Crab Nanoshots, Fast Radio Bursts and Cosmology

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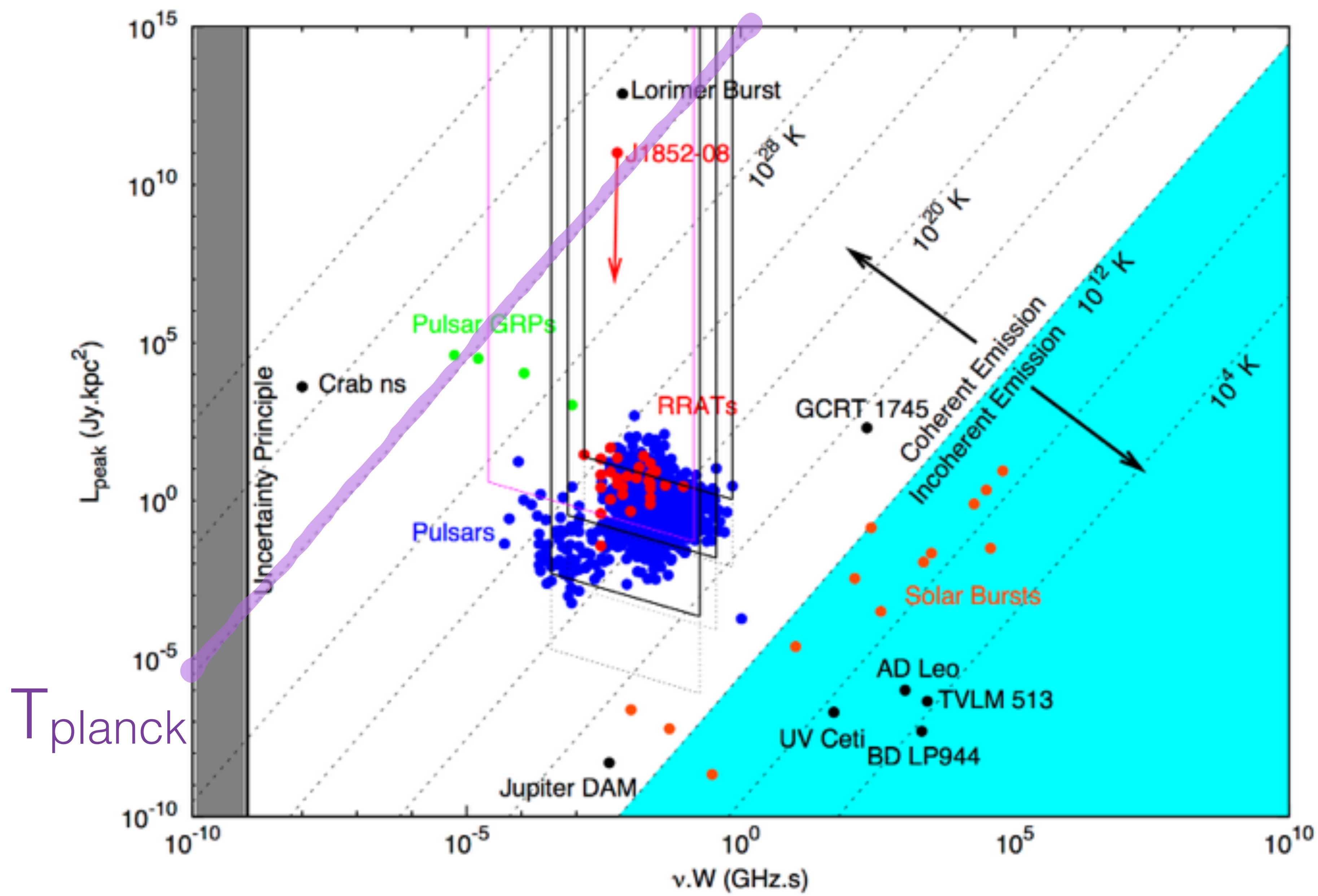
The Brightness Frontier

- In HEP-speak we have Energy, Intensity, Cosmic Frontiers
  - Radio astronomy has another interests frontier: Brightness
  - Short radio transients can be extremely bright!



ν - frequency

W - pulse width

L_ν - specific luminosity

$k_B T_b = \frac{1}{2}(c/\nu)^2 I_\nu$

GRP - giant radio pulse

ns - nanoshot

fast radio bursts:
Lorimer / J1825-08

RRAT - rotating radio transient

DAM - decametric radiation

Coherent vs Incoherent Radiation

Incoherent radiation

charged particles moving independently

$I_\nu \propto N$

synchrotron, free-free, …

Coherent radiation

charged particles moving synchronously

$I_\nu \propto N^2$

electro-magnetic pulse (EMP)

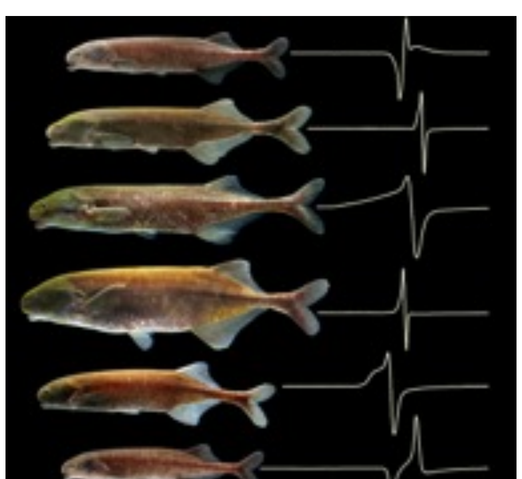
Macroscopic E&M and Thermodynamics

- the large T_b indicates a large amount of energy crammed into a small amount of phase space

- super-Planckian “T” is common for macroscopic motions

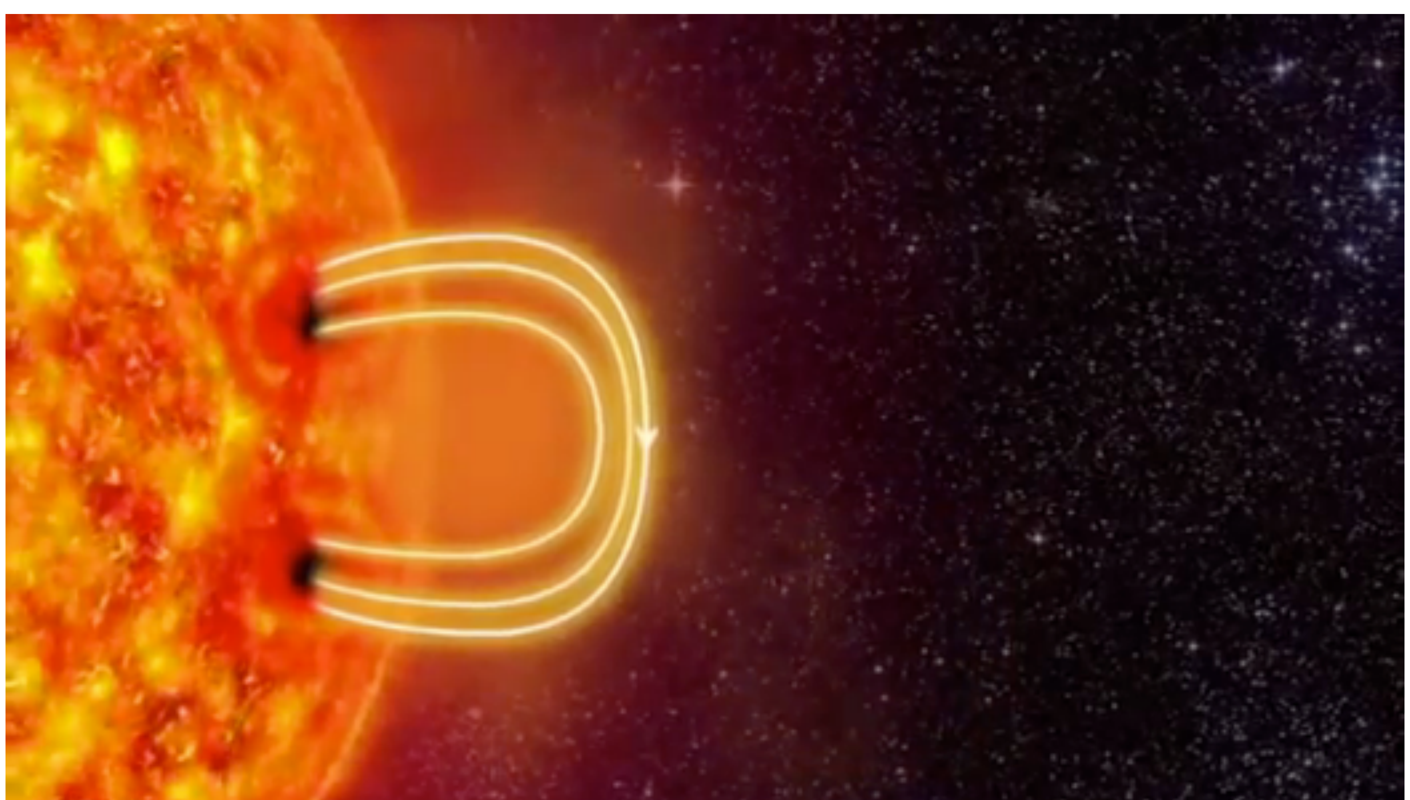
- super-Planckian T_b is a manifestation of **macroscopic** electro-magnetic phenomena

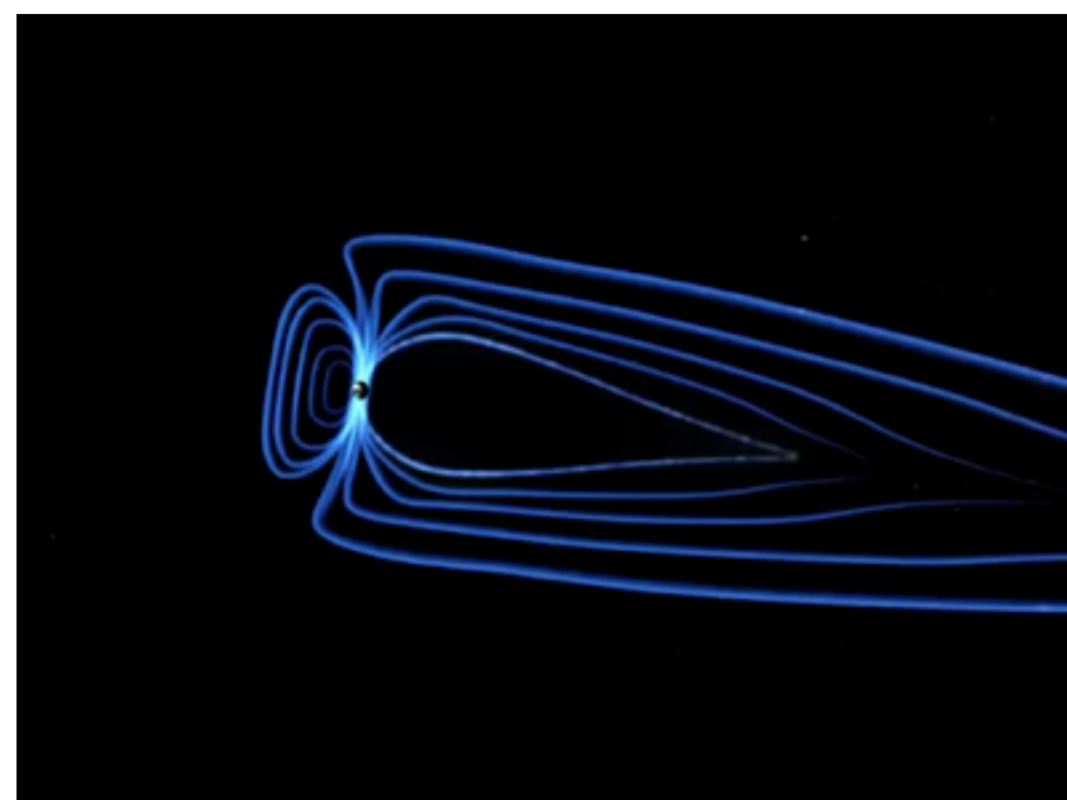
- macroscopic modes are usually very out of thermodynamic equilibrium and find various pathways to thermalize this energy.



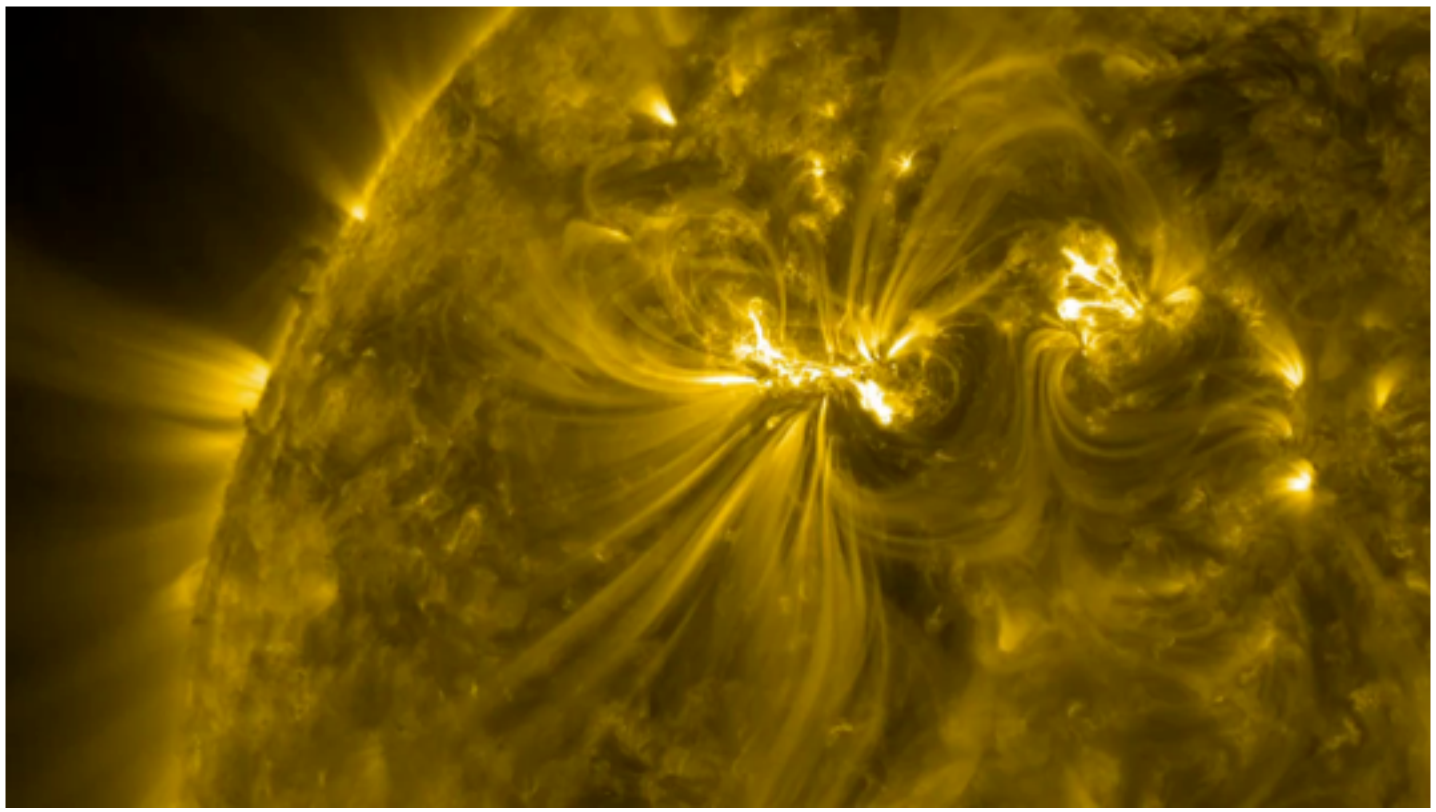

Magnetic Field Reconnection and Astrophysical EMP

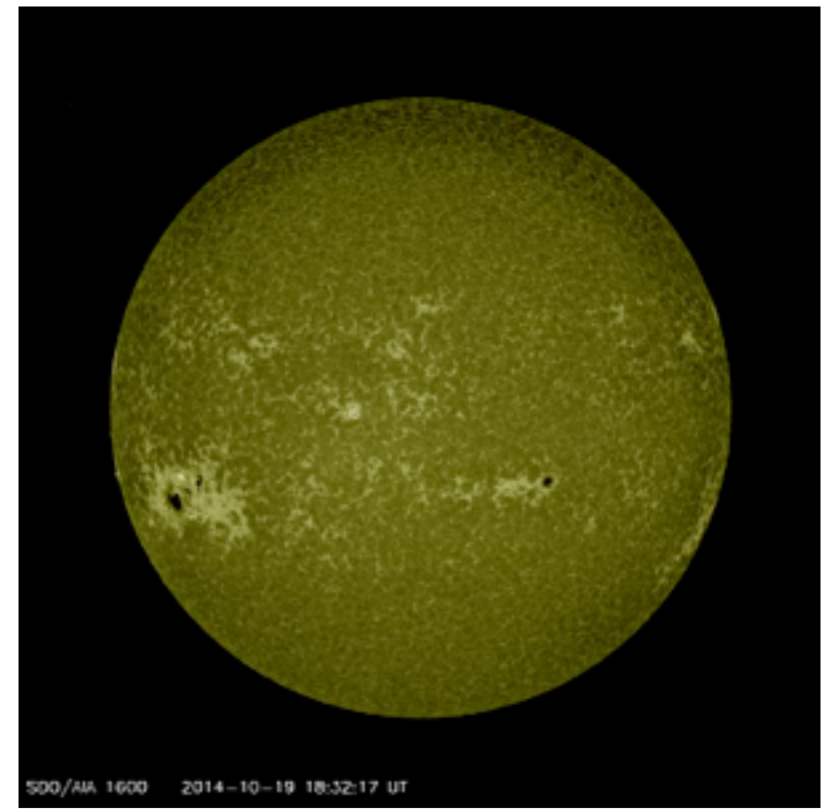
- Very large magnetic fields (up to 10^{15} G) are often frozen into astrophysical plasmas but this energy is occasionally violently released in *magnetic field reconnection* events. On short timescales a B field can oscillate into an E field which accelerates and separates charges and also produces large EMP.

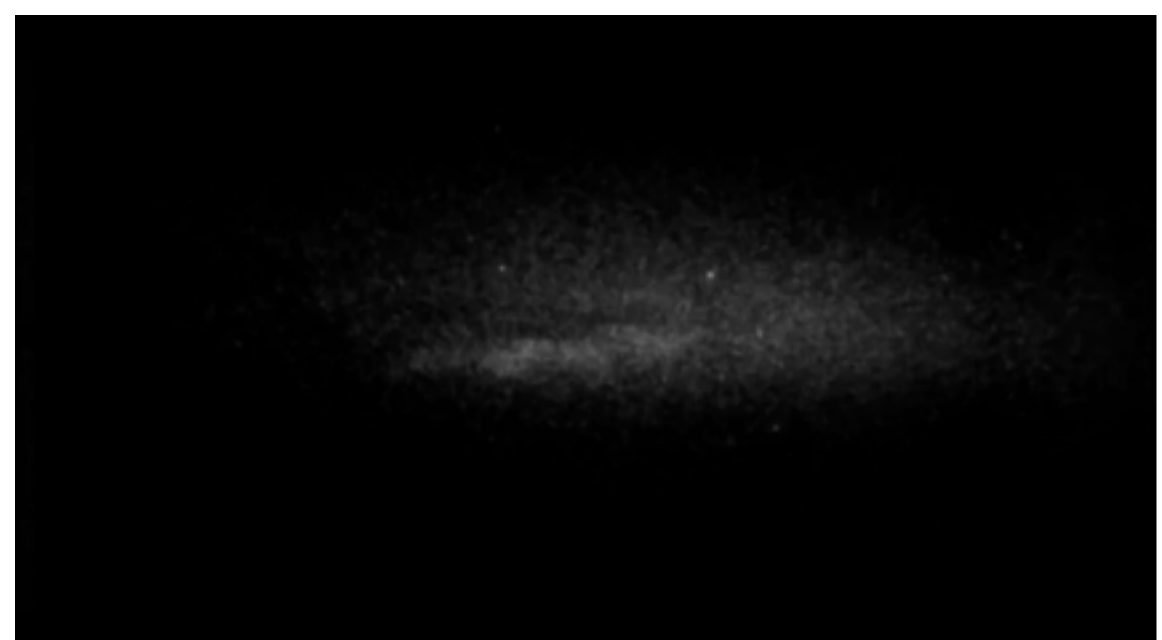




Magnetic Field Reconnections and other types of Sparks are Bright !

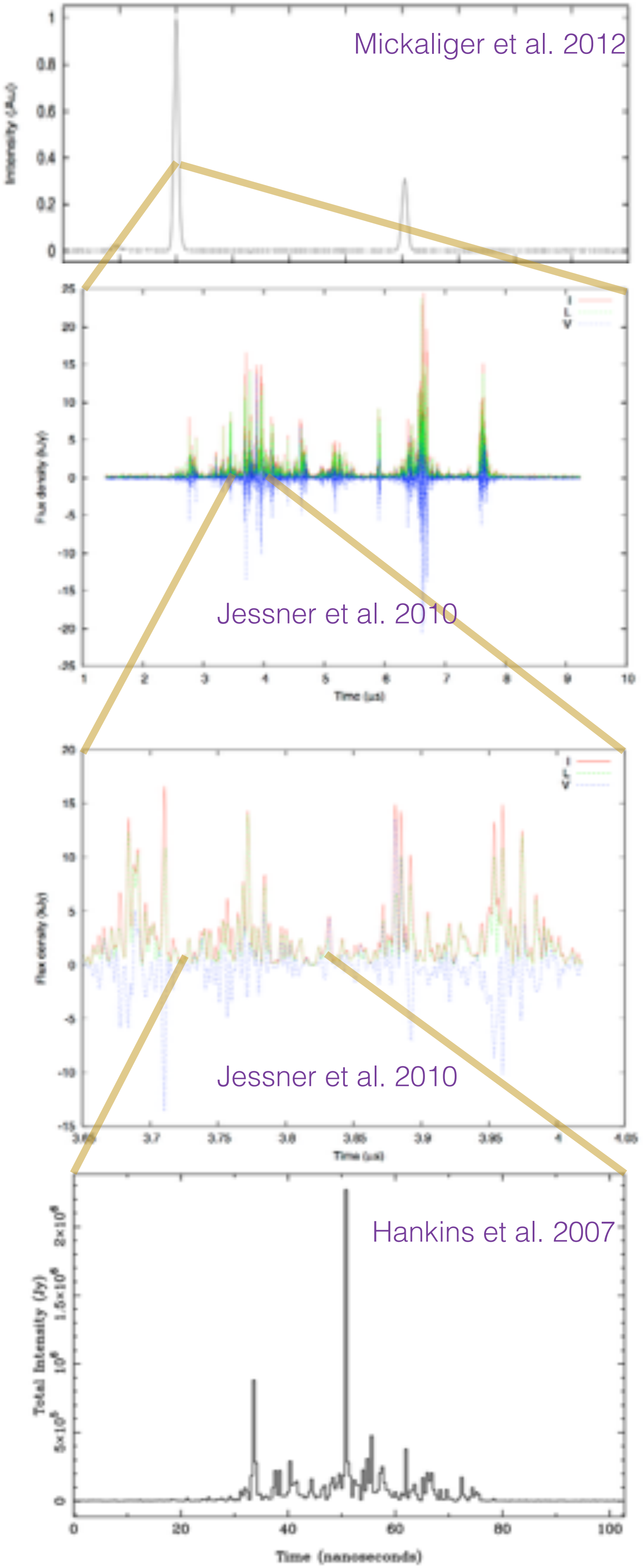






High Time Resolution needed to see High Brightness Events

Crab Radio Pulse Structure

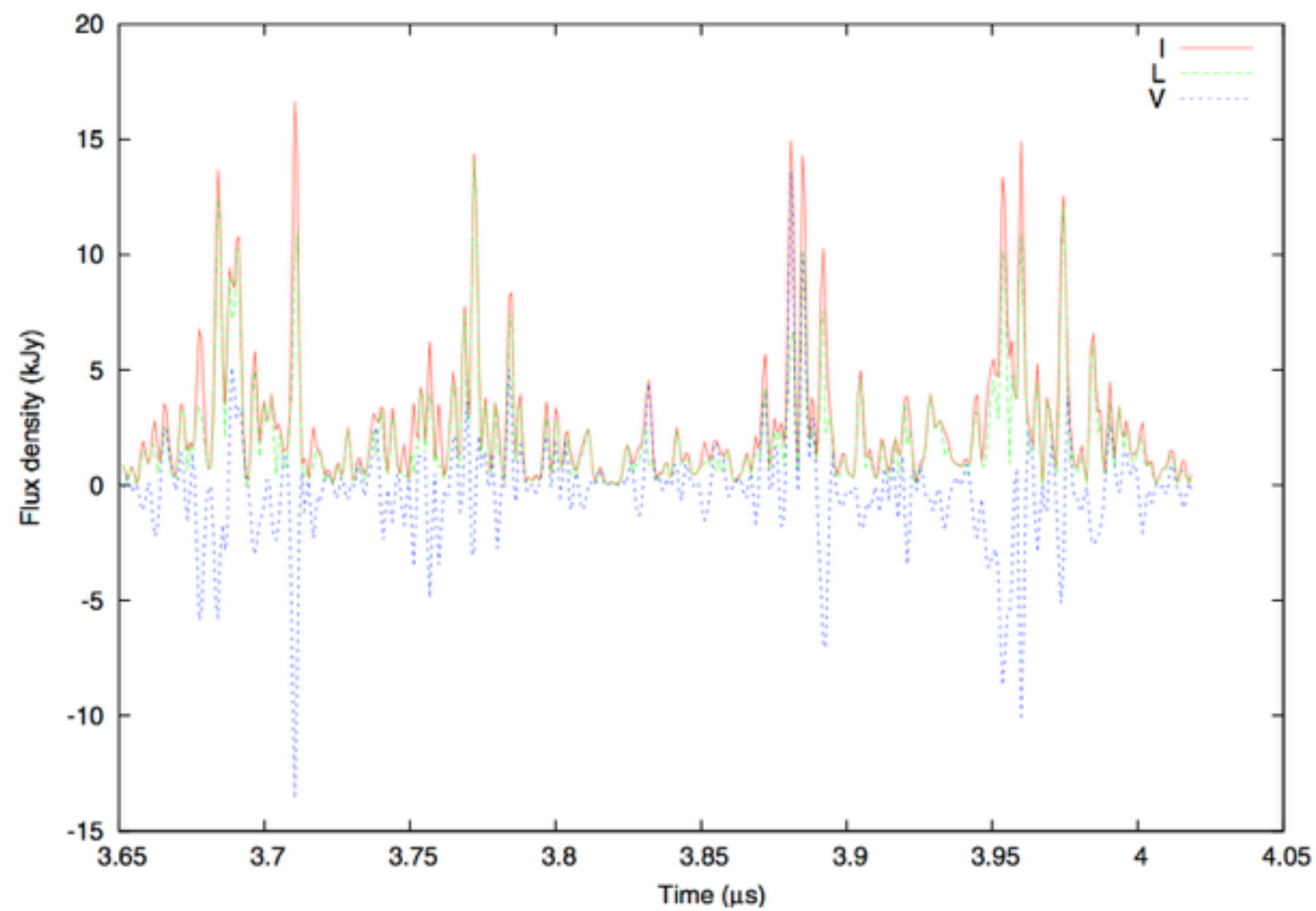


Mean Pulse

Occasional Giant Pulse

Micro Burst

Nano Shot

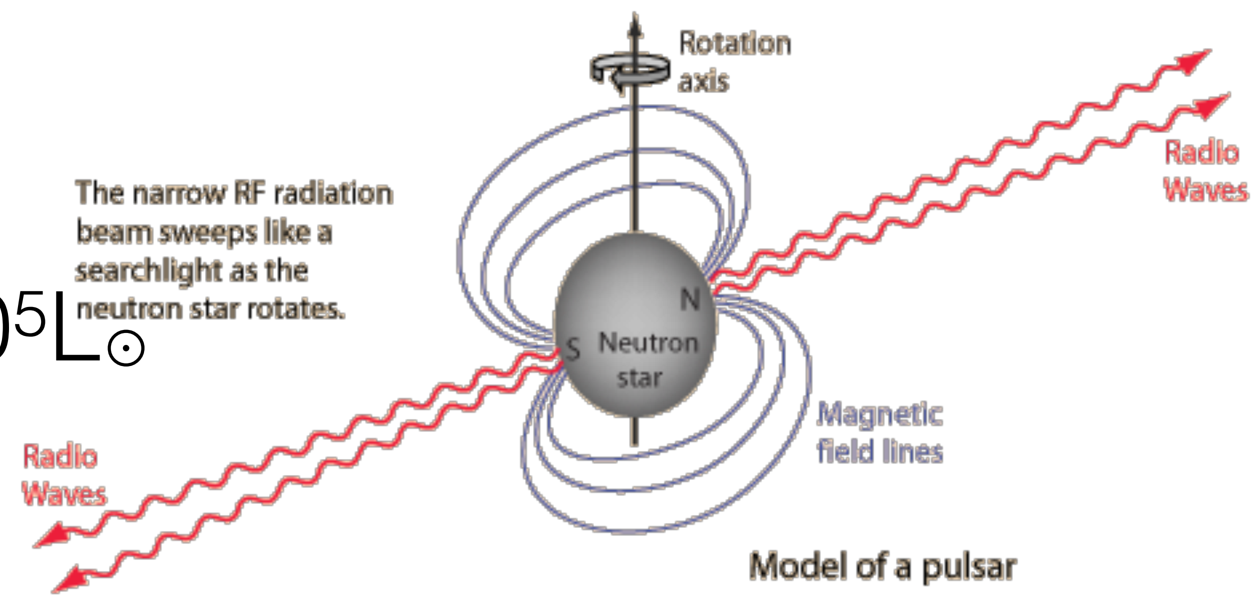


This record nanoshot had peak observed flux of 2MJy, astounding for an source 2kpc away!
only ~10^4 radio γ's/m^2 - observed at Arecibo

Crab Nanoshot Numerology

- (Assuming no significant relativistic beaming)
- size: ≲30cm [c ns]
- energy: ≲10^{28}erg [4π D^2 MJy ns GHz]
- peak luminosity: ≲$1.5\times10^3 L_\odot$ [4π D^2 MJy nsec GHz]
- electric field: ≲2×10^{12}G [4π D / ns √(MJy GHz / c^3)]
- charge: ≲5 Mole e [4π D ns √(MJy GHz c)]
- $e^\pm$ energy: ≲15 PeV [4π D e √(MJy GHz / c)]

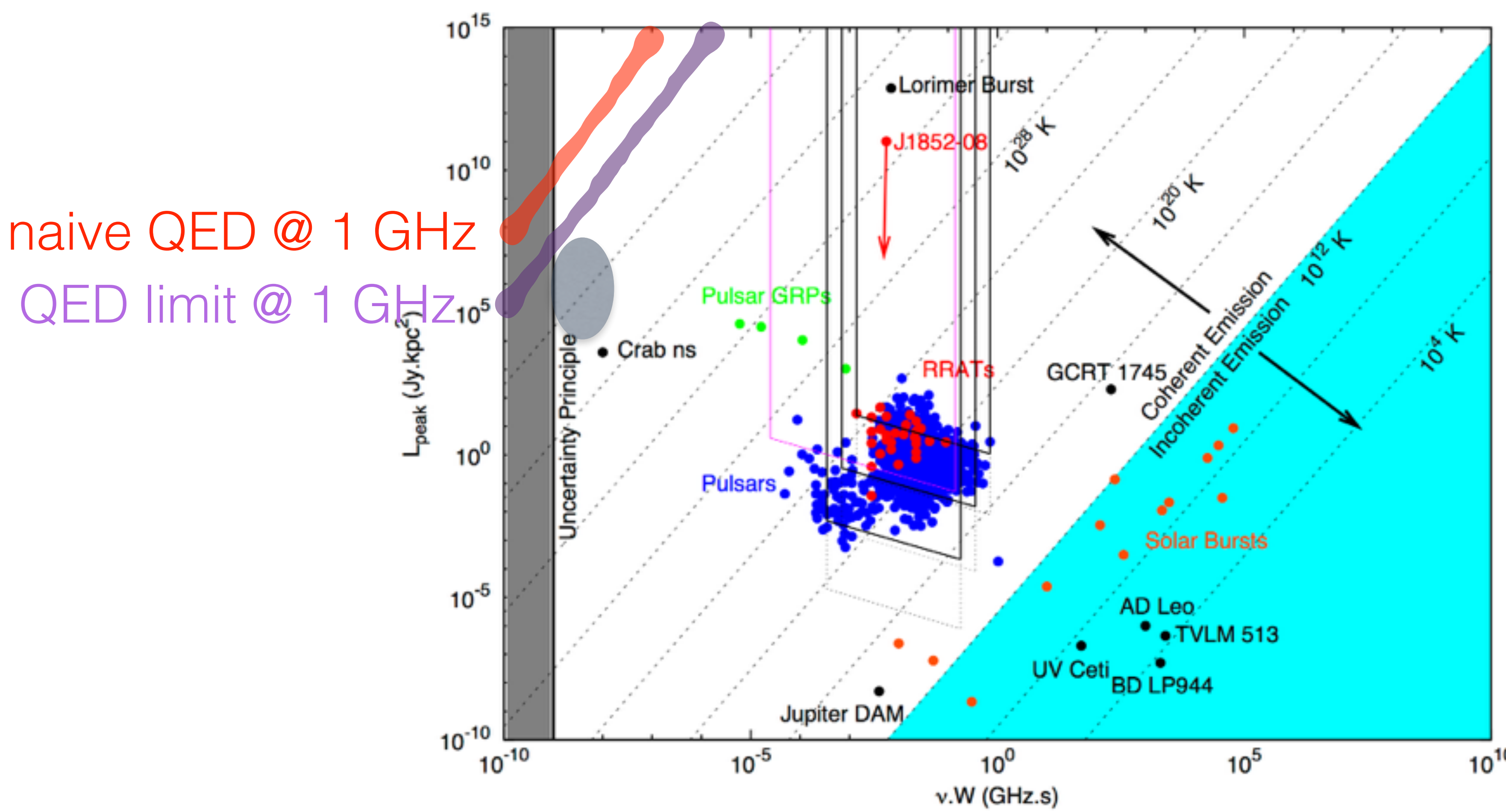
Crab Pulsar Magnetosphere Numerology



- inner radius: 10km
- spin down luminosity: ~$10^5 L_\odot$
- magnetic field: ~3×10^{13}G
- particle density: ~0.004 mole/m^3
- plasma frequency: 250 GHz at surface
- nanoshot questions: small size? large charge? hi v?

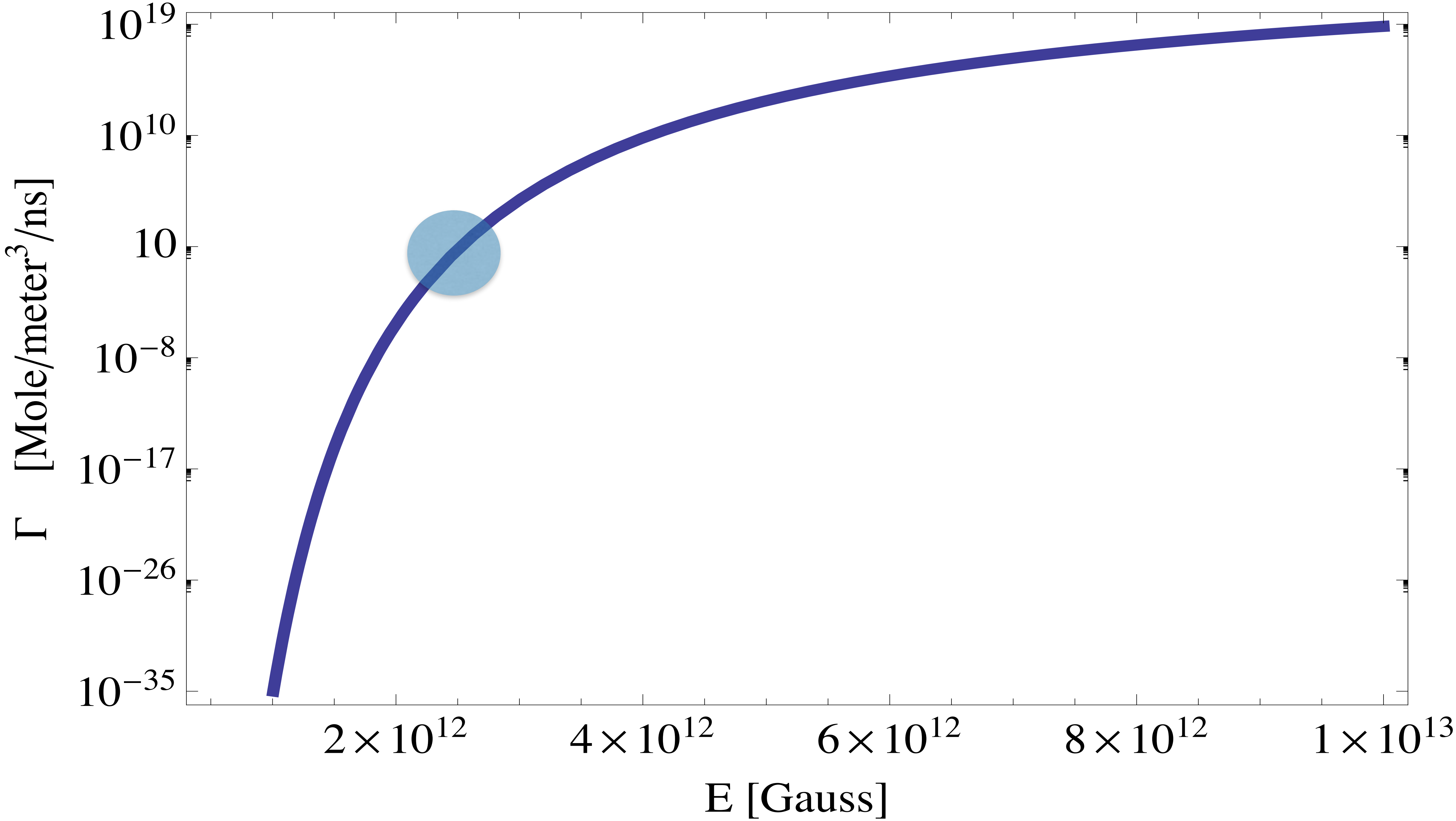
Radio Transients & QuantumElectroDynamics

- In QED electric or magnetic fields are said to be *strong* if E,B ≳ $m_e^2c^3/(e\hbar)$. (in CGS units this is the *Schwinger critical field*)
- Neutron stars with magnetic fields are called *magnetars*. These exhibit interesting QED phenomena such as photon splitting.
- If we know the distance to the source one can estimate the electromagnetic field strength at emission (neglecting relativistic beaming): $E \approx \sqrt{(4\pi\ \nu\ L_\nu\ \Delta t / (c\ \Delta t)^3)}$



A closer look will reveal that QED effects are likely important for nanoshots.

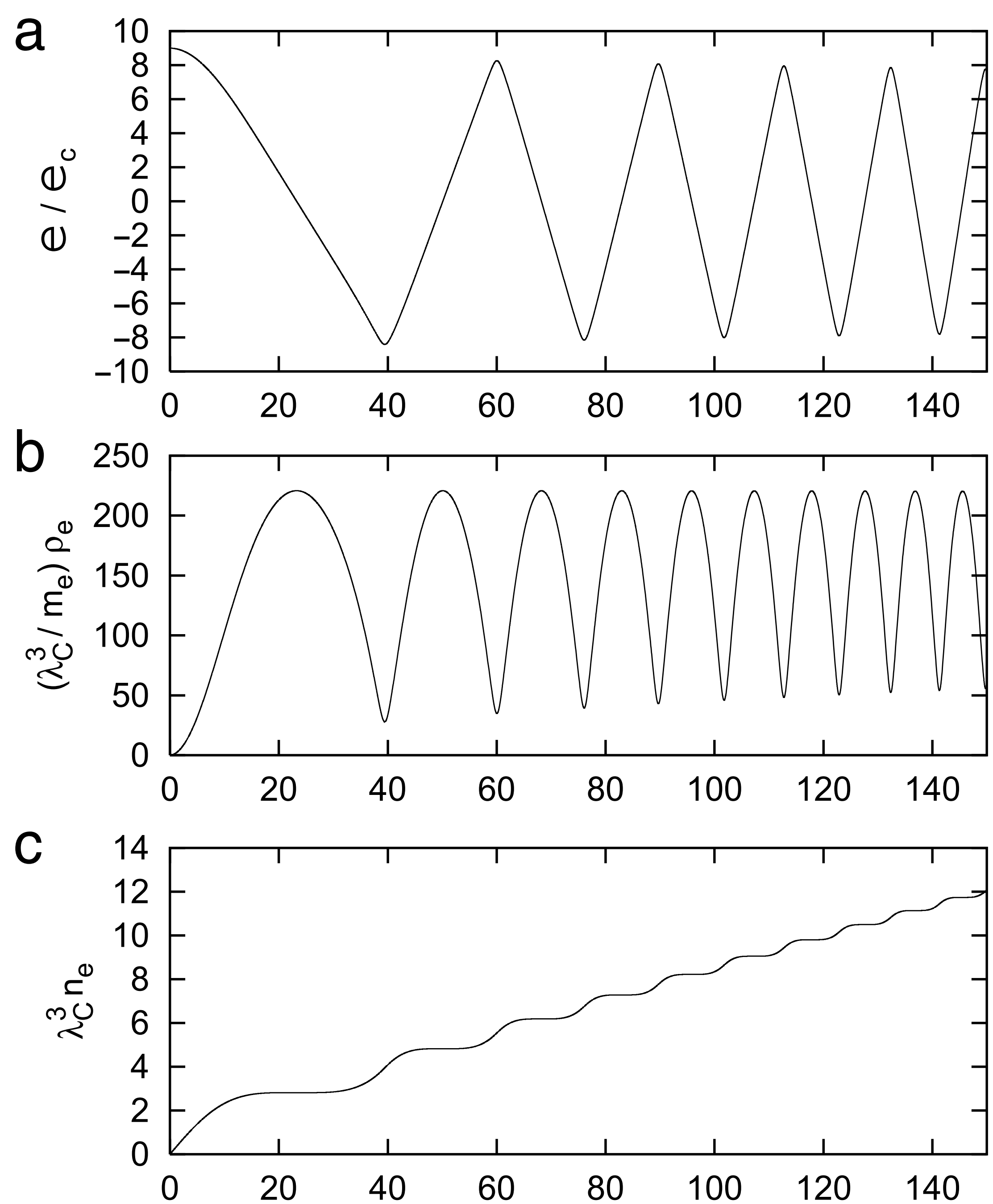
Schwinger Pair Production



- $E_{lim} = \pi E_S/\ln[4e^3 B\, \delta t^2/\hbar^2] \cong 2.5\times10^{12}$G *extremely insensitive* to parameters!

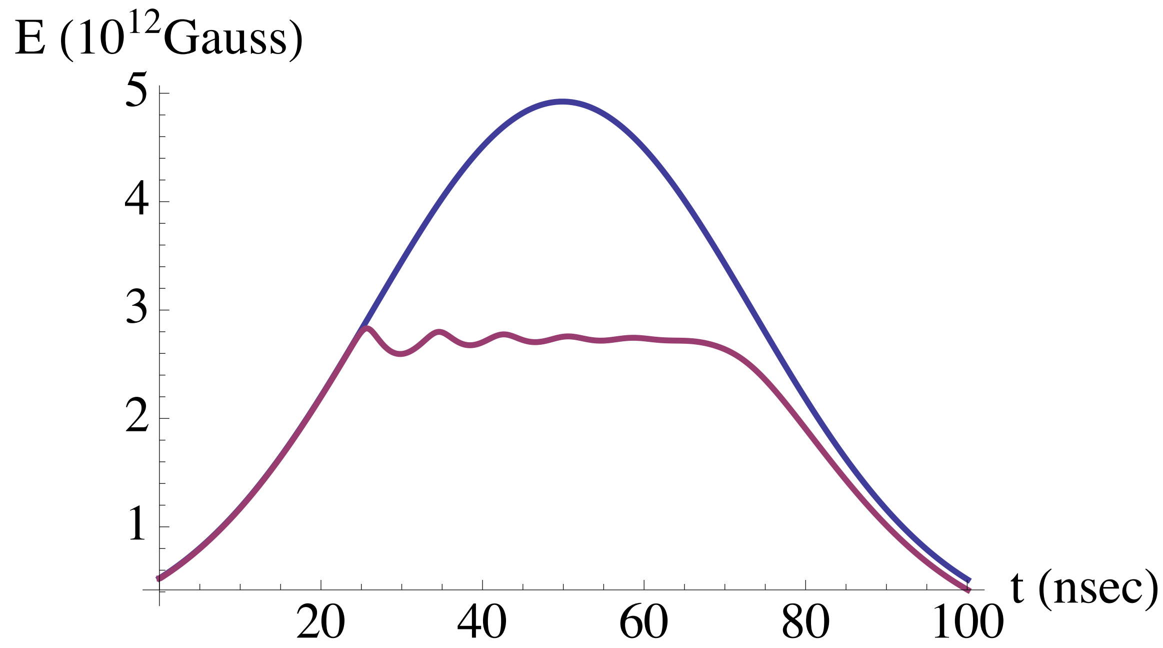
For Large Uniform Fields

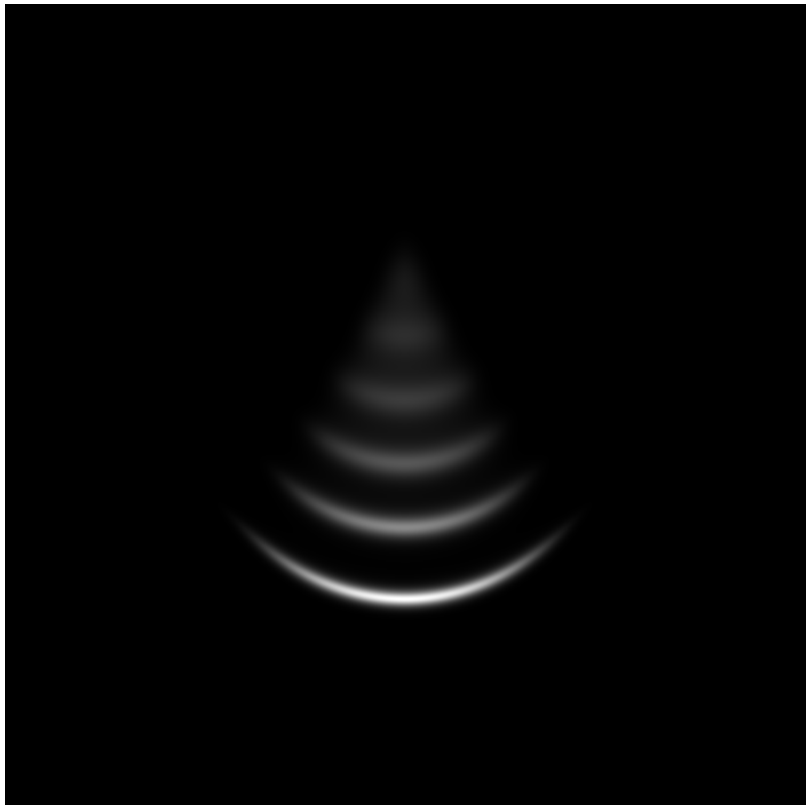
- **Plasma Oscillations** (see Ruffini, Vereshchagin, Xue 2010)

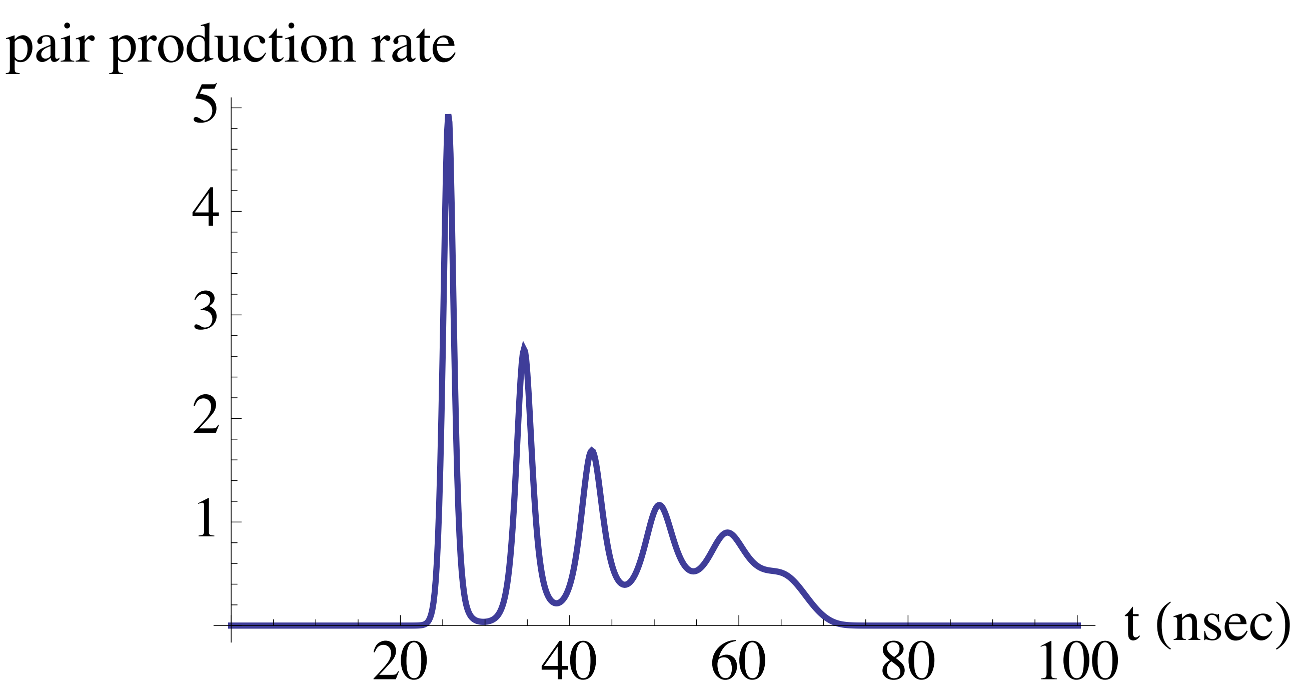


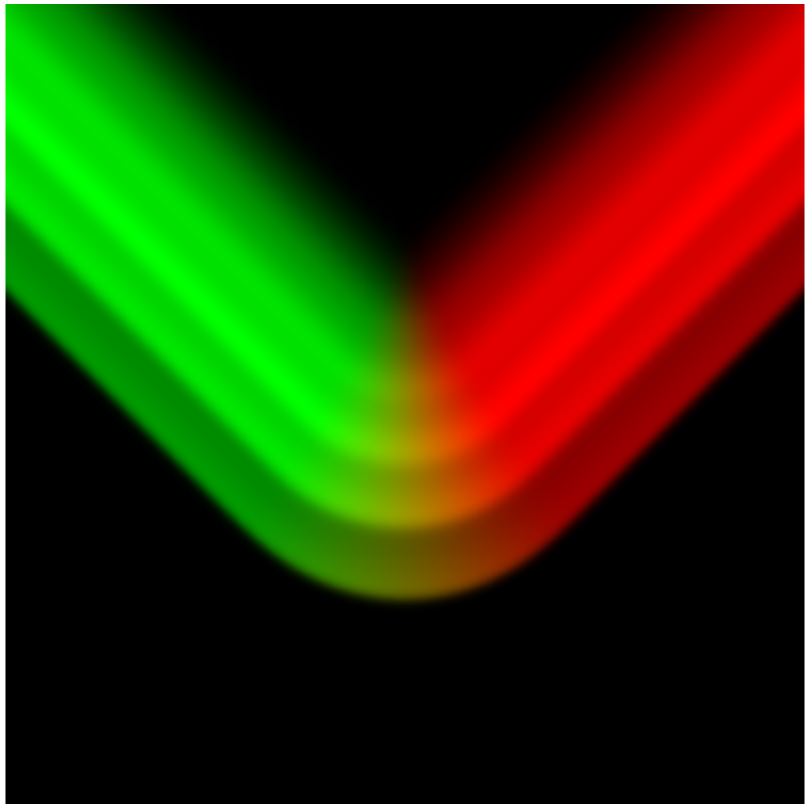
For Smaller Schwinger Sparks

1⁺D simulation (Stebbins, Yoo 2015)









Schwinger Spark ElectroMagnetic Pulse

$$\dot{\boldsymbol{Q}} = 2\,e\,\dot{N}\,\mathrm{Sec}[\theta]^2\,\hat{\boldsymbol{z}} \qquad \dot{N}[\boldsymbol{x},t] \equiv \int d^3\boldsymbol{x}'\,\Gamma\!\left[\boldsymbol{x}', t - \frac{|\boldsymbol{x}-\boldsymbol{x}'|}{c}\right]$$

$$\boldsymbol{S}[\boldsymbol{x},t] \equiv \frac{c}{4\pi}(\boldsymbol{E}\times\boldsymbol{B}) = \frac{\dot{\boldsymbol{Q}}\cdot\dot{\boldsymbol{Q}} - (\hat{\boldsymbol{r}}\cdot\dot{\boldsymbol{Q}})^2}{4\pi D^2 c}\,\hat{\boldsymbol{r}} = \frac{(2\,e\,\dot{N})^2}{4\pi D^2 c}\,\mathrm{Sec}[\theta]^2\,\hat{\boldsymbol{r}}$$

$$F_\nu[\boldsymbol{x}] \equiv \int_{-\infty}^{\infty} dt\, S_\nu[\boldsymbol{x},t] = \frac{(2\,e)^2}{4\pi D^2 c}\left|\int_{-\infty}^{\infty} dt\, e^{-i\,2\pi\nu t}\,\dot{N}[\boldsymbol{x},t]\right|^2 \mathrm{Sec}[\theta]^2$$

$$F_\nu \to F_0 = \frac{(2\,e\,N\,\mathrm{Sec}[\theta])^2}{4\pi\,c\,D^2} \qquad N \equiv \int_{-\infty}^{\infty} dt \int d^3\boldsymbol{x}\,\Gamma[\boldsymbol{x},t]$$

$$\mathcal{E}_\mathrm{P} = \left(\frac{g_\mathrm{P}}{2\pi}\right)^2 (c\,\delta t_\mathrm{P})^3\, E_\mathrm{P}^{\mathrm{lim}\,2} = 2\times10^3\, L_\odot\,\mathrm{nsec}\left(\frac{\delta t_\mathrm{P}}{\mathrm{nsec}}\right)^3\left(\frac{E_\mathrm{P}^{\mathrm{lim}}}{2.8\times10^{12}\,\mathrm{Gauss}}\right)^2$$

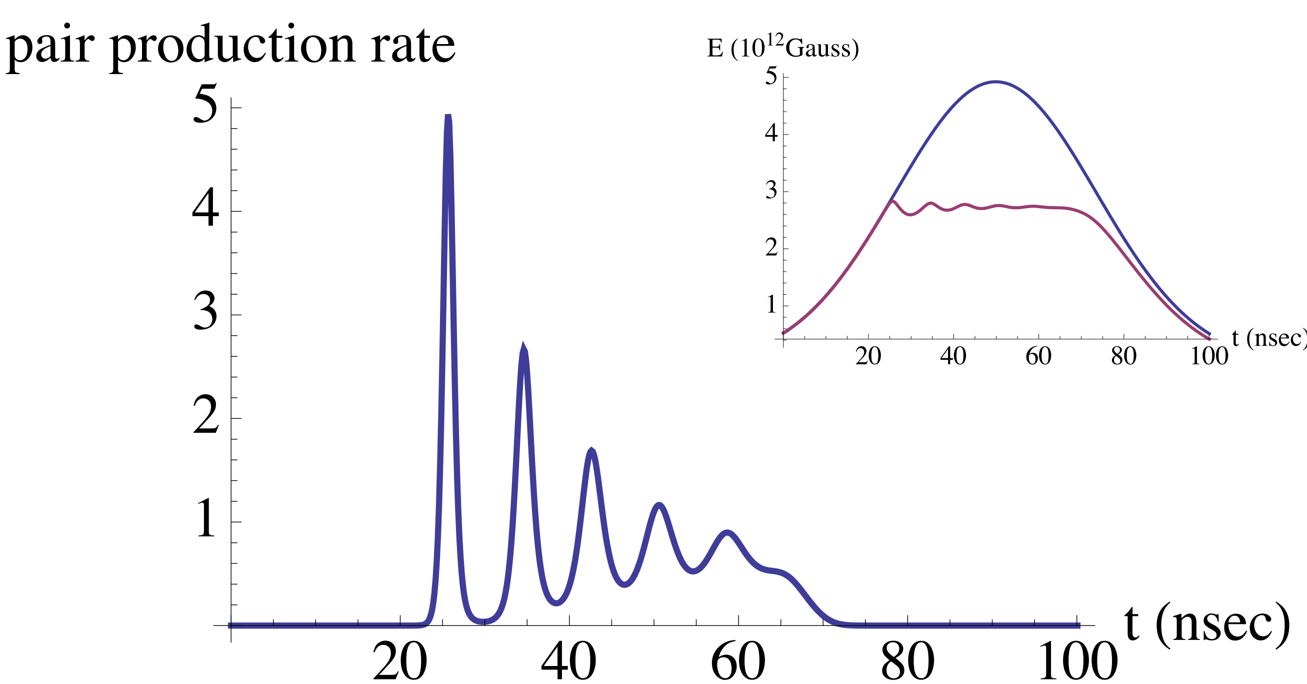
If created pairs are rapidly accelerated to speed of light the EMP just traces the pair production rate.

EMP is “charge separation” radiation

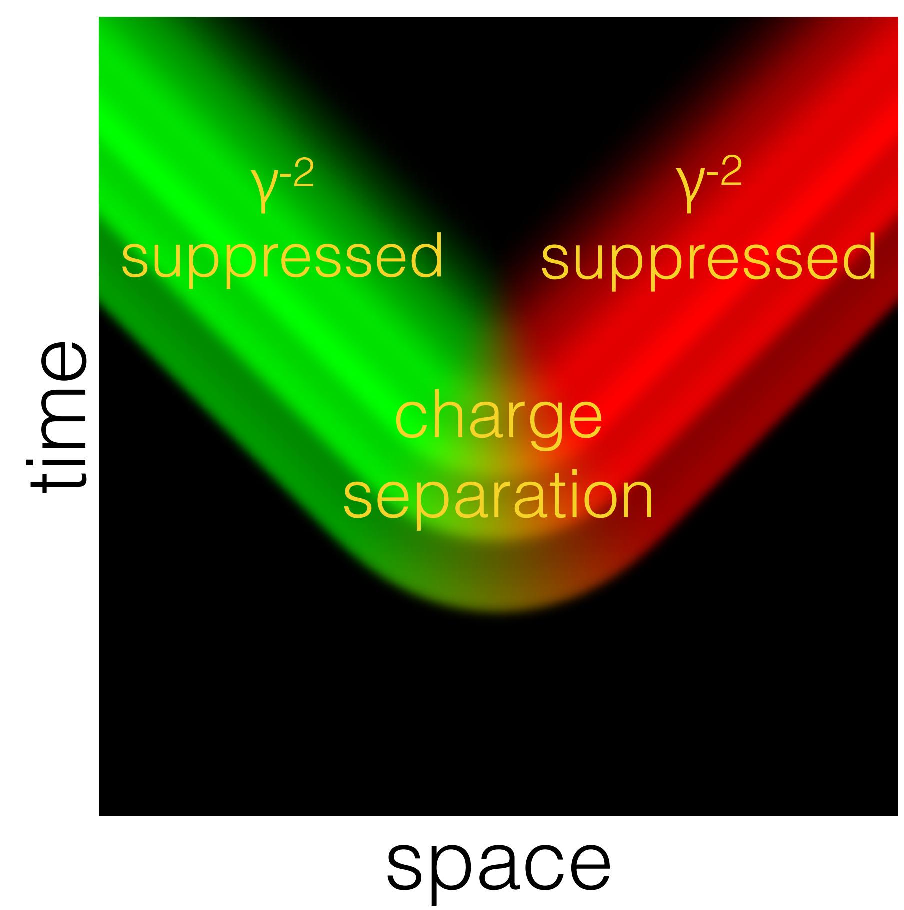
EMP spectrum depends on shape of electric field.

Schwinger sparks up-converts electro-magnetic energy.

Total energy scales with cube of pulse length: ν_{max}^{-3}.

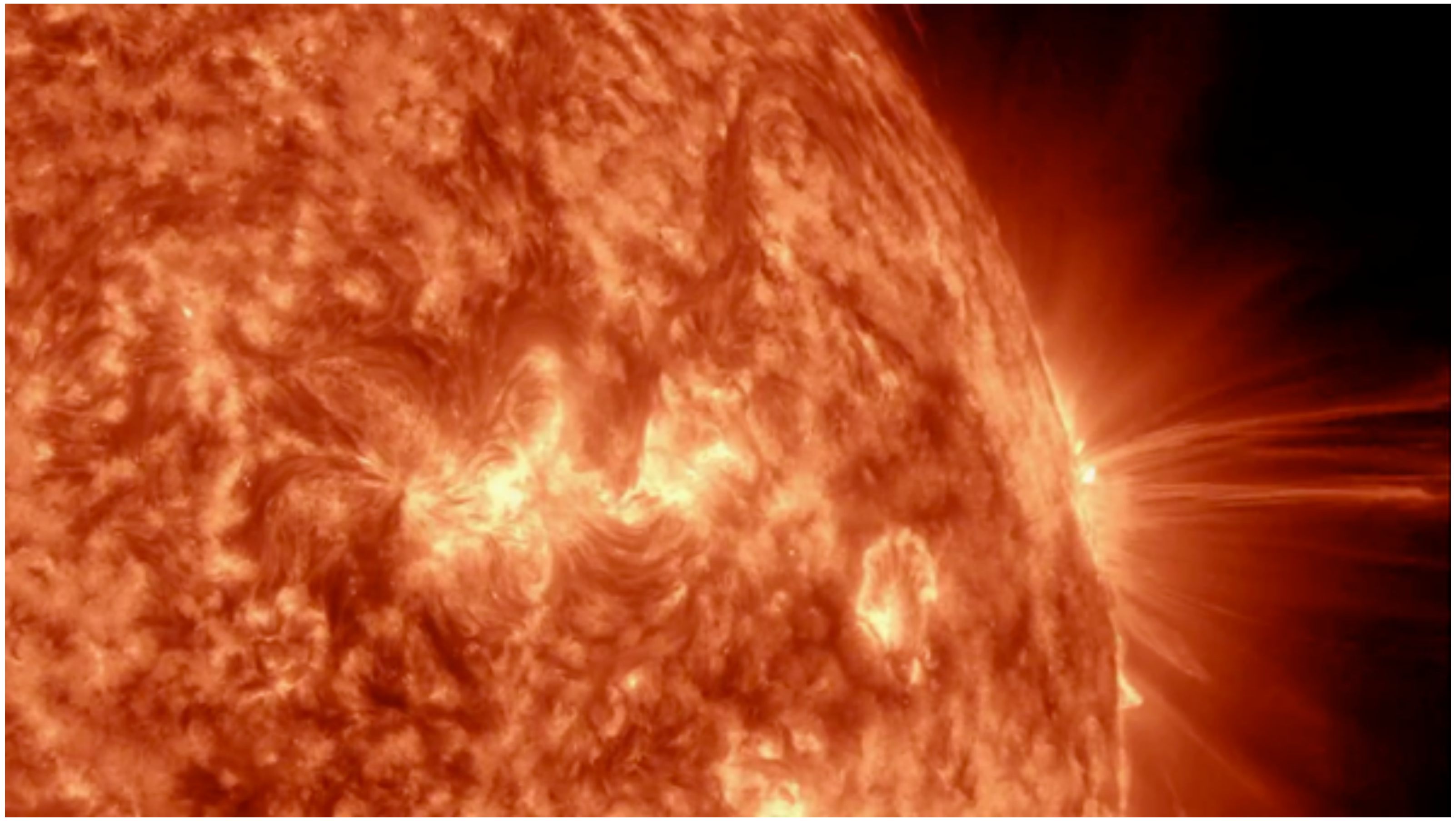


Stebbins, Yoo 2015

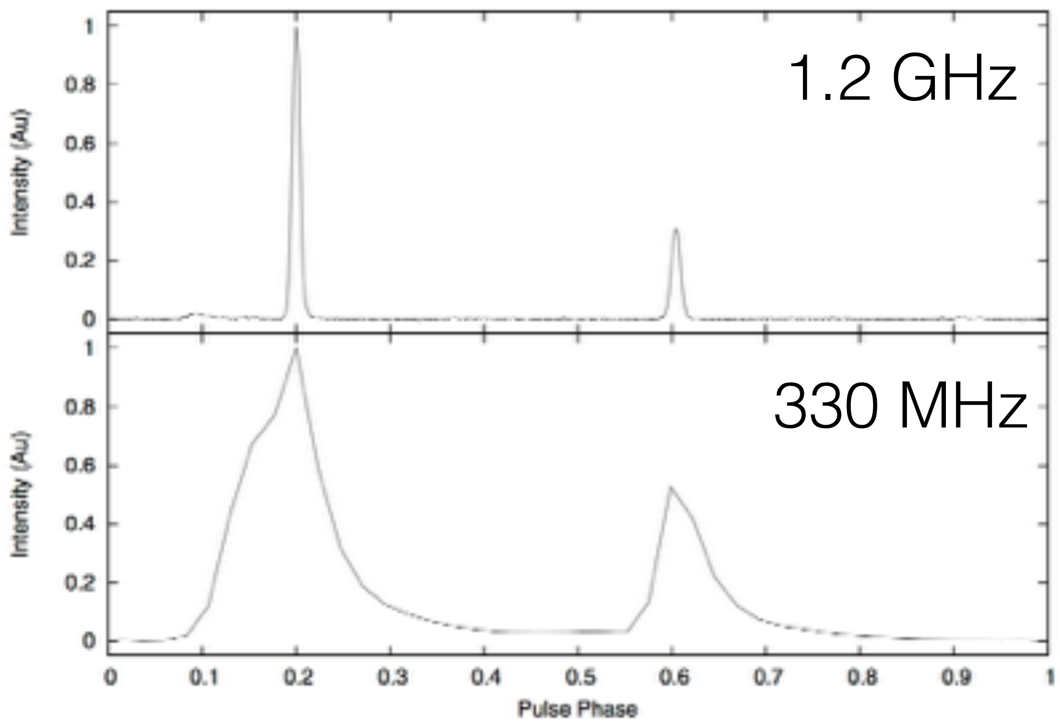


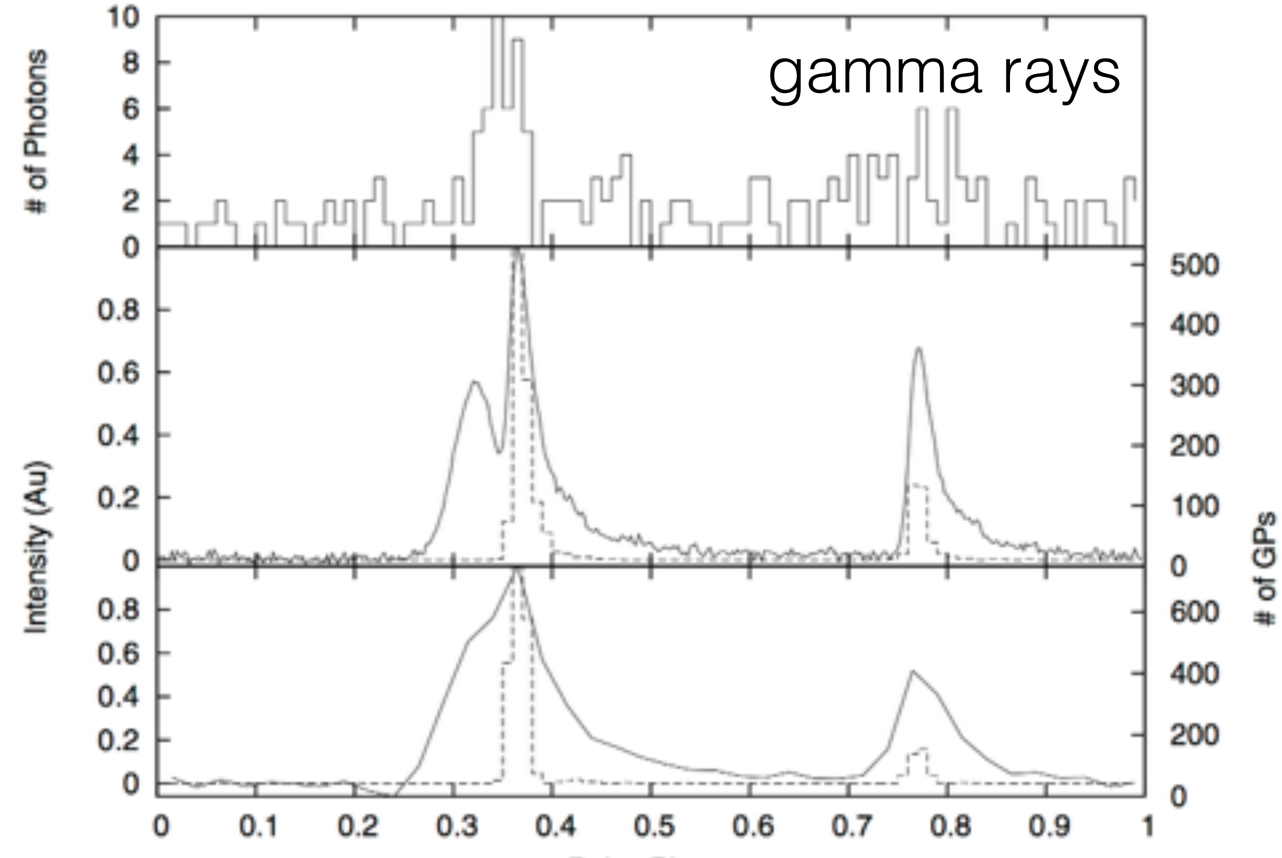
EMP Propagation Through Magnetosphere?

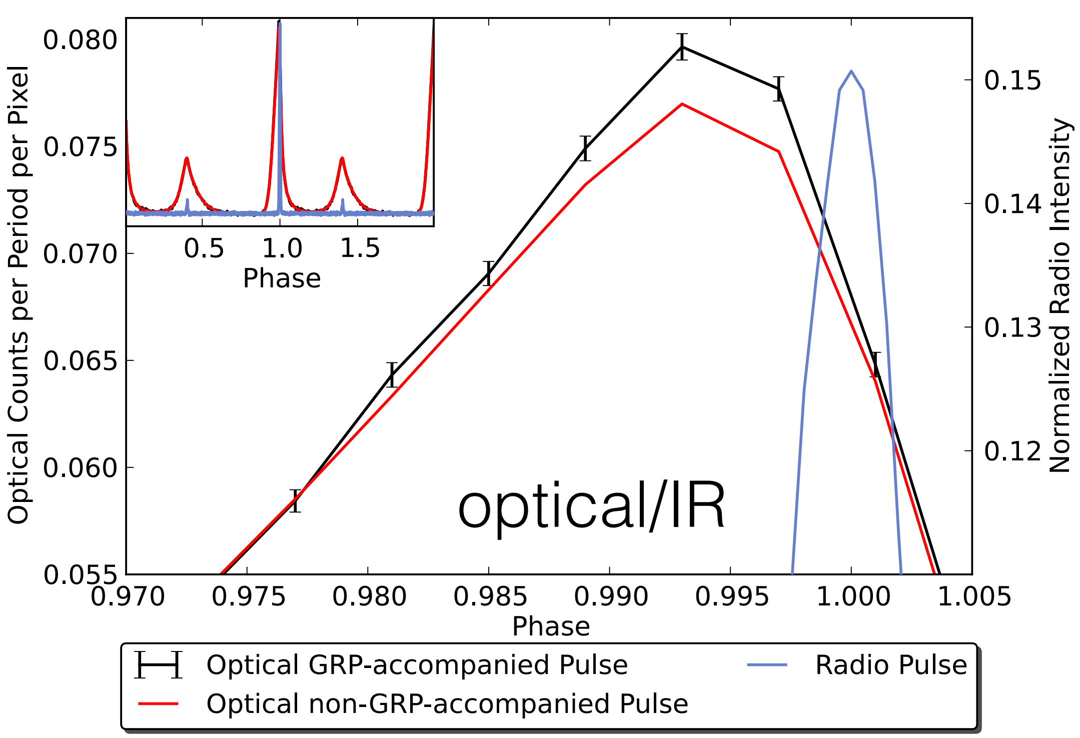
- observed frequency smaller than magnetosphere plasma frequency **but**
- EMP energy density higher than that of magnetosphere!
- will accelerate any $e^{\pm}$ in path to ultra-relativistic energies
- trains of nanoshots could “blast” through magnetosphere
- or temporarily push plasma out of the way

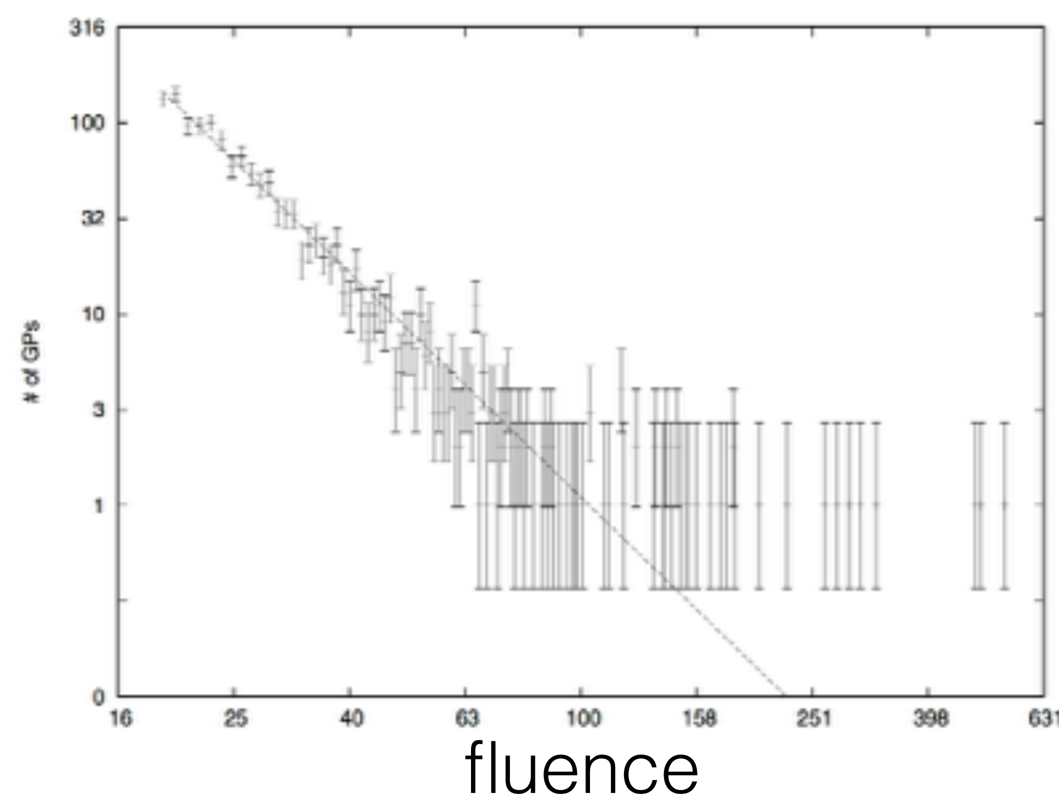


Crab Giant Pulse Phenomenology









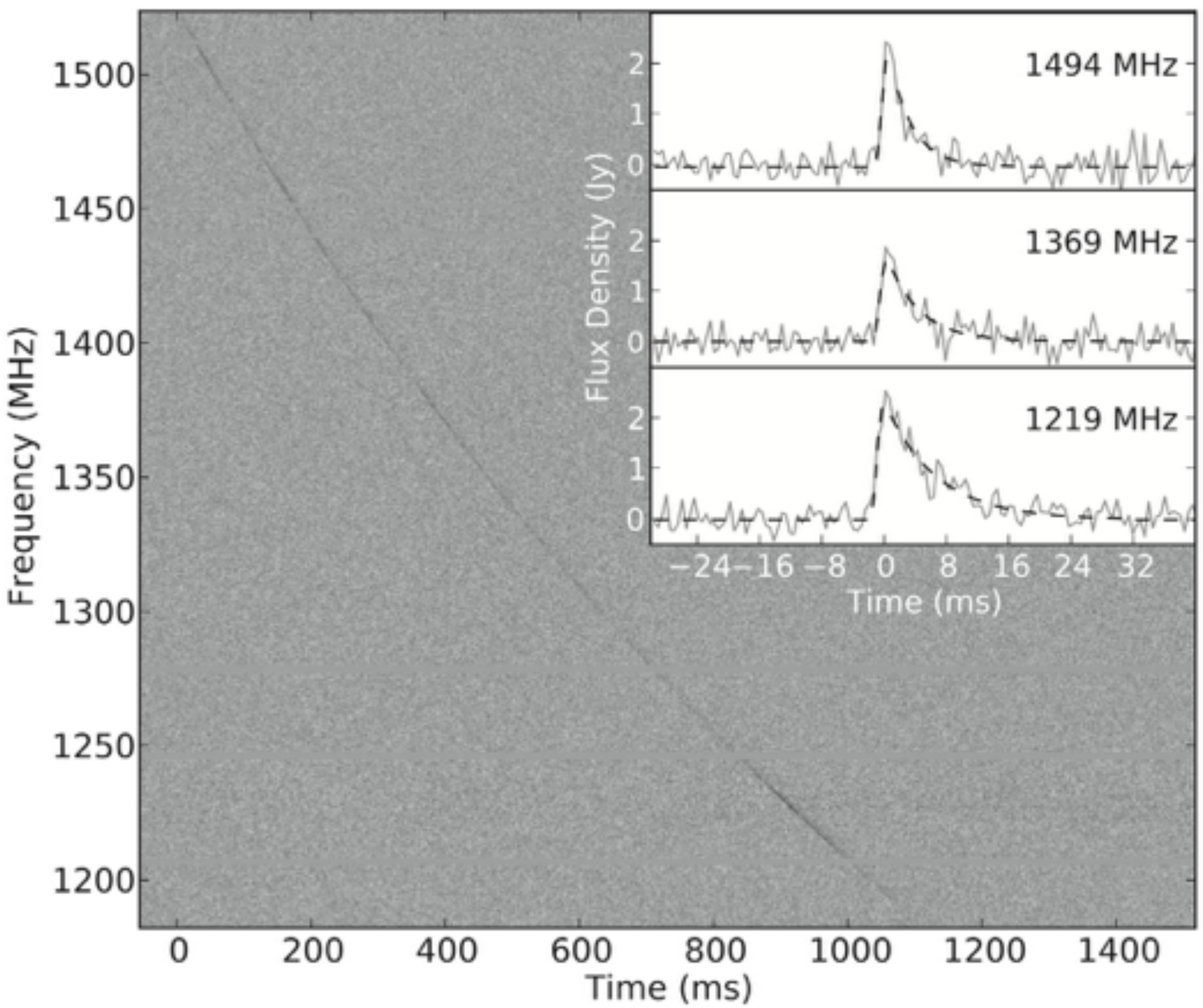
Pulses are different at different frequencies. Why?

- multi-wavelength / high time resolution (nsec) studies may provide clues
- One narrative:
  - GHz γ's only have narrow window of escape
  - 100 MHz radiation transferred to plasma waves which radiate further out
  - IR-Opt-UV-X-γ's not as blocked by magnetosphere
    - these photons would allow us to see more of the giant pulses/nanoshots
- Prospects for IR-Opt-UV-X-γ measurements
  - coherent emission mechanism will not persist to higher frequencies
  - at higher frequencies quickly become photon limited
  - temporal correlations can be studied
- Radio receivers and X-γ cameras naturally have high time resolution
- High time resolution astronomical cameras becoming more common
  - transients telescopes, ULTRACAM, MAMA, TRIFFID, OPTIMA, AquEYE, Iqueye, NanoCam (FNAL)
  - low photon flux can be compensated by very large optical telescopes (GMT, TMT, E-ELT)

Why Nanosecond?

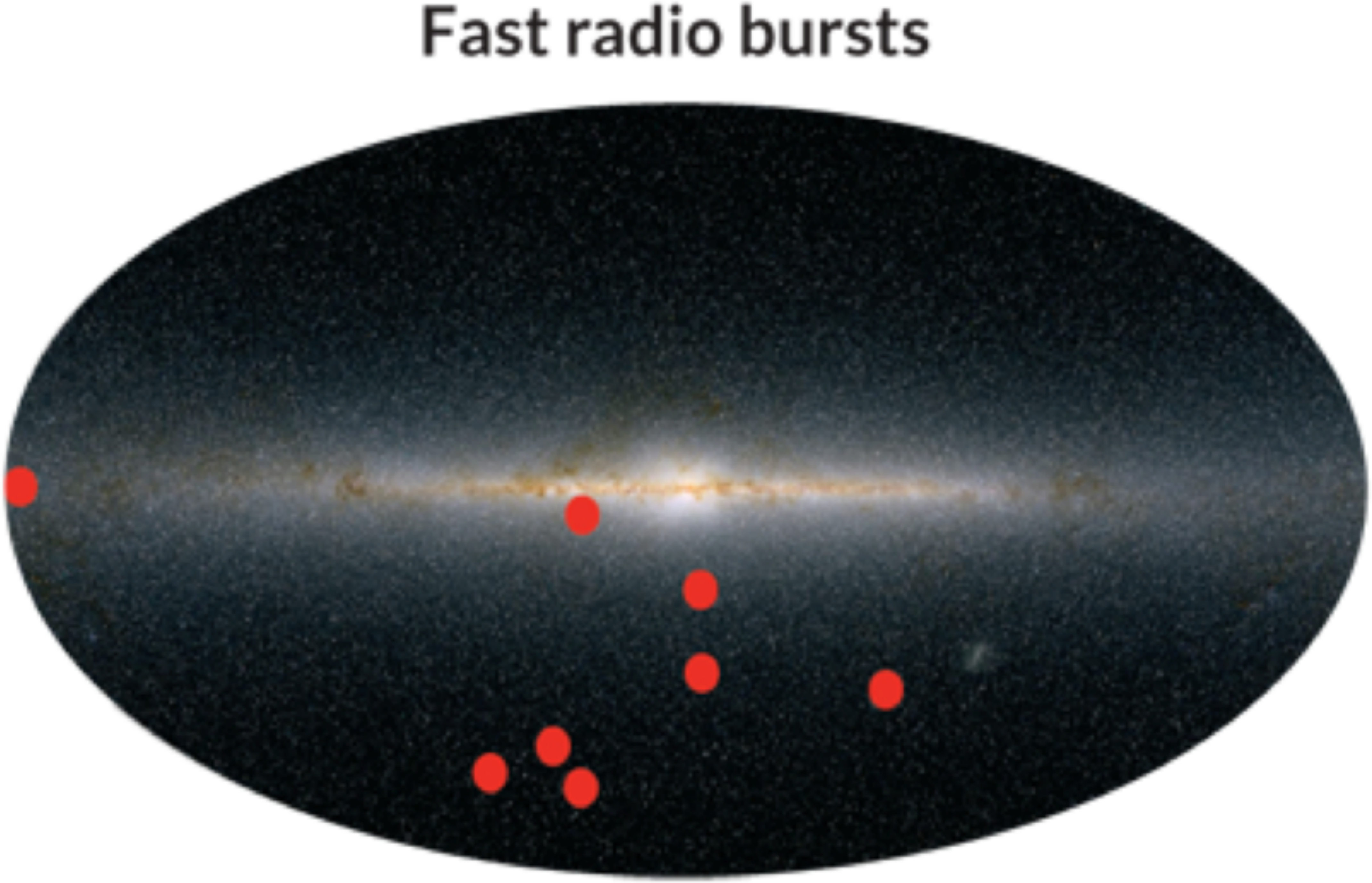
- Characteristic scale of magnetic feature on surface?
- Perhaps these are only the EMPs that get out?
- Coincidence: 10 PeV is both spark voltage and voltage to which particles accelerated in magnetosphere (Goldreich Julian)

Fast Radio Bursts (FRBs)

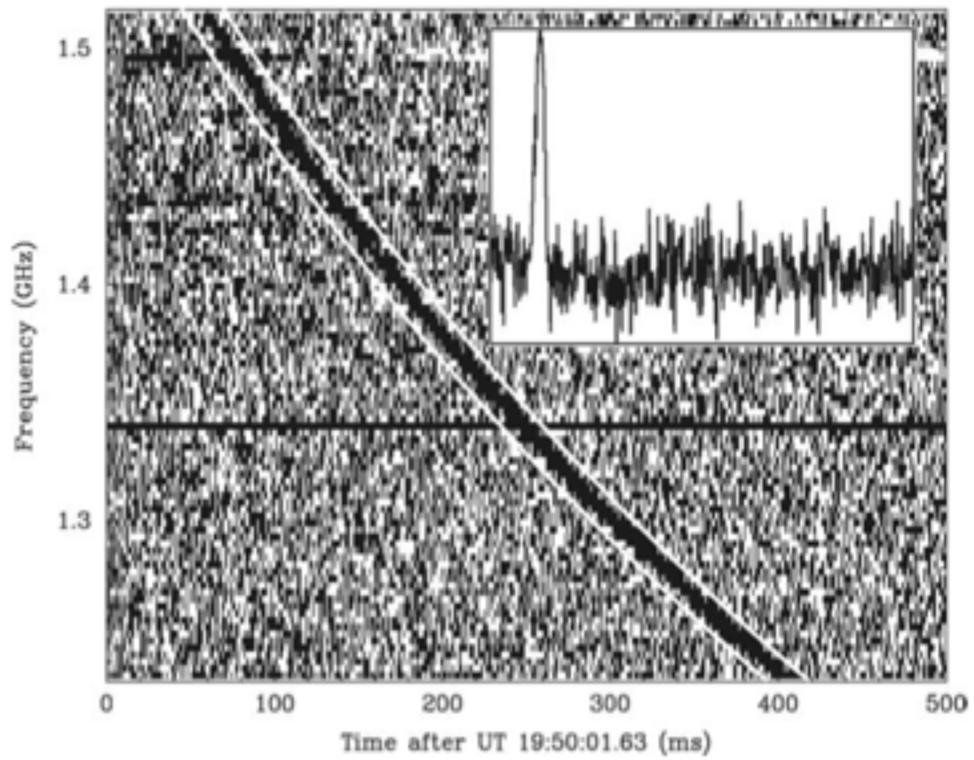


Lorimer et al.	2007	(1)	Burke-Spolaor et al.	2014	(1)
Keane et al.	2011	(1)	Petroff et al.	2014	(1)
Thornton et al.	2013	(4)	Ravi et al.	2014	(1)
Spitler et al.	2014	(1)	.		
Petroff et al.	2014	(0)	.		

FRBs: bright (& non-Galactic?)



Fast Radio Bursts: Cosmological Dispersion Measure?



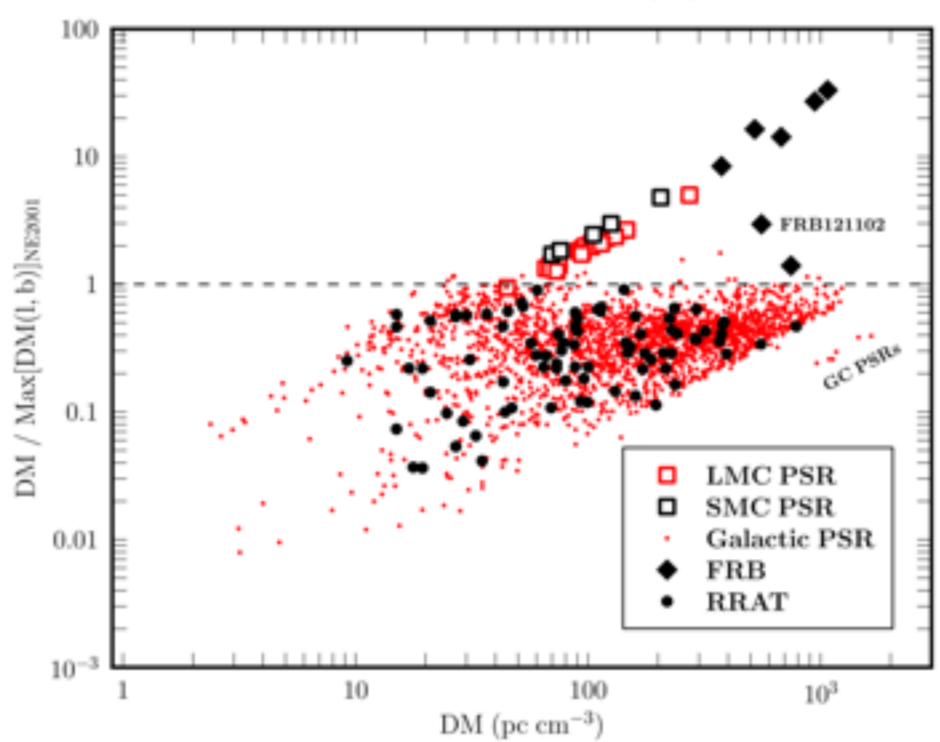
$$\Delta t_{\rm delay} = \frac{e^2}{2\pi m_e c^3}\left(\lambda^2\,{\rm DM}\right)$$

$$= 1.5\times10^{-24}\,{\rm s}\left(\lambda^2\,{\rm DM}\right)$$

$${\rm DM} \equiv \int d\ell\, n_e \;= 375\pm1\,{\rm cm}^{-3}\,{\rm pc}$$

$$\delta t_{\rm width} \;=\; 4.6\,{\rm ms}\left(\frac{\nu}{1.4\,{\rm GHz}}\right)^{-4.8\pm0.4}$$

$$\int dt\, I_\nu \simeq 150\pm50\,{\rm Jy\,ms}\;\;@\;1.4\,{\rm GHz}$$



	DM	redshift	energy	Δt
FRB010220	375- 25-100	~0.3	~10	5ms
J1852-08	745-533-100	~0.09	~10	7ms
FRB110220	944- 34-100	~0.81	~10	5.6ms
FRB110627	723- 46-100	~0.61	~10	<1.4ms
FRB110703	1103- 31-100	~0.96	~10	<4.3ms
FRB120127	553- 32-100	~0.45	~10	<1.1ms
FRB121102	557-188-100	~0.26	~10	3.0ms
FRB-011025	790-110-100	~0.59		5ms
FRB-140514	562- 35-100	~0.40	~10	[2.1,6.2]ms
FRB-131104	779- 77-100	~0.6		[1.5,2.8]ms

FRBs: what are they?

reasoning by rates

R_{FRB} ⇒ 10^4/sky/day @ 3 Jy ms

⇒ 10^4/sky/day (3 Jy ms/F)^(3/2) (assume Euclidean)

⇒ $10^4/\mathrm{Gpc}^3$/day (believe extraGalactic distances)

⇒ 10^{-3}/MWEG/yr (believe extraGalactic distances)

MWEG = Milky Way Equivalent Galaxy

Gamma Ray Bursts: $R_{FRB} \gg R_{GRB} = 10^{-6}$/MWEG/yr (GRBs beamed)

Core Collapse Supernovae: $R_{FRB} \ll R_{CC} = 10^{-2}$/MWEG/yr

Compact Binary Coalescence: R_{FRB} ?~? $R_{CBC} \in 10^{-4+1/-2}$/MWEG/yr (NS+NS➔NS/BH)

extragalactic: subclass of CCs (SURON/Blitzar), nearly all CBCs, magnetar masers

galactic: flaring stars, erratic pulsars, white dwarf mergers

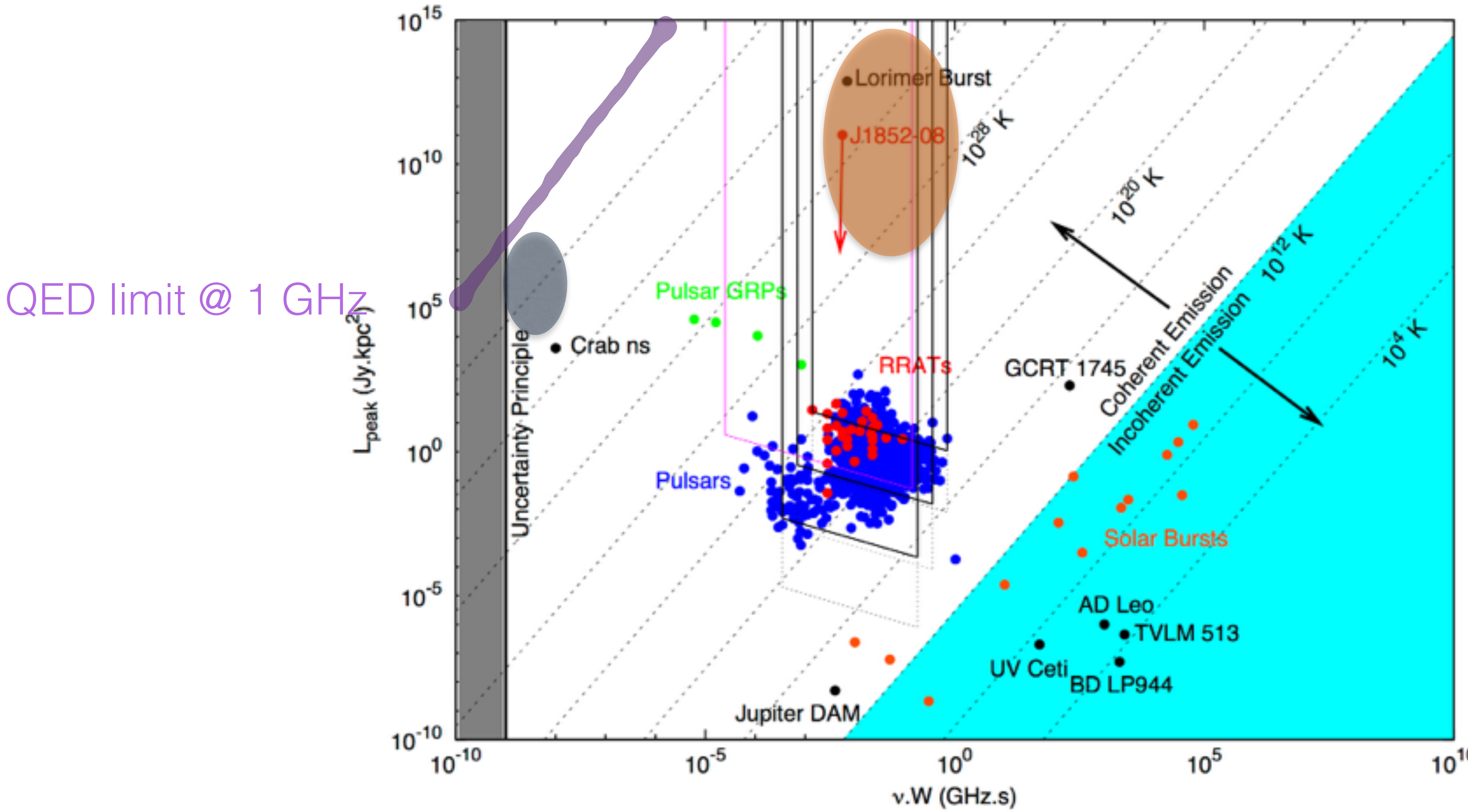
solar system: colliding mini-asteroids

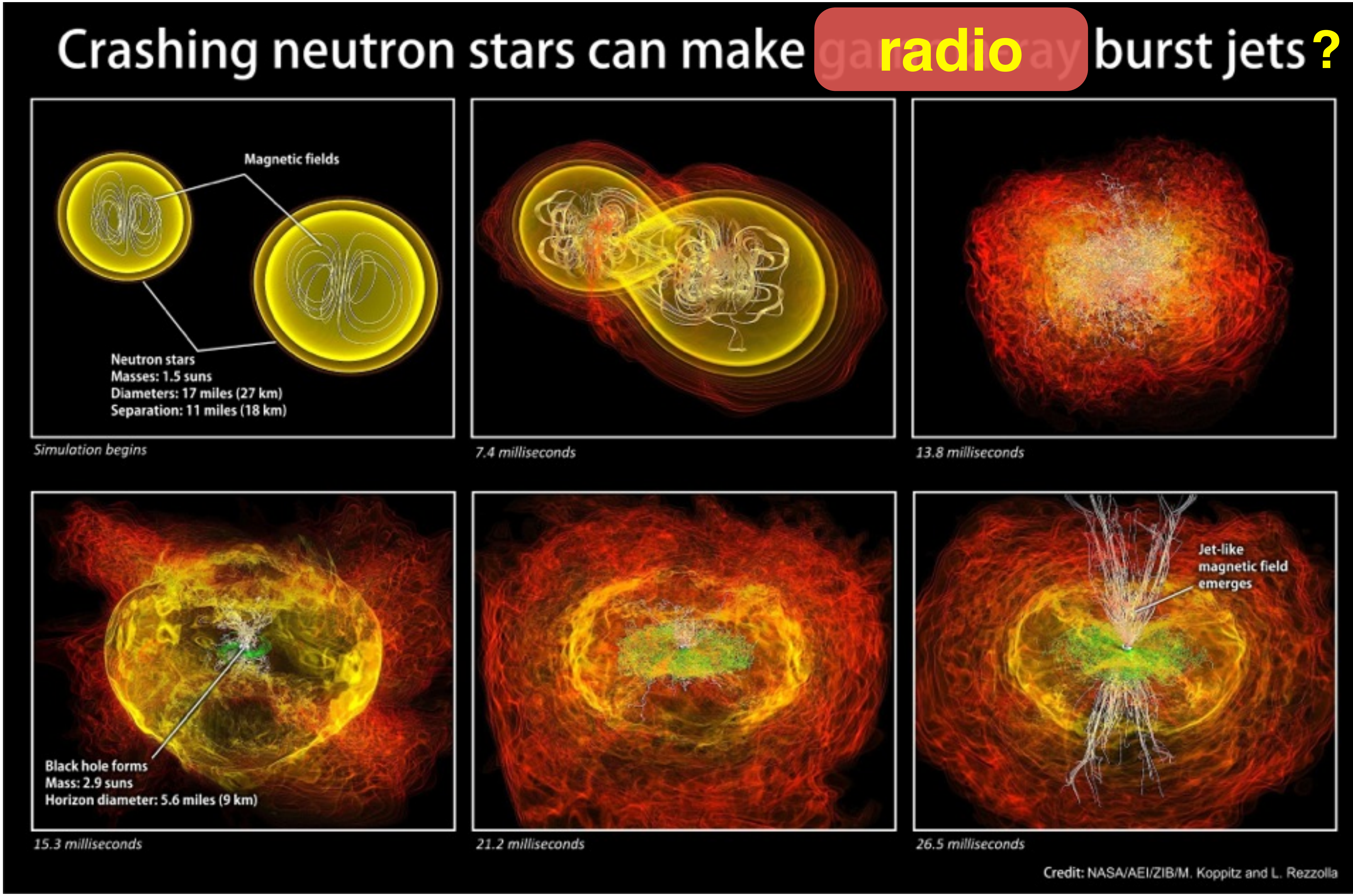
terrestrial: perytons

Loeb et al.	2013
Kashiyama et al.	2013
Lyubarsky	2014
Zhang	2014
Falke et al.	2014
Kulkarni et al.	2014
Guillochon	2014

Schwinger Model of FRBs

- **Blitzar**: ~billion Schwinger Sparks within a few msec.





Rapid turn off due to increasing opacity (plasma oscillations)?

FRBs: frequent

Lorimer (2013) extrapolated to all sky: 10^4/day ~ $4\text{x}10^6$/year

4 *D. R. Lorimer et al.*

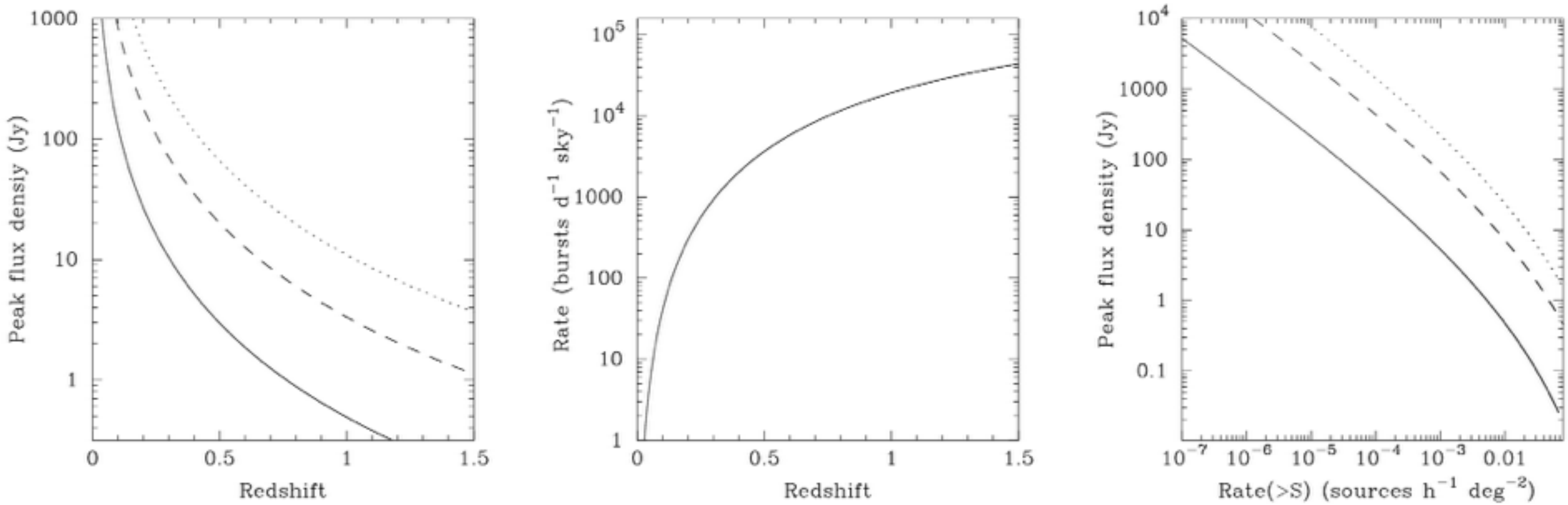


Figure 2. Predictions from our FRB population model. The left panel shows flux–redshift relationships for surveys carried out at 1400 MHz (solid line), 350 MHz (dashed line) and 150 MHz (dotted line). The centre panel shows the event rate normalized such that at $z = 0.75$ the implied event rate is 10,000 FRBs per day per sky as inferred by Thornton et al. (2013). The right panel shows the predicted burst rates above some threshold flux density S at 1400 MHz (solid line), 350 MHz (dashed line) and 150 MHz (dotted line).

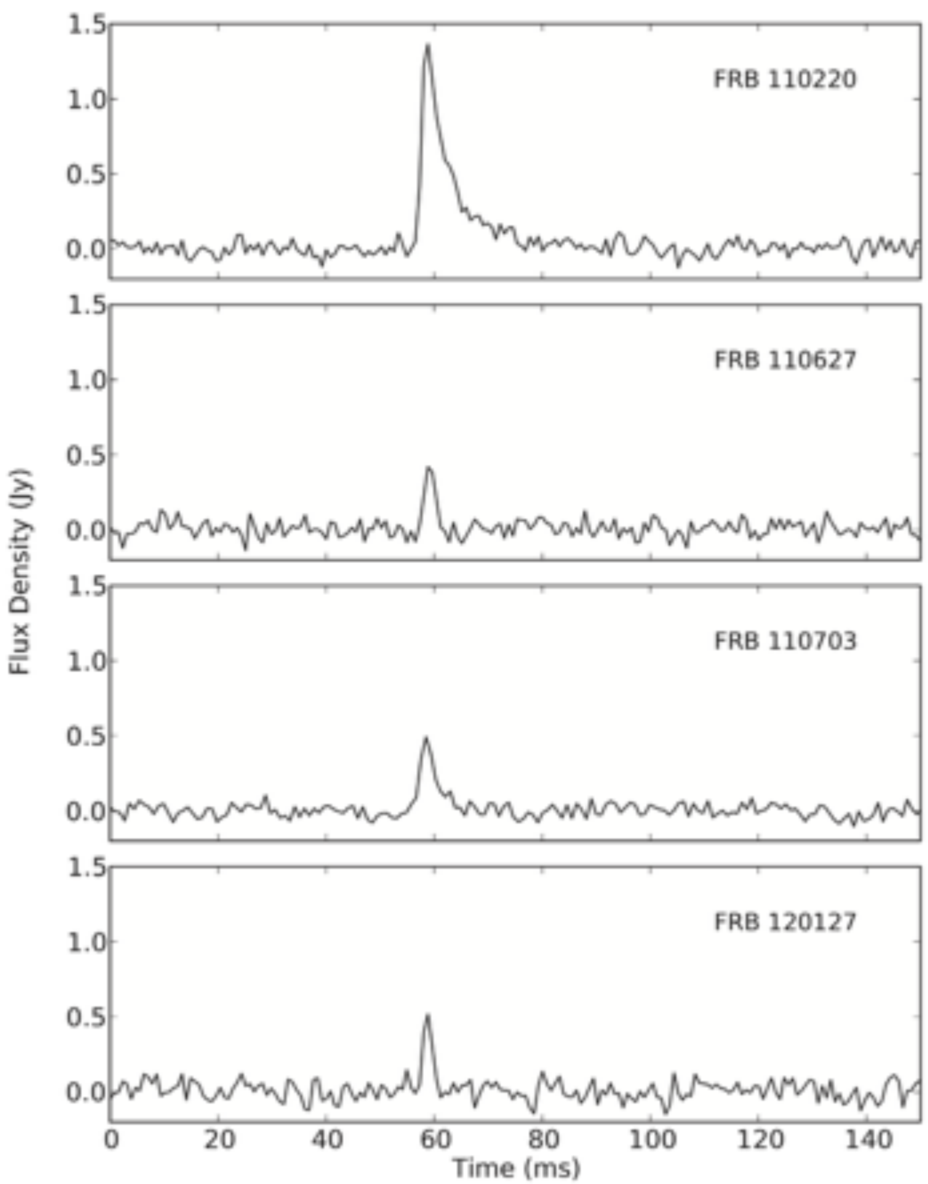
FRBs as Cosmological Tool

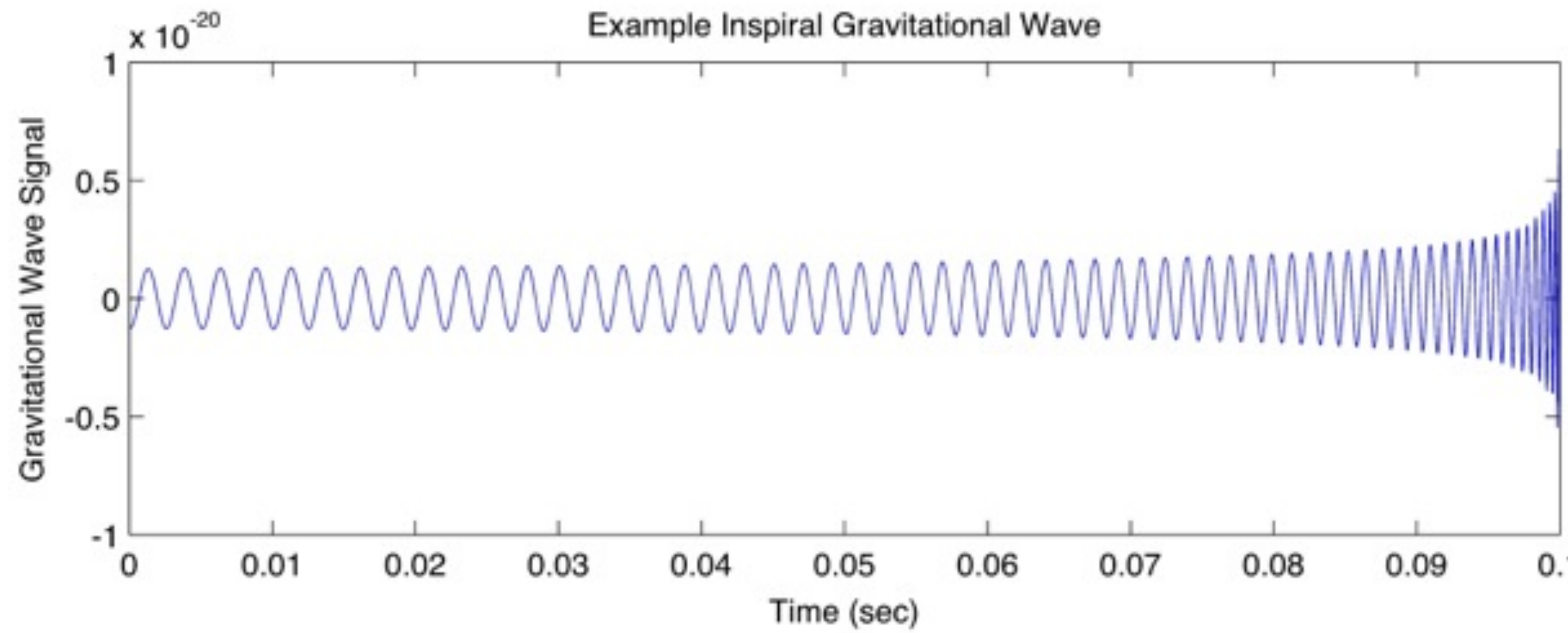
- Assume that FRBs signal a major life event for a neutron star:
  - birth (CC), marriage (CBC), death (SURON)

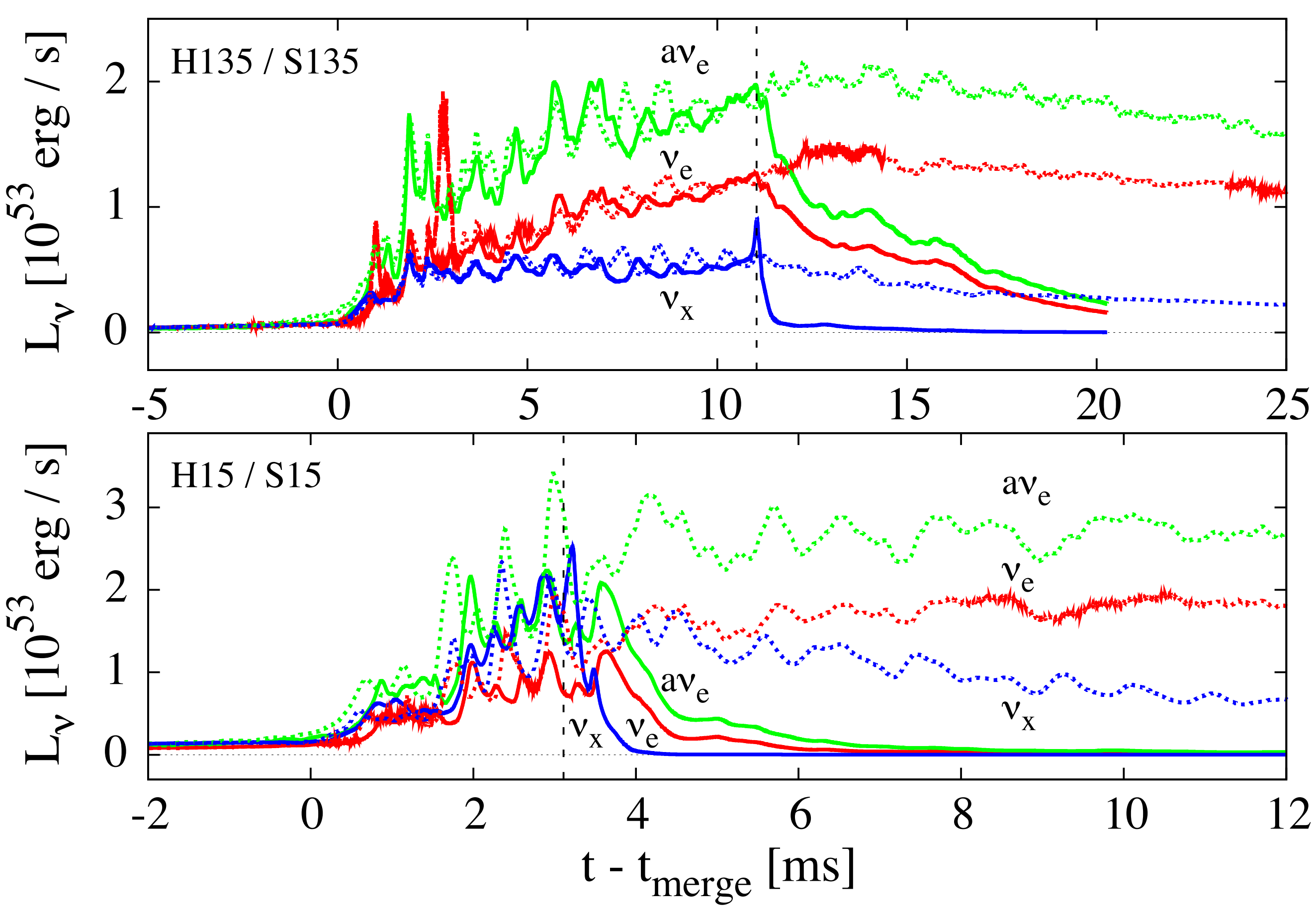
- Such events coincide with emission of copious neutrinos and gravitational waves.
  - CCs are best for neutrinos, CBCs best for gravitational waves.
  - These are all the sky all the time telescopes.

- If sufficiently motivated one might be able to detect $\gtrsim 10^6$ FRBs per year ($\gtrsim$6 per minute) with $\lesssim$1 msec timing accuracy
  - dispersion measure provides a rough redshift (just how rough TBD) msec triangulation would provide ~1 degree directional accuracy
  - GHz waveform correlation could provide up to 10'' directional accuracy
  - with the later one could identify the host galaxy and possibly have a pre-measured redshift

Coincidence of Timescales for NS+NS⇒NS CBCs







Kiuchi et al. 2012

FRB Triggers Increase Reach of Neutrino Telescopes

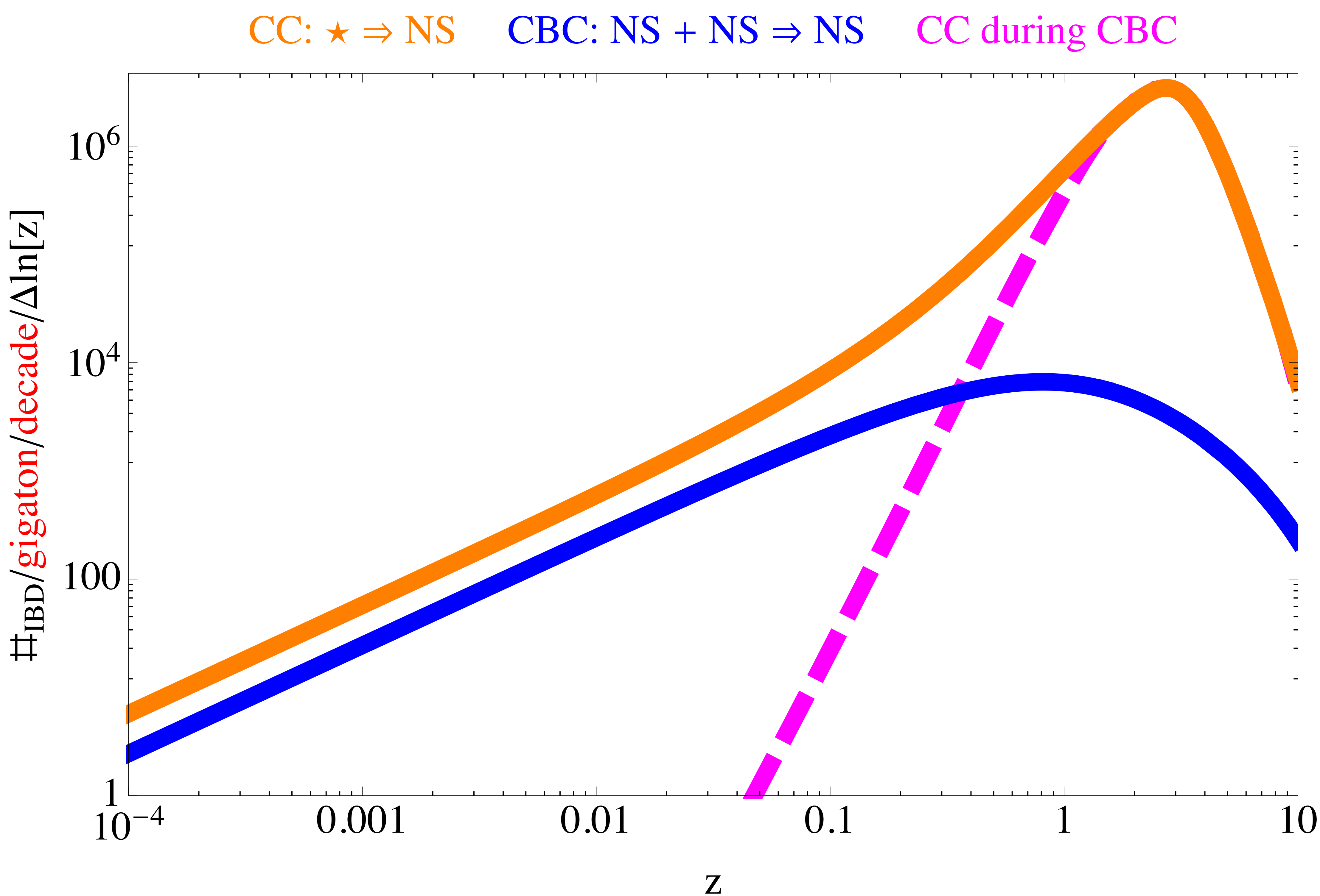
- It is believed that Gadolinium doped water Cerenkov detectors can reduce 12-30 MeV background (mostly atmospheric ν's) events below the Diffuse Supernova Neutrino Background (DSNB).

- The DSNB is the irreducible background for ν's associated with FRBs.

- Gadolinium plus FRB timing reduces backgrounds to FRB associated ν's to negligible levels for FRBs with $z \lesssim 2$.

- However to get a significant signal one requires extremely large detectors ($M \gg 1$ megaton).

FRB Associated Neutrinos



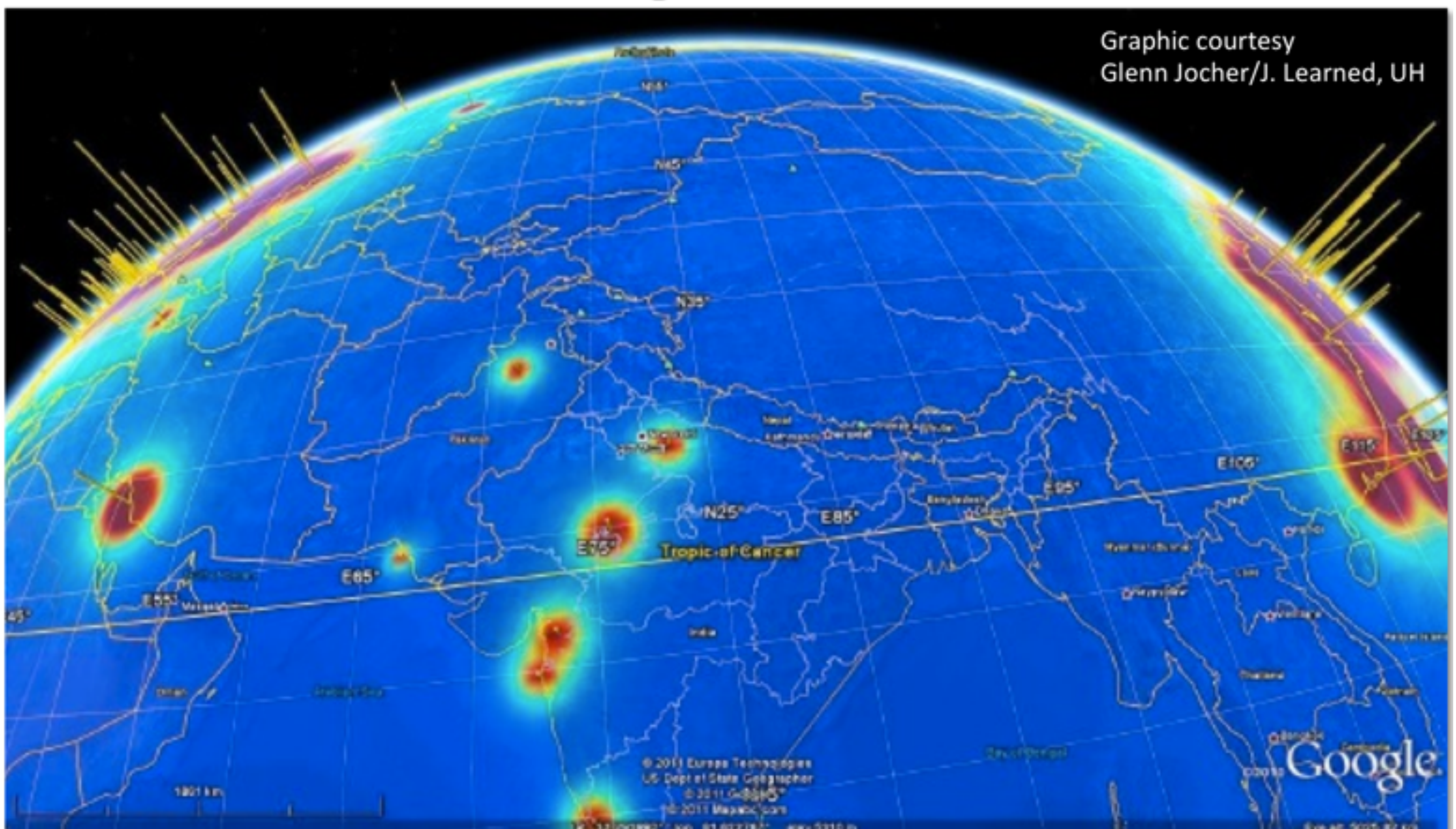
With FRB triggers “negligible" backgrounds for z≲0.2

Who would build a Gigaton ν Detector?
Big Brother?

WATCHMAN

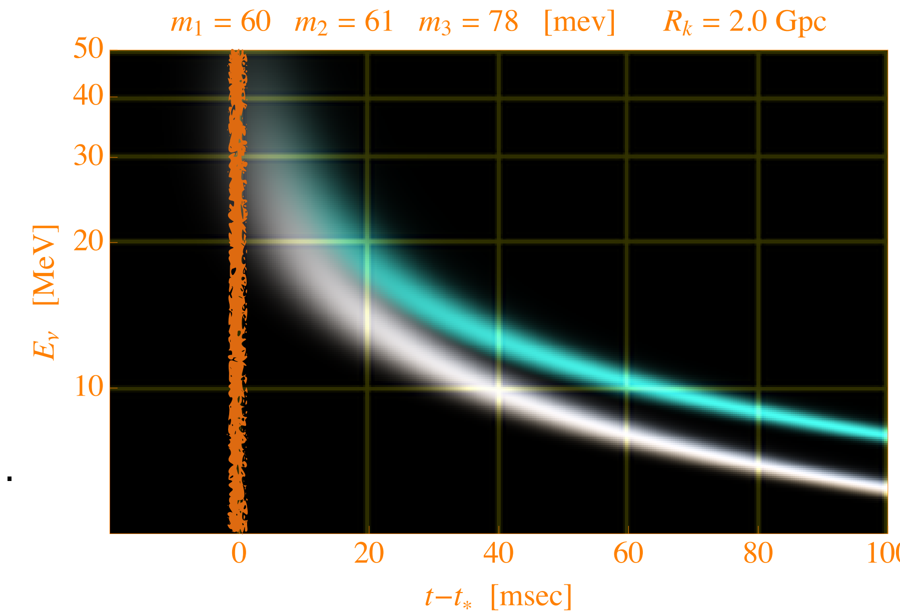
WATer **CH**erenkov **M**onitoring of **A**nti-**N**eutrinos

Marc Bergevin, UC Davis



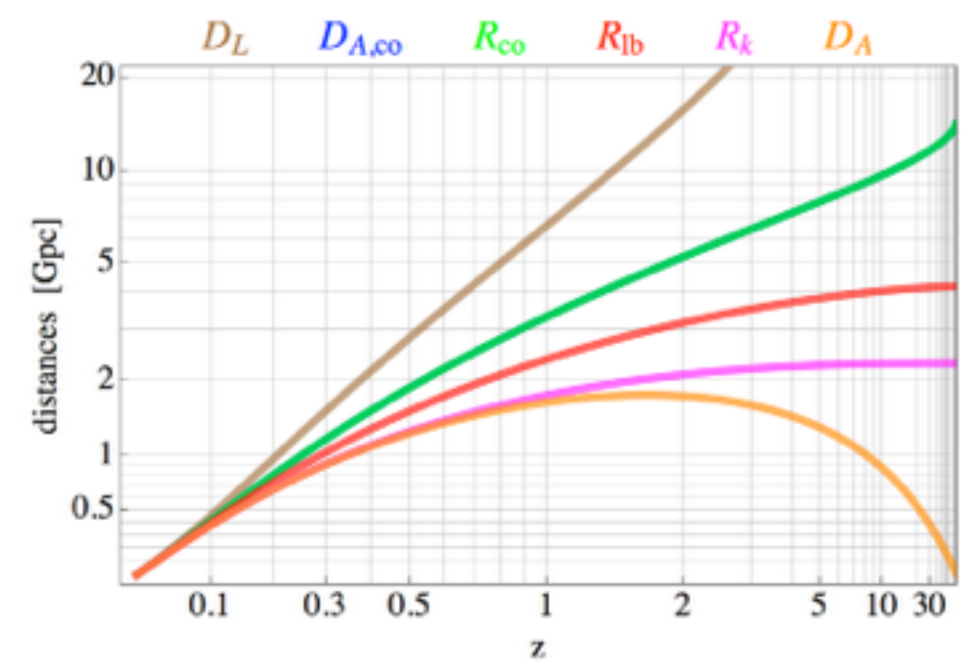
What to do with 1000s of FRB ν's?

- Learn about FRB progenitors.
- Measure the Hubble Constant
  - massive ν time of arrival energy dependent
  - we don't know absolute mass scale of ν's but we might soon.



$$\Delta t = \frac{1}{2}\left(\frac{m}{E}\right)^2 \frac{R_\mathrm{k}}{c} = 10\,\mathrm{sec}\left(\frac{m}{0.1\,\mathrm{eV}}\;\frac{10\,\mathrm{MeV}}{E}\right)^2 \frac{R_\mathrm{k}}{2\,\mathrm{Gpc}}$$

- N.B. For small z since $\Delta t \propto R$ while $\#_\nu \propto R^{-2}$ the Fisher information for H_0 is contributed equally for each FRB.
- A gigaton detector operating for a decade could in principle yield % level determination of H_0.



$$R_\mathrm{lb}[z] = c\int_0^z \frac{dz}{(1+z)\,H[z]} \qquad D_{A,\mathrm{co}}[z] = \begin{cases} \frac{\mathrm{Sin}\left[\sqrt{K}\,R_\mathrm{co}[z]\right]}{\sqrt{-K}} & K>0 \\ R_\mathrm{co}[z] & K=0 \\ \frac{\mathrm{Sinh}\left[\sqrt{-K}\,R_\mathrm{co}[z]\right]}{\sqrt{-K}} & K<0 \end{cases} \qquad D_\mathrm{A}[z] = \frac{1}{1+z}\,D_{A,\mathrm{co}}[z]$$

$$R_\mathrm{co}[z] = c\int_0^z \frac{dz}{H[z]} \qquad D_\mathrm{L}[z] = (1+z)\,D_{A,\mathrm{co}}[z] \qquad R_\mathrm{k}[z] = c\int_0^z \frac{dz}{(1+z)^2\,H[z]}$$

FRB Triggers Increase Reach of GW Telescopes

- It is normally thought that gravitational radiation detectors may provide triggers for other observations but the reverse may be true in the case of FRBs.

- For triggers it is quantity that matters.
  - FRBs occur 10 to 100 times more frequently than GRBs and are shorter.
  - While core collapses SNe occur more frequently than FRBs the time of core collapse can at best be determined to ~1 day accuracy and one is in the confusion limit.

- With 10^6 triggers one increases $\langle h^2\rangle/\langle n^2\rangle$ of incoherent signal by 10^3, bringing effective S/N distance of co-added z~0.7 events down to z~0.02 or 100Mpc.
  - if there were a component to the gravitational radiation waveform correlated with the radio burst trigger one could decrease this much more: down to z~0.0007 or 3 Mpc.

SUMMARY

- Enigmatic ultra-bright phenomena are seen in the GHz radio band.
- A heretofore unobserved QED phenomena, the Schwinger mechanism, may play important role in producing some of these phenomena.
- We propose Schwinger sparks as the emission mechanism of both Crab nanoshots and Fast Radio Bursts.
    - neutron star senility: young neutron star behavior re-exhibited as an adult
- Irrespective of emission mechanism, if FRBs are neutron star major life events, they could be extremely valuable for gravitational radiation astronomy, neutrino astronomy, and cosmology.