Fast Radio Bursts

from Axion Stars in a Pulsar Magnetosphere

(J. H. Buckley, BD, F. Ferrer, F. P. Huang, arXiv: 2004.06486 [astro-ph.HE])

Bhupal Dev

Washington University in St. Louis

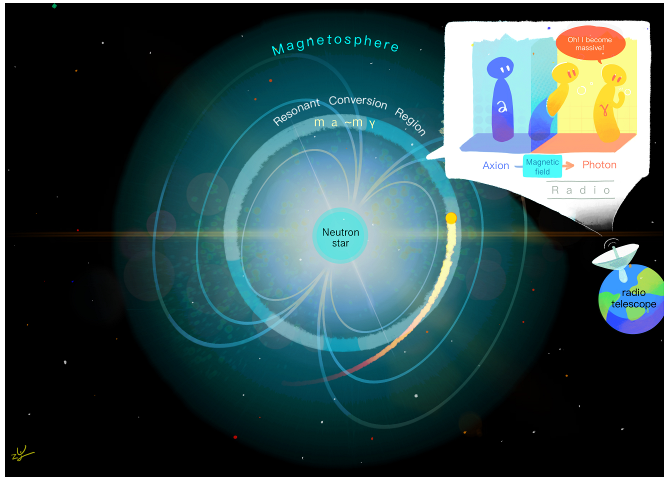
HET Seminar

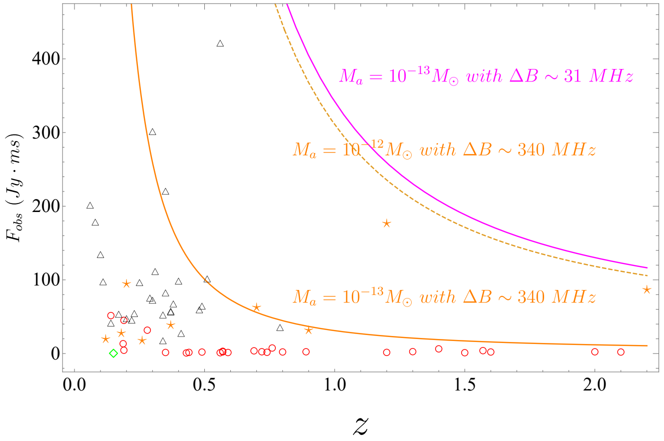
Brookhaven National Laboratory

July 29, 2020

Outline

- The FRB mystery
- An axion star – neutron star encounter
- Resonant conversion of axions to photons
- Fitting the FRB data
- Conclusion and Outlook





Fast Radio Bursts (FRBs)

- **Millisecond bursts of GHz radiation from "cosmological distances".**
- First detected in 2007 ('Lorimer burst') using archival data from Parkes radio dish. [Lorimer *et al* (Science '07)]
- More than 100 FRBs detected so far. [FRBCAT]
- More likelihood of extragalactic origin. [Thornton *et al* (Science '13)]
- A handful of them are repeaters, with wildly varying periods [Spitler *et al* (Nature '16); Andersen *et al* (ApJL '19); Amiri *et al* (Nature '20)]
- Mechanism of emission, source of energy, and emitting astronomical objects mostly unknown. [Katz (MNRAS '20)]

What makes them so mysterious?

- Isotropically distributed on sky: none in our Galaxy.
- Large dispersion measure (300-1600 pc cm^{-3}). So must come from cosmological distances (z~0.1-2).
- Huge intrinsic radio power output (~10^{43} ergs/s).
- Extraordinary brightness temperature (~10^{35} K) implies coherent emission.
- Burst source must be compact enough to produce (sub)ms pulses.
- A few known to repeat, with different periodicities (few days to half a year to sporadic).

Alien Activity?

Estimated < 10^4 FRB-producing civilizations in a galaxy of size similar to ours.

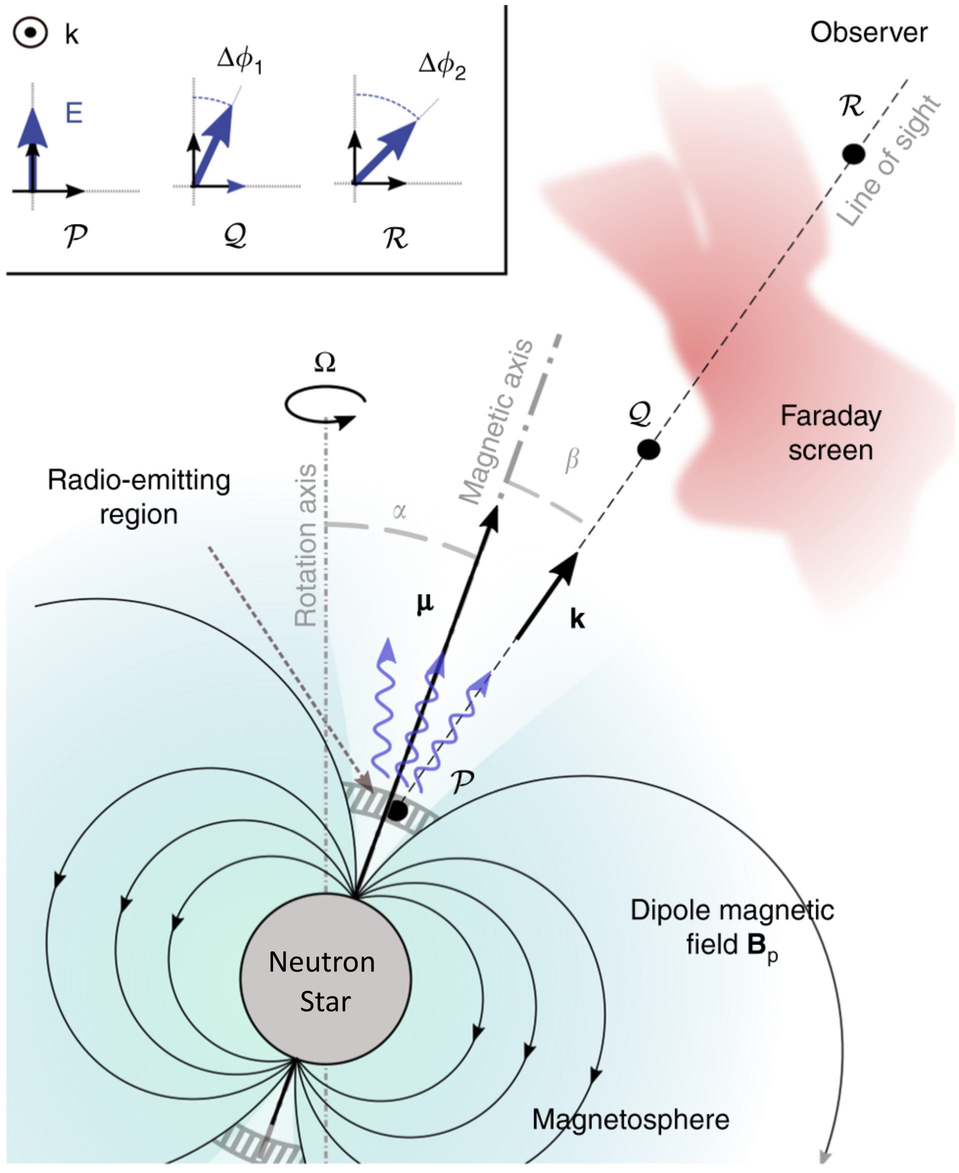
[Lingam, Loeb (ApJL ’17)]

Pulsar Origin

- **Advantages:**
  - Compact sources.
  - Enormous magnetostatic and rotational energies.
  - Typical rotation period $P \sim O(\text{ms to s})$.
  - Known to exist in binary systems.
  - Coherent dipole emission.
  - Best candidates: Young magnetars that later fade into regular pulsars [Munoz, Ravi, Loeb (ApJ ’20)]

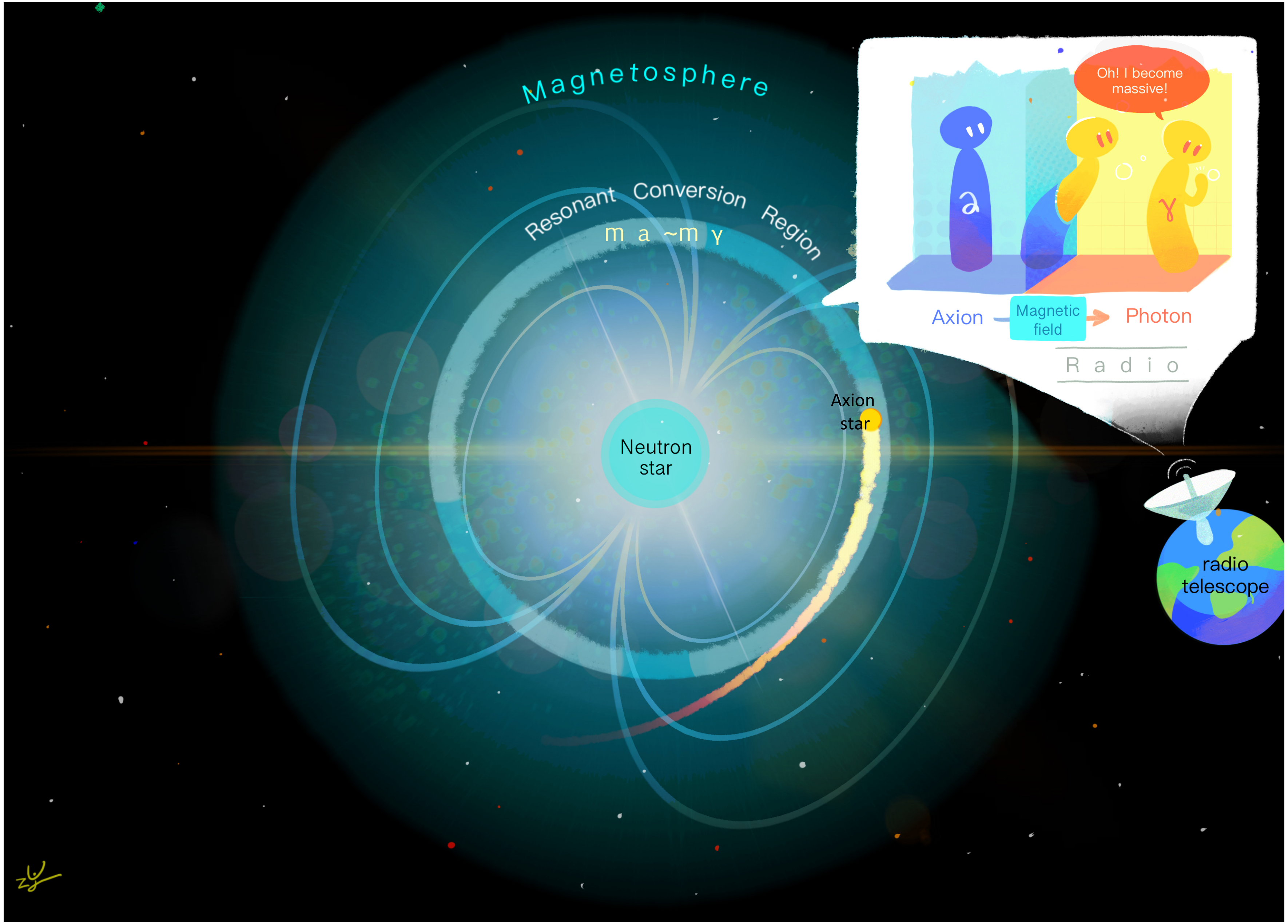
- **Problems:**
  - Energetics: inferred power ($\sim 10^{43}$ ergs/s) requires extreme parameters (spin rate and magnetic field) and very short lifetimes [Katz (MPLA ’16; PPNP ’18)]
  - Periodicity: Burst separations must be integer multiples of rotational period.
  - Period should increase over time, and luminosity should decrease, due to spin-down.
  - No correlation found between magnetar-associated soft gamma repeaters and FRBs.

Other ideas?



[Gueroult, Shi, Rax, Fisch (Nature Communications ’19)]

Our Proposal: Axion Star – Neutron Star Encounter



Why Axion Stars?

- Axion is one of the best motivated candidates for particle dark matter. [Preskill, Wise, Wilczek (PLB ’83); Abbott, Sikivie (PLB ’83); Dine, Fischler (PLB ’83)]
- A collection of axions can condense into a bound BEC. [Sikivie, Yang (PRL ’09); Guth, Hertzberg, Prescod-Weinstein (PRD ’15); BD, Lindner, Ohmer (PLB ’17); Levkov, Panin, Tkachev (PRL ’18)]
- The axion BEC can form gravitationally bound configurations (**axion stars)**. [Tkachev (PLB ’91); Braaten, Zhang (Rev. Mod. Phys. ’19)]
- Can *coherently* convert to photons in a pulsar magnetosphere.
- Energy released by FRBs is about $10^{-13}\ M_\odot$ which is typical for an axion star mass.
- Observed FRB frequencies (MHz-GHz) coincide with that expected from ~μeV axion particles.
- Small incident angles can explain the ms duration for the pulses.

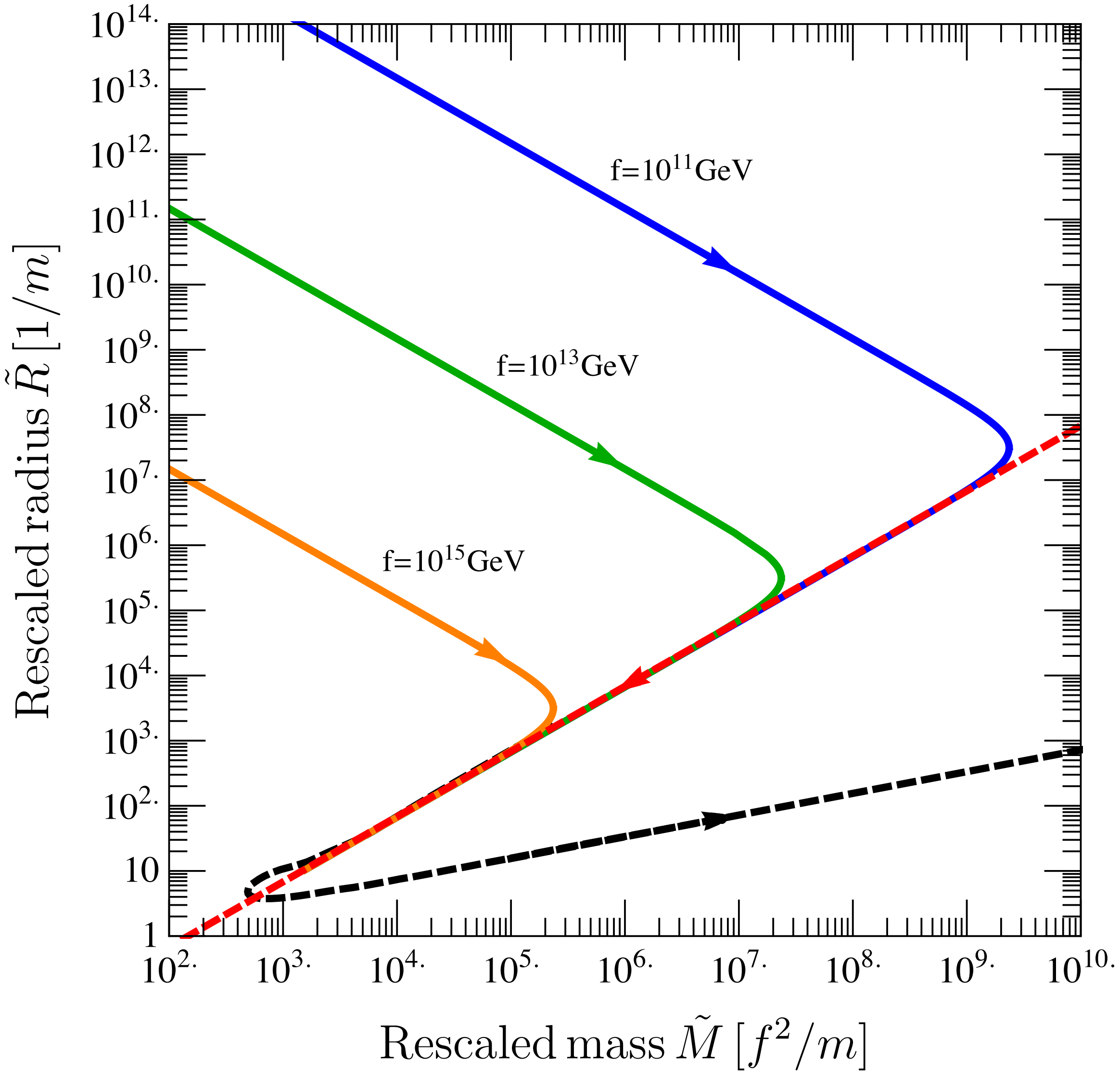
Stability of Axion Stars

Two (meta)stable branches:

- **Dilute axion star:** gravitational energy density comparable to potential energy density (small *r*) or kinetic energy density (large *r*). [Barranco, Bernal (PRD '10)]

- **Dense axion star:** gravitational contribution to total energy density is negligible for all *r* [Braaten, Mohapatra, Zhang (PRL '16)]

Axion star radius vs mass



[Visinelli, Baum, Redondo, Freese, Wilczek (PLB '18)]

FRBs with Dilute Axion Stars

$$R_a^{\rm dilute} \sim \frac{1}{G_N M_a m_a^2} \cong (270\ \ {\rm km}) \left(\frac{10\ \mu{\rm eV}}{m_a}\right)^2 \left(\frac{10^{-12} M_\odot}{M_a}\right)$$

[Chavanis, Delfini (PRD ’11)]

- Typical radius of O(100 km) for $M_a \sim 10^{-13}\ M_\odot$.
- Tidal disruption at Roche limit: $r_t = R_a \left(\frac{2M_{\rm NS}}{M_a}\right)^{1/3}$
- A 100 km dilute axion star will be destroyed at $r_t \sim 10^6$ km, well before reaching magnetosphere (typically extending to only ~ 1000 km).
- Stream of axion debris entering the NS magnetosphere could produce multiple radio signals.
- Repeating FRBs with no apparent periodicity.

FRBs with Dense Axion Stars

$$R_a^{\rm dense} \sim (0.47\,{\rm m})\sqrt{g_{a\gamma\gamma} \times 10^{13}\ {\rm GeV}\frac{10\ \mu{\rm eV}}{m_a}}\left(\frac{M_a}{10^{-13}M_\odot}\right)^{0.3}$$

[Braaten, Mohapatra, Zhang (PRL ’16)]

- Typical size is O(1 m) for $M_a \sim 10^{-13}\ M_\odot$ and $g_{a\gamma\gamma} \sim 10^{-13}$ GeV^{-1}.
- Roche limit $r_t \sim 10$ km, much smaller than the NS magnetosphere.
- Tidal deformation is negligible: $\frac{\delta R_a}{R_a} = \frac{9M_{\rm NS}}{8\pi\rho_{\rm AS}r^3} \sim$ O(10^{-3}).
- Enters NS magnetosphere almost intact.
- A single passage gives a non-repeating FRB.
- Dense AS-NS binary with an elliptical orbit could enable several passages.
- Repeating FRBs with a given periodicity (depending on eccentricity).

Axion-Photon Conversion

$$\mathcal{L} = -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

- Resonant conversion when the axion mass equals the photon mass in the plasma [Huang, Kadota, Sekiguchi, Tashiro (PRD '18); Hook, Kahn, Safdi, Sun (PRL '18)]

$$m_\gamma(r) \simeq \omega_p = \sqrt{\frac{e^2 n_e}{m_e}} = \sqrt{\frac{n_e}{7.3 \times 10^8 \text{ cm}^{-3}}} \ \mu\text{eV}$$

- We use the Goldreich-Julian charge distribution:

$$n_e(r) = 7 \times 10^{-2} \frac{1 \text{ s}}{P} \frac{B(r)}{1 \text{ G}} \text{ cm}^{-3},$$

- Dipole approximation for pulsar magnetic field:

$$B(r) = B_0 \left(\frac{r_{\text{NS}}}{r}\right)^3$$

Conversion Rate

- Critical radius: $$\left(\frac{r_{\rm NS}}{r_c}\right)^3 \sim \left(\frac{m_a}{\mu{\rm eV}}\right)^2 \frac{10^{10}\ {\rm G}}{B_0}\frac{P}{1\ {\rm s}}.$$

- Non-adiabatic conversion with Landau-Zener probability: $P_{a\to\gamma} = 1 - e^{-2\pi\beta}$.

$$\beta = \left.\frac{\left(g_{a\gamma\gamma}\omega B_0\right)^2/2\bar{k}}{\left|{\rm d}\omega_p^2/{\rm d}r\right|}\right|_{r=r_c}. \qquad \bar{k} \equiv \sqrt{\omega^2 - (m_a^2+\omega_p^2)/2}$$

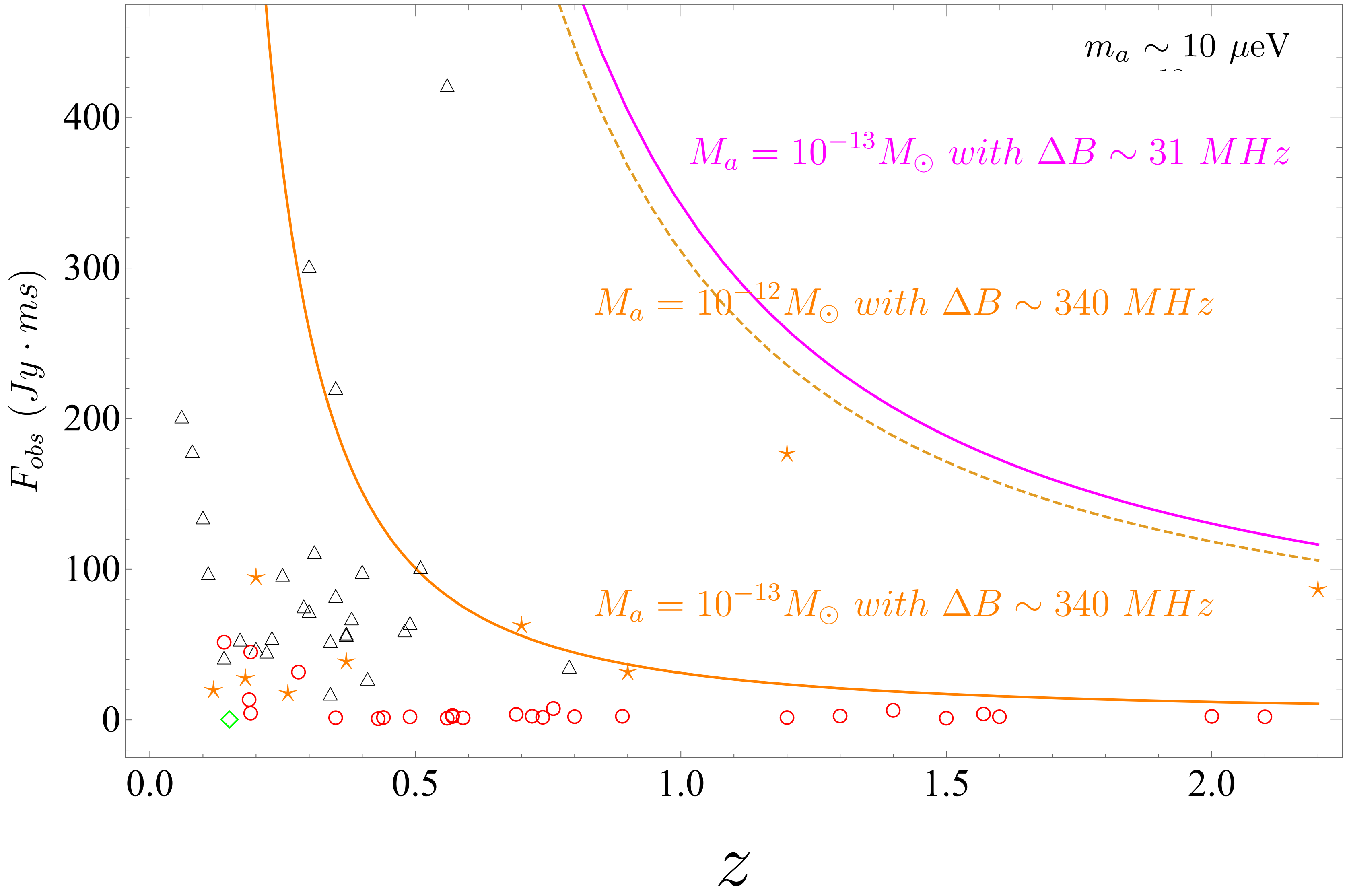
- Conversion Power: $\dot{W} = P_{a\to\gamma}{\rm d}M_a/{\rm d}t$

$$\dot{W} \sim \left(\frac{M_a}{10^{-13}M_\odot}\right)\left(10^7 \times P_{a\to\gamma}\right)\left(10^{44}\ {\rm GeV}\cdot{\rm s}^{-1}\right)$$

- Energy released: $$\frac{E_{\rm FRB}}{\rm J} = \frac{F_{\rm obs}}{{\rm Jy}\cdot{\rm ms}}\frac{\Delta B}{\rm Hz}\left(\frac{d}{\rm m}\right)^2 \times 10^{-29}(1+z),$$

- Density flux (Fluence): $\mathcal{S} \sim \dot{W}/(4\pi d^2\Delta B)$

Fitting the FRB Data



(Red circles: 27 Parkes, Black triangles: 28 ASKAP, Green diamond: 1 Arecibo, Orange star: 9 UTMOST)

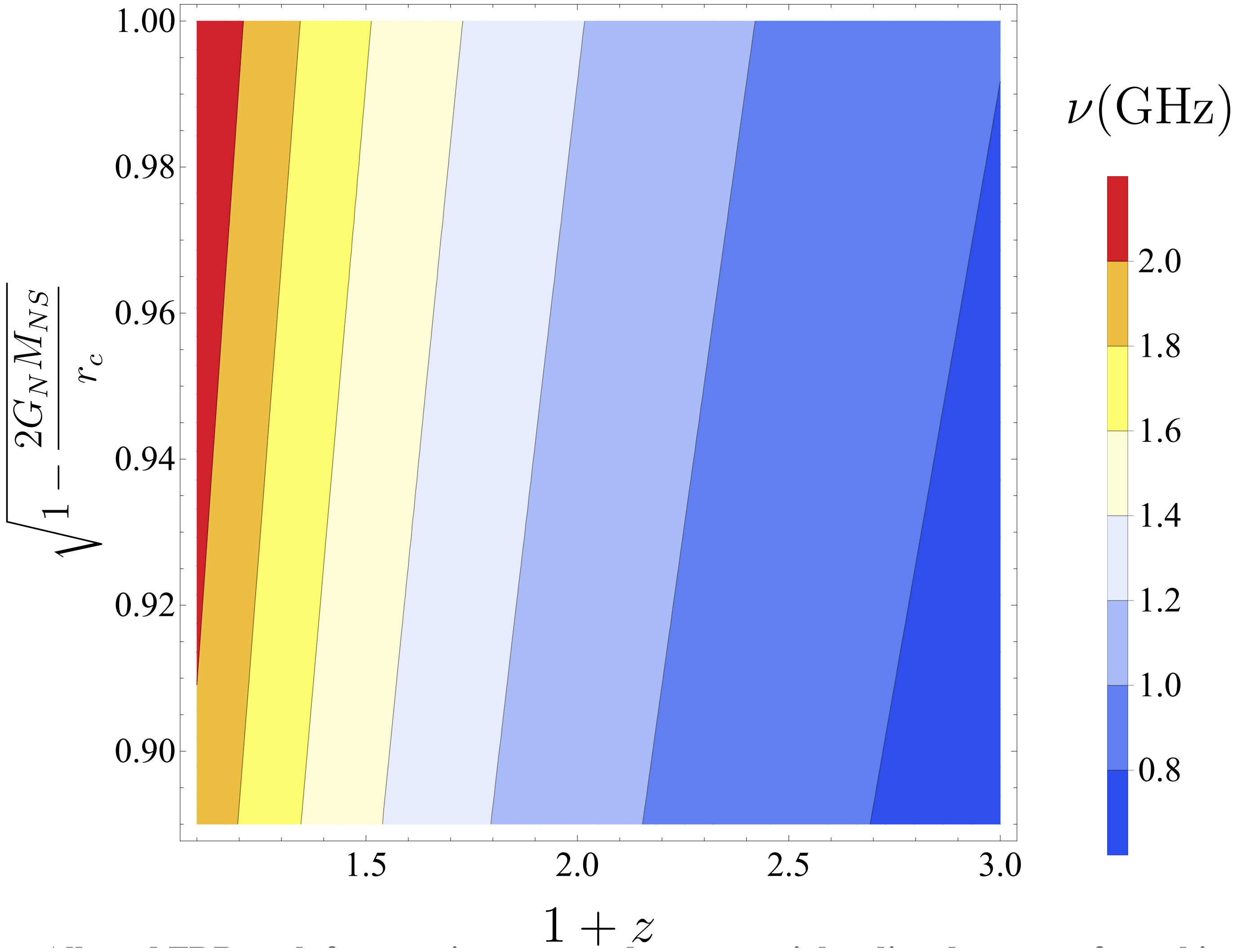
Frequency Dispersion

- Peak frequency fixed by axion mass:

$$\nu_0 = m_a/2\pi = 2.42\ \mathrm{GHz}(m_a/10\ \mu\mathrm{eV})$$

- Cosmological and gravitational redshifts can account for the frequency spread:

$$\nu = \frac{\nu_0}{1+z}\sqrt{1 - \frac{2G_N M_{\mathrm{NS}}}{r_c}}$$



Predicted Event Rate

- Smallest detectable flux density:

$$\mathcal{S}_{\rm min} \approx 0.09\ {\rm Jy}\ \left(\frac{1\ {\rm MHz}}{\Delta B}\right)^{1/2} \left(\frac{1\ {\rm ms}}{t_{\rm obs}}\right)^{1/2} \left(\frac{10^3 {\rm m}^2/{\rm K}}{A_{\rm eff}/T_{\rm sys}}\right)$$

- Taking SKA Phase-1 as example: $\mathcal{S}_{\rm min} \sim 5 \times 10^{-3}\ {\rm Jy}$
- Event rate: $\frac{N}{\rm year} = \sigma v_0 n_{\rm AS} n_{\rm NS} f_{\rm NS} V$

$$\sigma = \pi b^2 = \pi r_c^2 v_c^2 / v_0^2 (1 - 2 G_N M_{\rm NS}/r_c)^{-1}$$

For the whole Universe, the event rate per day is: $10^{13} \kappa_{\rm AS} f_{\rm NS}/365 \sim 1000$

Conclusion

- Sources and mechanisms of FRBs are one of the most prominent mysteries of modern astronomy.
- We have proposed a new explanation for the origin of FRBs in terms of axion stars encountering neutron stars.
- Resonant axion-to-photon conversion in the NS magnetosphere.
- Observed FRB energy output can be naturally explained for an AS mass of $M_a \sim 10^{-13}\ M_\odot$.
- Frequencies of most of the observed events can be explained with an axion mass of $m_a \sim 10$ μeV.
- Can potentially explain both repeaters and non-repeaters.
- Predicted event rate can be tested at SKA.