Using Giant Telescopes as Microscopes

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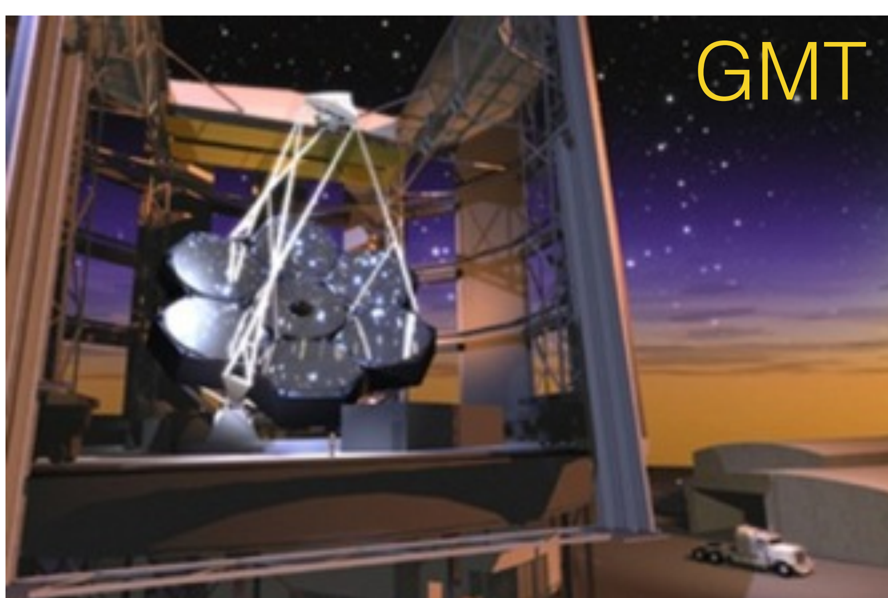
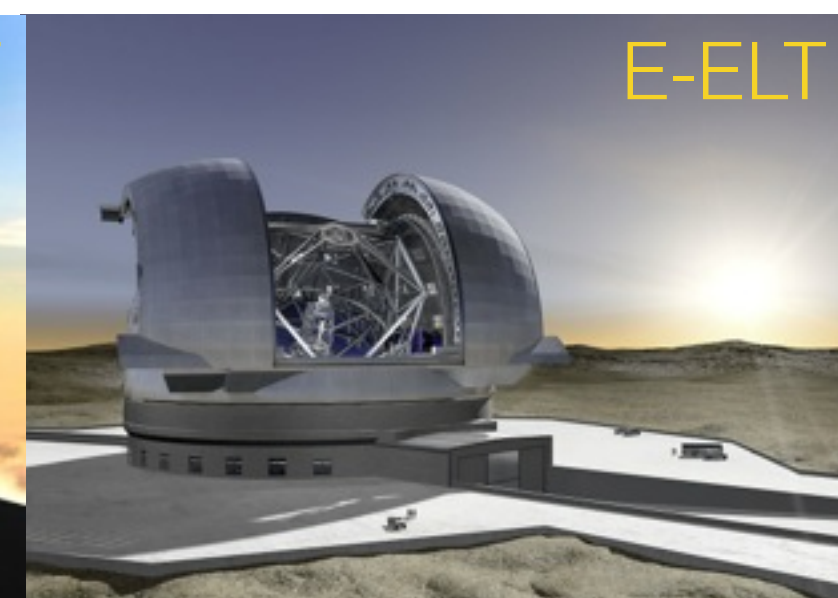


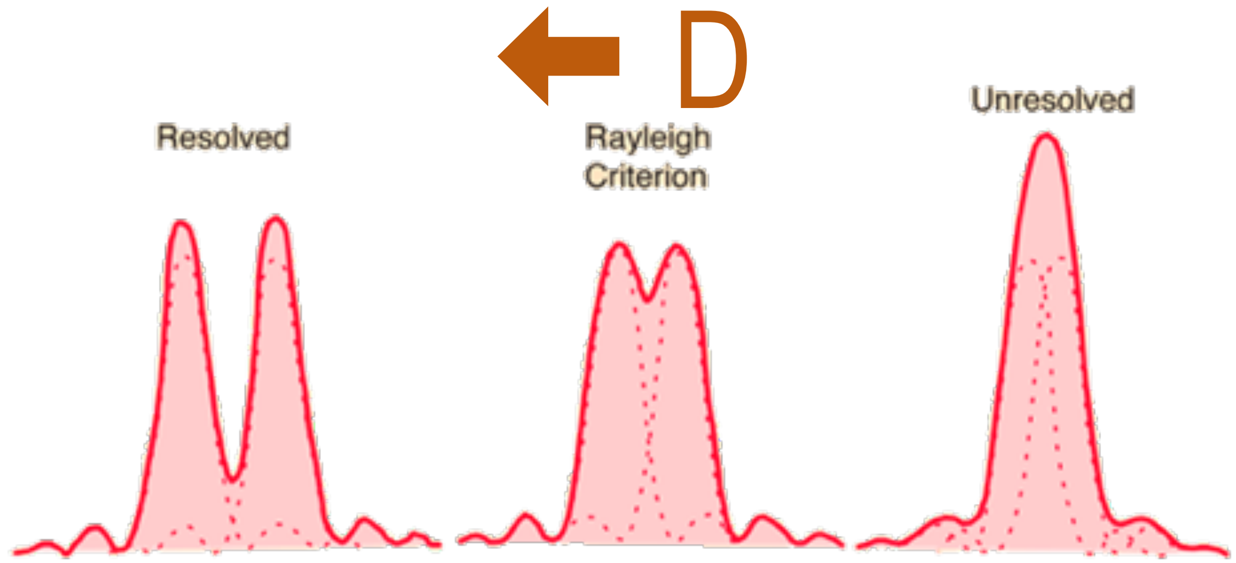


Big Telescopes See Better

Diffraction Limit:

$\delta x_{\perp} \gtrsim \lambda R / D$

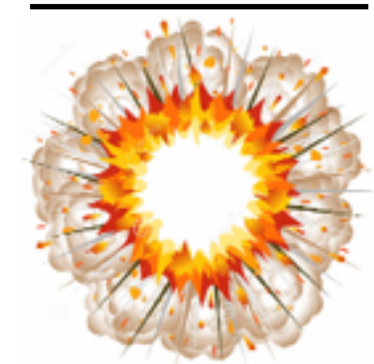
$= 10^6 \text{km} \; (\lambda/\mu\text{m}) \; (30\text{m}/D) \; (R/\text{pc})$



For relativistic transients:

$\delta x_{\parallel} \gtrsim v \, \delta t = 30\text{cm} \; (v/c) \; (\delta t/\text{nsec})$

c δt



small # of γ's in short δt requires large aperture

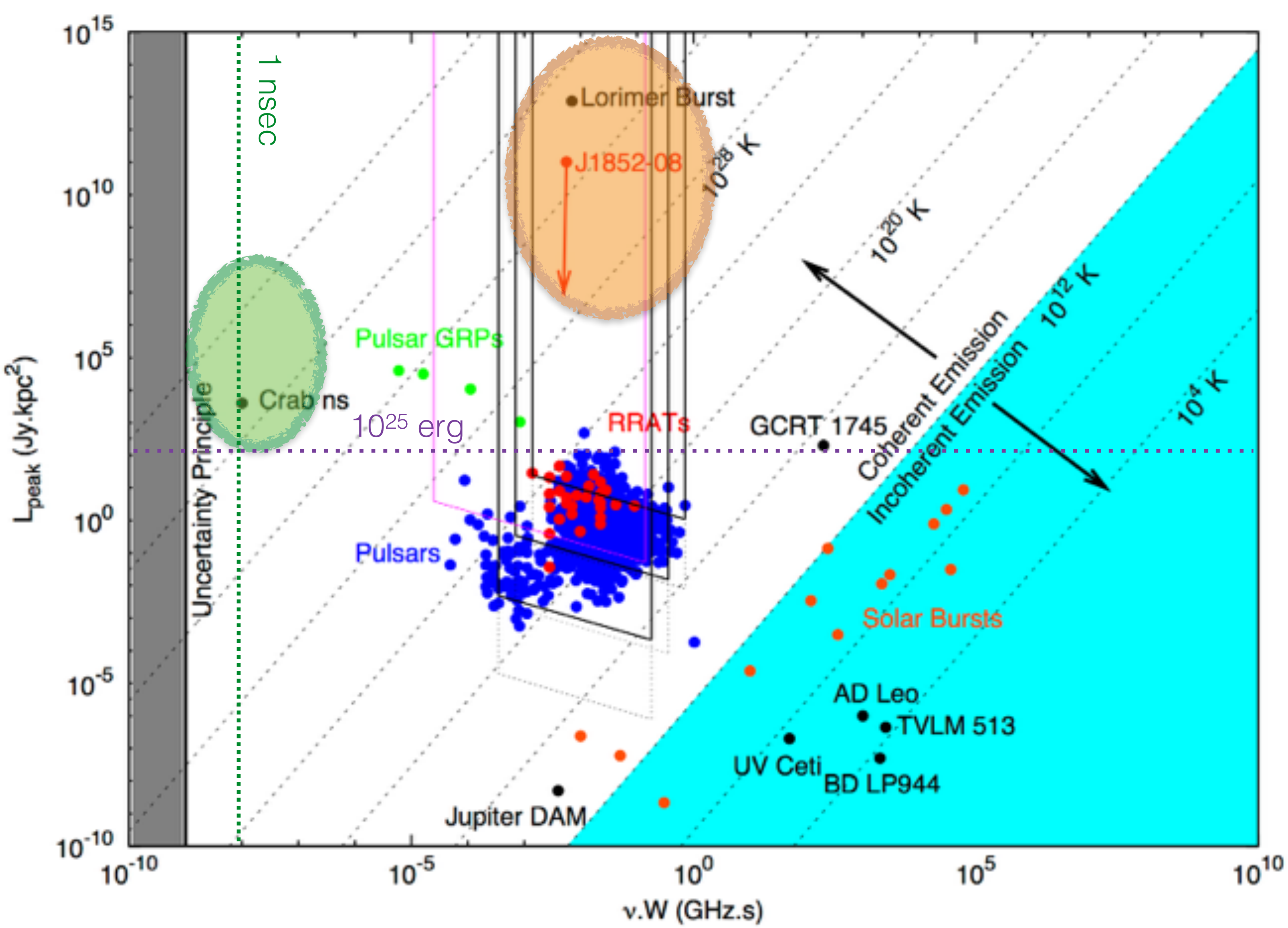
$\#_{\gamma} \sim \pi D^2 \, \underset{\text{fluence}}{\overset{\text{flux}}{f \, \delta t}} \, \delta \nu \, / \, h\nu \sim 42 \; (\delta t/\text{nsec}) \; (f/\text{Jy}) \; (D/30\text{m})^2 \; (\delta\nu/\nu)$

<u>extreme energetics</u> required

$\mathcal{E}/\#_{\gamma} = 4 \, (R/D)^2 \, h\nu = 10^{25} \text{erg} \; (30\text{m}/D)^2 \; (R/\text{kpc})^2 \; (\mu\text{m}/\lambda)$

The Brightness Frontier

- In terms bright transients radio astronomy far ahead of IR/O/UV
  - shortest radio transients are brightest in terms of brightness temperature
  - radio detectors easily adapted to high temporal resolution



ν - frequency

W - pulse width

L_ν - specific luminosity

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

RRAT - rotating radio transient

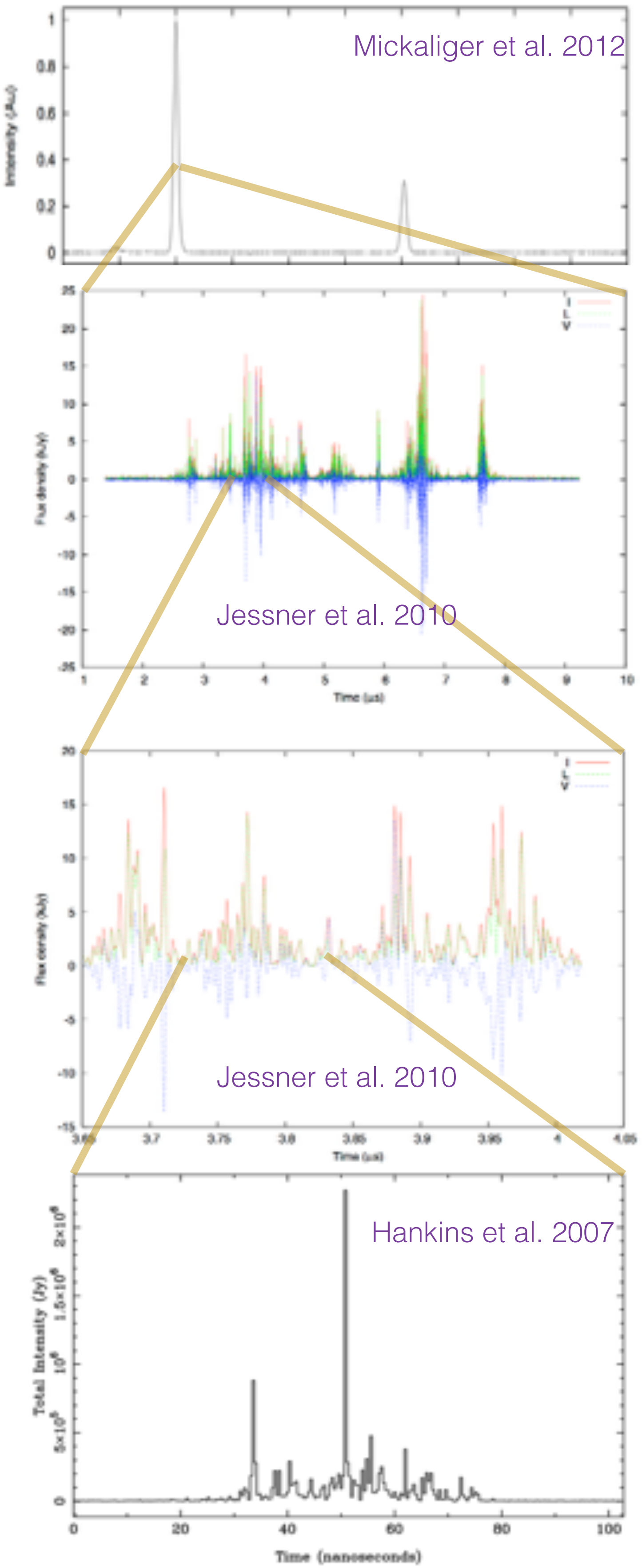
DAM - decametric radiation

GRP - giant radio pulse

ns - nanoshot

FRB - fast radio bursts:

Crab Radio Pulse Structure

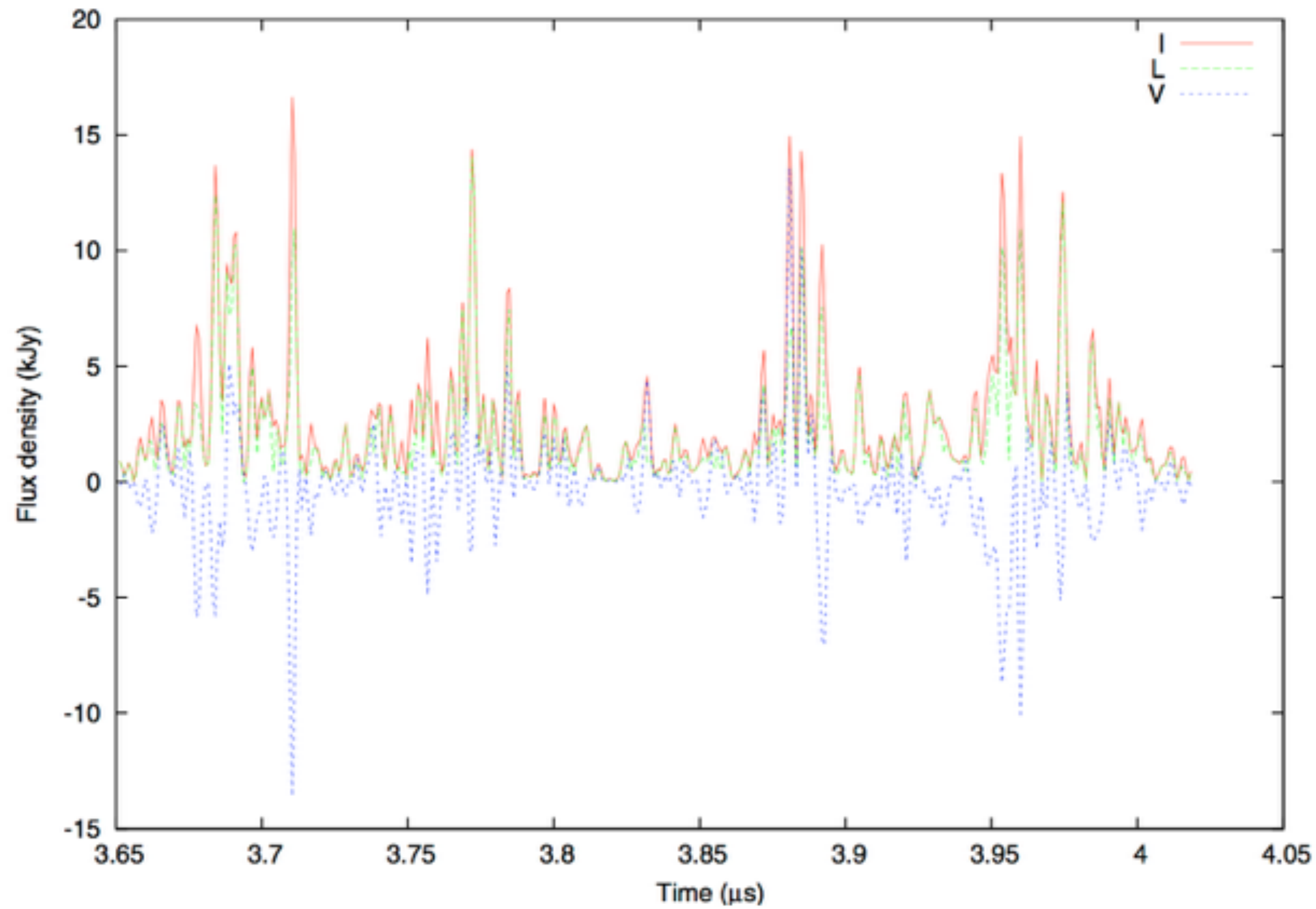


Mean Pulse

Occasional Giant Pulse

Micro Burst

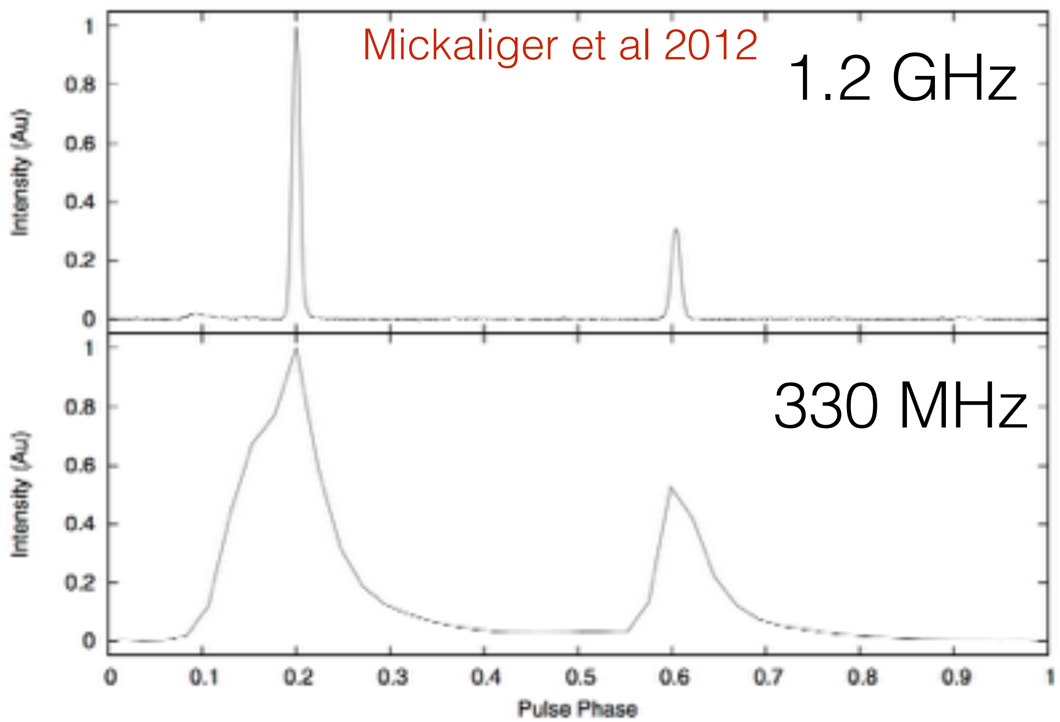
Nano Shot

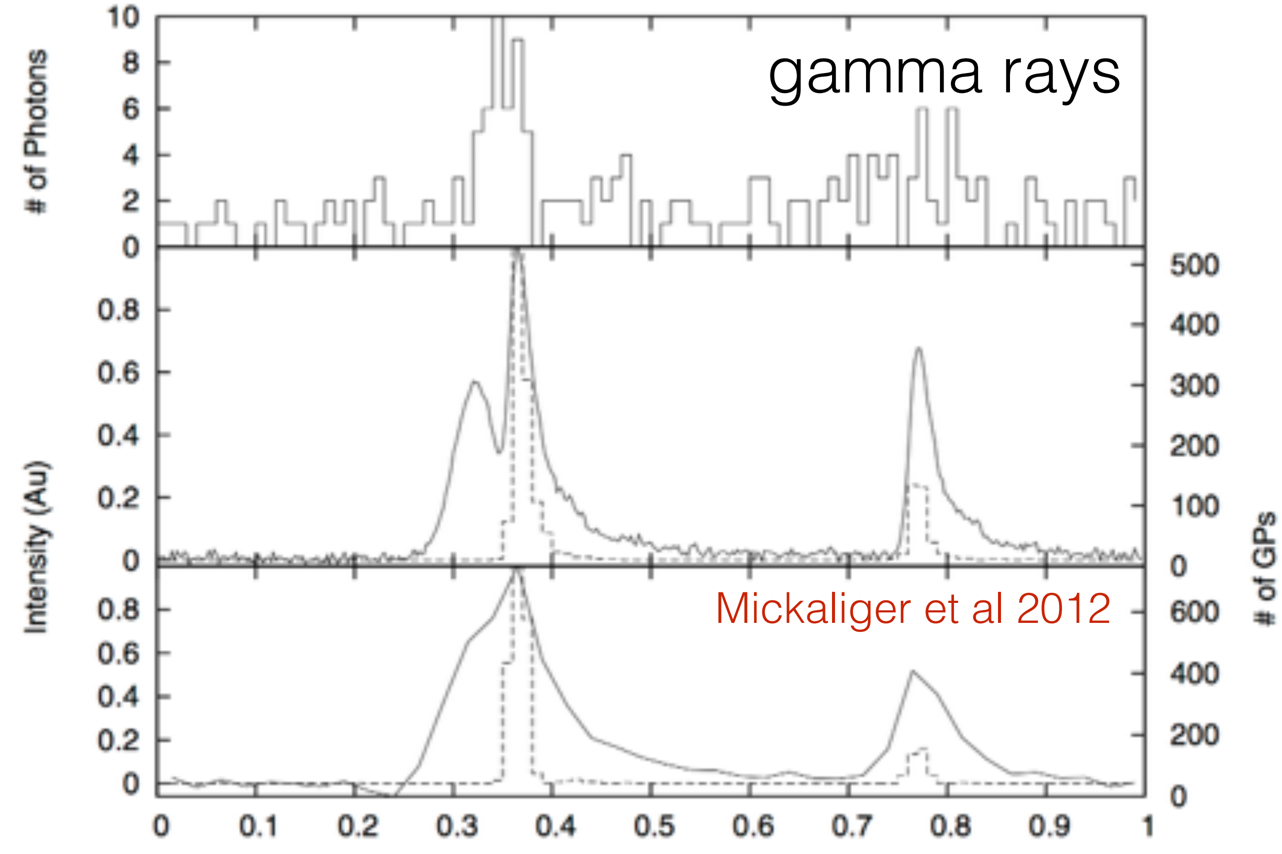


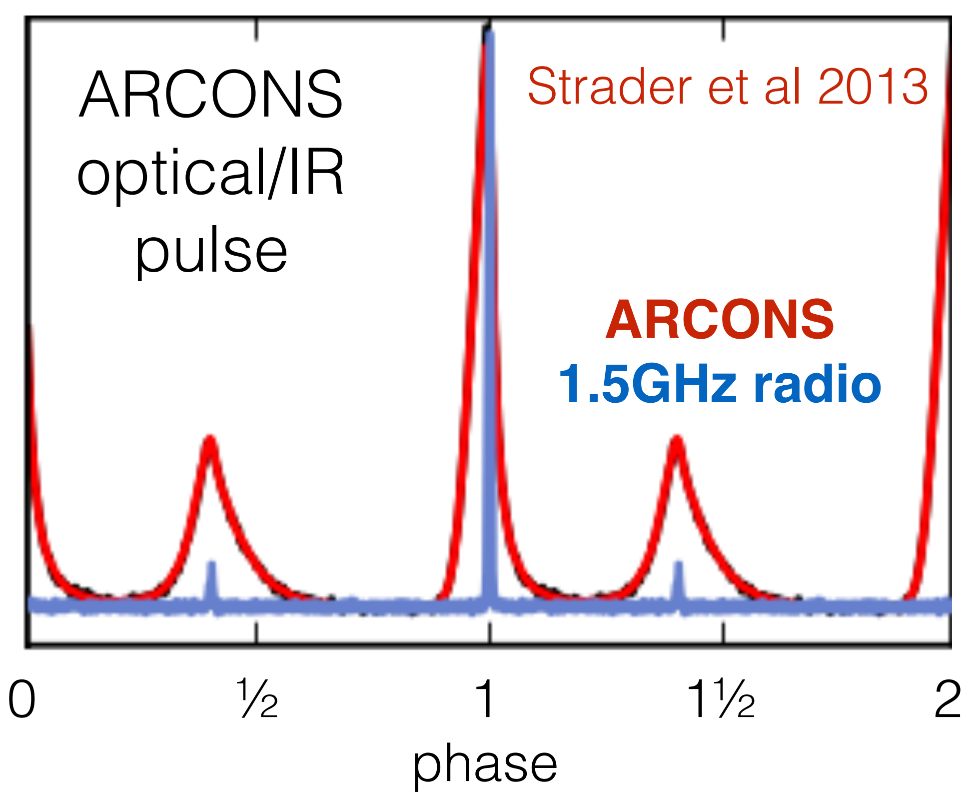
This record nanoshot had peak observed flux of 2MJy, astounding for an source 2kpc away!

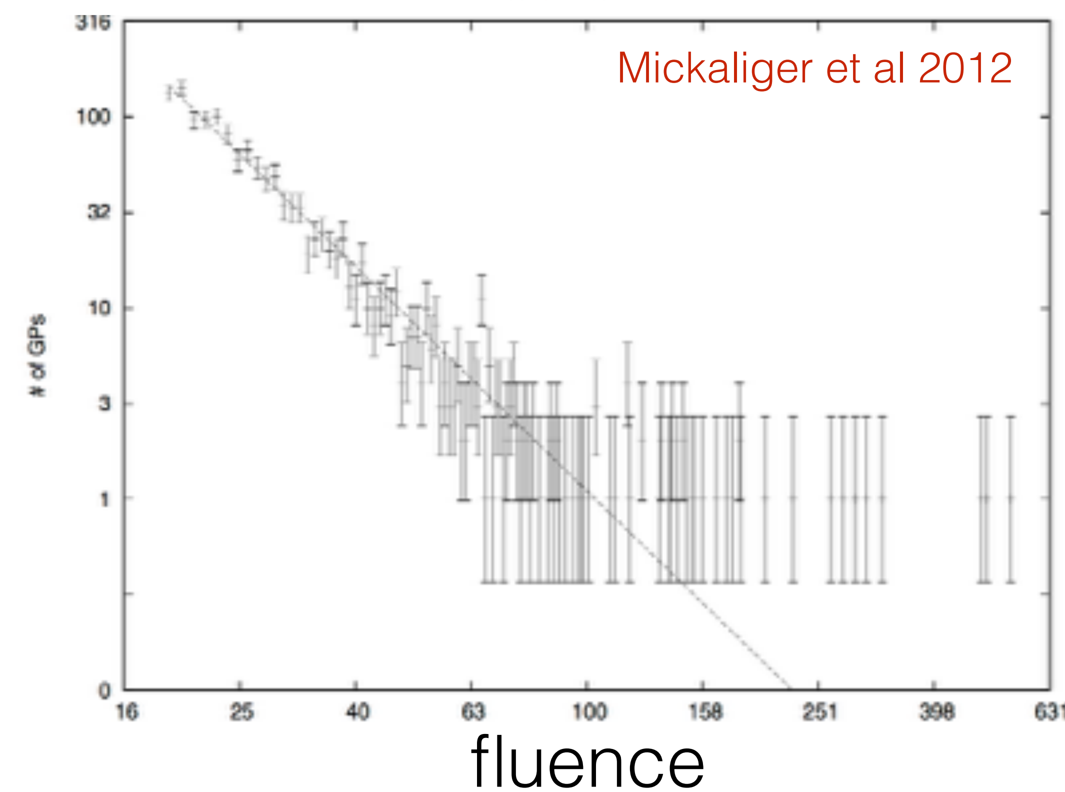
only ~10^4 radio γ's/m^2 - observed at Arecibo

Crab is Optical / γ-ray Pulsar

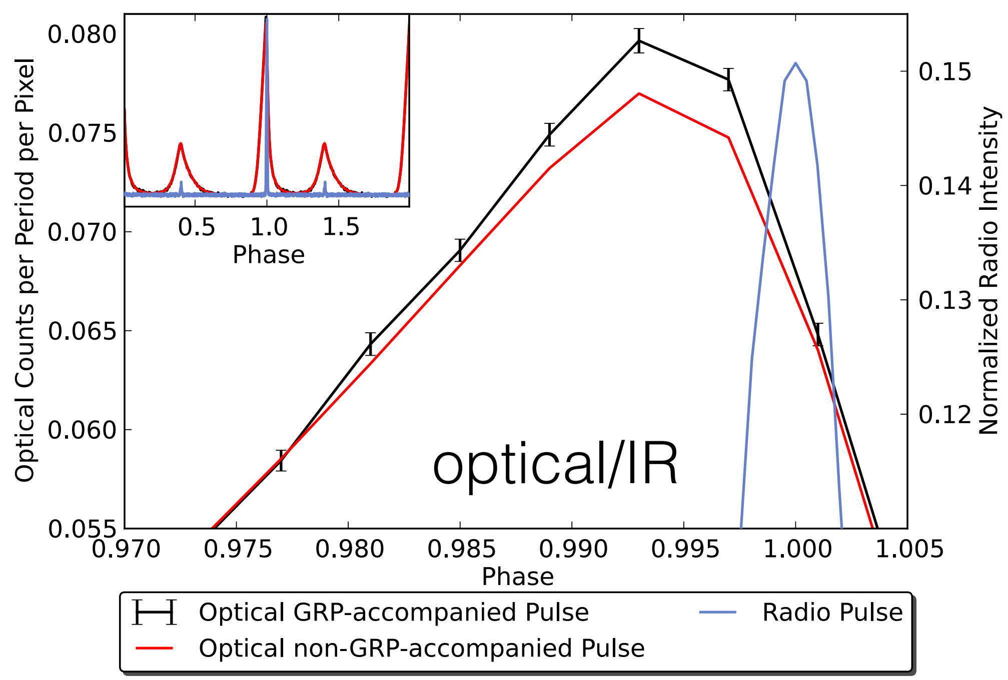








GRP Enhanced Optical Pulses

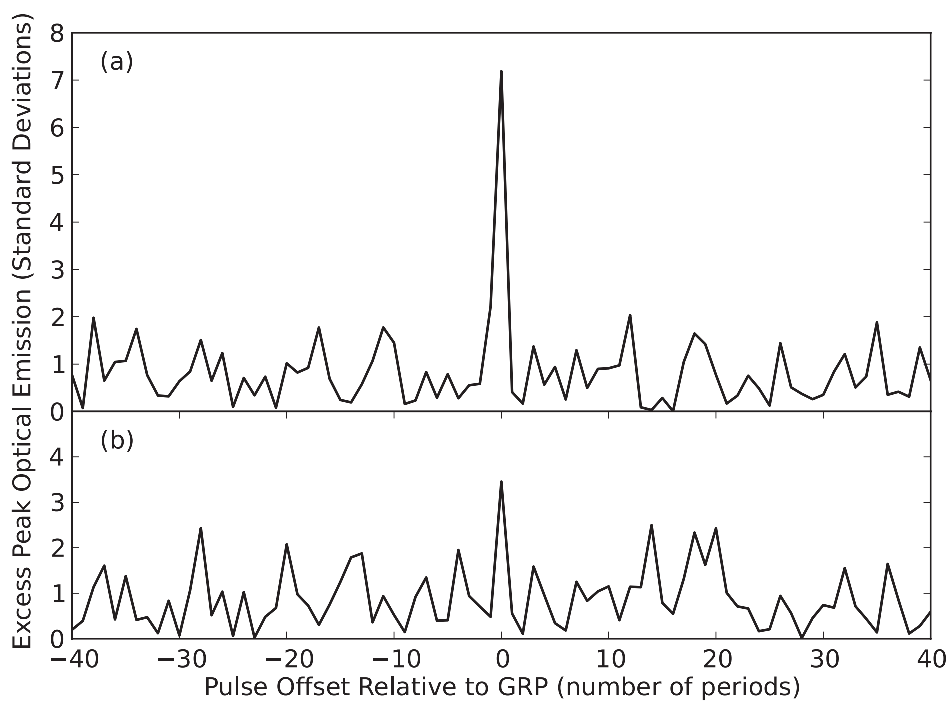


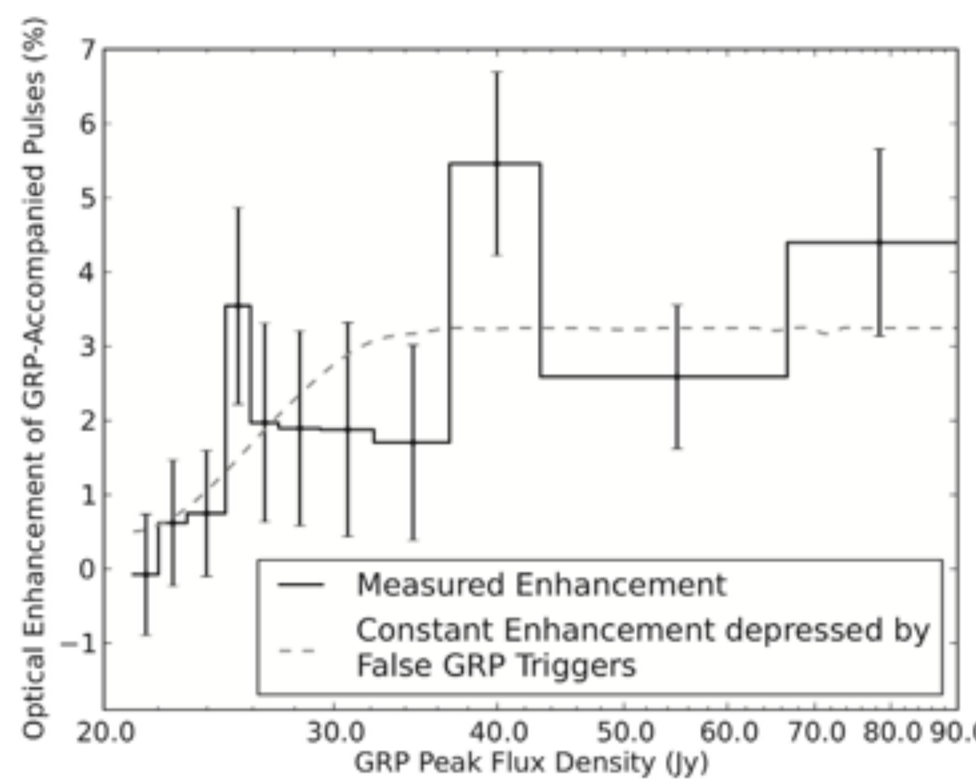
ARCONS camera on Hale 200”

Strader *et al.* 2013

ARCONS has ~μs temporal resolution

After “stacking” find 3% increase in optical flux during GRP





confirms results of Shearer *et al.* 2003

Optical/Radio Co-observing

Fine scale temporal distribution of GRP correlated photons unknown

- Do they have microburst or nanoshot substructure?

Strategies:

- Auto correlate IR/O/UV photon time of arrivals
- Cross correlate IR/O/UV photon time of arrivals with radio.

Need fast (nsec) detectors to match radio phenomenology!

telescope	observatory	aperture	seeing	sky brightness	mean # of Crab photons per pulse	mean # of "GRP" photons per pulse	mean # of sky photons per pulse
Copernicus	Yerkes	24"	5"	19.0 mag/(")	1.5	0.05	1
Hale	Palomar	200"	1"	21.5 mag/(")	105	3	0.3
TMT	Mauna Kea	30m	0.01"	22.3 mag/(")	3600	108	10

Selected Fast Cameras

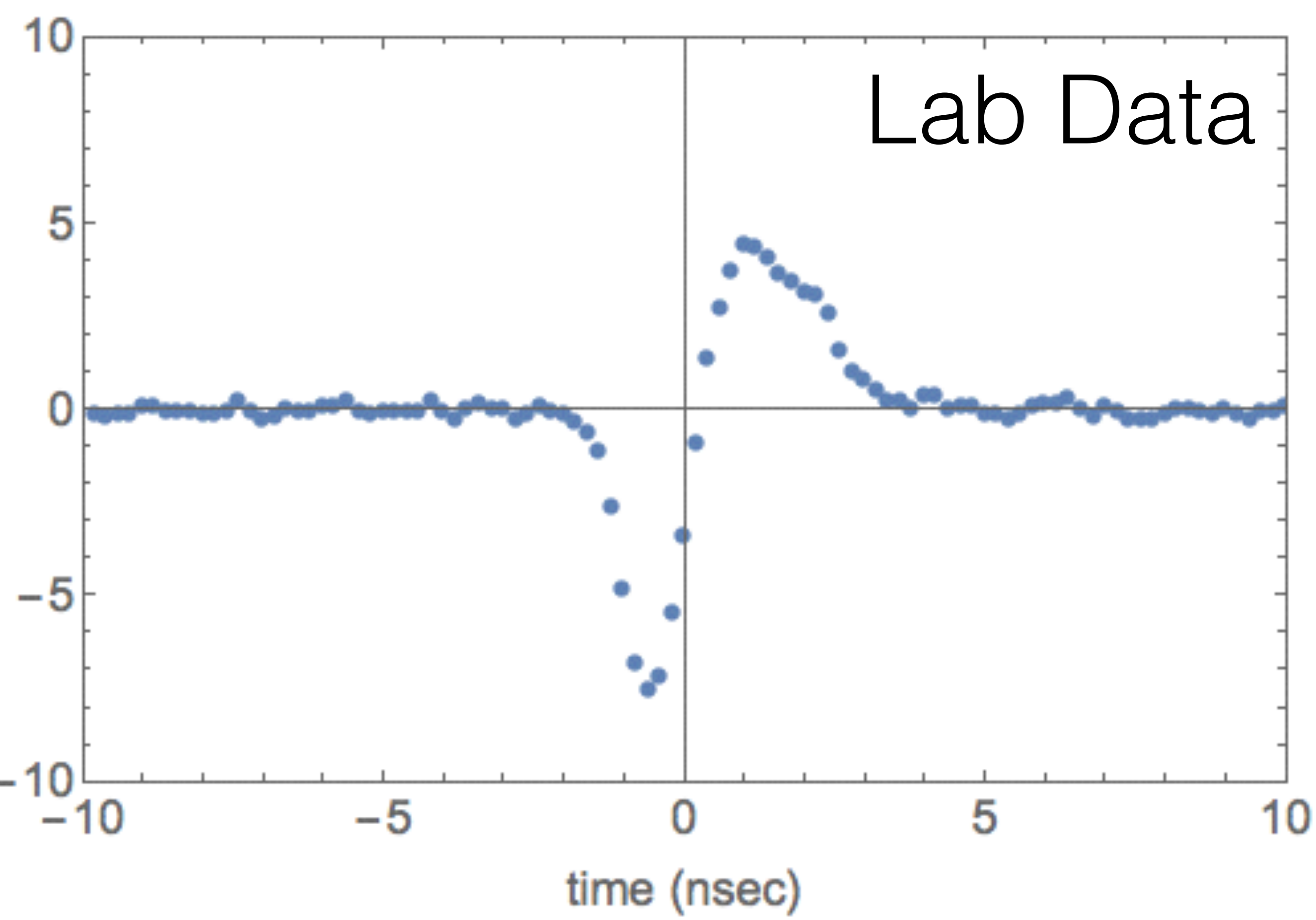
camera	relative temporal resolution	technology
LuckyCam	33 msec	EM-CCD
UltraCam	2 msec	CCD
Fordham et al.	45 μsec	MicroChannel Plate Intensified CCD
ARCONS	1 μsec	Microwave Kinetic Inductance Device
TRIFFID OPTIMA	1 μsec	Avalanche Photo Diode
AquEYE IquEYE	10 psec	Silicon Photo Avalanche Diode
Fermilab NanoCam	1 nsec	Photo Multiplier Tube w/ Microchannel Plate

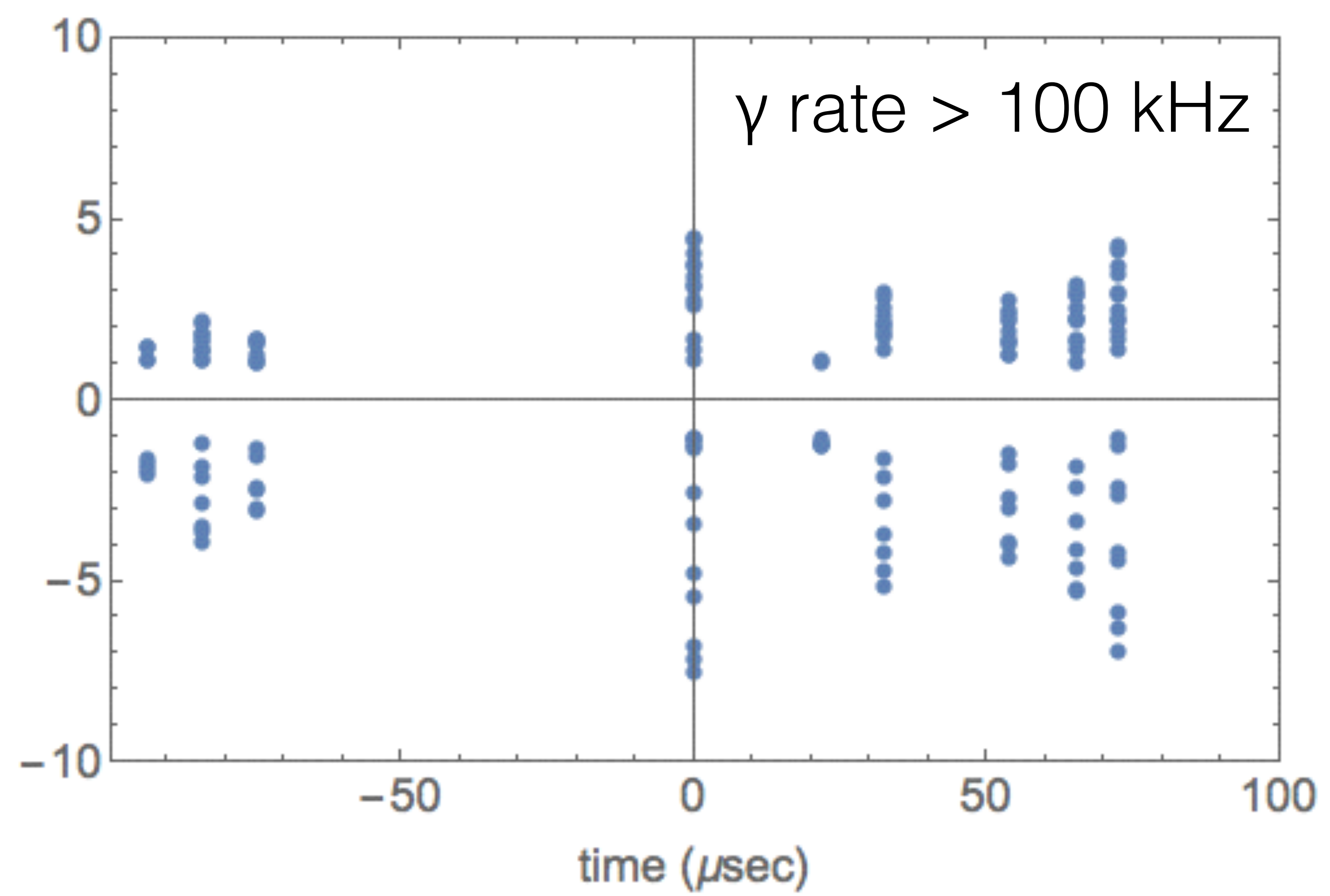
In addition to resolving small structures can be used for:

- intensity interferometry (HBT) w/ separated telescopes for size
- astrophysical photon quantum statistics

Fermilab NanoCam

Using recycled PMT and DAQ from GammeV experiment





Interesting Physics
(one idea)

Coherent vs Incoherent Radiation

Incoherent radiation

charged particles moving independently

$I_\nu \propto N$

synchrotron, free-free, …

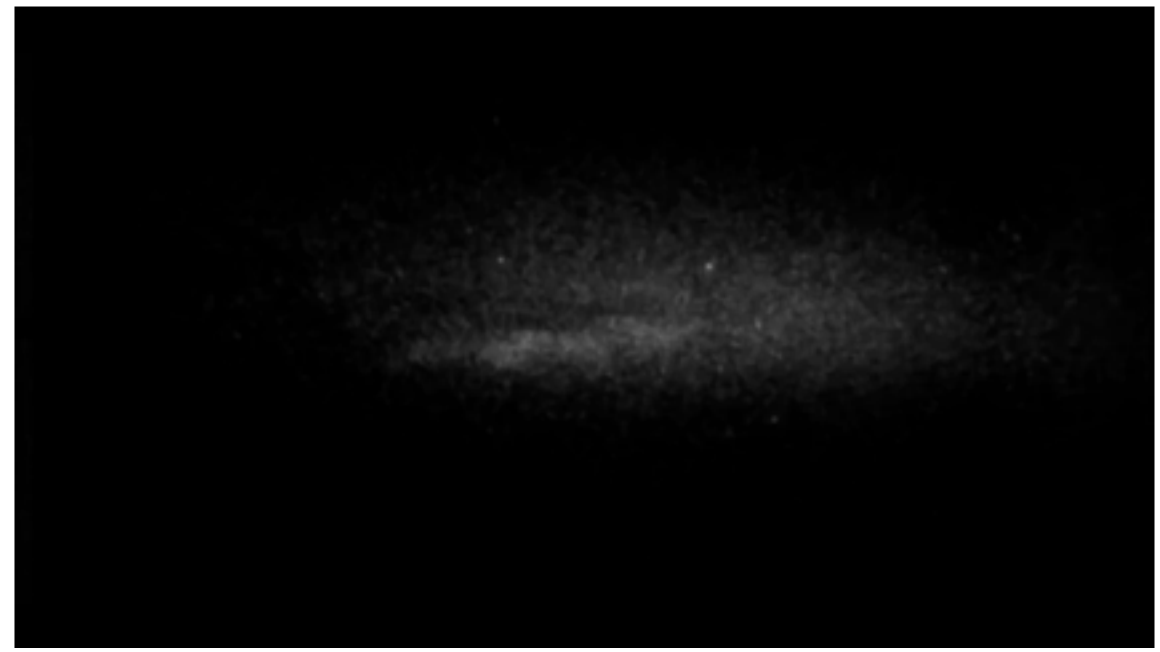
Coherent radiation

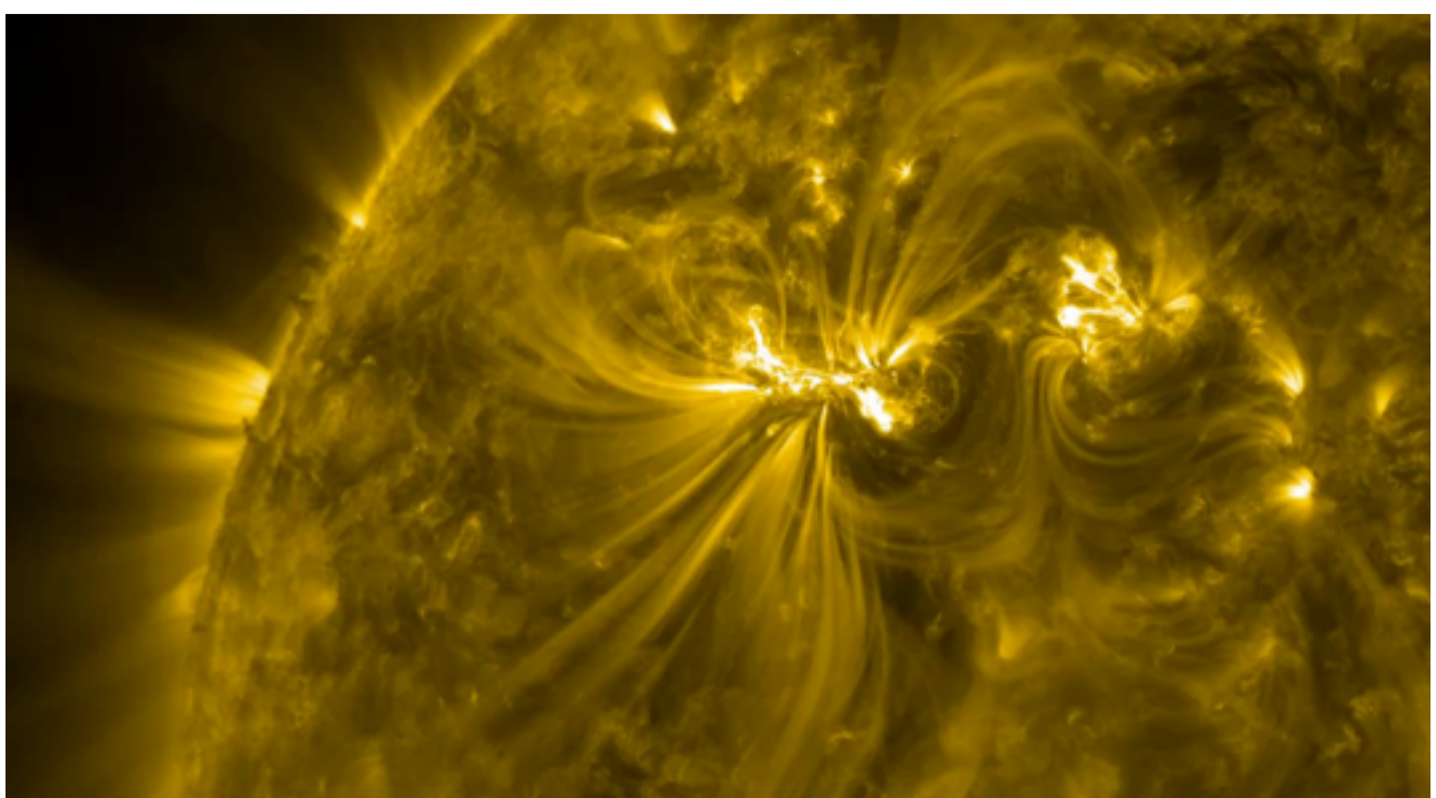
charged particles moving synchronously

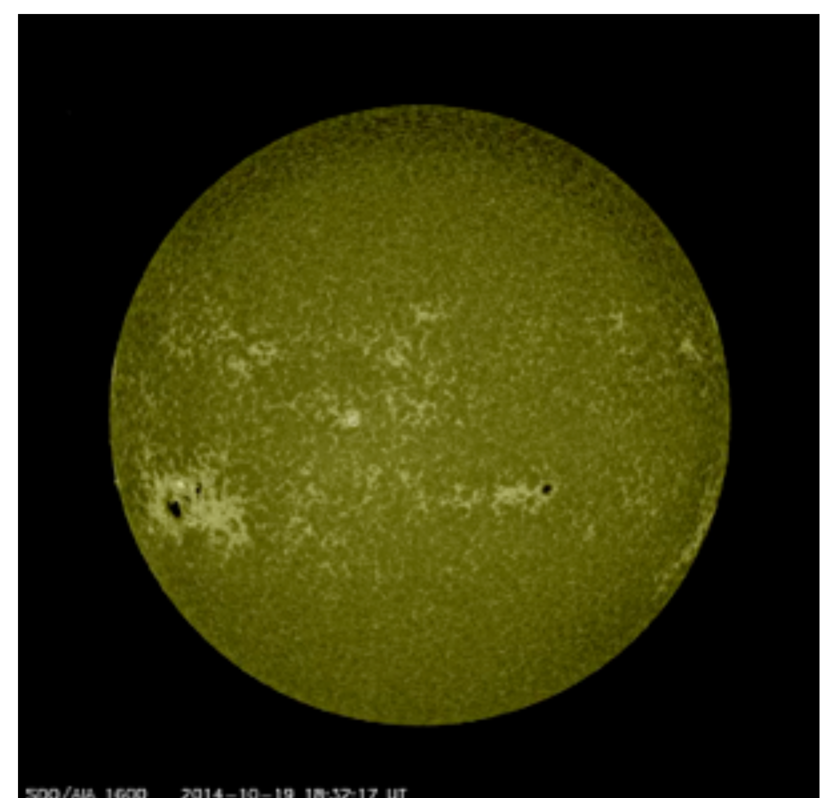
$I_\nu \propto N^2$

electro-magnetic pulse (EMP)

Sparks are Optically Bright and Even Brighter in Radio!





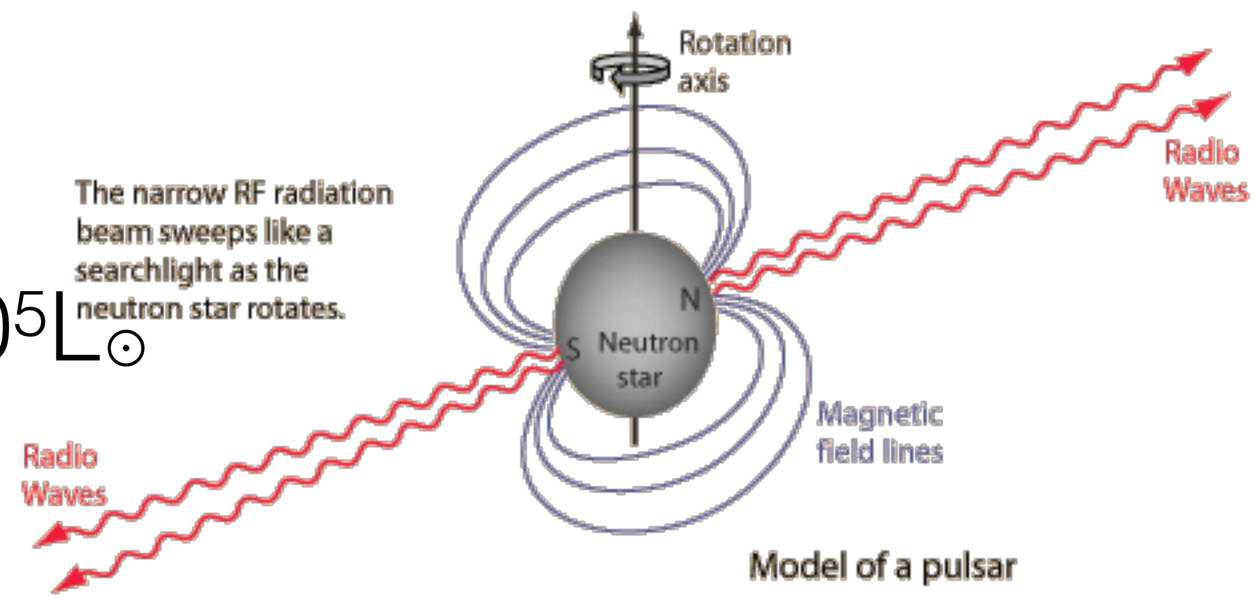


Crab Nanoshot Numerology

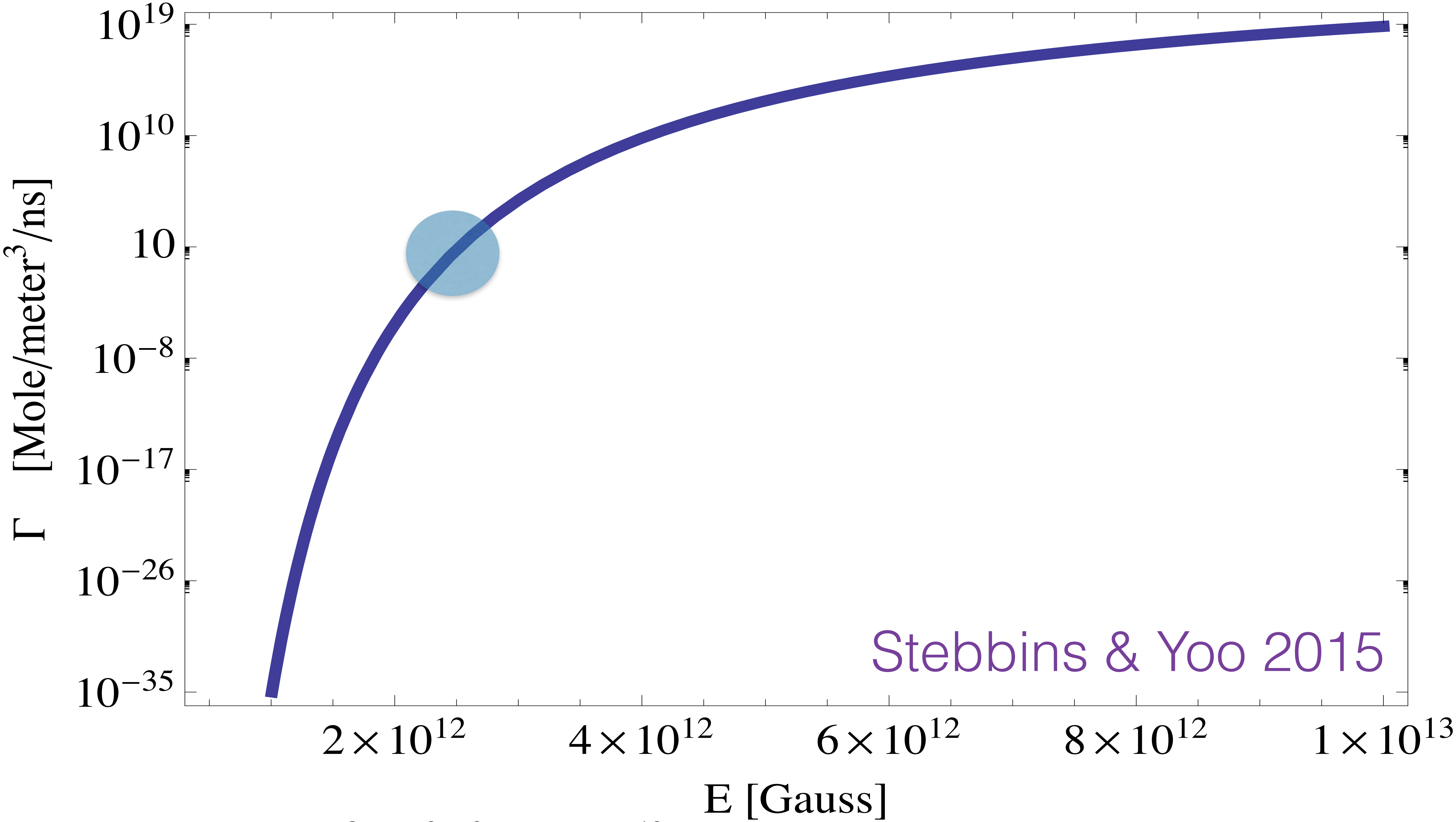
- (Assuming no significant relativistic beaming)
- size: $\lesssim$30cm [c ns]
- energy: $\lesssim 10^{28}$erg [4π D^2 MJy ns GHz]
- peak luminosity: $\lesssim 1.5\times10^{3}L_\odot$ [4π D^2 MJy nsec GHz]
- electric field: $\lesssim 2\times10^{12}$G [4π D / ns $\sqrt{(\mathrm{MJy\ GHz} / c^3)}$]
- charge: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

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?



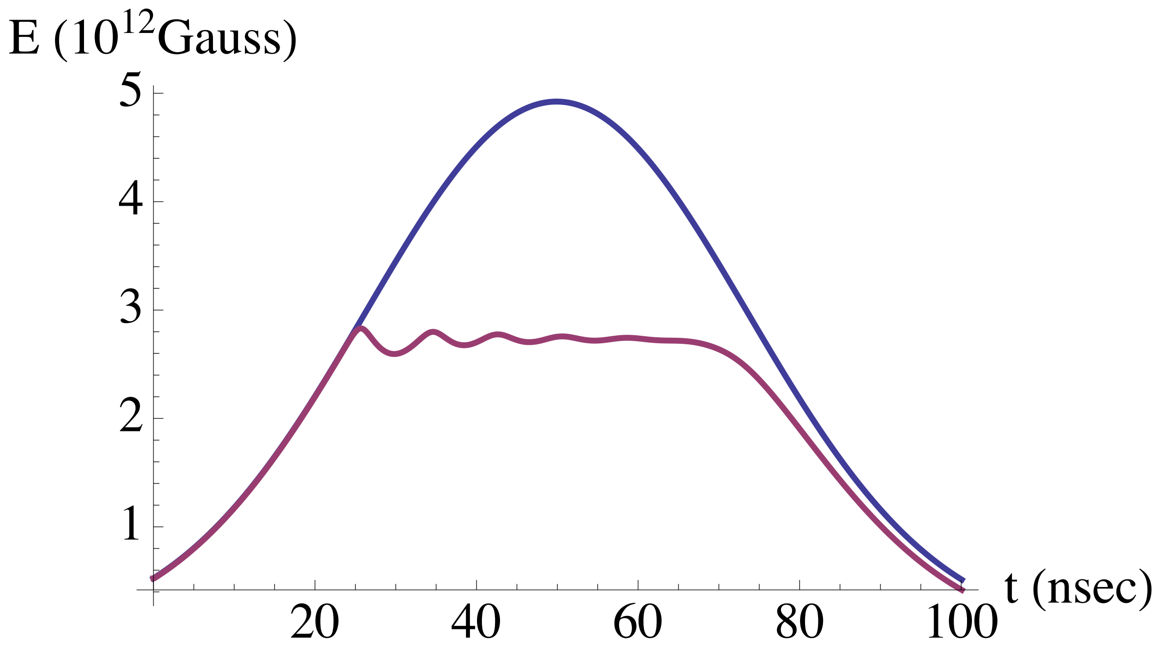
Schwinger Pair Production

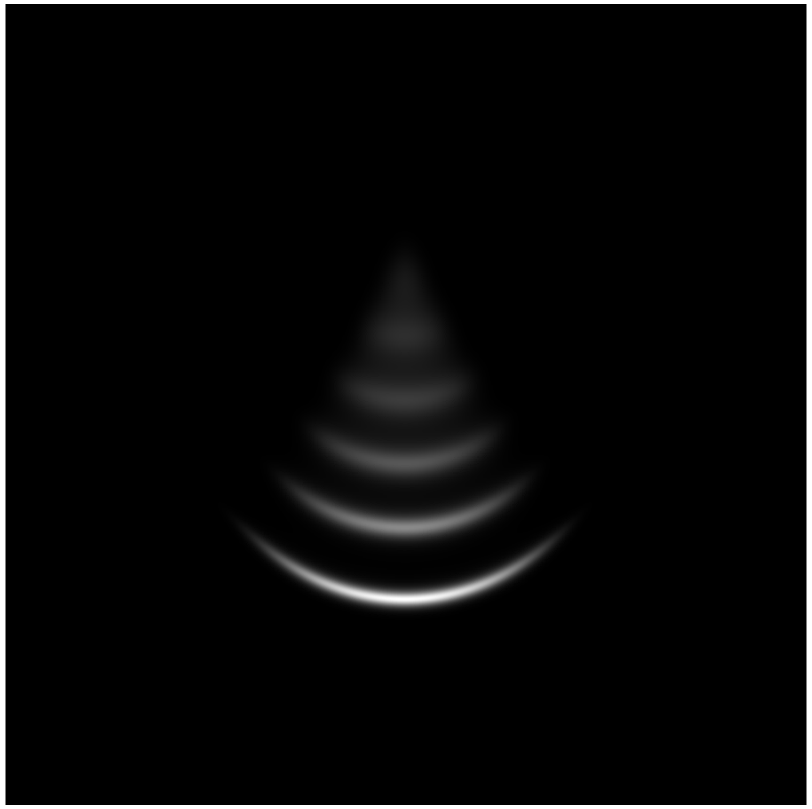


- $E_{lim} = \pi\, E_S/\ln[4e^3 B\, \delta t^2/\hbar^2] \cong 2.5\times10^{12}$G *extremely insensitive* to parameters!
- $E_{lim} \cong E_{nanoshot}$

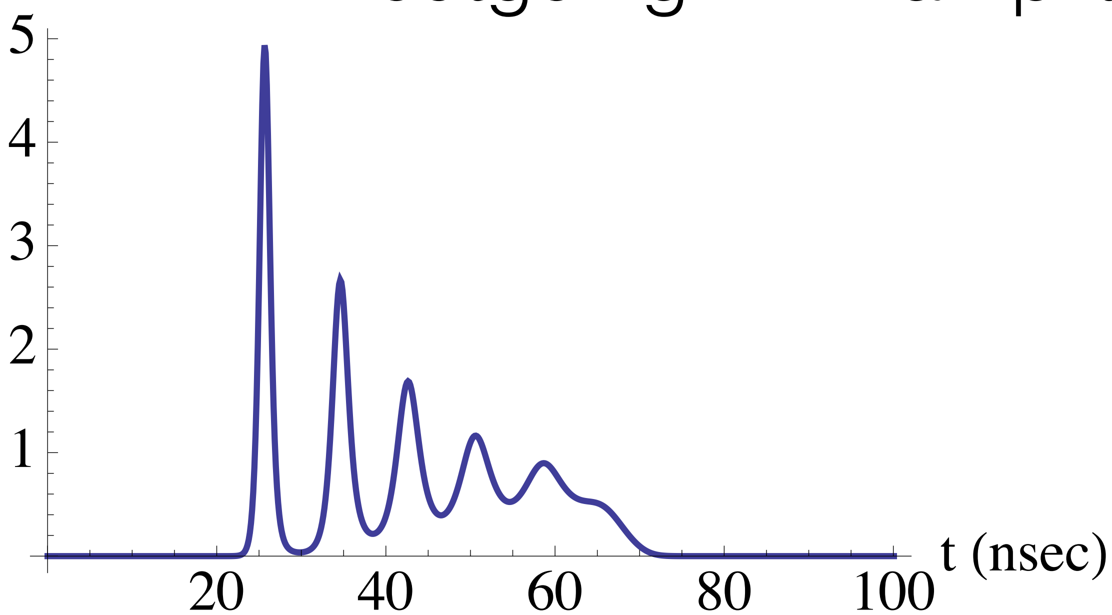
Schwinger Sparks

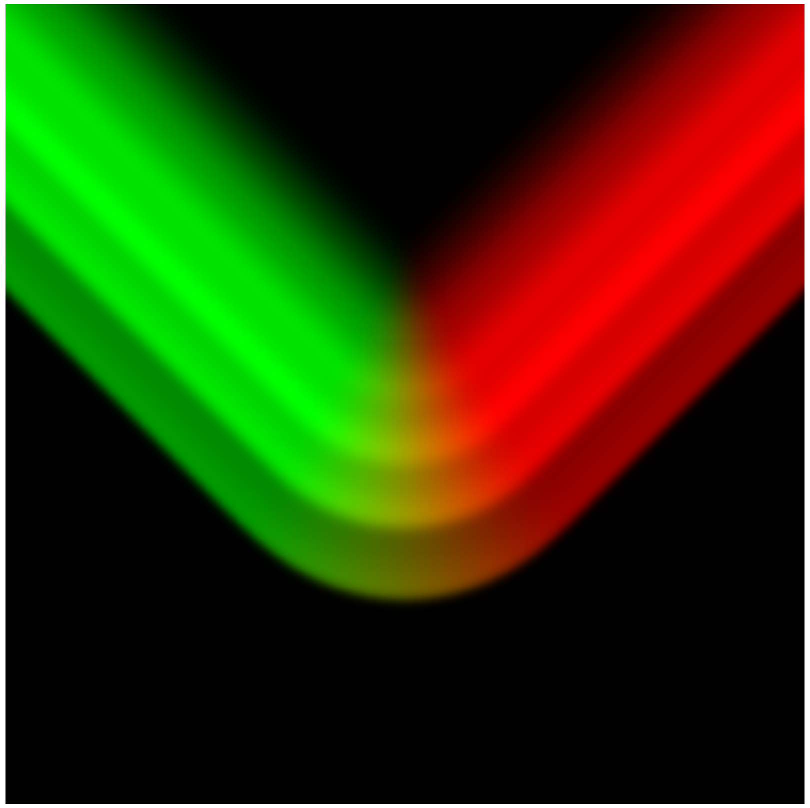
1^{+}D simulation (Stebbins & Yoo 2015)



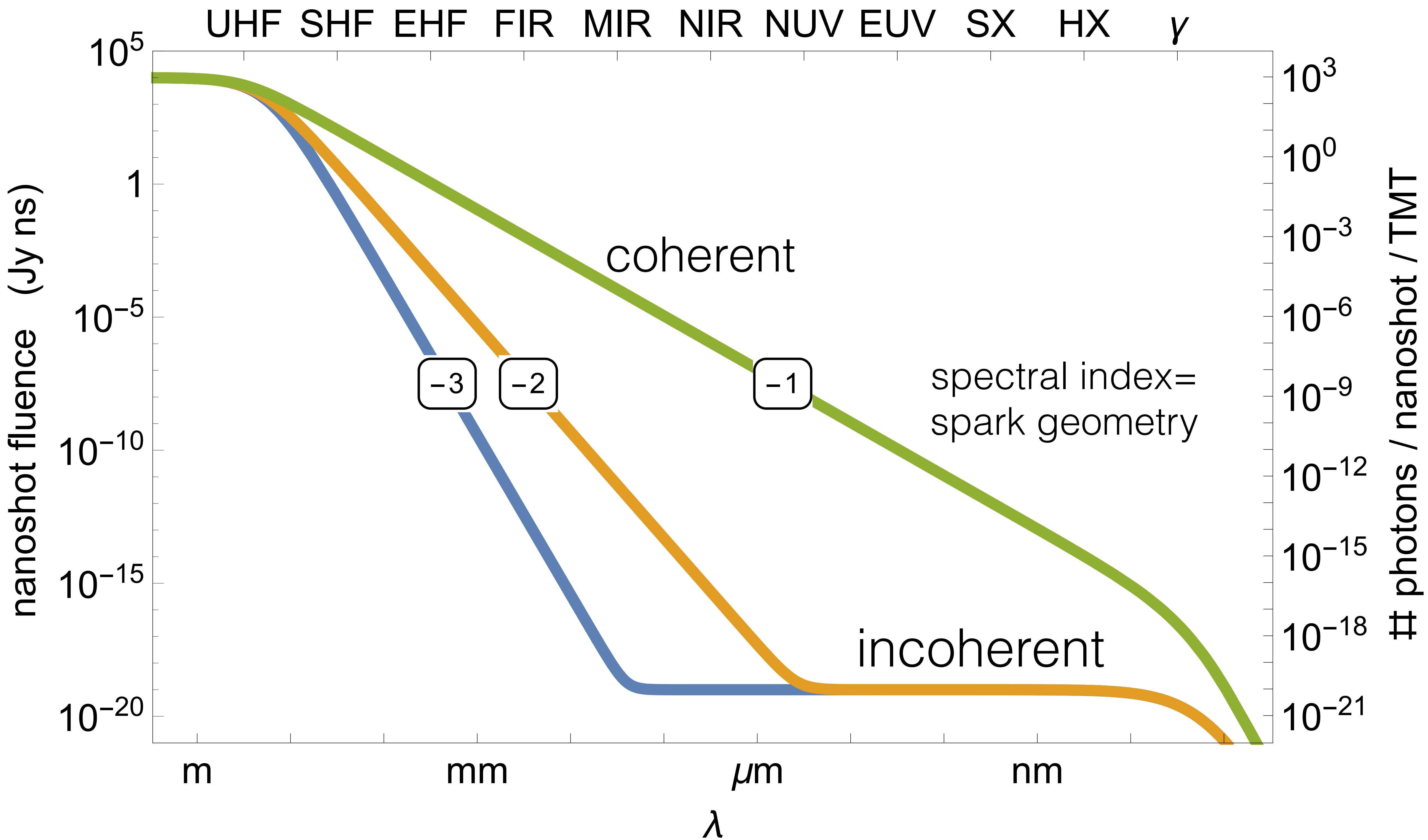


pair production rate = outgoing EMP amplitude





Schwinger Spark Spectrum



Other source of IR/O/UV follow-on emission?

BIG QUESTIONS

- Is there **nanosecond astronomy**?
  - surprisingly **YES** at least in one environment in radio.
- Is there **nanosecond IR/O/UV astronomy**?
  - **POSSIBLY** we should look and see!
- Is there **microsecond IR/O/UV astronomy**?
  - **LIKELY** Giant Radio Pulse associated photons have μsec structures.
- **What other short timescale phenomena are there?**

ANSWERS

- **Very short timescale astronomy is photon starved!**
- **Instrument very large telescopes (e.g. TMT) with high time resolution (single pixel) camera.**
- low cost instruments with limited number of targets
- very unexplored phenomena space

SUMMARY

- Large telescopes can resolve extremely small structures, temporally
  - need a large "light bucket" to capture small number of photons in small time intervals
- The brightest emission yet seen are "nanoshots" emitted from some pulsars
  - pulses observed at 1-10GHz some emitting $\sim 10^{30}$ erg in longer than1 nsec
- Coherent emission by synchronized motion of $\sim 10^{23}$ $e^{\pm}$ in very small volume
  - origin of synchronized motion unclear (propose vacuum pair production plays a role)
  - coherence decreases at higher frequencies so likely IR/O/UV emission likely faint
  - correlated optical emission has already been detected
- Temporal structure of IR/O/UV auto and cross w/ radio good diagnostic.
  - IR/O/UV could probe truly microscopic scale EM structure!
- Fast Radio Bursts …

Schwinger Model of FRBs

- Are FRBs millions Schwinger Sparks going off in a few msec?
- "**Blitzar**" ~ literally "**lightning star**"