Axion–like dark matter and Bose stars

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Light Axion–Like Particles (ALP)

$\boxed{a(x)}$

- (pseudo)scalars
- low mass m_a

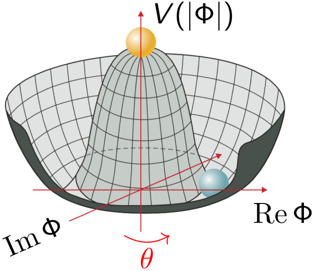
} Pseudo–Nambu–Goldstone bosons

Low energies: $\Phi = f_a \cdot \mathrm{e}^{i\theta(x)}$

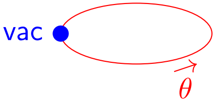
$$\mathcal{L}_{\rm eff} \sim \underbrace{\overset{\text{theory scale}}{\overset{\downarrow}{f_a^2}}(\partial_\mu\theta)^2}_{\text{Goldstone theorem}} - \underbrace{\overset{\text{breaking scale}}{\overset{\downarrow}{\Lambda^4}}\mathcal{V}(\theta)}_{\text{explicit breaking}}$$

- $\boxed{\theta = a(x)/f_a}$ — canonical field
- $\mathcal{V} = \underbrace{(\Lambda^2/f_a)^2}_{m_a^2\text{ — mass}} a^2 - \underbrace{(m_a/f_a)^2}_{\lambda\text{— coupling}} a^4 + \dots$
- Interactions are suppressed! $(\theta = a/f_a)$:

$$\mathcal{L}_{\rm eff} \supseteq \underbrace{g_{a\gamma\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}}_{f_a^{-1}\times\text{ photons}} + \underbrace{g_{a\psi}\, \partial_\mu a\, \bar{\psi} i\gamma^\mu\gamma^5\psi}_{f_a^{-1}\times\text{ fermions}}$$



$\boxed{\text{Low E: } \Phi = f_a \cdot \mathrm{e}^{i\theta(x)}}$



- Breaking: 1 vacuum

Popular models

QCD axions

Peccei, Quinn '77

- Strong CP–problem:

  $\Delta\mathcal{L}_{QCD} \sim \theta\, G_{\mu\nu}\tilde{G}^{\mu\nu}$, $\underbrace{\theta < 10^{-10}}_{\text{experiment}}$

- Solution — field $\Phi(x)$!

  low E: $\Phi = f_a \cdot \mathrm{e}^{i\theta(x)}$

  explicit breaking $\equiv$ anomaly

  $\mathcal{V} \sim \theta(x)\, G_{\mu\nu}\tilde{G}^{\mu\nu}$

  $\langle\mathcal{V}\rangle_{QCD} \sim f_\pi^2 m_\pi^2\, [1 - \cos\theta]$

- Axion field: $\boxed{\theta = a(x)/f_a}$

  mass: $m_a \sim f_\pi m_\pi / f_a$

  interactions: *e.g. di Cortona et al '16*

  $g_{a\gamma\gamma} = c f_a^{-1}$, $10^{-4} \lesssim c \lesssim 1$

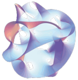
  $g_{ap} \sim g_{an} \sim f_a^{-1}$

String axions

e.g. Arvanitaki et al '10

- Strings live in

  $10d = 4d \quad \times$



  6d Calabi–Yau

- Axions = CY «symmetries» $\theta_i(x)$

  typically $\sim$ 30 axions

  scale: $f_a \equiv a/\theta \sim 10^{-2}\, M_{pl}$

  explicit breaking $\equiv$ instantons

- Interactions are tiny!

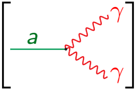
  mass: $m_a \propto \underbrace{\mathrm{e}^{-S_{inst}/2}}_{\text{arbitrary!}}$

  $g_{a\gamma\gamma} \sim g_{ap} \sim g_{an} \propto f_a^{-1}$

  $\lambda \sim m_a^2/f_a^2 \sim 10^{-100}$

Light axions form good dark matter!

- They are long–living:



$$\Gamma\left[\ a \to \gamma\gamma\ \right] \sim \underbrace{g_{a\gamma\gamma}^2 m_a^3}_{\propto m_a^5} \ll \left(10^{10}\ \text{yr}\right)^{-1}$$

$$\Rightarrow \boxed{m_a \ll 100\ \text{eV}}\ \text{(QCD axions)}$$

- They should fit into galaxies:

$$(m_a v)^{-1} \lesssim \text{kpc} \quad \Rightarrow \quad \boxed{m_a \gtrsim 10^{-22}\ \text{eV}}$$

- Quantum («fuzzy») dark matter:

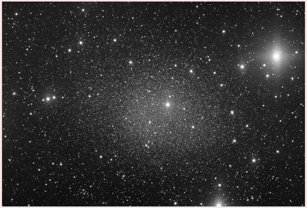
$$(m_a v)^{-1} \sim \text{kpc} \quad \Rightarrow \quad m_a \sim 10^{-22}\ \text{eV}$$

- Large occupation numbers:

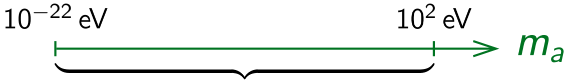
$$m_a \ll 100\ \text{eV} \quad \Rightarrow \quad f \sim N_a/(R m_a v)^3 \gg 1$$

thermalization ⇒ Bose–Einstein condensation

Fornax galaxy



$\rho_{dm} \sim 0.1\ M_\odot/\text{pc}^3$
$R \sim \text{kpc}$
$v \sim 10\ \text{km/s}$



10^{-22} eV

10^2 eV

m_a

Axion–like dark matter

Generation: vacuum realignment at $f_a > H_{\text{infl}}$

- Works for string axions & low-mass QCD axions
- $\Phi = f_a \cdot \mathrm{e}^{i a(t,\boldsymbol{x})/f_a}$ prior to inflation
- After inflation: $a = a(t)$

$$\underbrace{\ddot a + m_a^2\, a}_{\text{pendulum}} + \underbrace{3H(t)\,\dot a}_{\substack{\text{friction}\\ H \propto t^{-1}}} = 0$$

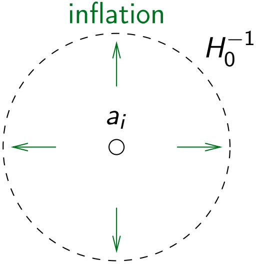
- Solution: $a \sim \begin{cases} \text{const}\,, & m_a < 3H \\ a_i\, t^{-3/4} \underset{\uparrow}{\cos(m_a t)}\,, & m_a > 3H \end{cases}$

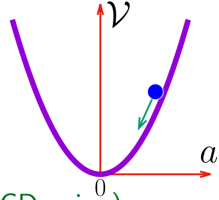
waves (particles) with $\boldsymbol{p} = \boldsymbol{0}$

- Present–day density: $\rho_a \propto \underbrace{a_i^2\, m_a^2 \sim 25\%\, \rho_c}_{\text{fixes } a_i}$

Antropic window: $\underbrace{a_i \ll 2\pi f_a}_{\text{fine-tuning}}$ if $m_a \ll 2 \cdot 10^{-5}$ eV (QCD axion)

- Constraints from inflation: $H_{\text{infl}} \lesssim 10^{14}\,\text{GeV} \left(\dfrac{10^{-11}\,\text{eV}}{m_a}\right)^{1/4}$

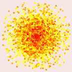




Generation: vacuum realignment at $f_a < H_{\rm infl}$

- Spontaneous breaking: $\Phi = f_a \cdot \mathrm{e}^{ia(x)/f_a}$ at $T \lesssim f_a$
  - $\to$ volumes $l_H = H^{-1}$ are causally disconnected
  - $\Rightarrow$ different $a(x)$ inside each l_H
  - $\Rightarrow$ strings of thickness f_a^{-1} *Kibble '76*
- $m_a < 3H$ — massless $a(x)$
  - $\Rightarrow$ mix inside l_H
- $m_a \gtrsim 3H$ — massive $a(x)$ & a single vacuum $a = 0$
  - $\to$ dust: $a \propto \cos(m_a t)$
  - $\Rightarrow$ **inhomogeneities of size l_H: $m_a \sim 3H$!**
  - $\to$ but also: domain walls form $0 \to a \to 2\pi f_a$
    strings & walls annihilate!

Inhomogeneities $\Rightarrow$ axion miniclusters *Kolb, Tkachev '94*



grav/bound

Now (QCD axions): 70% in miniclusters,

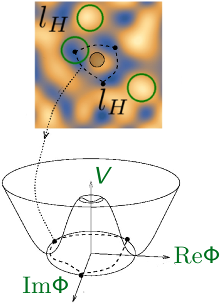
$R_{\rm mc} \sim 10 \div 500$ AU, $M_{\rm mc} \sim 10^{-(10\div 18)} M_\odot$

Pierobon et al '23

- QCD axions: $T \sim$ GeV (QCD phase transition)

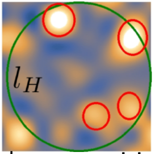
$m_a < 3H(t)$

radiation



$m_a > 3H(t)$

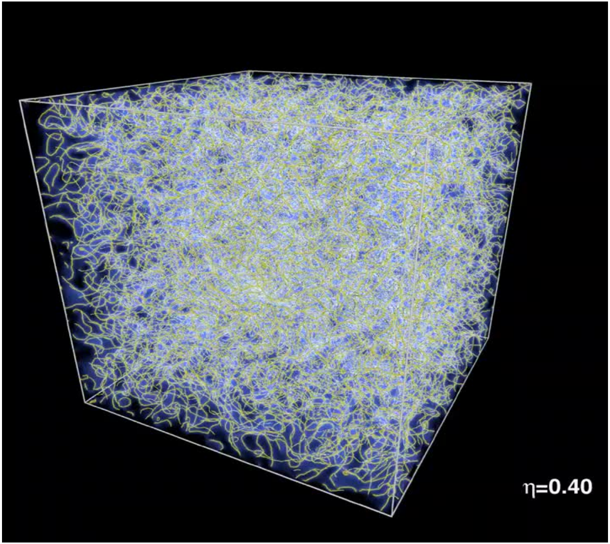
dust = «sand»



inhomogeneities

Simulation of QCD phase transition

Buschmann, Foster, Safdi '19



Simulations:

Kolb, Tkachev '94

Klaer, Moore '17

Buschmann et al '19 '22

Ghorghetto et al '20

$$\rho_a = 25\%\,\rho_c$$

$$\Downarrow$$

$$m_a = \underbrace{10^{-5}\dots10^{-3}}\,\text{eV}$$

Systematics: $\frac{f_a}{H} \sim 10^{30}$

$$\Downarrow$$

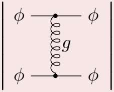
minicluster uncertainties

Bose–Einstein condensation via gravitational scattering

DL, Panin, Tkachev '18

- Gravitational relaxation:

Rutherford cross section



$$\sigma_{gr} = \left| \cdots \right|^2 \propto \frac{(m_a G)^2}{v^4}$$

$$t_{gr} \sim \frac{1}{\sigma_{gr}\, v\, n\, f}$$

Bose amplification

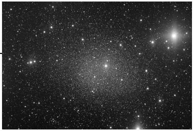
(phase density)

$$f \propto \frac{n}{m_a^3 v^3}$$

large factors at $\boxed{v \ll 1,\ f \gg 1}$

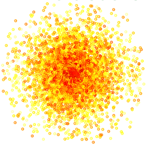
- «Fuzzy» DM in dwarf galaxies:
  $m_a \sim 10^{-22}$ eV $\Rightarrow t_{gr} \gtrsim 10^6$ yr
  Ly-α bound: $m_a \gtrsim 2 \cdot 10^{-20}$ eV $\Rightarrow t_{gr} \gtrsim 10^{14}$ yr
  Rogers, Peiris '20

dwarf galaxy



- QCD axions in miniclusters:
  $m_a \sim 10^{-4}$ eV, $t_{gr} \gtrsim$ hr

miniclusters



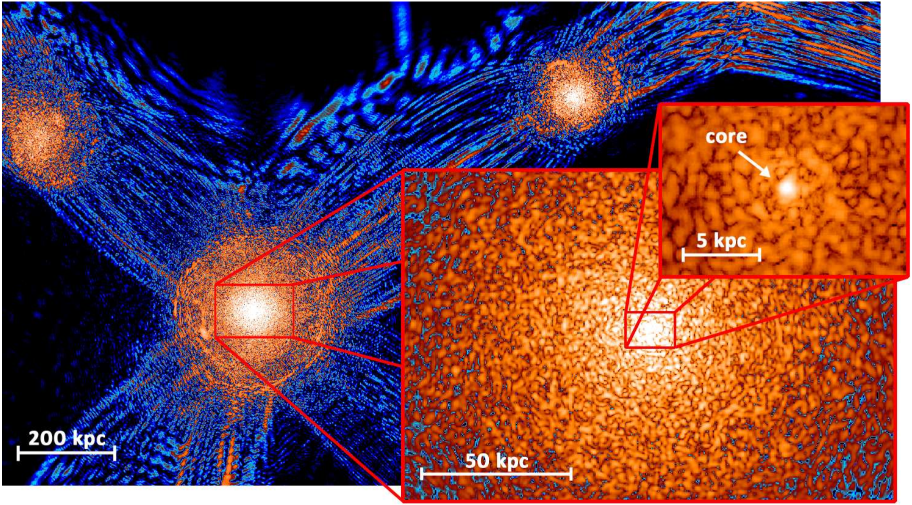
- $\boxed{f \gg 1}$ $\begin{cases} \text{relaxation} \Rightarrow \text{Bose condensation} \\ \text{classical field } a(x) \end{cases}$

Bose–Einstein Condensate in miniclusters!

Condensate in «fuzzy» dark matter, $m_a \sim 10^{-22}$ eV

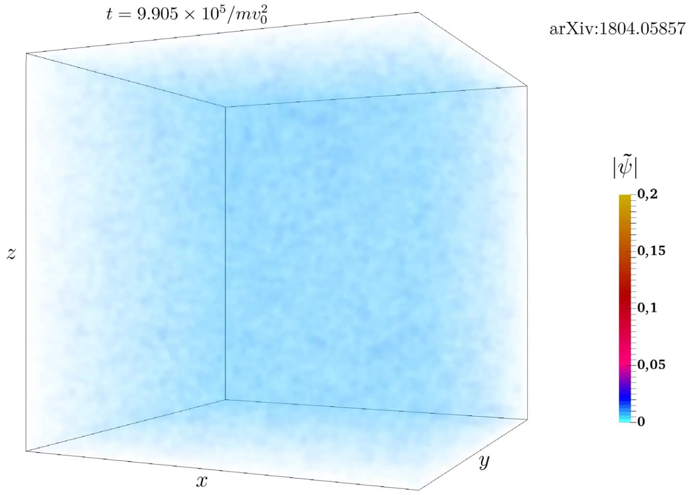
Dwarf galaxy $\sim$ Fornax:

$M \sim 4 \times 10^9 \, M_\odot$, $M_{\text{BEC}} \sim 10^8 \, M_\odot$ *Schive, Chiueh, Broadhurst '14*



Simulation of Bose condensation

Start: virialized (random) gas in the box

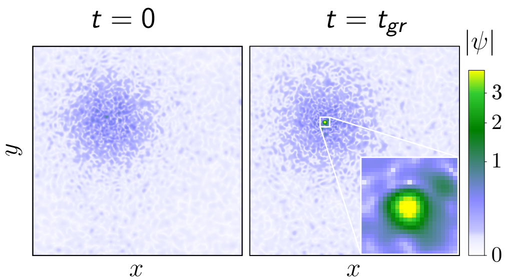


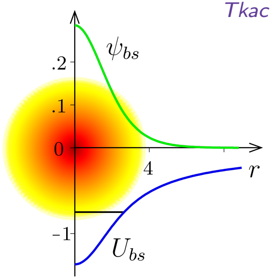
DL, Panin, Tkachev '18

Condensate + gravity = Bose (axion) star

Ruffini, Bonazzola '69

Tkachev '86





- All axions $\in$ ground level of $U_{bs}(\boldsymbol{x})$

Growth of Bose stars

see A. Dmitriev's talk

→ Simulations: stop growing at $M_{bs} \propto \underbrace{\sqrt{M_{\text{mc}}/R_{\text{mc}}}}_{\text{“core-halo”}}$ — small!

Schive et al '14

→ Self–similar kinetics: $M_{bs} \propto t^{1/3}$ — slow growth continues!

⇒ $O(1)$ of miniclusters is eaten by Bose stars

Dmitriev et al '23

Bose stars form $10 \div 50\%$ of dark matter

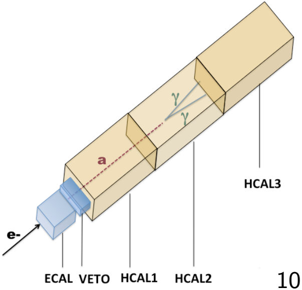
We need precise & realistic simulations!

Direct constrains: NA64 experiment

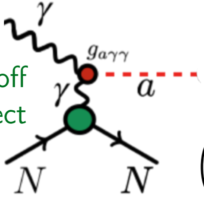
see I.Tlisova, D.Kirpichnikov's talks

→ 16 institutes + CERN SPS

NA64 '20



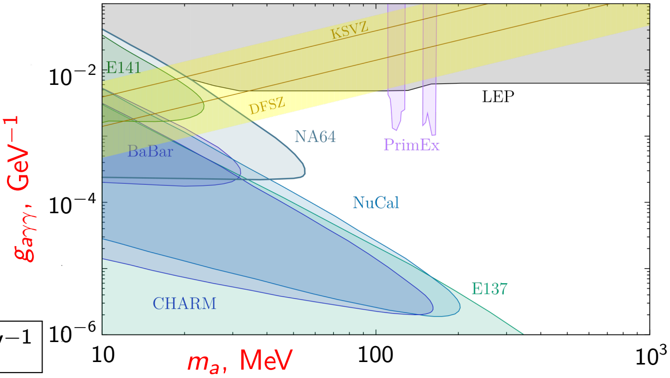
Primakoff effect



energy disappearence

↑

(in contrast to other exp-s)



at $m_a \ll 10$ MeV

$$\boxed{g_{a\gamma\gamma} \lesssim 2\cdot 10^{-4}\ \text{GeV}^{-1}}$$

Some experiments: axions

см. Irastorza, Redondo '18

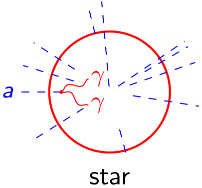
- **Star cooling**

  Axion emission from $\mathrm{Vol}_{\mathrm{star}}$ $\Rightarrow$ faster evolution

  $\Rightarrow$ too many red giants

  SN1987a: shorter ν signal

  $\boxed{g_{a\gamma\gamma} \lesssim 10^{-10}\,\mathrm{GeV}^{-1}}$

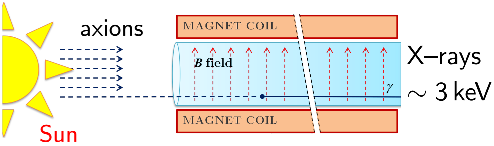


- **Helioscopes [CAST, IAXO]**

  (planned)

  Axions from the Sun

  $\boxed{g_{a\gamma\gamma} \lesssim 10^{-10}\,\mathrm{GeV}^{-1}}$ (CAST)

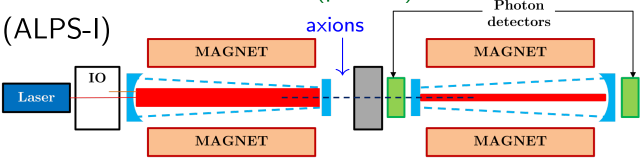


- **Light through the wall [ALPS, OSQAR, ALPS-II, III]**

  (planned)

  $\boxed{g_{a\gamma\gamma} \lesssim 10^{-7}\,\mathrm{GeV}^{-1}}$ (ALPS-I)

  visible light

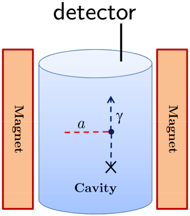


Some experiments: dark matter axions

см. Irastorza, Redondo '18

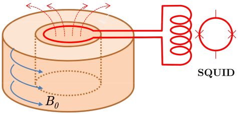
- $f_a \sim 10^{27}\,(m_a/\mu\text{eV})^{-4} \gg 1$ — coherent amplification!
- **Haloscopes (ADMX)**
  - + resonance: $m_a = \omega \sim L^{-1} \sim \mu\text{eV}$
    $\Rightarrow$ high sensitivity!
  - − resonance: scan over $\omega = m_a$

$$\boxed{g_{a\gamma\gamma} \lesssim 10^{-15}\,\text{GeV}^{-1} \quad \text{at} \quad m_a \sim 2-3\,\mu\text{eV}}\quad \text{(ADMX)}$$

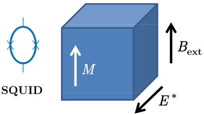


- **Plethora of other ideas!**

$m_a \ll \mu\text{eV}$ — large volume

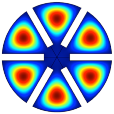


LC–SQUID
(ABRACADABRA)
(DM-Radio)

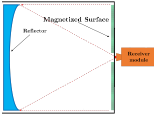


NMR
(CASPEr)
↑
$\partial_\mu a\, \bar{N} i \gamma^5 N$

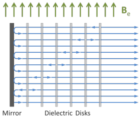
$m_a \gg \mu\text{eV}$ — small volume



pizza
(prototype)



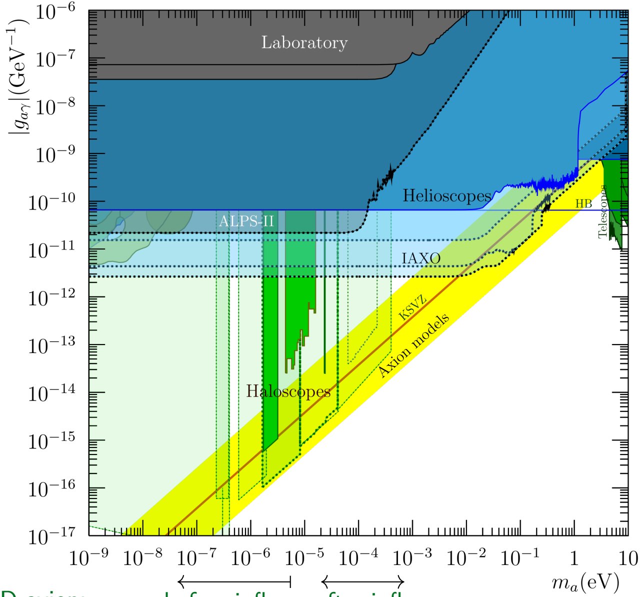
dish antenna
(BRASS)



dielectric
(MADMAX)

Experimental constraints on axion-like dark matter

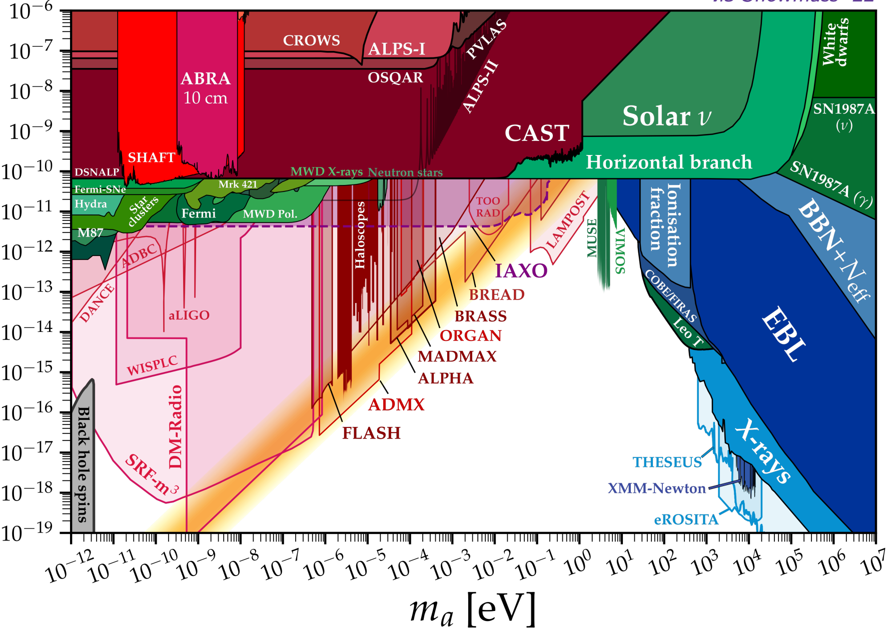
из Irastorza, Redondo '18



QCD axion: before infl after infl

Planned experiments

из Snowmass '22



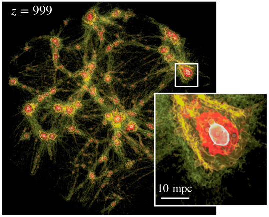
Manifestations of miniclusters

- **Suppression of the signal** *Eggemeier et al '22*

  miniclusters ⇒ mini–voids

  → mean signal $\times \underbrace{\sqrt{30\%}}_{0.5}$

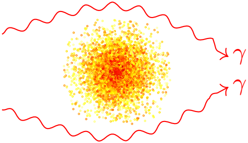
  → in mini–voids: signal/3.5



- **Microlensing?** *Kolb, Tkachev '94*

  → only if $\underbrace{M_{\mathrm{mc}} \gtrsim 10^{-11}\, M_\odot, \quad m_a \gtrsim 10^{-3}\,\mathrm{eV}}_{\text{not for QCD axions?}}$ *Ellis et al '22*

  ⇒ challenging for future exps.



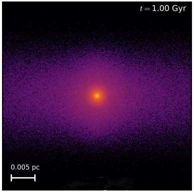
- **Tidal streams** *Tinyakov et al '15; Shen et al '22*

  → meet the minicluster: once per 10^5 yr

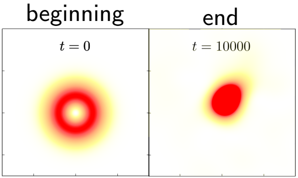
  → But: minicluster + star = tidal stream

  → meet the stream: **once per** ~ 20 **yr**

  ⇒ haloscopes may be lucky!



Manifestations of Bose stars (A. Panin's talk)



- **Rotating Bose stars decay**

  shade off angular moment *Dmitriev et al '21*

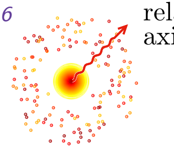
  ⇒ **bad** black hole impostors *Sanchis-Gual '19*

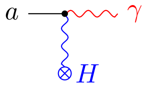
- **Heavy stars collapse** *DL, Panin, Tkachev '16*

  $-\lambda a^4$ attraction ⇒ $\underbrace{\text{bosenova}}$

  QCD axions: $M_{bs} \gtrsim 10^{-13}\, M_{\odot}$

  + magnetic field ⇒ flashes! *Arakawa '24*



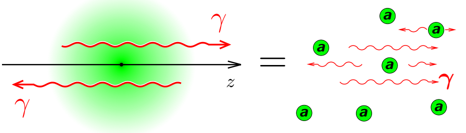


- **Axion laser = avalanche $a \to \gamma\gamma$**

  → $g_{a\gamma\gamma} \gtrsim 10^2 \cdot g_{a\gamma\gamma}^{\text{QCD}}$

  DL, Panin, Tkachev '20

Tkachev '87



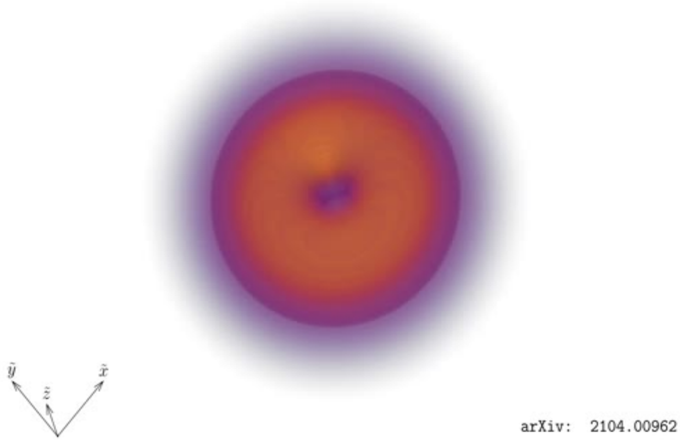
⇒ Flashes in the sky! — Fast Radio Bursts?

→ Can be triggered by a bosenova

⇒ Reionization of the Universe *Escudero et al '23*

⇒ Constributes into diffuse radiobackground *Eby, Takhistov '24*

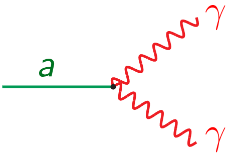
Instability of a rotating Bose star



arXiv: 2104.00962

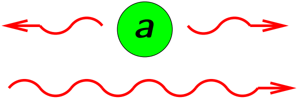
Interaction of QCD axions with photons

$$\mathcal{L}_{\rm int} \propto g_{a\gamma\gamma}\; a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$



spontaneous decay

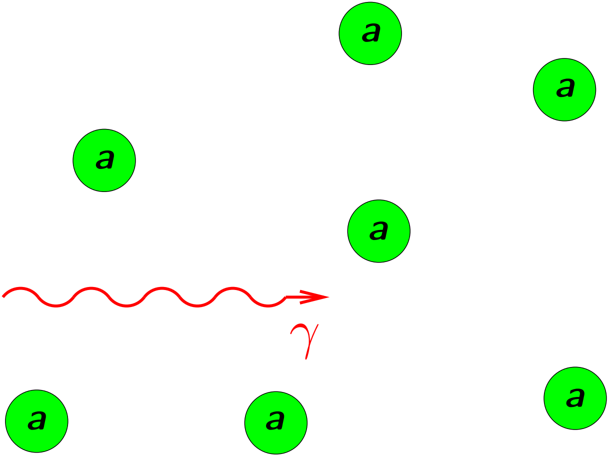
$\mathcal{P}$



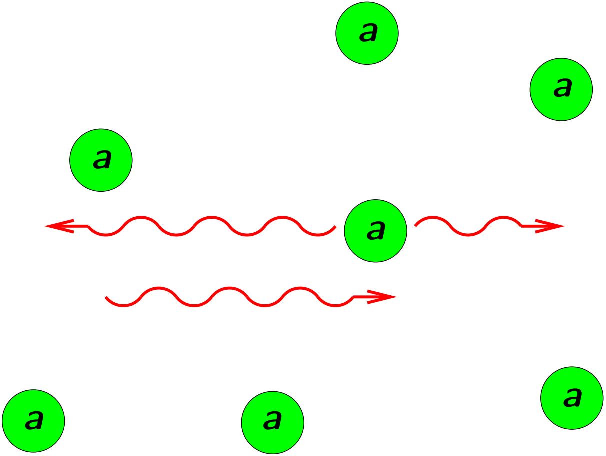
stimulated decay

$\mathcal{P} \times N_\gamma$

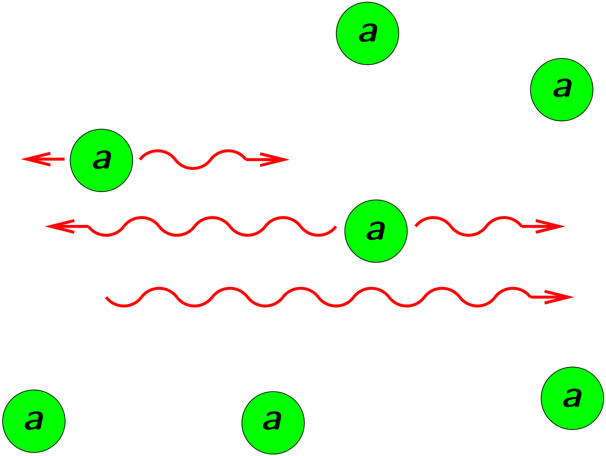
Axion laser: avalanche $a \to \gamma\gamma$



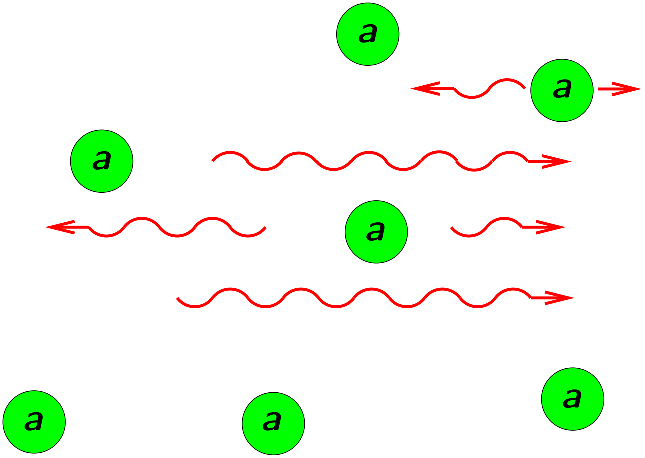
Axion laser: avalanche $a \to \gamma\gamma$



Axion laser: avalanche $a \to \gamma\gamma$



Axion laser: avalanche $a \to \gamma\gamma$



Condition: at least one decay per γ pass

Tkachev '87; Riotto, Tkachev '00; Hertzberg, Schiappacasse '18

Conclusions

Ultralight (axion–like) dark matter is:

- Motivated theoretically
- Leads to unusual cosmology

  with miniclusters and Bose stars
- Search for axions is is a creative business!

Heavy dark matter is classics	While the light one is a heavy metal!
	

Thank you for attention!

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