Title: Crab Nanoshots, Fast Radio Bursts and Cosmology

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Abstract: <p>We explore the brightness frontier in time domain radio astronomy and its possible usefulness for cosmology. It is argued that the brightest known source of emission, Crab nanoshots, are caused by Schwinger pair production. The same mechanism may be the source of Fast Radio Bursts (FRBs) if this emission is form coalescing neutron stars. It is then shown how using FRBs as triggers can extend the reach of gravitational radiation and neutrino telescopes. Finally we discuss how combining FRB monitoring, large neutrino telescopes, combined with preexisting galaxy catalogs could provide an accurate cosmological distance estimator.</p>

Crab Nanoshots, Fast Radio Bursts and Cosmology

Albert Stebbins
Fermilab
w/ Hojin Yoo (LBNL)

Perimeter Institute
13 January 2015
Waterloo, Canada

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!

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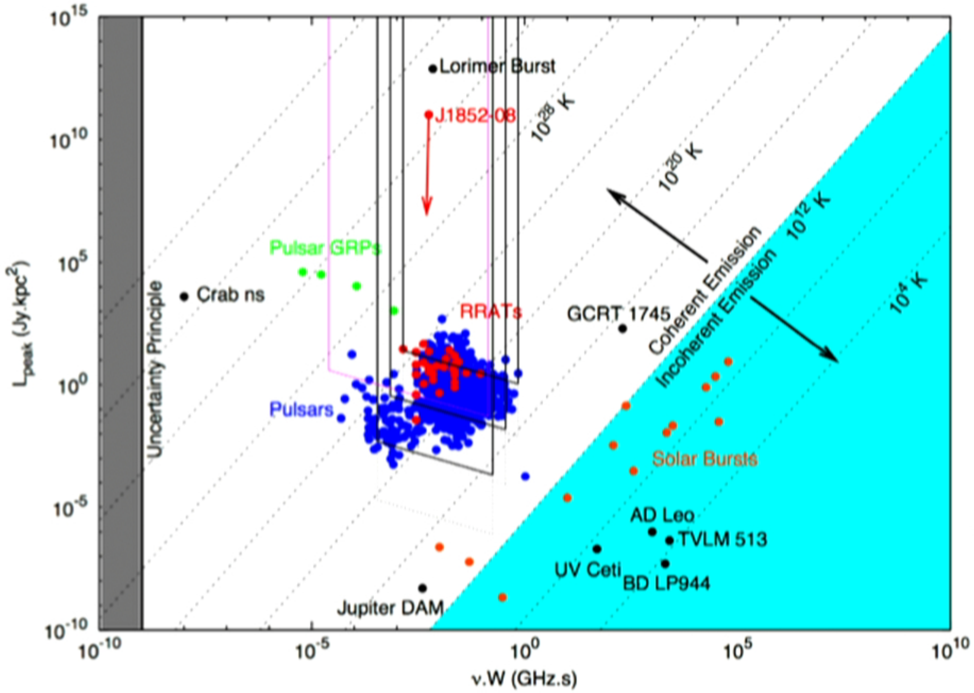

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W - pulse width

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

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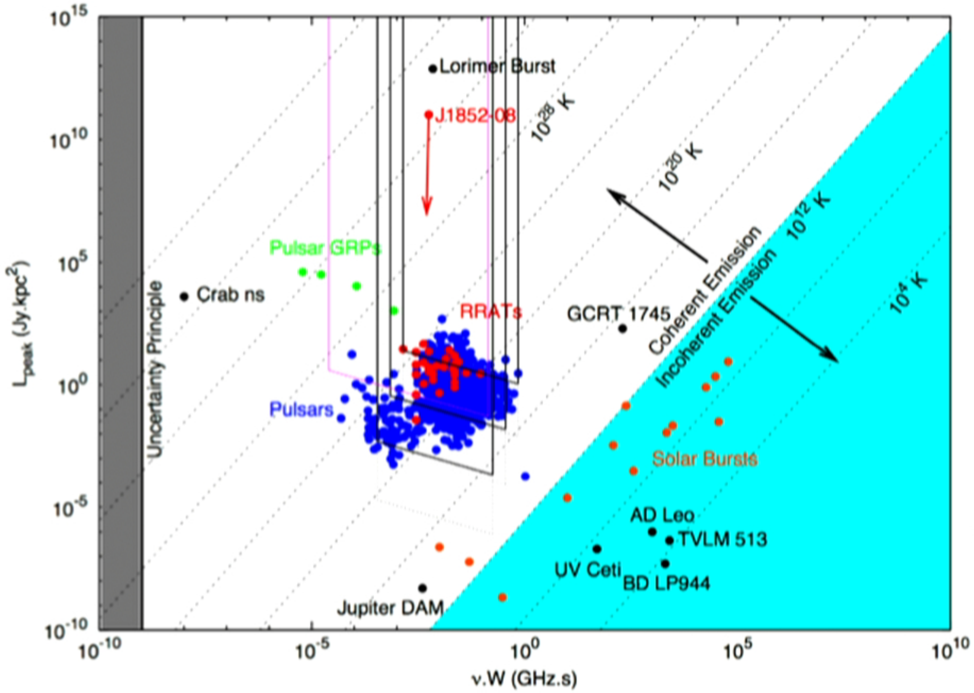

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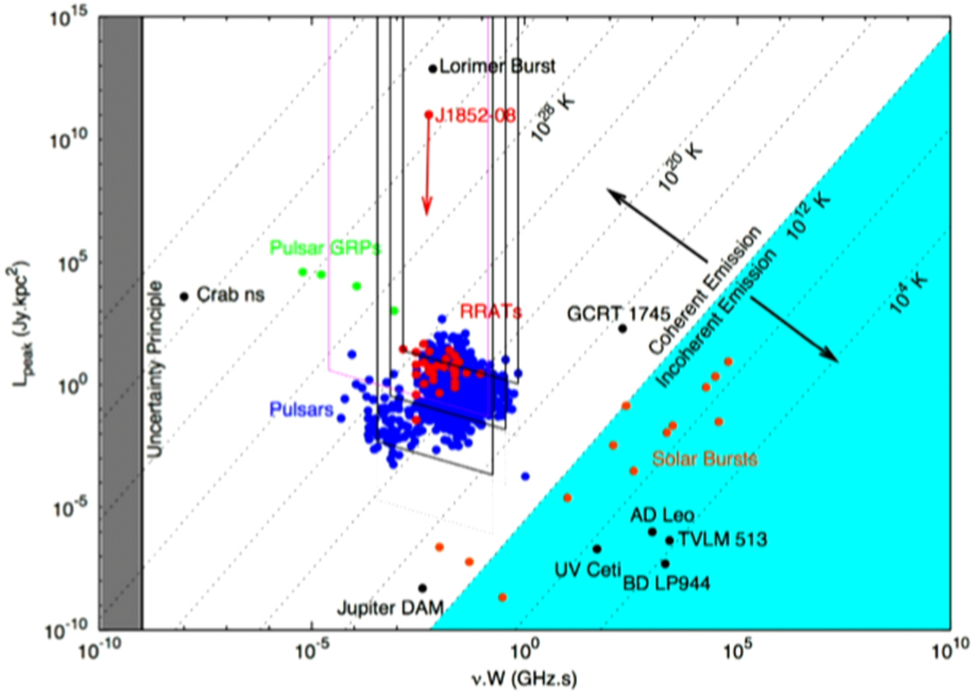

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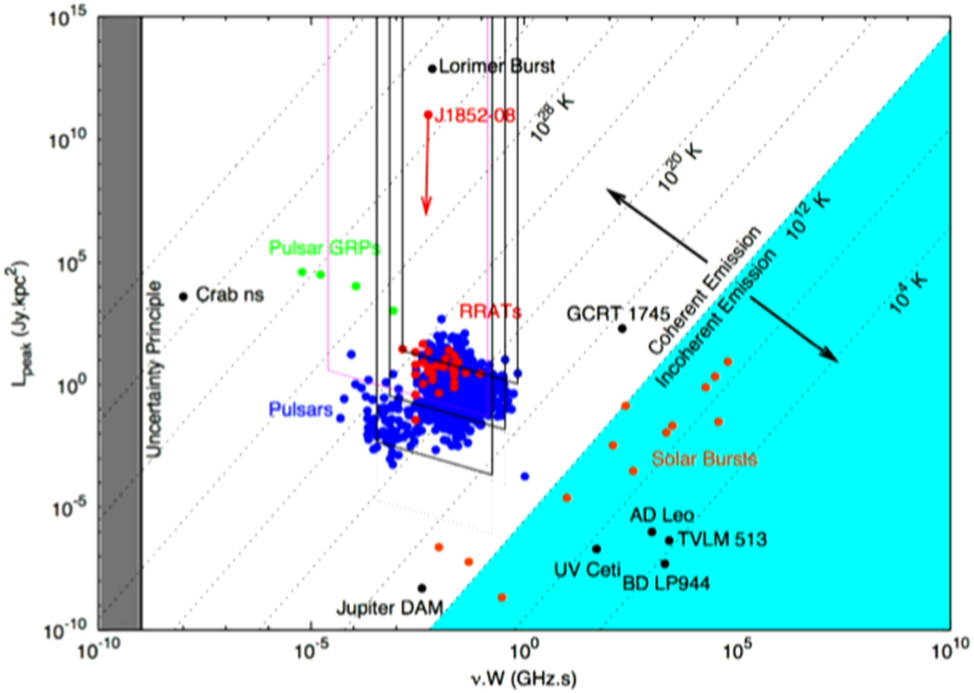

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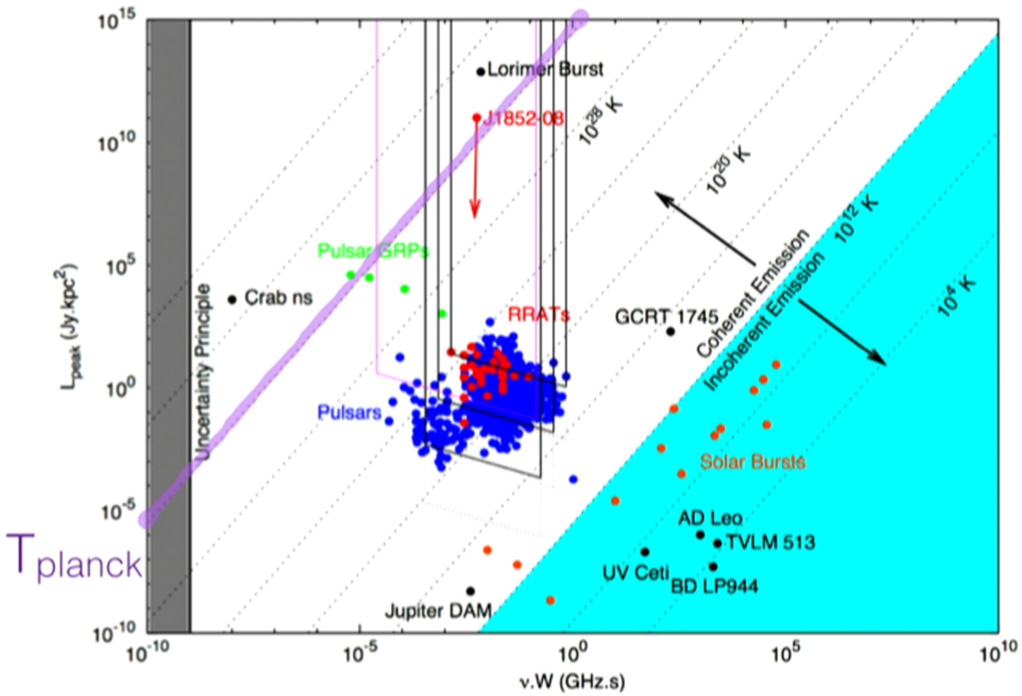

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Coherent vs Incoherent Radiation

Incoherent radiation

charged particles moving independently

$I_\nu \propto N$

synchrotron, free-free, …

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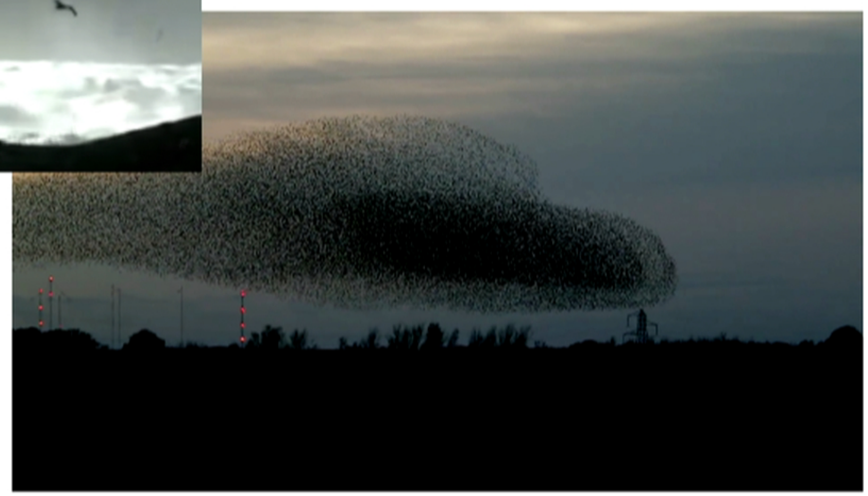

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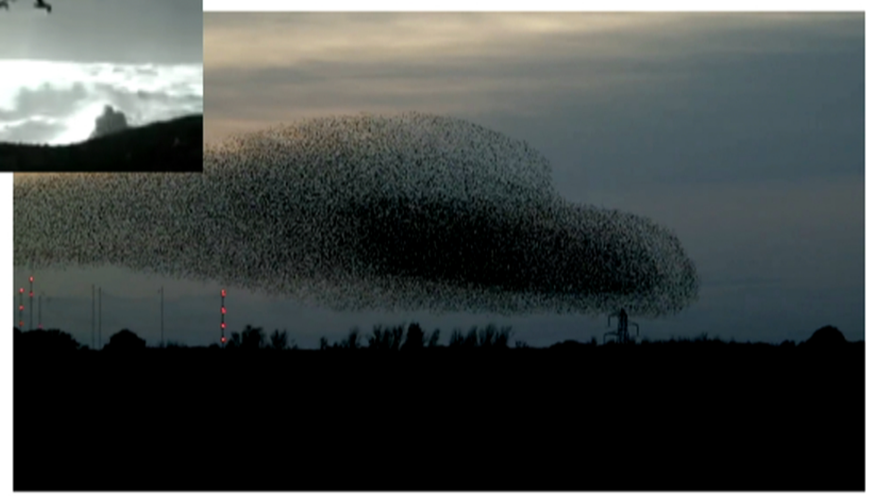

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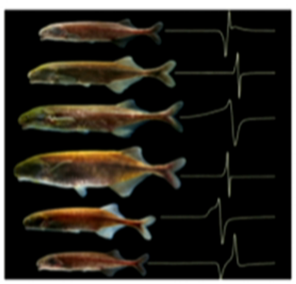
Macroscopic E&M and Thermodynamics

- 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.

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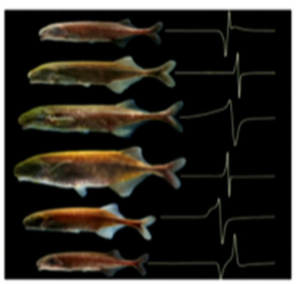
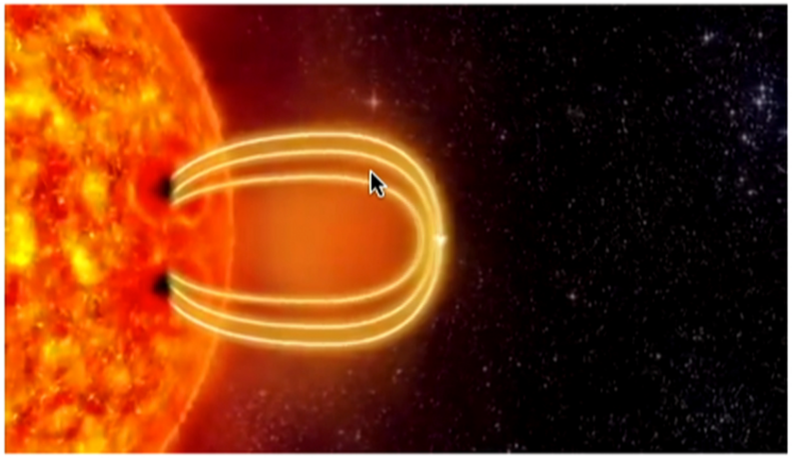
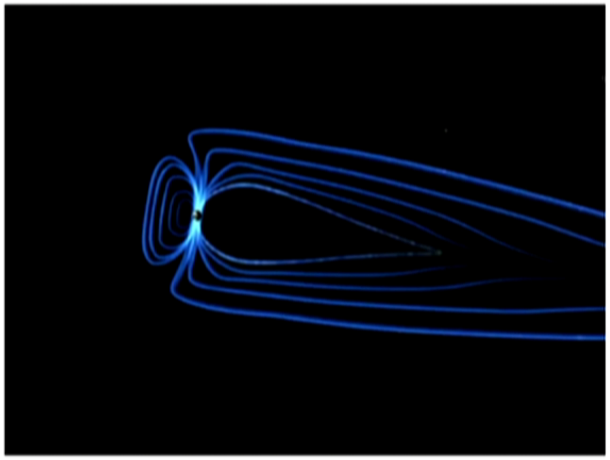



Magnetic Field Reconnection and Astrophysical EMP

- 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 the B field can oscillate into E field which accelerates and separates charges which also produces large EMP.





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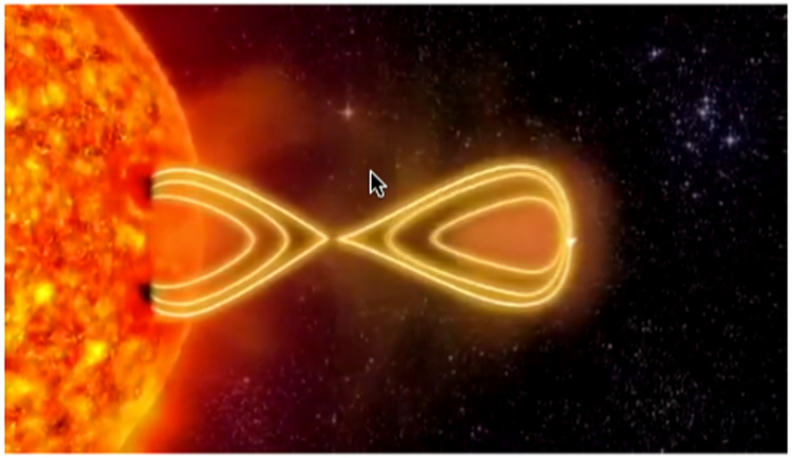

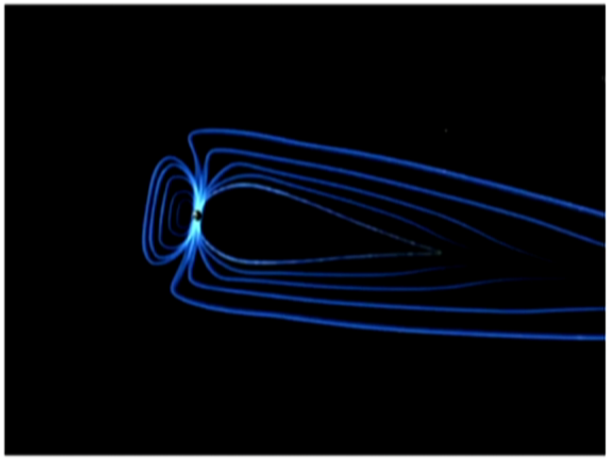

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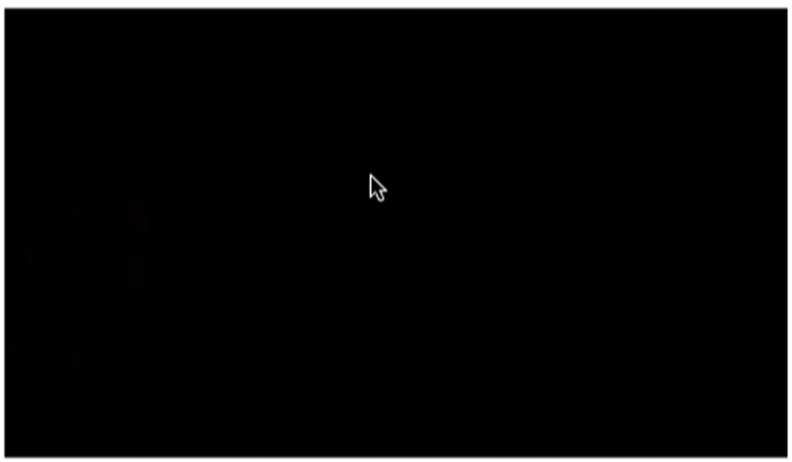

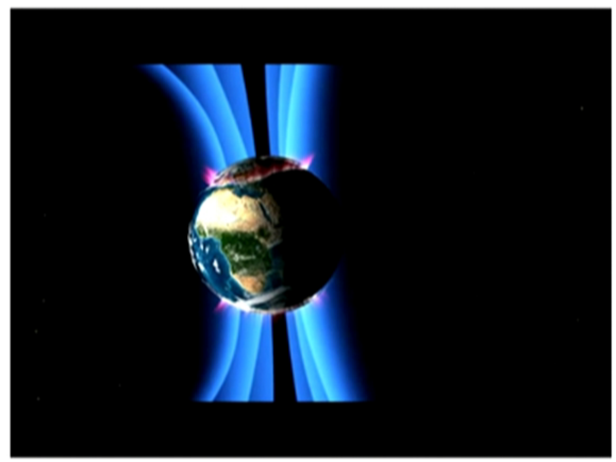

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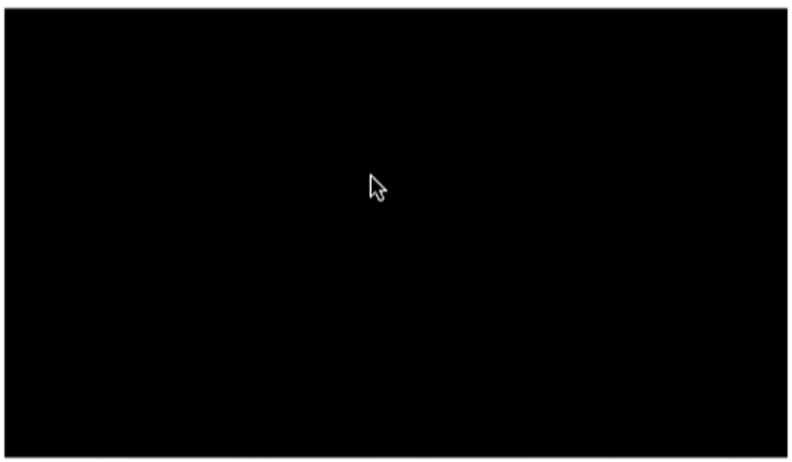
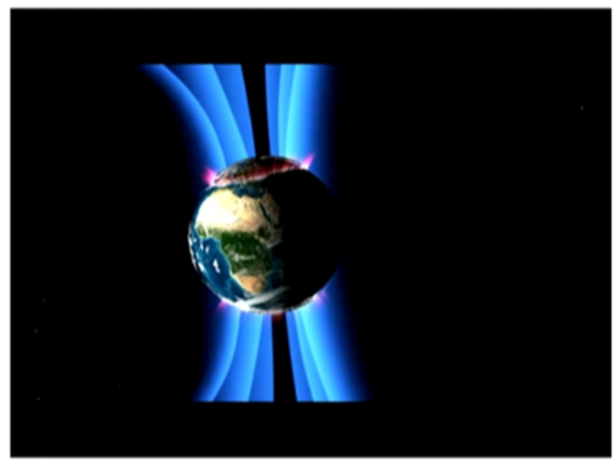
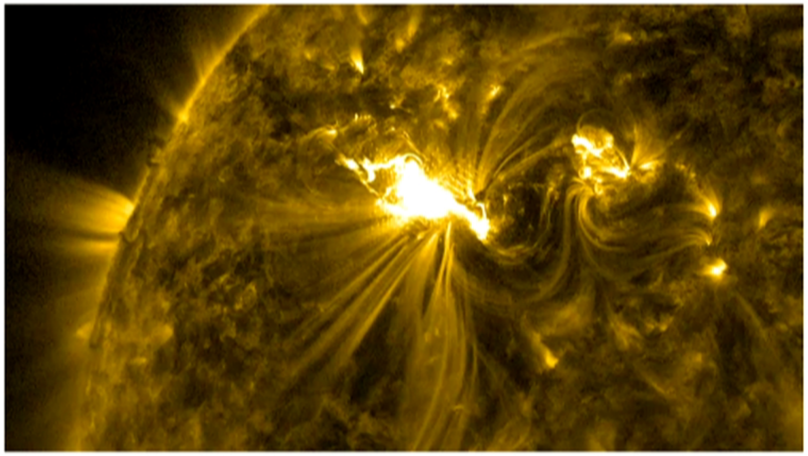
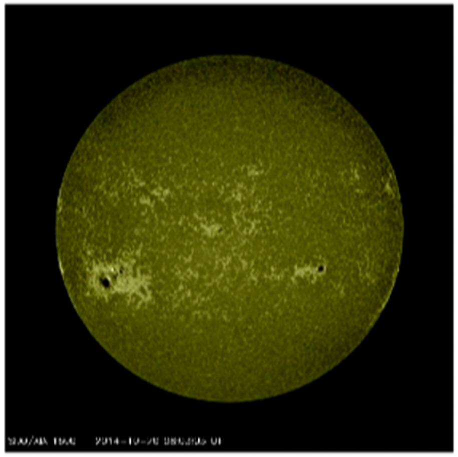




Magnetic Field Reconnections and other types of Sparks are Bright !





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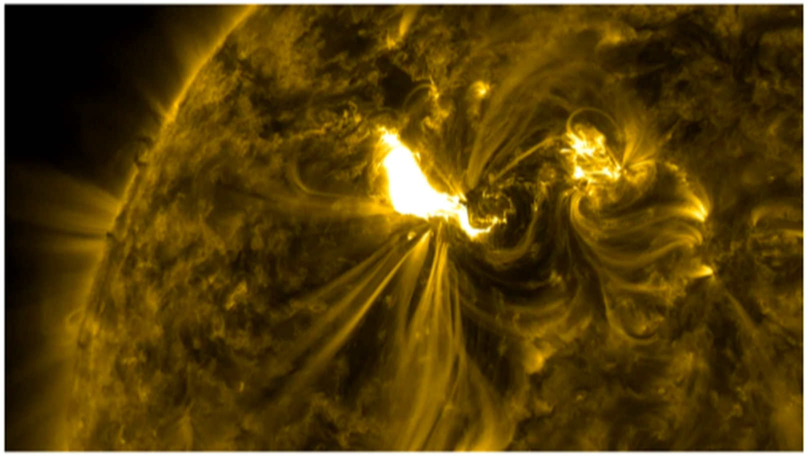

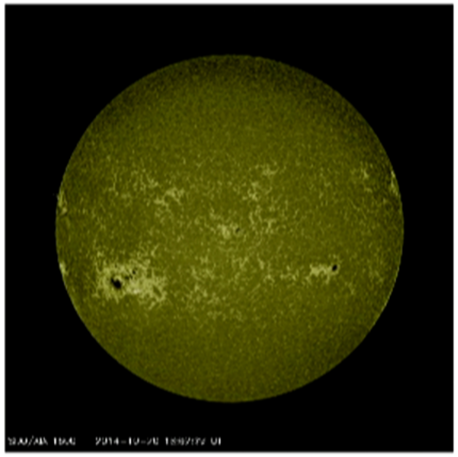

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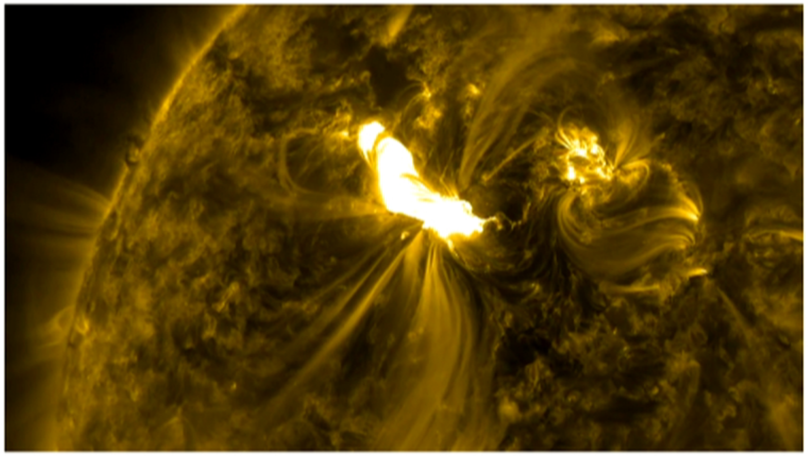
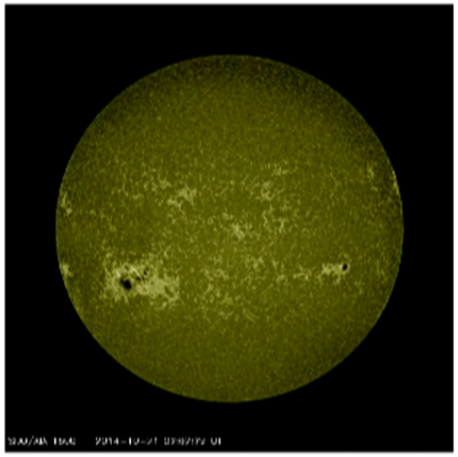
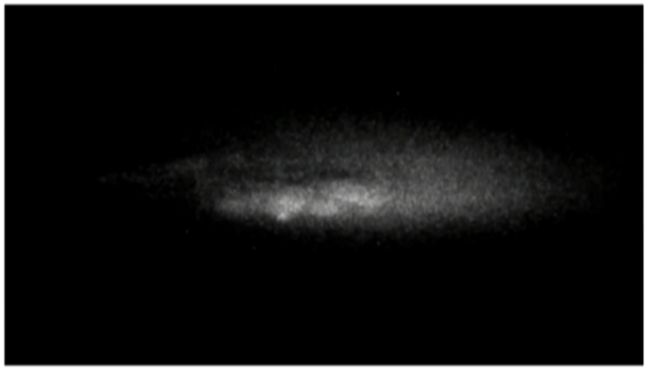
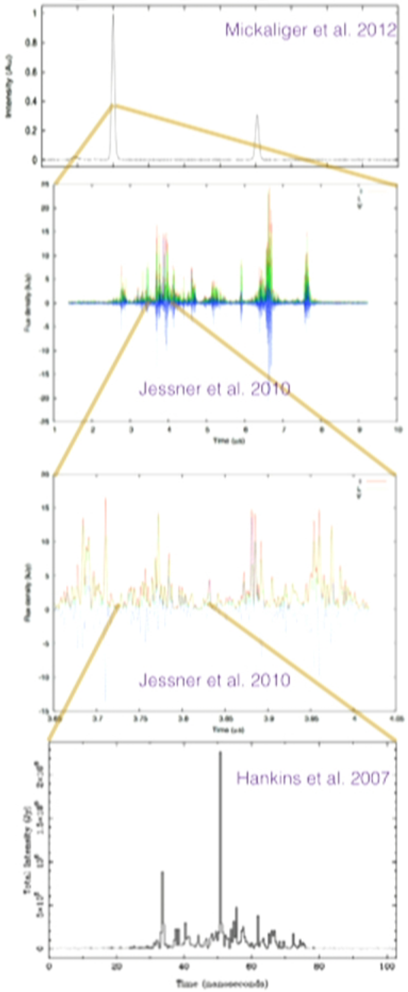






Crab Radio Pulse Structure



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Occasional Giant Pulse

Micro Burst

Nano Shot

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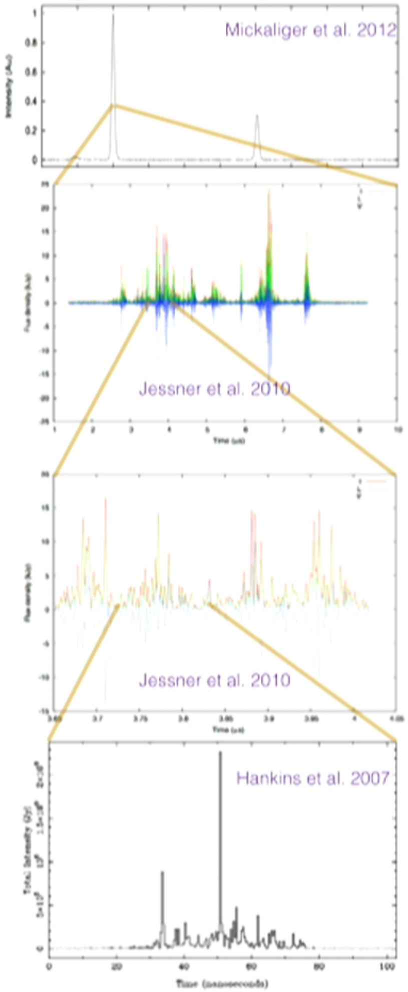

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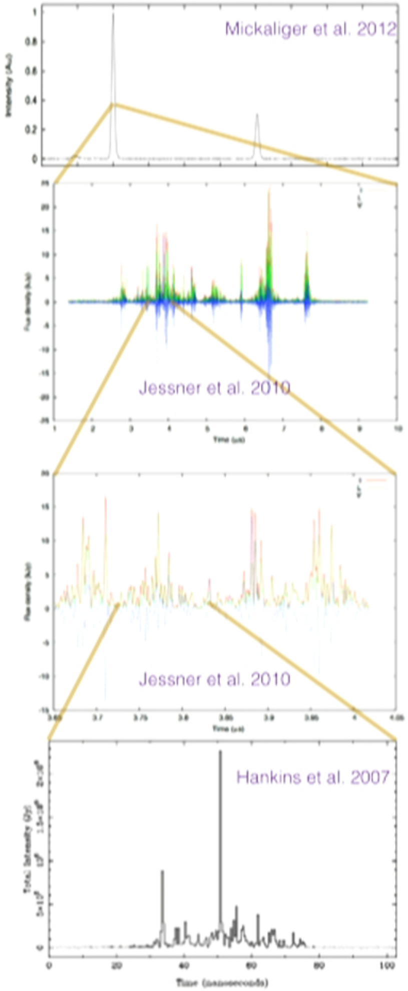

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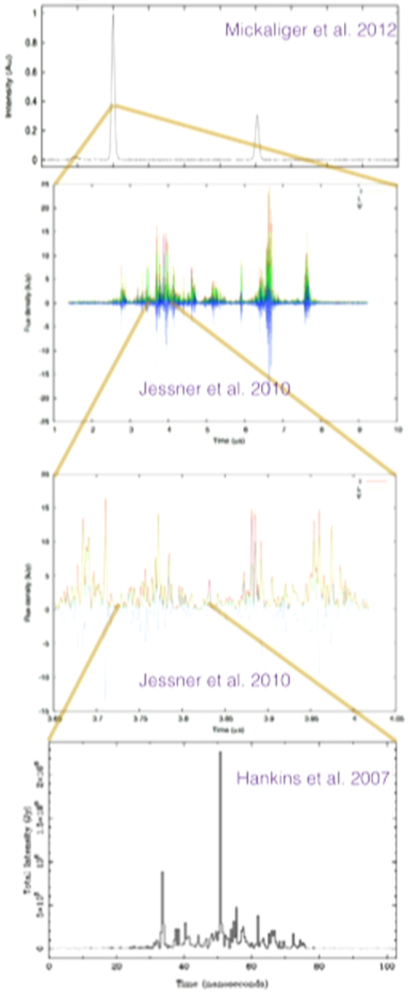

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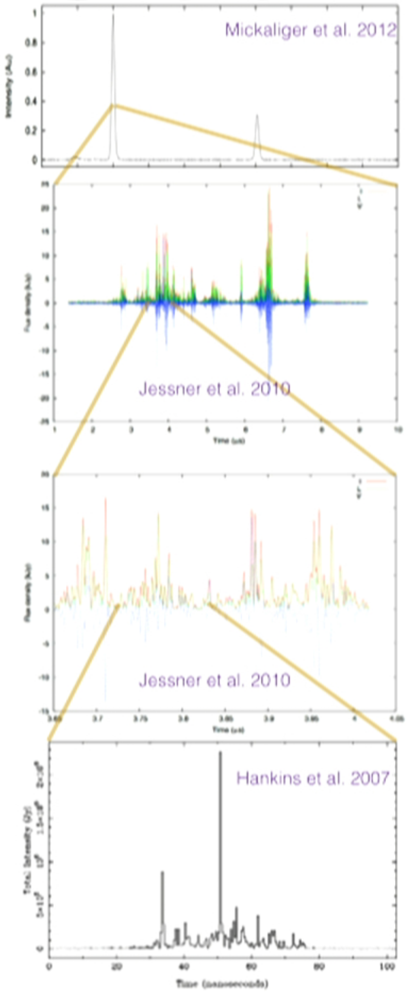

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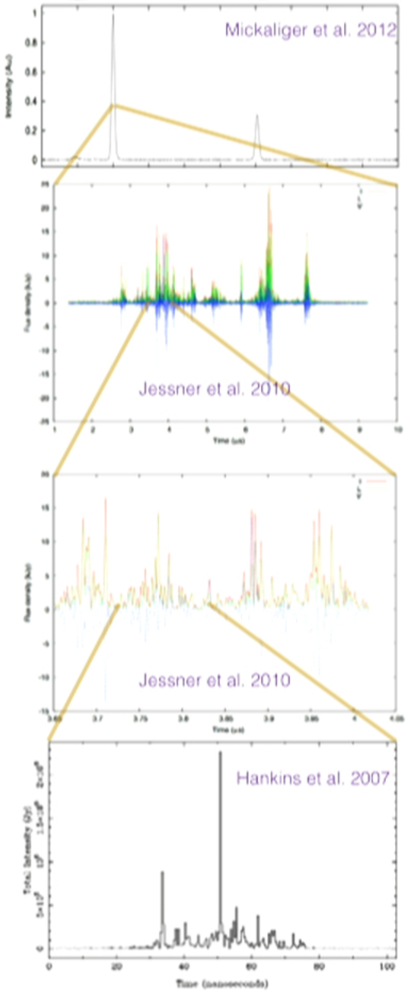

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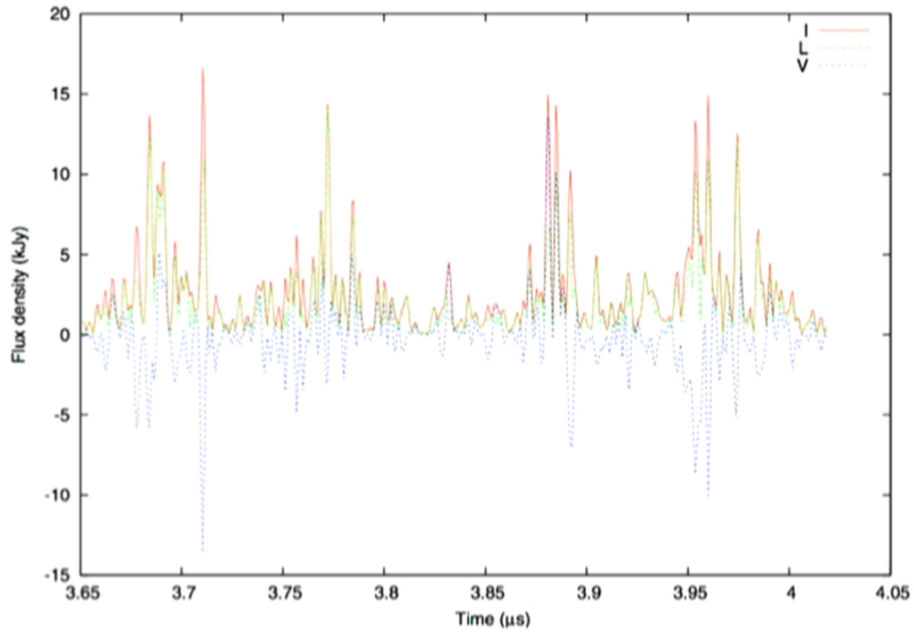

This record nanoshot had peak observed flux of 2MJy, astounding for an object 2kpc away!

Crab Nanoshot Numerology

- (Assuming no significant relativistic beaming)
- size: ≲30cm [c ns]
- energy: $\lesssim 10^{28}$erg [$4\pi\ D^2$ MJy ns GHz]

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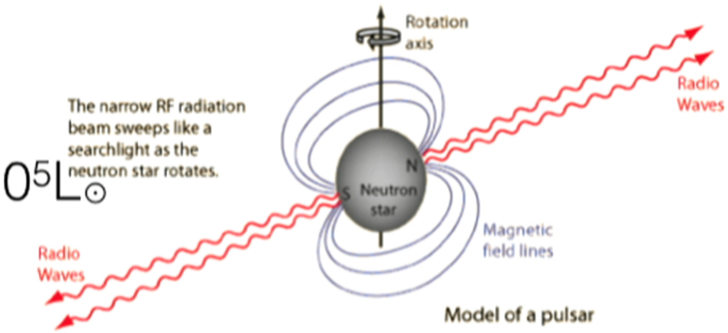
- peak luminosity: ≲$1.5\times10^3 L_\odot$ [4π D^2 MJy nsec GHz]
- electric field: ≲2×10^{12}G [4π D / ns √(MJy GHz / c^3)]
- charge: ≲5 Mole e [4π D ns √(MJy GHz c)]
- $e^\pm$ energy: ≲15 PeV [4π D e √(MJy GHz / c)]

Crab Pulsar Magnetosphere Numerology

- inner radius: 10km
- spin down luminosity: $\sim 10^5 L_\odot$



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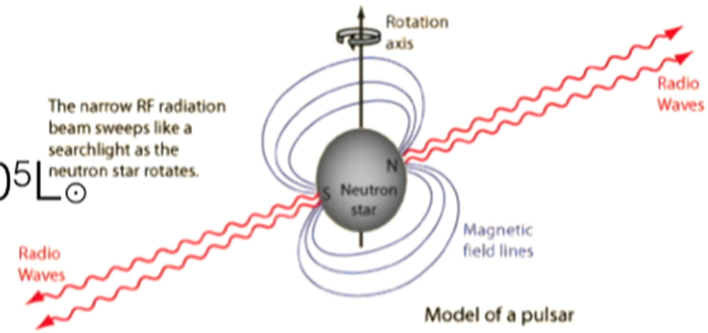
- particle density: ~0.004 mole/m^3



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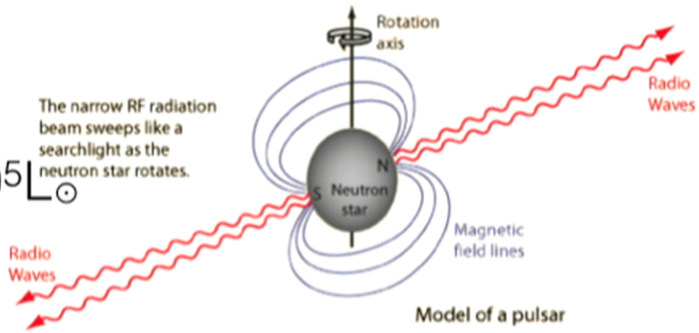
- plasma frequency: 250 GHz at surface



Radio Transients & QuantumElectroDynamics

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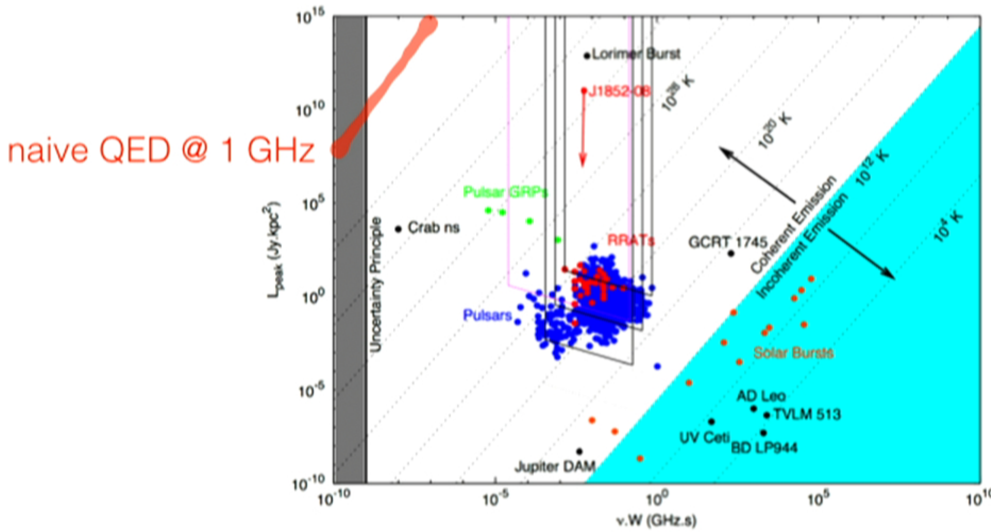
- Neutron stars with magnetic fields are called *magnetars*. These exhibit interesting QED phenomena such as photon splitting.
- If we know the distance to the source one can estimate the electromagnetic field strength at emission (neglecting relativistic beaming): $E \approx \sqrt{4\pi\, \nu\, L_\nu\, \Delta t / (c\, \Delta t)^2}$

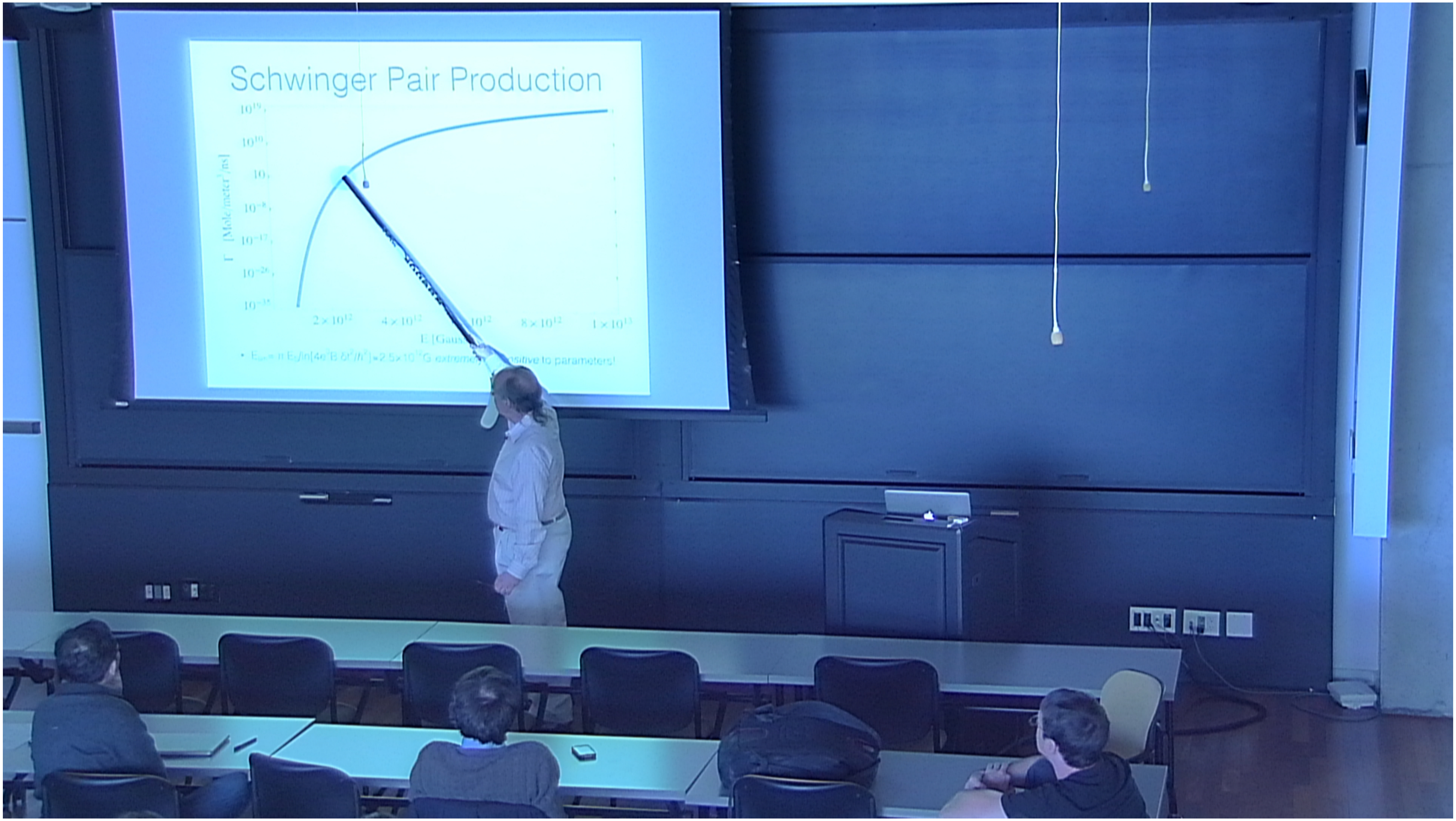


Schwinger Pair Production

- required pair production rate is ~0.2 Mole/m^3/ns
- In the presence of a strong electric field pairs are spontaneously produced out of the vacuum.
- in co-linear frame (**E∥B**) in terms of $E_S \equiv m_e^2c^3/(e\hbar)=4\times10^{14}$G

$$\Gamma = \frac{e^2}{\pi c \hbar^2} E\,B \sum_{n=0}^{\infty} \sum_{s=\pm1} e^{-\pi \frac{e E_S + (2n-s+1) e B}{e E}} \cong \frac{e^2}{\pi c \hbar^2} E\,B\, e^{-\pi \frac{E_S}{E}}$$

- Note $(e\,E_S)^2/(\pi c\hbar^2)=7\times10^{24}$Mole/m^3/ns is too large! E never approaches E_S
- electric field will saturate when **shorted**
  - pair production rate exceeds rate of field increase
  - all speeds ultra-relativistic
- $E_{lim}= \pi\, E_S/\ln[4e^3B\,\delta t^2/\hbar^2] \cong 2.5\times10^{12}$G *extremely insensitive* to parameters!


Schwinger Pair Production
10^{19}
10^{10}
10
10^{-8}
10^{-17}
10^{-26}
10^{-35}
Γ [Mole/meter^3/ns]
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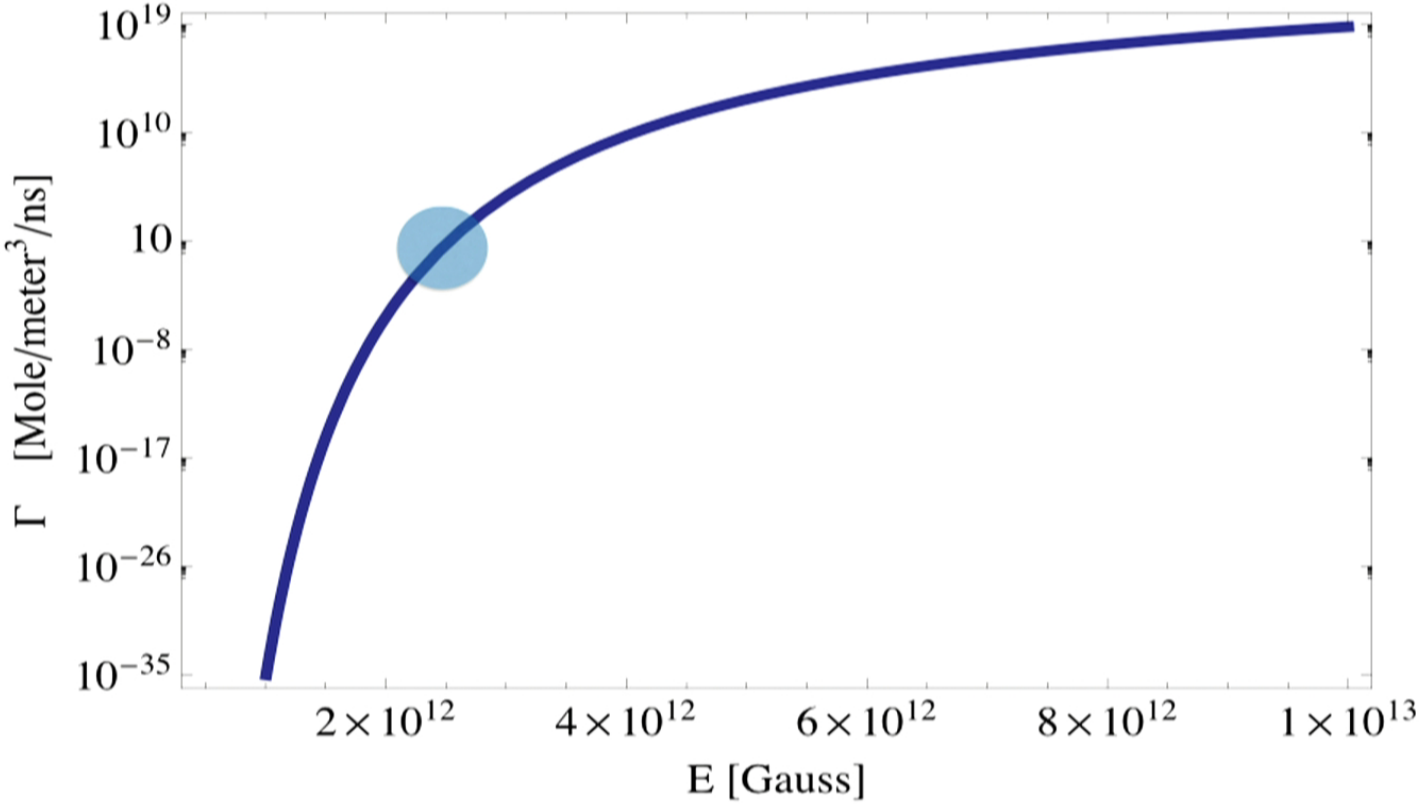

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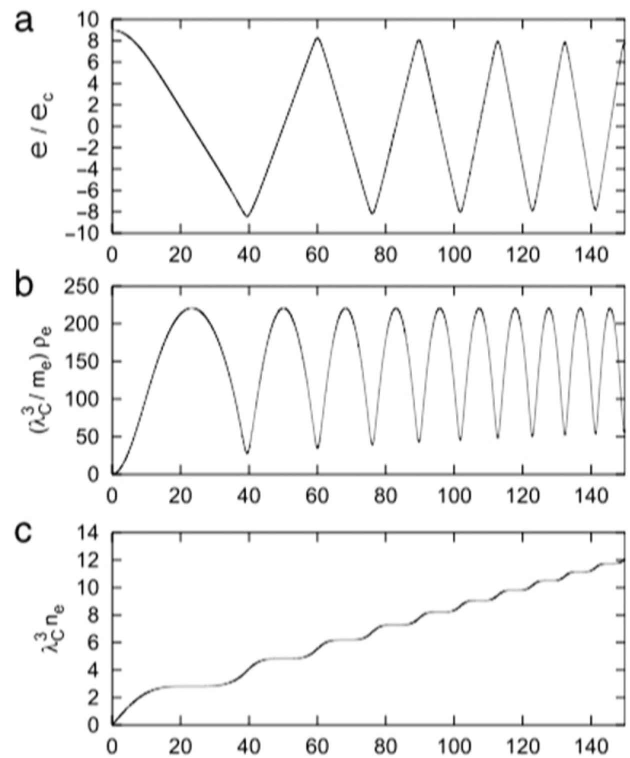
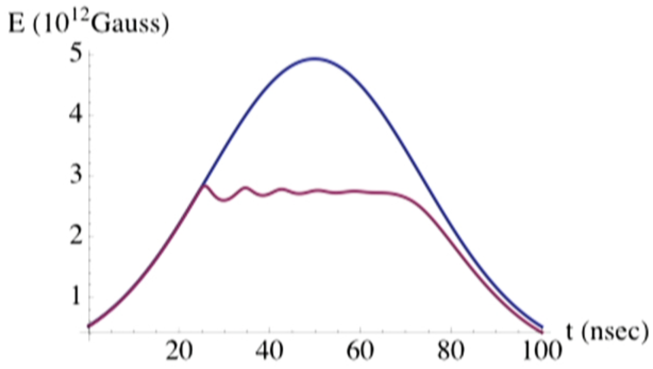
For Large Uniform Fields

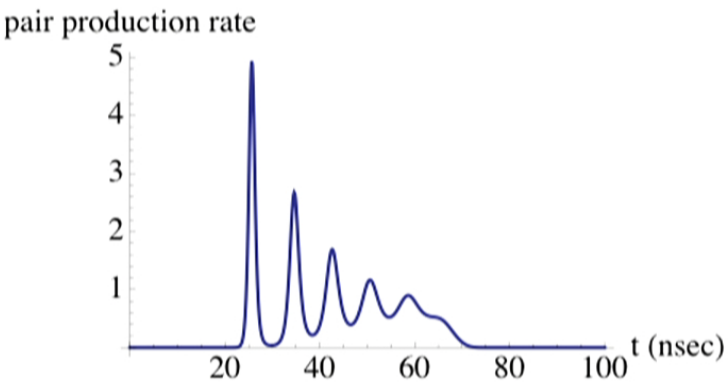
- **Plasma Oscillations** (see Ruffini, Vereshchagin, Xue 2010)

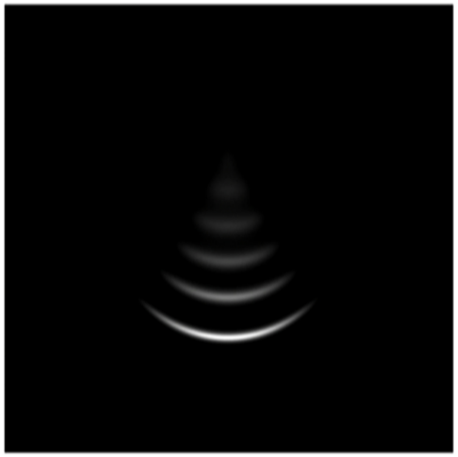


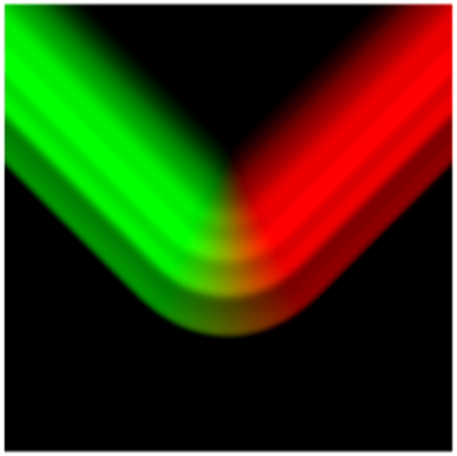
For Smaller Schwinger Sparks

1^{+}D simulation (Stebbins, Yoo 2015)









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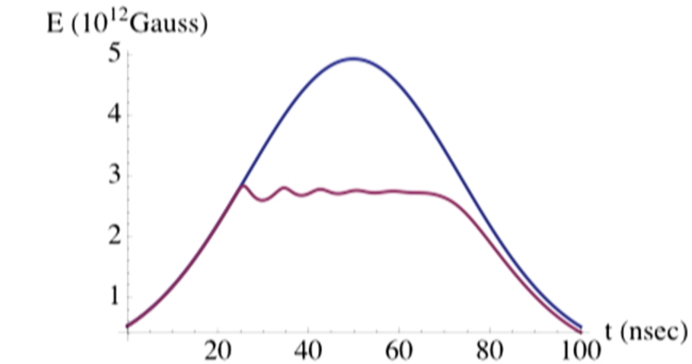

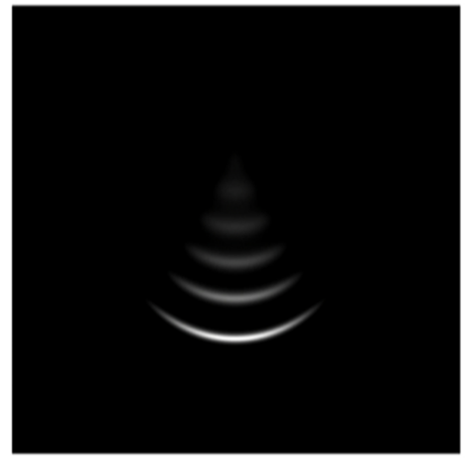

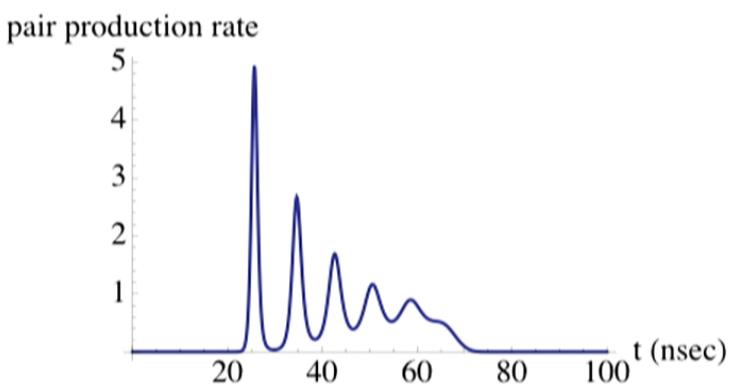

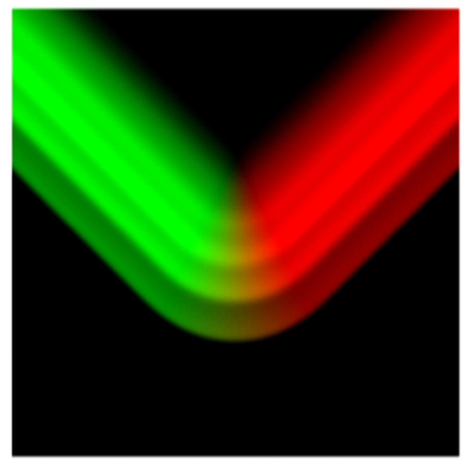

Schwinger Spark ElectroMagnetic Pulse

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

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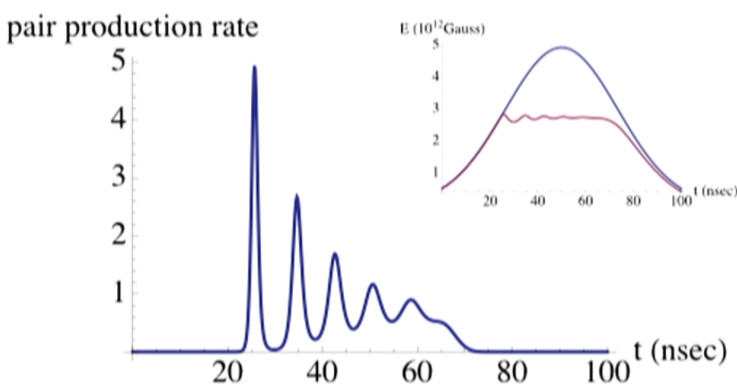

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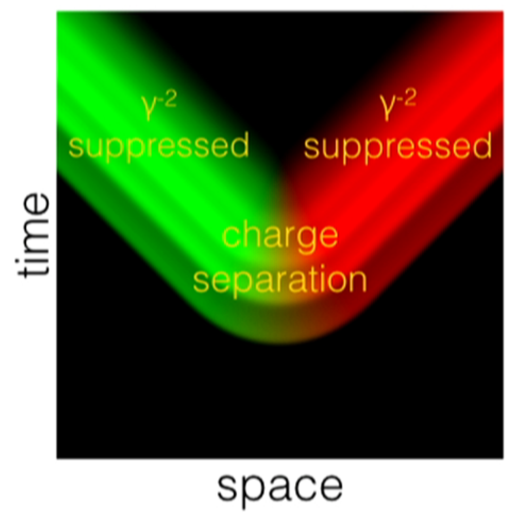
If created pairs are rapidly accelerated to speed of light the EMP just traces the pair production rate.

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}.



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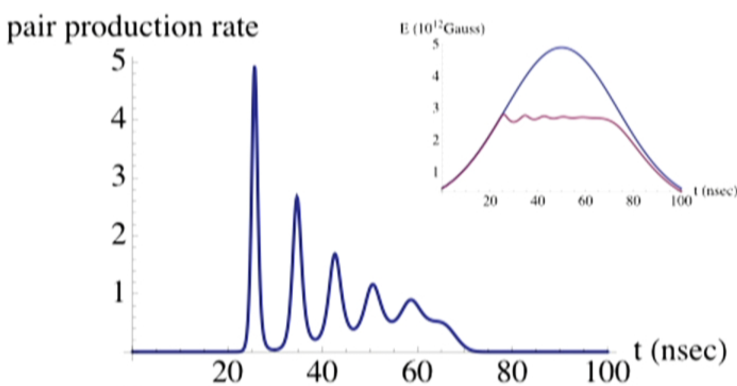

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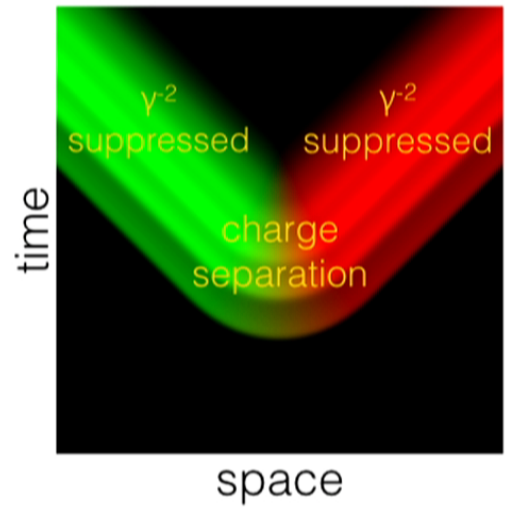

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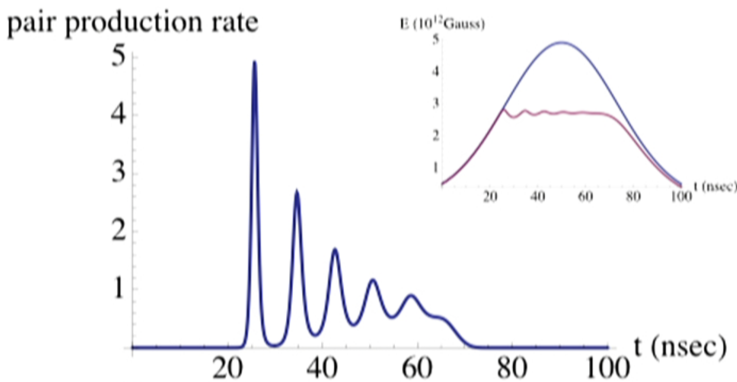

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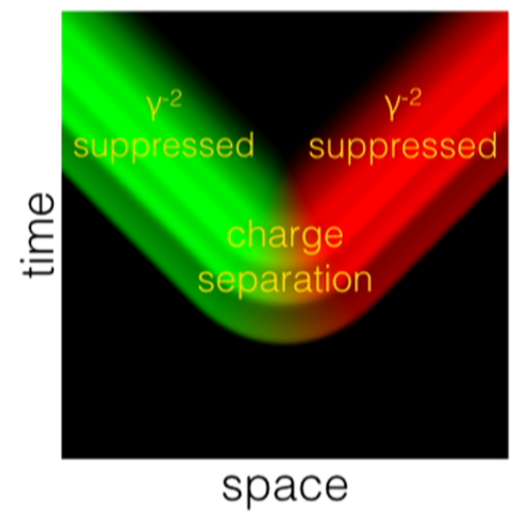
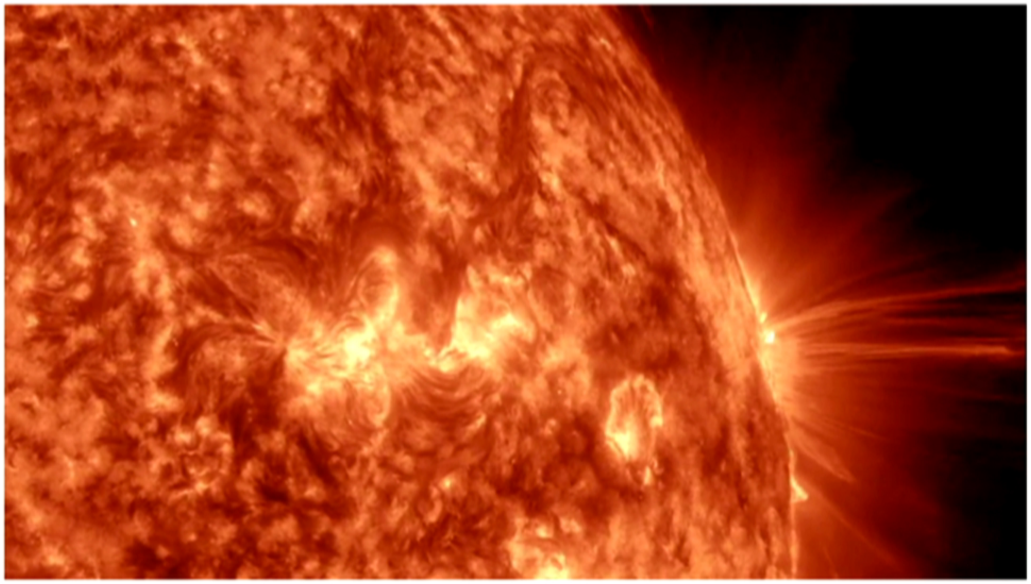


EMP Propagation Through Magnetosphere?

- EMP energy density higher than that of magnetosphere!
- will accelerate any $e^{\pm}$ in path to ultra-relativistic energies



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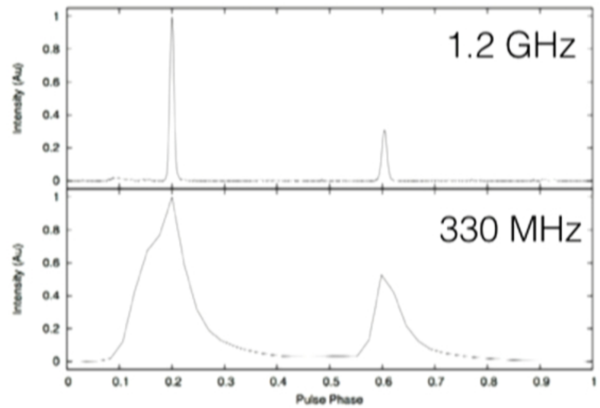
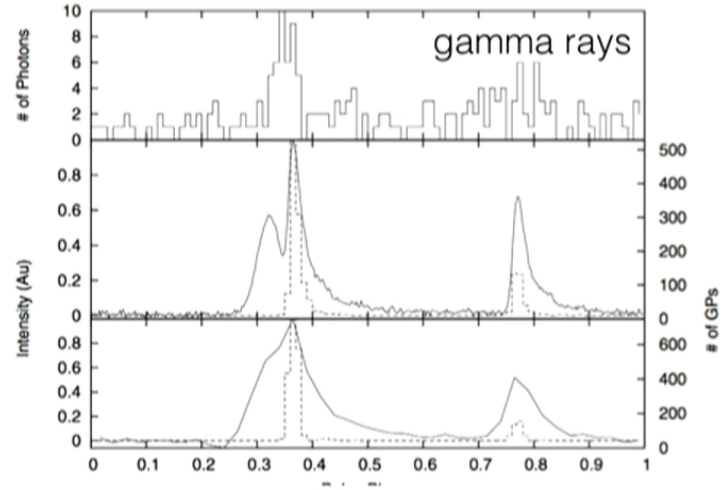
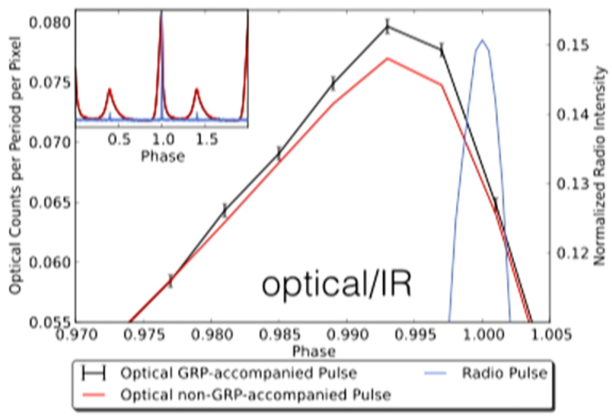
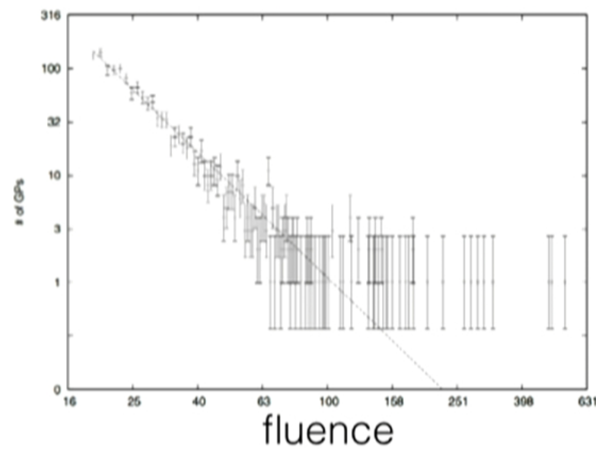
- trains of nanoshots could “blast through magnetosphere

Crab Giant Pulse Phenomenology

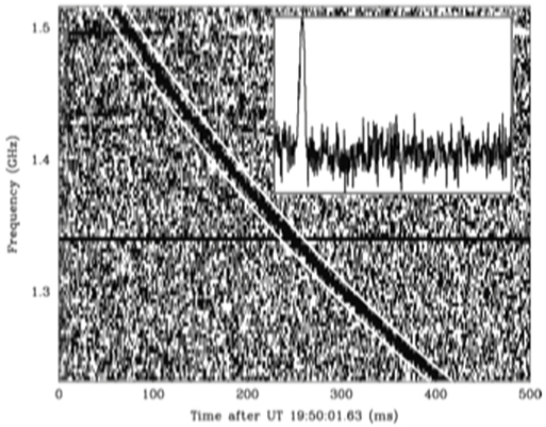








Fast Radio Bursts: Cosmological Dispersion Measure?



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

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

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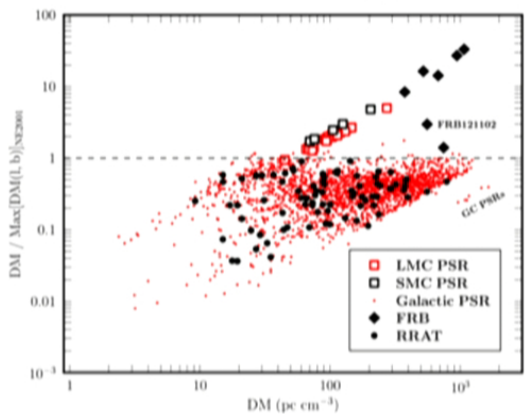

	DM_{IGM}	redshift	$energy_{GHz}$	Δt
FRB0102	375- 25-100	~0.3	~10^{40} erg	5ms
J1852-08	745-533-100	~0.09	~10^{39} erg	7ms
FRB1102	944- 34-100	~0.81	~10^{40} erg	5.6ms
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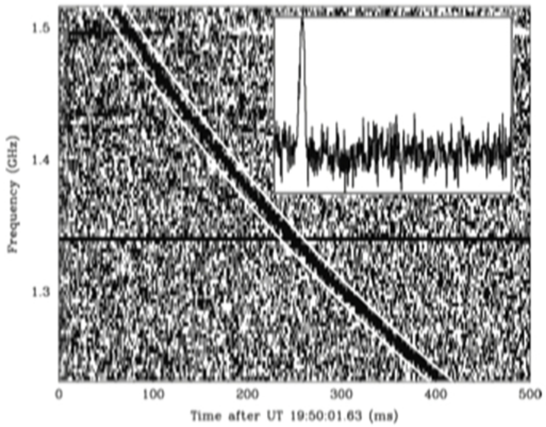

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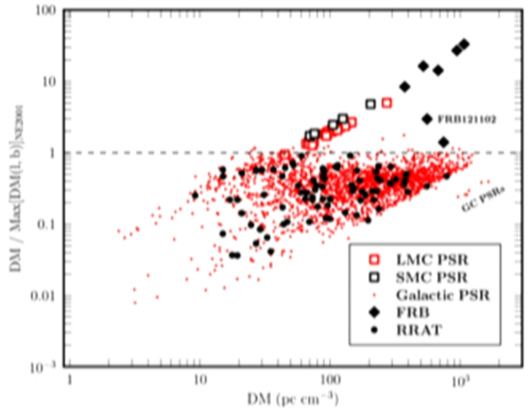

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FRBs: what are they?

reasoning by rates

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galactic: flaring stars, erratic pulsars, white dwarf mergers

solar system: colliding mini-asteroids

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Loeb et al. 2013
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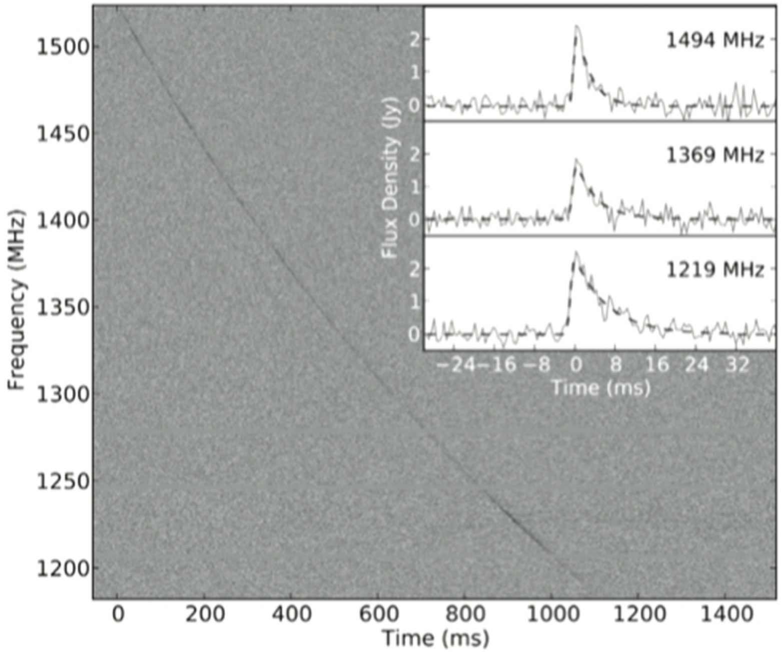

Lorimer et al. 2007 (1)
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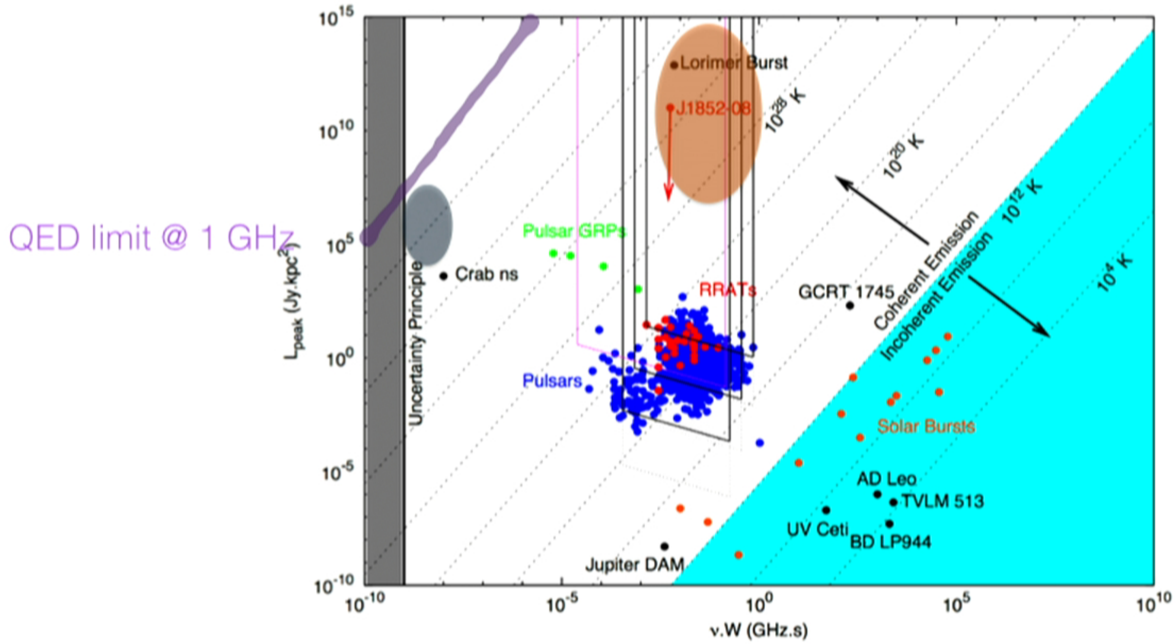
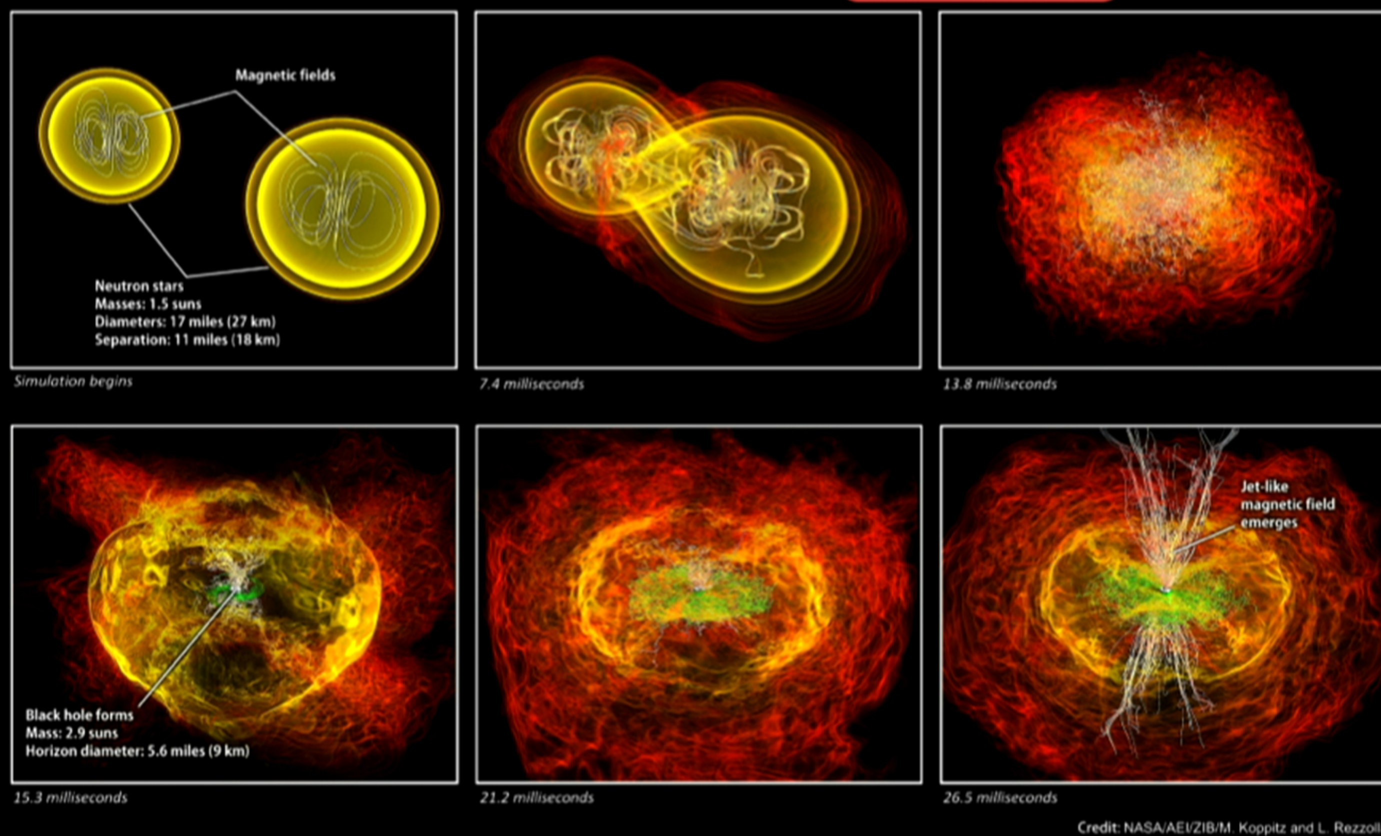
Schwinger Model of FRBs

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



Crashing neutron stars can make radio burst jets?



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

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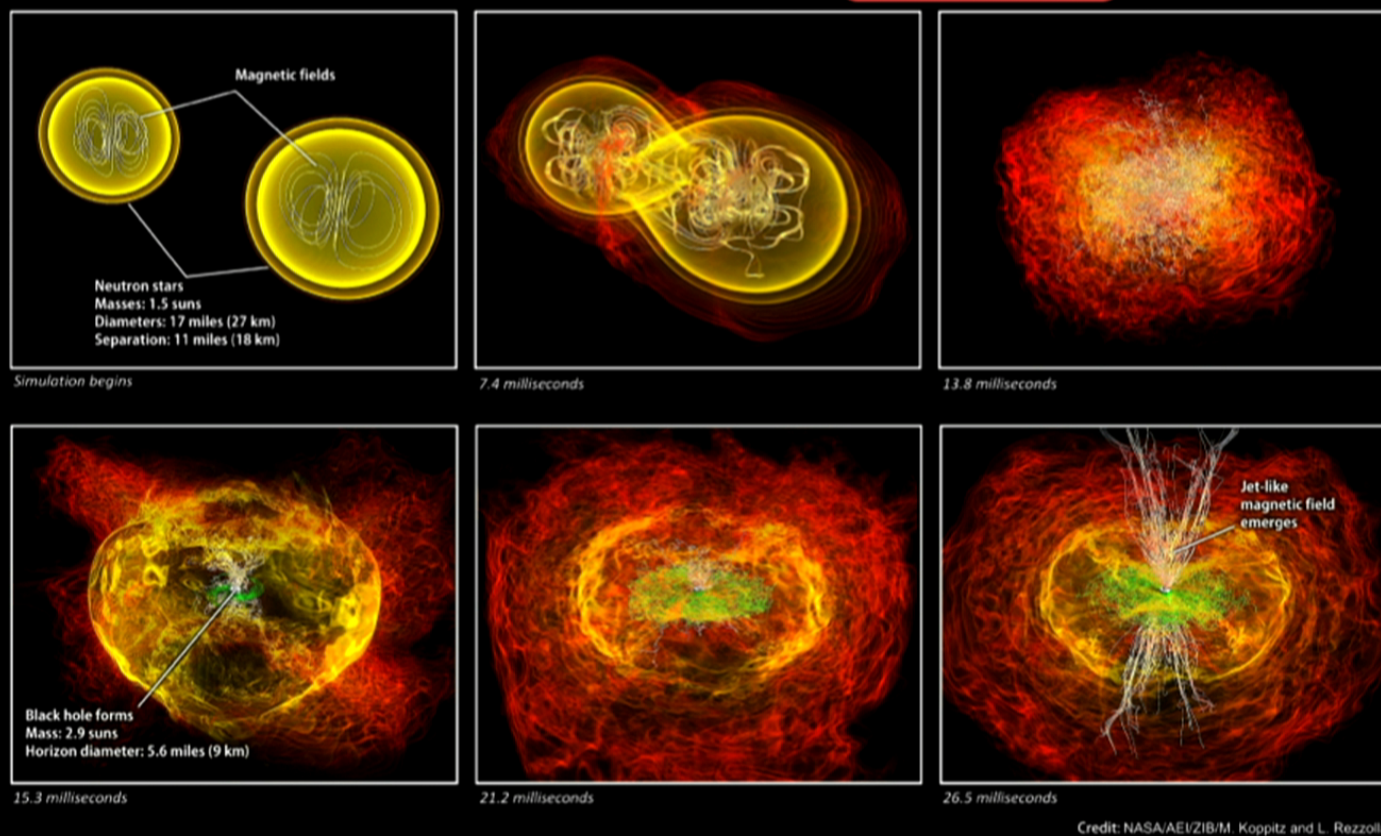

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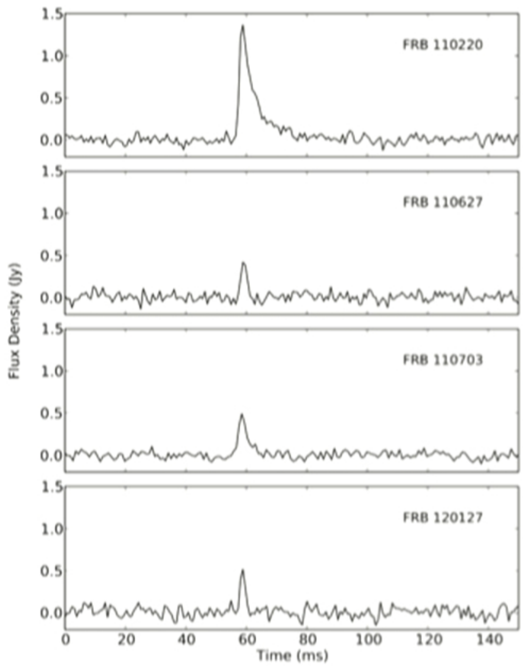
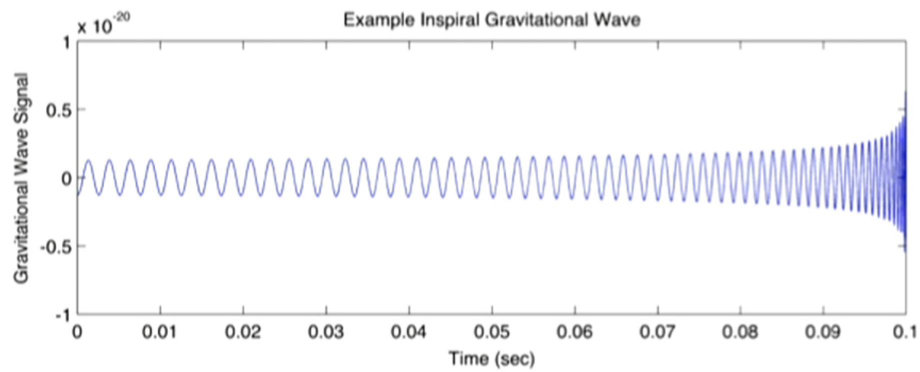
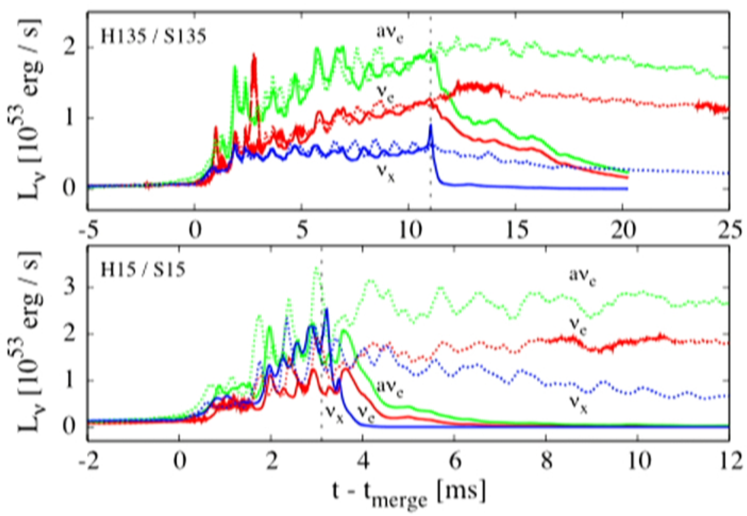
Coincidence of Timescales for NS+NS⇒NS CBCs

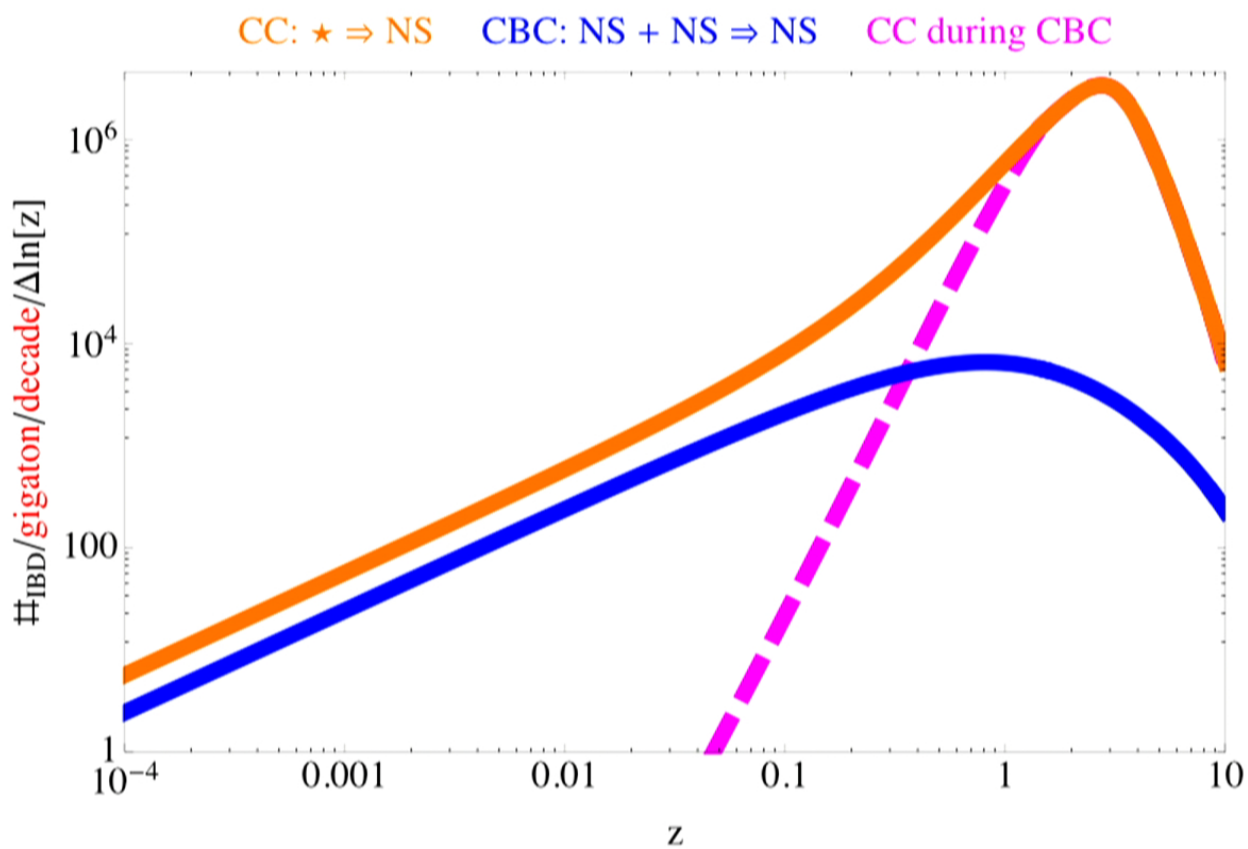






Kiuchi et al. 2012

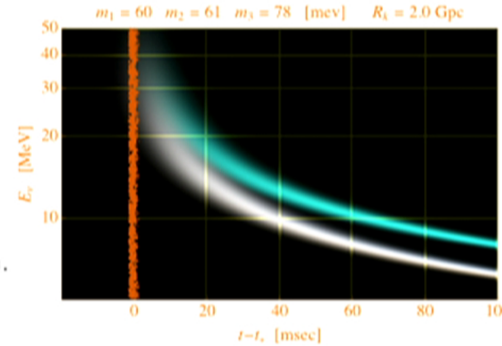
FRB Associated Neutrinos



With FRB triggers “negligible" backgrounds for z≲0.2

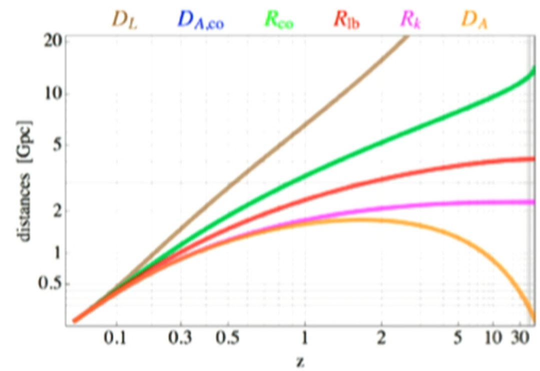
What to do with 1000s of FRB ν's?

- 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.



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

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

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.

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- 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