# Merger of Dark Matter Axion Clumps and Resonant Photon Emission

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DESY.

# Overview

- Axion clumps (stars): gravitationally bound objects from axions.
- Can originate from
  - PQ symmetry breaking after inflation, primordial black holes, instabilities, …
- Clumps above critical mass $M_\star$ an undergo parametric resonance into photons.

$$\mathcal{L}_{a\gamma\gamma} = g_{a\gamma\gamma}\phi\mathbf{E}\cdot\mathbf{B}$$

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- Can such phenomena take place today in the Milky way?
  - **Mergers of clumps**
- Outline of the talk
  - Field theory of axions and photons.
  - Axion star collisions and mergers.
  - Signatures via photon emission.

# Axion field theory

- Axion dark matter: high occupancies, classical field theory

$$\lambda = -\gamma \frac{m_\phi^2}{F_a^2}$$

$$\mathcal{L} = \sqrt{-g}\left[\frac{\mathcal{R}}{2\kappa^2} + \frac{g^{\mu\nu}}{2}\nabla_\nu\phi\nabla_\mu\phi - V(\phi)\right]$$

$$V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \mathcal{O}(\lambda^2\phi^6/m_\phi^2)$$

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$$\mathcal{L} = \sqrt{-g}\left[\frac{\mathcal{R}}{2\kappa^2} + \frac{g^{\mu\nu}}{2}\nabla_\nu\phi\nabla_\mu\phi - V(\phi)\right] \qquad V(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\lambda}{4!}\phi^4 + \mathcal{O}(\lambda^2\phi^6/m_\phi^2)$$

- Focus on the nonrelativistic regime: $\phi(\mathbf{x},t) = \frac{1}{\sqrt{2m_\phi}}\left[\mathrm{e}^{-im_\phi t}\psi(\mathbf{x},t) + \mathrm{e}^{im_\phi t}\psi^*(\mathbf{x},t)\right]$ .
  - The Hamiltonian (nonexpanding background)

$$H_{\rm nr} = H_{\rm kin} + H_{\rm int} + H_{\rm grav}\,,$$

where

$$H_{\rm kin} = \frac{1}{2m_\phi}\int d^3x \nabla\psi^*\cdot\nabla\psi\,,$$

$$H_{\rm int} = \frac{\lambda}{16m_\phi^2}\int d^3x\, \psi^{*2}\psi^2\,,$$

$$H_{\rm grav} = -\frac{G_N m_\phi^2}{2}\int d^3x\int d^3x' \frac{\psi^*(\mathbf{x})\psi^*(\mathbf{x}')\psi(\mathbf{x}')\psi(\mathbf{x})}{|\mathbf{x}-\mathbf{x}'|}\,.$$

  - Equations of motion:

$$\begin{cases} i\dot\psi = -\frac{1}{2m_\phi}\nabla^2\psi + m_\phi\psi\phi_N - \frac{|\lambda|\,\psi^*\psi^2}{8m_\phi^2} \\ \nabla^2\phi_N = 4\pi G_N m_\phi|\psi|^2\,. \end{cases}$$

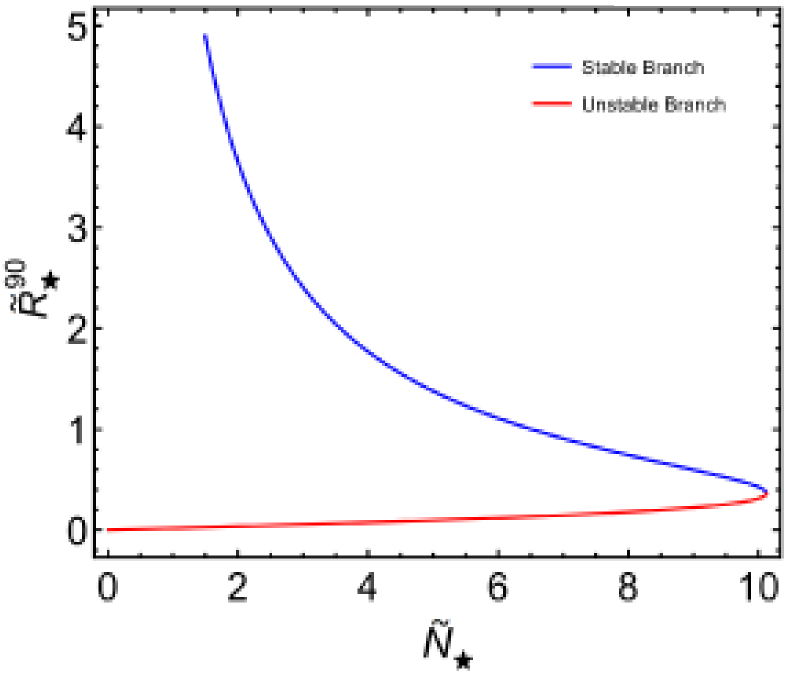
# Axion clumps/stars

- Spherically symmetric solutions, e.g. sech-profile: $\Psi_R(r) = \sqrt{\frac{3N_\star}{\pi^3 R^3}}\,\mathrm{sech}(r/R)$

# Axion clumps/stars

- Spherically symmetric solutions, e.g. sech-profile: $\Psi_R(r) = \sqrt{\frac{3N_\star}{\pi^3 R^3}}\,\mathrm{sech}(r/R)$
- Energy of axion star: $\tilde{H}(\tilde{R}) = a\frac{\tilde{N}_\star}{\tilde{R}^2} - b\frac{\tilde{N}_\star^2}{\tilde{R}} - c\frac{\tilde{N}_\star^2}{\tilde{R}^3}$

$$H = \left(\frac{F_a^3}{m_{Pl} m_\phi \gamma^{3/2}}\right)\tilde{H}\,, \quad R = \left(\frac{m_{Pl}\gamma^{1/2}}{m_\phi F_a}\right)\tilde{R}\,, \quad N_\star = \left(\frac{m_{Pl} F_a}{m_\phi^2 \gamma^{1/2}}\right)\tilde{N}_\star$$




Two branches:

- Stable (blue) and unstable (red) branches
- Gravity or self-interactions dominant

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Maximum mass: $M_{\star,\max} = N_{\star,\max} m_\phi$

$$M_\star(R_\star) = \alpha\, M_{\star,\max}(R^{90}_{\star,\min})\,,$$
$$R_\star = g(\alpha)\, R^{90}_{\star,\min}\,,$$

$$g(\alpha) \equiv (1 + \sqrt{1-\alpha^2})/\alpha \quad \text{with} \quad \alpha \in (0, 1].$$

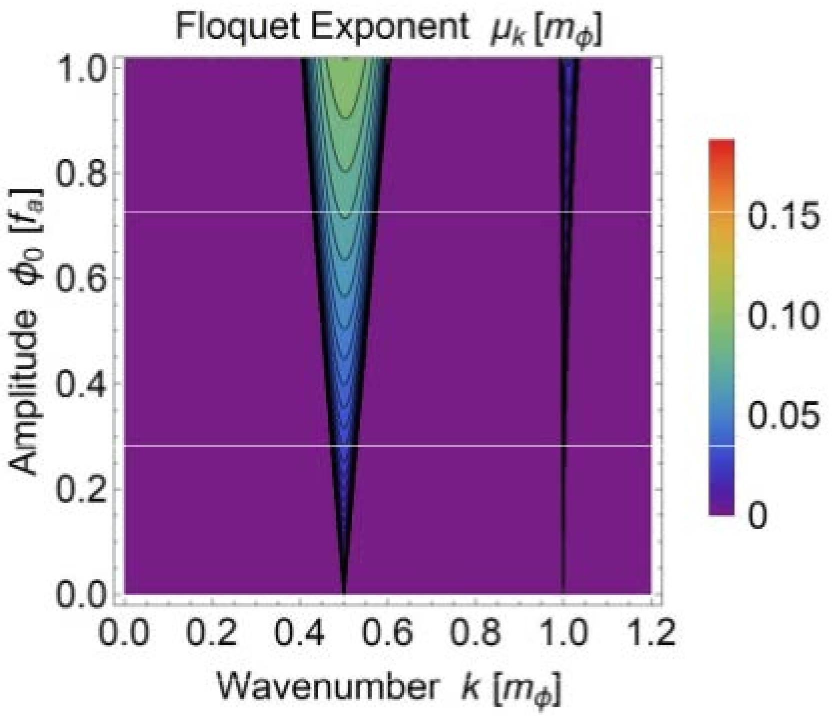
# Parametric resonance into photons

- Number conservation.
  - But there can be number-changing process via **decay into photons,** $\phi \to \gamma\gamma$.

- Equations of motion:
  - Homogeneous axion field: $\phi(t) = \phi_0 \cos(\omega_0 t)$
  - Coulomb gauge, $\nabla \cdot \hat{\mathbf{A}} = 0$

$$\ddot{\hat{\mathbf{A}}} - \nabla^2 \hat{\mathbf{A}} + g_{a\gamma\gamma} \nabla \times (\partial_t \phi \hat{\mathbf{A}}) = 0$$

- Parametric resonance.
  - Most unstable mode: $k \approx m_\phi / 2$



# Parametric resonance into photons

- Equations of motion:
  - Axion clump: expand in spherical harmonics

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$$\hat{\mathbf{A}}(\mathbf{x},t) = \int \frac{d^3k}{(2\pi)^3} \sum_{\mathrm{lm}} \left[\hat{a}(k) v_{\mathrm{lm}}(k,t) \mathbf{M}_{\mathrm{lm}}(k,\mathbf{x}) - \hat{b}(k) w_{\mathrm{lm}}(k,t) \mathbf{N}_{\mathrm{lm}}(k,\mathbf{x}) + h.c.\right]$$

where

$$\mathbf{M}_{\mathrm{lm}}(k,\mathbf{x}) = \frac{i j_{\mathrm{l}}(kr)}{\sqrt{\mathrm{l}(\mathrm{l}+1)}} \left[\frac{i\mathrm{m}}{\sin\theta} Y_{\mathrm{lm}} \hat{\theta} - \frac{\partial Y_{\mathrm{lm}}}{\partial \theta} \hat{\varphi}\right]$$

$$ik\mathbf{N}_{\mathrm{lm}}(k,\mathbf{x}) = -\nabla \times \mathbf{M}_{\mathrm{lm}}(k,\mathbf{x}) \,,$$

  - Focus on specific harmonics, i.e. $l = 1, m = 0$.

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  - Focus on specific harmonics, i.e. $l = 1, m = 0$.
- Parametric resonance.
  - Resonance condition: $g_{a\gamma\gamma} F_a > 0.28 \left(\frac{\gamma}{0.3}\right)^{1/2} \left[\frac{g(\alpha)}{\alpha}\right]^{1/2} > 0.28 \left(\frac{\gamma}{0.3}\right)^{1/2}$
  - Inefficient for conventional axions, $g_{a\gamma\gamma} F_a \sim O(10^{-2})$.

# Numerical setup

- Rectangular lattice + absorbing boundary conditions: “sponge” potential

$$V_{\text{sponge}} = -i\frac{V_0}{2}\left[2 + \frac{\tanh(\tilde{r} - \tilde{r}_{\text{sponge}})}{\delta} - \tanh(\tilde{r}_{\text{sponge}}/\delta)\right]$$

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- Split-step beam method:

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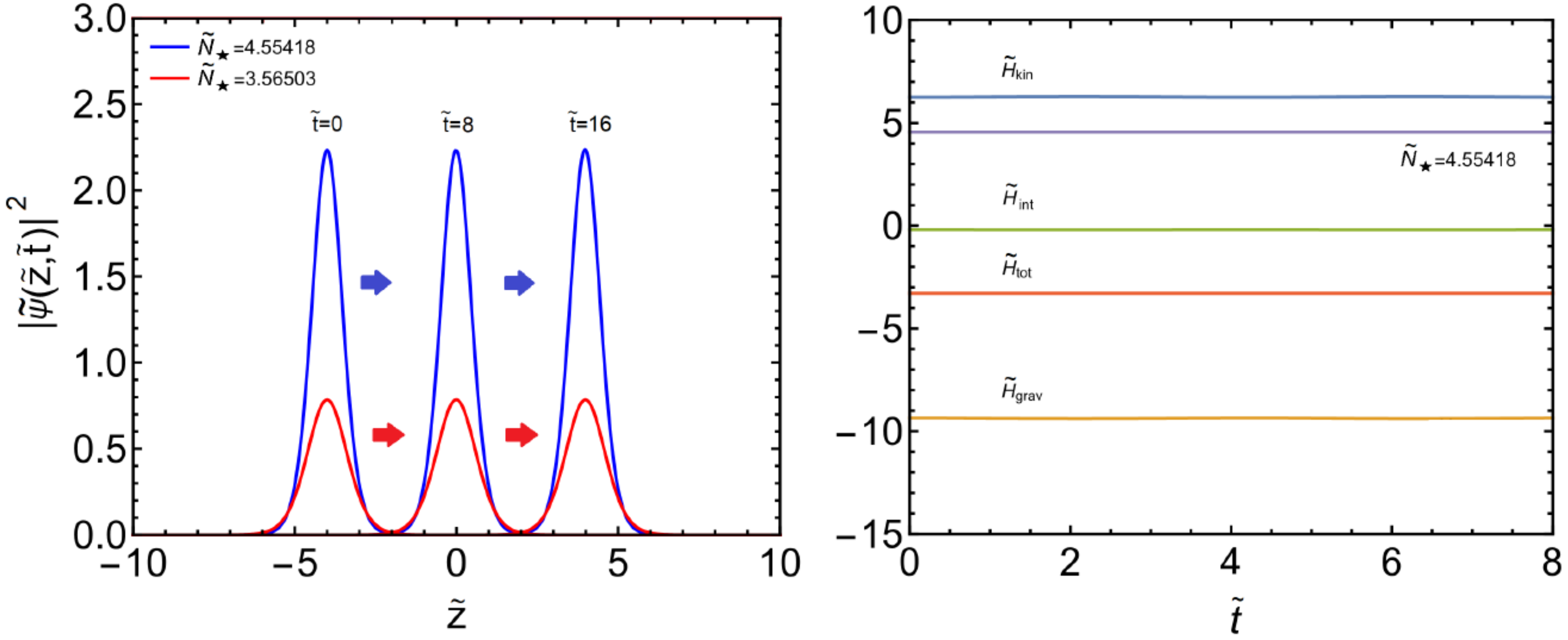
- Split-step beam method:

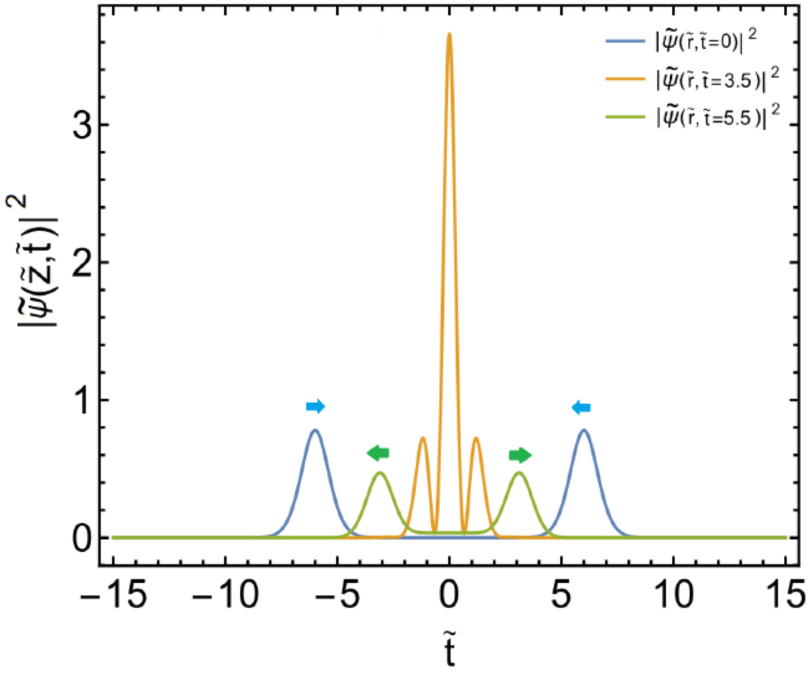
- Test
    - evolve individual clumps in the ground state configuration

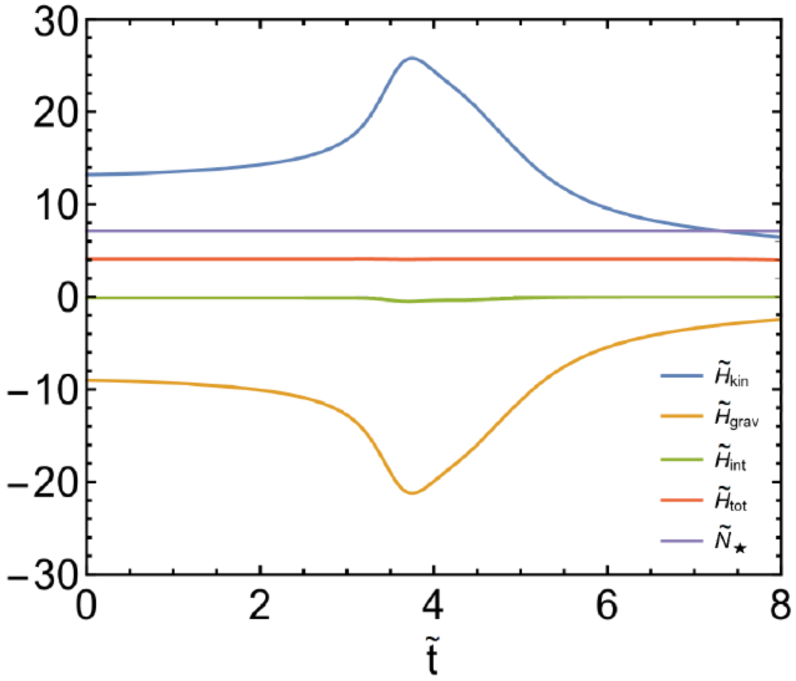


# Collisions of axion stars

- Case 1
  - Head on
  - $N_{1\star} = N_{2\star}$,
  - zero phase difference.
  - Large relative velocity: $E_{\text{tot}} > 0$.

No merger!



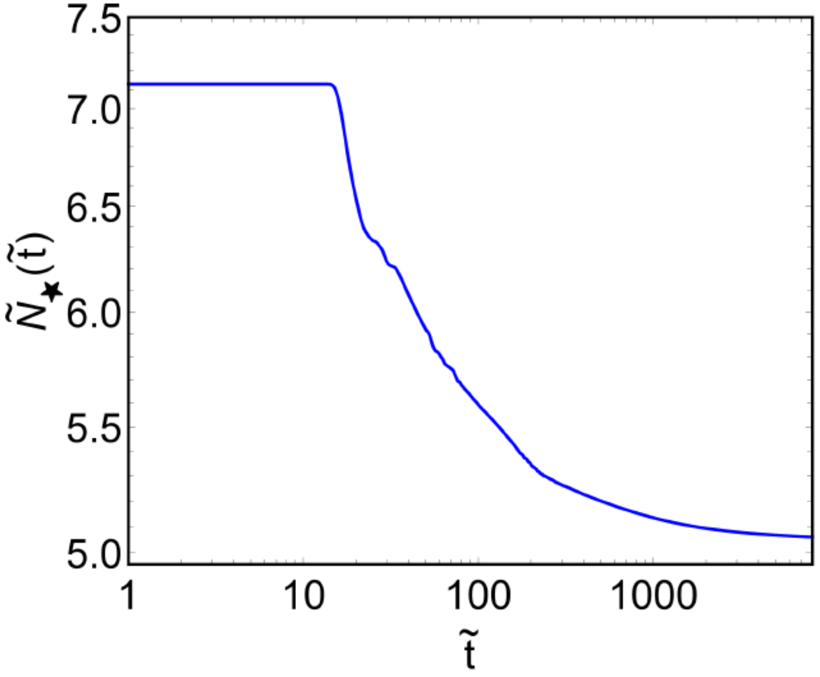



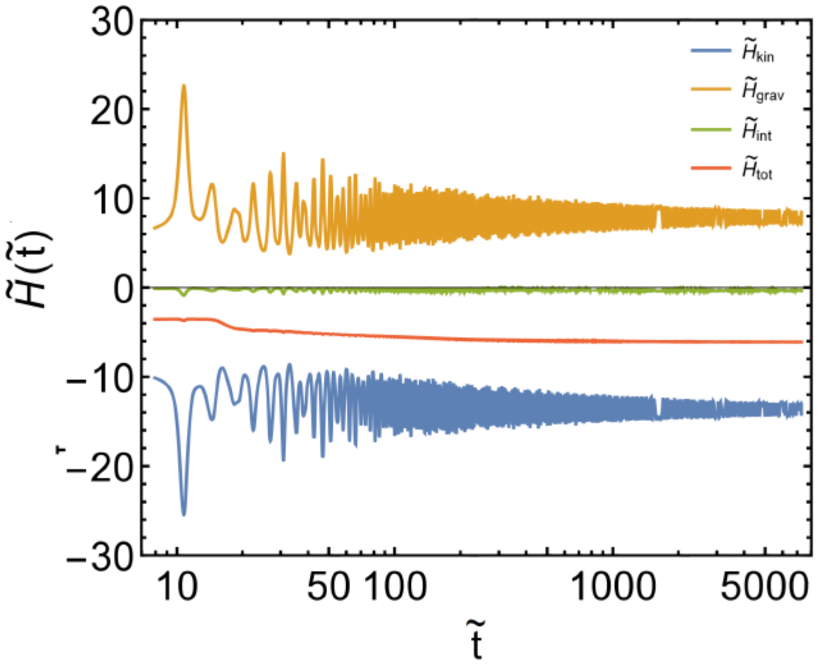
# Collisions of axion stars

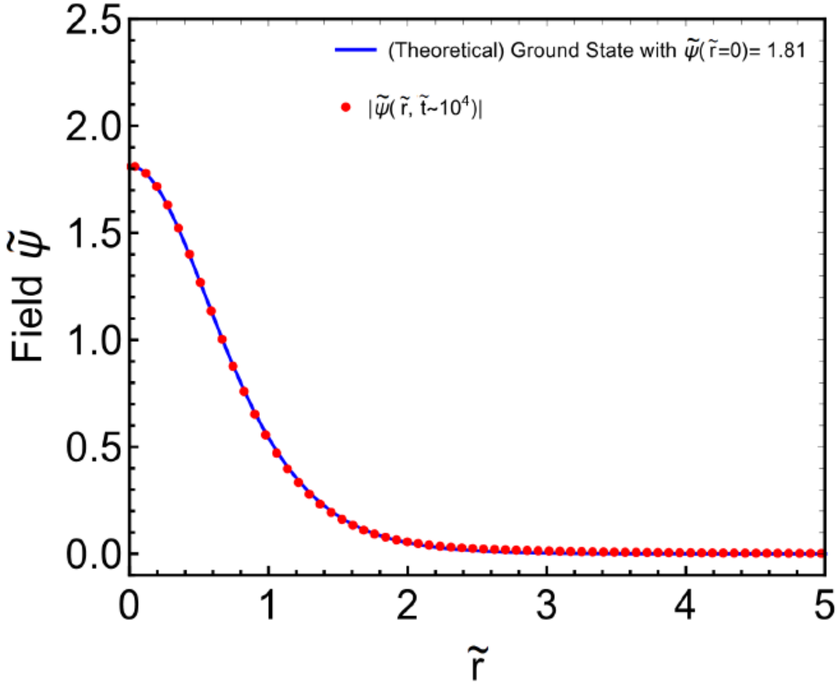
- Case 2
  - Head on
  - $N_{1\star} = N_{2\star}$,
  - zero phase difference.
  - Small relative velocity: $E_{\text{tot}} < 0$.

Merger!

$$N^{\star}_{\text{final}} \simeq 0.7(N_{\star,1} + N_{\star,2})$$

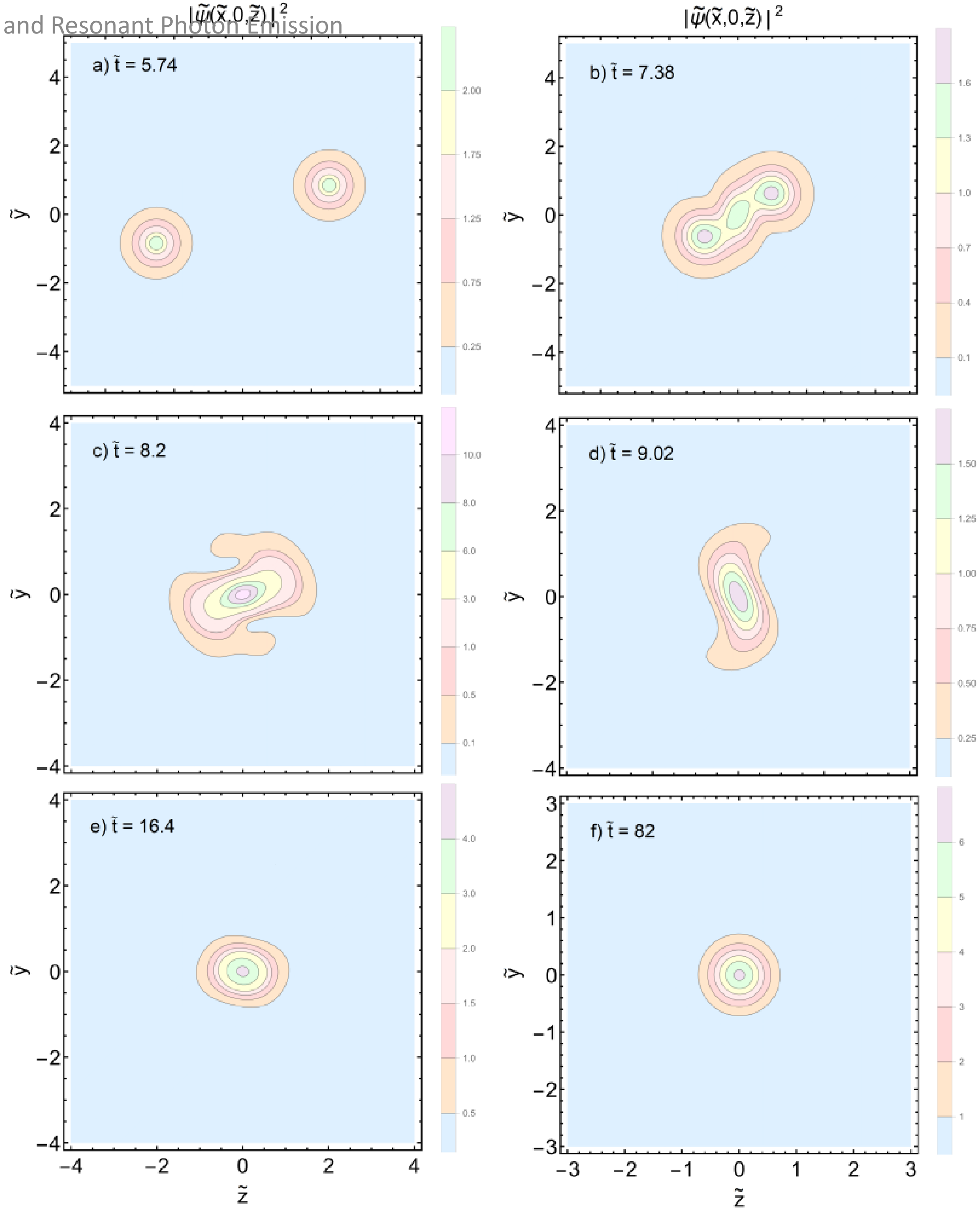


# Collisions of axion stars

- Case 3
  - Nonzero impact parameter on
  - $N_{1\star} = N_{2\star}$,
  - zero phase difference.
  - Small relative velocity: $E_{\text{tot}} < 0$.

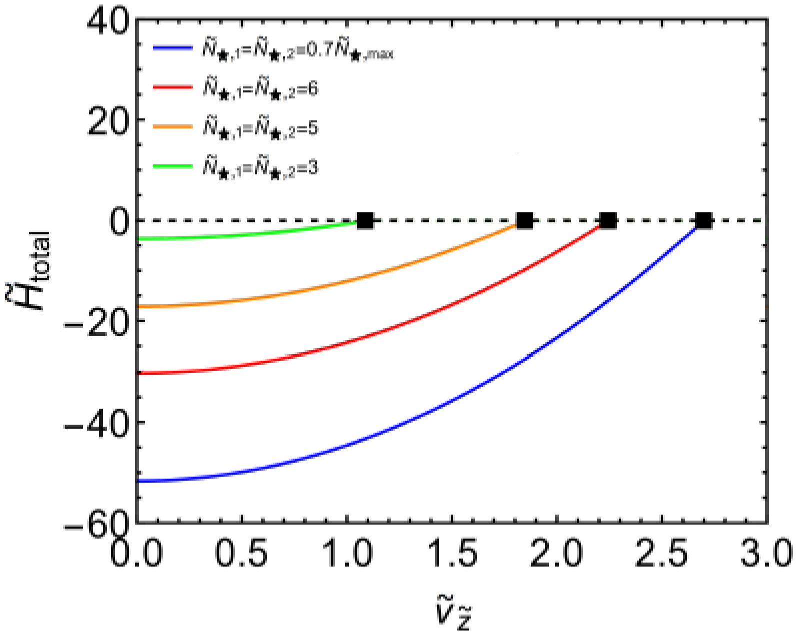


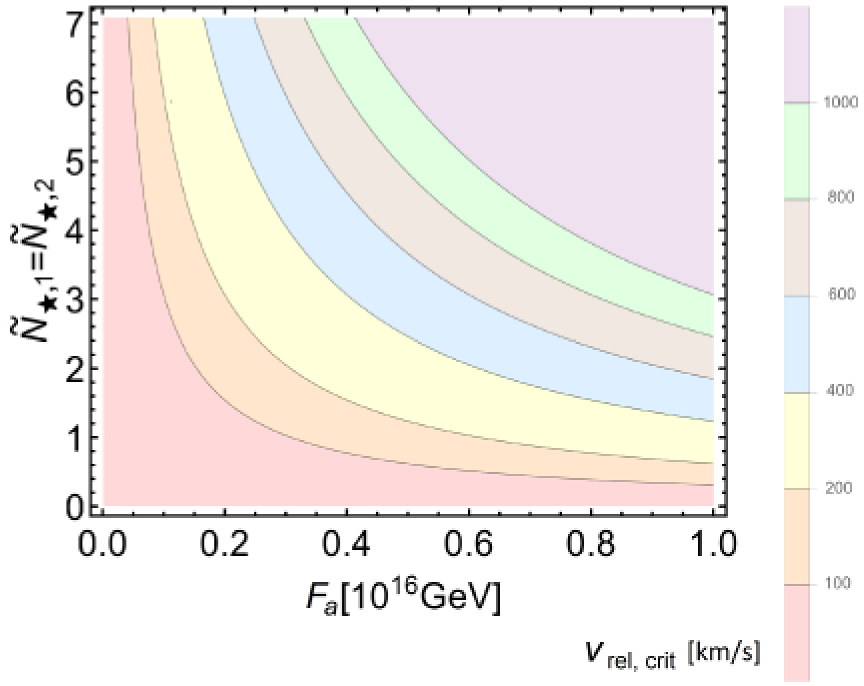
# Parameter space for merger

- If the total energy of the colliding clumps is negative, they will merge.

$$H_{\rm tot}^{\rm initial} \simeq 2H_{\rm kin} + 2H_{\rm grav} + 2H_{\rm int} + 2H_{\rm kin}^{\rm cm} + H_{\rm grav}^{\star-\star}$$

- Mergers are common for $F_a > 10^{16}\text{GeV}$ and rare if $F_a > 10^{16}\text{GeV}$.



# Interference

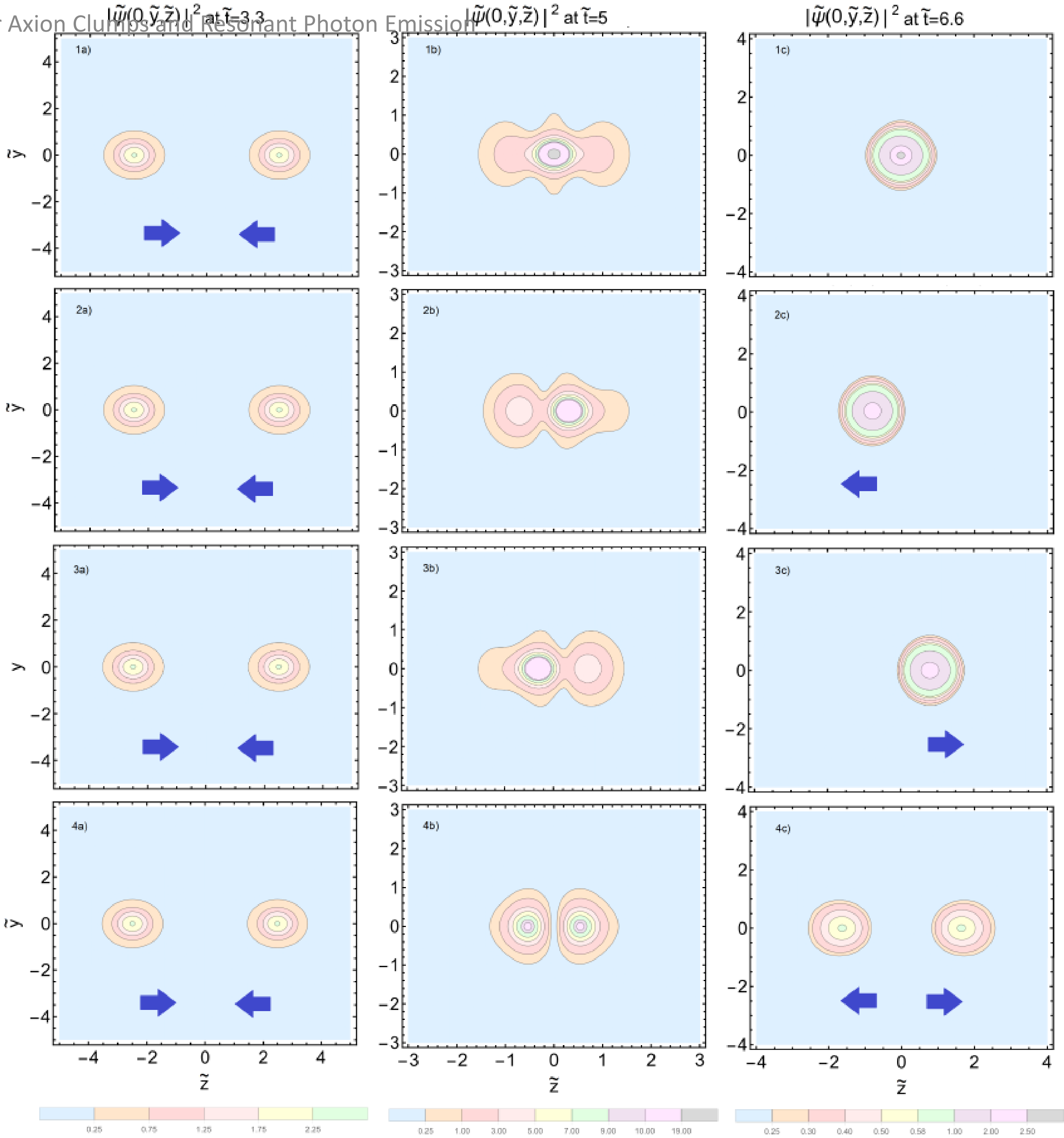
Case of nonzero phase difference

$\delta = 0$

$\delta = \frac{\pi}{2}$

$\delta = \frac{3\pi}{2}$

$\delta = \pi$



# Interference

## Case of nonzero phase difference

$$\tilde{\psi}(\tilde{\mathbf{x}},\tilde{t}) = \tilde{\psi}(\sqrt{\tilde{x}^2+\tilde{y}^2+(\tilde{z}+\tilde{z}_0)^2})e^{i(\tilde{v}_z\tilde{z}+\tilde{\mu}\tilde{t})} + \tilde{\psi}(\sqrt{\tilde{x}^2+\tilde{y}^2+(\tilde{z}-\tilde{z}_0)^2})e^{-i(\tilde{v}_z\tilde{z}-\tilde{\mu}\tilde{t}+\delta)} \,,$$

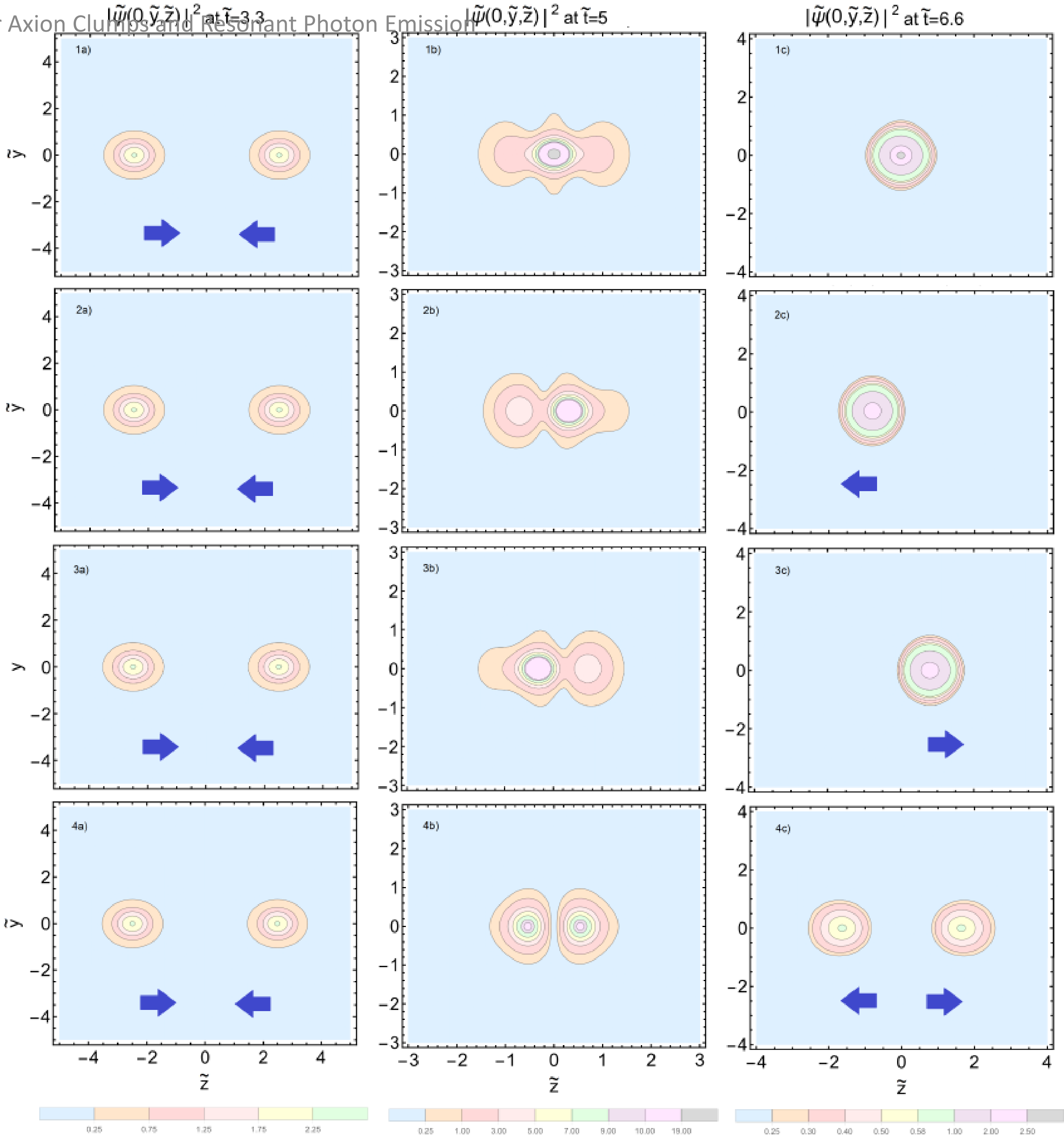
$$|\tilde{\psi}(\tilde{\mathbf{x}},\tilde{t}_{\rm int})|^2 = 2|\tilde{\psi}\sqrt{\tilde{x}^2+\tilde{y}^2+\tilde{z}^2}|^2\left[1+\cos(2\tilde{v}_z\tilde{z}+\delta)\right] .$$

$\delta = 0$

$\delta = \frac{\pi}{2}$

$\delta = \frac{3\pi}{2}$

$\delta = \pi$



# Collision and merger rate

$f_\star^{DM}$ fraction of DM in axion stars

- Collision rate: $$\Gamma_{\star-\star} = 4\pi \int_0^{R_{\mathrm{halo}}} \frac{r^2}{2} \left( \frac{\rho_{\mathrm{halo}}(r) f_\star^{\mathrm{DM}}}{M_\star} \right)^2 \langle \sigma_{\mathrm{eff}}(v_{\mathrm{rel}}) v_{\mathrm{rel}} \rangle \, dr$$

Averaged collision cross-section

$$\langle \sigma_{\mathrm{eff}}(v) v \rangle = 4\pi \int_0^{v_{\mathrm{esc}}} p(v) \sigma_{\mathrm{eff}}(v) v^3 dv$$

$$\sigma_{\mathrm{eff}}(v_{\mathrm{rel}}) = \pi (R_\star + R_\star)^2 \left( 1 + \frac{v^2_{\star,\mathrm{esc}}}{v^2_{\mathrm{rel}}} \right)$$

$$p(v) = p_0 \exp[-v^2/v_0^2]$$

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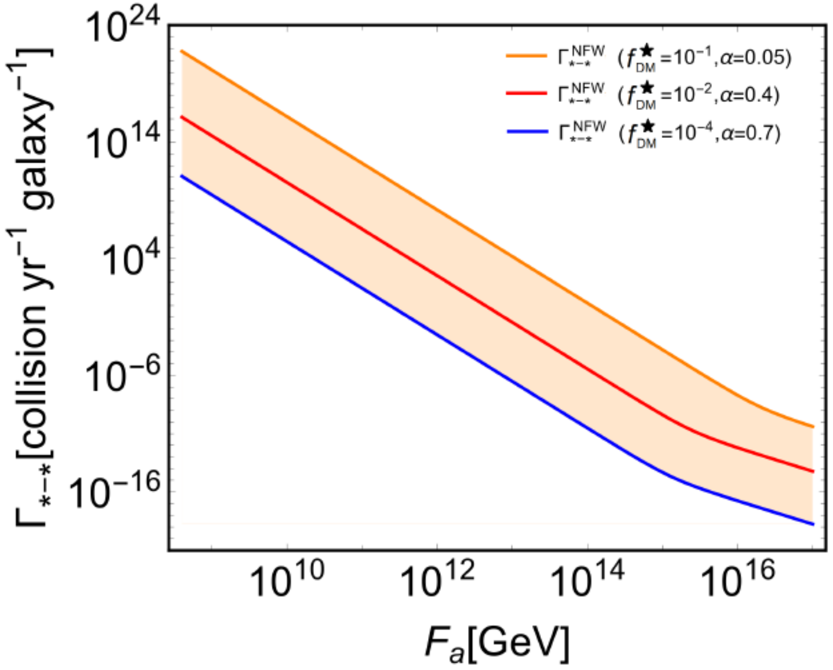
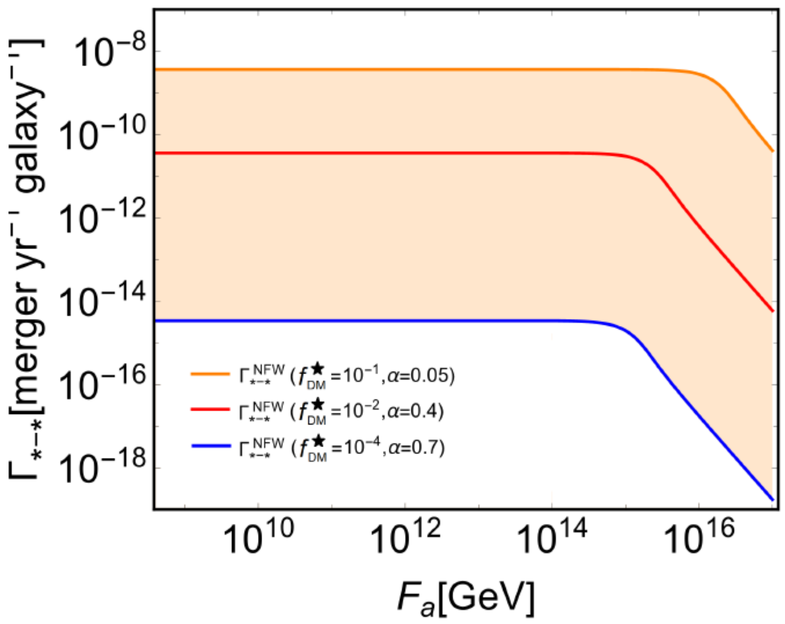
## Collision rate




## Merger rate



# Photon emission

- Axion star formation in the early universe
  - Supercritical stars undergo parametric resonance
  - Subcritical stars capture axions from the background

⟹ A pile-up of clumps of unique value of mass

- Merger of clumps → decay into photons: $E_{\star,\gamma} = m_\phi\left[0.7\left(N_{\star,1} + N_{\star,2}\right) - N_c\right]$

- Center frequency of the signal: $\nu_{\mathrm{EM}} \approx 1.2\,\mathrm{GHz}\left(\frac{m_\phi}{10^{-5}\,\mathrm{eV}}\right)$

- Typical energy flux: $S = \frac{\Delta E/\Delta t}{4\pi D^2} \sim 5\times 10^{-3}\,\mathrm{W/m^2}\left(\frac{\alpha - 0.71\alpha_c}{g(\alpha)}\right)\left(\frac{F_a}{6\times 10^{11}\,\mathrm{GeV}}\right)^2\left(\frac{50\,\mathrm{kpc}}{D}\right)^2\left(\frac{0.3}{\gamma}\right)$

(for comparison, $S_{sun} = 1370\,\mathrm{W/m^2}$.)

# Detectability

- For $10^{10}\,\mathrm{GeV} \lesssim F_a \lesssim 10^{13}\,\mathrm{GeV},$ the central frequency is in the range

$$70\,\mathrm{MHz} \lesssim \nu_{\mathrm{EM}} \lesssim 70\,\mathrm{GHz}$$

  - Covered by current (and prospective) radio telescopes: Arecibo, FAST, JVLA, GBT, SKA.

- For $F_a \gtrsim 10^{15}\,\mathrm{GeV}$, the frequencies are even lower
  - absorption and scattering produced by the ionosphere.
  - requires a space or Lunar-based radio telescope.

# Discussion

- A novel way for detecting axion dark matter explored.
- Mergers can lead to super-critical mass clumps, which can undergo parametric resonance into photons, depending on the axion-photon coupling.
- For smaller $F_a$ collision rate is large, but typically no mergers
- For larger $F_a > 10^{15}\mathrm{GeV}$, typical collision leads to mergers, but the rate is small, and low-frequency telescopes required.

# Thank you for your attention!