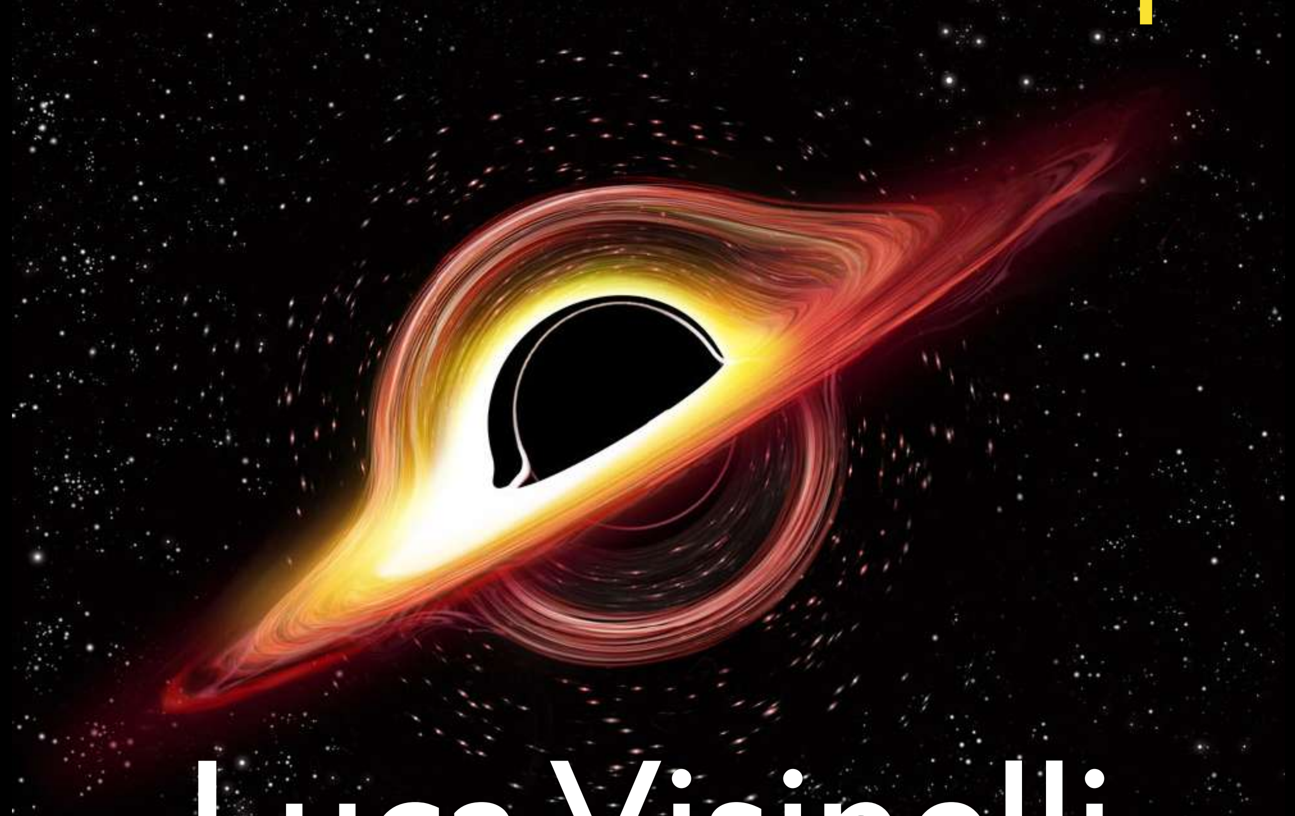
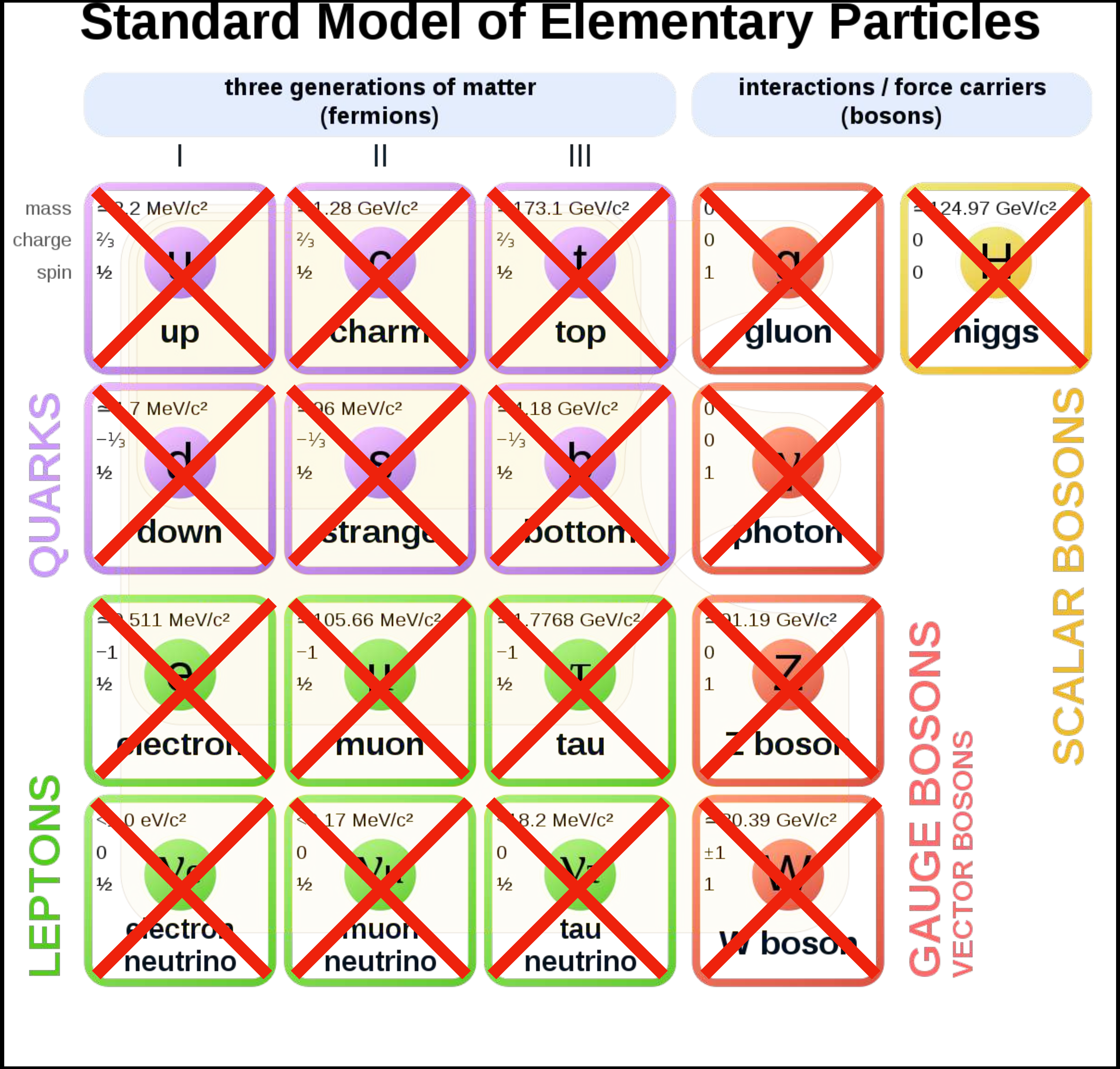
The astrophysics of compact objects and dark matter: Recent and future developments



Luca Visinelli

GRAPPA University of Amsterdam & LNF-INFN

Cracks in the Standard Model

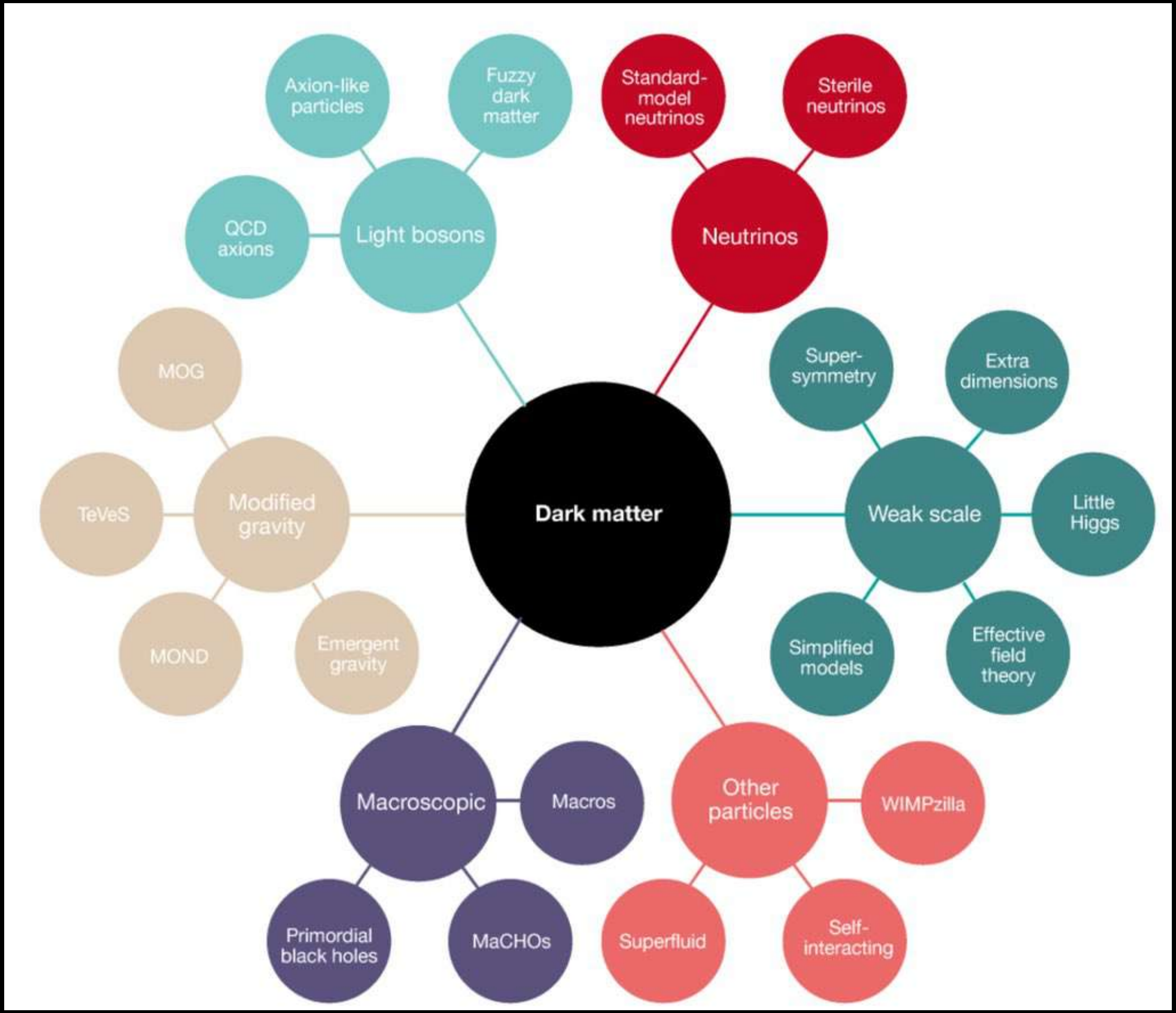


- No candidates for the dark matter
  1. No charged particles
  2. Stable
  3. Massive

Also:

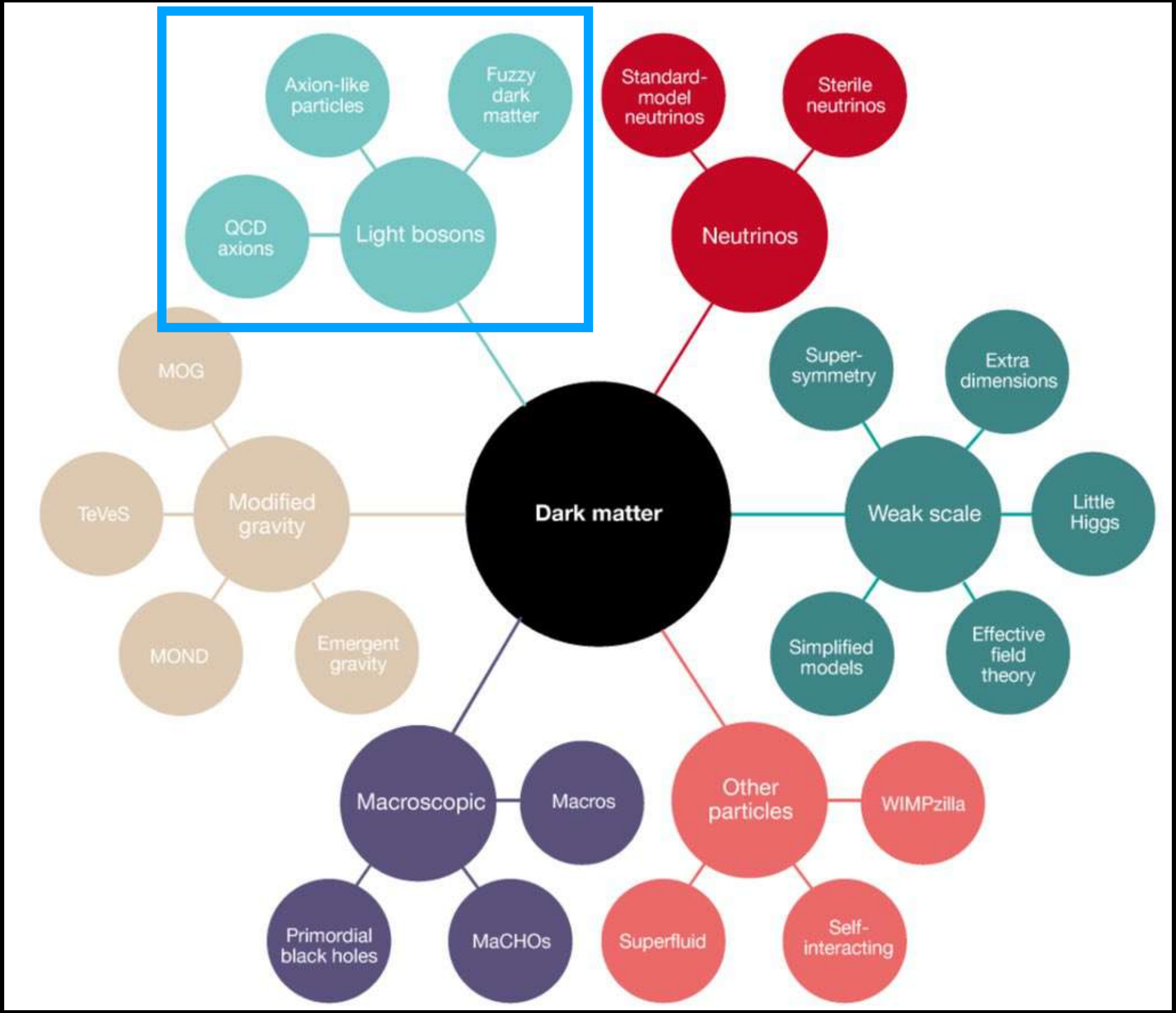
- No neutrino masses
- No quantum theory of gravity
- No dark energy
- No Baryogenesis
- …

Ideas for dark matter candidates

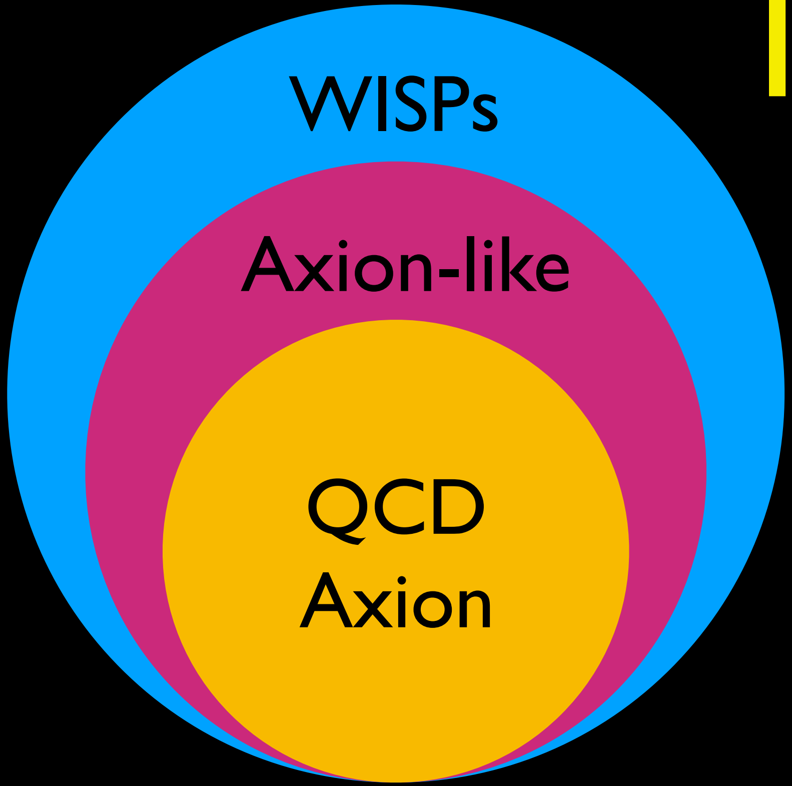


Ideas for dark matter candidates

Weakly Interacting Scalar Particles (WISPs)



The QCD



The QCD axion is the archetype of WISPs

The SM predicts CP violation from the strong sector which is <u>not</u> observed experimentally (Strong-CP problem)

Roberto Peccei

Helen Quinn

Peccei-Quinn (PQ) introduce a new field which rolls to zero dynamically
This solves the Strong-CP problem in SM

Steven Weinberg

Frank Wilczek

The quantum of the theory is a new particle: <u>the axion</u>

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Axion energy scale

Cosmic WISPers in the dark universe

Equation of motion: $\ddot{\phi} + 3H\dot{\phi} + m_{\rm DM}^2\phi = 0$

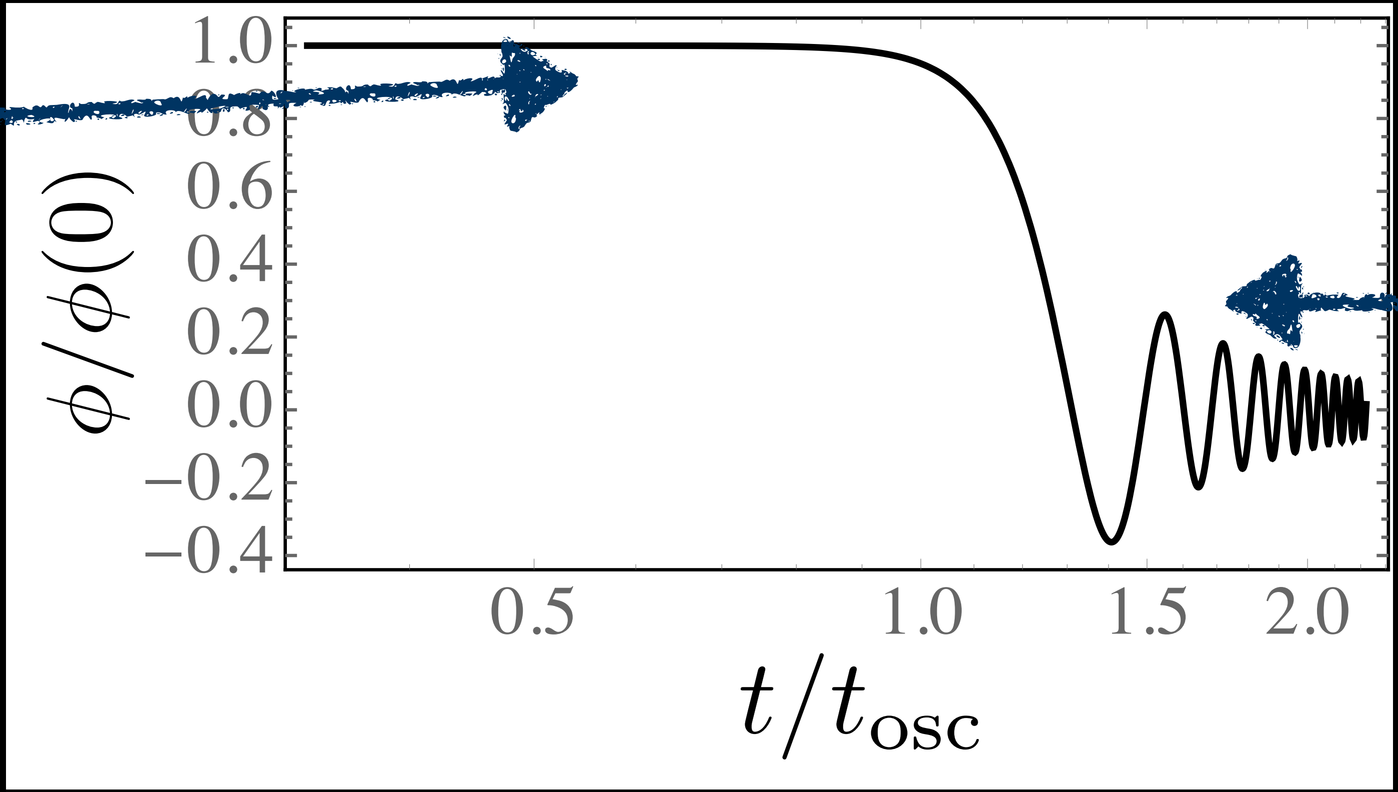
For super-horizon modes $|\nabla\phi| \approx 0$ and for a quadratic potential

The transition is regulated by $3H(t_{\rm osc}) \approx m_{\rm DM}$

Behaves as dark energy

$\ddot{\phi} + 3H\dot{\phi} \approx 0$

$\rho_\phi \approx \text{const.}$

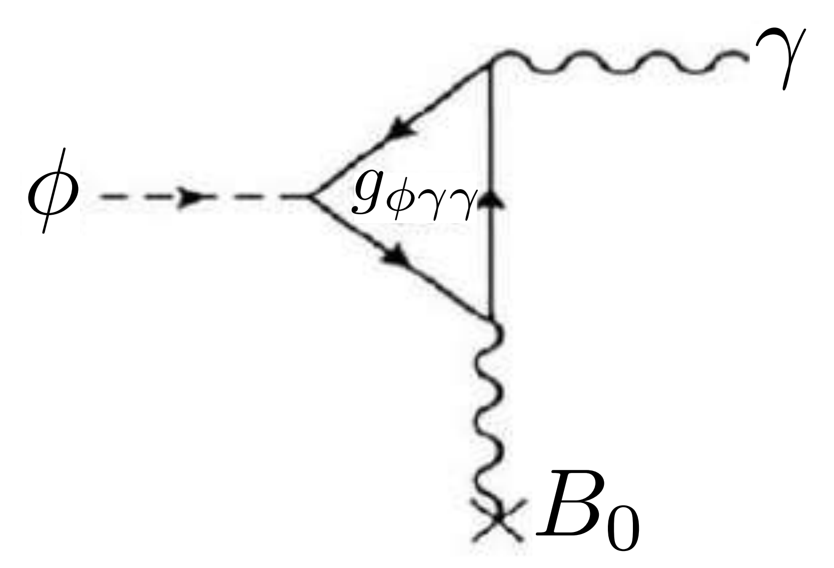


Behaves as dark matter

$\rho_\phi \propto R^{-3}$

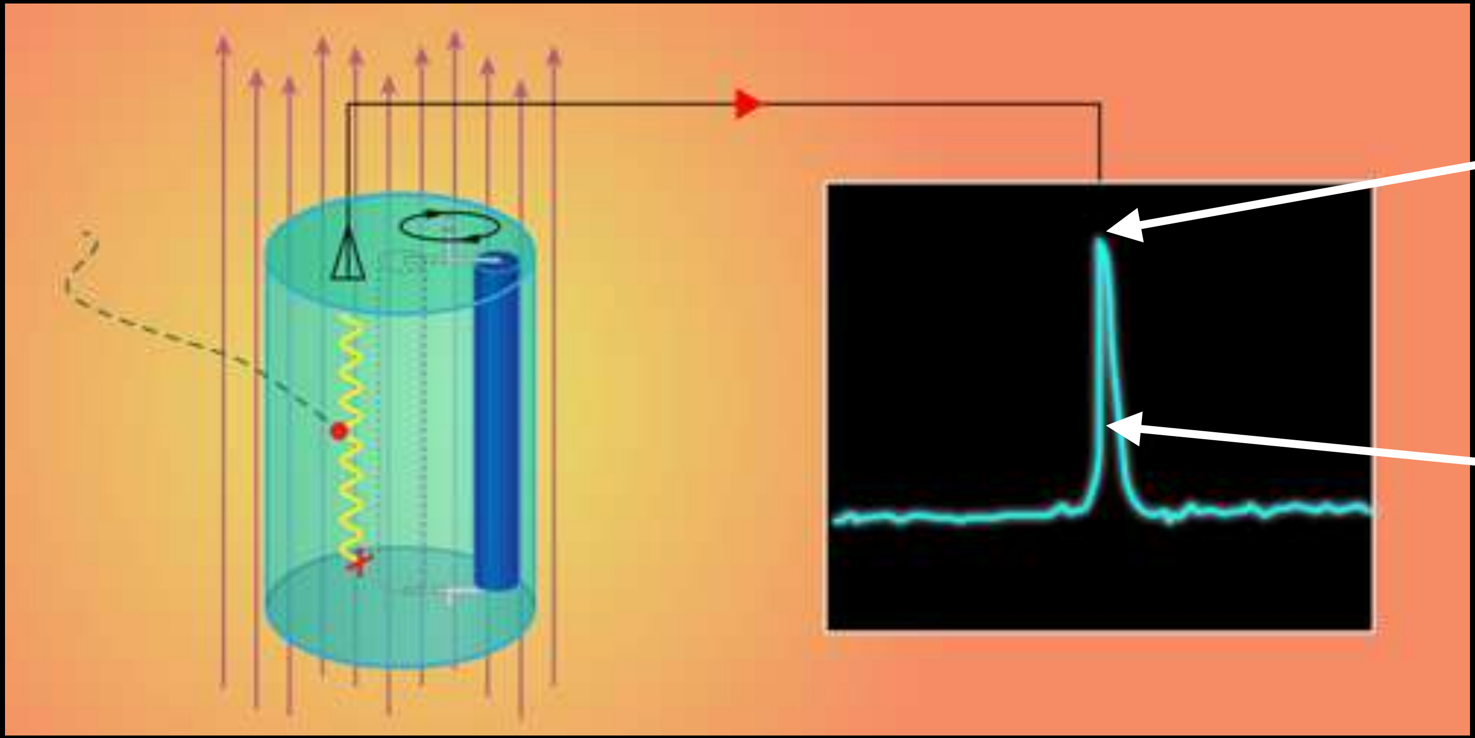
Lab searches for WISPs

WISP-photon coupling



“Sikivie-type” resonant microwave cavity with superconducting magnet

Galactic WISPs interacts with the B field and converts into a pulse resonantly: $\nu \approx m_{\rm DM}c^2/h$



Signal in the GHz

Broadening in the kHz

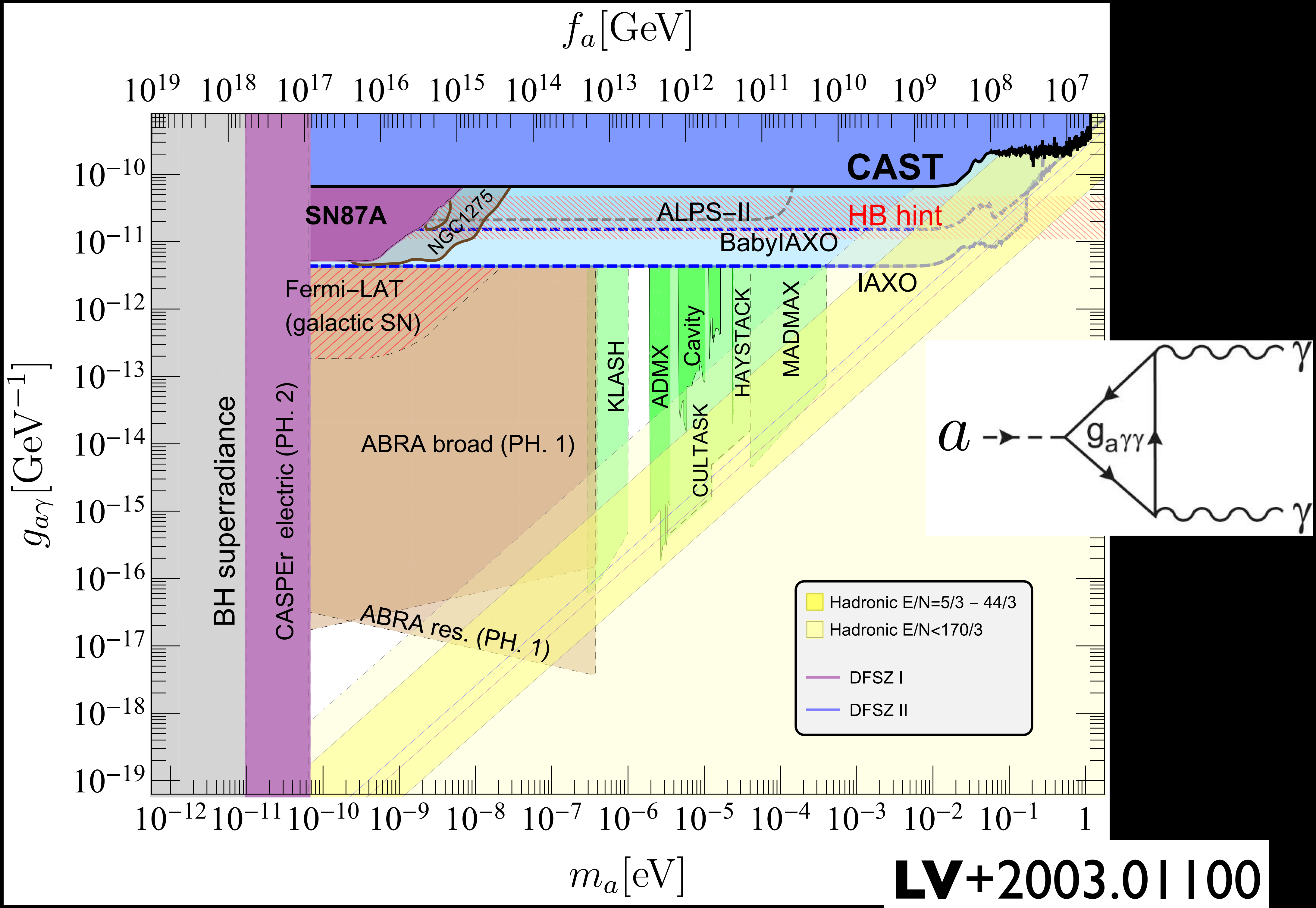
$$\Delta\nu \approx m_{\rm DM}v^2/h$$

Because $v/c \sim 10^{-3}$

P. Sikivie, Phys. Rev. Lett **51**, 1415 (1983)

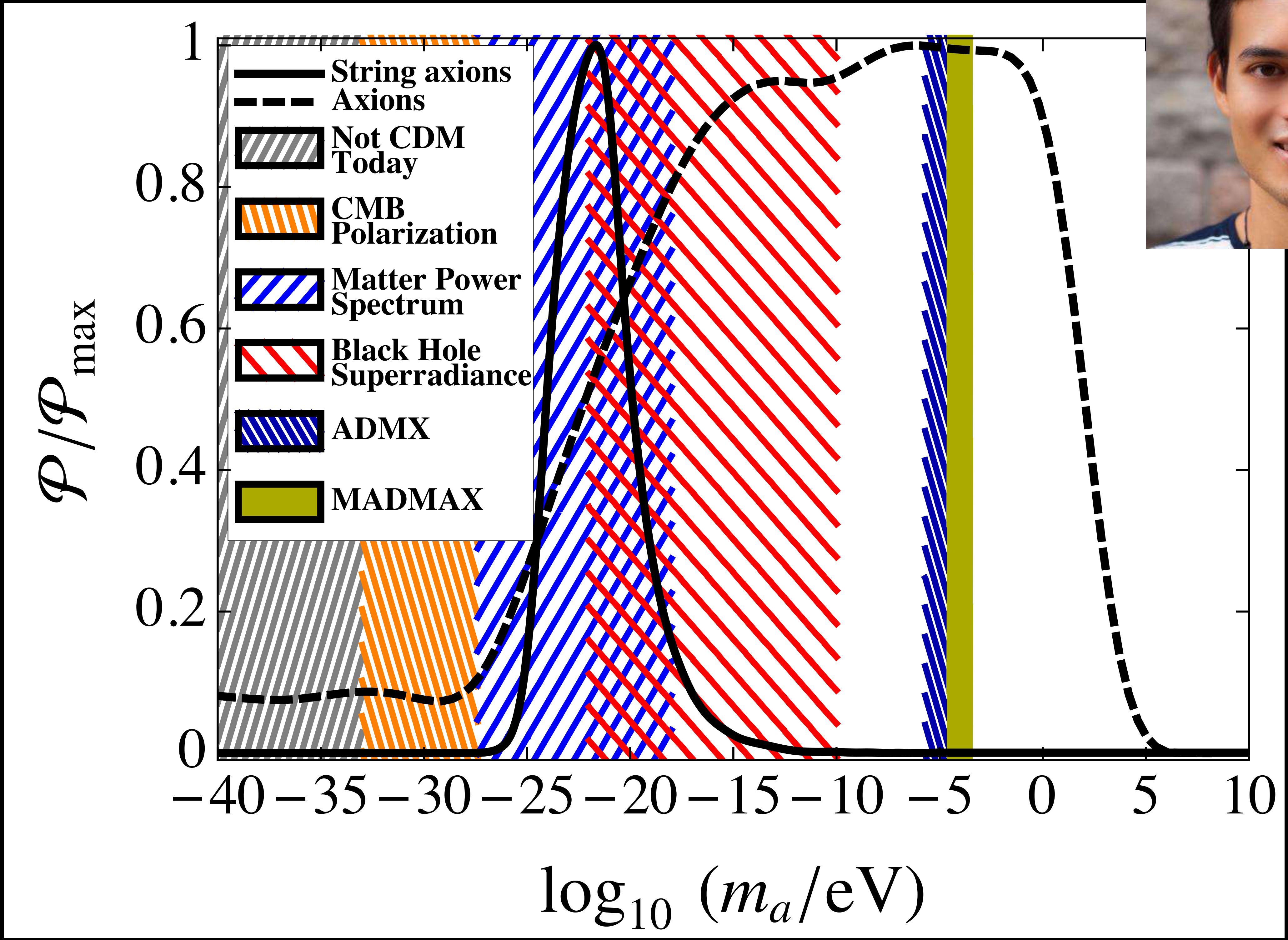
One-parameter theory, falsifiable

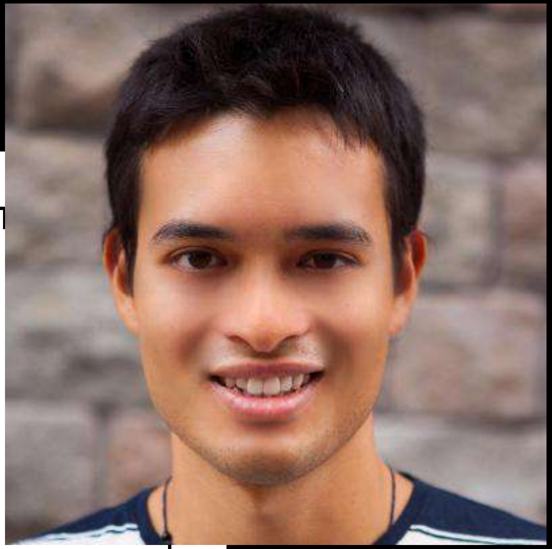
$$\mathcal{L}_{\rm axion-photon} = -\frac{g_{a\gamma\gamma}}{4}\, a\, F^{\mu\nu}\, \tilde{F}_{\mu\nu}$$



LV+2003.01100

Axions from String Theory

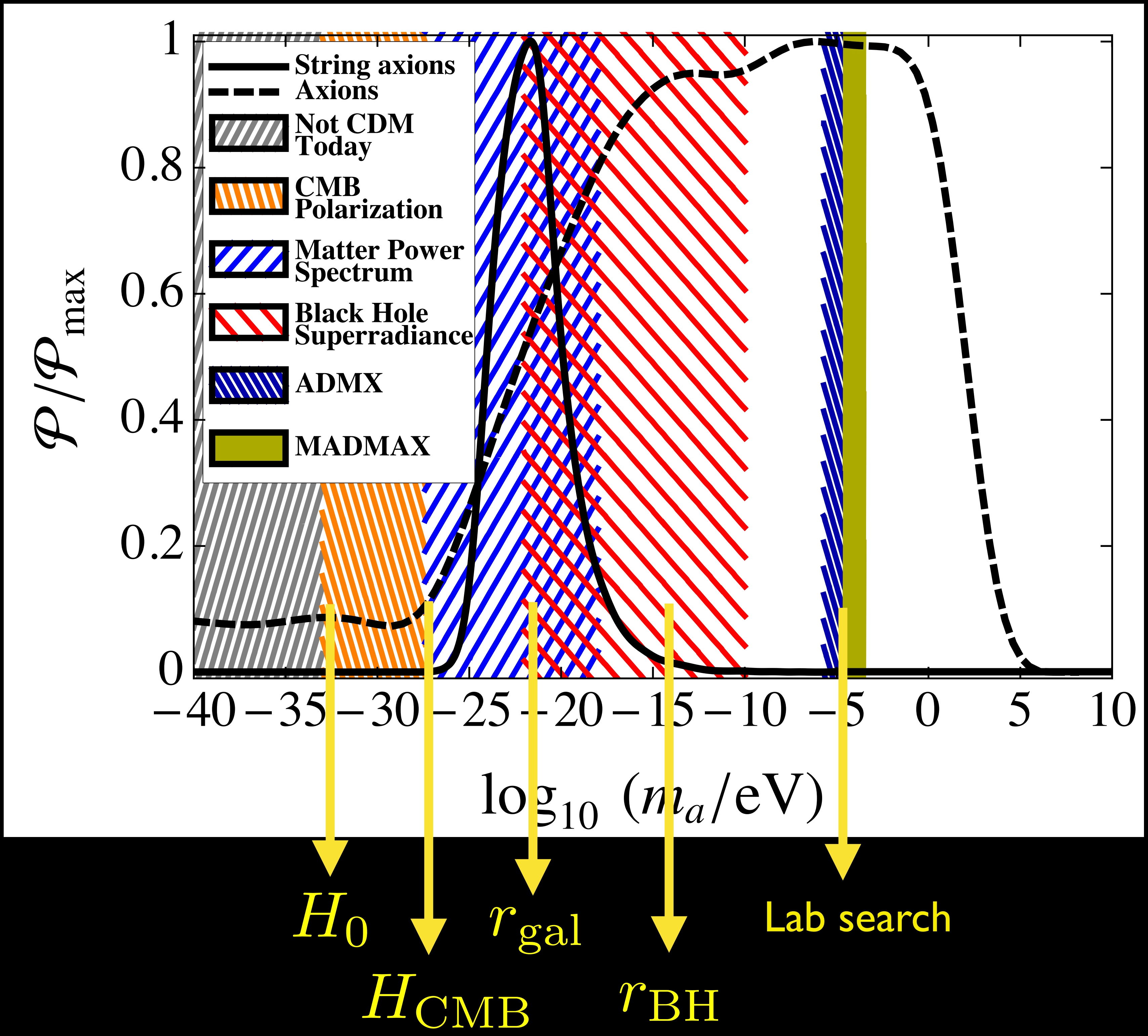




Visinelli and Vagnozzi PRD 99 063517 (2019)

Future WISP searches

LV+, Phys. Rev. D **99**, 063517 (2019)



WISPs of mass $m \sim H_0$
can be the *dark energy*

WISPs of mass $\sim 10^{-27}\,{\rm eV}$
affect the CDM power spectrum

WISPs of mass $\sim 10^{-22}\,{\rm eV}$
affect the galactic cores

WISPs of mass $\sim 10^{-15}\,{\rm eV}$
have a wavelength comparable to the size of stellar BHs

WISPs of mass $\sim 10^{-5}\,{\rm eV}$
are the dark matter axions currently being searched in labs

Compact objects

Large inhomogeneities in the axion field lead to gravity-bound objects
Axion "miniclusters" [Hogan&Rees1988; Kolb&Tkachev 1993,1994]

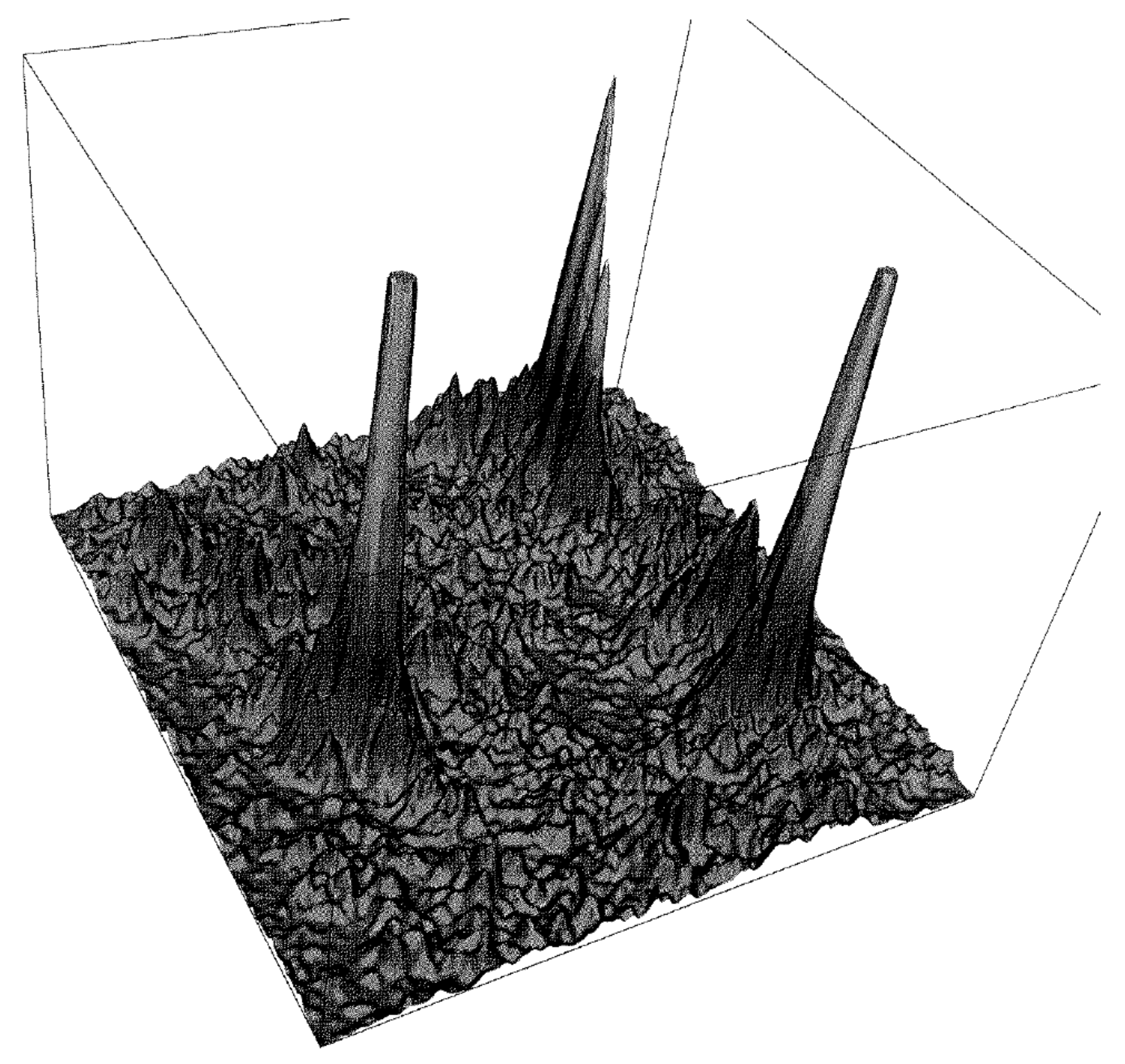
Distribution of axion energy density
2D slice of comoving length 0.25 pc
[Kolb&Tkachev96]

$$T_{\rm collapse} \approx \frac{\delta\rho}{\rho} T_{\rm eq}$$

Typical mass $\sim 10^{-11}\,M_\odot$

Typical radius $\sim 10^{12}\,{\rm cm}$

See e.g.
LV & J. Redondo 1808.01879

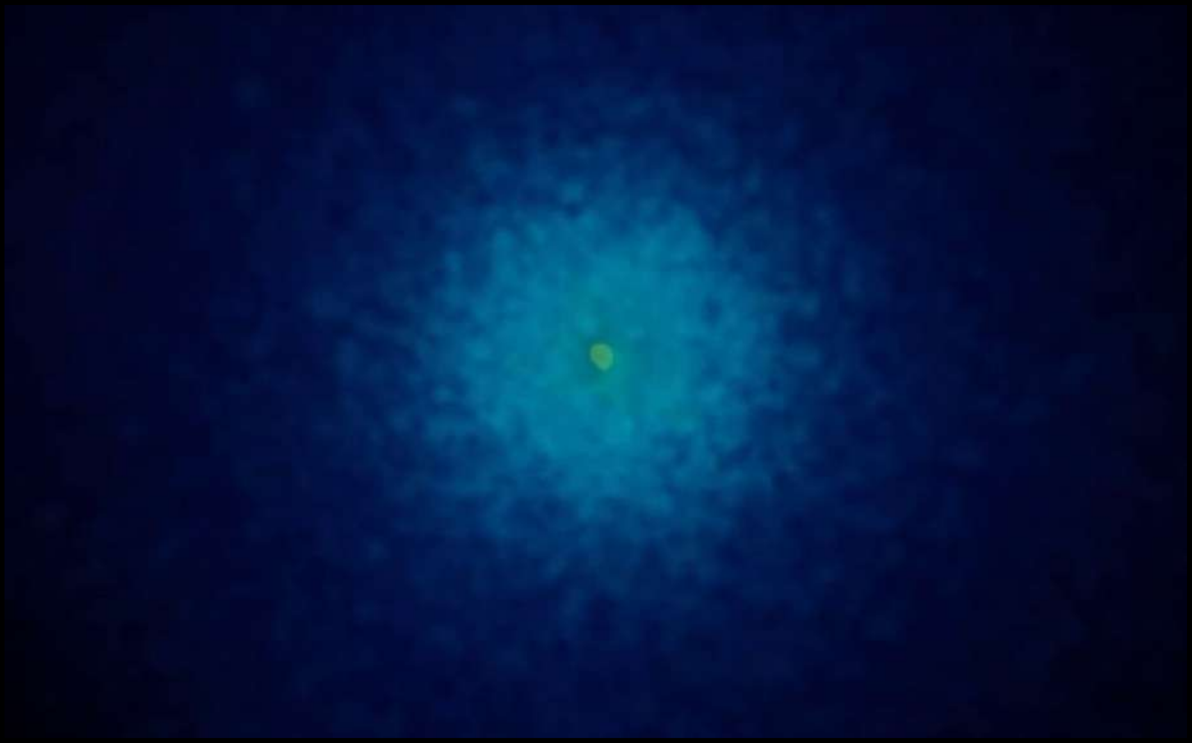


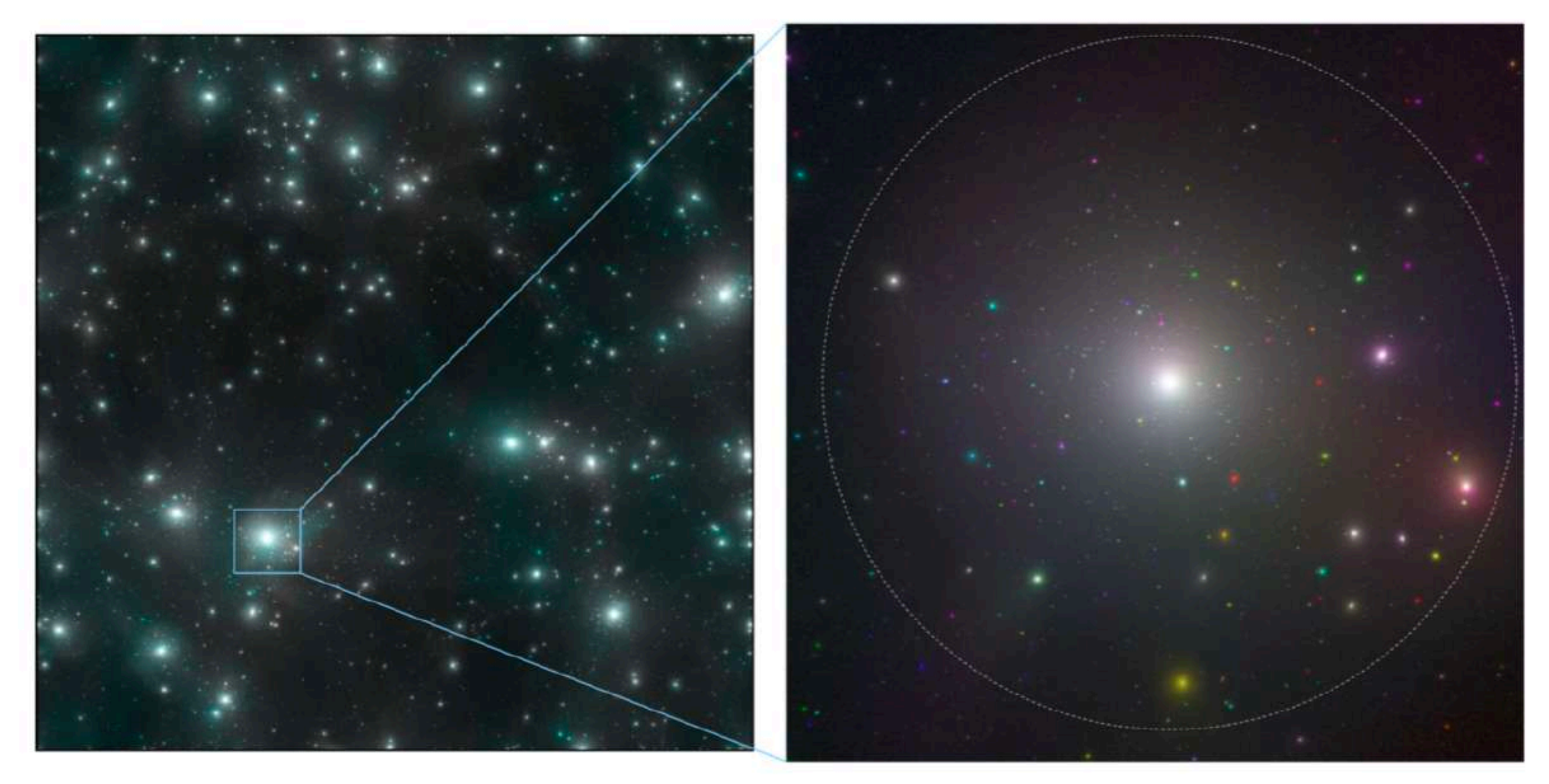
N-body simulation

We assume two different profile distributions for the individual minicluster:

1) Power-Law (PL) $\rho \propto r^{-9/4}$

2) NFW $\rho = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2}$

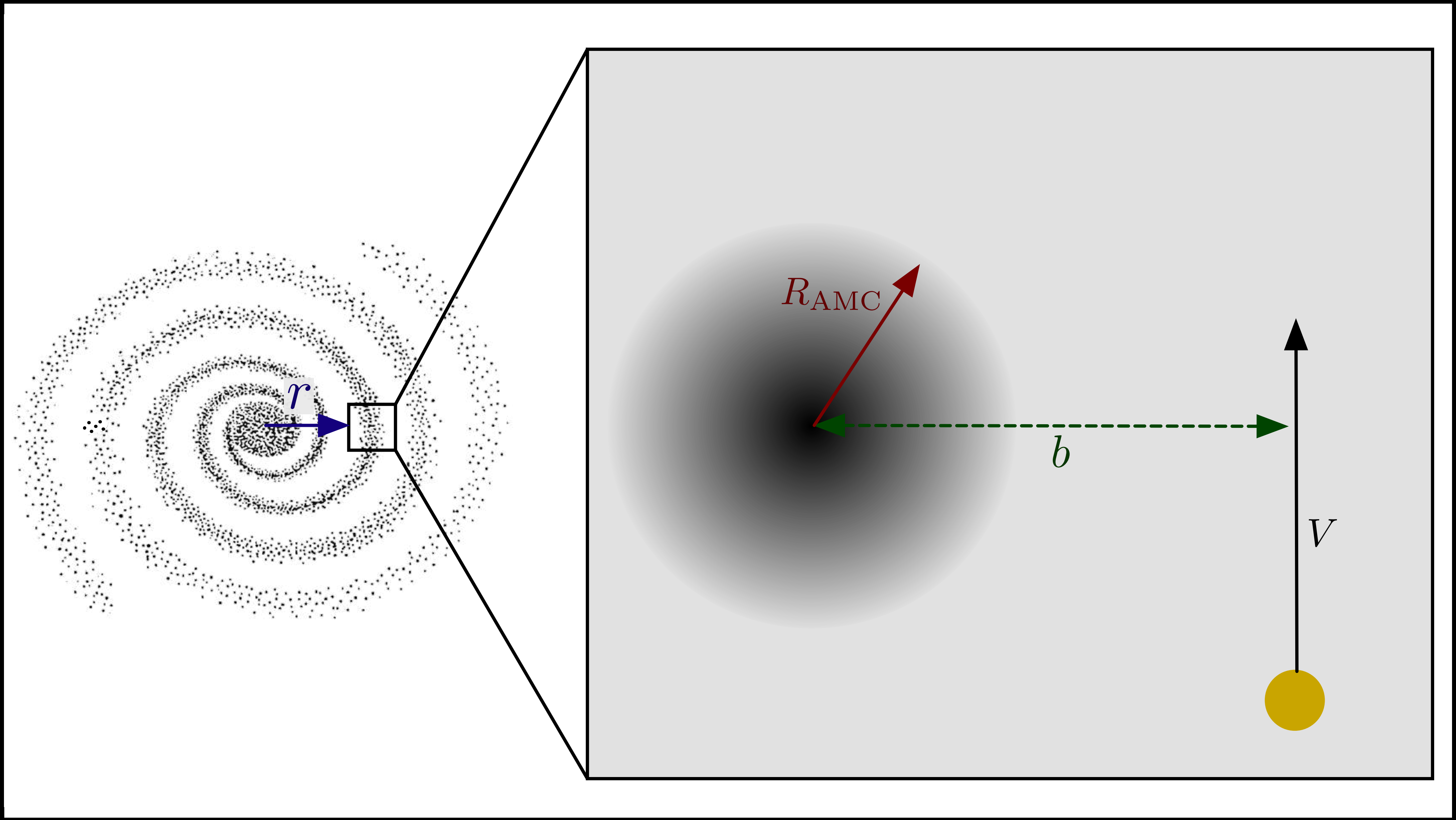


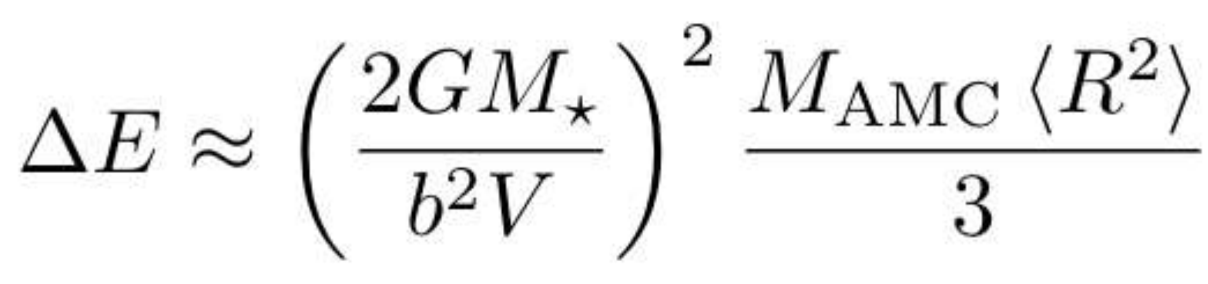


Projected axion density at z = 99 Enlargement of the largest minicluster

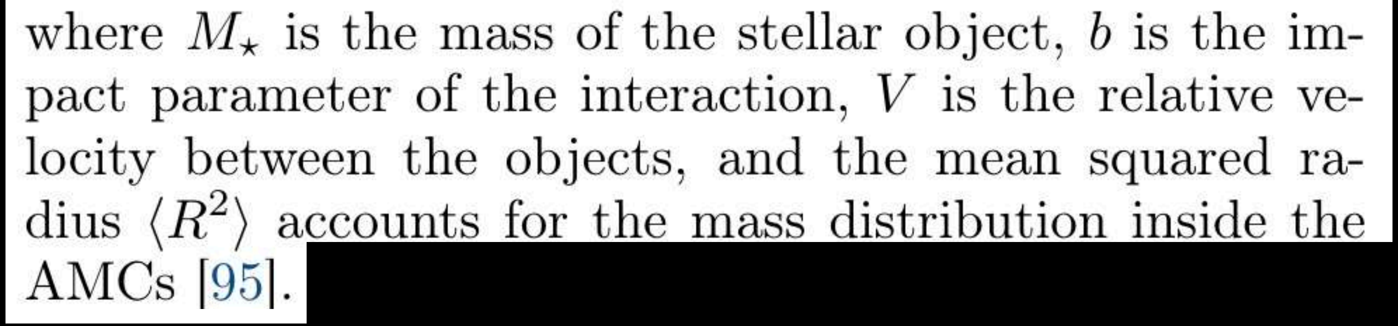
Eggemeier+ 1911.09417

Survival of axion miniclusters





$$\Delta E \approx \left(\frac{2GM_\star}{b^2 V}\right)^2 \frac{M_{\rm AMC}\,\langle R^2\rangle}{3}$$



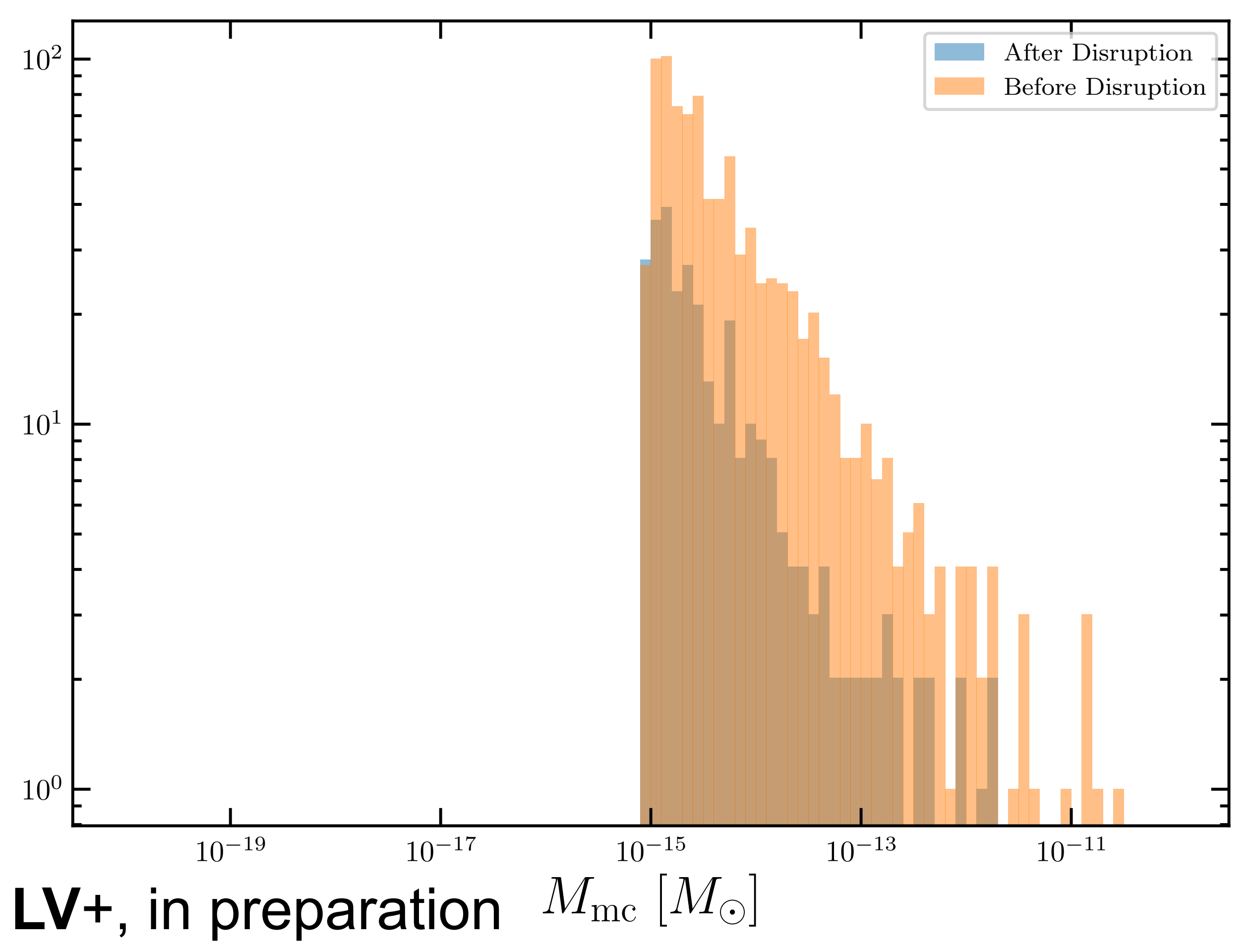
where $M_\star$ is the mass of the stellar object, b is the impact parameter of the interaction, V is the relative velocity between the objects, and the mean squared radius $\langle R^2\rangle$ accounts for the mass distribution inside the AMCs [95].

Survival of axion miniclusters

Axion miniclusters are disrupted by the encounter with stars

Initial halo mass function from N-body simulation

$$\frac{dn}{d\ln M} \propto M^{-0.7}$$



LV+, in preparation

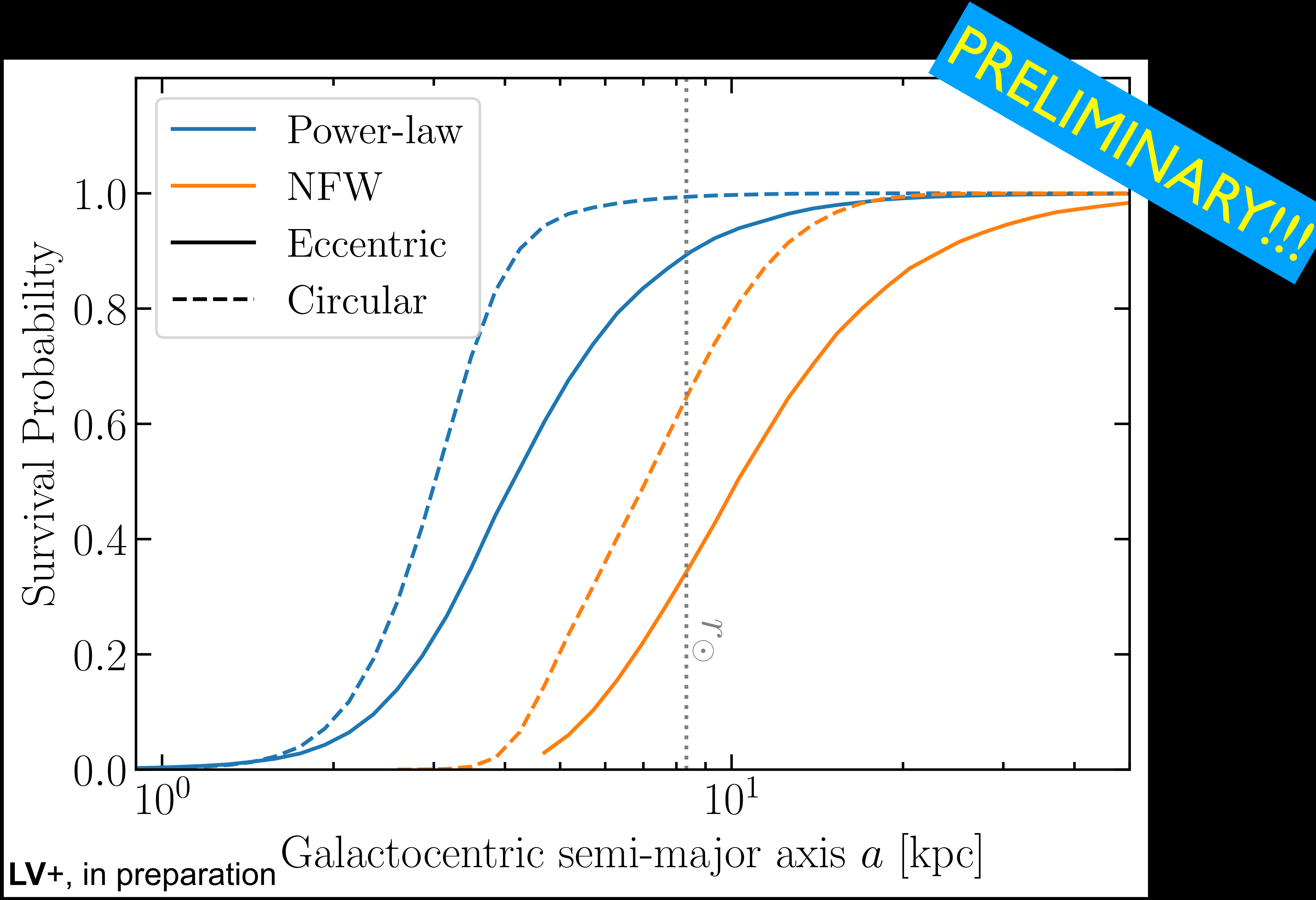
With:

Thomas Edwards

Bradley Kavanagh

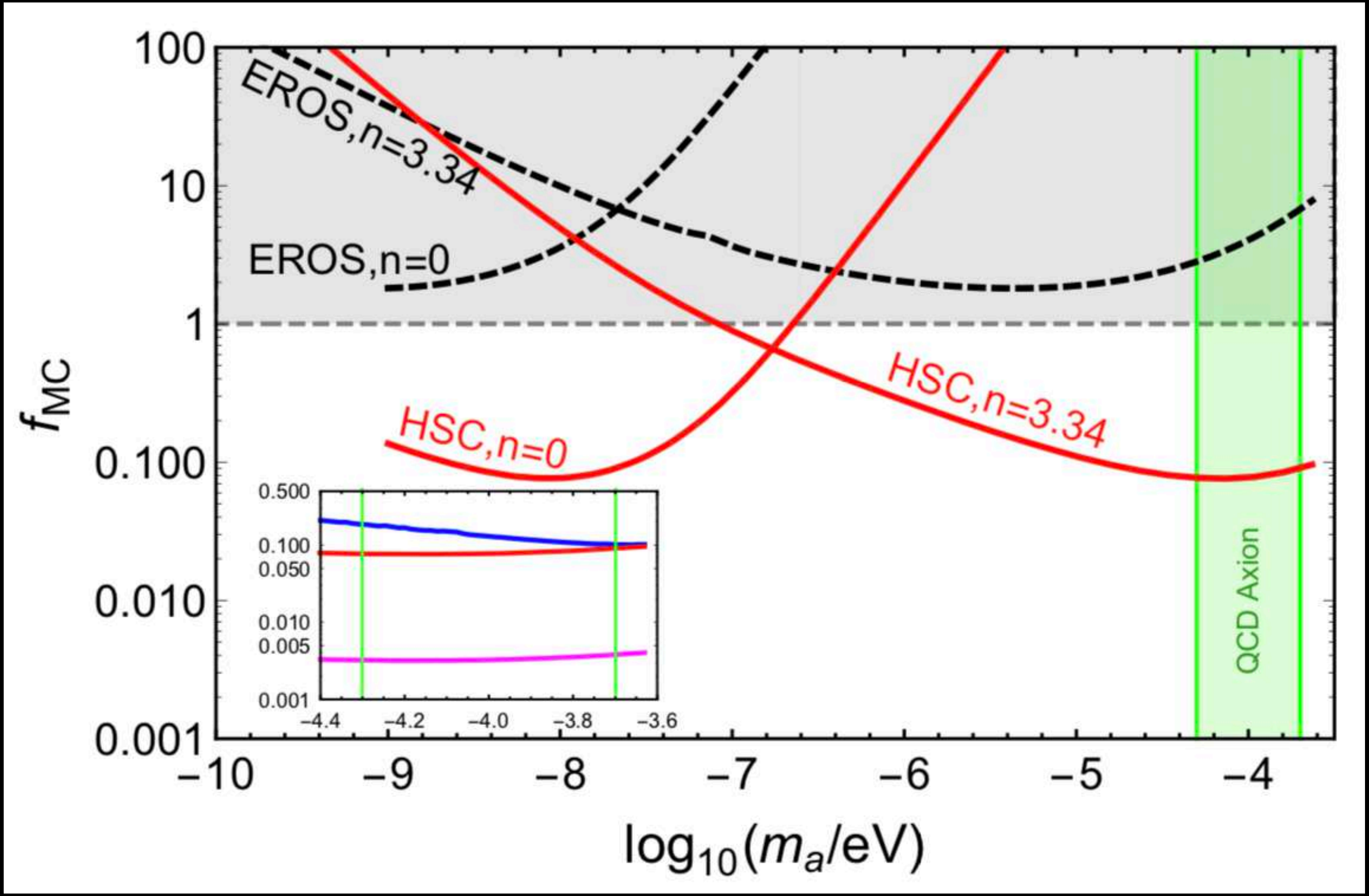
Christoph Weniger

Survival of axion miniclusters



LV+, in preparation

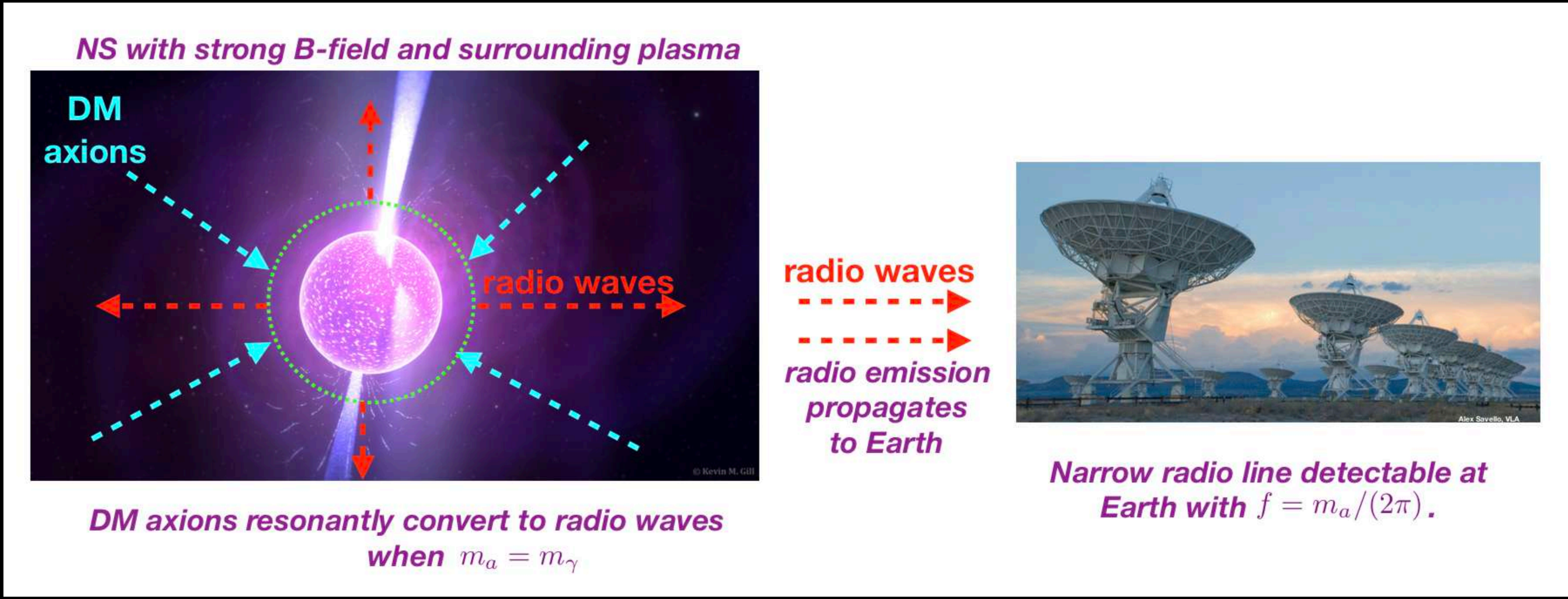
Application: microlensing



Fairbairn+ 1707.03310

Future projects:
Axion radioastronomy

Neutron stars “eat up” dark matter overdensities



NS with strong B-field and surrounding plasma

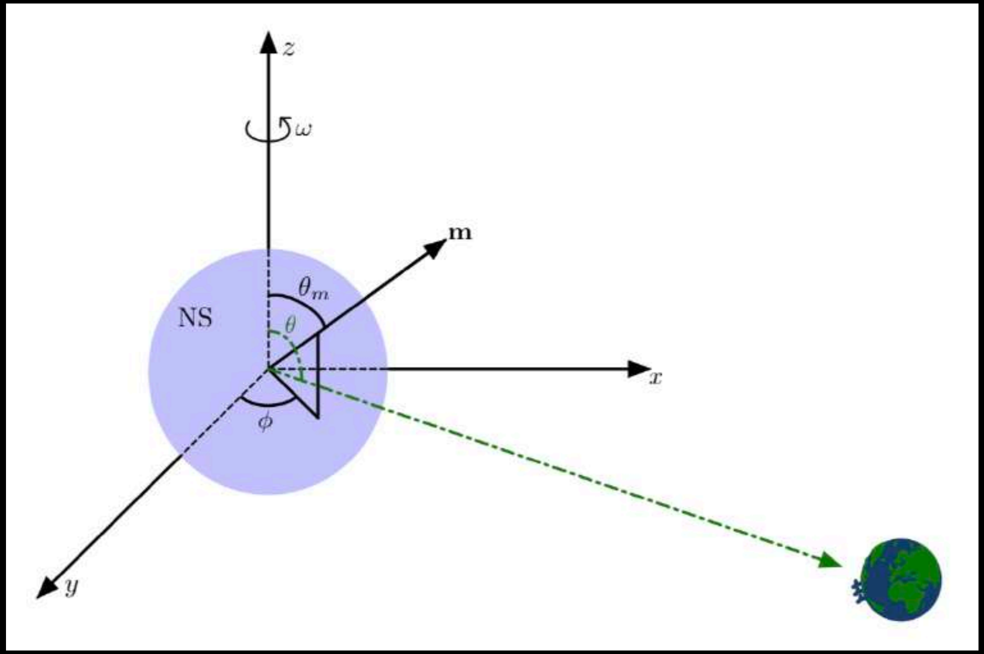
DM axions resonantly convert to radio waves when $m_a = m_\gamma$

radio emission propagates to Earth

Narrow radio line detectable at Earth with $f = m_a/(2\pi)$.

Courtesy of Ben Safdi (Michigan)

Axion radio-interferometry

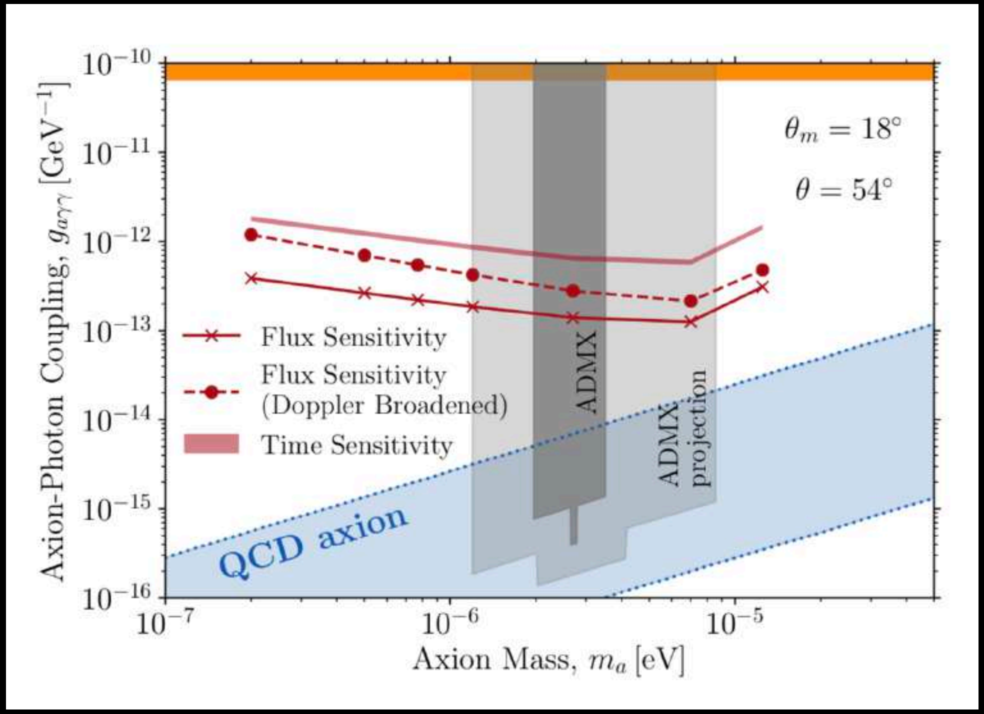


$$B(\theta) = \frac{B_0}{2}\left|3\cos^2\theta + 1\right|^{1/2}$$

Goldreich–Julian Relation

$$n_c = \frac{2\mathbf{\Omega}\cdot\mathbf{B}}{e} + (\text{relativistic corrections})$$

axion-photon conversion
is possible for $\omega_p(B) \approx m_a$



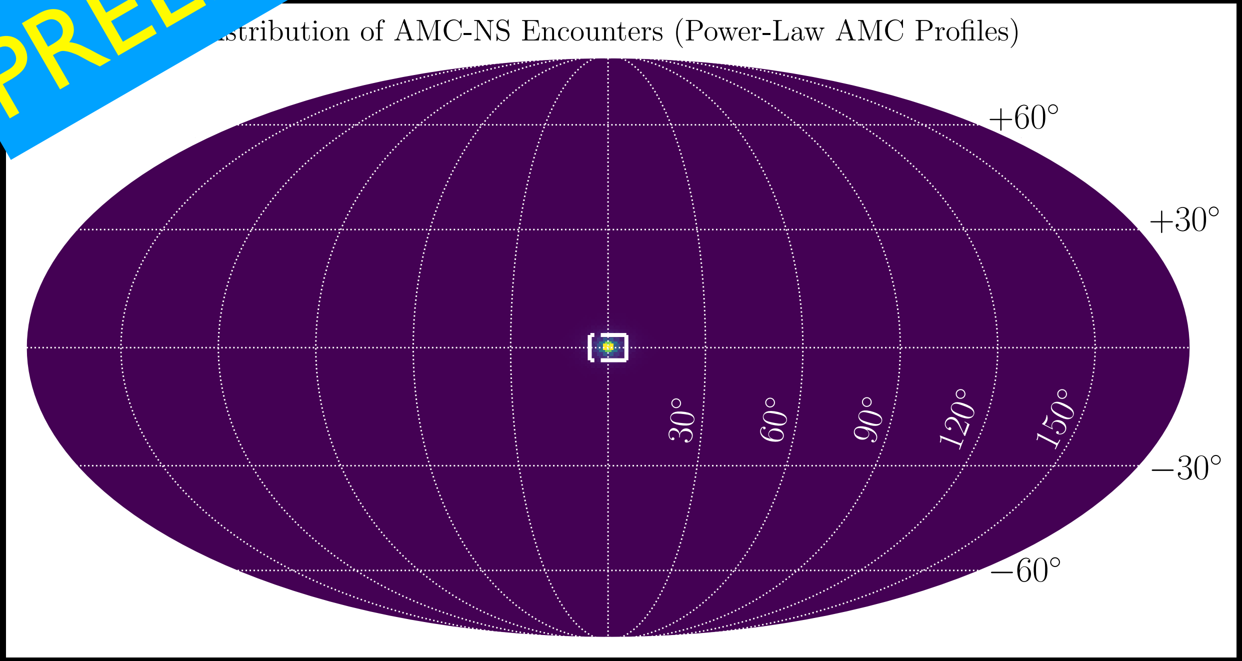
Leroy+1912.08815

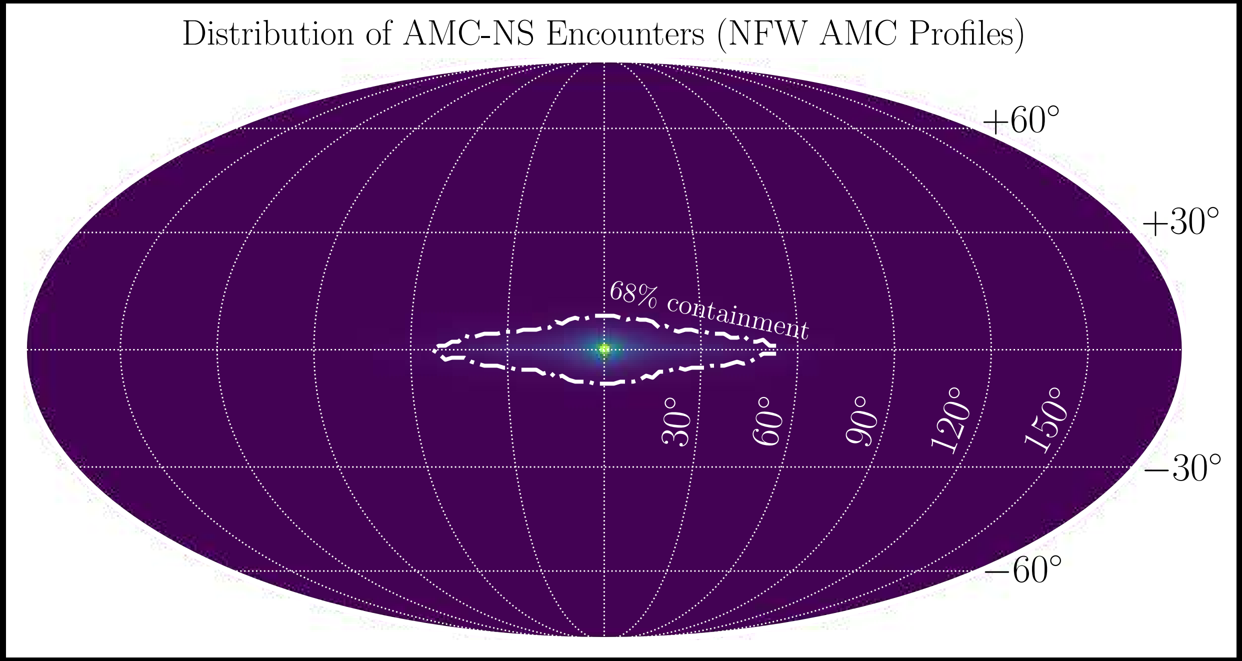
Radioastronomy Axion Miniclusters

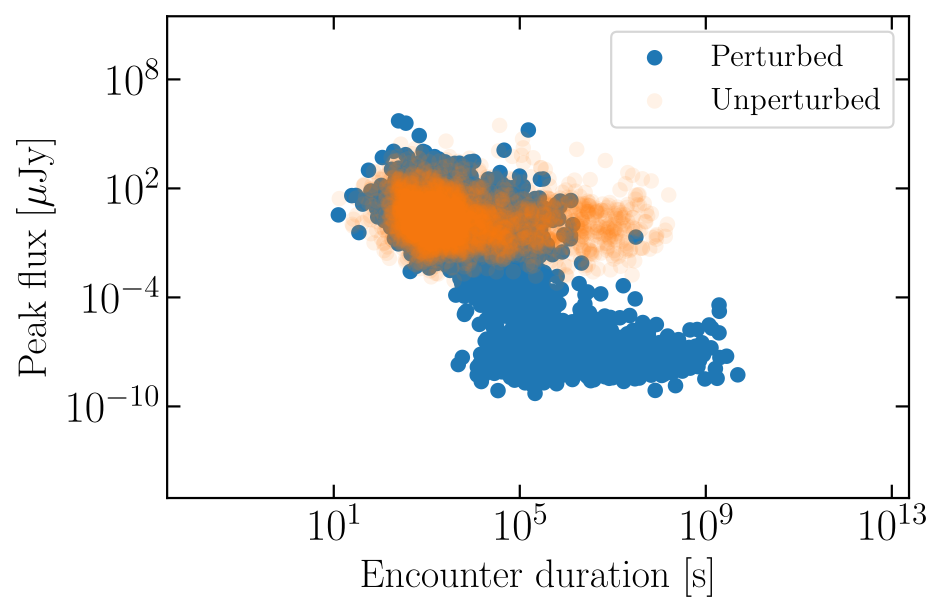
PRELIMINARY!!!

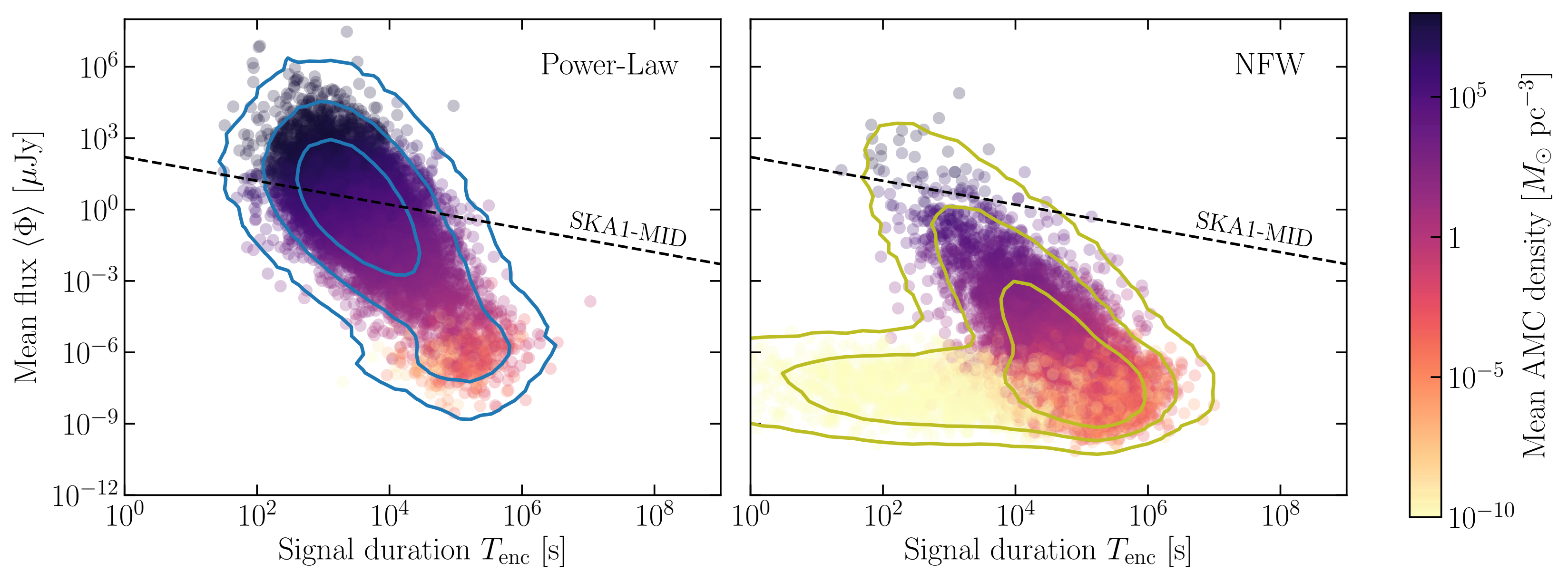
$m_a \sim 25\,\mu\mathrm{eV}$ or $\nu = \dfrac{m_a}{2\pi} \sim 6\,\mathrm{GHz}$

LV+, in preparation

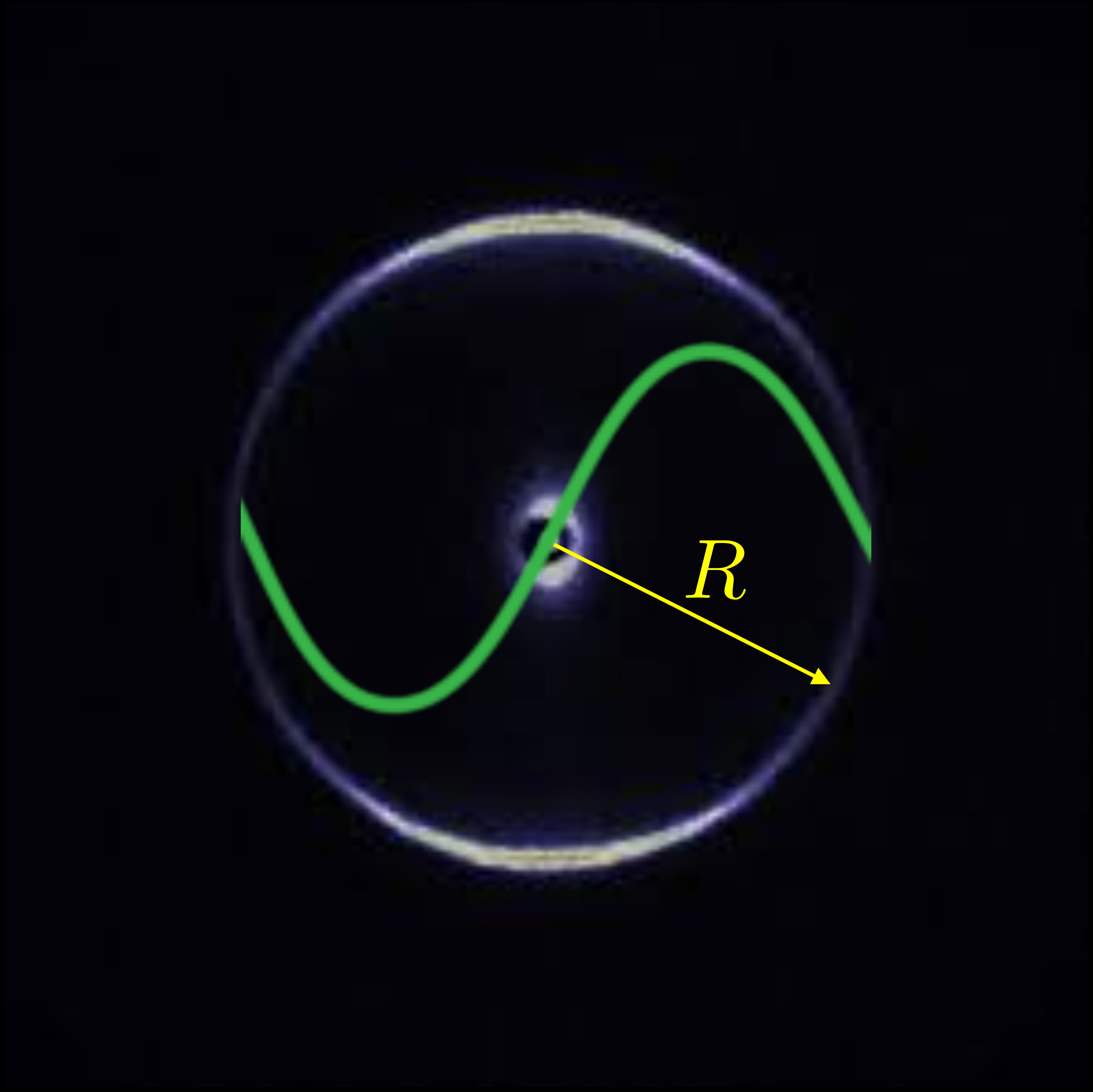








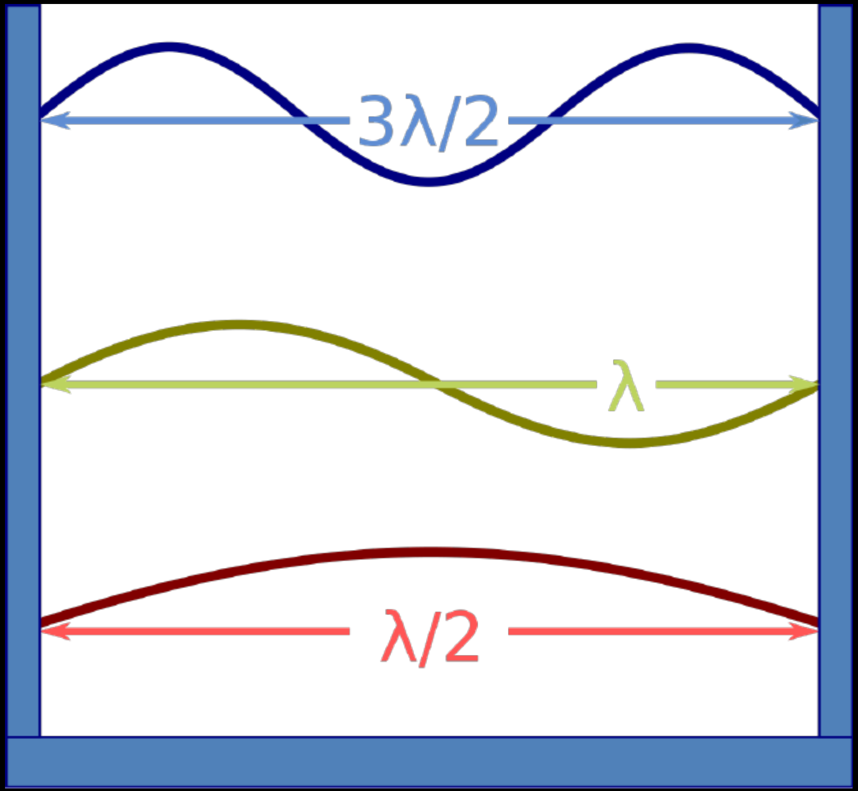
Phenomenology: axion stars



Phenomenology: axion stars

A bosonic field can arrange into a self-gravitating & compact equilibrium configuration

Particle in a box:



Particles in a box of size $R_{\rm star}$ in lowest state

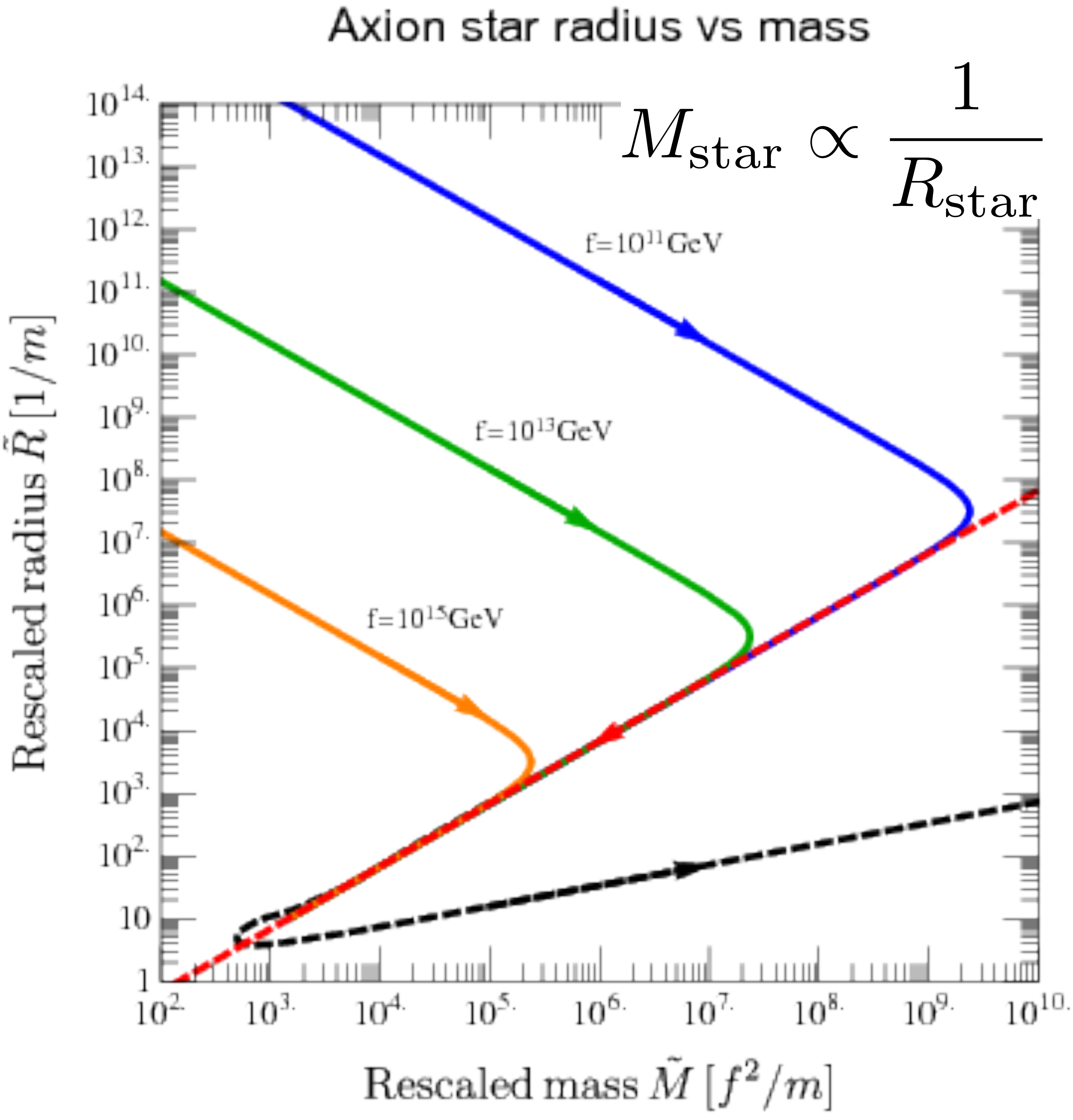
Velocity: $$v \sim \frac{\hbar}{m_{\rm DM}\, R_{\rm star}}$$

Equilibrium: $$\frac{1}{2} M_{\rm star} v^2 \sim \frac{G M_{\rm star}^2}{R_{\rm star}}$$

$$\Rightarrow \quad M_{\rm star} \propto \frac{1}{R_{\rm star}}$$

One-parameter model depending on $M_{\rm star}$

Phenomenology: axion stars

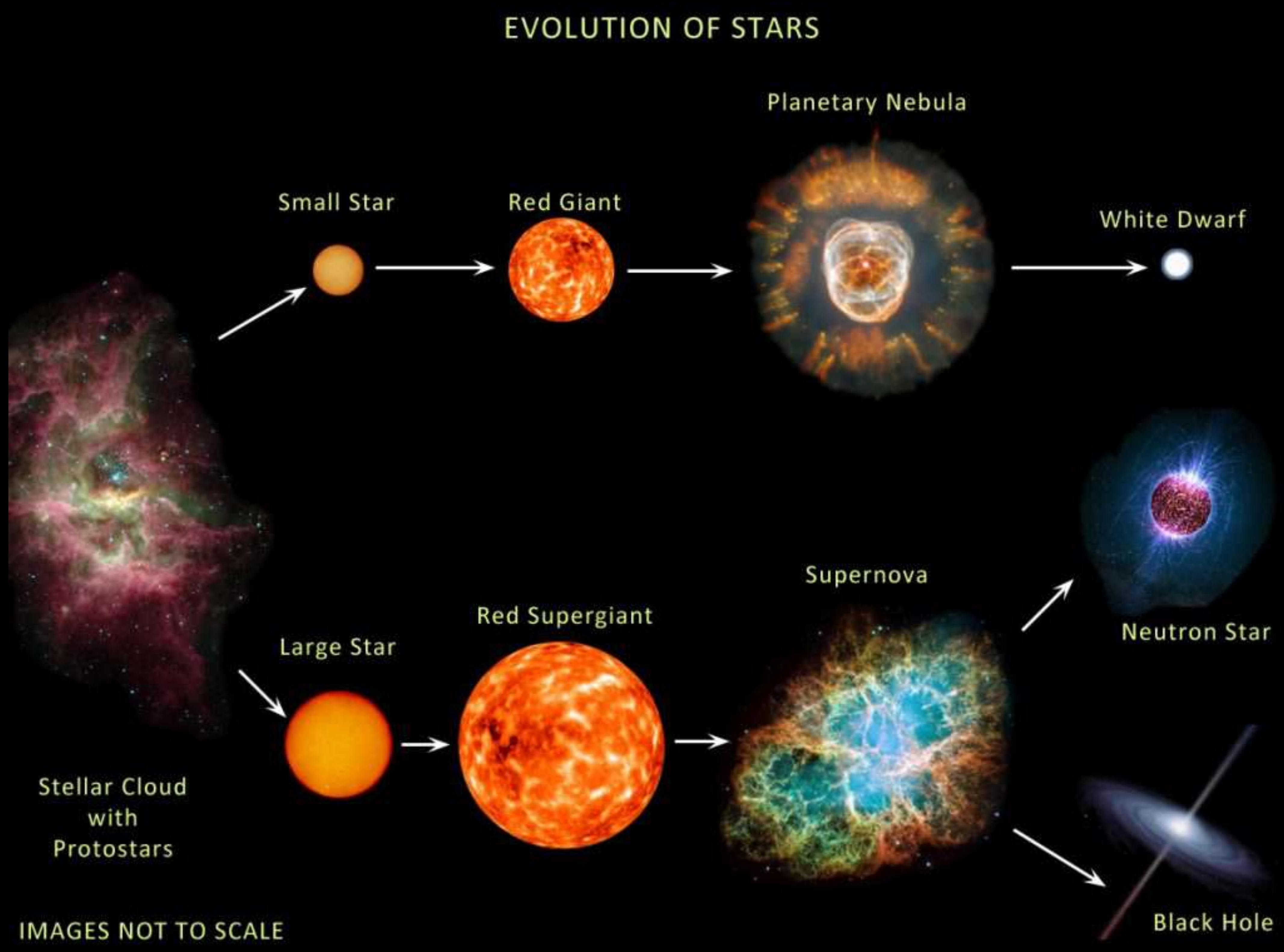


$$M_{\rm star} \propto \frac{1}{R_{\rm star}}$$

LV+, Phys. Lett. B **777** 64 (2018)

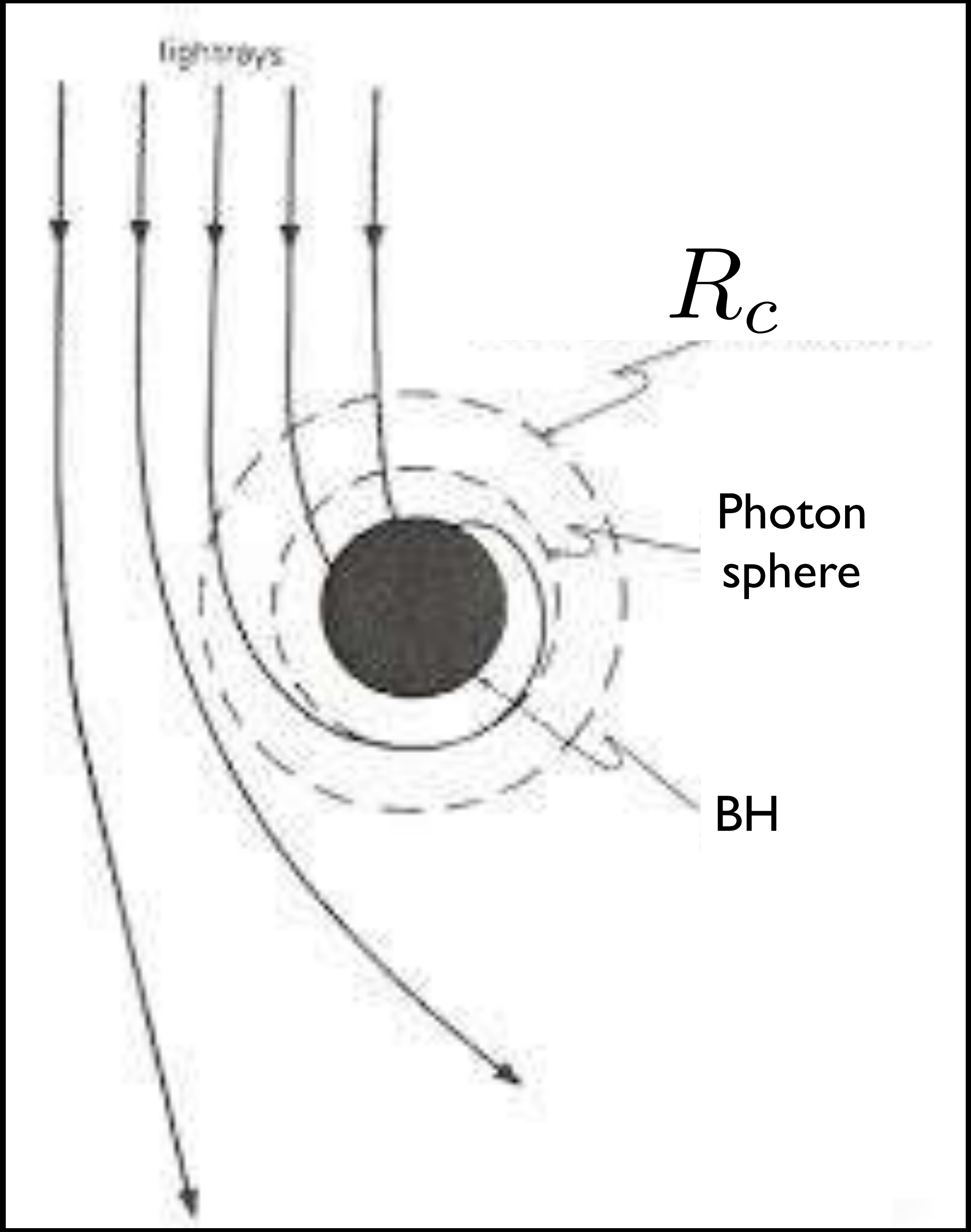

With: K. Freese, S. Baum


J. Redondo, F. Wilczek


EVOLUTION OF STARS
Small Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Cloud with Protostars
Large Star
Red Supergiant
Supernova
Neutron Star
Black Hole
IMAGES NOT TO SCALE

Shadow of a BH: dark area in the image of an optically thin region around the compact object.

Shadow ⟷ photon capture radius



Non-rotating BH:

$$r_g = GM_{\rm BH}/c^2$$

$$R_s = 2r_g$$

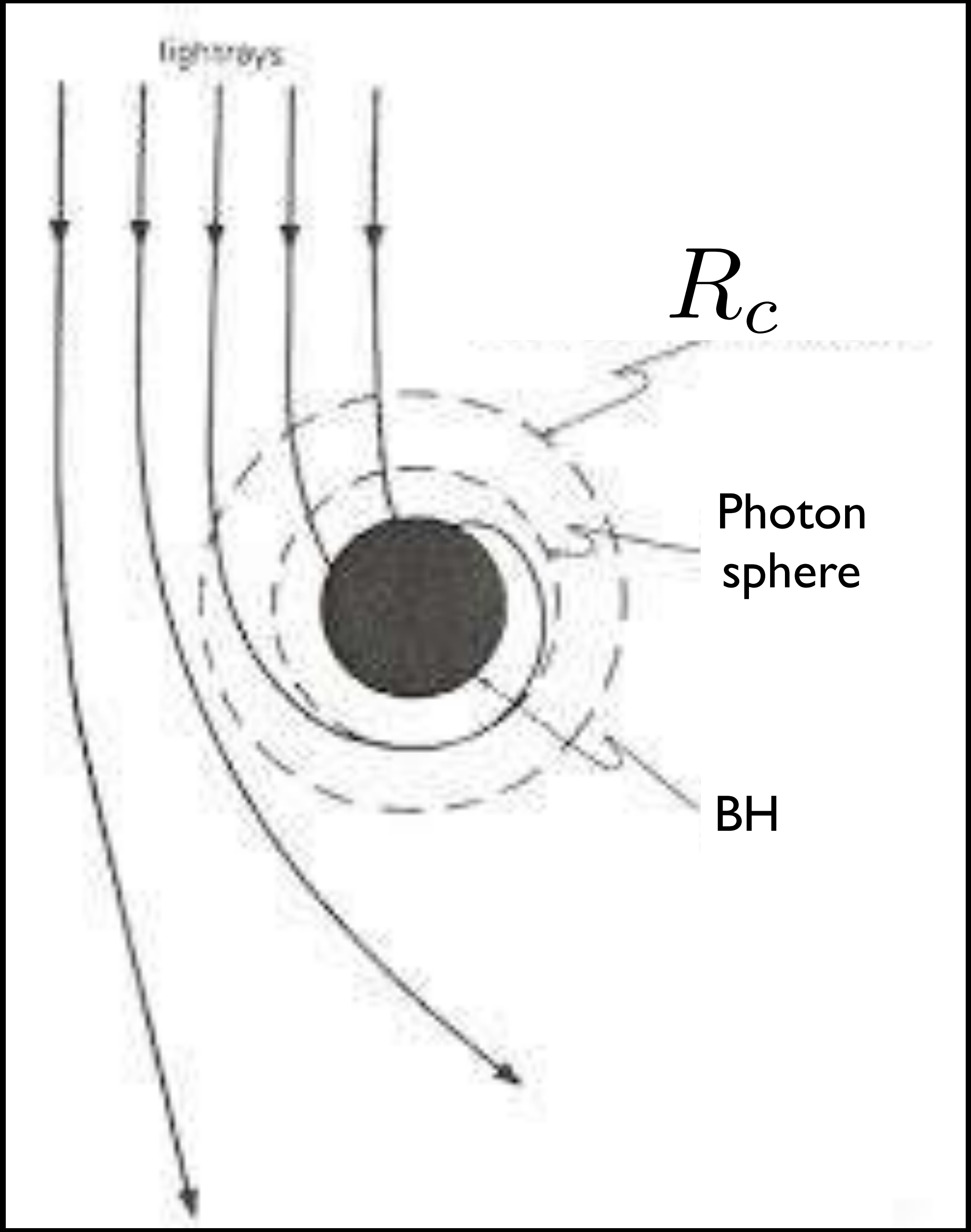
$$R_c = \sqrt{27}r_g$$

Angular diameter of the image:

$$\theta = \frac{2R_c}{D}$$

Shadow of a BH: dark area in the image of an optically thin region around the compact object.

Shadow ⟷ photon capture radius



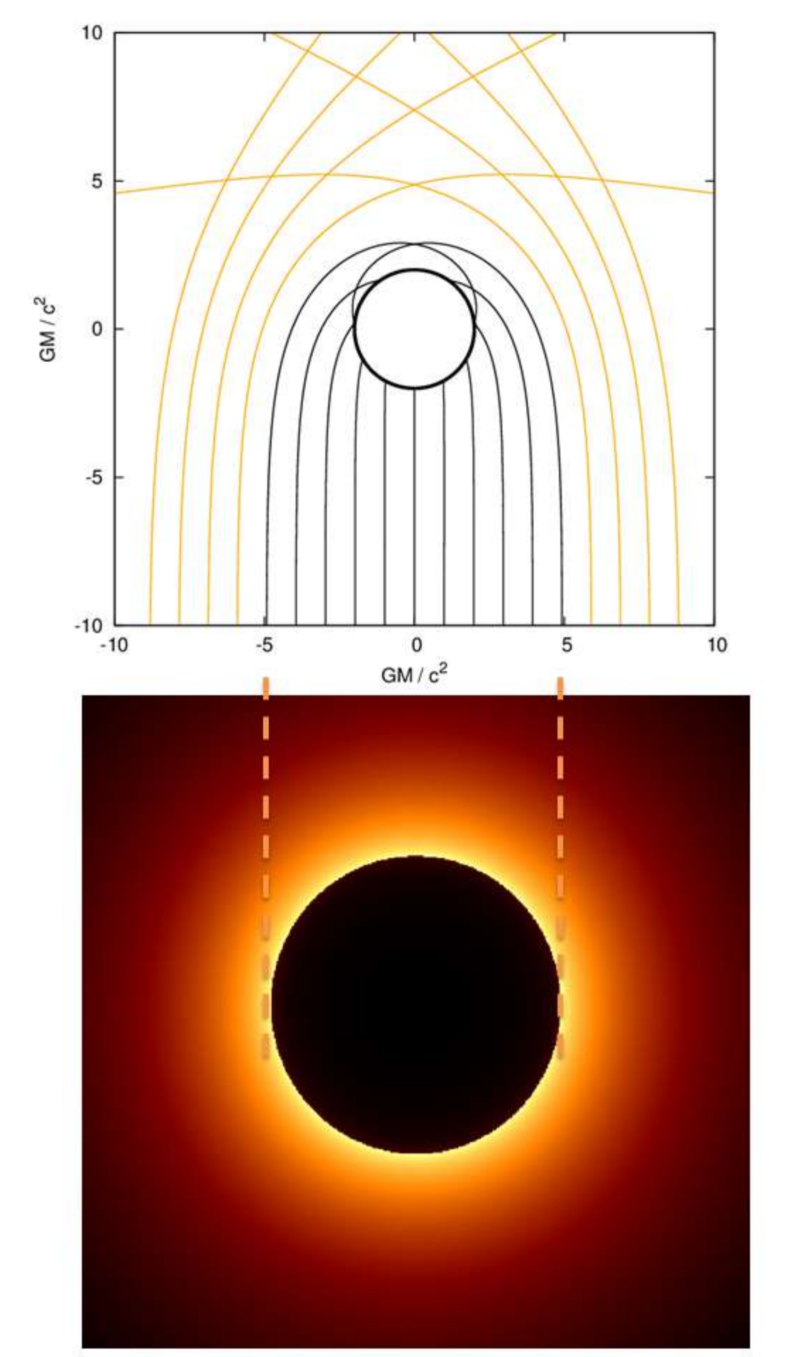
Rotating BH:

$$r_h = M + \sqrt{M^2 - a^2}$$

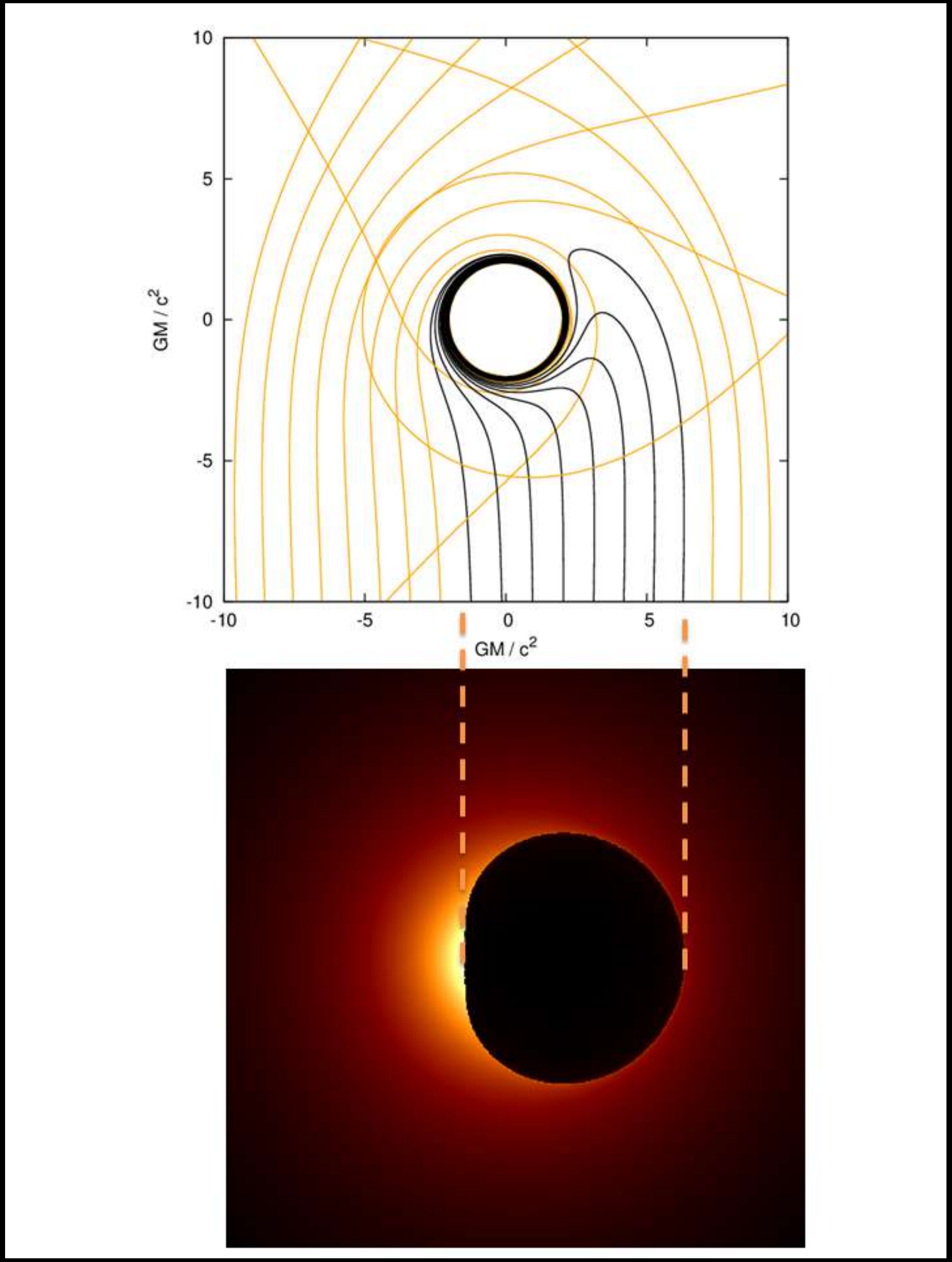
Kerr bound: $|a| \leq M$

The Kerr bound expresses the cosmic censorship conjecture (see Hartle, *Gravity*)

Photon trajectories around a BH + shadow image



Non-rotating

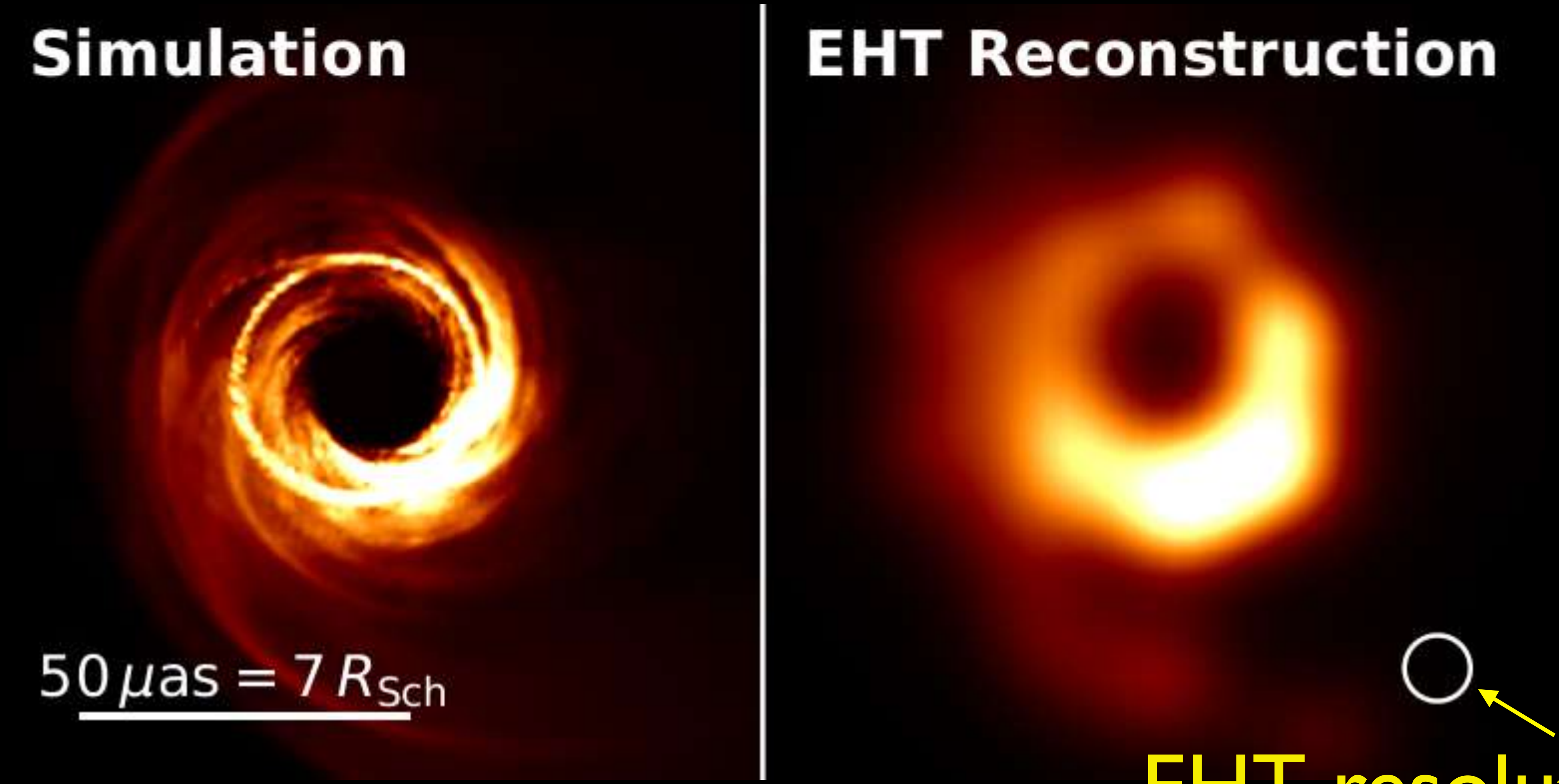


Rotating

Event Horizon Telescope

VLBI observing M87* and Sagittarius A* at Resolution at $10\,\mu\mathrm{arcsec}$

Event Horizon Telescope



EHT resolution

Left: simulation of M87* at 230GHz

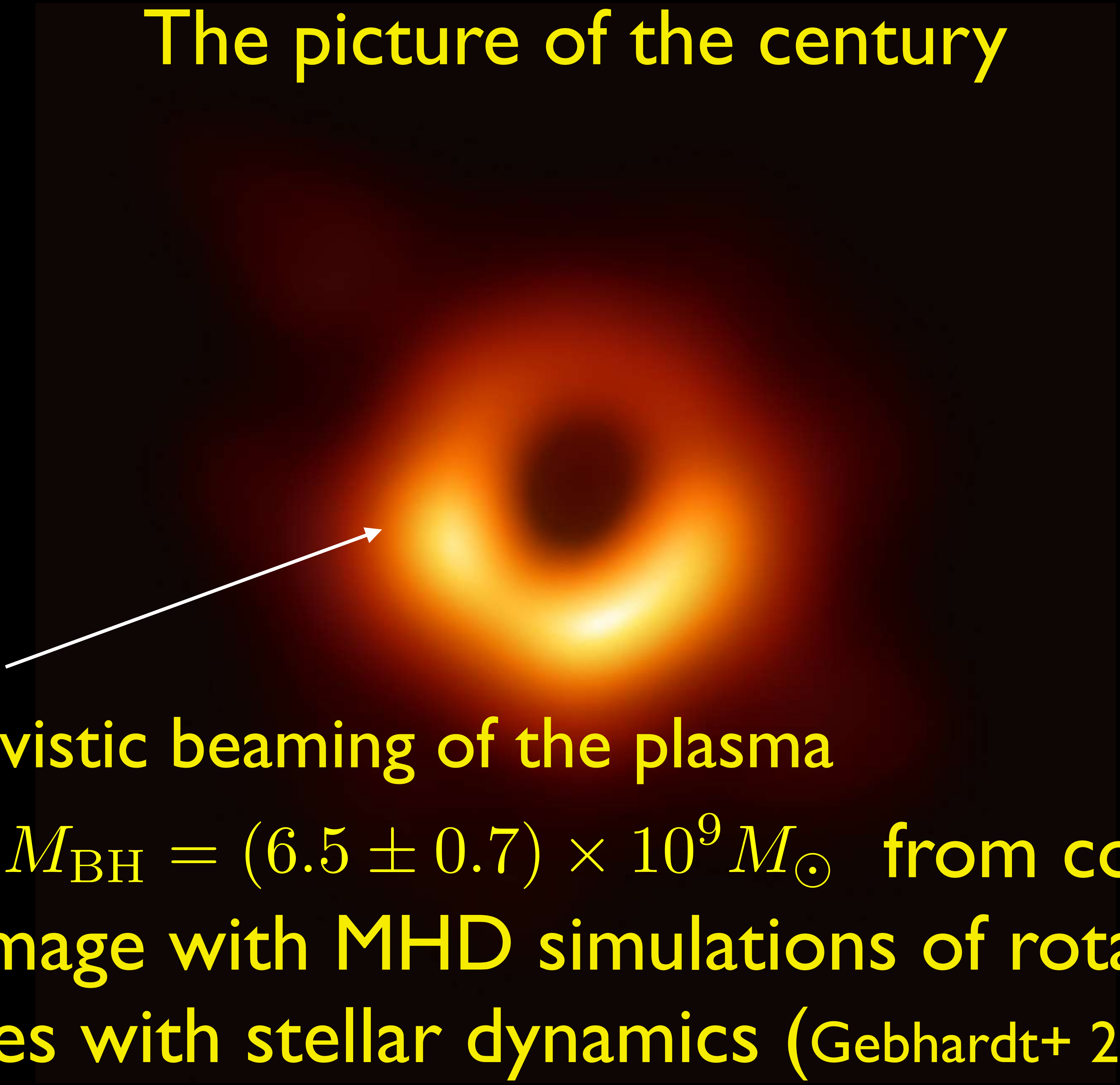
Right: Image reconstructed from simulated data using https://github.com/achael/eht-imaging

The picture of the century

EHT Collaboration, Astrophys. J. **875** (2019)

- Event Horizon Telescope (April 2019)
- 10 days acquisition + 2 years analysis

The picture of the century



- Relativistic beaming of the plasma
- Mass $M_{\rm BH} = (6.5 \pm 0.7) \times 10^9 M_\odot$ from comparing the image with MHD simulations of rotating BH
- Agrees with stellar dynamics (Gebhardt+ 2011)
- Angular diameter $(42 \pm 3)\,\mu{\rm as}$

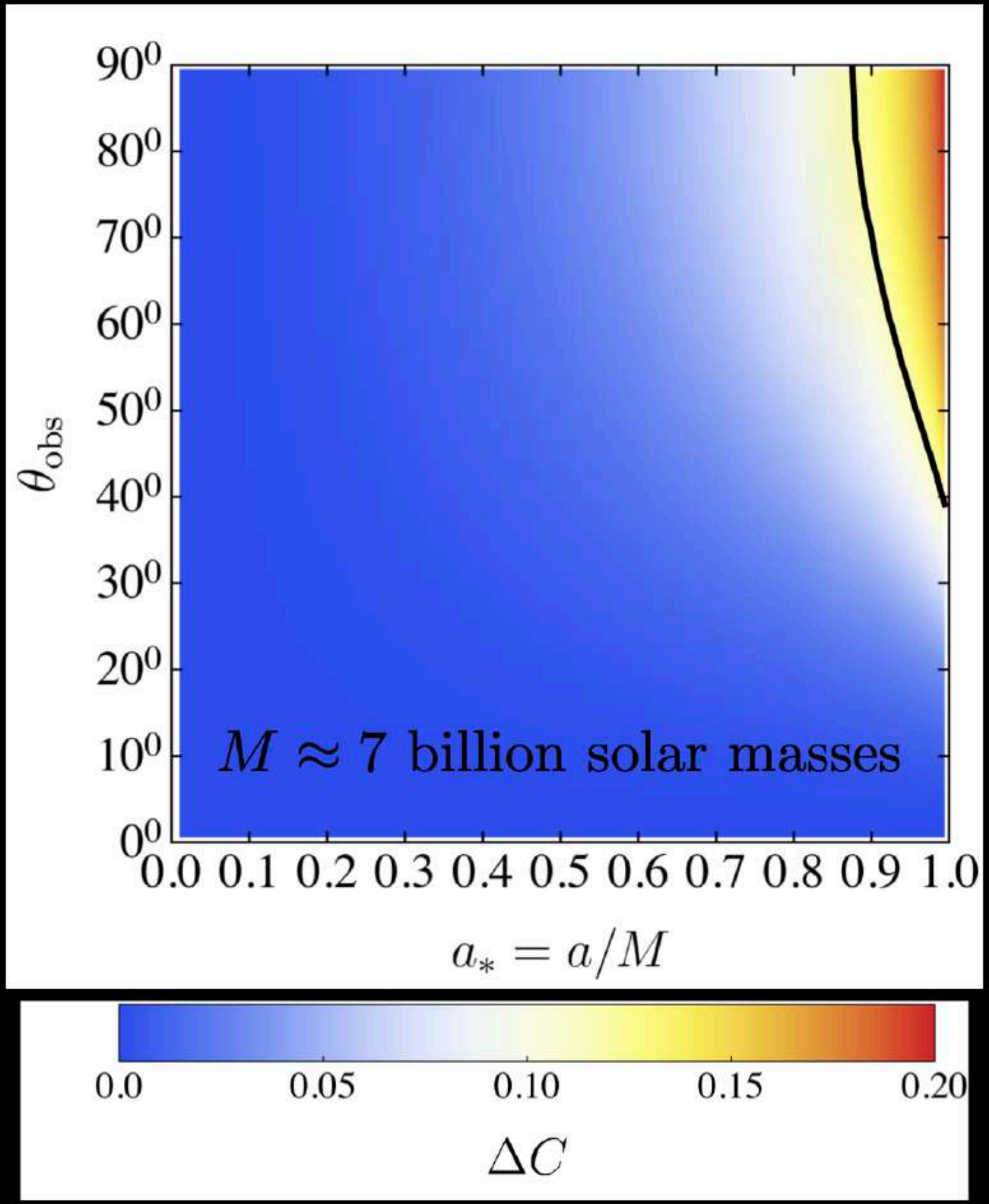
Framing the properties of M87*

Cosimo Bambi (Fudan U.)

Katherine Freese

(Austin&Stockholm)

Sunny Vagnozzi (Cambridge)



Bambi, Freese, Vagnozzi, **LV**, PRD **100** 044057 (2019) 1904.12983

Vagnozzi, **LV**, PRD **100** 024020 (2019) 1905.12421

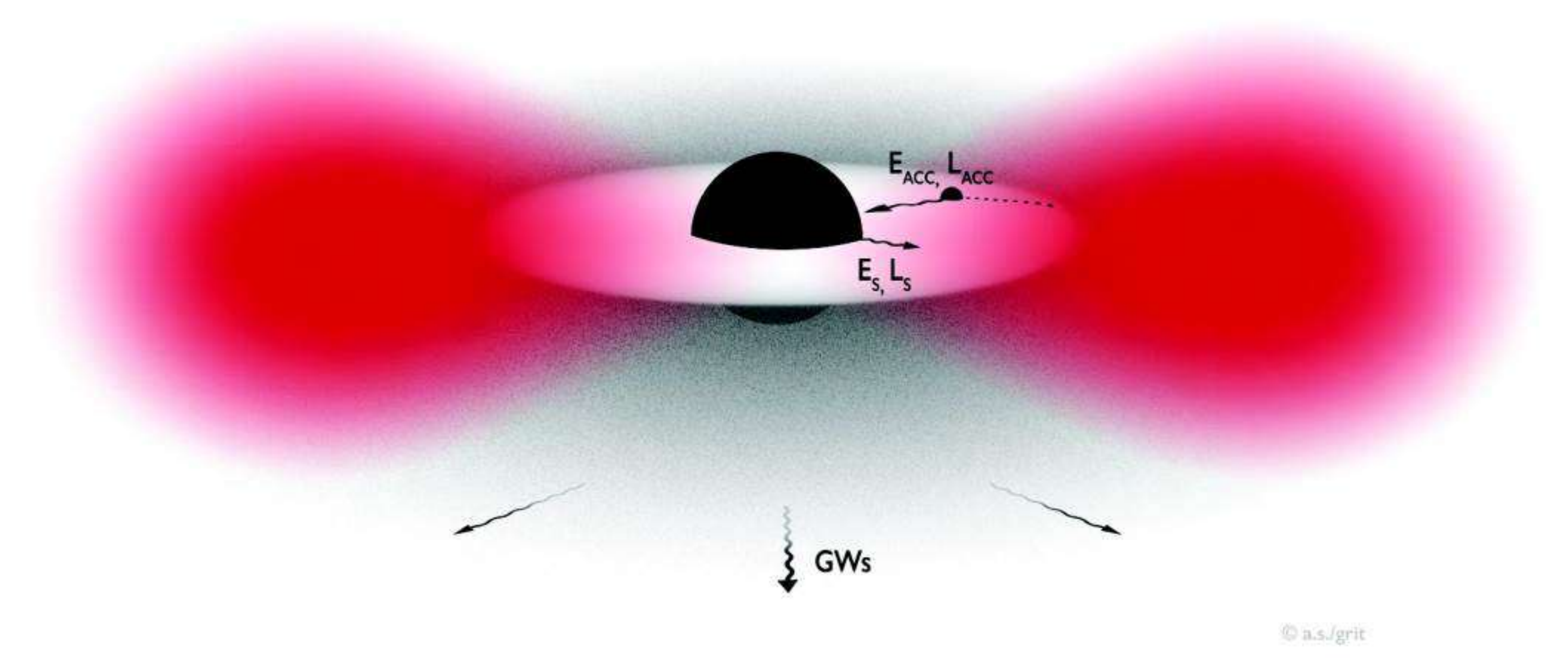
Vagnozzi, Bambi, **LV**, CQG **37** 8 087001 (2020) 2001.02986

Projects I am currently involved

2. Is the BH shadow affected by superradiance?

Light bosons form a cloud around rotating BHs and extract rotational energy from it.

How is the shadow modified? See 1906.03190



Conclusions

- It is an exciting period to work on dark matter compact objects and on exotic light bosons!

- Details require much further efforts. Work in progress...

- Axion Miniclusters and axion stars are laboratories for physics beyond the Standard Model!

- We entered the era of black hole precision physics.

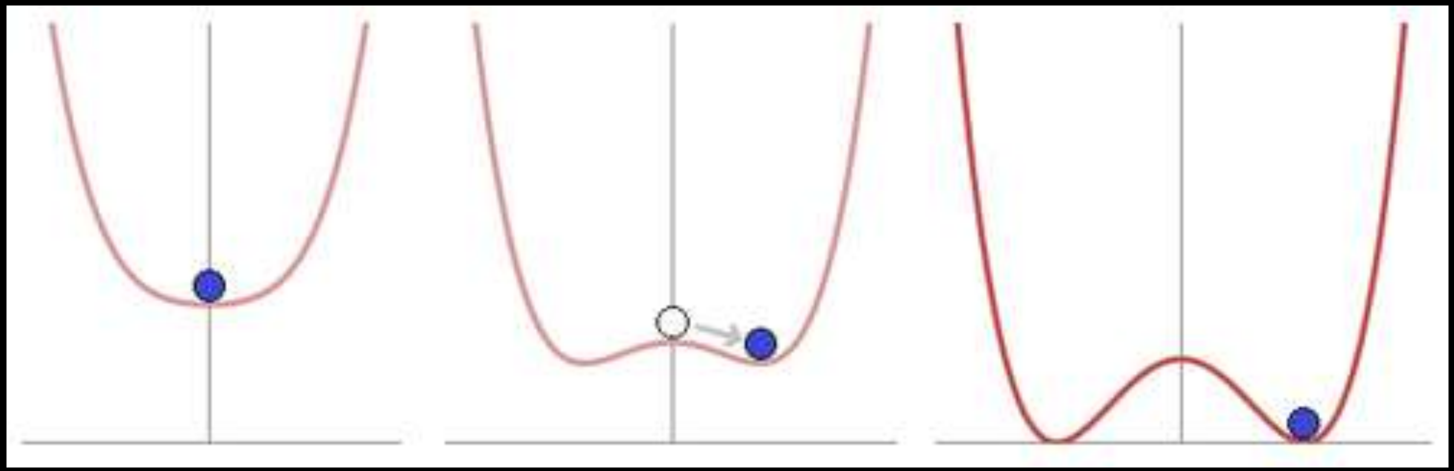
Thank you all for the attention!

Axion: Early-Universe dynamics

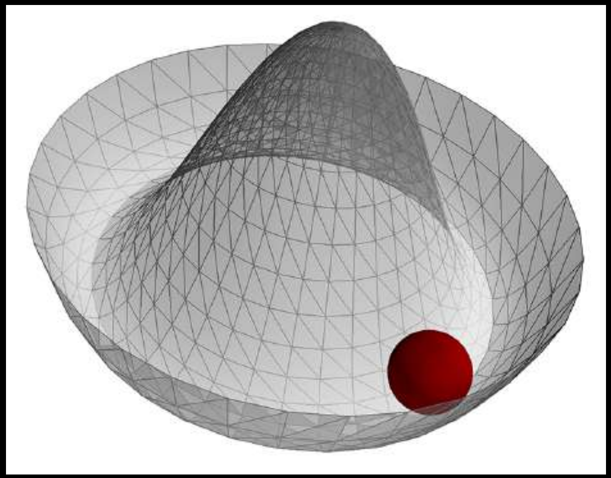
PQ Field $\Phi = \frac{1}{\sqrt{2}}(f_a + \rho_a)\exp\left(\frac{ia}{f_a}\right)$

$$V(\Phi) = \lambda\left(|\Phi|^2 - \frac{f_a^2}{2}\right)^2$$

$$V_{\rm np}(T) \approx \chi_0\left(\frac{T_C}{T}\right)^d$$

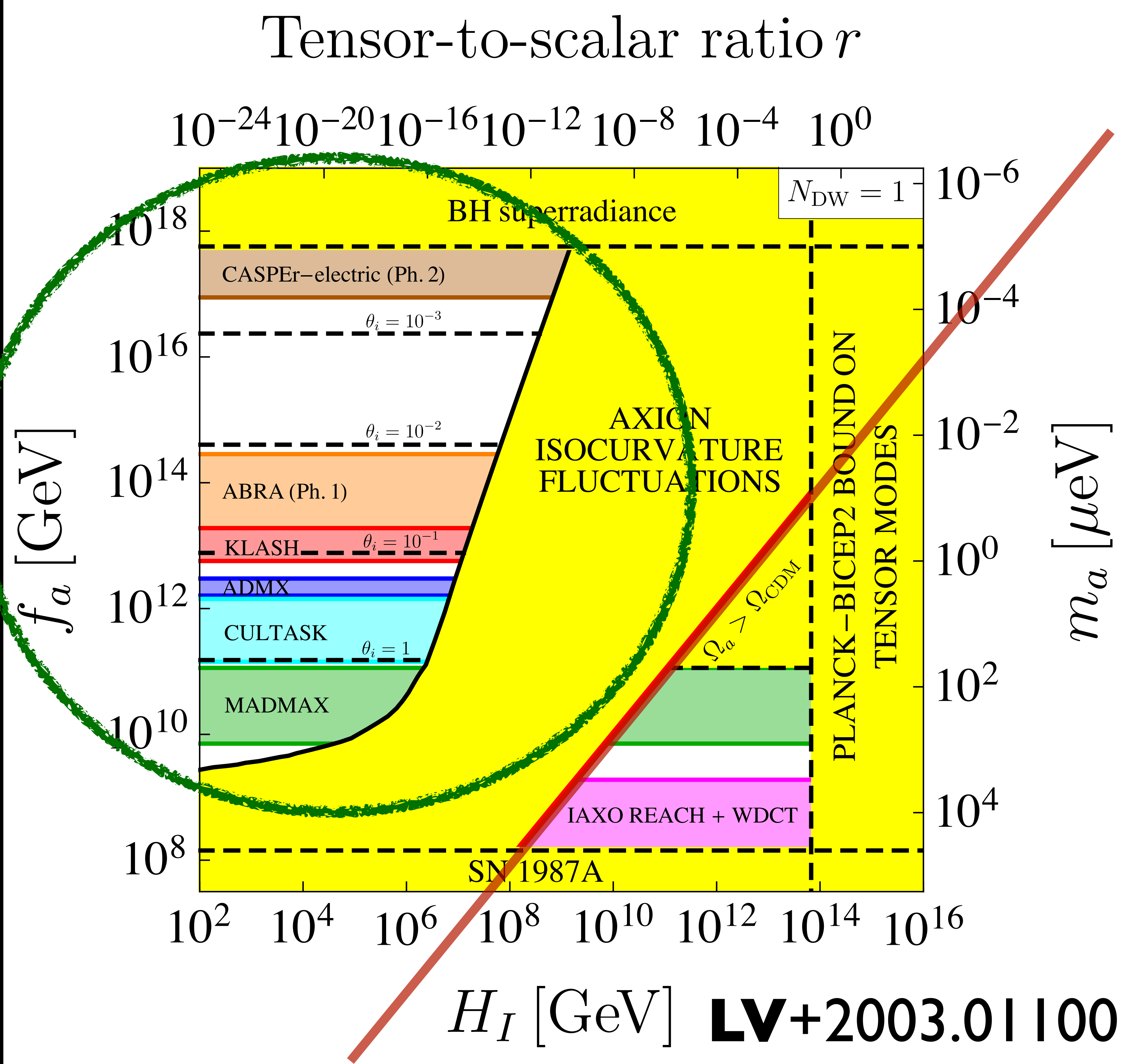


$T \gtrsim f_a$ $T \sim f_a$ $T \lesssim f_a$



$T \sim \Lambda_{\rm QCD} \ll f_a$

Scenario I - Broken PQ symmetry during inflation



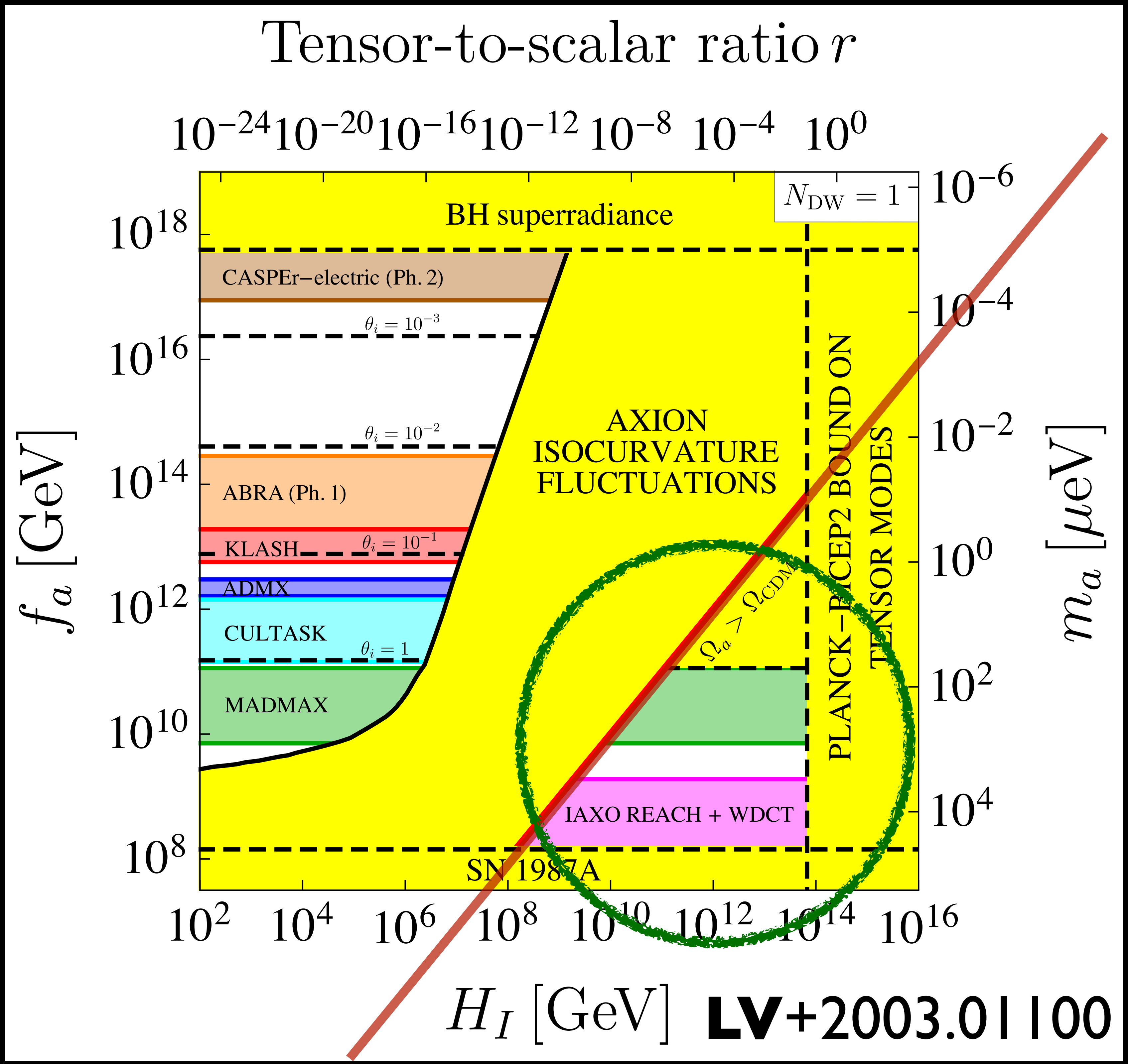
LV+2003.01100

$$f_a > \max\left(H_I, T_{\max}\right)$$

Isocurvature suppression
Hamann+ 0904.0647
Evans, Yanagida+ 1402.5989
Yanagida+1507.00119

Models with low r,
Tenkanen&**LV** 1906.11837

Scenario: Unbroken PQ symmetry during inflation



LV+2003.01100

Inflation first, then
PQ symmetry breaking

Topological defects appear (strings and walls)

Numerical simulations are needed.

$$m_a \approx (10 - 100)\,\mu\mathrm{eV}$$

Hiramatsu+ 1012.5502, 1202.5851

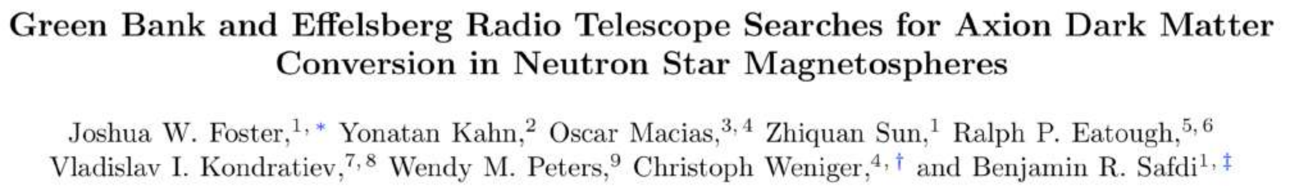
Klaer&Moore 1708.07521

Buschmann+ 1906.00967

Radioastronomy Axion Miniclusters

奇台县 Qitai radio telescope scheduled to complete by 2023

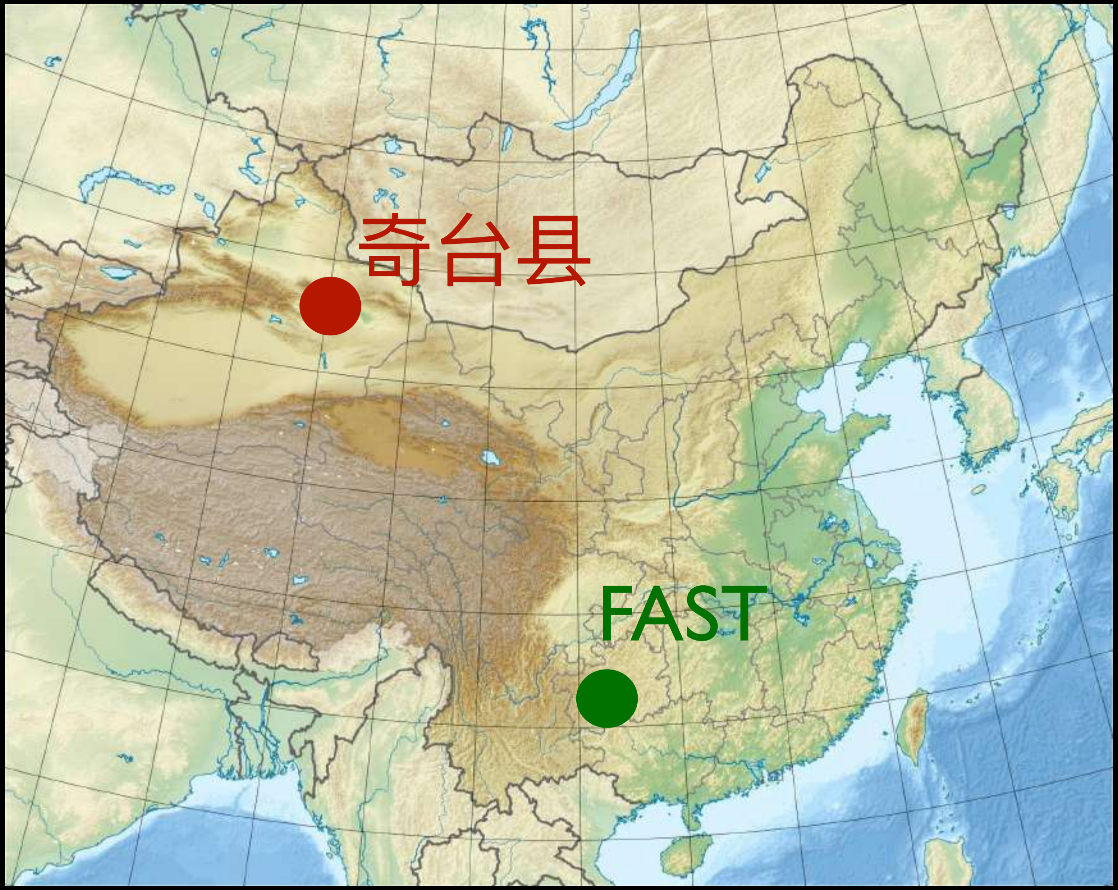
Fully steerable, like Green Bank Telescope and Effelsberg 100-m Radio Telescope.



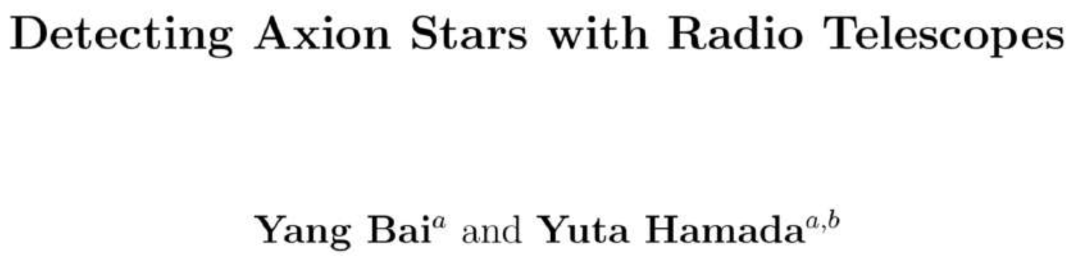
Green Bank and Effelsberg Radio Telescope Searches for Axion Dark Matter Conversion in Neutron Star Magnetospheres

Joshua W. Foster,[1,*] Yonatan Kahn,[2] Oscar Macias,[3,4] Zhiquan Sun,[1] Ralph P. Eatough,[5,6] Vladislav I. Kondratiev,[7,8] Wendy M. Peters,[9] Christoph Weniger,[4,†] and Benjamin R. Safdi[1,‡]

2004.00011
See also 1910.11907



FAST radio telescope: $\nu = (0.07 - 3)\,\mathrm{GHz}$
Sensitivity $= 0.92\,\mu\mathrm{Jy}\,(\mathrm{hr}/t_{\mathrm{obs}})^{1/2}$ at $\nu = 0.8\,\mathrm{GHz}$



Detecting Axion Stars with Radio Telescopes

Yang Bai[a] and Yuta Hamada[a,b]

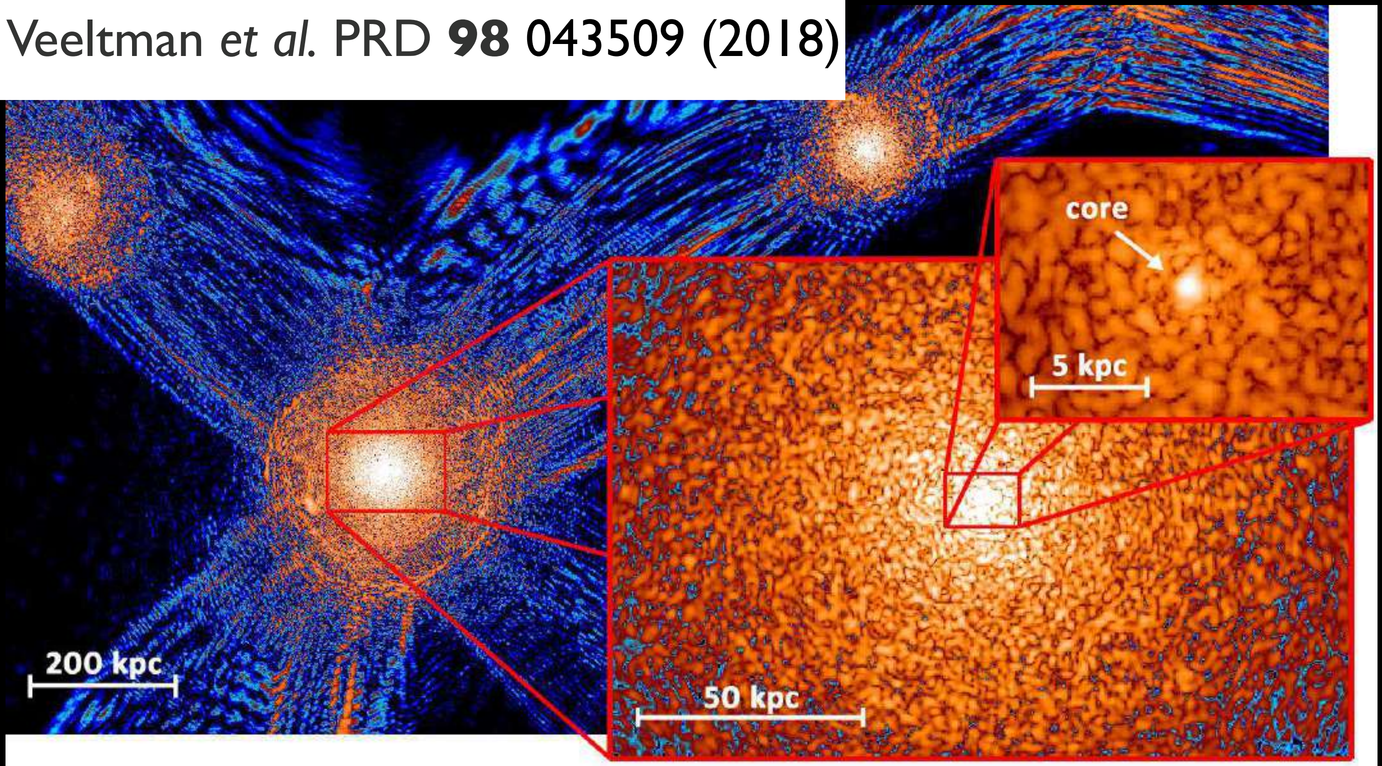
1709.10516

However, dense axion stars are killed in my paper with Wilczek *et al.*, see next part of talk

Soliton cores and boson stars

Schive *et al.* Nature **10** 496 (2014)

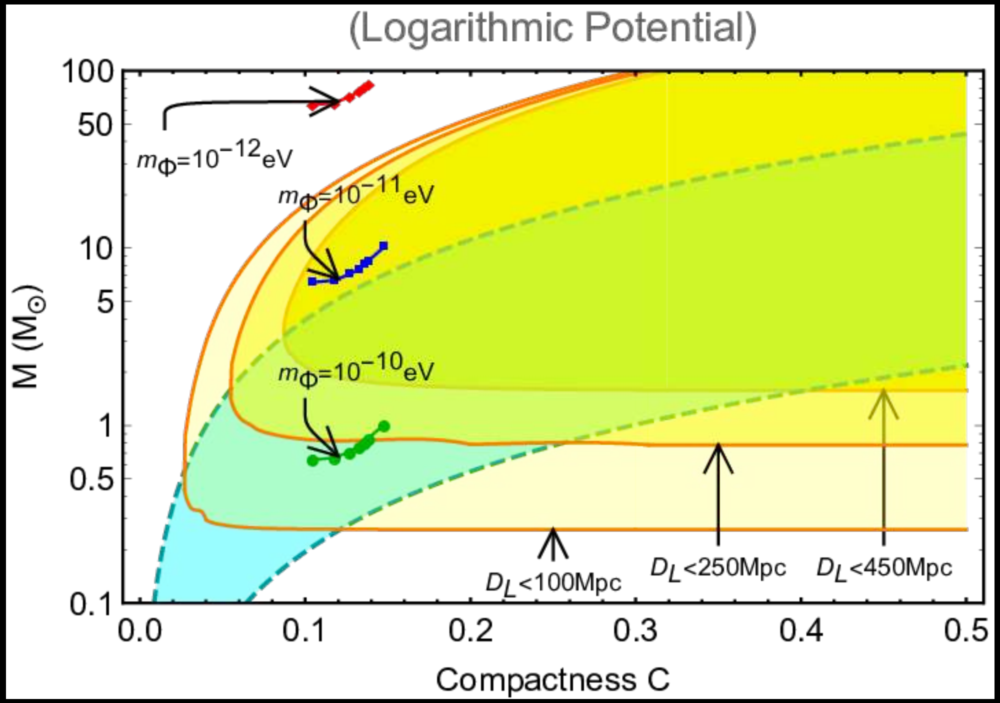
Veeltman *et al.* PRD **98** 043509 (2018)



Ultra-light axion DM is indistinguishable from CDM on large scales....

... galactic-size self-gravitating soliton cores are produced

Boson star binaries are also potentially detectable in GW



H-J He+ 1906.02094