FRB scintillation, lensing and as probes of Cosmology

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Outline†

- FRB circular polarization – scintillation in magnetized plasma
- Gravitational lensing + wave scattering in plasma
- 217 ms periodicity of 191221A and radiation physics
- Cosmology

Cornell, Oct 2022

Lensing by a point mass located in a plasma screen

Kumar & Beniamini, 2022

The flux observed from an astronomical source when photons travel through a gravitational potential and plasma on their way to the observer is given by

$$f(\omega,\vec{\beta}) = \frac{1}{i\theta_F^2}\int d^2\theta \,\exp\left\{\frac{i\pi|\vec{\theta}-\vec{\beta}|^2}{\theta_F^2} - i\omega\left[\psi(\vec{\theta}) - \delta t_p(\vec{\theta})\right]\right\}$$

where $$\theta_F = \left[\frac{\lambda d_{sl}}{d_{lo} d_{so}}\right]^{1/2}$$ **Is the Fresnel angle**

$$\psi(\vec{\theta}) = \int d\ell \,\frac{\Phi(\vec{x})}{c^3}(1+n_r^2)$$

is the time delay due to travel in the gravitational potential Φ

$$\delta t_p = (4.4\, ms)\, \nu_{\rm GHz}^{-2}\, {\rm DM}(\vec{\theta})$$

plasma time delay

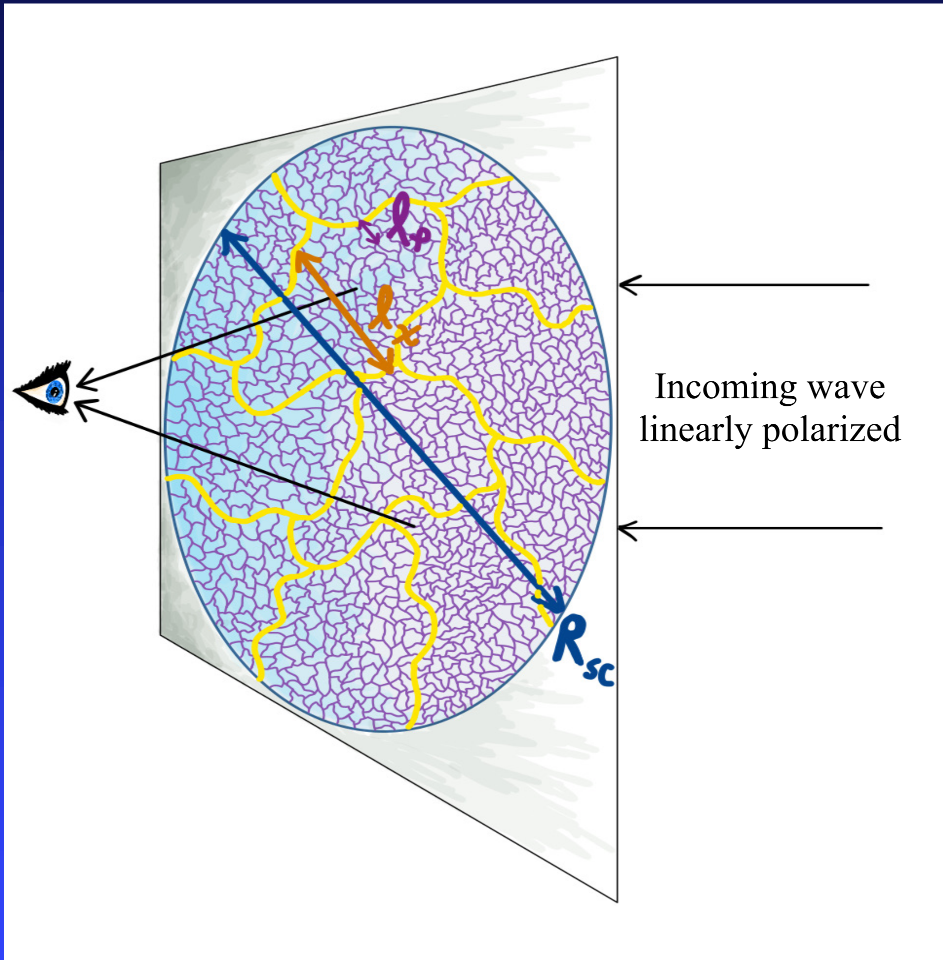
The above integral reduces to geometric optics description when the gravitational radius of the object is ≫ λ

Induced circular polarization by a magnetized-scintillating screen

Linearly polarized EM wave passing through a scintillating screen undergoes different phase and PA changes from different parts of screen. The wave can:

Become partially depolarized

Get converted to partially circularly polarized wave



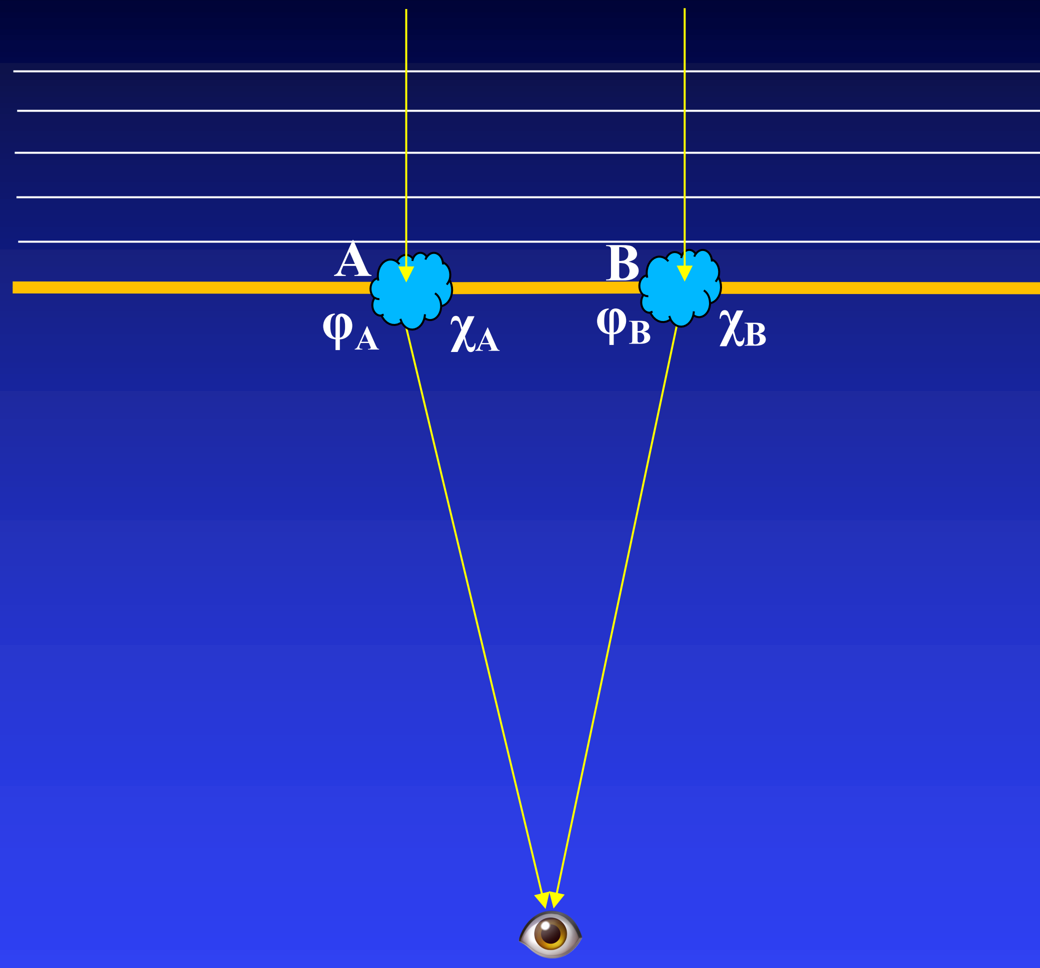
This is distinct from depolarization due to large RM, or small circular polarization from "generalized Faraday rotation"

Toy model – Double slit experiment

A monochromatic, linearly polarized, plane EM wave passing through 2-slits

φ_A : phase shift suffered by the wave while passing through slit "A"

χ_A : wave electric field rotation angle after passing through slit "a"



$$E_1(\tilde{\nu}) = \frac{1}{\sqrt{2}}\left[\cos(\chi_A/\tilde{\nu}^2)e^{i\phi_A} + \cos(\chi_B/\tilde{\nu}^2)e^{i\phi_B}\right]$$

$$E_2(\tilde{\nu}) = \frac{1}{\sqrt{2}}\left[\sin(\chi_A/\tilde{\nu}^2)e^{i\phi_A} + \sin(\chi_B/\tilde{\nu}^2)e^{i\phi_B}\right]$$

Stokes parameters

$$I = E_1E_1^* + E_2E_2^* = 1 + \cos(\Delta\phi)\cos(\Delta\chi)$$

$$Q = E_1E_1^* - E_2E_2^* = \frac{1}{2}\cos(2\chi_A) + \frac{1}{2}\cos(2\chi_B) + \cos(\Delta\phi)\cos(2\bar{\chi})$$

$$U = E_1E_2^* + E_1^*E_2 = \frac{1}{2}\sin(2\chi_A) + \frac{1}{2}\sin(2\chi_B) + \cos(\Delta\phi)\sin(2\bar{\chi})$$

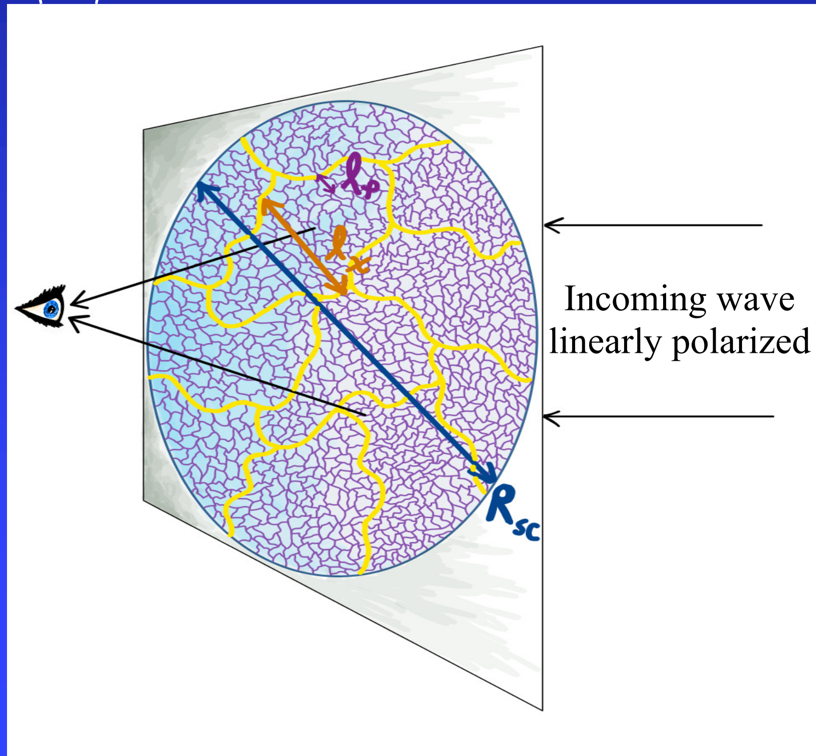
$$V = \frac{1}{i}\left[E_1E_2^* - E_1^*E_2\right] = \sin(\Delta\phi)\sin(\Delta\chi)$$

In general, $\phi_A \neq \phi_B$

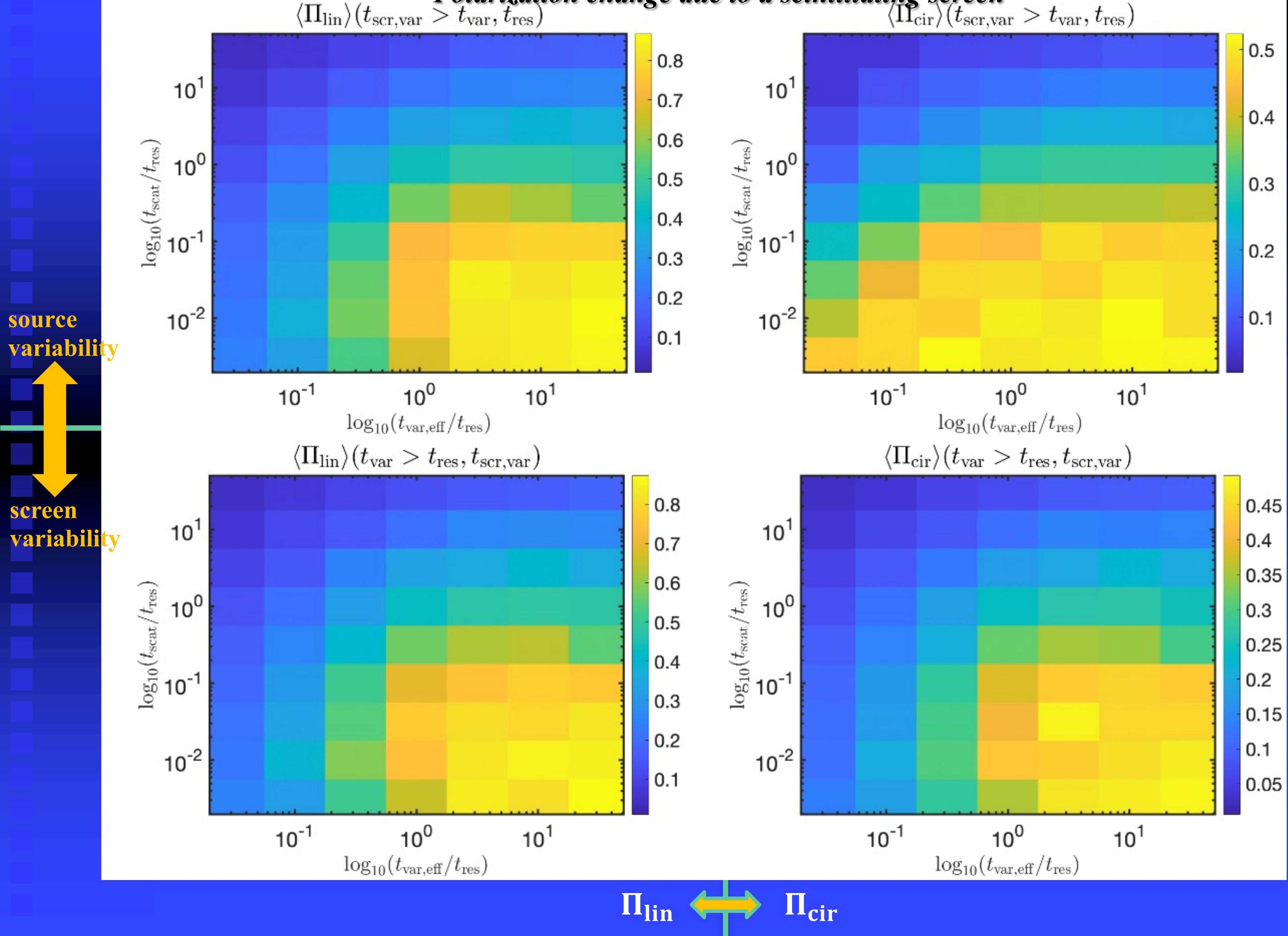
If $\chi_A \neq \chi_B$, $V \neq 0 \implies$ induced Π_{cir}

Scintillation in magnetized medium – generation of circular polarization

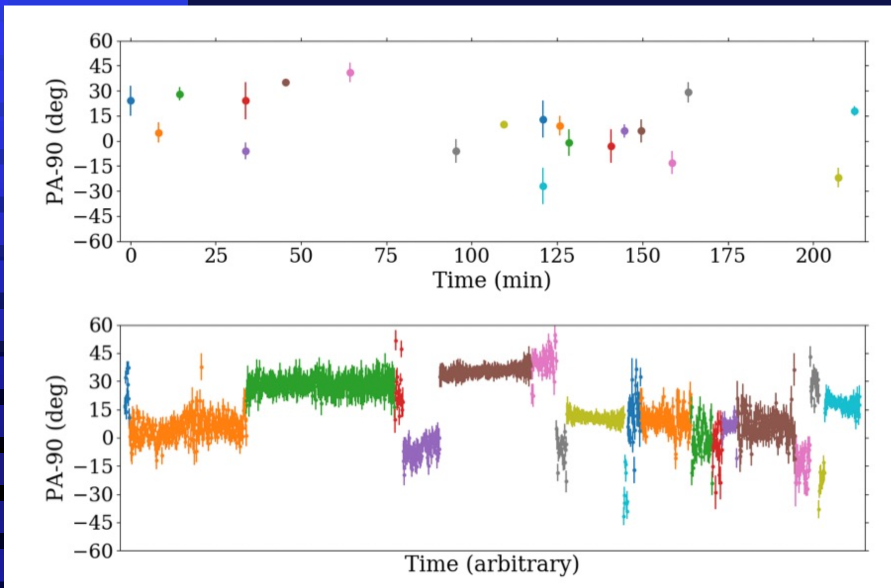
- **Rotation of electric field by turbulent eddy of size l:** $\delta\chi \sim \chi_0 \left(\frac{l}{L}\right) \left(\frac{l}{l_{max}}\right)^{1/3}$
- **For eddy size l_χ, $\delta\chi(l_\chi) = 1$, l_χ: rotation length; $\delta\phi(l_\phi) = 1$, l_ϕ: diffraction length**
- **Mean rotation small compared to mean phase** $\frac{\chi_0}{\phi_0} \sim \left\langle \frac{\omega_B}{\omega} \right\rangle \ll 1$
- $\frac{l_\chi}{l_\phi} \sim \left(\frac{\omega}{\omega_B}\right)^{6/5} \sim \left(\frac{3\cdot 10^8 \nu_9 DM_s}{RM_s}\right)^{6/5} \gg 1$
- ***But*, as long as $l_\chi < R_{sc}$ induced Π_{cir} will be of the order of Π_{tot} ; R_{sc} is scattering radius**
- **Effect relies on fluctuations in $n_e, B_{||}$**



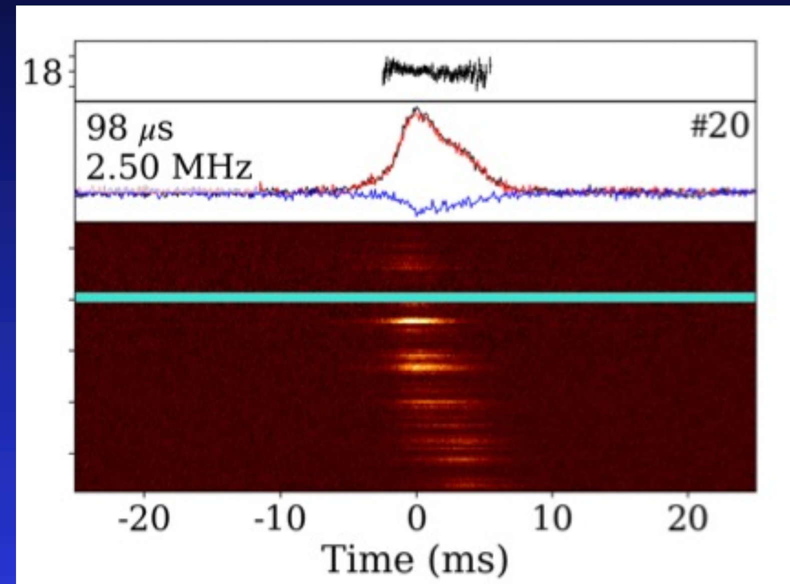
Polarization change due to a scintillating screen



Comparison with observations - FRB 201124A



Hilmarsson et al. 2021



- Effelseberg and FAST measured large circular polarization: $0.06 < \Pi_{cir} < 0.75$
- Large (fluctuating) RM$\sim 600 \frac{rad}{m^2}$ ($l_\chi < l_{max}$ which is necessary for induced Π_{cir})
- $\nu_{co} \sim 1.2\text{MHz} < 2.5\text{MHz} \sim \nu_{res} \Longrightarrow$ slight spectral depolarization expected from screen
- Highest circular polarization when RM is highest
- *However*: rapid PA swings (tens of degrees in 30 ms) not from the scattering screen

Gravitational lensing of FRBs and plasma scattering of radio waves

Lensing probability (without plasma)

1. **Galaxies & other massive objects:** $P(>\mu) \approx \frac{0.3\,\Omega_{gal}}{\mu^2} \sim \frac{5\text{x}10^{-3}}{\mu^2}$ **(z>2)**

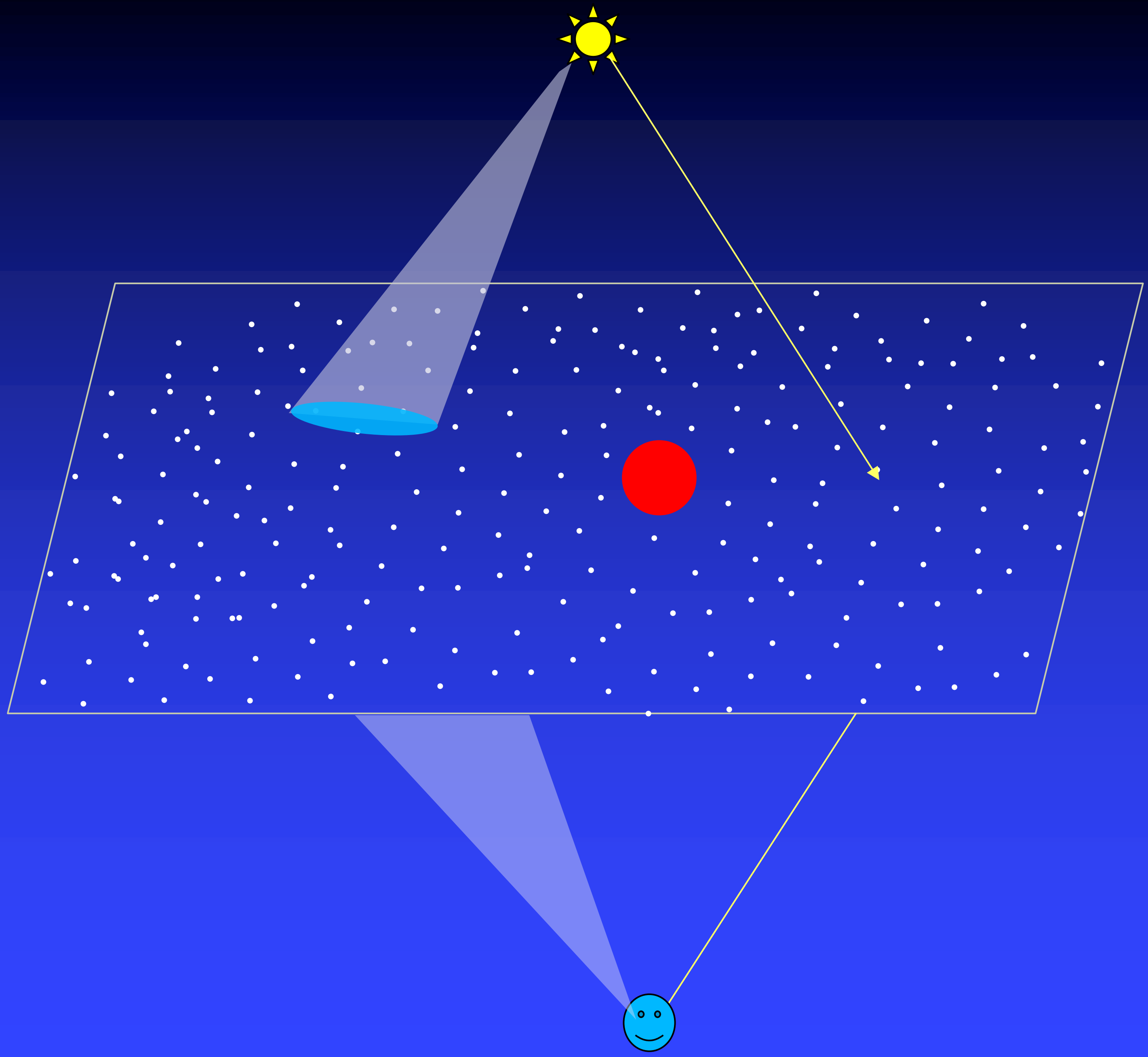
(Narayan & Bartelmann, 1996)

2. **Stellar mass objects:** $P(\mu \sim 1) \approx 2.5\text{x}10^{-4}\,\frac{\Omega_{M_\odot}}{0.004}$ $(Z \lesssim 0.5)$

(Madau & Dickinson, 2014)

Future surveys with 10^4 FRBs should find 10s of lenses, with arrival time delay measured to an accuracy of ~1ms, $\frac{\delta T}{T} \sim 10^{-10}$ for galactic mass lens (~1 for stellar mass lens).

Lensing by a point mass located in a plasma screen



Gravitational Lensing with wave scattering in plasma has several effects:

1. **Magnification is reduced – because source size is broadened**

2. **Optical depth to lensing is modified – due to magnification cap**

3. **Time delay between images is modified by the non-unit index of refraction of the medium**

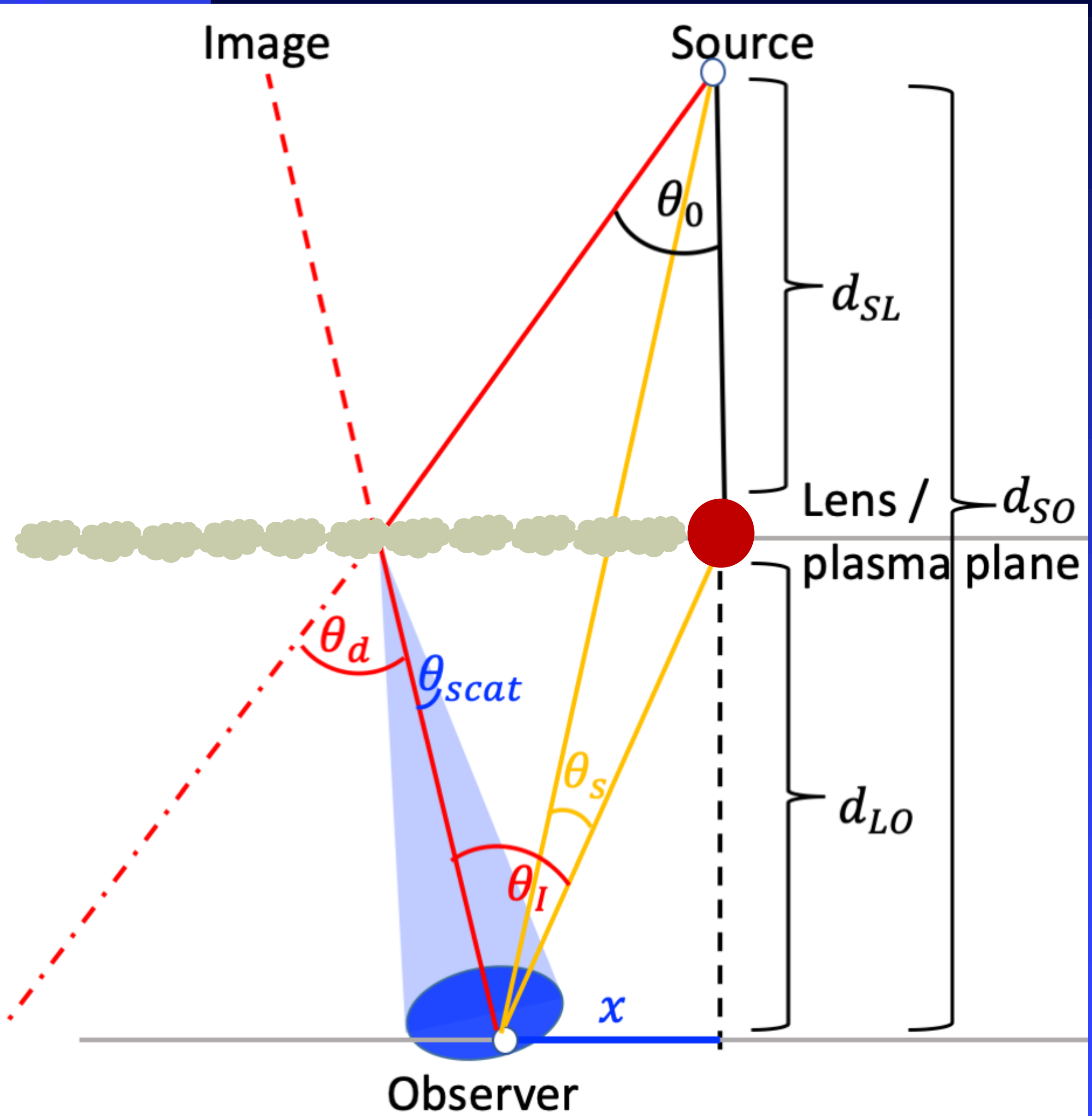
4. **Lightcurves of different images are broadened (or smeared) by different amounts due to turbulence along different photon trajectories.**

5. **Measurement of differential-DM over short distances**

6. **Conversion of linear to Circular polarization**

Lensing by a point mass located in a plasma screen

Kumar & Beniamini, 2022



Lens equation

$$\frac{\theta_I - \theta_S}{\theta_E^2} - \frac{1}{\theta_I} + \frac{c}{2R_s}\left[\frac{\partial t_p}{\partial \theta}\right]_{\theta_I} = 0$$

Where:

$$\theta_E = \left[\frac{2\, R_s d_{SL}}{d_{SO} d_{LO}}\right]^{\frac{1}{2}}$$

is Einstein angle

R_S: gravitational radius of the lens

t_P: time delay due to propagation through plasma

Maximum magnification:

$$\mu = min\left(\frac{\theta_E}{2\theta_s}, \frac{\theta_E}{4\theta'_{scat}}\right)$$

Order of magnitude estimate for θ_E & θ_{scat}

For a stellar mass lens with $d_{LO} \sim 1$ Mpc (1 Gpc) & $d_{SO} \sim 2$ Gpc:

$$\theta_E = 5\text{x}10^{-10} \;\; (2\text{x}10^{-11}) \text{ rad}$$

The diffraction scale for Galactic IGM is, $\ell_{diff} \approx 10^{10}$ cm

$$\therefore \qquad \theta_{scat} \sim \frac{\lambda}{\ell_{diff}} \sim 3\text{x}10^{-9} \quad \text{(at 1 GHz)}$$

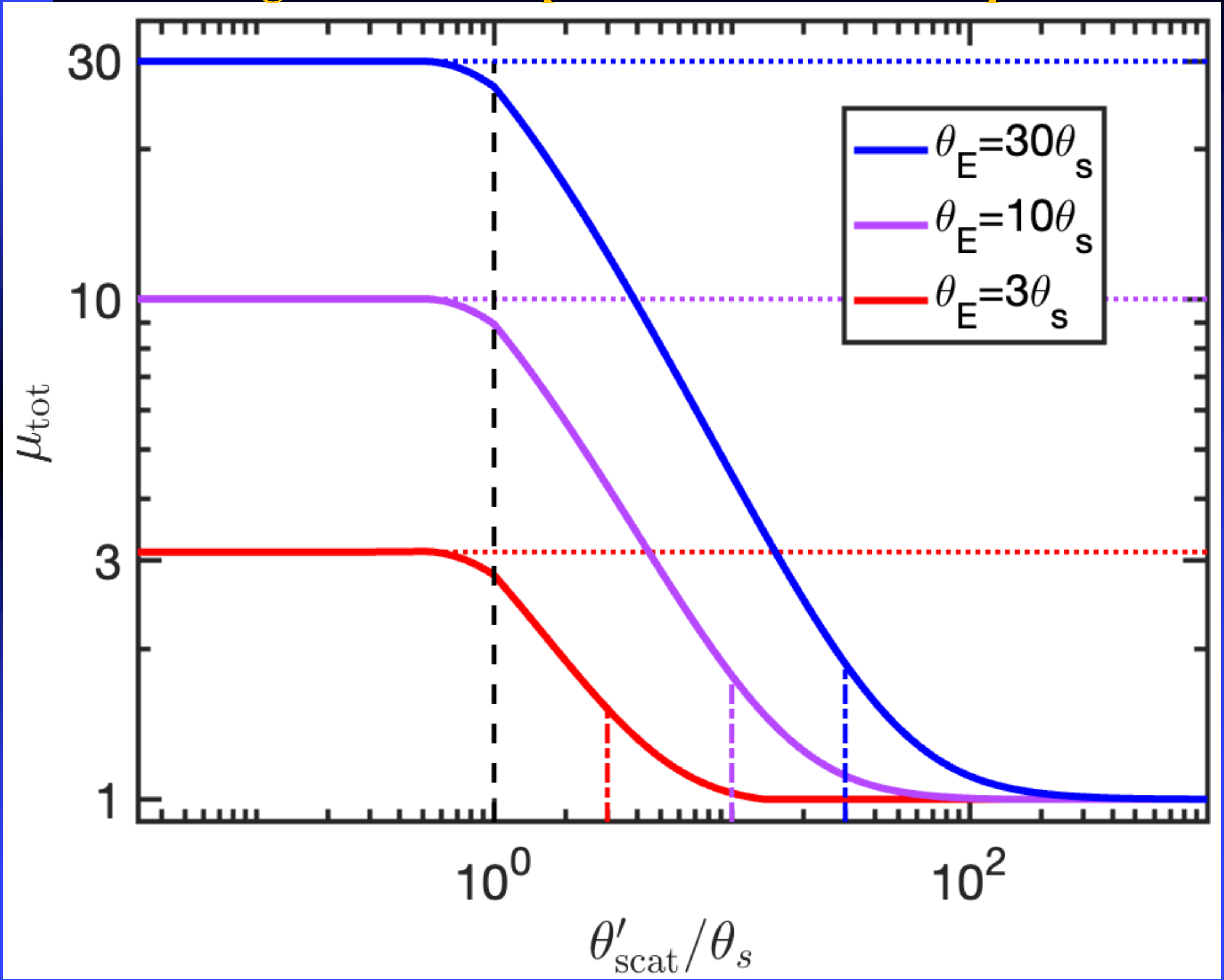
Thus, magnification is suppressed for lens mass $\lesssim 10^2\, M_\odot$ ($10^4\, M_\odot$) when plasma screen is in the lens plane; the effect is much weaker when plasma & gravitational lens planes are far apart.

The precise limit is (Kumar & Beniamini, 2022):

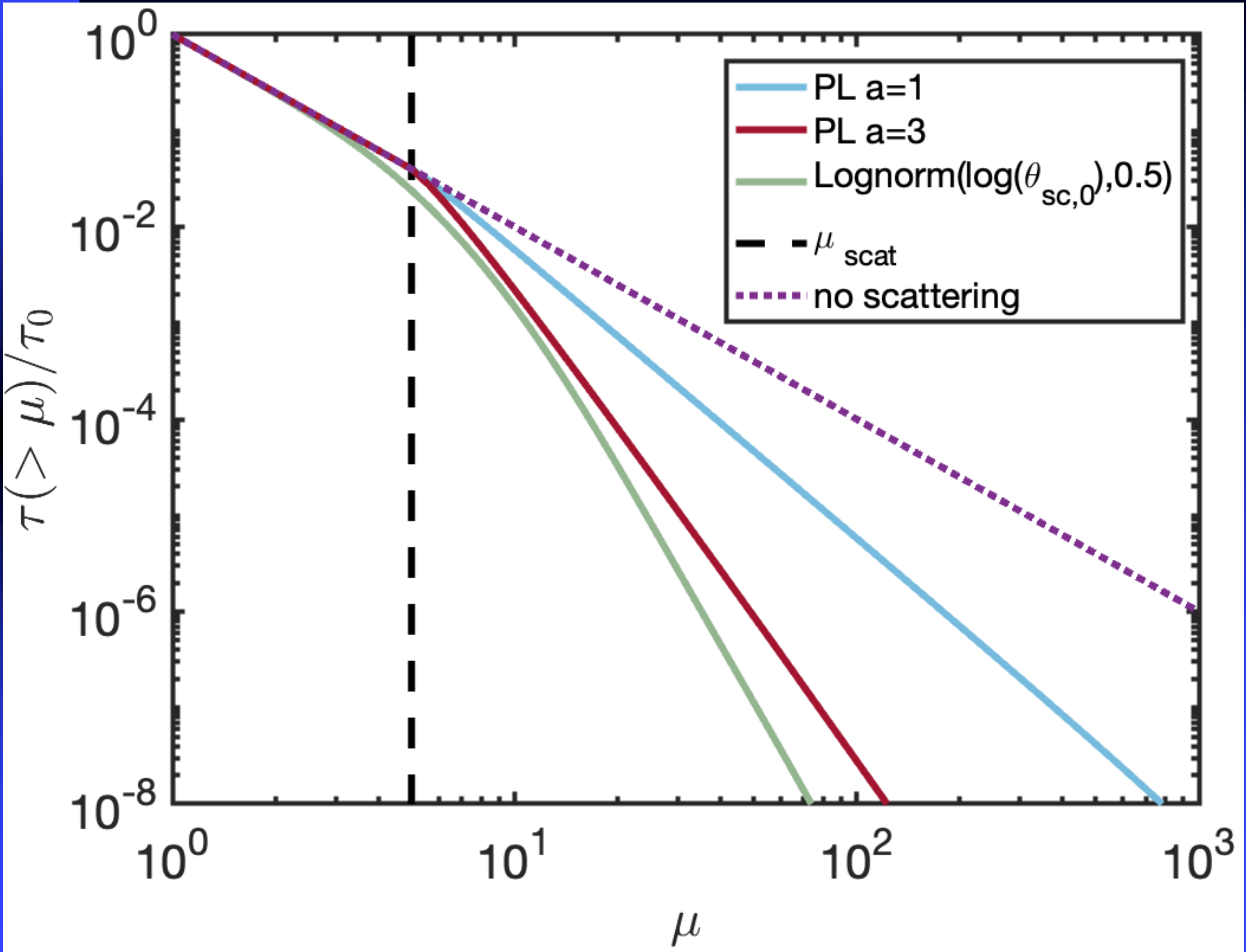
$$M_{min}(\mu_{max}) = 7\, M_\odot\, f_d^2\, \mu_{max,1}^2\, \theta_{scat,-9}^2\, d_{LO,22}\, (d_{SL}/d_{SO})$$

where $f_d = d_{PO}/d_{LO}$ when $d_{LO} > d_{PO}$ else $f_d = d_{PS}/d_{LS}$

Magnification in presence of turbulent plasma

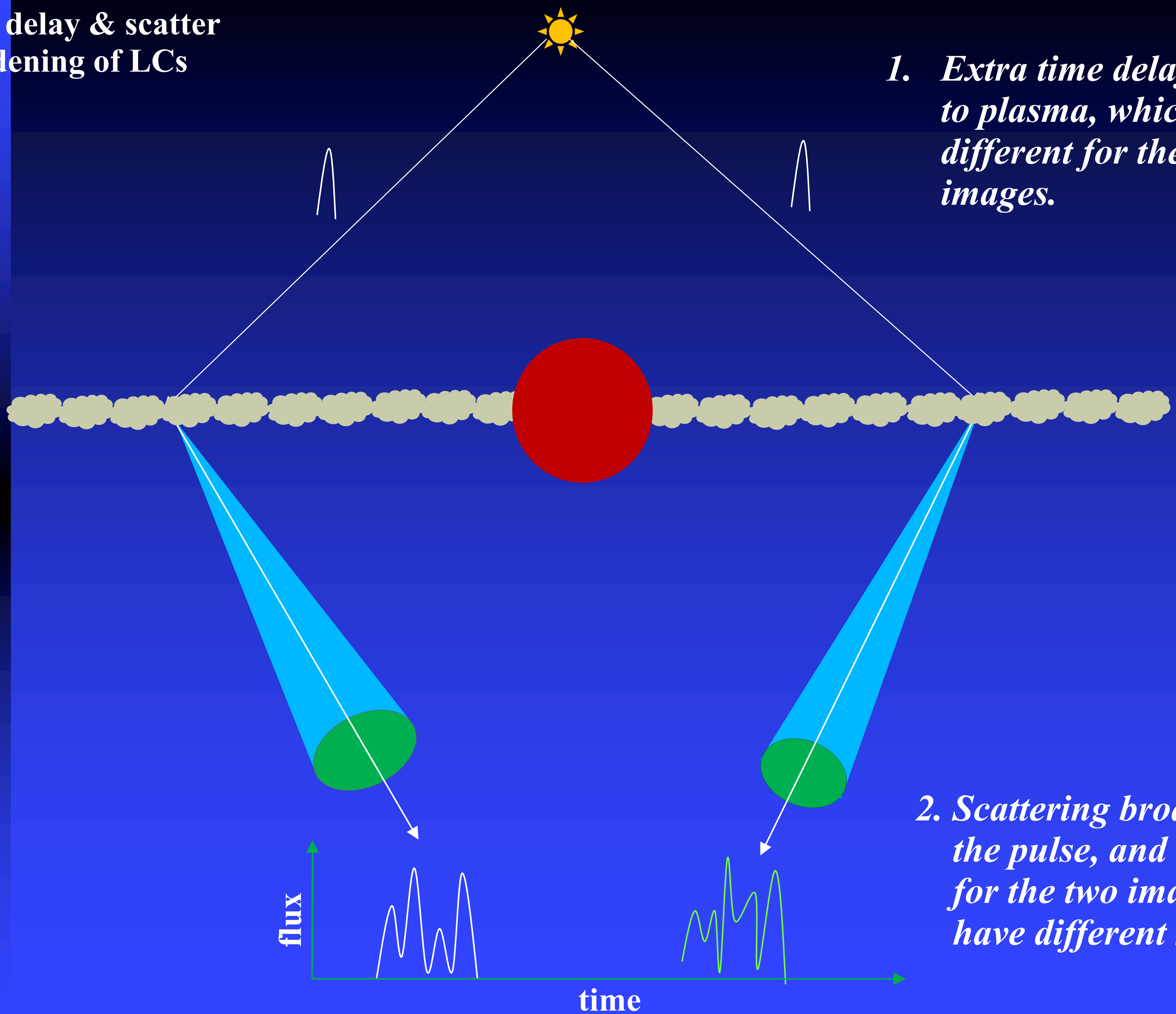


Modification to Lensing probability by plasma screen



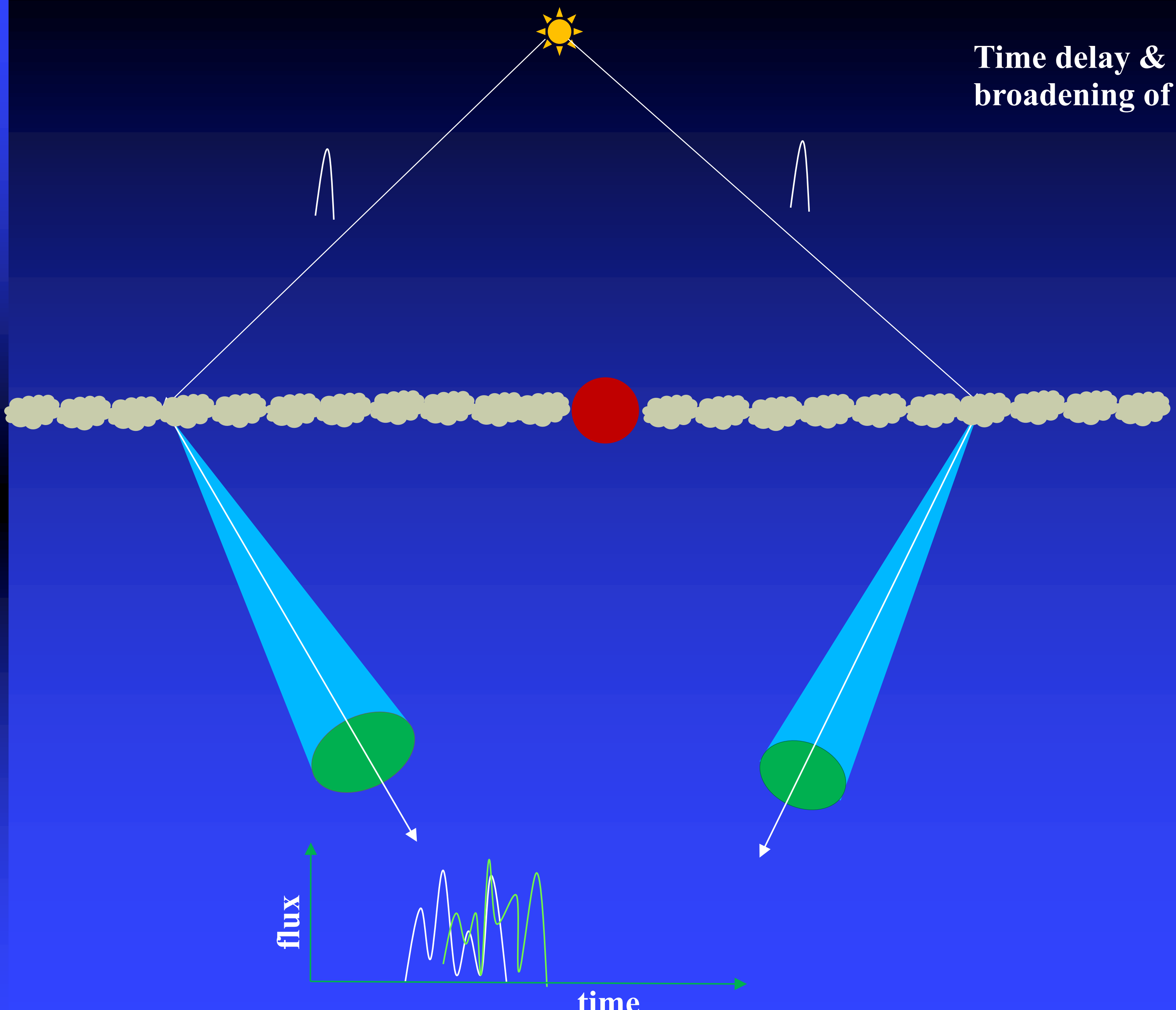
Time delay & scatter broadening of LCs

1. *Extra time delay due to plasma, which is different for the two images.*



2. *Scattering broadens the pulse, and the LCs for the two images have different shapes.*

Time delay & scatter broadening of LCs



It can be shown that the time scale for scatter broadening of an FRB pulse by turbulent plasma is

$$t_{sc} \approx \frac{\theta_{scat}^2 \, d_{SL} d_{LO}}{c \, d_{SO}} = \frac{2\,R_s}{c} \frac{\theta_{scat}^2}{\theta_E^2} \frac{d_{SL}^2}{d_{SO}^2}$$

The geometric+gravitational time delay between the two images is:

$$\Delta t = \frac{4\,R_s \theta_s}{c\,\theta_E} \approx \frac{4\,R_s}{c} \qquad \therefore \qquad t_{sc} < \Delta t \quad \text{when} \quad \frac{\theta_{scat}\, d_{SL}}{d_{SO}} < \theta_E$$

This is the same condition as the suppression of magnification by plasma

Thus, the two image LCs can be separated for lens mass $\gtrsim 10^2 M_\odot$

(when plasma is in the lens plane)

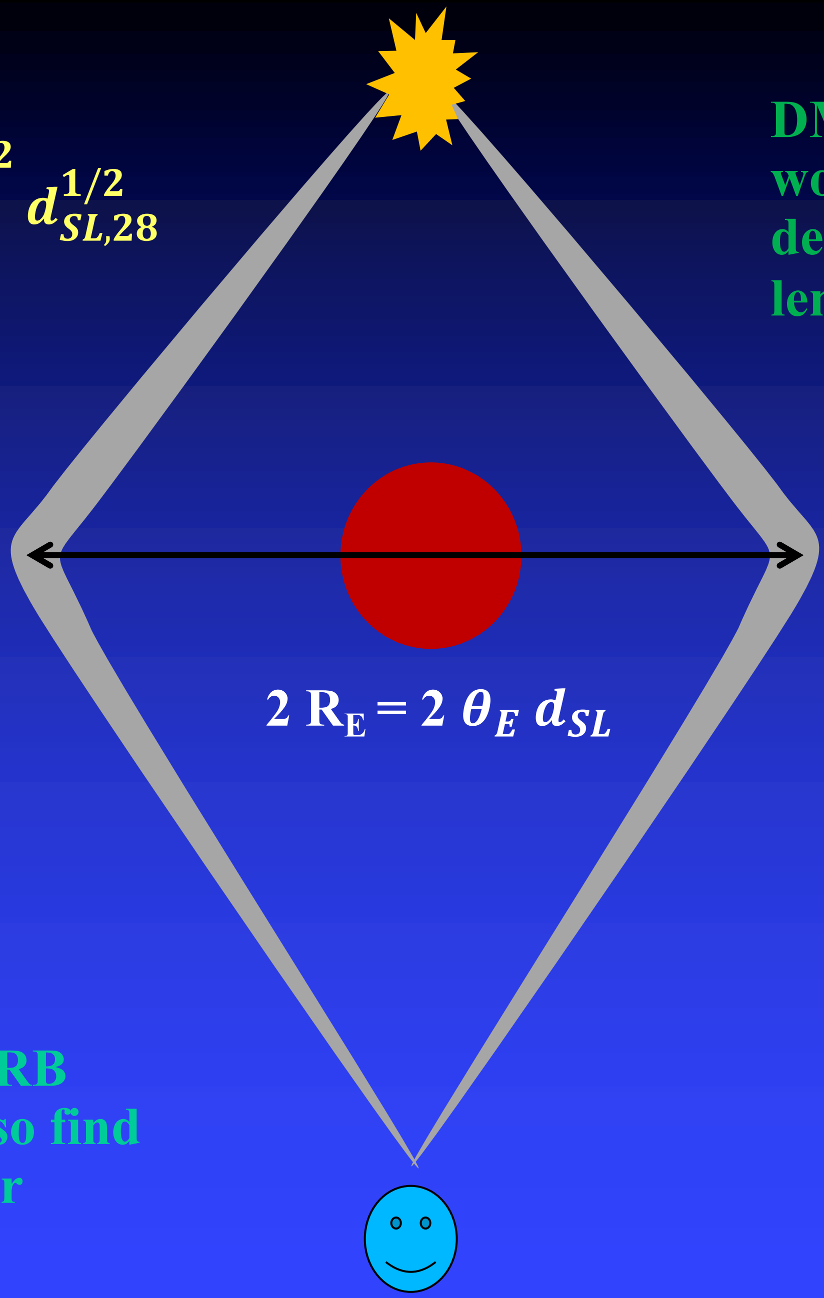
One can explore lower mass lens at $\uparrow \nu$, as $M_{min} \propto \nu^{-\frac{24}{7}}$

[M_{min} is smaller (by f_d) when plasma screen is not in the lens plane]

Another problem posed is that even when the time difference between the two images is much larger than the burst duration and the turbulence broadening time, the lightcurves for the two images would look very different because photons have traveled through different turbulent eddies.

Therefore, one would need additional information, such as angular separation between images to identify lensing event.

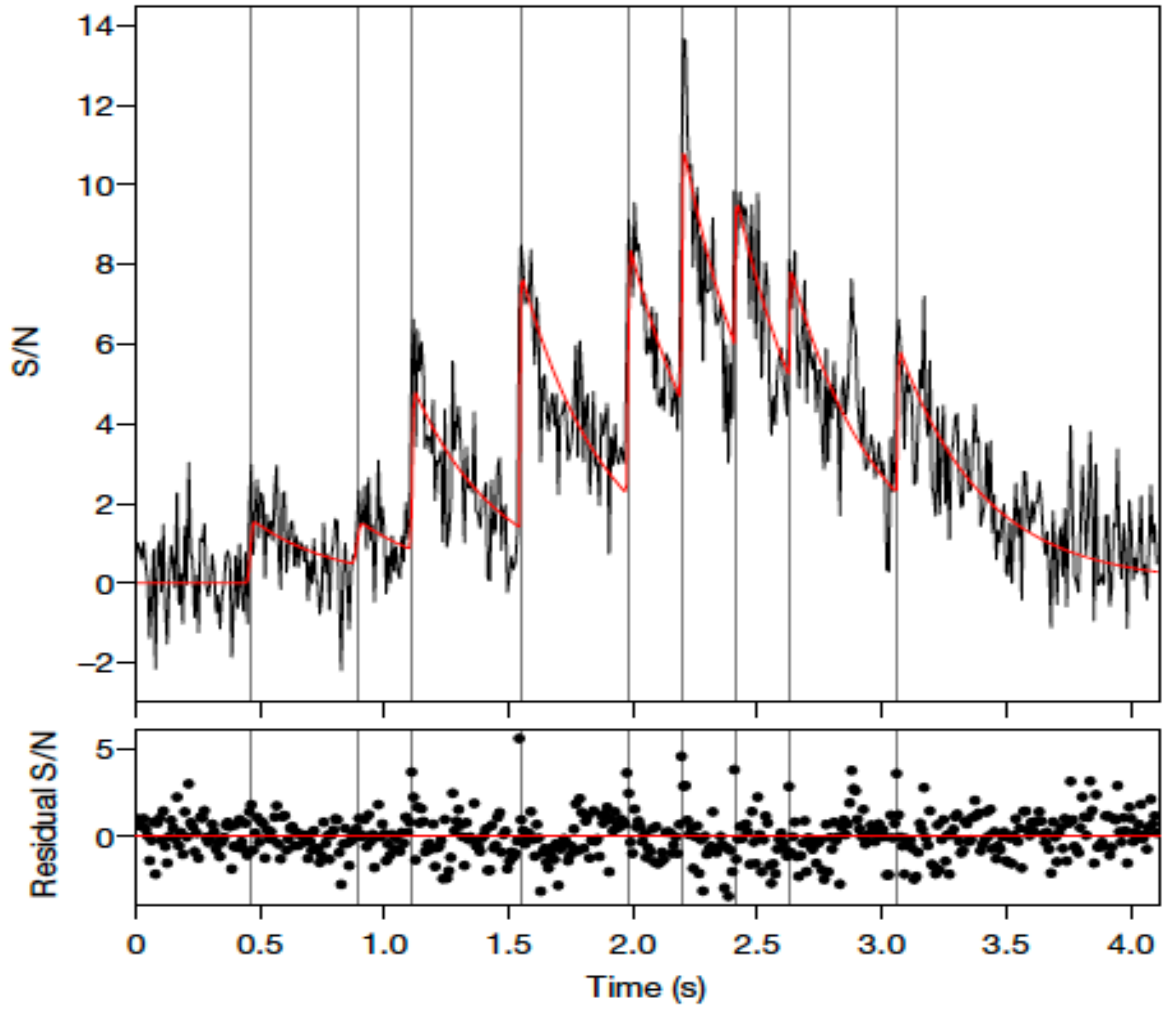
$$R_E \sim \sqrt{R_S d_{SL}} \sim 1 \text{ kpc} \left[\frac{M_L}{10^9 M_\odot}\right]^{1/2} d_{SL,28}^{1/2}$$



DMs for different images would determine plasma density fluctuations on length scale of ~ kpc

By monitoring an FRB repeater, one can also find out the time scale for density fluctuation.

FRB 20191221A with 217 ms periodicity



CHIME/FRB collaboration (2022)

Implications of FRB 20191221A's 217-ms periodicity

- Radio bursts from this object couldn't be rotation powered – required B $\gtrsim 10^{17}$ G
- CHIME team reports the periodicity to very high accuracy 216.8 $\pm$ 0.1 ms. And find average pulse width to be 4 $\pm$ 1 ms. If these claims are correct then they constrain the possible physics and radiation mechanism for this object severely.

Could this periodicity be due to NS crust oscillation?

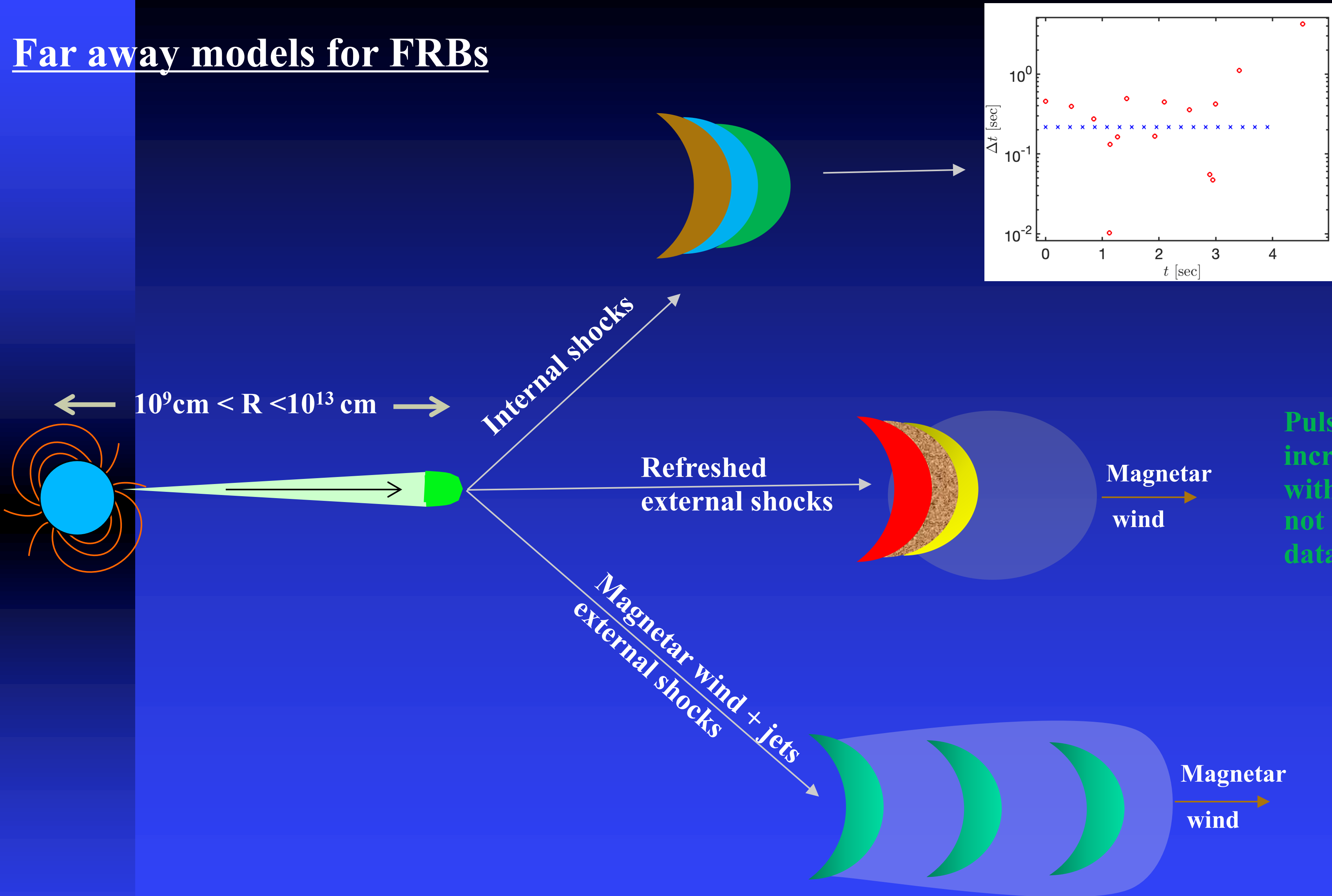
Seems unlikely as QPOs have frequencies $\gtrsim$ 10 Hz. Moreover, crustal oscillations have frequency ~10^2 Hz, which should show up in the data for FRBs with duration > 20 ms, but nothing like that has been seen.

If the 217-ms periodicity due to NS spin period:

Suggests a young magnetar with age ~ 10 yrs

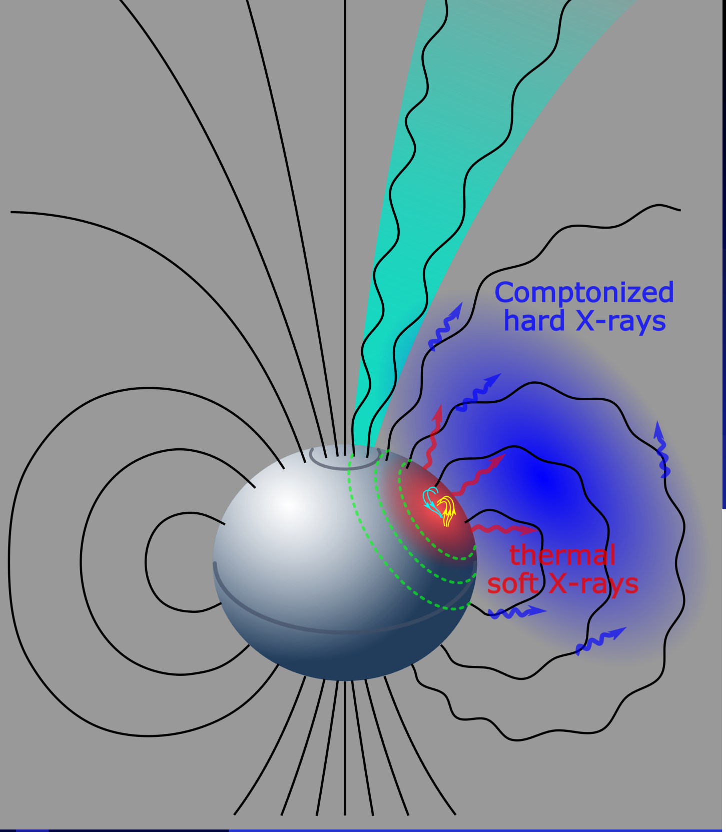
Several other implications of this periodicity is still being worked out. I hope to have that completed by the time of the Cornell workshop.

Far away models for FRBs

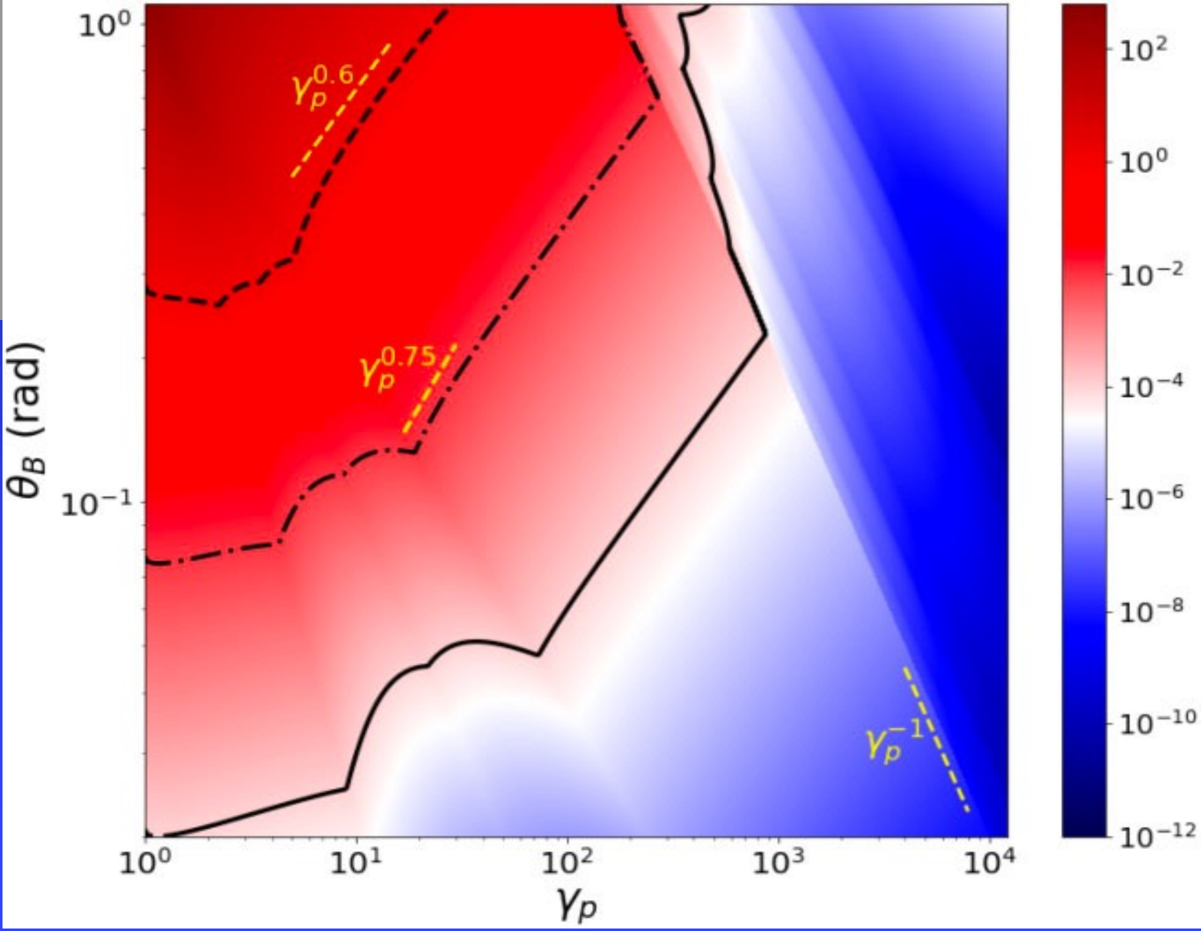


Pulse width increases with time; not what the data shows

This might work if $\frac{\sigma^{1/2} L_w^{3/4}}{L_{flare}^{1/4} \Gamma_w^2}$ **is constant**



FRB coherent radiation can escape from the NS magnetosphere if $e^{\pm}$ stream along field lines in the outer magnetosphere with LF $\gtrsim 10^2$



If FRB 20191221A radiation originates in the magnetosphere then its 217-ms periodicity is likely the result of a narrow beam of opening angle 10^{-2} rad for a aligned rotator NS model; for a non-aligned rotator, the beaming angle can be larger. The model is still under development, and I hope to have something more concrete in two weeks.

FRBs for probing the reionization era?

Exploring the hydrogen reionization epoch using FRBs

(Beniamini, Kumar, Ma & Quataert, 2021)

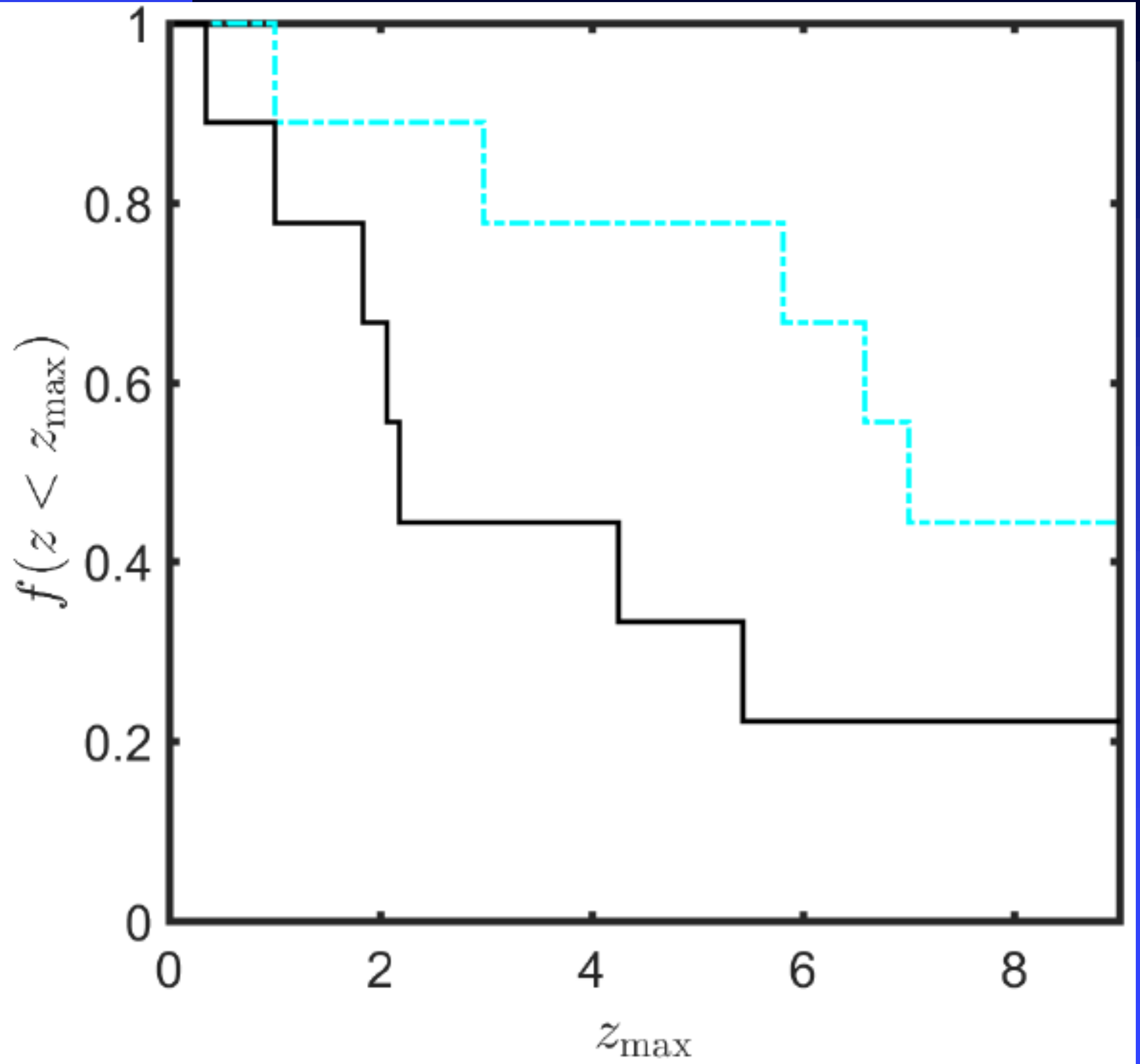
Do we expect FRBs at high redshifts (z>6)?

- **UV photons for the cosmic reionization (z>6) are supplied by stars $\geq 10M_\odot$**
- **About 40% of massive stars produce magnetars at z=0 (Beniamini et al. 2019)**
- **High z, metal poor, stars have faster rotation rates. They are likely to leave behind fast rotating compact remnants with strong magnetic fields as per the mechanism suggested by Thompson & Duncan.**
- **In any case, we know that there are GRBs at z > 6, including one at 9.4 (Cucchiara et al. 2011). These high-z GRBs have properties similar to their lower-z cousins.**

GRBs require strong magnetic field & a compact object (BH or NS)

So, it is not a big stretch to assume that magnetars and FRBs should be there during the reionization epoch waiting to be discovered

Detectability of FRBs at z>6

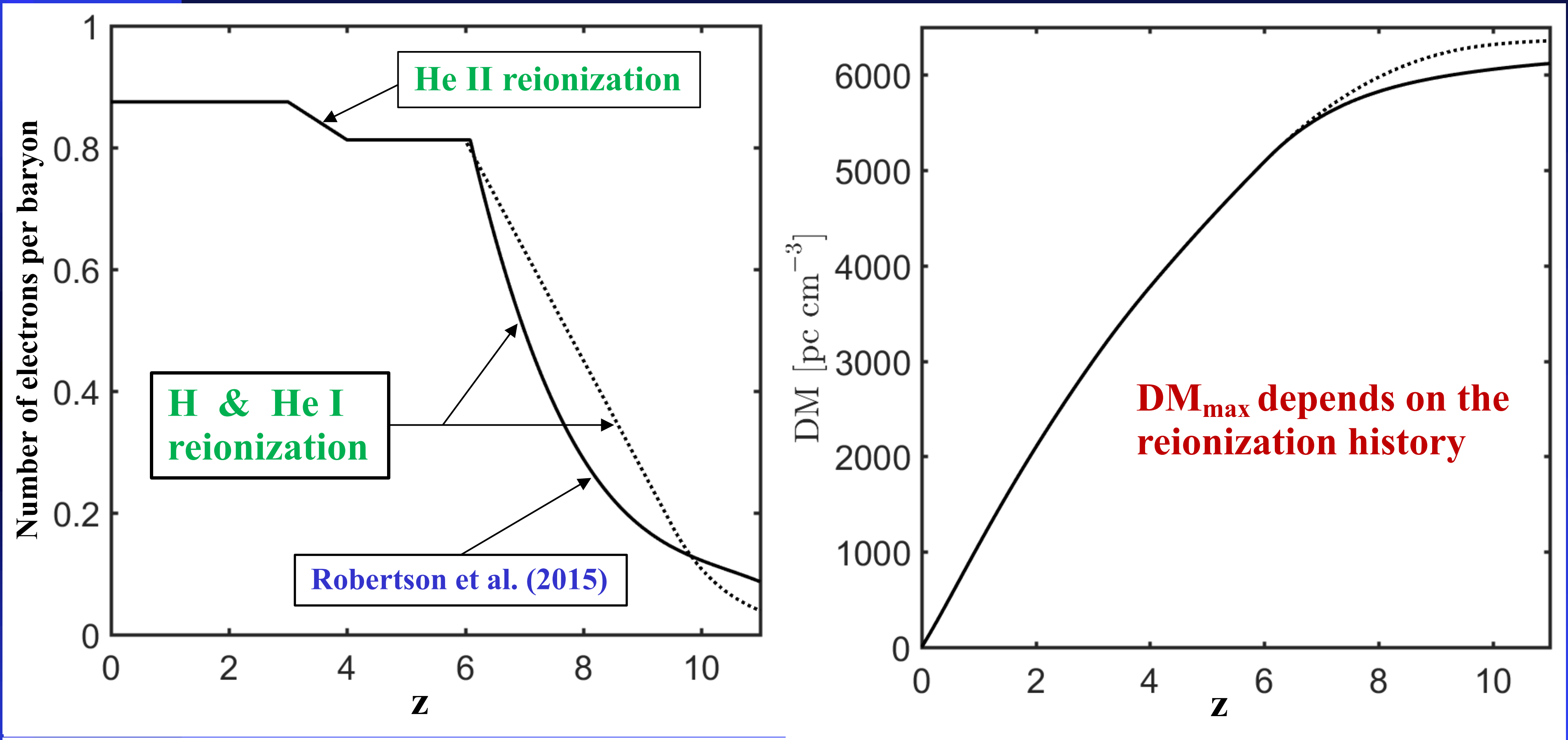


The fraction of 9 FRBs with known redshifts which would be detectable up to a redshift z. Results are shown as a solid (dot-dashed) curve for the specific-fluence threshold of 1 Jy ms (0.1 Jy ms) at 500 MHz and assuming a spectral slope of α = -1.5 ($f_\nu \propto \nu^{\alpha}$)

Beniamini et al. 2020

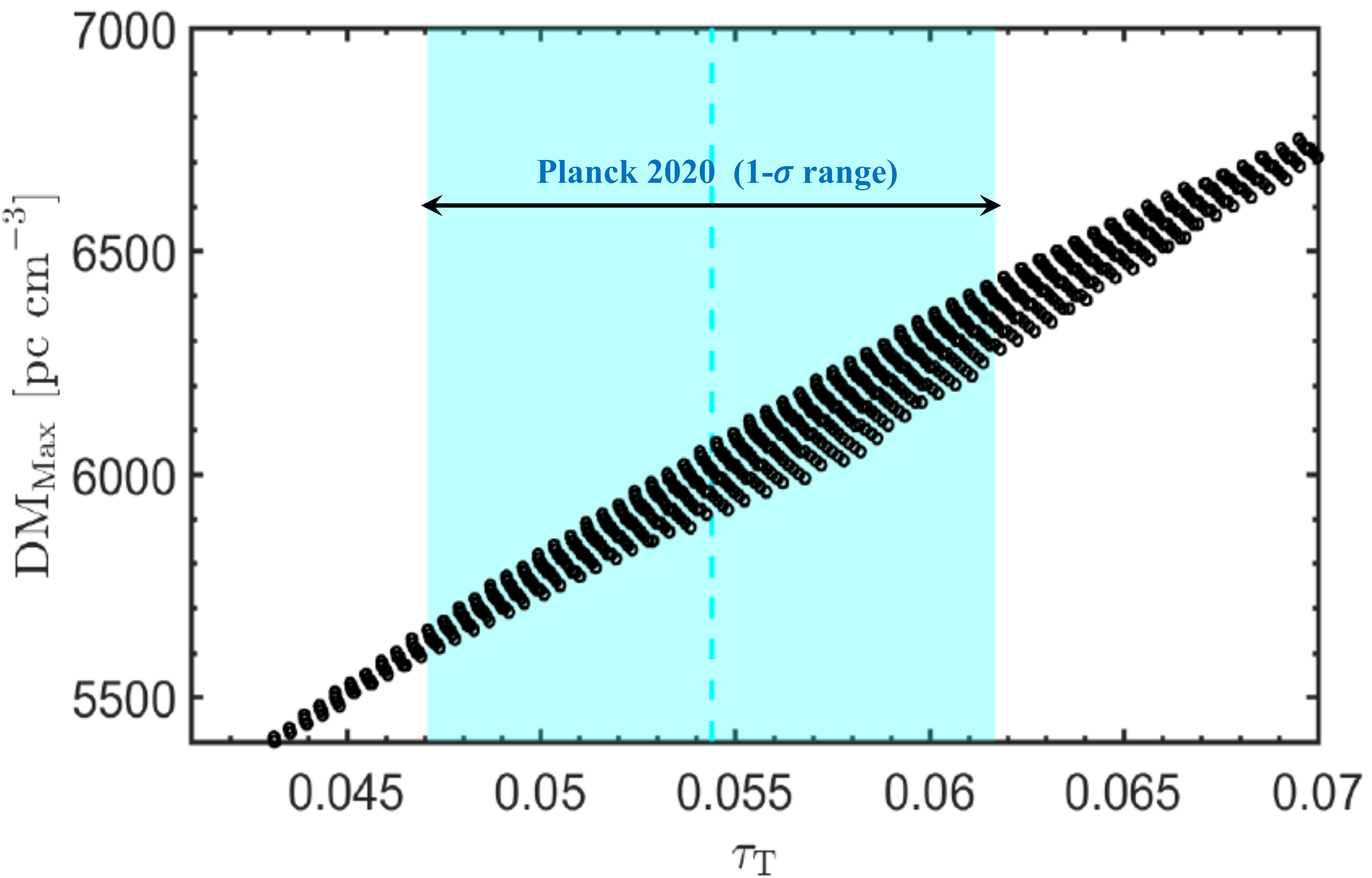
Exploring Hydrogen Reionization Epoch

Beniamini, Kumar, Ma & Quataert (2021)



$$\Delta DM_{max} = 500\, pc\ cm^{-3} \rightarrow \Delta\tau_T \leq 0.008 \quad (better\ than\ Planck)$$

Beniamini, Kumar, Ma & Quataert (2020)



Summary

- Some cases of circular polarization of FRBs could be the result of radio waves propagating through a magnetized, turbulent, plasma.
- Gravitational lensing of FRBs is modified by waves moving through turbulent plasma. The effect is move severe for lens mass $\lesssim 10\ M_{\odot}$. But cannot be ignored even for galactic mass lens.
- FRB 201221A with reported 217 ms periodicity provides useful constraints on the object properties and radiation physics.
- FRBs are useful probes for baryon distribution and possibly also of He and H reionization era.