Hunting for axions in the solar basin

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Outline

- **Introduction:** What is a stellar basin?
- **Part I:** Axions in the solar basin
- **Part II:** Data and results

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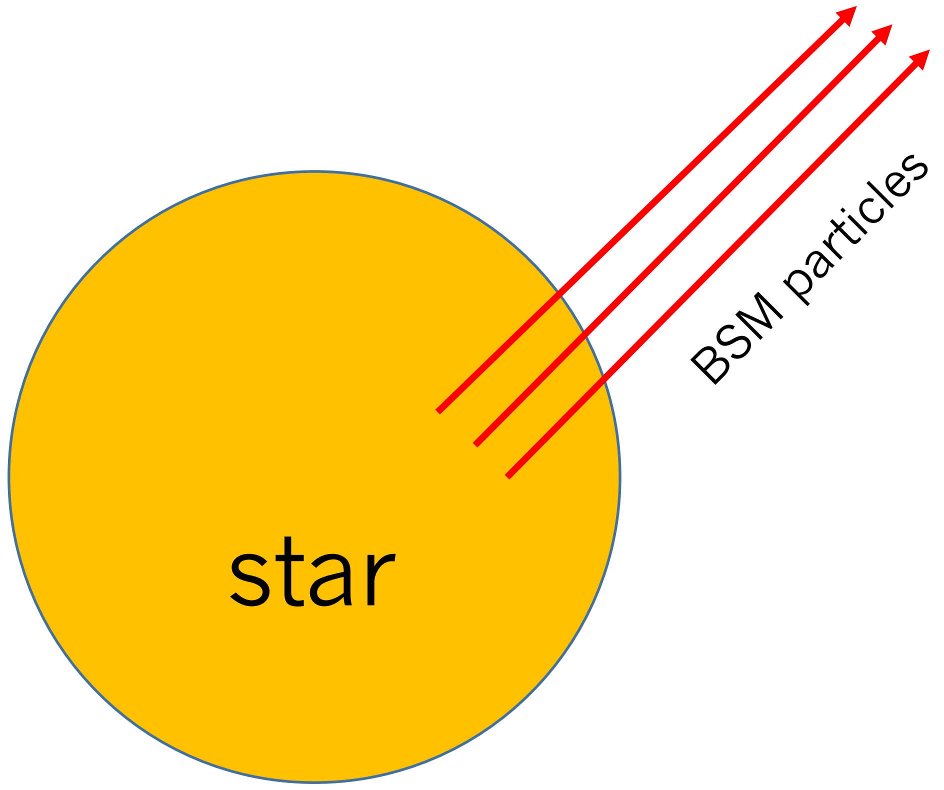
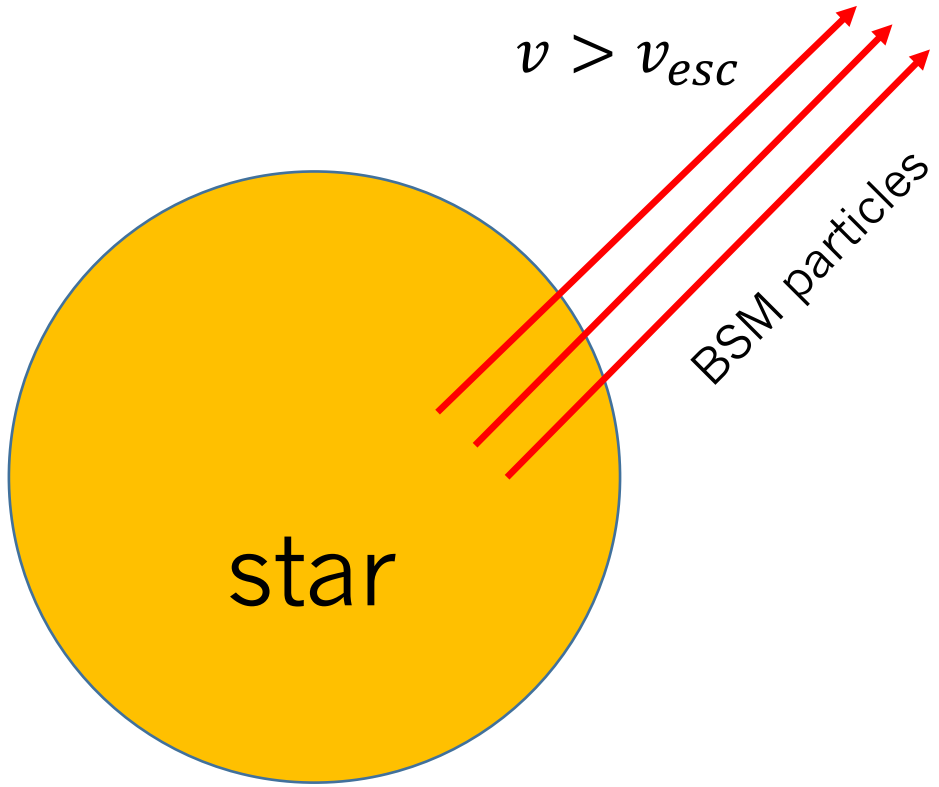
Motivation

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



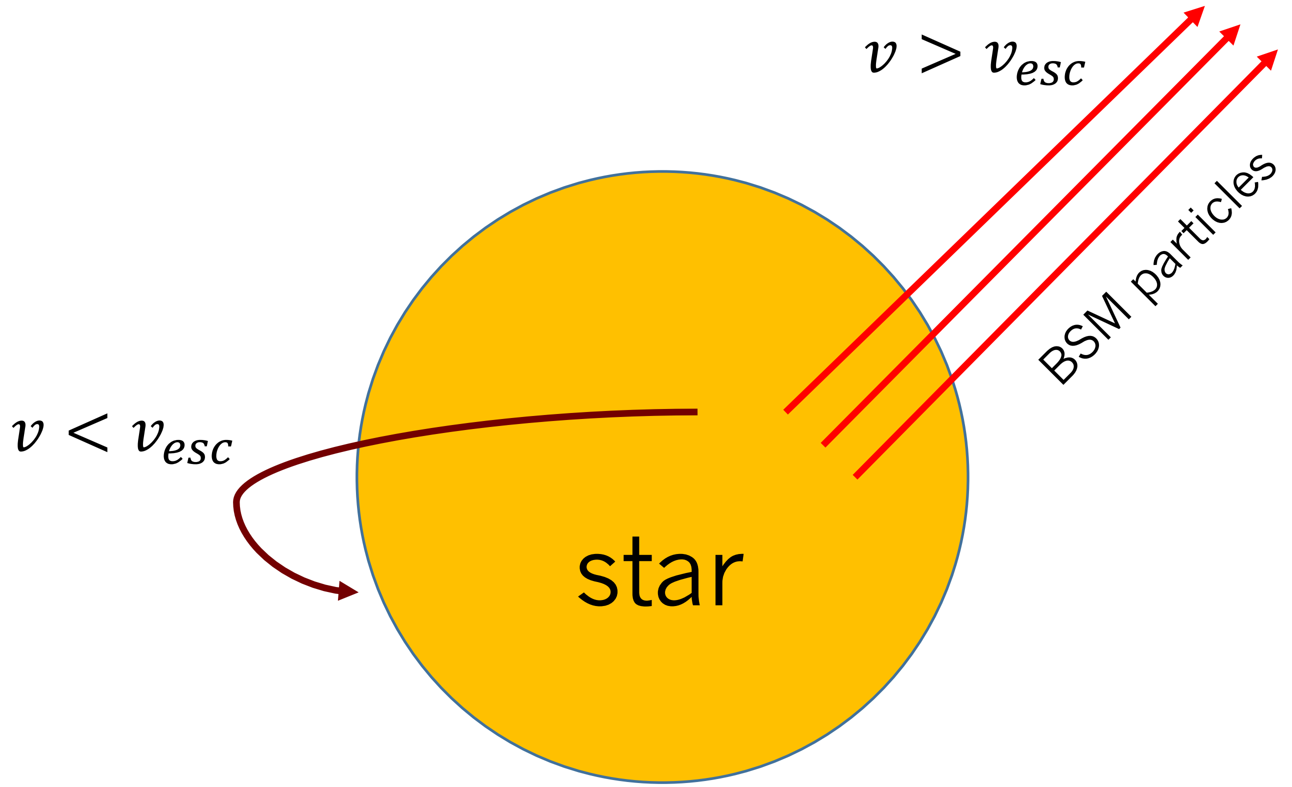
Motivation

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



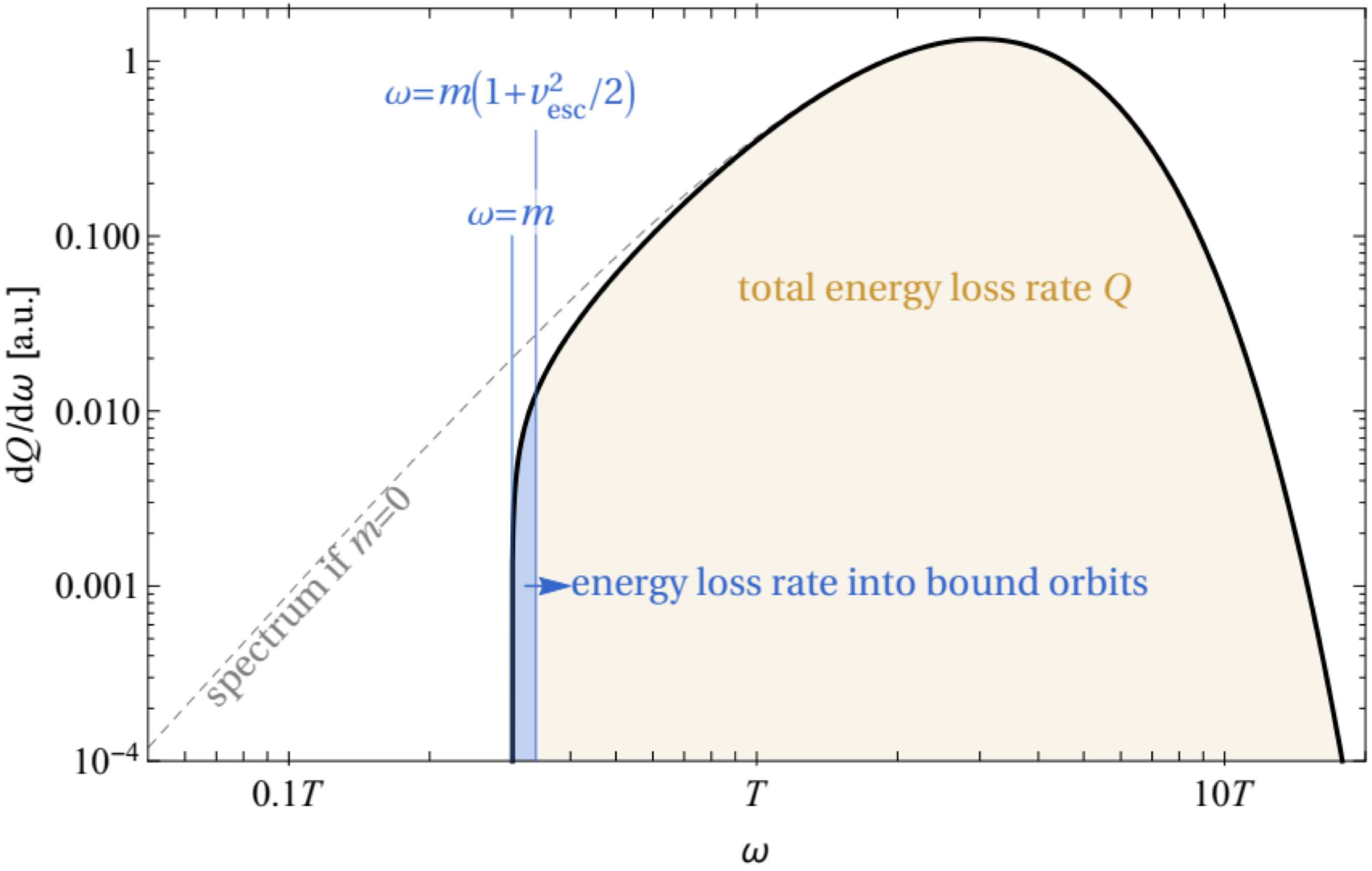
Gravitational trapping

- Low-velocity particles cannot escape gravitational well



Low-velocity tail

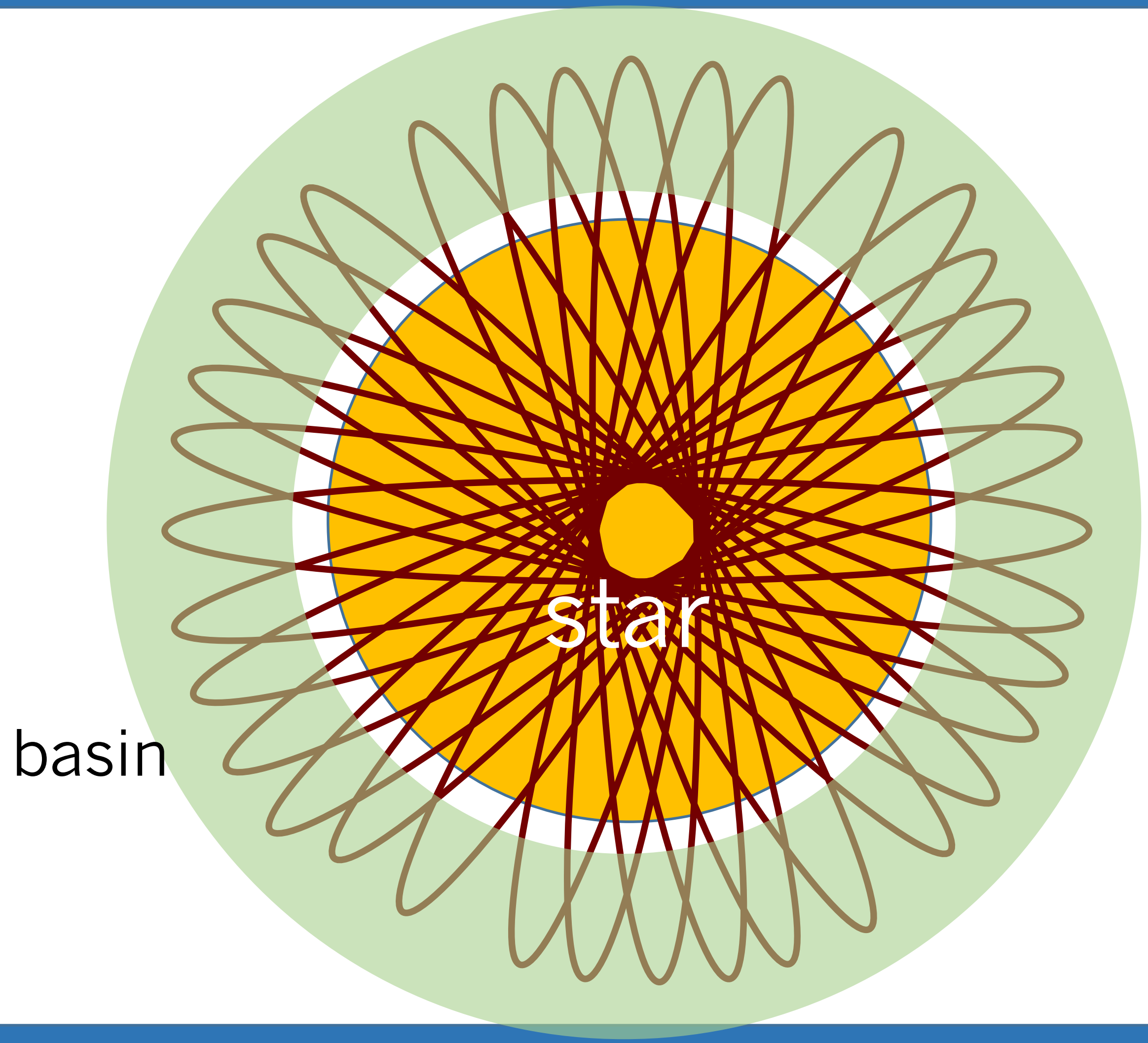
- Low-velocity particles cannot escape gravitational well
- Small fraction of spectrum



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

Stellar basin

- Low-velocity particles cannot escape gravitational well
- Small fraction of spectrum
- Particles accumulate to form "**stellar basin**"



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Model

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

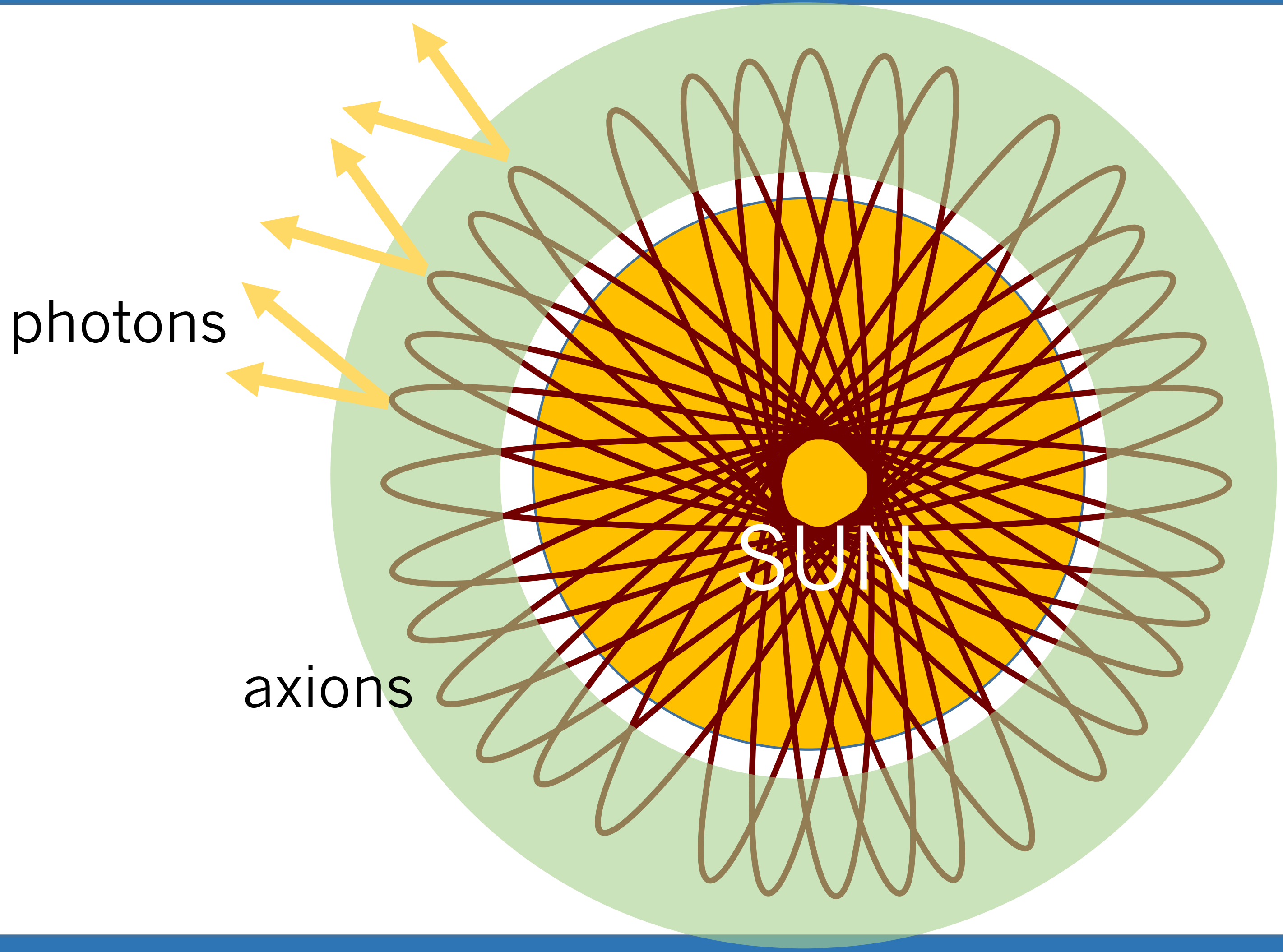
Mass near temperature of solar core

Production by electrons in solar core

Decay to two photons/ Primakoff production

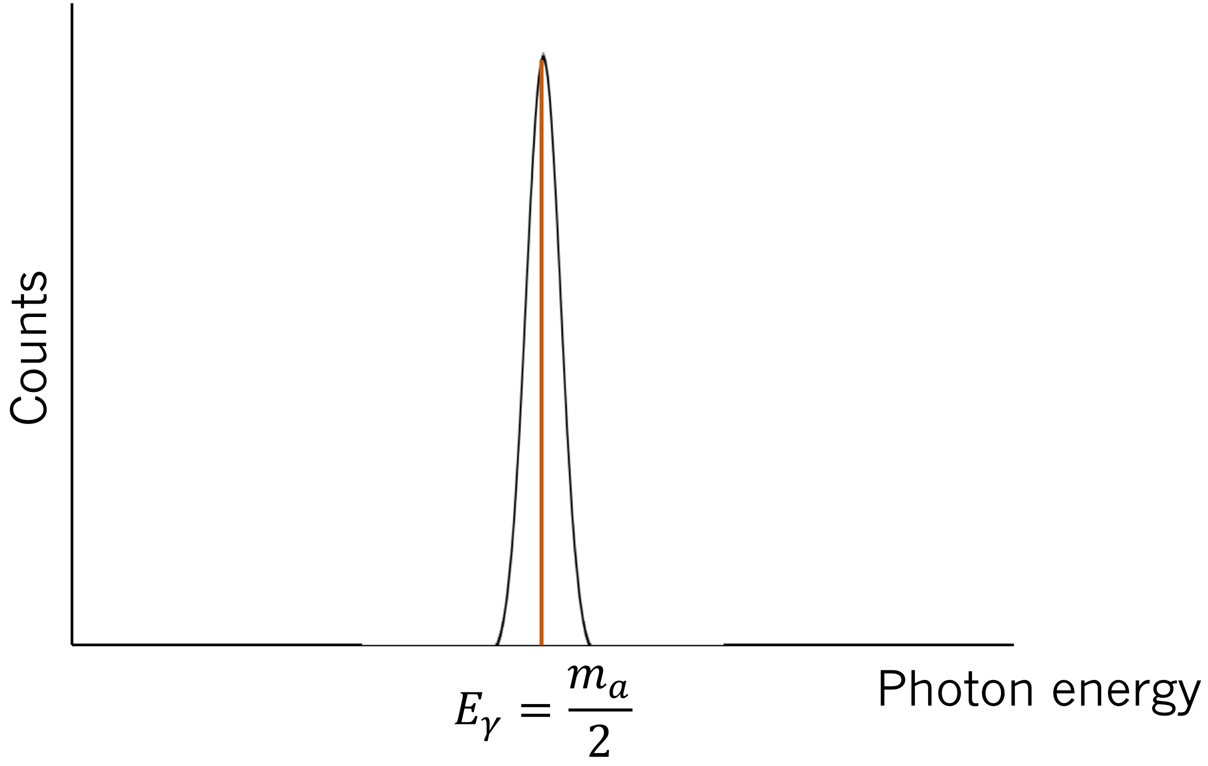
Indirect detection

- Low-velocity particles cannot escape gravitational well
- Particles accumulate to form "**stellar basin**"
- Axions produced in solar core accumulate around the Sun for ~ axion lifetime
- Decay to two photons is observable



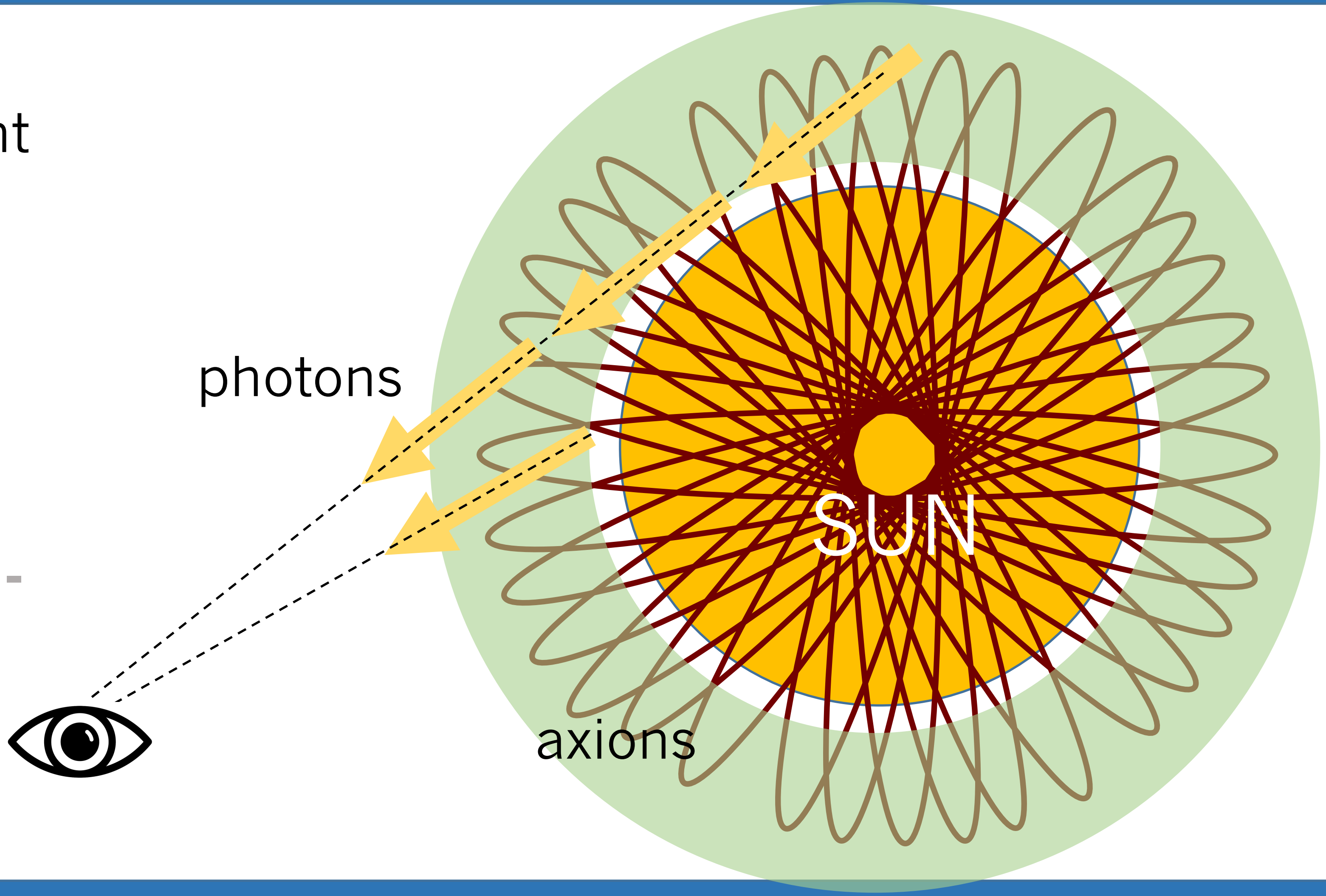
Decay signatures: energy spectrum

- Signal maximized at $m_a \sim$ temperature of solar core
  - Lower mass harder to trap
  - Higher mass Boltzmann-suppressed
- Axions decay near rest
- **X-ray line at ~ keV energy**



Decay signatures: spatial template

- Integrated line of sight doubles at solar limb
- Characteristic $\theta^{-3} \propto R^{-4}$ falloff
- **Profile with ~ arcmin-scale features**



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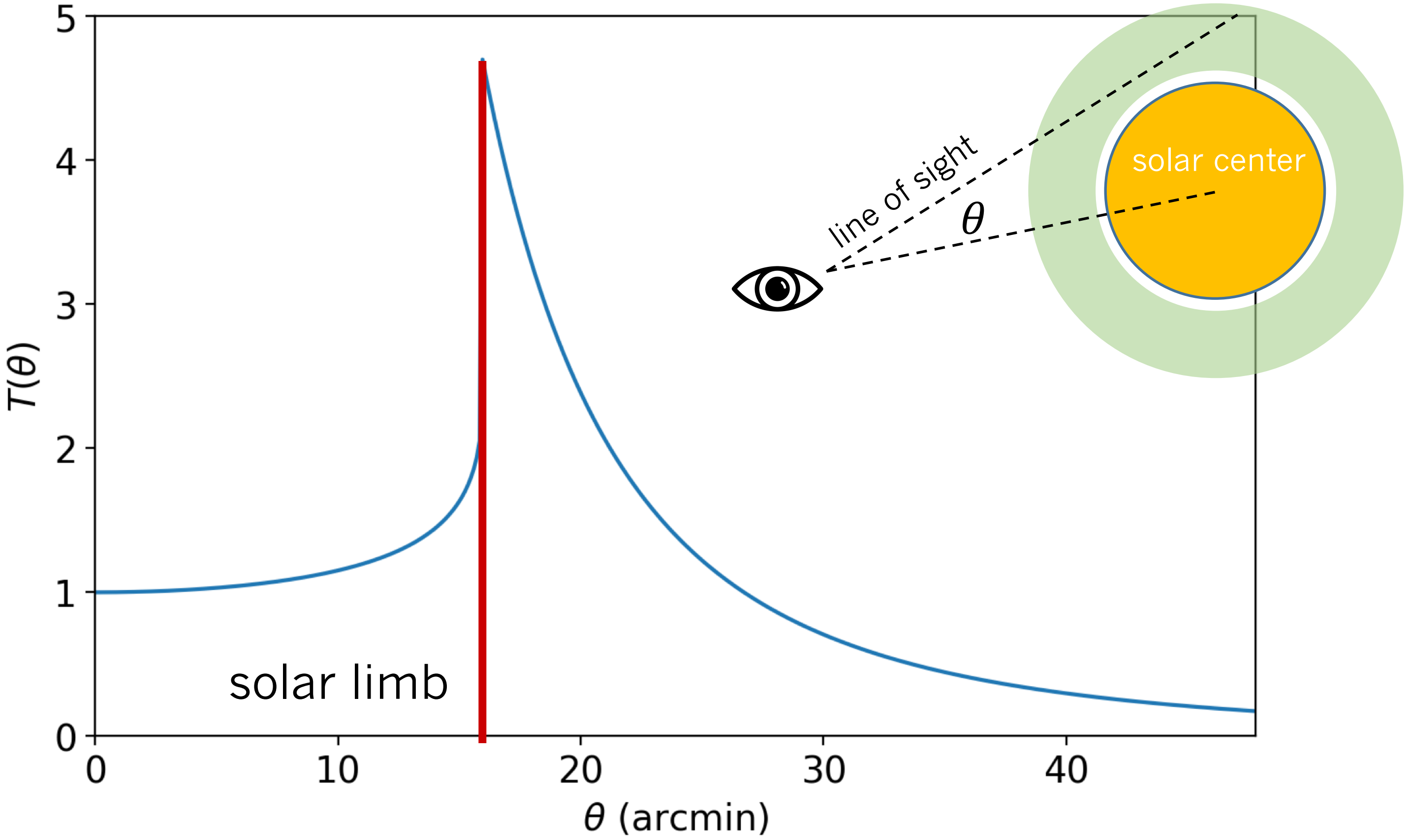

$\theta \equiv$ angle from solar center

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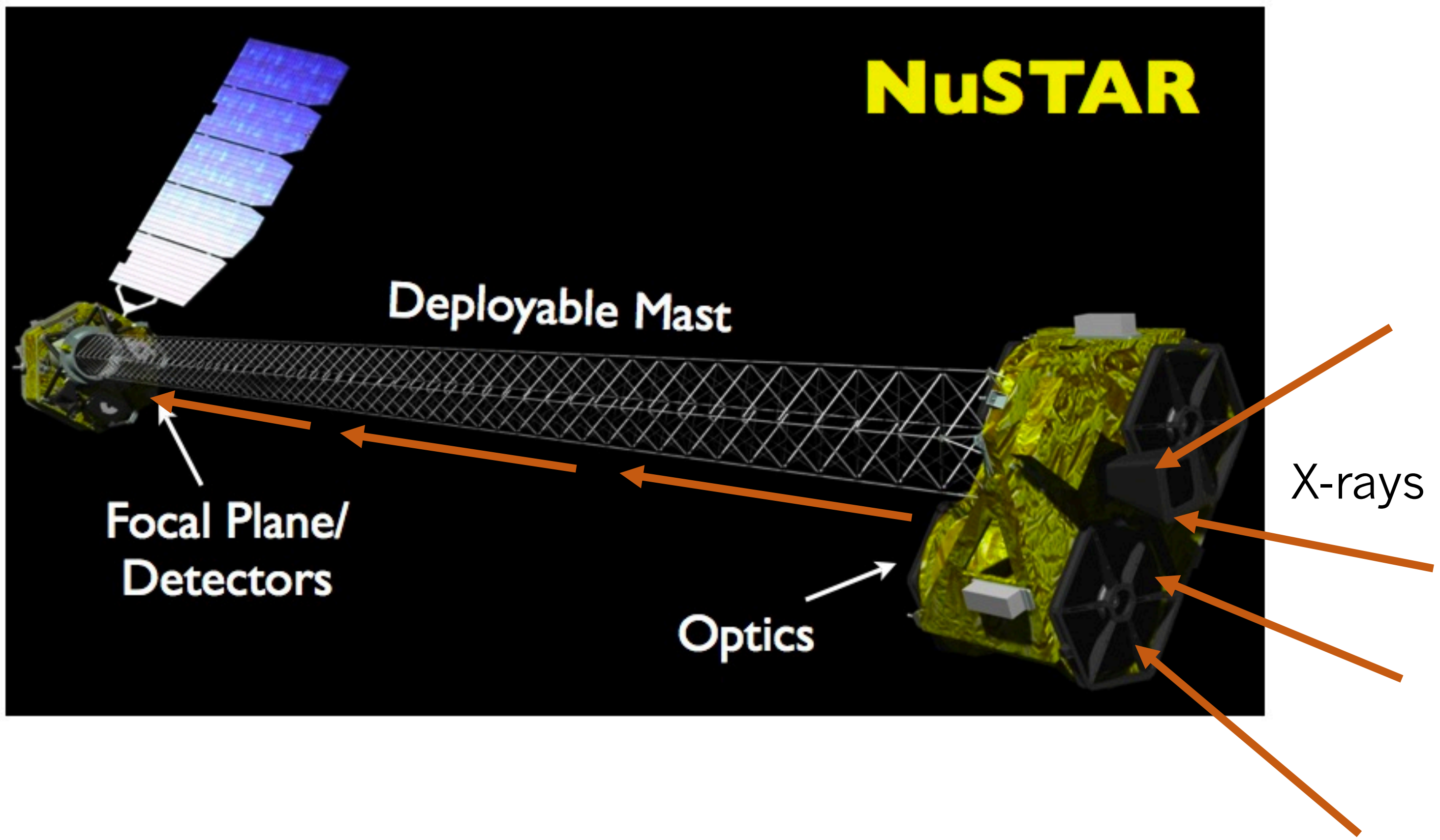
NuSTAR specs

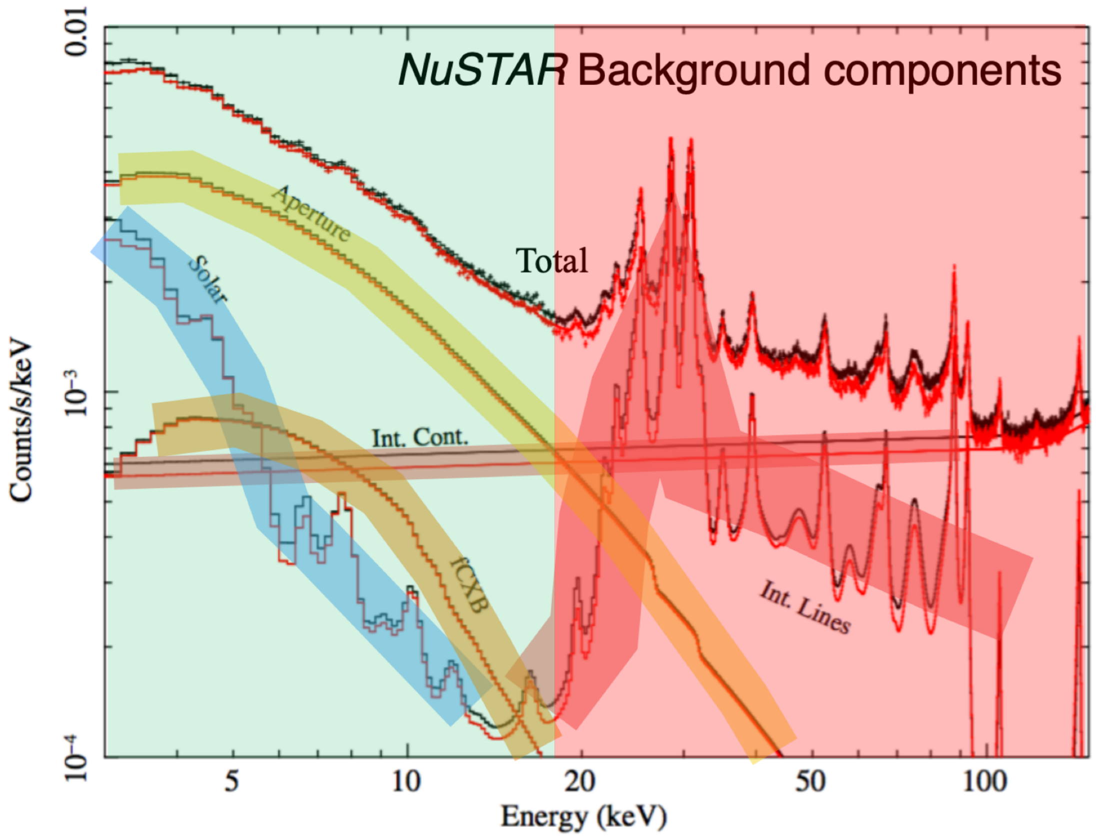
- Orbital X-ray telescope
- Energy:
  - 3 - 78 keV
  - ~200 eV resolution
- Angular resolution
  - ~0.3 arcmin



Backgrounds

- Background well-characterized
- Dominant background in relevant range due to stray X-rays entering detector (aperture)
- Solar lines are subdominant

Boltzmann suppressed

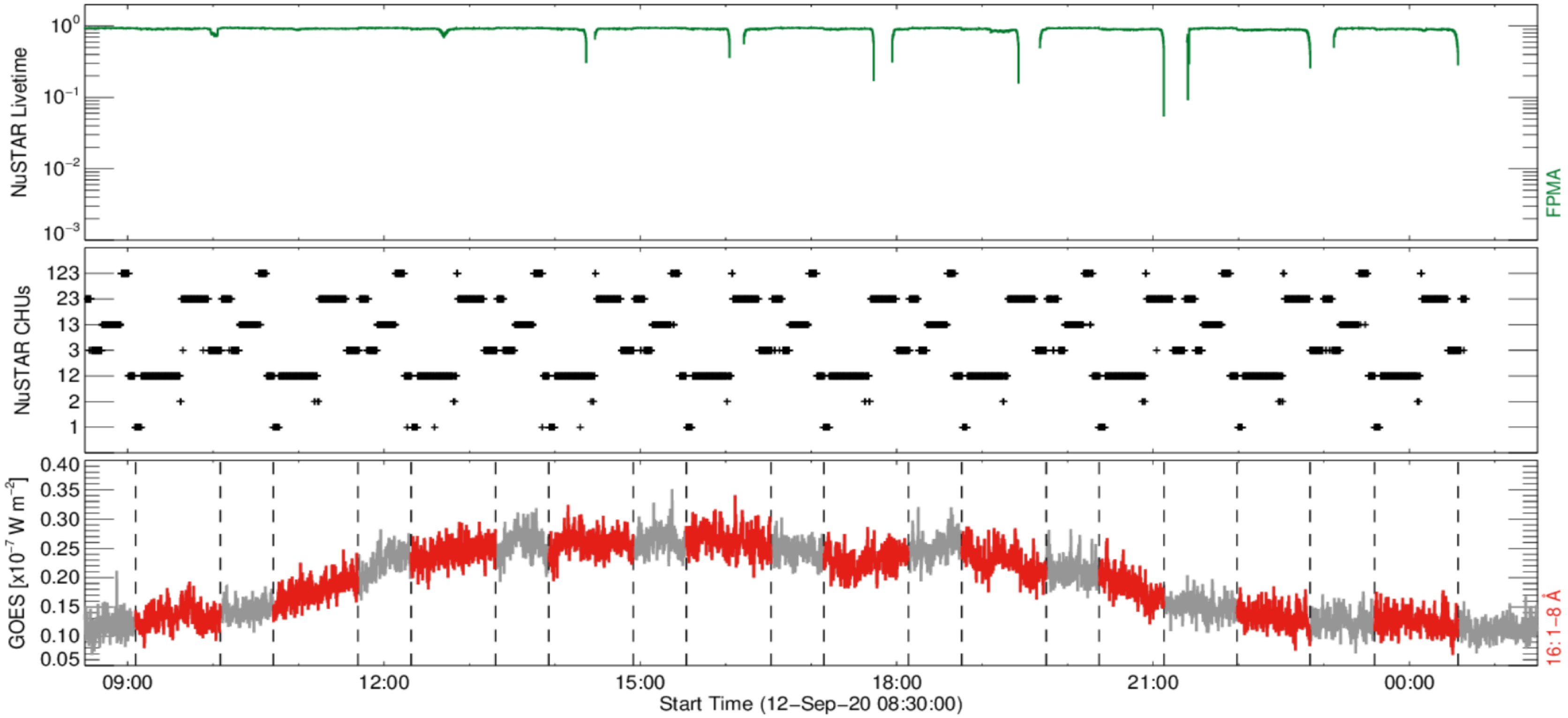


mass range of interest

https://www.astro.utah.edu/~wik/courses/astr5590spring2020/slides/NuSTARintroWik.pdf

NuSTAR solar observations

- Recent quiescent limb dwells (September 2020)
- Low contamination from localized flares
- Orbit 2, CHU12 configuration
  - Least spatial variability
  - Avoids SAA deadtime
  - Longest continuous CHU configuration



https://github.com/ianan/nsigh_all/blob/master/

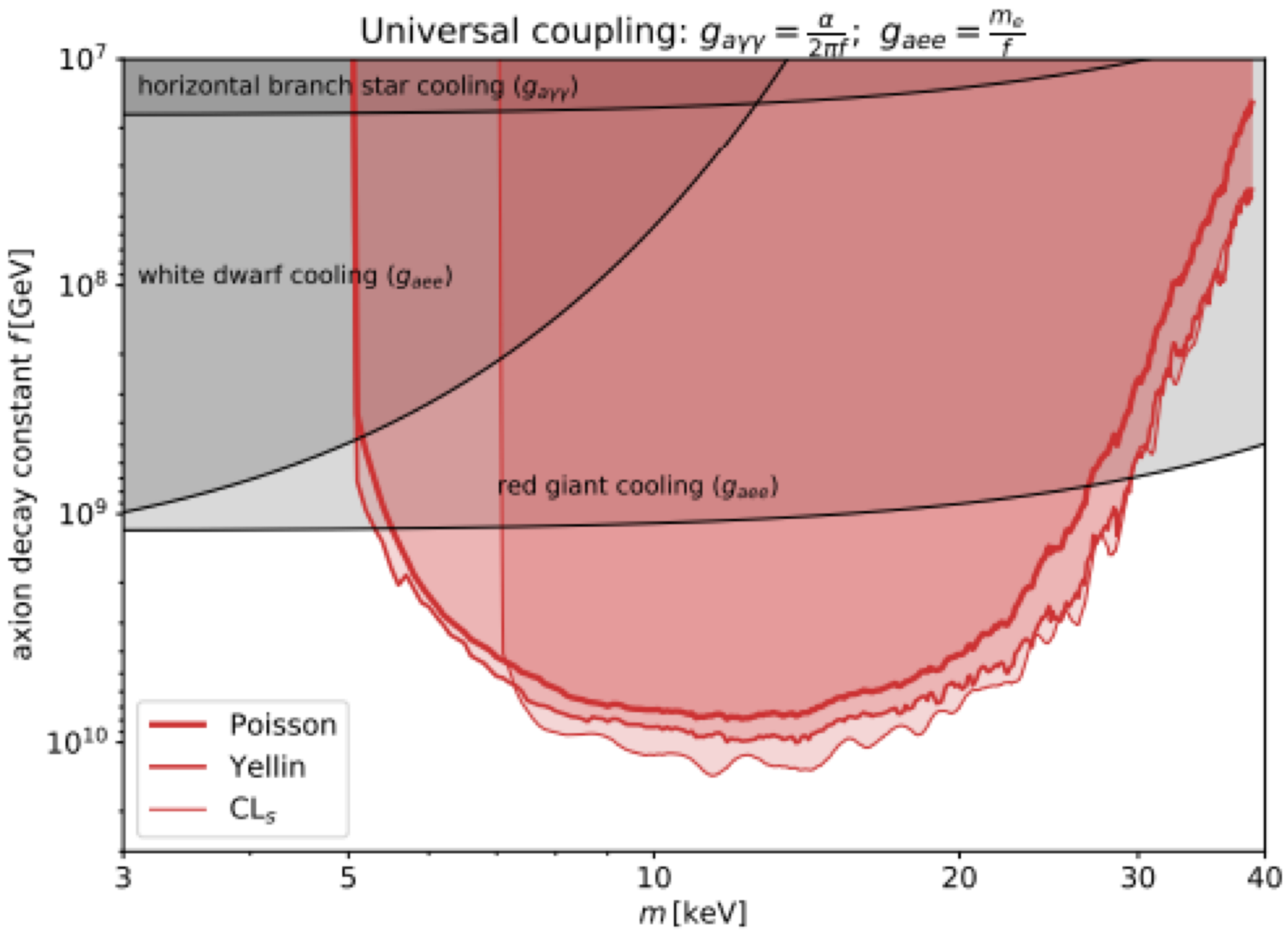
Limit-setting

Method	Requires signal model	Does not require background model	Uses spectral information	Uses spatial information	Not computationally intensive
Poisson	~	✓	X	X	✓
CL_s	~	X	✓	✓	~
Yellin (optimum interval)	~	✓	✓	✓	X

- **Poisson:** For total number of observed events, how large can signal be?
- **CL_s:** For best signal and background model, how large can signal be?
- **Yellin:** For the largest underdensities in the data, how large can signal be?

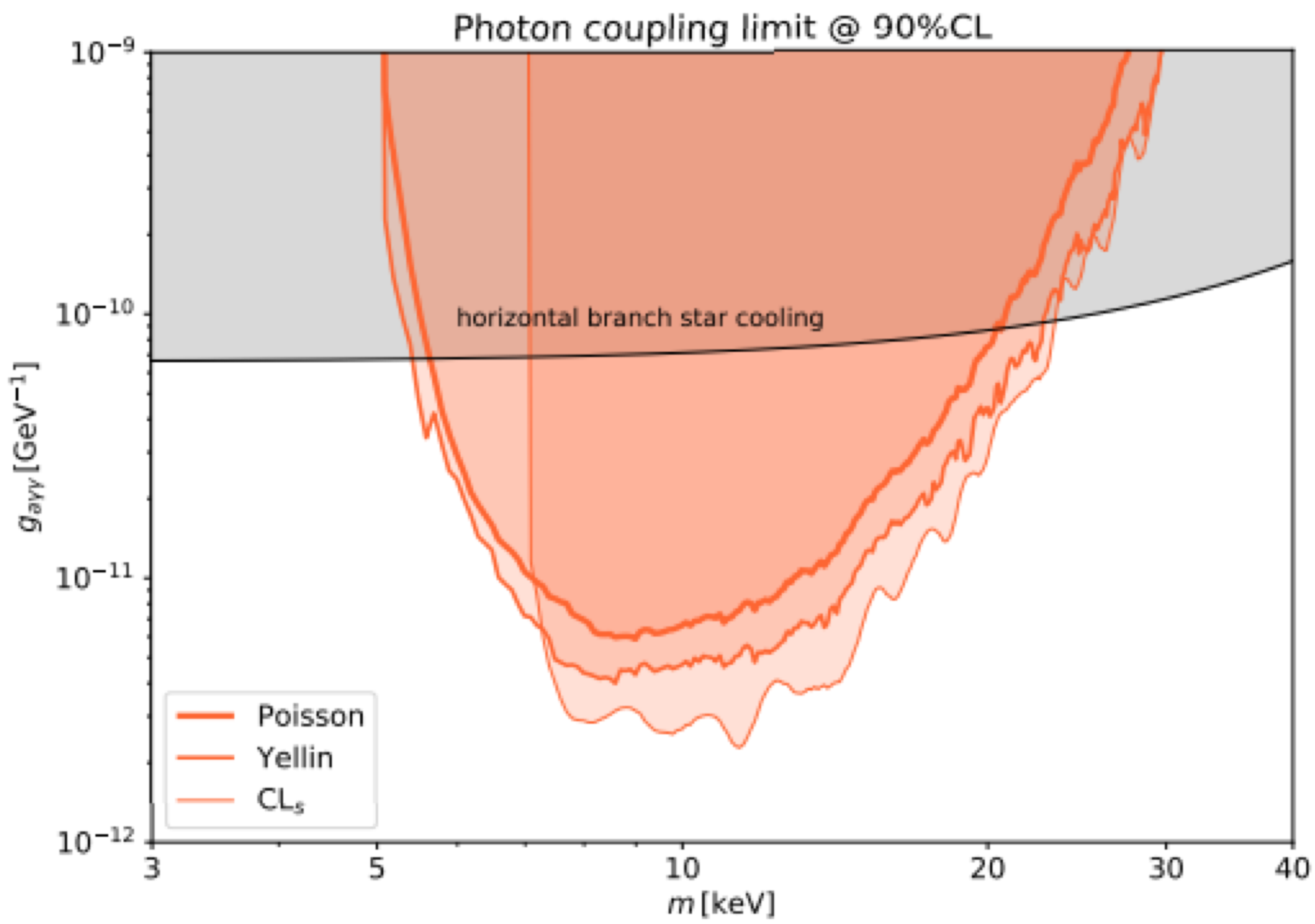
Results: universal coupling

- Universal coupling relates photon and electron couplings
- Yellin clearly outperforms Poisson
- CL_s places strongest constraint at higher mass



Results: photon-only coupling

- Electron coupling taken to zero = production via Primakoff
- Yellin clearly outperforms Poisson
- CL_s places strongest constraint at higher mass



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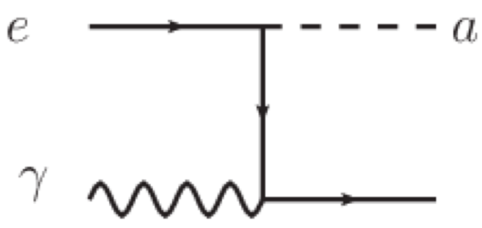
- **Part II:** Data and results
  - Multiple limit-setting methodologies constrain couplings well below an order of magnitude beneath existing bounds.

Thank you for listening!

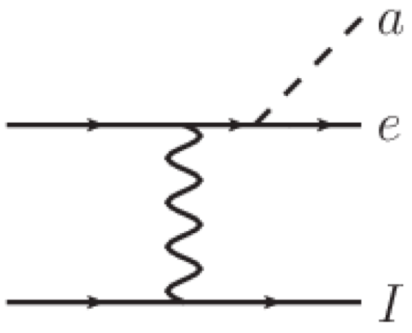
BACKUP

Production

- Electron coupling
  - **Compton scattering:** dominates for $m_a > 5$ keV
  - **Electron-ion bremsstrahlung:** contributes at $m_a < 5$ keV

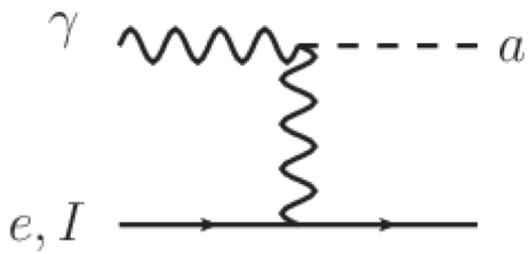


Compton



Electron-ion bremsstrahlung

- Photon coupling
  - **Primakoff process:** dominates for $\frac{g_{a\gamma\gamma}}{GeV^{-1}} \gtrsim 10^3 g_{aee}$



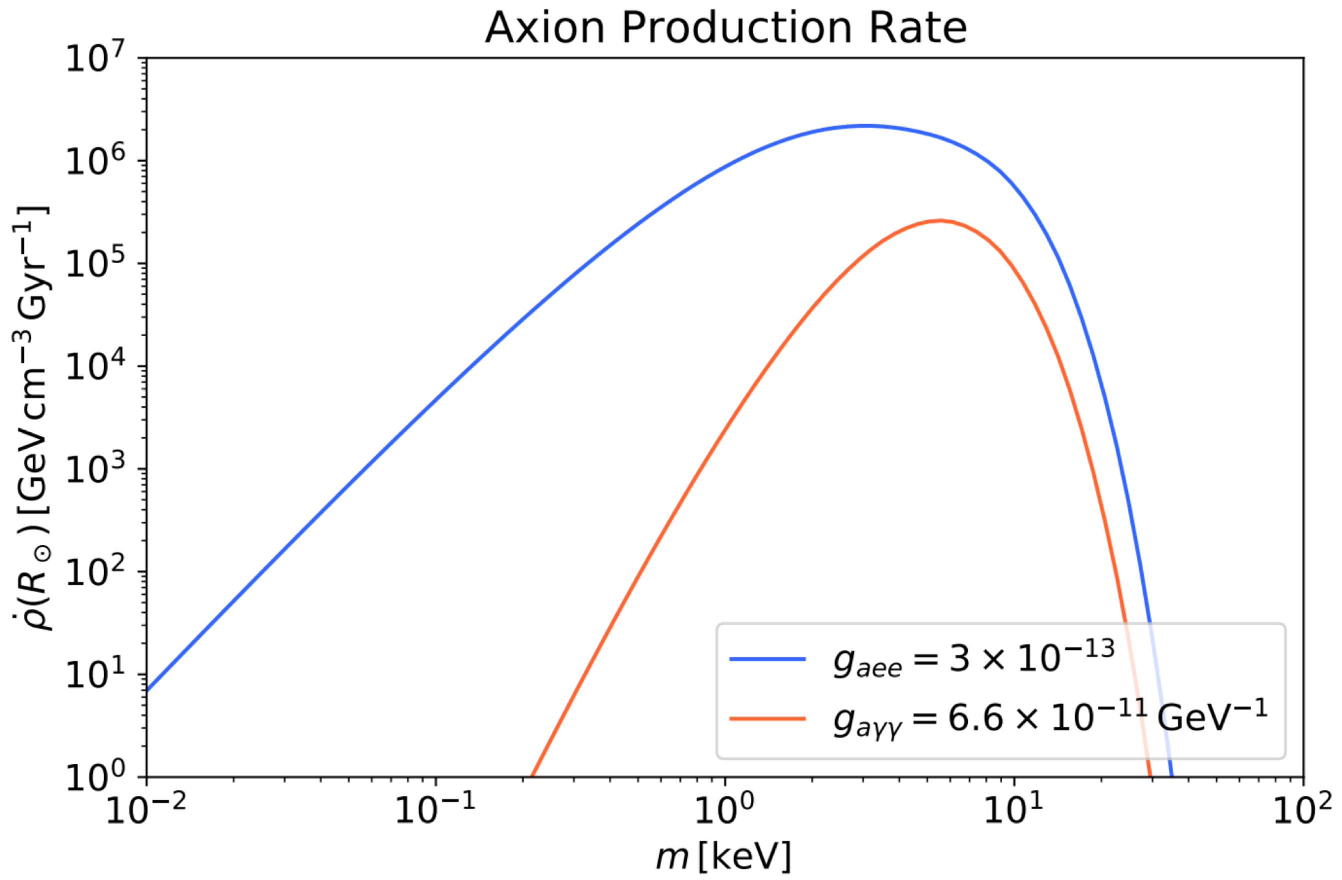
Primakoff

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}



Radial scaling

typical energy

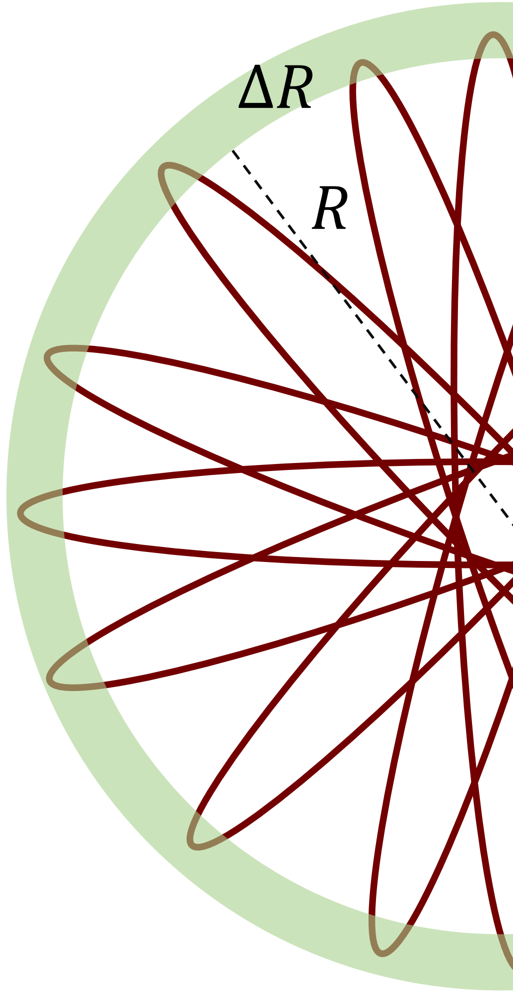
fraction that turn around in shell

$$\dot{\rho}_b \sim m \times \frac{dN}{dt} \times \left(\frac{GM\Delta R}{R^2}\right) \times \left(\frac{1}{4\pi R^2 \Delta R}\right) \propto \frac{1}{R^4}$$

energy injected into basin (per volume per time)

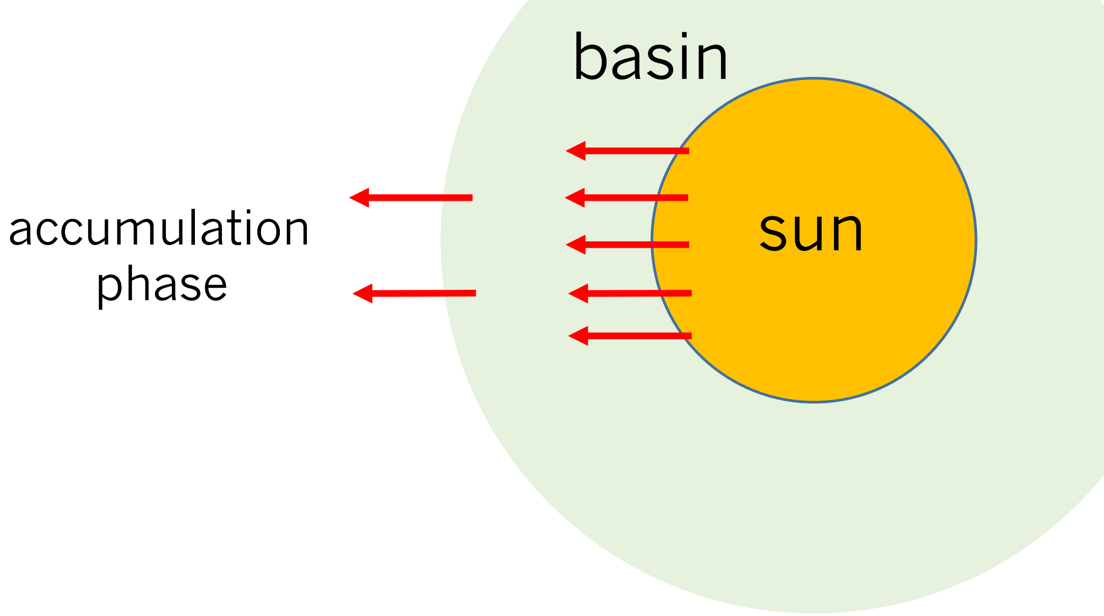
total production rate

volume of shell



Formation of a basin

- *Accumulation phase:* axions are slowly accumulated for a basin lifetime

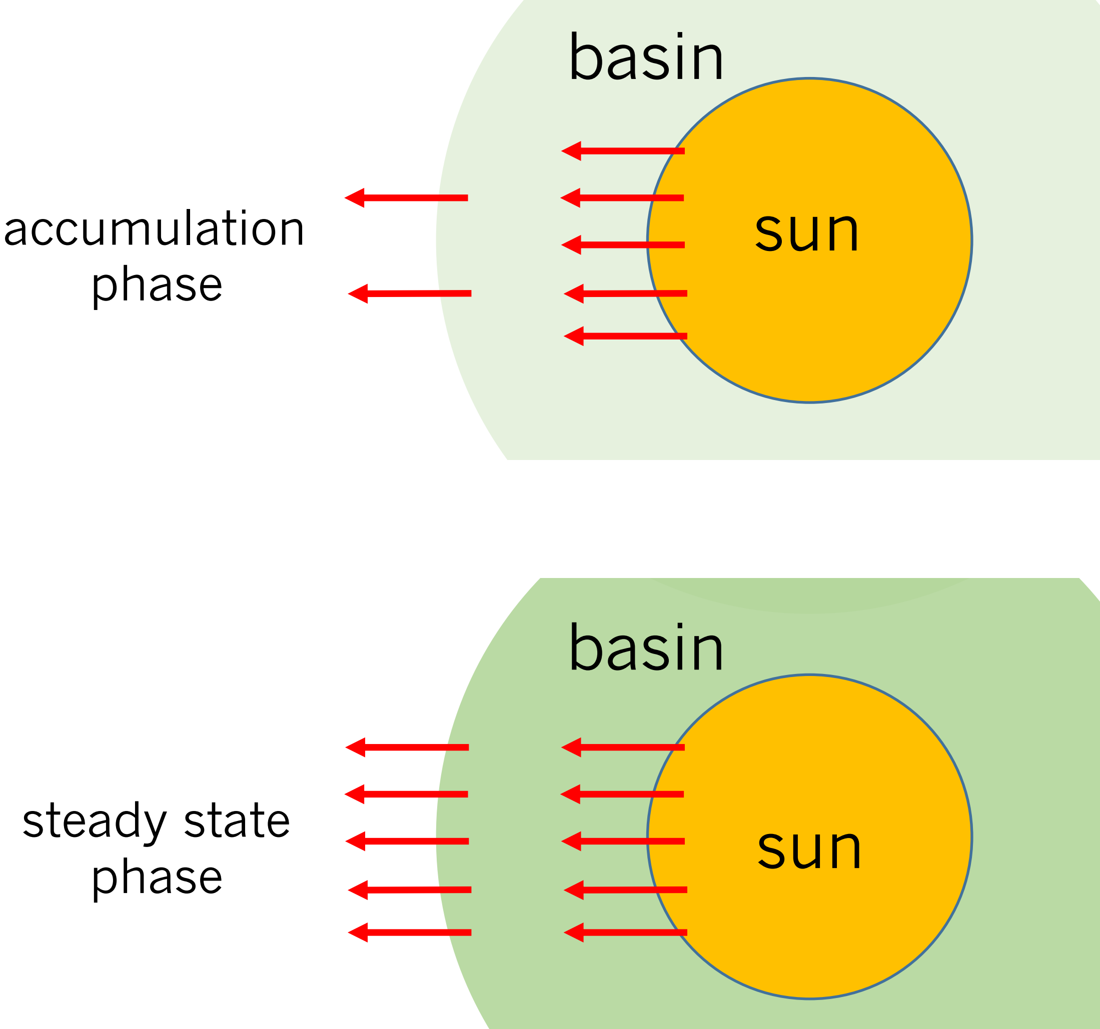


Formation of a basin

- *Accumulation phase:* axions are slowly accumulated for a basin lifetime
  - Lifetime set by axion decays

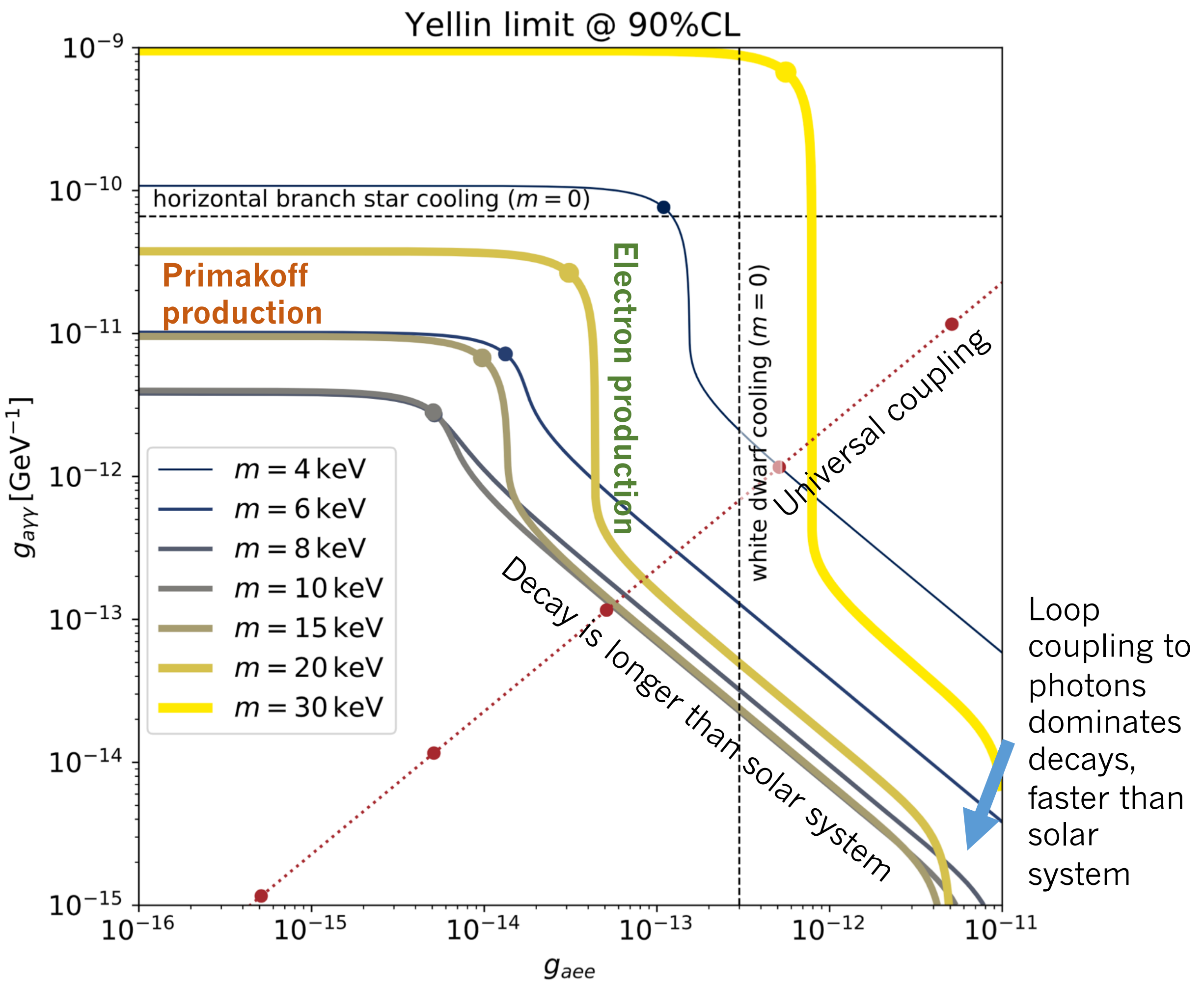
$$\tau_{\text{lifetime}} = \Gamma_{\text{decay}}^{-1}$$

- *Steady-state phase:* axion decay rate matches injection rate



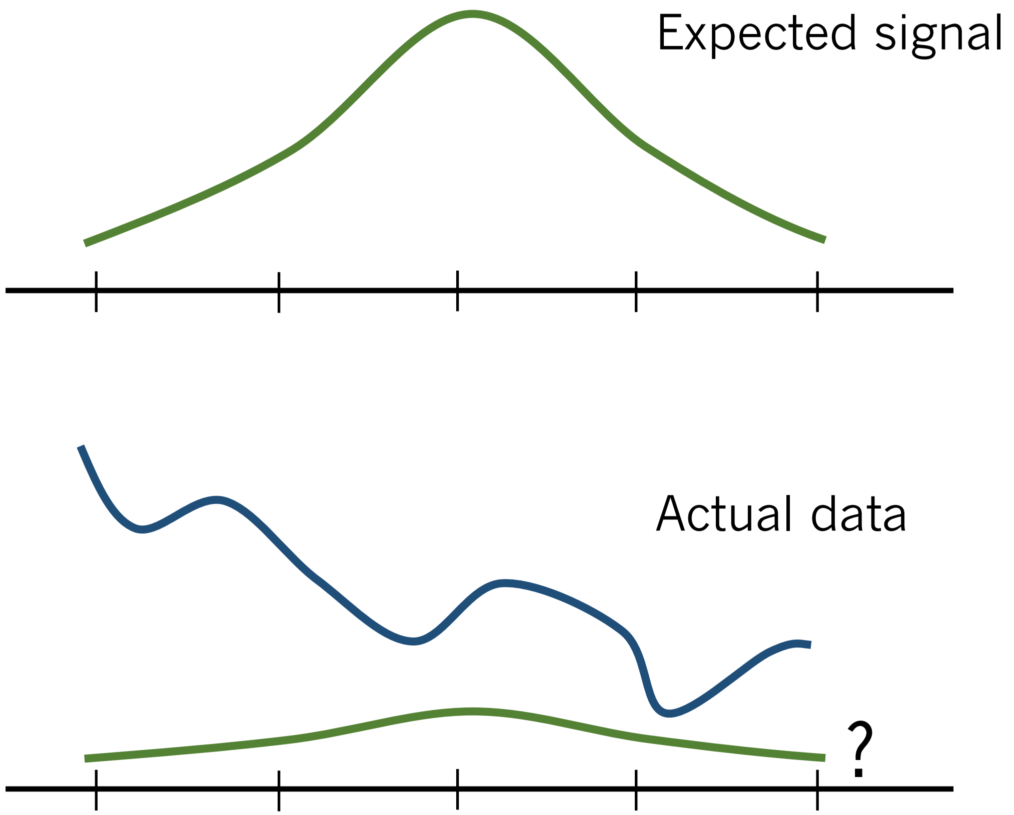
Full parameter space

- **Low electron coupling:** Primakoff dominates
- **Low photon coupling:** decay longer than age of solar system (accumulation phase)
- **Very high electron coupling:** loop-coupling to photons dominates the decay



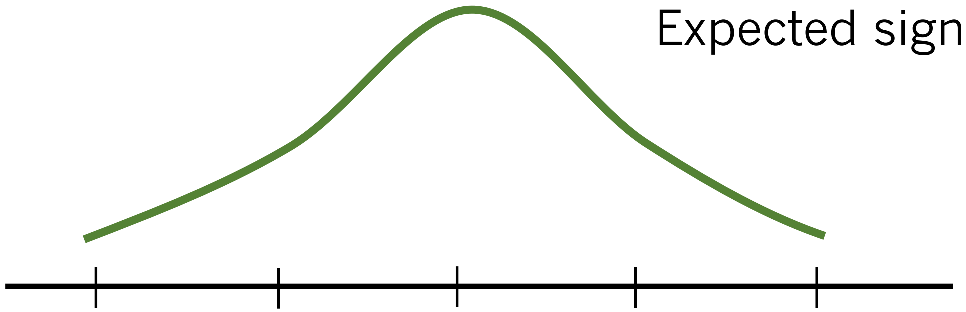
Data analysis strategies

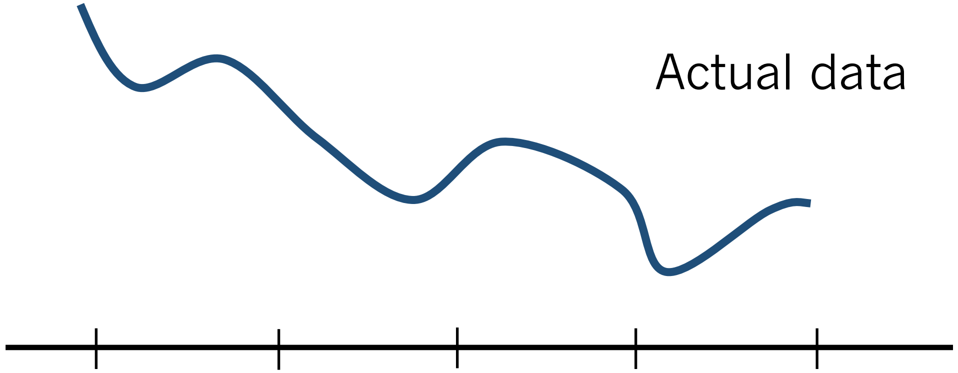
- Poisson limit
- CL_s limit
- Yellin limit



Poisson limit

- Poisson limit
  - Integrate all data to get total counts
  - Data is signal + background → expected signal counts cannot be more than **total** counts
- CL_s limit
- Yellin limit





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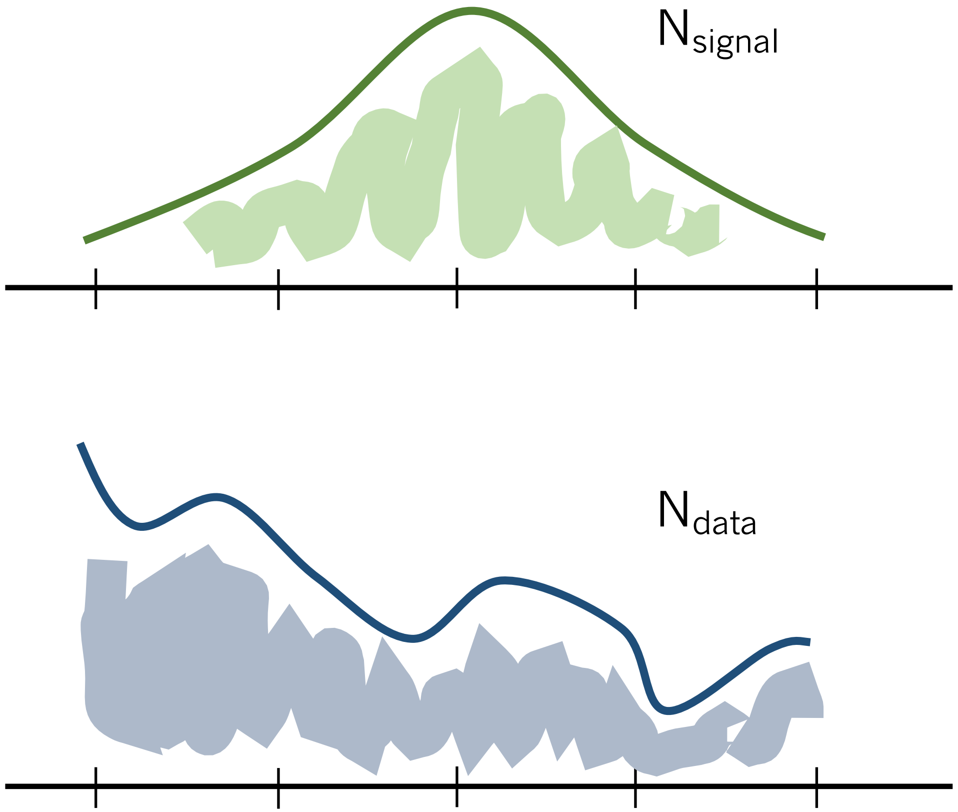

→ $N_{signal} < N_{data}$

CL_s limit

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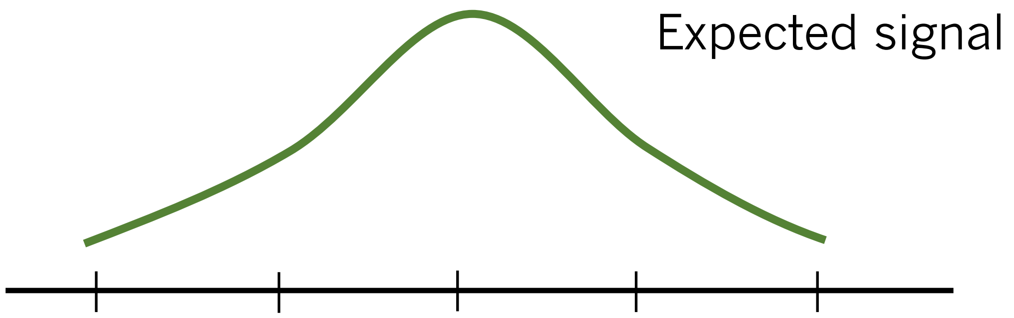
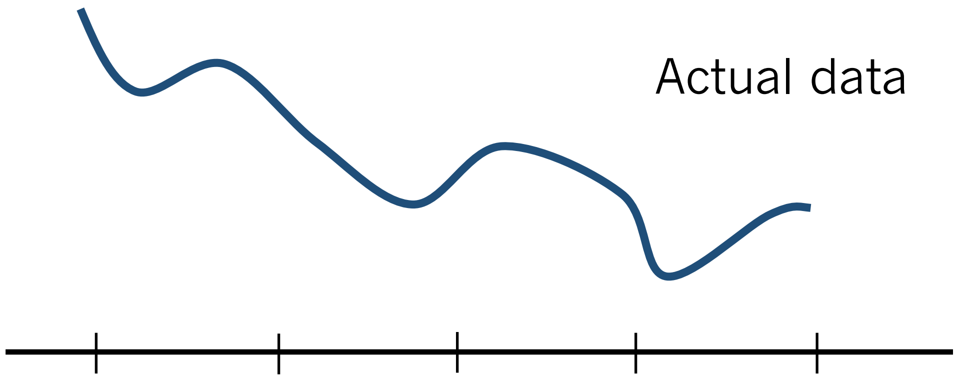
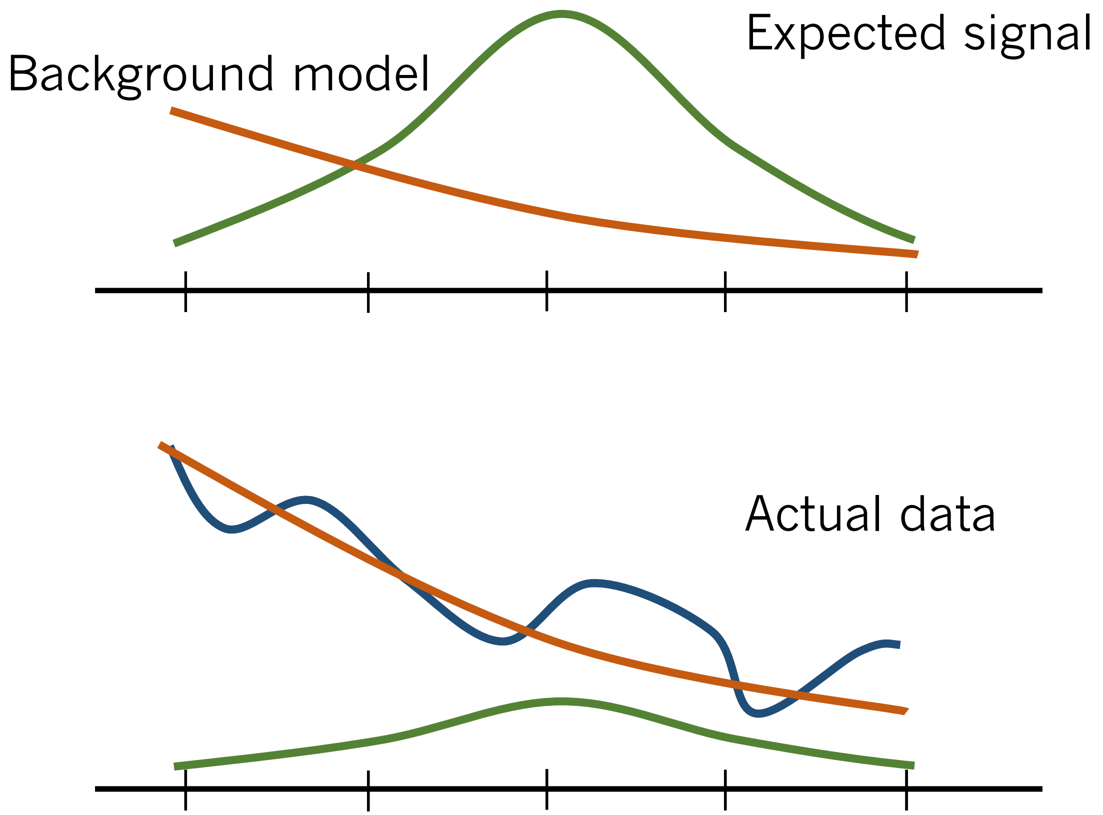




CL_s limit

- Poisson limit
  - Integrate all data to get total counts
  - Data is signal + background → expected signal counts cannot be more than **total** counts
- CL_s limit
  - Need signal **and** background models
  - Find maximal signal that is constrained for any parameters of background model
- Yellin limit



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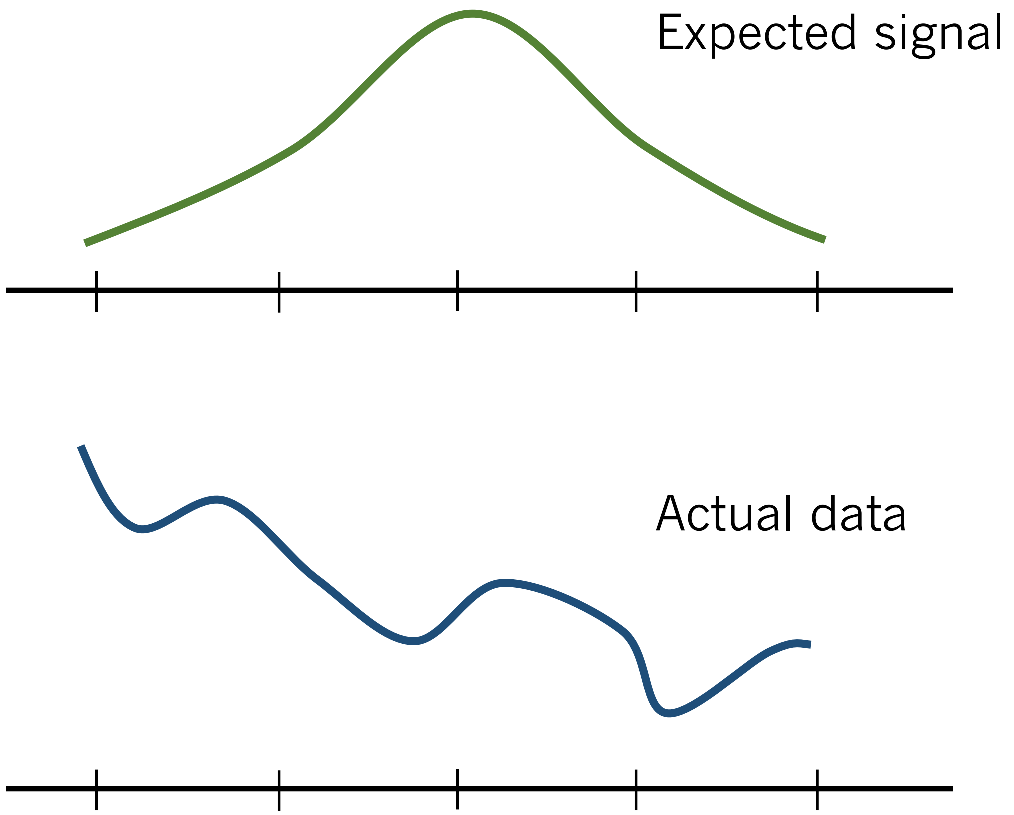

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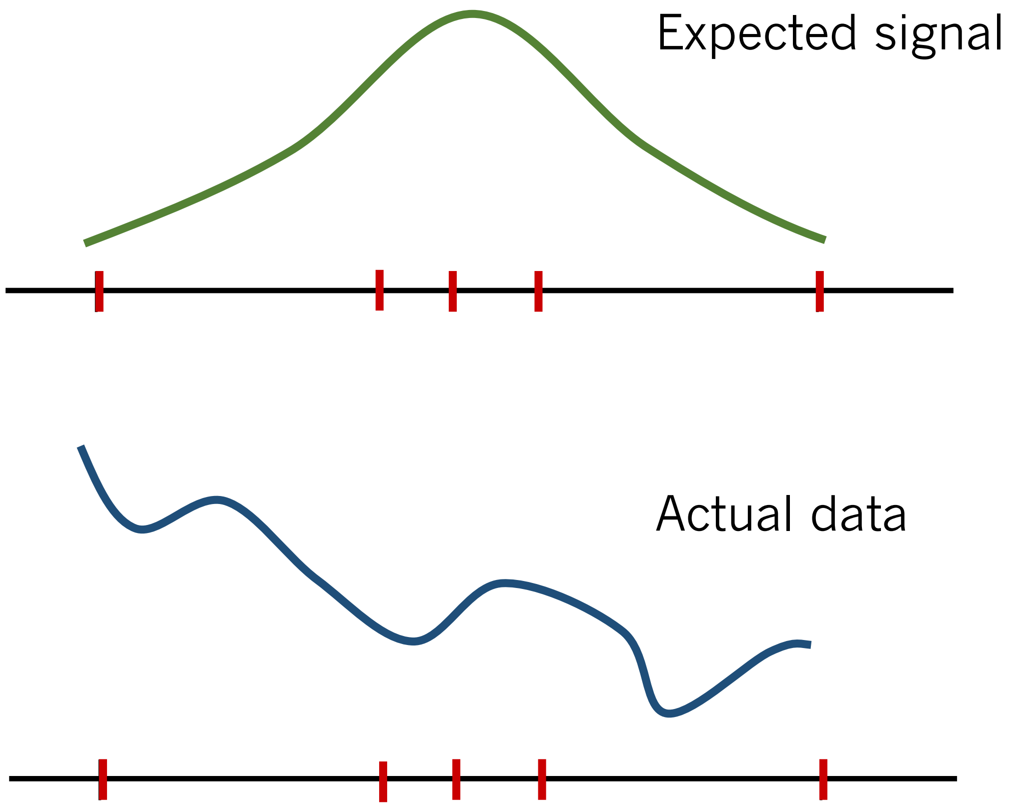
- Yellin limit
  - Change coordinates so signal model is uniform



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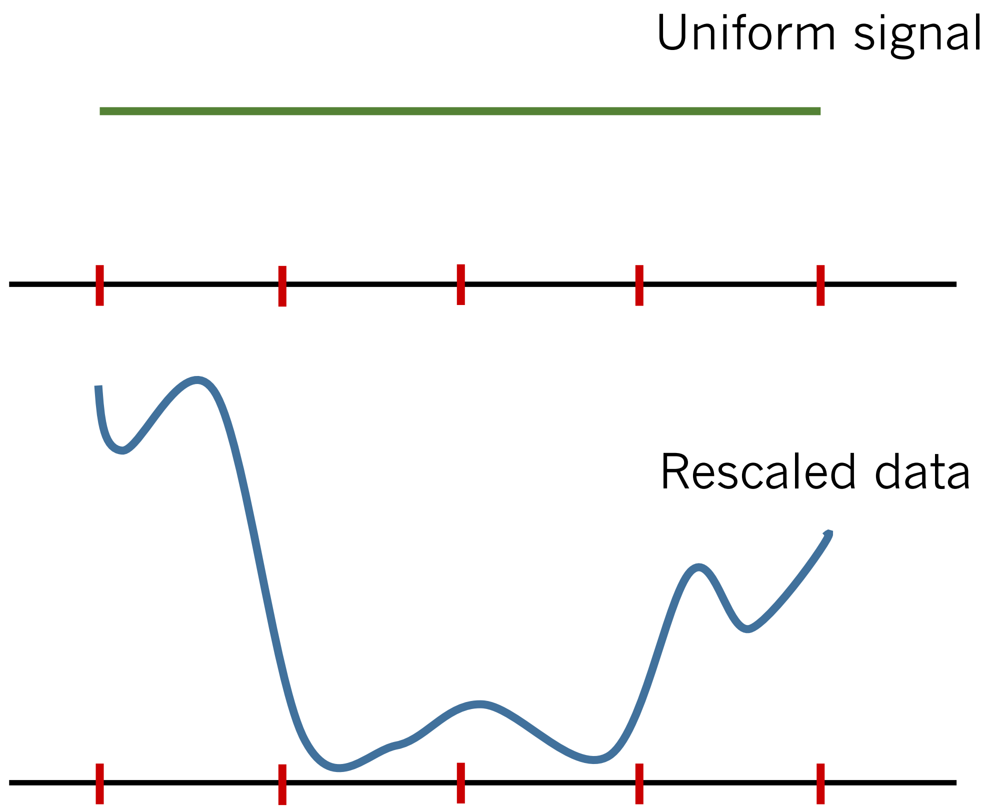

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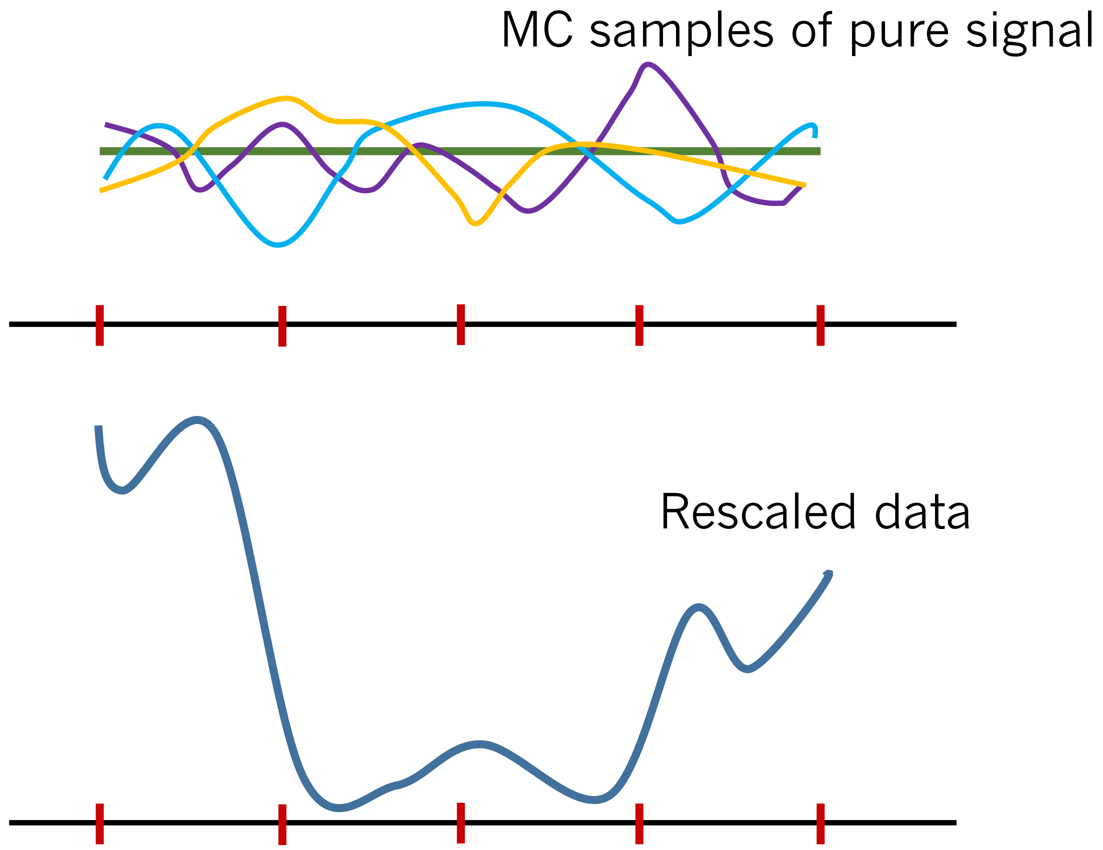
  - Change coordinates so signal model is uniform
  - Look for largest deviations from uniformity in data



Comparison

- Poisson limit
  - Pro: simple
  - Con: no spatial information
- CL_s limit
  - Pro: powerful
  - Con: need background model
- Yellin limit
  - Pro: works within unknown background
  - Con: computationally intensive