Detecting Cosmic Strings with Fast Radio Bursts

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Fermilab Theory Seminar

Storyline

- An overview of cosmic strings
- Another overview of Fast Radio Bursts (FRBs)
- How lensed FRBs probe cosmic strings
- Some new ideas of using FRBs to detect other new physics

Cosmic strings

During spontaneous symmetry breaking, different vacua are chosen in different spatial domains because they are casually disconnected. The non-trivial topology of the vacuum manifold implies the formation of strings. (Kibble 1976)

Strings formed in the early Universe will become **cosmic scales objects** as the Universe expands.

Historically, cosmic strings were considered as the candidate of the primordial seeds of large scale structures. This motivation is no longer valid, but cosmic strings still provide a window onto the early Universe dynamics.

Cosmic Strings

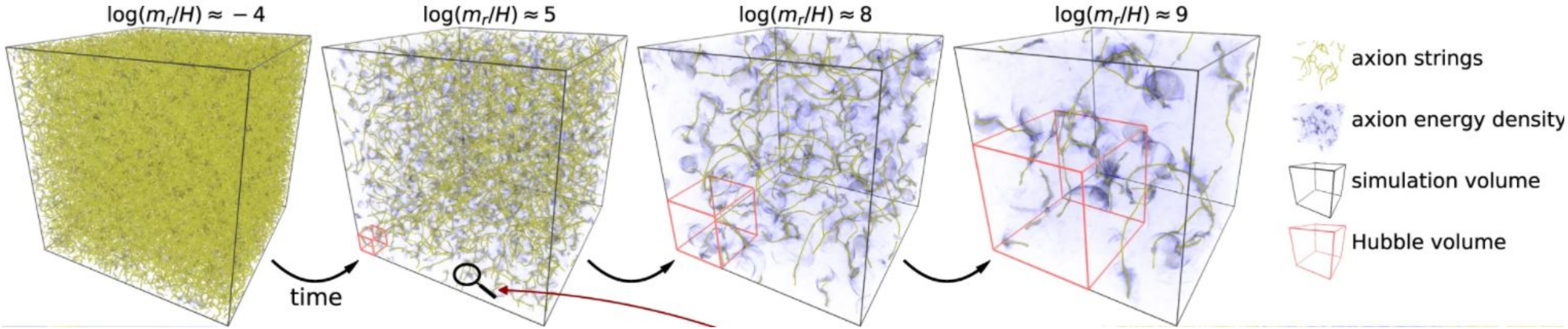


Figure from M. Buschmann, J. W. Foster, A. Hook, A. Peterson, D. E. Willcox, W. Zhang, and B. R. Safdi, 2021

Cosmic Strings

A stable solution of the field configurations.

A closed path that wraps around the circle.

Cannot be continuously contracted to a point, therefore represents a string solution.

The tension of the strings μ is determined by the symmetry breaking scale. The energy fraction in strings is ($N_{\rm str}$ is the number of strings per horizon)

$$\Omega_{\rm str} \sim N_{\rm str} G\mu$$

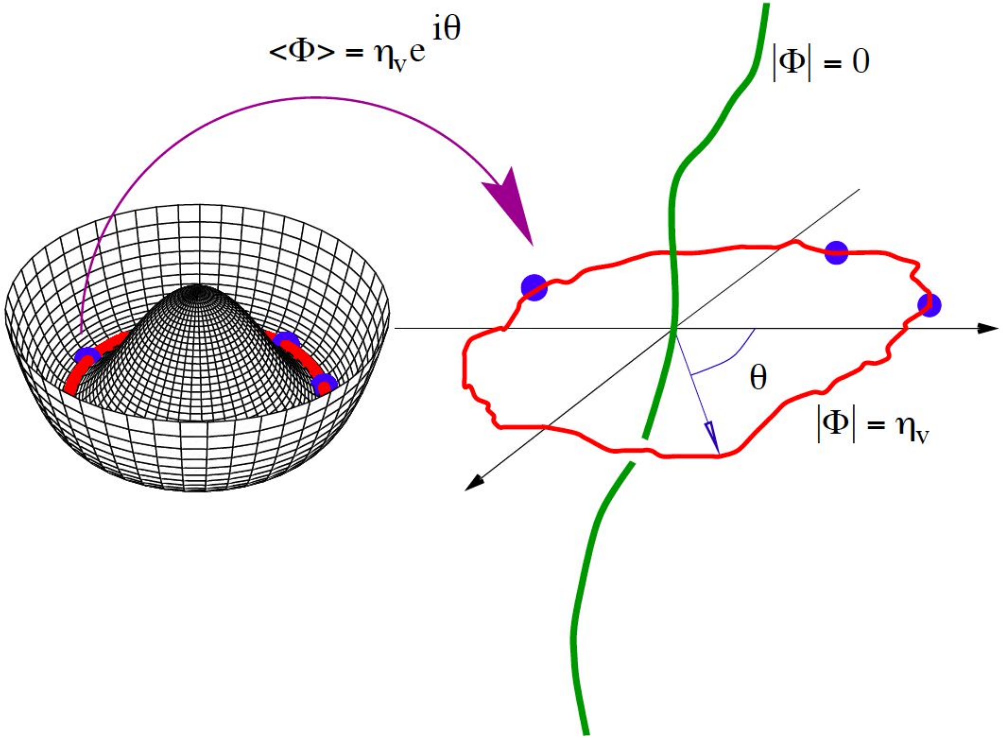


Figure from Ringeval, 2010.

Gauge strings and global strings

- Spontaneous breaking of gauge symmetries vs global symmetries.
- Gauge strings have more localized profiles while global strings (such as axion strings) have a string tension which is logarithmically divergent.
- Most of the studies have been focused on local gauge strings networks, including the CMB constraints, gravitational wave signatures. People recently think axion strings might also generate gravitational waves.

Existing Constraints

CMB places constraints on the string tension μ

For ordinary string networks: $G\mu < 1.1 \times 10^{-7}$ ⟹

Lensing of galaxies: $G\mu < 3 \times 10^{-7}$ ⟹

Not expected to improve significantly

$G\mu \sim 10^{-7} - 10^{-10}$ (GUT scale strings) can explain the stochastic gravitational wave background detected by pulsar timing arrays. This statement will depend on the loop size.

We need **new ideas** for cosmic strings!

Fast Radio Bursts

- Transient radio pulses with lengths of ~1ms (very brief);
- Detected at high redshifts (z~1).
- Each FRB has unique fingerprint. Information contained in the burst profile (and you can correlate them).
- Very bright (1-200 Jy)
- A tremendous amount of FRBs (~1000 per day) expect to be detected in the future.
- Unknown origin.

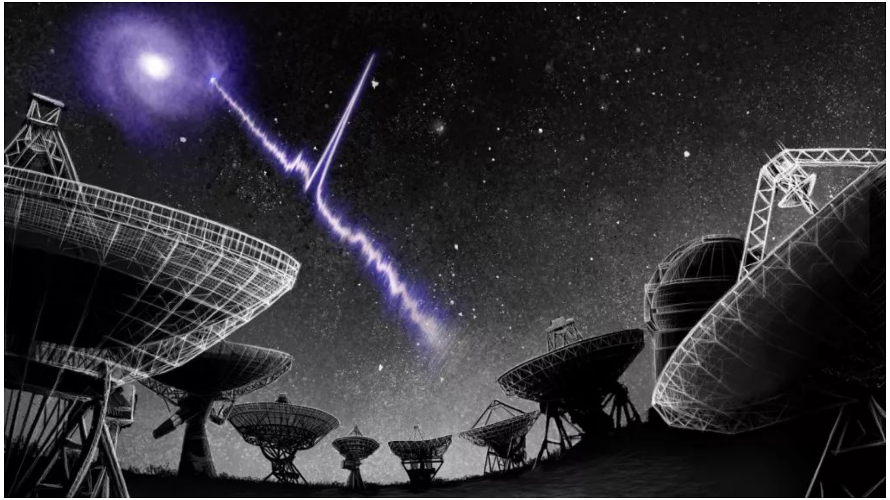
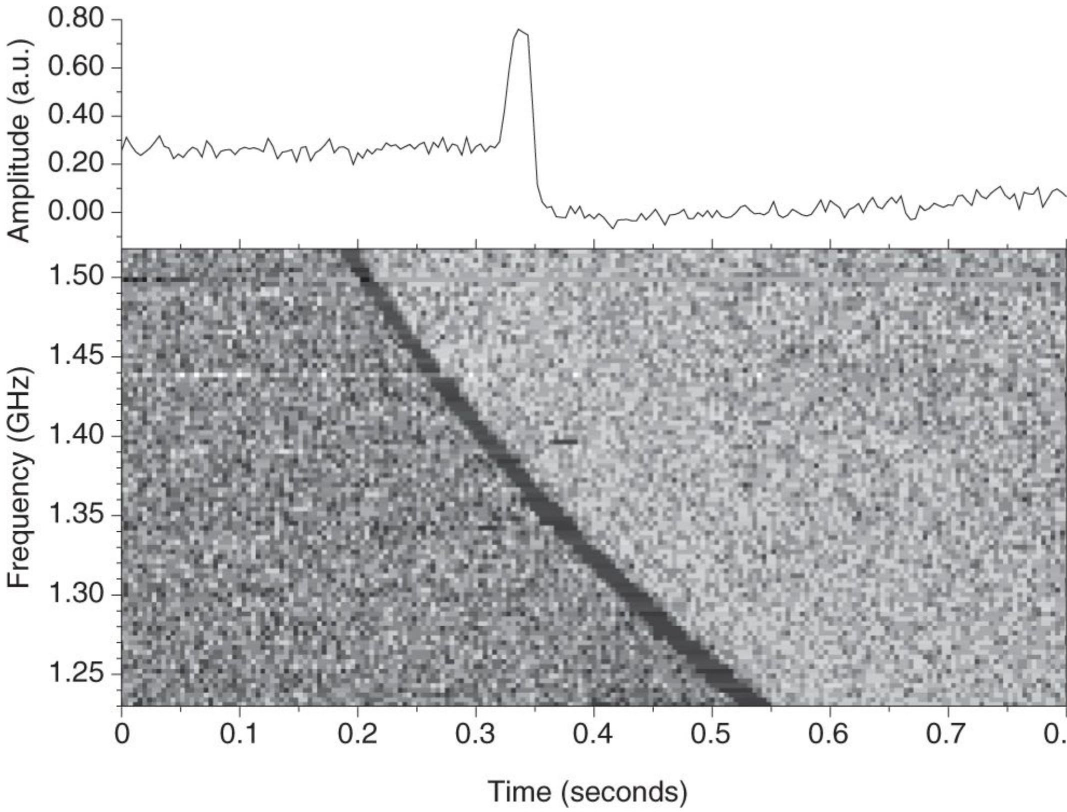


Image credit: Danielle Futselaar/artsource.nl

Dispersion Measure

Dispersion measure (DM), refers to broadening of an otherwise sharp pulse when a pulsar is observed over a **finite bandwidth**. It's a measure of integrated column density of free electrons between an observer and the source.

Originally used in pulsar astronomy, now an active area of measuring the gas distribution in the galaxies using FRBs.



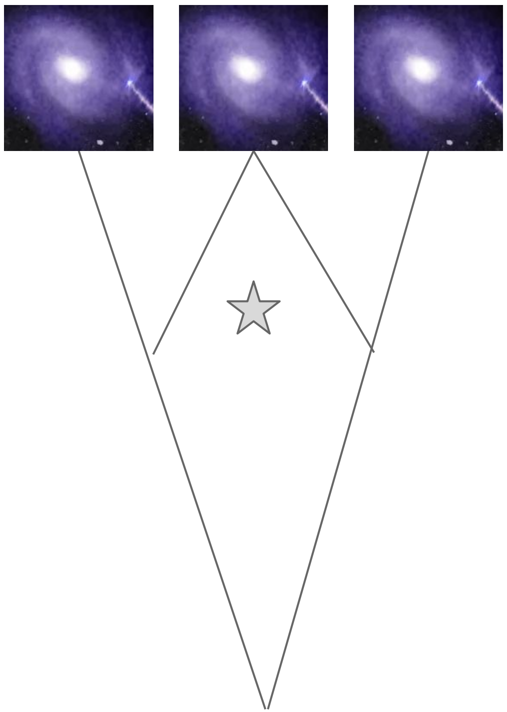
The original FRB 010724, Credit: Evan Keane

The Source of FRBs

- Messages from extraterrestrial civilizations?
- Clearly, the emission mechanism is nonthermal. The peak flux density of FRBs with the width and distance corresponds to a blackbody temperature of 10^35 K.
- The Magnetar (very young neutron stars with very strong magnetic fields) is our best guess. It’s favored due to the energetics, short timescales and star formation association.
- We also see FRBs in globular cluster of M81. It’s not a star-forming region, suggesting that magnetars are probably not the whole story.

Strong Lensing of Fast Radio Bursts

- Does not require any angular resolution (Galaxy surveys are limited by this). If time delay between images is larger than ~1ms, two images are separable.
- Each FRB has unique fingerprint, so we can tell images from the same source by correlating the electric field profile.
- Many FRBs expect to be detected even at high redshift, increasing the lensing rate.



Strong Lensing by Straight Cosmic Strings

In Minkowski space, where we can use the conformal temporal gauge, the energy-momentum tensor of a straight string on the z axis is

$$T^{\mu\nu} = \mu \, \mathrm{diag}(1, 0, 0, -1)\delta(x)\delta(y)$$

The metric is

$$ds^2 = dt^2 - dz^2 - dR^2 - (1 - 4G\mu)^2 R^2 d\phi^2$$

Therefore, the spacetime is seen to be flat everywhere but with the angular coordinate running from 0 to $2\pi - \delta$, with $\delta = 8\pi G\mu$.

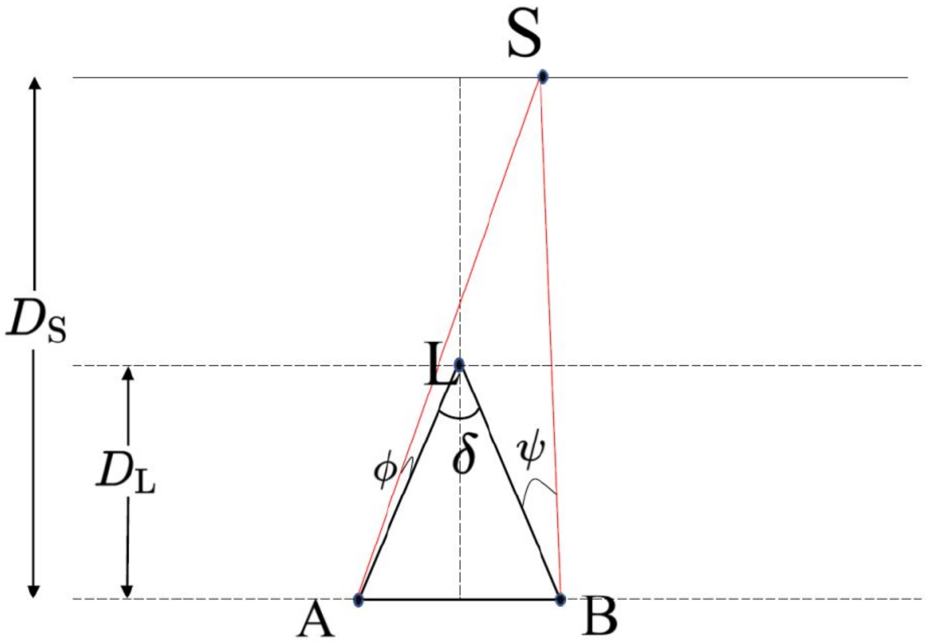
Strong Lensing by Straight Cosmic Strings

The geometry is very simple: flat space with a deficit angle:

$$\delta = 8\pi G\mu$$

We expect to see two **identical** images from FRBs.

Time delay



$$\Delta t = \frac{1}{2}\left(1 + z_{\rm L}\right) d_L\, \Delta\theta\, |\phi - \psi| \sim 500\,{\rm s} \left(\frac{G\mu}{10^{-8}}\right)^2 \left(\frac{D}{\rm Gpc}\right)$$

Uniqueness of Lensing by Cosmic Strings

- Cosmic strings are relativistic objects, very different from other lens in the Universe. If the FRB is repeating, we can measure the time delay difference:

$$\delta t = (1 + z_{\rm L})\, \delta d_t\, \Delta\theta\, (d_L/d_S) \sim 0.8\,{\rm s} \left(\frac{v_s\, {\rm sin}k}{0.1c}\right) \left(\frac{T_{\rm obs}}{1{\rm yr}}\right) \left(\frac{G\mu}{10^{-8}}\right)$$

- The magnification is exactly 1 (negligibly small change from weak lensing by large scale structure).

- The time delay is a few hundred seconds, much longer than lensing by stars but shorter than galaxies.

Lensing Rate by Cosmic Strings

The lensing rate of FRBs depends on the **redshift distribution** of cosmic strings and the **redshift distribution** of FRBs. We understand that the number of strings per horizon is roughly a constant (~10) from simulations. It's less certain for FRBs.

$$P(z_S) = \int_0^{z_S} \frac{16}{3}\pi N_{\rm str} \frac{d_{\rm L} d_{\rm LS} H(z_L)}{d_{\rm S}} \frac{dz_L}{1+z_L} G\mu$$

Given the redshift distribution of FRBs and the number of FRBs, the total rate of detection is

$$P_{\rm obs} = \int \frac{dN_{\rm FRB}}{d\Omega dz_S} P(z_S) d\Omega dz_S .$$

Redshift Distribution of FRBs

Redshift distribution of FRBs is not well constrained now. It depends on various things including the intrinsic redshift distribution, luminosity function, and detection threshold.

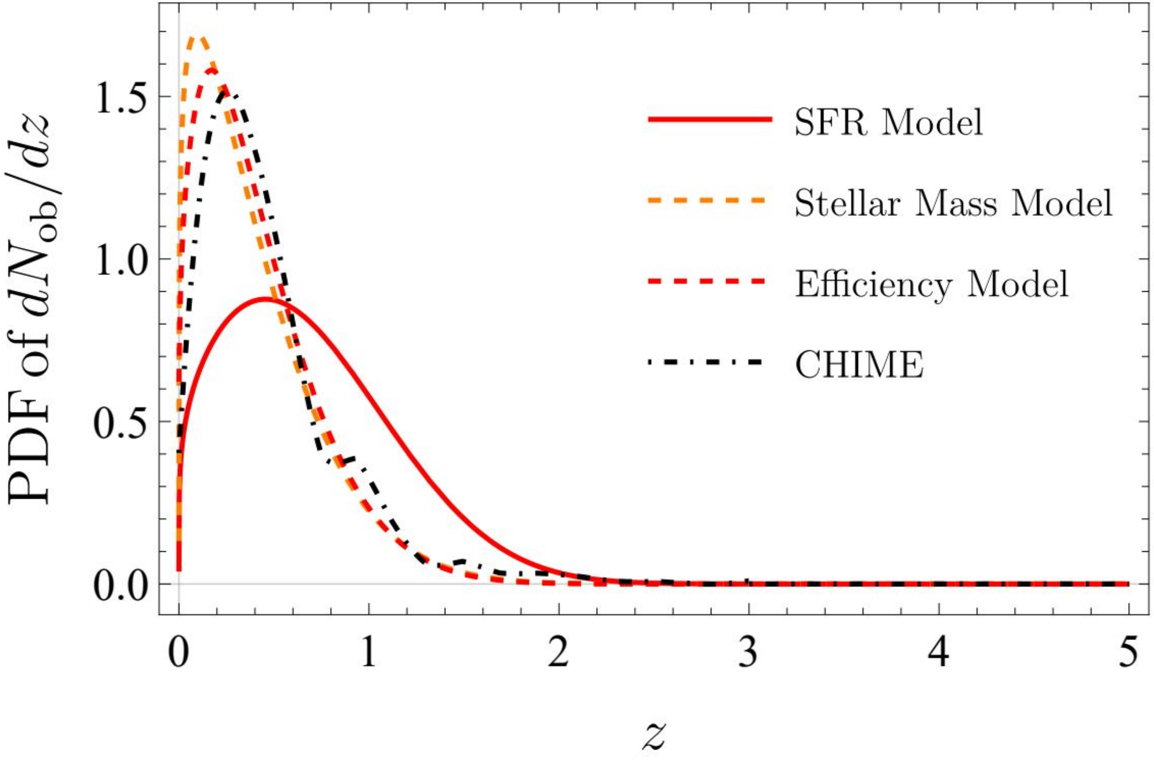
$$\frac{dN_{\rm FRB}(z, > F)}{dz} = \int_{E_{\rm min}(F)}^{\infty} dE \overbrace{(1+z)^{-1}}^{\text{time dilation}} \times \frac{d\dot{n}_{\rm FRB}(z)}{dE} \left(4\pi D_c^2\right) \frac{dD_c}{dz}$$

Detection threshold $E_{\rm min}(F) = F\,(4\pi\, d_L^2)\, K_\nu/(1+z)$

Redshift Distribution of FRBs

We have two models for the intrinsic redshift distribution. The star formation rate model is the more likely one.

Here we show different models as well as CHIME observations.



Lensing Rate of Cosmic Strings

If there are ~10^5 FRBs detected, we can obtain competitive bounds as CMB

$$P \approx \left(\frac{N_{\rm FRB}}{10^5}\right)\left(\frac{N_{\rm str}}{30}\right)\begin{cases}(G\mu)/(1.9\times10^{-7}) & \text{SFR;}\\ (G\mu)/(5.2\times10^{-7}) & \text{Stellar Mass.}\end{cases}$$

Eventually FRB would win because we expect to see more and more of them.

Detection Rate of FRBs

Signal to noise ratio:

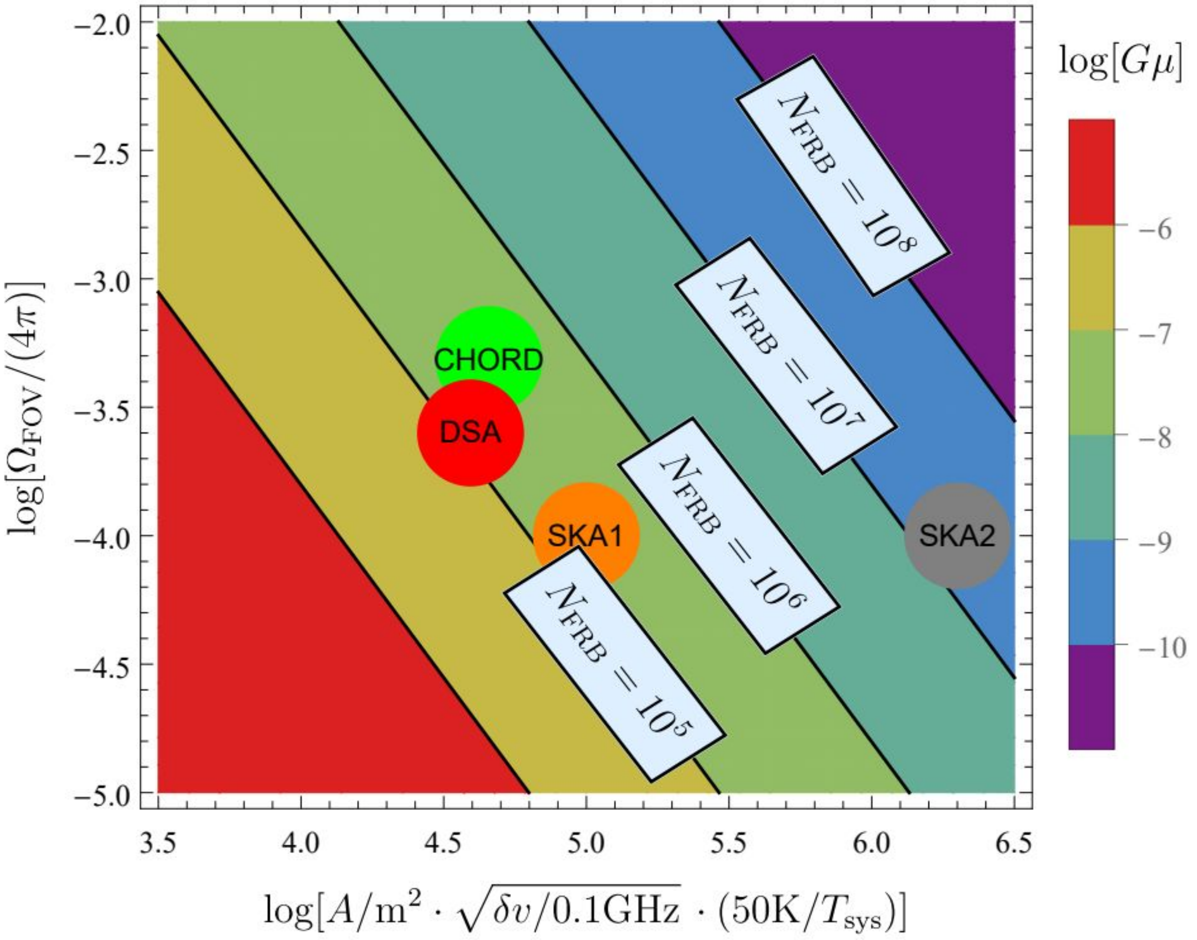
$$\frac{S}{N} = \frac{A\,F}{2\,k_{\rm B}T_{\rm sys}\,\tau_0}\sqrt{\Delta\nu\,\tau_0}$$

The detection rate above a certain threshold scales as $R(>F_{\rm min}) \propto F_{\rm min}^{-3/2}$

So the detection rate as a function of the collecting area and field of view of telescopes is

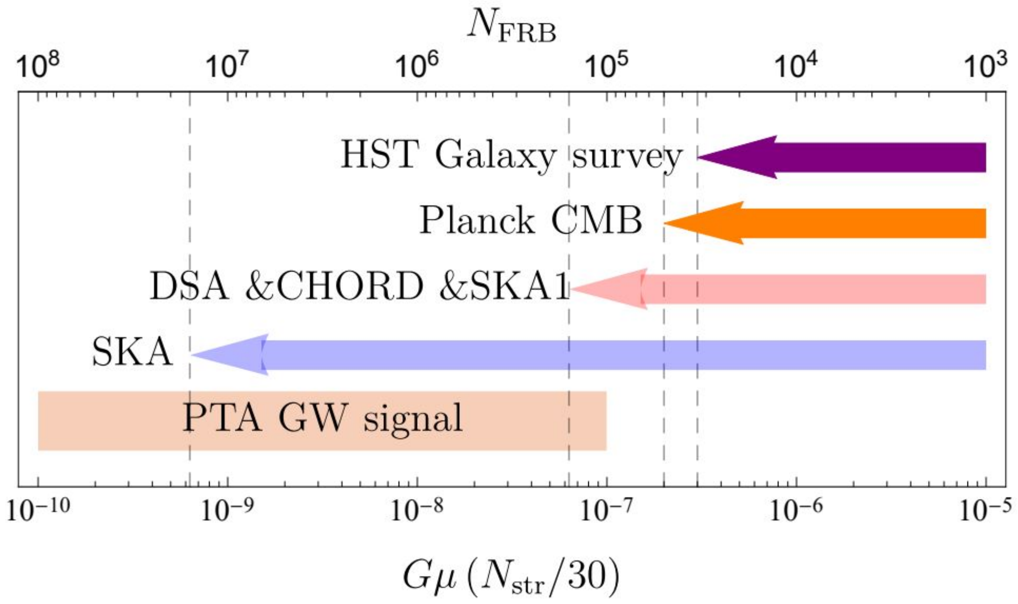
$$\begin{aligned} R &\sim 820\,{\rm day}^{-1}\left(\frac{\Omega_{\rm FOV}}{4\pi}\right)\left(\frac{F_{\rm min}}{5\,{\rm Jy\cdot ms}}\right)^{-\frac{3}{2}} \\ &\sim 990\,{\rm day}^{-1}\left(\frac{\Omega_{\rm FOV}}{4\pi}\right)\left(\frac{A}{10^3\,{\rm m}^2}\right)^{\frac{3}{2}}\left(\frac{\Delta\nu}{0.1\,{\rm GHz}}\right)^{\frac{3}{4}}\left(\frac{\tau}{1\,{\rm ms}}\right)^{\frac{3}{4}}\left(\frac{S/N}{10}\right)^{-3/2}, \end{aligned}$$

Sensitivity Forecast: Only the field of view and the collecting area will be relevant to us since we only care about the number (detection rate) of FRBs. 10 years of data is assumed to produce this plot.



Sensitivity Comparison

The sensitivities of different radio telescopes, CMB, and galaxy surveys are plotted.



Other New Physics with FRBs?

Matter power spectrum on small scales

Preliminary calculations based on ongoing work with Liang Dai and Matt Mcquinn:

- FRBs are highly coherent point source. By correlating the electric field, one could measure the time delay between lensed images to a precision of **nanosecond** or even subnanosecond.
- Dark matter substructures, arising from early Universe dynamics such as early matter domination, axions, vector dark matter during inflation, can leave unique fingerprints on power spectrum on small scales.
- Therefore, measuring matter power spectrum on small scales, provide a new window onto new physics on the early Universe.

Some estimates

Imagine we have two dishes. Dark matter clumps in the cone is

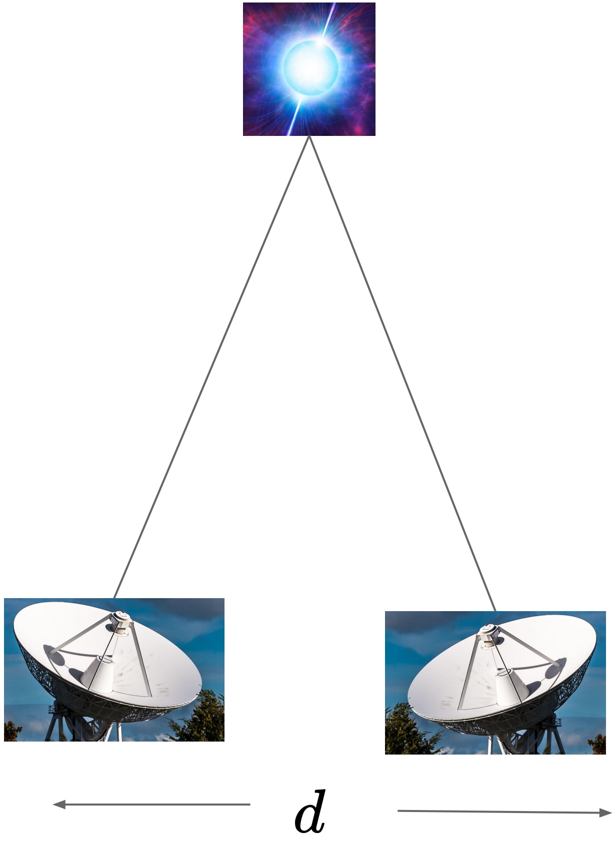
$$N = \frac{\pi d^2 D_s \rho_m}{M_h} = 8.3 \left(\frac{10^{-6} M_\odot}{M_h}\right)\left(\frac{d}{50\mathrm{AU}}\right)^2,$$

The Shapiro time delay induced by individual clumps is

$$\delta t = G M_h \ln(d_{\mathrm{dish}}/D)$$

The variance on the time delay is

$$\Delta t = \sqrt{N_h}\delta t = 0.85\,\mathrm{ns}\left(\frac{d}{50\mathrm{AU}}\right)\left(\frac{M_h}{10^{-6} M_\odot}\right)^{1/2}$$



More careful estimates

Assuming a Newtonian potential, the variance of the Shapiro delay between two sightlines separated by x can be estimated by

$$\Delta t \approx \frac{3(4\pi G\bar{\rho})^2 d\, x^4}{8} \int \frac{dk}{2\pi} k P_\delta(k)$$

With nanosecond precision, x=50 AU. we will be able to probe $k \sim \mathrm{kpc}^{-1}$

Conclusion

1. The strong lensing signal by cosmic strings is very clean and unique, especially for FRBs.
2. The sensitivity of FRBs to cosmic strings only depends on the number of FRBs. We expect to see many of them in the future and this will be a very powerful tool to detect cosmic strings.
3. FRBs are also promising to measure the matter power spectrum on the smallest scales, which provides a direct probe to the early Universe.

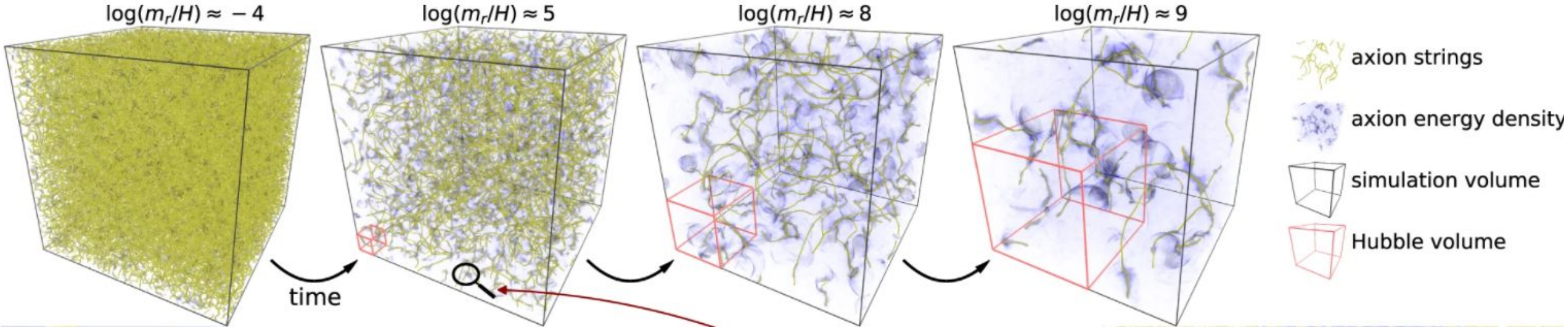
String Loops

According to simulations, a large fraction of the string network (roughly 80% in the simplest formation models) is in infinite strings and the rest is in loops with a scale-invariant distribution. (Vachaspati and Vilenkin 1984) This is confirmed by the study of axion strings (Gorghetto, Hardy, Villadoro, 2018).

The evolution of cosmic strings

The number of strings per horizon grows logarithimically:

$$\xi = \alpha_1 + \alpha_2 \ln(\frac{f}{H})$$



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