Beware of the dark side:

Some astrophysical limits to unconventional sources of stress and energy

Daniel Grin
Advisor: Marc Kamionkowski

Candidacy Presentation

December 5, 2007

Outline

- Telescope searches for decaying relic axions
- Cosmological axion constraints in non-standard thermal histories
- The evolution and scatter of dark matter halo concentrations
- Fat gravitons
- Ideas for future work

Telescope searches for decaying relic axions

Collaborators:
G. Covone, J.P. Kneib, M. Kamionkowski, Andrew Blain, Eric Jullo

1) Phys. Rev. D75, 105018 (2007), astro-ph/0611502
2) ESO VLT Programme 080.A-0628

Outline: Axions, Part I

- Axion background / past work
- Data / analysis
- New limits to ~eV axions
- VLT proposal

What are axions?

- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n = 10^{-16}\,\theta \text{ e cm} \qquad\qquad \theta \lesssim 10^{-10}$$

- New field and U(1) symmetry dynamically drive CP-violating term to 0

$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\mathrm{a}}} g^2 G\tilde{G}$$

- Axions have a mass

$$m_{\mathrm{a}} \simeq \frac{m_\pi f_\pi}{f_{\mathrm{a}}} \frac{\sqrt{r}}{1+r} \qquad\qquad r \equiv m_{\mathrm{u}}/m_{\mathrm{d}}$$

What are axions?

- Axions interact weakly with SM particles $\Gamma, \sigma \propto \alpha^2$
- Axions have a two-photon coupling

$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_{\mathrm{a}}}\xi \qquad \xi \equiv \frac{4}{3}\left\{E/N - \frac{2\,(4+r)}{3\,(1+r)}\right\}$$

- Two populations of axions:

Cold (nonthermal) axions

$$m_{\mathrm{a}} \lesssim 10^{-2}\ \mathrm{eV}$$

$$\Omega_{\mathrm{a}} h^2 \simeq 0.13 \left(\frac{m_{\mathrm{a}}}{10^{-5}\ \mathrm{eV}}\right)^{-1.18}$$

Hot (thermal) axions

$$m_{\mathrm{a}} \gtrsim 10^{-2}\ \mathrm{eV}$$

$$\Omega_{\mathrm{a}} h^2 \simeq \frac{m_{\mathrm{a}}}{130\ \mathrm{eV}} \left(\frac{10}{g_{*\mathrm{S},\mathrm{F}}}\right)$$

Axion decay

- Axion decays monochromatically via $a \longrightarrow \gamma\gamma$ with in source frame $\lambda_a = \frac{24,800\text{Å}}{m_{\mathrm{a,eV}}}$
- For galaxies/clusters, line comparable to sky background

$$I_{\lambda_o} \propto m_{\mathrm{a}}^7 \xi^2 \Sigma / \left(1 + z_{\mathrm{cl}}\right)^4$$

- First attempt made at KPNO 2.1m using Gold spectrograph on Abell clusters A1413, A2218, and A2256:

$$3 \text{ eV} \leq m_{\mathrm{a}} \leq 8 \text{ eV}$$

$$\xi \leq 0.08$$

The modern advantage

- 8-meter-class telescope: Sensitivity to fainter signal
- IFU (Integrated Field Unit) spectroscopy: Spatial Resolution!
- Lensing maps: no dynamical assumptions, better sky subtraction

Seeking axions with the VIMOS IFU

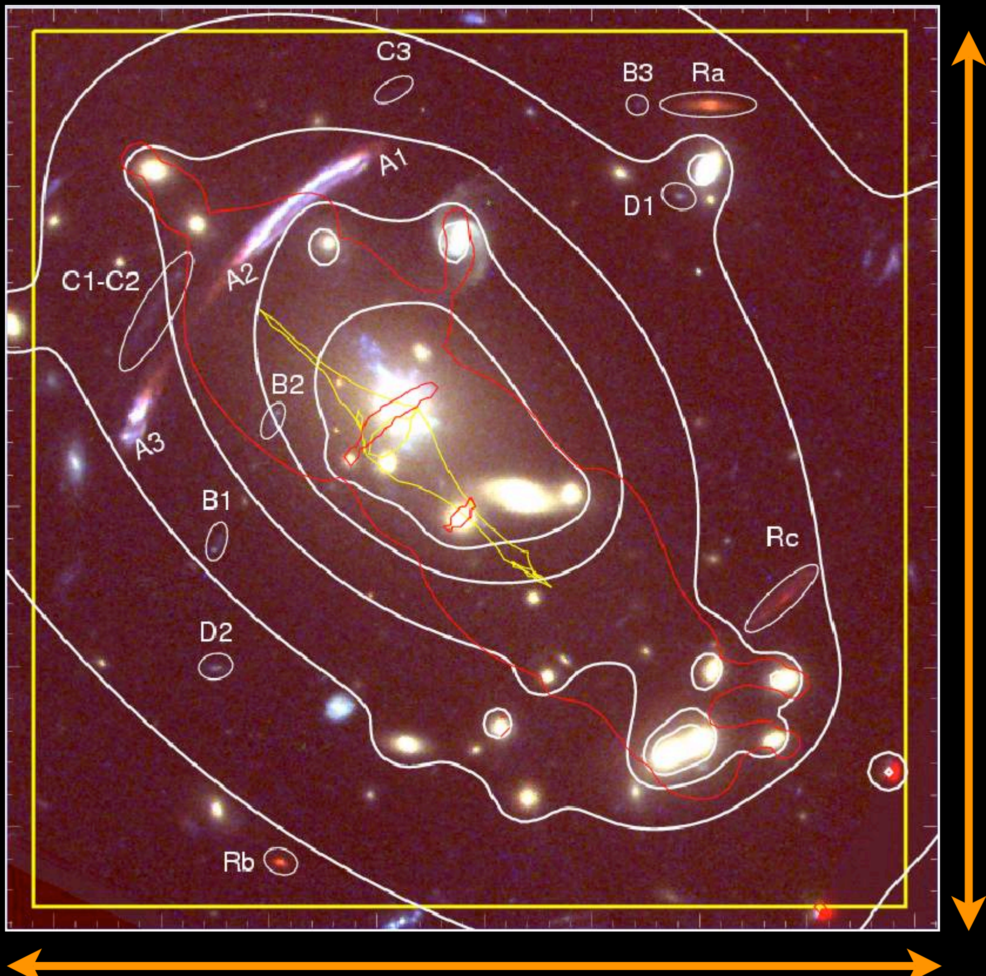
- ✳ VIMOS IFU (VLT, 6400 fibers) has largest f.o.v. of any instrument in its class: 54″x54″ mode used
- ✳ LR-Blue grism used: $4000\text{Å} \leq \lambda \leq 6800\text{Å}$ $(4.5 \text{ eV} \leq m_{\rm a} \leq 7.7 \text{ eV})$. Dispersion of 5.4Å adequate to resolve axion line:

$$\delta\lambda = 195\ \sigma_{1000}\ m_{\rm a,eV}^{-1}\ \text{Å}$$

- ✳ 10.8 ksec exposures of A2667 (z=0.233, 1 pointing) and A2390 (z=0.228, 3 pointings) taken as part of VIMOS study of these clusters

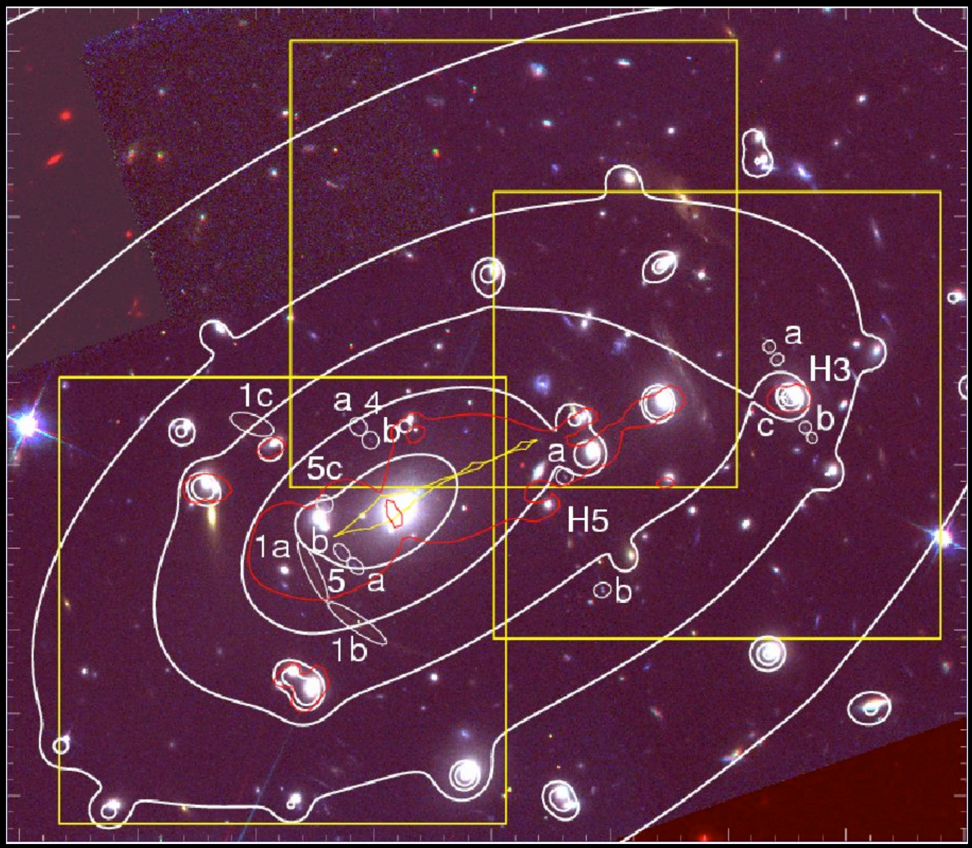
Applying the imaging

A2667



200 kpc

A2390



✳Bright sources masked

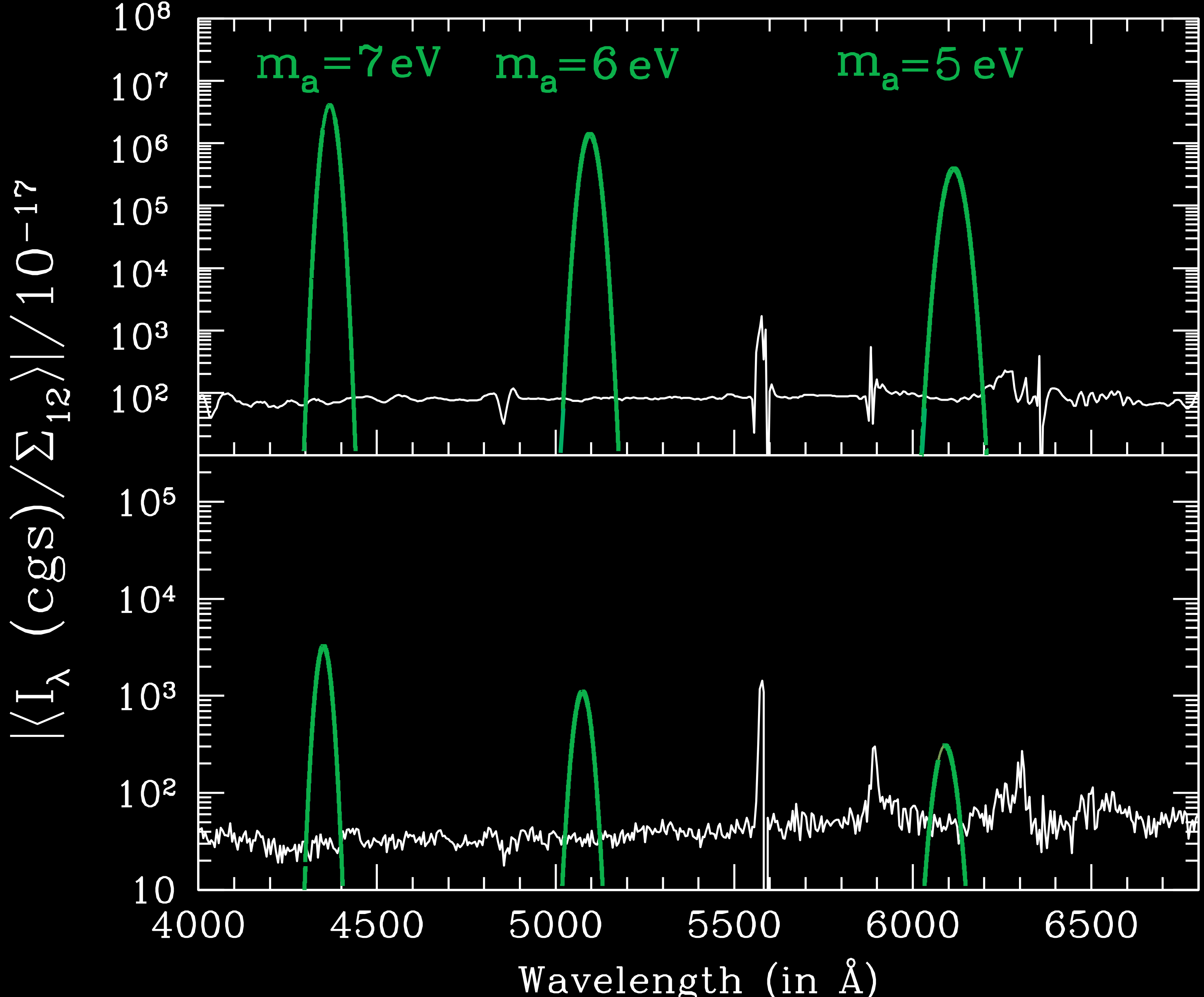
Data analysis

- Signal modeled as sum of density-dependent signal and uniform sky background with noise (Poisson, CCD bias, read-out, flat-fielding, fiber crosstalk , mass map errors)

$$I_{\lambda,\mathrm{i}}^{\mathrm{mod}} = \langle I_\lambda / \Sigma_{12} \rangle \, \Sigma_{12,\mathrm{i}} + b_\lambda$$

- End result is a 1D spectrum of the cluster. Fibers weighted to extract density-dependent part of signal: $\langle I_\lambda / \Sigma_{12} \rangle$

Data analysis



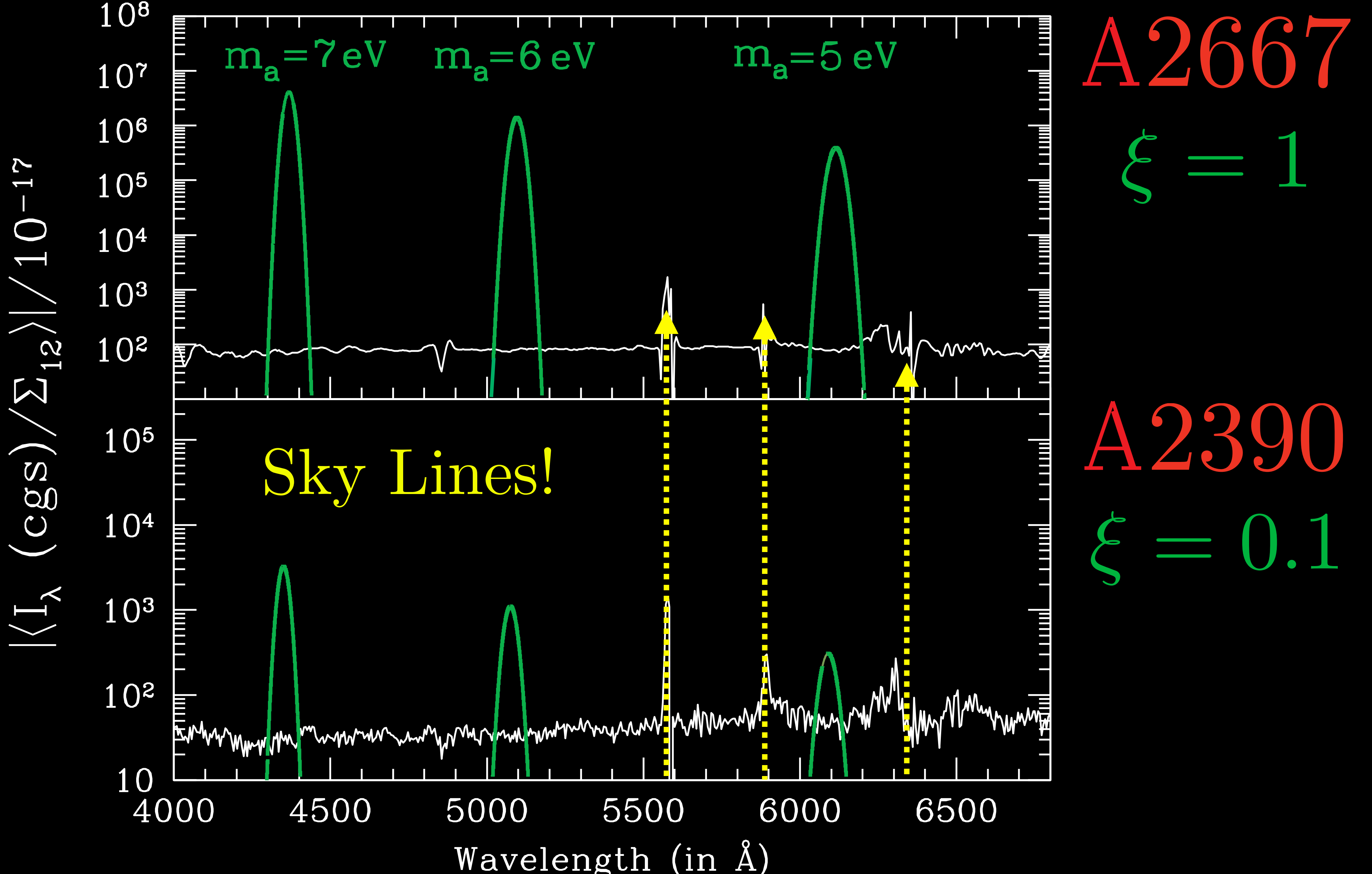
A2667

$\xi = 1$

A2390

$\xi = 0.1$

Data analysis



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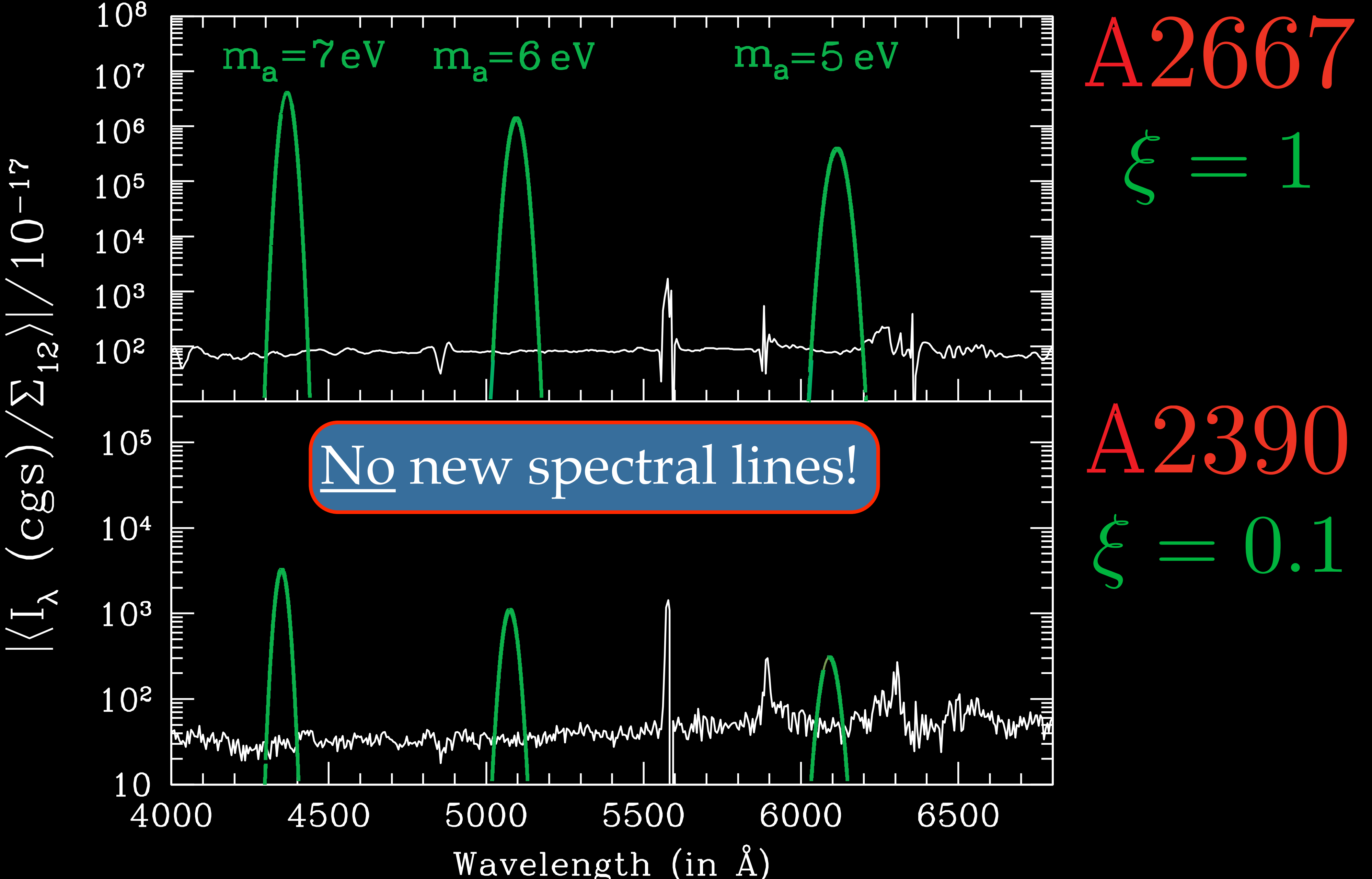
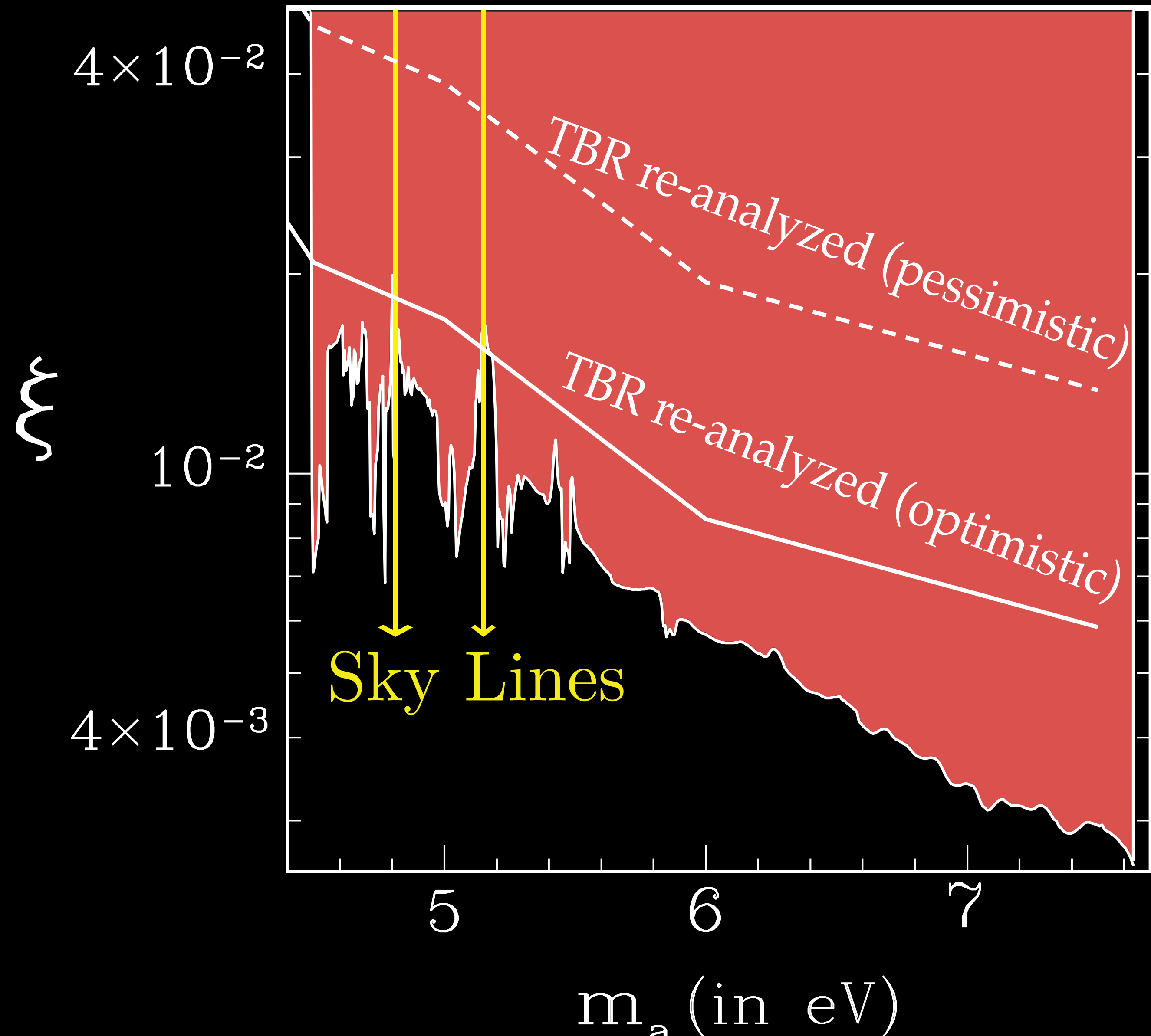
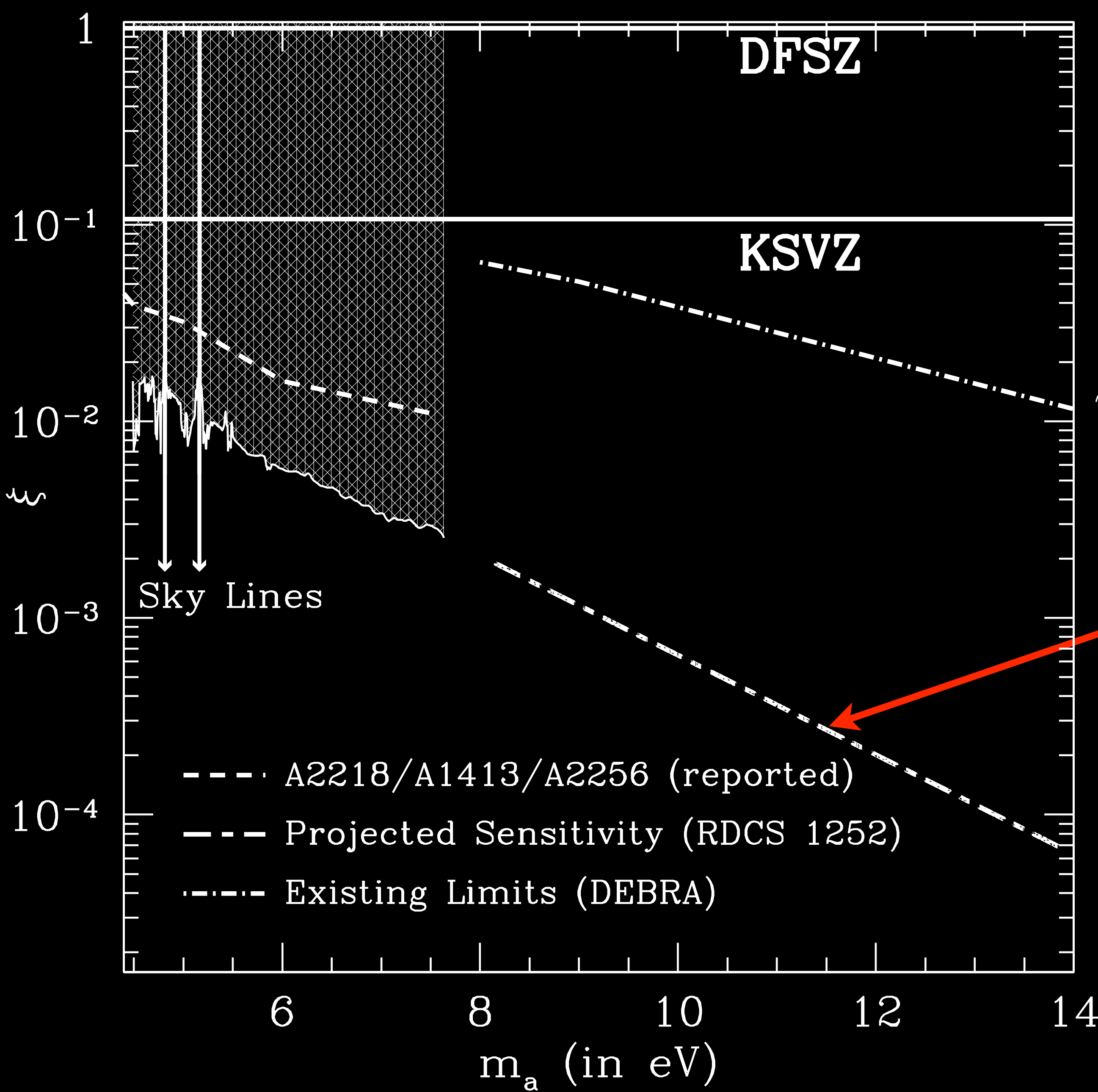


New limits to KSVZ/DFSZ axions: standard production mechanism



Extending the optical axion window



- Sensitivity improves at higher redshift!

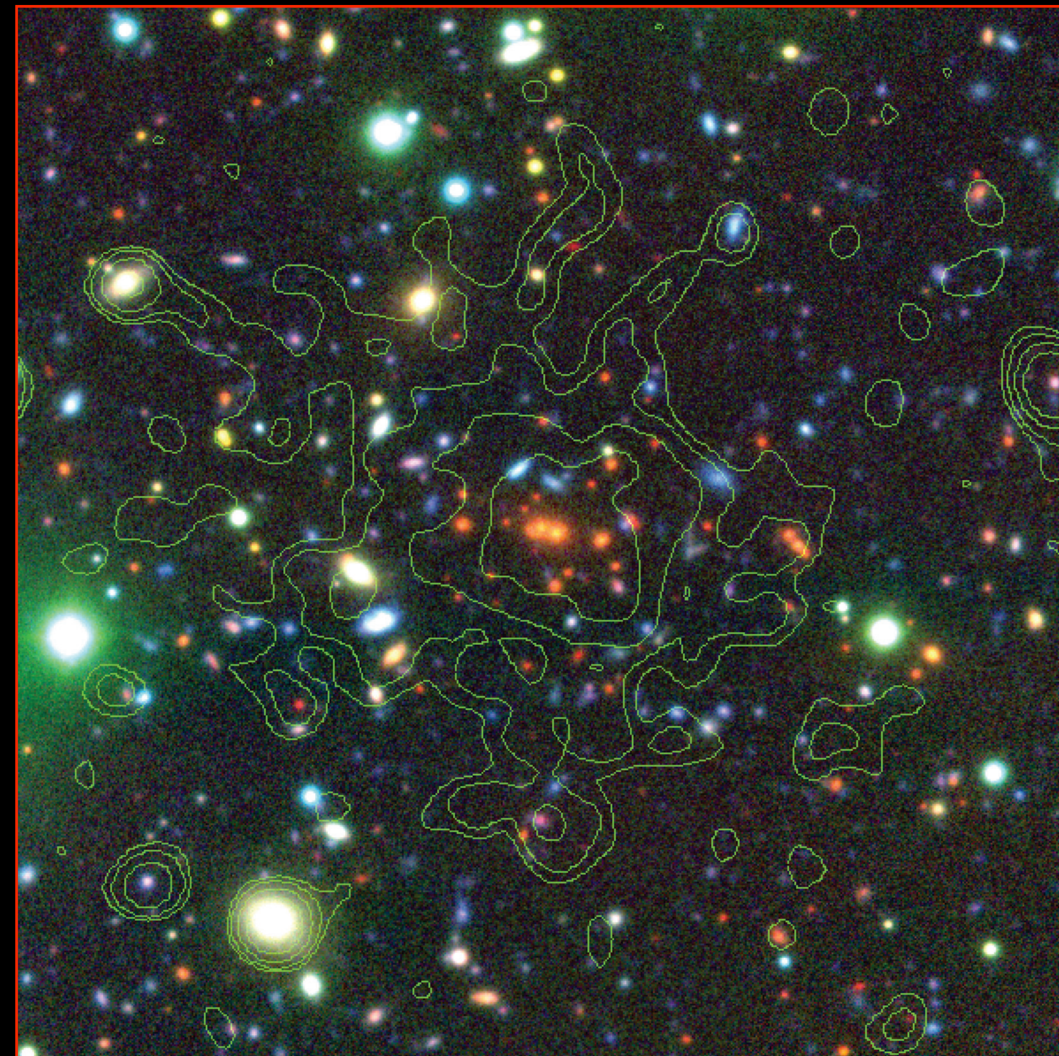
$$I_{\lambda_o} \propto m_a^7 (1 + z_{cl})^{-4}$$

$$m_a = 24,800 \text{ Å} (1 + z_{cl}) / \lambda_a$$

$$\xi \propto I_{\lambda_o}^{1/2} (1 + z_{cl})^{-3/2}$$

RDCS 1252

- RDCS 1252 is a $8 \times 10^{14} M_{\odot}$ cluster at $z = 1.237$
- Allotted 25 hrs of time for VIMOS IFU spectra using LR-Blue grism
- Publicly available weak-lensing mass maps (Lombardi et al. 2005), 2 arcs?



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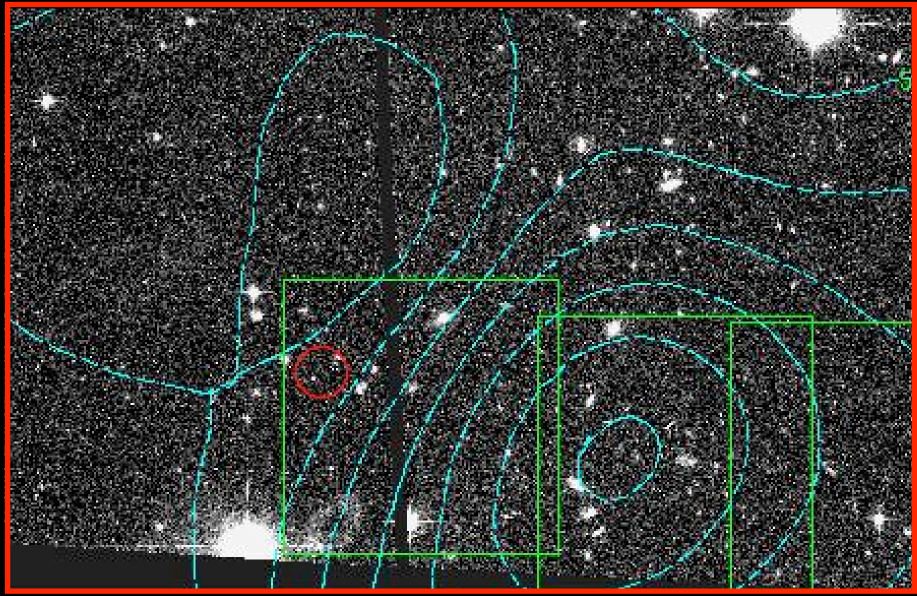

3 pointings cover range of WL mass contours

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Cosmological axion constraints in non-standard thermal histories

Collaborators: Tristan Smith and Marc Kamionkowski

arXiv:0711.1352
Submitted to Phys. Rev. D.

Outline: Axions, Part II

- Motivation for considering low-temperature reheating (LTR)
- Cosmological axion constraints
- LTR details
- New Constraints

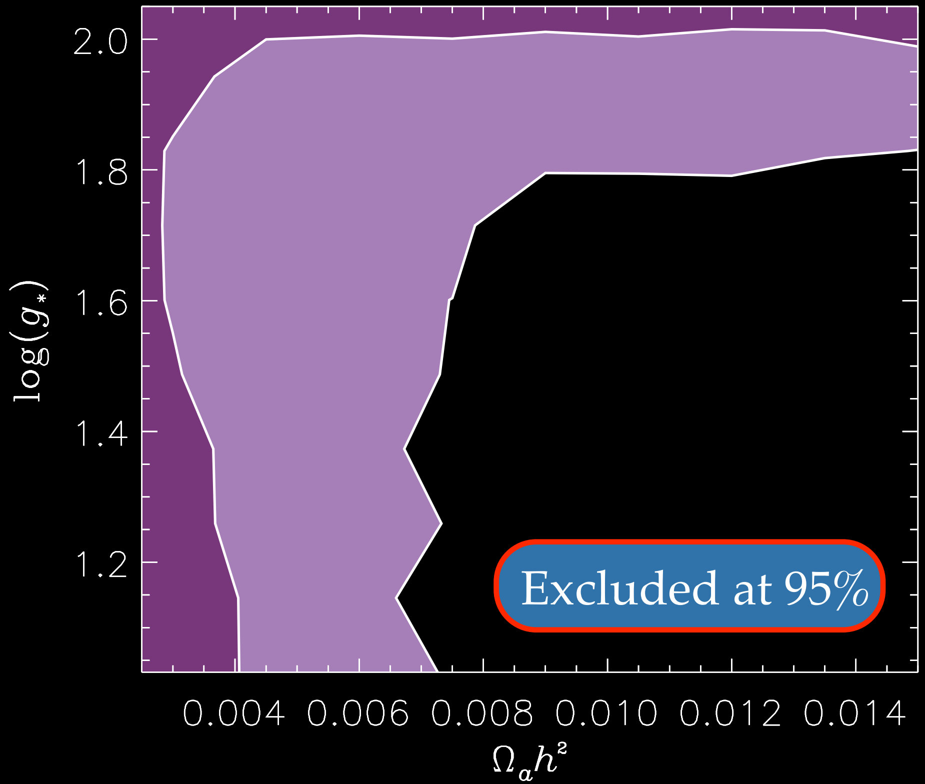
Motivation for low-temperature reheating

- No strong evidence for nature of expansion history before 4 MeV
- Thermal gravitino bounds (closure, BBN) require $T_{\rm rh} \lesssim 10^8~\text{GeV}$ or $T_{\rm rh} \lesssim 1~\text{GeV}$
- Light SM neutrinos become a viable WDM candidate if $T_{\rm rh} \sim 1 - 10~\text{MeV}$

The physics of cosmological axion constraints

- Axions are relativistic at early times, free stream and suppress power by $\Delta P/P \simeq -8\Omega_{\rm a}/\Omega_{\rm m}$ when $\lambda \lesssim \lambda_{\rm fs}$

- SDSS galaxy P(k) and WMAP1 yield exclusion region (Hannestad et al. 2004)



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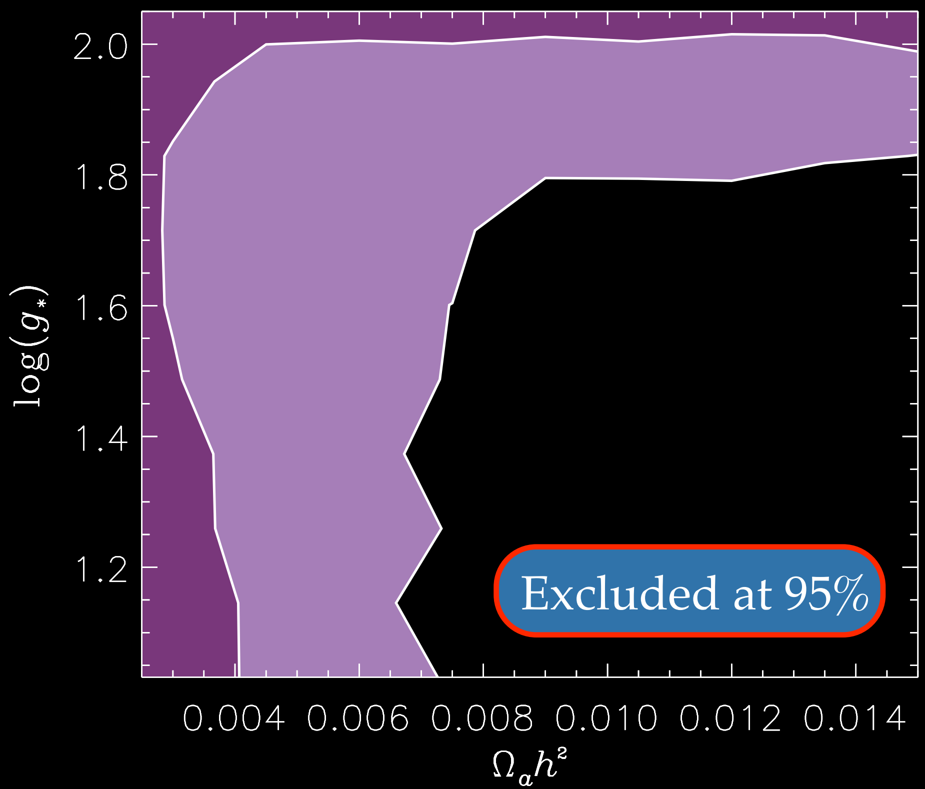

$$\frac{T_{\rm a}}{T_\nu} \simeq \left(\frac{10.75}{g_{*{\rm S},{\rm F}}}\right)^{1/3}$$

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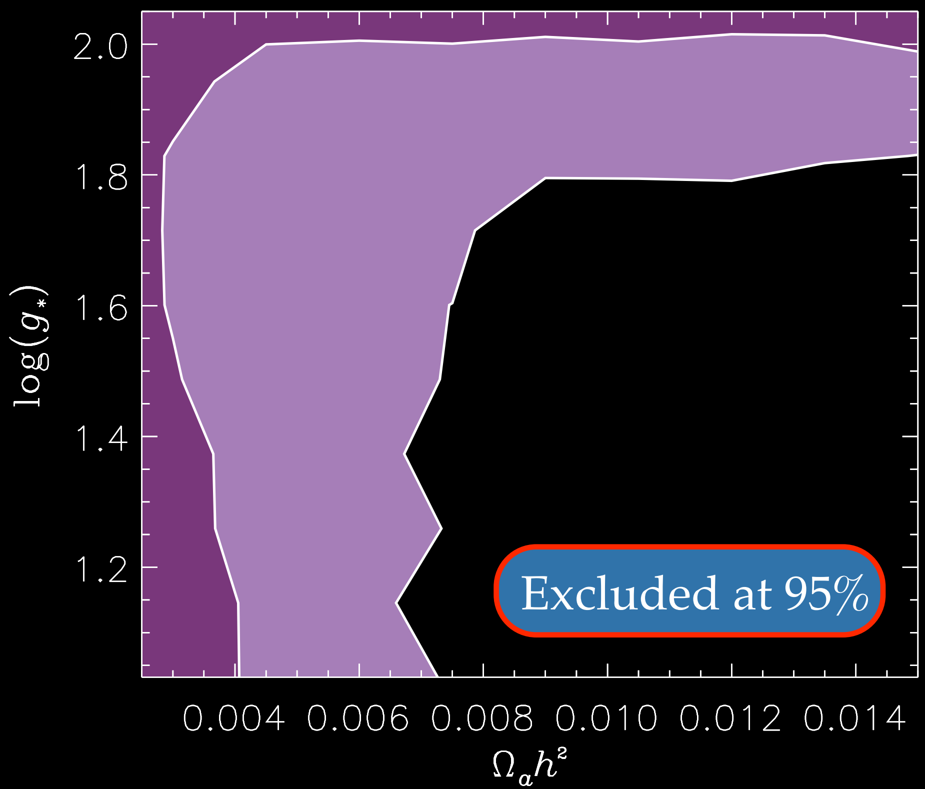

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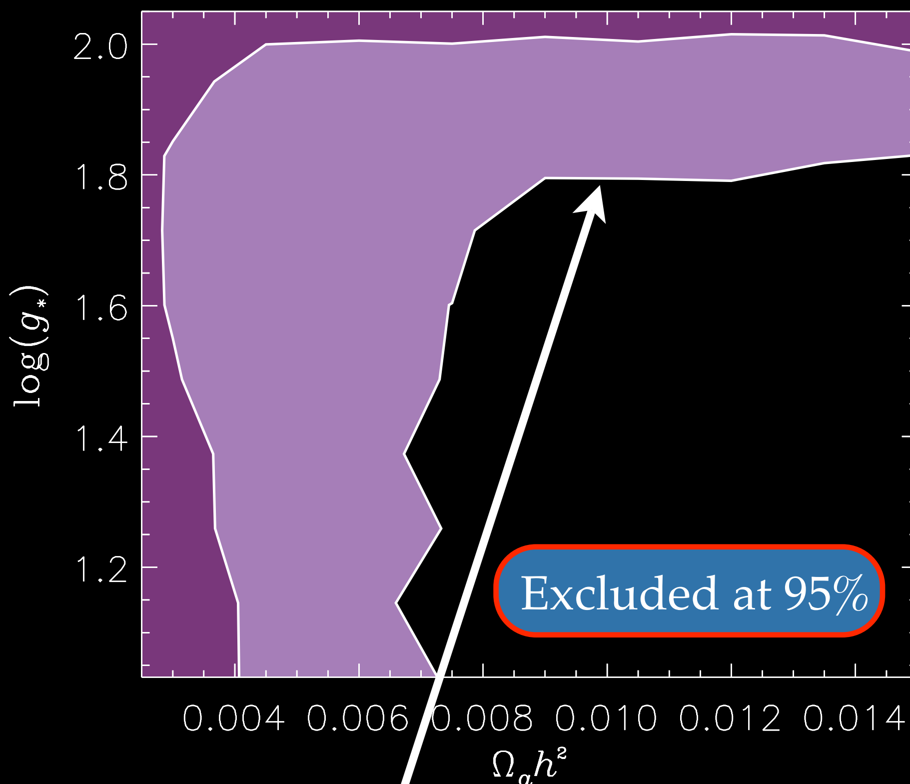


$\lambda_{\rm fs} \rightarrow \lambda_{\rm nl} \simeq 30\ h^{-1}\ {\rm Mpc}$

Low-temperature reheating (LTR)

- Simple model in which $\phi \rightarrow$ radiation is responsible for extended reheating phase

$$\frac{d\rho_{\rm R}}{dt} + 4H\rho_{\rm R} = \Gamma_\phi \rho_\phi \qquad \frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi$$

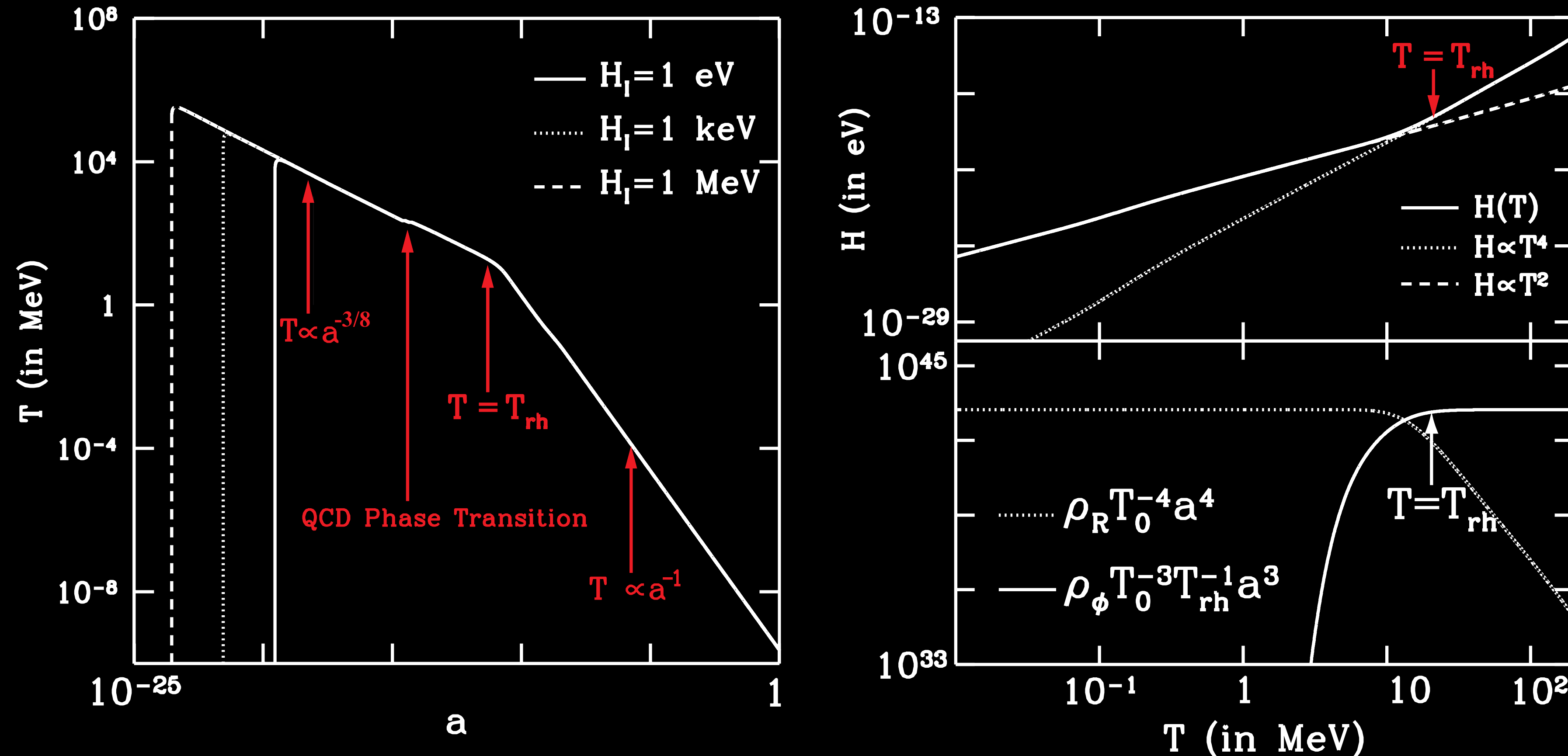
- $T_{\rm rh} \gtrsim 4$ MeV to avoid changing successful predictions of BBN

- Decay products thermalize and entropy generated

$$T = \left[\frac{30}{\pi^2 g_*(T)}\right]^{1/4} \rho_{\rm R}^{1/4}$$

- Past work considered effects on WIMP, SM neutrino, sterile neutrino, and cold axion abundances and constraints. New work: LSS/CMB/total density constraints to hot axions in LTR

Low-temperature reheating (LTR)



✳ Entropy generation slows down temperature decrease

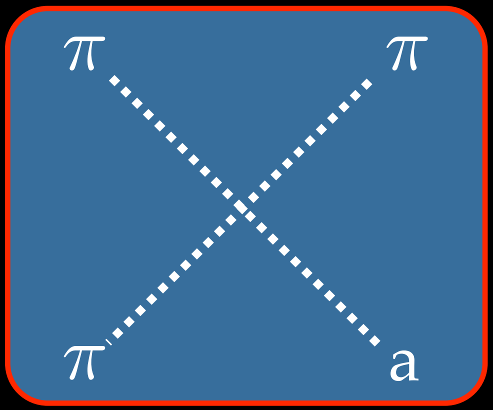
$$T \propto a^{-3/8} \text{ until } T \lesssim T_{\rm rh}, \text{ then } T \propto a^{-1}$$

✳ Hubble expansion is faster

$$H \propto T^4 \text{ until } T \lesssim T_{\rm rh}, \text{ then } H \propto T^2$$

Hot axion production at early times

Axion Production:



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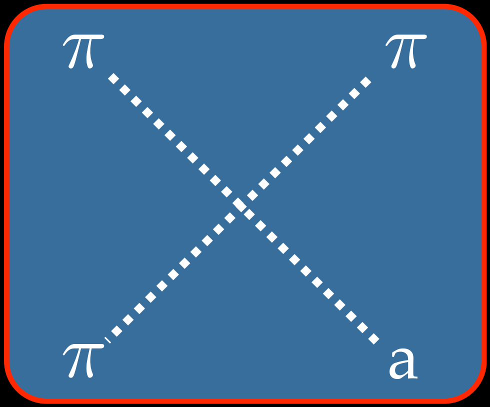
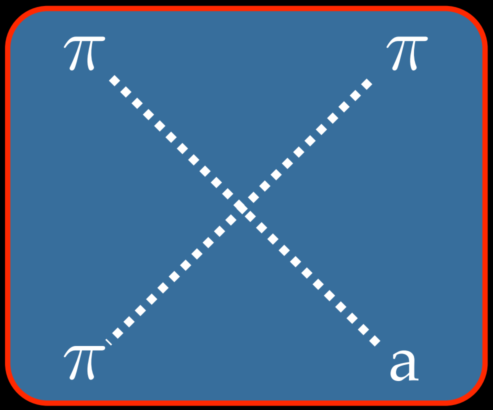


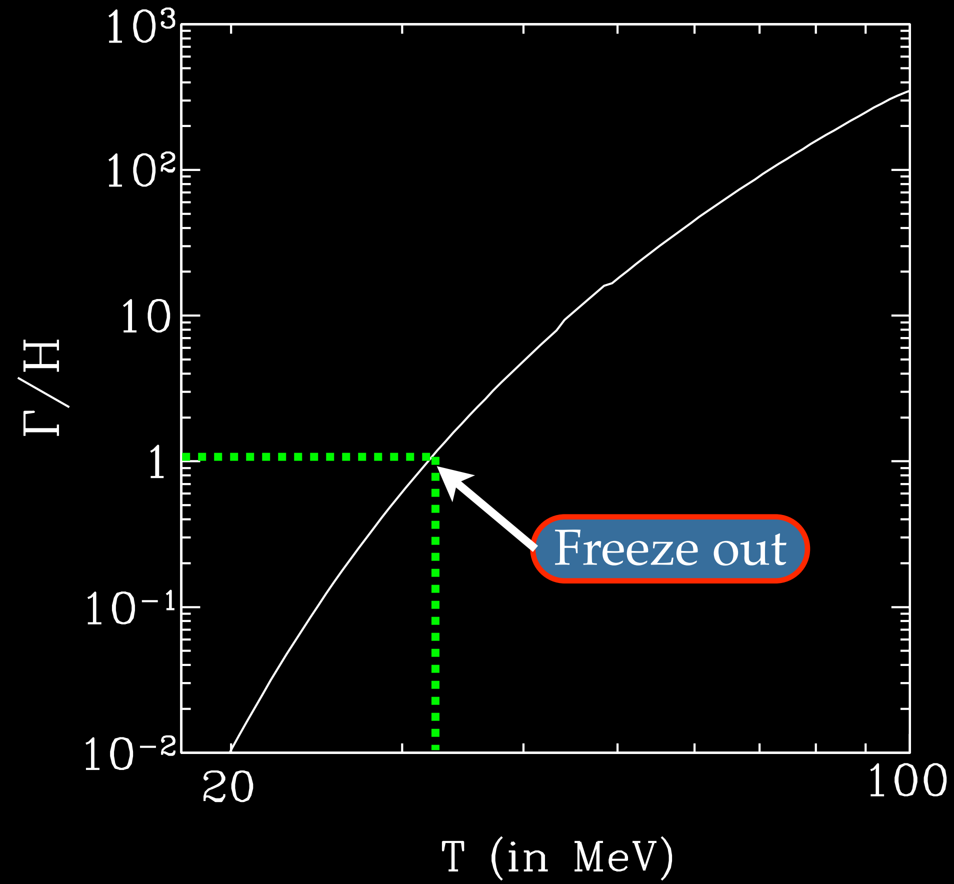
- Axions produced through interactions between non-relativistic pions in chemical equilibrium with rate

$$\Gamma \sim n_\pi \langle \sigma v \rangle = \frac{T^2 m_a^2 (1-r)^2}{9 z f_\pi^4 m_\pi^2} \left(\frac{m_\pi T}{2\pi} \right)^{3/2} e^{-m_\pi/T}$$

Hot axion production at early times

Axion Production:





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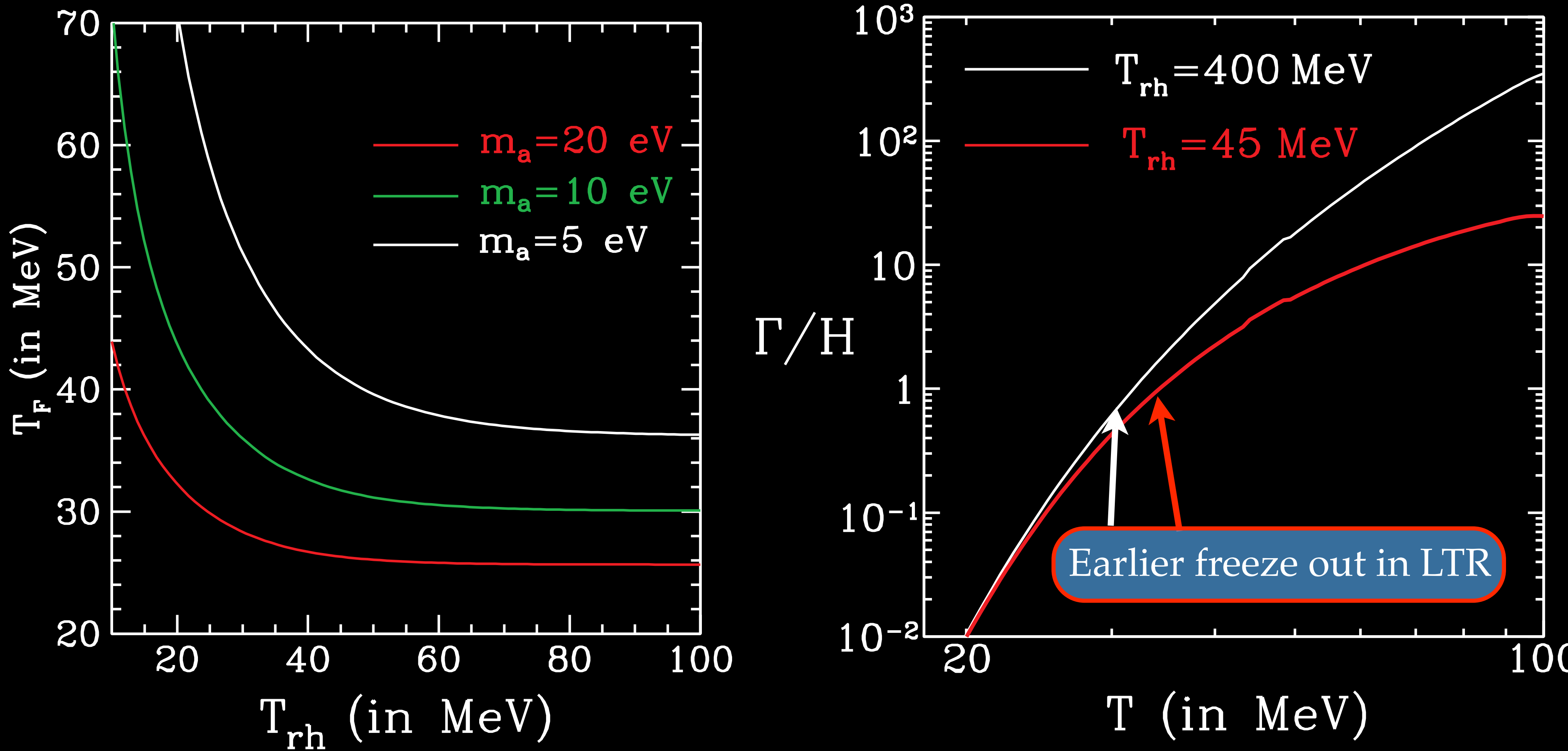
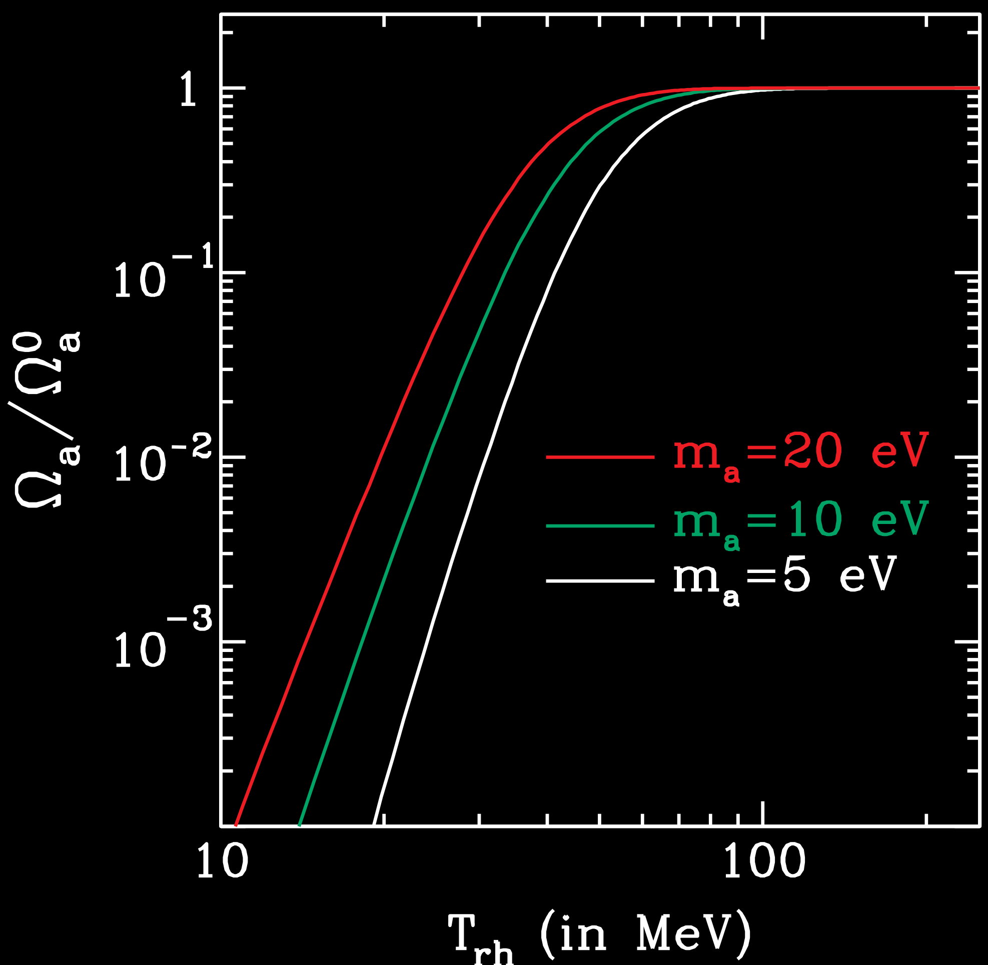
Axion freeze out in LTR



- ✳ Faster expansion: freeze-out is earlier
- ✳ When $T_{\rm rh} \gg T_{\rm F,0}$, standard results are recovered
- ✳ $\Gamma \propto f_{\rm a}^{-2} \propto m_{\rm a}^{2}$, so more massive axions freeze out later

Axion abundance in LTR

- Higher $T_{\rm F}$ means higher initial equilibrium abundance
- Entropy generation dramatically suppresses abundances



Axion temperature in LTR

- Entropy generation leads to $T_\mathrm{a} \propto a^{-1}$, while $T_\gamma \propto a^{-3/8}$:

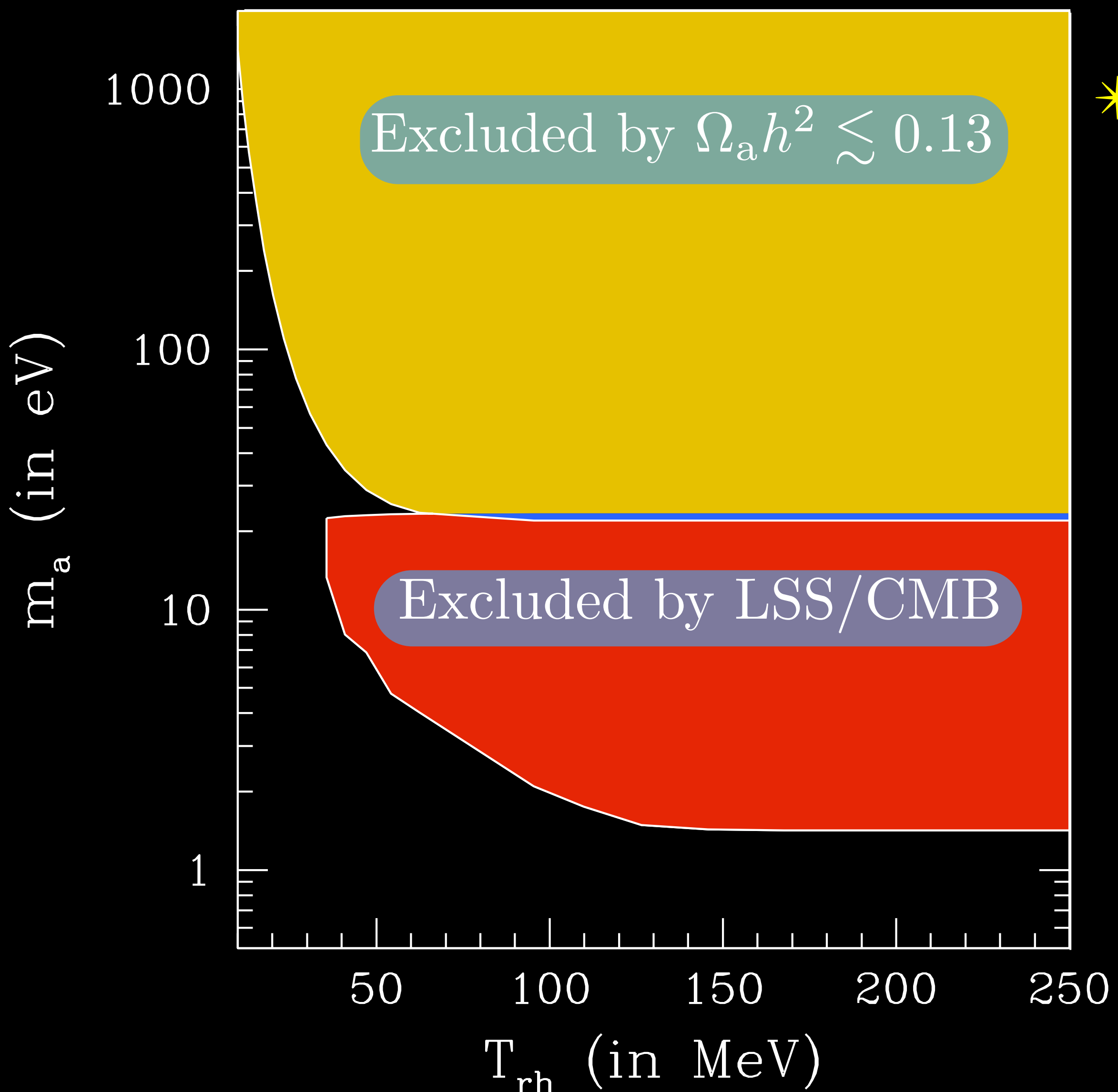
$$\frac{T_\mathrm{a}}{T_\nu} \approx (10.75/g_{*\mathrm{S},\mathrm{F}})^{1/3}, \qquad \text{if } T_\mathrm{F} < T_\mathrm{rh}.$$

$$\frac{T_a}{T_\nu} \simeq \left(\frac{11}{4}\right)^{1/3} \left(\frac{T_\mathrm{rh}}{T_\mathrm{F}}\right)^{5/3} \left(\frac{g^2_{*,\mathrm{RH}} g_{*\mathrm{S},0}}{g^2_{*,\mathrm{F}} g_{*\mathrm{S},\mathrm{RH}}}\right)^{1/3} \qquad \text{if } T_\mathrm{F} > T_\mathrm{rh}.$$

- Axions non-relativistic earlier: Smaller free-streaming length!

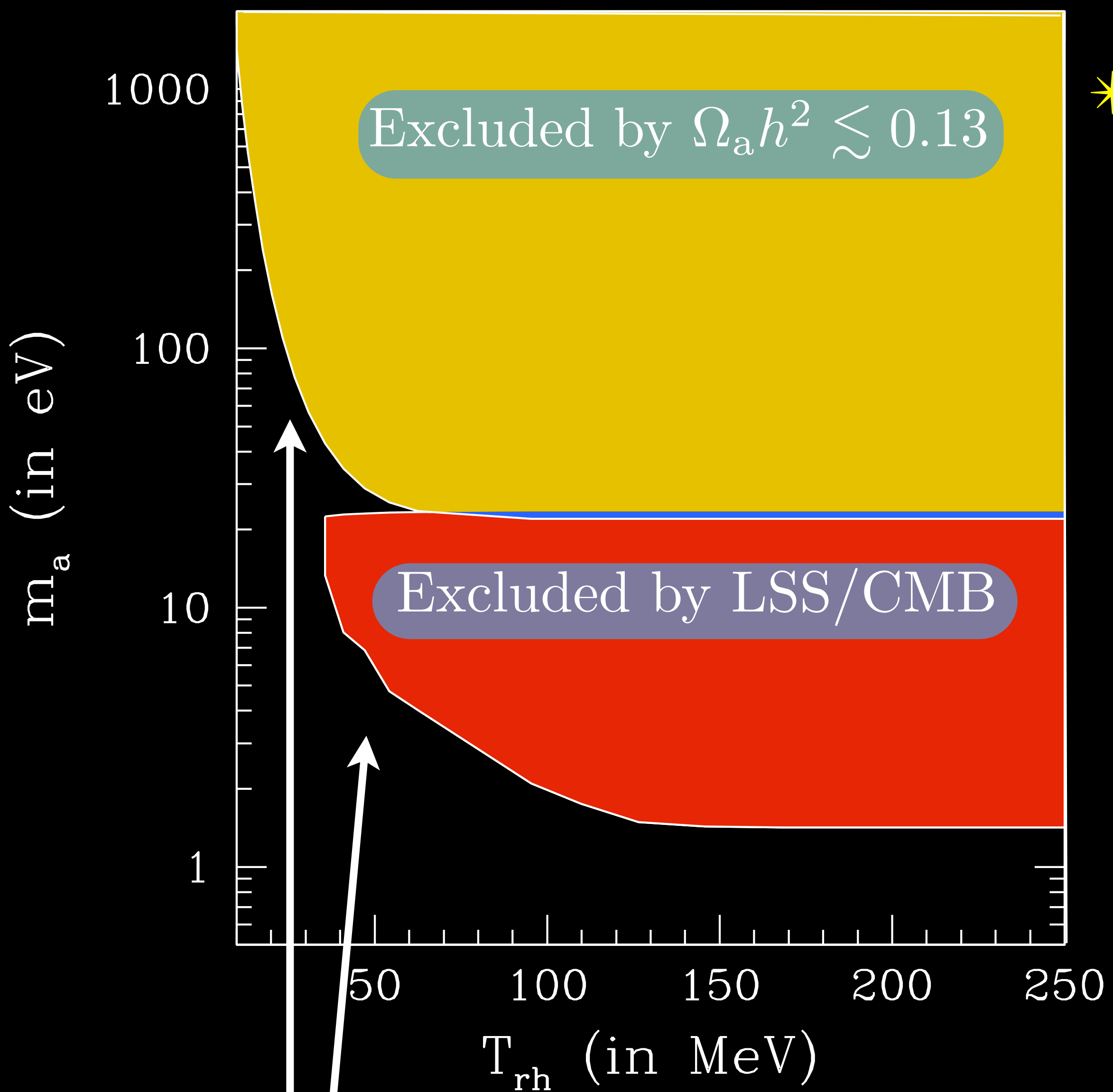
$$\lambda_\mathrm{fs} \simeq \frac{196\ \mathrm{Mpc}}{m_{\mathrm{a,eV}}} \left(\frac{T_\mathrm{a}}{T_\nu}\right) \left\{1 + \ln\left[0.45 m_{\mathrm{a,eV}} \left(\frac{T_\nu}{T_\mathrm{a}}\right)\right]\right\}.$$

New constraints



- $\lambda_{fs}(T_{rh}, m_a)$ & $\Omega_a h^2 (T_{rh}, m_a)$ calculated to trace out allowed region

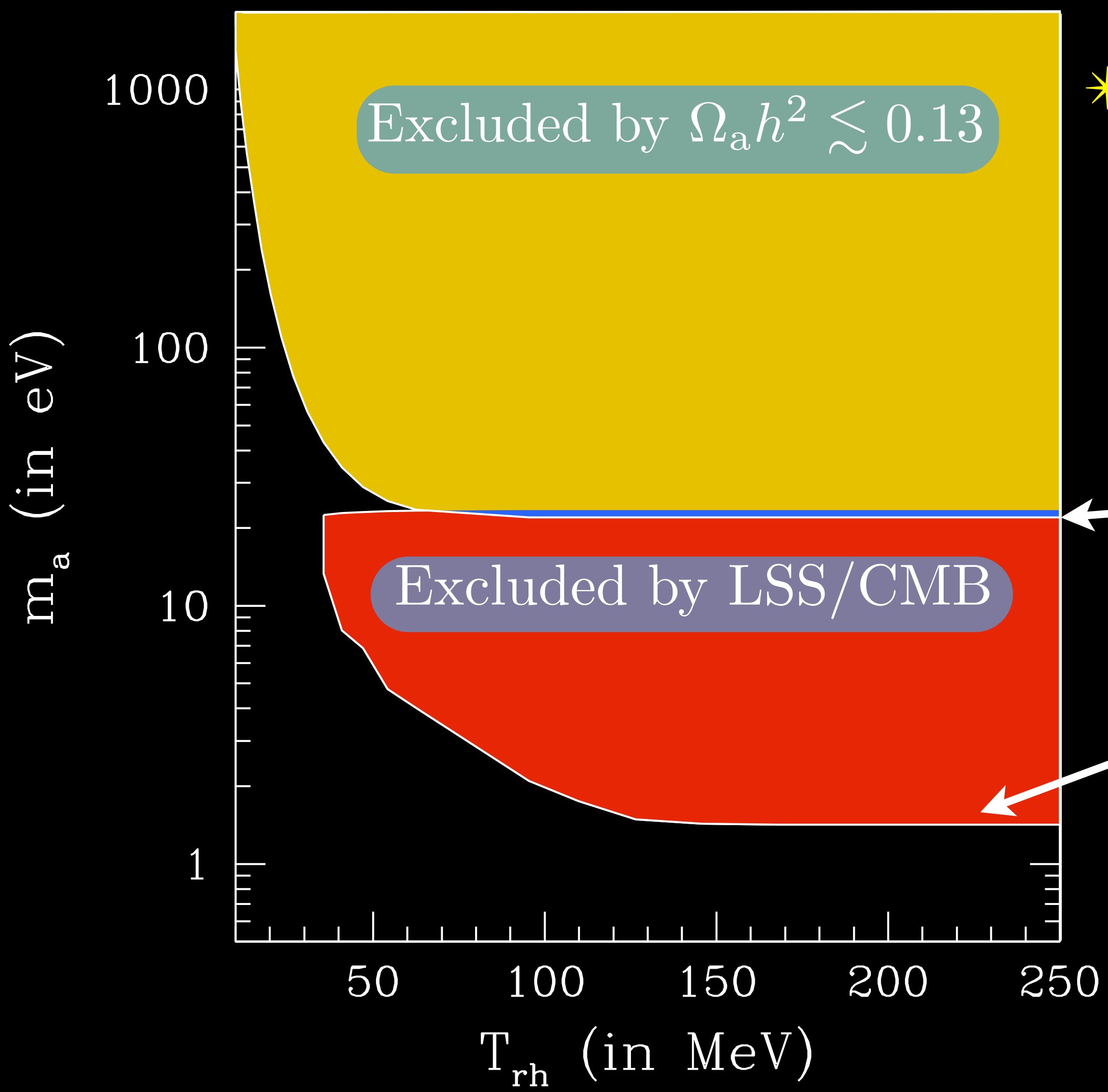
New constraints



- ✳ $\lambda_{fs}\,(T_{rh}, m_a)$ & $\Omega_a h^2\,(T_{rh}, m_a)$ calculated to trace out allowed region

Both constraints loosened as T_{rh} lowered

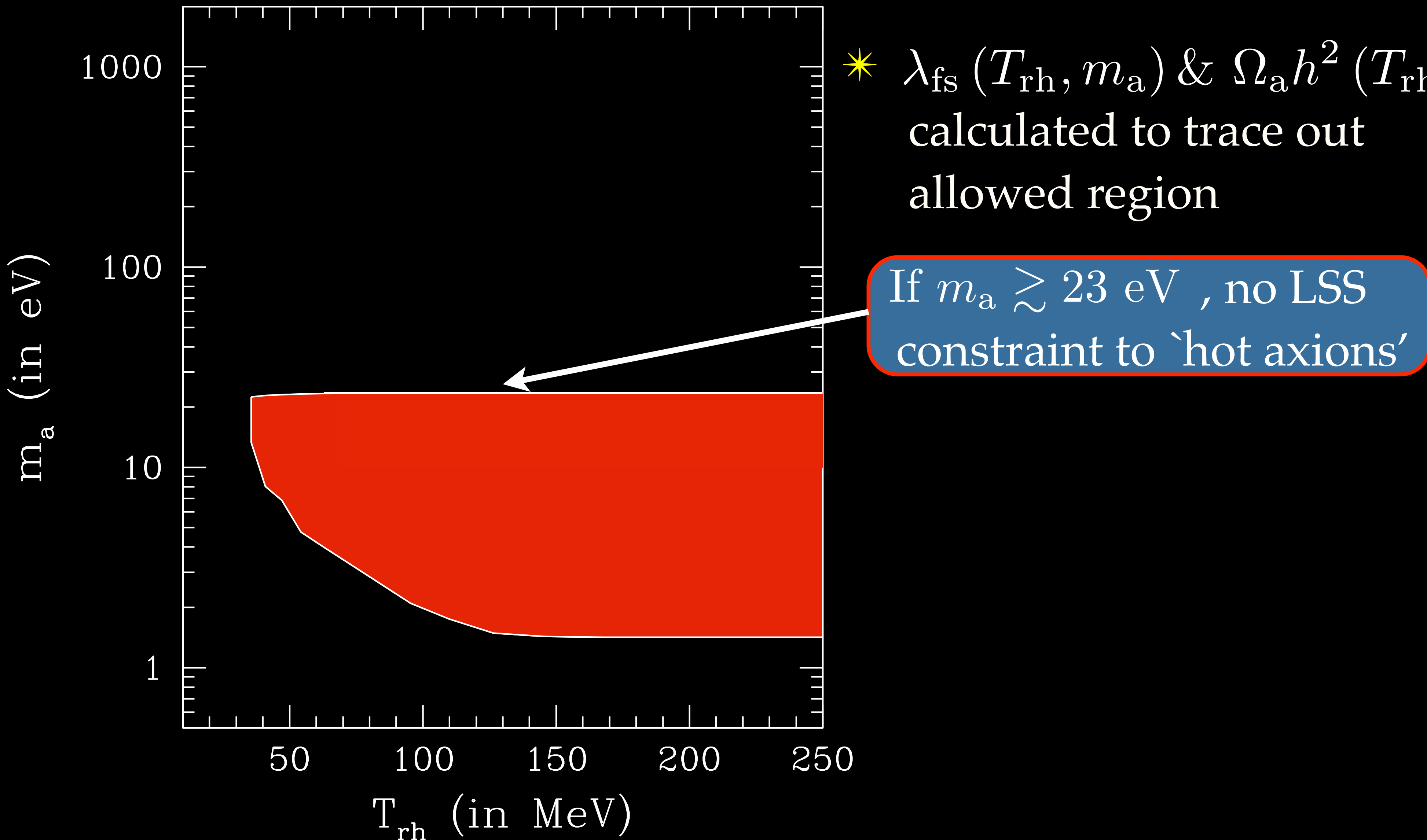
New constraints



- $\lambda_{fs}(T_{rh}, m_a)$ & $\Omega_a h^2 (T_{rh}, m_a)$ calculated to trace out allowed region

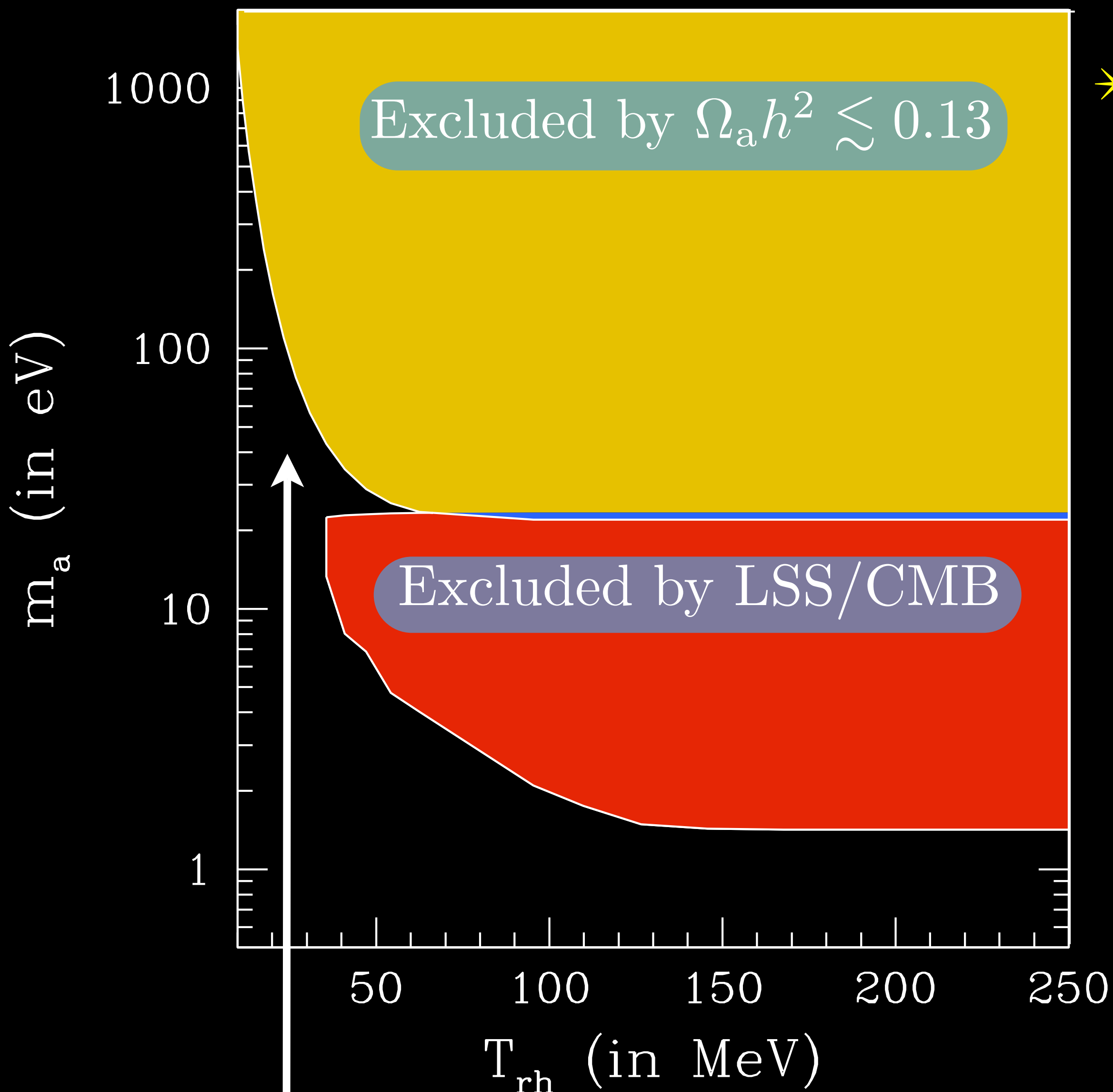
Standard constraints recovered if $T_{rh} \gtrsim 170$ MeV

New constraints



- $\lambda_{\rm fs}\,(T_{\rm rh}, m_{\rm a})$ & $\Omega_{\rm a} h^2\,(T_{\rm rh}, m_{\rm a})$ calculated to trace out allowed region

New constraints

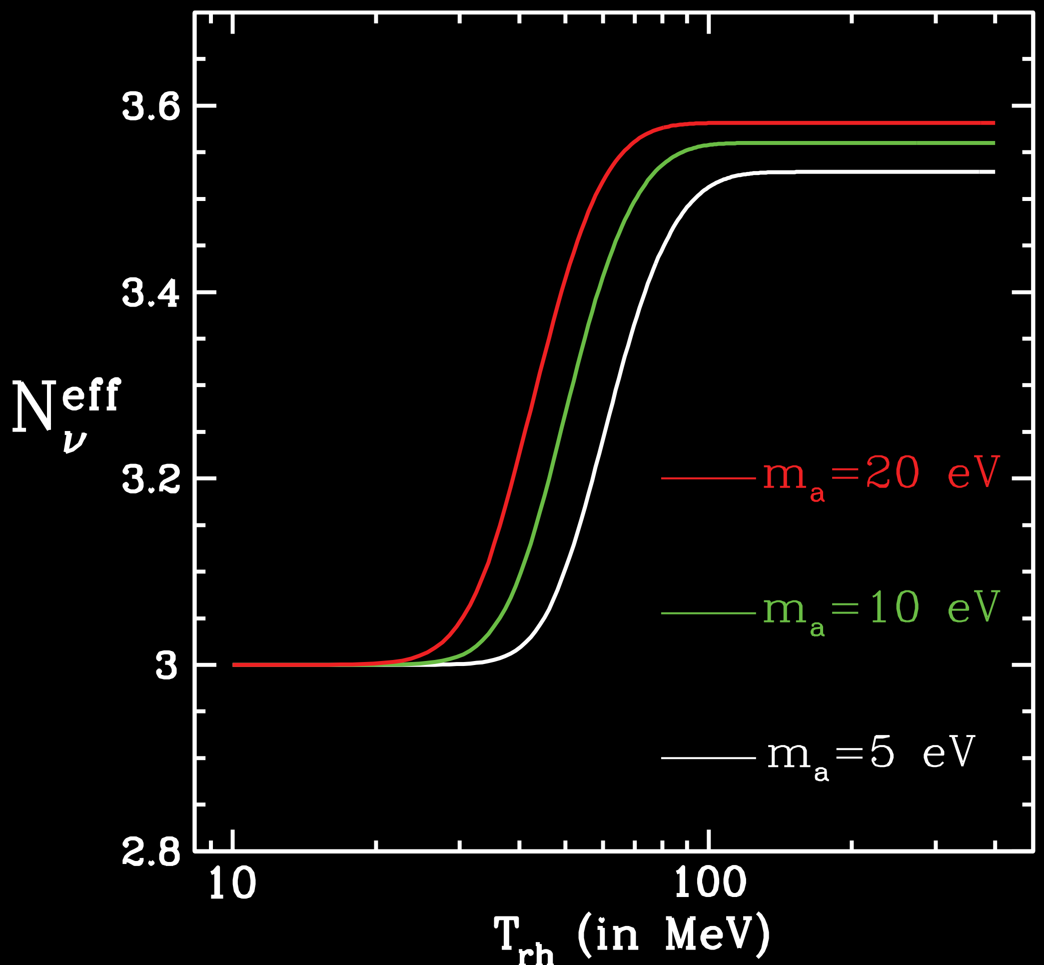


- $\lambda_{fs}(T_{rh}, m_a)$ & $\Omega_a h^2 (T_{rh}, m_a)$ calculated to trace out allowed region

If $T_{rh} \lesssim 35$ MeV, $\lambda_{fs} \lesssim \lambda_{nl}$, LSS constraints completely relaxed

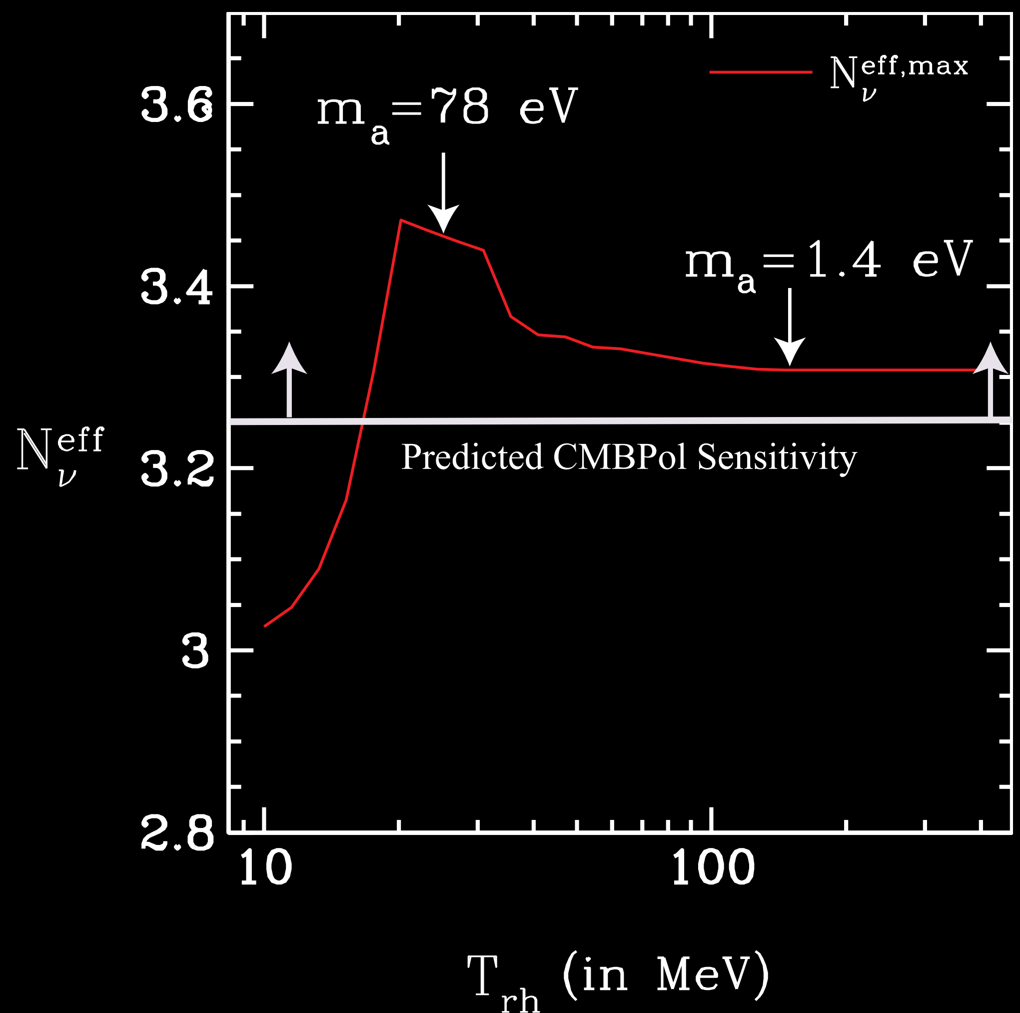
Axionic contribution to pre-BBN radiation energy density in LTR

- Axions are relativistic at T~ 1 MeV and contribute to $N_\nu^{\rm eff}$
- Entropy generation suppresses the axionic contribution to $N_\nu^{\rm eff}$



Future limits from abundance of ^{4}He

- $N_\nu^{\rm eff}$ contributes to $H(T)$ during radiation domination, setting the abundance of ^{4}He
- Current measurements yield constraint $N_\nu^{\rm eff} \leq 3.8$
- ^{4}He affects CMB TT, TE, and EE spectra: CMBPOL constraints!



Future work: Lifting the veil of ignorance at T > 100 MeV

in collaboration with Tristan Smith and Sean Tulin

- WIMPs freeze out at $20\ \mathrm{GeV} < T < 100\ \mathrm{GeV}$
- Upcoming colliders (LHC/ILC) may discover a WIMP
- WIMP M/σ that overcloses the universe in the standard picture would be a smoking gun for a non-standard thermal history

The evolution and scatter of dark matter halo concentrations

Work in progress, in collaboration with Andrew Benson

Outline: Halo Concentrations

- Background: A universal dark matter halo profile
- The consequences: Implications for galaxy formation
- The controversy over evolution and scatter of concentrations
- A new approach/comparison with ‘data’

The NFW halo profile

- Simulations (NFW1995-7 and others) note a nearly universal halo density (two-parameter family) profile

$$\rho = \frac{\delta_c \rho_{\rm crit}}{\left(\frac{r}{r_{\rm s}}\right)\left[1+\left(\frac{r}{r_{\rm s}}\right)\right]^2} \qquad \delta_c = \frac{\Delta_{\rm vir}}{3} \frac{c^3}{\ln(1+c) - c/(1+c)}$$

$$c = r_{\rm vir}/r_{\rm s}$$

$$M_{\rm vir} = (4\pi/3)\, r_{\rm vir}^3 \Delta_{\rm vir} \rho_{\rm crit}$$

- Halo concentration is a model-independent notion, e.g.

$$\rho \propto r^{-\alpha}\,(B+r)^{-\beta} \qquad c = r_{\rm vir}/r_{-2}$$

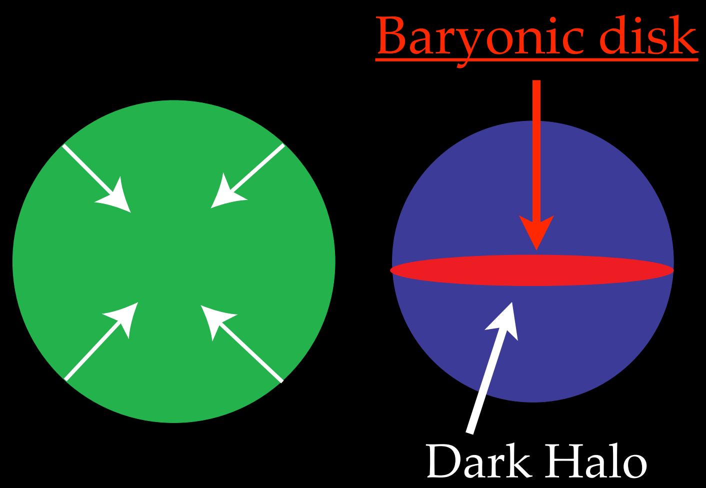
- Halo concentration is inversely related to halo mass. Sensible in a hierarchical picture

$$c_{200} \simeq 5.3 \left(\frac{M_{200}}{10^{14} h^{-1} M_\odot}\right)^{-0.10}$$

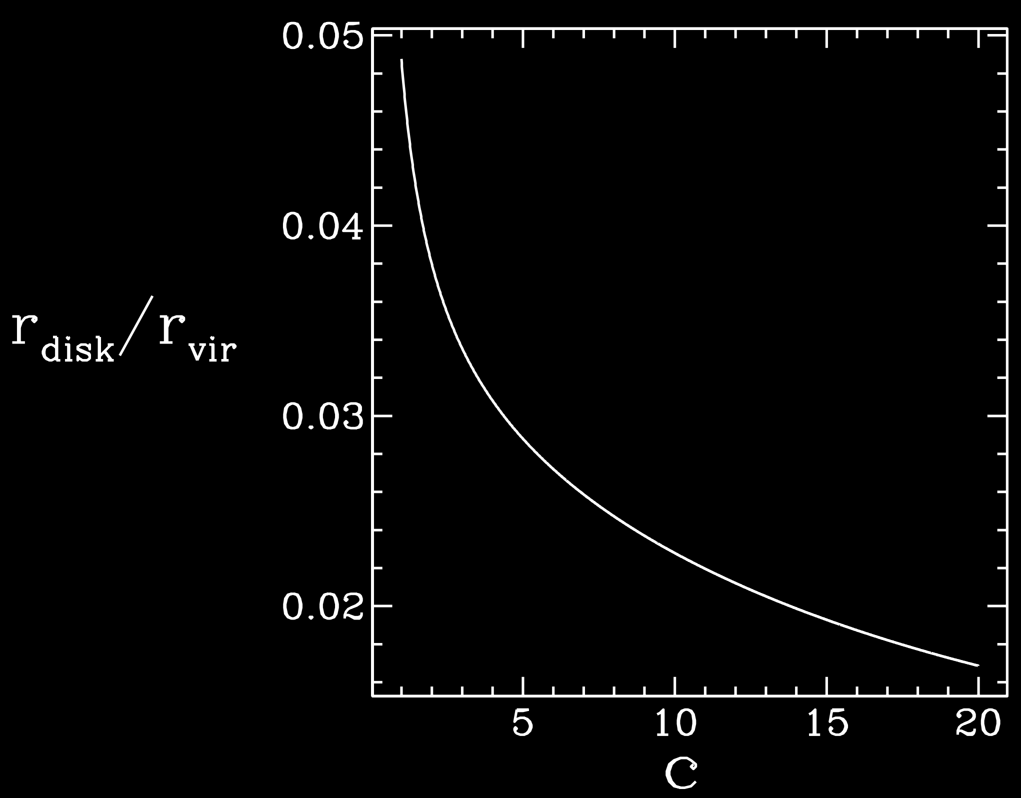
- Considerable scatter about mean relation (robust to halo and particle sampling issues): $\left\langle \log_{10}^2(c_{200}) - \log_{10}^2(\bar{c}_{200}) \right\rangle \simeq 0.1$

Also sensible in a hierarchical picture, but how sensible? But first, why bother?

Concentrations and galaxies

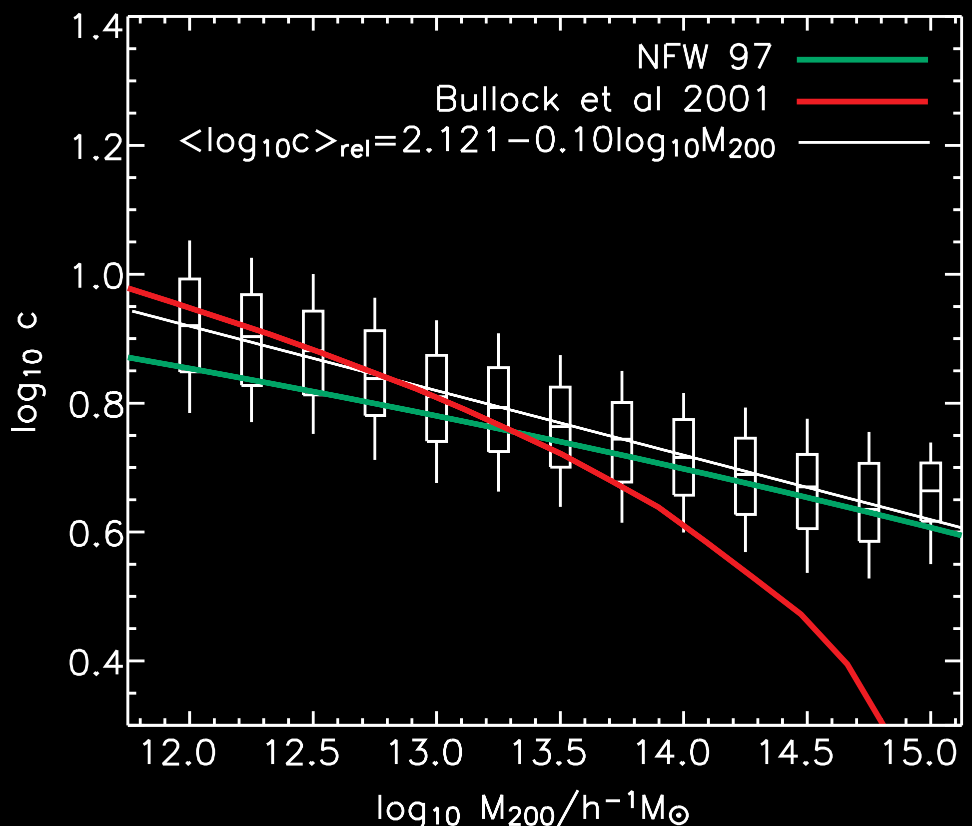


- Baryons collapse and cool, force adiabatic contraction of halo (Blumenthal 86)
- `Explains' Tully-Fisher (TF) relation $L \propto v_c^3$
- Scatter relevant for expected scatter in TF relation
- Relevant for setting size of galactic bulge (GALFORM)



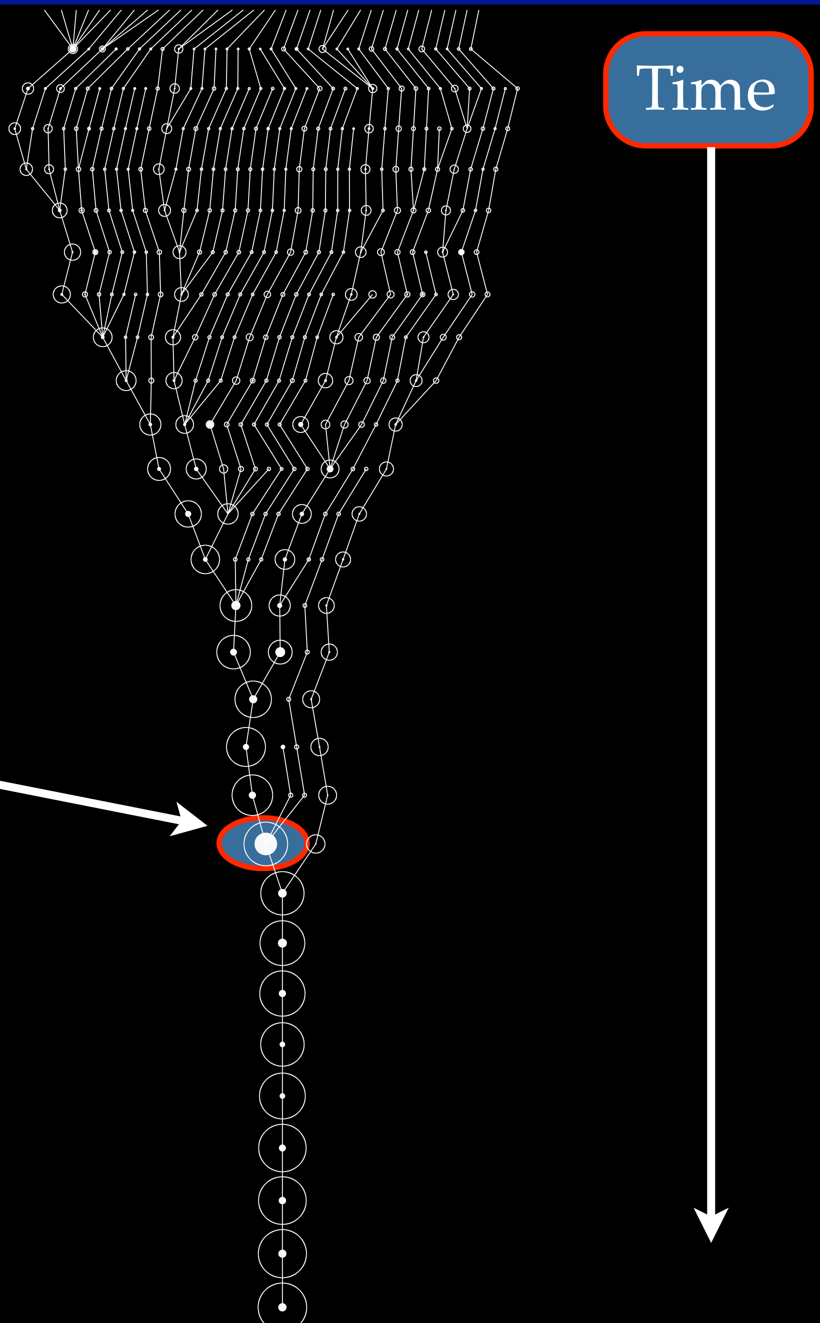
Millenium weighs in...

- The Millenium simulation follows $N = 2160^3$ particles in a $L = 500h^{-1}$ Mpc box using WMAP1+2dFGRS cosmo parameters $M_{\rm part} = 8.6 \times 10^8\ h^{-1}\ M_\odot$
- Using relaxed $N_{\rm FOF} > 500$ halos, concentrations are fit (Neto et al. 2007)



- Bullock et al. model fails at high M
- No model accounts for more than 30% of scatter
- Different prescriptions for $z_{\rm coll}$ tried. NFW works best: Hints that details of merger history matter
- Bullock et al. model gets redshift wrong

Ingredients of a new approach



- A model for evolution/scatter in all info in halo merger history

- Model for each merger:

  $(M_1, M_2, ...M_\mathrm{n}; c_1, c_2, ...c_n) \rightarrow c_\mathrm{f}$

- Single-node model+prescription for accretion to obtain $\bar{c}\,(M, z)$ and

  $\left\langle \log_{10}^2 (c_{200}) - \log_{10}^2 (\bar{c}_{200}) \right\rangle (M, z)$

A simple model of post-merger halos

- Conserve mass $M_{\rm vir,f} = M_{\rm vir,1} + M_{\rm vir,2}$
- Conserve internal energy (Assume 2T+V=0)

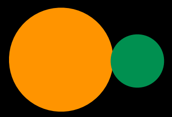
$$E_{\rm b} = -\int \frac{GM(\leq r)}{r} dM = -\frac{H_0^4 r_{\rm vir}^5 \Delta_{\rm vir}^2}{4G} f(c)$$

$$f(c) \equiv \frac{c}{\left[\ln(1+c) - c/(1+c)\right]^2} \frac{c(c+2) - 2(c+1)\ln(1+c)}{2(1+c)^2}$$

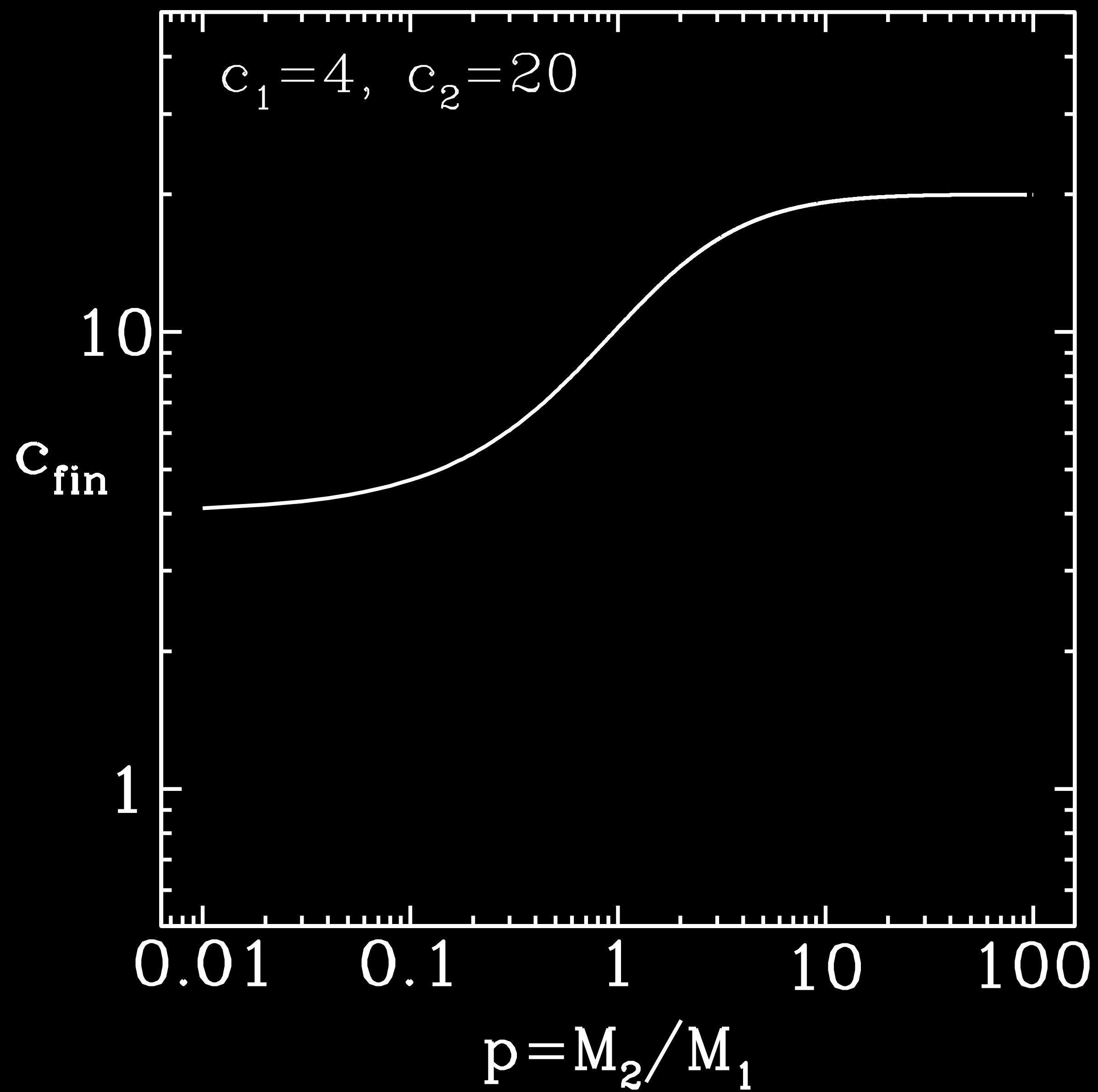
- Assume final halo relaxes to NFW

$$f(c_{\rm f}) = \frac{f(c_1) + p^{5/3} f(c_2)}{(1+p)^{5/3}} \longrightarrow c_{\rm f}(p, c_1, c_2) \qquad p \equiv m_2/m_1$$

Adding 2 pieces to the puzzle

- If $p = \mathcal{O}(1)$, mutual two-halo T/V are non-negligible. Treat this as an inelastic collision. Two prescriptions:
  - Use mean $v_{\mathrm{rel}_{\theta,\mathrm{r}}} = v_{\mathrm{vir},2} a_{\theta,r}(z)$ from Benson 2004 at  moment in merger
  - Use actual simulation kinematics!
- Real NFW halos are still accreting matter $2T + V = \int P\vec{r} \cdot d\vec{S}$
  - Solve Jeans Equation: $$\frac{1}{\rho}\frac{d(\rho\sigma^2)}{dr} = -\frac{GM(\leq r)}{r^2}$$
  - Non-trivial correction: $(2T/|V|)_{\mathrm{vir}} \simeq 1.3$ confirmed by simulations (Cole/Lacey 93)

Post-merger predictions



- Solutions asymptote to properties of most massive progenitor in EMR limit

Calculating the c distribution today

- Use 1.7×10^7 merger trees in Millenium simulation. Set initial concentration using NFW prescription
- At nodes, apply preceding prescription to progenitors
- Assume remaining mass difference is due to accretion and contributes only to $r_{\rm vir}$
- The good news: 30% scatter about mean relation
- The bad news: Predicted c(M,z) falls too quickly with M
- First thing to check: Does our model accurately predict what happens in a single merger?
- Initial conditions/tree time-step errors?

Halos emerging from single mergers

- Progenitors of halos with fit concentrations identified at z=0.02 ($1\Delta t_{\rm output}$).
- Neto et al. have provided us with concentrations at z=0.02. 34 useful mergers
- 24 mergers with 30% errors or less, 9 mergers with 30-60% errors, 2 mergers off the charts
- Neto et al. have repeated exercise for adjacent time steps near z=1,2,3, and 4, and will shortly provide us with more mergers to test our model

Troubleshooting the model

- Resolution issues?
- Obvious mass loss
- Large fraction of mass in progenitors with no reliably measured concentration?
- Improper accretion recipe?
- Insufficient time for halos to relax?
- Implementation of Millenium kinematics/variation between actual kinematics and assumed distribution
- Subtle mass loss
- Energy loss: Ejected particles are probably most energetic

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- ~~Improper accretion recipe?~~ Accretion beyond merger at node recipe marginal
- ~~Insufficient time for halos to relax?~~ Naive condition $t_{\rm dyn}/\left(10t_{\rm merge}\right) < 1$ met
- Implementation of Millenium kinematics/variation between actual kinematics and assumed distribution
- Subtle mass loss
- Energy loss: Ejected particles are probably most energetic

What's next

- Zero-in on when model fails for single mergers
- If necessary, tune the model: fit coefficients of fitting formula for c_f to actual merger results
- Re-run tree algorithm using actual Millenium kinematics, variety of initial concentration prescriptions
- Test model using EPS and other semi-analytic merger trees

A lower limit to the scale of an effective theory of gravitation

In collaboration with R.R. Caldwell

astro-ph/0606133
Phys. Rev. Lett. accepted

Outline: Fat gravitons

- Motivation: Why is the cosmological constant small?
- Linear theory calculation
- Observational limits
- Subtleties/open questions/future work

`Fat gravitons' and Λ

- A variety of data hint at new physics at a surprisingly low energy scale:

$$\rho_\Lambda = \frac{1}{2}\int_0^\mu \frac{d^3k}{(2\pi\hbar)^3} kc = \Omega_\Lambda \rho_{\rm crit} \rightarrow \mu \simeq 10^{-3}\ {\rm eV}$$

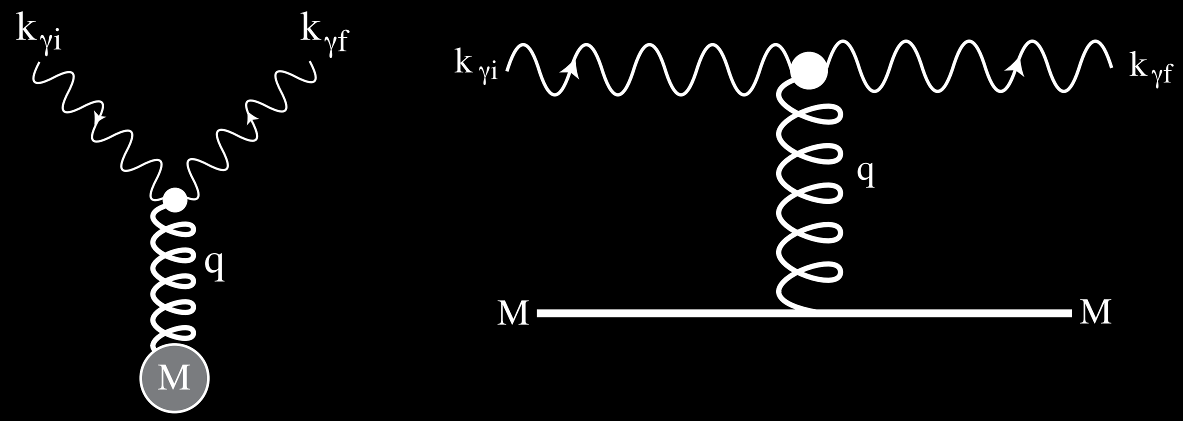
- Alternative to usual approach: Modify gravity, e.g. a cutoff $q^\nu q_\nu \leq \mu^2$ on graviton 4-momentum

- Modified propagator arises from a weak-field, harmonic gauge `fading' gravity Lagrangian with

$$\mathcal{L}_g = \left(h^{\alpha\beta} - \frac{1}{2}\eta^{\alpha\beta} h\right) \mathcal{G}^{-1}\left(\Box/\mu^2\right) \Box h_{\alpha\beta}$$

$$D_{\rho\nu\lambda\sigma}(q) = \frac{\left(\eta_{\rho\lambda}\eta_{\nu\sigma} + \eta_{\rho\sigma}\eta_{\nu\lambda} - \eta_{\rho\nu}\eta_{\lambda\sigma}\right) e^{-q/\mu}}{q^2 + i\epsilon}$$

Linear calculation of M-γ scattering



- Interaction described by $\mathcal{L}_{\rm I} = -\sqrt{32\pi G} h_{\mu\nu} T^{\mu\nu}/2$

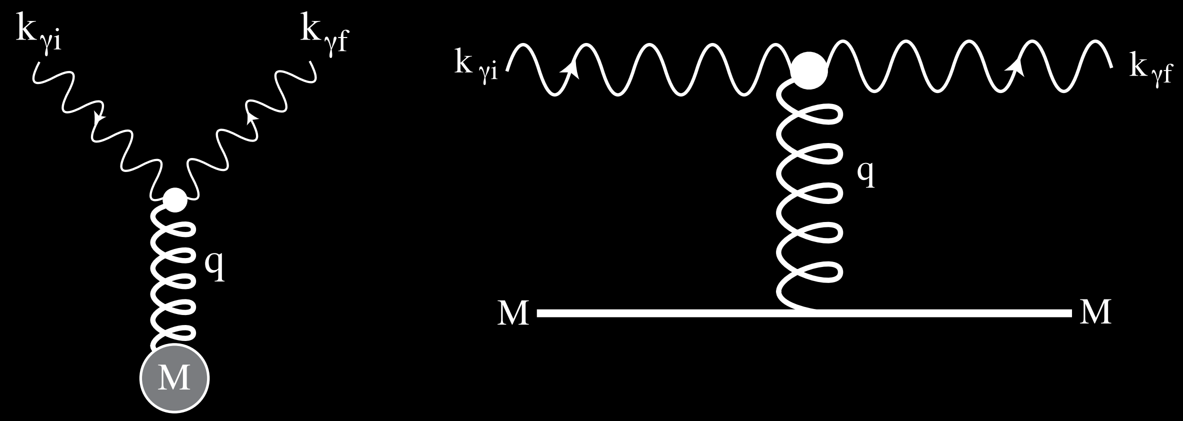
For EM $T^{\mu\nu} = F^{\mu\rho} F^{\nu}_{\rho} - \frac{1}{4}\eta^{\mu\nu} F_{\alpha\beta} F^{\alpha\beta}$

- For an elastic collision, external field approach/Feynman rules yield (for small angles)

Same as GR Result!

$$\frac{d\sigma}{d\Omega} = \frac{(4GM)^2}{(c\theta)^4} \longrightarrow d\sigma = 2\pi b db \longrightarrow \theta = \frac{4GM}{c^2 b}$$

Linear calculation of M-γ scattering



We expect a lack of high-frequency gravitationally lensed images if a cutoff exists

- For an elastic collision, external field approach/Feynman rules yield (for small angles)

$$\frac{d\sigma}{d\Omega} = \frac{(4GM)^2}{(c\theta)^4} e^{-2k_\gamma \theta/\mu}$$

Functional form of cutoff is irrelevant

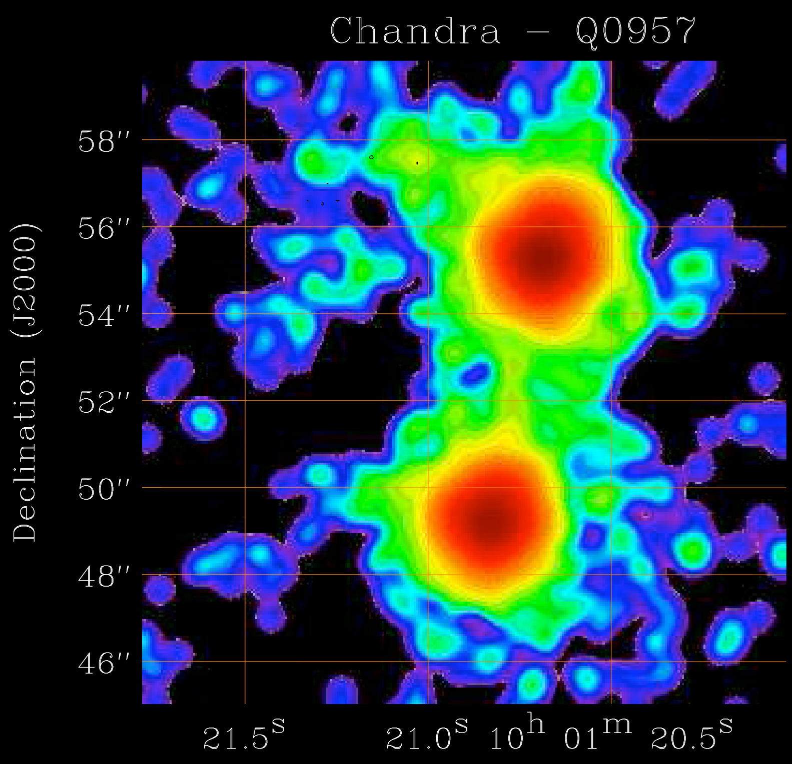
- $|k_{\gamma,\mathrm{f}} - k_{\gamma,\mathrm{i}}| \simeq k_\gamma \theta > \mu$ deflections are suppressed

Astrophysical vs. lab constraints

✳ Gravitational lenses have been observed from x-ray to radio frequencies

✳ The best limits will come from the highest-energy photons: x-ray lenses!

✳ Pair of images in GL system Q0957+561: QSO lensed by galaxy. Deflection angle $\alpha \simeq 7.8''$



✳ Lens images unchanged for $E_\gamma < 5$ keV

$$\rightarrow \mu > 0.38 \text{ eV}/c \gg 10^{-3} \text{ eV}/c$$

✳ Experiments confirm inverse square law (e.g. EOT-WASH) down to

$$l_0 = \hbar c/\mu \simeq 56 \ \mu\text{m} \longrightarrow \mu > 0.0035 \text{ eV}/c$$

Subtleties / Caveats

- The effect does not go away for composite sources
- We are unable to recover the effect from the classical EOM of our Lagrangian: Has a tree-level amplitude become a QM object by the introduction of a new scale?
- Born approximation is exact
- We can write down a classical force-term which mimics this effect, but not one that obviously comes from our Lagrangian
- Does the formalism used to derive Feynman rules break down for our Lagrangian?

Ideas for future Work

- Complete halo concentration project
- Use Millenium merger trees to predict SMBH merger rates
- Obtain new constraints to entropy generation
- Understand subtleties of fat/massive graviton theories
- Analyze new axion search data

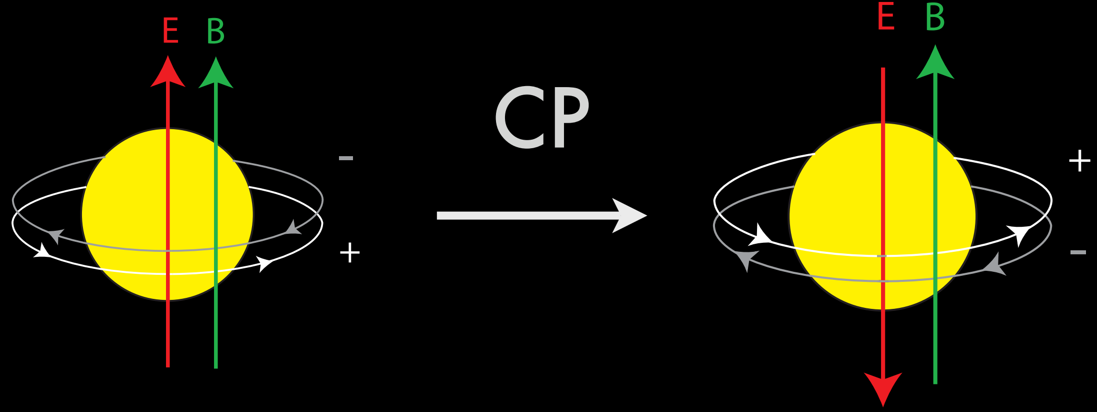
Axions solve the strong CP problem

- Strong interaction violates CP through θ -vacuum term

$$\mathcal{L}_{\rm CPV} = \frac{\theta g^2}{32\pi^2} G\tilde{G}$$

- Limits on the neutron electric dipole moment are strong. Fine tuning?

$$d_n \simeq 10^{-16}\ \theta \text{ e cm}$$
$$\theta \lesssim 10^{-10}$$



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- New field (axion) and U(1) symmetry dynamically drive net CP-violating term to 0

$$\mathcal{L}_{\mathrm{CPV}} = \frac{\theta g^2}{32\pi^2} G\tilde{G} - \frac{a}{f_{\mathrm{a}}} g^2 G\tilde{G}$$

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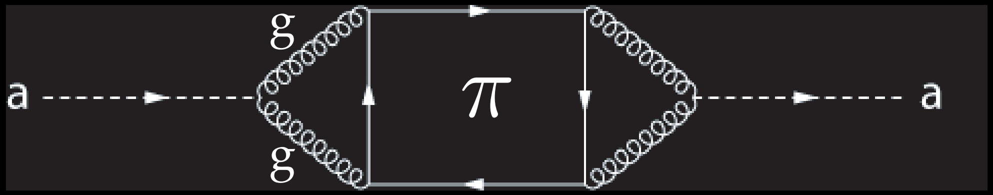
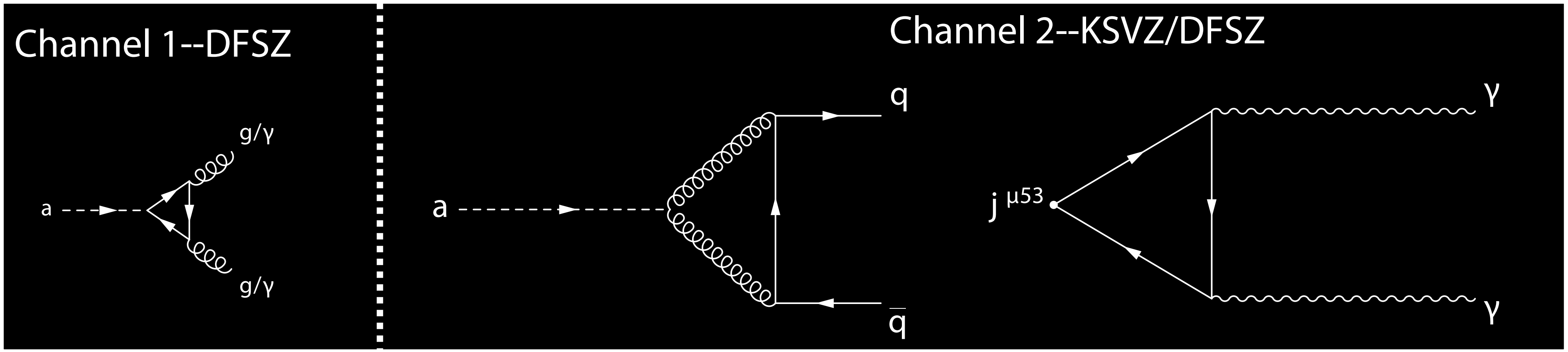
- Through coupling to pions, axions pick up a mass



$$m_{\rm a} \simeq \frac{m_\pi f_\pi}{f_{\rm a}} \frac{\sqrt{z}}{1+z}$$

$$z \equiv m_{\rm u}/m_{\rm d}$$

Axion models and EM couplings



- Axions interact weakly with SM particles $\Gamma, \sigma \propto \alpha^2$

- Axions have a two-photon coupling

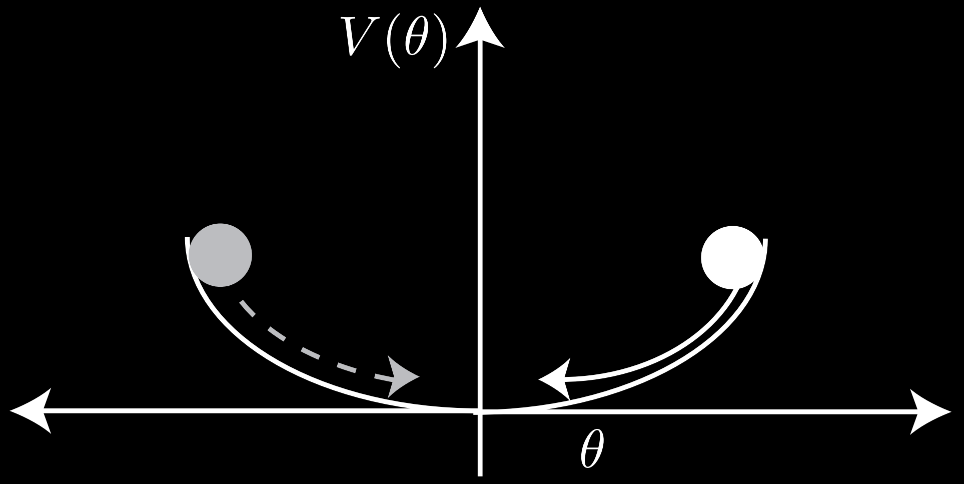
$$g_{a\gamma\gamma} = -\frac{3\alpha}{8\pi f_{\rm a}}\xi$$

$$\xi \equiv \tfrac{4}{3}\left\{E/N - \tfrac{2(4+z)}{3(1+z)}\right\}$$

- ξ is model-dependent and may vanish

$$\xi = \tfrac{4}{3}\left\{E/N - 1.92 \pm 0.08\right\}$$

2 axion populations: Cold axions



- Before PQ symmetry breaking, θ is generically displaced from vacuum value
- EOM: $\ddot{\overline{\theta}} + 3H\dot{\overline{\theta}} + m_{\rm a}^2(T)\,\overline{\theta} = 0$ $\quad m_{\rm a}(T) \simeq 0.1 m_{\rm a}(T=0)\left(\Lambda_{\rm QCD}/T\right)^{3.7}$
- After $m_{\rm a}(T) \gtrsim 3H(T)$, coherent oscillations begin, leading to $n_{\rm a} \propto a^{-3}$
- Relic abundance $\Omega_{\rm a} h^2 \simeq 0.13 \times g(\theta_0)\left(m_{\rm a}/10^{-5}{\rm eV}\right)^{-1.18}$
- Particles are cold

Galaxy clusters are axion reservoirs

- ~eV Axions will fall into cluster potential wells

$$\langle v_{\rm a}^2/c^2\rangle^{1/2} = 4.9\times 10^{-4} m_{\rm a,eV}^{-1} \rightarrow v_{\rm a} \lesssim 1000~{\rm km~s^{-1}}$$

- Generalization of Gunn-Tremaine bound for bosons is unrestrictive for clusters

$$x_{\rm a}^{\rm max} \sim 10^{-2} m_{\rm a,eV}^4 \left(\frac{a}{250~h^{-1}{\rm kpc}}\right)^2 \left(\frac{\sigma}{1000~{\rm km~s^{-1}}}\right)$$

$$x_a = \Omega_a/\Omega_m$$

- 10^{77} *hot* axions in a $10^{14}~M_\odot$ cluster

Axion decay

- Axion decays monochromatically via $a \longrightarrow \gamma\gamma$ with $\lambda_a = \frac{24,800\text{Å}}{m_{\rm a,eV}}$ in source frame

- For galaxies/clusters, line comparable to sky background

$$I_{\lambda_0} = 2.68 \times 10^{-18} \times \frac{m_{\rm a,eV}^7 \xi^2 \Sigma_{12} \exp\left[-\left(\lambda_{\rm r} - \lambda_{\rm a}\right)^2 c^2 / \left(2\lambda_a^2 \sigma^2\right)\right]}{\left(\frac{\sigma}{1000\ \rm km\ s^{-1}}\right)\left(1 + z_{\rm cl}\right)^4 S^2\left(z_{\rm cl}\right)} \times \text{ergs s}^{-1}\ \text{cm}^{-2}\text{Å}^{-1}\text{arcsec}^{-2}$$

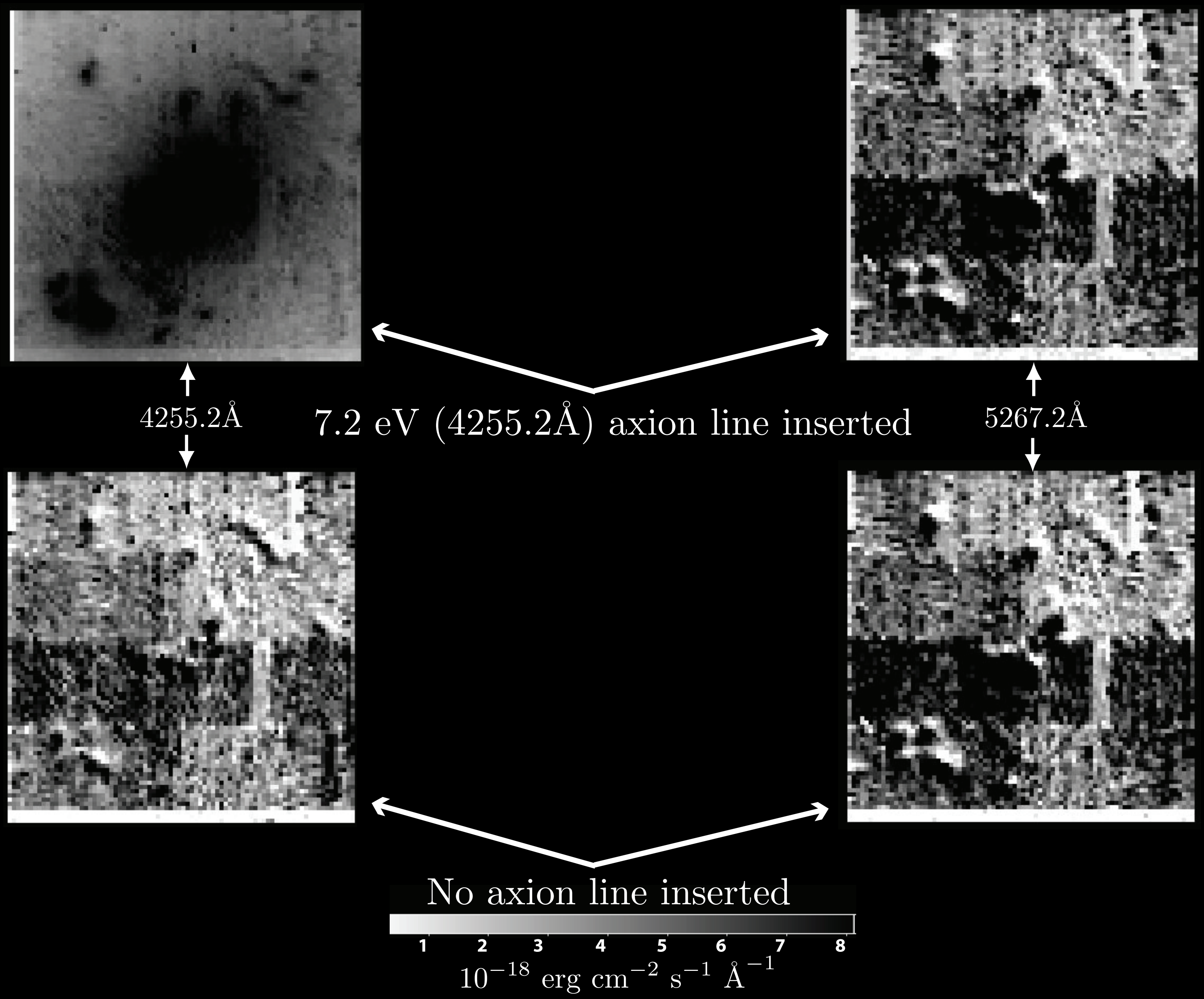
$$\Sigma_{12} \equiv \Sigma / \left(10^{12}\ M_\odot\ \text{pixel}^{-2}\right) \qquad \lambda_r = \lambda_o / (1 + z_{\rm cl})$$

$$S(z_{\rm cl}) \equiv d_a(z_{\rm cl}) / \left[c / \left(100\ \text{km s}^{-1}\ \text{Mpc}^{-1}\right)\right]$$

- First attempt made at KPNO 2.1m using Gold spectrograph on Abell clusters A1413, A2218, and A2256: $3\ \text{eV} \le m_{\rm a} \le 8\ \text{eV}$

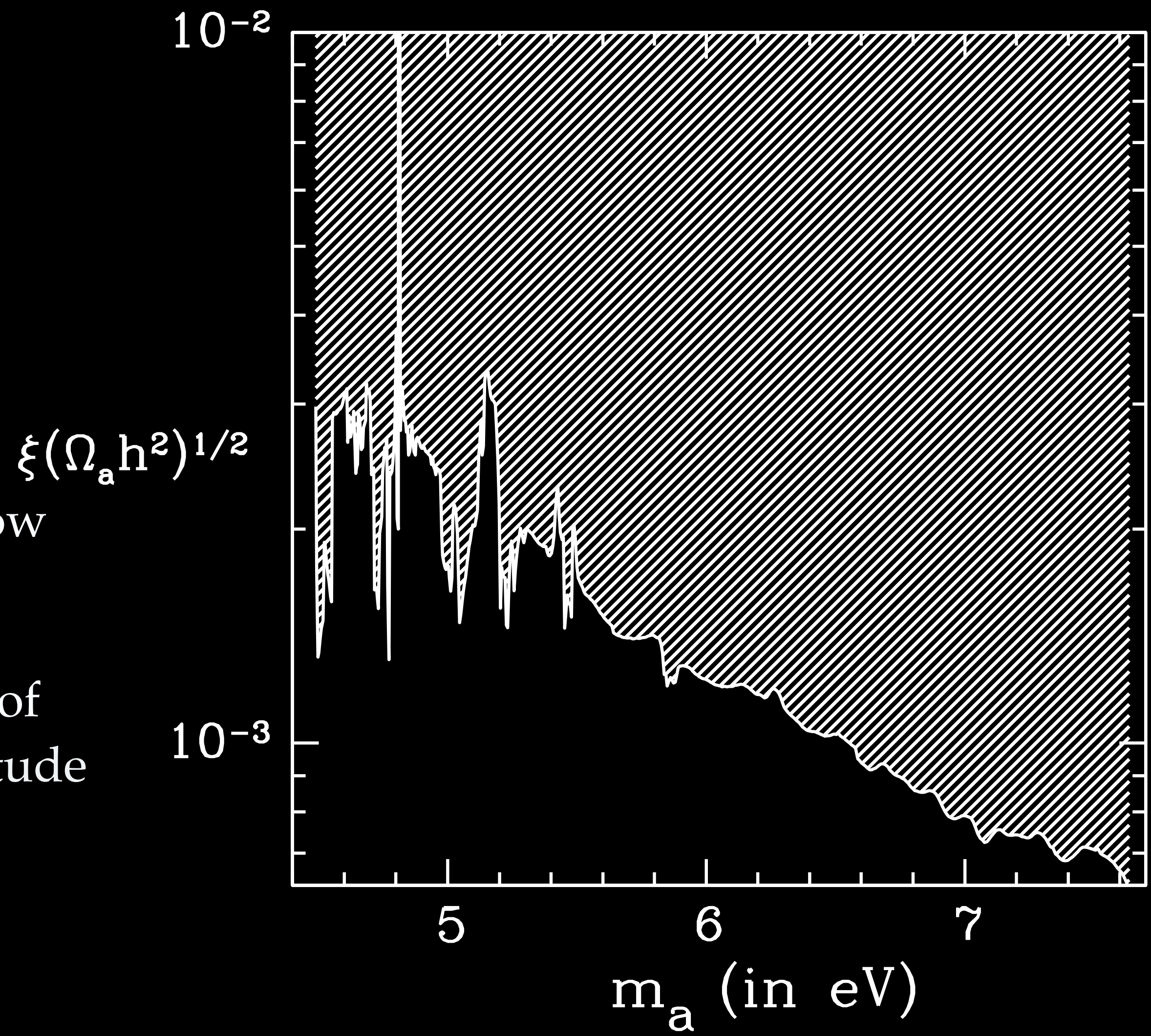
$$\xi \le 0.08$$

Are we kidding ourselves? <u>No</u>!

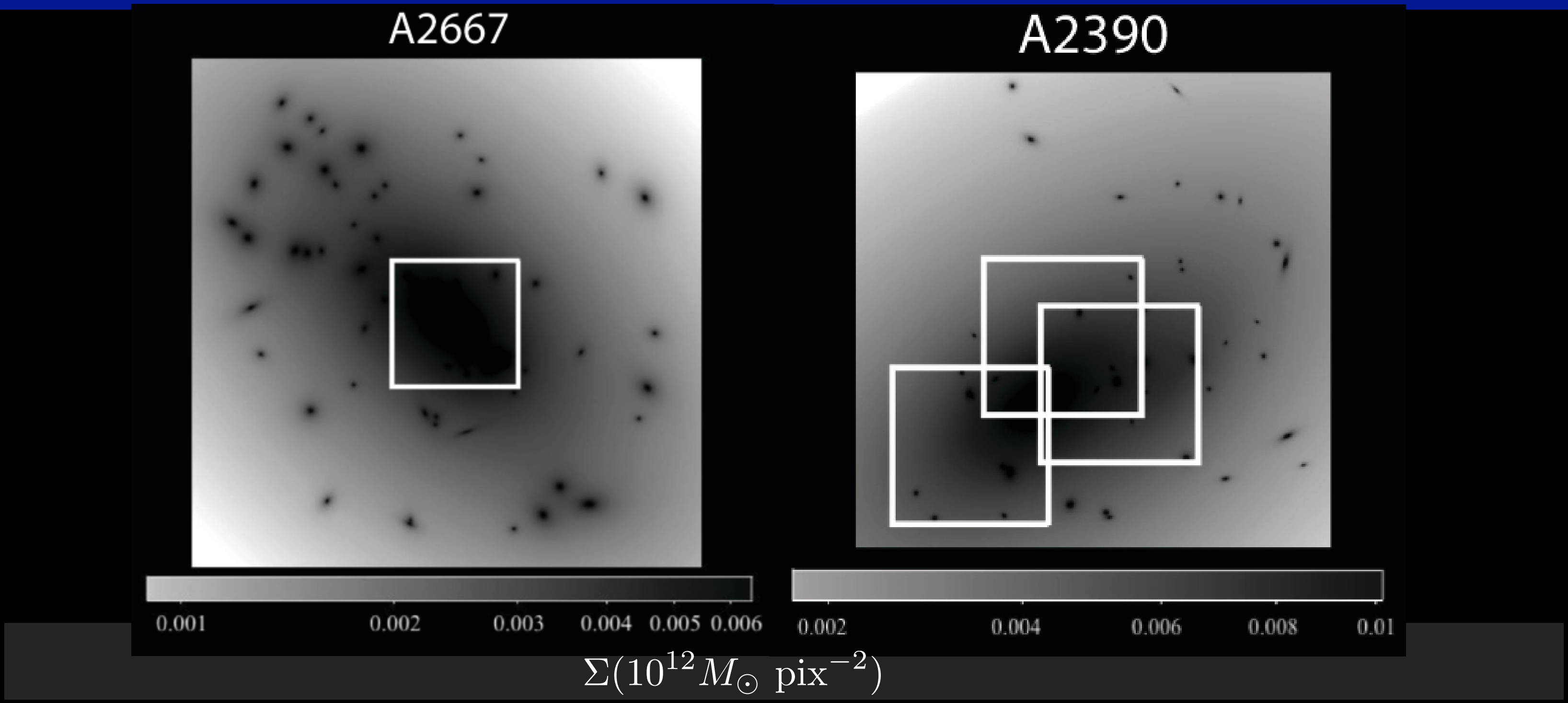


More general constraints

* Constraints can be generalized to allow non-standard $\Omega_a h^2$
* For usual range of $0.1 \lesssim \xi \lesssim 1$, limit of $\Omega_a h^2 \lesssim 10^{-4}$ is ~1-2 orders of magnitude better than limit from LSS/CMB



Lensing maps

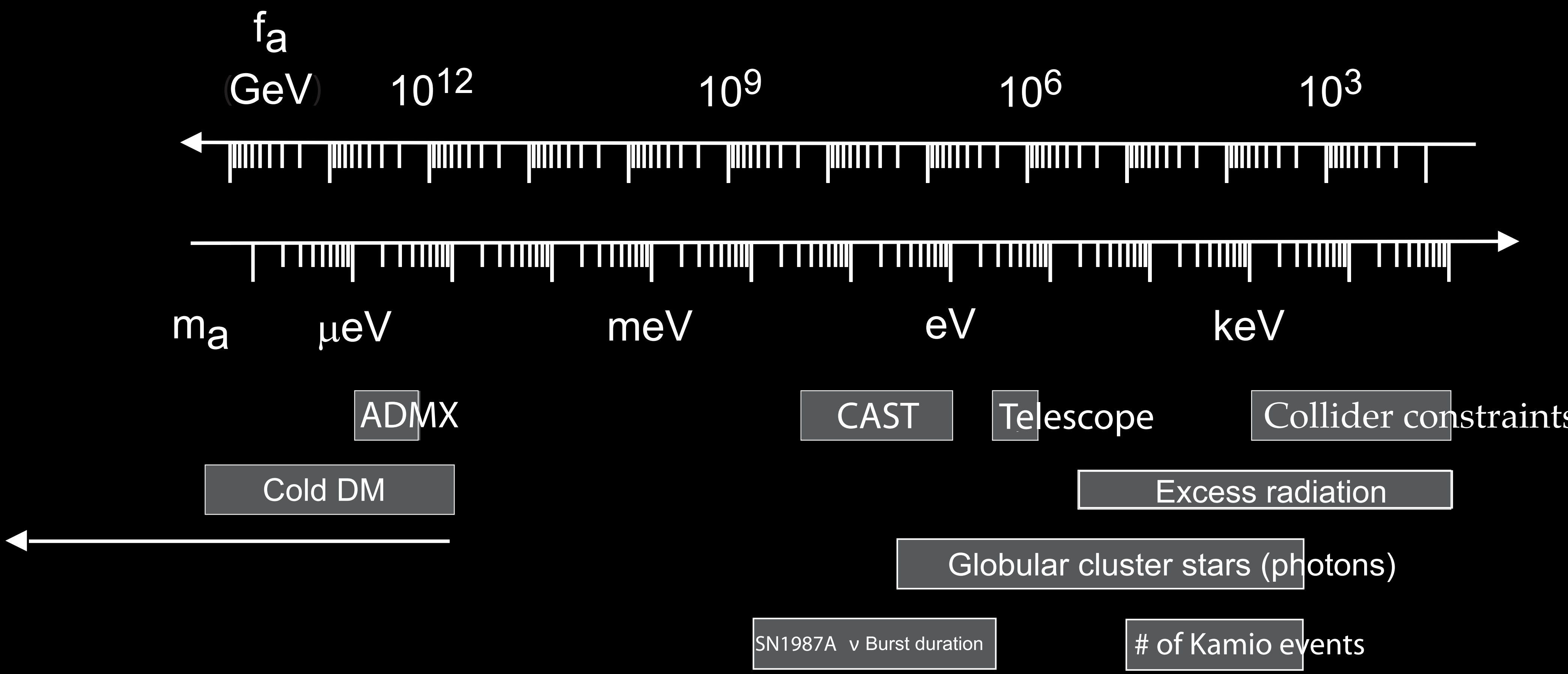


- Cluster galaxies selected by redshift
- BCG, galaxies near arcs, cluster-scale mass component modeled individually
- PIEMD (Pseudo-isothermal elliptical mass distribution) assumed

$$\Sigma(R) = \frac{\Sigma_0 r_0}{1 - r_0/r_{\rm t}} \left(\frac{1}{\sqrt{r_0^2 + R^2}} - \frac{1}{\sqrt{r_{\rm t}^2 + R^2}} \right)$$

- Remaining galaxies modeled as ensemble with M/L=$CL^{0.3}$ $r_0 = D\sqrt{L}$

Context: Axion constraints



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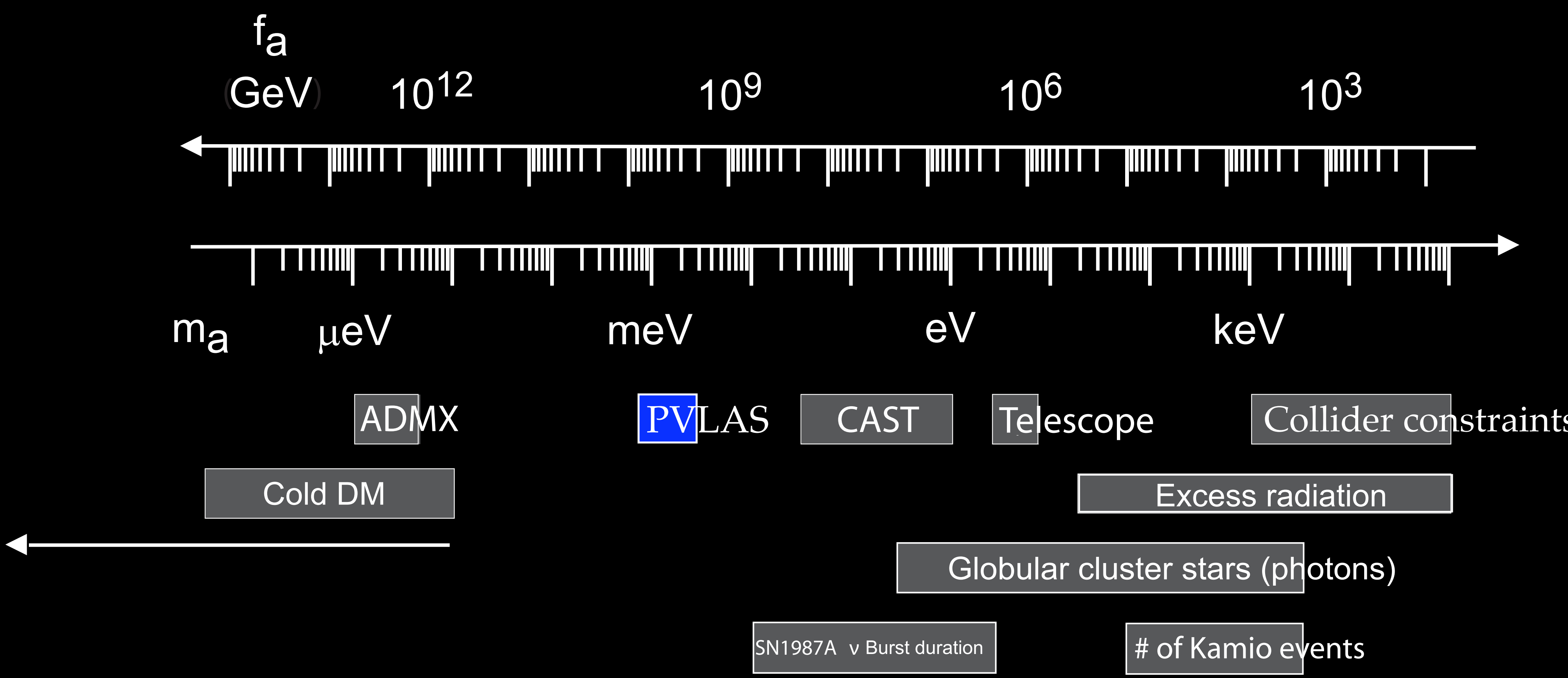

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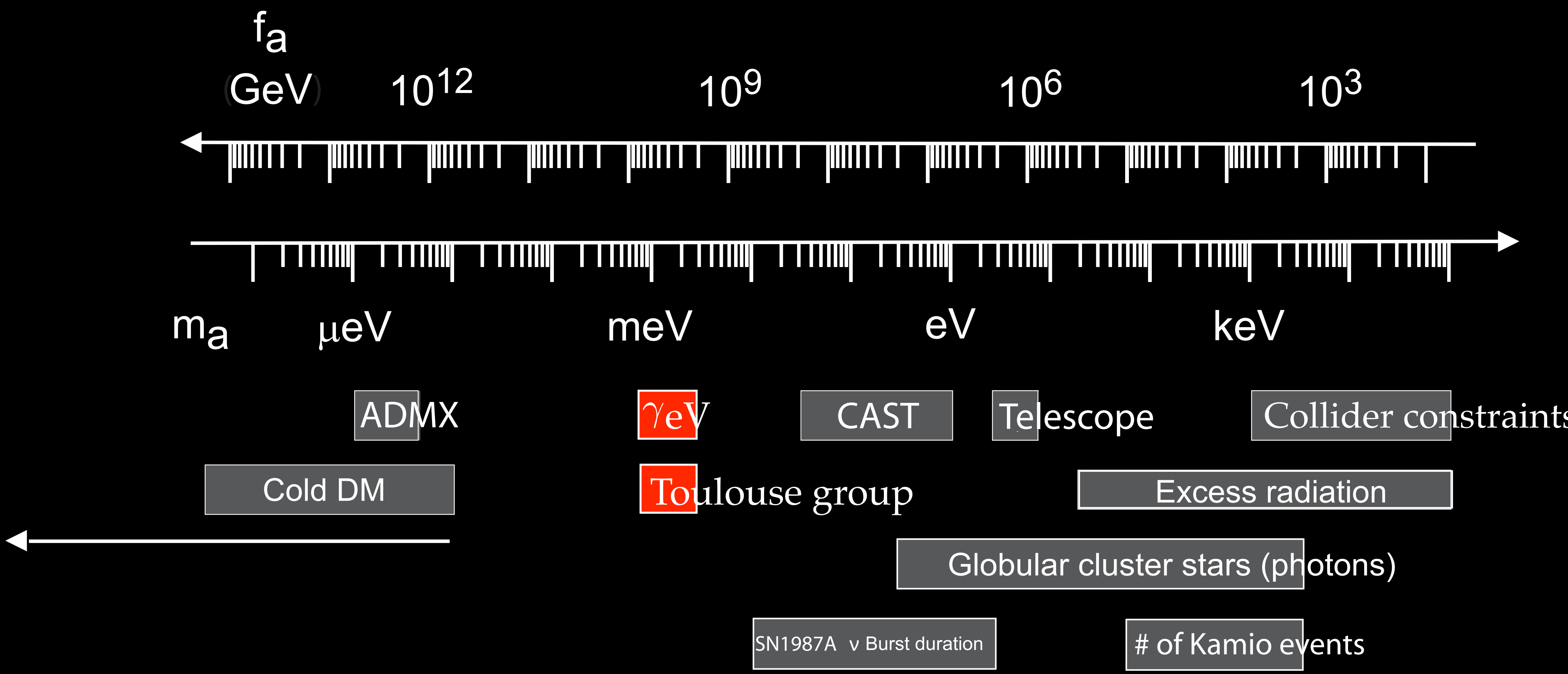

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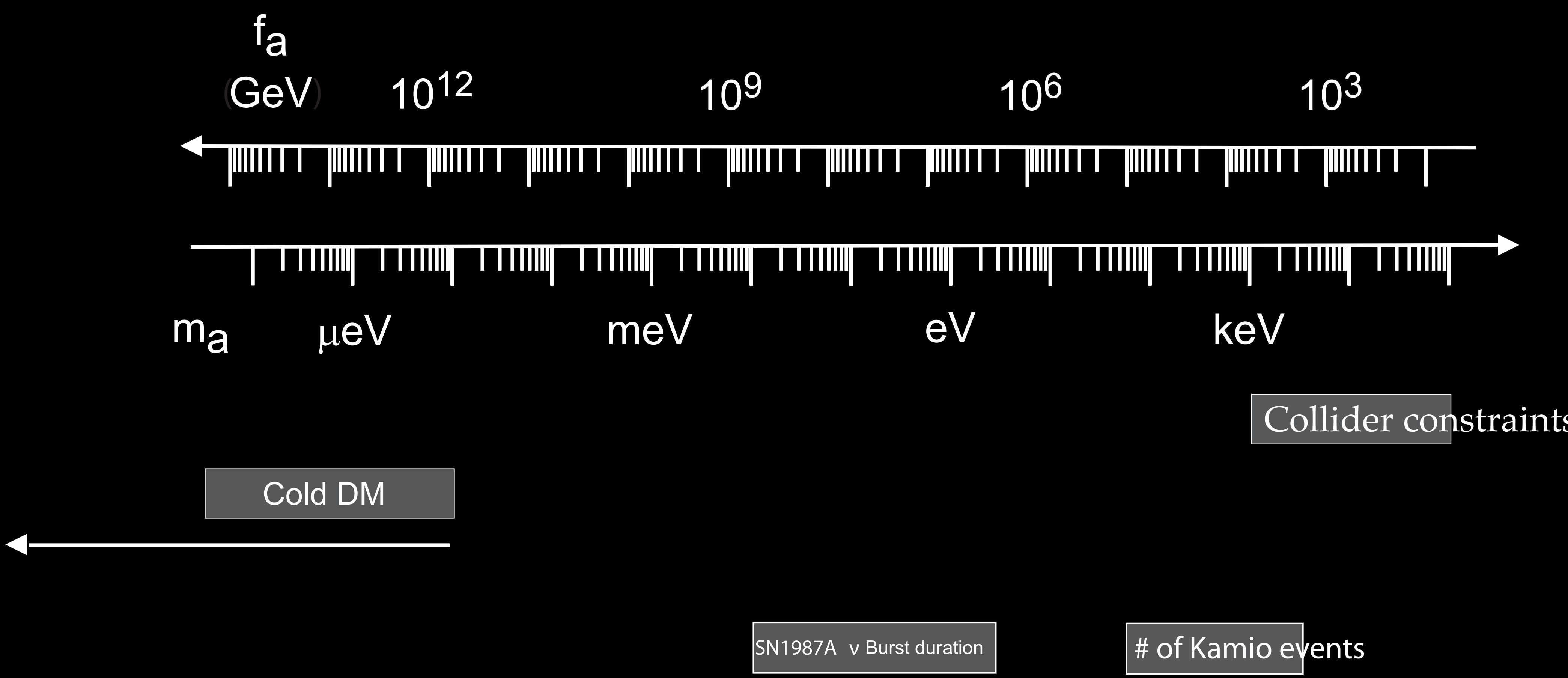

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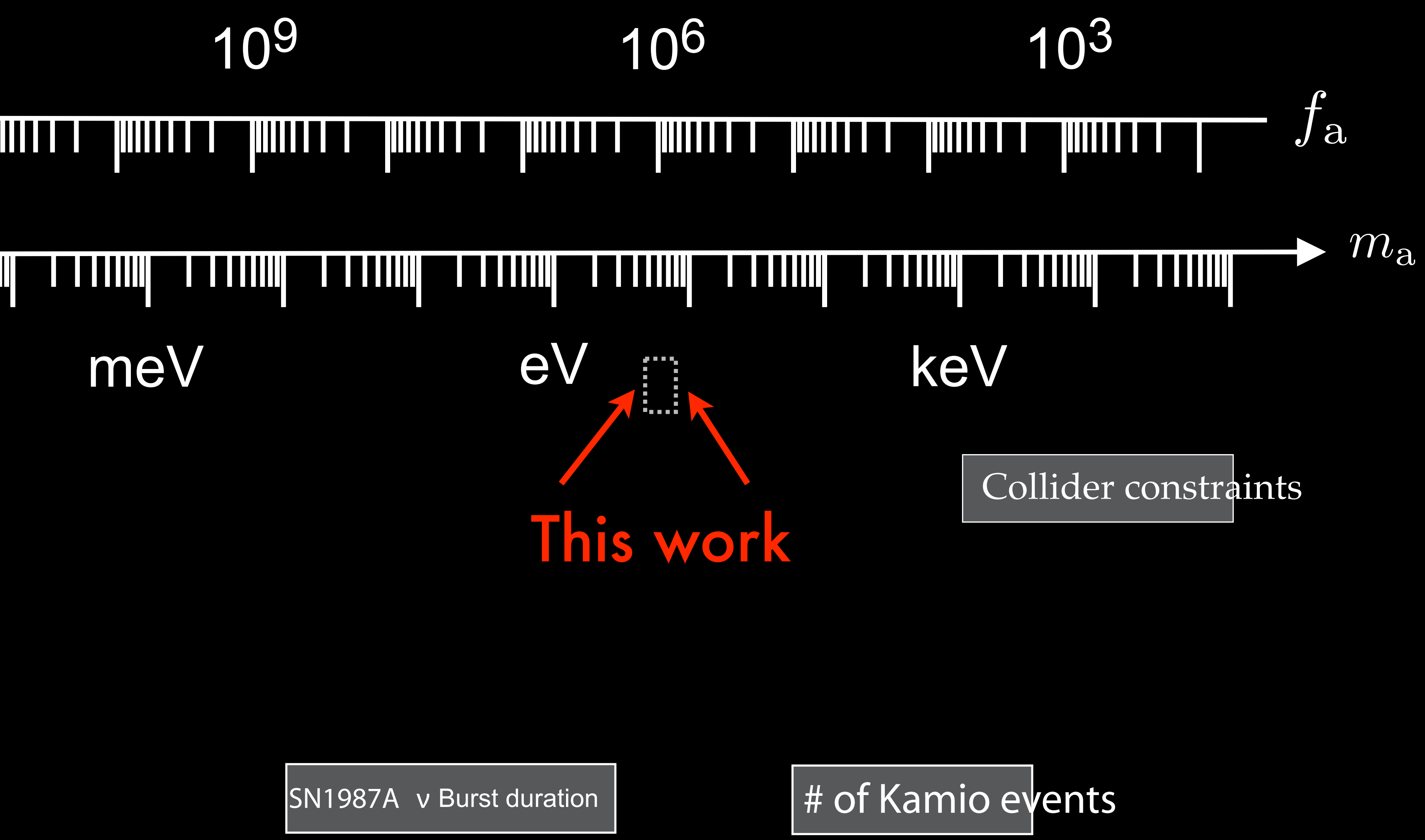
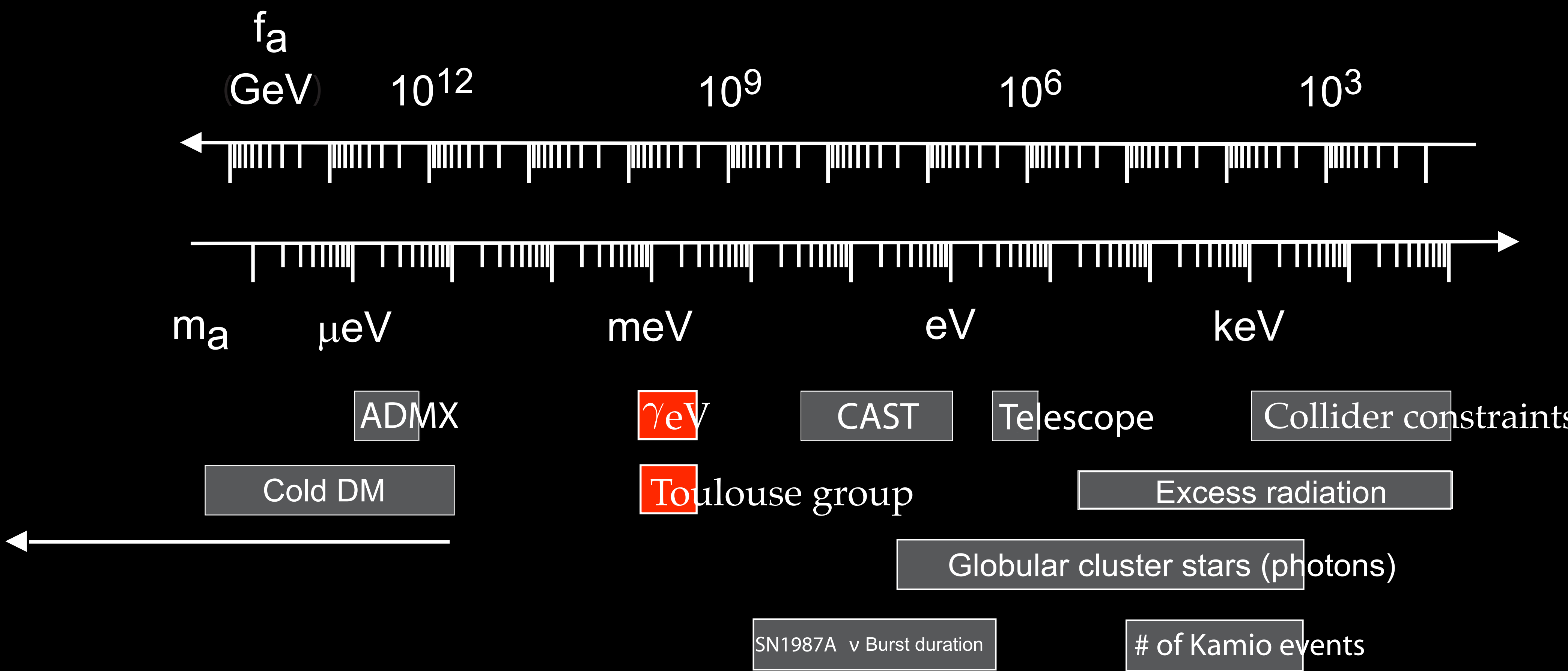


Pitfalls of direct axion searches



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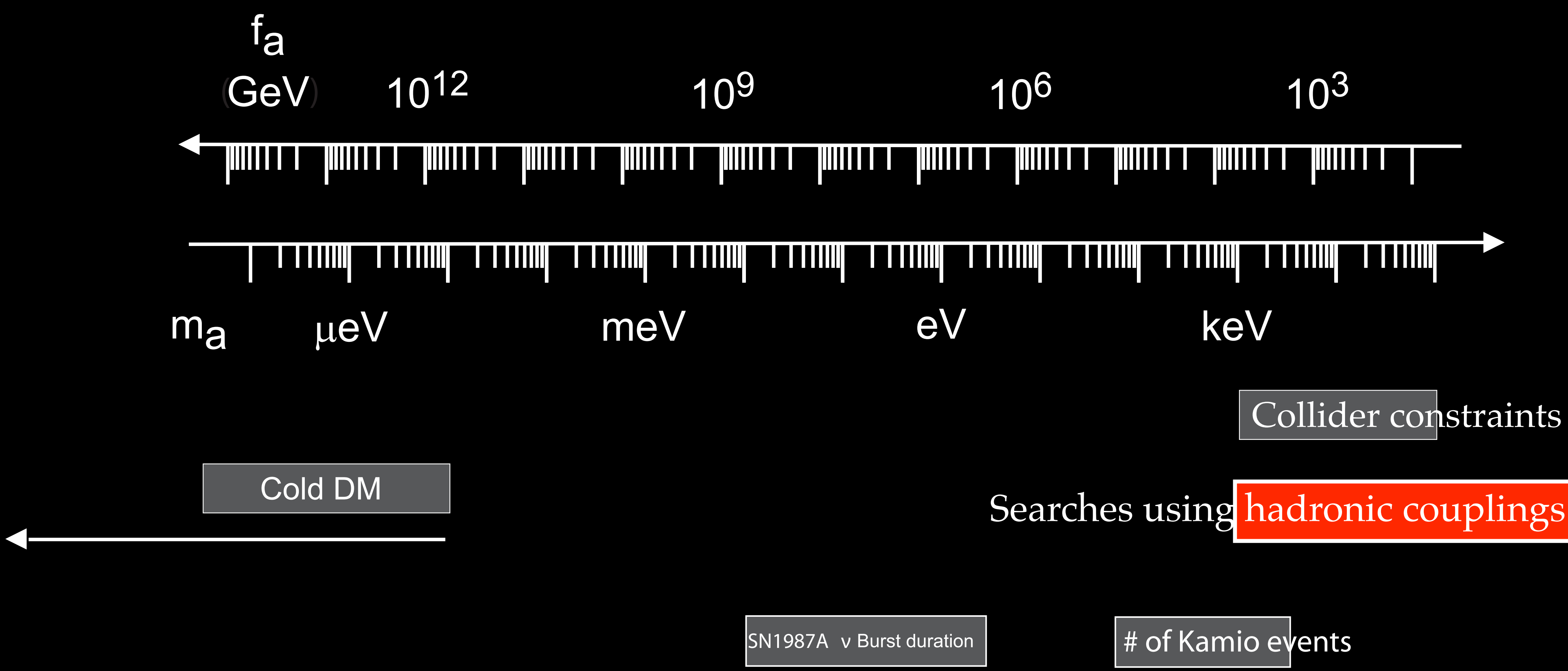
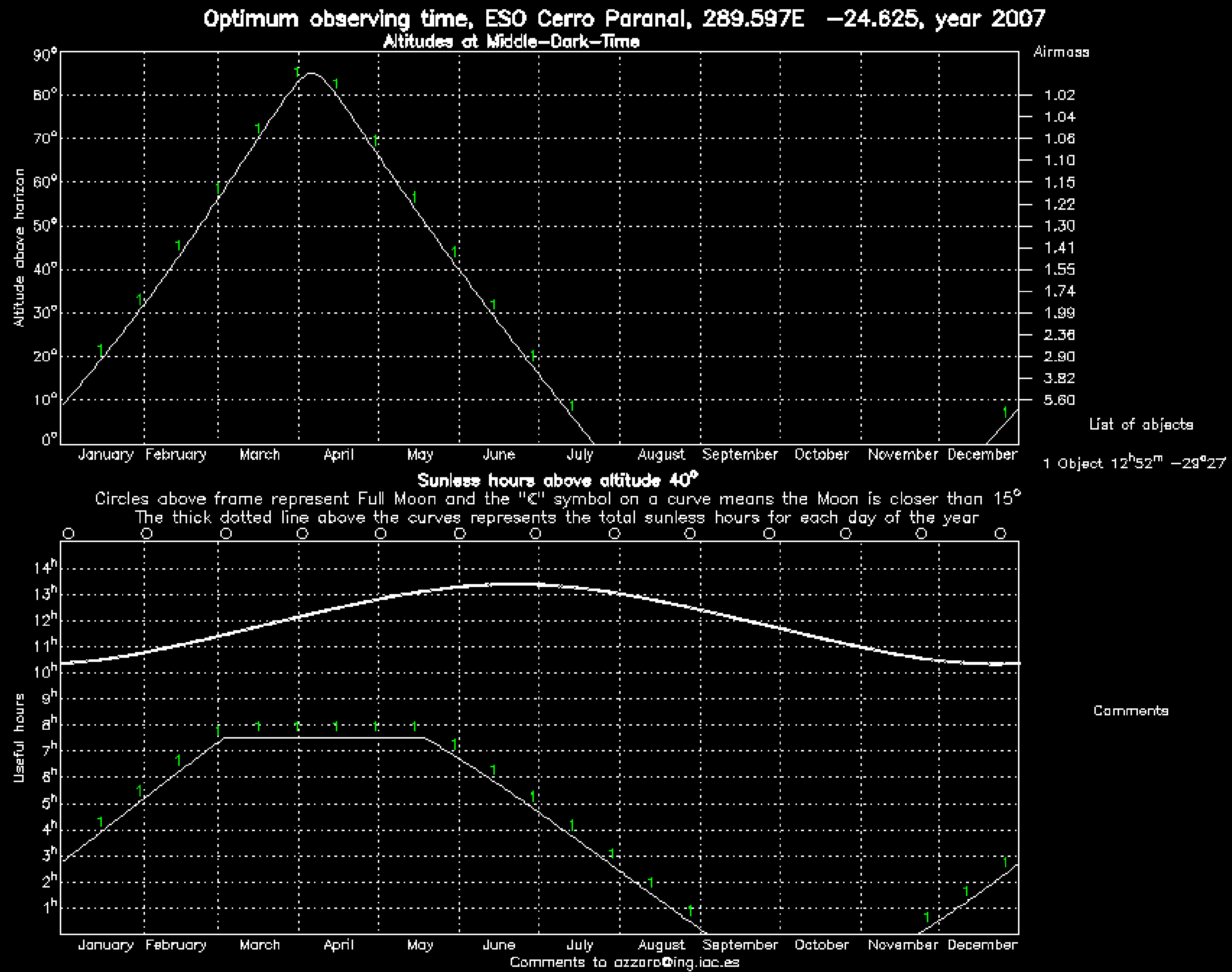


✳ Searches using non-vanishing nuclear couplings (resonant detection of solar axions using Fe, Kr, and Li) yielding first results

✳ Other model independent constraints desirable

RDCS 1252



Optimum observing time, ESO Cerro Paranal, 289.597E −24.625, year 2007
Altitudes at Middle-Dark-Time
Altitude above horizon
Airmass
1.02
1.04
1.06
1.10
1.15
1.22
1.30
1.41
1.55
1.74
1.99
2.36
2.90
3.82
5.60
January
February
March
April
May
June
July
August
September
October
November
December
List of objects
1 Object 12h52m −29°27
Sunless hours above altitude 40°
Circles above frame represent Full Moon and the "€" symbol on a curve means the Moon is closer than 15°
The thick dotted line above the curves represents the total sunless hours for each day of the year
Useful hours
Comments
Comments to azzaro@ing.iac.es

Kination

- Kination refers to an epoch (typically pre-BBN) during which the universe's energy budget is dominated by the *kinetic* energy of a scalar field

$$T/V = \dot{\phi}^2/2V(\phi) \gg 1 \rightarrow w = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)} \simeq 1$$
$$\rho \propto a^{-3(1+w)} \qquad H \propto T^3$$

- Kination may alleviate the challenges of EW baryogenesis and be relevant in quintessential inflation

- No entropy generation during kination, so kination complements LTR

- Analysis does not rely on details of kination models, general for models with $H = H_{\rm rad}(T/T_{\rm kin})$ until $T_{\rm kin}, H = H_{\rm rad}$ afterwards

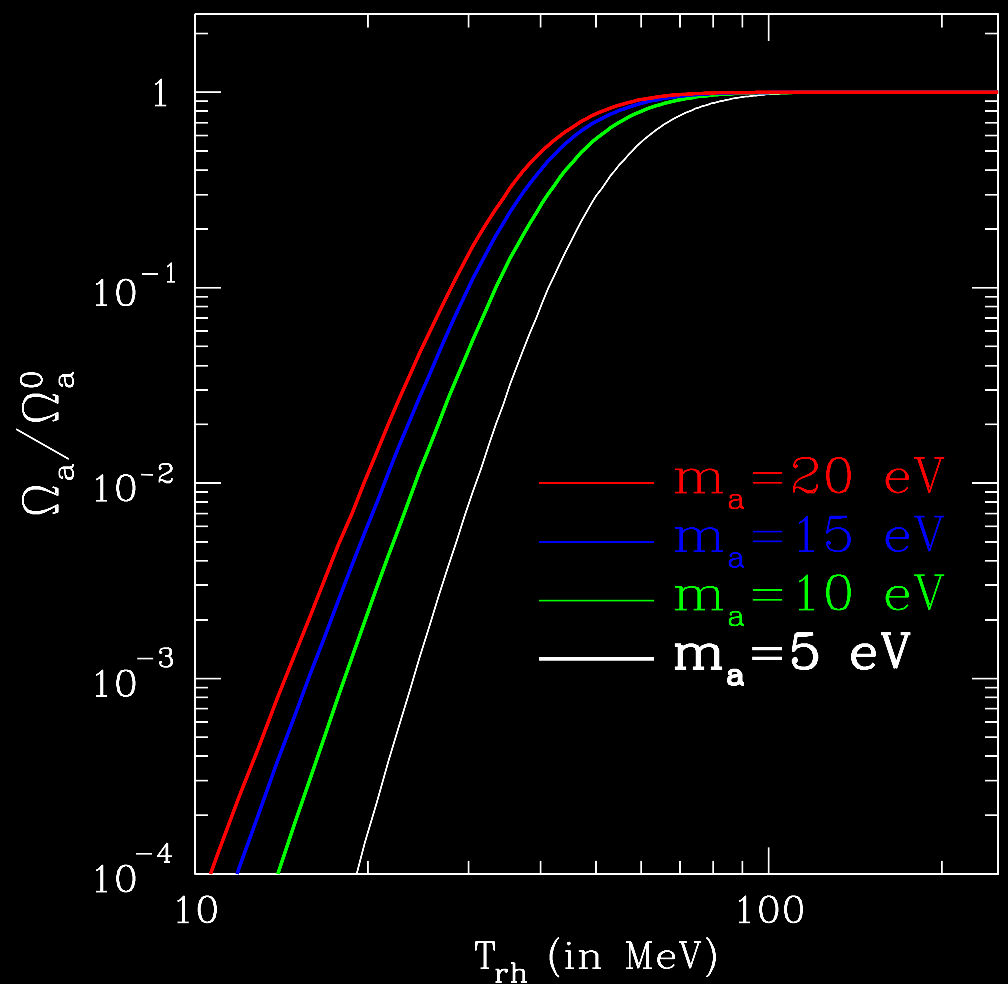
- Past work considered neutralino abundance in kination models. *New work: LSS/CMB/ total density constraints to hot axions in kination models*

Axion abundance in LTR

- Higher T_{F} means higher initial equilibrium abundance
- Entropy generation dramatically suppresses abundances:

$$\Omega_{\mathrm{a}}h^2 = \frac{m_{\mathrm{a,eV}}}{130}\left(\frac{10}{g_{*\mathrm{S,F}}}\right)\gamma\left(T_{\mathrm{rh}}/T_{\mathrm{F}}\right)$$

$$\gamma(\beta) \sim \begin{cases} \beta^5 \left(\frac{g_{*,\mathrm{rh}}}{g_{*,\mathrm{F}}}\right)^2 \left(\frac{g_{*\mathrm{S,F}}}{g_{*\mathrm{S,rh}}}\right) & \text{if } \beta \ll 1, \\ 1 & \text{if } \beta \gg 1 \end{cases}$$



- Abundance suppression less dramatic in kination case due to lack of entropy generation:

$$\Omega_{\mathrm{a}}h^2 = \frac{m_{\mathrm{a,eV}}}{130}\left(\frac{10}{g_{*\mathrm{S,F}}}\right)$$

with different $g_{*\mathrm{S,F}}$

Axion temperature in LTR

- Entropy generation leads to $T_\mathrm{a} \propto a^{-1}$, while $T_\gamma \propto a^{-3/8}$:

$$\frac{T_\mathrm{a}}{T_\nu} \approx (10.75/g_{*\mathrm{S,F}})^{1/3}, \qquad \text{if } T_\mathrm{F} < T_\mathrm{rh}.$$

$$\frac{T_a}{T_\nu} \simeq \left(\frac{11}{4}\right)^{1/3} \left(\frac{T_\mathrm{rh}}{T_\mathrm{F}}\right)^{5/3} \left(\frac{g^2_{*,\mathrm{RH}}\, g_{*\mathrm{S},0}}{g^2_{*,\mathrm{F}}\, g_{*\mathrm{S},\mathrm{RH}}}\right)^{1/3} \qquad \text{if } T_\mathrm{F} > T_\mathrm{rh}.$$

- Axions non-relativistic earlier: Smaller free-streaming length!

$$\lambda_\mathrm{fs} \simeq \frac{196\ \mathrm{Mpc}}{m_{\mathrm{a,eV}}} \left(\frac{T_\mathrm{a}}{T_\nu}\right) \left\{1 + \ln\left[0.45 m_{\mathrm{a,eV}} \left(\frac{T_\nu}{T_\mathrm{a}}\right)\right]\right\}.$$

- In the kination case, $\frac{T_\mathrm{a}}{T_\nu} \approx (10.75/g_{*\mathrm{S,F}})^{1/3}$, with different $g_{*\mathrm{S,F}}$

New constraints

✳ In the case of kination, the new constraints are less dramatically different:
If $T_{\rm kin} \simeq 10$ MeV, the allowed regions are $m_{\rm a} \lesssim 3.2$ eV and $17 \text{ eV} \lesssim m_{\rm a} \lesssim 26 \text{ eV}.$
If $T_{\rm kin} \gtrsim 110$ MeV, standard results are recovered.

Subtleties

- Non-equilibrium production
- $T_{\rm F} \gtrsim 200$ MeV necessitates use of different cross sections
- At low values of $m_{\rm a}$, coherent oscillation may become important
- For very low $T_{\rm rh}$, ν may not have time to thermalize, and π may fall out of equilibrium
- All these effects negligible for $T_{\rm rh} \gtrsim 10$ MeV and $m_{\rm a} \gtrsim 0.6$ eV

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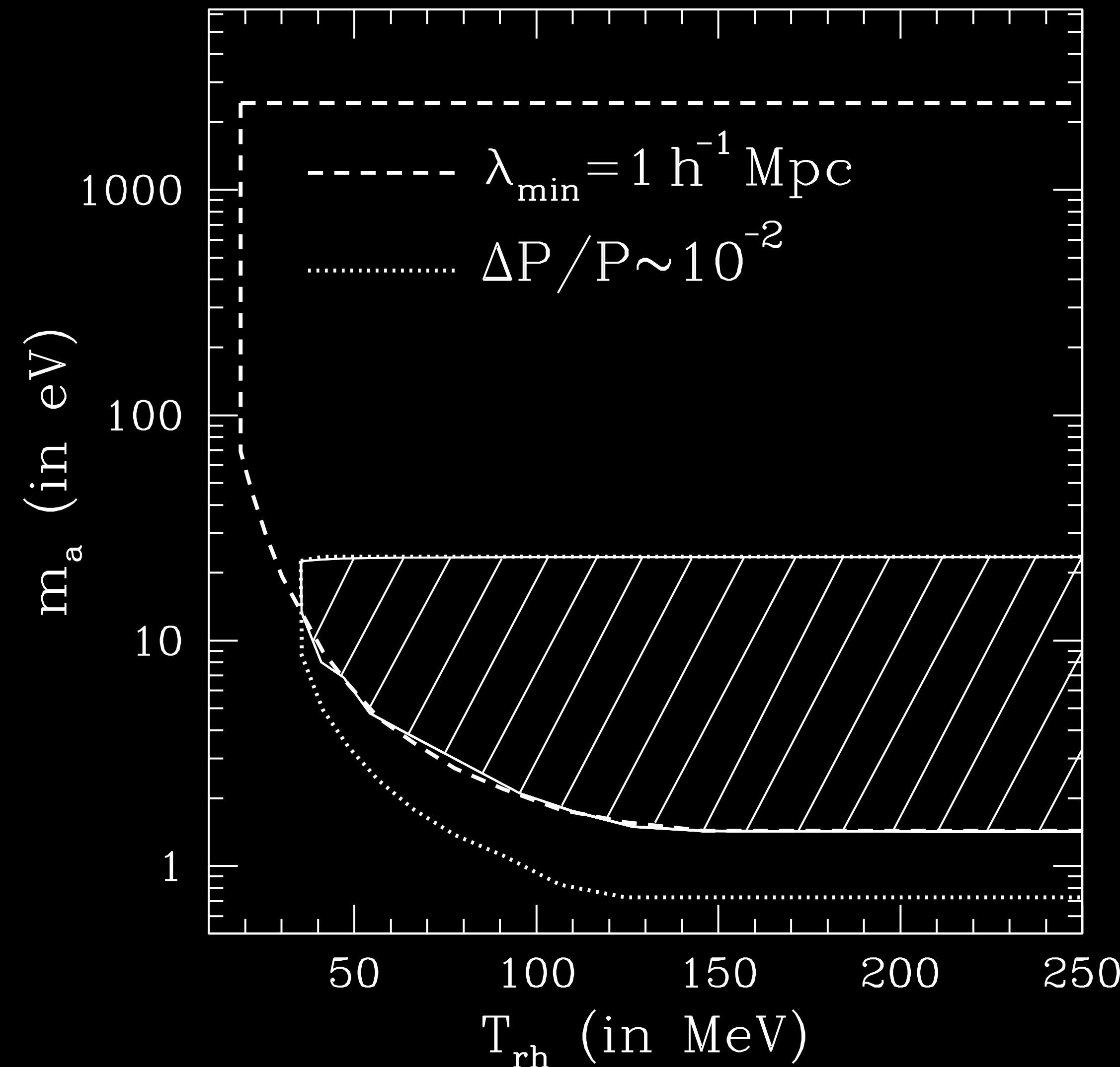
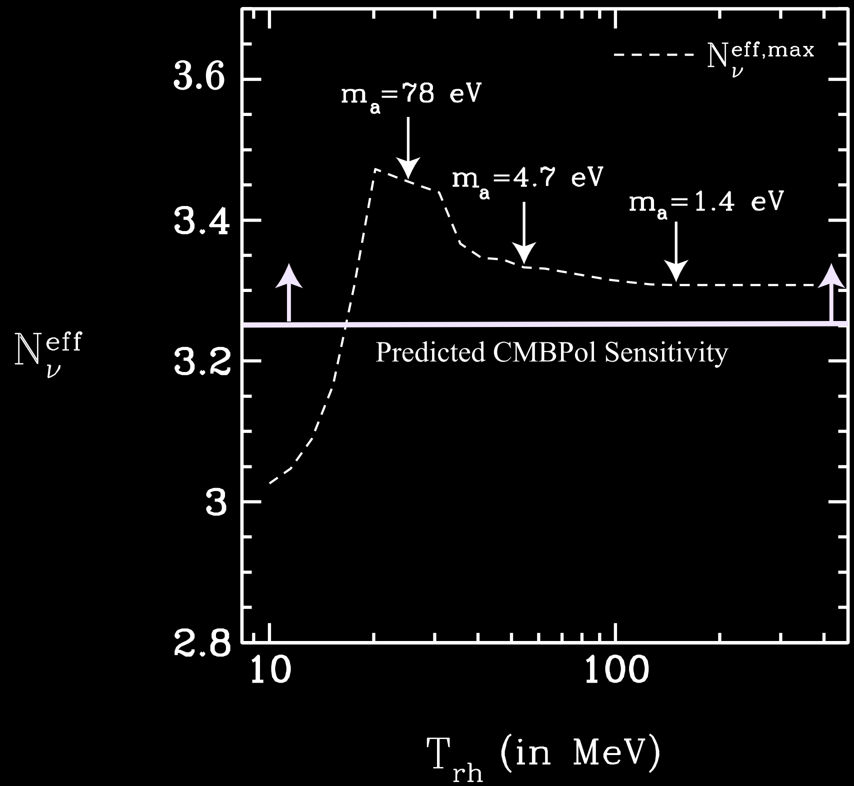
Future surveys

- LSST predicted to reach $\Delta P/P \sim 10^{-2}$ for a sample population similar to SDSS main
- Assuming 21-cm or Lyα observations on very small comoving scales, limits at low reheating temperatures may be improved



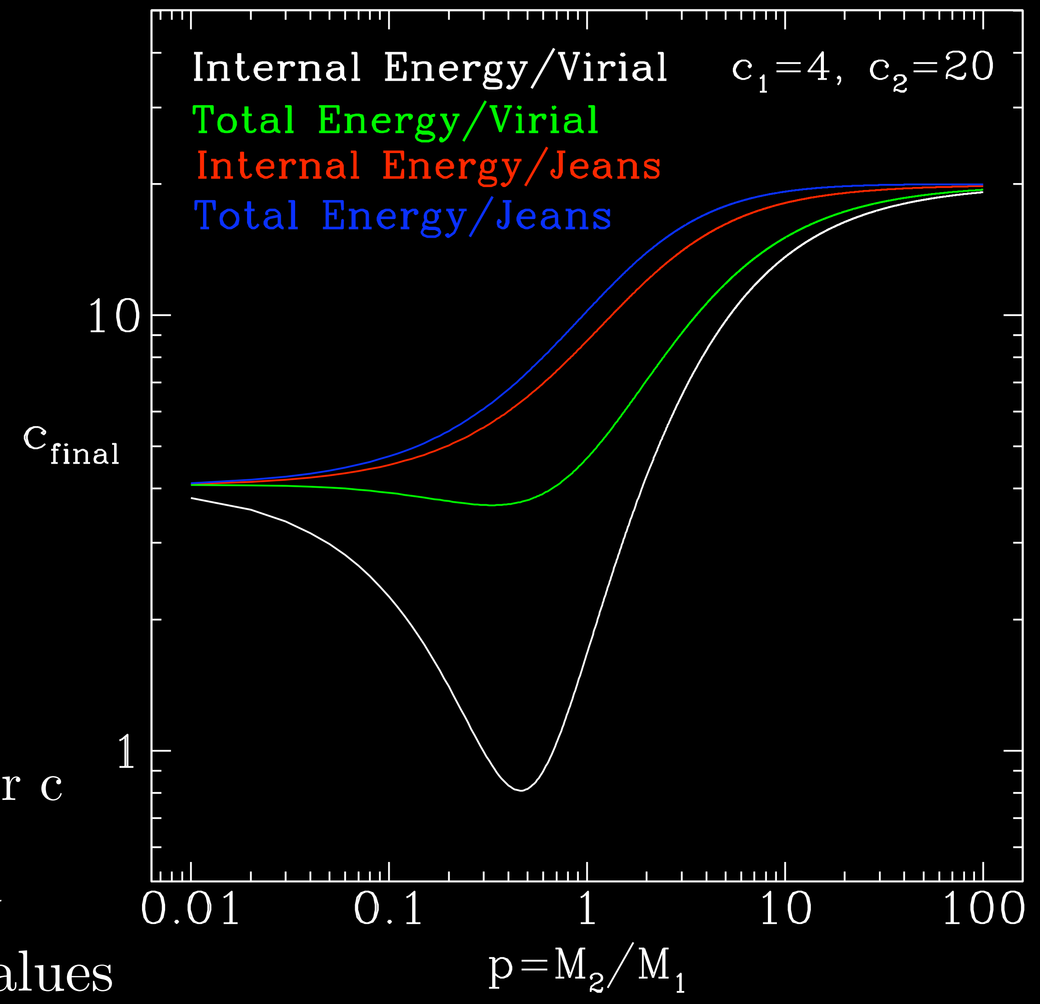
More details on Helium



- $N_\nu^{\rm eff}$ contributes to $H(T)$ during radiation domination, setting the abundance of ^{4}He
- For fixed η, $\Delta N_\nu^{\rm eff} = \dfrac{\Delta Y_p}{0.016}$
- Folding in systematic errors, current measurements yield constraint $N_\nu^{\rm eff} \leq 3.8$
- $Y_{\rm p}$ affects ionization history, and thus CMB TT, TE, and EE spectra
- CMBPol may begin to impose interesting constraints to axions and LTR

Post-merger predictions

- Solutions asymptote to properties of most massive progenitor in EMR limit
- Less concentrated halos are the least bound. For $p \sim 1$, the merger is less bound than it is massive, forcing very low concentration
- Adding 2-halo terms generally adds more potential energy than kinetic energy $\rightarrow$ more bound halos with higher c
- Non-virial contribution to kinetic energy $\rightarrow$ lower $|E|$ at fixed $c \rightarrow$ higher c values



Existing models of the scatter

* NFW model: Scale density of halo set when its `progenitor' collapses

$$P\left(>fM, z|M, z_0\right) = \mathrm{erfc}\left\{\frac{\delta_{\mathrm{crit}}\left(z_{\mathrm{coll}}\right) - \delta_{\mathrm{crit}}\left(z\right)}{\sqrt{2\left[\sigma^2\left(fM\right) - \sigma^2\left(M\right)\right]}}\right\} \equiv \frac{1}{2}$$

$\delta_c\left(M|f\right) \propto \left[1 + z_{\mathrm{coll}}\left(M, f\right)\right]^3$ ⟶ Prediction for c!

  * Scatter in c set by scatter in z_{coll}: Real collapse is probabilistic and halos of given M collapse at different times

$$\Delta\delta_c = 3\delta_c\Delta z_{\mathrm{coll}}/\left(1 + z_{\mathrm{coll}}\right)$$

* Bullock et al. model: Scale *radius* of halo set when its `progenitor' collapses (no dependence on `observation epoch')

$$\sigma(fM) = \delta_{\mathrm{crit}}\left(z_{\mathrm{coll}}\right) \qquad r_s\left(M\right) = r_{\mathrm{vir}}\left(fM, z_{\mathrm{coll}}\right)/K$$

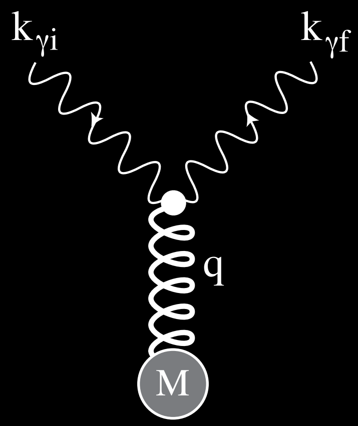
  * Followed by `inside-out' accretion onto a seed of mass *fM* and scale radius r_s

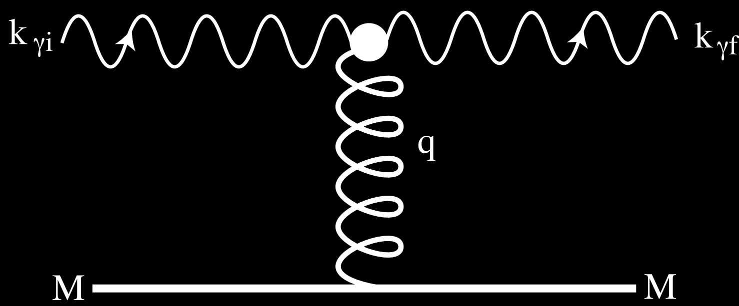
$$c(M, a) = r_{\mathrm{vir}}\left(M, a\right)/r_{\mathrm{s}}(M)$$

  * Scatter still set by scatter in z_{coll}

$$\Delta c = c\Delta z_{\mathrm{coll}}/\left(1 + z_{\mathrm{coll}}\right)$$

Linear calculation of M-γ scattering





We expect a lack of high-frequency gravitationally lensed images if a cutoff exists

- For an elastic collision, external field approach/Feynman rules yield (for small angles)

$$\frac{d\sigma}{d\Omega} = \frac{(4GM)^2}{(c\theta)^4} e^{-2k_\gamma \theta/\mu}$$

⟵ **With a cutoff** ⟶

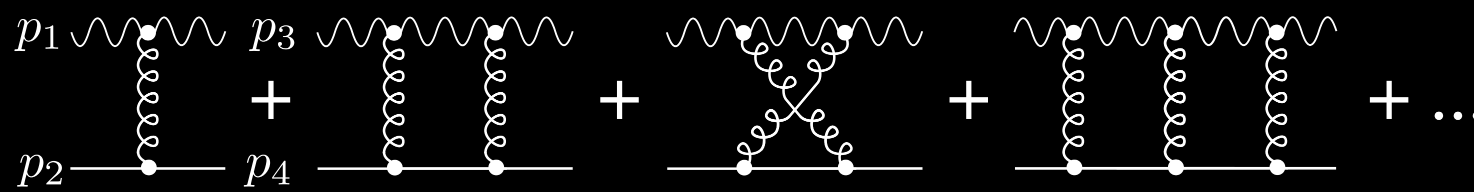
$$\theta = \frac{4GM}{c^2 b} F\left(2\theta k_\gamma/\mu\right)$$

$$F(x) = \sqrt{(1-x)e^{-x} - x^2 \mathrm{Ei}\left(-x\right)} \quad \mathrm{Ei}\left(x\right) \equiv -\int_{-x}^{\infty} e^{-t} dt/t$$

- $|k_{\gamma,\mathrm{f}} - k_{\gamma,\mathrm{i}}| \simeq k_\gamma \theta > \mu$ deflections are suppressed

Functional form of cutoff is irrelevant

To higher <u>order</u> in the eikonal limit...



- ✳ Perturbative QG is non-renormalizable (loop diagrams are infinite!)

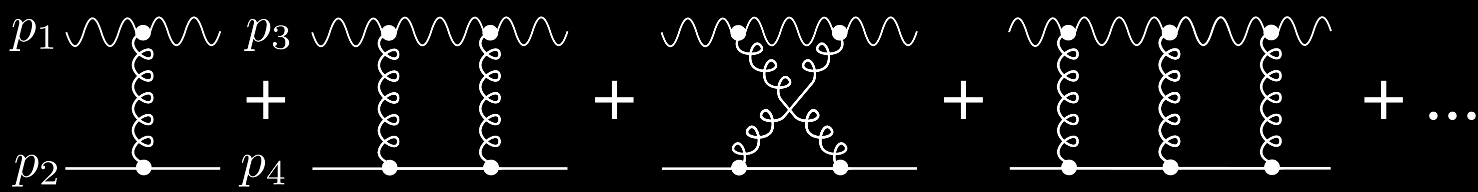
- ✳ In the eikonal limit $s = -(p_1 + p_2)^2 \gg t = -(p_1 - p_3)^2$, divergent diagrams are suppressed by powers of $\gamma = \dfrac{s}{M_{\rm pl}^2}$ and are dropped to yield result convergent at all orders

$$\mathcal{M} = \mathcal{M}_{\rm Born} \times \frac{\Gamma\left(1 - i\alpha(s)\right)}{\Gamma\left(1 + i\alpha(s)\right)} \times \left(\frac{4k_{\rm IR}^2}{-t}\right)^{-i\alpha(s)}$$

$\alpha = 2GME_\gamma$ **Kabat and Ortiz 92**

- ✳ We are deep in the eikonal limit $-t \simeq \dfrac{(h\nu\theta)^2}{4} \ll -s \simeq M^2$

To higher order in the eikonal limit...



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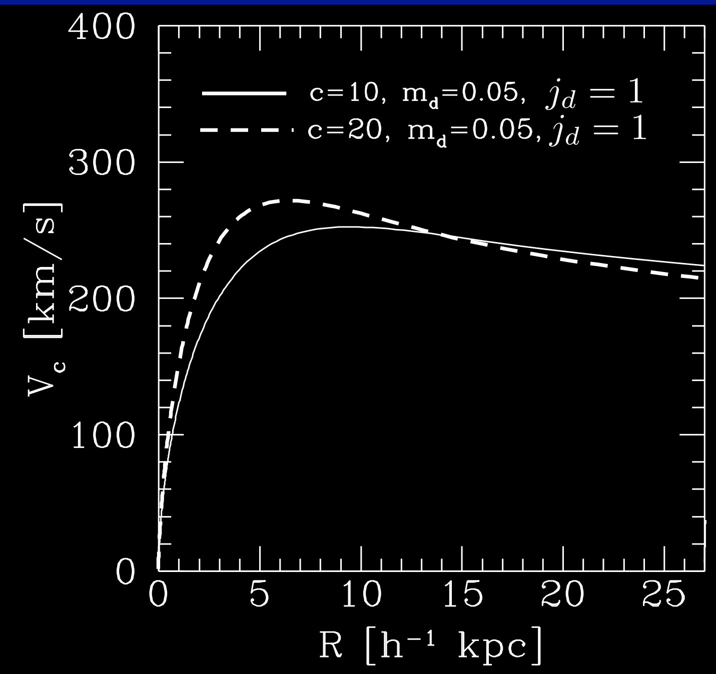
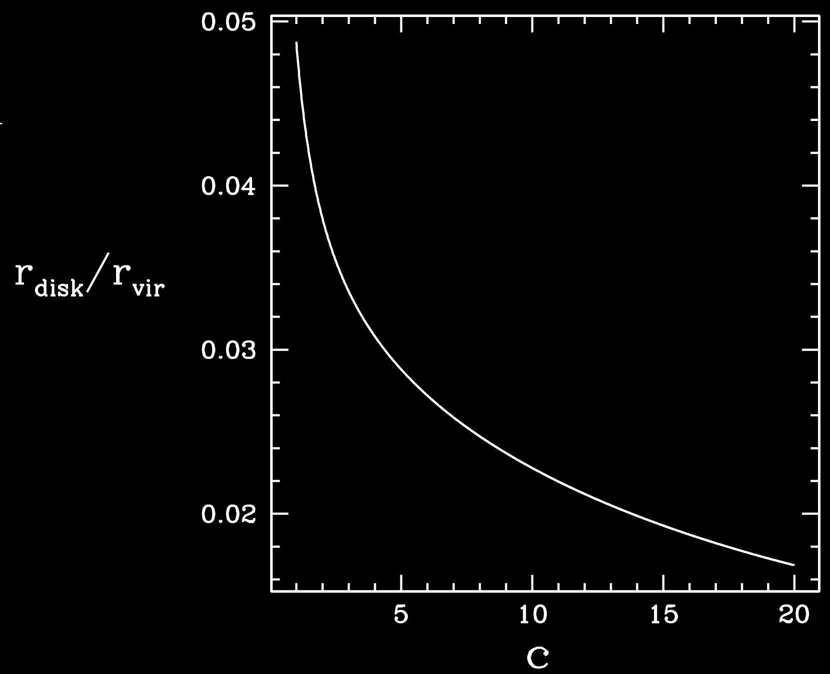
We repeat the exercise with a cutoff at each propagator

- In the eikonal limit our tree-level result for is exact up to a phase $\mathcal{M}$, so the tree-level cross-section is exact

Concentrations and galaxies



- Baryons collapse and cool, force adiabatic contraction of halo (Blumenthal 86)
- `Explains' Tully-Fisher (TF) relation $L \propto v_c^3$
- Scatter relevant for expected scatter in TF relation
- Relevant for setting size of galactic bulge (GALFORM)



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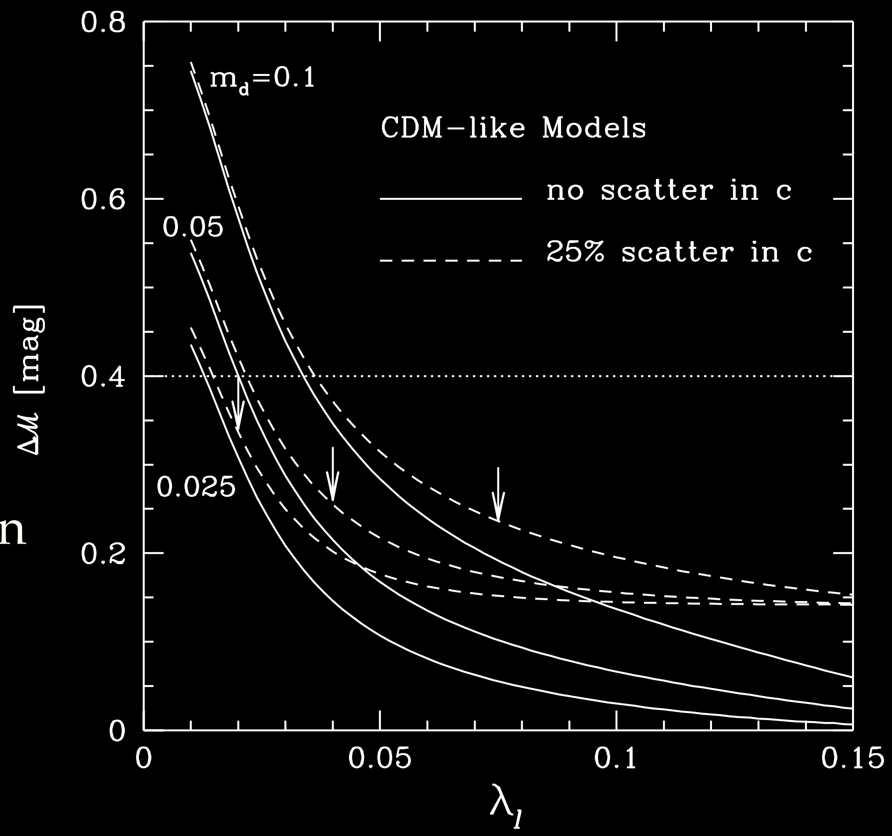

Axion abundance in LTR

- Higher $T_{\rm F}$ means higher initial equilibrium abundance
- Entropy generation dramatically suppresses abundances:

$$\Omega_{\rm a} h^2 = \frac{m_{\rm a,eV}}{130} \left(\frac{10}{g_{*{\rm S},{\rm F}}}\right) \gamma\left(T_{\rm rh}/T_{\rm F}\right),$$

$$\gamma(\beta) \sim \begin{cases} \beta^5 \left(\frac{g_{*,{\rm rh}}}{g_{*,{\rm F}}}\right)^2 \left(\frac{g_{*{\rm S},{\rm F}}}{g_{*{\rm S},{\rm rh}}}\right) & \text{if } \beta \ll 1, \\ 1 & \text{if } \beta \gg 1 \end{cases}$$