what happens when axion strings interact with the standard model plasma?

(Clue: *axions gain weight*)

Rajrupa Mondal (*in collaboration with* Anson Hook, Shourya Mukherjee) arXiv:2603.00237

1. Introduction to Axion Strings and Friction

2. Finding n_a : A Semi-Analytic Model with Simulation Inputs

3. Conclusion

giving birth to axions

UV

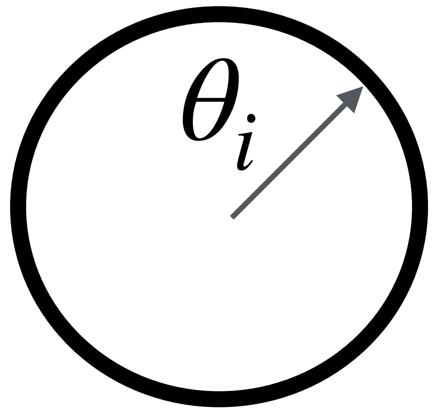
$$\mathcal{L}(\phi) = \frac{1}{2}|\partial_\mu \phi|^2 - \lambda(|\phi|^2 - f_a^2)^2$$ ← Anomalous $U(1)_{PQ}$

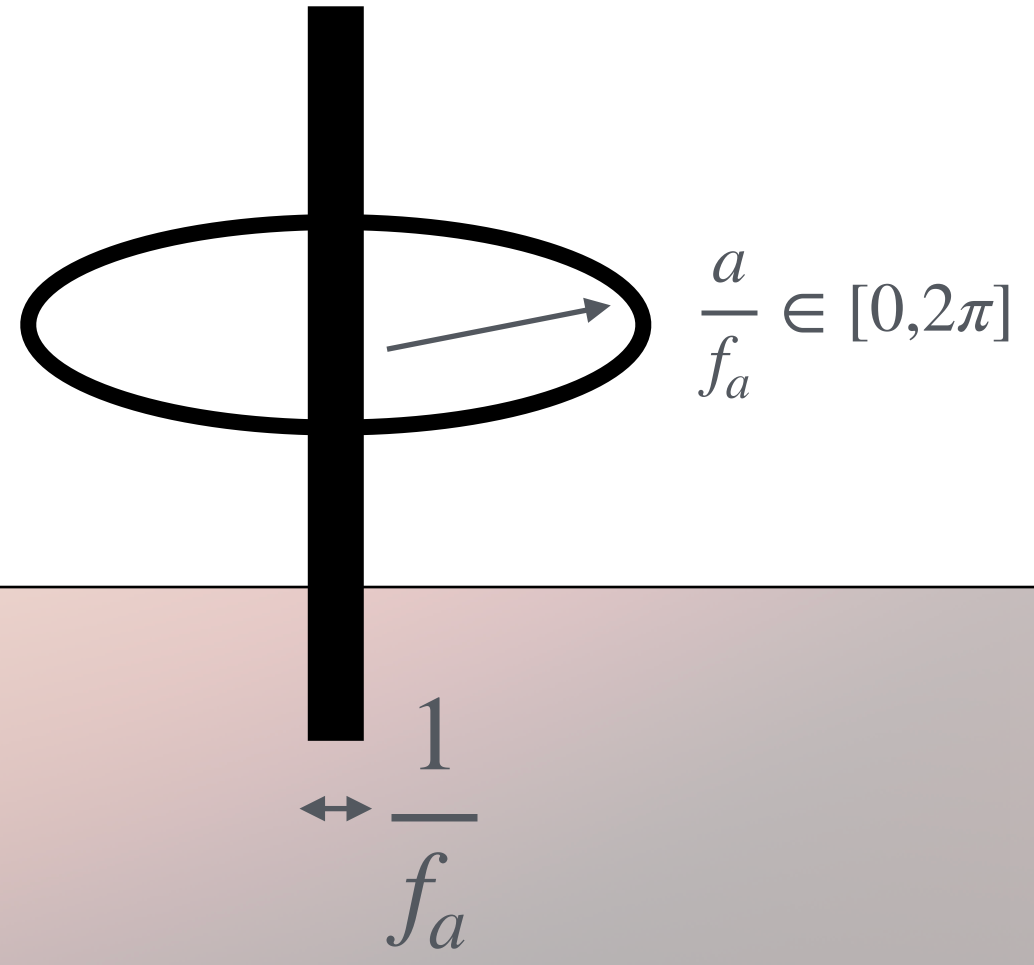
$$\phi = (f_a + r)e^{i\frac{a}{f_a}}$$

a: angular mode of ϕ

Symmetry breaking around f_a $\mathcal{O}(10^7 - 10^{12}\ \text{GeV})$

Misalignment Mechanism	**Topological Origin**
$U(1)_{PQ}$ symmetry breaking during inflation (or restoration during reheating)	$U(1)_{PQ}$ symmetry breaking after inflation





$$\mathcal{L}_{EFT} = \frac{1}{32\pi^2}\left(\theta + \frac{a}{f_a}\right)G\tilde{G}$$

IR

Cold dark matter

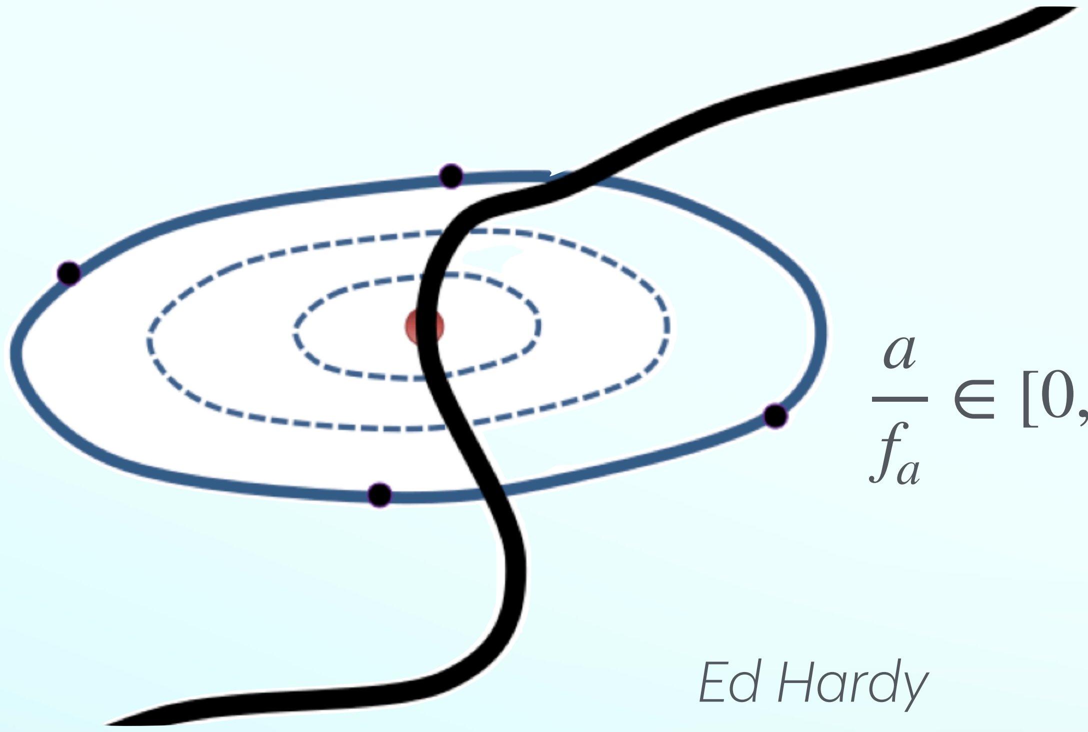
QCD phase transition $\mathcal{O}(\text{GeV})$

universe of (QCD) axion strings (and loops)

Symmetry breaking AFTER inflation

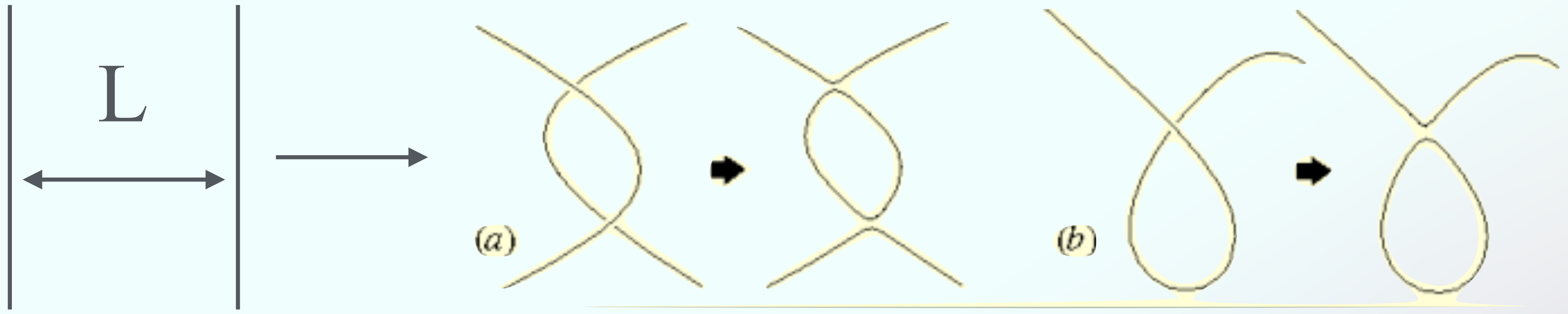
UV

$$\mathscr{L}(\phi) = \frac{1}{2}|\partial_\mu \phi|^2 - \lambda(|\phi|^2 - f_a^2)^2$$



$\frac{a}{f_a} \in [0,2\pi]$

Ed Hardy

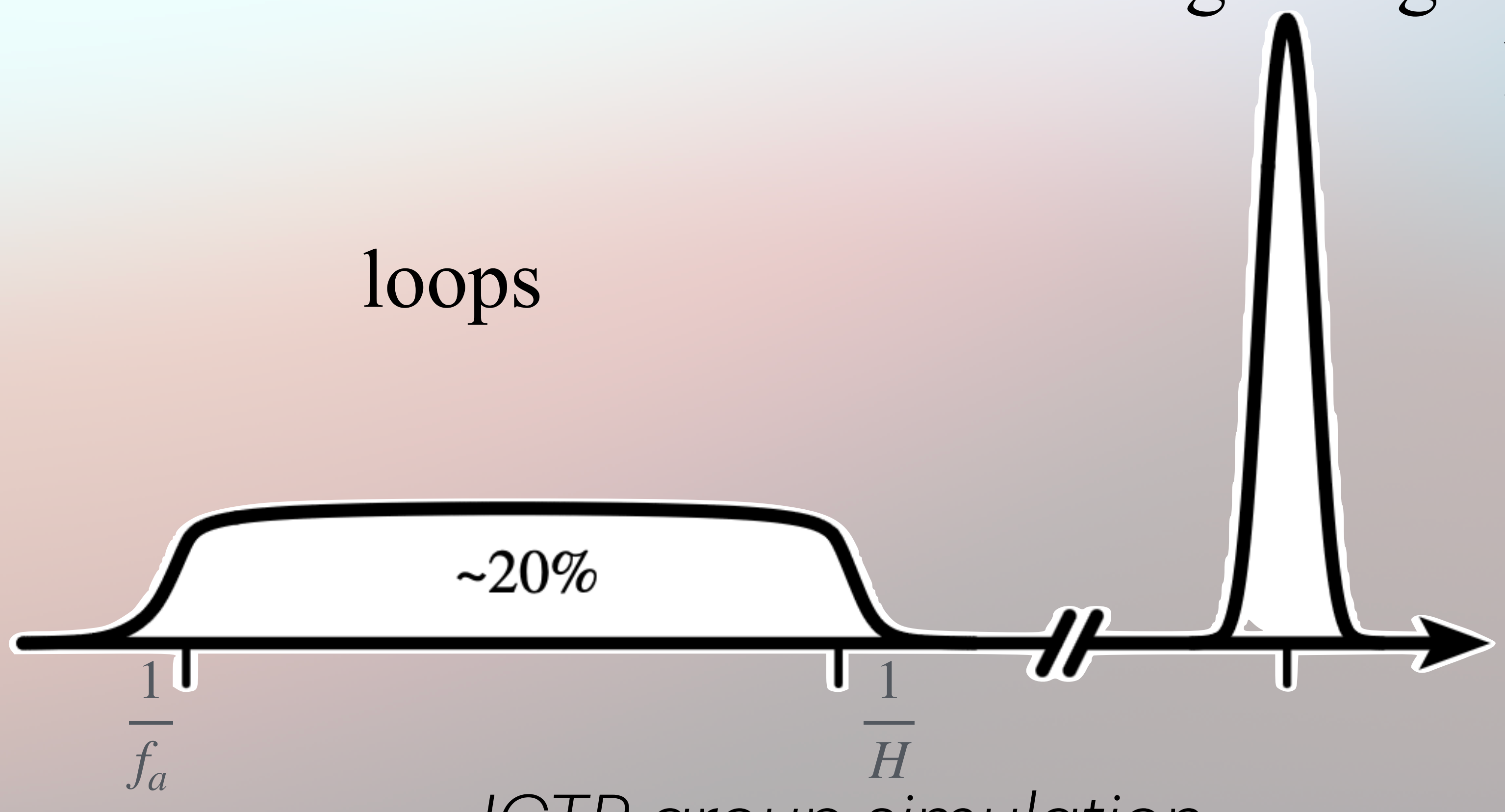


Stephen Hawking CTC

radiation (axions)

long strings (of correlation length 'L')

loops



ICTP group simulation

IR

QCD phase transition $\mathcal{O}(\text{GeV})$

Cold dark matter

why is friction (with SM particles) important?

number of strings per Hubble volume

Energy density $\rho_s(t) \equiv \dfrac{\xi(t)\ \mu}{t^2}$ ← $f_a^2 \ln \dfrac{f_a}{H}$

After formation, *intuitively*,

$$\xi(t) \equiv \left(\frac{t}{L}\right)^2 \propto t$$

From simulations,

$$\xi(t) = 0.2 \ln\left(\frac{f_a}{H}\right) \propto \ln t$$

Hence , intercommutation ($\propto \xi(t)$) is unexpected

Higher string tension μ ($\propto f_a^2$) slows down loop formation for higher f_a values.

Observed dark matter abundance for $f_a \sim 10^{12}$ GeV

why is friction (with SM particles) important?

number of strings per Hubble volume

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Higher string tension ($\propto f_a^2$) slows down loop formation for higher f_a values.

For lower f_a values, something similar to string tension is required, which decreases interaction

Friction does the job! DM relic abundance satisfied with $f_a \sim 10^8$ GeV

(leading) sources of friction

Spin 0

$$\mathcal{L}_{int} = -\lambda\delta^2(\vec{x})\phi^\dagger\phi$$

$$\frac{d\sigma}{dz} \approx \frac{\lambda^2}{8\pi q}$$

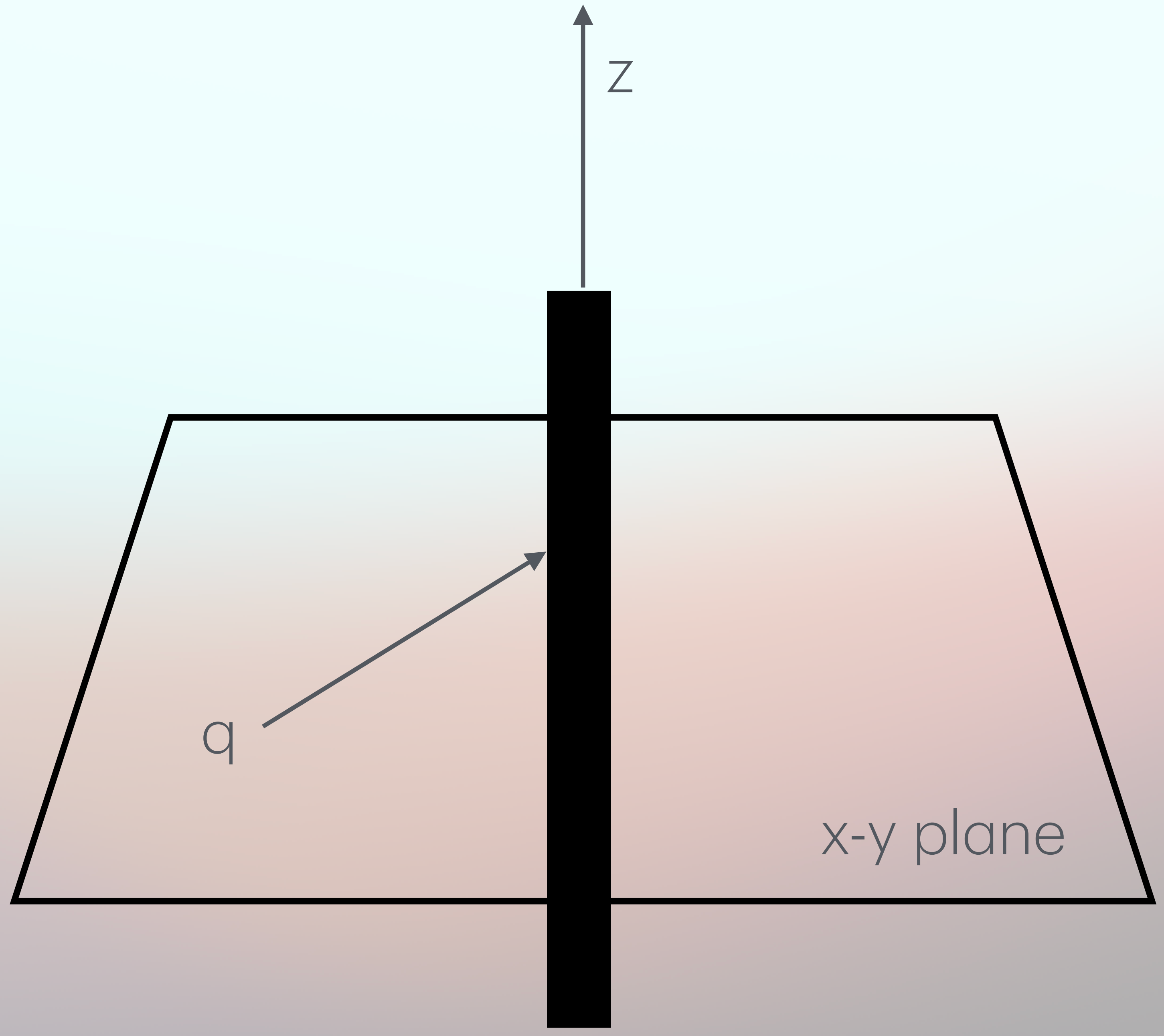
Everett, Vilenkin

Spin $\frac{1}{2}$

$$\mathcal{L}_{int} = c_{af}\frac{\partial_\mu a}{2f_a}\bar{\psi}\gamma^\mu\gamma_5\psi$$

$$\left(i\gamma^\mu\partial_\mu - \frac{\partial_\mu a\gamma^\mu\gamma_5}{2f_a}\right)\psi = 0$$

$$\frac{d\sigma}{dz} = \frac{2\sin^2(\frac{\pi c_{af}}{2})}{q}$$



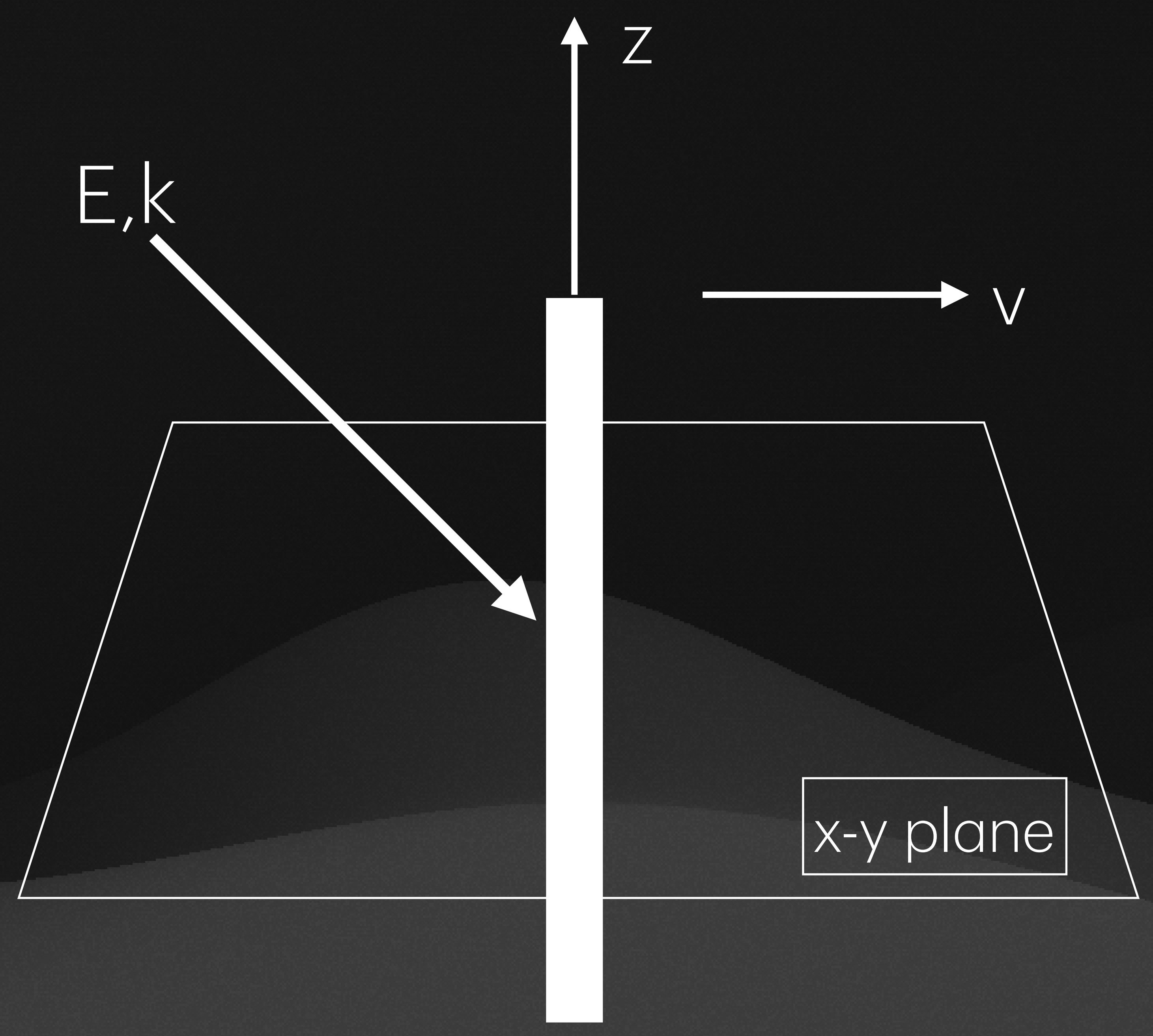
Spin 1

$$\mathcal{L}_{int} = \alpha_{EM}\delta^2(\vec{x})A_\mu A^\mu$$

$$\frac{d\sigma}{dz} \approx \frac{\alpha_{EM}^2}{q}$$

PA,Anson Hook,JH and GMT

calculating friction…



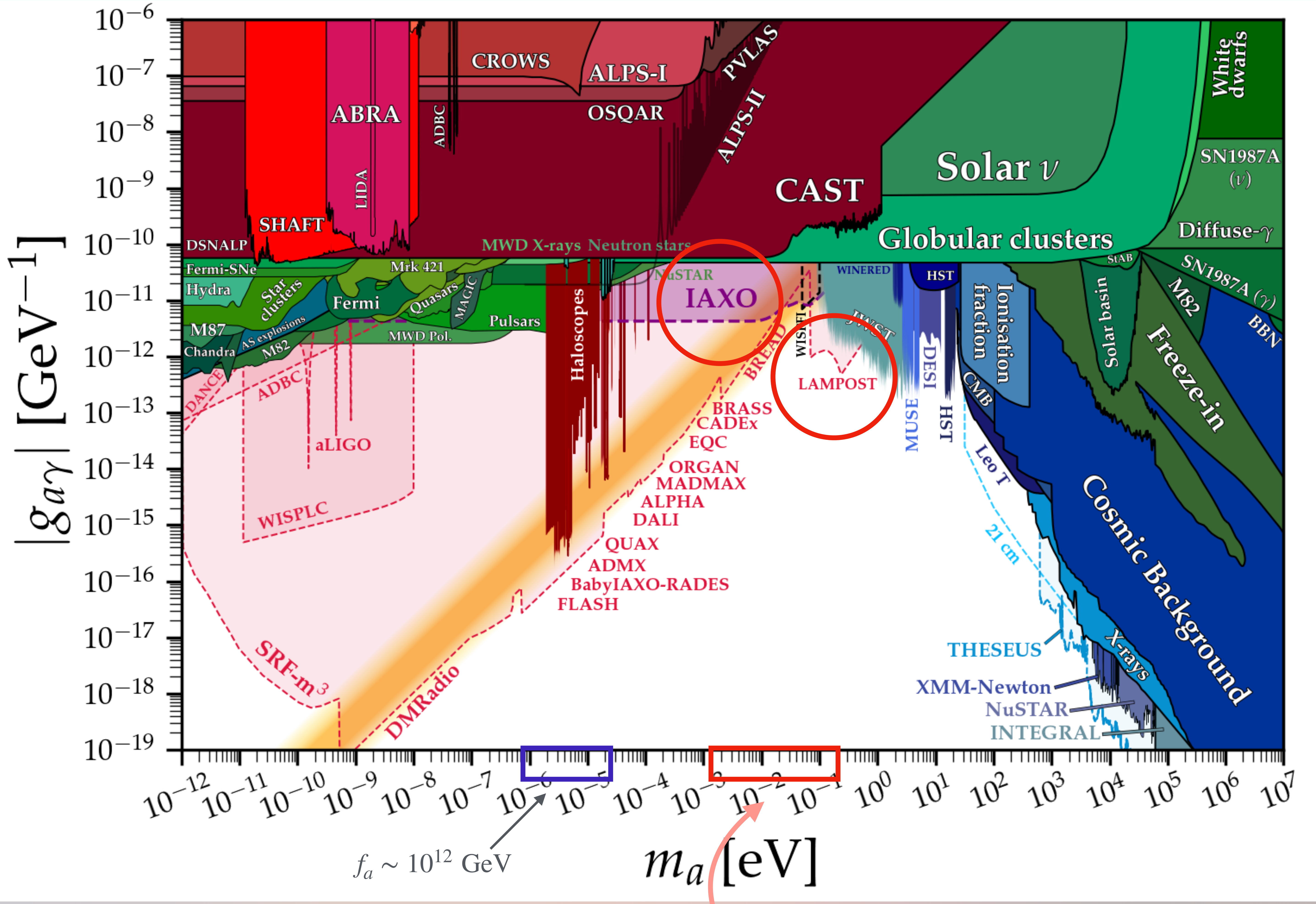
$$n_k = n\left(\frac{\gamma E + \gamma \vec{v}\cdot\vec{k}}{T}\right)$$

$$\frac{F}{l} = \text{Incident Flux} \times \frac{d\sigma}{d\theta\ dz} \times \text{momentum change}$$

$$= \int_0^\infty \frac{d^3k}{(2\pi)^3} n_k \frac{q}{|k|} \int_0^{2\pi} d\theta \frac{d\sigma}{d\theta\ dz} k(1-\cos\theta)$$

$$\frac{F}{l} = \begin{cases} -\frac{\lambda^2\zeta(3)}{2\pi^2} v\gamma T^3 & \text{(scalar)} \\ -\beta_{AB} v\gamma T^3 \quad \left[\beta_{AB} = \frac{3}{2\pi^2}\zeta(3)\sin^2\left(\frac{\pi c_{af}}{2}\right)\right] & \text{(fermion)} \\ -2\alpha_{EM}^2 v\gamma T^3 & \text{(photon)} \end{cases}$$

experimental motivation

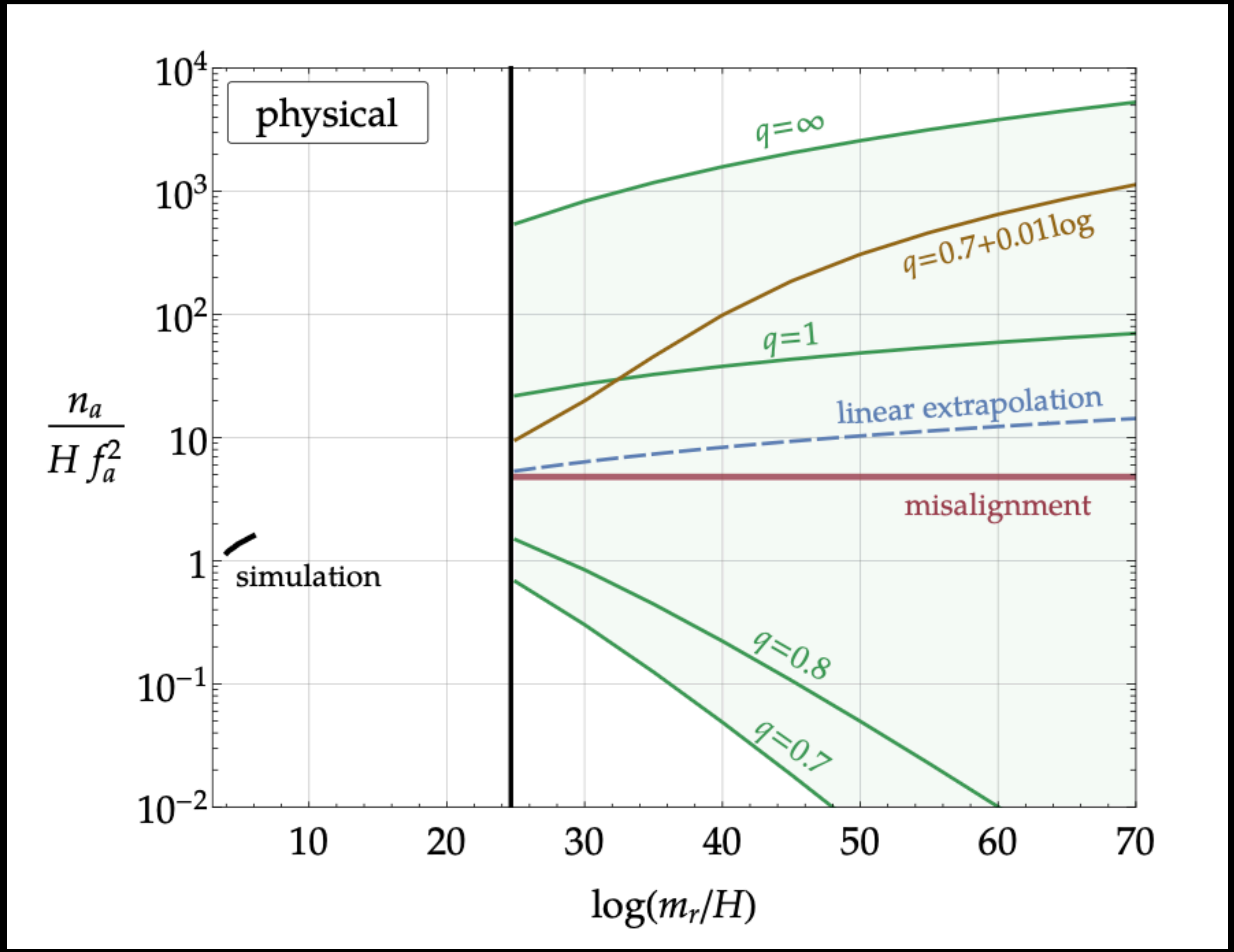


cajohare.github.io/AxionLimits/

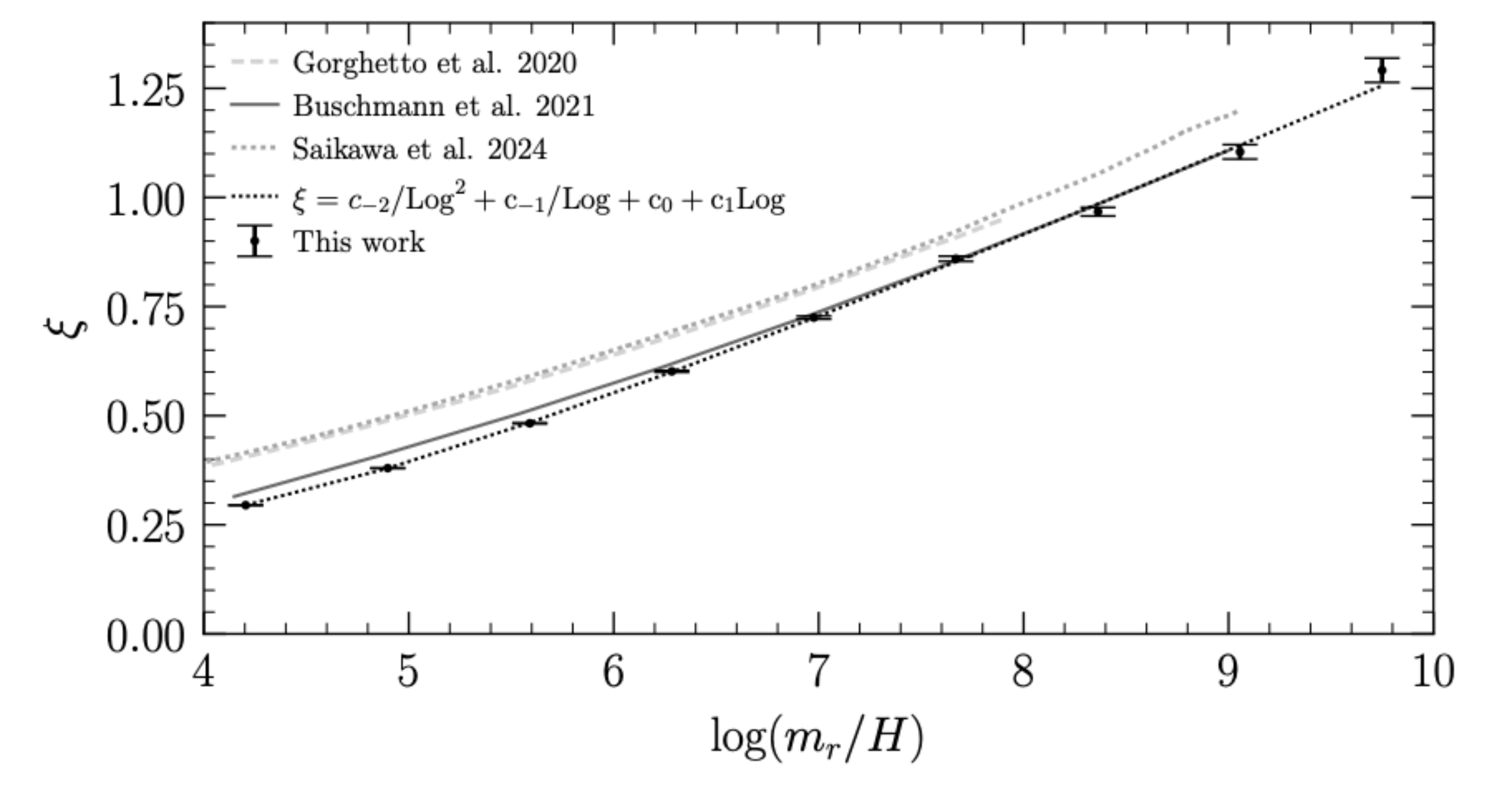
$$10^7 \text{ GeV} \leq f_a \leq 10^9 \text{ GeV}$$

but numerics is HARD!

(Previous Work)



ICTP group



Berkeley group

the Velocity One Scale (VOS) model

$$2\frac{dL}{dt} = 2HL(1+v^2) + cv + \frac{Lv^2}{\ell_f}$$

$$\frac{dv}{dt} = (1-v^2)\left[\frac{k}{L} - v\left(2H + \frac{1}{\ell_f}\right)\right]$$

$$\ell_f = \frac{\mu}{\beta T^3}$$

$$\theta = \frac{\beta}{\sqrt{f}}\left(\frac{t_c}{t_{Pl}}\right)^{\frac{1}{2}}$$

c: loop chopping efficiency

k: momentum parameter

c = k = 1

time

Stretching

$$t_c \propto \frac{1}{f_a^2}$$

$$L \propto t^{\frac{1}{2}}$$

$$v = \frac{\ell_f}{L}$$

Kibble (friction)

$$t_K \propto t_c^{\frac{4}{3}}$$

$$L = \sqrt{\frac{3}{2\theta(1+c)}}\frac{t^{\frac{5}{4}}}{t_c^{\frac{1}{2}}}\sqrt{\ln N}$$

$$v = \sqrt{\frac{2(1+c)}{3\theta}}\left(\frac{t}{t_c}\right)^{\frac{1}{4}}\sqrt{\ln N}$$

Scaling

$$t_* : 2H = \ell_f^{-1}$$

$$L = \sqrt{k(k+c)}\,t$$

$$v = \sqrt{\frac{k}{k+c}}$$

importance of friction

without friction

time

$t_c \propto \frac{1}{f_a^2}$

$t_K \propto t_c^{\frac{4}{3}}$

$t_* : 2H = \ell_f^{-1}$

$$t_* = \frac{\beta^2}{f \ln^2 N} t_c^2 M_{Pl}$$

QCD PHASE TRANSITION

with friction

time

$t_c \propto \frac{1}{f_a^2}$

$t_K \propto t_c^{\frac{4}{3}}$

kibble regime extends till

oscillations start for

$10^7 \text{ GeV} \leq f_a \leq 2 \times 10^9 \text{ GeV}$

QCD PHASE TRANSITION

$t_* : 2H = \ell_f^{-1}$

calculating number density

$$n(t_0) = \int_{t_K}^{t_0} d\tilde{t} \left(\frac{dn}{d\tilde{t}}\right) \left[\frac{a(\tilde{t})}{a(t_0)}\right]^3$$

Inputs :

Rescale ρ_s :

$$\rho_s(t) = \frac{\frac{4}{5}\rho_{\rm num}^{\rm scaling}(t)}{\rho_{\rm VOS}^{\rm scaling}(t)} \; \rho_{\rm VOS}^{K}(t)$$

method: log-uniform distribution

Set the length scale:

$$\ell_{\rm crit}(t) = \min\{\alpha\ \ell_f(t), \frac{\beta}{x_{IR}} L(t)\}$$

simulation input

$$k_{\rm min}(t) = \max\{(\alpha\ \ell_f(t))^{-1}, (\frac{\beta}{x_{IR}} L(t))^{-1}\}$$

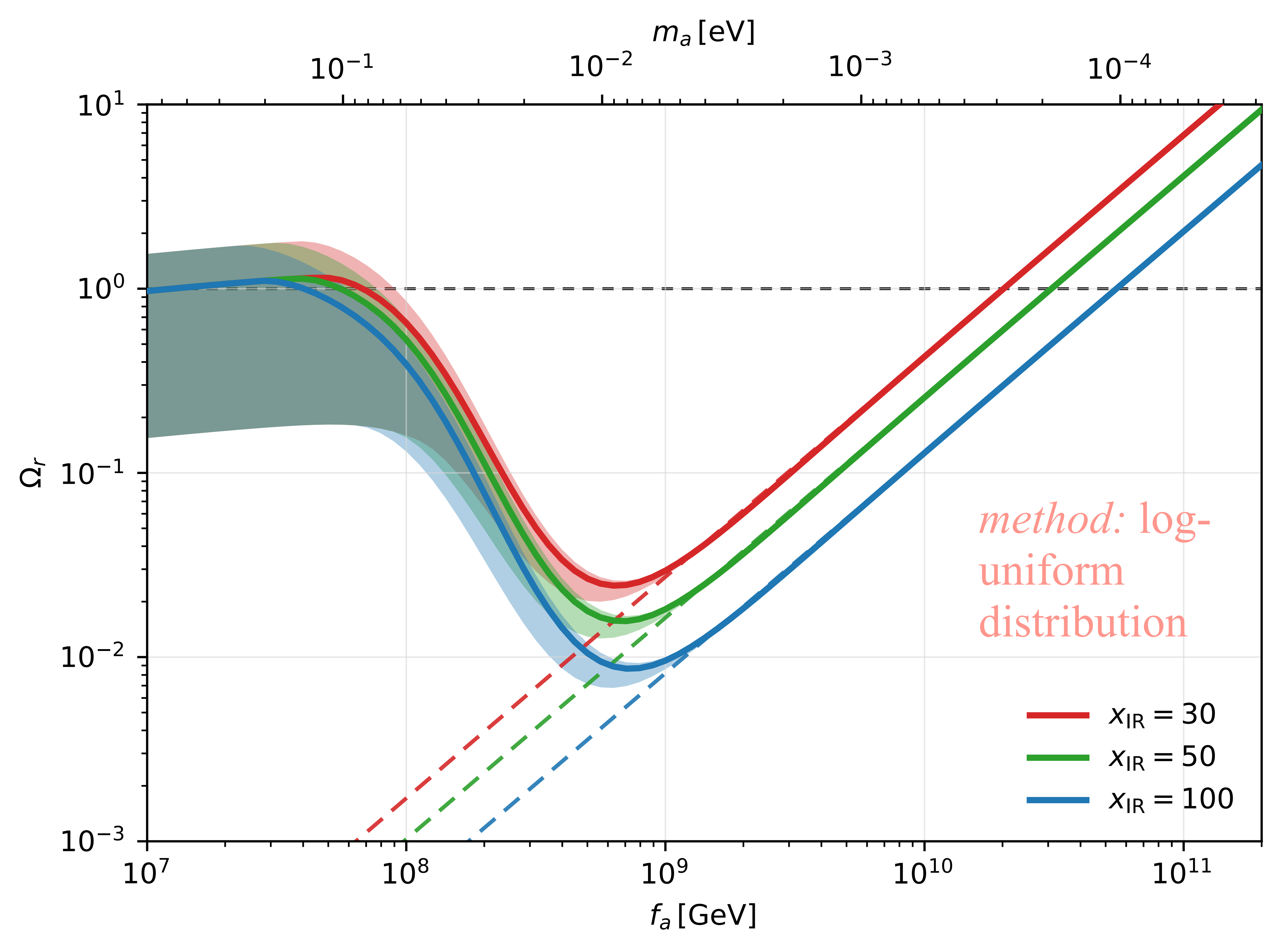
method: varying emission spectrum

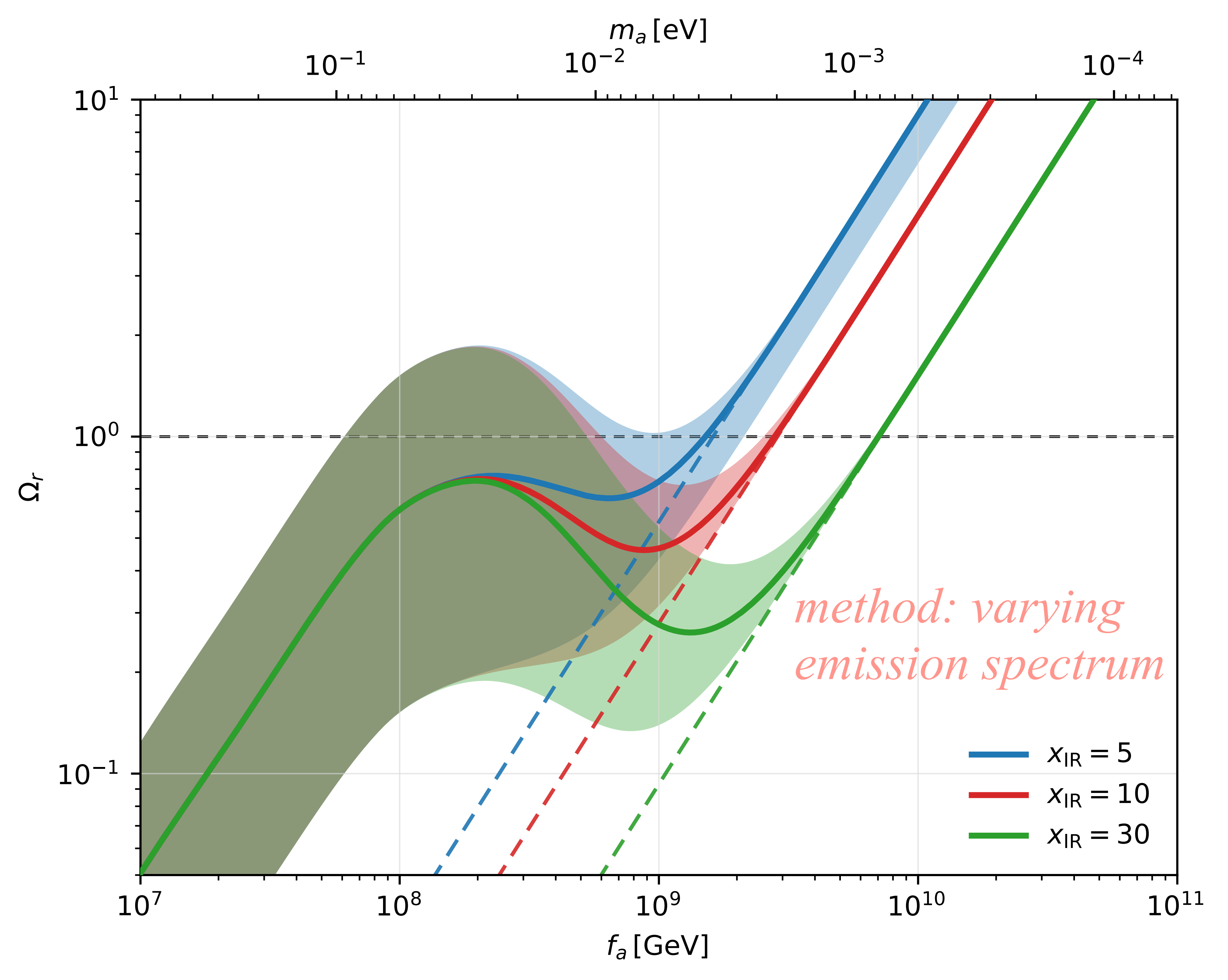
calculating number density

$$\Omega_r(t_{today}) = \frac{n(t_{today})}{n_{\rm DM}^{\rm req}(t_{today})}$$

$$n(t_0) = 0.2\frac{\Gamma_a f_a^2}{2\pi}\frac{1}{t_0^{3/2}}\int_{t_K}^{t_0} d\tilde{t}\,\frac{\xi^{3/2}(\tilde{t})}{\tilde{t}^{3/2}} l_{\rm crit}(\tilde{t})$$

$$n_a(t_0) = \int_{t_K}^{t_0} d\tilde{t}\,\left[\frac{a(\tilde{t})}{a(t_0)}\right]^3 \int_{max[\frac{1}{HL},\frac{1}{H\ell_f}]}^{f_a} d\left(\frac{k}{H}\right)\frac{1}{k}\frac{d\dot{\rho}_a}{d\ln k}$$





Non-Linear Effects

t_0 → t_l

$H = m_a$

$\rho(t_0) \gg m_a^2(t_0) f_a^2$

(even for soft modes)

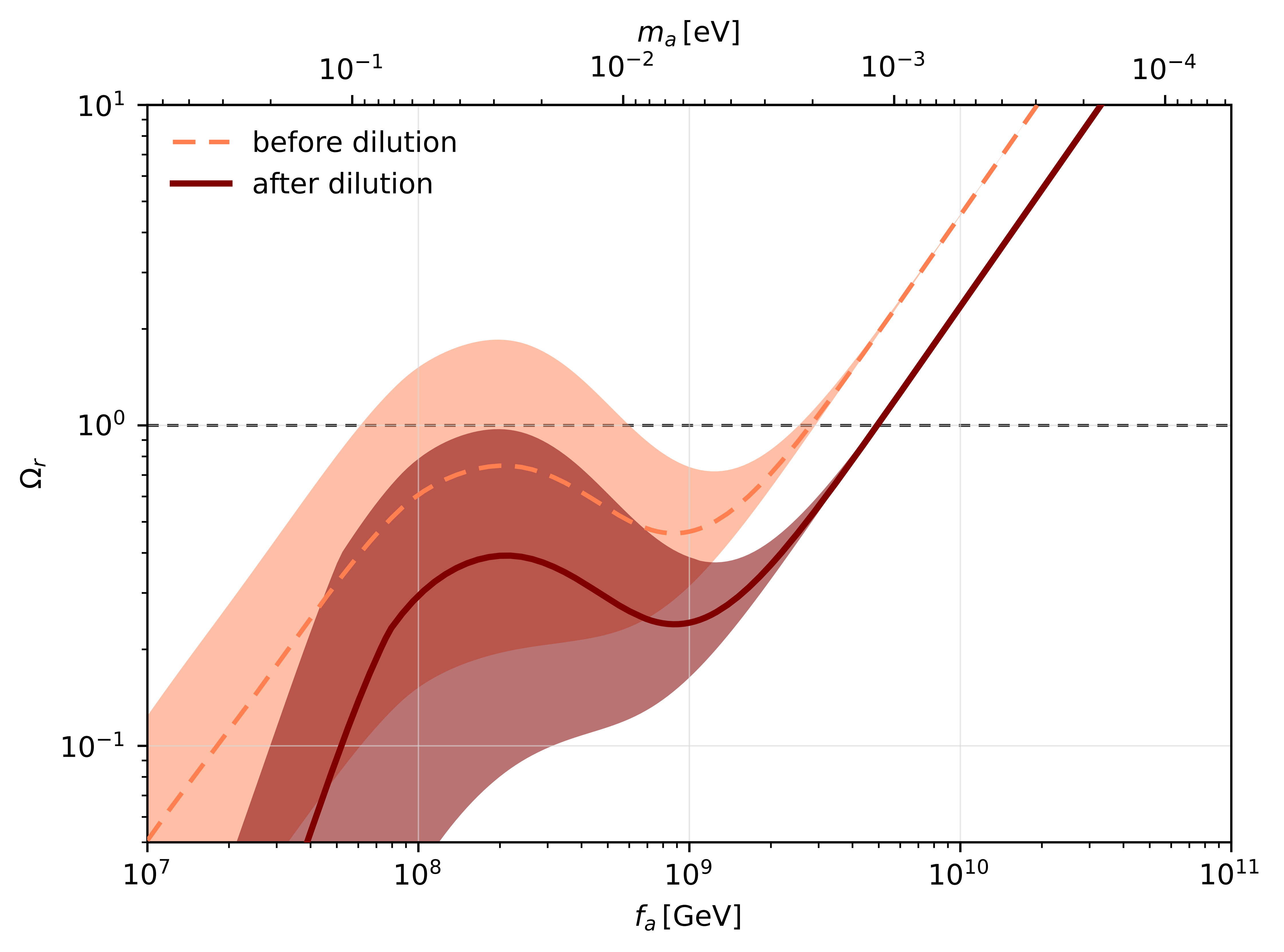
$$\frac{\partial \rho_a}{\partial k}(t,k) = \left[\frac{a(t_{\rm osc})}{a(t)}\right]^3 \frac{\partial \rho_a}{\partial k}\left(t_{\rm osc}, k_{\rm osc}\right)$$

$$m_a(t) \approx m_a(t_0)\left(\frac{t}{t_0}\right)^2$$

$\rho_{\rm IR}(t_l) \simeq \; m_a^2(t_l) f_a^2$

$$\Omega_r \equiv \frac{\rho_a}{\rho_{\rm DM}} = \frac{m_a^0\, n_a(t_\ell)}{\rho_{c,0}\,\Omega_c} \left[\frac{a(t_\ell)}{a_0}\right]^3$$

dilution (varying emission spectrum)

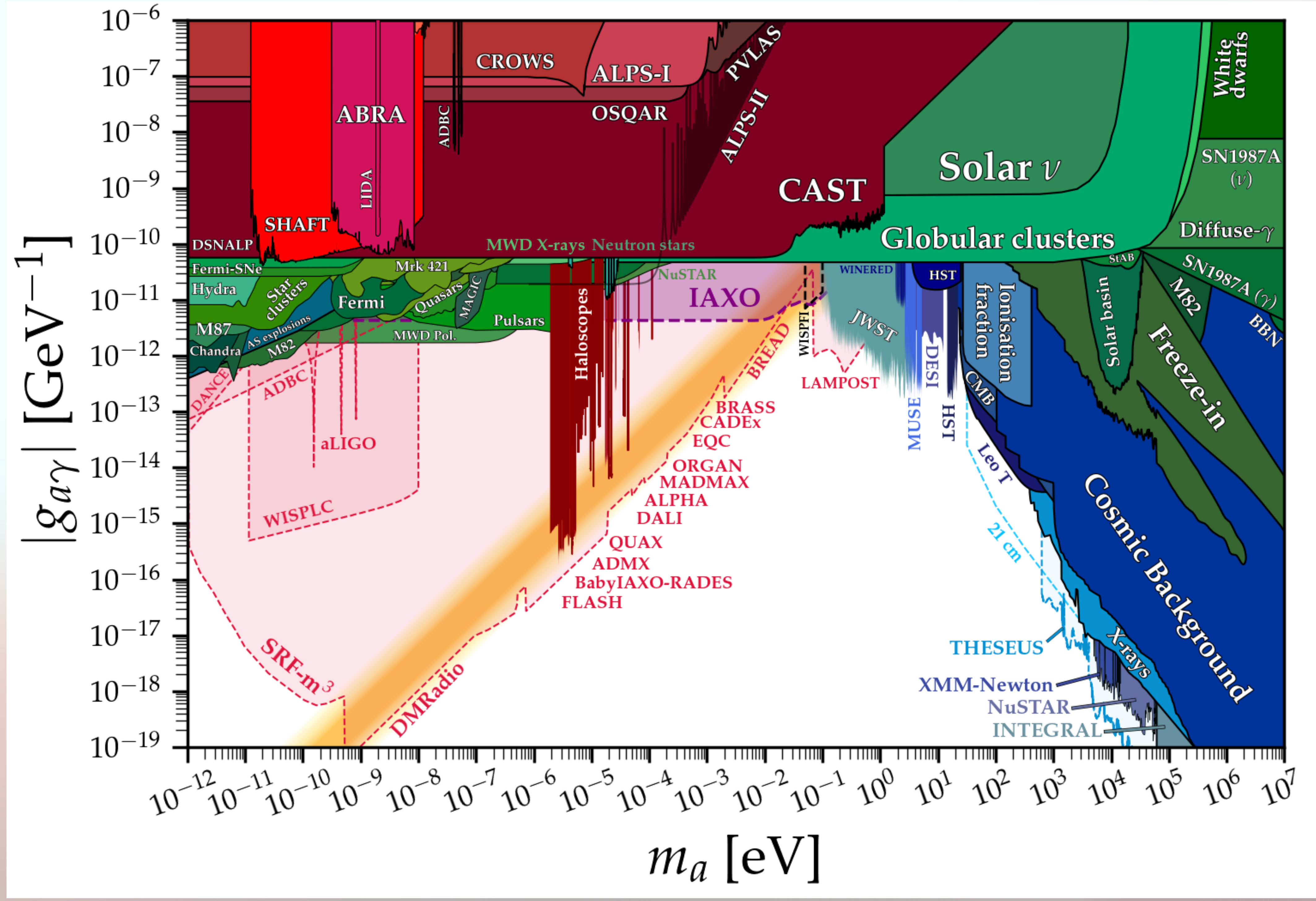


in conclusion

what happens when axion strings interact with the standard model plasma?

$$\text{meV} \le m_a \le 0.1\text{eV}$$

in addition to $m_a \sim \mu\text{eV}$



arXiv:2603.00237

calculating number density

$$n(t_0) = \int_{t_K}^{t_0} d\tilde{t} \left(\frac{dn}{d\tilde{t}}\right) \left[\frac{a(\tilde{t})}{a(t_0)}\right]^3$$

$$\frac{dn(\tilde{t})}{d\tilde{t}} = \int_0^{\ell_{\rm crit}(\tilde{t})} d\ell \, \frac{dn_\ell(\tilde{t})}{d\ell} \frac{dN_a}{d\tilde{t}}\Bigg|_\ell$$

$$\frac{dN_a}{dt} = \frac{\frac{dE_a}{dt}}{k} = \Gamma_a f_a^2 \ell$$

$\mathcal{O}(10^2)$

We integrate between all acceptable loop sizes

$$n(t_0) = 0.2 \frac{\Gamma_a f_a^2}{2\pi} \frac{1}{t_0^{3/2}} \int_{t_K}^{t_0} d\tilde{t} \, \frac{\xi^{3/2}(\tilde{t})}{\tilde{t}^{3/2}} l_{\rm crit}(\tilde{t})$$

method:
log-uniform
distribution

calculating number density (again)

$$n_a(t_0) = \int_{t_K}^{t_0} d\tilde{t} \left[\frac{a(\tilde{t})}{a(t_0)}\right]^3 \int d\left(\frac{k}{H}\right) \frac{1}{k} \frac{d\dot{\rho}_a}{d\ln k}$$

$$\frac{d\dot{\rho}_a}{d\ln k}(t) = \Gamma_K(t)\, \rho_s(t)\, F\left(x \equiv \frac{k}{H}, y \equiv \frac{m_r}{H}\right)$$

$$= \int_{t_K}^{t_0} d\tilde{t} \left[\frac{a(\tilde{t})}{a(t_0)}\right]^3 \frac{\Gamma_K(\tilde{t})}{H(\tilde{t})}\, \rho_s(\tilde{t}) \int_{k_{\min}(\tilde{t})}^{m_r} \frac{dk}{k} F\left(\frac{k}{H(\tilde{t})}, \frac{m_r}{H(\tilde{t})}\right)$$

$$F(x, y) \propto \frac{1}{x^q}$$

We integrate between all applicable k modes

$$n(t_0) = 3\frac{0.2 \ln N \mu_0 \ln N}{\xi_0 t_0^{3/2}} \frac{q-1}{q} \int_{t_K}^{t_0} d\tilde{t} \frac{\tilde{t}^{3/2}}{L_K^2(\tilde{t})} \left(\frac{x_0^q - y^q}{x_0^q y - y^q x_0}\right)$$

method: varying emission spectrum

calculating number density (again)

$$\Omega_r(t_0) = \frac{n(t_0)}{n_{\mathrm{DM}}^{\mathrm{req}}(t_0)}$$

method: varying emission spectrum

comparing the methods

$$\left(\frac{dn}{dt}\right)_{\mathrm{M1}} \propto \mathcal{N}(t)\,\ell_{\mathrm{crit}}(t) \sim \frac{\rho_s(t)}{L(t)}\,\ell_{\mathrm{crit}}(t)$$

$$\left(\frac{dn}{dt}\right)_{\mathrm{M2}} \propto \int_{k_{min}}^{m_r} \frac{dk}{H}\frac{1}{k}\frac{d\dot{\rho}_a}{d\ln k}$$

$$\sim \int_{k_{min}}^{m_r} \frac{dk}{H}\frac{1}{k^2}\Gamma_k \rho_s$$

$$\sim H\rho_s \ell_{crit}$$

they differ in considering the length scale over which density changes,

while being similar for q=1, when friction not included