Fast Radio Bursts for physics

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Outline

Introduction

LETTER

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The host galaxy of a fast radio burst

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In recent years, millisecond-duration radio signals originating in distant galaxies appear to have been discovered in the so-called fast radio bursts[1–9]. These signals are dispersed according to a precise physical law and this dispersion is a key observable quantity, which, in tandem with a redshift measurement, can be used for fundamental physical investigations[10,11]. Every fast radio burst has a dispersion measurement, but none before now have had a redshift measurement, because of the difficulty in pinpointing their celestial coordinates. Here we report the discovery of a fast radio burst and the identification of a fading radio transient lasting ~6 days after the event, which we use to identify the host galaxy; we measure the galaxy's redshift to be $z = 0.492 \pm 0.008$. The dispersion measure and redshift, in combination, provide a direct measurement of the cosmic density of ionized baryons in the intergalactic medium of $\Omega_{\mathrm{IGM}} = 4.9 \pm 1.3$ per cent, in agreement with the expectation from the Wilkinson Microwave Anisotropy Probe[12], and including all of the so-called 'missing baryons'. The ~6-day radio transient is

Upon detection of FRB 150418 at Parkes, a network of telescopes was triggered across a wide range of wavelengths (see Methods). Beginning two hours after the FRB, observations with the Australia Telescope Compact Array (ATCA) were carried out at 5.5 GHz and 7.5 GHz, identifying two variable compact sources. One of the variable sources is consistent with a GHz-peaked-spectrum source, with a positive spectral index, as previously identified in observations at these frequencies[16]. The other variable source (right ascension, RA 07 h 16 min 34.6 s; declination, dec. −19° 00′ 40″), offset by 1.944 arcmin from the centre of the Parkes beam, was seen at 5.5 GHz at a brightness of 0.27(5) mJy per beam just 2 h after the FRB. The source was then seen to fade over subsequent epochs, settling at a brightness of ~0.09(2) mJy per beam (Fig. 2). The source is also seen at 7.5 GHz at 0.18(3) mJy per beam in the first epoch but subsequently not detected. These observations indicate a ~6-day transient with a negative spectral index; we obtain $\alpha = -1.37$ in the first epoch, for a power-law spectrum of the form $F_\nu \propto \nu^\alpha$. The subsequent quiescent level is consistent with the level

This cosmoclub discuss the use of fast radio burst in physics and cosmology through the analysis of 2 recent papers. Last year, the first claim of detection of the host of a FRB was published.

What are fast radio bursts?

- ~ 1 ms bursts first found in archival data from the Parkes telescope (2007)
- Bursts also detected with other radio telescopes: Arecibo, Green Bank.
- Total of 17 found (2016)
- Mechanism for emissions not clear.
- Large dispersion measures $\Longrightarrow$ extragalactic origin.

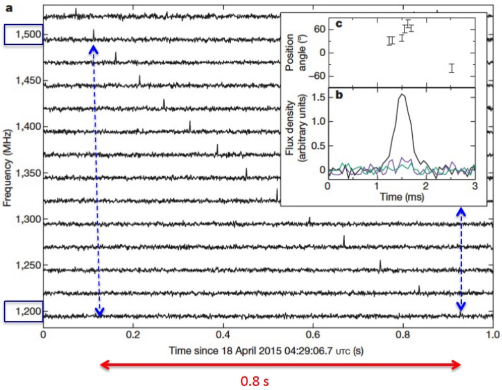
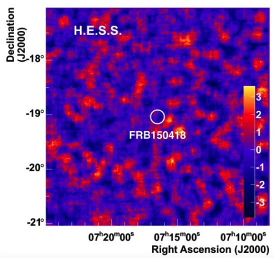


Figure 1 | The FRB 150418 radio signal. **a,** A waterfall plot of the FRB signal with 15 frequency sub-bands across the Parkes observing bandwidth, showing the characteristic quadratic time–frequency sweep. To increase the signal-to-noise ratio, the time resolution is reduced by a factor of 14 from the raw 64-μs value. **b,** The pulse profile of the FRB signal with the total intensity, linear and circular polarization flux densities shown as black, purple and green lines respectively. **c,** The polarization position angle is shown with 1σ error bars, for each 64-μs time sample where the linear polarization was greater than twice the uncertainty in the linear polarization.

FRB 150418

- Detected online by the SUPERB collaboration
- Pulse width 0.8 ± 0.3 ms (actually unresolved by instrument).
- Follow-up by telescopes in other passbands (including H.E.S.S.!)
- Claimed detection of the host galaxy at $z = 0.492$
- Thanks to this, could measure the cosmic density of ionized baryons $\Omega_{\rm IGM} = 0.049 \pm 0.013$ in agreement with WMAP.
- However counterpart detection controversial



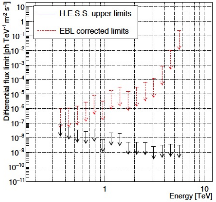


Fig. 3. VHE gamma-ray flux limits $\Phi_{\rm UL}$ at 99 % CL derived from the H.E.S.S. follow-up on FRB150418 (black triangles) assuming an E^{-2} energy spectrum. The EBL de-absorption is based on the model from (Franceschini et al. 2008) and assumes the FRB distance of z = 0.492 (Keane et al. 2016).

H.E.S.S. null result: H.Abdalla et al. (H.E.S.S. collaboration), A & A (2017), main author Fabian S.

Dispersion measure of FRB

- Speed of light in plasmas

$$v = c\sqrt{1 - \frac{\nu_p^2}{\nu^2}} \simeq c(1 - \frac{\nu_p^2}{2\nu^2})$$

where ν is the light frequency and ν_p is the plasma cut-off frequency:

$$\nu_p^2 = \frac{n_e e^2}{m_e \epsilon_0}$$

with $n_e(z)$ the local electron density.
- Relative time delay of light of frequency ν travelling the distance L during time t is:

$$\Delta t = \int dl \frac{\nu_p^2}{2\nu^2} = \frac{e^2}{m_e \epsilon_0} \int dl \frac{n_e}{2\nu^2}$$

- Redshift dependance
  - $\nu(z) = \nu(0)(1+z)$.
  - $dl = \frac{c}{H_0}\frac{dt}{a(t)} = (z+1)\frac{dt}{dz}dz$
  - Electron density scales as $n_e(z) = n_e(0)(z+1)^3$ as usual for massive particles

$$\Delta t = \frac{e^2 n_e(0)}{2 m_e \epsilon_0 \nu(0)^2} \int dt (z+1)^2 = \frac{e^2 n_e(0)}{2 m_e \epsilon_0 H_0 \nu(0)^2} \int \frac{dz(z+1)}{\sqrt{\Omega_M (1+z)^3 + (1-\Omega_M)}}$$

This equation can be restated as:

$$\boxed{\Delta t_{DM} = (415\ \mathrm{s}) \left(\frac{1\ \mathrm{GHz}}{\nu(0)}\right)^2 \left(\frac{n_e c/H_0}{10^5 \mathrm{pc.cm}^{-3}}\right) \int \frac{dz(z+1)}{\sqrt{\Omega_M(1+z)^3 + (1-\Omega_M)}}} \quad (1)$$

-

$$\frac{n_e c}{H_0} = \frac{3 c H_0 f \Omega_b}{8\pi G m_p} \quad (2)$$

where Ω_b : fraction of critical density in baryons
f: ionization fraction $\simeq 0.9$

FRB 150418 measurements

- dispersion index =-2.00 $\pm$0.01 $\implies$ compatible with pure photon in plasma dispersion
- FRB dispersion measure $DM_{\mathrm{FRB}} = 776.2 \pm 0.5\ \mathrm{cm}^{-3}\ \mathrm{pc}$
- contribution from Milky way to dispersion $DM_{\mathrm{MW}} = 188.5\ \mathrm{cm}^{-3}\ \mathrm{pc}$ (from models, precision: 20%)
- contribution from Galactic halo $DM_{\mathrm{halo}} = 30\ \mathrm{cm}^{-3}\ \mathrm{pc}$ (modelled)
- contribution from host galaxy $DM_{\mathrm{host}} = 37/(z+1)$ (20% precision)
- Systematics from Intergalactic Medium (IGM) inhomogeneity: $100\ \mathrm{cm}^{-3}\ \mathrm{pc}$

$$DM_{\mathrm{FRB}} = 532 \pm 107(\mathrm{systematics})\ \mathrm{cm}^{-3}\mathrm{pc}$$

From this, the Nature paper authors find:

$$\Omega_{IGM} = \left(\frac{f}{0.88}\right) 0.049 \pm 0.013$$

compatible with WMAP results.

Introduction

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Photon mass limits from fast radio bursts

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We dedicate this paper to the memory of Lev Okun, an expert on photon mass

ABSTRACT

The frequency-dependent time delays in fast radio bursts (FRBs) can be used to constrain the photon mass, if the FRB redshifts are known, but the similarity between the frequency dependences of dispersion due to plasma effects and a photon mass complicates the derivation of a limit on m_γ. The dispersion measure (DM) of FRB 150418 is known to $\sim 0.1\%$, and there is a claim to have measured its redshift with an accuracy of $\sim 2\%$, but the strength of the constraint on m_γ is limited by uncertainties in the modelling of the host galaxy and the Milky Way, as well as possible inhomogeneities in the intergalactic medium (IGM). Allowing for these uncertainties, the recent data on FRB 150418 indicate that $m_\gamma \lesssim 1.8 \times 10^{-14}$ eV c^{-2} (3.2×10^{-50} kg), if FRB 150418 indeed has a redshift $z = 0.492$ as initially reported. In the future, the different redshift dependences of the plasma and photon mass contributions to DM can be used to improve the sensitivity to m_γ if more FRB redshifts are measured. For a fixed fractional uncertainty in the extra-galactic contribution to the DM of an FRB, one with a lower redshift would provide greater sensitivity to m_γ.

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The purpose of the paper is to look for anomalous dispersion of FRB, which could be due to a photon mass effect.

Time delay due to photon mass

- The source is located at a fixed comobile coordinate l and emits 2 photons with energies E_1 and E_2 at the same universal time (redshift z_0).
- The photon velocity is:

$$\frac{dl}{dt} = \frac{p}{a^2(t)\sqrt{\frac{p^2}{a(t)^2} + m^2c^4}} \simeq \frac{1}{a(t)}\left(1 - \frac{1}{2}\frac{m^2c^4a(t)^2}{p^2c^2}\right)$$

- The first photon is received at $z = 0$ and the second at $z = -\epsilon$ with $\epsilon \ll 1$. $\Longrightarrow$

$$l = \int_0^{z_0} \frac{dz}{a(0)H(z)}\left(1 - \frac{1}{2}\frac{m^2c^4}{(z+1)^2p_1^2c^2}\right) = \int_{-\epsilon}^{z_0} \frac{dz}{a(0)H(z)}\left(1 - \frac{1}{2}\frac{m^2c^4}{(z+1)^2p_2^2c^2}\right)$$

Rearranging:

$$\int_0^{z_0} \frac{dz}{a(0)H(z)}\frac{1}{2}\frac{m^2c^4}{(z+1)^2}\left(\frac{1}{p_1^2c^2} - \frac{1}{p_2^2c^2}\right) = -\int_{-\epsilon}^{0} \frac{dz}{a(0)H(z)}\left(1 - \frac{1}{2}\frac{m^2c^4}{(z+1)^2p_2^2c^2}\right) \simeq \frac{\Delta T}{a(0)}$$

- The difference in arrival time is:

$$\boxed{\Delta T = \frac{m^2c^4}{2H_0}\int_0^{z_0} \frac{dz}{(z+1)^2\sqrt{\Omega_M(1+z)^3 + (1-\Omega_M)}}\left(\frac{1}{p_1^2c^2} - \frac{1}{p_2^2c^2}\right)} \quad (3)$$

Limits on the photon mass

- The authors of paper use only 2 frequencies: 1.2 GHz and 1.5 GHz (on both sides of average 1.382 GHz, bandwidth 340 MHz).
- Time lag $\Delta t_{\text{lag}} \simeq 0.8$s
- Assume all photons are emitted at the source at the same time.
- The time lag is the sum of the plasma dispersion delay part and the mass related delay.

$$\Delta t_{\mathrm{lag}} = \frac{m_\gamma^2}{2H_0} \cdot F(E_1, E_2) \cdot H_\gamma(z) + \Delta t_{\mathrm{DM}},$$

where $F(E_1, E_2) \equiv \left(\frac{1}{E_1^2} - \frac{1}{E_2^2}\right)$ and $H_\gamma(z) \equiv \int_0^z \frac{dz'}{(1+z')^2\sqrt{\Omega_\Lambda + (1+z')^3\Omega_m}}$

Turning around, the photon mass can be expressed for FRB150418 as:

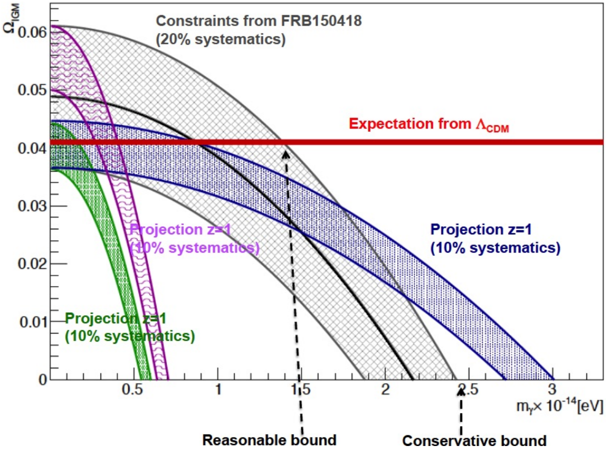
$$m_\gamma = \left(2.96 \cdot 10^{-14}\,\mathrm{eV} \cdot \mathrm{s}^{-1/2}\right)\sqrt{B - C}$$

with $B = (103.1\,\mathrm{s}) \cdot \frac{\mathrm{DM}_{\mathrm{IGM}}^{\mathrm{obs}}}{10^5\ \mathrm{pc\ cm}^{-3}}$.

- Full delay due to mass: $DM_{\mathrm{IGM}}^{obs} < 532 + 2 \cdot 107$, (95% C.L.), C=0
  $\Longrightarrow\ m_\gamma < 2.6 \cdot 10^{-14}\,\mathrm{eV} \cdot \mathrm{s}^{-1/2}$ (95% C.L.)
- Substraction of expected Λ_{CDM} DM delay,
  $C = \frac{0.041}{0.049} 532 = 445 \ \Longrightarrow\ \boxed{m_\gamma < 1.7 \cdot 10^{-14}\,\mathrm{eV} \cdot \mathrm{s}^{-1/2}}$ (95% C.L.)

Prospects

Influence of photon mass is larger on dispersion of photons from low-redshift sources.



Introduction

PRL **117,** 091301 (2016) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2016

Lensing of Fast Radio Bursts as a Probe of Compact Dark Matter

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The possibility that part of the dark matter is made of massive compact halo objects (MACHOs) remains poorly constrained over a wide range of masses, and especially in the 20–100 $M_\odot$ window. We show that strong gravitational lensing of extragalactic fast radio bursts (FRBs) by MACHOs of masses larger than $\sim 20\ M_\odot$ would result in repeated FRBs with an observable time delay. Strong lensing of a FRB by a lens of mass M_L induces two images, separated by a typical time delay $\sim$few $\times$ $(M_L/30\ M_\odot)$ msec. Considering the expected FRB detection rate by upcoming experiments, such as canadian hydrogen intensity mapping experiment (CHIME), of 10^4 FRBs per year, we should observe from tens to hundreds of repeated bursts yearly, if MACHOs in this window make up all the dark matter. A null search for echoes with just 10^4 FRBs would constrain the fraction $f_{\rm DM}$ of dark matter in MACHOs to $f_{\rm DM} \lesssim 0.08$ for $M_L \gtrsim 20\ M_\odot$.

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The purpose of the paper is to study the use of FRB to detect compact objects.The compact objects, like in the EROS/MACHO/OGLE surveys, deflect light and produce **gravitational lensing**.

Fermat potential and lens equation

Light trajectory in a lens background determined by an equivalent "Fermat principle" with potential:

$$T = (z_L + 1)(\frac{1}{D_{OL}} + \frac{1}{D_{LS}})\left(\frac{1}{2}(r - r_0)^2 - r_E^2 \ln|r| + D_0^2\right)$$

where

$$r_E = \sqrt{\frac{4GM(D_{OL} + D_{LS})}{D_{OL}D_{LS}}} \tag{4}$$

is the **Einstein radius**.

- time delay has 2 contributions: geometrical + Shapiro effect.
- minimizing with respect to r gives the **lens equation**:

$$r - r_0 = \frac{r_E^2}{r} \tag{5}$$

with solutions:

$$r_\pm = \frac{1}{2}\left(r_0 \pm \sqrt{r_0^2 + 4r_E^2}\right)$$

- 2 light paths (gravitational mirage)

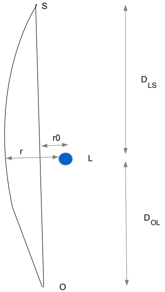


Image magnification and time delay

Image magnification $\mu_\pm$ obtained by comparing the elementary surface elements in spherical coordinates.

$$\mu_\pm = |\frac{r_\pm dr_\pm}{r_0 dr_0}| = \frac{1}{2}\frac{r_0^2 + 2r_E^2 \pm r_0\sqrt{r_0^2+4r_E^2}}{r_0\sqrt{r_0^2+4r_E^2}}$$

The total magnification is

$$\mu = \mu_+ + \mu_- = \frac{r_0^2 + 2r_E^2}{r_0\sqrt{r_0^2+4r_E^2}}$$

$\rightarrow$ well known (to microlensing teams) "Paczynski curve".
Define

$$y_0 = \frac{r_0}{r_E}, \quad y = \frac{r}{r_E},$$

The magnification ratio is:

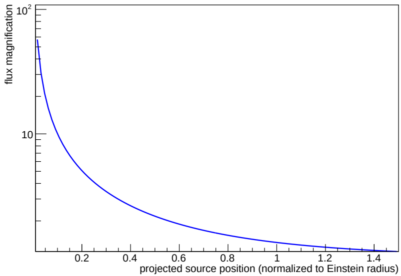
$$R = \frac{\mu_+}{\mu_-} = \frac{y^2+2+y\sqrt{y^2+4}}{y^2+2-y\sqrt{y^2+4}} \tag{6}$$

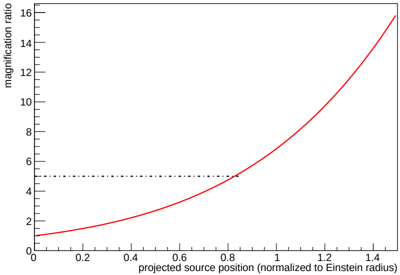
The time difference comes up to be:

$$\boxed{\Delta T = t_+ - t_- = -10\mu s(z_L+1)\frac{M}{M_\odot}\left(\frac{1}{2}(y_0\sqrt{4+y_0^2}) + \ln|\frac{y_0+\sqrt{4+y_0^2}}{y_0-\sqrt{4+y_0^2}}|\right)} \tag{7}$$

(note the sign difference with the paper).

Image magnification and time delay (2)

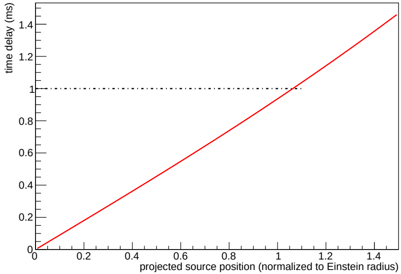


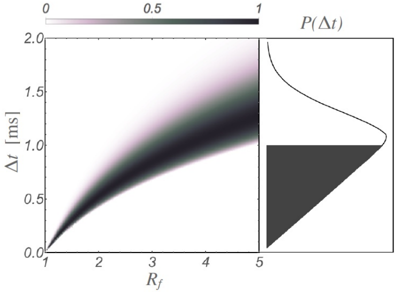


(Flux magnification of source with $\frac{r_0}{r_E} < 1$) > 1.34

(Magnification ratio < 5) requires $\frac{r_0}{r_E} < 0.8$

Image magnification and time delay (3)





$\Delta t > 1$ ms requires $\frac{r_0}{r_E} > 1$ (position cut depends on lens mass and redshift)

(Magnification ratio < 5) and $\Delta t > 1$ ms (from paper)

Lensing optical depth

- Best reference on this topic: paper by Fukugita, Futamase, Kasai and Turner, ApJ 1992.
- Lensing optical depth depends strongly on assumed cosmology. In the paper probably (?) FRW with $\Omega_K = 0$ and $\Omega_\Lambda + \Omega_M = 1$.
- Distances D_{OL} etc are **angular diameter distances**
- Let $n(0)$ be the present *numeric* density of lenses. Then the density at redshift z_L is $n(0)(z_L+1)^3$ since lenses are massive and non relativistic.
- Cross-section for being lensed inside radius yr_E :

$$\sigma = y^2 \pi r_E^2 = y^2 \frac{4\pi GM}{c^2} \frac{D_{OL} D_{LS}}{D_{OS}}$$

- Lensing probability per unit distance is thus

$$\frac{dP}{a(t) d\chi} = \frac{dP}{dt} = n(z_L)\sigma(z_L)$$

- The total probability for a fixed source (optical depth):

$$\tau = \int_0^{z_S} n(0)(z_L+1)^3 \sigma \left|\frac{dt}{dz_L}\right| dz_L$$

Since

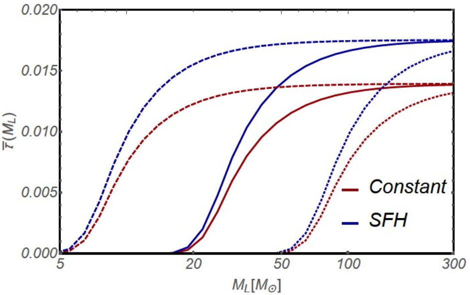
$$\frac{dt}{dz_L} = -\frac{c}{H_0(1+z_L)} \frac{1}{\sqrt{\Omega_M(1+z_L)^3 + (1-\Omega_M)}}$$

with the mass density $n_M = n(0)M$ and $\Omega_L(0) = \frac{8\pi G n_M}{3H_0^2}$

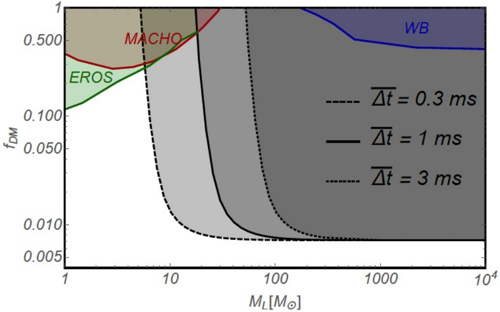
$$\boxed{\tau = \frac{3}{2}\Omega_L \int_0^{z_S} y^2 (z_L+1)^2 \frac{D_{OL} D_{LS} H_0}{D_{OS}} \frac{1}{\sqrt{\Omega_M(1+z_L)^3 + (1-\Omega_M)}} dz_L} \quad (8)$$

Lensing optical depth (2)

- In the paper, the lenses are selected between 2 values of y:
  - $\geq y_{min}$: minimal delay between image arrival
  - $\leq y_{max}$: minimal magnification ratio.
- the optical depth is averaged over the measured distribution of source redshifts.
- Optical depth $\sim 0.01 - 0.02$
  $\rightarrow$ need 50-100 FRB to observe 1 lensing event if dark matter entirely in compact objects.



Expected limits on density of compact objects



- survey with 10^4 FRB detected (CHIME?)
- No quoted CL for the limits! Probably "less than one event" assumed.

Spot the mistakes..

... in pages 4-5 of Munoz et al (PRL 117, 091301 (2016)).

Finite size of lenses and sources

Note that, due to our requirement that they behave as point lenses, MACHOs need to be smaller than their Einstein radii. This constrains the size of a MACHO of mass M_L to be more compact than $\sim$0.1 pc $\times \sqrt{M_L/30\ M_\odot}$.

- Effect of lens size depends on whether or not the lens is transparent.
- If the size of the lens is larger than the Einstein radius and:
  - lens opaque (e.g lensing by the sun), then occultation possible
  - lens transparent (e.g. dark matter clumps), sensible only to enclosed mass
- Lens size effects generally irrelevant.
- **source size** effects are more important to consider (could wash out entirely the lensing effect)
  - Projected size of the emission region of the source has to be compared to Einstein radius ($r_E \simeq 0.1$ pc $\sqrt{\frac{M_L}{M_\odot}} = 10^7 \mathrm{s} \sqrt{\frac{M_L}{M_\odot}}$)
  - Size of emission region is $S \simeq (10ms)D$ where D is a possible jet Doppler factor (< 1000.)
  - $S \ll r_E \implies$ source size effect unimportant.

femtolensing

An effect similar to femto- or nanolensing of gamma-ray bursts could be observed in FRBs [50,51], albeit, given the relatively low frequency ($\nu \sim$ GHz) of FRBs, one could probe lenses only with masses higher than $M_L \sim 10^{-5}\ M_\odot$, since lower masses would create a time delay smaller than $1/\nu$ and not cause interference. An experiment with bandwidth $\Delta\nu \sim 20$ kHz could probe a maximum mass $M_L \sim 0.1\ M_\odot$ with nanolensing (higher masses would cause time delays longer than $1/\Delta\nu$ and interfere within each

Femtolensing (2)

In the femtolensing regime, the 2 light paths interfere.
Signature: modulation on the observed spectrum, component of wavelength λ gets attenuated by

$$A \simeq (1 + \cos K \frac{4GM_L}{c^2\lambda})$$

where K is a constant.
The effect gets washed out when

$$\frac{4GM_L}{c^2\lambda} \gg 1$$

- $\frac{4GM_L}{c^2} = 3km \frac{M_L}{M_\odot}$
- With optical light (EROS, MACHO) $\lambda \simeq 0.5\mu m$ and $\frac{4GM_L}{c^2\lambda} \simeq 10^7 \frac{M_L}{M_\odot} \gg 1$ for ordinary stars $\implies$ no femtolensing.
- With X-rays (GRB lensing) $\lambda \simeq 10^{-10} m$ and femtolensing occurs for masses **less** than $10^{-11} M_\odot$. See Barnacka, Glicenstein and Moderski, PRD 2012.
- With radio waves $\lambda \simeq 10cm$, $\frac{4GM_L}{c^2\lambda} \simeq 3000 \frac{M_L}{M_\odot}$ so femtolensing occurs for masses **less** than $10^{-5} M_\odot$.

microlensing by MACHOs, constraints from FRB121002

It has been argued that we could be preferentially observing strongly lensed FRBs [47,48]. If this is the case, most observed FRBs will be lensed by intervening objects, such as galactic halos, on their way to Earth. This would create a double image with a time delay on the order of weeks [49]. More importantly, when crossing those galactic halos the probability to be microlensed by a MACHO is close to unity, which would help detect more microlensed FRBs or improve our constraints on f_{DM}.

In galactic halos, ordinary stars will also contribute to microlensing, possibly much more than MACHOs. It is not clear to me that the constraints will improve, due to these systematics.

Among the FRBs found to date, there is one particular event, FRB 121002, which has been observed with a double peak delayed by 5.1 ms [21]. This delay could have been caused by a MACHO lens of mass $M_L \gtrsim 200\ M_\odot$. The second image of FRB 121002 appears brighter, however, which contradicts the usual lensing prediction. In Ref. [52], we will assess how likely it is that this delay is due to lensing and study further cosmological applications of lensing of FRBs.

According to formulas in section "Gravitational lensing in 3 transparencies", having the brighter image come last does not contradict usual lensing predictions. Let's then wait for reference [52]!

Conclusion

- FRB are powerfull probes of the Intergalactic medium history (in principle, could get baryon ionisation vs redshift).
- Could be used to probe photon masses provided the systematic uncertainties of Galactic electron distribution are reduced.
- Could be used to constrain the density of compact objects in the [20-100] $M_{\odot}$ range with lensing provided future surveys detect $> 10^3$ FRB.
- May also be used to further constrain the very low mass range with femtolensing provided usable spectra are available.