Astrophysical signatures of axion-like-particle clumps

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WHY AXIONS?

- Well-motivated: strong CP-problem, promising DM candidates, . . .
- Broad experimental program based on the Primakoff process: axions transform into photons in external magnetic fields (and vice versa).
- Less constrained ALPs naturally appear in UV completions of the SM.
- Interesting phenomenology of dark matter distribution.

OUTLINE

1. PBHs from topological defects
2. Fast radio bursts from compact axion stars
3. Axion stars and Gegenschein

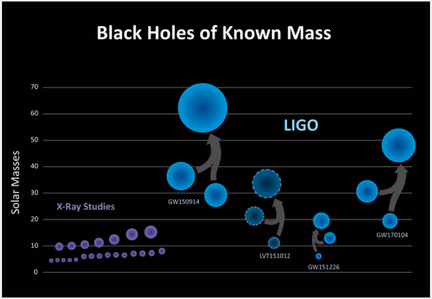
`FF, E. Massó, G. Panico, O. Pujolàs, F. Rompineve, PRL 122, 101301 (2019)`

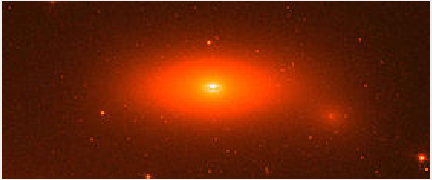
`J. Buckley, B. Dev, FF, F. P. Huang, PRD 103, 043015 (2021)`

`B. Dev, FF, T. Okawa, in progress.`

PBHS FROM TOPOLOGICAL DEFECTS

NON-ASTROPHYSICAL BHS?





ALTERNATIVE MECHANISMS?

Phase transitions in the early universe provide a potential avenue: Several violent phenomena naturally occur that can assist in generating large overdensities that gravitationally collapse into BHs: bubble collisions, topological defects, . . .

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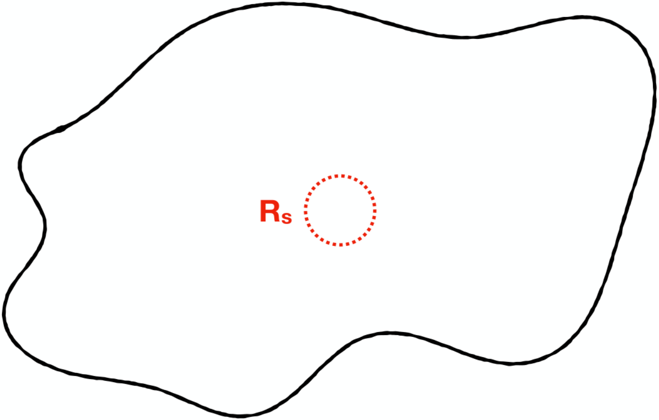
Phase transitions in the early universe provide a potential avenue: Several violent phenomena naturally occur that can assist in generating large overdensities that gravitationally collapse into BHs: bubble collisions, topological defects, . . .

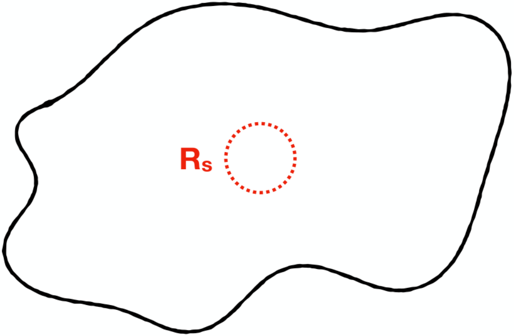
- We will consider axionic string-wall networks.

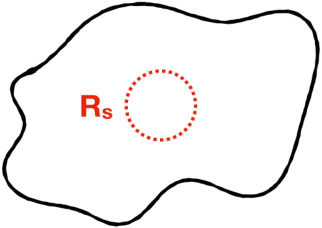
T. Vachaspati, 1706.03868

FF, E. Massó, G. Panico, O. Pujolàs, F. Rompineve, PRL 122, 101301 (2019)

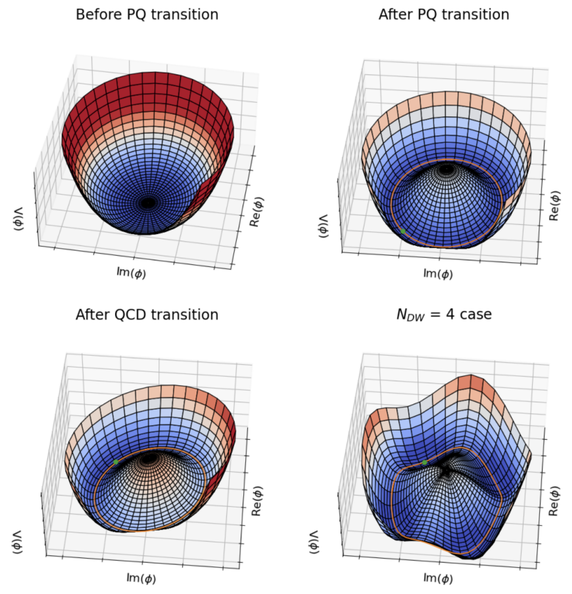
FORMING THE BLACK HOLE




R_s

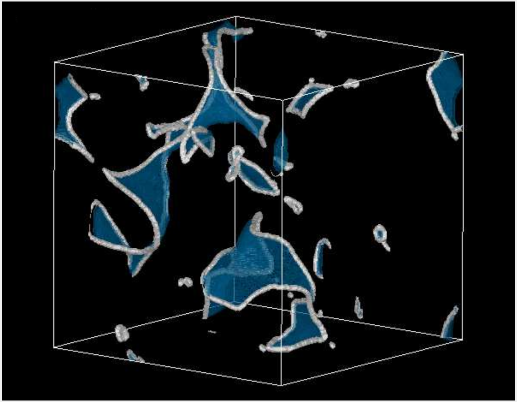

R_s


Rs


Before PQ transition
After PQ transition
After QCD transition
N_{DW} = 4 case
$V(\phi)$
$\mathrm{Re}(\phi)$
$\mathrm{Im}(\phi)$

$N_{\mathrm{DW}} = 1$

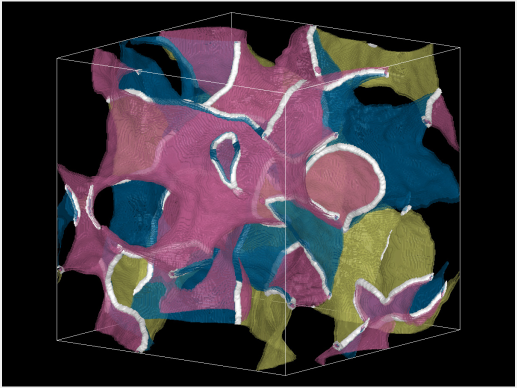
Only one domain wall is attached to each string. Such topological configurations quickly annihilate leaving behind a population of barely relativistic axions.



`T. Hiramatsu,` *et al.*, `PRD 85, 105020 (2012)`

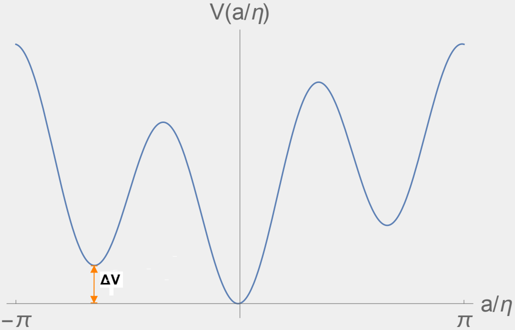
$N_{\mathrm{DW}} > 1$

There are N_{DW} domain walls attached to every string, each one pulling in a different direction. The network can actually be stable, and dominate the universe.



T. Hiramatsu, *et al.*, JCAP 1301 (2013) 001

Lift the degeneracy of axionic vacua by introducing a bias term (dark QCD?). The energy difference between the different minima acts as a pressure force on the corresponding domain walls.



PBHS FROM STRING-WALL DEFECTS

A closed DW of size R_* will rapidly shrink because of its own tension, once $R_* \sim H^{-1} \approx g_{\mathrm{eff}}(T_*)^{-1/2} M_p / T_*^2$.
Its mass has contributions from the wall tension and from any difference in energy density between the two regions separated by the DW:

$$M_* = 4\pi\sigma R_*^2 + \frac{4}{3}\pi\Delta\rho R_*^3 \approx 4\pi\sigma H_*^{-2} + \frac{4}{3}\pi\Delta\rho H_*^{-3}$$

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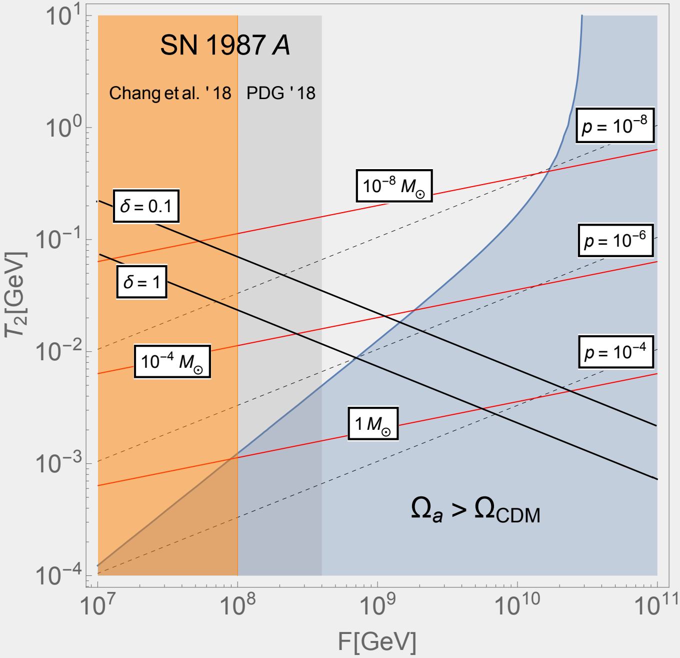
The Schwarzschild radius of the collapsing defect is $R_{S,*} = 2G_N M_*$, and the *figure of merit* for PBH formation is:

$$p \equiv R_{S,*}/R_* \sim \frac{\sigma H_*^{-1}}{M_p^2} + \frac{\Delta\rho H_*^{-2}}{3M_p^2}$$

⇒ Heavier black holes form from DW which collapse later in cosmological history.


SN 1987 A
Chang et al. '18
PDG '18
$\delta = 0.1$
$\delta = 1$
$10^{-8}\,M_\odot$
$10^{-4}\,M_\odot$
$1\,M_\odot$
$p = 10^{-8}$
$p = 10^{-6}$
$p = 10^{-4}$
$\Omega_a > \Omega_{\rm CDM}$
T_2[GeV]
F[GeV]
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}

LATE COLLAPSES

Most of the axionic string-wall network disappears at T_2, which is when the vacuum contribution starts dominating, and both p and M_* increase steeply.

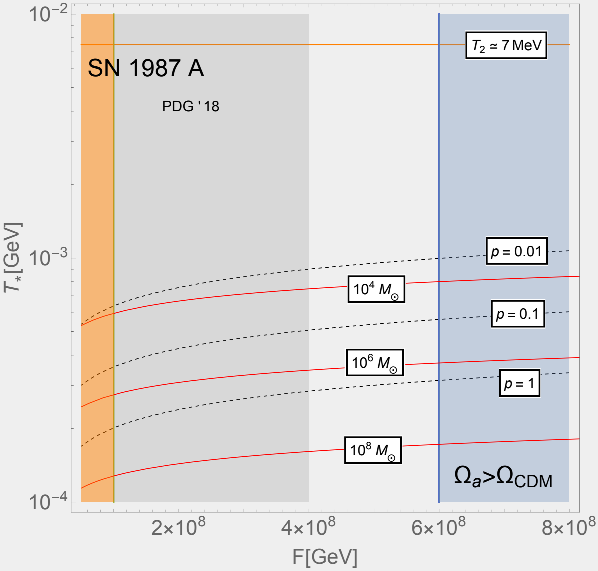
But, $1-10\%$ of the walls survive until $\sim 0.1\,T_2$, when:

- $p \sim 1$
- $M_* \sim 10^6 M_\odot$

$\Rightarrow$ A fraction $f \sim 10^{-6}$ of the DM end up forming SMBHs!

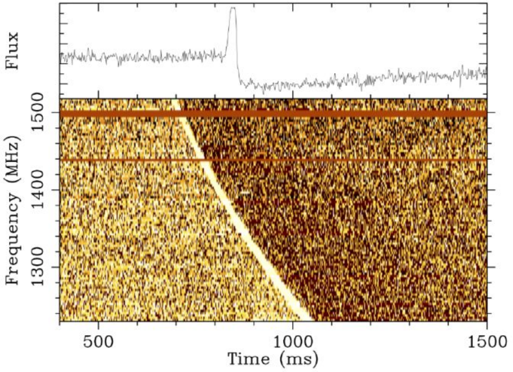
`B. Carr & J. Silk, 1801.00672`

LATE COLLAPSES



FAST RADIO BURSTS FROM COMPACT AXION STARS

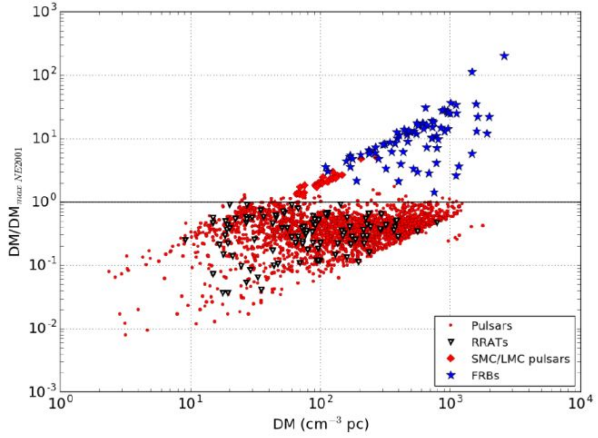
FRB 010724



Lorimer *et al.* 2007

$$\Delta t = \frac{e^2}{2\pi m_e c}\left(\nu_{lo}^{-2} - \nu_{hi}^{-2}\right)\mathrm{DM} \approx 4.15\left(\nu_{lo}^{-2} - \nu_{hi}^{-2}\right)\mathrm{DM\ ms}$$

DISTANCE



E.g. FRB 140514 has DM 563 cm^{-3} pc so $z \sim 0.56$ and $d_L \sim 3.3$ Gpc.

SUMMARY OF BASIC PROPERTIES

- Short $\sim$ms pulses of radio frequencies. The sources are at cosmological distances and they are very bright. Some are repeaters.
- Isotropic distribution, roughly 10^3 FRBs per day over the whole sky above a fluence $\mathcal{F} \gtrsim 1$ Jy ms. Up to $z \sim 1$ the rate per volume 2×10^3 Gpc^{-3} yr^{1} is two orders of magnitude than core-collapse SN.
- No electromagnetic counterparts have been detected in other energy bands.

PROGENITOR MODELS

For a long time there were more theories than FRB events . . .

`E. Platts` *et al.*`, “A living theory catalogue for fast radio bursts”, Phys Rep 2019`

Some highlights from the *Theory Wiki* (`frbtheorycat.org`):

- Compact object mergers/interactions (WD, NS, BH)
- Collapse of objects (DM or BH induced)
- SN remnants, AGN
- Collisions with axion stars
- Alien light sails

AXION STARS

If PQ is broken after inflation, the DM distribution is expected to be highly inhomogeneous. As soon as the Universe becomes matter dominated,

Axion miniclusters ⇒ Dense boson stars

Axion stars (dominated by self-gravity) or axitons (self-interactions) could be seen in microlensing surveys, but typically in the hard to measure femtolensing regime. Their radio signals are our best chance to unveil them!

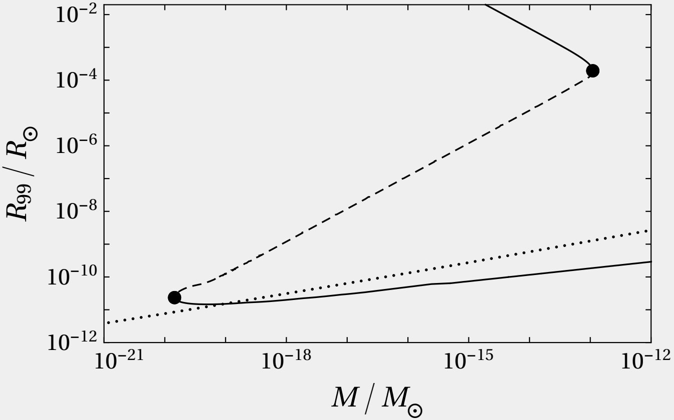
PROPERTIES OF AXION STARS

Need to find solutions of

$$S = \int \mathrm{d}^4 x \, \sqrt{-g} \left(\frac{1}{2} \partial_\mu a \partial^\mu a - V(a/f) \right)$$

Typically expand scalar field in the non-relativistic regime, choose coupling constant f_a and central density.

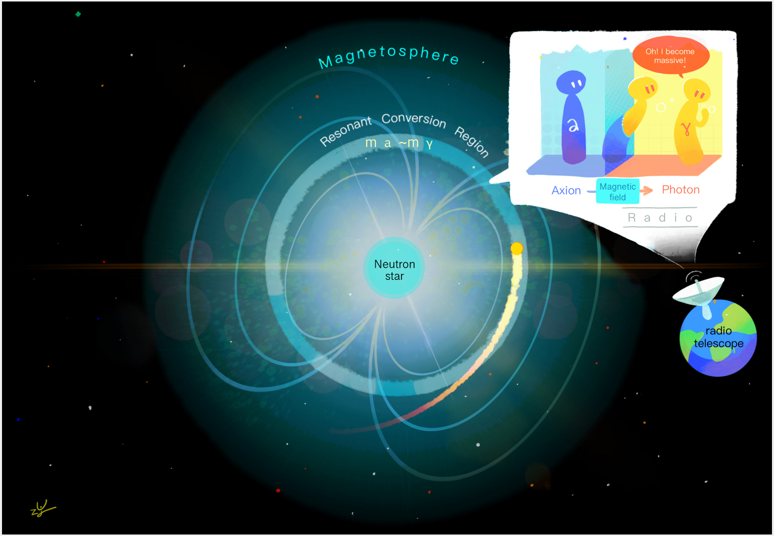
SOLUTIONS


10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$R_{99} / R_\odot$
10^{-21}
10^{-18}
10^{-15}
10^{-12}
$M / M_\odot$

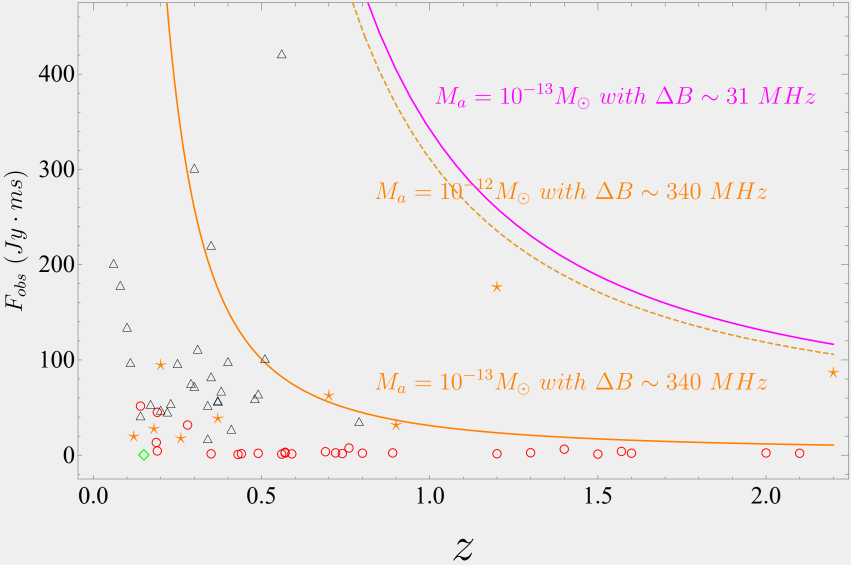
SETUP

- We are interested in dense stars to avoid tidal stripping.
- The conversion occurs before reaching the NS surface, at the resonant region, ~ 100 km.
- Other possibilities are resonant decay of the whole star away from any object (Tkachev 2015)

SETUP

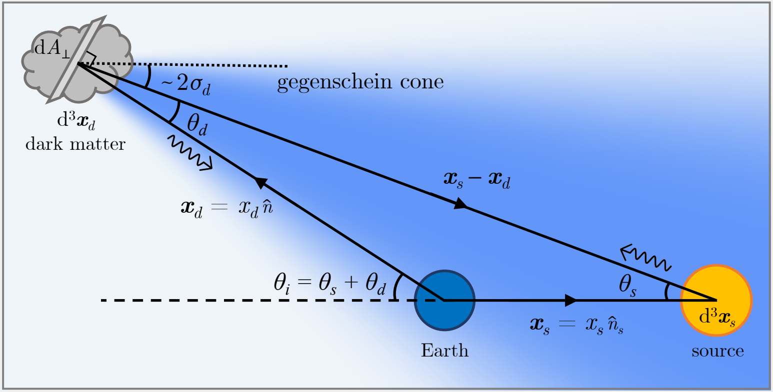

Magnetosphere
Resonant Conversion Region
ma ~mγ
Neutron star
Oh! I become massive!
a
γ
Axion
Magnetic field
Photon
Radio
radio telescope

OBSERVATIONAL CONSTRAINTS



AXION STARS AND GEGENSCHEIN

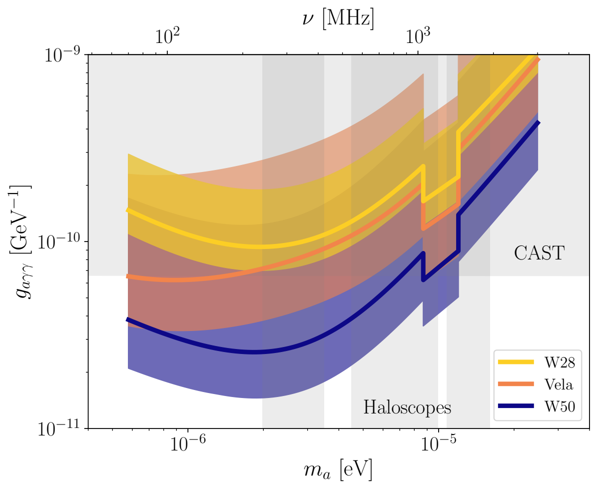
AXION GEGENSCHEIN



Ghosh, Salvadó & Miralda-Escudé, 2008.02729; A. Arza & P. Sikivie, PRL 123 (2019) 131804;

Y. Sun, K. Schutz, A. Nambrath, C. Leung & K. Masui, PRD 105 (2022) 063007

AXION GEGENSCHEIN



Y. Sun, K. Schutz, A. Nambrath, C. Leung & K. Masui, PRD 105 (2022) 063007

CAN WE DETECT AXION STARS?

Let us assume that 10% of the axion DM is in the form of compact axion stars. Does this change the integral along the l.o.s?

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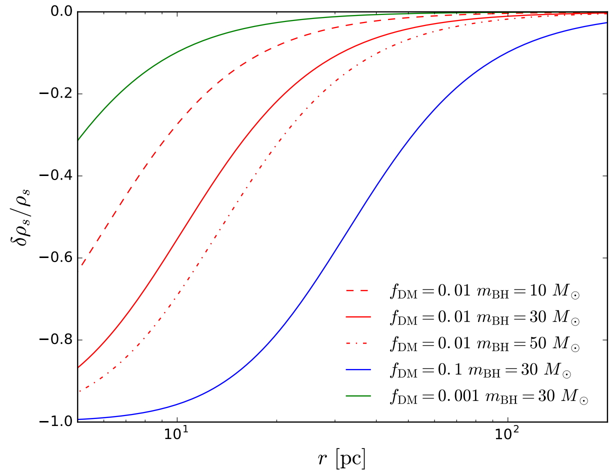
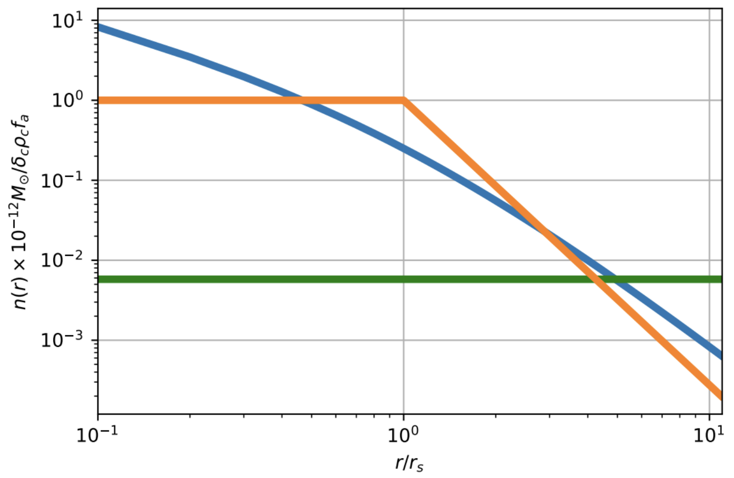
- Random fluctuations $\propto 1/\sqrt{N_{a*}}$
- Dynamical friction: the more massive regular stars heat up the gas of axion stars.



T.D. Brandt, ApJ 2016; Koushiappas & Loeb, 1704.01668



Echo flux can increase by up to 40%!

CONCLUSIONS

- Inhomogeneous distributions of axion-like-particles through cosmic history could be linked to several astrophysical phenomena.
- The collapse of axionic topological defects can potentially generate PBHs of up to $10^6 M_\odot$.
- Compact axion stars crossing the resonant region of a NS atmosphere can be behind some of the mysterious FRBs.
- The spatial distribution of these stars might be different than that of the smooth halo, which could boost the Gegenschein emission fluxes.