How the ngVLA can enable gravitational-wave science

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With Shri Kulkarni and Sterl Phinney, and with thanks to the NRAO ngVLA community studies program.

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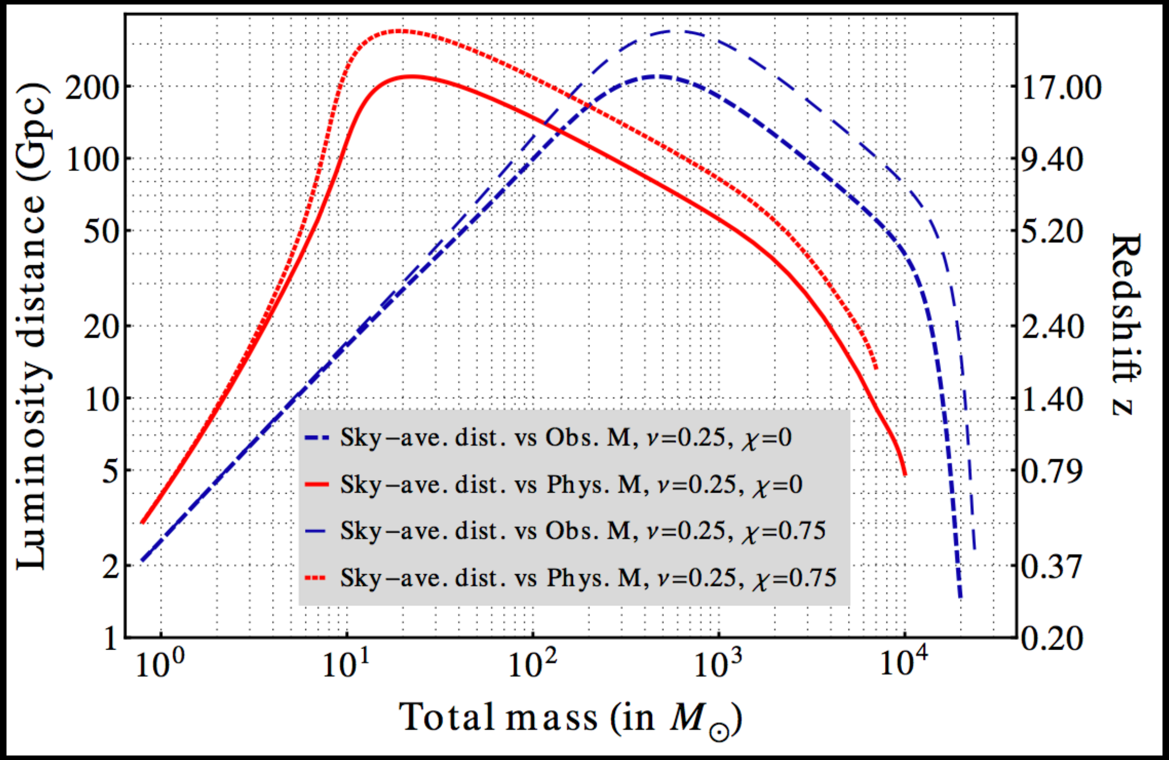
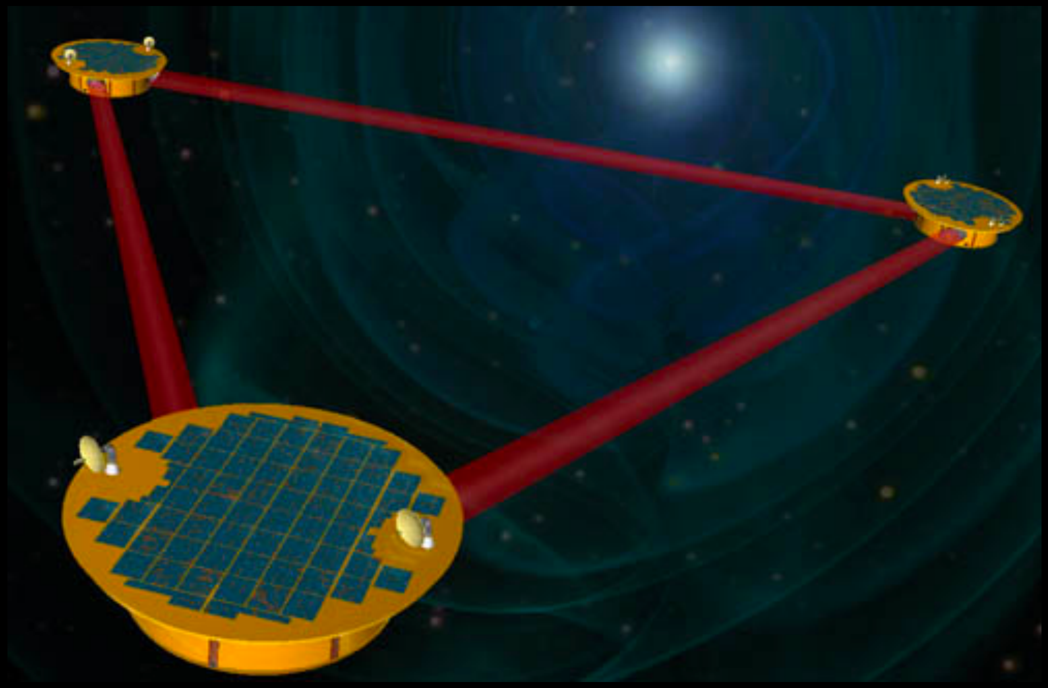
2nd and 3rd generation ground-based GW detectors

2nd gen. aLIGO, VIRGO, KAGRA, INDIGO: up to 10-100 binary NS mergers per yr.

3rd gen. Einstein telescope: 10x better frequency coverage, 10x better sensitivity

e.g., Nissanke et al. 2013, Sathyaprakash et al. 2012

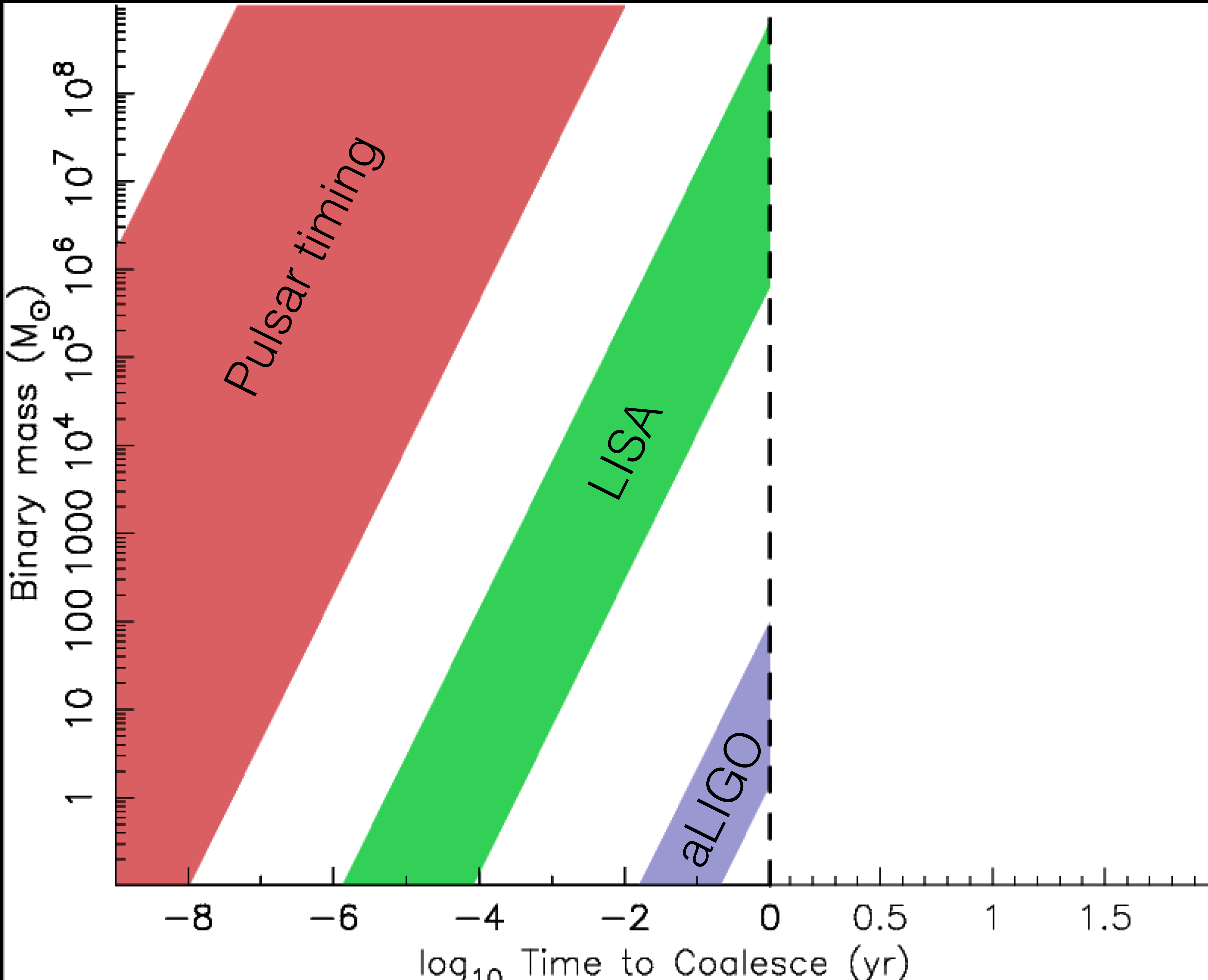


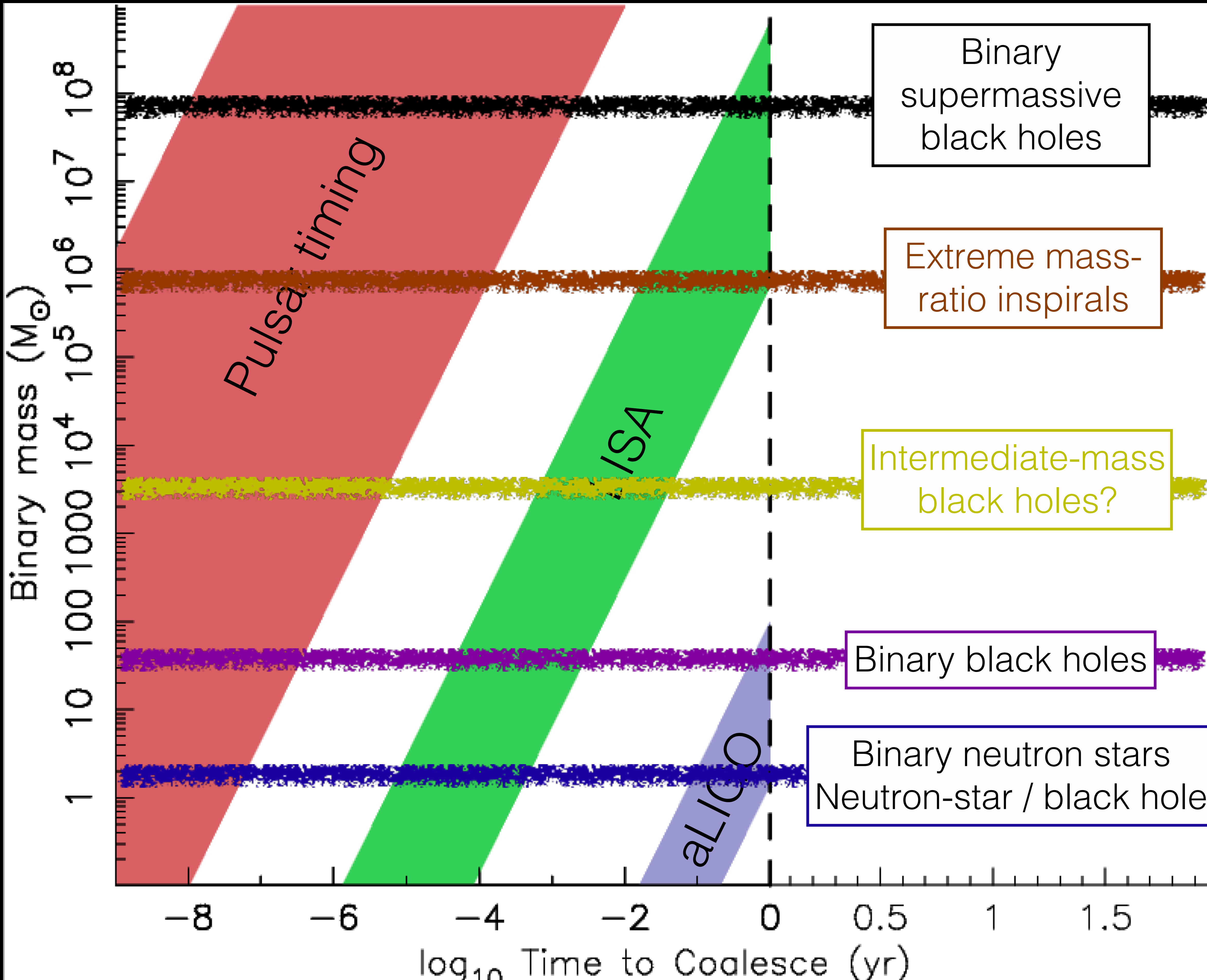


e.g., Amaro-Seoane et al. 2012

2034 launch, with three identical spacecraft.
SMBH coalescences [~100],
extreme mass-ratio inspirals [~100],
compact stellar binaries [~10^6].

LISA - selected as ESA L3 mission, NASA support


Pulsar timing
LISA
aLIGO
Binary mass ($M_\odot$)
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
−8
−6
−4
−2
0
0.5
1
1.5
$\log_{10}$ Time to Coalesce (yr)

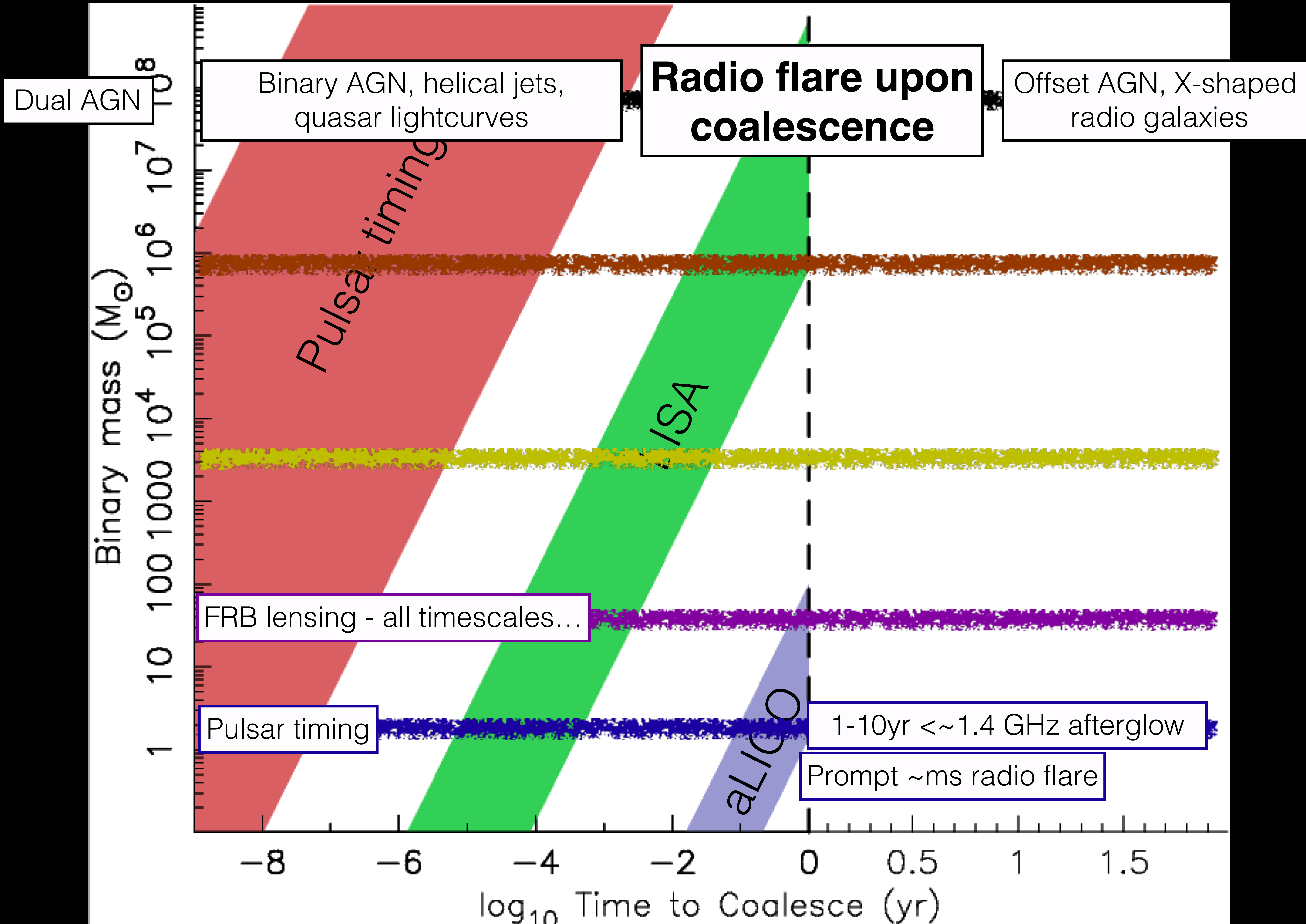


Binary supermassive black holes
Extreme mass-ratio inspirals
Intermediate-mass black holes?
Binary black holes
Binary neutron stars
Neutron-star / black hole
Pulsar timing
LISA
aLIGO
Binary mass (M⊙)
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
−8
−6
−4
−2
0
0.5
1
1.5
log10 Time to Coalesce (yr)

Necessity for electromagnetic counterparts to GW sources

1. **NS - compact object mergers**
   - Outflow characteristics depend on nature of *r*-process nucleosynthesis in ejecta.
   - Persistent NS, or collapse to black hole? Depends on NS equation of state.
   - Redshifts -> component masses.
   - Astrophysics of NS evolution tested by e.g., accurate localization within galaxies.

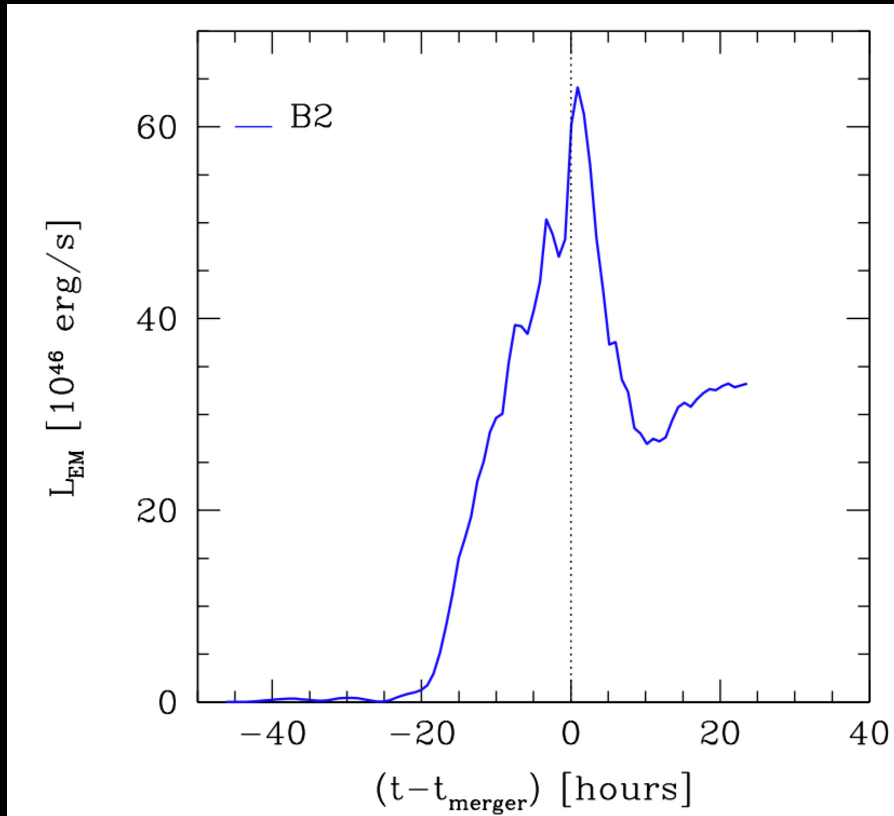
2. **Supermassive black hole mergers**
   - Direct cosmological tests and component mass measurements from redshift measurements.
   - Tests of GRMHD models for accretion during merger.
   - Astrophysics of (binary) supermassive black hole formation.



Dual AGN
Binary AGN, helical jets, quasar lightcurves
Radio flare upon coalescence
Offset AGN, X-shaped radio galaxies
Pulsar timing
LISA
aLIGO
FRB lensing - all timescales…
Pulsar timing
1-10yr <~1.4 GHz afterglow
Prompt ~ms radio flare
Binary mass ($M_\odot$)
1
10
100
1000
10^4
10^5
10^6
10^7
10^8
−8
−6
−4
−2
0
0.5
1
1.5
$\log_{10}$ Time to Coalesce (yr)

Binary black hole merger simulation, with GRMHD treatment of circum-binary plasma, displaying matter-density

Giacomazzo et al. (2012), see also Moesta et al. (2012)



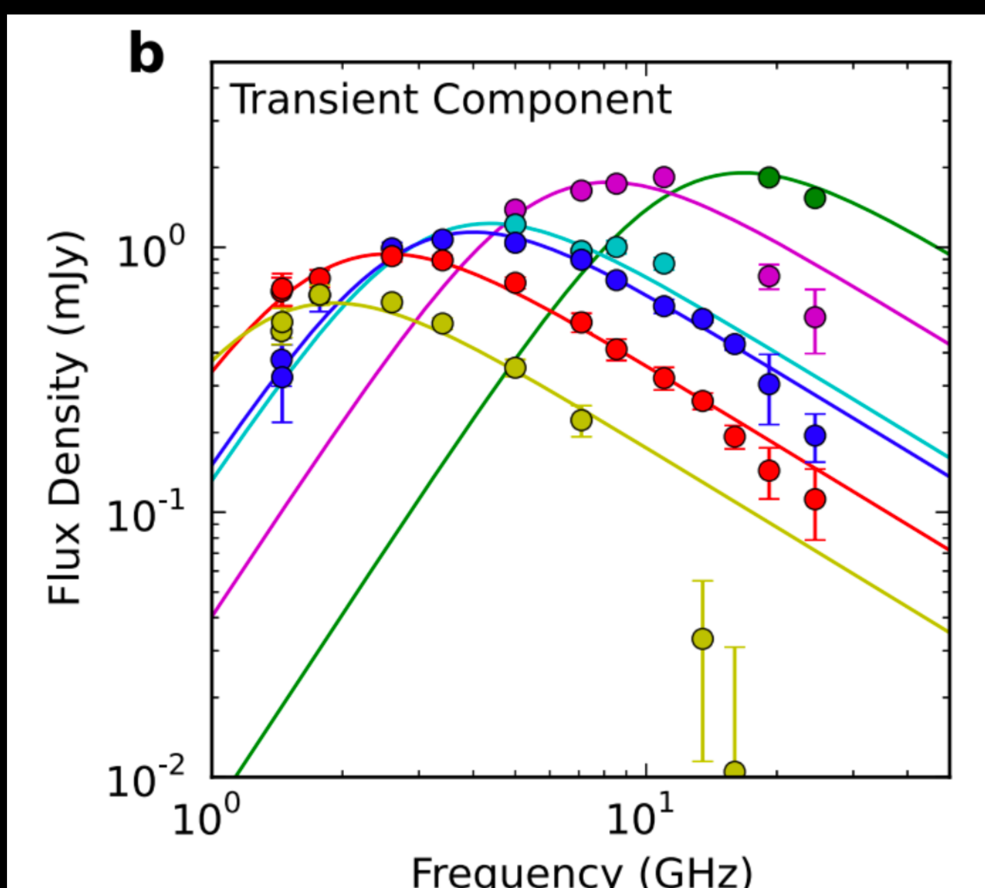
Collimated Poynting luminosity:

$\sim 10^{47}$ (M/10^8 Msun)^2 (B/10^4 G)^2 erg/s

~ 10x Eddington luminosity!

10^{-5} to 10^{-2} of the luminosity expected in the radio:

F_{peak} ~ 0.2-200 (D/60 Gpc)$^{-2}$ mJy



ASSASN-14li: Alexander et al. (2016)

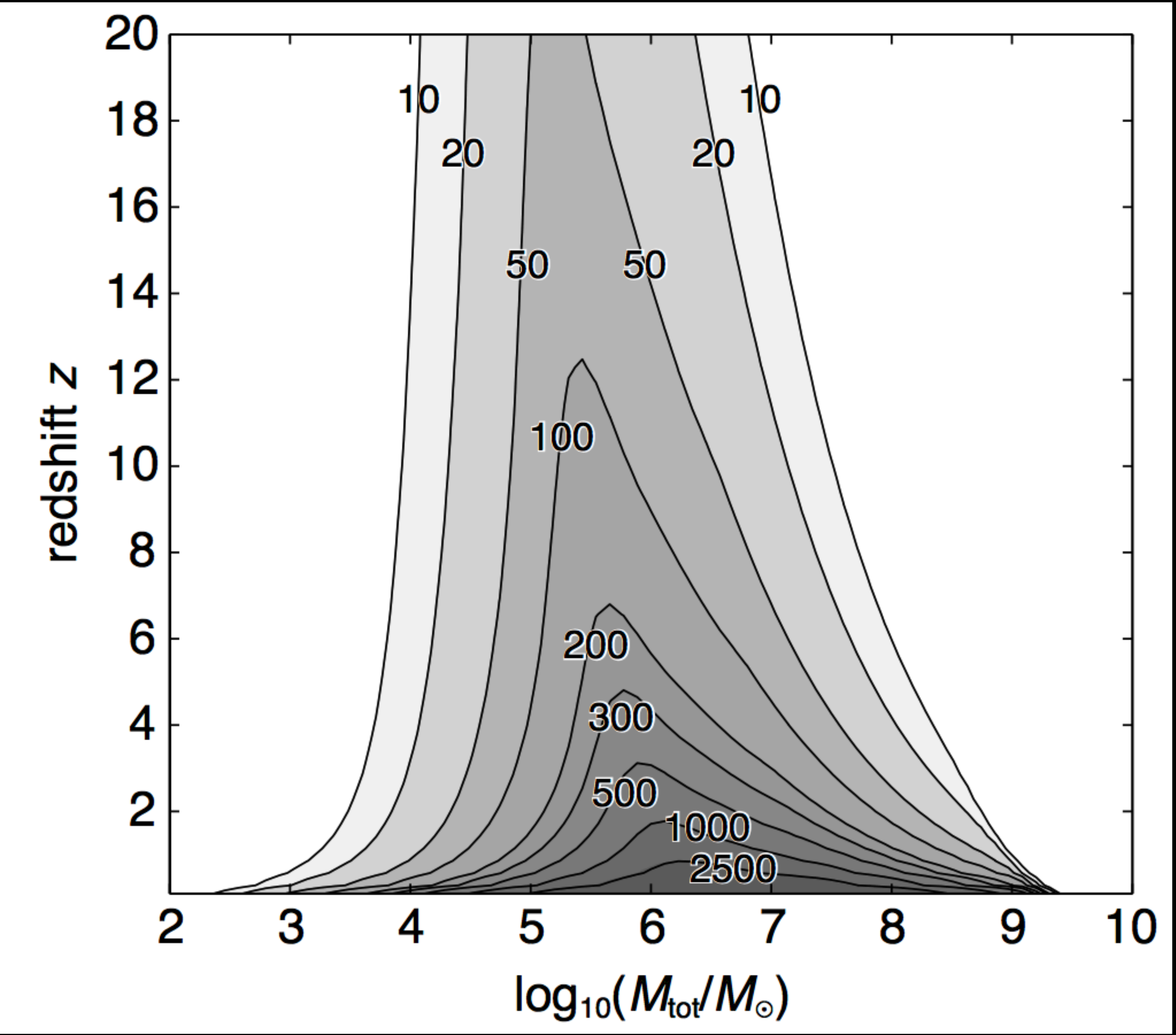
Time of peak flux in rest-frame:

1.4 (E/10^{48} erg)$^{1/3}$ (n/10^3 cm^{-3})$^{-1/3}$ days

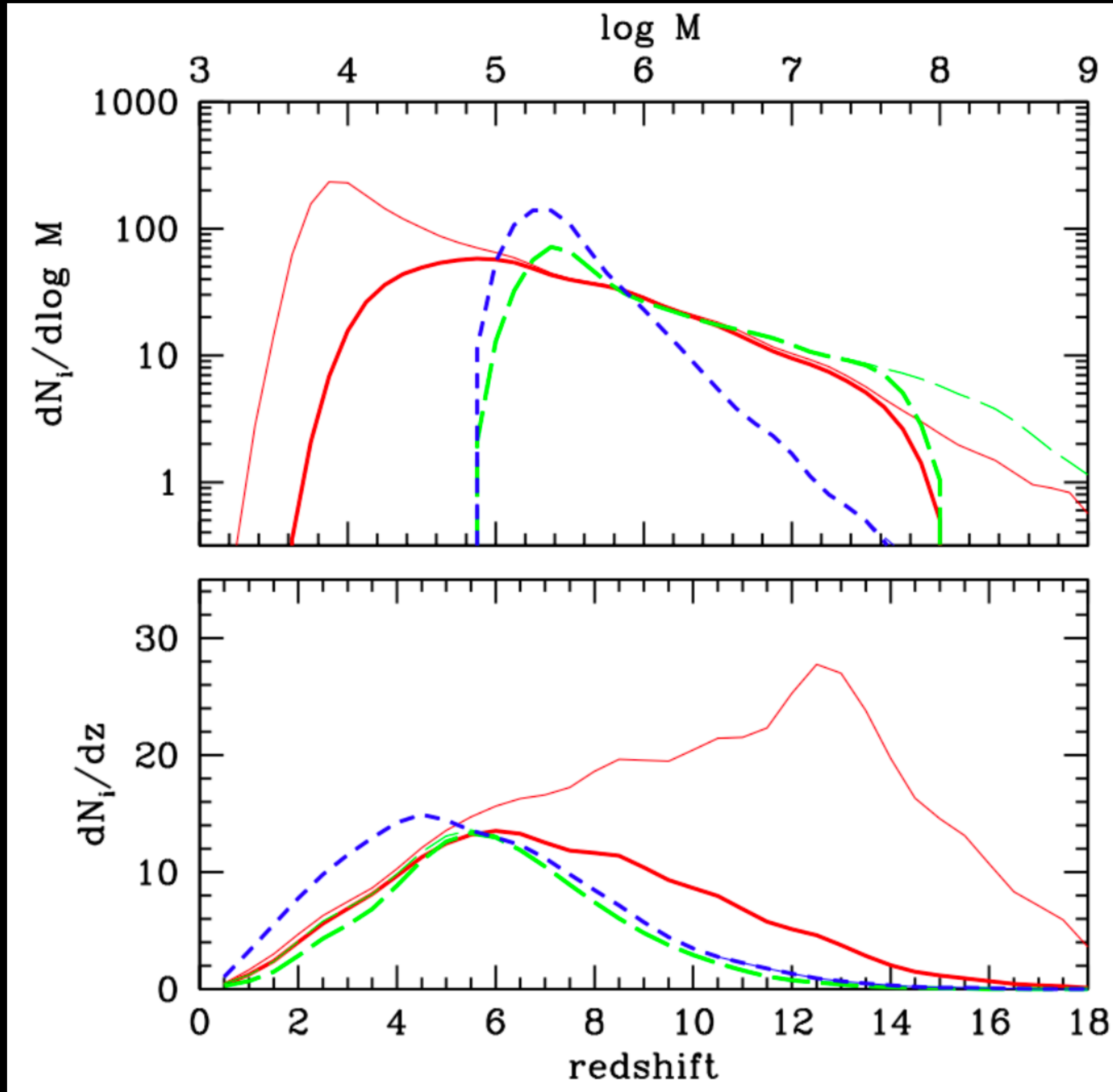
Freq. of peak flux in rest-frame:

30 (E/10^{48} erg)$^{1/6}$ (n/10^3 cm^{-3})$^{-5/9}$ GHz

Factor of few longer rise time, to factor of few lower peak, at lower frequencies

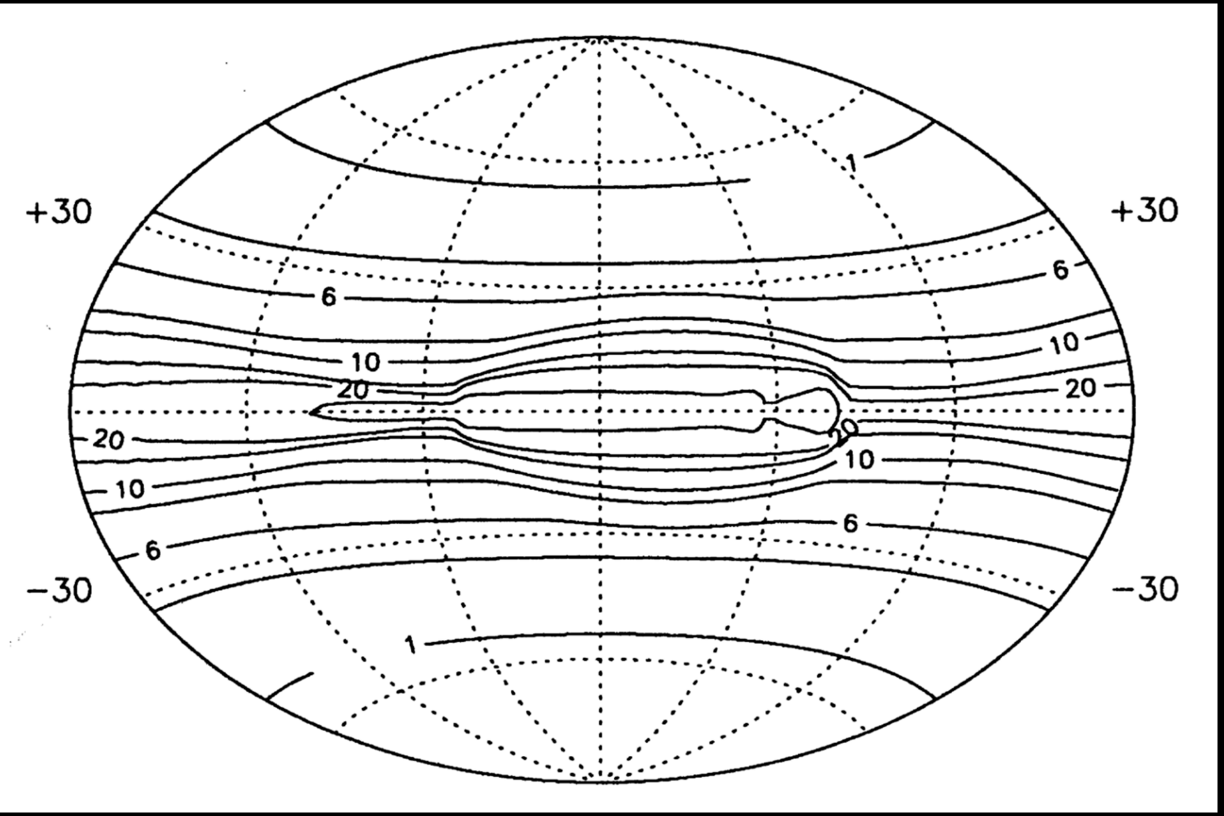


Amaro-Seoane et al. (2012)

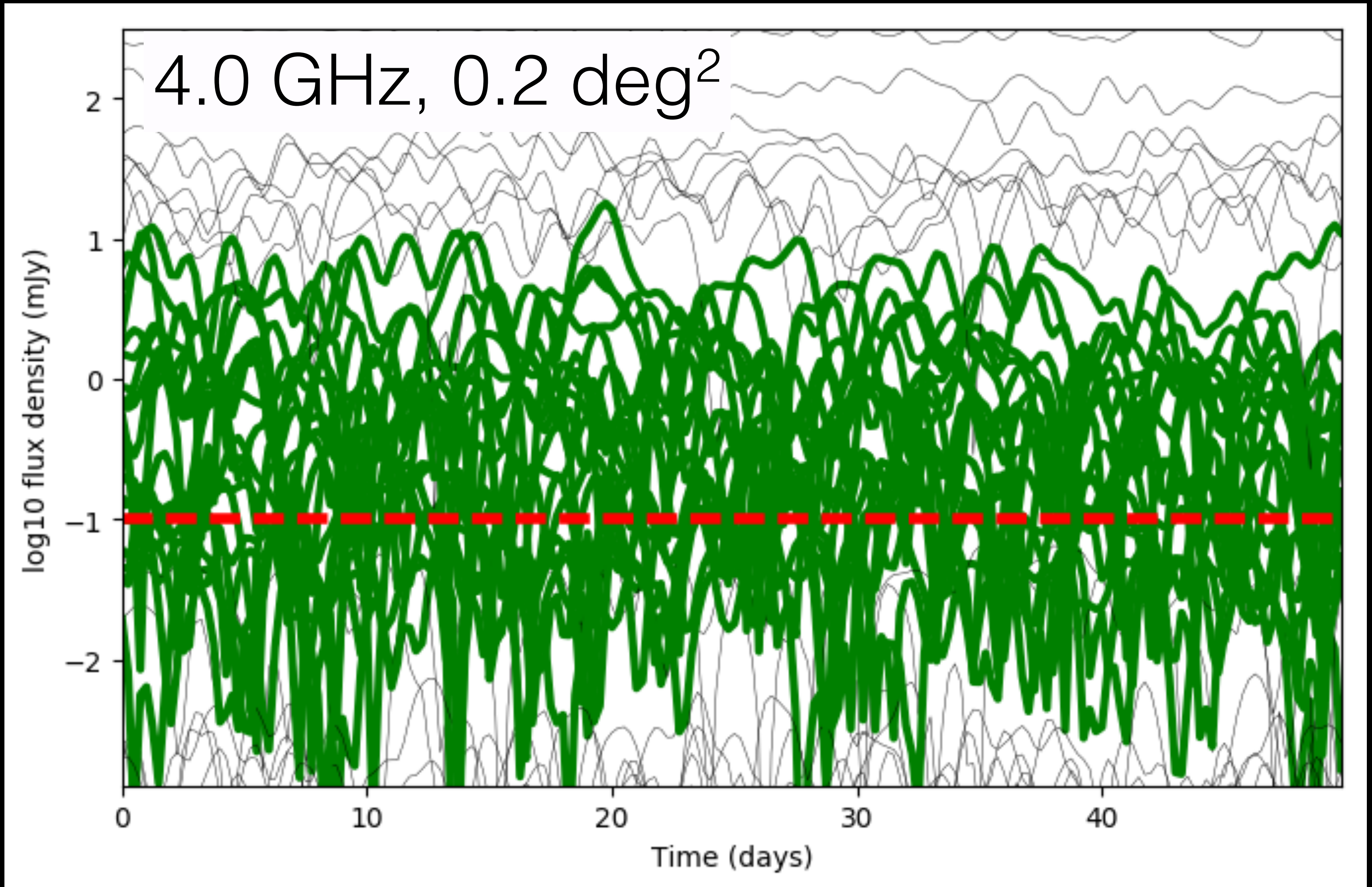


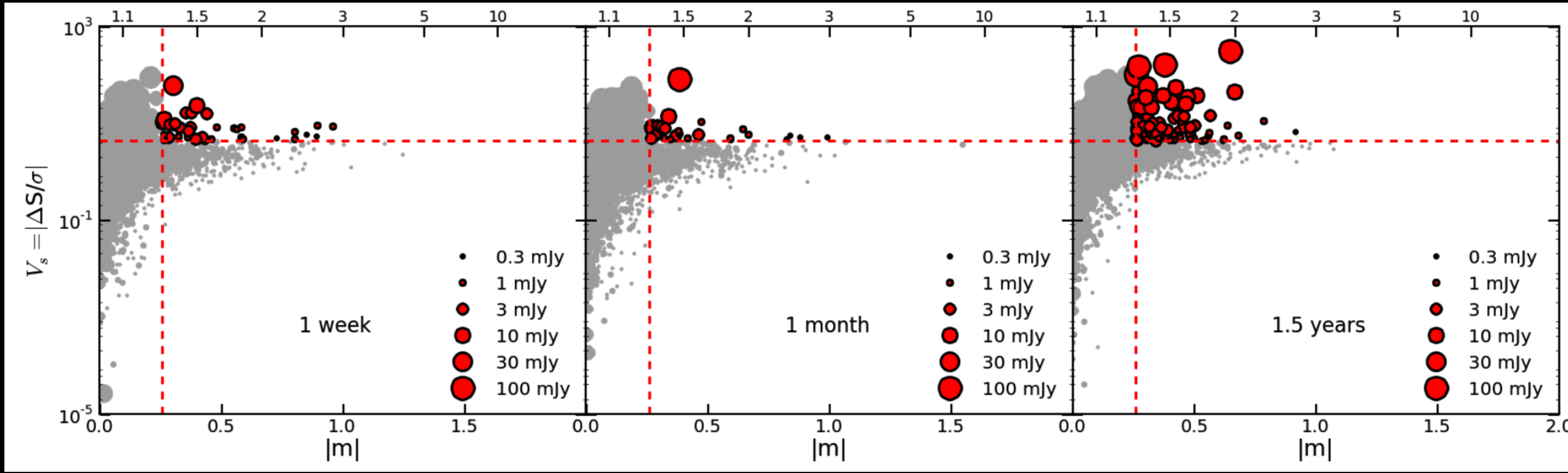
Sesana et al. (2011); see Tamanini et al. (2016) for
review of cosmological measurements with EM/GW LISA science

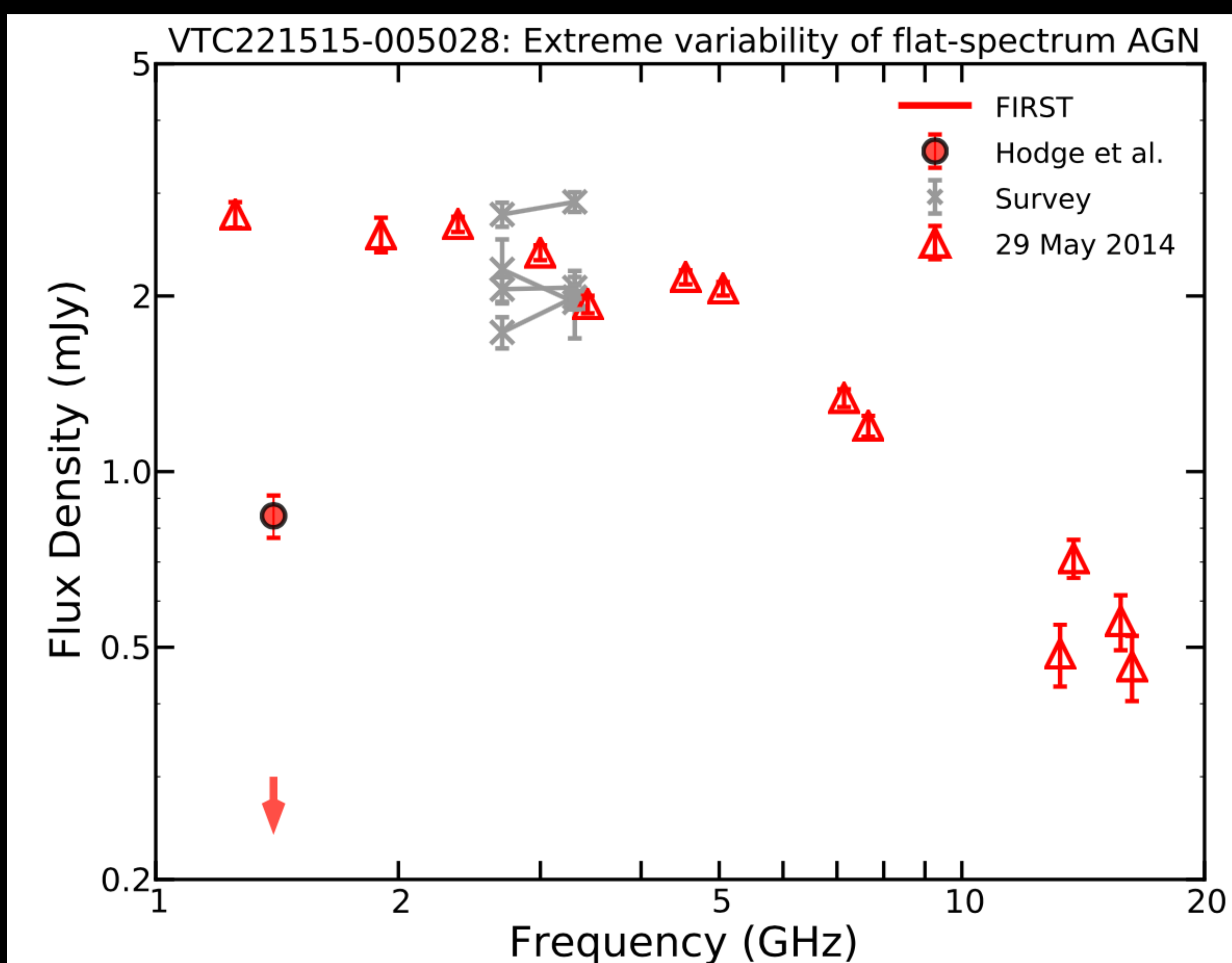
1. >50% of sources unresolved with the VLA will scintillate (e.g., Lovell et al. 2008).
2. Stronger, more rapid scintillations are expected at frequencies close to the transition frequency.
3. Weaker AGN may well turn out to have stronger scintillations, as they are smaller for fixed T_b.



Walker (1998)







1. Typical radio jet Lorentz factors imply that a few percent of radio AGN are viewed on-axis.
2. These sources are significantly variable, and can exhibit flares of over 10x.
3. Often hard to optically characterise.

Mooley et al. (2016)

LISA will localize (20 deg^2) ~100 binary SMBHs each year, with many at z~6.

These may produce >~100 uJy centimetric radio transients, sometimes relativistic, lasting several days.

At 6 GHz, expect ~2400 sources >100 uJy, of which ~40 will be on-axis. All will scintillate with modulation index ~$(S/100\ uJy)^{-1/2}$ on a few-hour timescale. The on-axis sources will generally vary, and flare every 5-10 years, with timescales of weeks to months.

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Likely require <10 seconds per pointing with ngVLA.

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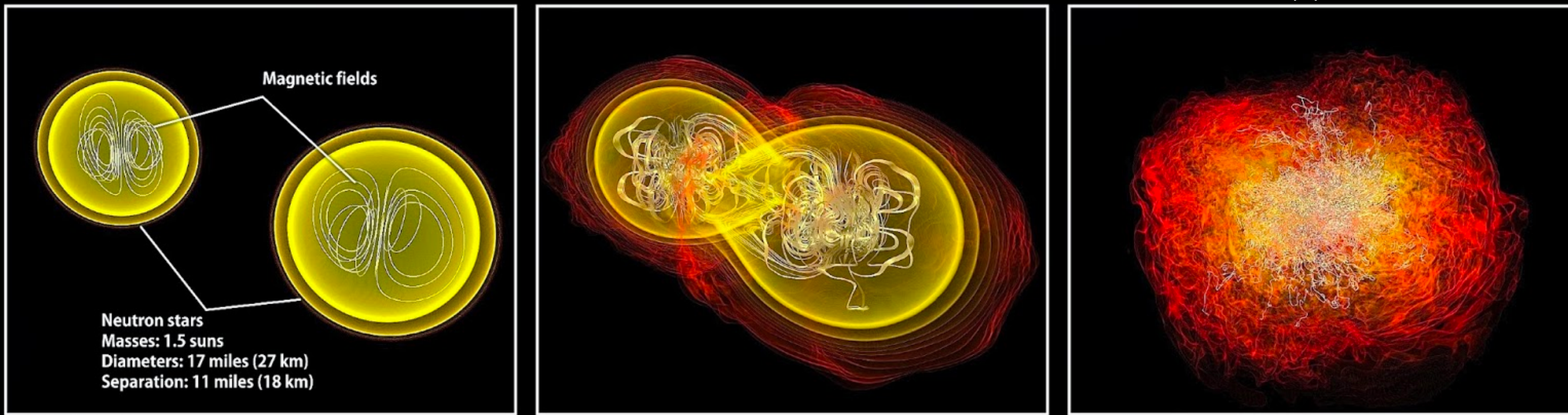
To be determined:

Are radio observations the most promising means of identifying LISA events?

What are the *resolution* and *spectral-coverage* requirements for the most efficient rejection of interlopers, and the best characterization of the transients?

NASA/ESA/AEI, M. Koppitz & L. Rezzolla



Simulation begins — *7.4 milliseconds* — *13.8 milliseconds*

See e.g. Yancey et al. (2015)

Hansen & Lyutikov (2001)

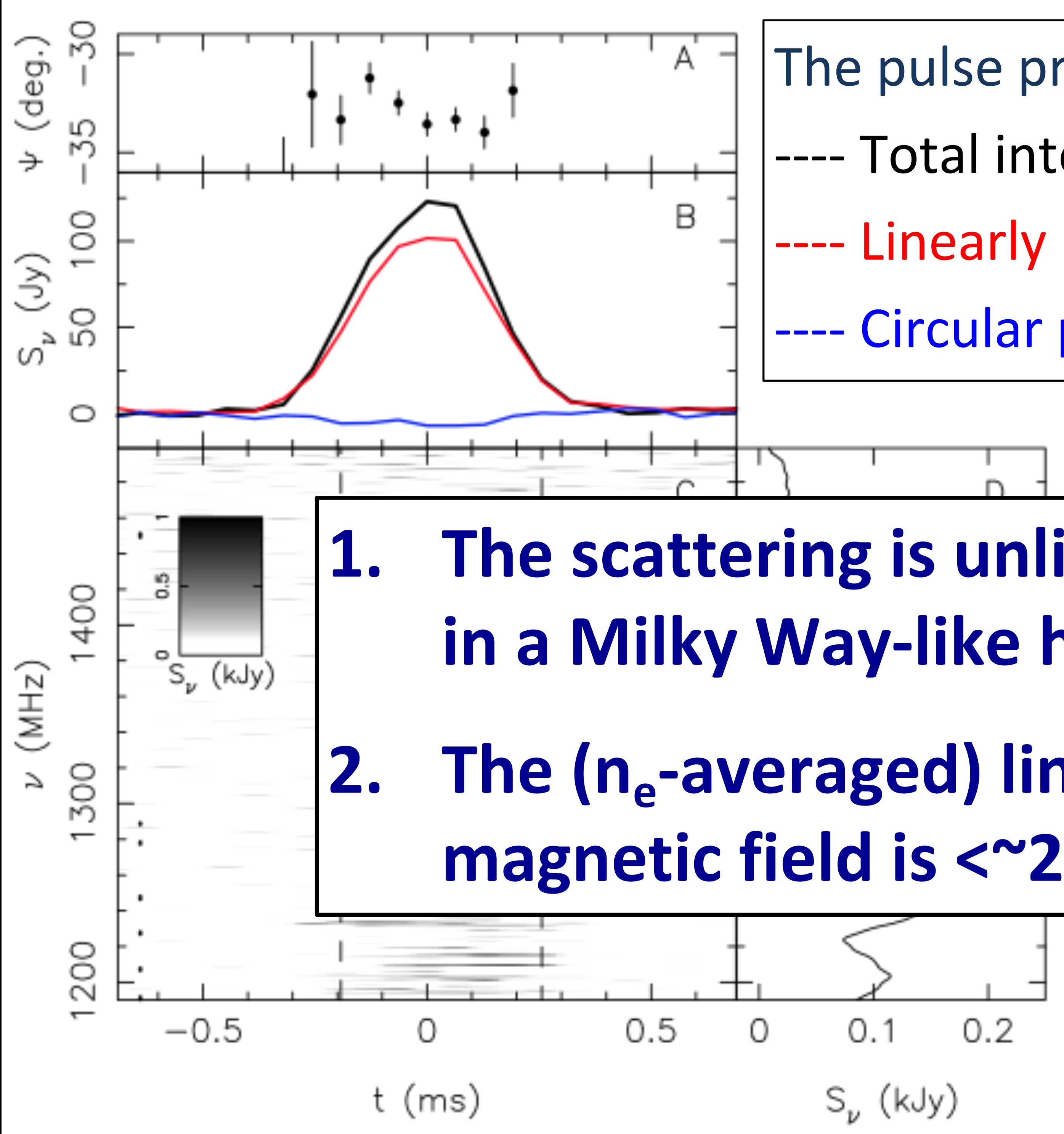
Induced "eddy current" charge acceleration from an MSP merging with a magnetar.

Expect bolometric luminosity of few x10^{36} erg/s in seconds before merger.

Pshirkov & Postnov (2010)

Differential rotation of hyper-massive NS briefly amplifies remnant magnetic field.

Expect bolometric luminosity of up to 10^{50} erg/s in milliseconds after merger.



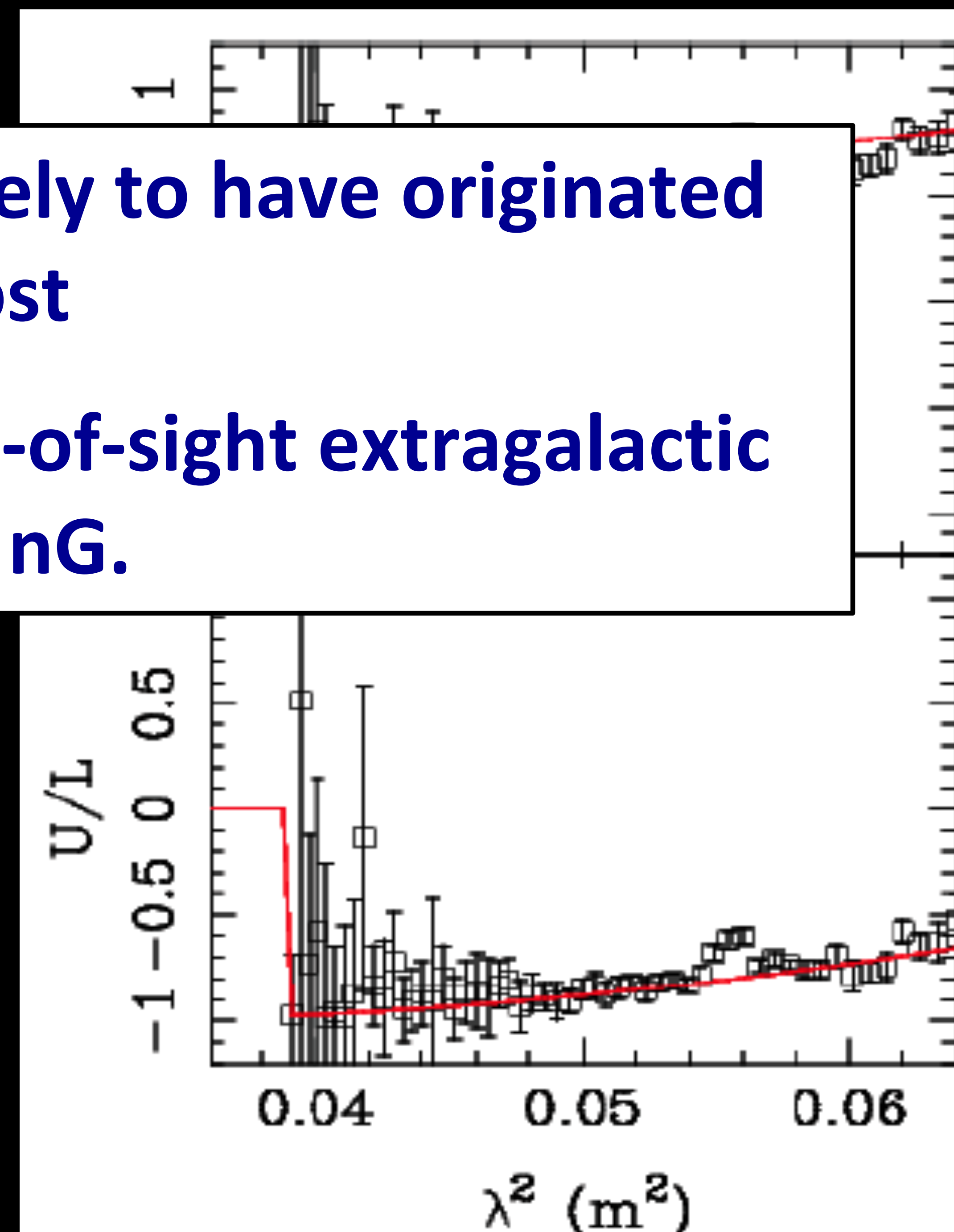
The pulse profile:

---- Total intensity

---- Linearly polarised intensity

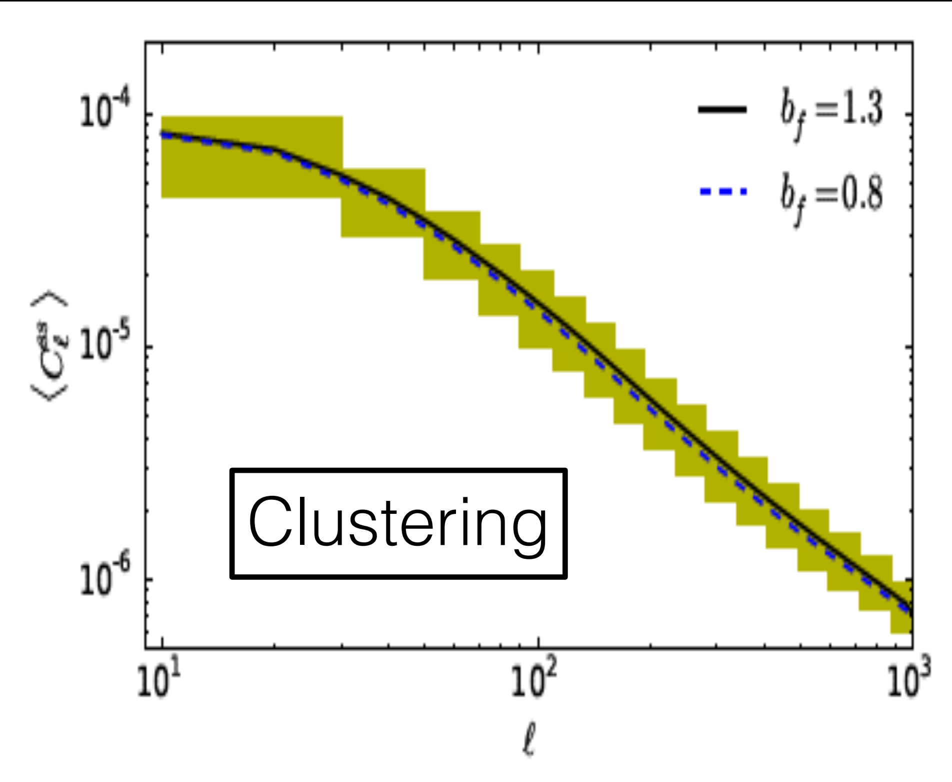
---- Circular polarisation

Ravi et al. (2016) Science, **354**, 1249

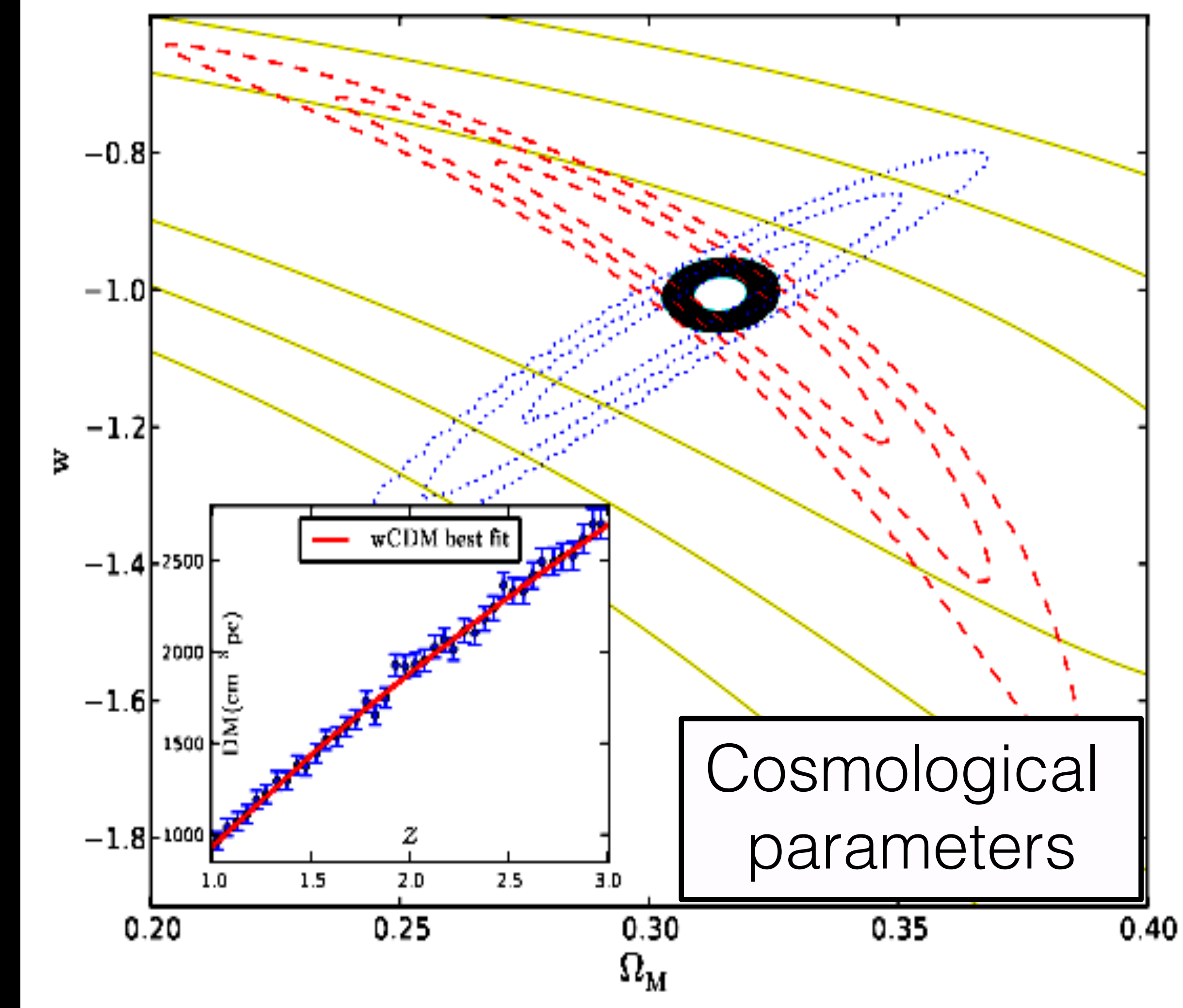


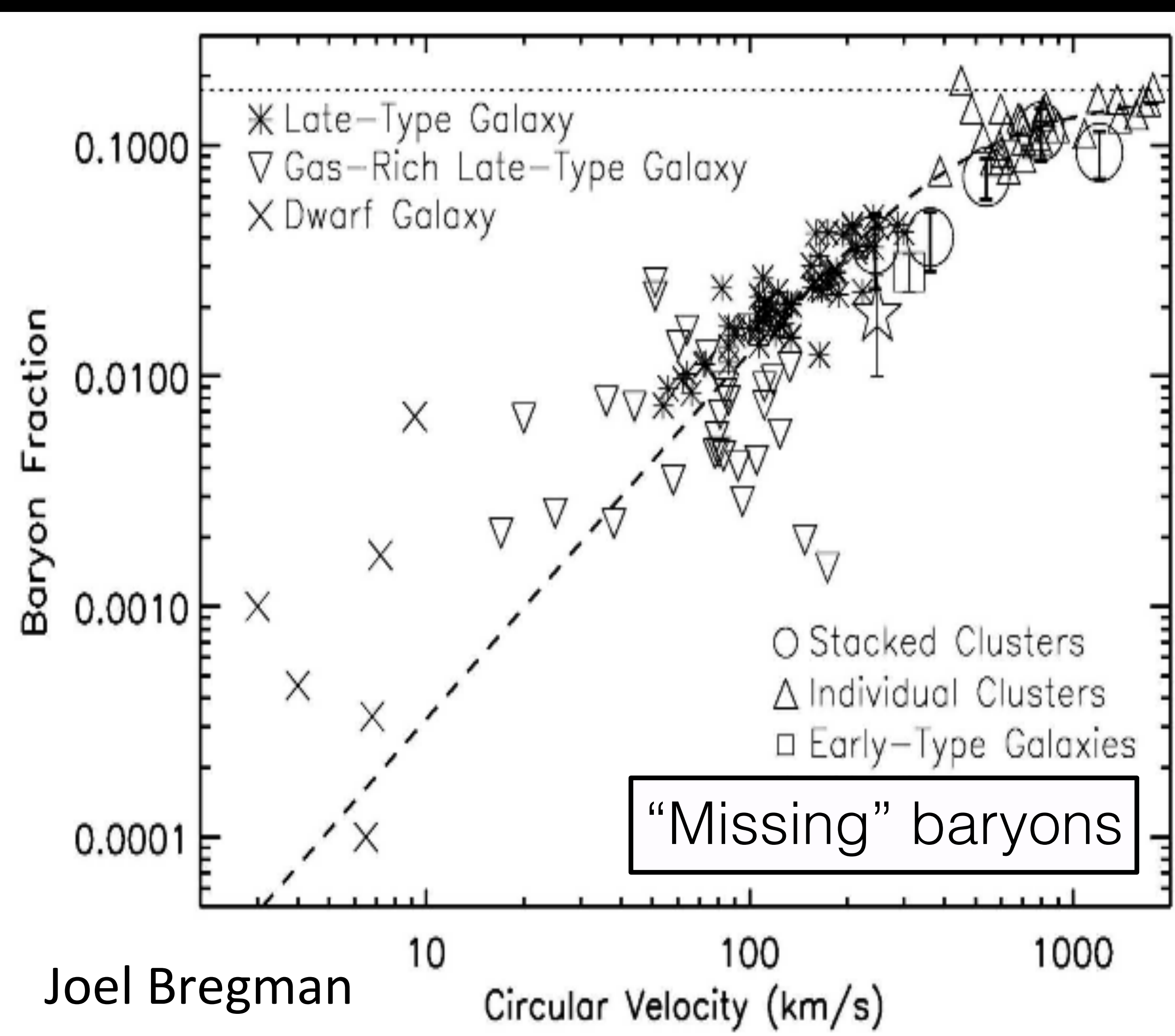
1. **The scattering is unlikely to have originated in a Milky Way-like host**
2. **The (n_e-averaged) line-of-sight extragalactic magnetic field is <~20 nG.**

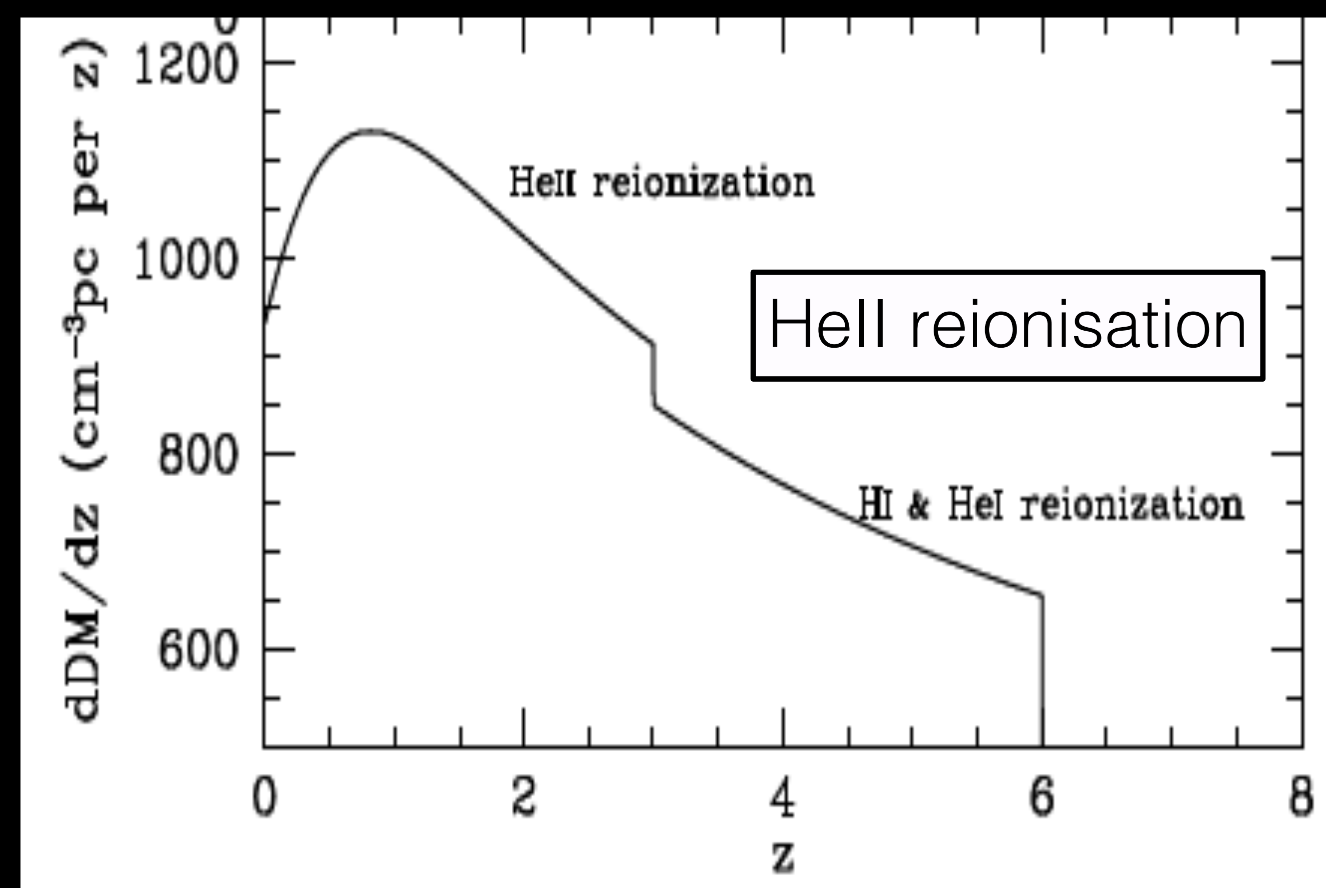
Up to 1 kJy flux densities
RM of 12.0±0.7 rad m^{-2} (consistent with Milky Way only)
100 kHz scintillation bandwidth

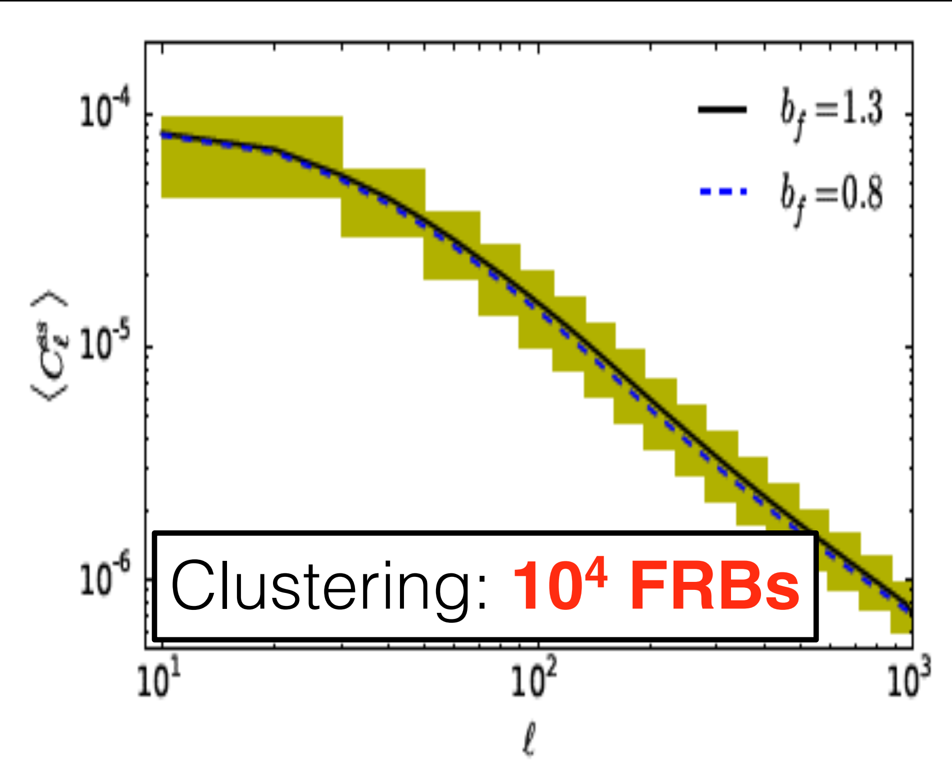


McQuinn (2014); Masui & Sigursdon (2015); Zhou et al. (2014), Zheng et al. (2015), Deng & Zhang (2015); Wei et al. (2015); Dolag et al. (2015)









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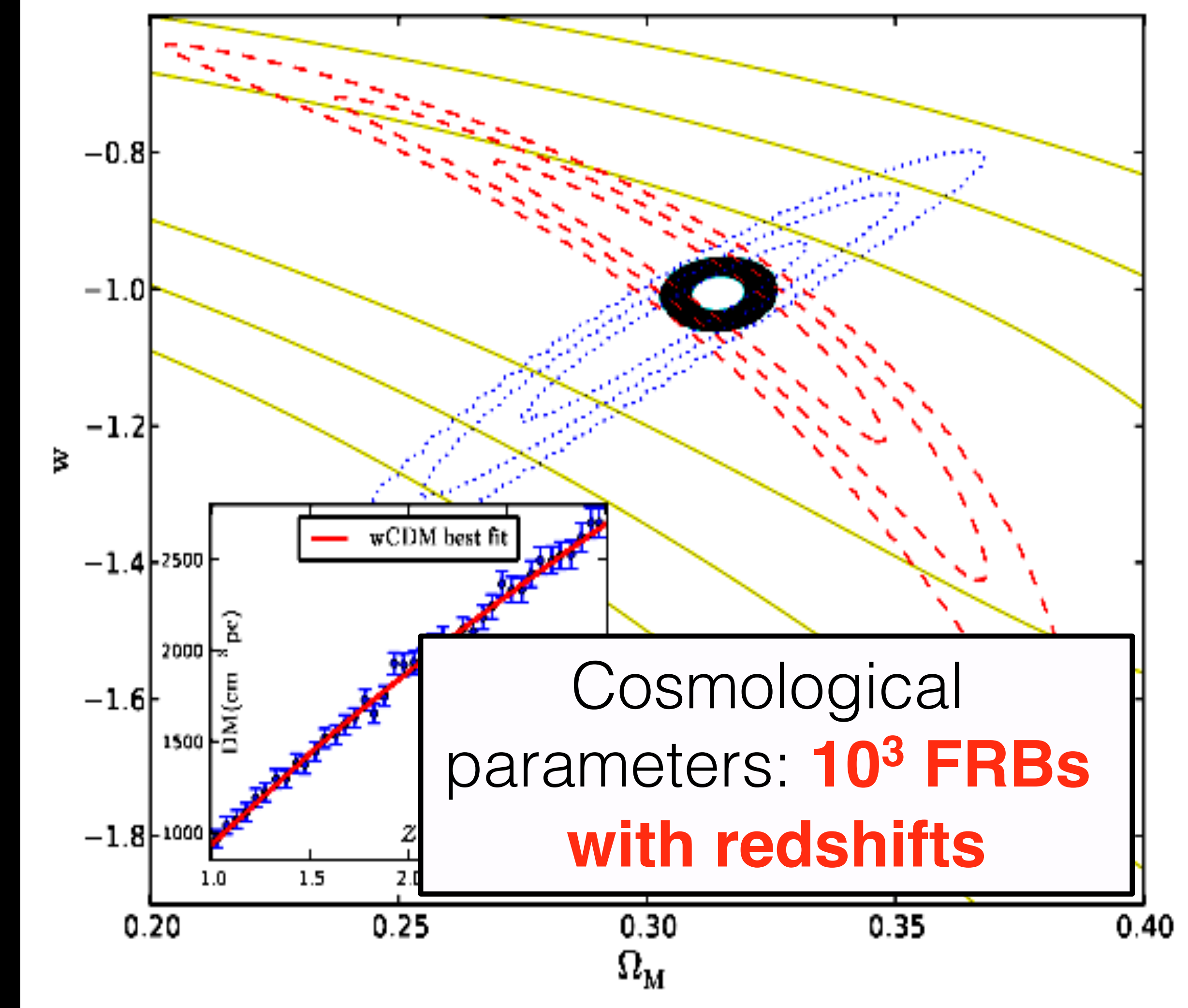
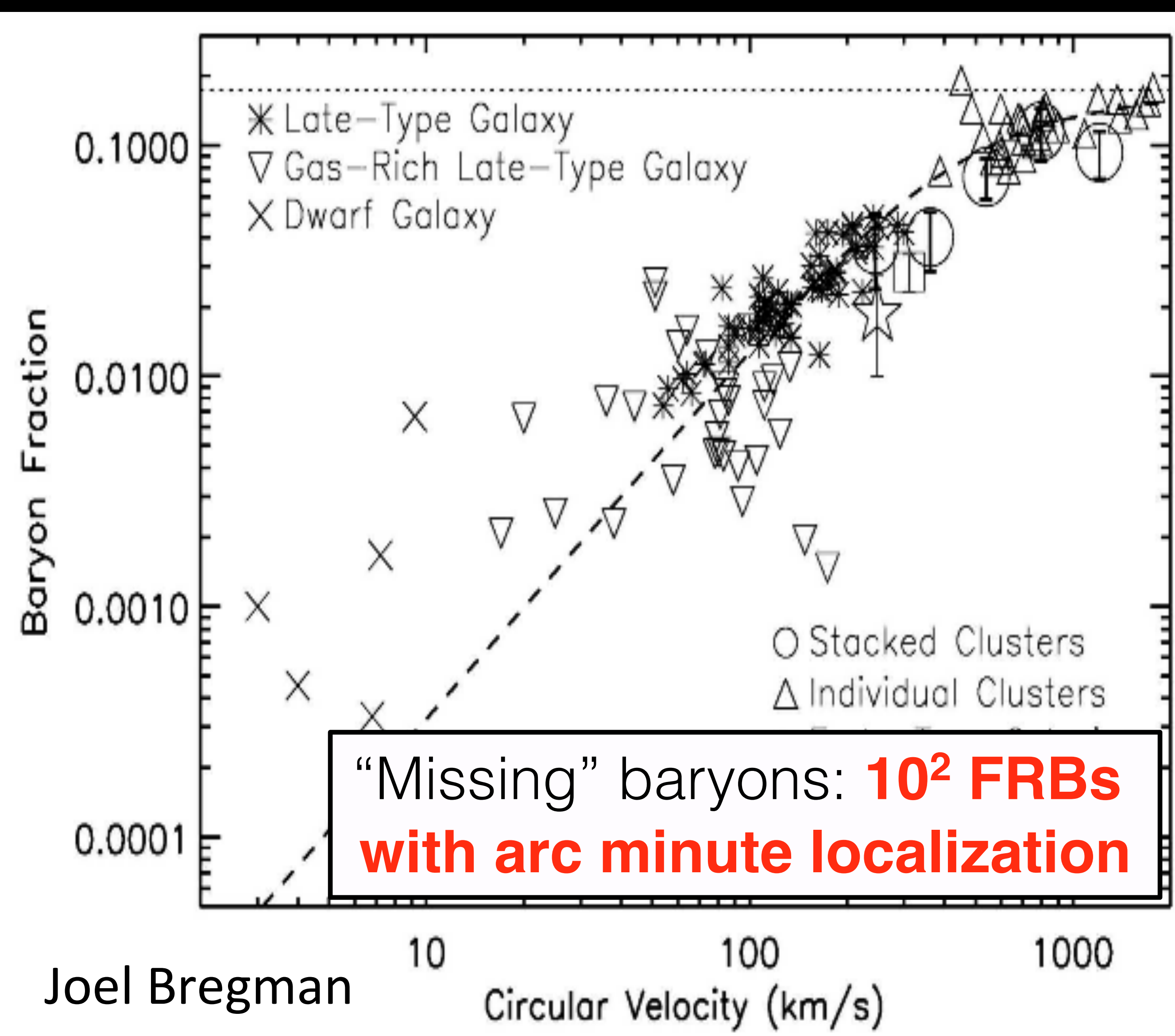
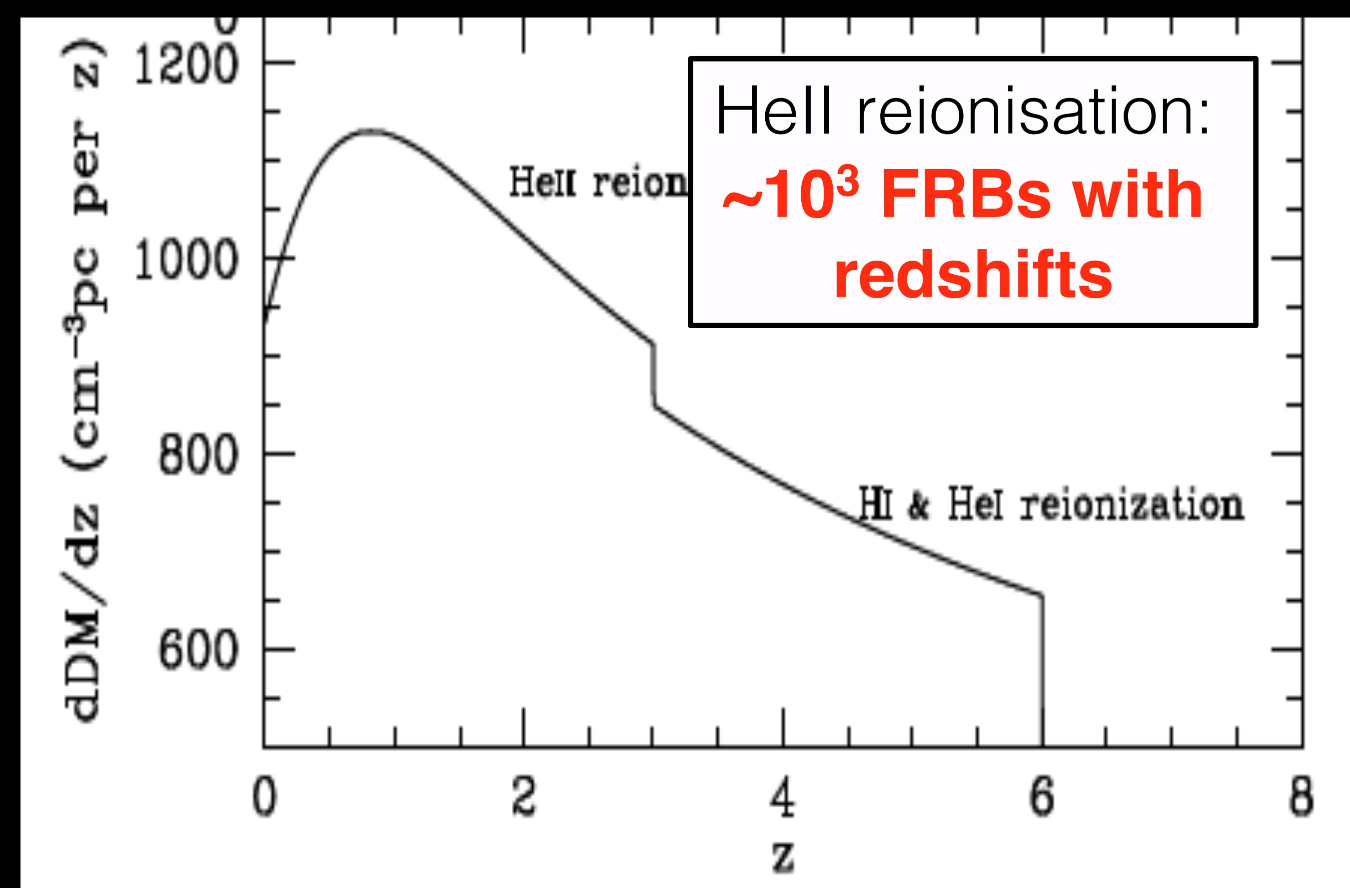




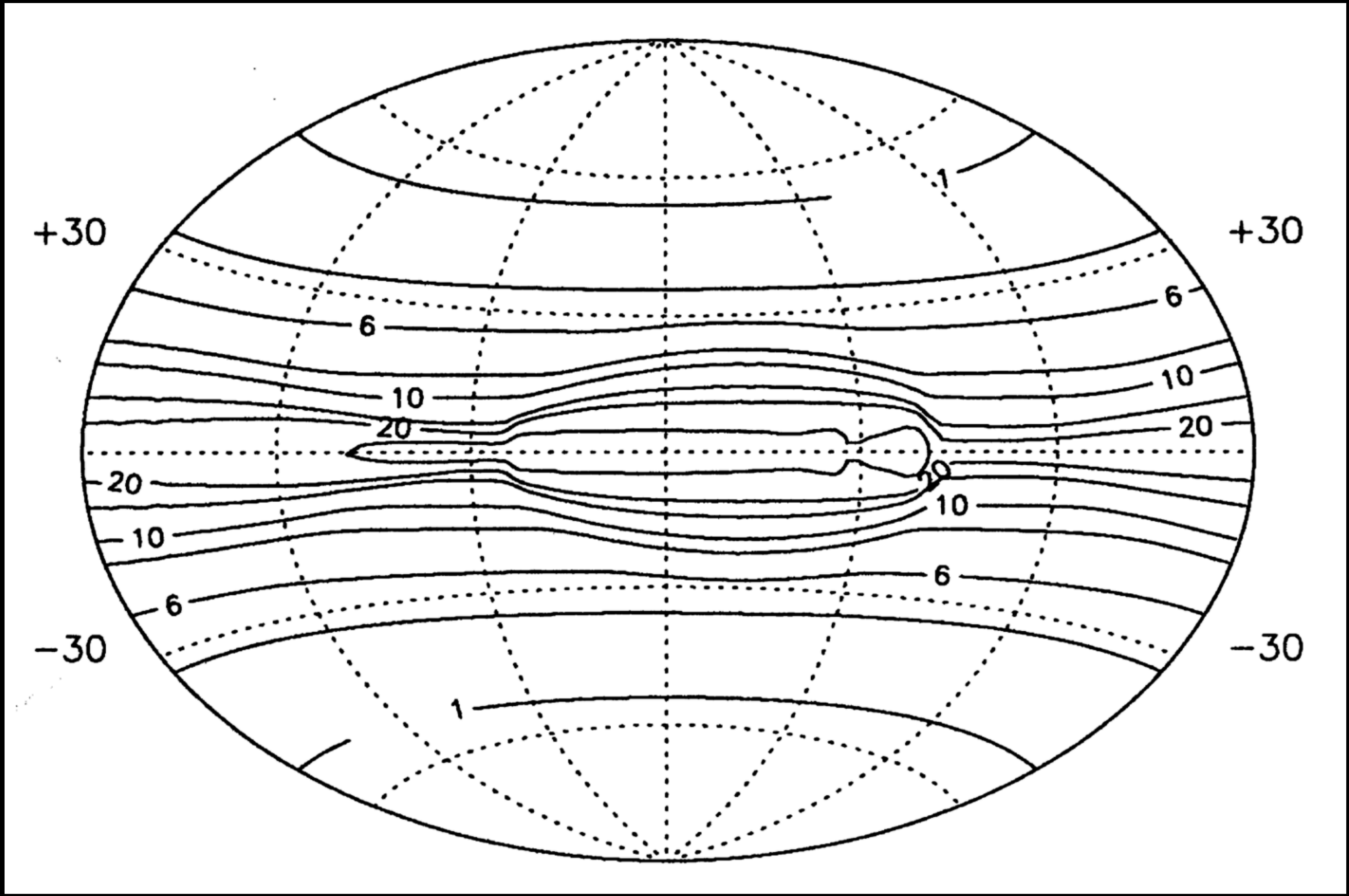
Joel Bregman



1. ***NS-NS and SMBH-SMBH mergers***, detectable with GW detectors on the SKA timescale, likely produce ***days-to-years 0.1 mJy transients***.

2. Although detectable, ***these transients will be dotted amongst a swarm of variables, and some AGN transients.*** E.g., one flaring >0.1 mJy source at any given time per 100 deg^2.

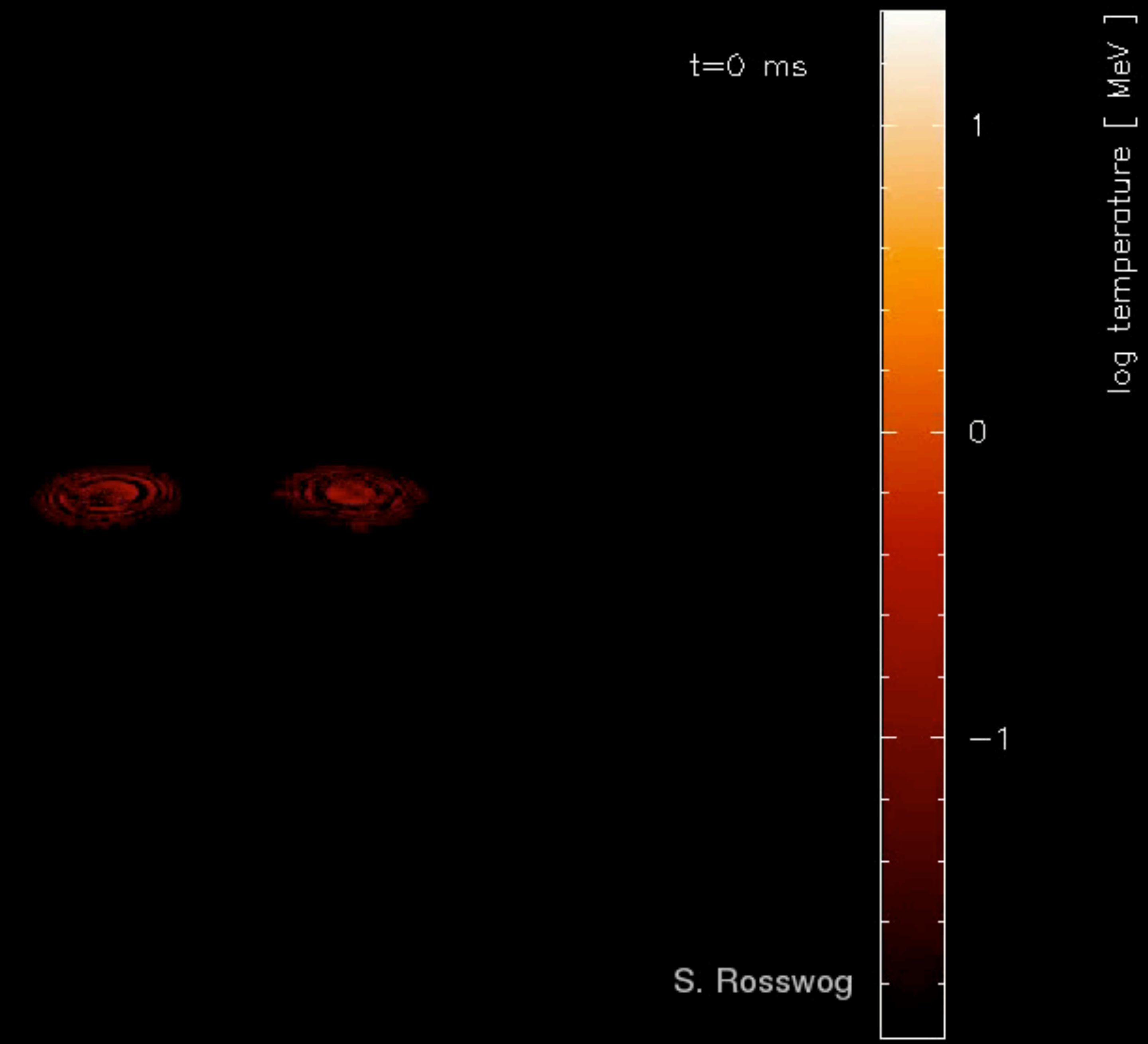
3. As one of the foremost astrophysical mysteries today, and as probes of diffuse ionized structures on cosmological scales, ***FRBs may substantially bolster the scientific impact of an appropriately designed SKA.***



Walker (1998): contours displaying the transition frequency between strong and weak scintillation regimes, in Galactic coordinates. Sources with components smaller than a few tens of microarcseconds with scintillate in the strong regime.

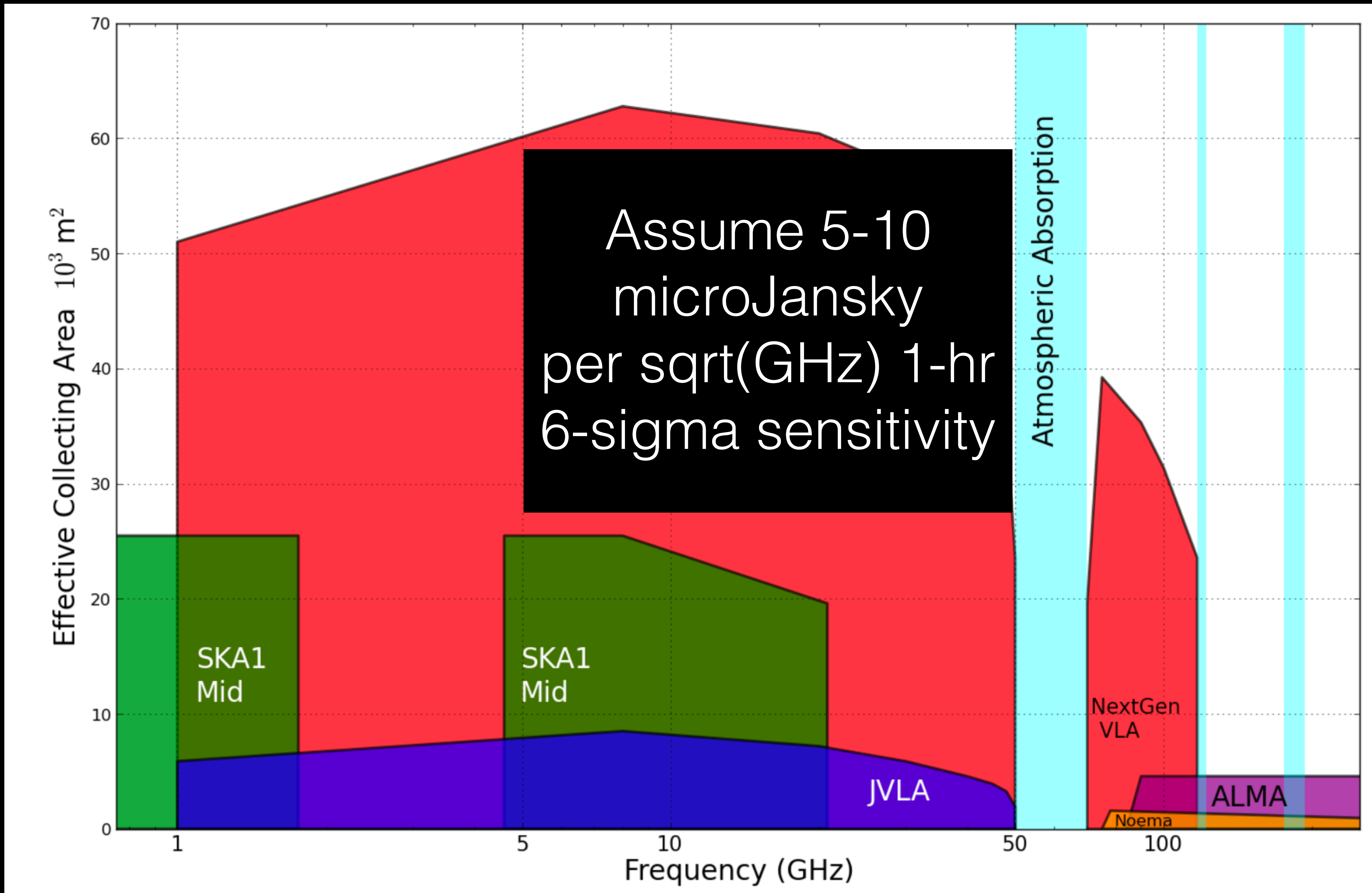
FRBs: 10^4 to 10^7 Gpc^{-1} yr^{-1}

- Core-collapse supernovae, including long GRBs: $2 \times 10^5\,\mathrm{Gpc^{-3}\,yr^{-1}}$.
- Short GRB progenitors: $100 - 1800\,\mathrm{Gpc^{-3}\,yr^{-1}}$.
- Binary neutron star coalescence: $3 \times 10^3\,\mathrm{Gpc^{-3}\,yr^{-1}}$.
- Soft gamma repeater giant flares: $< 2.5 \times 10^4\,\mathrm{Gpc^{-3}\,yr^{-1}}$.
- Type 1a supernovae: $10^5\,\mathrm{Gpc^{-3}\,yr^{-1}}$.
- Binary white dwarf coalescence: $10^4 - 10^5\,\mathrm{Gpc^{-3}\,yr^{-1}}$.



Binary neutron star merger simulation, displaying matter-temperature. Few 100 uJy, few year transient at few hundred Mpc.

Rosswog, Piran & Nakar (2013), see Hotokezaka et al. (2016) for detailed detectability predictions.



ngVLA memo #5, 2016

e.g., 1e31 erg/s/Hz @ z=6 is 2.3 uJy