Searching for Axion Stars

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Collaborators

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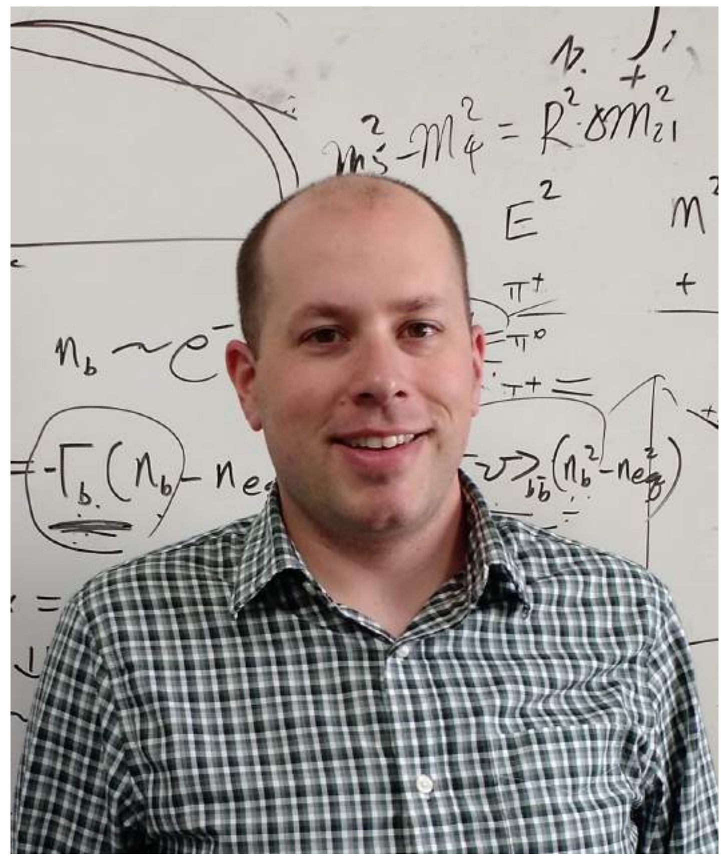
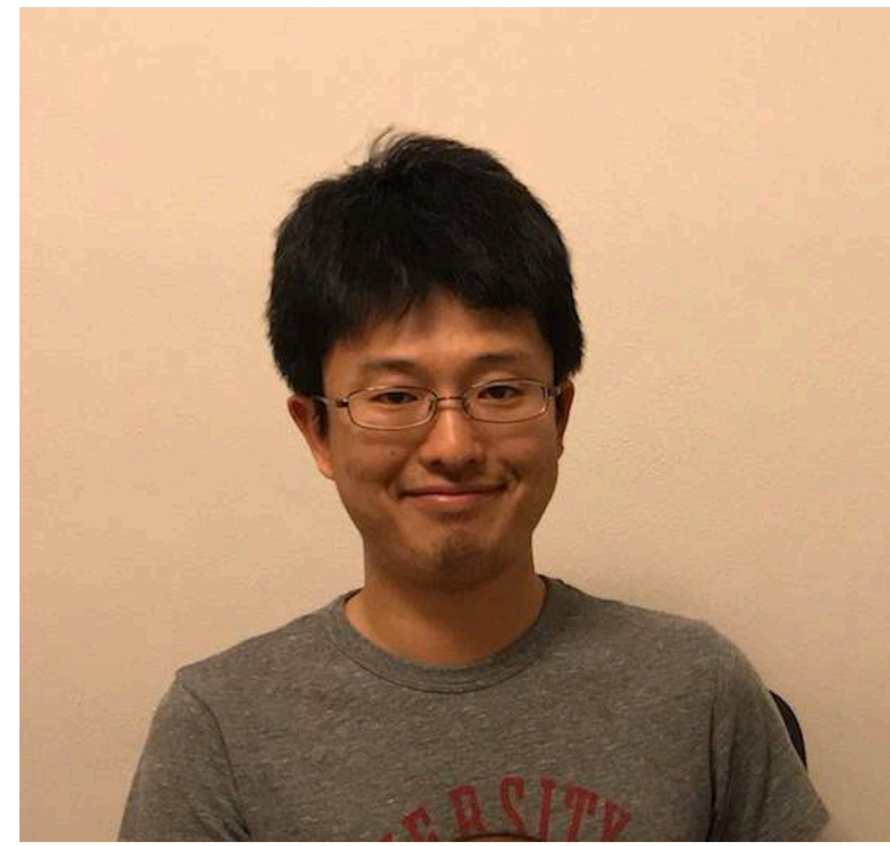




Vernon Barger **Joshua Berger** **Yuta Hamada**

arXiv:1612.00438, 1709.10516, and work in progress

Outline

- Motivations for QCD axion dark matter
- Formation of QCD axion stars (BEC)
- Detecting axion stars
  - Inside a planet
  - Radio signals
  - Hydrogen axion stars
  - Microlensing
- Stability of dense axion stars
- Conclusions

Strong CP Problem

- $\pi_{\mathbf{3}}(\mathrm{G}) = \mathbb{Z}$: **instanton solution for non-Abelian gauge theories**
- **It provides an explanation for the** $\mathrm{U}(1)'$ **problem or why** η' **is heavier than other mesons**
- **The consequence is that QCD has one more term of**

$$\mathcal{L}_\theta = -\frac{g_s^2}{32\pi^2}\,\theta\, G^a_{\mu\nu}\widetilde{G}^{a\mu\nu}$$

the quark-field redefinition-invariant quantity:

$$\overline{\theta} = \theta + \arg[\det(M_u\, M_d)]$$

- **This angle violates CP and contributes to neutron EDM, which need to have** $\overline{\theta} \lesssim 10^{-10}$**, from experimental limits.**

Possible Solutions

Peccei-Quinn Symmetry

$$V(\phi) \sim m_\pi^2 f_\pi^2 \cos\left(\frac{\phi}{f_a} - \overline{\theta}\right)$$

$$a = \phi - \langle\phi\rangle = \phi - f_a\,\overline{\theta}$$

axion particle

Weinberg '1978; Wilczek '1978

$$m_a\, f_a \approx m_\pi\, f_\pi$$

Nelson-Barr Mechanism

CP or P is a good symmetry at UV and broken in IR with a zero determinant of quark mass matrices

heavy vector-like quarks

LHC or future colliders

Axion as Cold Dark Matter

- **The thermal production is suppressed for $f_a \gtrsim 10^8$ GeV**

- **Based on the standard cosmology, the leading production mechanism is the misalignment mechanism.**

Preskill, Wise, Wilczek '1983, Abbott and Sikivie, '1983

- **For some cases, the axionic string decays also contribute with a large O(1-100) uncertainty**

see Masahide Yamaguchi and Giovanni Villadoro talks

- **In this talk, I will concentrate on the parameter space of**

$$f_a \lesssim \frac{H_I^{\rm end}}{2\pi}$$

with the end of inflation Hubble scale: $H_I^{\rm end} < 8.7 \times 10^{13}\ \mathrm{GeV}$ **from Planck 2015**

Misalignment Mechanism

- The initial angle could have random distributions from one patch of the sky to another
- Defining the dynamical field: $\theta(x) \equiv a(x)/f_a$, the EOM is

$$\ddot{\theta} + 3\,H(T)\,\dot{\theta} + \frac{1}{f_a^2}\frac{\partial V(\theta)}{\partial \theta} = 0$$

- The axion field is frozen to its initial value until the axion mass becomes comparable to $H(T)$. This happens at the oscillation temperature

$$m_a(T_1) = 3\,H(T_1)$$

- The temperature-dependent axion mass can be estimated using dilute instanton gas approximation. It can be numerically fit by

Turner, PRD 33, 889 (1986)

$$\frac{m_a(T)}{m_a} = b\left(\frac{\Lambda}{T}\right)^c [1 - \ln(\Lambda/T)]^d = (0.02 - 0.3)(\Lambda/T)^{3.7}$$

Misalignment Mechanism

- **The current axion relic energy density is then**

$$\rho^{\text{mis-align}} \approx \frac{m_a\, m_a(T_1)\, s(T_0)}{2\, s(T_1)}\, f_a^2\, \langle \theta_i^2\, f(\theta_i) \rangle$$

- **The axionic string decay can also contribute. Altogether,**

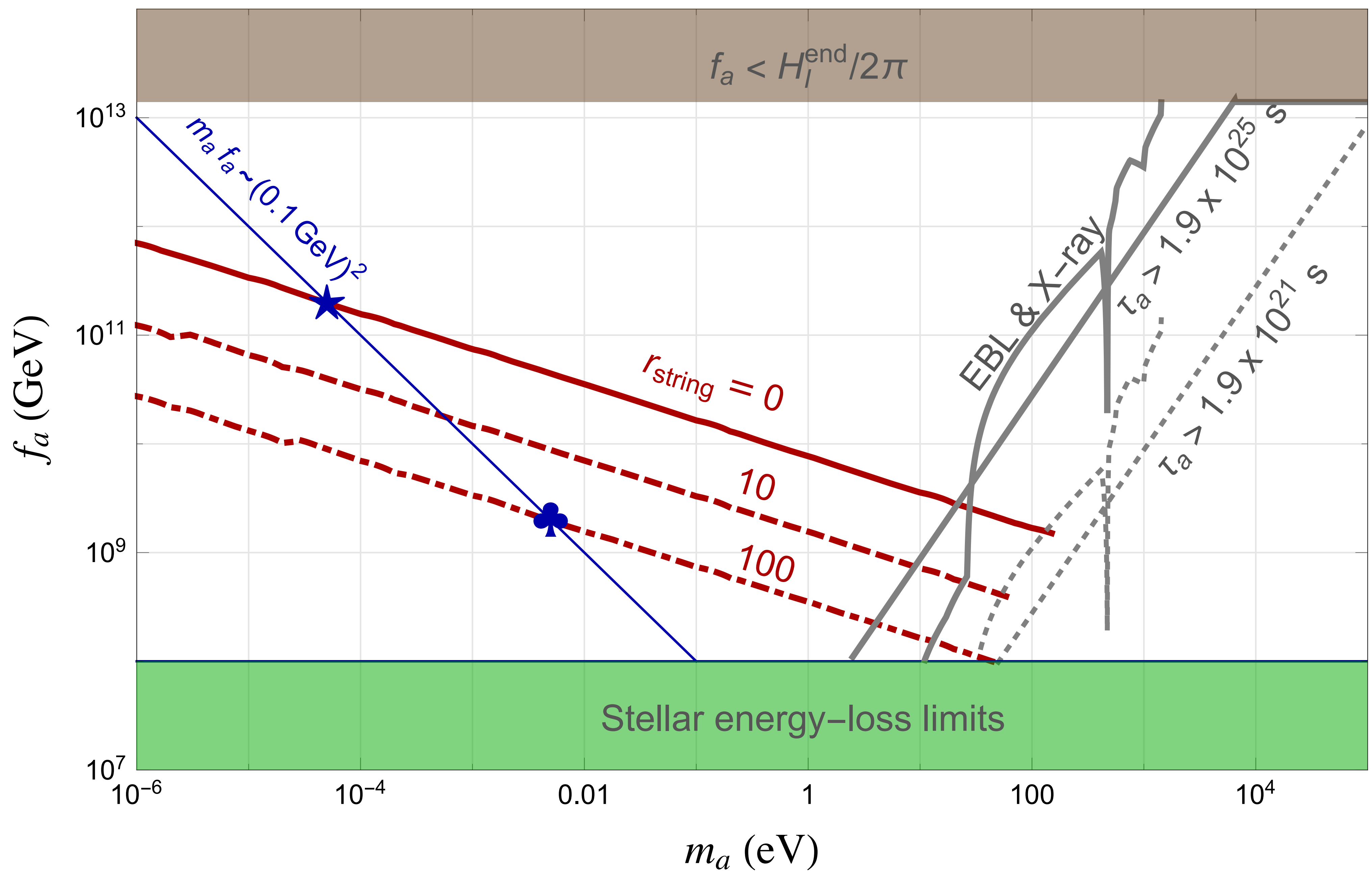
$$\Omega_a\, h^2 \approx 0.112 \left(\frac{1 + r_{\text{string}}}{1} \right) \left(\frac{m_a}{5 \times 10^{-5}\,\text{eV}} \right)^{1/2} \left(\frac{f_a}{2 \times 10^{11}\,\text{GeV}} \right)^{1.68} \left(\frac{0.02}{b} \right) \frac{\langle \theta_i^2 f(\theta_i) \rangle}{8.77}$$

see Giovanni Villadoro' talk for more precise value

- **If we impose the SM QCD relation:** $m_a f_a \sim m_\pi f_\pi$**. We anticipate the axion mass of** 10^{-5} **eV for** $r_{\text{string}} = O(1)$ **and** 10^{-2} **eV for** $r_{\text{string}} = O(100)$

- **On the other hand, the above relation can also be applied to other general QCD axion models, where additional contributions to its mass can happen:** $m_a f_a \geq m_\pi f_\pi$

Axion Dark Matter Parameter Space



- For a generic model, the axion mass should be below O(100 eV)

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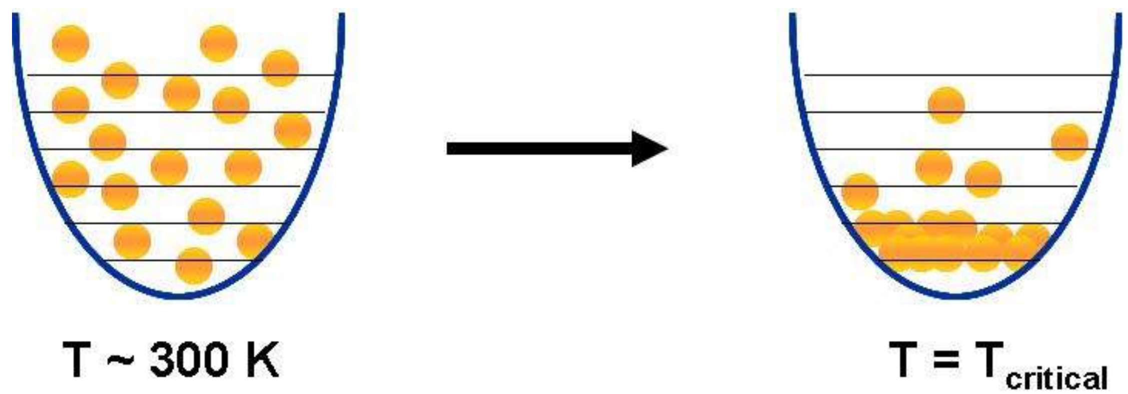
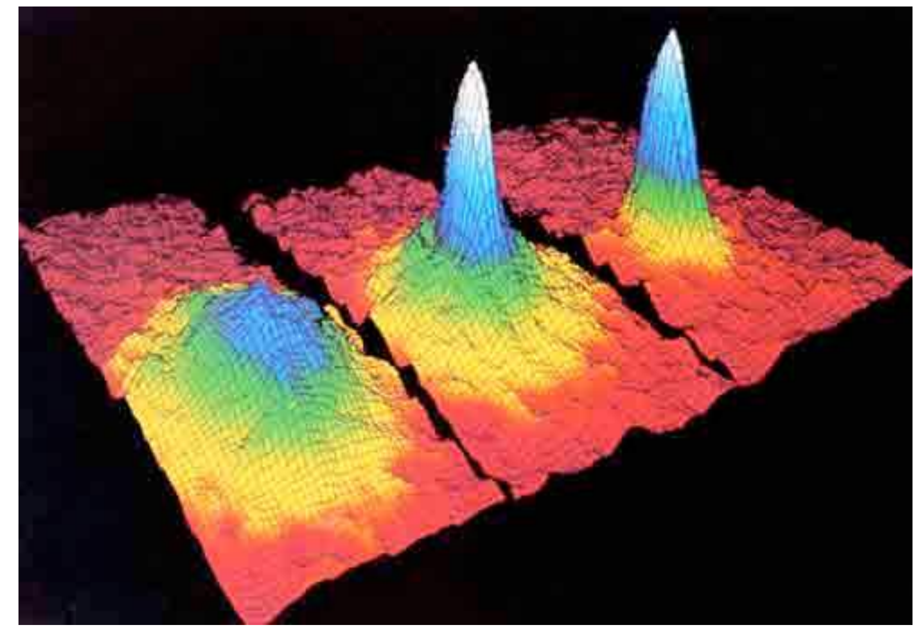
Bose-Einstein Condensation of Axions





- The axion field is expected to have different values from one Hubble patch to another
- They can develop structures much earlier than the ordinary large scale structure

Kolb, Tkachev, hep-ph/9303313 …..
Zurek, Hogan, Quinn, astro-ph/0607241
Sikivie and Yang, 0901.1106
Guth, Hertzberg, Prescod-Weinstein, 1412.5930
Eby, Suranyi, Vaz, Wijewardhana, 1412.3430, ……, 1712.04941
Braaten, Mohapatra, Zhang, 1512.00108, …
Raby, 1609.01694
Visinelli, Baum, Redondo, Freese, Wilczek, 1710.08910
……

Fraction of axions in Axion Star

- **Not an easy question. Numerical simulations required.**

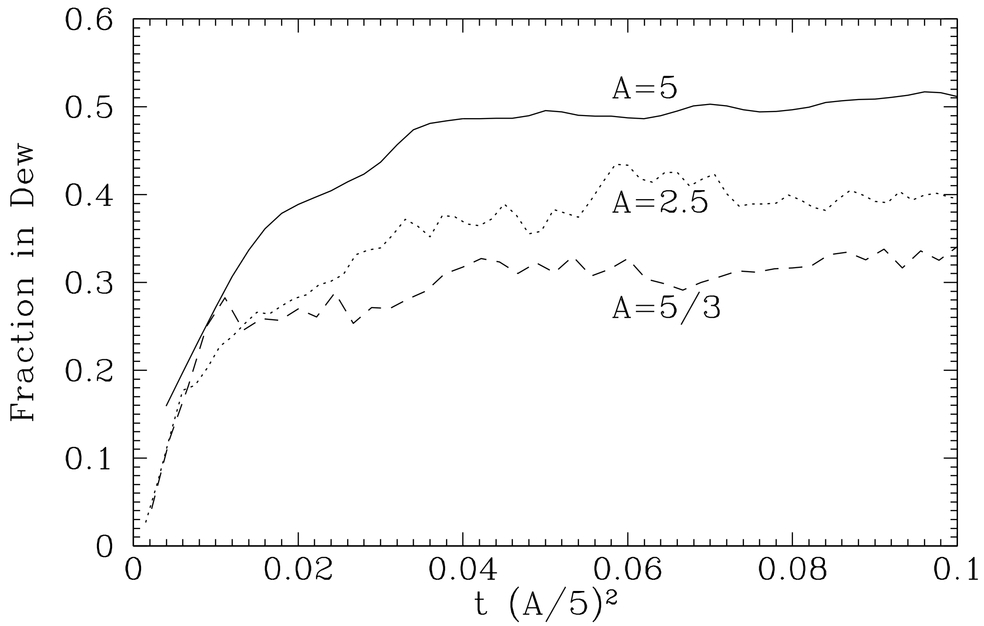


FIG. 2. Condensation process.

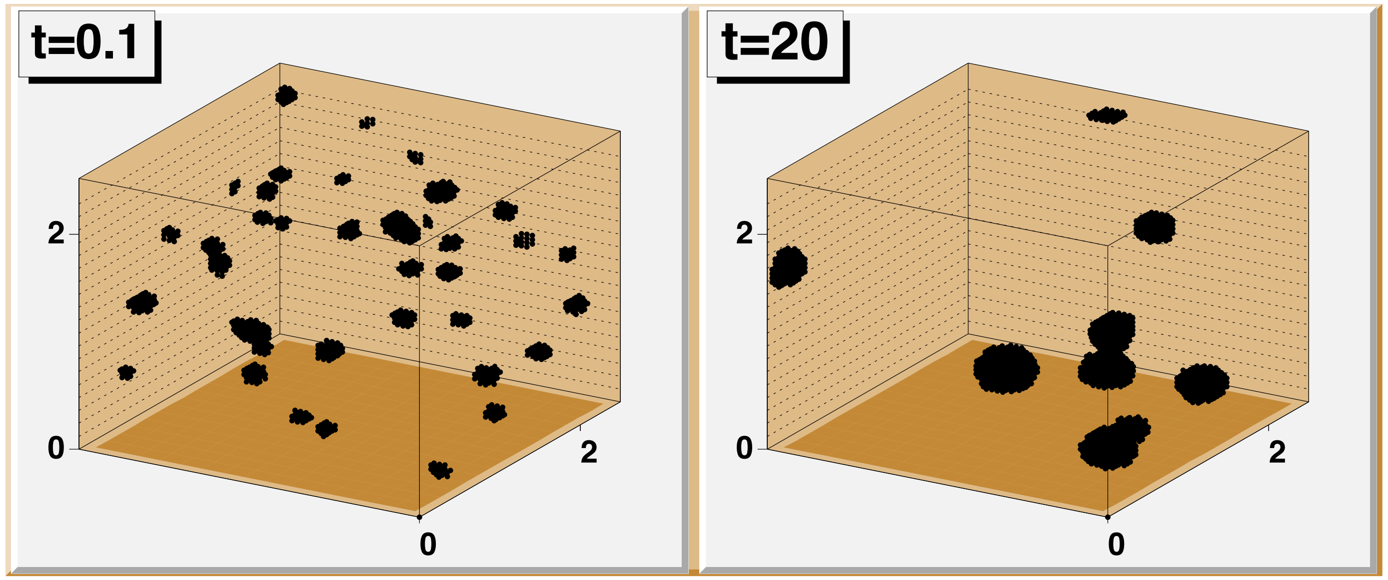


FIG. 1. Drops of dew at different moments of time.

Khlebnikov and Tkachev, hep-ph/9902272

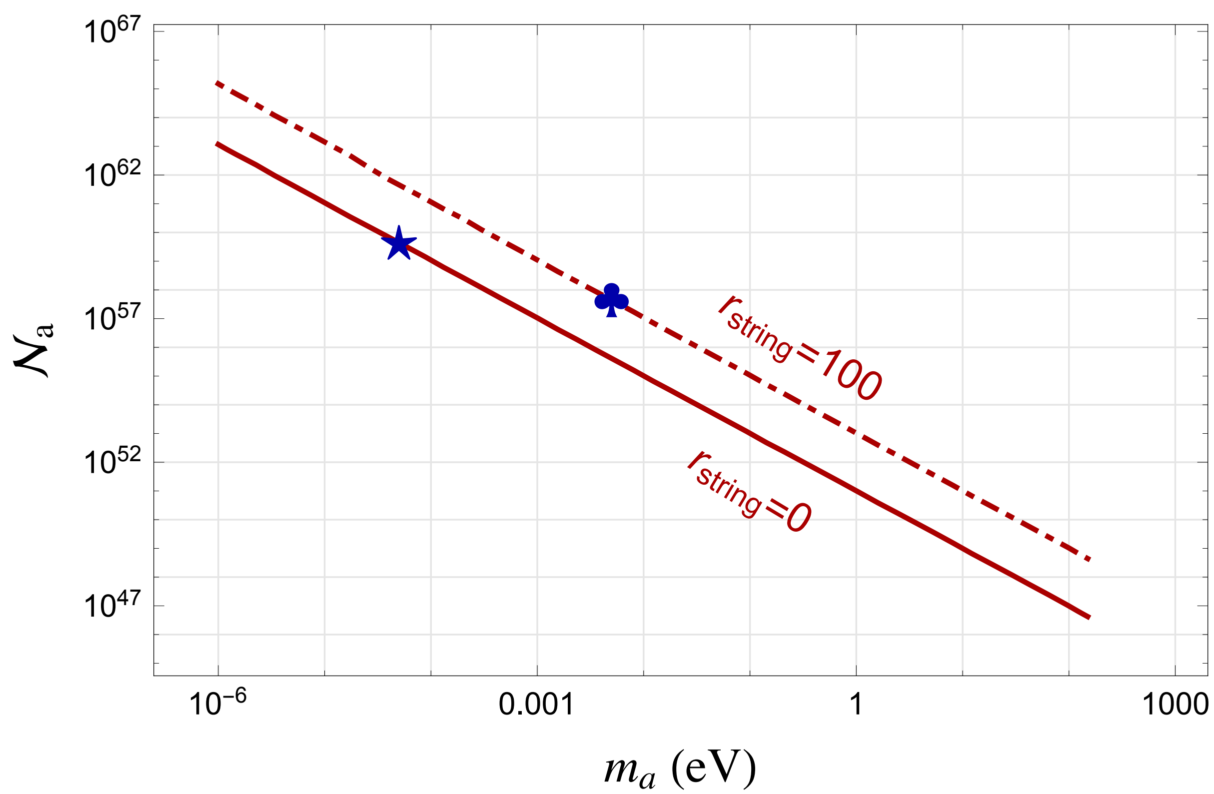
- **A more sophisticated simulation may be required to have different initial conditions.**

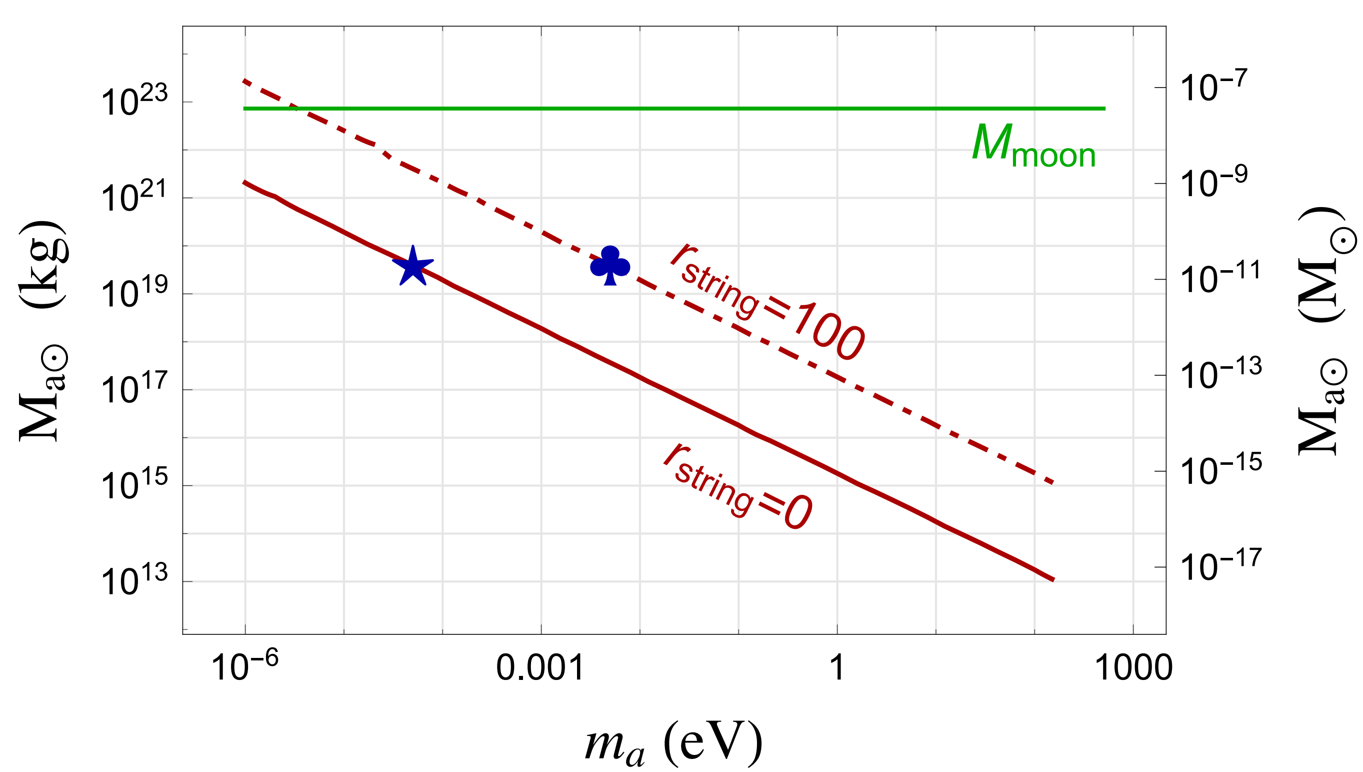
- **It also has important consequence for searching for axion dark matter in our halo.**

Axion Star Mass

- **From the misalignment mechanism, the axion starts to oscillate after the QCD (or mirror QCD) phase transition temperature.**
- **Using the total number of axions in the H($T_1 \sim \Lambda_{QCD}$) volume to estimate the total number in one axion star**

$$\mathcal{N}_a = \frac{n_a(T_1)}{H^3(T_1)} = 4\times 10^{57} \times \left[\frac{10}{g_*(T_1)}\right]^{1/2} \left(\frac{5\times 10^{-3}\,\mathrm{eV}}{m_a}\right)^{5/2} \left(\frac{2\times 10^{9}\,\mathrm{GeV}}{f_a}\right)^{3/2}$$





$$\mathbf{M_{a\odot} \approx 10^{-11}\, M_\odot}$$

Diluted Axion Stars

- **For the gravitational force to balance the quantum pressure:**

$$R_{\rm AS}^{\rm dilut} \sim \frac{1}{M_{a\odot}\, G_N\, m_a^2} \approx 2.7 \times 10^6\,{\rm m} \times \left(\frac{10^{-15}\,M_\odot}{M_{a\odot}}\right) \left(\frac{10^{-4}\,{\rm eV}}{m_a}\right)^2$$

- **For a heavier axion star mass, the radius decreases and the self-interacting energy increases**

$$E_{\rm self.} \approx \frac{M_{a\odot}^2}{m_a^2\, f^2\, R^3} \rightarrow E_{\rm grav.} \approx \frac{G_N\, M_{a\odot}^2}{R}$$

- **The diluted axion stars are justified for**

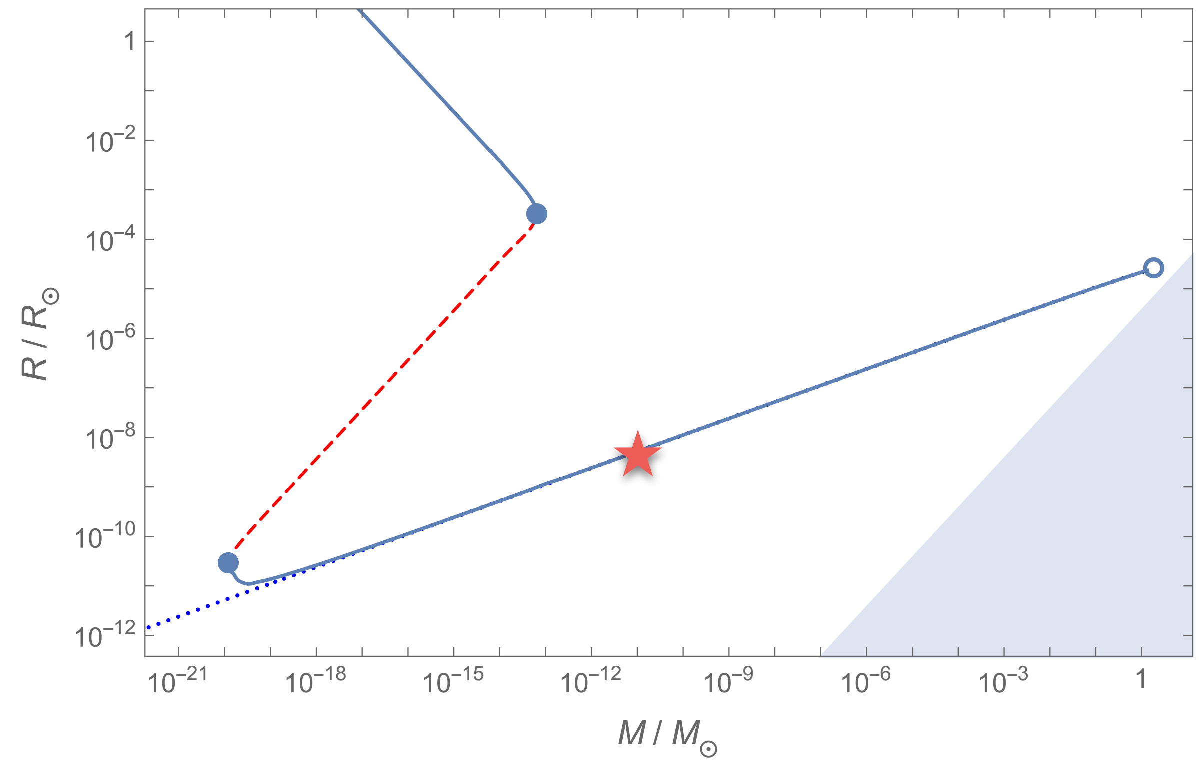
$$M_{a\odot} \lesssim 10.15\, f_a/(m_a G_N^{1/2})$$

Chavanis and Delfini: 1103.2054

- **Numerically, we find $M_{a\odot} \lesssim 4 \times 10^{-13}\, M_\odot$ for m_a =0.05 meV, with a stronger bound for a heavier m_a. The QCD axion stars could be beyond the diluted region**

Dense Axion Stars

- **The axion self-interactions can provide additional pressure to balance the gravitational attraction or among themselves**



- **The QCD axion star could be in the "dense axion star" branch**

$$R_{\rm AS}^{\rm dense} = 1.5\,{\rm m}\,\times\left(\frac{10^{11}\ {\rm GeV}}{f_a}\right)^{1/2}\left(\frac{10^{-4}\ {\rm eV}}{m_a}\right)^{1/2}\left(\frac{M_{a\odot}}{10^{-13}\,M_\odot}\right)^{0.3}$$

Braaten, Mohapatra, Zhang, 1512.00108

- **The calculation is based the Thomas-Fermi non-relativistic approximate, which is not consistent with the state obtained**

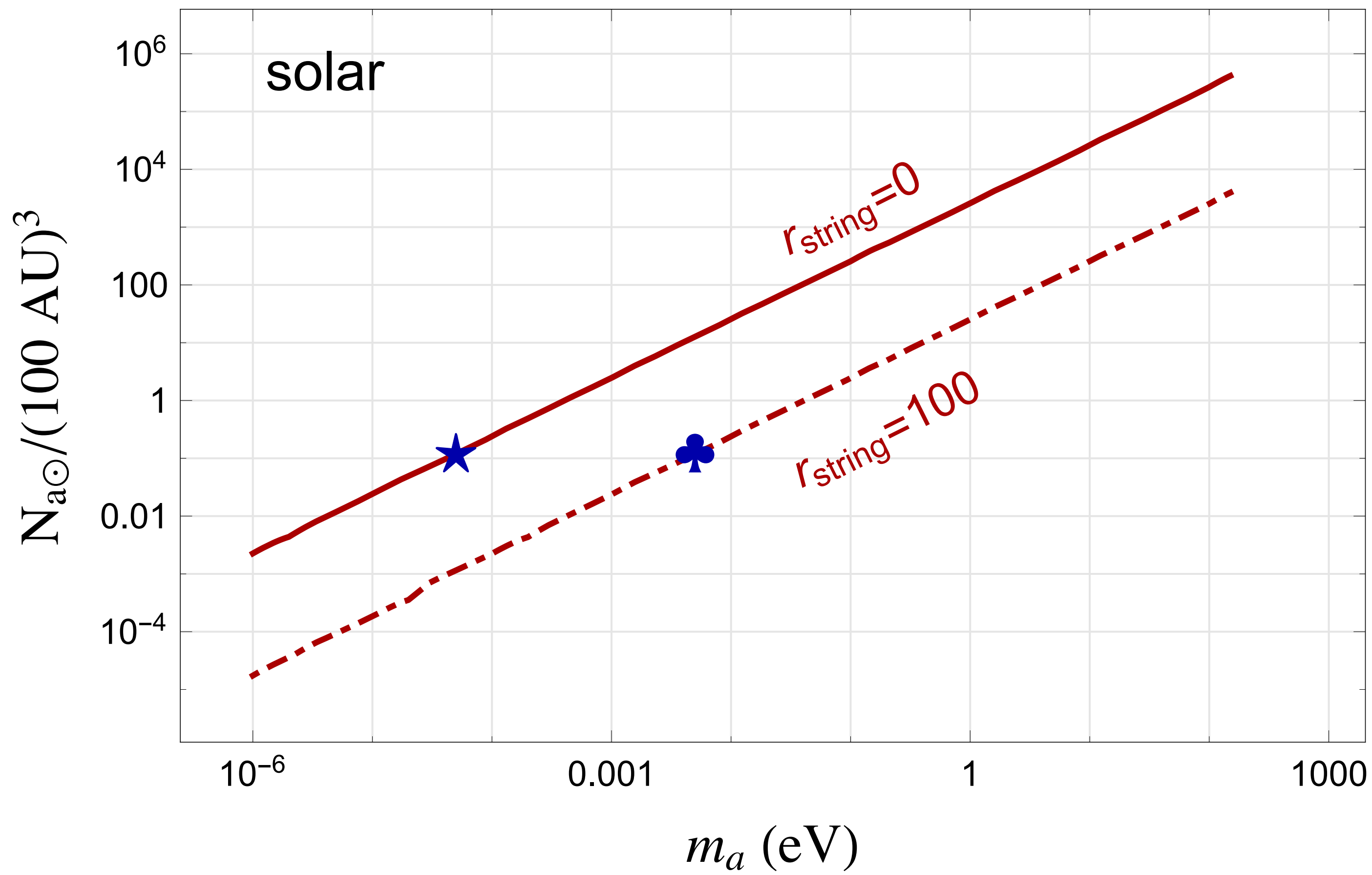
- **The existence of a dense QCD axion star is under debate in the literature. I will come back to this point later**

Population of Axion Stars

- The averaged population in the Universe is around

$$O(1) \times (0.1\,\mathrm{pc})^{-3}$$

- Inside a galaxy, the number density is enhanced



- We anticipate O(1) in our solar system. Where is it?

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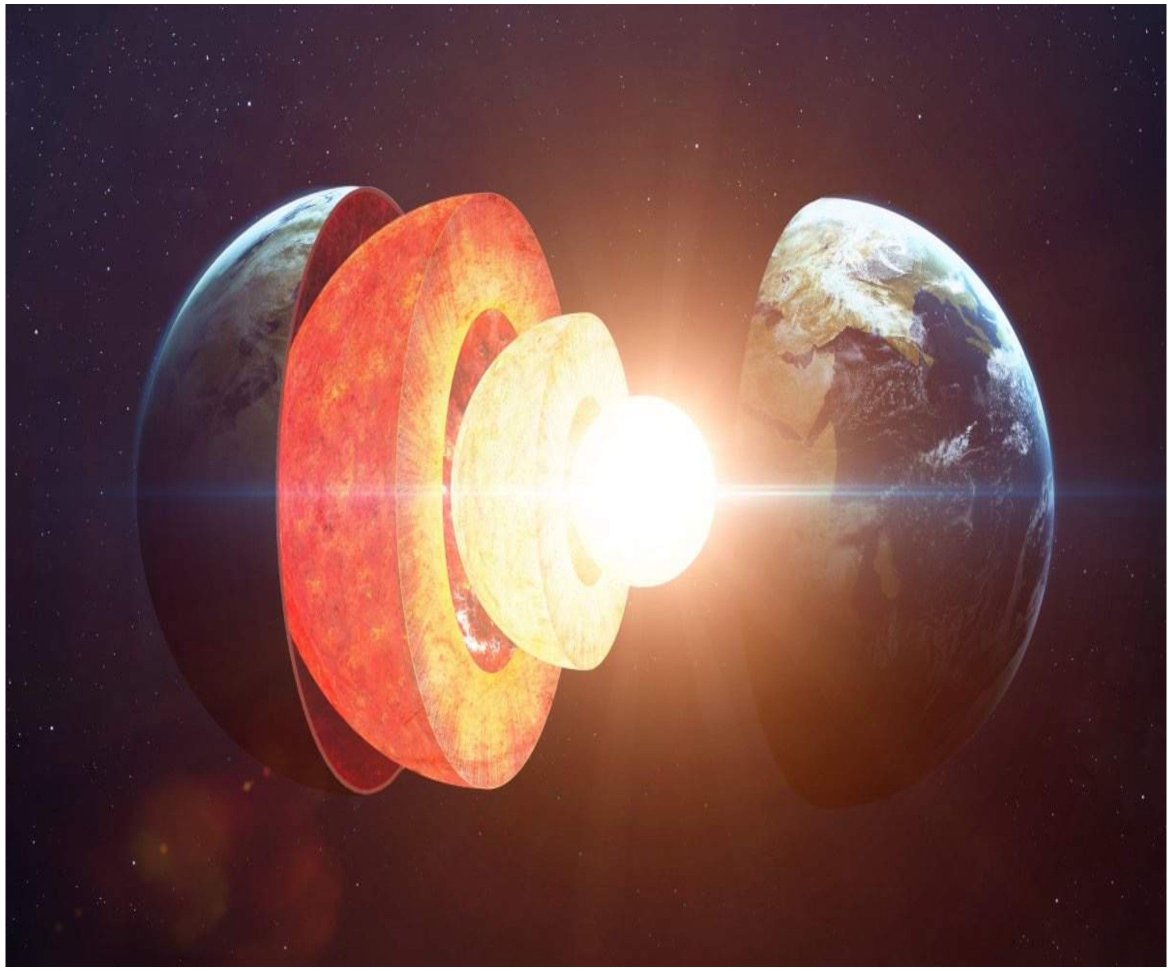
Seeding Dust Accretion

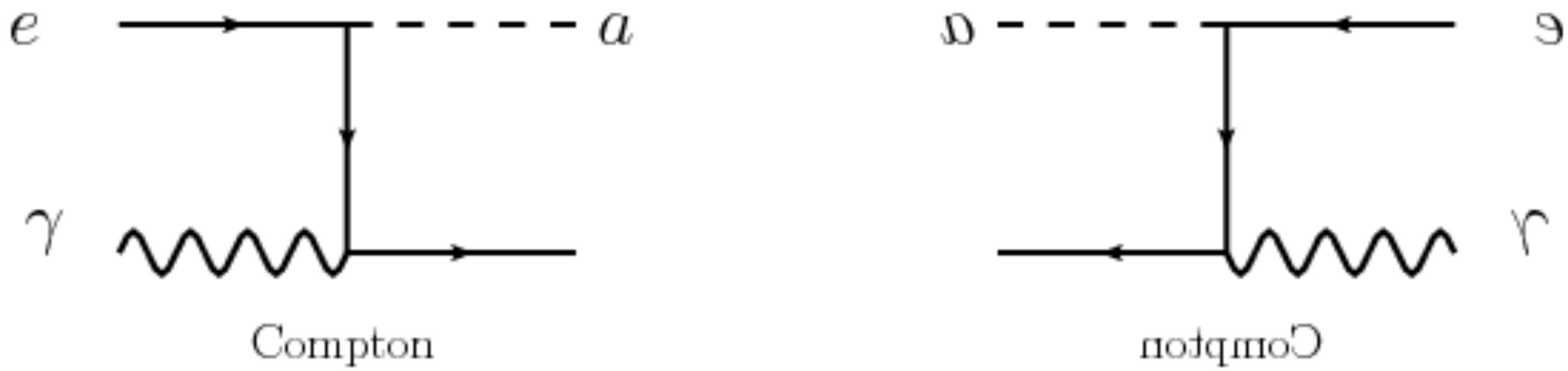
- The axion stars have its primordial formation. Their existence inside solar or solar-like system may change the formation of stars and planets.



- The axion stars could seed some planet formation. As a result, it may stay inside the core of a planet [O(10) in our Solar system]

How do we know its existence?

- **They may change the properties of a planet. The particle physics properties of axion may show up.**



- **The reverse process can have the ordinary matter absorb axions.**
- **Because of its pseudo-scalar nature, scattering off a non-relativistic electron should be proportional to** m_a^2/f_a^2
- **The absorption is similar to the E1 absorption of a photon:**

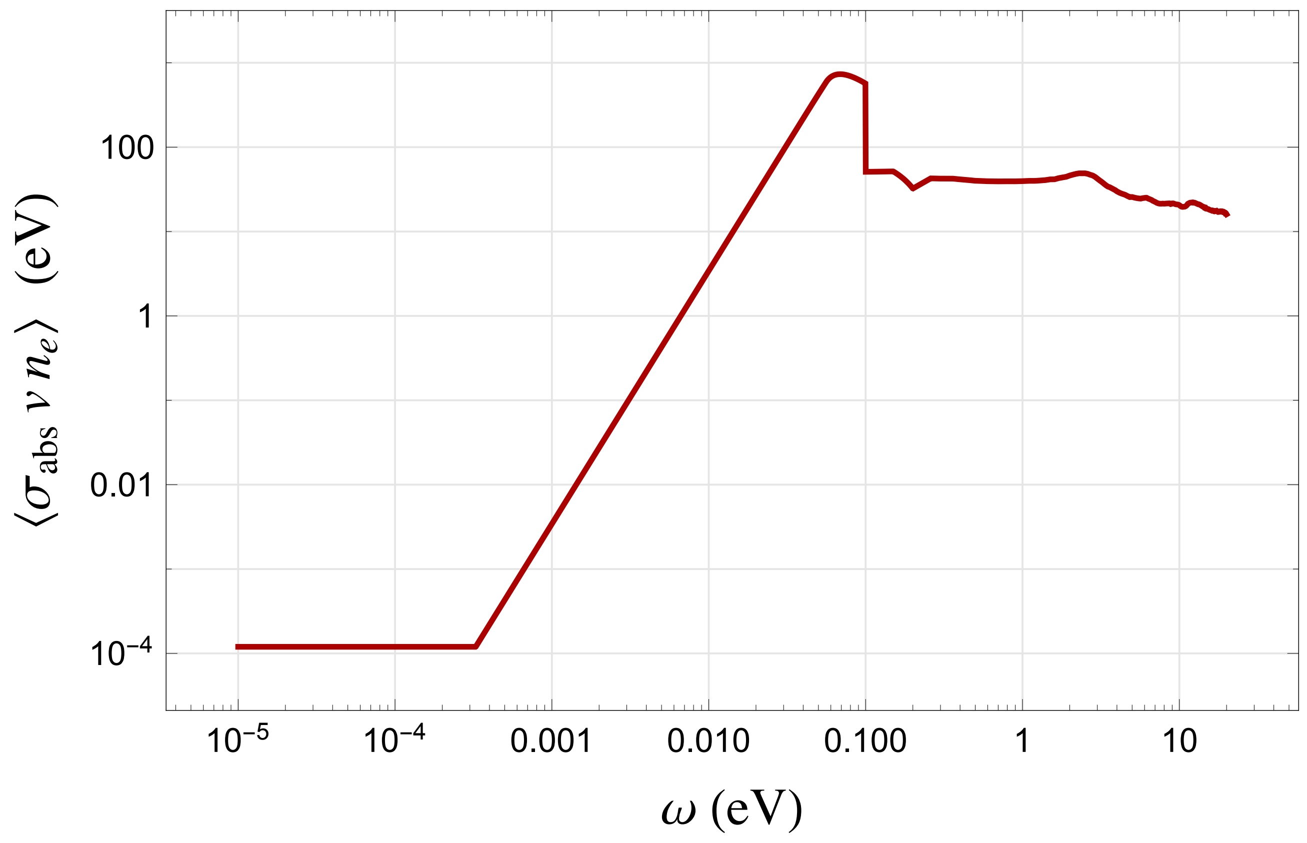
$$\frac{\sigma_{a\to\gamma}^{\mathrm{absorb}} v}{\sigma_{\mathrm{photo}}(\omega = m_a) c} \approx \frac{3\, m_a^2}{4\pi\, \alpha\, f_a^2}$$

Photon Absorption Rate

- For photon in high density (conductor) region, the absorption rate is related to the real part of the complex conductivity

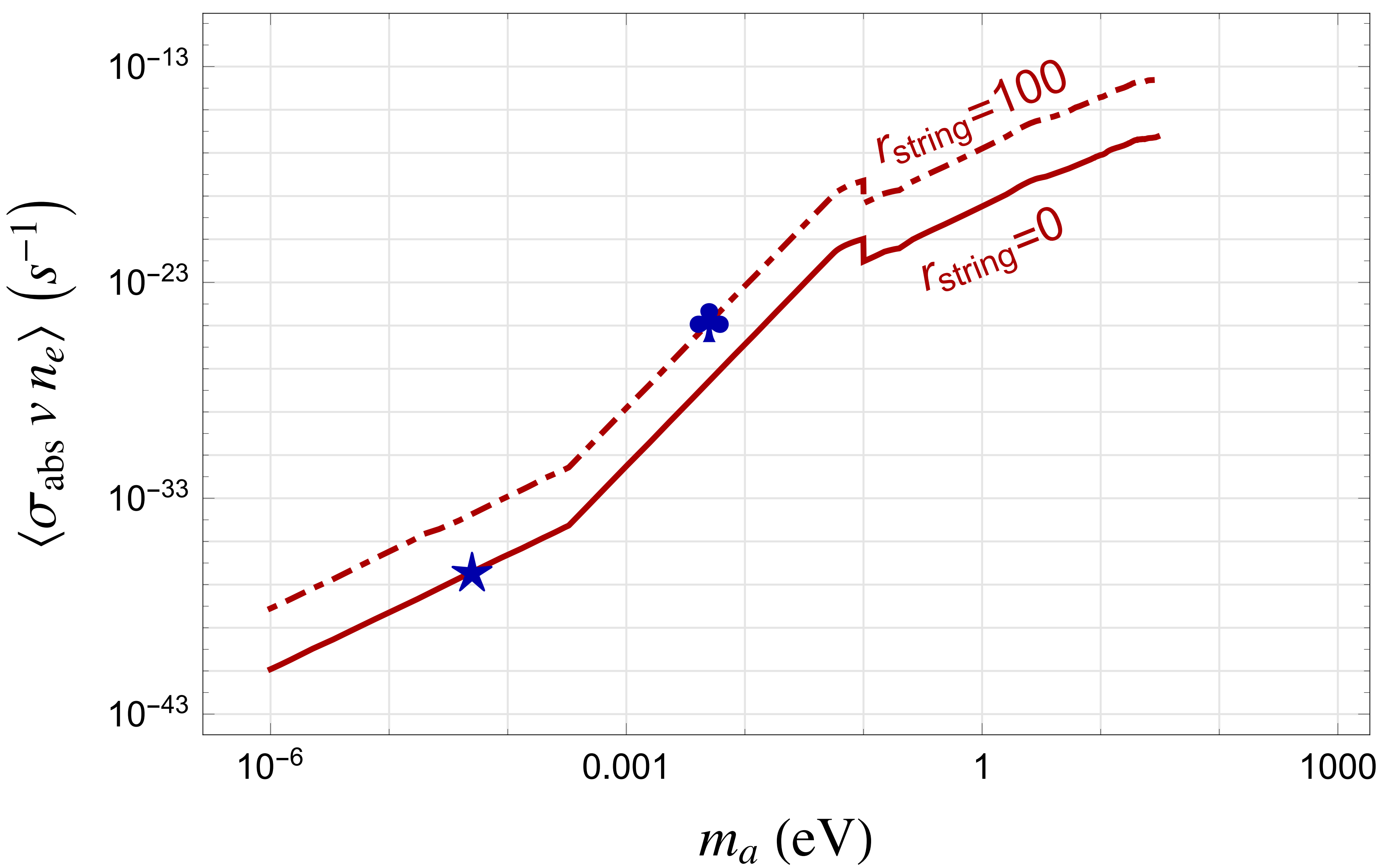
$$\langle n_e \sigma_{\mathrm{abs}} v_{\mathrm{rel}} \rangle = \sigma_1$$

- Based on the Drude model combining with experimental data, the photon absorption rate in iron is



Axion Absorption Rate

- Converted to our axion case, we have

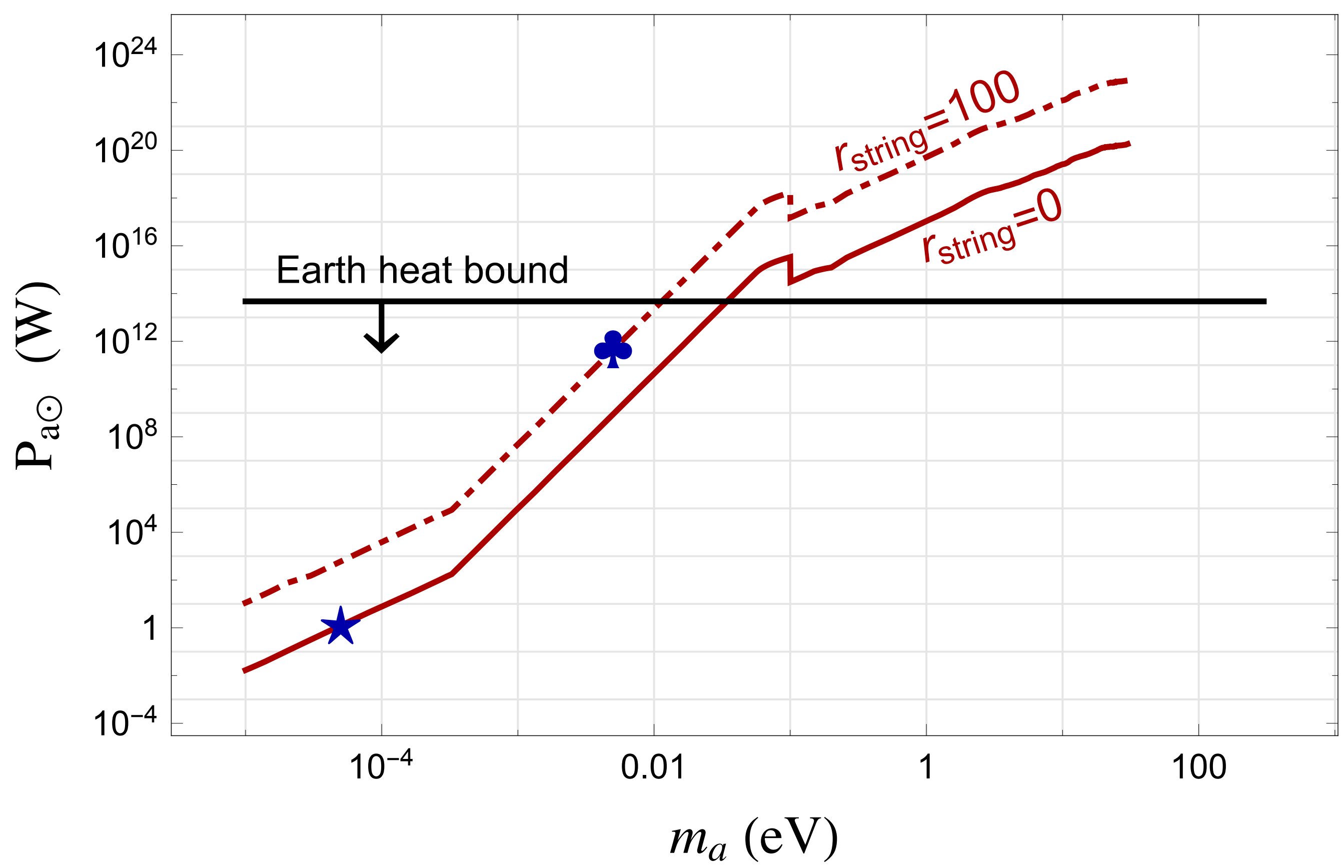


- It is much easier for a heavier axion to be absorbed

Power Generated by Axion Stars

- **The absorbed axions by the material in the core of a planet can provide additional power** $P_{a\to\gamma} = M_{a\odot} c^2 \sigma_{a\to\gamma} v n_e$

- **The absorption rate is related to the real part of the complex conductivity** $\langle n_e \sigma_{\rm abs} v_{\rm rel} \rangle = \sigma_1$



- **It is unlikely to have a axion star sitting in the core of a planet. We may look for some more trackable signatures**

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Axion Star meets Neutron Stars

- **In an external magnetic field, the axion-generated current**

$$j_a^0 = -\frac{c_\gamma\,\alpha}{\pi\,f_a}\,\nabla a\,\cdot\,\vec{B}\,, \qquad \text{and} \qquad \vec{j}_a = \frac{c_\gamma\,\alpha}{\pi\,f_a}\,\left[(\partial_t a)\vec{B} + (\nabla a)\times\vec{E}\right]$$

- **Using the Green's function method and taking the retarded boundary condition, the gauge field is**

$$A_a^\mu(\vec{x},t) = \frac{1}{4\pi}\int d^3y\,\frac{j_a^\mu(y,t-|\vec{x}-\vec{y}|)}{|\vec{x}-\vec{y}|} \;\simeq e^{i\,m_a\,t}\,\frac{e^{-i\,m_a\,r}}{4\pi\,r}\int d^3y\,j_a^\mu(y)\,e^{i\,m_a\,\vec{n}_x\cdot\vec{y}}$$

- **For a dense axion with 1S-like distribution function, the radiated power could be large**

$$\frac{dP}{d\Omega} \;=\; 4.2\times 10^{11}\,\mathrm{W}\times c_\gamma^2\,\sin^2\theta\,\left(\frac{10^{11}\,\mathrm{GeV}}{f_a}\right)^2\left(\frac{10^{-4}\,\mathrm{eV}}{m_a}\right)^6\left(\frac{|\vec{B}|}{10^{10}\,\mathrm{Gauss}}\right)^2\left(\frac{M_{a\odot}}{10^{-13}M_\odot}\right)\left(\frac{1.5\,\mathrm{m}}{R_{\mathrm{AS}}}\right)^5$$

- **The diluted axion stars have a too-large radius to emit a significant power. The dense axion stars may generate enough power**

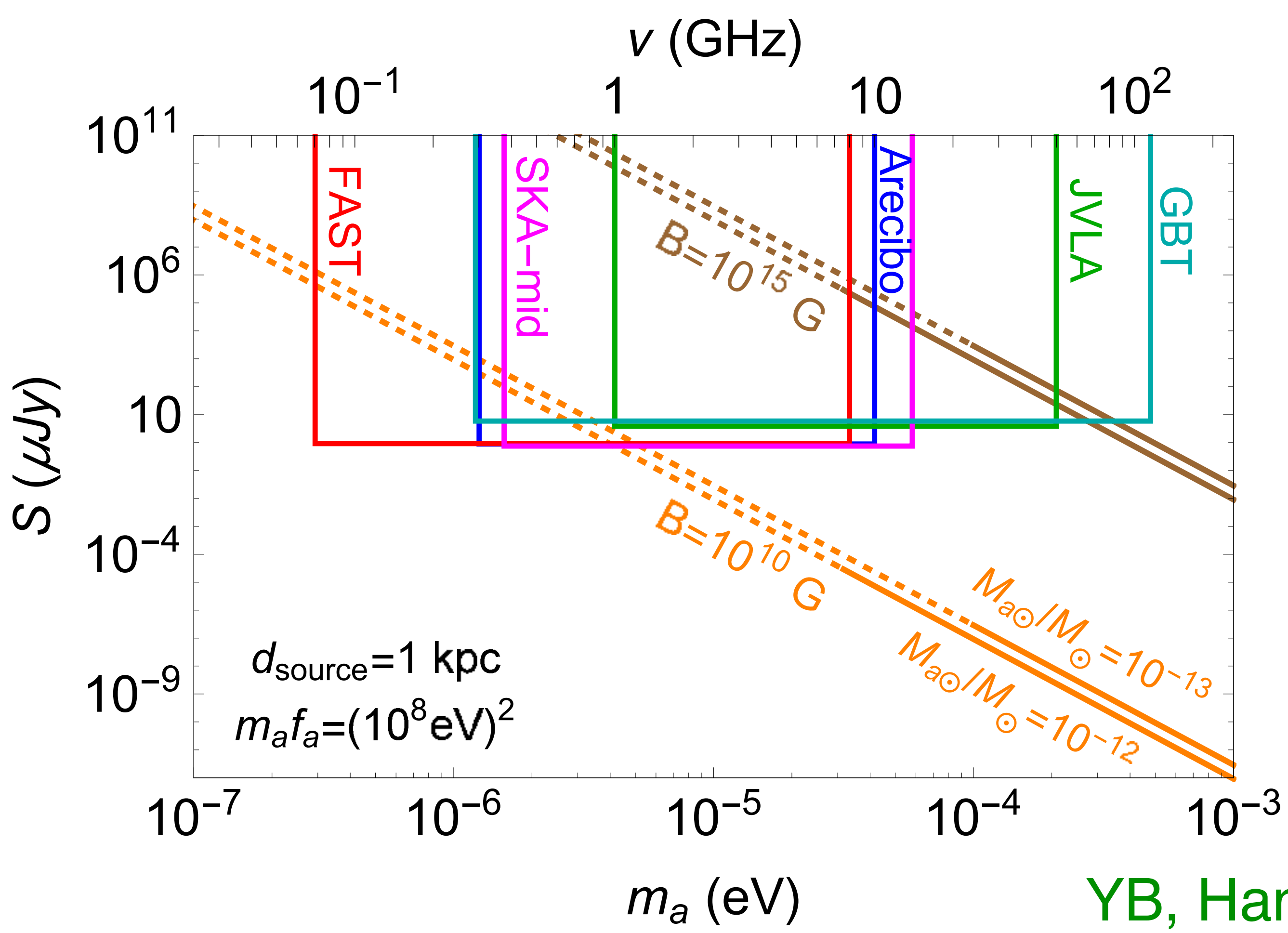
YB, Hamada, 1709.10516

Axion Star meets Neutron Stars

- **The encounter rate in our galaxy is estimated to be**

$$
\begin{aligned}
N_{\rm collision}/{\rm year} &= n_{\rm AS} \times n_{\rm NS} \times \sigma v \times V_{\rm galaxy} \simeq n_{\rm AS} \times N_{\rm NS} \times \sigma v_{\rm rel} \\
&= 0.003 \times \ell\, f_{\rm AS} \left(\frac{10^{-13}\, M_\odot}{M_{a\odot}} \right) \left(\frac{N_{\rm NS}}{10^9} \right) .
\end{aligned}
$$

- **A nearby source with a large magnetic field may have a chance**



YB, Hamada, 1709.10516

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Primordial Accretion of Baryons

- The axion star is formed below the QCD phase transition scale
- The baryons have approximately homogenous space distributions, except axion-star mass and size introducing another short-distance scale
- For fast enough thermalization and collapsing rates, the hydrostatic equilibrium equation is

$$\nabla P_b = -\rho_b \nabla \phi$$

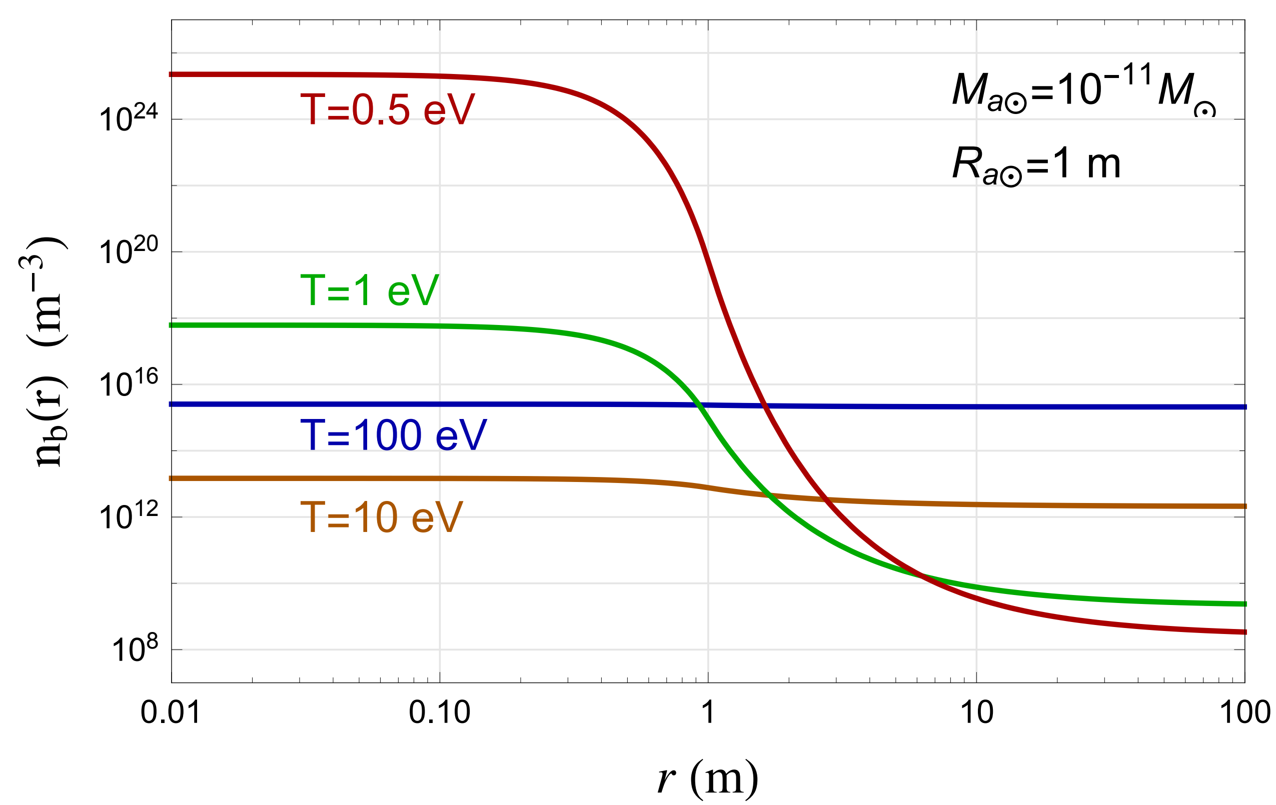
- Ignoring baryon self-gravitational interaction

$$\frac{1}{\rho_b}\frac{\partial P_b}{\partial r} = -\frac{G_N\, M_{\rm enc.}(r)}{r^2}$$

Isothermal Collapse

- **Before around one tens of the recombination temperature, the Compton interactions with CMB photon can keep a uniform temperature for the gas cloud** $\frac{P_b}{\rho_b} = \frac{T}{m_p}$

- **Depending on the relation of T and the virialized temperature:** $$T_{\rm vir} = \frac{G_N\, m_p\, M_{a\odot}}{R_{a\odot}} \approx 13 \text{ eV} \times \frac{M_{a\odot}}{10^{-11} M_\odot} \frac{1 \text{ m}}{R_{a\odot}}$$



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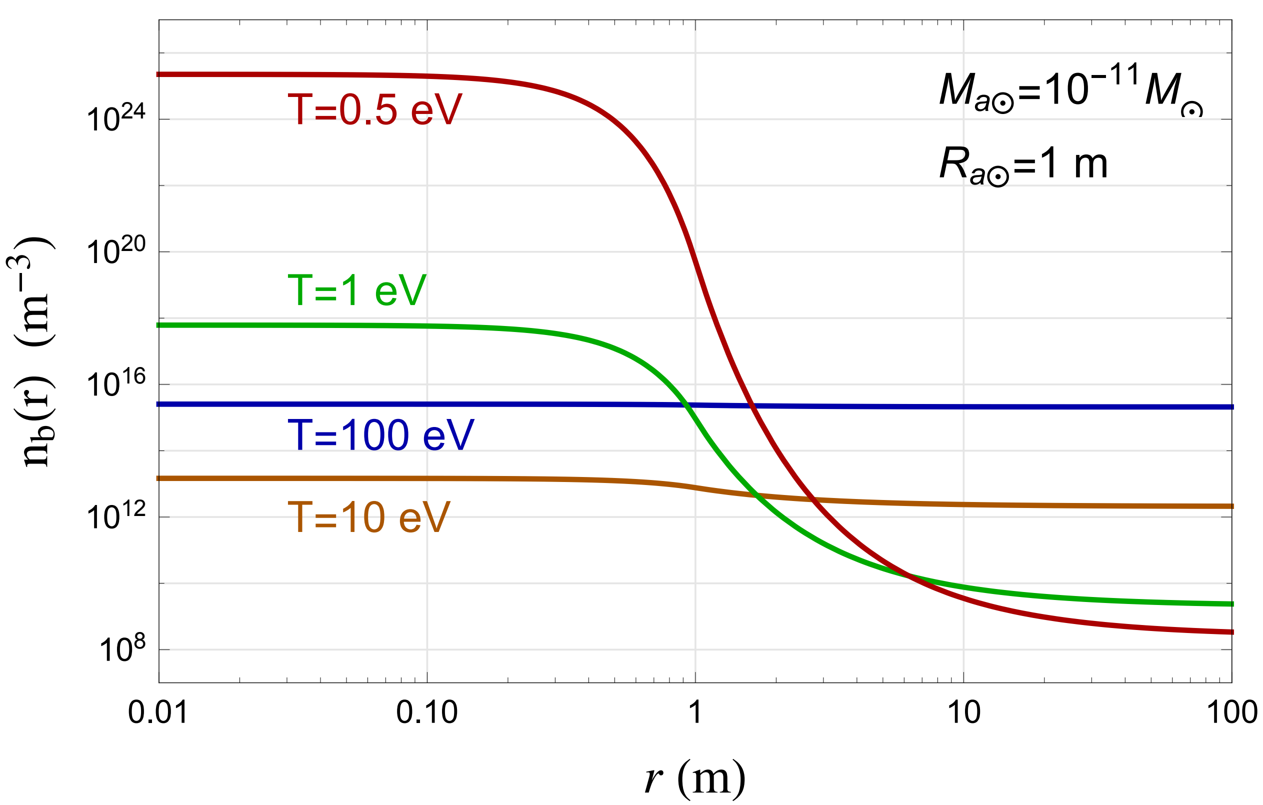

- Diluted axion stars do not accumulate too much baryons

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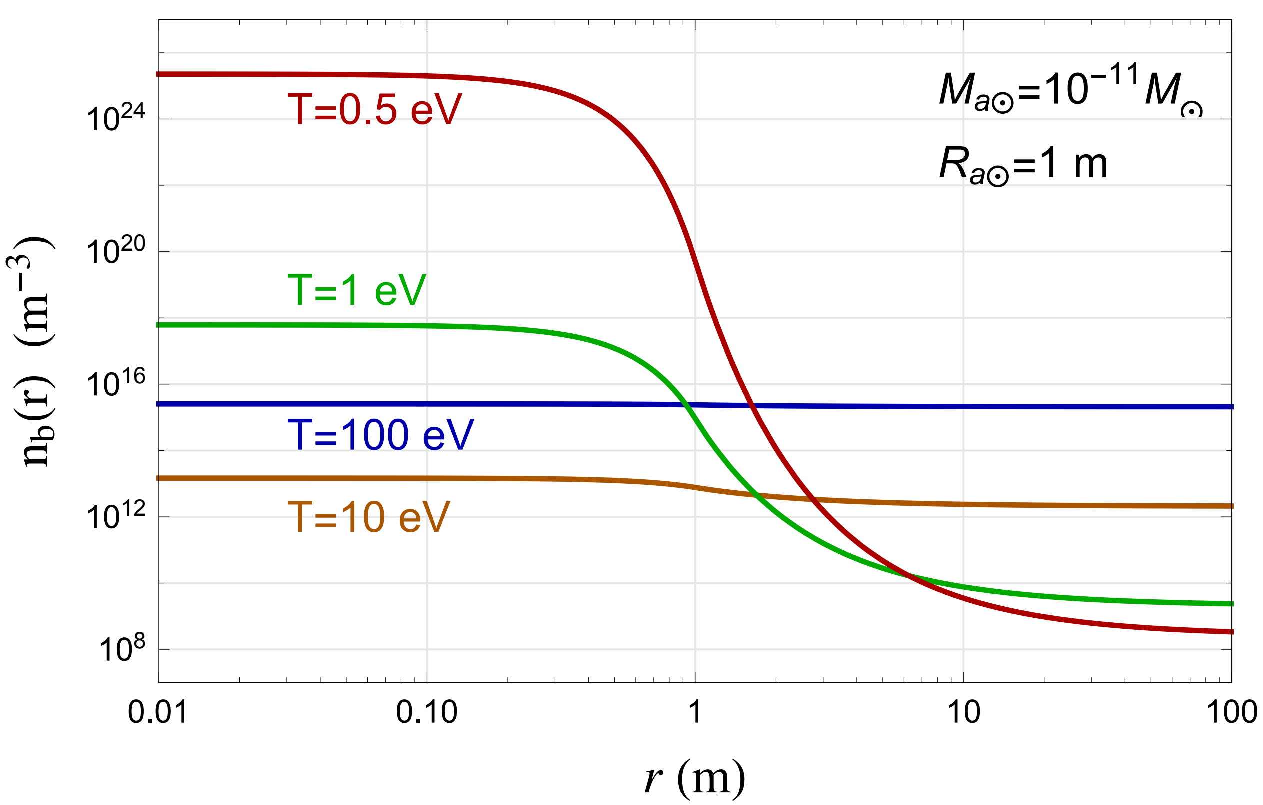
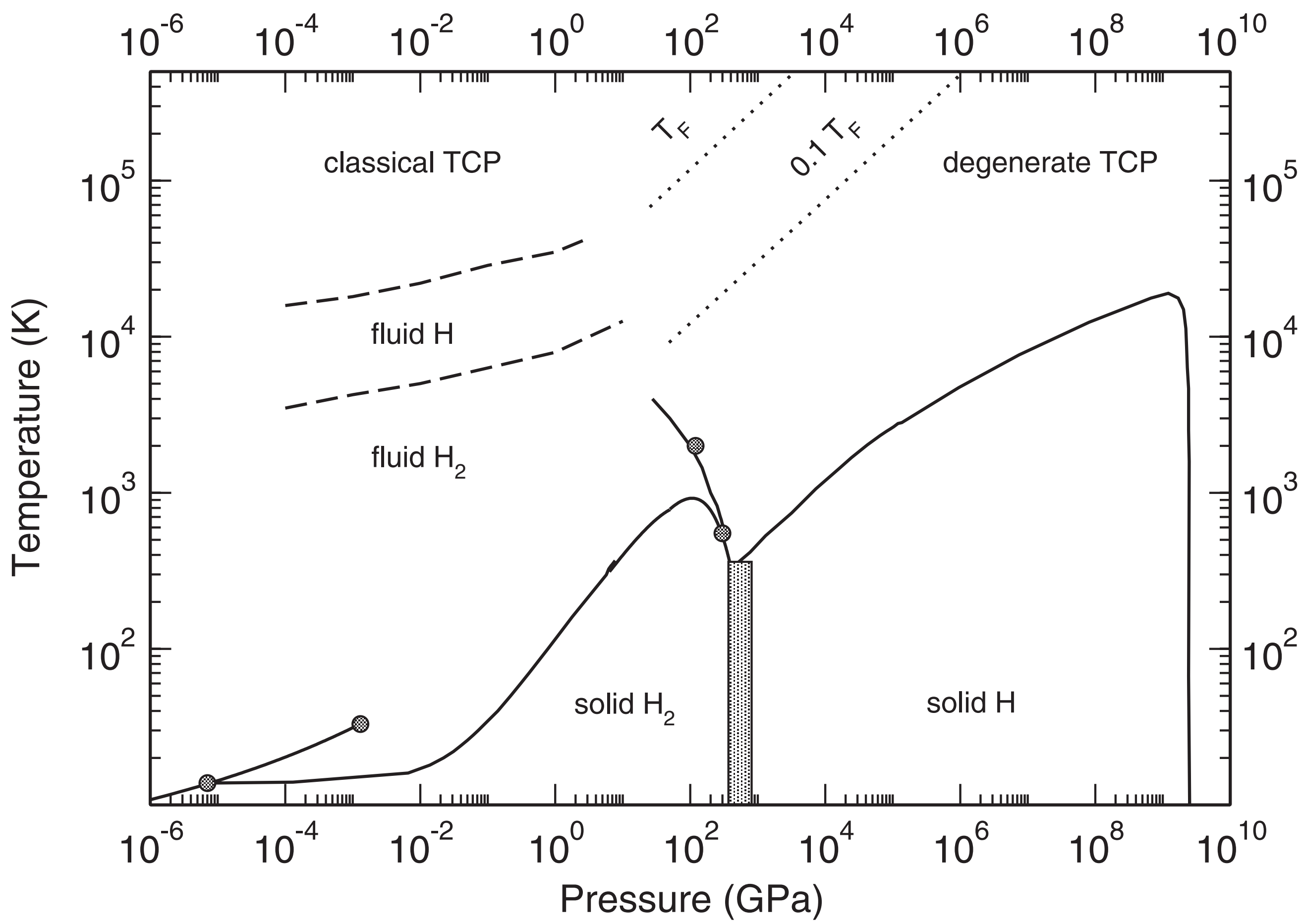


- Diluted axion stars do not accumulate too much baryons

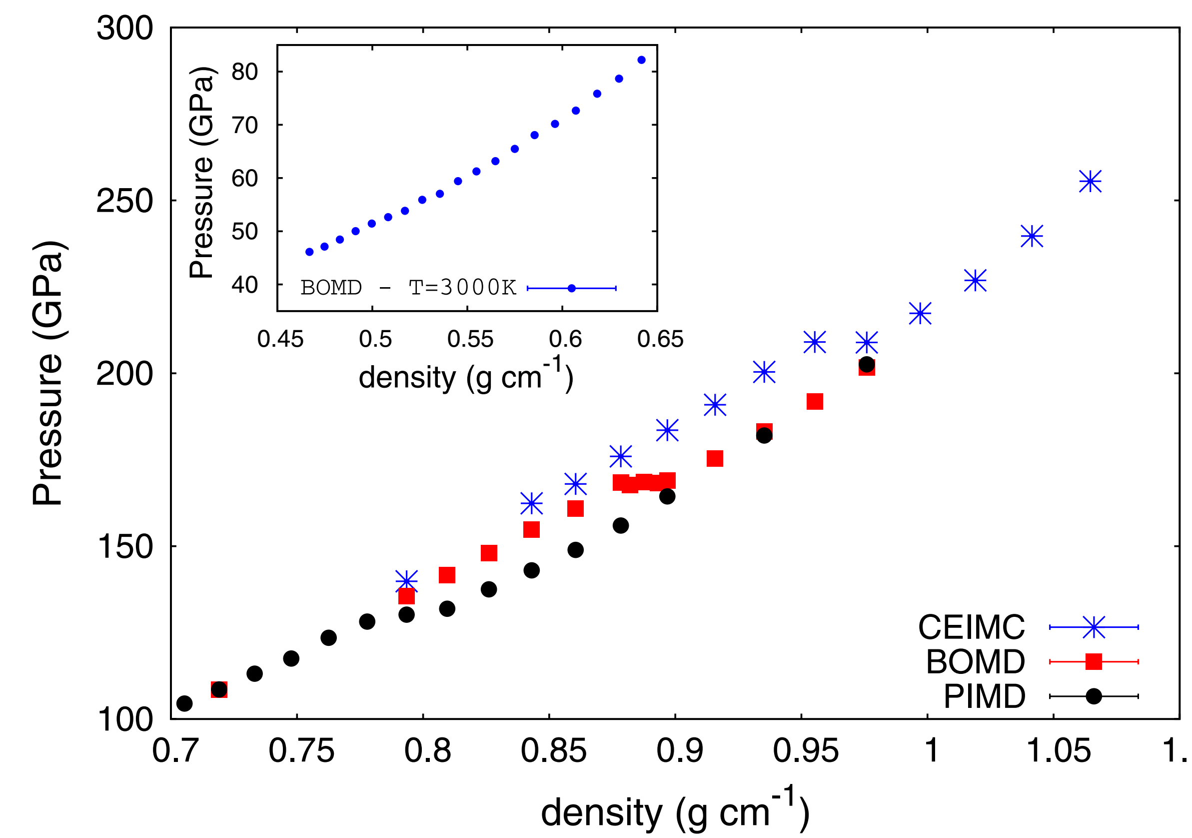
- Once the density is too high, we care about pressure from Fermi-degeneracy

Hydrogen EOM

- **Hydrogen has many phases in high pressure and temperature environment**



McMahon, et. al., RMP, 84, 1607



Morales, et. al., PNAS, 107, 12799

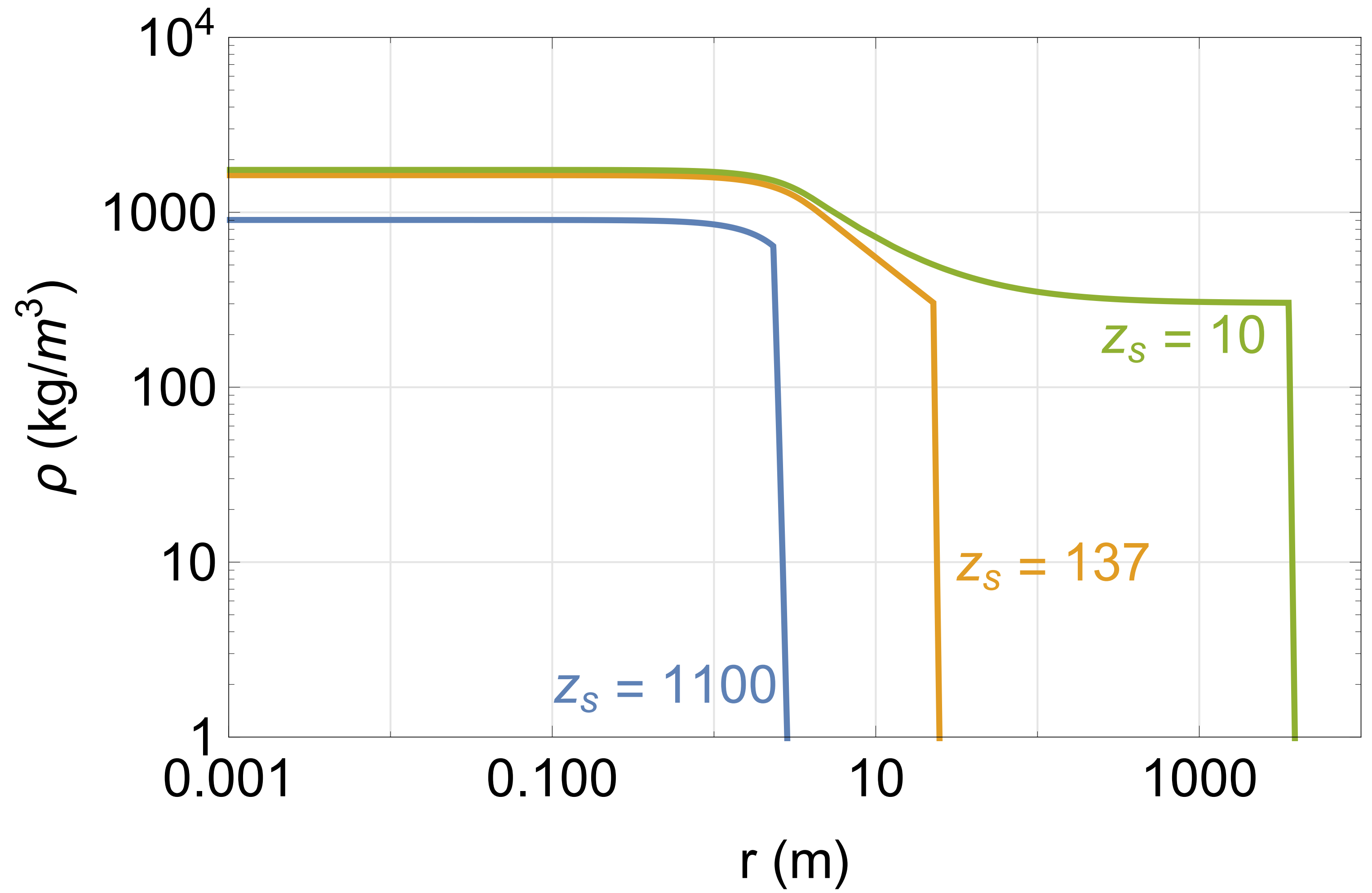
- **The liquid hydrogen state has EOM fitted as**

$$P = \frac{\rho\, k_B T}{2\, m_p} \left(\frac{\rho}{\rho_0}\right)^{\gamma_\rho} \left(\frac{T}{T_0}\right)^{\gamma_T}$$

$$\rho_0 = 51.33\ \mathrm{kg/m^3}, \quad T_0 = 1000\ \mathrm{K},$$
$$\gamma_\rho = 1.36, \quad \gamma_T = -0.89$$

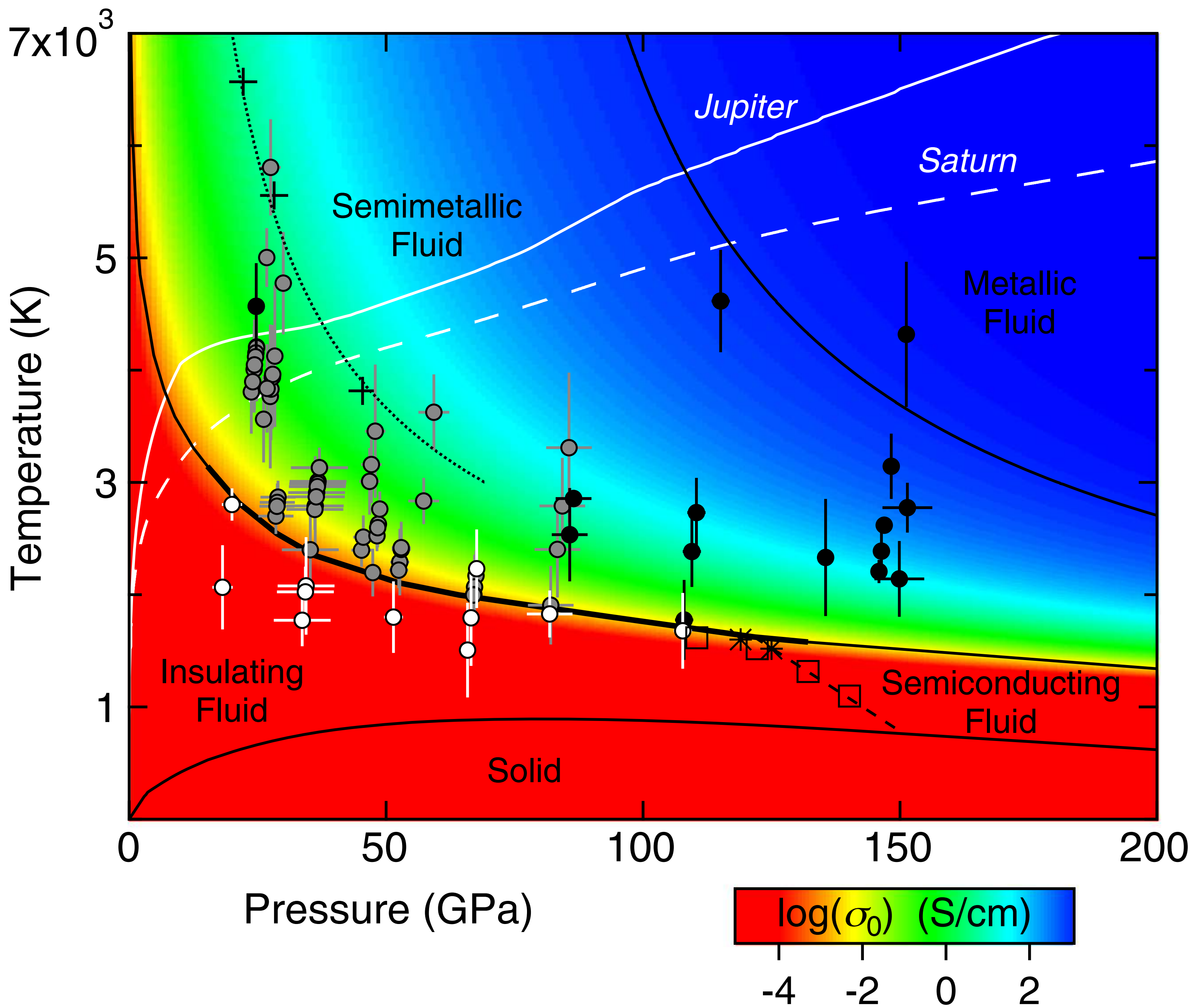
Hydrogen Density Profile

- For the benchmark point of $\mathbf{m_a = 5\ meV}$



- Here, z_s is the redshift to stop evolving the hydrogen cloud around the axion stars
- For z_s below 10, the reionization and star formation happen and the boundary properties vary a lot

Metallic Hydrogen Conductivity



McWilliams, et. al, PRL,116, 255501

- **The surrounding cloud is more like the metallic hydrogen fluid with a factor 10 higher conductivity than iron**

Power from Hydrogen Axion Stars (HAS)

- **The absorbed axion by the material in cloud (metallic hydrogen fluid) can provide additional power, which is insensitive to the stop-evolving redshift**

$$P_{a\odot} = M_{a\odot} c^2 \, \Gamma^a_{\rm abs.} = M_{a\odot} c^2 \, \frac{3\, m_a^2}{4\,\pi\,\alpha\, f_a^2} \, \frac{\sigma_0}{\epsilon_0} \approx \begin{cases} 2 \times 10^{13}\ \mathrm{W} & \text{for}\ \ m_a = 5\ \mathrm{meV}\,, \\ 2 \times 10^{5}\ \mathrm{W} & \text{for}\ \ m_a = 0.05\ \mathrm{meV} \end{cases}$$

- **The HAS generates photons via the blackbody radiation**

$$P_{a\odot} = 4\,\pi\, R^2_{\rm bound}\, \epsilon\, \sigma_{\rm SB}\, T^4_{\rm surf}$$

m_a	5 meV		0.05 meV	
z_s	$R_{\rm bound}$ (m)	$T_{\rm surf}$ (K)	$R_{\rm bound}$ (m)	$T_{\rm surf}$ (K)
1100	2.3	4.7×10^4	2.6	450
137	23	1.5×10^4	24	150
10	3700	1200	3800	12

- **A hot HAS is anticipated for a heavier axion mass**

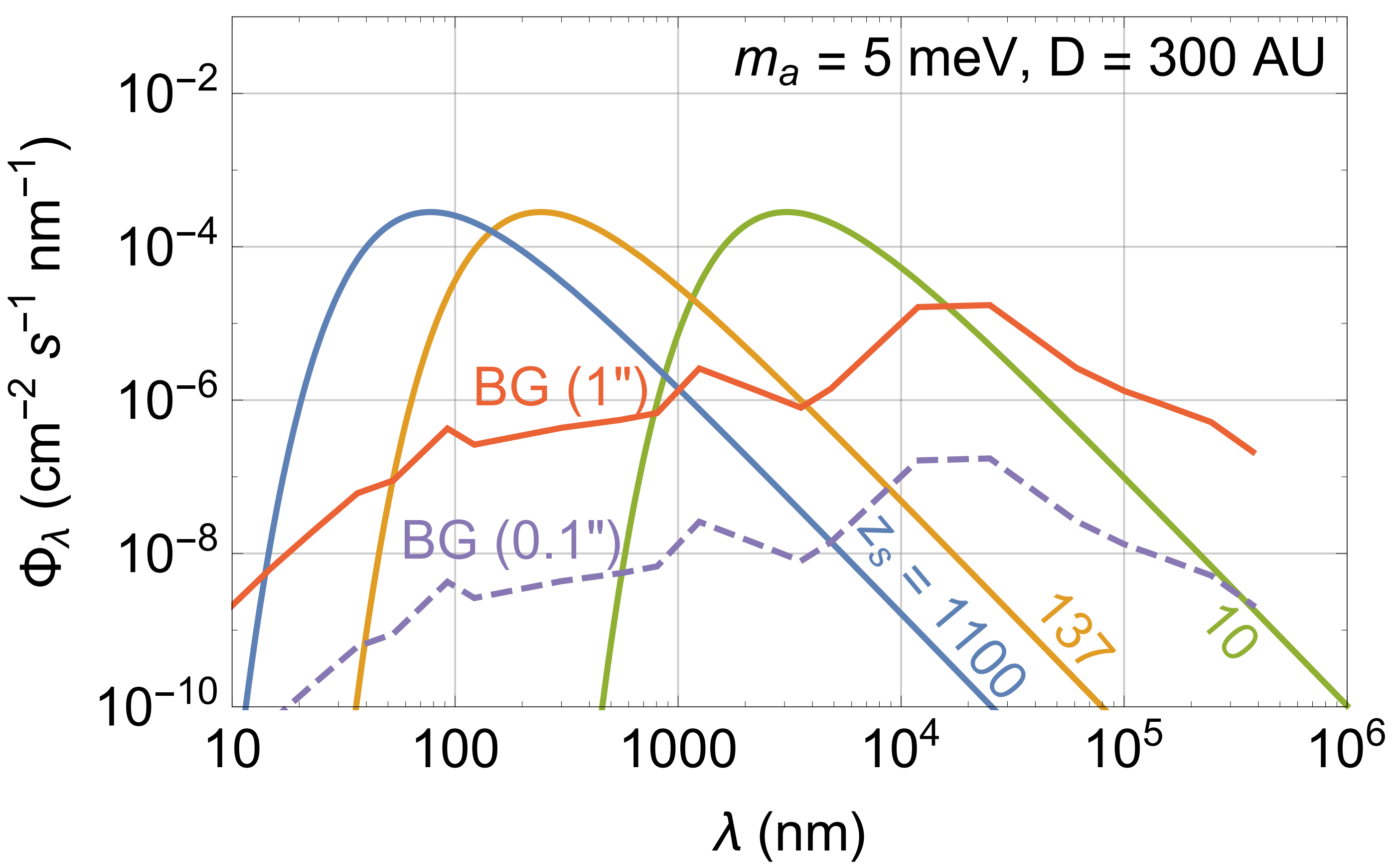
- **It behaves as a hot and medium-size asteroid**

Observing HAS Point Source

- **Its blackbody spectrum is**

$$\Phi_\lambda = \frac{d\Phi}{d\lambda} \equiv \frac{dN_\gamma}{dt\,dA\,d\lambda} = \left(\frac{R_{\rm bound}}{D}\right)^2 \frac{2\,\pi c}{\lambda^4} \frac{1}{e^{h\,c/\lambda\,k_B\,T_{\rm surf}} - 1}$$

- **It can be observed by a good-resolution telescope**



- **For instance, GAIA has an angular resolution of 0.1"**

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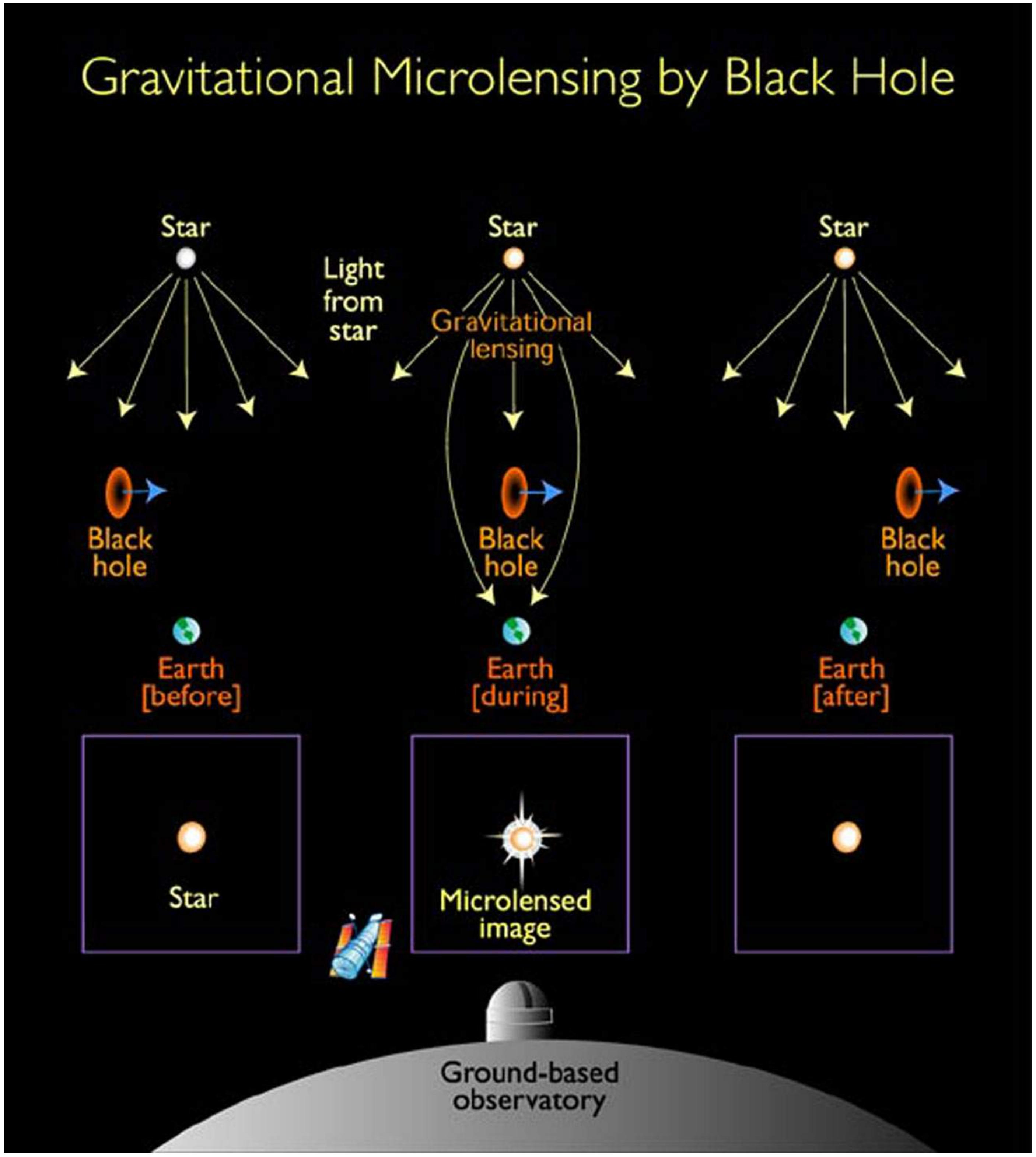
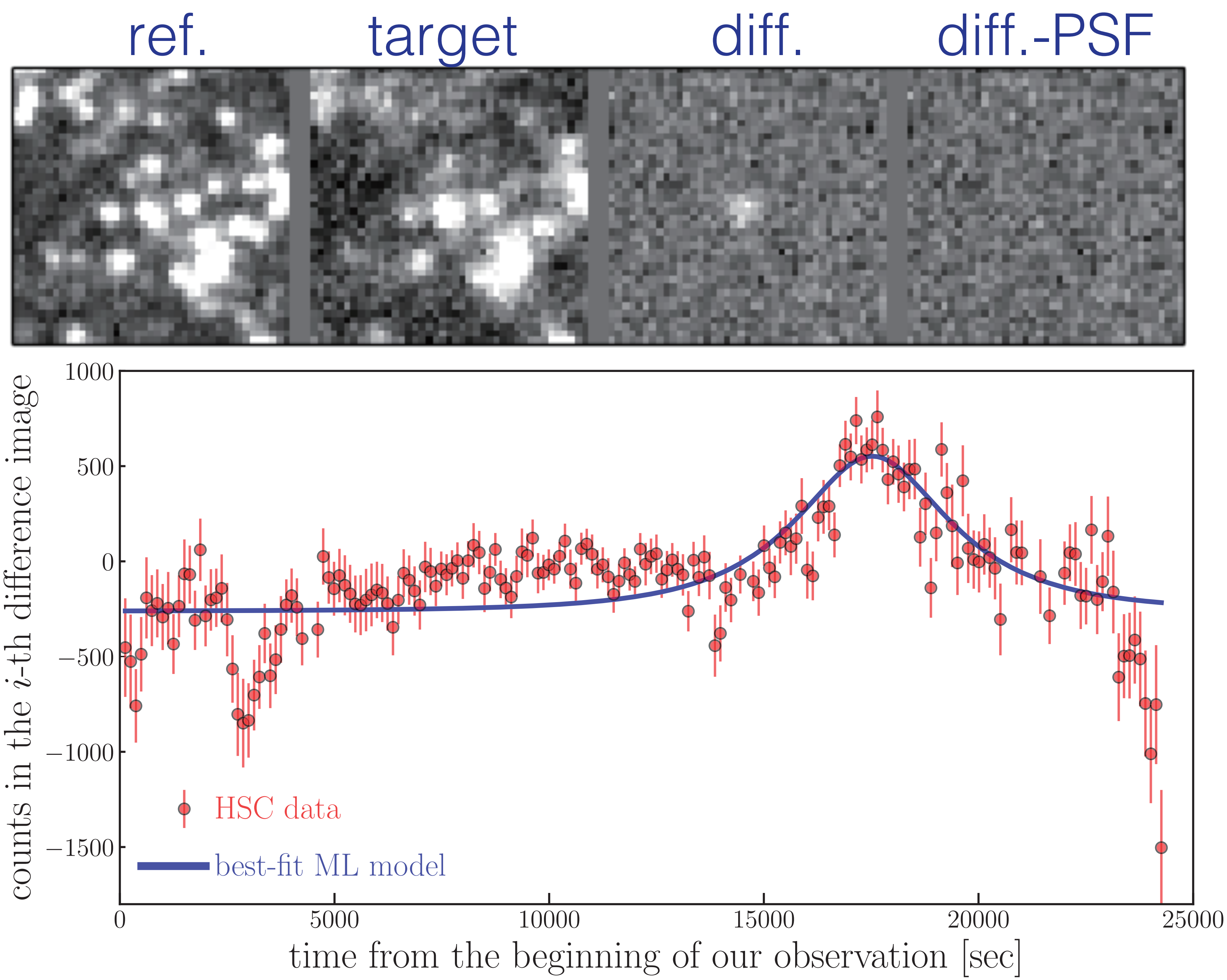
- Conclusions

Microlensing



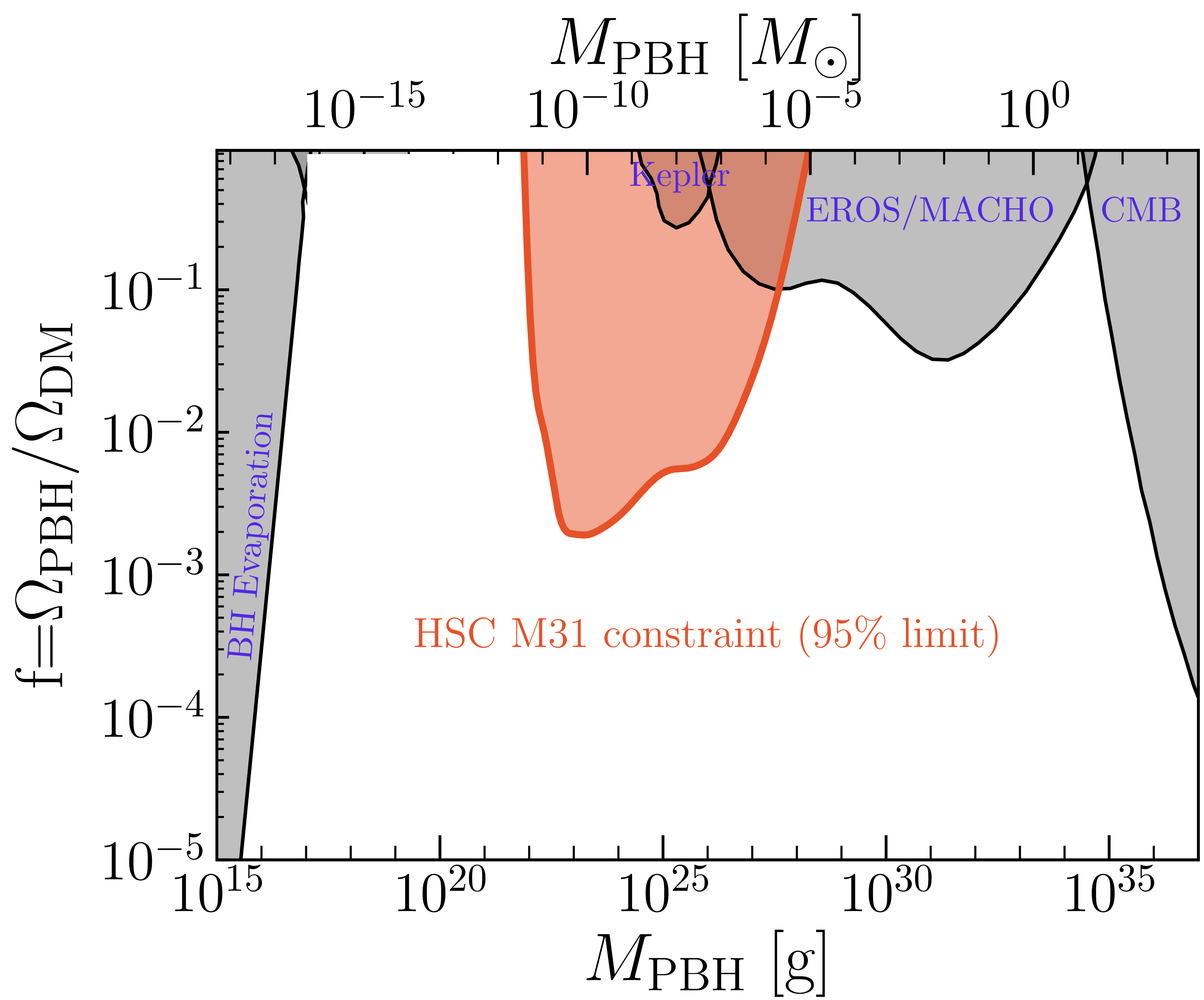
Credit: NASA/ESA

Microlensing

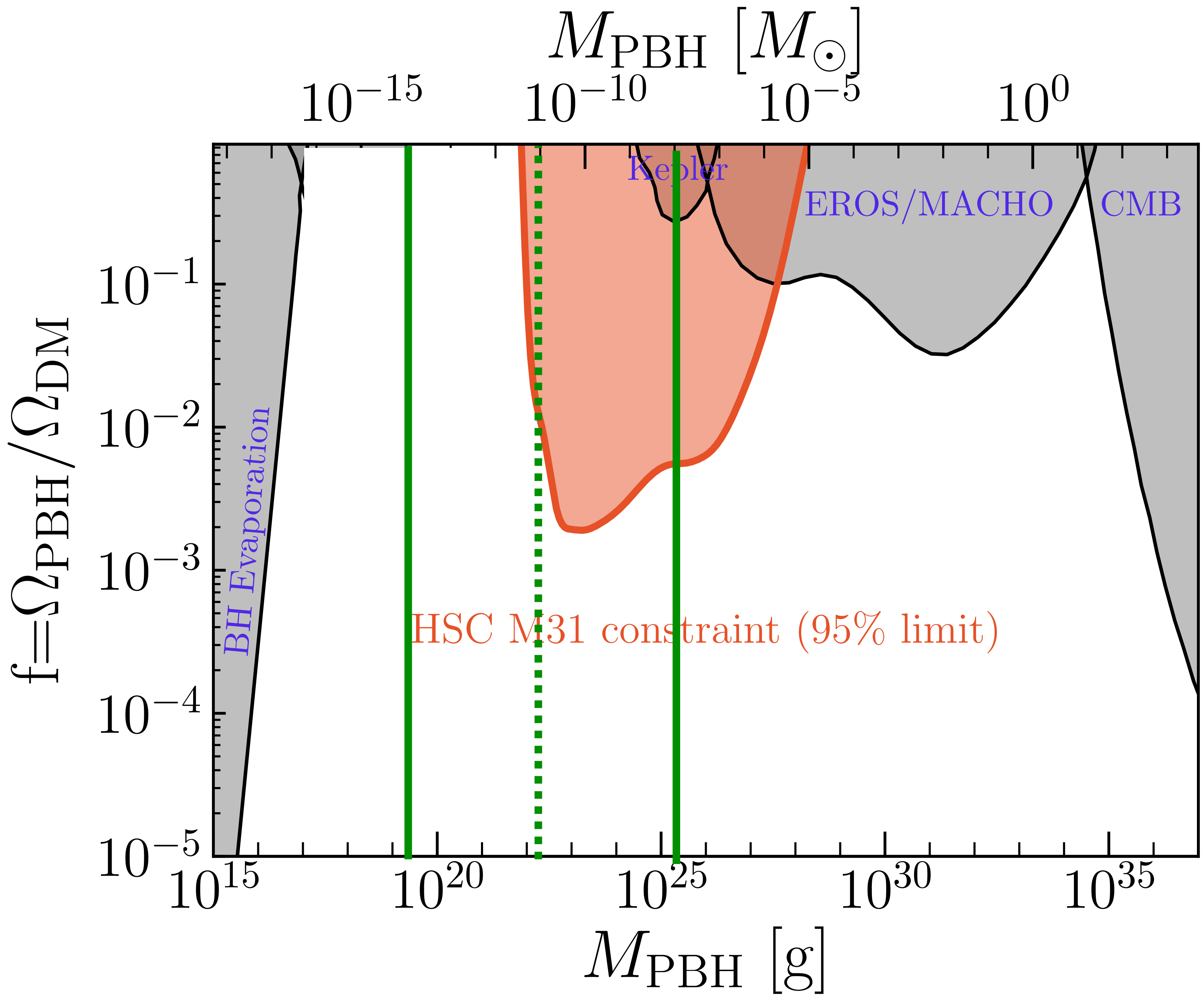


Subaru/HSC:
1701.02151

Constraints on PBH



Constraints on PBH

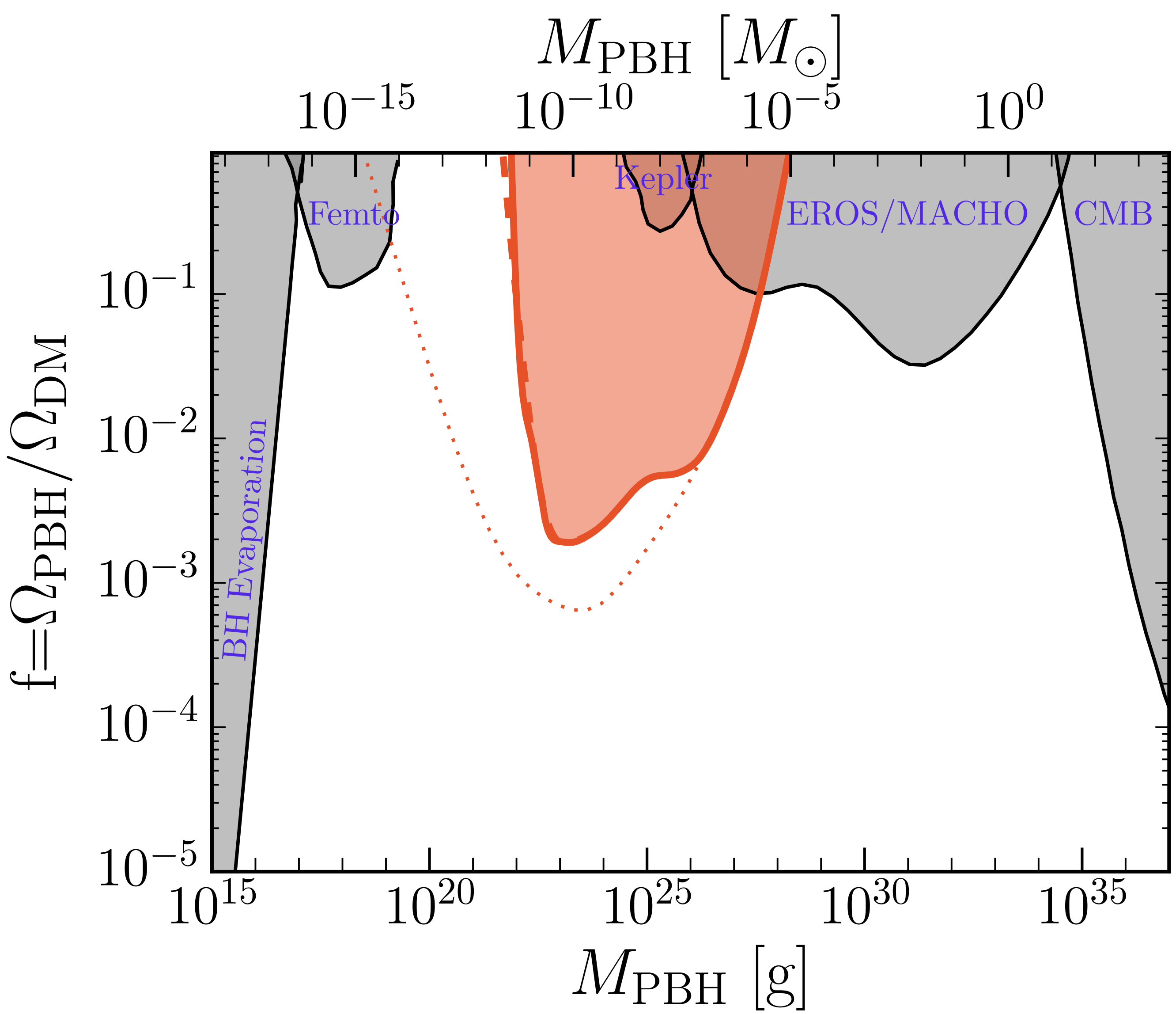


Wave Effects for Small Masses

- **The wave effects become important when**

$$G_N M_{BH} E_\gamma < 1 \qquad M_{BH} \lesssim (6.6 \times 10^{22}\,\mathrm{g}) \times (1\,\mathrm{eV}/E_\gamma)$$

- **Subaru/HSC early version missed this point**

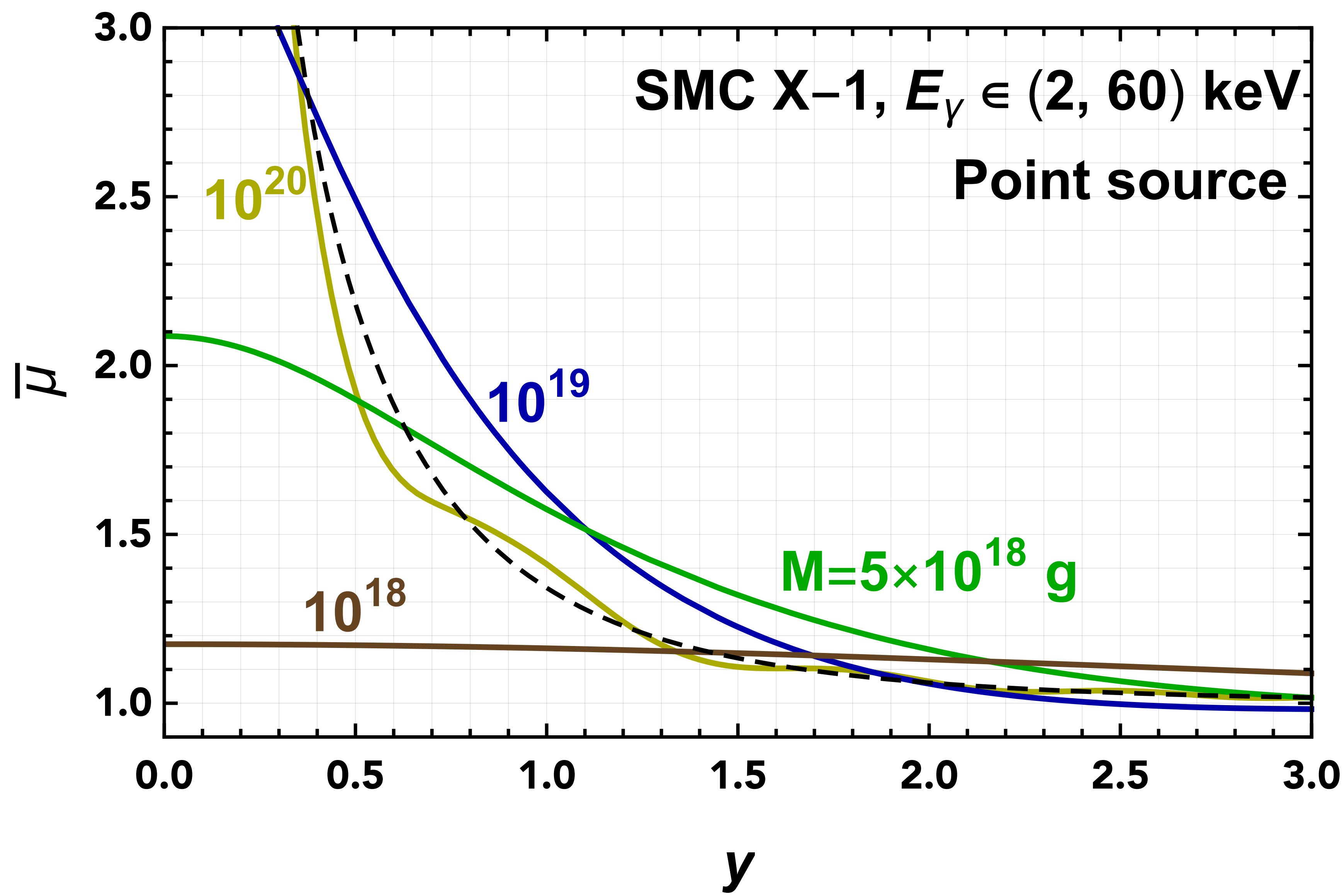


see: Smyth, Profumo, et. al., 1910.01285 for additional finite source size issue

Microlensing of X-ray Pulsars

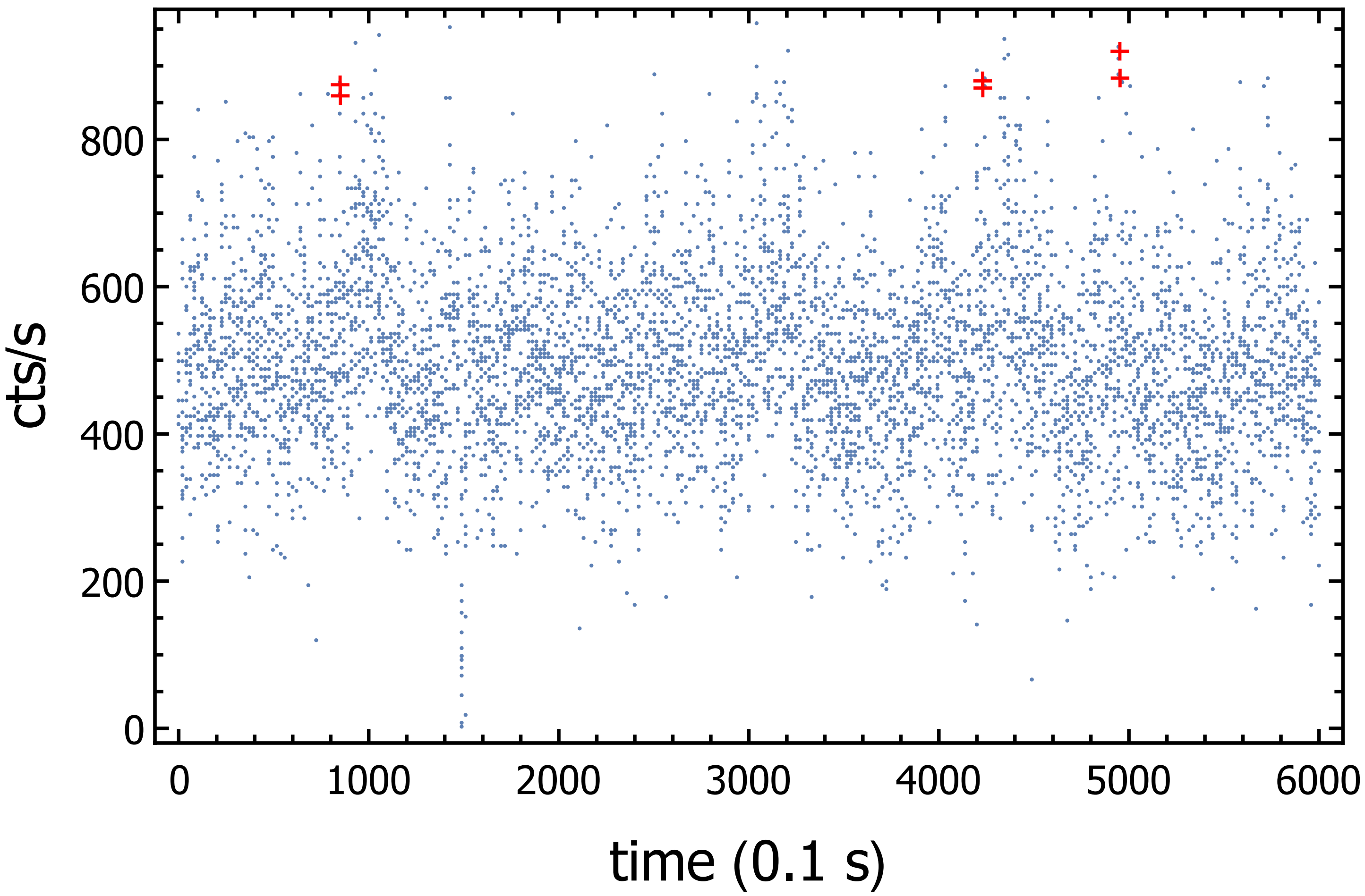
- **Choosing the sources with more energetic photons could extend the reach**

YB, Nicholas Orlofsky, 1812.01427



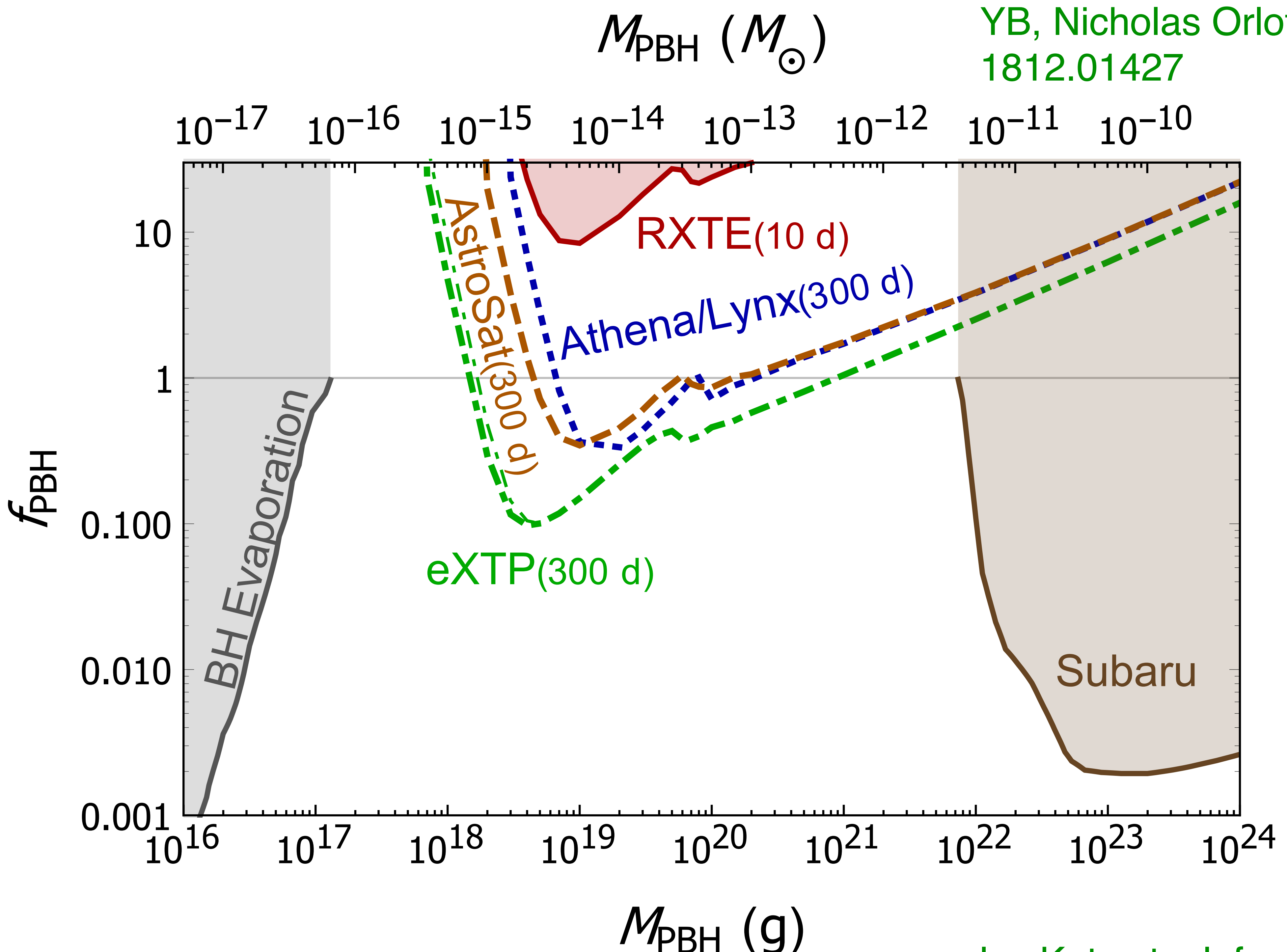
SMC X-1

- **The SMC X-1 in the Small Magellanic Clouds is a good source because of its larger luminosity**
- **The Rossi X-ray Timing Explorer Proportional Counter Array (RXTE PCA) has around 10 days observation time**



YB, Nicholas Orlofsky, 1812.01427

Microlensing of X-ray Pulsars



YB, Nicholas Orlofsky, 1812.01427

see also Katz et. al, for using GRB 1807.11495

Outline

- Motivations for QCD axion dark matter
- Formation of QCD axion stars (BEC)
- Detecting axion stars
  - Inside a planet
  - Radio signals
  - Hydrogen axion stars
  - Microlensing
- Stability of dense axion stars
- Conclusions

Stability of Dense Axion Stars

- **So far, we have shown several interesting signatures associated with a dense axion star**

- **In the non-relativistic limit,** $a(\mathbf{x},t) = [\psi(\mathbf{x})e^{-im_a t} + \psi^*(\mathbf{x})e^{im_a t}]/\sqrt{2m_a}$ **, the axion potential becomes**

$$V_{\text{eff}}(|\psi|^2) = m_a^2 f_a^2 \left[1 + \frac{|\psi|^2}{2\,m_a\,f_a^2} - J_0\left(\frac{\sqrt{2}\,|\psi|}{\sqrt{m_a}\,f_a}\right)\right]$$

Braaten, Mohapatra, Zhang, 1512.00108

- **One can solve the coupled Schrodinger and Poisson equations:**

$$\mu\,\psi = -\frac{\nabla^2\psi}{2\,m_a} + m_a\,\Phi\,\psi + \left[V'_{\text{eff}}(|\psi|^2) - m_a\right]\,\psi \qquad \nabla^2\Phi = 4\pi G_N\,m_a\,|\psi|^2$$

- **However, the Thomas-Fermi approximate is not reliable, because axion becomes relativistic inside a dense axion star**

Visinelli, Baum, Redondo, Freese, Wilczek, 1710.08910

Schiappacasse, Hertzberg, 1710.04729

Eby, Suranyi, Vaz, Wijewardhana, 1712.04941

Sine-Gordon Equation

- **In the dense axion star parameter region, the gravitational potential is negligible**
- **The relevant equation is simply to solve the sine-Gordon equation**

$$\ddot{\theta} - \nabla^2\theta + \sin\theta = 0$$

- **To evade the Derrick's theorem for the time-independent solutions, one seeks the breather solutions**
- **In 1+1 dimension, analytic and spacial-localized solutions have been found**

$$\theta(x,t) = 4\arctan\left[\frac{\sqrt{1-\omega^2}\,\sin\omega\,t}{\omega\,\cosh(\sqrt{1-\omega^2}\,x)}\right]$$

- **In higher dimensions, one relies on numerical simulations to look for stable breather solutions**

Spherical Breather Solutions

- **For spherical solutions in 1+d dimension,**

$$\ddot{\theta} - \theta_{rr} - \frac{d-1}{r}\theta_r + \sin\theta = 0$$

- **One could assume a periodic solution,** $f(r,t) \sim g(r)\sin\omega t$ **, to derive a spatial-only equation**

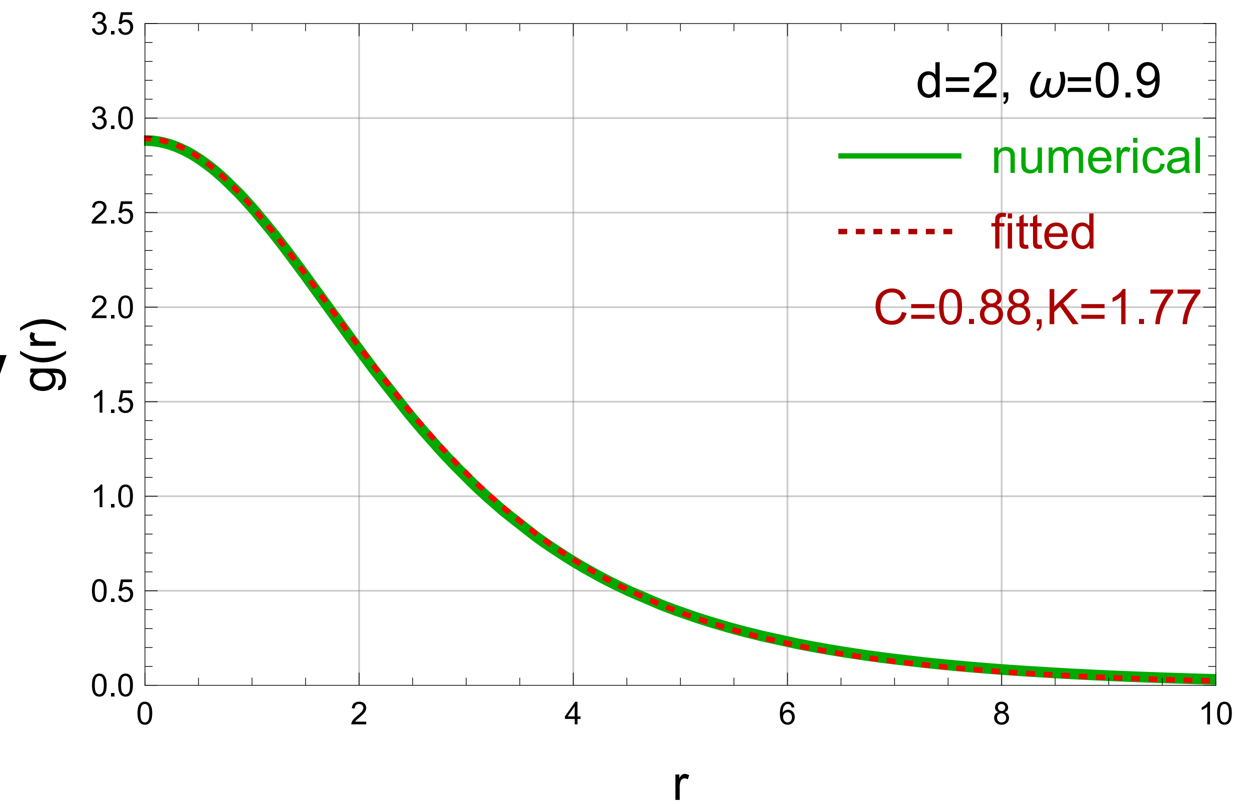
Piette and Zakrzewski, Nonliearity, 11, (1998) 1103

$$g_{rr}(r) + \frac{d-1}{r}g_r(r) + \omega^2 g(r) - 2J_1[g(r)] = 0$$

- **Using a shooting method to find g(r) as a good starting profile for f(r, t)**

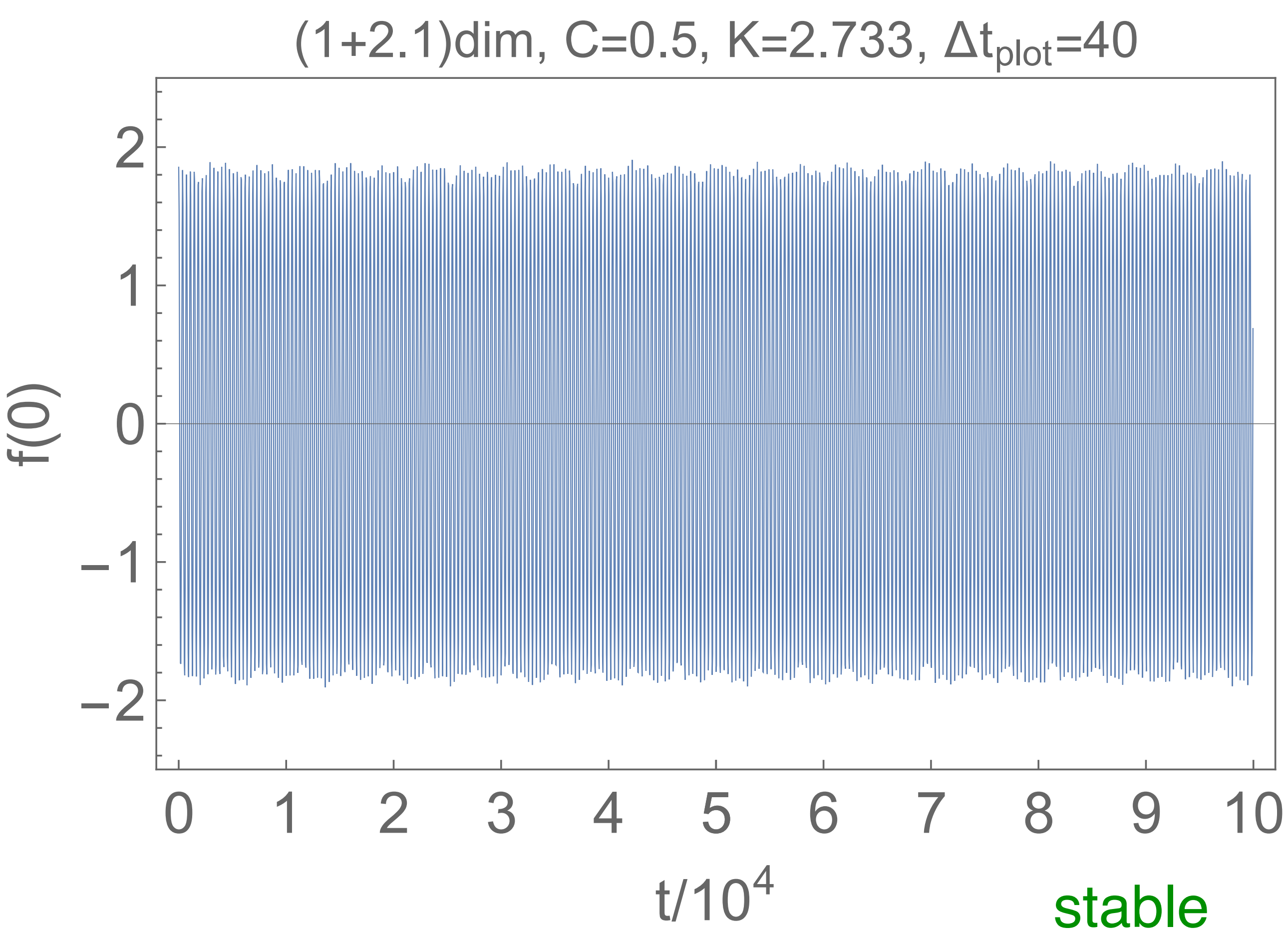
- **The solutions can be fitted by a simple function**

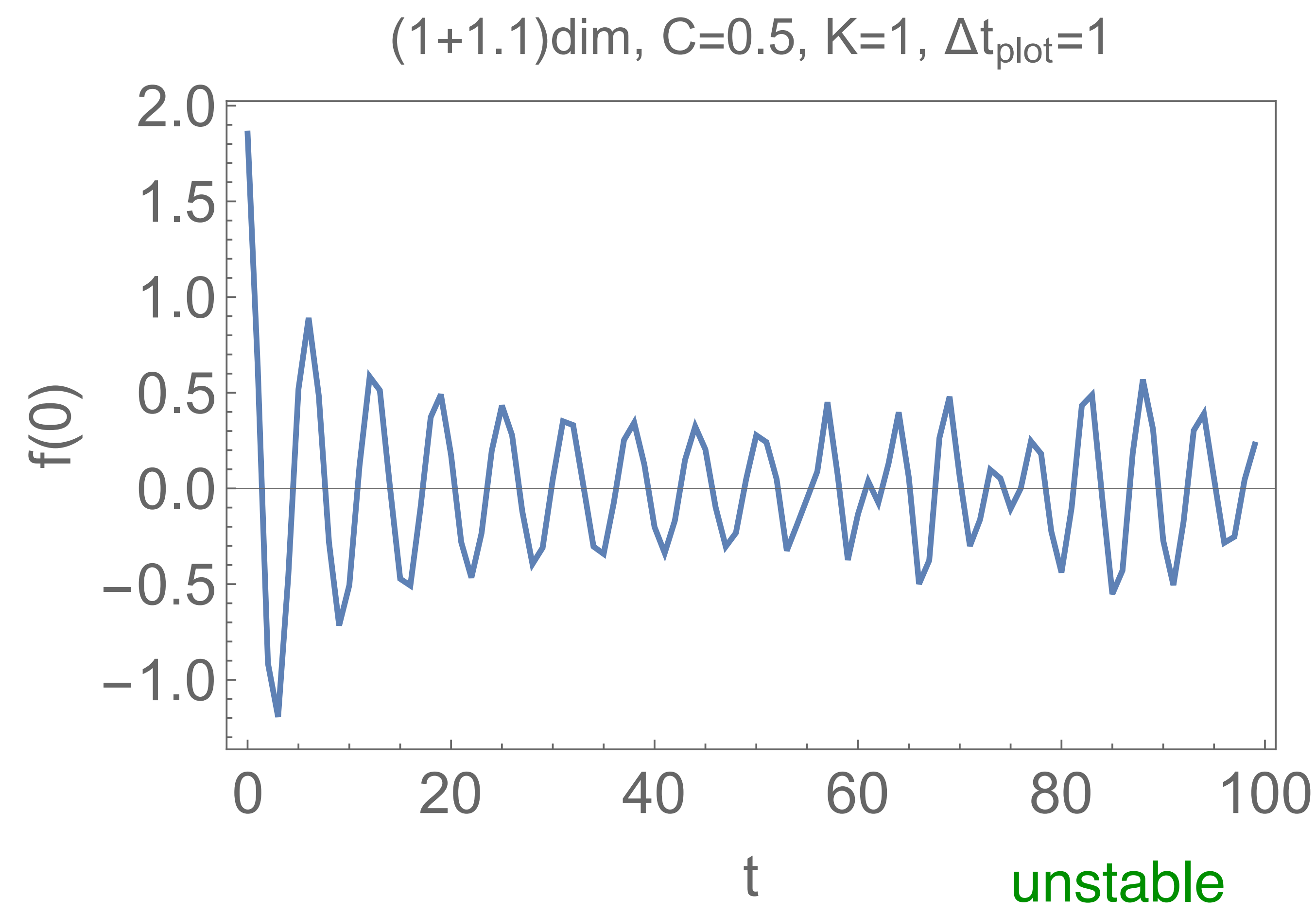
$$g(r) = 4\arctan\left[C\,e^{-\frac{2\,r}{K\,\pi}\arctan(\frac{r}{K})}\right]$$



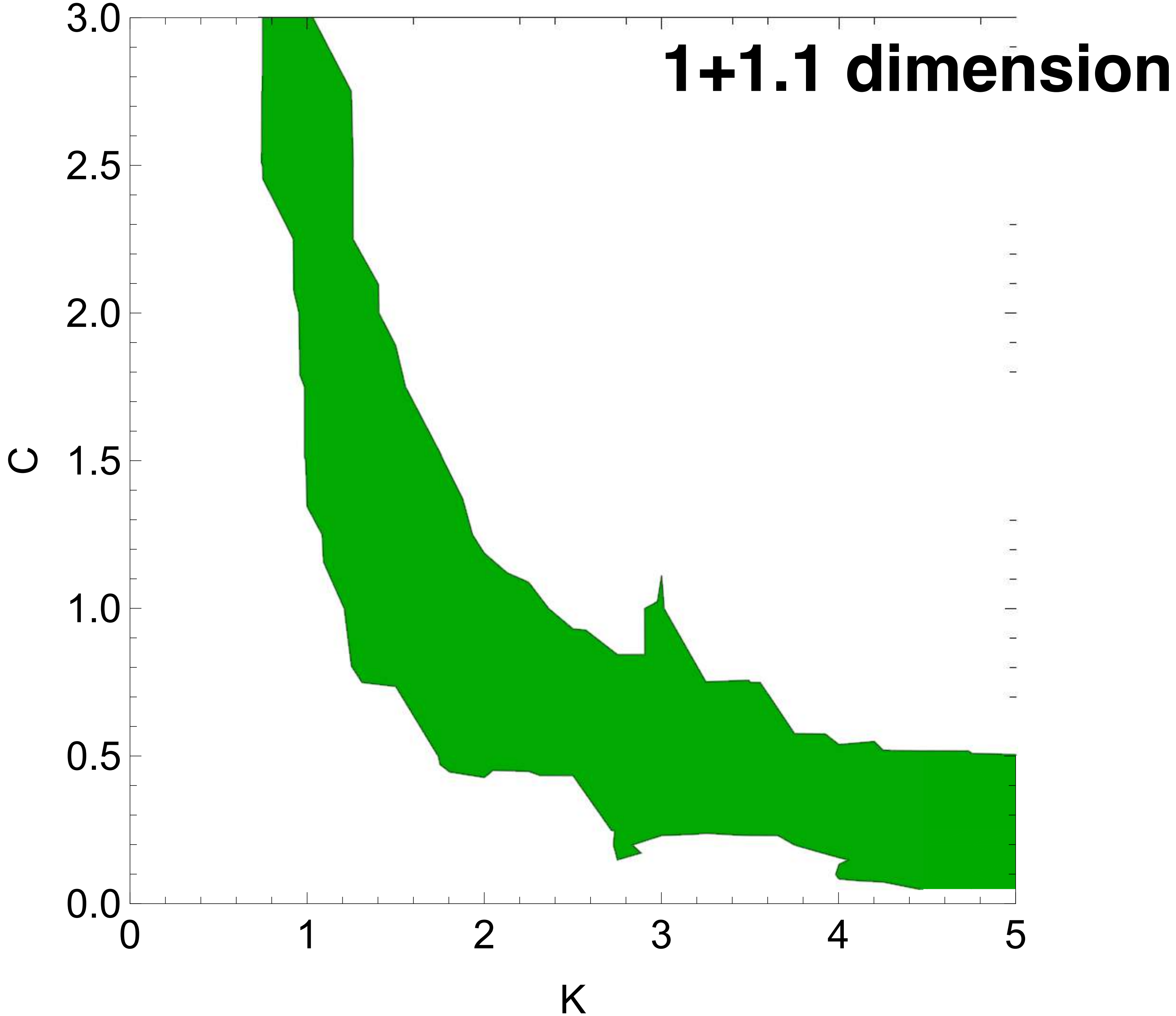
Spherical Breather Solutions

❖ **For instance, one can demonstrate stable breather solutions in a fractional dimension**





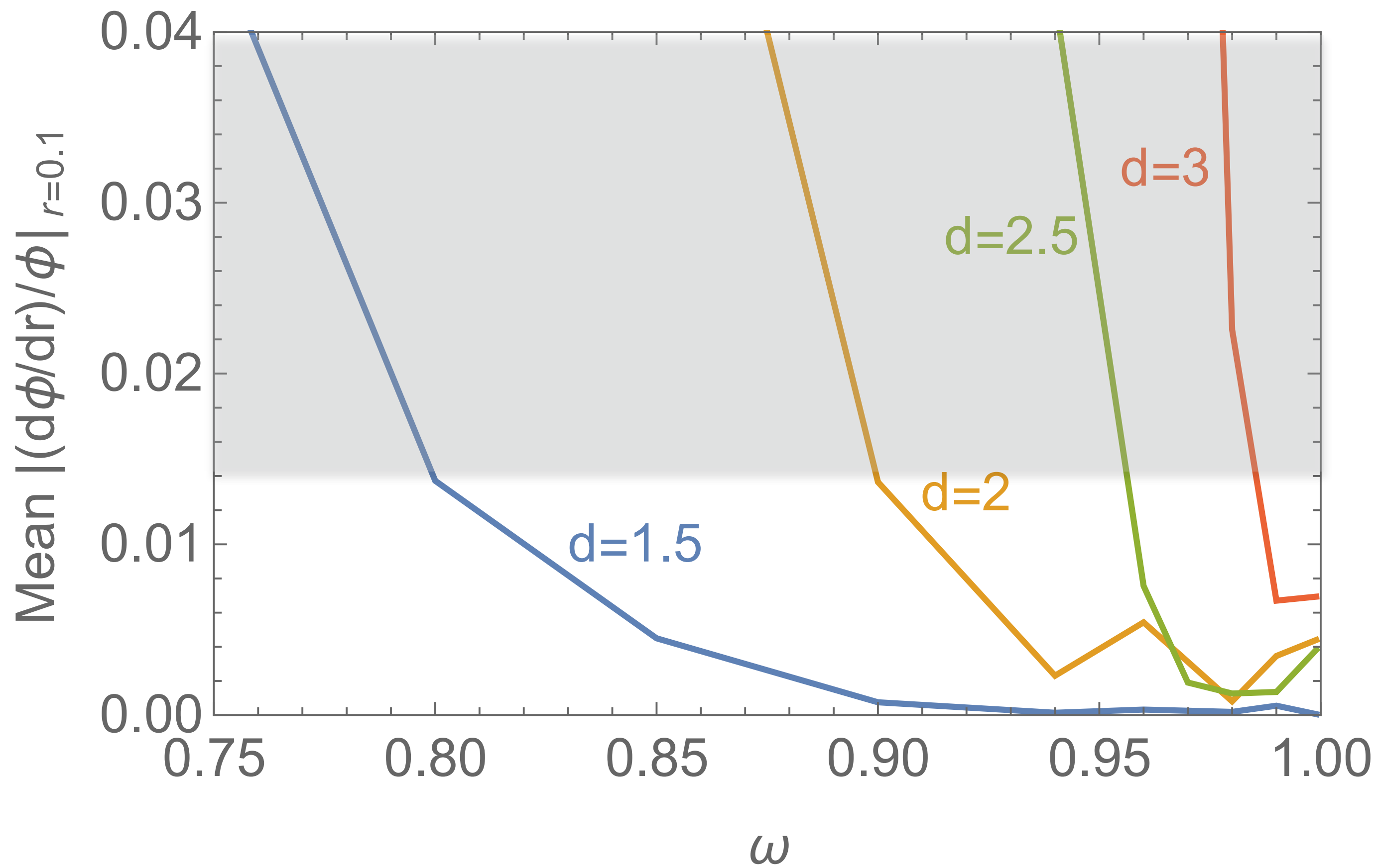
Spherical Breather Solutions



Spherical Breather in 1+d

- **Under numerical uncertainties, one can obtain the region of stable breather solutions**

- **As the dimension increases, the allowed frequency region becomes smaller**



- **It is not clear at this moment whether 1+3 has a stable spherical breather solution or not**

- **The current results show some possibilities of having non-spherical 1+3 stable breather solutions, which is still under investigation (GPU simulation)**

YB, Berger, Hamada, work in progress

Conclusions

- The QCD axions may form BEC and have macroscopic objects like axion stars.

- The axion stars can generate observable radio signals when they meet astrophysical objects with a large magnetic field like neutron stars and white dwarfs

- The axion stars can attract ordinary matter to form a metallic hydrogen cloud around: Hydrogen Axion Star (HAS), which can behave as a hot asteroid

- The stable breather solutions (of a dense axion star) for the sine-Gordon equation are still to be (numerically) proved for either spherical or non-spherical case

Thanks!

Observing HAS

- **For 5 meV axion mass, the apparent magnitude is**

$$
\begin{aligned}
\mathbf{m} &= 18.9 - 2.5\log_{10}\left[\left(\frac{P}{2\times 10^{13}\ \mathrm{W}}\right)\left(\frac{300\,\mathrm{AU}}{D}\right)^2\right] \\
&= 33.0 - 2.5\log_{10}\left[\left(\frac{P}{2\times 10^{13}\ \mathrm{W}}\right)\left(\frac{1\,\mathrm{pc}}{D}\right)^2\right].
\end{aligned}
$$

- **Our Sun is -26.74 and our full moon is -12.74**
- **The faintest object so far has an apparent magnitude of 36 by E-ELT. So, there could be a chance to observe this system**