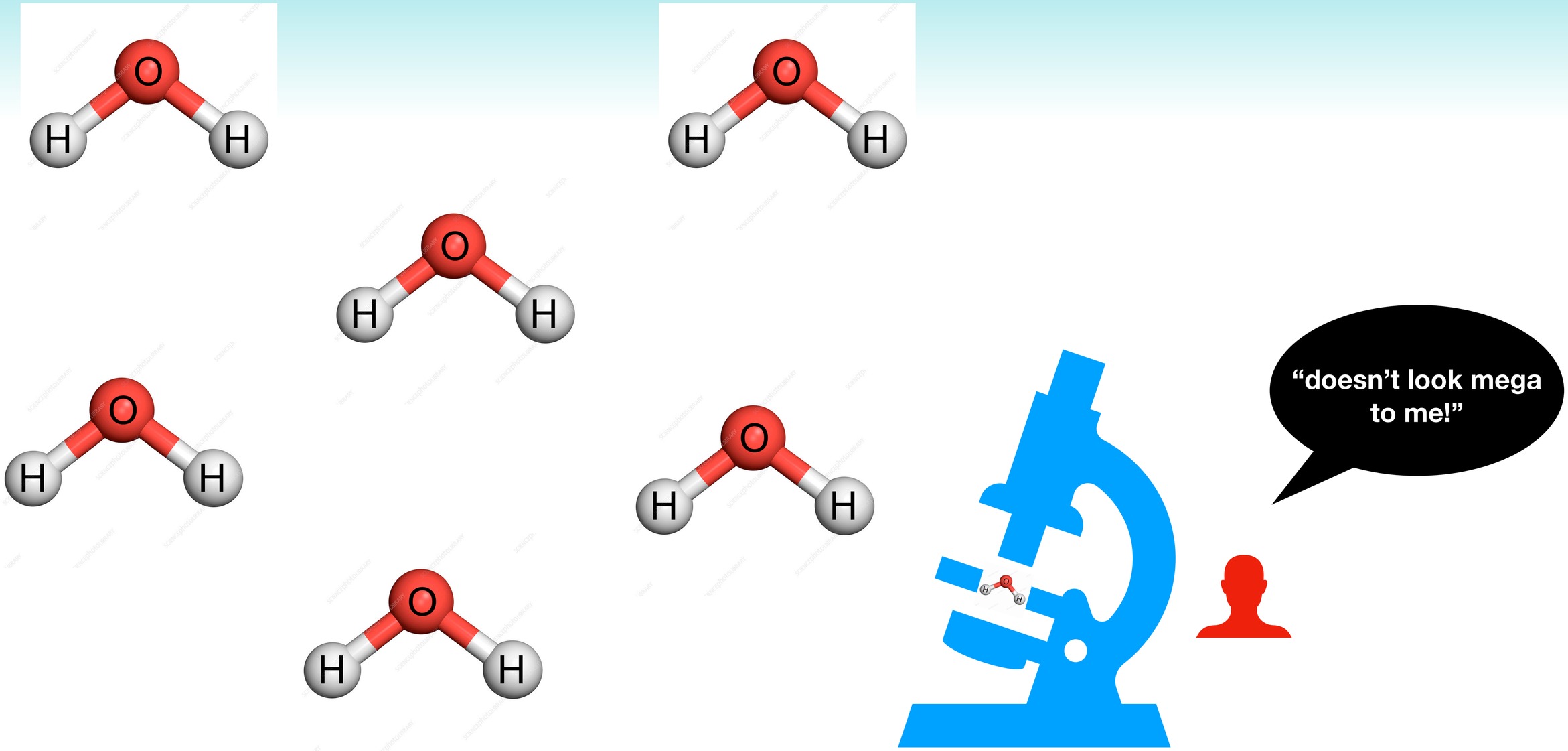
ULDM is MEGA

1. A little on the meta-mega issue
2. Do boson stars form? (pre-empting your questions)
3. Chalk talk:

Transient Signals from Relativistic Axion Bursts

Joshua Eby
Kavli IPMU, U Tokyo
MITP Mega DM Workshop
17/05/2022

This work was supported by the World Premier International Research Center Initiative (WPI), MEXT, Japan and by the JSPS KAKENHI Grant Numbers 21H05451 and 21K20366.


O
H
H
“doesn’t look mega to me!”


“doesn’t look mega to me!”

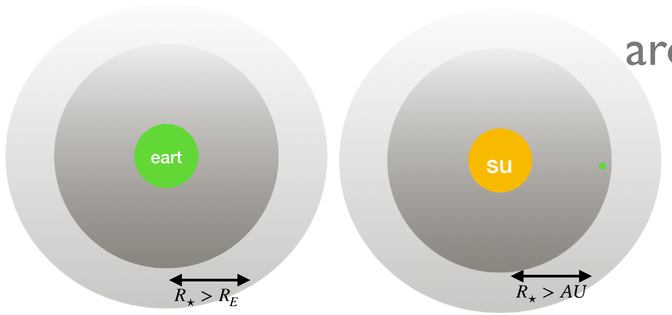
ULDM is MEGA

$$\lambda_{\rm dB} = \frac{1}{m_\phi \sigma_{\rm vir}}$$

Quasiparticles / granules / traveling waves

$$\sim R_E \left(\frac{10^{-10}\,{\rm eV}}{m_\phi}\right) \sim {\rm AU} \left(\frac{10^{-14}\,{\rm eV}}{m_\phi}\right) \sim {\rm kpc} \left(\frac{10^{-22}\,{\rm eV}}{m_\phi}\right)$$

Bound bosonic halos around the Earth or Sun



Boson stars / axion stars / oscillatons / non-topological solitons

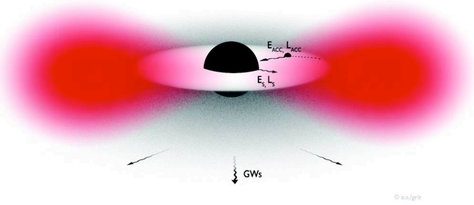
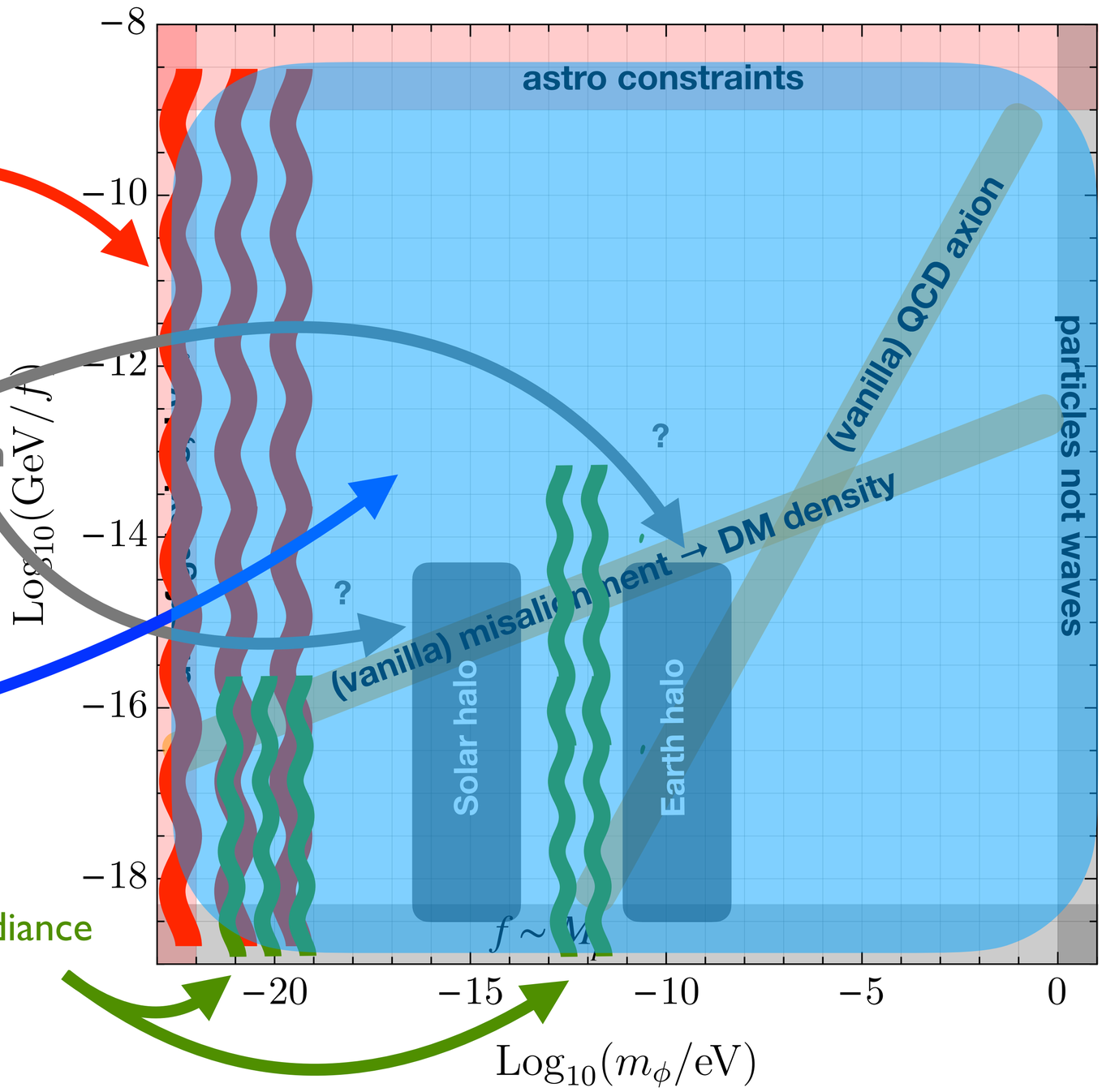


Image: Paolo Pani

Black hole superradiance of light scalar fields



ULDM is MEGA

◉ Quasiparticles / granules / traveling waves

$$\lambda_{\rm dB} = \frac{1}{m_\phi \sigma_{\rm vir}}$$

Earth size — solar system size — galaxy size

$$\sim R_E \left(\frac{10^{-10}\,{\rm eV}}{m_\phi}\right) \sim {\rm AU} \left(\frac{10^{-14}\,{\rm eV}}{m_\phi}\right) \sim {\rm kpc} \left(\frac{10^{-22}\,{\rm eV}}{m_\phi}\right)$$

Hui, Ostriker, Tremaine, Witten (1610.08297)
Bar-Or, Fouvry, Tremaine (1809.07673)

Church, Ostriker, Mocz (1809.04744)
Marsh, Niemeyer (1810.08543)
Dalal, Kravtsov (2203.05750)

++++++

◉ Black hole superradiance of scalar fields

Arvanitaki, Baryakhtar, Huang (1411.2263)
Arvanitaki, Baryakhtar, Dimopoulos, Dubovsky, Lasenby (1604.03958)
Stott, Marsh (1805.02016)
Baryakhtar, Galanis, Lasenby, Simon (2011.11646)
Chang, Zhang, Bao (2201.11338)

++++++

◉ Boson stars / axion stars

Kaup (Phys Rev 1968);
Ruffini+Bonazzola (Phys Rev 1969)
Chavanis (1103.2050) w/ Delfini (1103.2054)
JE, Suranyi, Wijewardhana (1712.04941)
w/ Leembruggen (1608.06911),
w/ Ma (1705.05385), w/ Street (2011.09087)

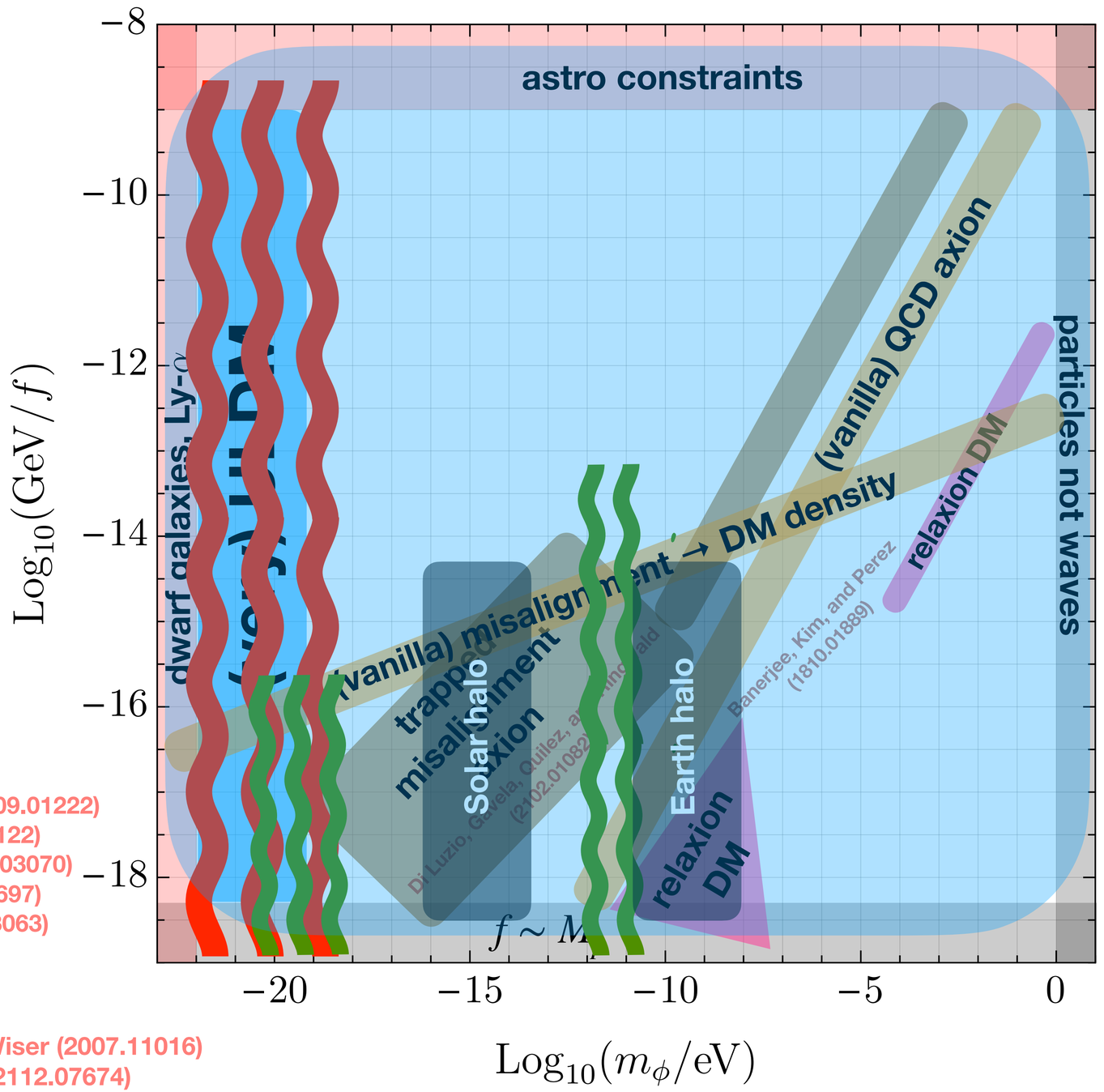
Iwazaki (1410.4323), Bai, Du, Hamada (2109.01222)
Bar, Blas, Blum, Sibiryakov (1805.00122)
w/ JE, Sato (1903.03402), w/ Sun (2111.03070)
Croon, McKeen, Raj, Wang (2007.12697)
Sugiyama, Takada, Kusenko (2108.03063)

++++++

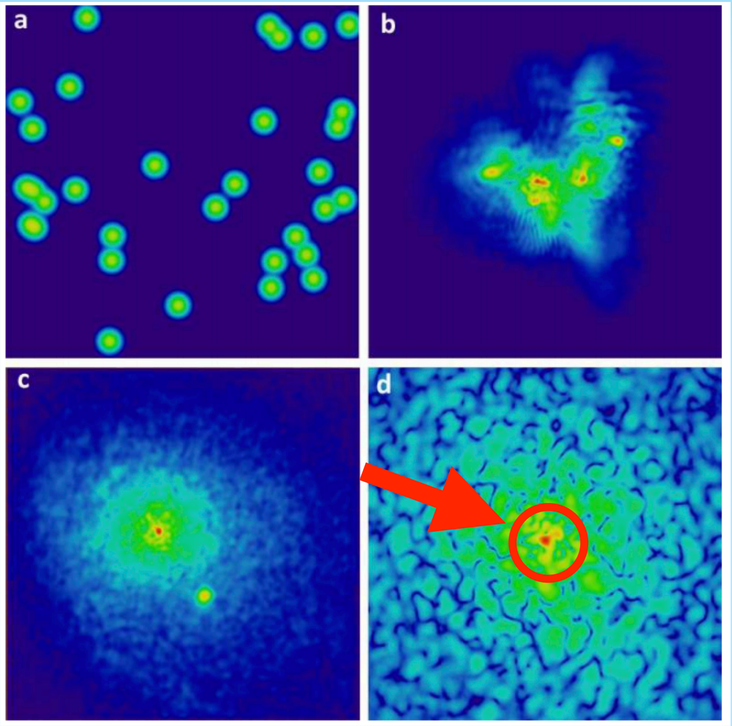
◉ Bound halos in the solar system

Banerjee, Budker, JE, Kim, Perez (1902.08212)
w/ Matsedonskyi, Flaumbaum (1912.04295)

Anderson, Partenheimer, Wiser (2007.11016)
JE, Tsai, Safronova (2112.07674)

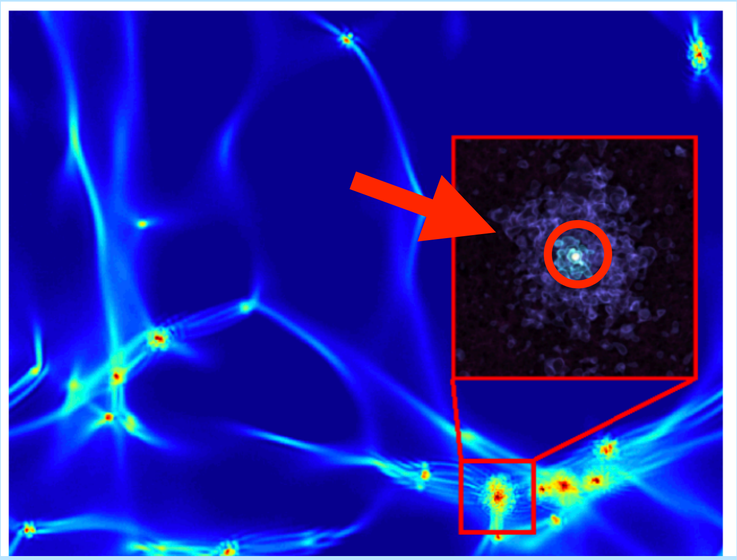


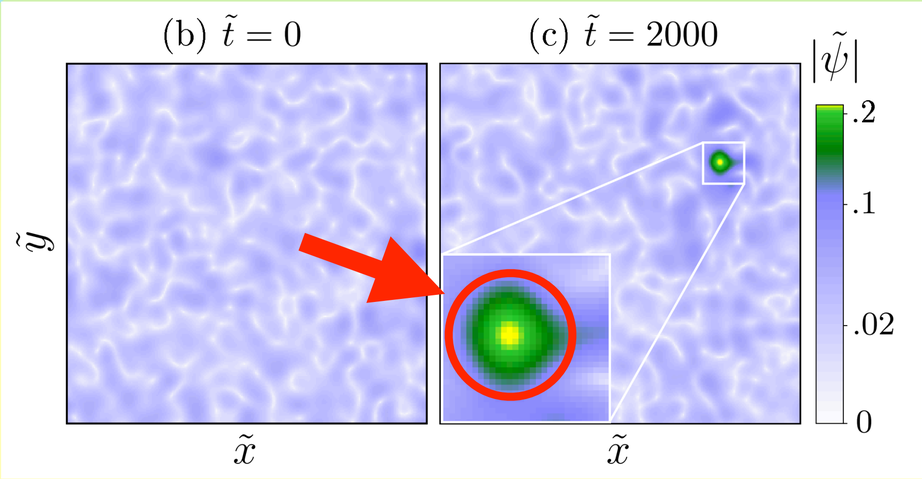
Formation of Boson Stars



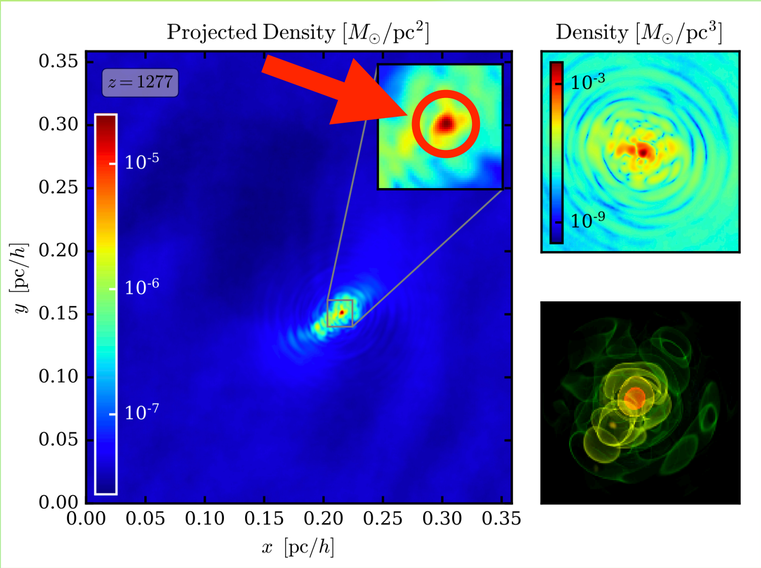
Schive et al.,
Phys. Rev. Lett. 113, 261302 (2014)

Mocz et al.,
MNRAS, Volume 471, Issue 4, November 2017





Levkov, Panin, Tkachev,
Phys. Rev. Lett. 121, 151301 (2018)



Eggemeier and Niemeyer,
Phys. Rev. D 100, 063528 (2019)

Two mechanisms (both shown to work):

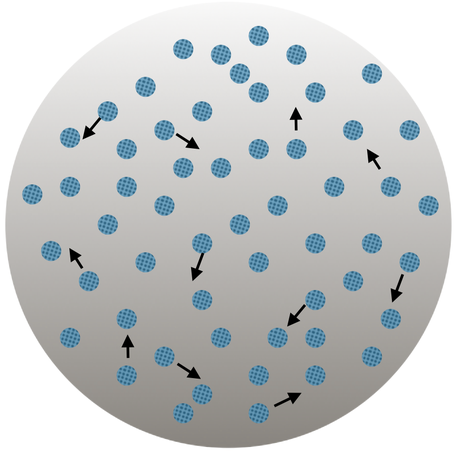
- **Gravitational relaxation**
- **Violent relaxation**

Formation: The calm way

- **Gravitational relaxation** of quasiparticles sufficient for formation

See e.g. Binney and Tremaine, "Galactic Dynamics, 2nd Edition"

Hui, Ostriker, Tremaine, Witten (1610.08297)
Bar-Or, Fouvry, Tremaine (1809.07673)



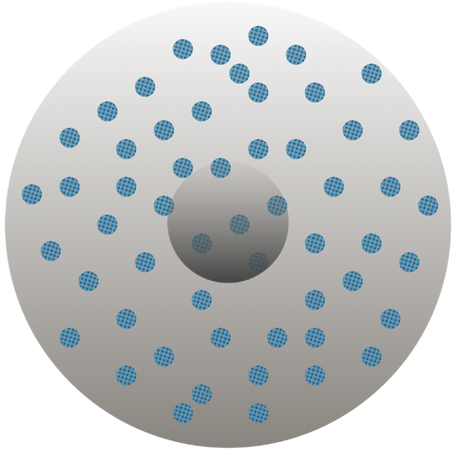
Quasiparticle dispersion

Velocity change per crossing

$$\Delta v^2 \simeq 8\,N \left(\frac{G\,M}{R_{\rm gal}\,v} \right) \ln N$$

Fractional velocity change

$$\frac{\Delta v^2}{v^2} \simeq \frac{8\,\ln N}{N}$$



Boson star formation

Relaxation to ground state

$$t_{\rm relax} \simeq \frac{0.1\,N}{\ln N} t_{\rm cross}$$

Analytic timescale matches simulation results!

Schive et al. (1407.7762, ++)
Levkov, Panin, Tkachev (1804.05857)

Formation: The messy way

Violent Relaxation

Eggemeier and Niemeyer (1906.01348)
Chen, Du, Lentz, Marsh, Niemeyer (2011.01333)

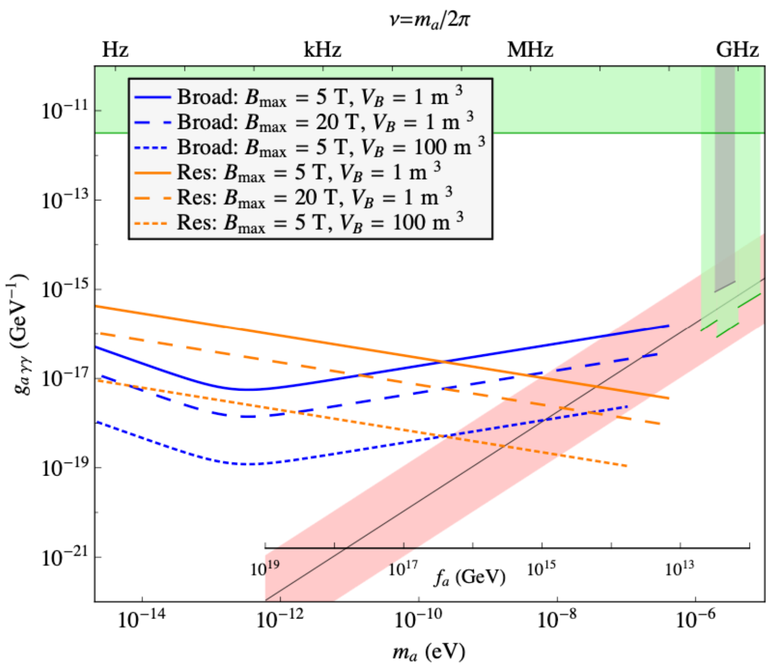
Now look over here
while I tell you about:

Transient Signals from Relativistic Axion Bursts

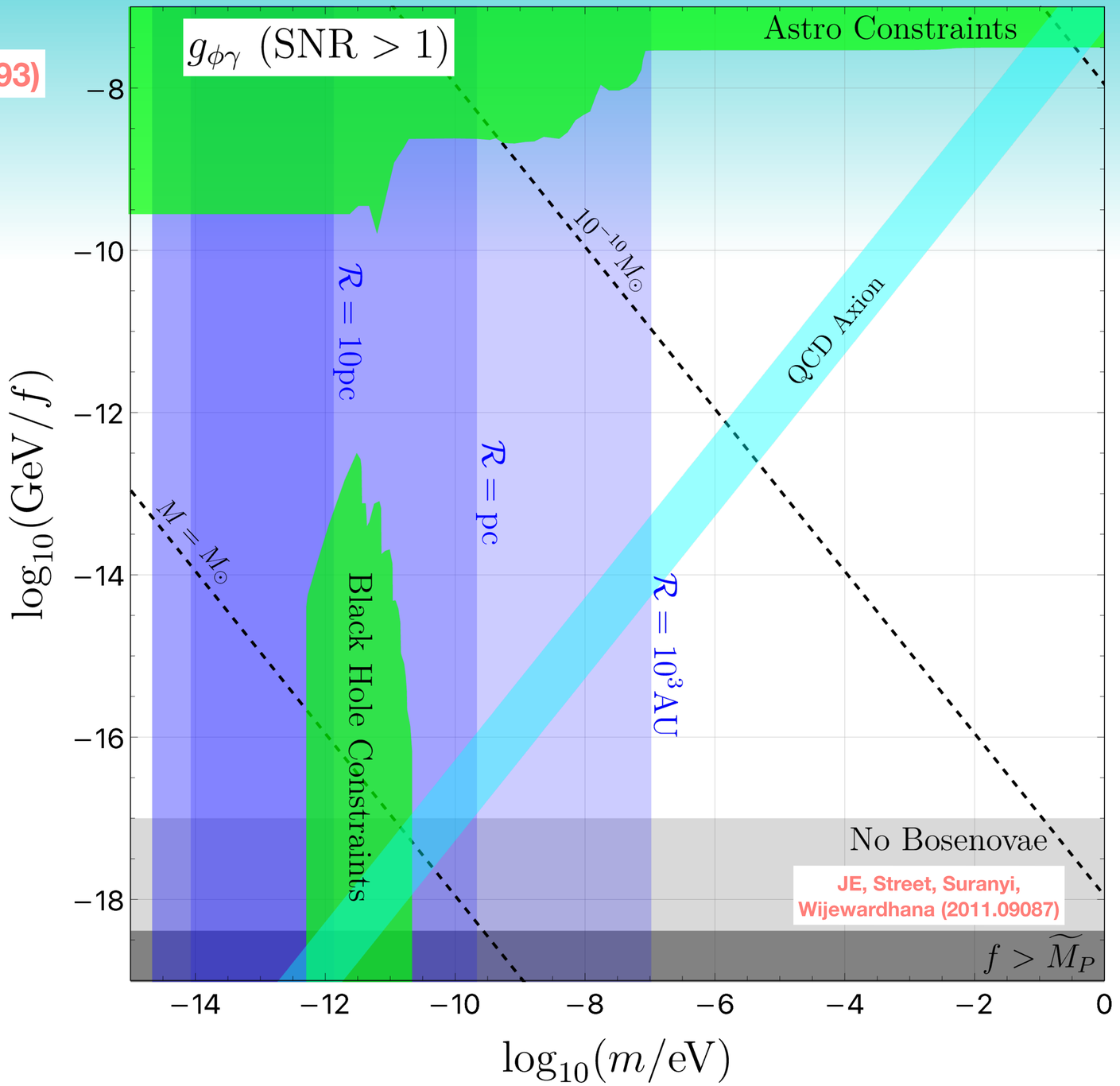
JE, Shirai, Stadnik, Takhistov (2106.14893)

For absolute sensitivity, we use ABRACADABRA broadband long-term reach

Kahn, Safdi, Thaler (1602.01086)



Though see also DMRadio (Snowmass2021) and SHAFT (2003.03348)



JE, Shirai, Stadnik, Takhistov (2106.14893)

Assume average time for burst $\tau = 10\text{Gyr}$

Check whether

$$\mathcal{N} \equiv N_{\text{star}}(\mathcal{R}) \times \left(\frac{1\,\text{yr}}{\tau}\right) > 1$$

(# bursts within $\mathcal{R}$ of Earth per year)

"How likely is it for a 'nearby' burst to occur within 1 year of experimental running?"

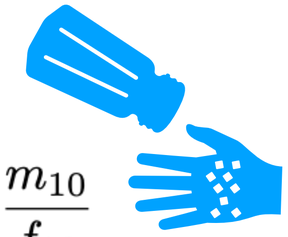
Define # of burst-making objects

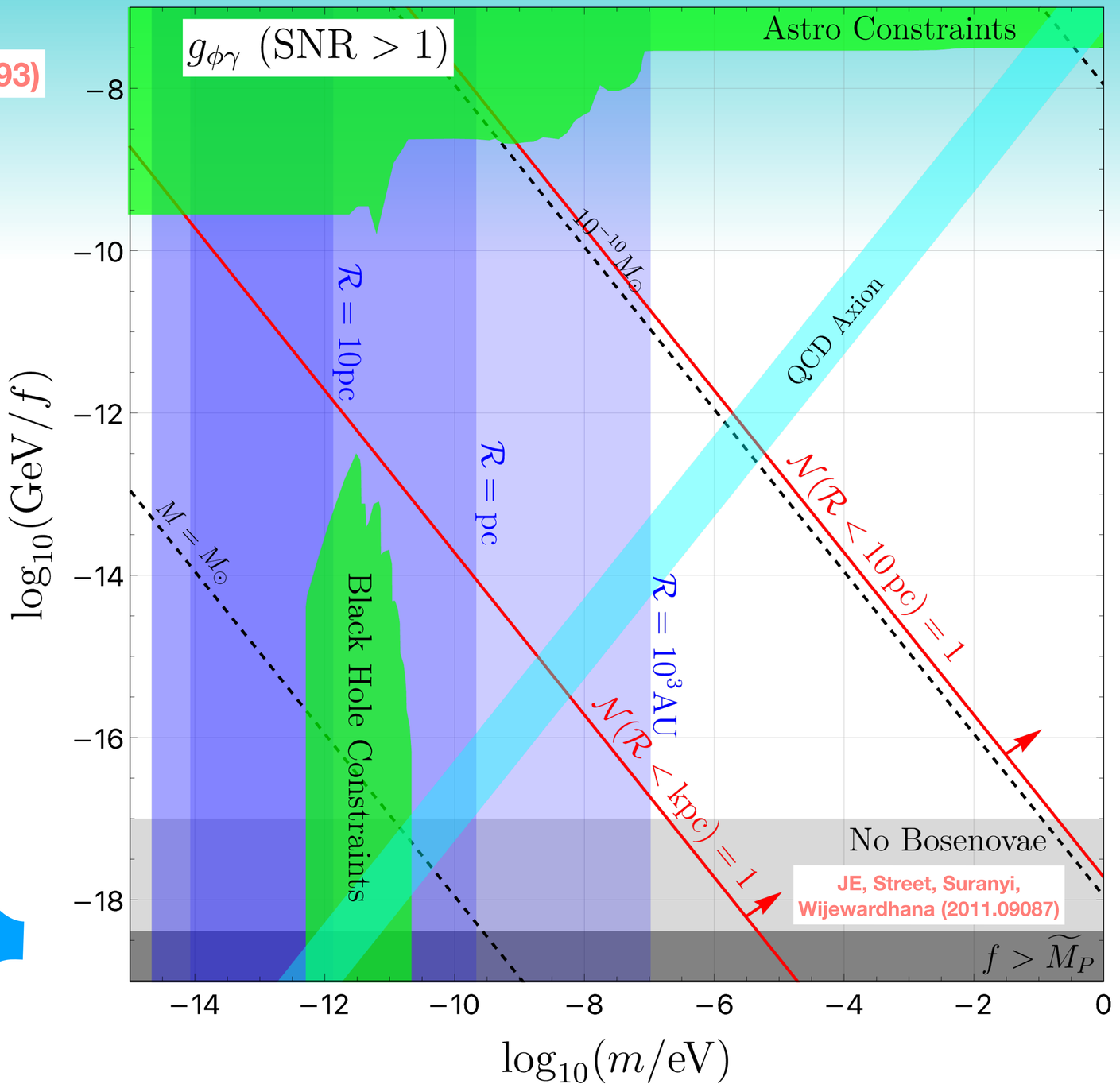
$$N(\mathcal{R}) = \frac{f_{\text{DM}}\rho_{\text{DM}}}{\mathcal{E}}\frac{4\pi\mathcal{R}^3}{3}$$

within $\mathcal{R}$ of Earth

For axion stars,

$$N_{\text{star}}(\mathcal{R}) \approx 40 f_{\text{DM}} \left(\frac{\mathcal{R}}{\text{pc}}\right)^3 \frac{m_{10}}{f_{16}}$$

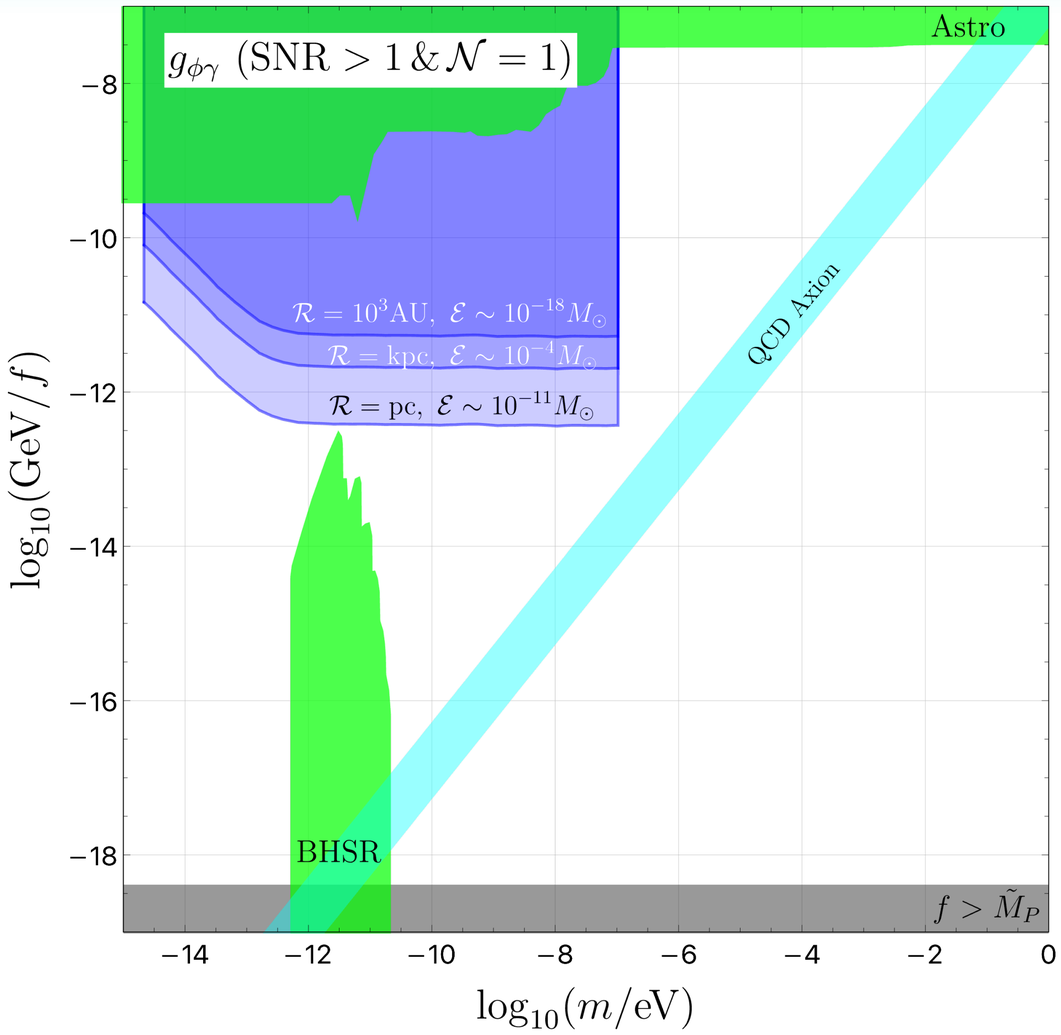


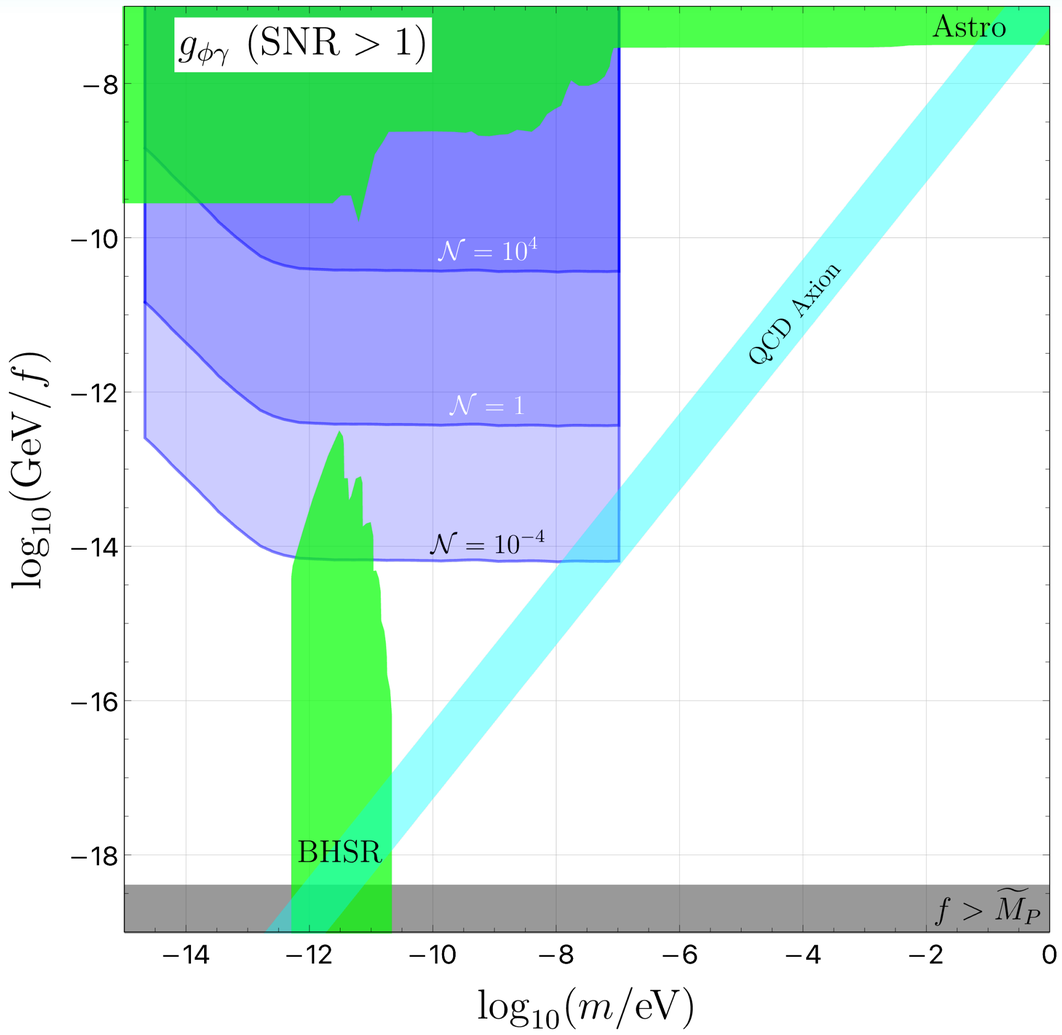


JE, Shirai, Stadnik, Takhistov (2106.14893)

General Burst Sensitivity

Total burst energy *E* as free parameter





Bonus Round

Transient Encounters

- Boson stars can transit through Earth

$$\Gamma \simeq n_\star \left(\pi R_\star^2\right) \sigma_{\rm vir} \simeq 10\, \mathscr{F}_{\rm DM} \left(\frac{m_\phi}{10^{-1}\,{\rm eV}}\right)^2 \left(\frac{R_\star}{10\, R_E}\right)^3 \frac{\text{encounters}}{\text{year}}$$

- Experiments: high density "bump" signal

$$\delta \equiv \frac{M_\star/(4\pi R_\star^3/3)}{\rho_{\rm local}} \simeq 10^3 \left(\frac{10^{-1}\,{\rm eV}}{m_\phi}\right)^2 \left(\frac{10\, R_E}{R_\star}\right)^3$$

Fraction $\mathscr{F}_{\rm DM}$ of DM in boson stars *not known* with confidence!

The present-day distributions $f(M_\star) \leftrightarrow f(R_\star)$ are *not known*!

Signals would have $m_\phi \gtrsim 10^{-7}\,{\rm eV} \;\Leftrightarrow\; \omega_\phi \gtrsim {\rm GHz}$

- Astrophysical mergers in the Milky Way

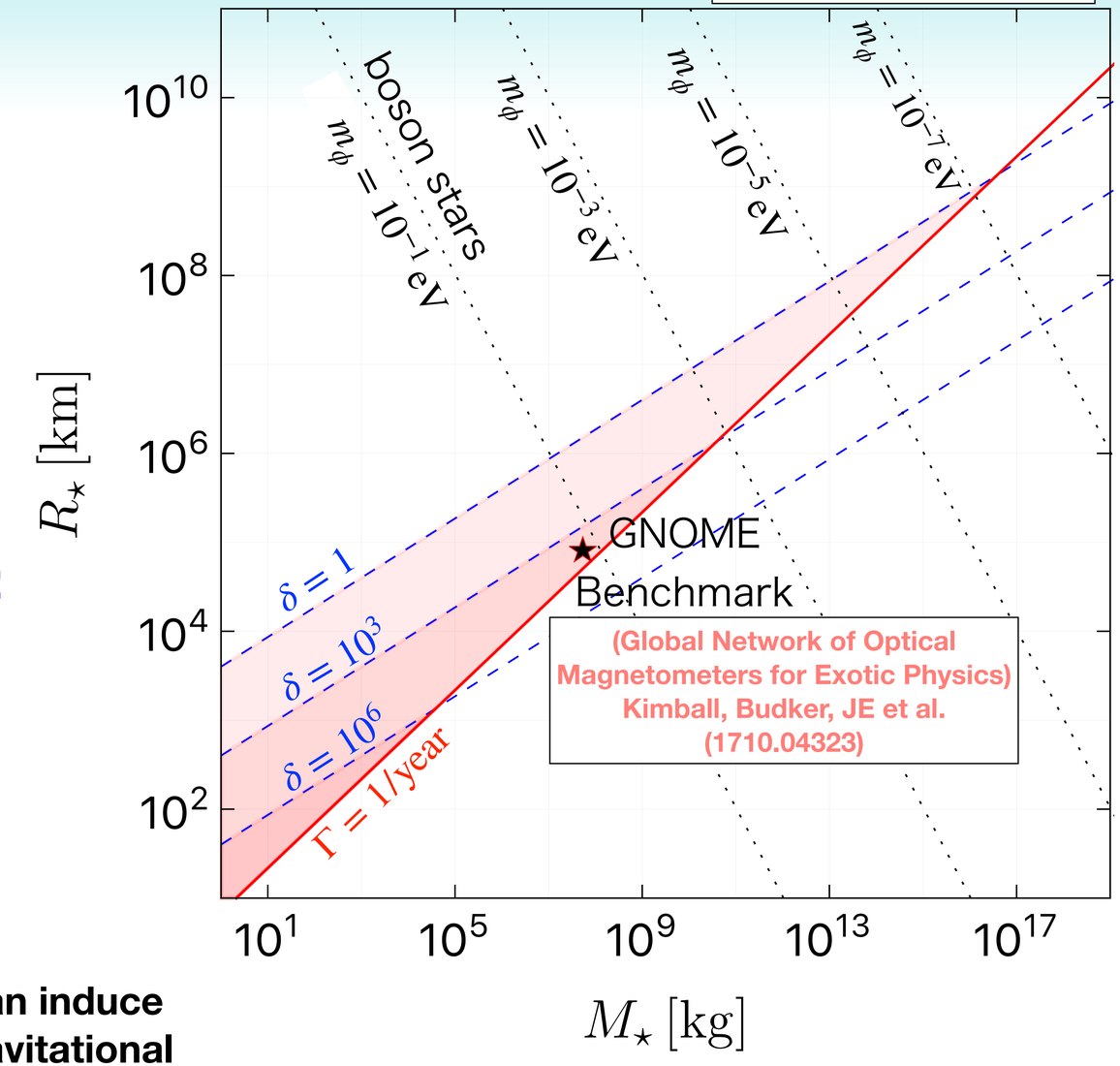
$$\Gamma_{\star\star} \simeq \int d^3r\, n_\star^2(r) \left(\pi R_\star^2\right) \sigma_{\rm vir}$$

$$\simeq 10^{33}\, \mathscr{F}_{\rm DM}^2 \left(\frac{m_\phi}{10^{-1}\,{\rm eV}}\right)^4 \left(\frac{R_\star}{10\, R_E}\right)^4 \frac{\text{encounters}}{\text{sec}}$$

JE, Leembruggen, Leeney, Suranyi, Wijewardhana, (1701.01476)

Can induce gravitational collapse!

Banerjee, Budker, JE, Kim, Perez (1902.08212)



(Global Network of Optical Magnetometers for Exotic Physics) Kimball, Budker, JE et al. (1710.04323)

arXiv.org > astro-ph > arXiv:1609.03611

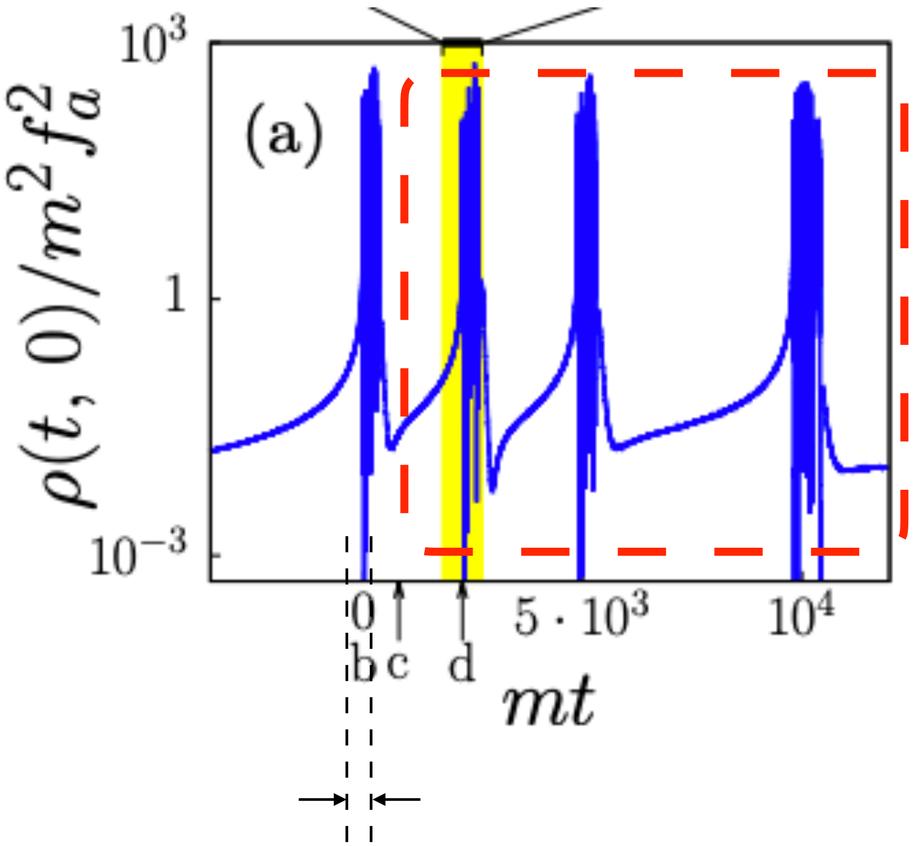
Astrophysics > Cosmology and Nongalactic Astrophysics

Relativistic axions from collapsing Bose stars

D.G. Levkov, A.G. Panin, I.I. Tkachev

(Submitted on 12 Sep 2016 (v1), last revised 5 Dec 2016 (this version, v2))

Simulation Results

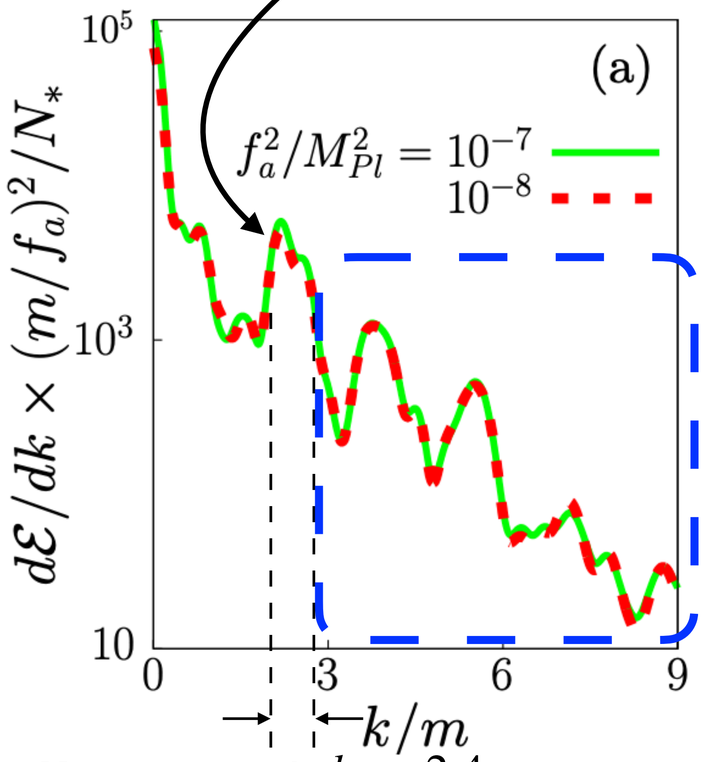


Multiple explosions per collapse! (Ignored here)

Short duration $\delta t_{\rm burst} \sim \mathcal{O}(400)/m$

Large integrated energy! In first peak,

$$\mathcal{E}_{\rm peak} \approx 3400\, m \frac{f^2}{m^2} \simeq 10^{41}\,{\rm GeV}\, \frac{f_{12}^2}{m_5}$$



Higher-energy peaks! (Ignored here)

Momentum peak $k_0 \simeq 2.4\, m$

with spread of $\delta k \sim m$

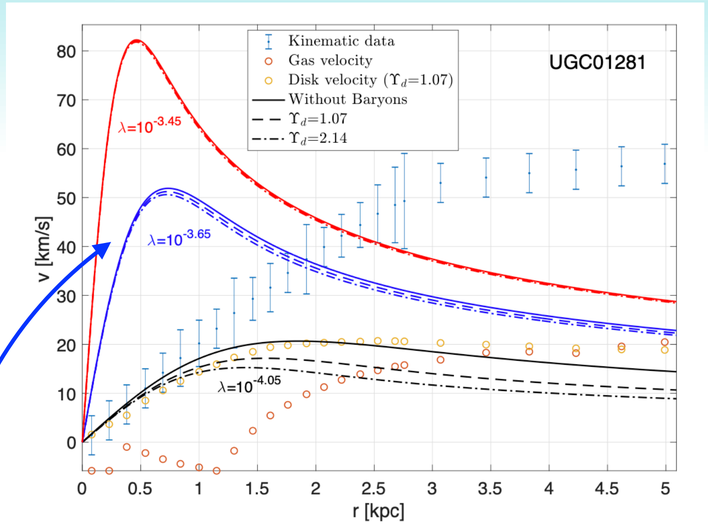
Ultralight Bosons

Bar, Blas, Blum, Sibiryakov (1805.00122)
w/ JE, Sato (1903.03402), w/ Sun (2111.03070)

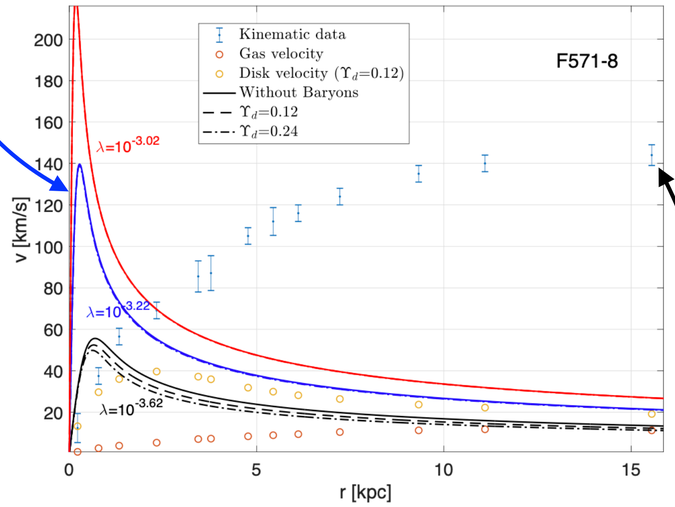
- For bosons of $m_\phi \simeq 10^{-22} - 10^{-21}\,\mathrm{eV}$, boson star of enormous size forms in the core of galaxies
- Simulations: Core-Halo Relation fixes boson star mass

$$M_\star \simeq 10^9 M_\odot \left(\frac{10^{-22}\,\mathrm{eV}}{m_\phi}\right)\left(\frac{M_{\mathrm{halo}}}{10^{12} M_\odot}\right)^{1/3}$$

- But this would imply a central peak in stellar rotational velocity distributions!
- Checked predictions also when
  - Deviating from Core-Halo Relation
  - Including gravitational effects from baryonic discs



Blue: CHR Prediction



Points: Measurements from SPARC galaxy database
(Similar predictions for ~180 galaxies!)

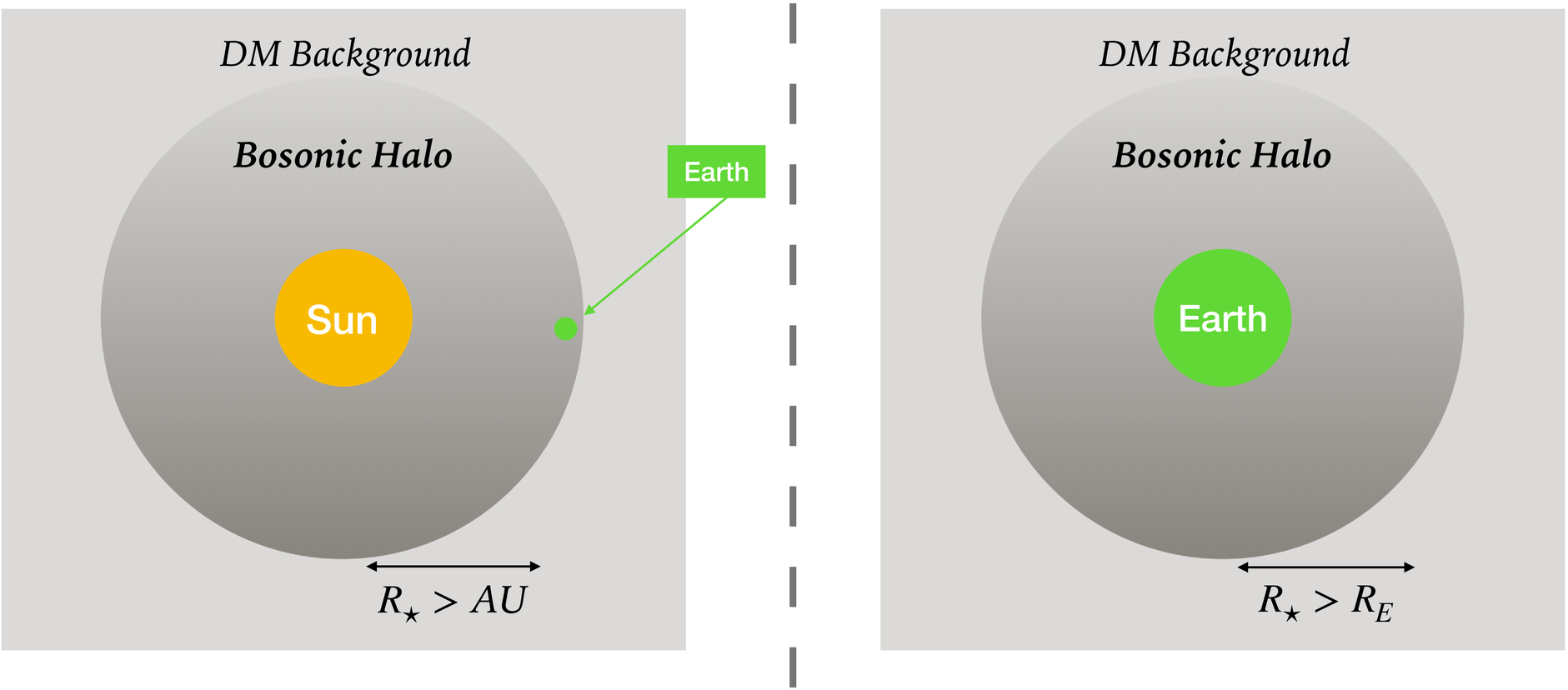
Bound Bosonic Halos

Can axions become bound to other gravitating objects (stars, planets)?

Halo supported by Sun
"Solar Halo"

$$R_\star \approx \frac{M_P^2}{m_\phi^2 M_{ext}}$$

Halo supported by Earth
"Earth Halo"

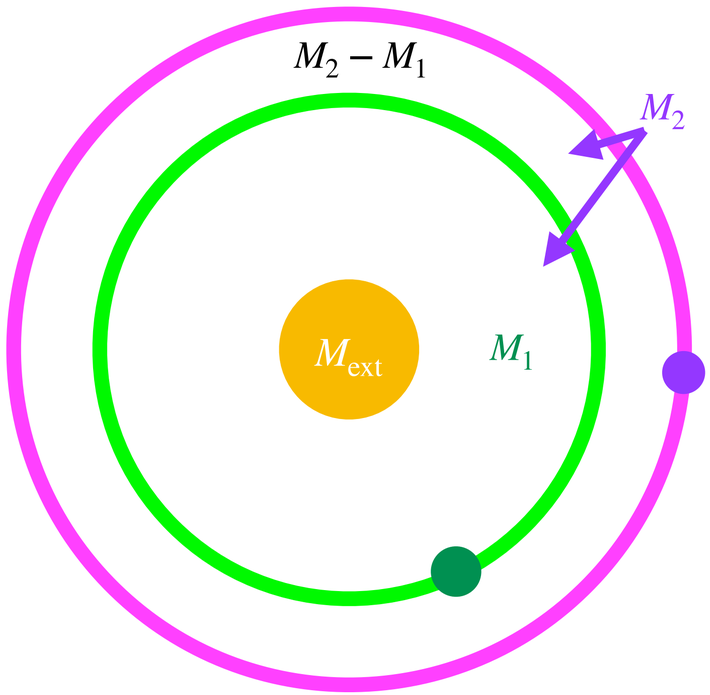


Banerjee, Budker, JE, Kim, Perez (1902.08212)

Constraints: "Extra" DM near Earth

Banerjee, Budker, JE, Kim, Perez (1902.08212)

Can measure effective mass nearby by comparing orbits:

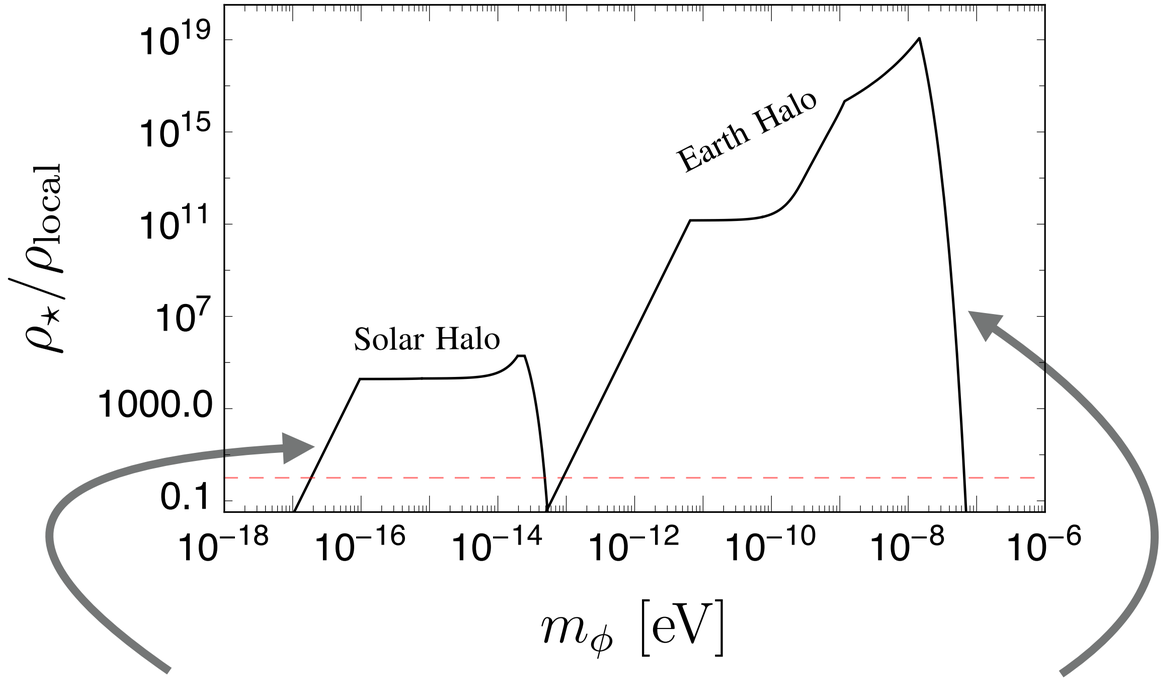


Inner orbit "measures" $M_1 + M_{\rm ext}$

Outer orbit "measures" $M_2 + M_{\rm ext}$

Comparison of the two "measures" $M_2 - M_1$**, gives "extra" mass contained between the orbits**

Density enhancement at position of Earth



Solar System Ephemerides (Mercury, Mars, Saturn)

Pitjev and Pitjeva (1306.5534)

Lunar Laser Ranging + LAGEOS Satellite

Adler (0808.0899)

Density can be very much enhanced relative to naive expectation $\rho_{\rm local}$ **!**

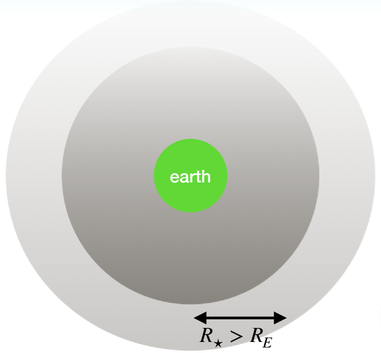
Detecting Bosonic Halos with Precision Physics

- Searches for oscillation of fundamental constants due to axion DM oscillations!

Scalar coupling to photons: $\mathscr{L} \supset \frac{g_\gamma}{4}\phi(t)\,F^{\mu\nu}F_{\mu\nu}$

⇒ Oscillation of fundamental constants

$$\frac{\alpha(t)}{\alpha_0} \simeq g_\gamma \phi(t)$$

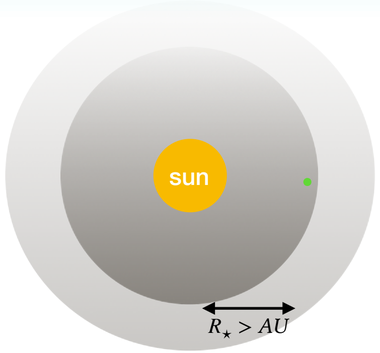


Experiments on Earth's surface

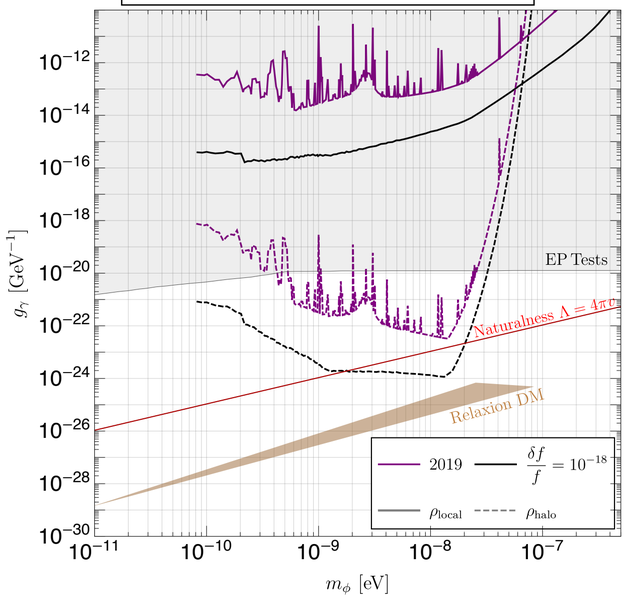
(Earth-bound halo)

Atomic clocks in space

(Solar-bound halo)



Banerjee, Budker, JE, Kim, Perez (1902.08212)



Now at least three independent searches for bound bosonic halos using atomic physics:

Ozeri et al., Phys. Rev. D 103, 075017 (2021)

WReSL Experiment (D. Budker) Quantum Sci. Technol. 6 (2021) 3, 034001

DAMNED Experiment (P. Wolf) Phys. Rev. Lett. 126 (2021) 5, 051301

Space-based atomic clocks will be useful for future spacecraft navigation and for solar science

As we have shown, also can be used to probe fundamental physics!

JE, Tsai, Safronova (2112.07674)