Recurrent Axinovae

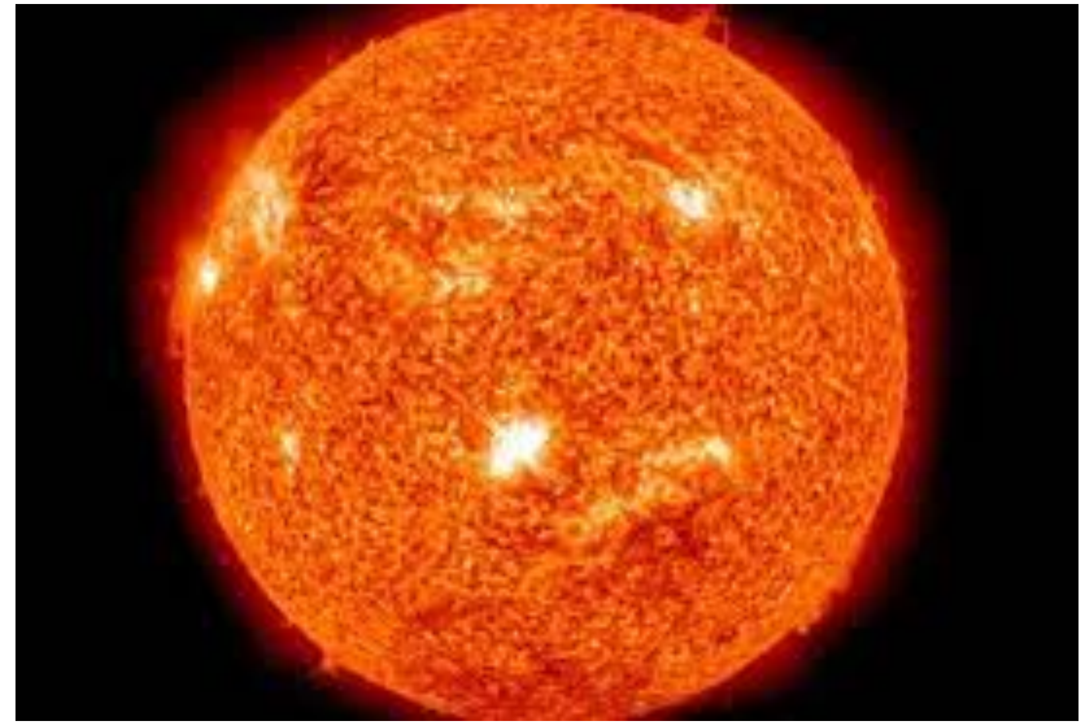
Patrick Fox

Fermilab

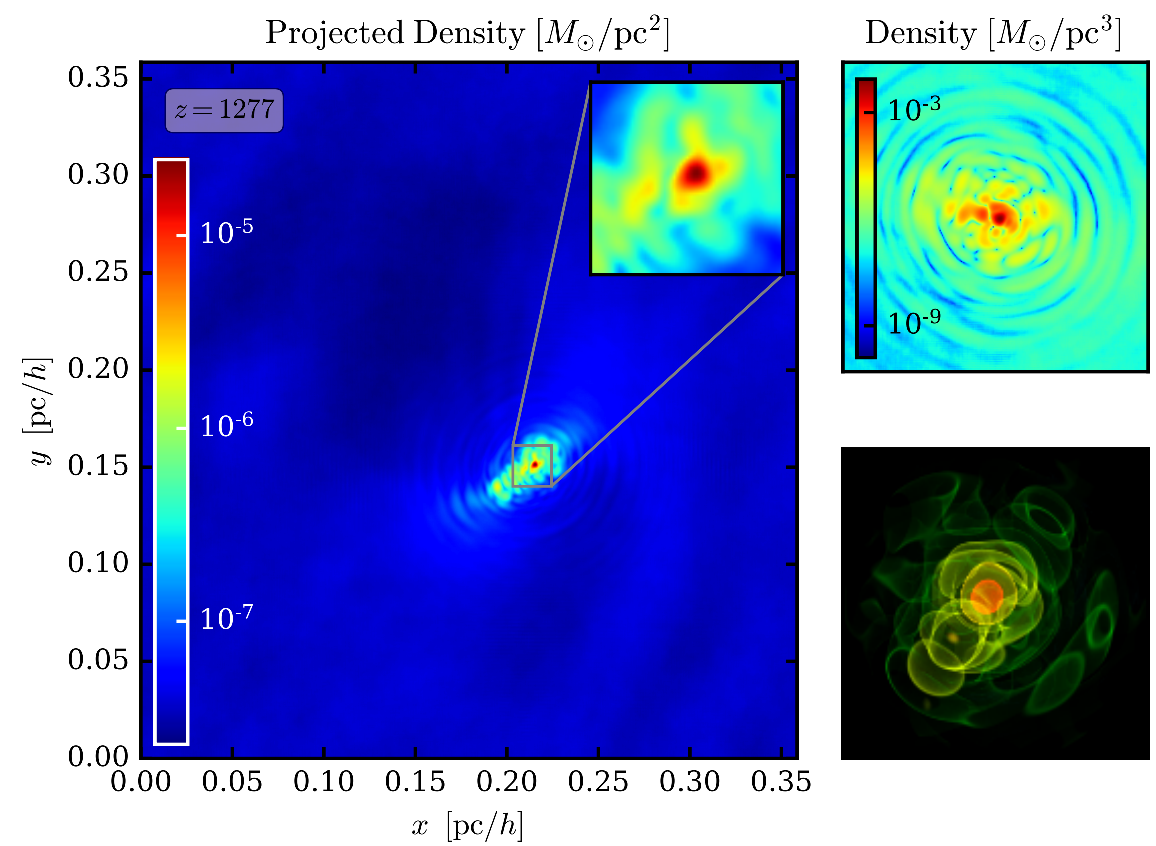
arXiv:2302.00685

PJF, Neal Weiner, Huangyu Xiao

Outline



- Axion “stars”
- Minihalos
- Axion cosmology
- Decaying DM bound
- Conclusions



Axion "stars"

Fermionic stars: gravity vs. thermal/degeneracy pressure

Can bosonic equivalent objects exist?

For non-relativistic scalars bound by gravity, solve Gross-Pitaevskii-Poission equations

$$V = \frac{1}{2} m_a^2 \phi^2 - \frac{\lambda}{4!}\phi^4 \qquad \phi \sim \psi e^{i m_a t} + \psi^* e^{-i m_a t}$$

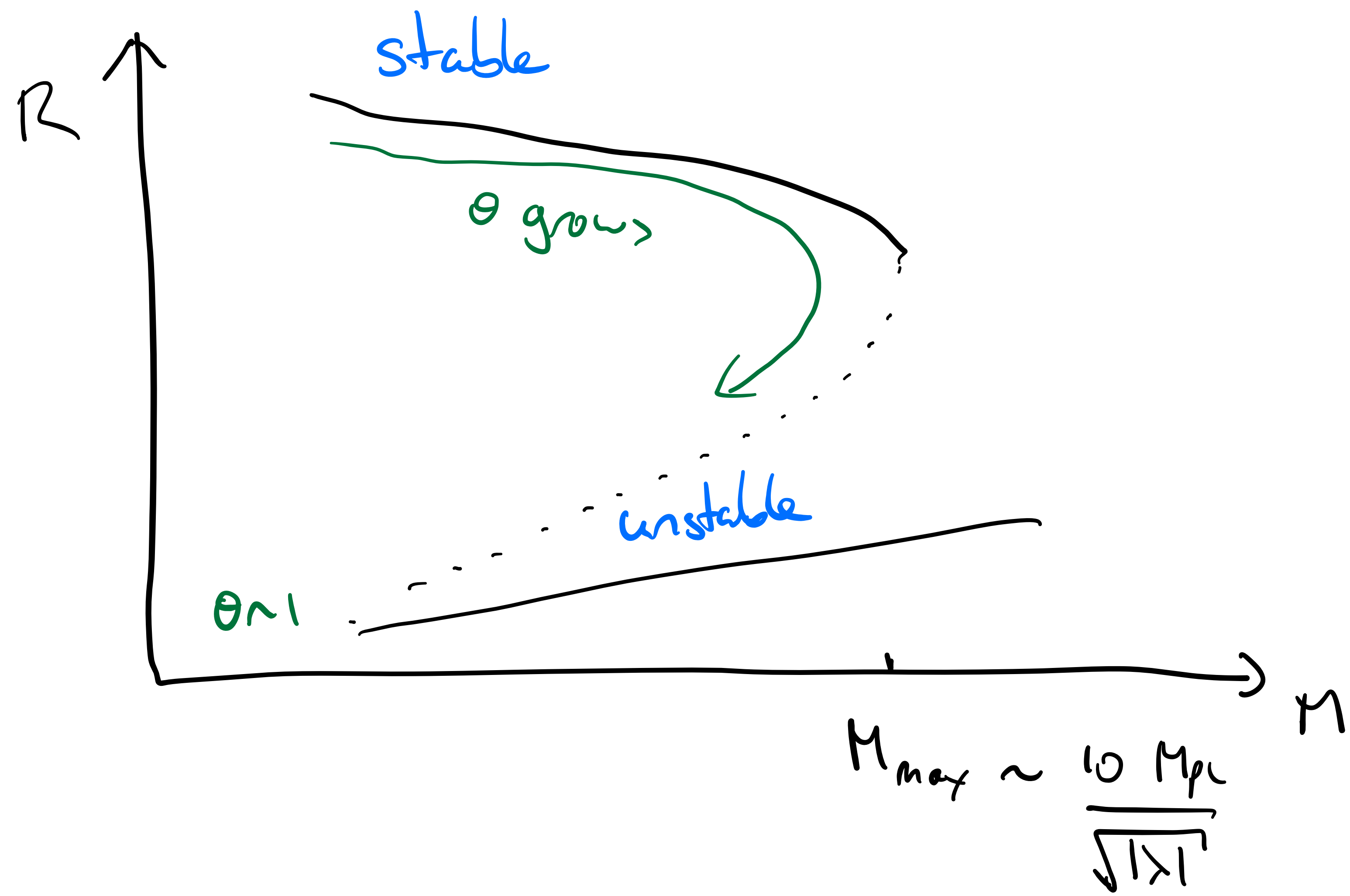
$$i\frac{\partial \psi}{\partial t} = -\frac{1}{2m_a}\nabla^2\psi + m_a \Phi \psi - \frac{\lambda}{m_a^3}|\psi|^2\psi$$

$$\nabla^2 \Phi = \left(\frac{f}{M_{pl}}\right)^2 m_a |\psi|^2$$

Axion stars

Energetics
$$E \sim M\dot{R}^2 - G_N\frac{M^2}{R} + \frac{M}{m_a^2 R^2} - |\lambda|\frac{M^2}{m_a^4 R^3}$$

Stable solution exists
$$R_* \sim \frac{M_{pl}^2}{m_a^2 M_*}\left(1 + \sqrt{1 - |\lambda|\frac{M_*^2}{M_{pl}^2}}\right)$$



Axion stars

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Gravitational self energy — gradient Pressure — self interactions

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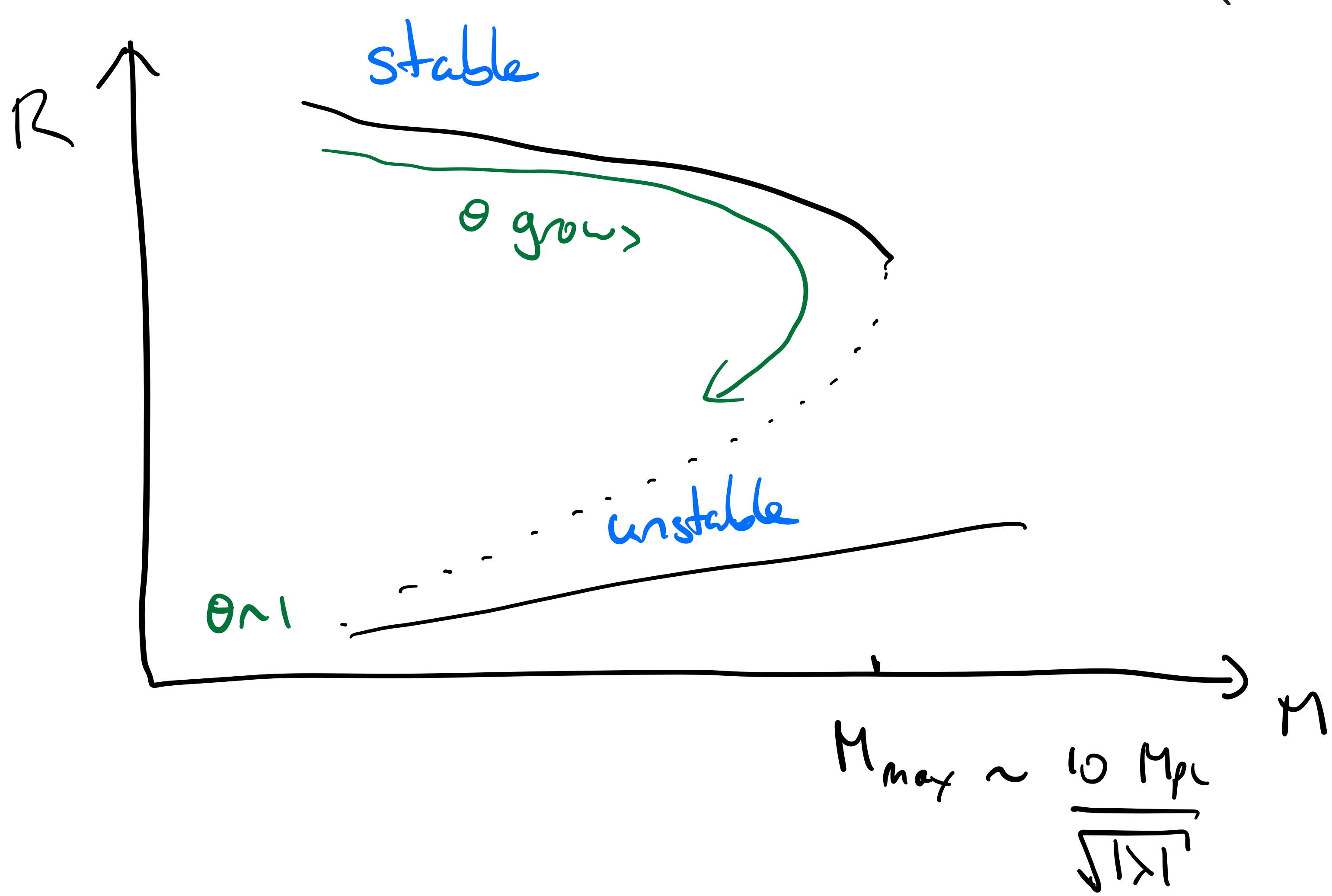
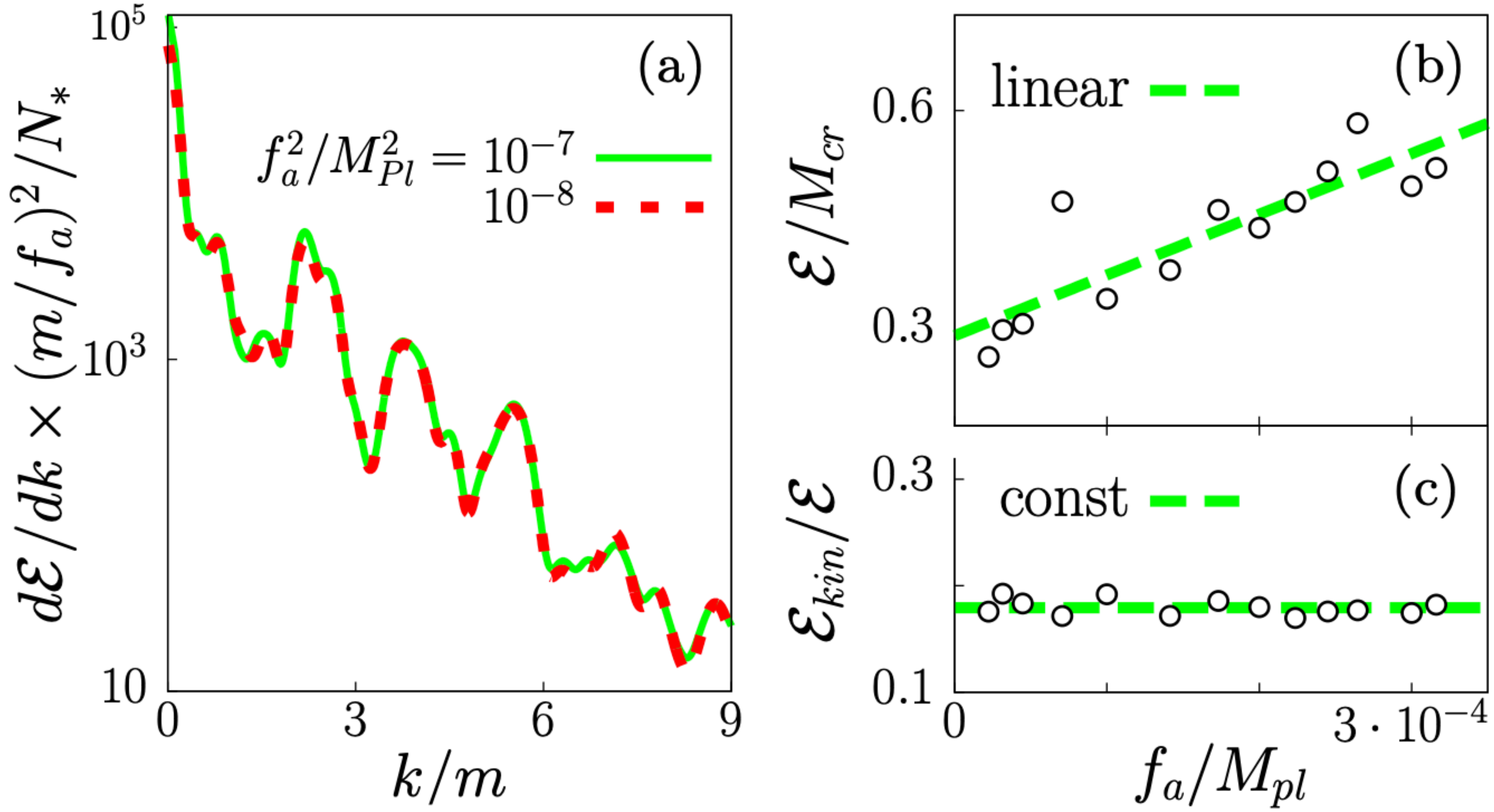


Axion stars

Levkov, Panin, Tkachev PRL118, 2017

Spectrum of emitted axions



Fraction of mass lost in explosion

Fraction in kinetic energy

Supercritical stars shrink, explode and emit (semi) relativistic axions, leaving a remnant

Axion stars

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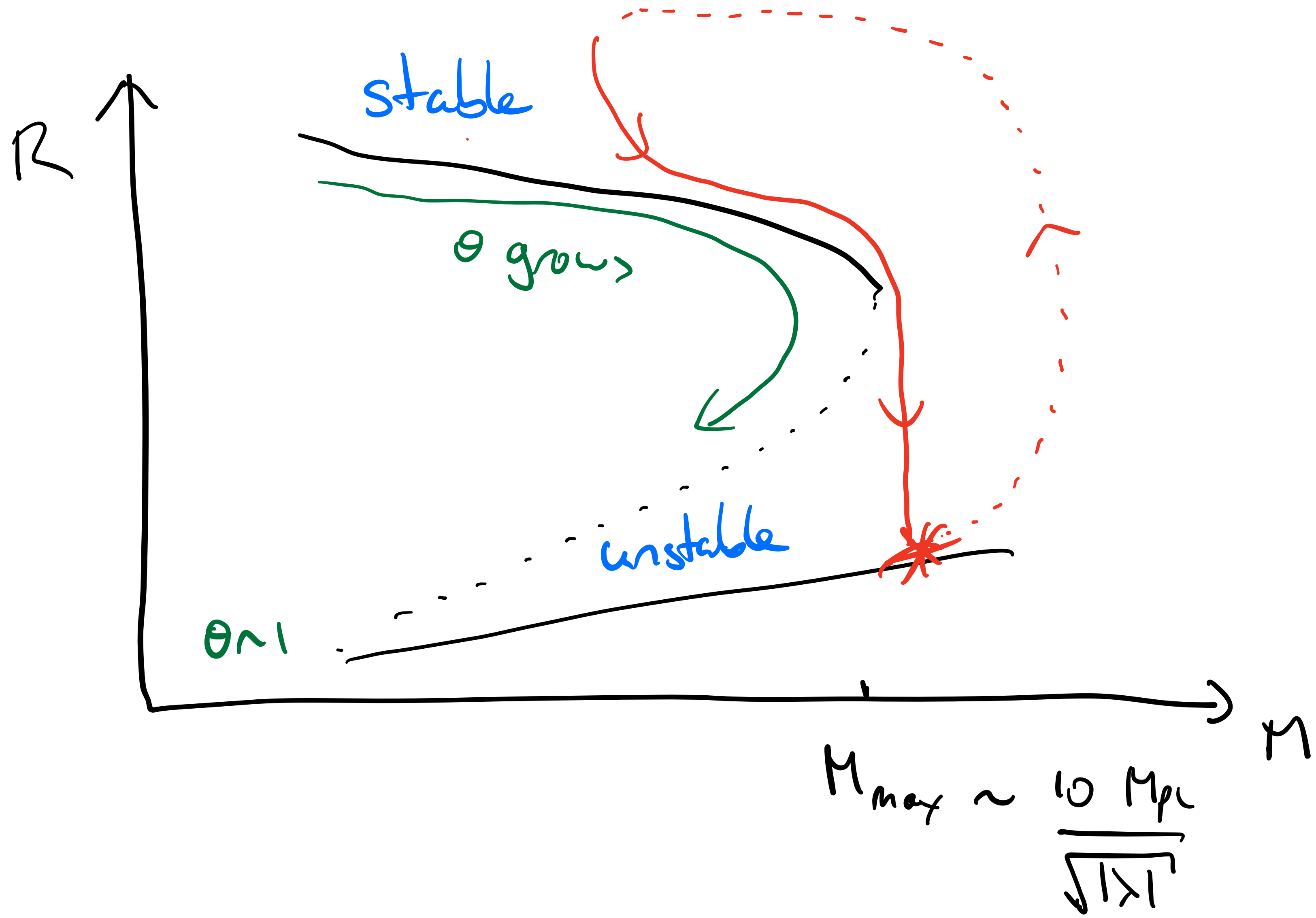


Supercritical stars shrink, explode and emit (semi) relativistic axions, leaving a remnant

Axion star formation and growth

Axions have high phase space density

Bose enhancement

Star forms in a gas of axions: condensation and evaporation

$$\Gamma_s = \frac{1}{M_s}\frac{dM_s}{dt}$$

Axion star growth timescales

Bose enhanced kinetic relaxation time

$$\tau \sim \left(f_{\mathrm{BE}} n \sigma v\right)^{-1} \qquad f_{BE} = 6\pi^2 \frac{n}{\lambda_{dB}^3} \sim \frac{n}{(m_a v)^3}$$

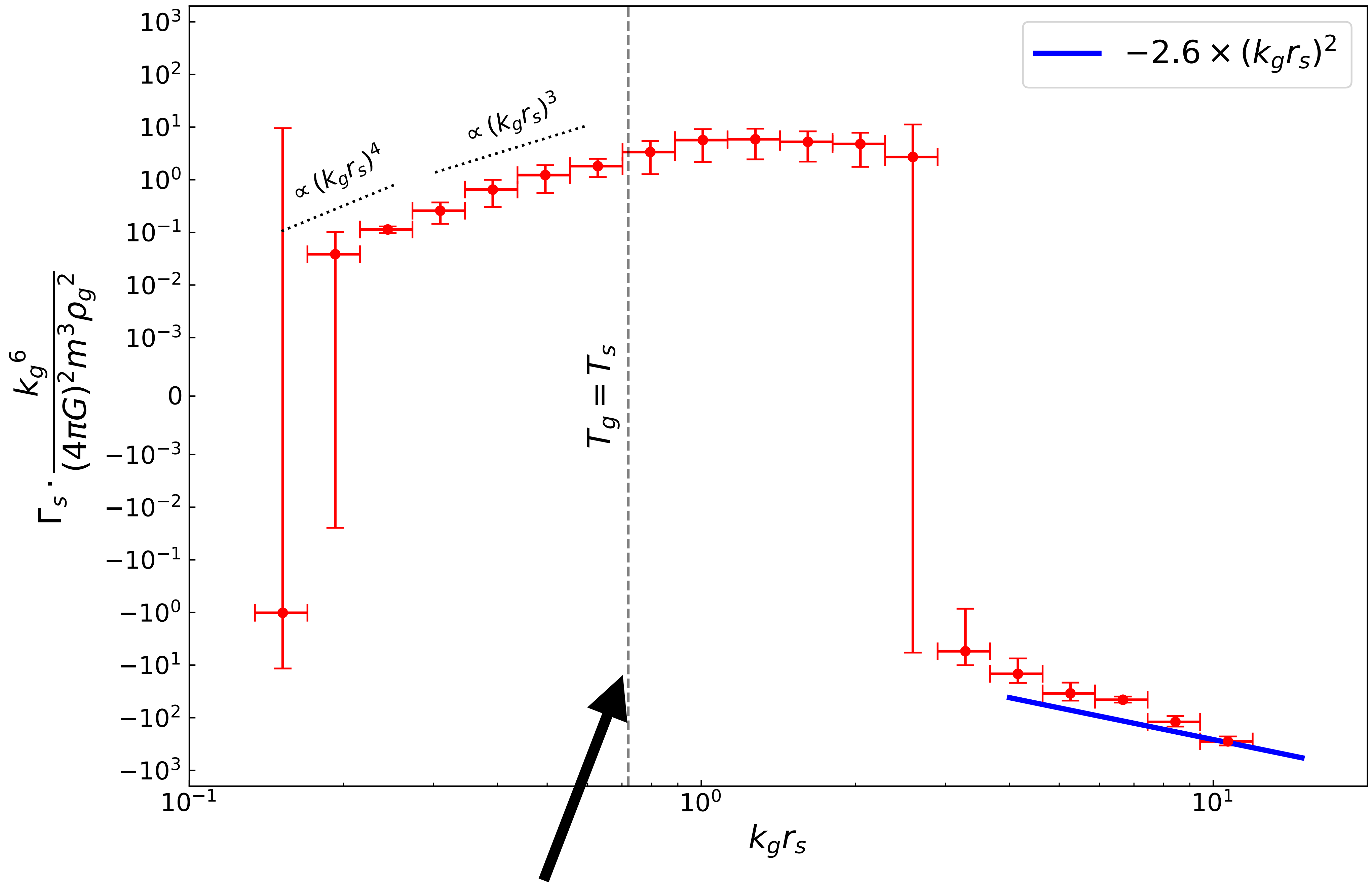
Gravity or self couplings

$$\sigma_{gr} = 8\pi \left(\frac{G_N m_a}{v^2}\right)^2 \log\left(m_a v R\right) \qquad \sigma_{self} = \frac{\lambda^2}{128\pi m_a^2}$$

$$\tau_{\mathrm{gr}} = \frac{b}{48\pi^3} \frac{m_a v^6}{G_N^2 n^2 \log\left(m_a v R\right)} \qquad \tau_{\mathrm{self}} = \frac{64 d m_a^5 v^2}{3\pi n^2 \lambda^2}$$

Axions can also evaporate from the star $\quad \Gamma_{evap} \sim \frac{(m_a v R)^2}{\tau}$

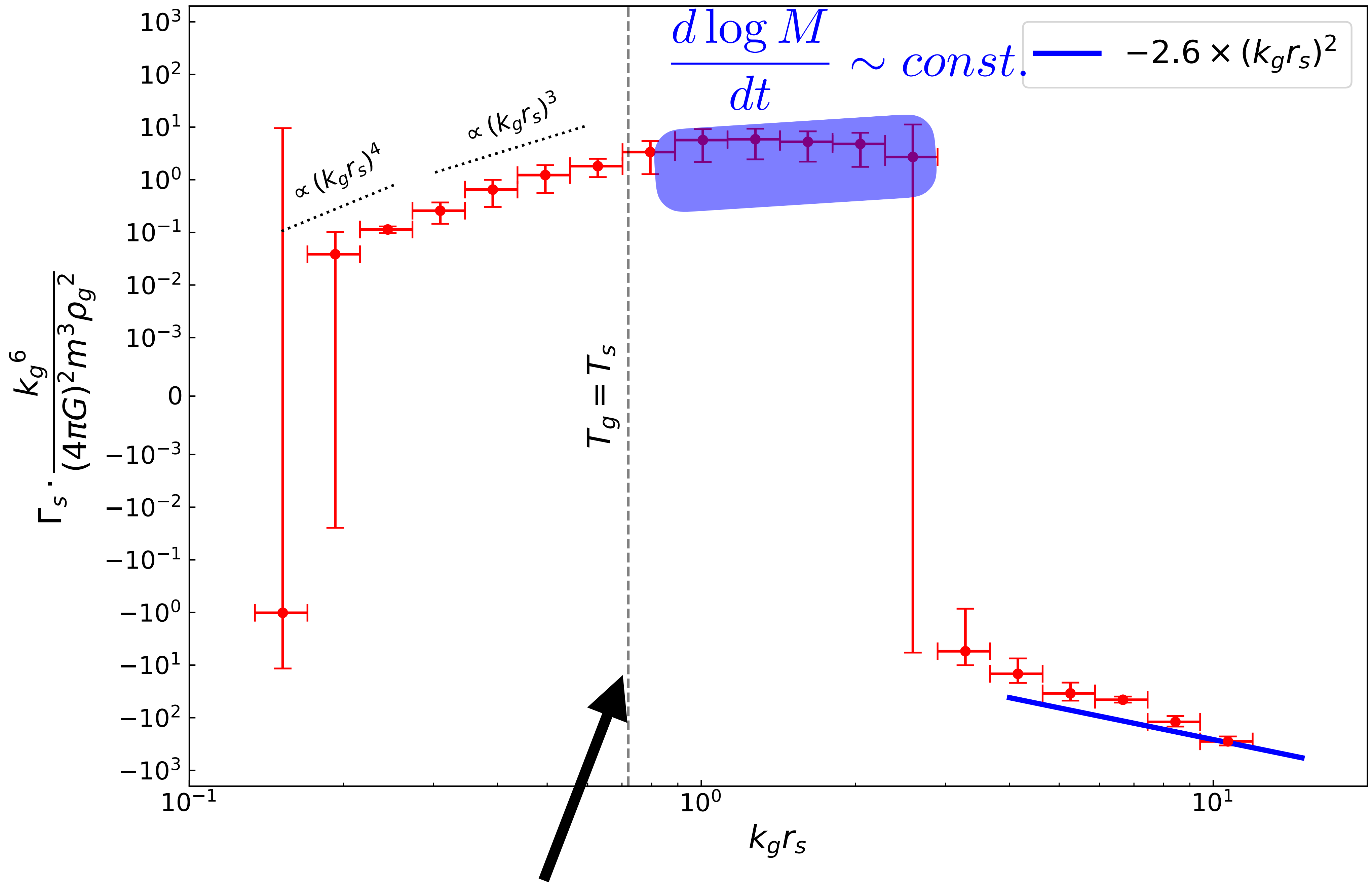
Chan, Sibiryakov, Xue (2207.04057)



Speed of axions in star ~ speed of axions in halo

$$\overline{M_*} \approx 3\rho_a^{1/6} G_N^{-1/2} m_a^{-1} M_h^{1/3}$$

Chan, Sibiryakov, Xue (2207.04057)



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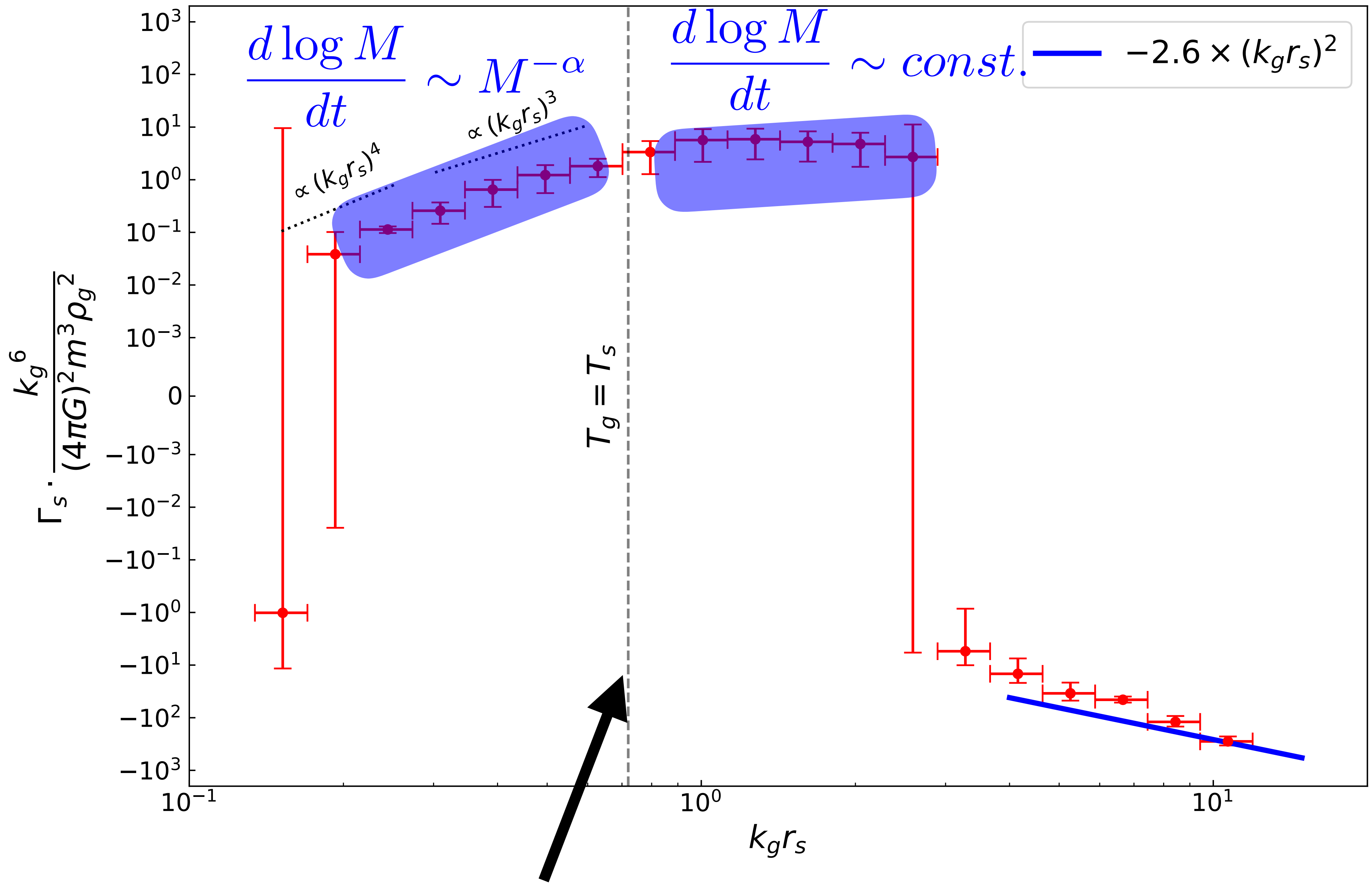

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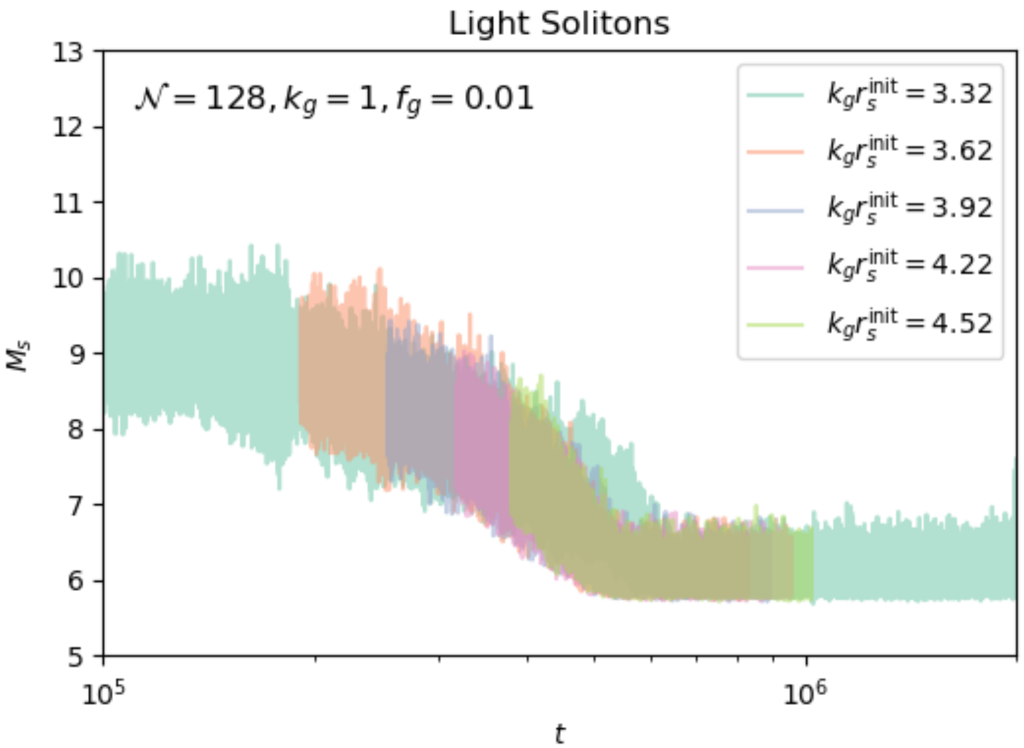
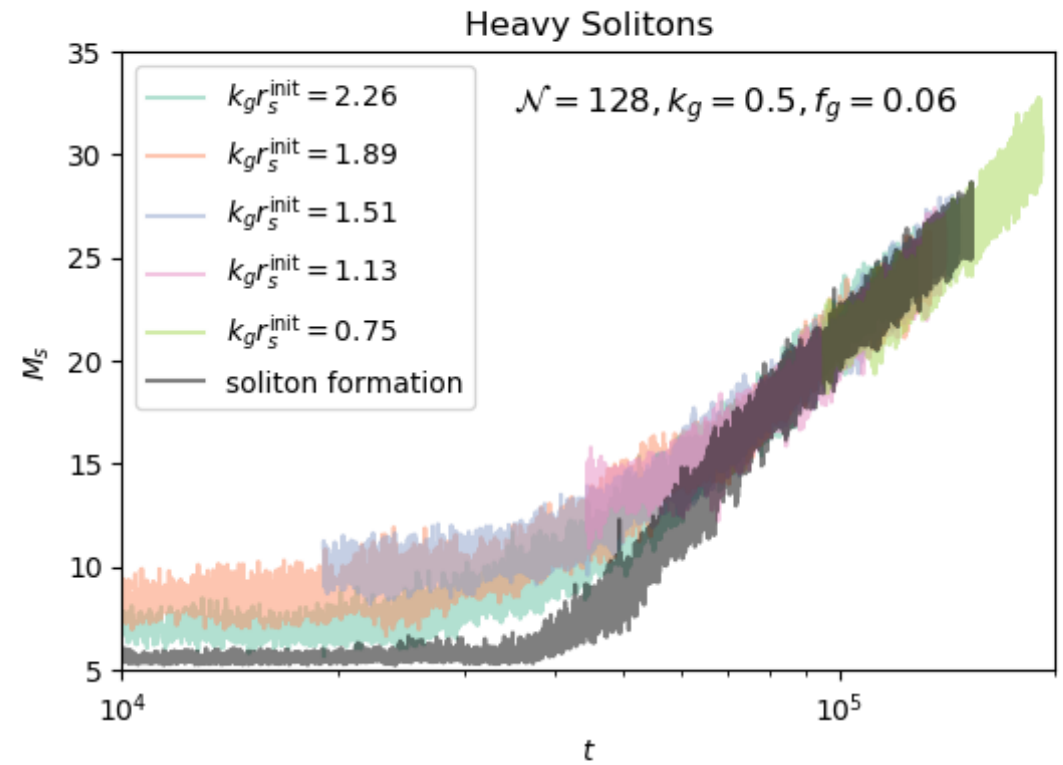
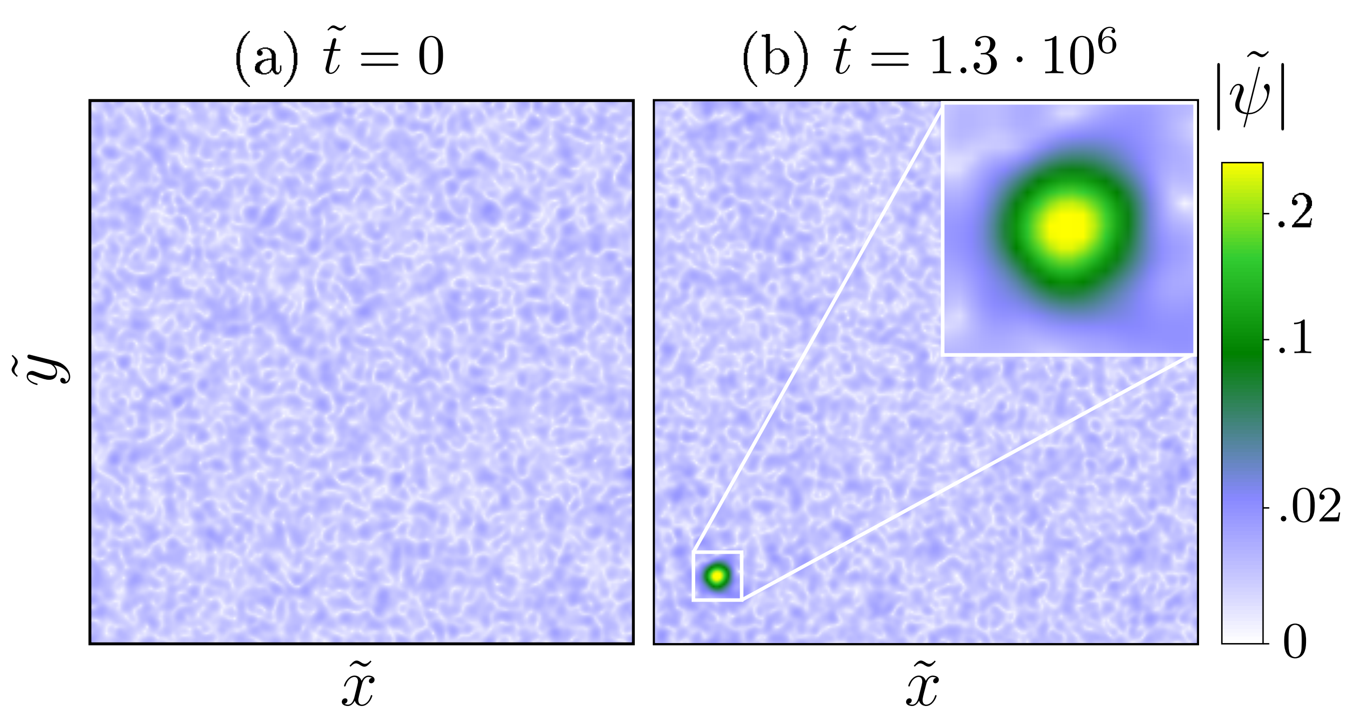
Axion star simulations

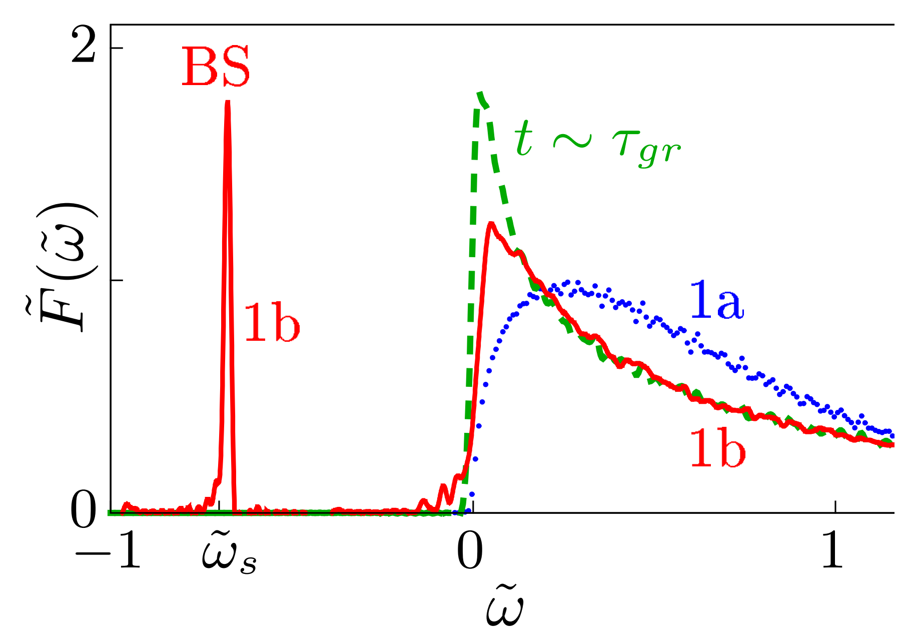
Chan, Sibiryakov, Xue (2207.04057)





Levkov, Panin, Tkachev PRL118, 2017

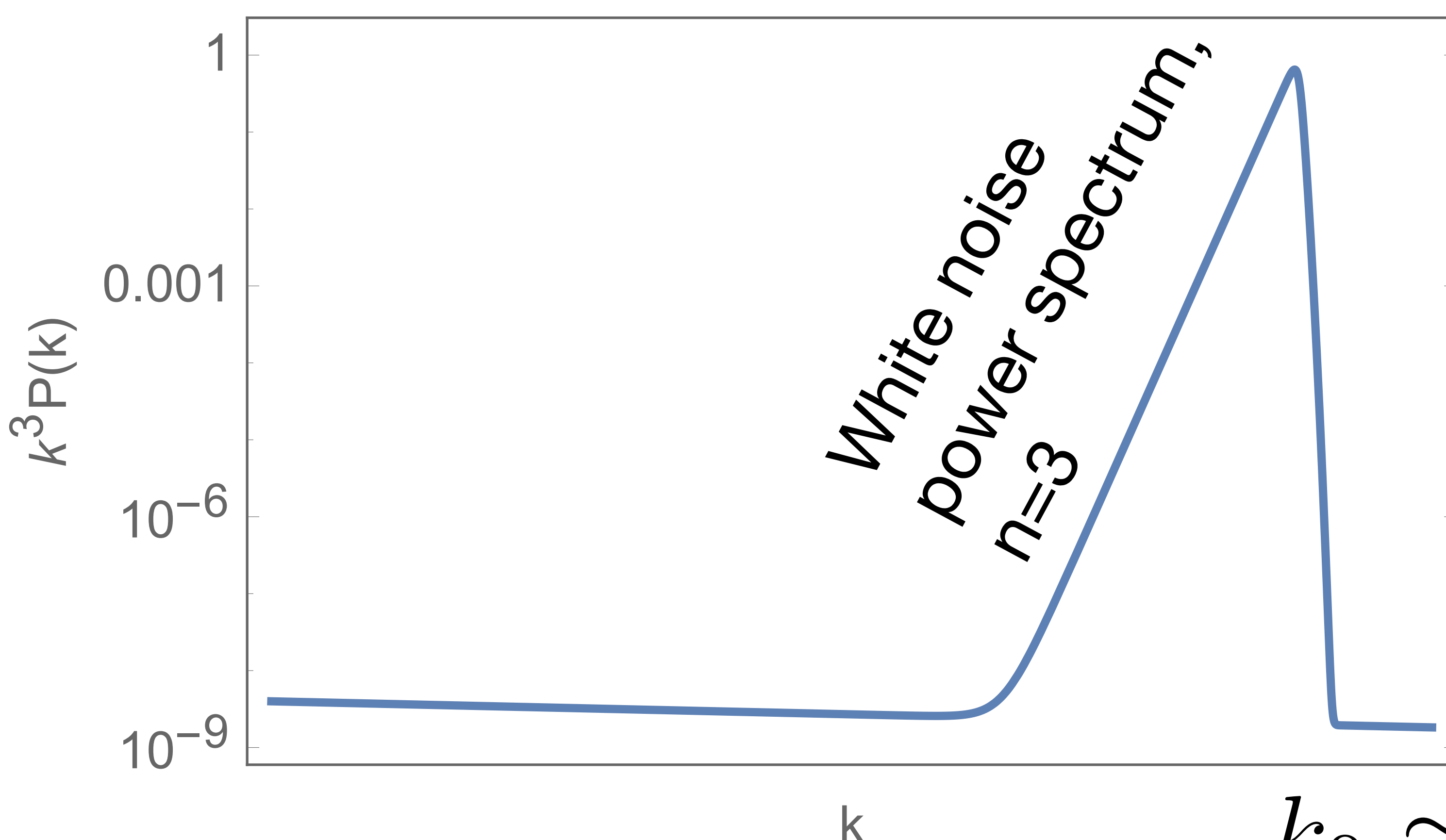




Axion minihalos

- PQ breaking after inflation
- Multiple causally disconnected patches
- Domain walls, strings, small scale power

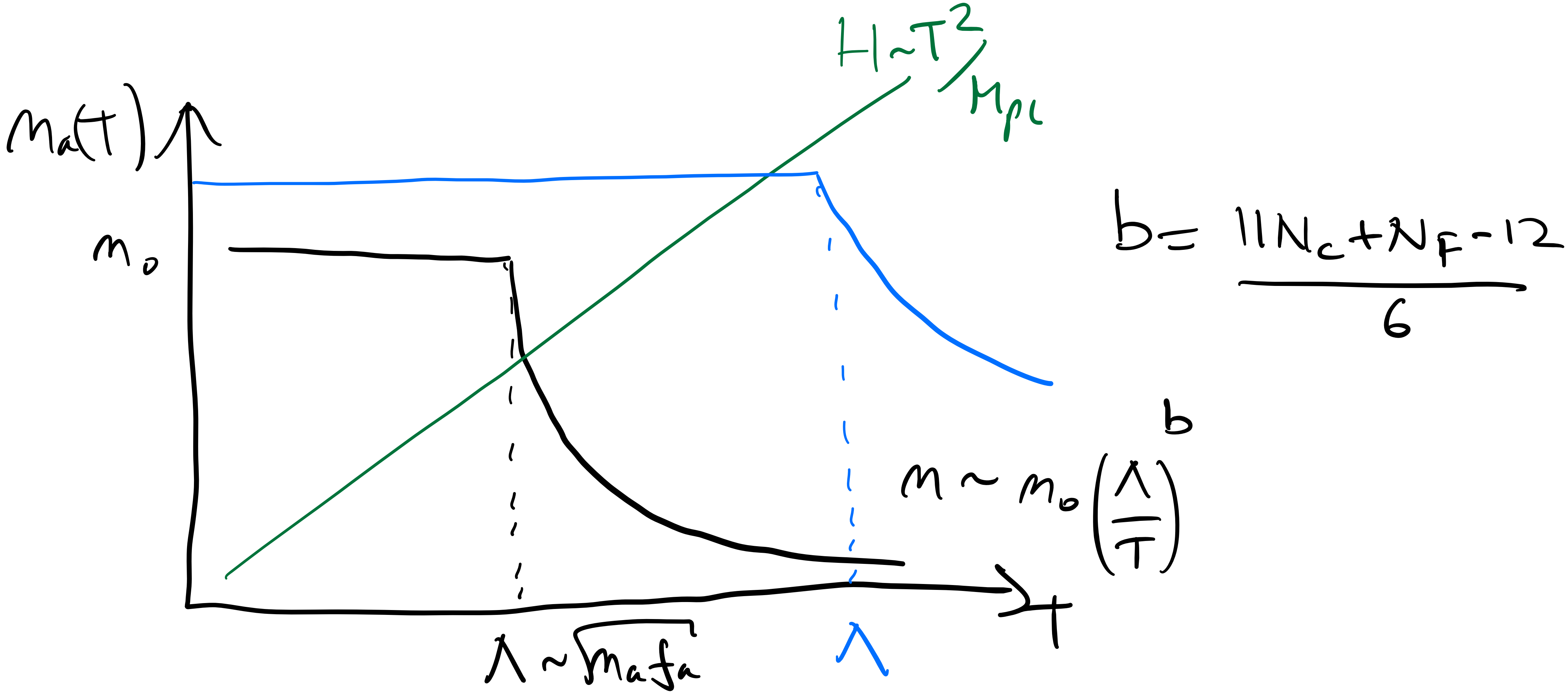
$$\langle\delta^2\rangle = \frac{2\pi^2}{k^3}\left(D_{adi}^2 I_1^2 L^2 A_s \left(\frac{k}{k_s}\right)^{n_s-1} + D_{iso}^2 A_0 \left(\frac{k}{k_0}\right)^{n} \Theta(k_0 - k)\right)$$



Horizon size
when axion
starts to oscillate

$$k_0 \approx a_{\rm osc} H_{\rm osc}$$

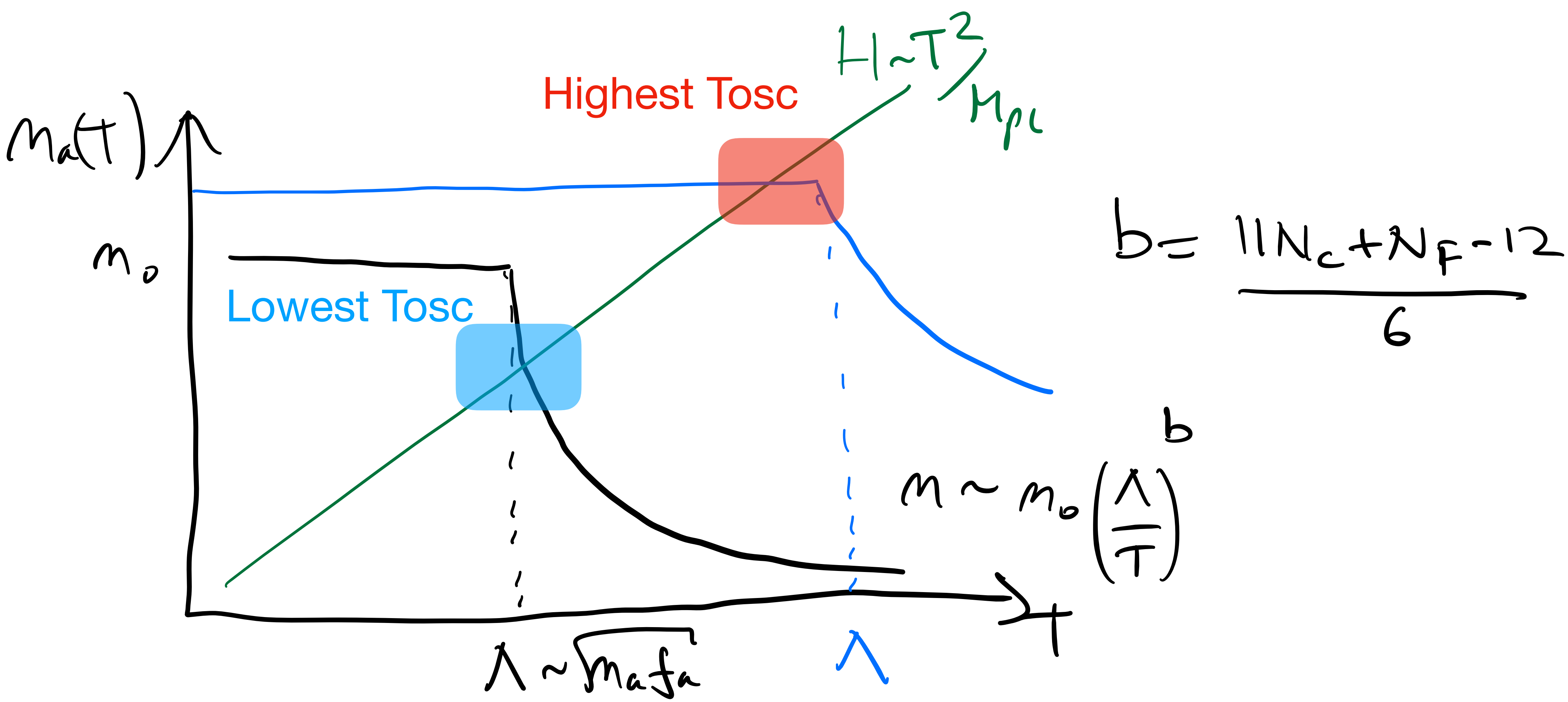
Oscillation temperature



Oscillation starts when $m_a(T) \sim (2+b)H$

$$M_h = \frac{4\pi}{3}\left(\frac{1}{a(T_{\rm osc})H(T_{\rm osc})}\right)^3 \bar{\rho}_0 \approx 2\times 10^8 M_\odot \left(\frac{\rm keV}{T_{\rm osc}}\right)^3$$

Oscillation temperature



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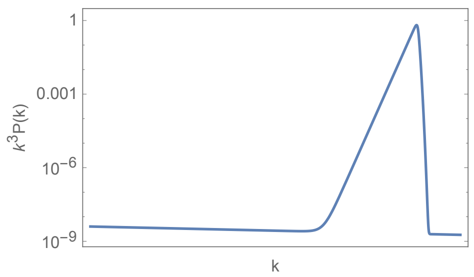
Axion minihalos



Press-Schechter to determine halo mass function

$$\frac{df}{dM} = \sqrt{\frac{2}{\pi}} \frac{\delta_c}{M\sigma} \left| \frac{d\log\sigma}{d\log M} \right| e^{-\delta_c^2/\sigma^2} \qquad \sigma^2(z,R) = \int \frac{d^3k}{(2\pi)^3} \langle \delta^2 \rangle \left| \widetilde{W}(kR) \right|^2$$

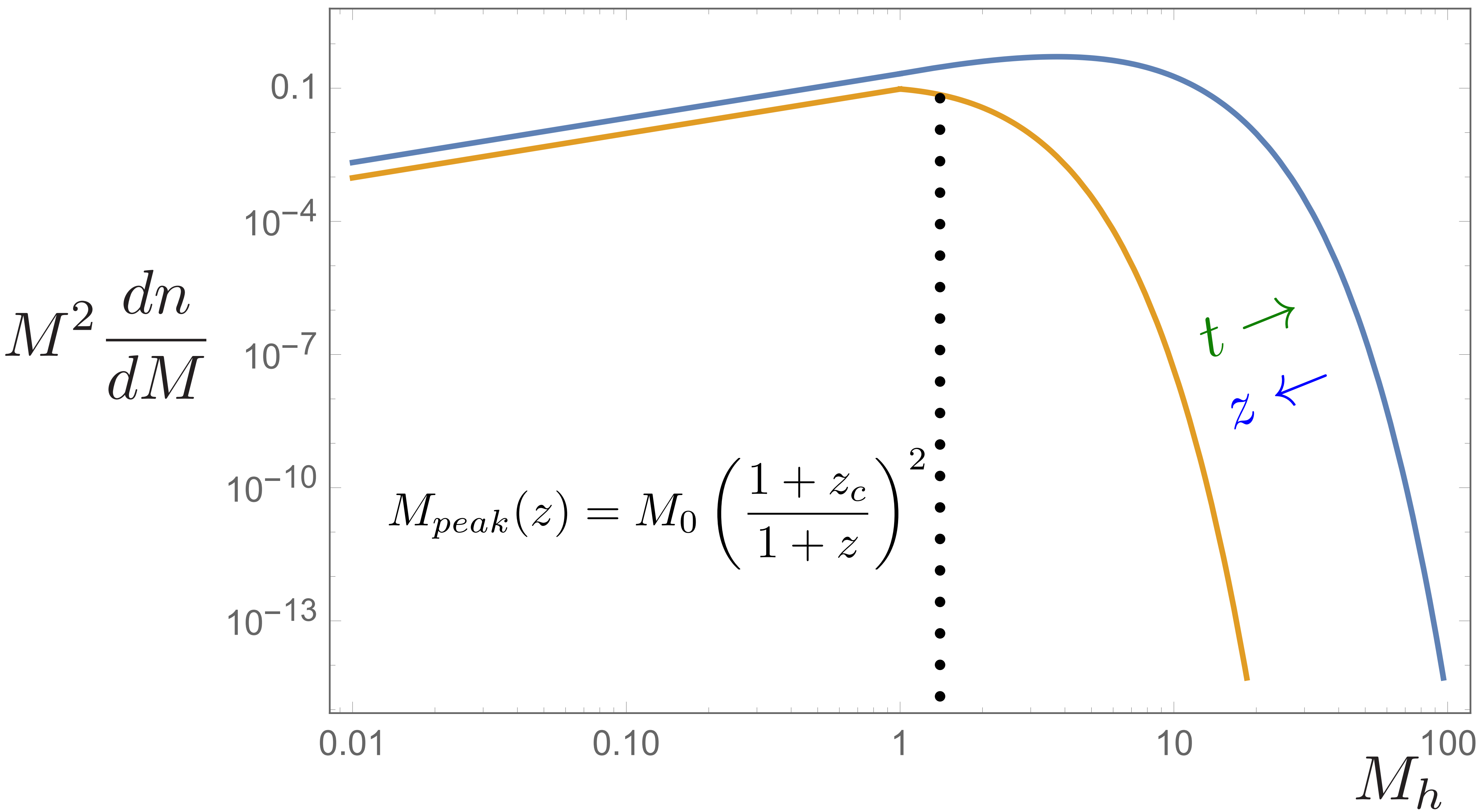
First halos form at $z_c \approx \sqrt{\frac{A_0}{n}} \frac{z_{\mathrm{eq}}}{\delta_c}$ With mass $M_0 \sim k_0^{-3}$

Then they grow with redshift squared, until z~20 when fall into large CDM halos

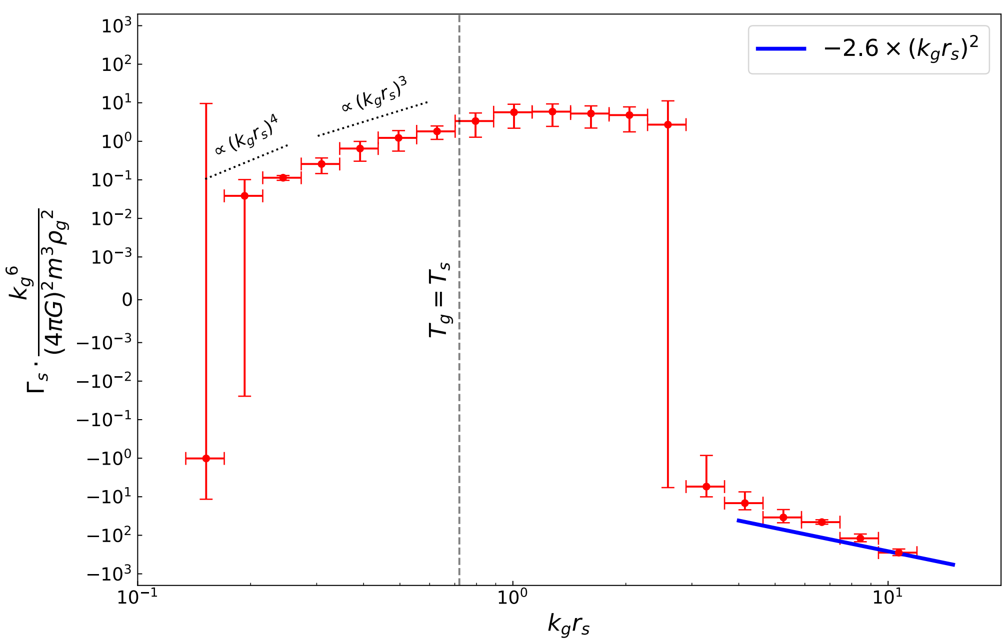
NFW halos, with concentration~4 when formed

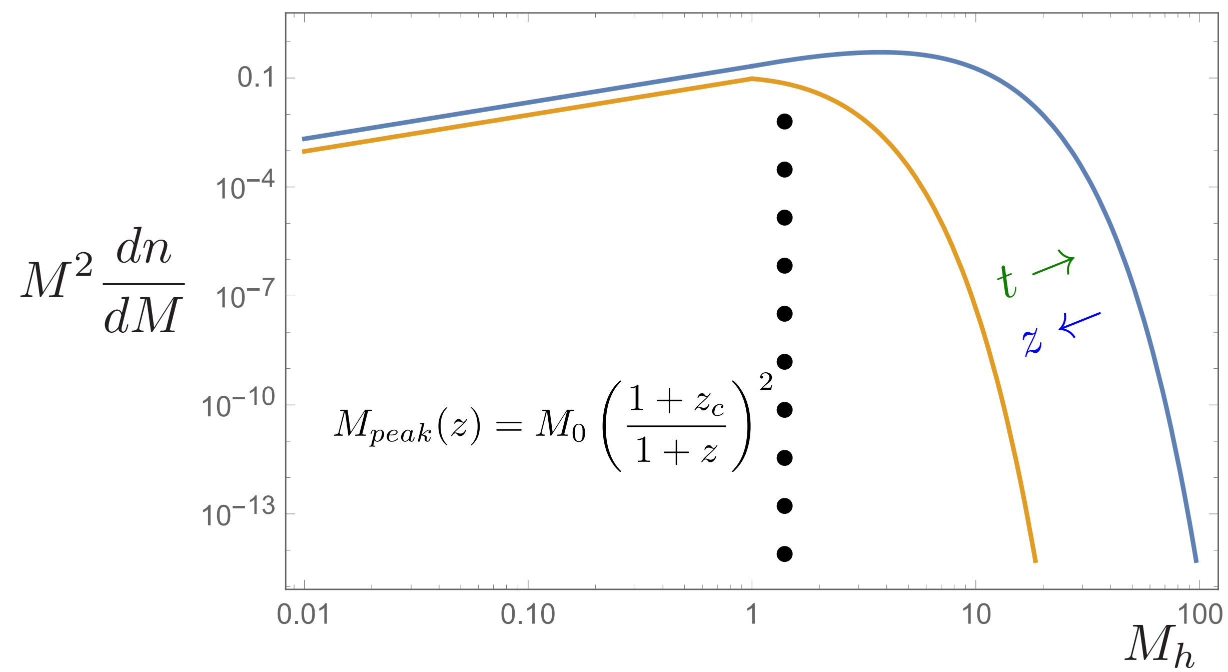
$$\rho(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

Axion minihalos

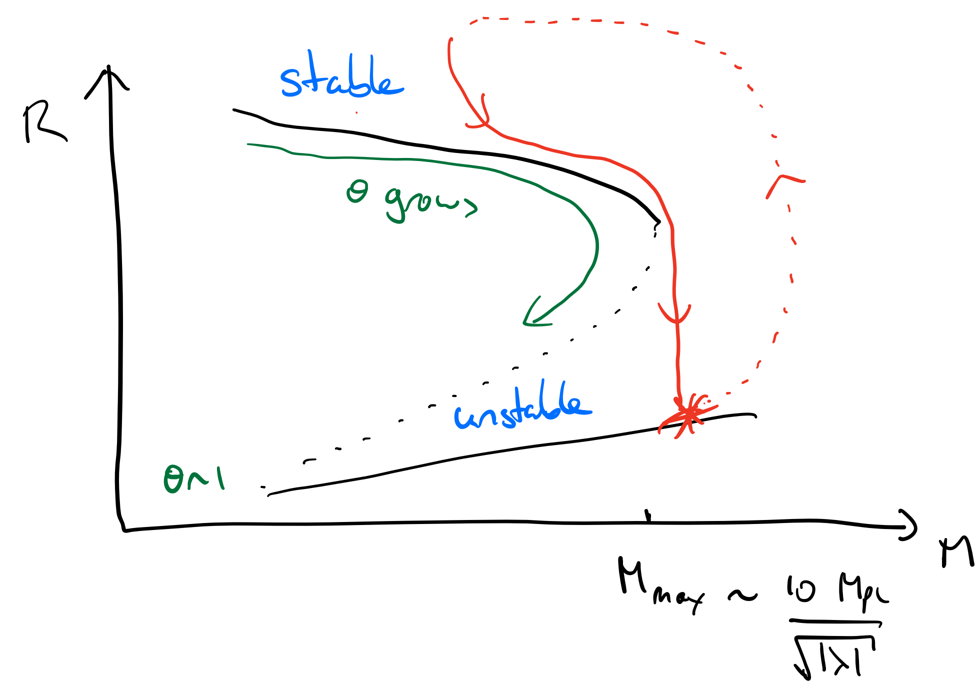


Put it all together



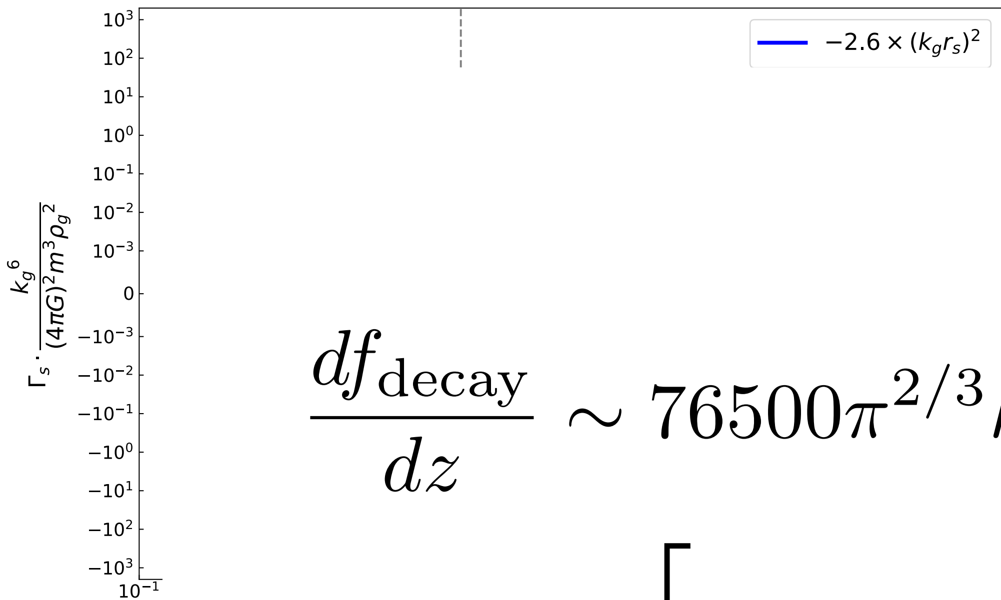


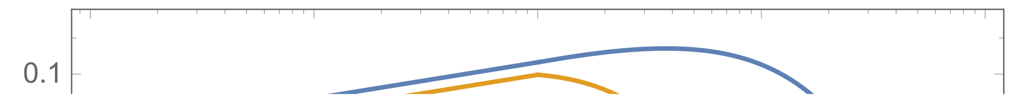
$$t_{\rm crit} = \tau \times \begin{cases} \log\left(\overline{M_*}/M_*^{\rm max}\right) + 1, & M_*^{\rm max} \le \overline{M_*} \\ \left(M_*^{\rm max}/\overline{M_*}\right)^{\alpha}, & M_*^{\rm max} > \overline{M_*} \end{cases}$$



$$\frac{df_{\rm decay}}{dt} = \frac{\kappa\, M_*^{\rm max}}{M_{\rm peak}(z)\, t_{\rm crit}}$$

Put it all together





$$
\frac{df_{\rm decay}}{dz} \sim 76500\pi^{2/3}\kappa \frac{M_{pl}^3\overline{\rho}_{\rm col}^2}{M_0 f_a^5 m_a^4}\left(\frac{1+z}{1+z_c}\right)^8 \frac{1}{(1+z)^{5/2}H_0}
$$

$$
\times\left[1+75\pi^{4/3}\left(\frac{f_a}{M_0^{1/3}\overline{\rho}_{\rm col}^{1/6}}\right)^4\left(\frac{1+z}{1+z_c}\right)^{2/3}\right]
$$

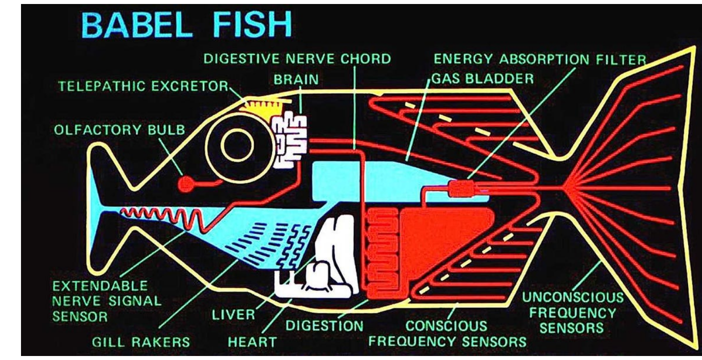
$$
\times\left(\frac{\overline{M_*}}{M_*^{\rm max}}\right)^{\alpha-2}\Theta\left(M_{peak}(z)-M_*^{\rm max}\right)\ ,
$$

$t_{\rm crit} =$

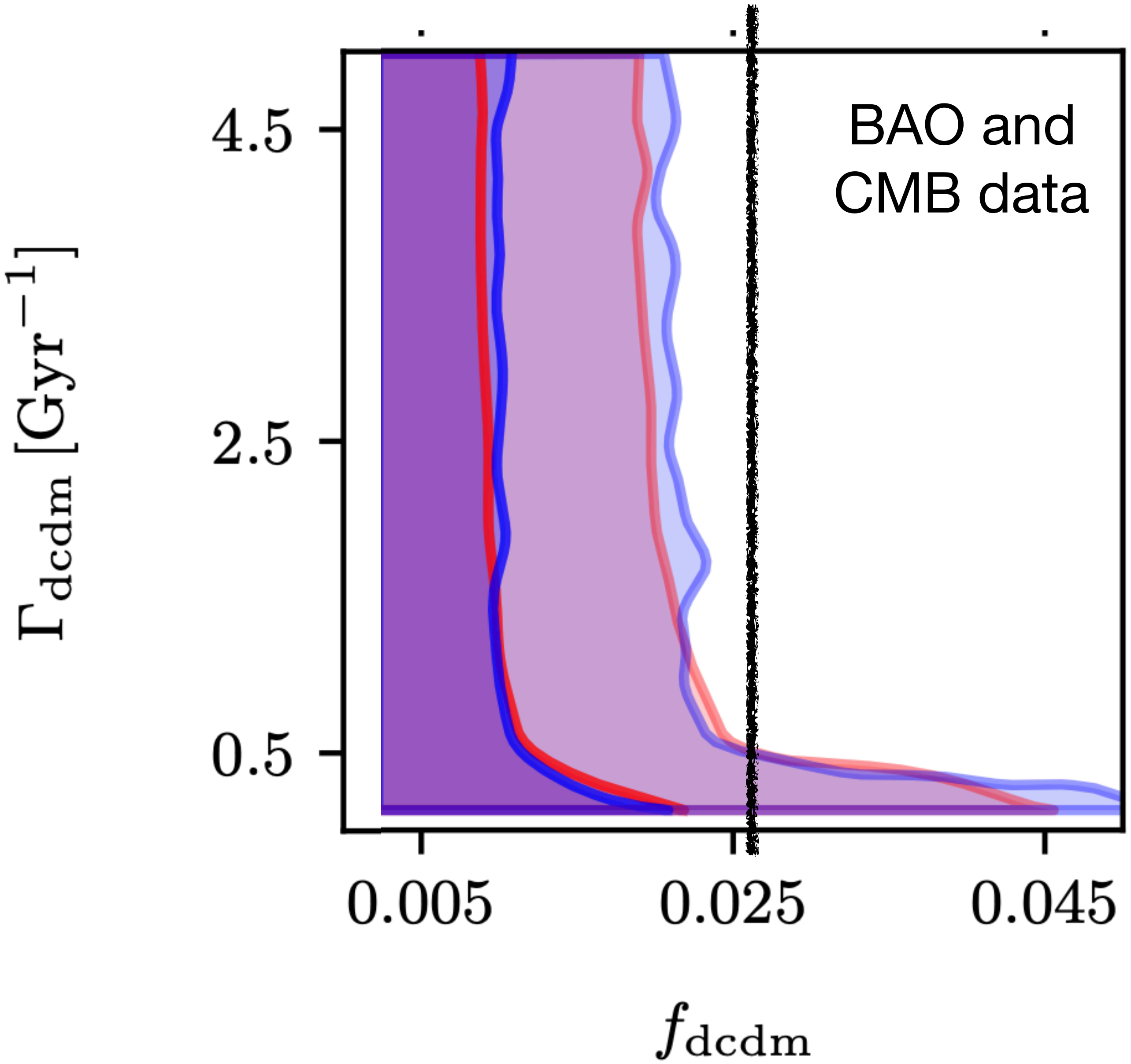
→ M

$$
\frac{df_{\rm decay}}{dt} = \frac{\kappa\, M_*^{\rm max}}{M_{\rm peak}(z)\, t_{\rm crit}}
$$

Decaying DM constraints



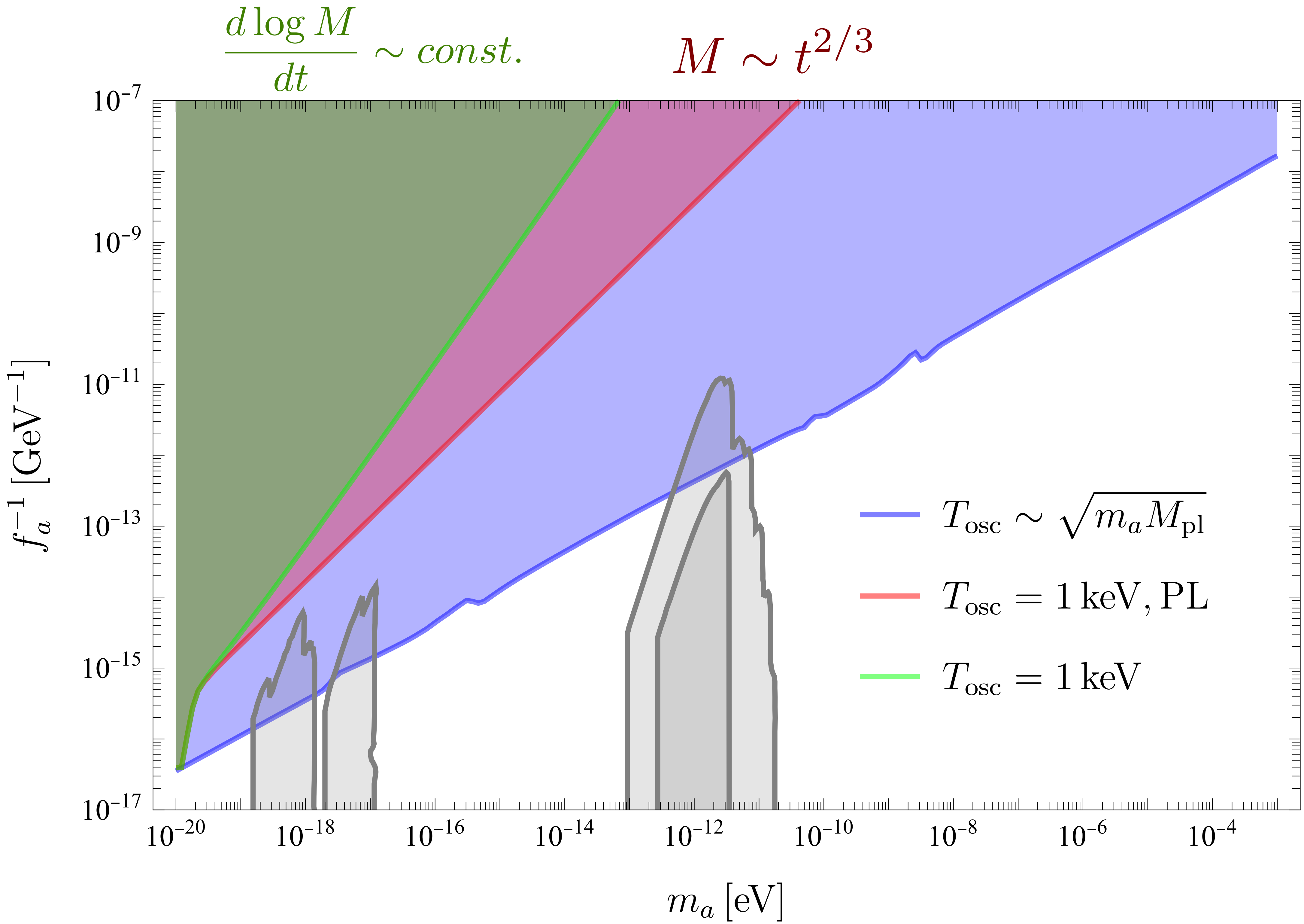
Nygaard, Tram, Hannestad (2011.01632)



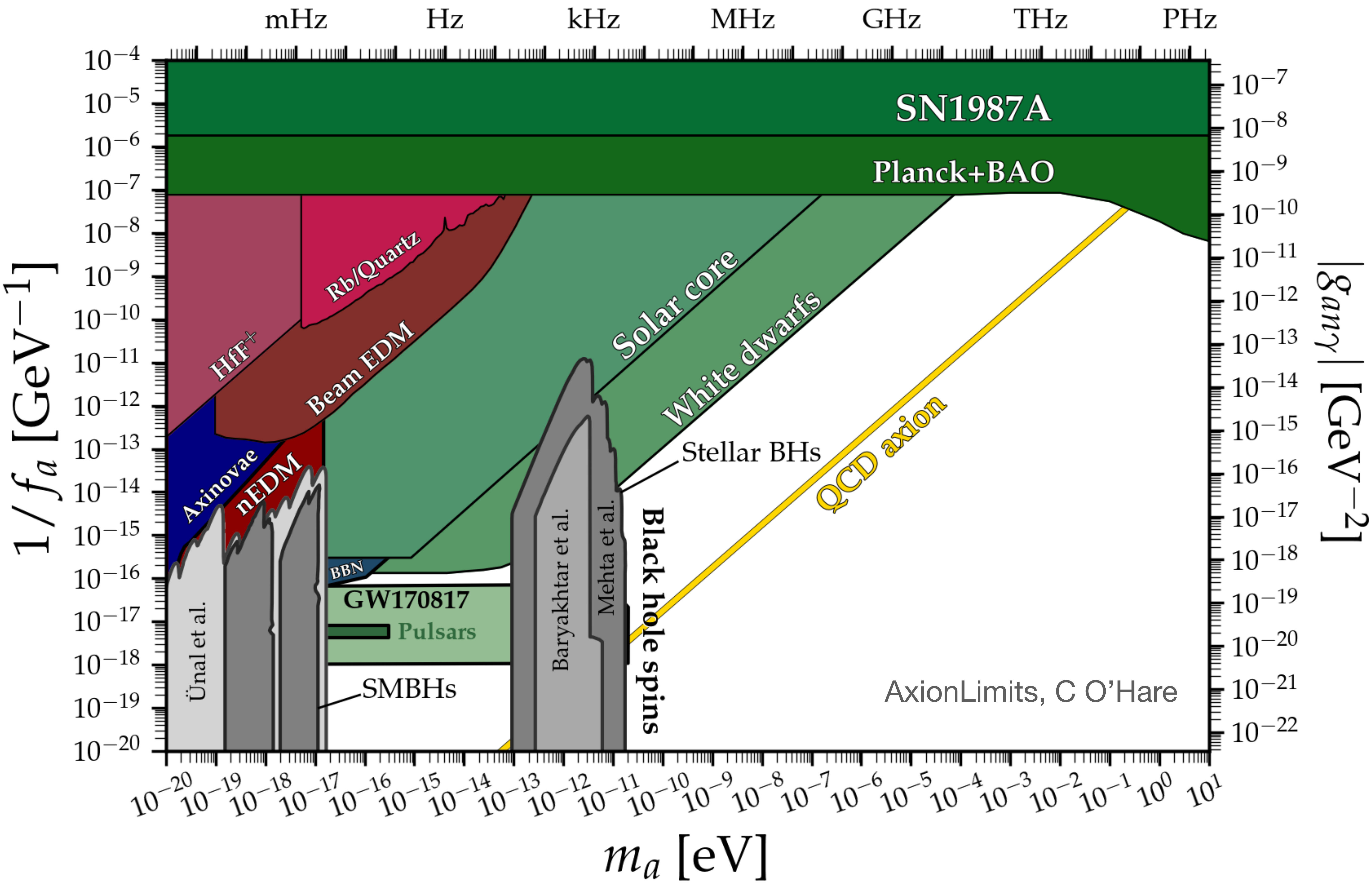
$$\int_{z_c}^{z=20} dz\,\frac{df_{\rm decay}}{dz} \leq 2.62\%$$

$$f_{dDM} \equiv \frac{\Omega_{dDM}}{\Omega_{dDM}+\Omega_{DM}} \leq 2.62\% \quad (\text{at } 2\sigma)$$

Recurrent Axinovae constraints



https://cajohare.github.io/AxionLimits/



Model Building

- Getting correct relic abundance requires delaying oscillation
    - Higher DS temperature
    - First order phase transition
    - Kinetic misalignment
    - Friendly axions
- Or increasing self coupling
    - Clockwork

R. T. Co, L. J. Hall, K. Harigaya, (1910.14152)

C.-F. Chang and Y. Cui (1911.11885)

D. Cyncynates, O. Simon, J. O. Thompson, Z. J. Weiner, arXiv:2208.05501

D. E. Kaplan and R. Rattazzi, arXiv:1511.01827

Conclusions

- Bosonic stars have stable configurations of (eg) axions supported by gradient pressure
- Can process large fraction of mass into k.e. which redshifts away
- Recurring process
- Only relies on gravity and self coupling
- Constrained by CMB observations
- Possible associated visible channels?