Parametric resonance of photons in axion backgrounds

Gonzalo Alonso-Álvarez

(based on arXiv:1911.07885
with J. Jaeckel, M. Spannowsky, and R. S. Gupta)

"Newton 1665" seminar series
Your living room, 23 April 2020

elusives
Horizon 2020
neutrinos, dark matter & dark energy physics

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

"la Caixa" Foundation

Axions, ALPs and all that…

- QCD axion: solution to the strong CP problem
- Axions / ALPs: pseudo NG bosons

Shift symmetry

$$\phi \equiv \phi + \mathrm{const} \quad \rightarrow \quad \phi \equiv \phi + 2\pi\mathrm{k},\ k \in \mathbb{Z}$$

- Lagrangian: $\mathcal{L} = \frac{1}{2}\left(\partial_\mu \phi\right)^2 - V(\phi) - \frac{1}{4} g_{\phi\gamma\gamma}\phi F\tilde{F}$

- Potential: $V(\phi) = \Lambda^4 \left(1 - \cos\frac{\phi}{f}\right) \simeq \frac{1}{2} m_\phi^2 \phi^2$

Axions as dark matter

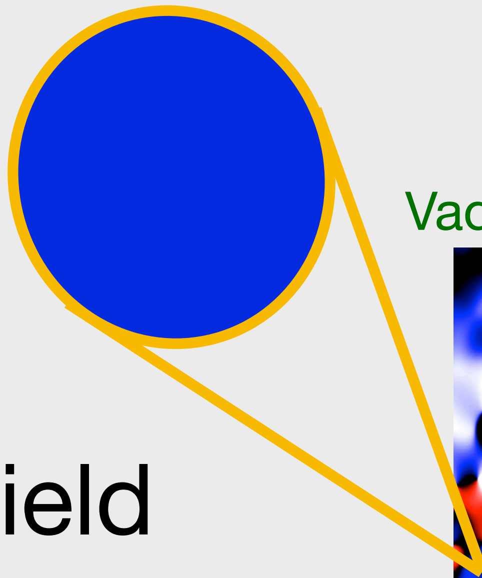
Extremely large occupation number

$$n_\phi \simeq \frac{\rho_{\rm DM}}{m_\phi} \to N_\phi \simeq \frac{n_\phi}{\frac{4\pi}{3}(m_\phi \delta v)^3/(2\pi)^3} \sim 10^{20}\left(\frac{10^{-4}\,{\rm eV}}{m_\phi}\right)^4$$

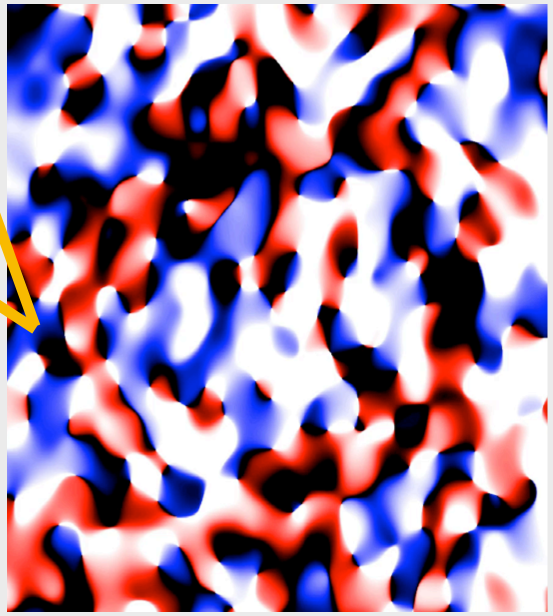
Classical field

Misalignment mechanism:

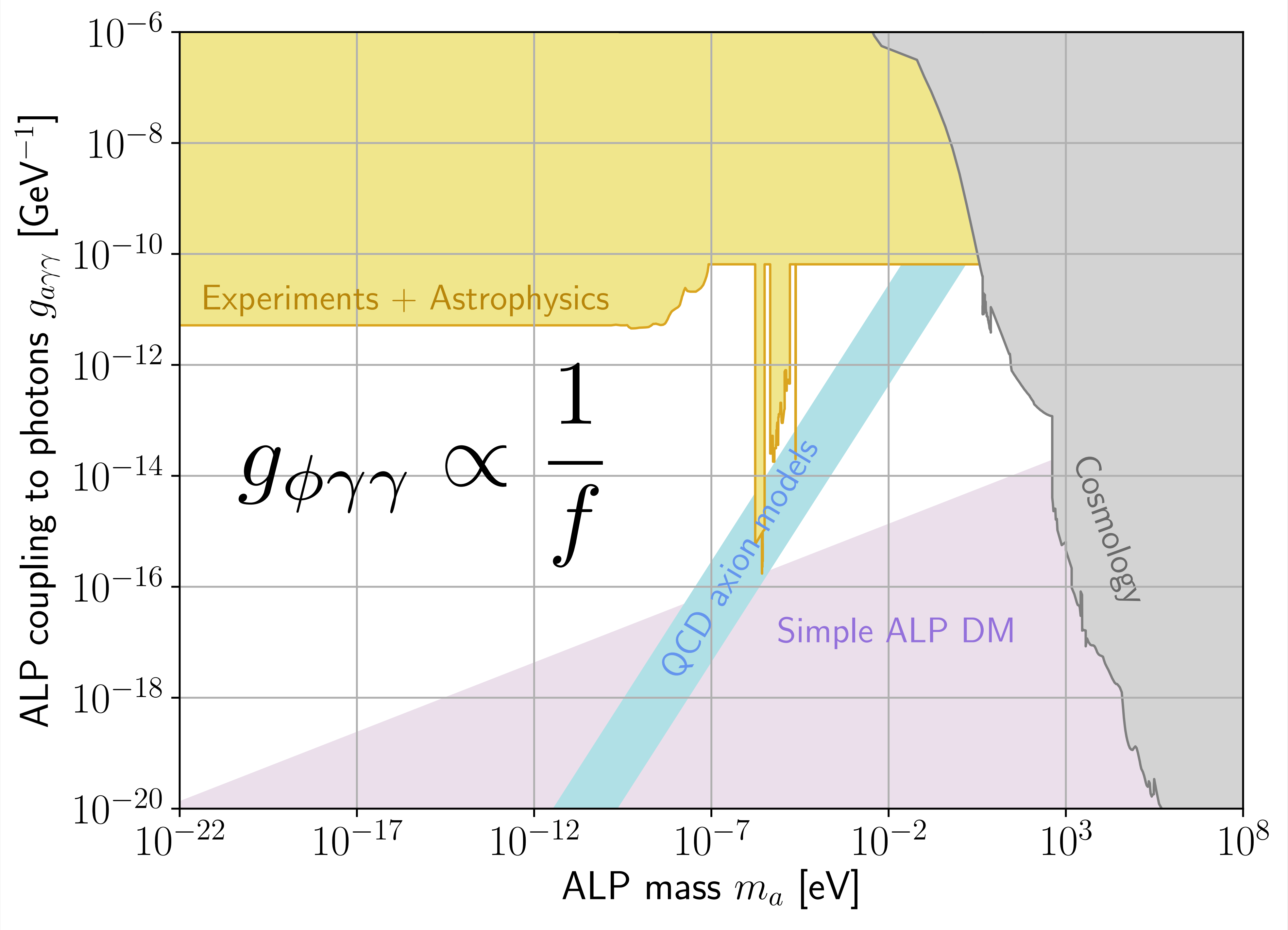
- Preinflationary: homogeneous field
- Postinflationary: axion miniclusters/stars



Vaquero *et al* [1809.09241]



Axions as dark matter



Outline

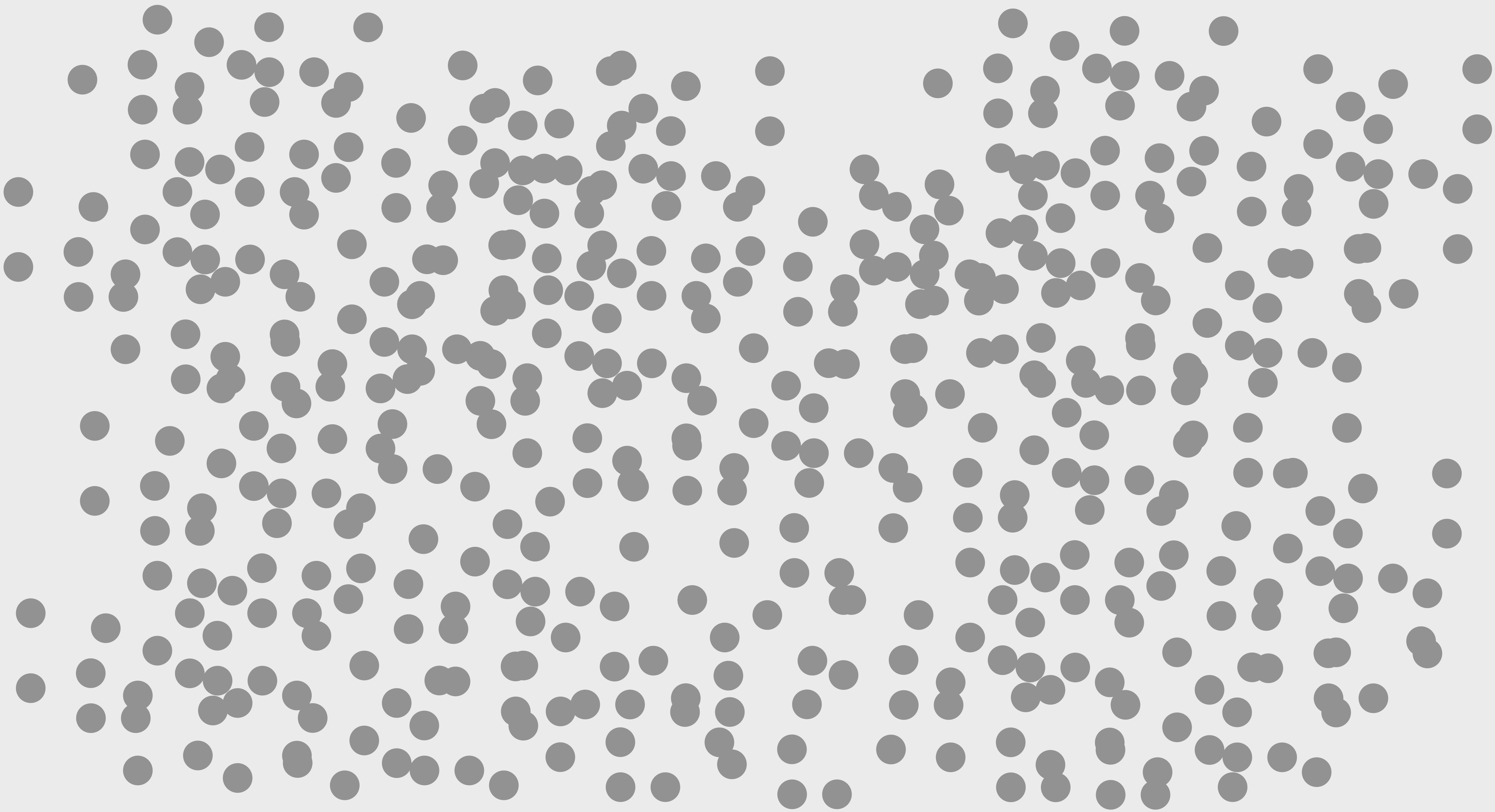
- Introduction

1. Bose enhancement & parametric instability
2. Homogeneous axion dark matter field
3. Axion clumps

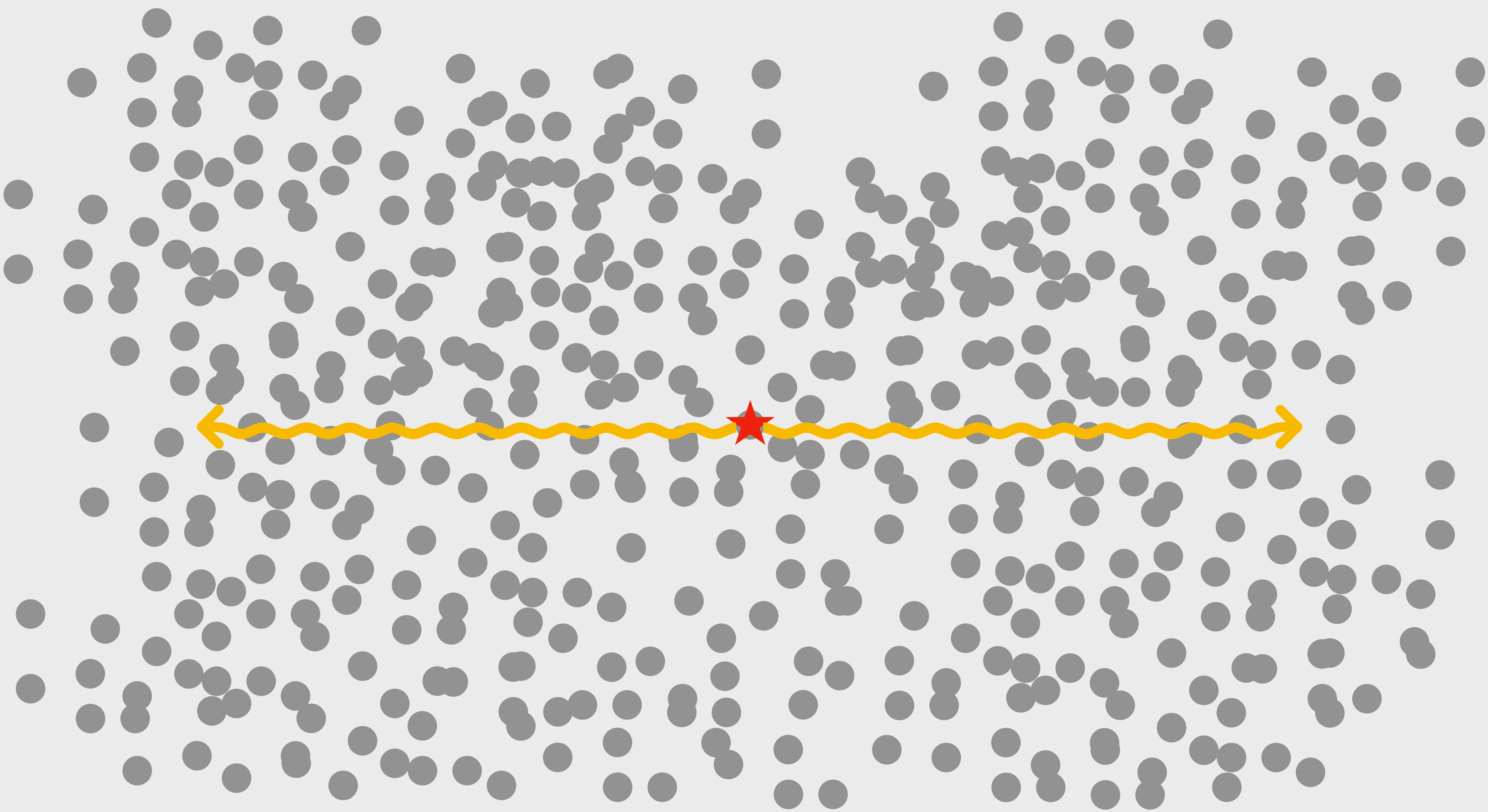
- Conclusions

Bose enhancement & parametric instability

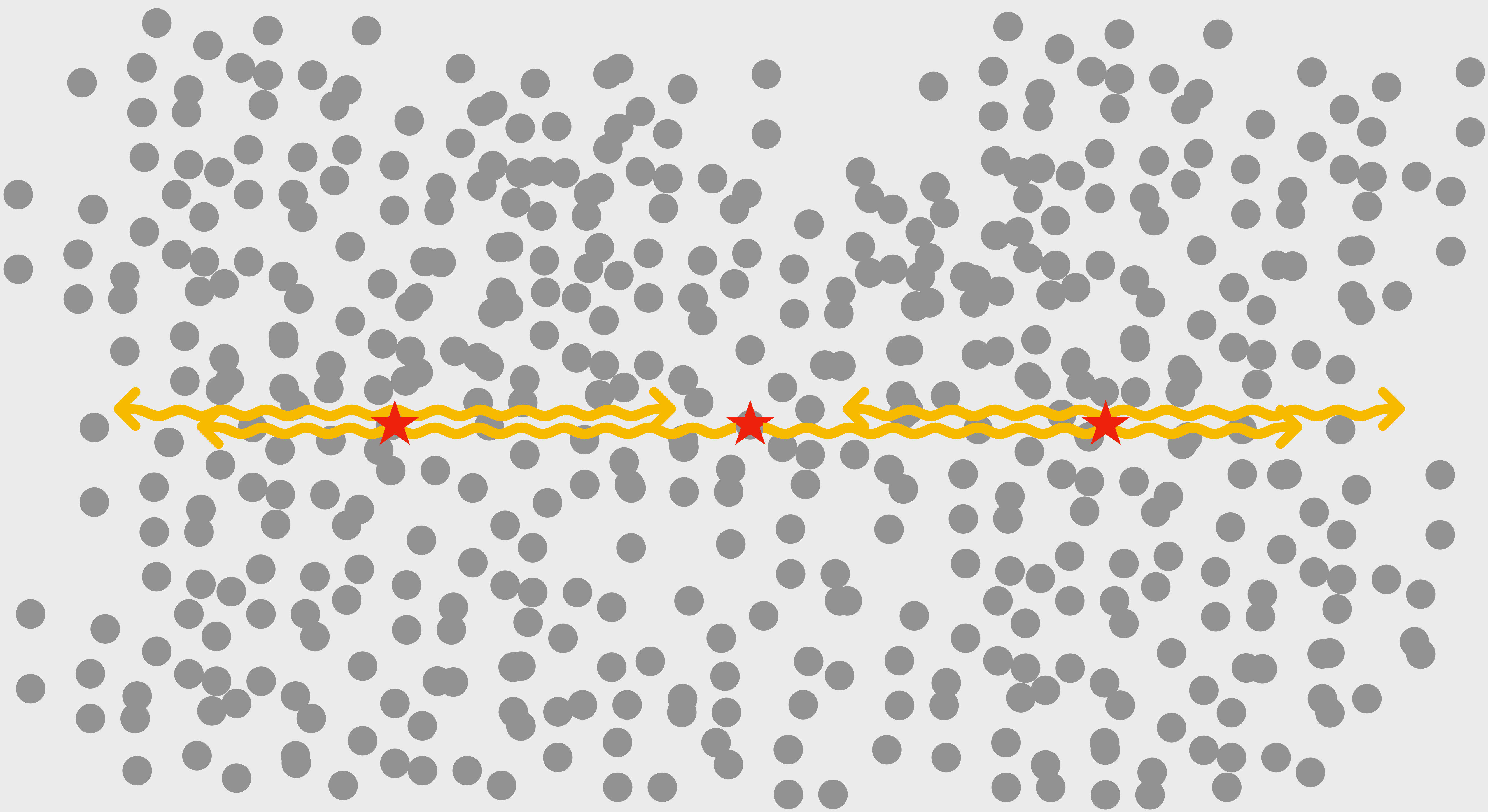
Pictorially: stimulated decay



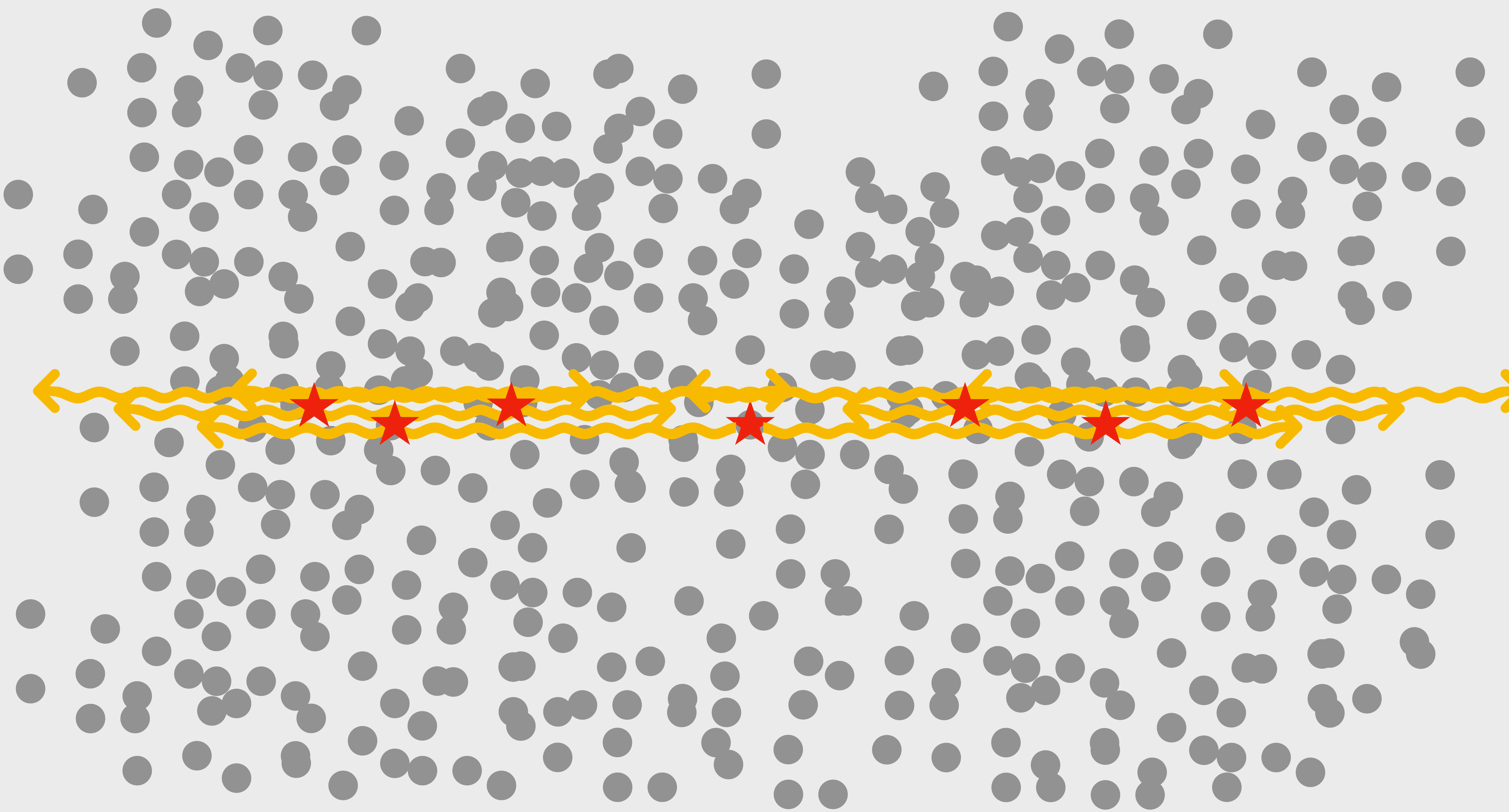
Pictorially: stimulated decay



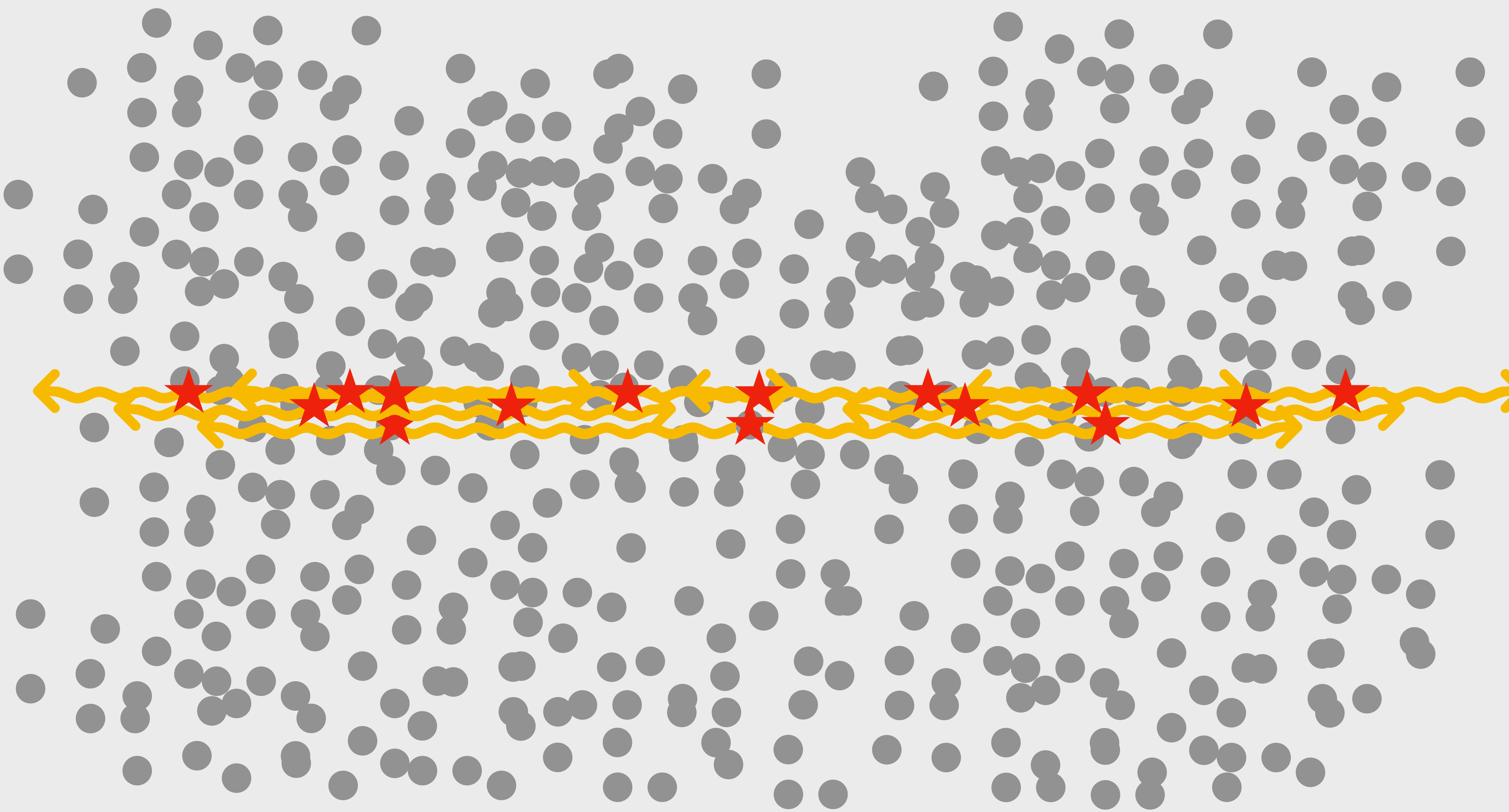
Pictorially: stimulated decay



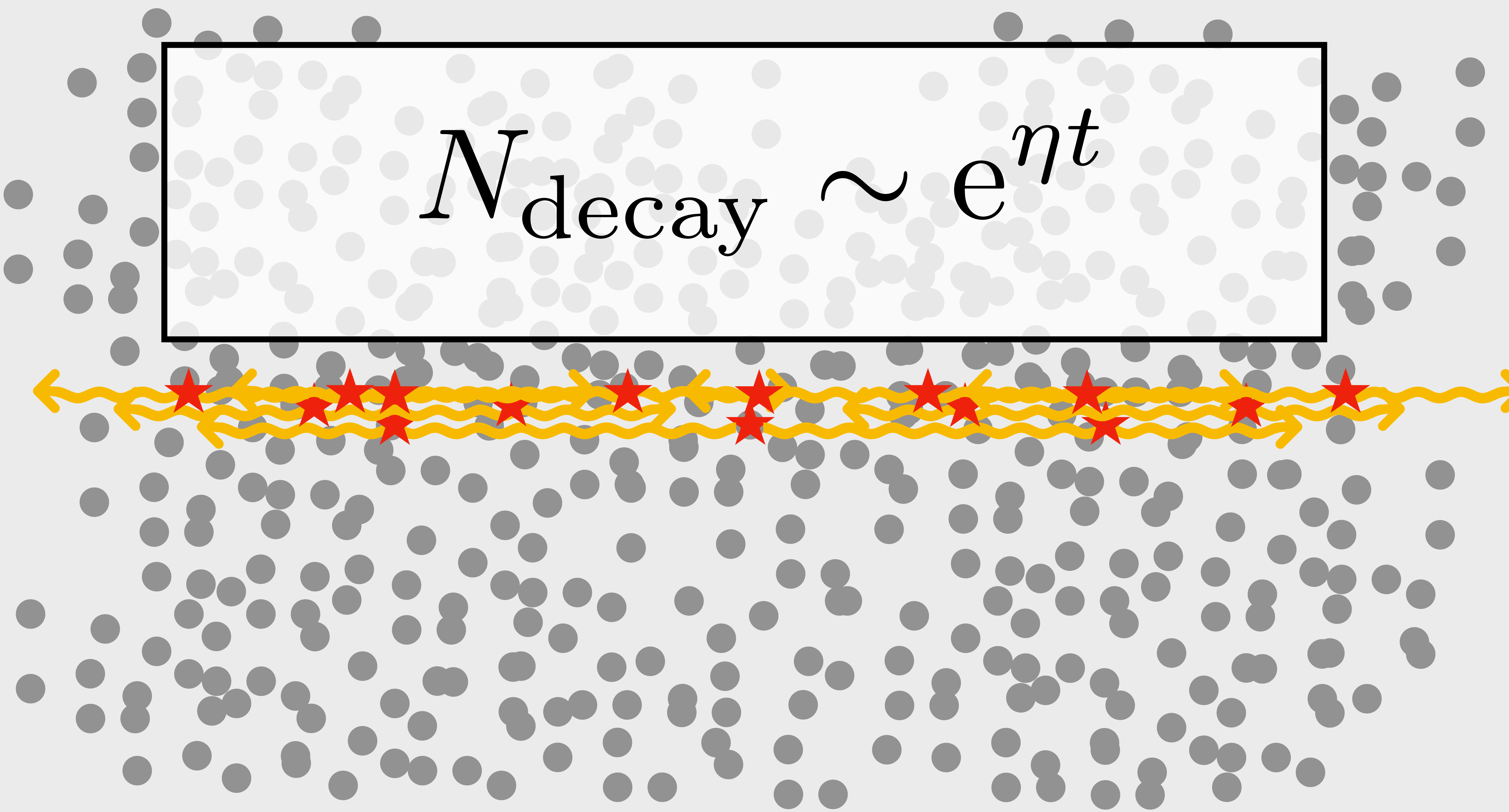
Pictorially: stimulated decay



Pictorially: stimulated decay



Pictorially: stimulated decay



$$N_{\rm decay} \sim \mathrm{e}^{\eta t}$$

EOM: parametric instability

Equation of motion for a photon mode with momentum k:

$$\ddot{A} + \left(k^2 - g_{\phi\gamma\gamma} k \dot{\phi}\right) A = 0$$

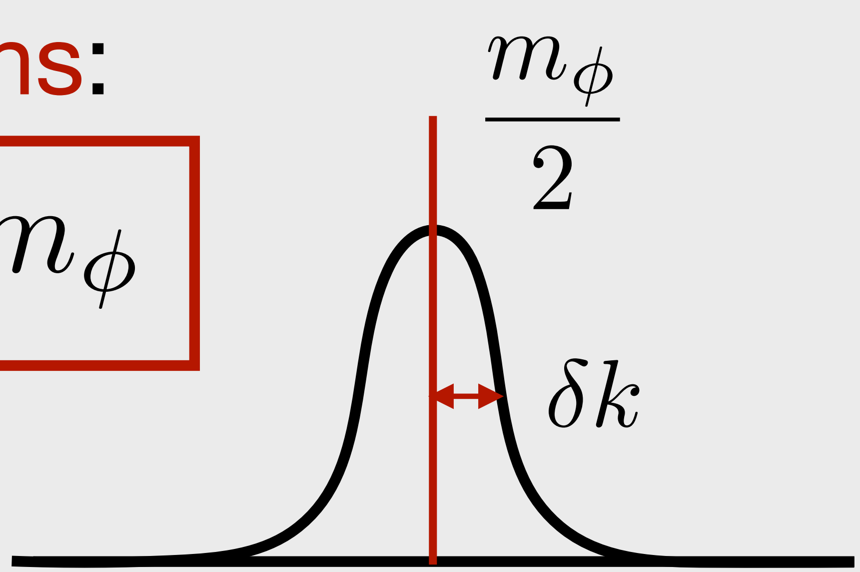
Background axion solution leads to a Mathieu equation:

$$\phi(t) = \phi \sin\left(m_\phi t\right) \quad \rightarrow \quad \frac{\mathrm{d}^2 A}{\mathrm{d}x^2} + \left(a - 2q\cos 2x\right) A = 0$$

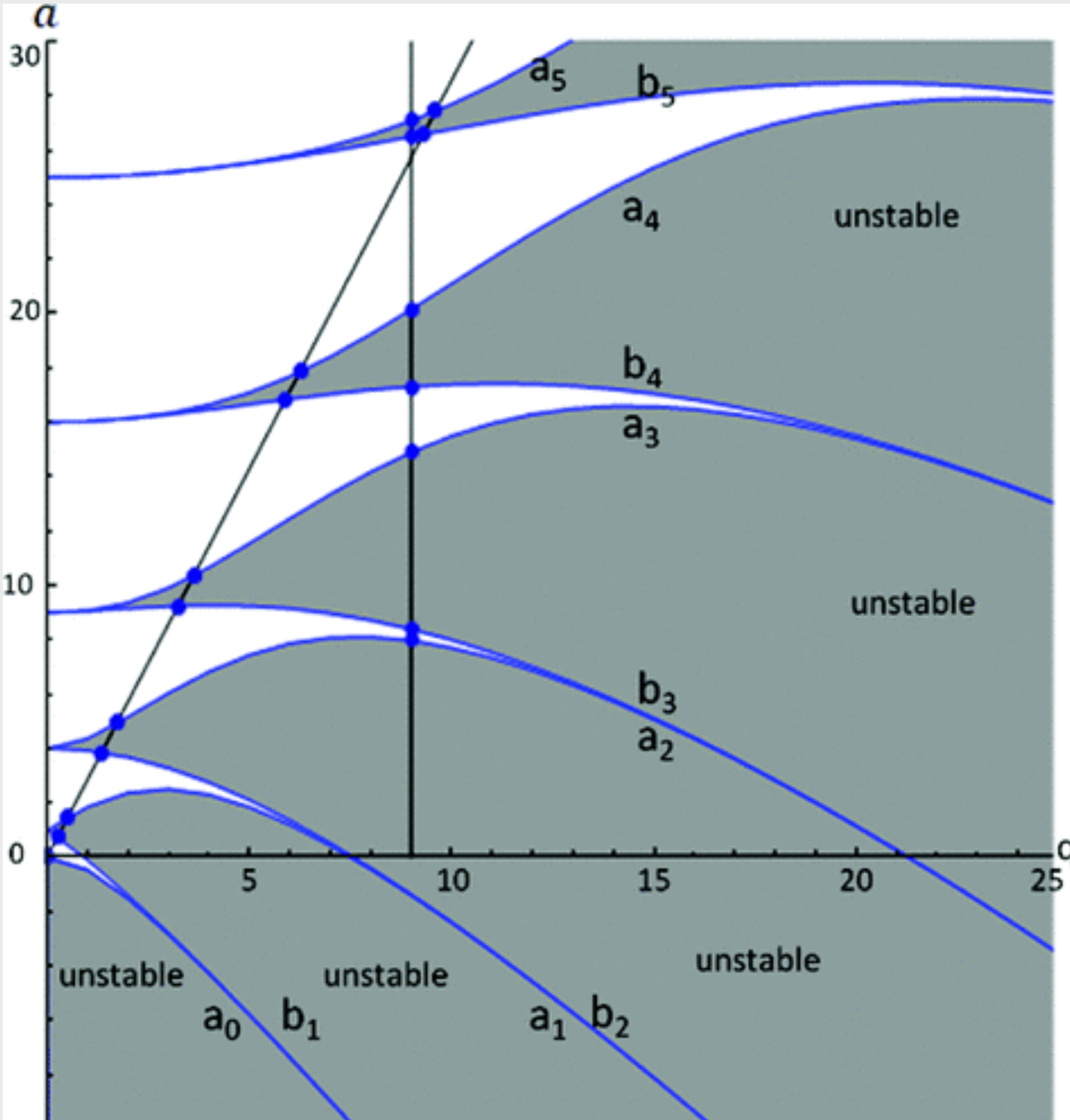
It admits exponentially growing solutions:

$$A \sim \mathrm{e}^{\eta t}, \quad \text{with} \quad \boxed{\eta \sim g_{\phi\gamma\gamma}\phi\, m_\phi}$$

If $\left|k - \frac{m_\phi}{2}\right| < \delta k \sim g_{\phi\gamma\gamma}\phi\, m_\phi/2$



EOM: parametric instability



oton mode with momentum k:

$$\gamma\gamma k\dot{\phi}\Big) A = 0$$

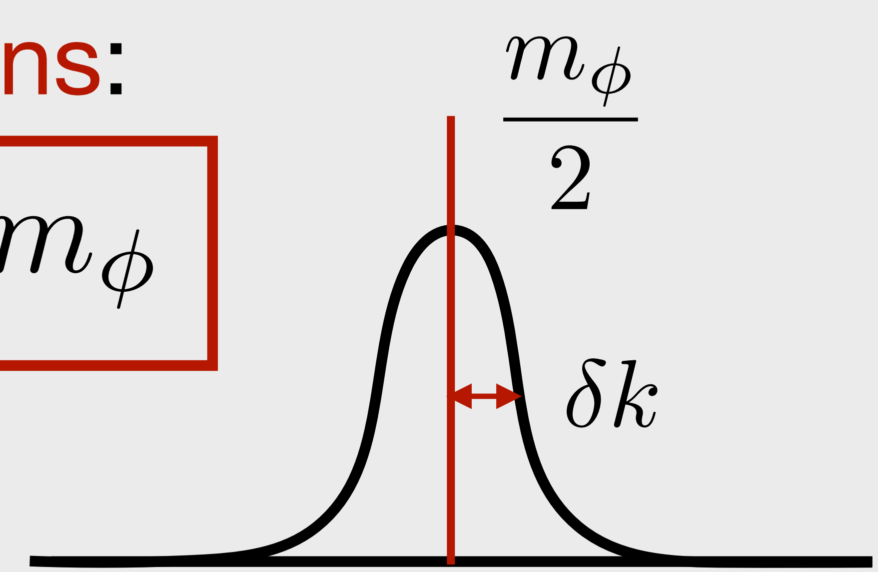
eads to a Mathieu equation:

$$\frac{\mathrm{d}^2 A}{\mathrm{d}x^2} + (a - 2q\cos 2x)\, A = 0$$

ing solutions:

$$\sim g_{\phi\gamma\gamma}\phi\, m_\phi$$

$$m_\phi/2$$



EOM: parametric instability

Equation of motion for a photon mode with momentum k:

$$\ddot{A} + \left(k^2 - g_{\phi\gamma\gamma} k \dot{\phi}\right) A = 0$$

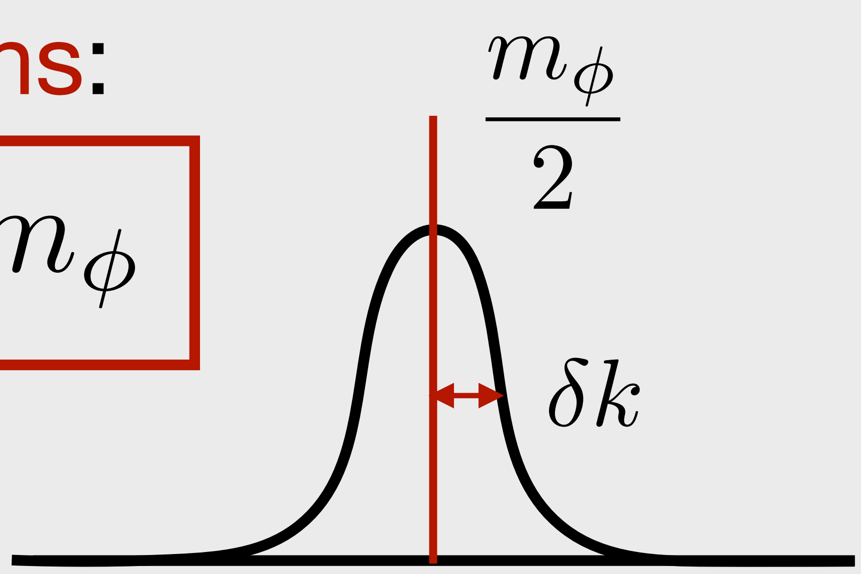
Background axion solution leads to a Mathieu equation:

$$\phi(t) = \phi \sin\left(m_\phi t\right) \quad \rightarrow \quad \frac{\mathrm{d}^2 A}{\mathrm{d}x^2} + \left(a - 2q\cos 2x\right) A = 0$$

It admits exponentially growing solutions:

$$A \sim \mathrm{e}^{\eta t}, \quad \text{with} \quad \boxed{\eta \sim g_{\phi\gamma\gamma}\phi\, m_\phi}$$

If $\left|k - \frac{m_\phi}{2}\right| < \delta k \sim g_{\phi\gamma\gamma}\phi\, m_\phi/2$

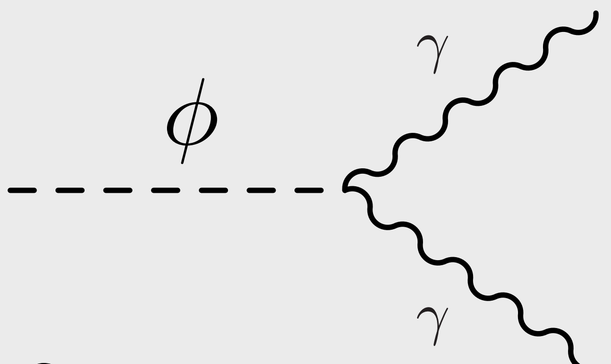


Boltzmann equation: Bose enhancement

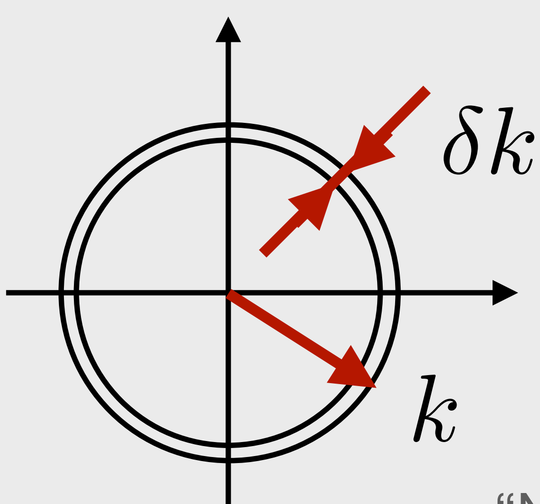
Boltzmann equation for photons with $k = m_\phi/2$:

$$\dot{n}_\gamma = 2\Gamma_{\rm pert}\,\underbrace{(1 + 2N_\gamma)}_{\text{Bose enhancement}}\,n_\phi$$

- $\Gamma_{\rm pert} = \dfrac{g_{\phi\gamma\gamma}^2 m_\phi^3}{64\pi}$



- $n_\phi = \dfrac{\rho_\phi}{m_\phi} = \frac{1}{2} m_\phi \phi^2$
- $N_\gamma \sim \dfrac{n_\gamma/2}{4\pi k^2 \delta k/(2\pi)^3}$



Boltzmann equation: Bose enhancement

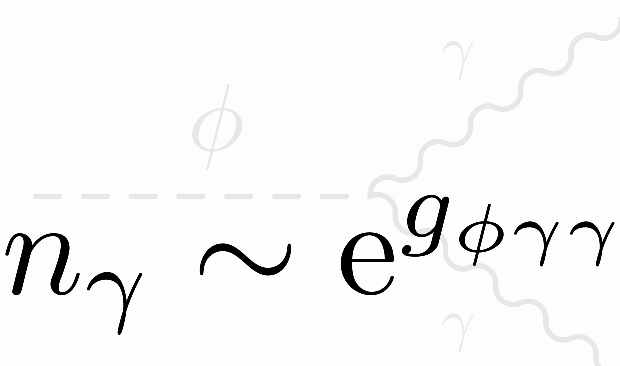
Boltzmann equation for photons with $k = m_\phi/2$:

$$\dot{n}_\gamma = 2\Gamma_{\rm pert}\,(1+2N_\gamma)\,n_\phi$$

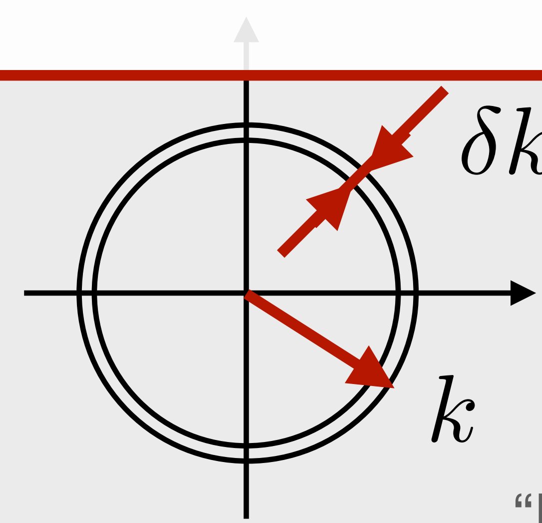
Bose enhancement

$$N_\gamma \gg 1 \rightarrow \quad n_\gamma \sim e^{g_{\phi\gamma\gamma}\phi m_\phi t}$$

- $\Gamma_{\rm pert} = \frac{g^2_{\phi\gamma\gamma} m^3_\phi}{64\pi}$



- $n_\phi = \frac{\rho_\phi}{m_\phi} = \frac{1}{2} m_\phi \phi^2$
- $N_\gamma \sim \frac{n_\gamma/2}{4\pi k^2 \delta k/(2\pi)^3}$



Homogeneous ALP dark matter field

Example: QCD axion with $f = 10^{12}\,\mathrm{GeV}$

Perturbative calculation

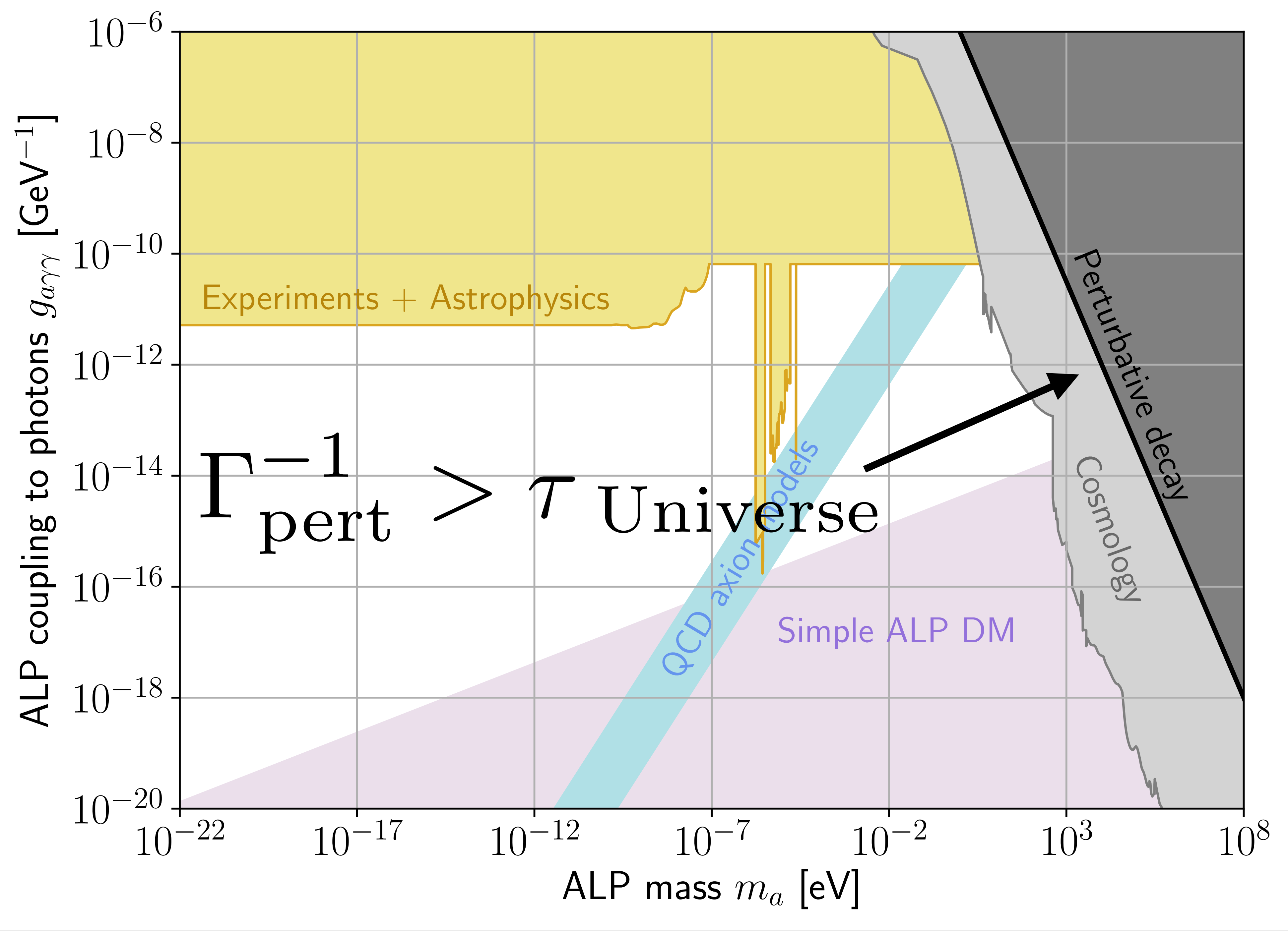
$$\Gamma^{-1}_{\rm pert} = \frac{64\pi}{g^2_{\phi\gamma\gamma} m^3_\phi} \sim 10^{51}\,\mathrm{s} \gg \tau_{\rm\ Universe}$$

Parametric instability (Bose enhancement)

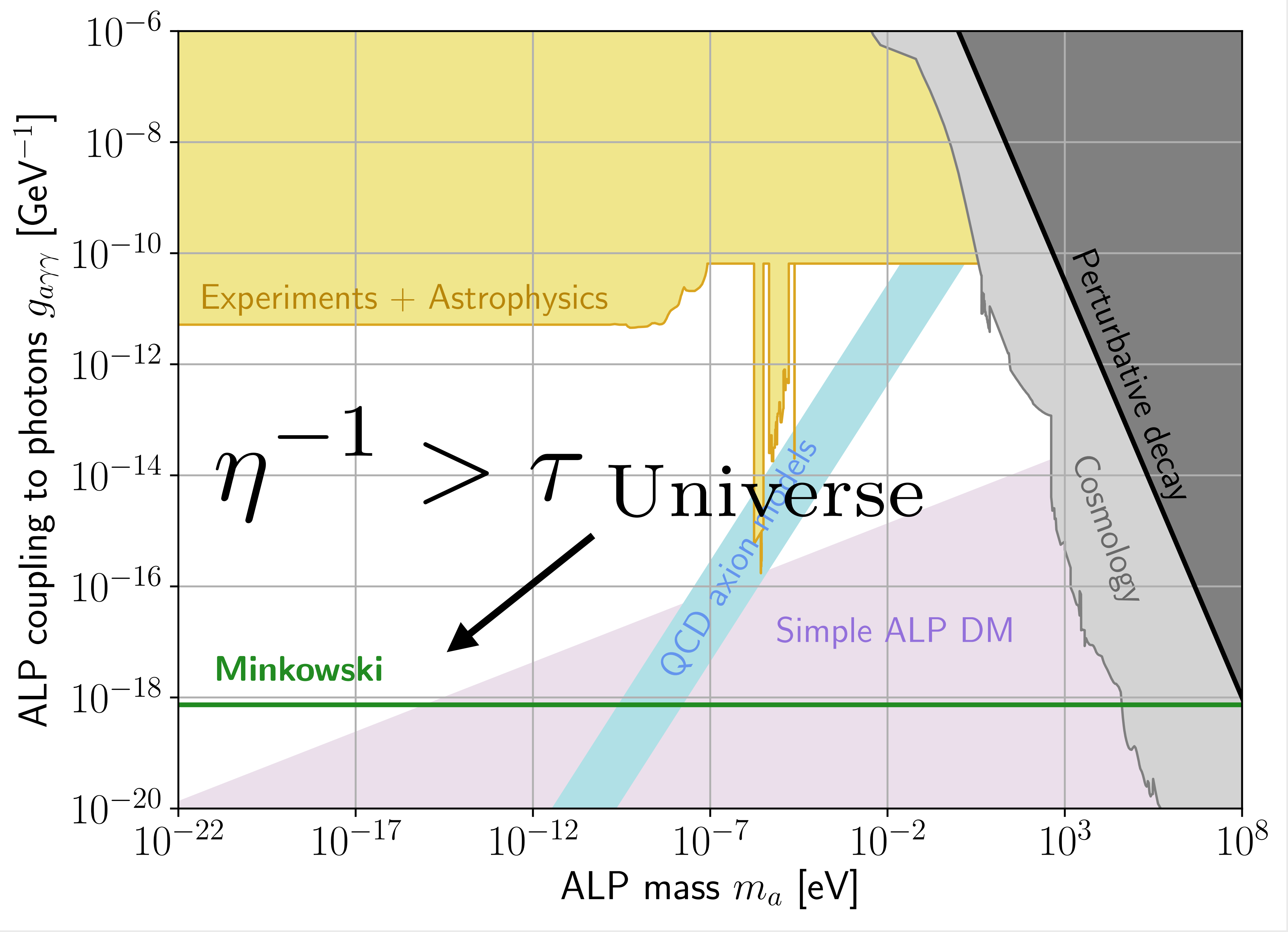
$$\eta^{-1} \sim \frac{1}{g_{\phi\gamma\gamma}\phi\, m_\phi} \sim \frac{1}{g_{\phi\gamma\gamma}\sqrt{\rho_{\rm DM}}} \sim 10^{15}\,\mathrm{s} \ll \tau_{\rm\ Univ}$$

Assumption: all axions are in the same state

Perturbative decay



Bose-enhanced decay



Bose-enhanced decay

Volume 120B, number 1,2,3 PHYSICS LETTERS 6 January 1983

Also discussed in Abbot & Sikivie (1983)

COSMOLOGY OF THE INVISIBLE AXION

John PRESKILL [1], Mark B. WISE [2]
Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

and

Frank WILCZEK
Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106, USA

Received 10 September 1982

Let us now examine whether the axion energy density can be dissipated by particle production [18 Naively, particle production is insignificant, because the invisible axion with $f_a \gtrsim 10^9$ GeV has a lifetime

10^{-22} 10^{-17} 10^{-12}

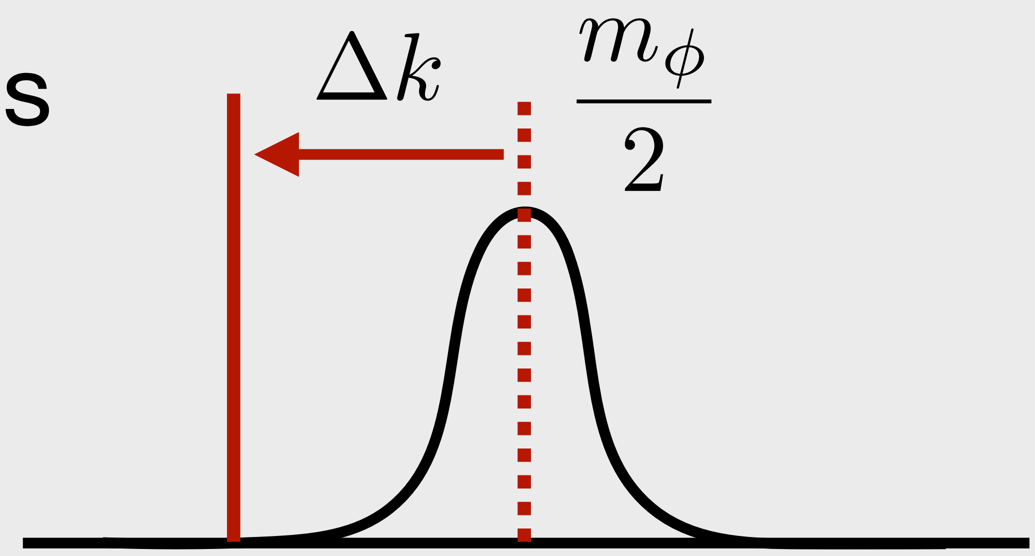
ALI

which far exceeds the age of the universe. However, the oscillating axion field represents a coherent space consisting of a large density of zero-momentum axions, and one wonders whether coherence effects can greatly amplify the rate at which this state decays. We will show that in fact the cosmological red shift prevents such coherence effects from substantially reducing the axion energy density.

Expansion prevents growth

The momentum of photons redshifts

$$\frac{\Delta k}{k} \simeq H\,\Delta t$$



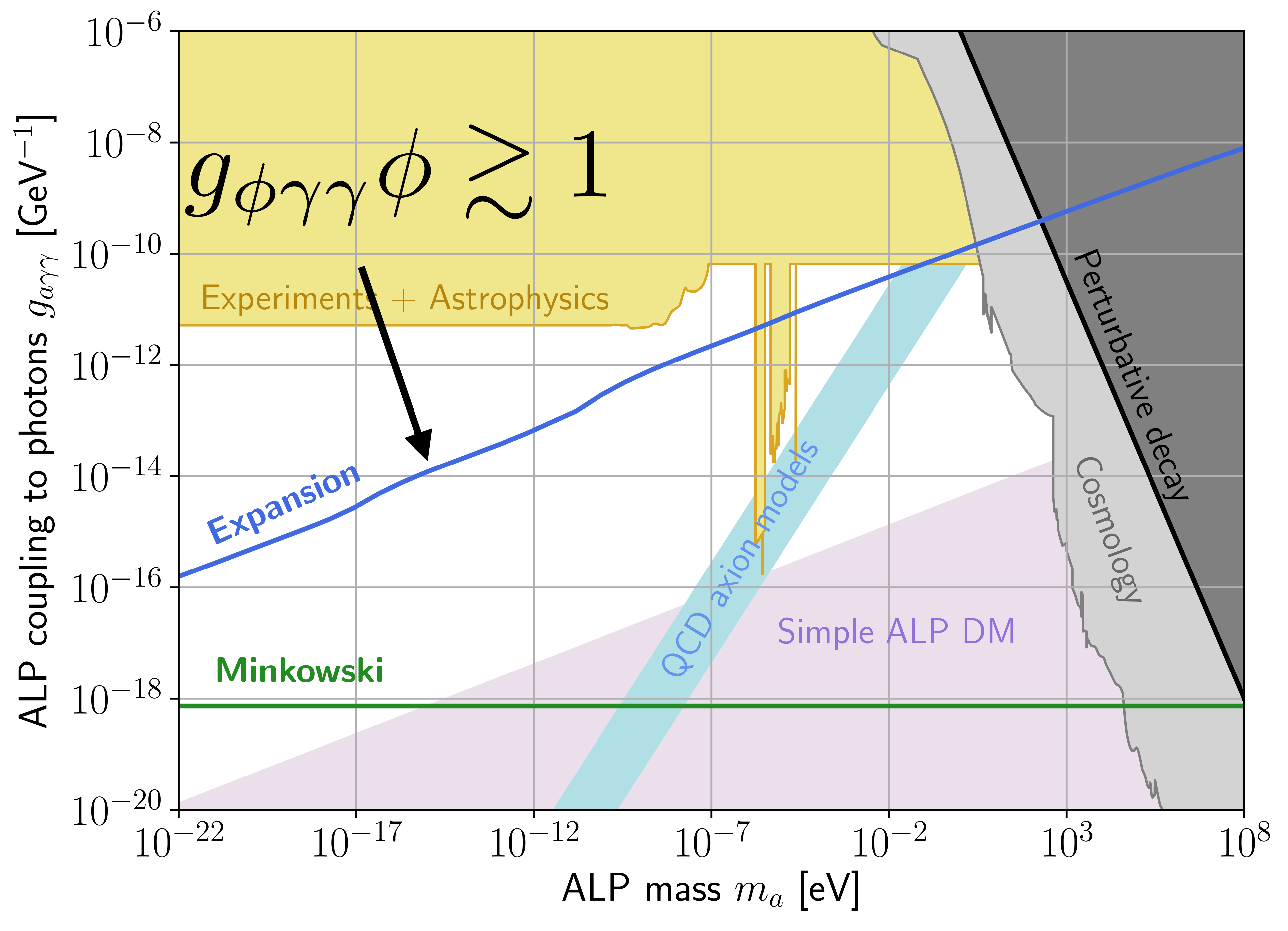
The instability has to happen fast

$$\frac{1}{\eta} \sim \Delta t_{\rm growth} \lesssim \Delta t_{\rm redshift} \sim \frac{\delta k}{m_\phi/2}\frac{1}{H}$$

The condition for instability becomes

$$g^2_{\phi\gamma\gamma}\phi^2(t) \gtrsim \frac{H(t)}{m_\phi} \text{ for any } t$$

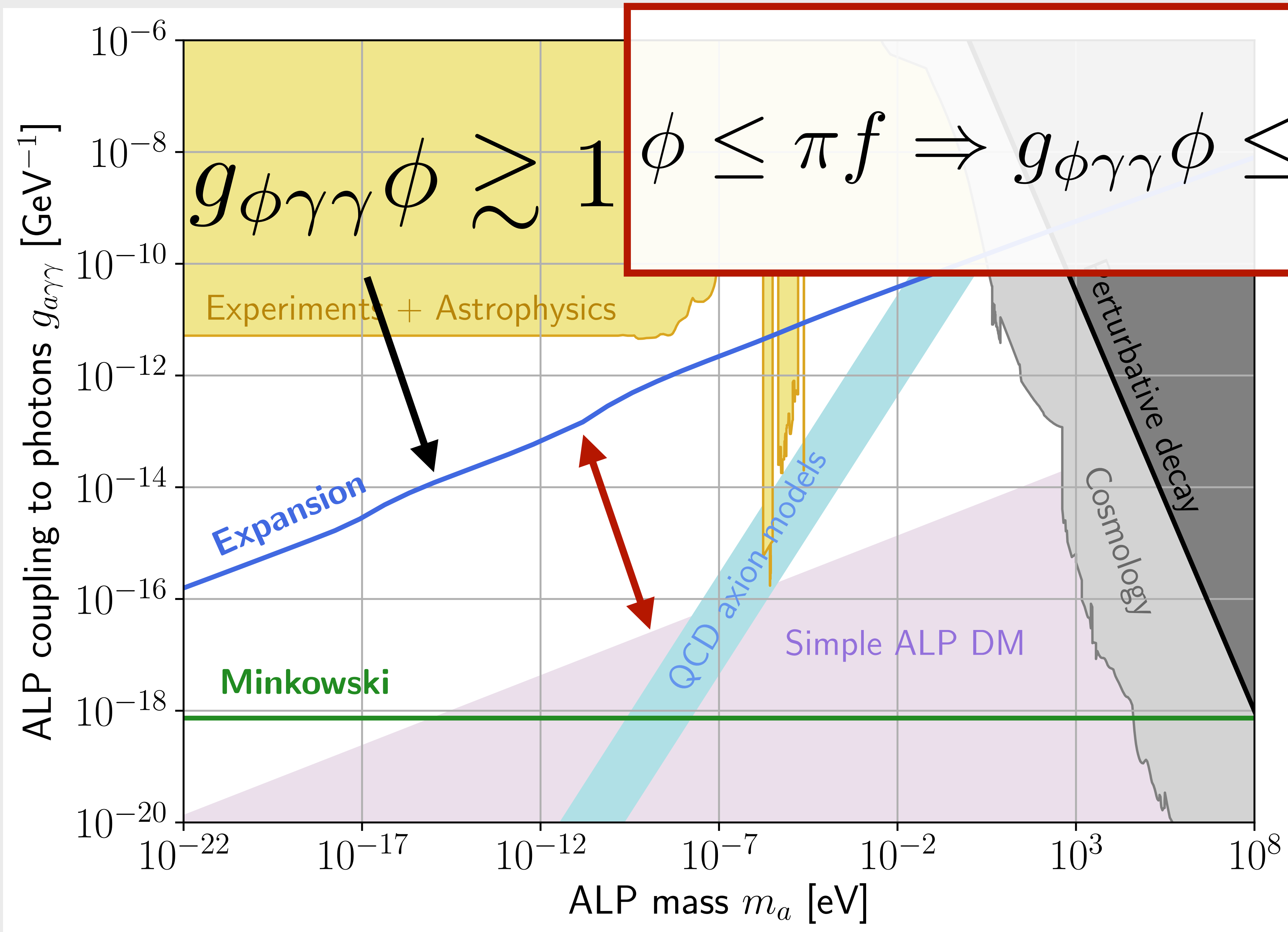
Expansion prevents growth



Expansion prevents growth

$$g_{\phi\gamma\gamma}\phi \gtrsim 1$$

$$\phi \leq \pi f \Rightarrow g_{\phi\gamma\gamma}\phi \leq \frac{C\alpha_{\mathrm{em}}}{4}$$



Plasma effects prevent early decay

The Universe is filled with an optically thick plasma

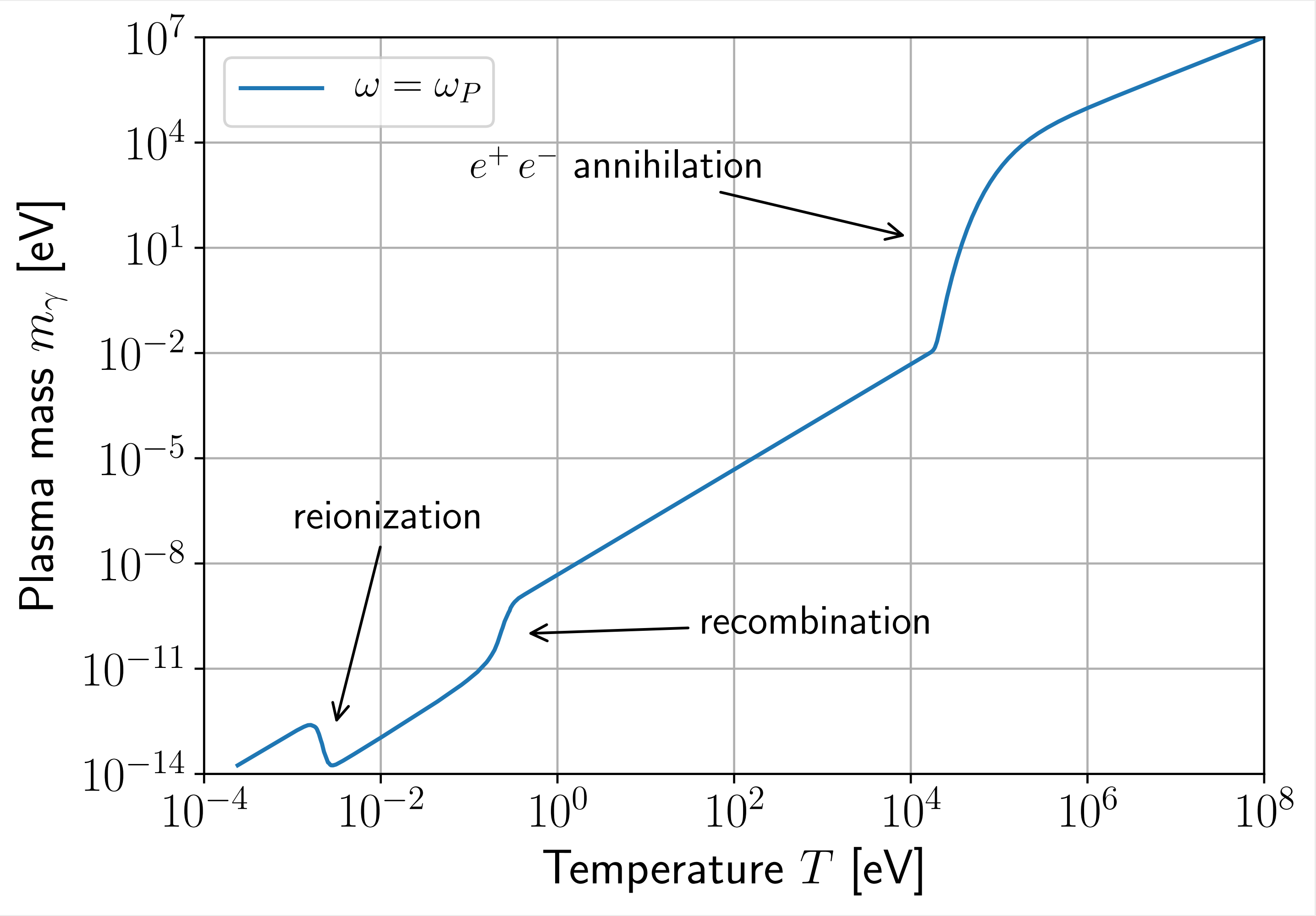
Photons below a cutoff cannot propagate

"Plasma mass" m_γ

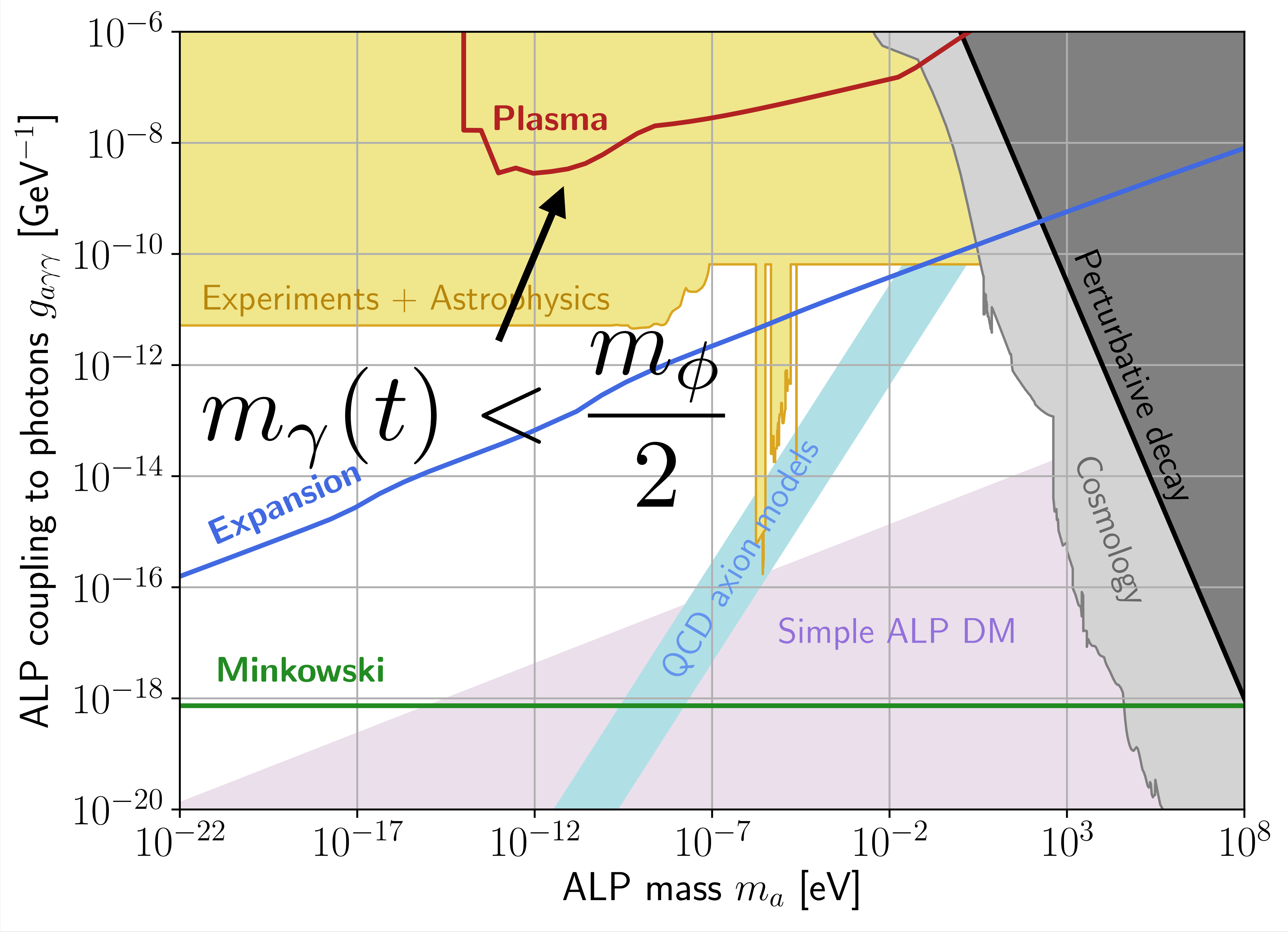
New resonance condition

$$\left| \sqrt{k^2 + m_\gamma^2} - \frac{m_\phi}{2} \right| < \delta k$$

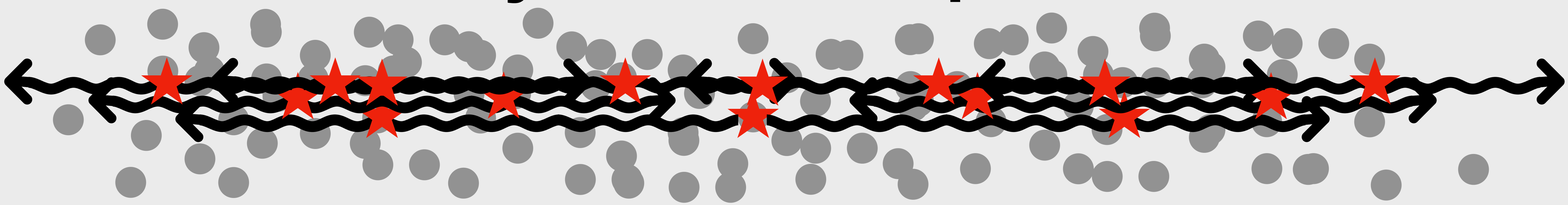
Need $$m_\gamma < \frac{m_\phi}{2}$$



Plasma effects prevent early decay



Decay into dark photons



The resonance is easier to reach because

1. There is no dark photon plasma mass
2. The axion-dark photon coupling is less constrained

Can be used to

- Deplete overabundance of axions
  Agrawal *et al* [1708.05008], Kitajima *et al* [1711.06590]
- Produce dark photon dark matter
  Agrawal *et al* [1810.07188], Dror *et al* [1810.07195]
- Produce gravitational waves
  Machado *et al* [1811.01950, 1912.01007]

Axion clumps

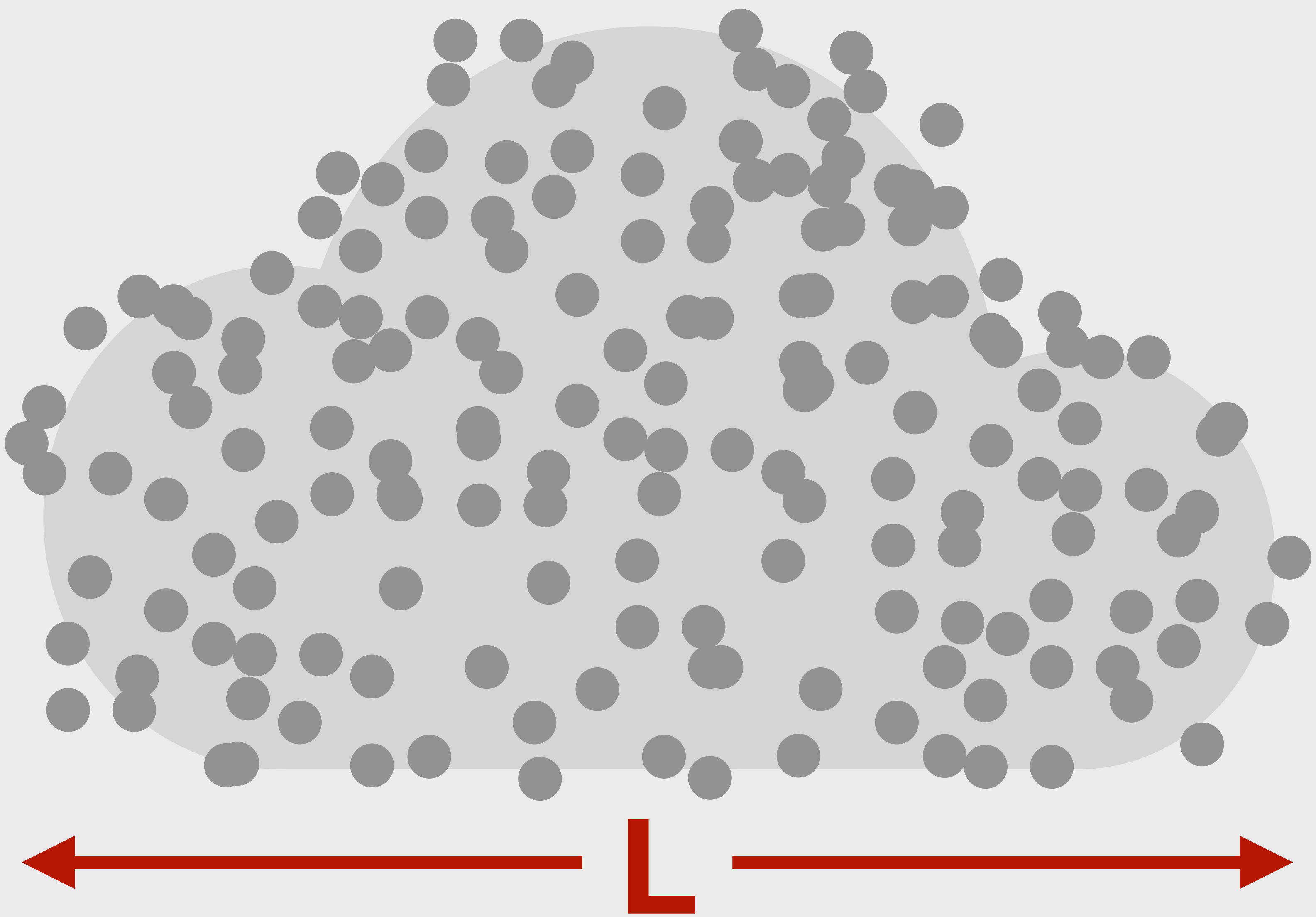
Many kinds of structures

- Clouds of diffuse axions
- Axion miniclusters
- Axion stars
- Bose-Einstein condensates?
- Superradiant clouds around black holes

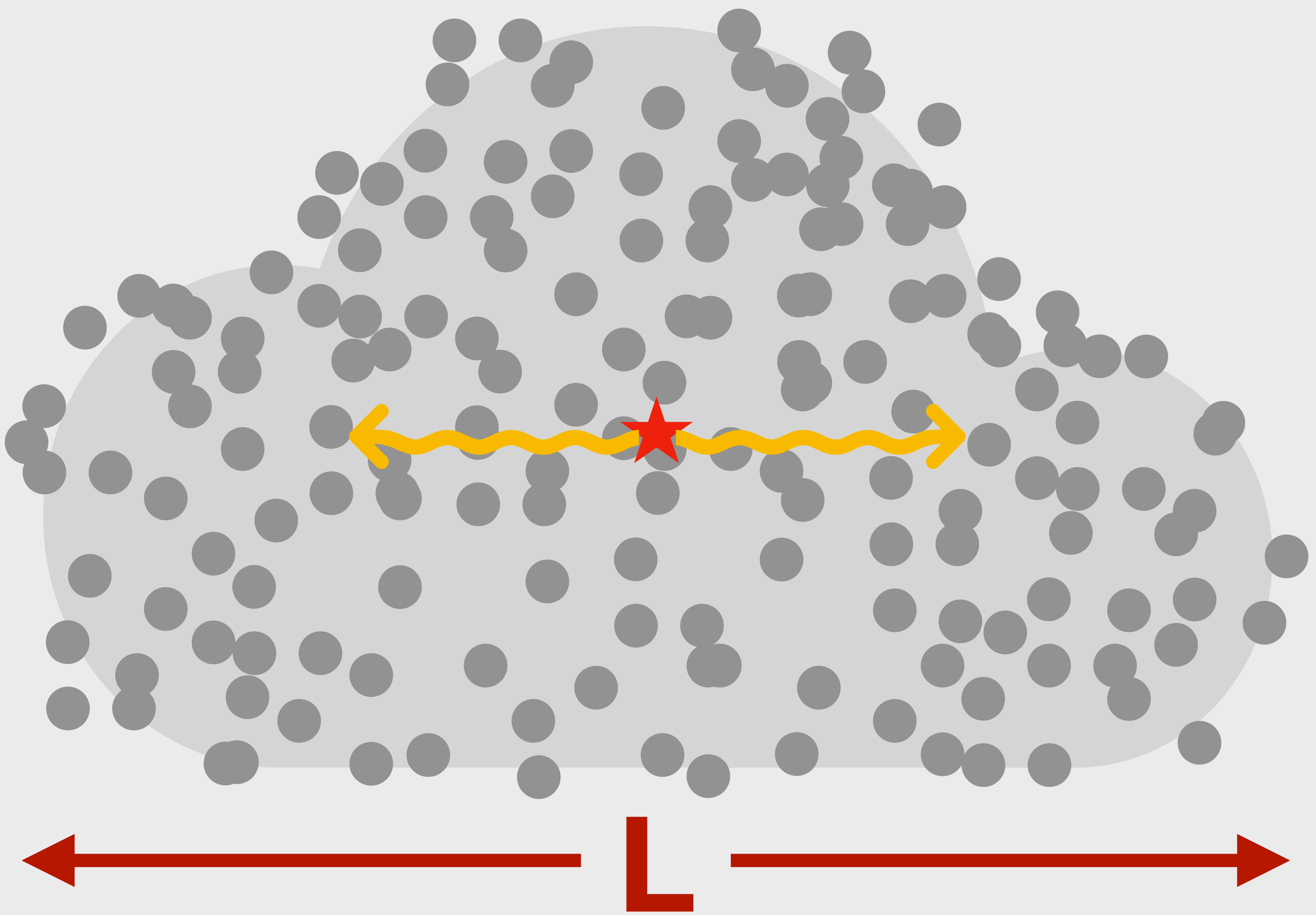
$$\eta \sim g_{\phi\gamma\gamma}\phi\, m_\phi \sim g_{\phi\gamma\gamma}\sqrt{2\rho_\phi}$$

Higher density —> Faster decay

Pictorially: now in a finite frame

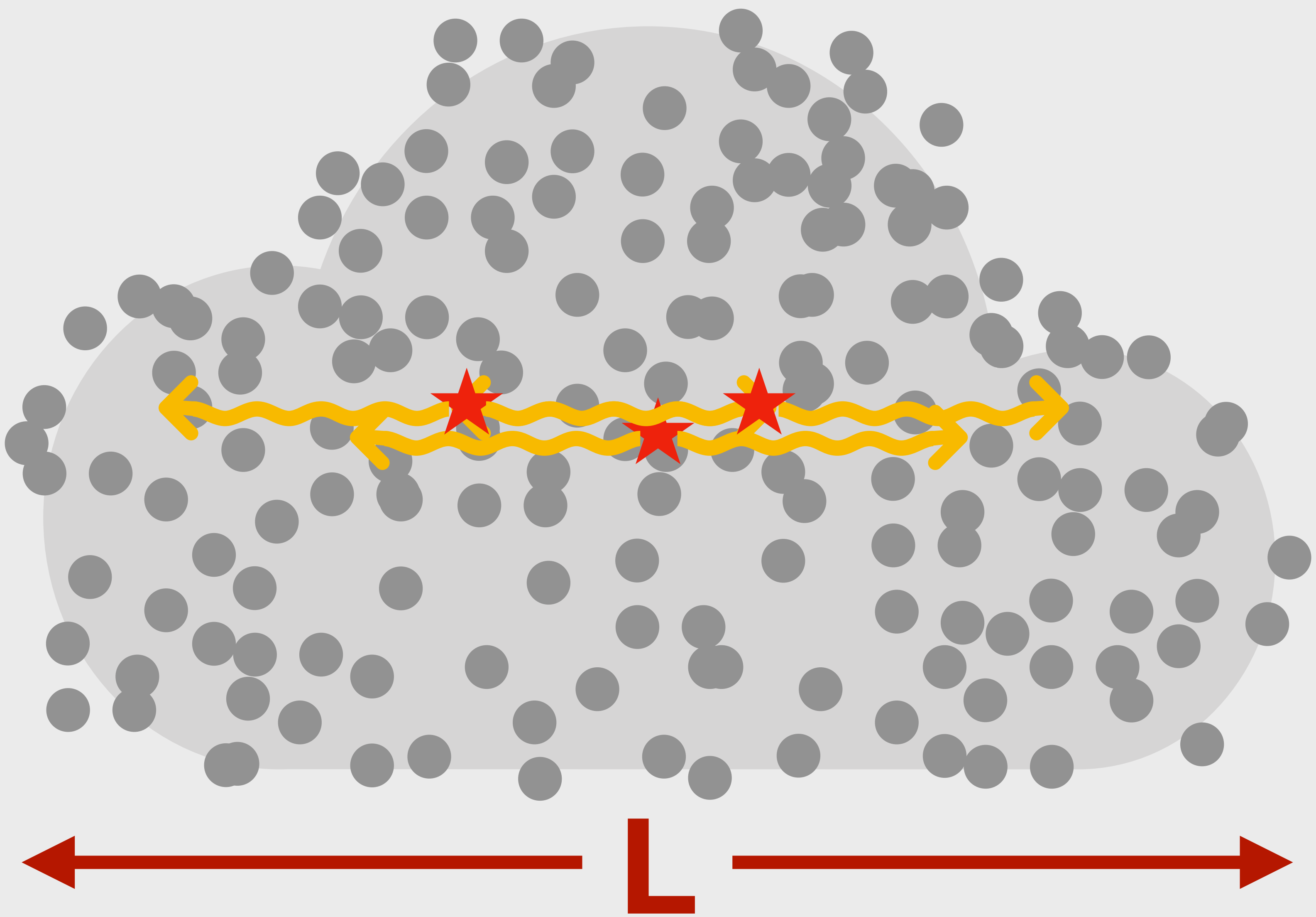


Pictorially: now in a finite frame



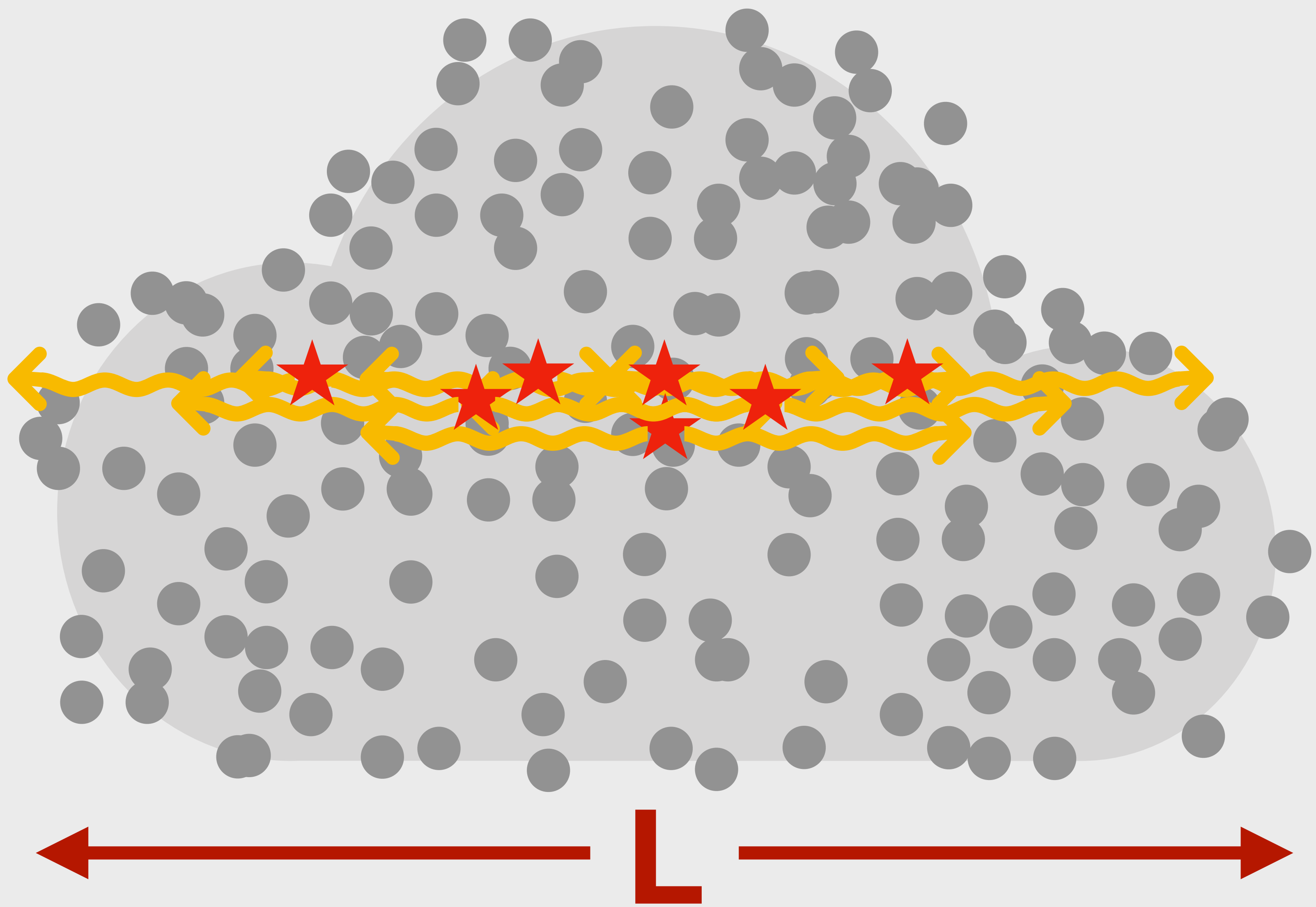
$$\eta L \gtrsim 1$$

Pictorially: now in a finite frame



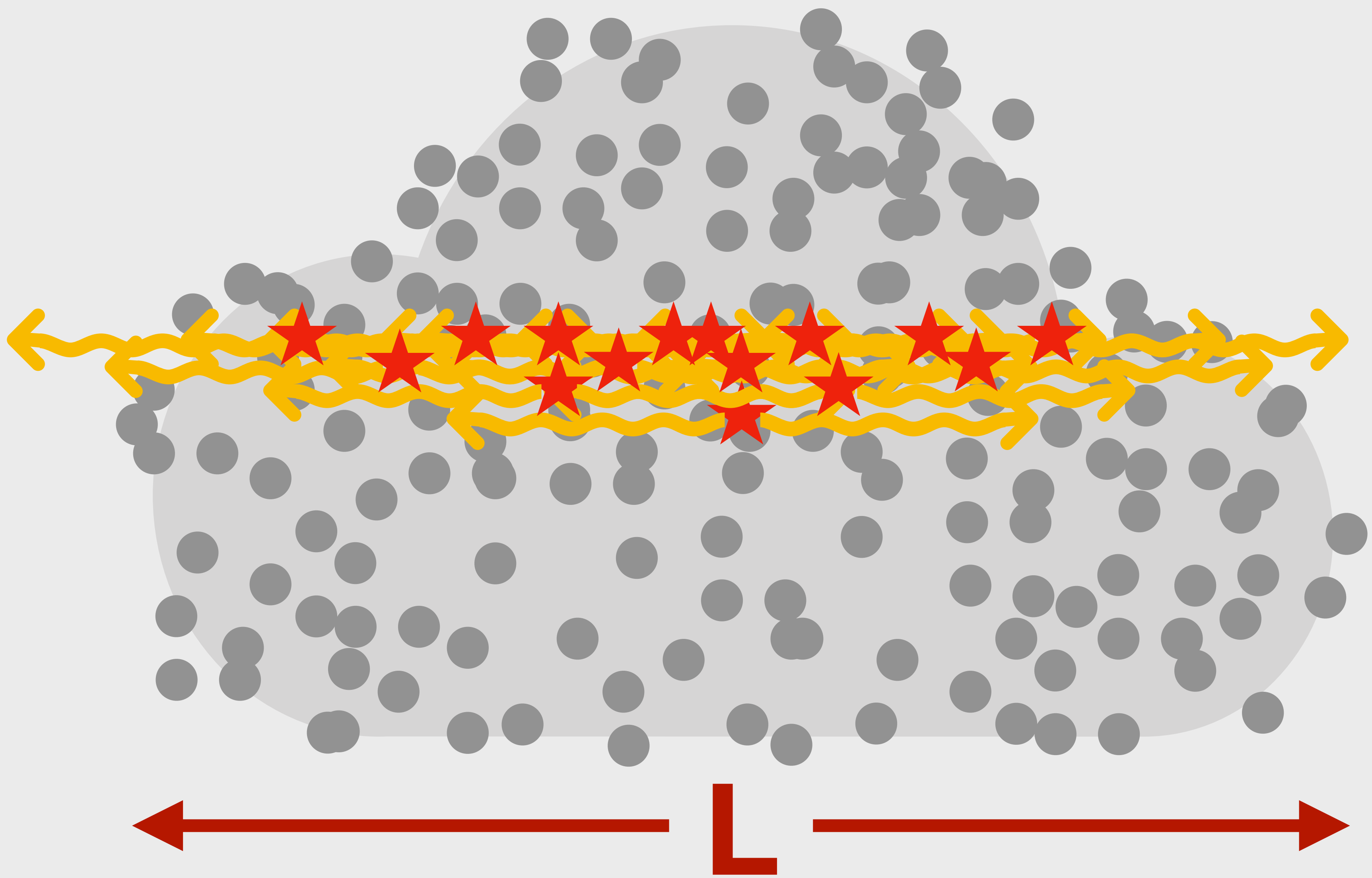
$$\eta L \gtrsim 1$$

Pictorially: now in a finite frame



$$\eta L \gtrsim 1$$

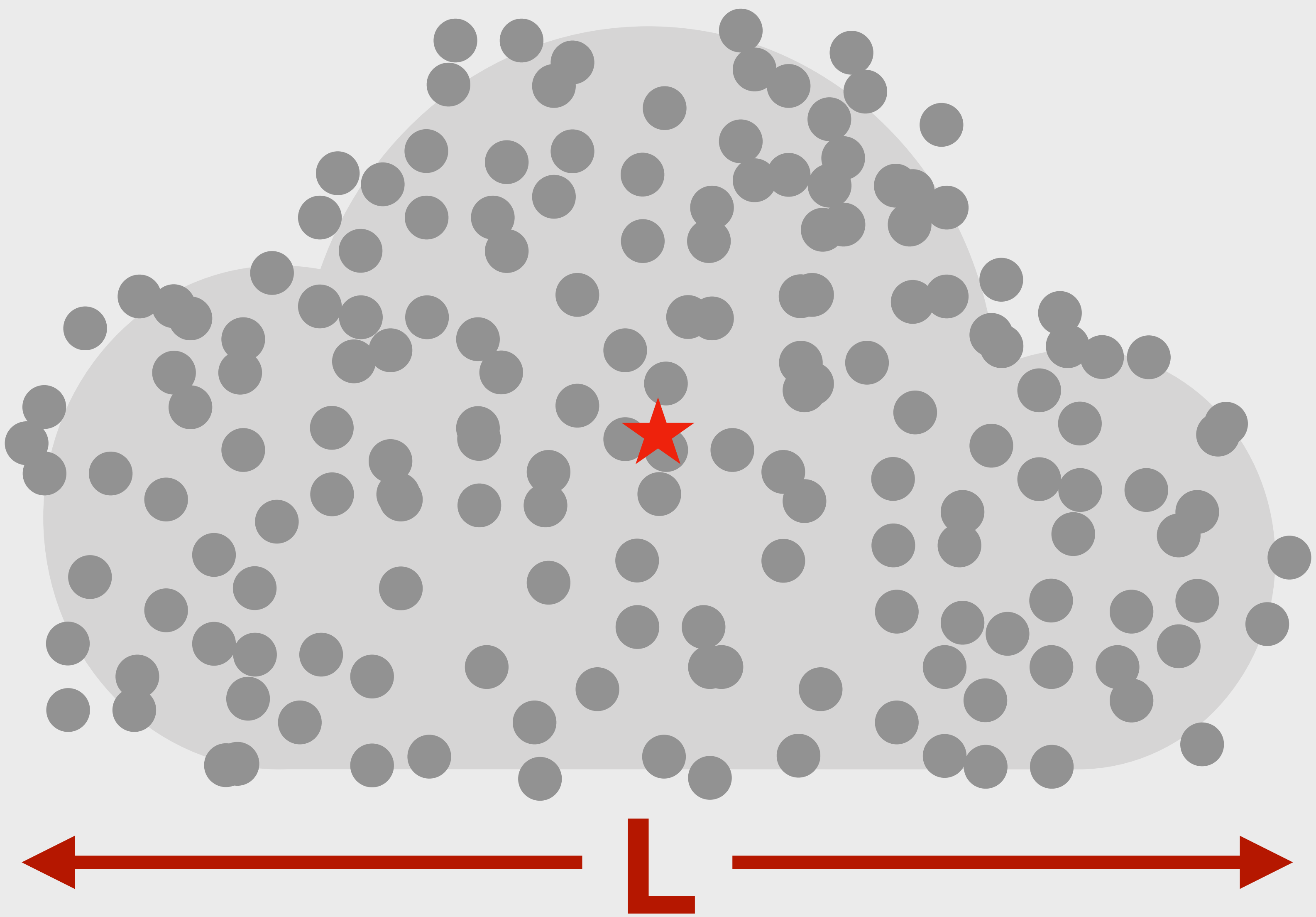
Pictorially: now in a finite frame



$$\eta L \gtrsim 1$$

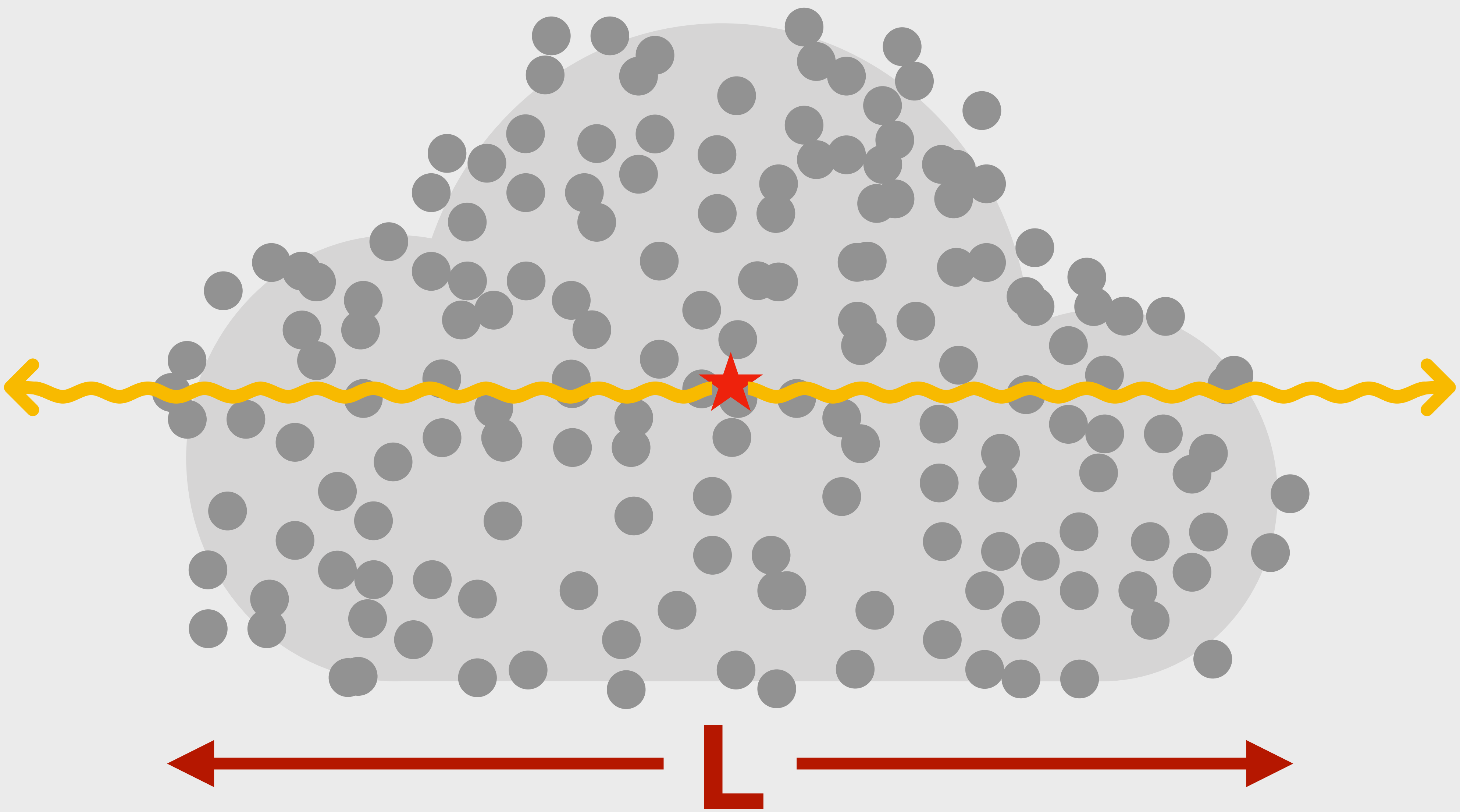
Resonance

Pictorially: now in a finite frame



$$\eta L \lesssim 1$$

Pictorially: now in a finite frame



$$\eta L \lesssim 1$$

No resonance

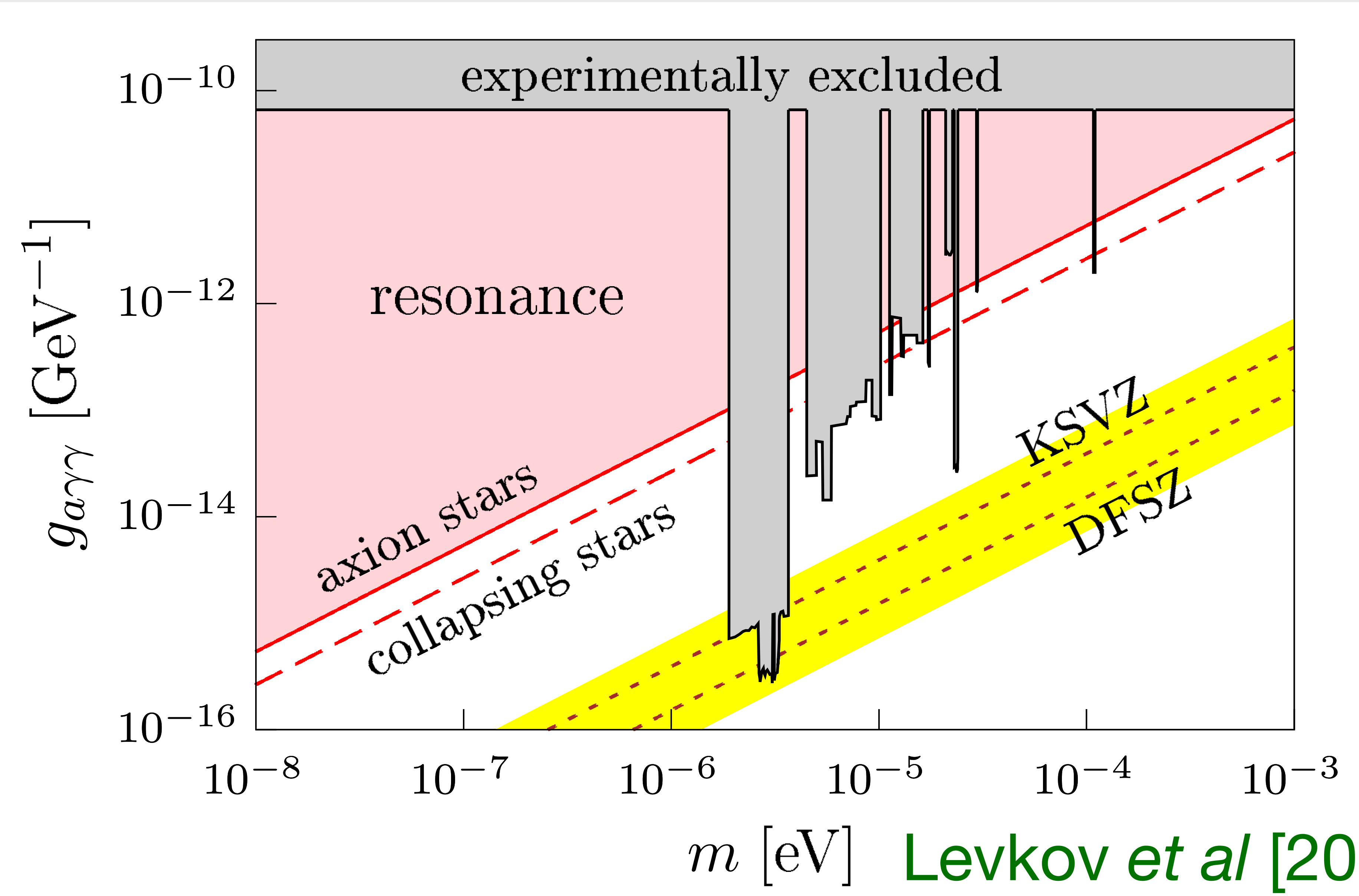
Instability in axion clumps

- Galactic condensates

  Carenza *et al* [1911.07838],
  Wang *et al* [2002.09144]

- Axion miniclusters
  Kephart & Weiler (1987, 1995), Tkachev [1411.3900],
  Sawyer [1809.01183], Chen & Kephart [2002.07885],
  Arza *et al* [2004.01669]
- Axion stars
  Tkachev (1986, 1987),
  Hertzberg & Schiappacasse [1805.00430],
  Levkov *et al* [2004.05179]
- Superradiant clouds around black holes
  Rosa & Kephart [1709.06581], Sen [1805.06417],
  Ikeda *et al* [1811.04950]

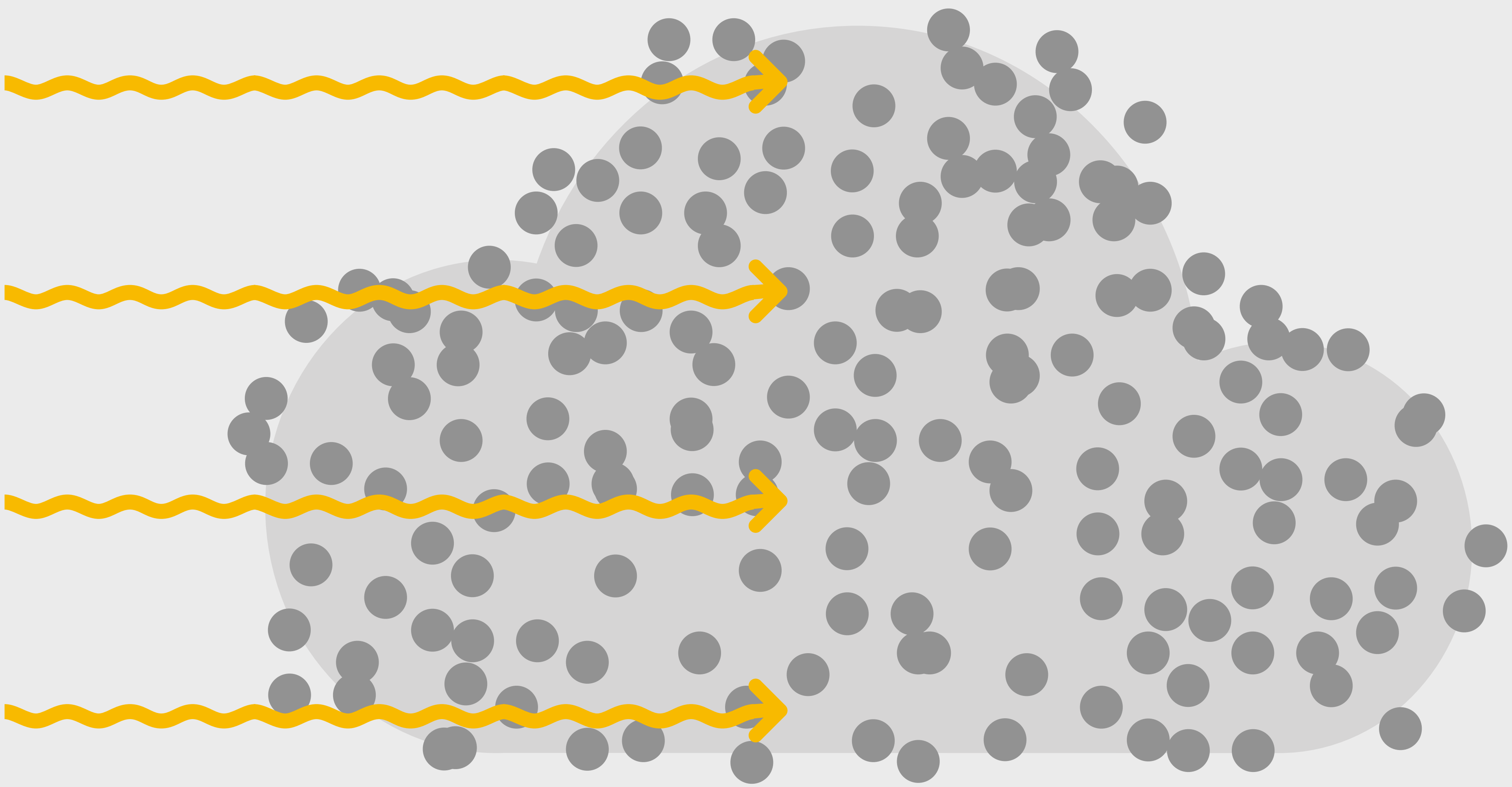
An example: QCD axion stars



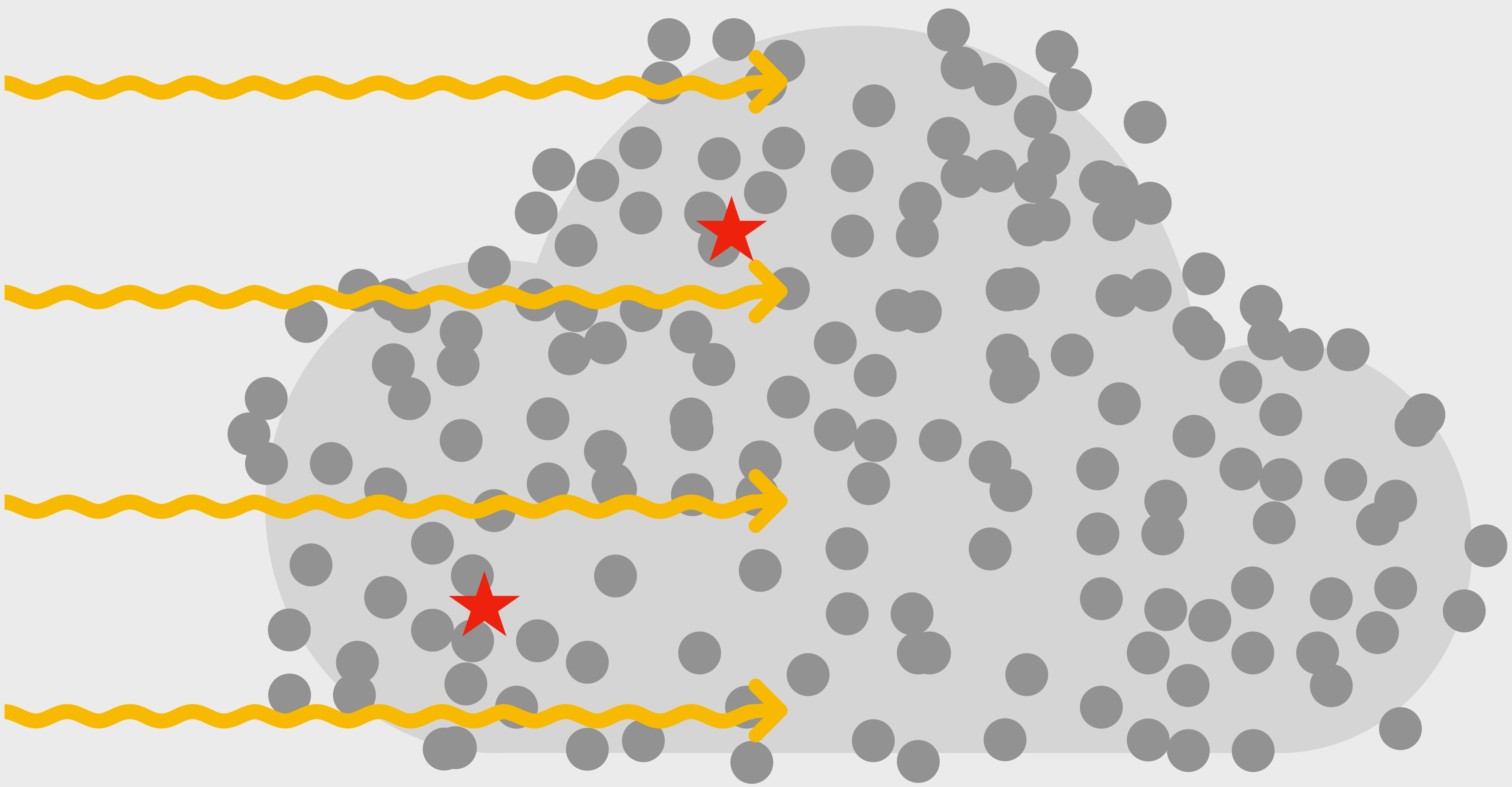
Levkov *et al* [2004.05179]

The instability is not reached, even in a critical star

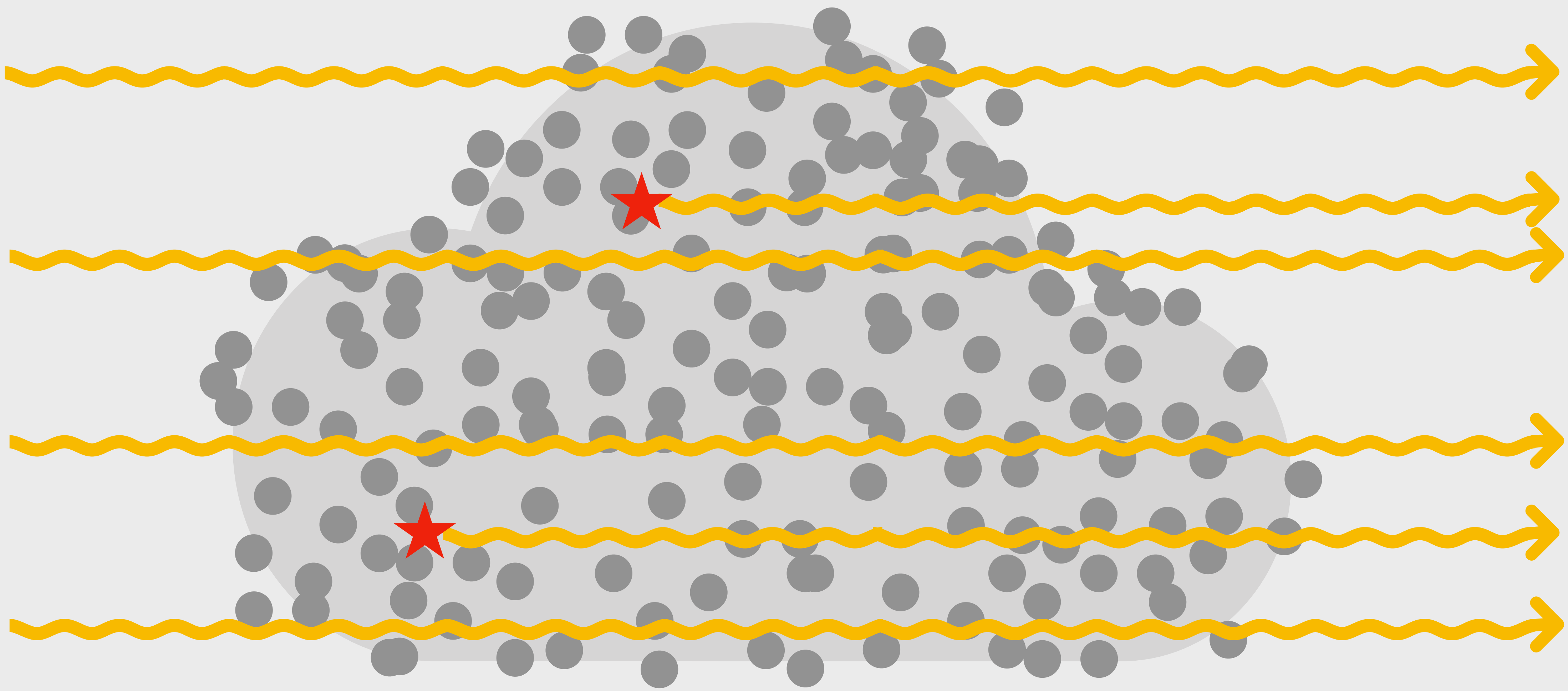
Amplification of background radiation



Amplification of background radiation



Amplification of background radiation



Effective also in the $\eta L \lesssim 1$ regime

Amplification of background radiation

- Photon propagation in axion backgrounds
  Espriu & Renau [1106.1662], Yoshida & Soda [1710.09198]
- Galactic condensates
  Arza [1810.03722], Sigl & Trivedi [1907.04849]
- Amplification of radio waves from axion decay
  Caputo *et al* [1805.08780]
- Axion stars
  Levkov *et al* [2004.05179]
- Axion dark matter echo
  Arza & Sikivie [1902.00114]

Conclusions

1. Axions with large occupation numbers are prone to parametric instabilities
    - Bose enhancement/stimulated decay
2. Expansion of the Universe and photon plasma mass shuts off the resonance
    - The ALP field is cosmologically stable
3. Axion clumps do not resonantly decay
    - Amplification effects can be important

Conclusions

1. Axions with large occupation numbers are prone to parametric instabilities
   - Bose enhancement/stimulated decay
2. Expansion of the Universe and photon plasma mass shuts off the resonance
   - The ALP field is cosmologically stable
3. Axion clumps do not resonantly decay
   - Amplification effects can be important

Thanks!