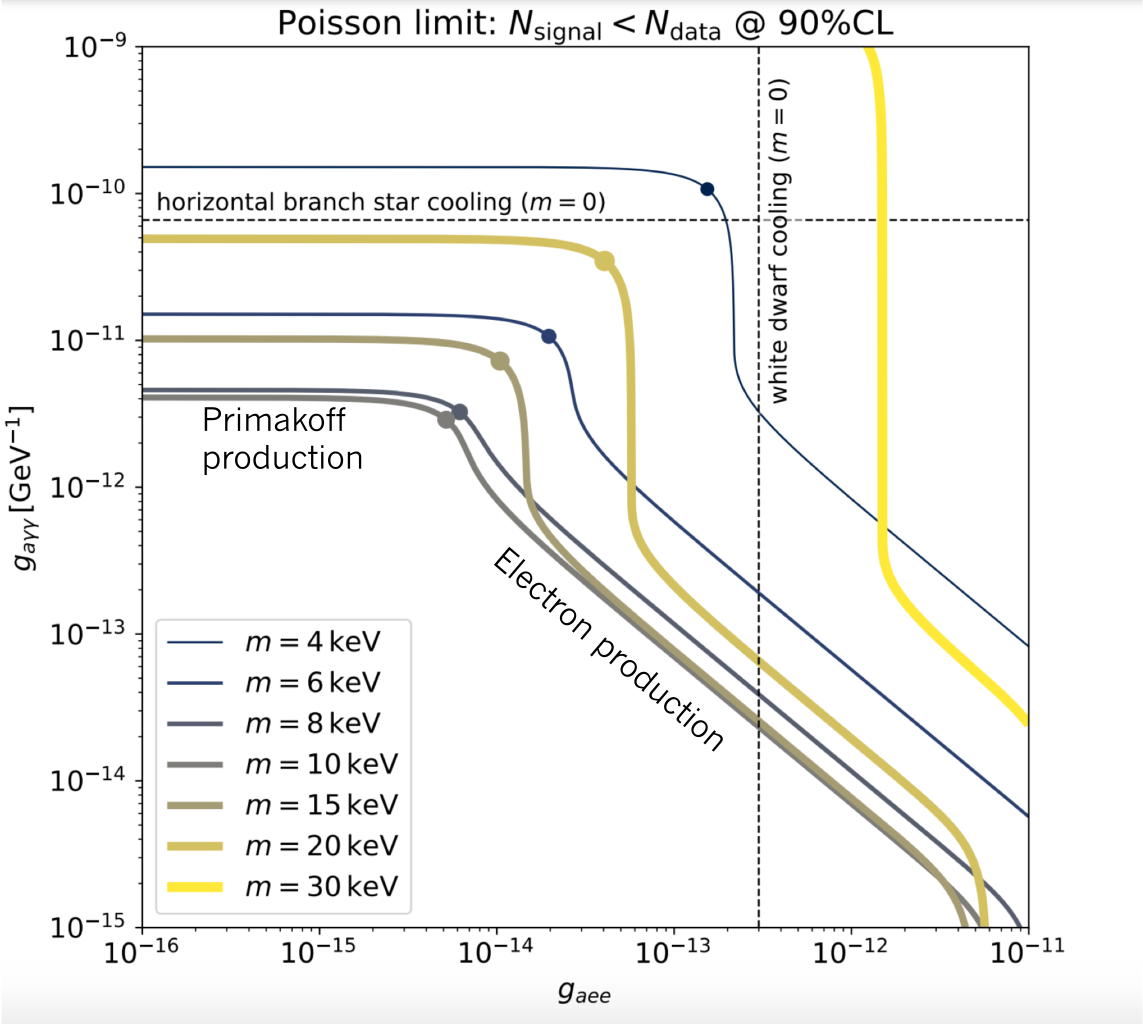
Thank you for listening!

BACKUP

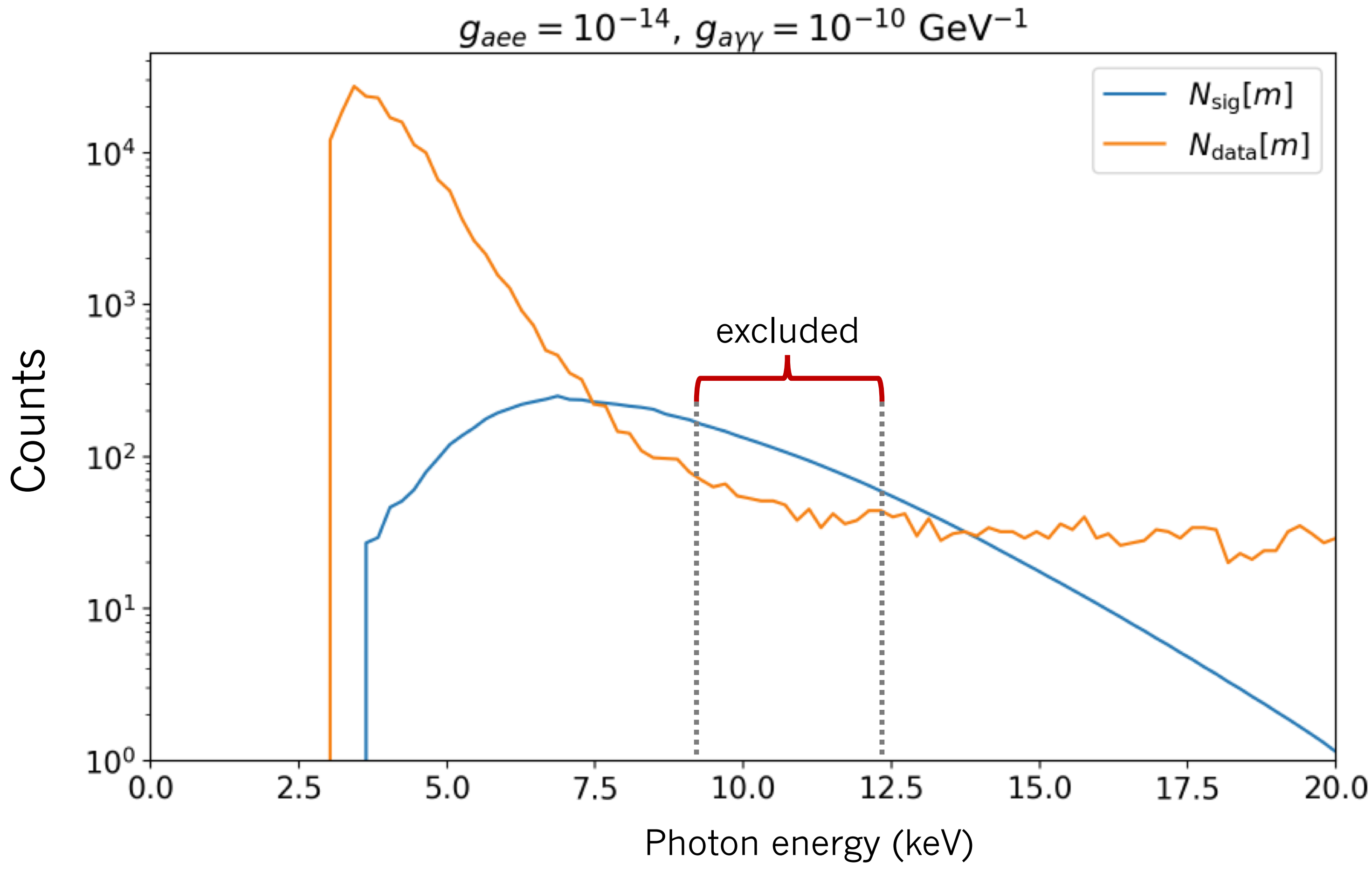
Full parameter sapce

- Naive Poisson limit
- **Improves constraints by two orders of magnitude**



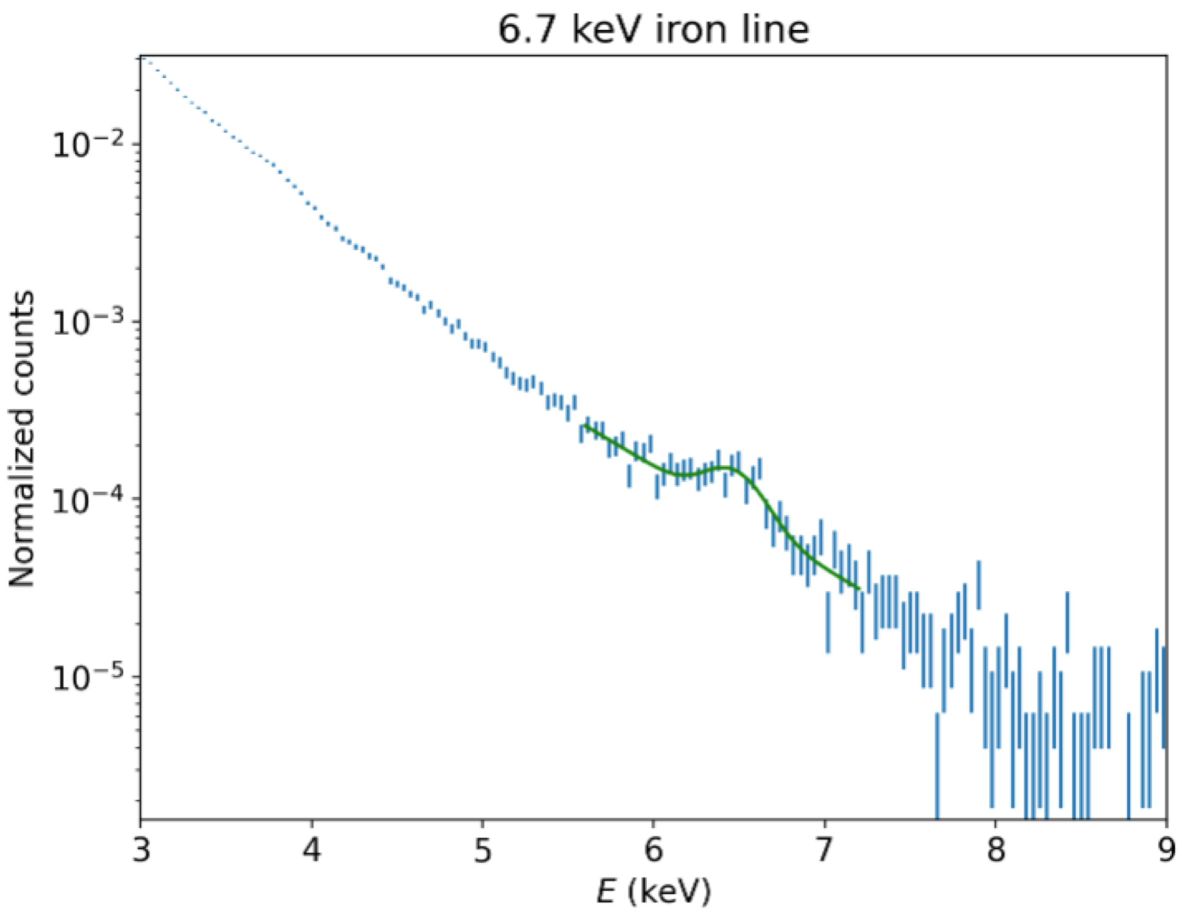
Poisson Limit

- Expected signal in a bin exceeds observed counts by ~$1.65\boldsymbol{\sigma} = 1.65\sqrt{N_{data}}$ (90% CL)
- Crude initial estimate
- Cannot be used for discovery



Resolution effects

- Known X-ray line broadened by detector effects



Radial scaling

1 Injection rate radial scaling

Between any given radii R and $R+\Delta R$, the only particles contributing appreciably to the basin are produced in the Sun with $\sqrt{\frac{2GM}{R+\Delta R}} < v < \sqrt{\frac{2GM}{R}}$ because these are the ones that turn around between R and $R+\Delta R$, hence spend the longest time there. In terms of energy, they have $m(1+\frac{GM}{R+\Delta R}) < \omega < m(1+\frac{GM}{R})$.

The luminosity of all particles (bound and unbound) is

$$L = \int_{\text{Sun}} dV \int_m^\infty d\omega \frac{dQ}{d\omega}$$

The fraction of the luminosity that will actually contribute to the basin between R and $R+\Delta R$ is then just

$$L_{bound} = \int_{\text{Sun}} dV \int_{m(1+\frac{GM}{R+\Delta R})}^{m(1+\frac{GM}{R})} d\omega \frac{dQ}{d\omega}$$

We can evaluate the integral by assuming $dQ/d\omega$ is approximately constant in this narrow window of energy and then just multiplying the integrand by the energy difference

$$L_{bound} \approx \int_{\text{Sun}} dV \left[m(1+\frac{GM}{R}) - m(1+\frac{GM}{R+\Delta R}) \right] \frac{dN}{dV\,dt}$$

We can integrate over the Sun's volume and are left with

$$L_{bound} \approx \left[\frac{GM}{R} - \frac{GM}{R+\Delta R} \right] \frac{m\,dN}{dt}$$

where dN/dt is the total number of particles of all energies being produced by the Sun per unit time.

Expanding in small ΔR gives

$$\begin{aligned} L_{bound} &\approx \left[\frac{GM}{R} - \frac{GM}{R}(1+\frac{\Delta R}{R})^{-1} \right] \frac{m\,dN}{dt} \\ &\approx \left[\frac{GM}{R} - \frac{GM}{R}(1-\frac{\Delta R}{R}) \right] \frac{m\,dN}{dt} \\ &\approx \left[\frac{GM\Delta R}{R^2} \right] \frac{m\,dN}{dt} \end{aligned} \tag{1}$$

The flux of relevant bound particles through R is $F_{bound} = L_{bound}/(4\pi R^2)$, so the energy injection rate is

$$\dot{\rho}_b = \lim_{\Delta R \to 0} \frac{\Delta F}{\Delta R} \approx \frac{m}{4\pi R^2} \left[\frac{GM}{R^2} \right] \frac{dN}{dt} \propto \frac{1}{R^4}$$

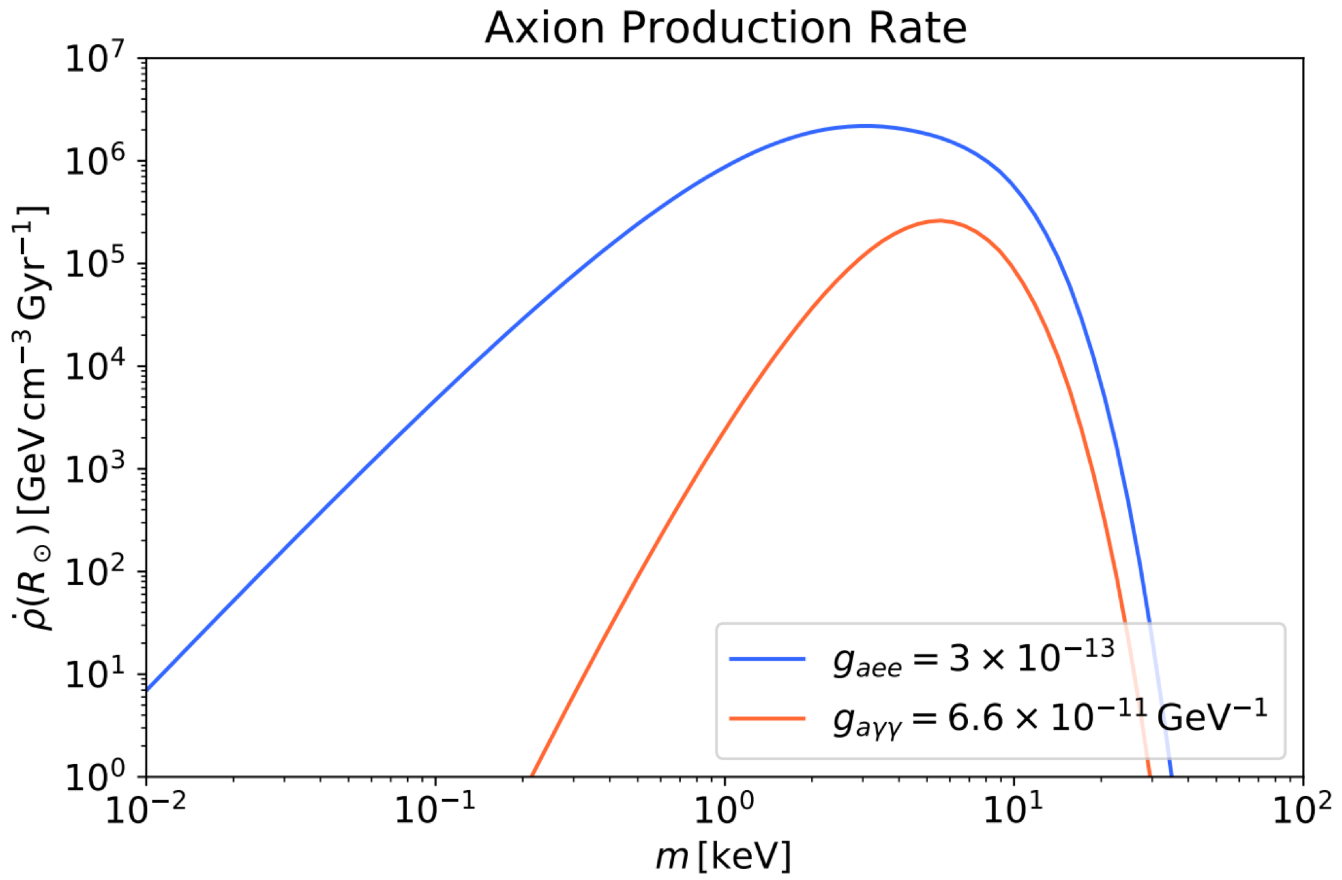
as expected.

Stellar basin

- Long accumulation time!

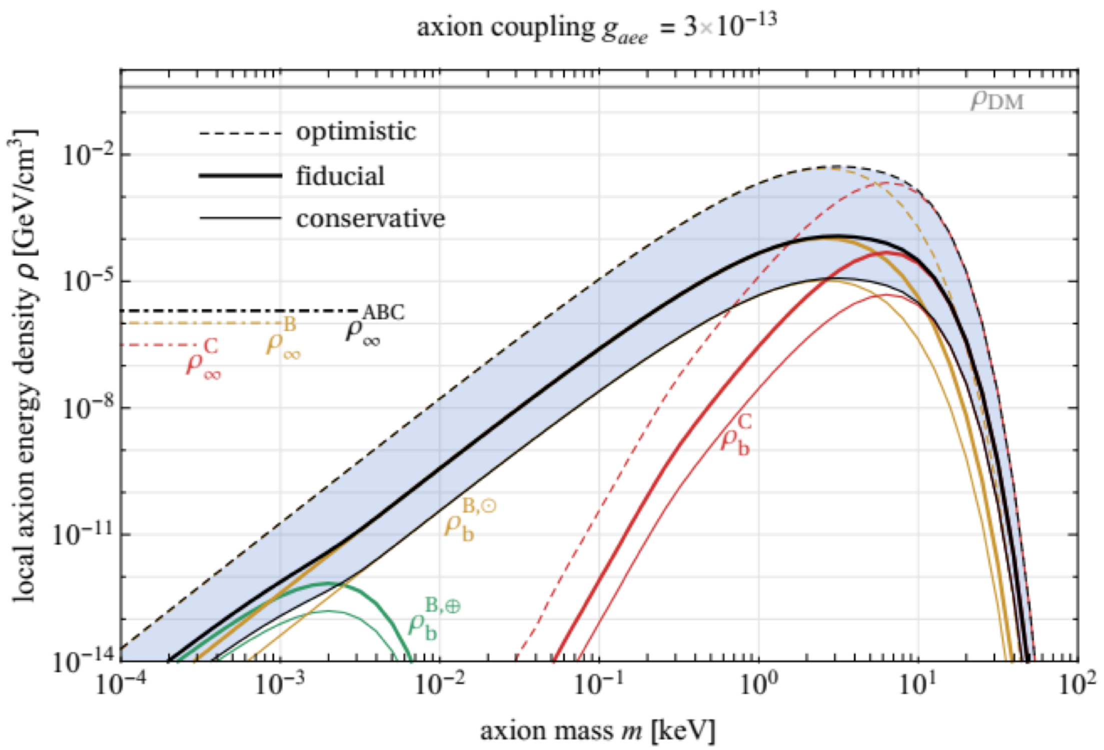
$$\rho_b(r) \sim \dot{\rho_b}(r)\tau$$
$$\Rightarrow \rho_b\ (r) \gg \rho_{DM}$$

- Even for kyr accumulation times, this region in parameter space exceeds ρ_{DM}



Production rate

- Falloff at low mass due to phase space of NR brem



$\tilde{\omega}_k \equiv (\omega - m)/m \simeq \mathbf{k}^2/2m^2$, one finds in general that

$$\frac{dQ}{d\tilde{\omega}_k} \simeq \sum_p \tilde{Q}_p(R')\tilde{\omega}_k^{n_p/2} + \ldots$$

$$\dot{\rho}_b(R) = \frac{7}{32\pi}\frac{G_N M_*}{R^4}\int d^3R' \sum_p \tilde{Q}_p(R')\,|\Phi(R')|^{\frac{n_p}{2}} .$$

$$\tilde{Q}_B^{ND} \simeq \frac{\alpha^2 g_{aee}^2}{2\pi^{3/2}}\frac{\overline{n}_N n_e m^3}{m_e^{7/2}T^{1/2}}\int_0^1 d\epsilon\, \frac{\ln\frac{2+2\sqrt{1-\epsilon}-\epsilon+\xi}{\epsilon+\xi}}{\exp\{\frac{m}{\epsilon T}\}} .$$

The screening measure ξ is quite small in practice.