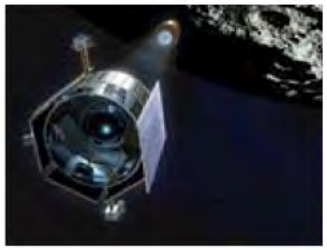
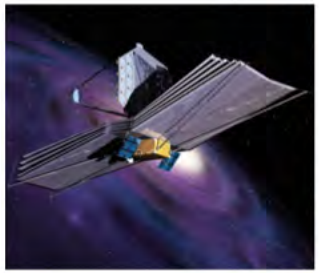
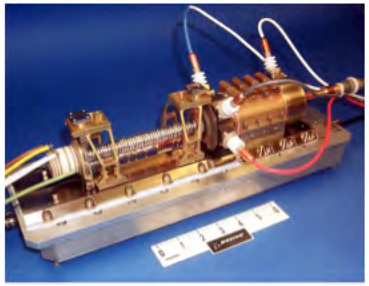
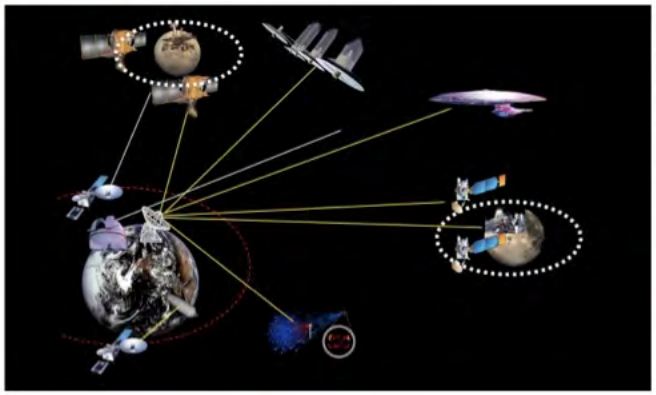
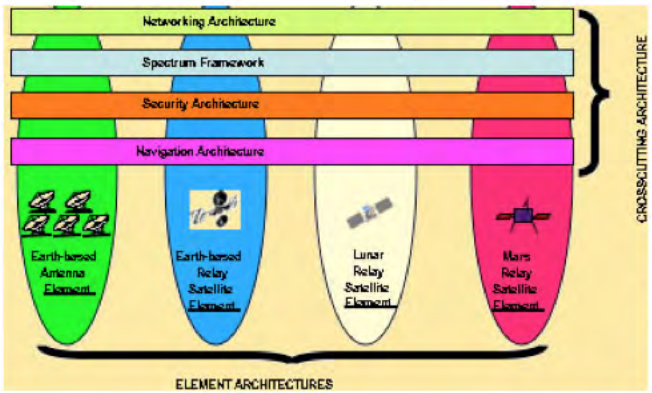
Re-discovering The Radio Transient Sky

Joseph Lazio
Jet Propulsion Laboratory, California Institute of Technology

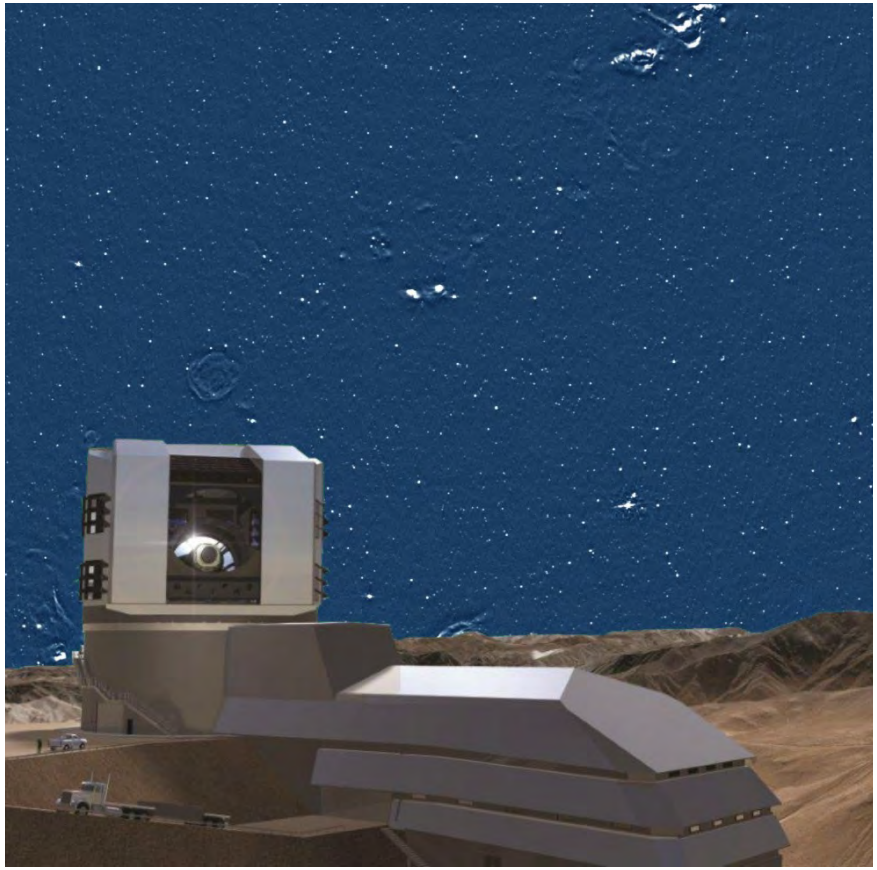



Radio Astronomy in the LSST Era

- **Community workshop**

  Charlottesville, VA; May 6--8
- **Themes**
  - **Time Domain**
  - **Sky Surveys**
- **White paper *submitted* to *PASP***
- **Presentations available online**



https://science.nrao.edu/science/event/RALSST2013

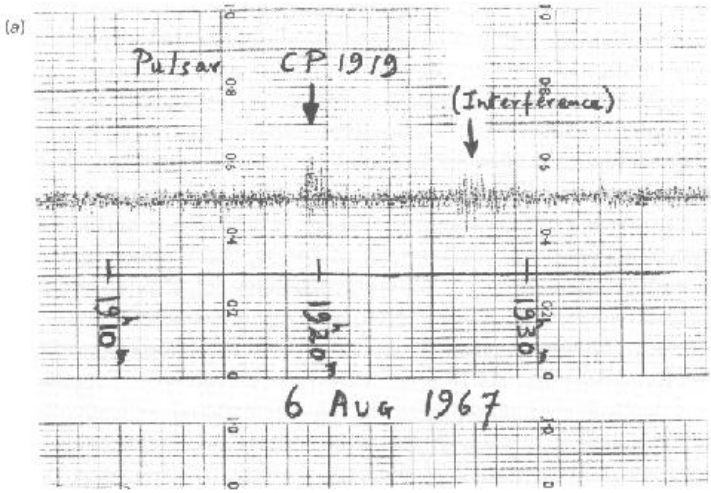
Deep Space Network

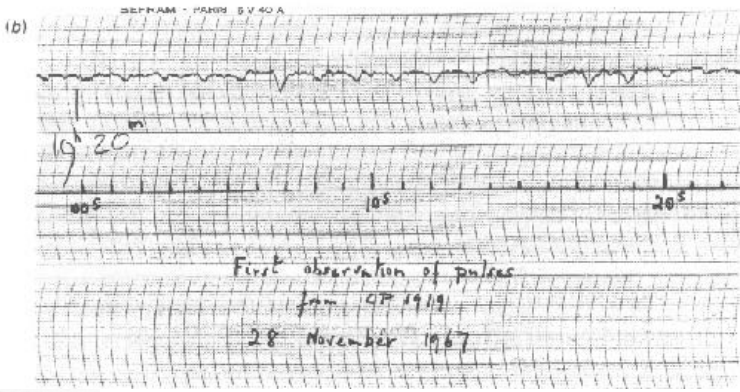
- **Three major tracking sites around the globe, with 16 large antennas, provide continuous communication and navigation support for the world's deep space missions**
- **Currently services ~ 35 spacecraft both for NASA and foreign agencies**
  - **Includes missions devoted to Planetary, Heliophysics, and Astrophysical sciences as well as to technology demonstration**
- **Spigot for science data from most spacecraft instruments exploring the solar system, as well as a critical element of radio science instruments**
- **$2B infrastructure that has been critical to the support of 10's of $B of NASA spacecraft engaged in scientific exploration over the last few decades**

Discovery of Neutron Stars

- **Baade & Zwicky (1934) introduce concept of neutron star.**
  - **Unobservable because the Universe is thermal**
- **Observed (1967)**

  - **In telescope designed to exploit time domain, but …**
  - **Serendipitously**
  - **Could differentiate celestial and terrestrial interfering signals (RFI)**





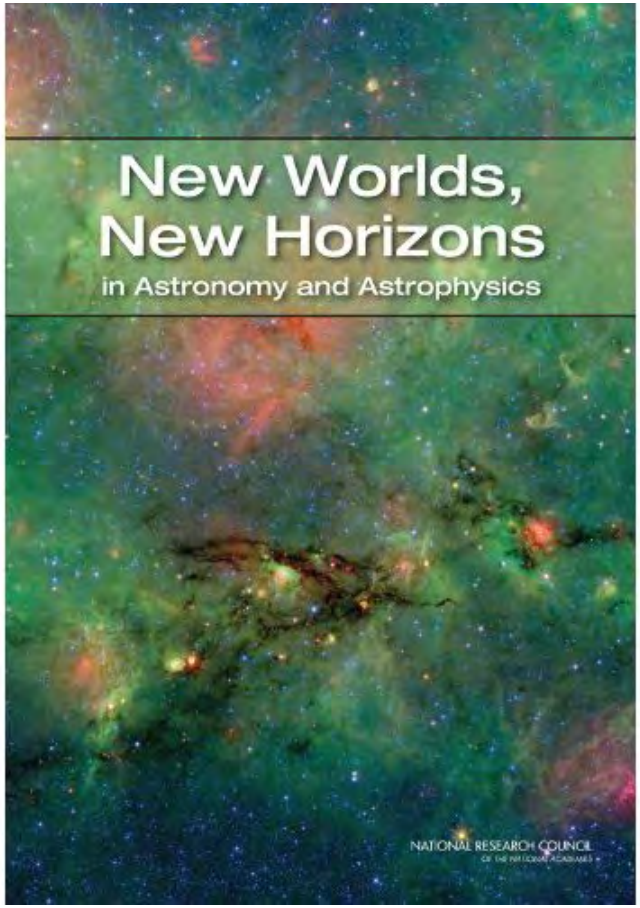
Jocelyn Bell, 1967

Time Domain Astronomy

"New technologies, observing strategies, theories, and computations open vistas on the Universe and provide opportunities for transformational comprehension, i.e., discovery.

"Science frontier discovery areas are:

- Identification and characterization of nearby habitable exoplanets
- Gravitational wave astronomy
- Time-domain astronomy
- Astrometry
- The epoch of reionization



21st Century Astrophysics

Fundamental Forces and Particles

- Gravity
- Magnetism
- Strong force

Origins

- Galaxies and the Universe
- Stars, Planets, and Life

"The Universe is patiently waiting for our wits to grow sharper."

- Frequency / wavelength / energy
- Solid angle
  - Angular Resolution
  - Field of View
- Polarization
- Sensitivity
- Time

Radio Transients

Coherent ("Fast")

- **Generated by particles radiating in phase**

  $L \propto N^2$

Incoherent ("Slow")

- **Generated by independent particles**

  $L \propto N$

Radio Transient Phase Space

Raleigh-Jeans law

$$S = \frac{2k_B T_B}{\lambda^2}\Omega$$

- S = flux density
- T_B = brightness temperature
- λ = wavelength
- $\Omega = (ct/D)^2$ = solid angle

$$\boxed{SD^2 = 2kT_B\,(t\nu)^2}$$

pseudo-luminosity

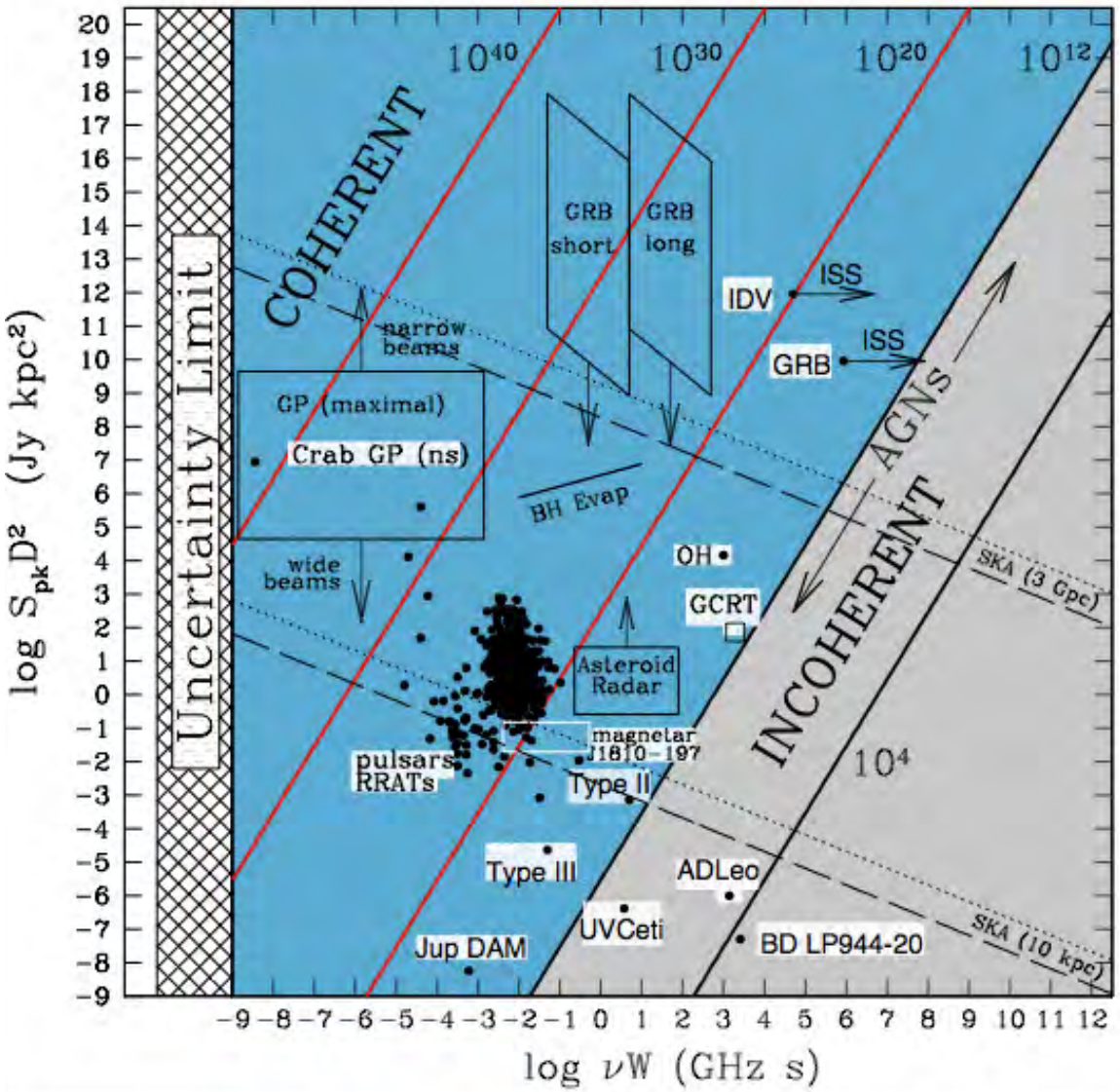
"uncertainty" relation

Radio Transient Phase Space

$\nu t = \nu W$ = dimensionless pulse width, uncertainty-like relation

SD^2 = pseudo-luminosity

- Considerable phase space to explore!



J. Cordes

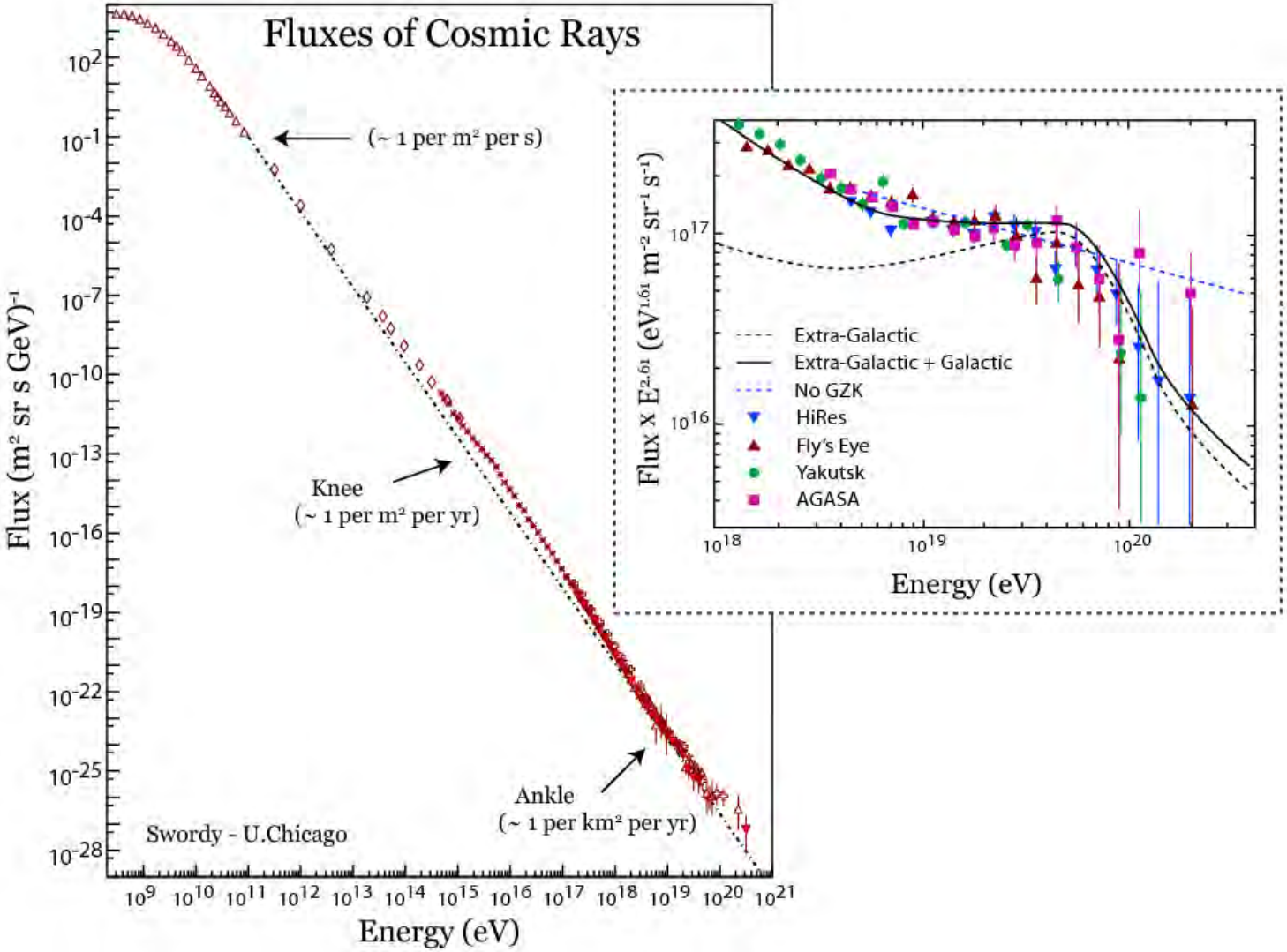
Radio Transients

Class	Object	Timescale	Δt_{opt}
Extragalactic incoherent	SNe, GRBs, TDEs	Tens of minutes-years	Lags by minutes-months
	AGN	Tens of minutes-years	Lags by days-months
	GW counterparts?	Minutes to years?	Lags?
Extragalactic coherent	Fast ra		own
	GW co		own
Galactic coherent	Maser interst		
	Neutro		taneous, if present
	Sub-st		own
Galactic incoherent	X-ray binaries, novae, stellar flares	Minutes-hours	Lags by minutes
Unknown	"Hyman bursters"	Minutes	unknown
Propagation effects	Affects pulsars, extragalactic sources	Minutes-days (pulsars) Years (AGN)	N/A

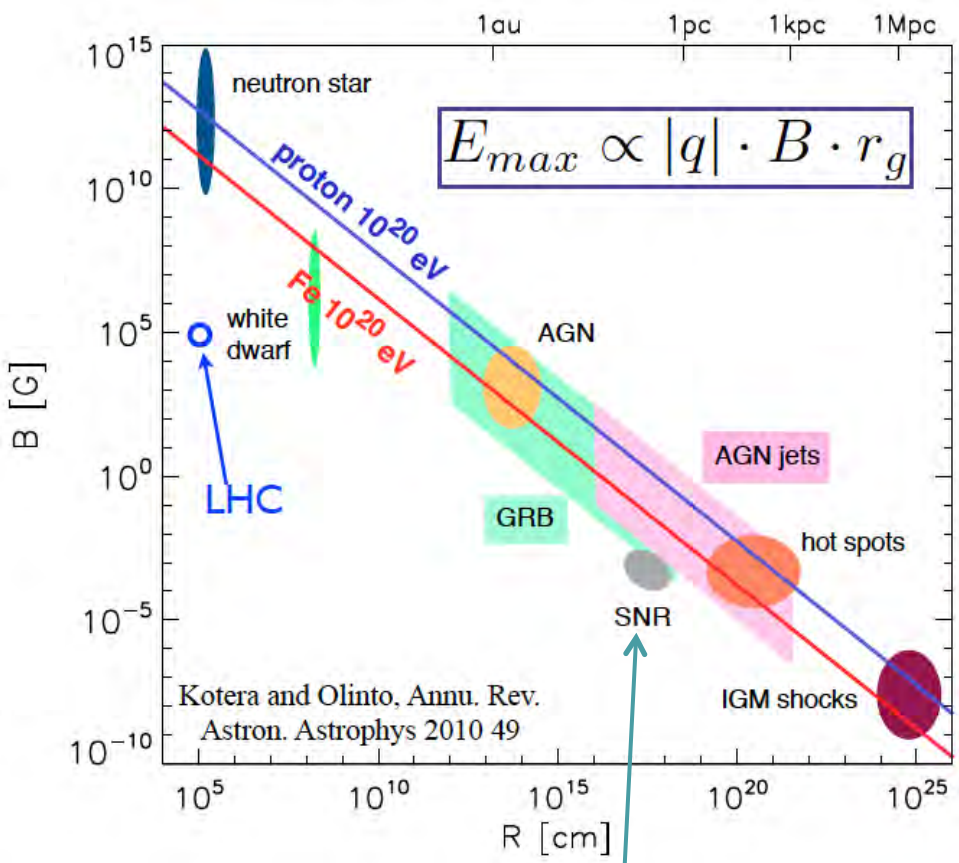
- **Is all of it worth exploring?**
  - I. Cosmic accelerators
  - II. Intergalactic bursts
  - III. Extrasolar planets
  - IV. Gravitational wave events

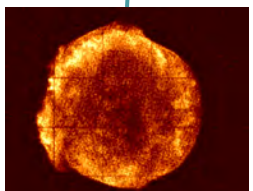
I. Cosmic Accelerators

Viktor Hess discovers energetic extraterrestrial particles in 1912



I. Cosmic Accelerators



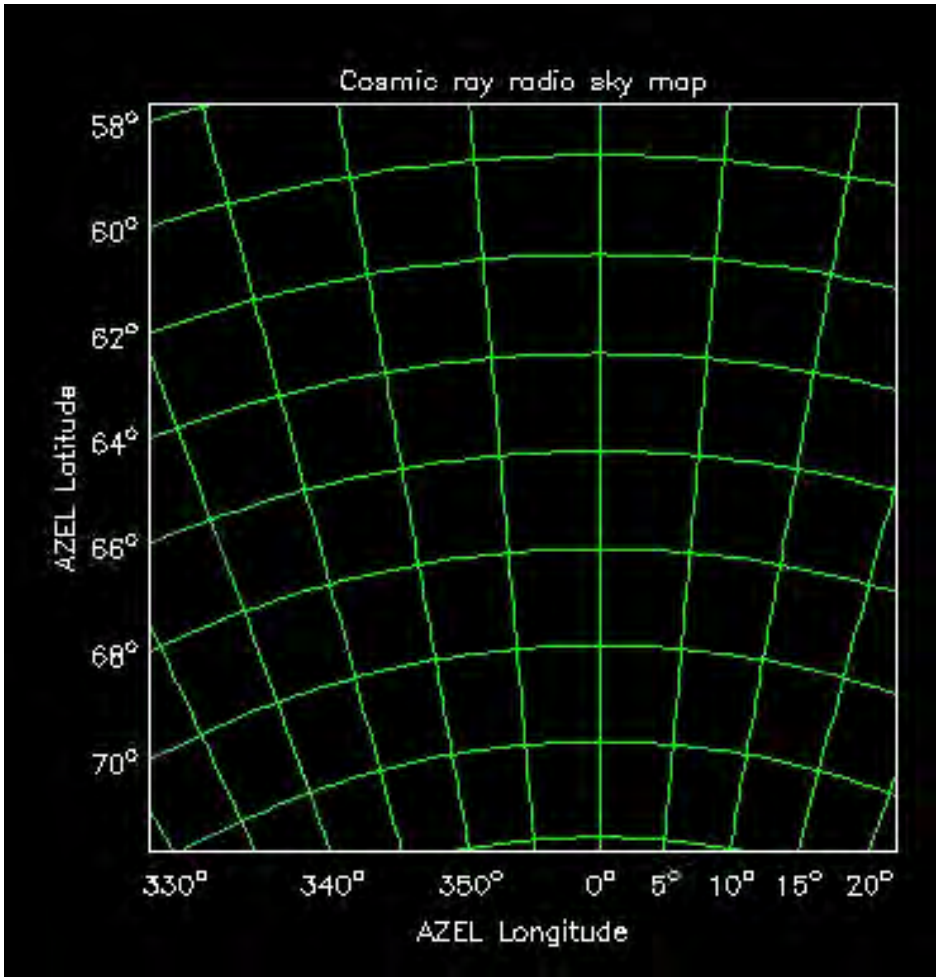


- **Fermi acceleration involves particle gaining energy as it scatters across a magnetic field**
- **Maximum energy depends on**
  - **charge (*q*);**
  - **magnetic field strength (B); and**
  - **size of accelerating region**

➢ **Identification of actual accelerators complicated by interstellar and intergalactic magnetic fields**

I. Radio Pulses from UHECRs and UHEν's

UHECR = Ultra-High Energy Cosmic Ray



LOIS-LOFAR movie

- **Radio pulses produced when UHECRs hit atmosphere**

  Shower of secondary particles emits in geomagnetic field

- **May tell us about the most powerful accelerators in the Universe**

  - **What is composition?**

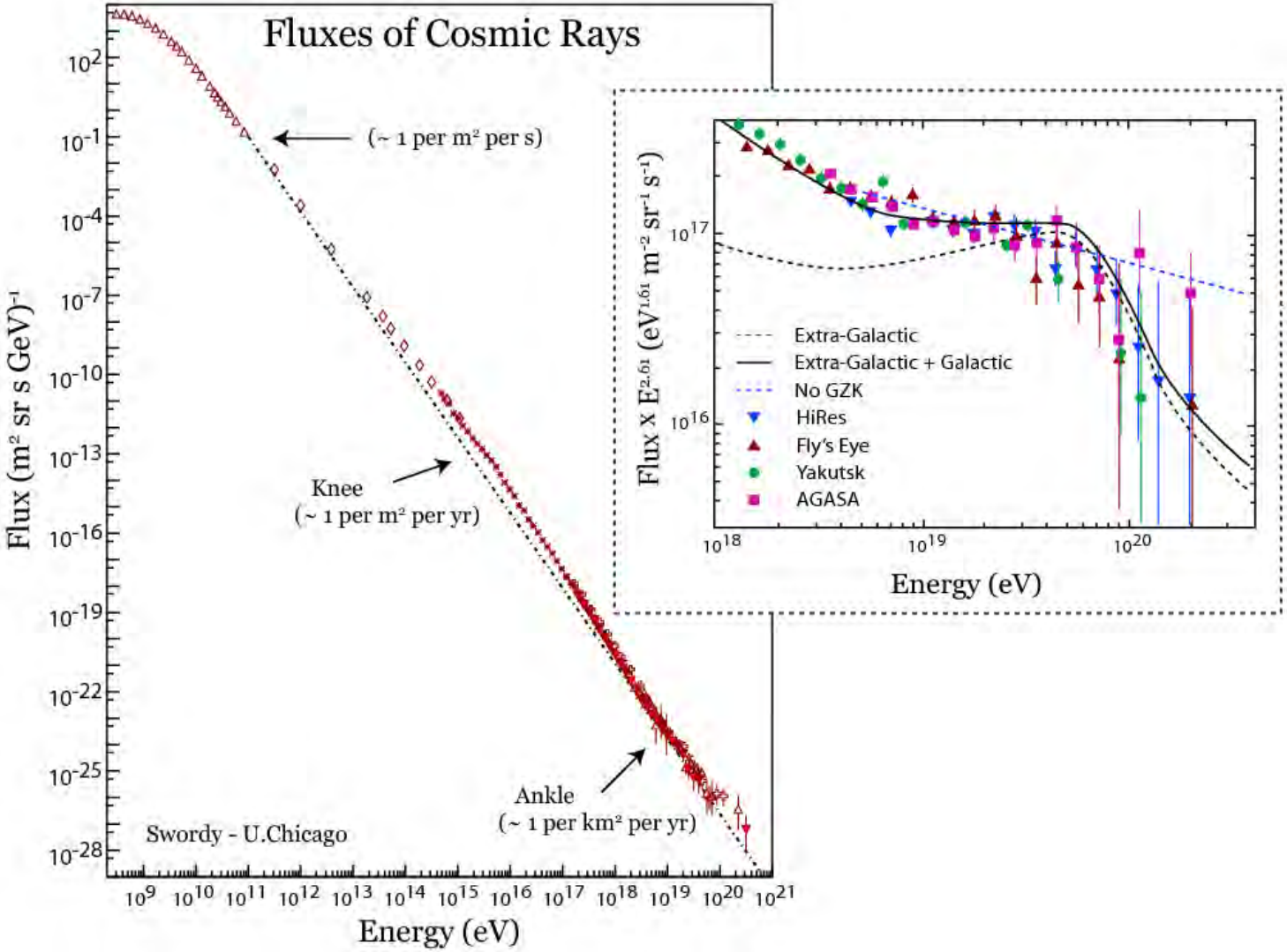
    p vs. Fe

  - **What is origin?**

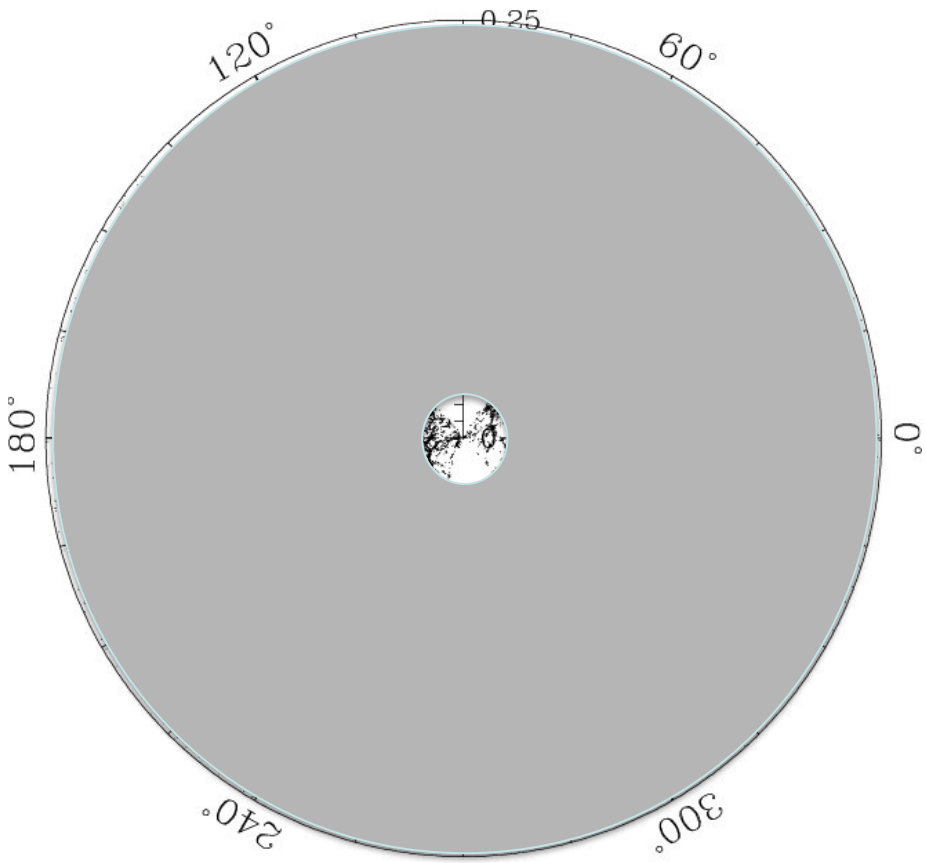
    "bottom up" vs. "top down"

I. Cosmic Accelerators

Viktor Hess discovers energetic extraterrestrial particles in 1912



I. Cosmic Ray Horizon



- **Greisen-Zatsepin-Kuzmin (GZK) limit**

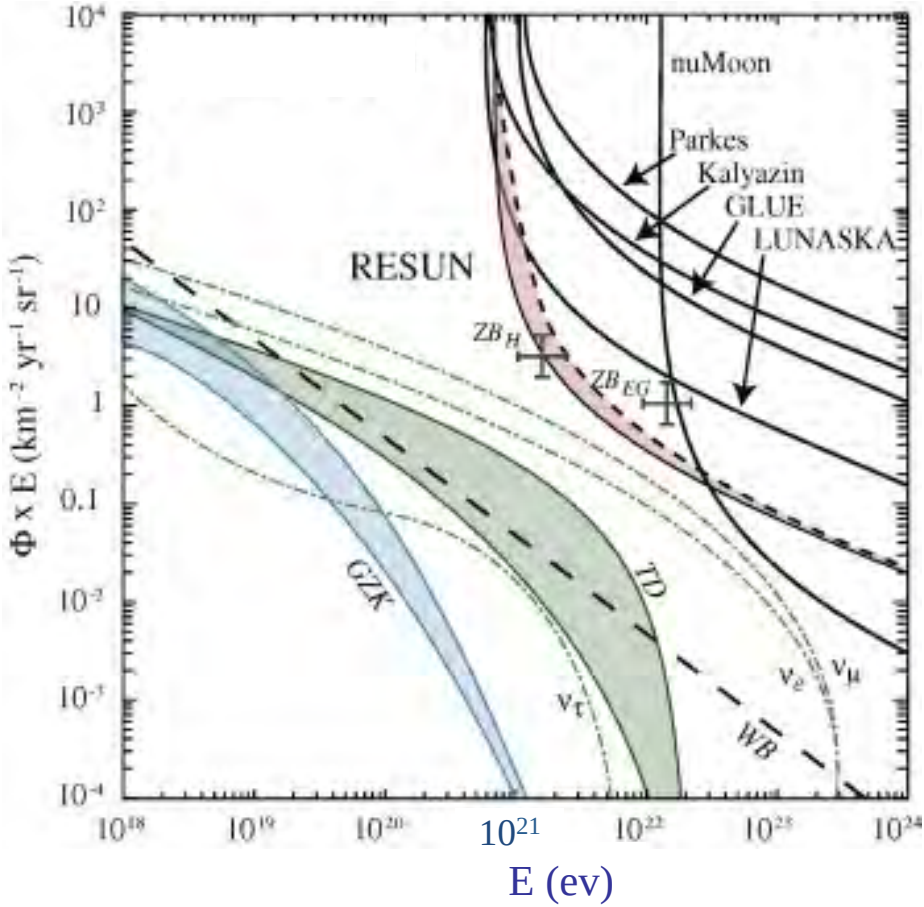
$$p + \gamma \rightarrow \pi^0 + p$$
$$\rightarrow \pi^+ + n$$

- **Cosmic ray horizon is about 50–100 Mpc**

I. Radio Pulses from UHEν's

- **Neutrinos travel unimpeded across cosmological distances**
  No G-Z-K effect!

- **Moon as a beam dump**
  - **Ultra-high energy ν initiates particle shower**
    $E_\nu \sim 10^{20}$–10^{22} eV (or higher?)
  - **Negative charge excess develops**
    - **Coherent radio pulse**
      - **Askar'yan effect**
      - **Effect demonstrated at terrestrial accelerators**



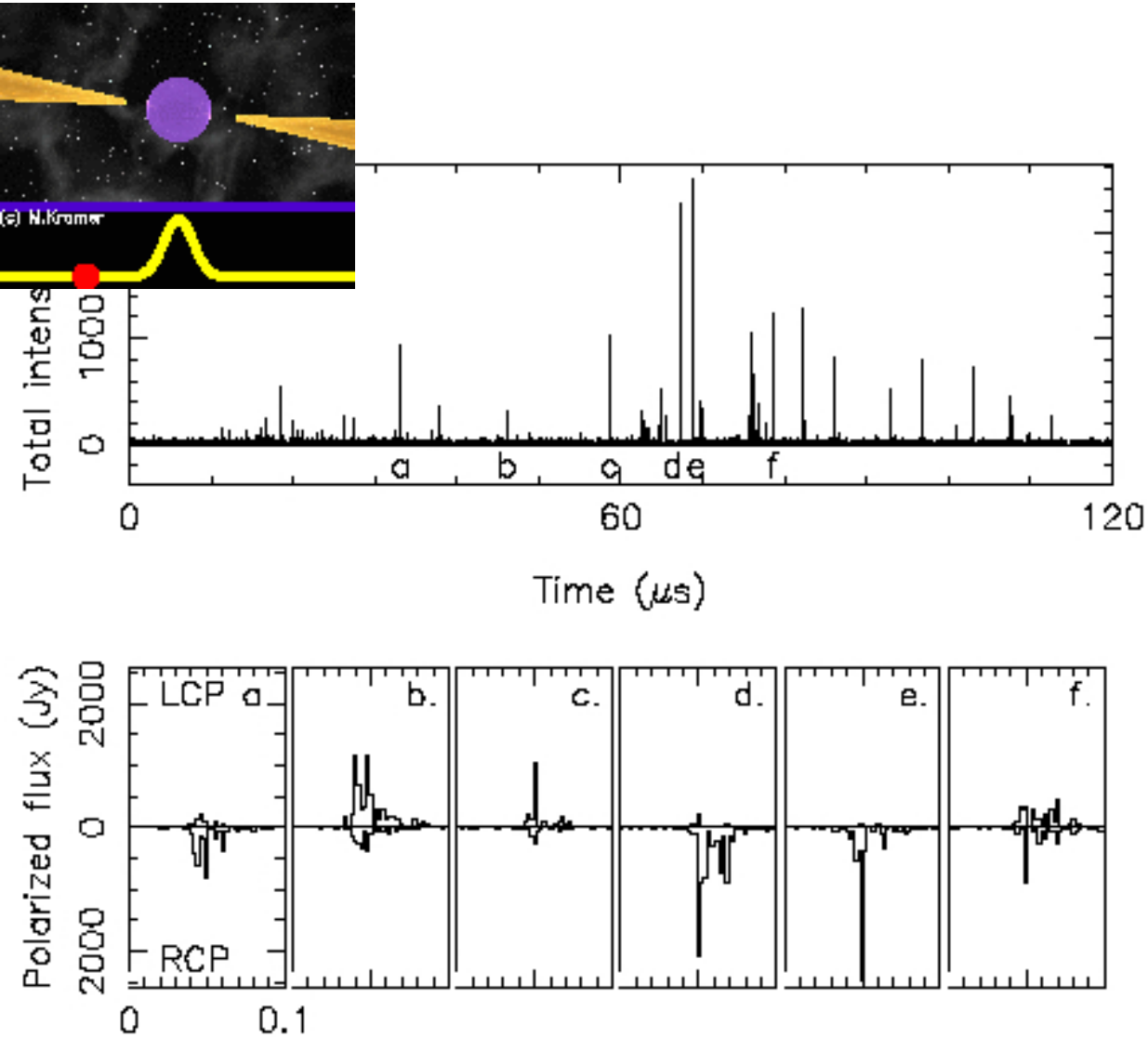
What are the most powerful cosmic accelerators?

Radio Transients

Class	Object	Timescale	Δt_{opt}
Extragalactic incoherent	SNe, GRBs, TDEs	Tens of minutes-years	Lags by minutes-months
	AGN	Tens of minutes-years	Lags by days-months
	GW counterparts?	Minutes to years?	Lags?
Extragalactic coherent	Fast ra		own
	GW co		own
Galactic coherent	Maser interst		
	Neutro		taneous, if present
	Sub-st		own
Galactic incoherent	X-ray binaries, novae, stellar flares	Minutes-hours	Lags by minutes
Unknown	"Hyman bursters"	Minutes	unknown
Propagation effects	Affects pulsars, extragalactic sources	Minutes-days (pulsars) Years (AGN)	N/A

- **Is all of it worth exploring?**
  - I. Cosmic accelerators
  - **II. Intergalactic bursts**
  - III. Extrasolar planets
  - IV. Gravitational wave events

II. Giant Pulses from Radio Pulsars



Crab pulsar (Hankins et al. 2003)

- **On ~ 2 ns**
- **Off ~ 10 min**
- **$T_B > 10^{30}$ K**

  Second brightest objects in the Universe?
- **Probe of**
  - **pulsar emission mechanism**
  - **scattering environment?**

➢ **Arecibo can detect a Crab-like pulsar to 1.4 Mpc**

II. Pulses and Media

- **Refractive index of plasma is frequency dependent**
- **Arrival time of pulse is frequency dependent**

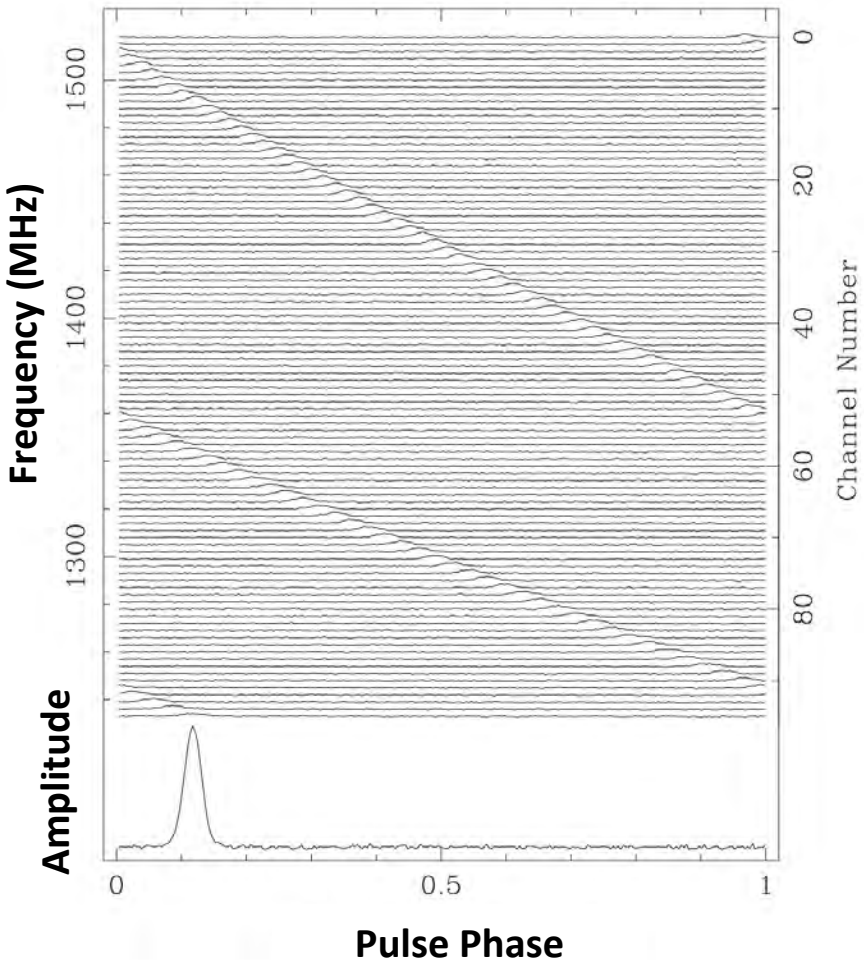
$$t = \mathrm{DC} * \mathrm{DM}/\nu^2$$

$$\mathrm{DM} = \int n_e(z)\, dz$$

  – **Lower frequencies arrive later**

➢ **Arrival time differences between different frequencies are a direct probe of an intervening medium**

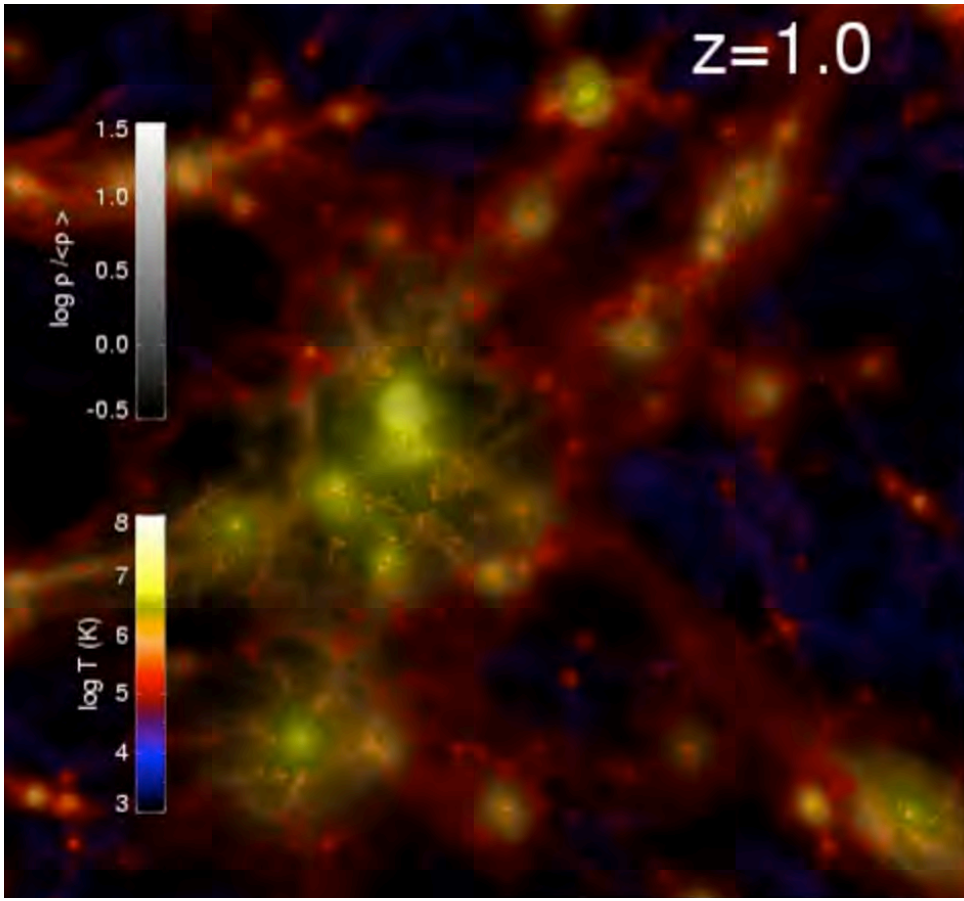
  ➢ **If a radio pulse can be produced by an object at intergalactic distances, direct measure of intergalactic medium (IGM)**



Lorimer & Kramer

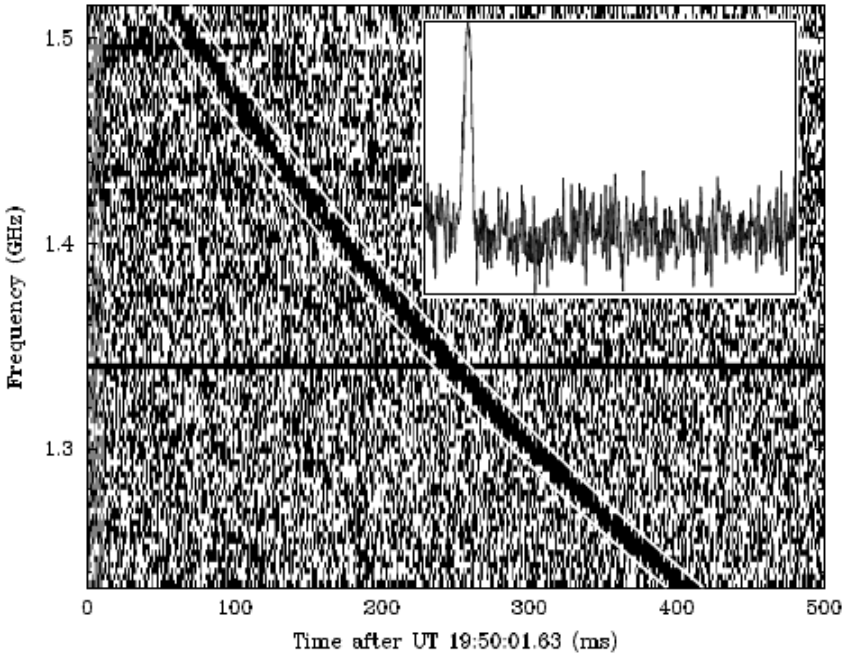
II. Intergalactic Medium and Giant Pulses

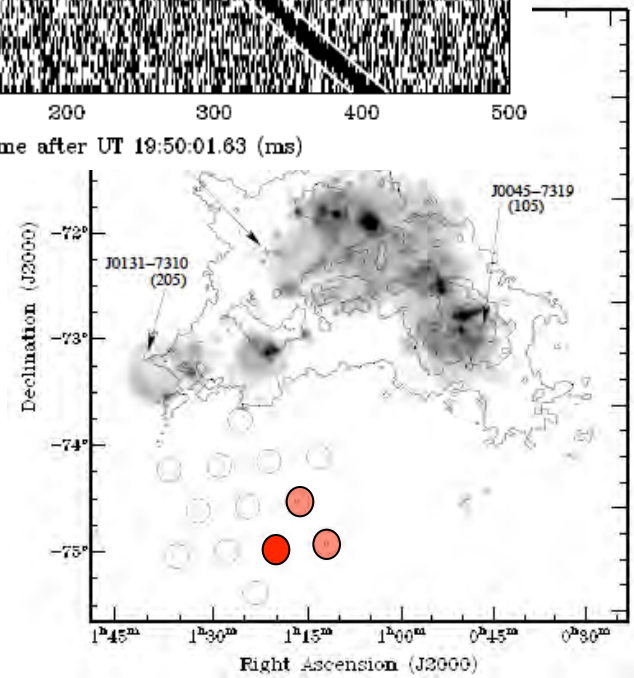
- **Intergalactic medium consists of dilute, largely ionized plasma**
  - **Clusters of galaxies form at intersections of high-density filaments**
- **~ 50% of baryons resident in intergalactic medium**
- **Hints from highly ionized species of Oxygen and Neon**
- **Dispersion from pulses would be *direct* probe!**



II. An Extragalactic Pulse?

- Intense (30 Jy), short (5 ms), dispersed signal detected in re-analysis of Parkes survey
- Dispersion measure (375 pc cm^{-3}) in excess of Galactic + SMC value
- Pulse appears scatter broadened
- Implied extragalactic (d ~ 1 Gpc)!
- … until more discovered

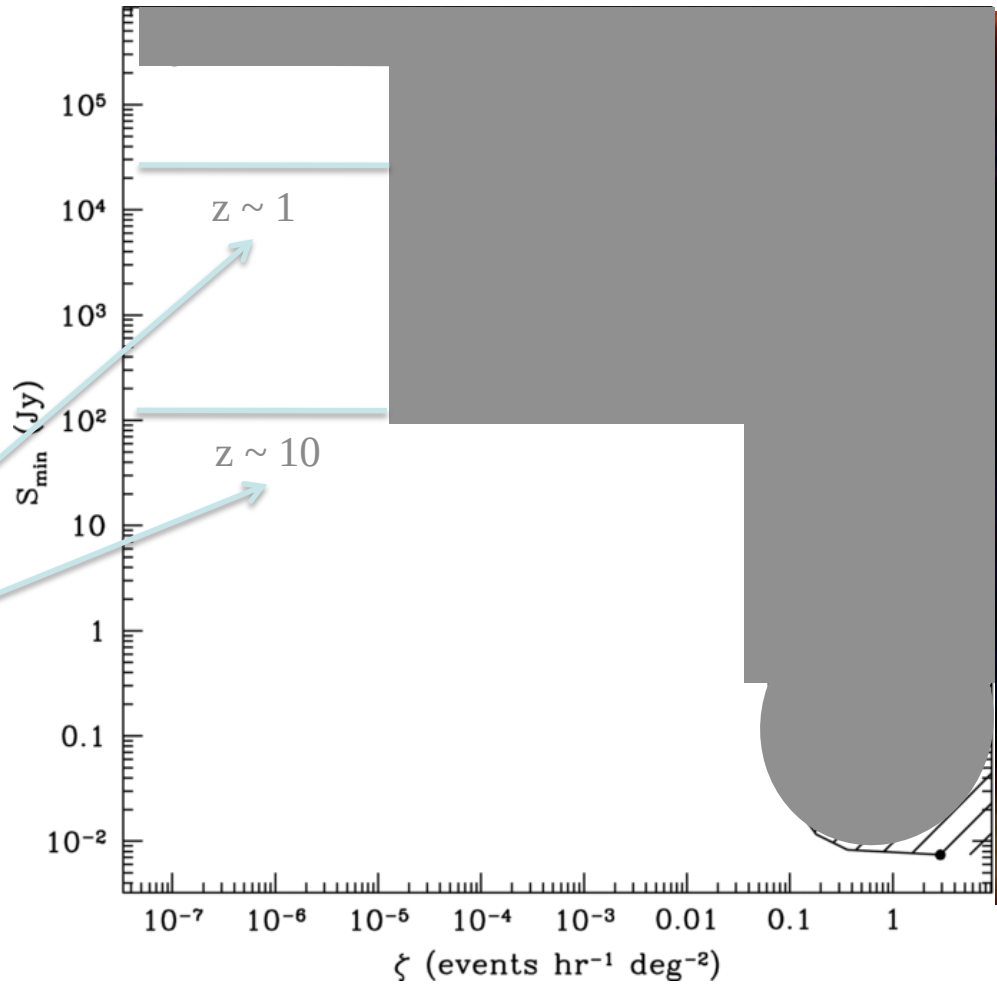




II. Intergalactic Medium and Giant Pulses

- **How far could we see?**
  - **$E = M_{\odot}c^2$**
  - **$\varepsilon \sim 10^{-6}$**
  - **$\Delta t \sim 1$ s**

$$S \sim \frac{\varepsilon Mc^2}{\Delta t\,\Delta\nu\left(4\pi D_L^2\right)}$$



(Deneva et al. 2009; Siemion et al. 2012; Wayth et al. 2012)

II. Pulses and the Intergalactic Medium (?)

Thornton et al. announces discovery of fast radio bursts

- **DM values suggest extragalactic origin**

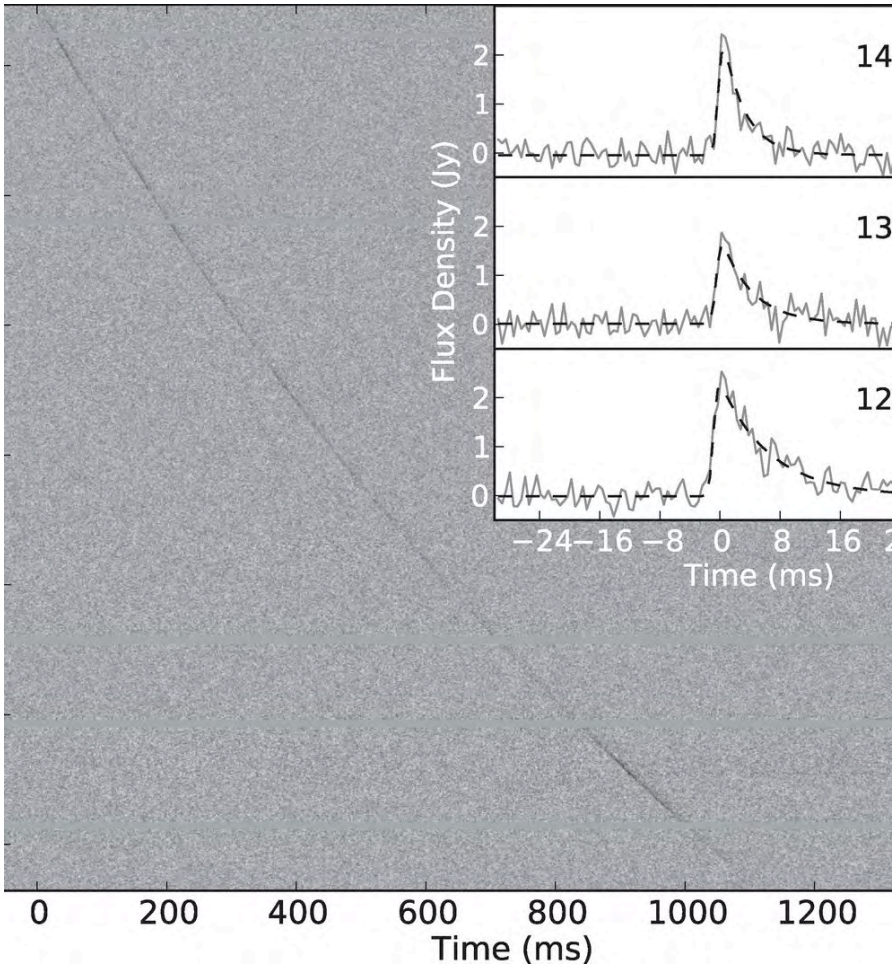
  500 pc cm^{-3} <~ DM <~ 1100 pc cm^{-3}

- **Potentially entirely new class of objects**

  … or associated with coherent emission from stellar flares?

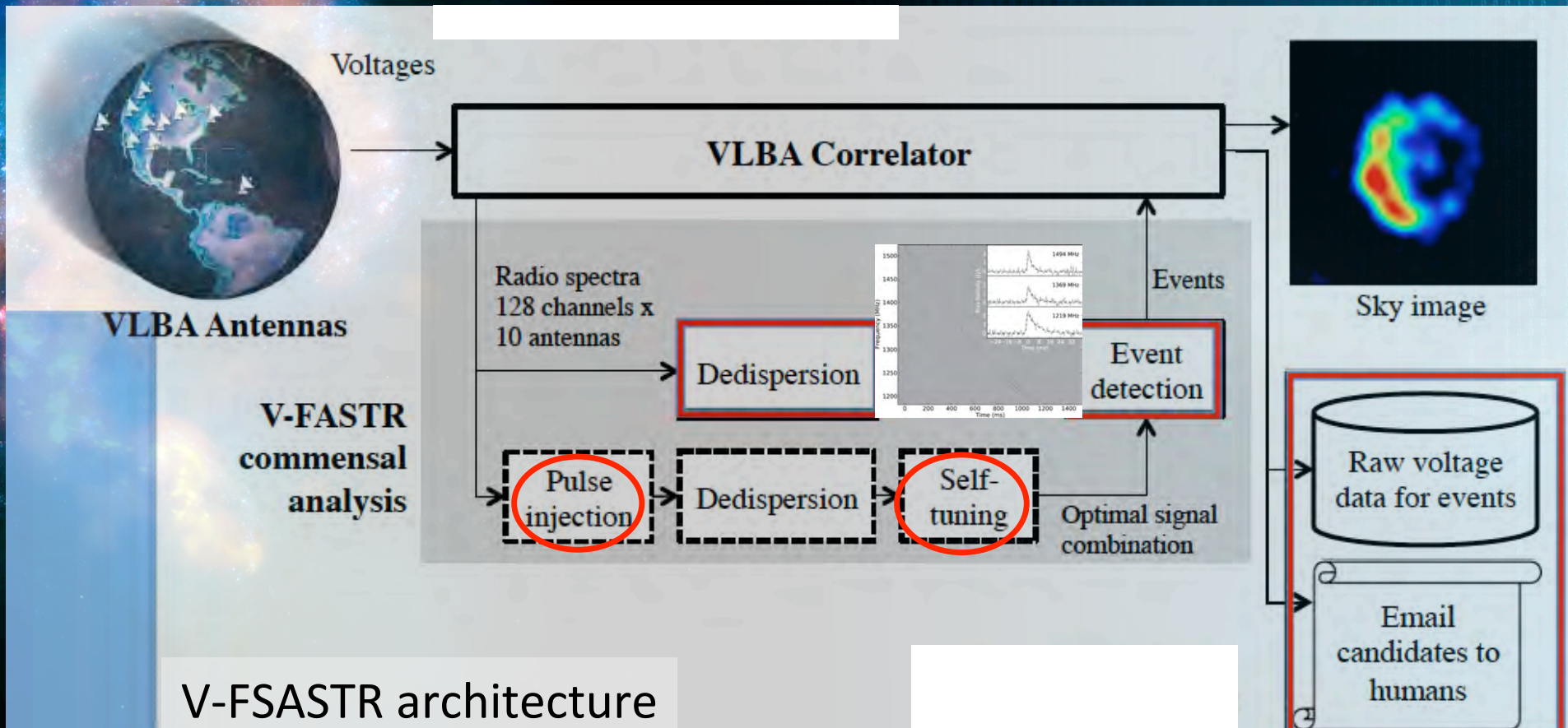
➢ **How to "follow-up" millisecond-duration pulses?**

- **"co-observing"?**
- **Value of knowing instrument well, flexibility**



Machine learning technologies

a.k.a. The Rise of the Machines



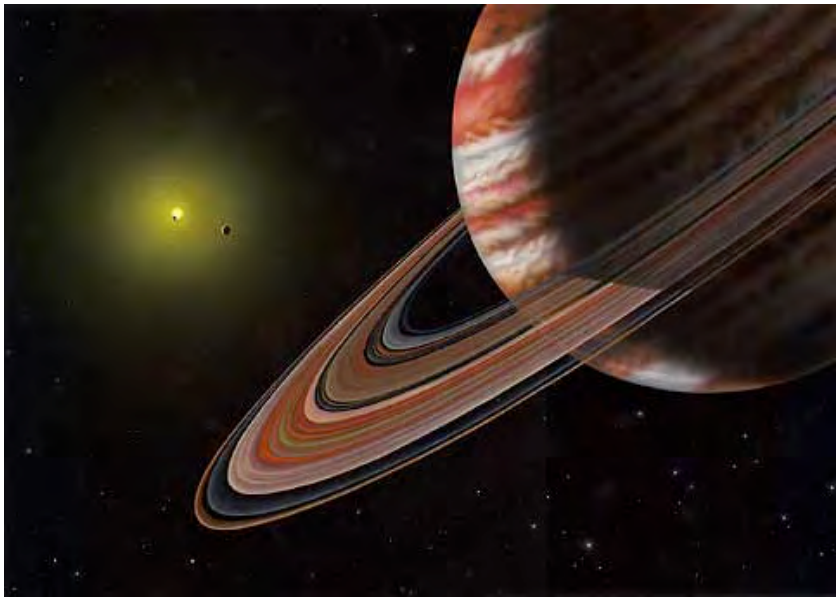
V-FSASTR architecture

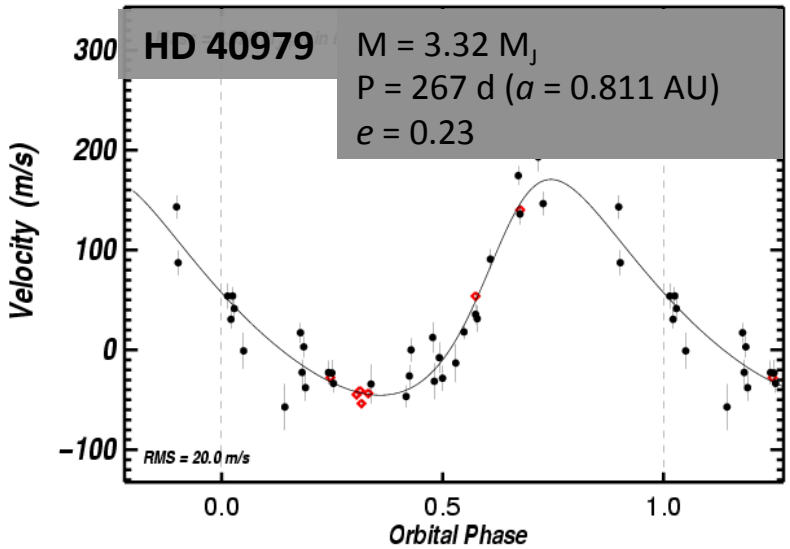
Radio Transients

Class	Object	Timescale	Δt_{opt}
Extragalactic incoherent	SNe, GRBs, TDEs	Tens of minutes-years	Lags by minutes-months
	AGN	Tens of minutes-years	Lags by days-months
	GW counterparts?	Minutes to years?	Lags?
Extragalactic coherent	Fast ra		own
	GW co		own
Galactic coherent	Maser interst		
	Neutro		taneous, if present
	Sub-st		own
Galactic incoherent	X-ray binaries, novae, stellar flares	Minutes-hours	Lags by minutes
Unknown	"Hyman bursters"	Minutes	unknown
Propagation effects	Affects pulsars, extragalactic sources	Minutes-days (pulsars) Years (AGN)	N/A

- **Is all of it worth exploring?**
  - I. Cosmic accelerators
  - II. Intergalactic bursts
  - **III. Extrasolar planets**
  - IV. Gravitational wave events

III. Extrasolar Planetary Radio Emission





Discovery of extrasolar planets!

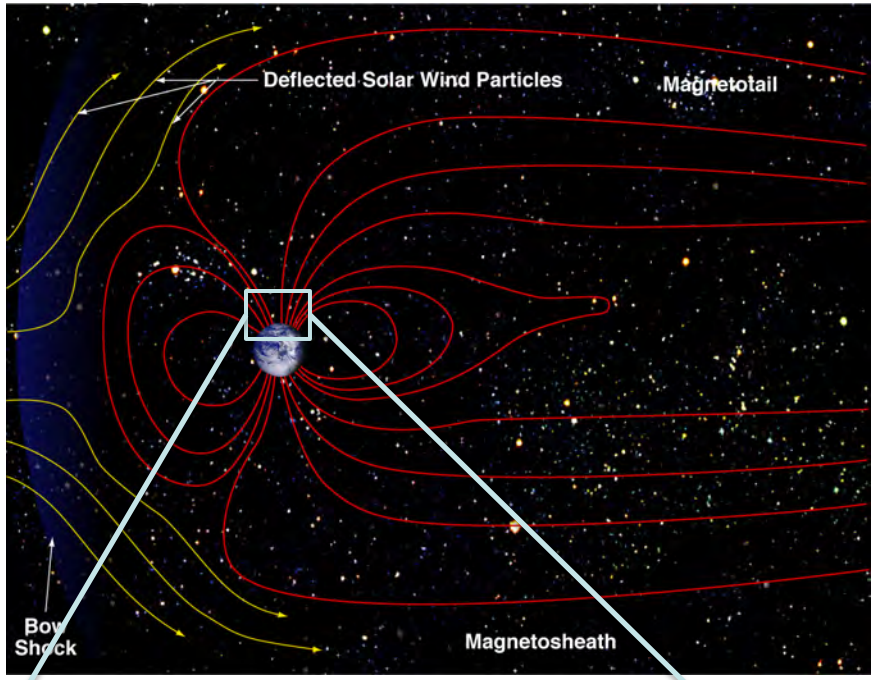
- ~ 10^3 extrasolar planets
- Indirect detection via optical signature
- Direct detection via their shadow

Detecting ⇒ characterizing

- What are their properties?
- Can we detect planets at other wavelengths?
  - ✓ IR thermal emission detected
  - ? Magnetospheric radio (viz. Jupiter)
- Implications for habitability?

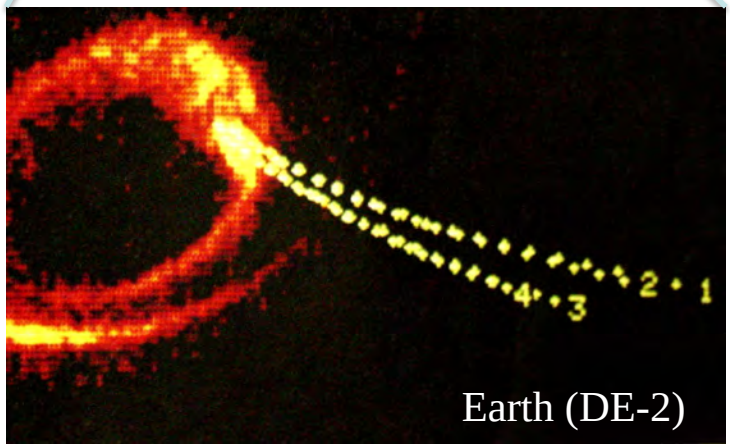
➢ Keck Institute for Space Studies "Planetary Magnetic Fields: Planetary Interiors and Habitability"

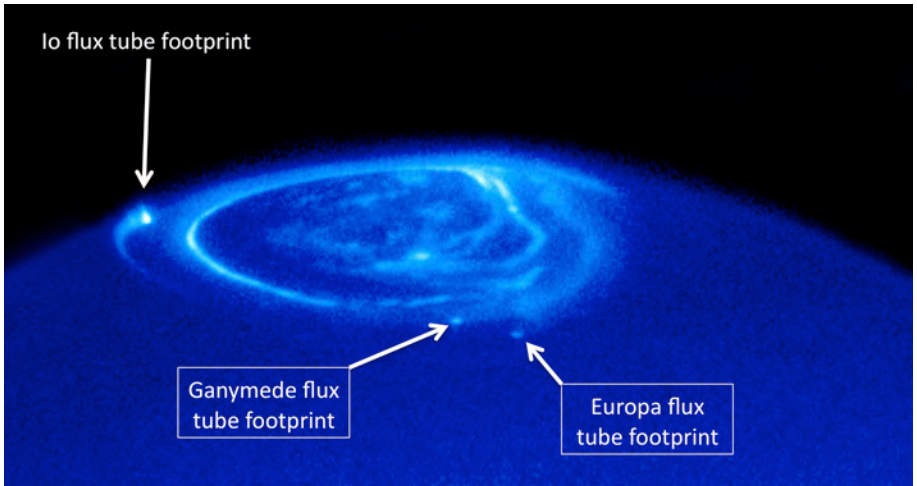
Magnetospheric Emissions



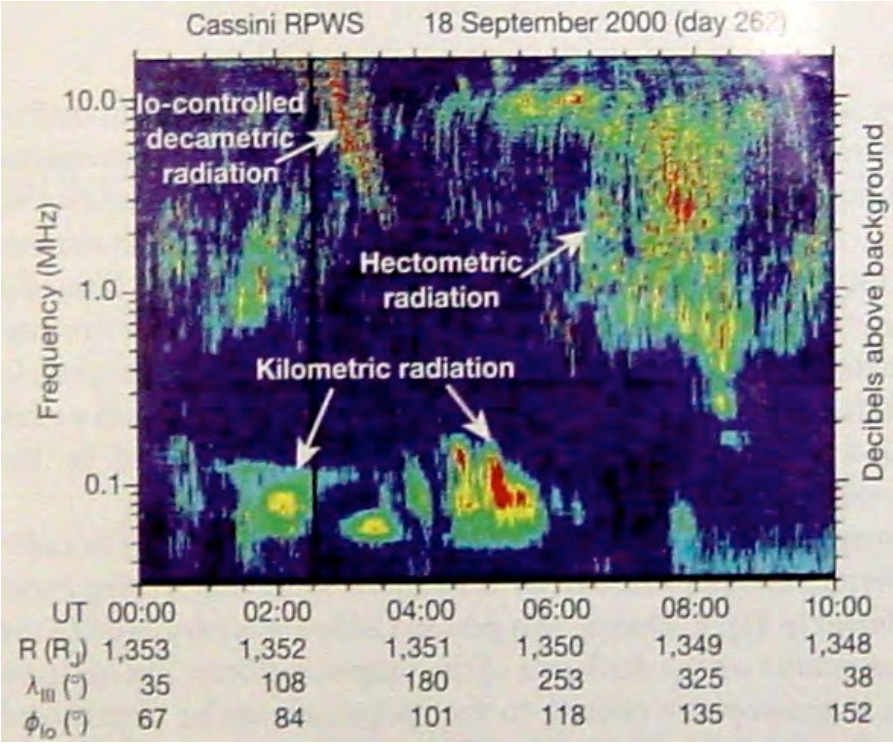
Stellar wind provides energy source to magnetosphere

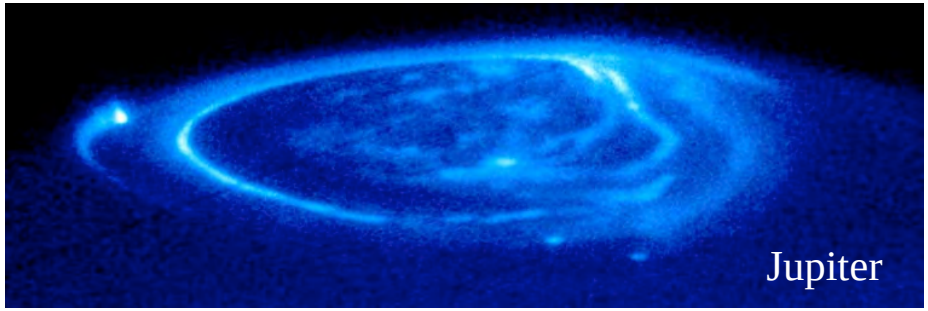
- **~ 1% of input energy to auroral region emitted in UV**
- **~ 1% of auroral input energy into electron cyclotron maser radio emission**





III. Planetary Radio Emission (in the Solar System)

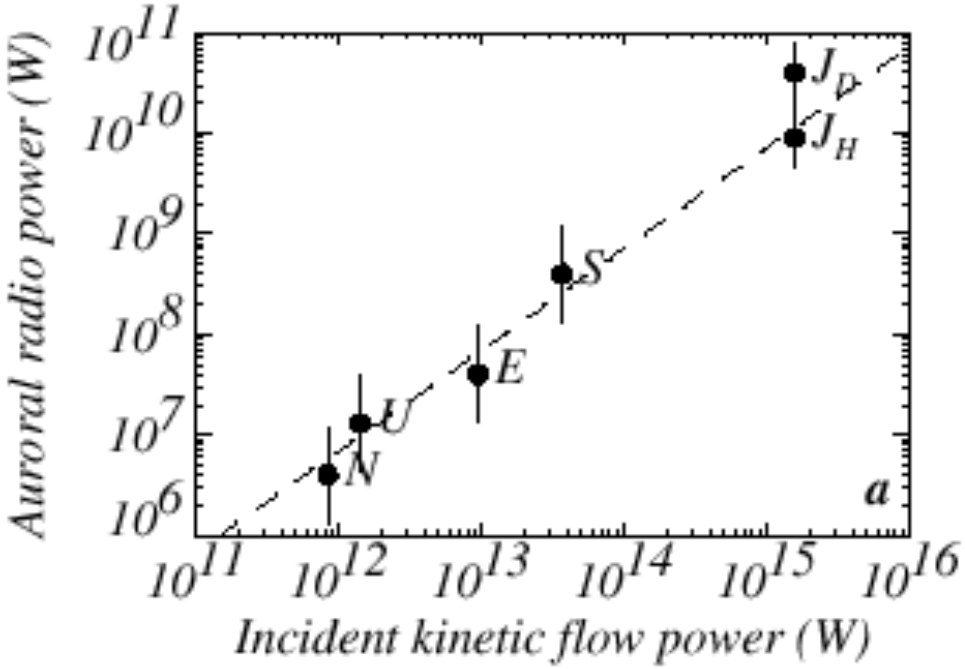




- **Burke & Franklin (1955) discover Jovian radio emission.**
- **Late 1960s/70s: Earth's polar region recognized as radio source (10^7 W).**
- ***Voyagers*: Opens up field**
- **All gas giants have strong planetary magnetic fields and auroral/polar cyclotron emission.**

  Jupiter: Strongest at 10^{12} W

III. Radiometric Bode's Law

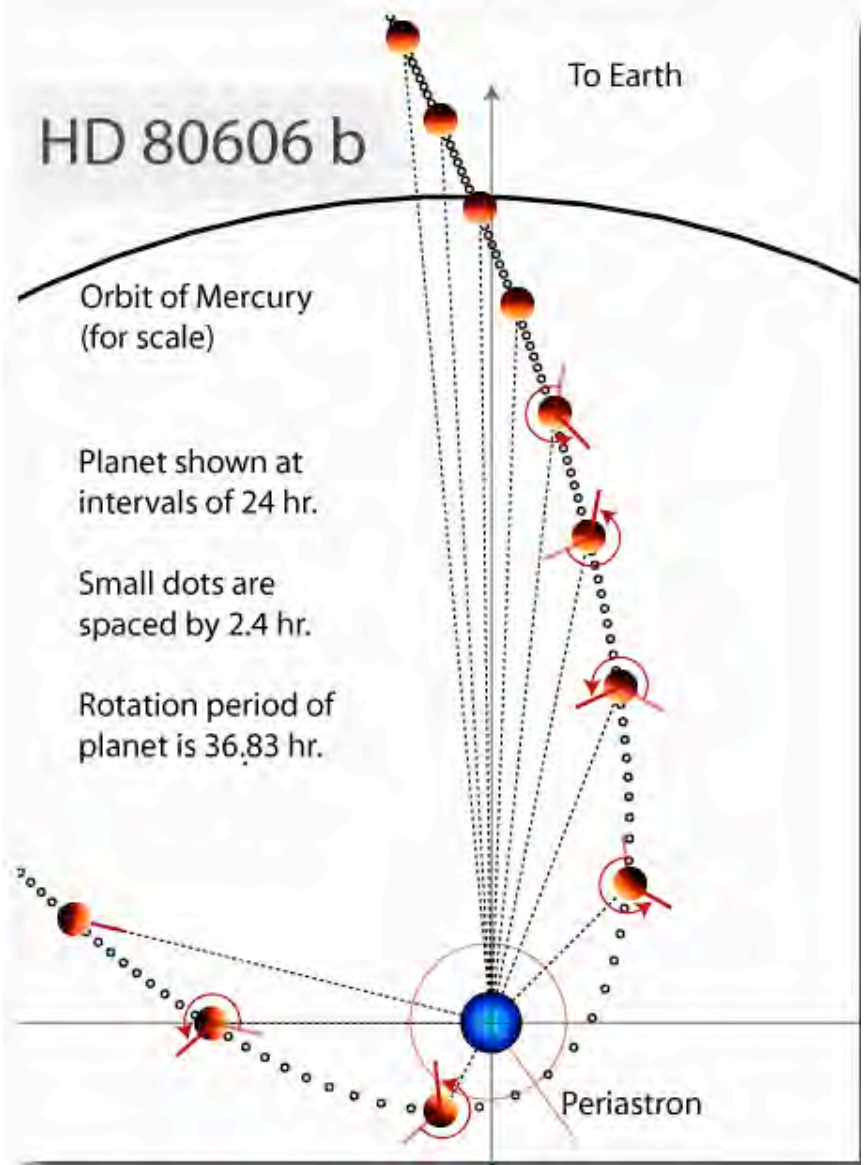


- Zarka (1997), Farrell et al. (1999) extend to extrasolar planetary systems
- Predict radiated power levels and emission frequency
  - M = planetary mass
  - d = distance from host star
  - ω = rotation rate
  - R = planetary radius

$$P \sim 4 \times 10^{11}\ \mathrm{W}\ \omega^{0.79}\ M^{1.33}\ d^{-1.60}$$

$$\nu_c = 23.5\ \mathrm{MHz}\ \ \omega\ M^{1.66}\ R^{3}$$

III. HD 80606b

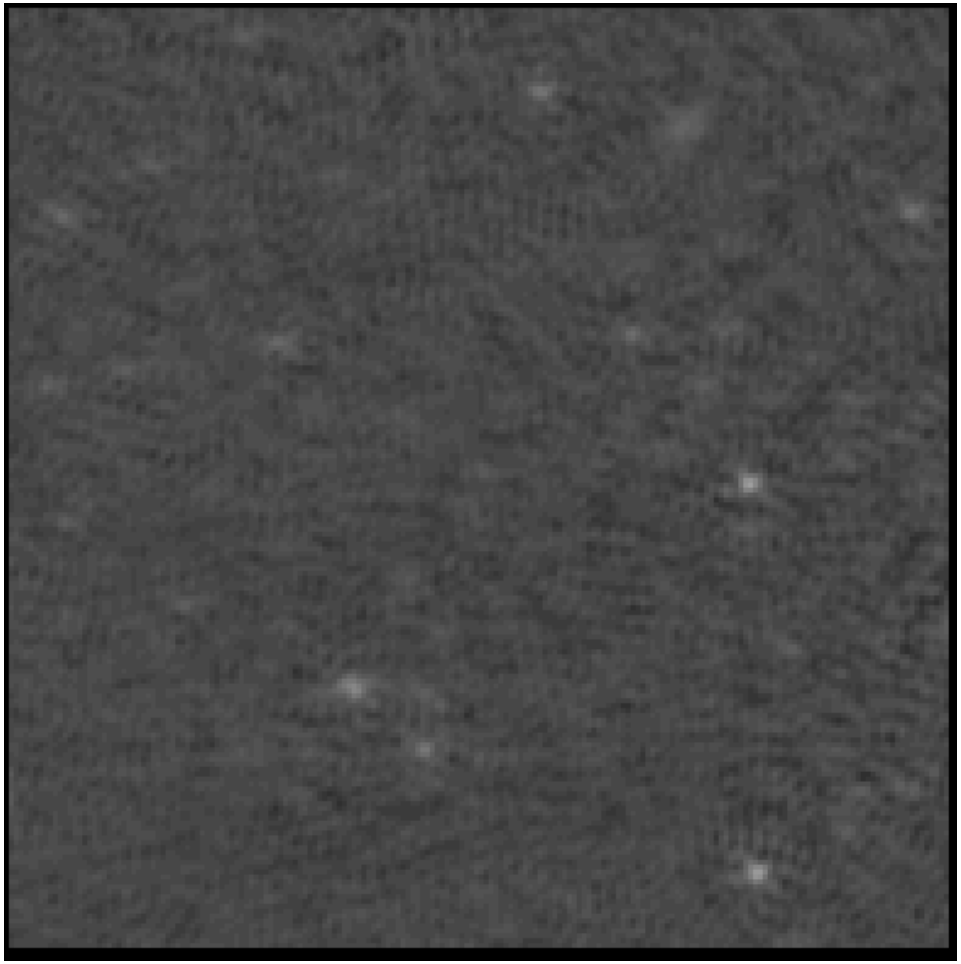


- **G5 star**
- **4 M_J planet, 111 day orbit, e = 0.93 (!)**
- **2007 November 20 periastron; observations at 90 cm (330 MHz) and 20 cm (1400 MHz)**

  Upper limits ~ 1 mJy (Lazio et al. 2010)
- **Rotation period ~ 40 hr**
  - **Pseudo-synchronous rotation**
  - **Not appreciated at time of observation**
  - **Rotation period ➔ magnetic field strength ➔ characteristic wavelength/frequency**

➢ **Future observations need to be below 90 MHz (> λ3m)**

III. HD 80606b



LOFAR, 2013 January 24; 63 MHz

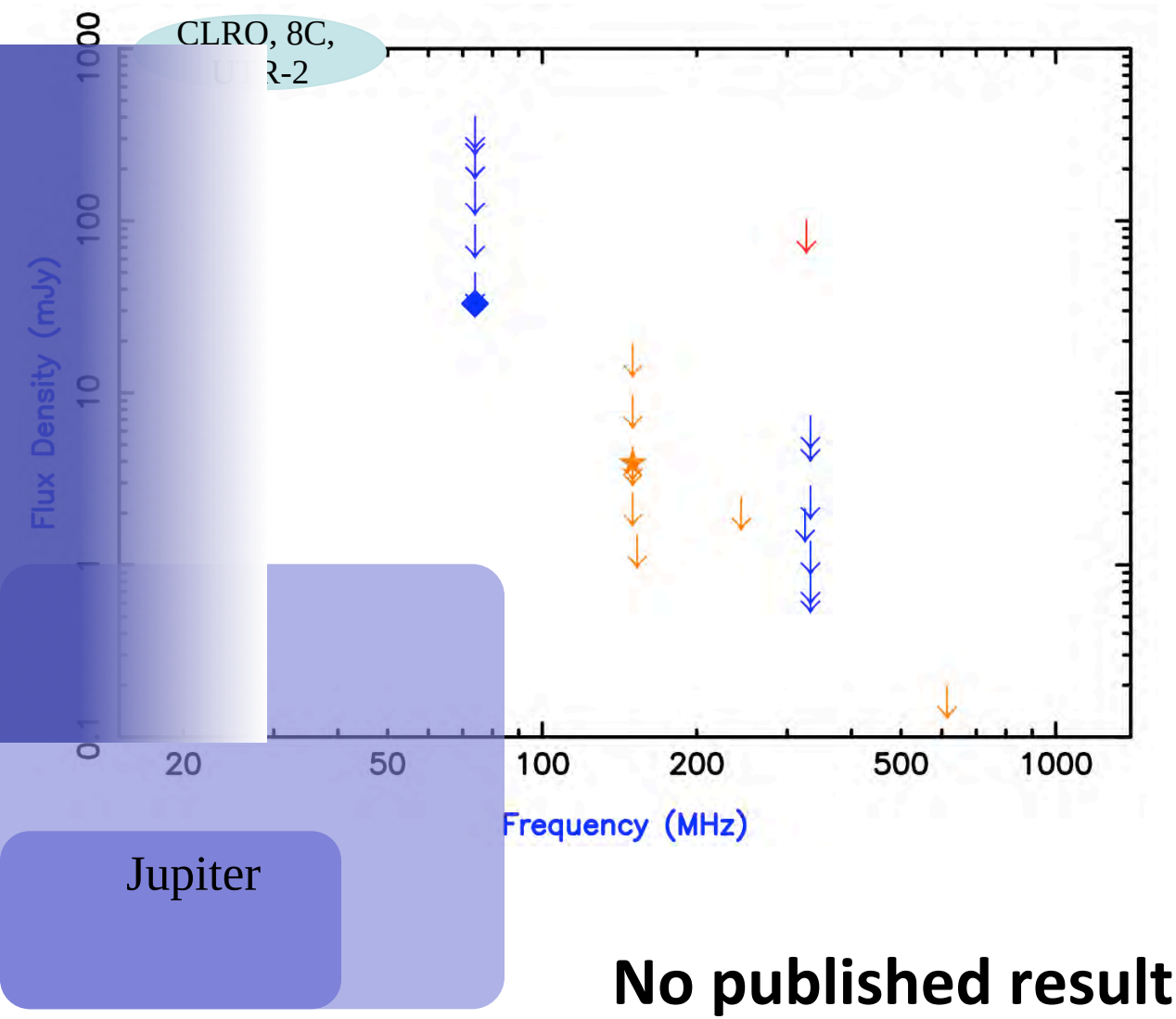
LOFAR observations

- **Periastron pass January 24--28**

  4 epochs, 2 on approach, 2 receding

- **31--75 MHz**

III. Extrasolar Planetary Radio Emission



- **VLA**

- **GMRT**

- **GBT**

No published results from LWA, LOFAR, MWA

Radio Transients

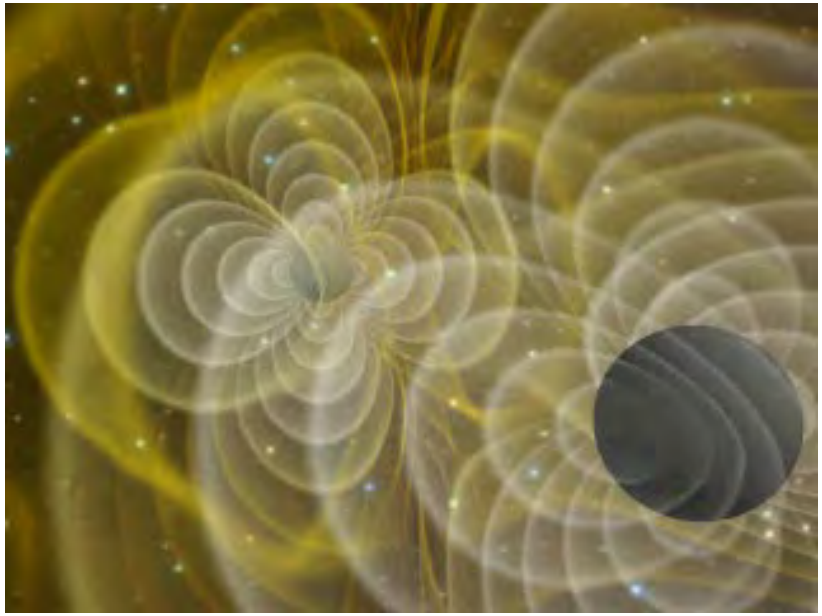
Class	Object	Timescale	Δt_{opt}
Extragalactic incoherent	SNe, GRBs, TDEs	Tens of minutes-years	Lags by minutes-months
	AGN	Tens of minutes-years	Lags by days-months
	GW counterparts?	Minutes to years?	Lags?
Extragalactic coherent	Fast ra		own
	GW co		own
Galactic coherent	Maser interst		
	Neutro		taneous, if present
	Sub-st		own
Galactic incoherent	X-ray binaries, novae, stellar flares	Minutes-hours	Lags by minutes
Unknown	"Hyman bursters"	Minutes	unknown
Propagation effects	Affects pulsars, extragalactic sources	Minutes-days (pulsars) Years (AGN)	N/A

- **Is all of it worth exploring?**
  - I. Cosmic accelerators
  - II. Intergalactic bursts
  - III. Extrasolar planets
  - IV. **Gravitational wave events**

IV. GW Astronomy and the Time Domain

$$L_0 = 2.03 \times 10^5\, c^2\, M_\odot\, s^{-1}$$

- **Generation of GWs requires large masses, high velocities, or both**
- **Potential sources include**
  - ✧ **Mergers**
    - **NS-NS, NS-BH, BH-BH**
  - ✧ **Supernovae (asymmetric)**
  - ✧ **Rapidly rotating asymmetric neutron stars**
  - ✧ **Cosmic strings**
  - ✧ **…**



IV. Gravitational Wave Events

Why electromagnetic?

More complete under-standing of GW candidate

- **Nature of progenitor**
- **Environment**
- **…**
- **Confirmation**

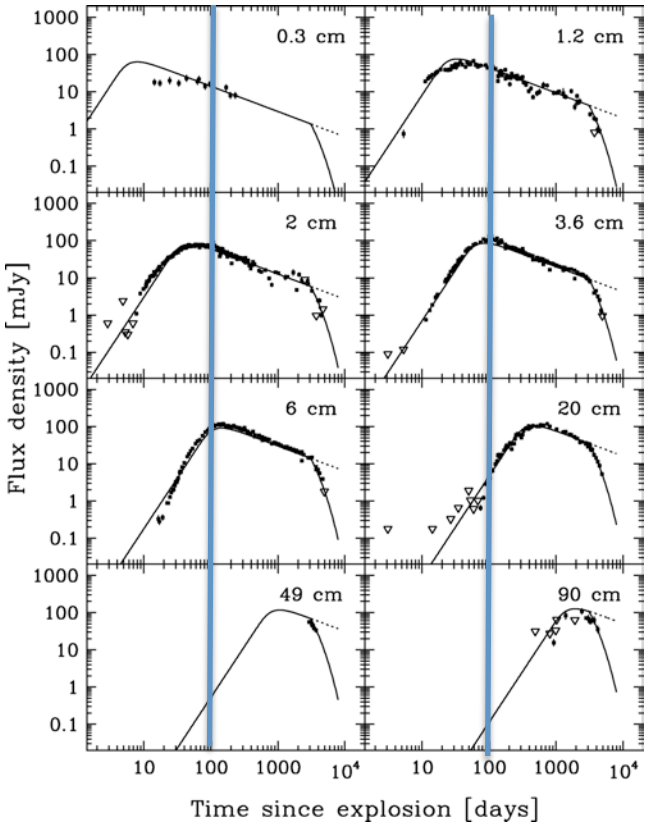
Why radio wavelengths?

- **Non-thermal (high-energy) particle emission**
- **Precision astrometry**
- **Unaffected by dust obscuration**
- **Observe during daytime**
- **Time delays due to propagation through interstellar & intergalactic media**

  $\tau \propto \lambda^2$, "leisurely" slews based on trigger

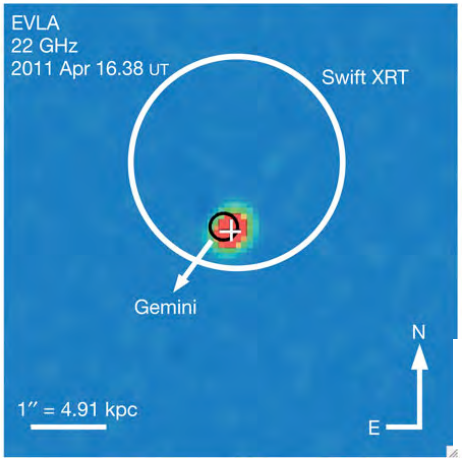
IV. "Slow" Radio Transients

- **Explosive Events**
  - **E.g., expanding synchrotron fireball, radio emission from blast wave impacting surrounding medium and accelerating particles**
    - ✦ **Radio supernovae, gamma-ray bursts, …**
    - ✦ **"Clean" environments likely to be faint? (BH-BH merger?)**



(Radio supernovae, Weiler et al.)

- **Relativistic Jets**
  - **Magnetically collimated relativistic plasma**
    - **X-ray binaries, AGN, tidal disruption events**

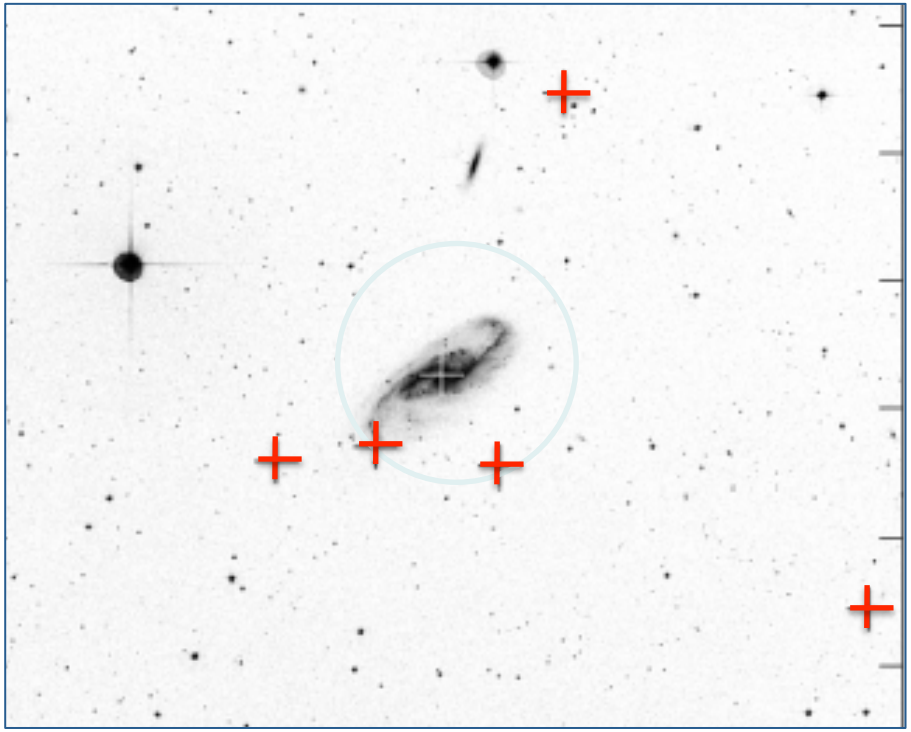


(Jet from tidally disrupted star, Zauderer et al.)

IV. EVLA Followup of LIGO-Virgo Candidates

- **Observations during 2010Q3**
- **~ 4" angular resolution, ~ 0.4" localization for s-to-n ratio = 5**
  - **EVLA C configuration**
  - **5 GHz / λ 6cm**
- **2 LIGO-Virgo triggers observed**
  - **6 galaxies**

    later trimmed to 5 as one target galaxy found to be more distant than 40 Mpc
  - **Observations covered under MoU between LIGO-Virgo Collaboration and EVLA team**



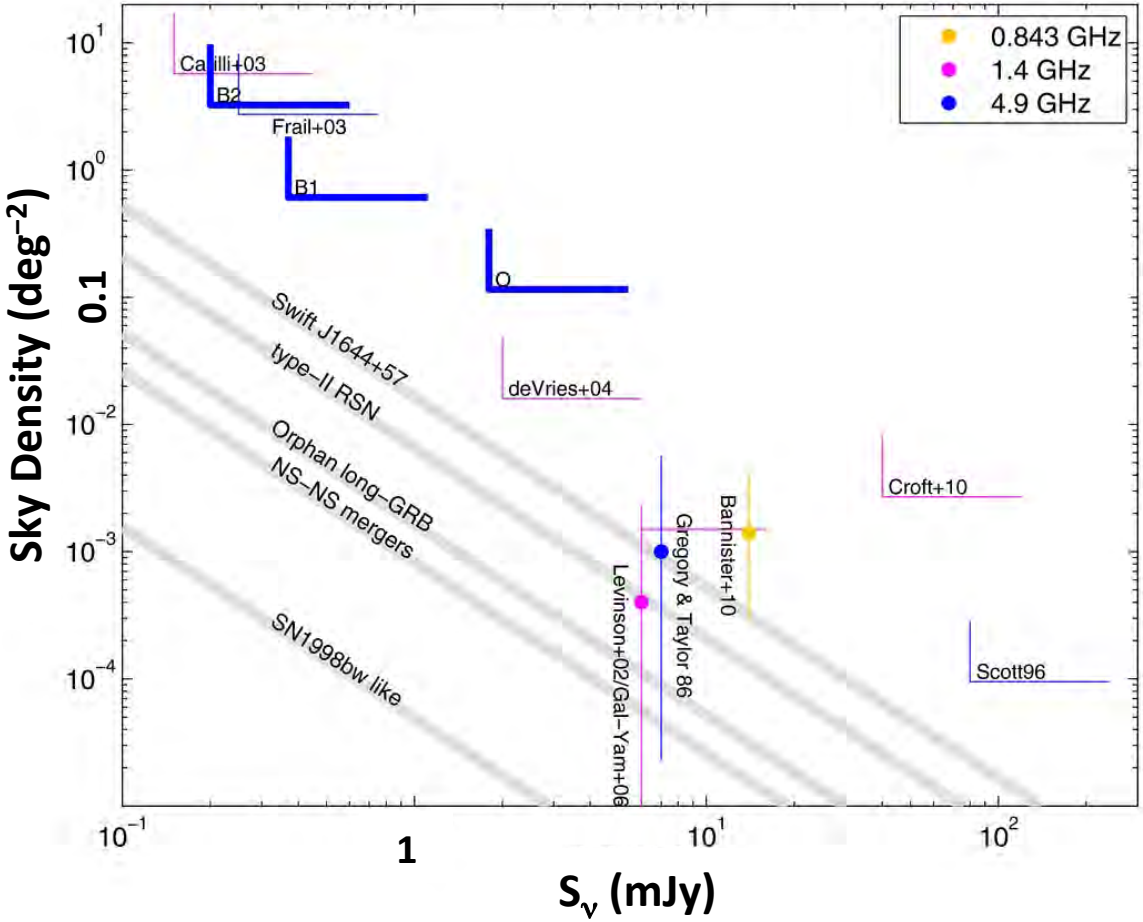
EVLA FoV, detected sources on DSS image

Lazio et al.; Keating et al.

IV. "Slow" Radio Transient Sky

- **Radio sky appears to be quiet**
  - **… at least at centimeter wavelengths**
  - **… at least at current sensitivities**
- **Refractive effects?**
- **New populations?**

  Would need to avoid shorter wavelength emissions?



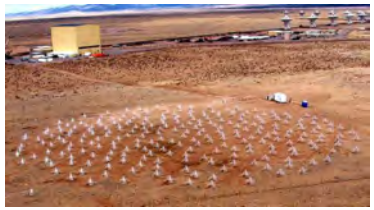
(Frail et al. 2012)

Radio Astronomy Landscape

Jet Propulsion Laboratory
California Institute of Technology

Meter and decameter wavelengths

Coherent emitters



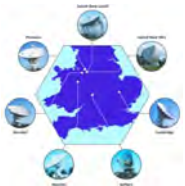
Single dishes:
Decimeter and centimeter wavelengths

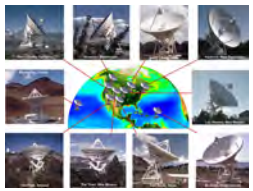
Coherent, some incoherent emitters

Interferometers:
Decimeter and centimeter wavelengths

Coherent or incoherent emitters

ν <~ 50 GHz

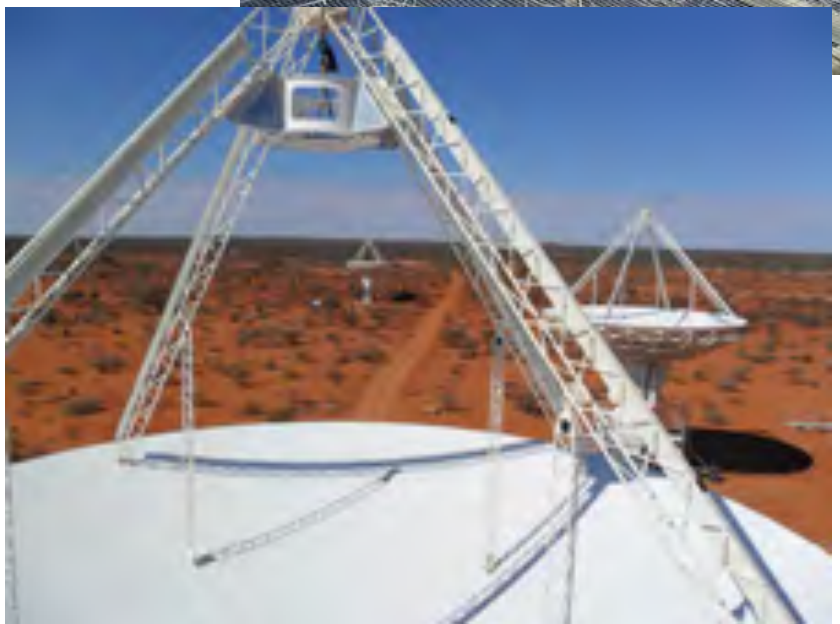




SKA Precursors

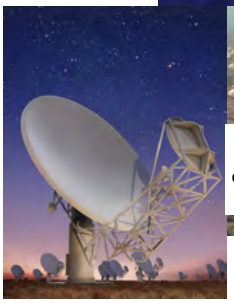
MWA (Australia) 128 × 16 dipole tiles

MeerKAT (South Africa) 64 x 13.5 m dishes



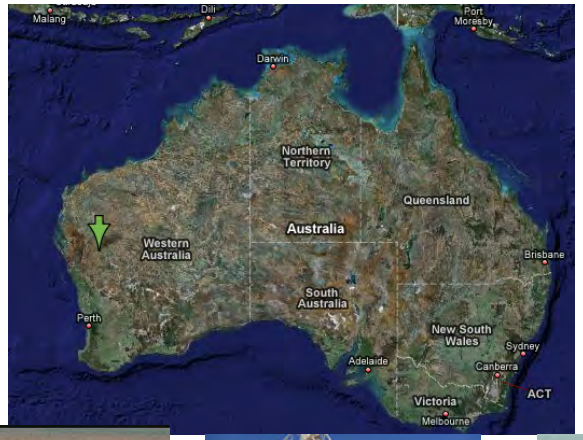
ASKAP (Australia) 36 × 12 m dishes

SKA1 Dual Site Implementation



+

SKA1_Mid



SKA1_Low

+

SKA1_AIP_Survey

	SKA Element	Location	Comment
Dish Array	SKA1_Mid	RSA	190 SKA + 64 MeerKAT
Low Frequency Aperture Array	SKA1_Low	ANZ	50 stations
Survey Instrument	SKA1_AIP_Survey	ANZ	60 SKA + 36 ASKAP

SKA2 Dual Site Implementation

SKA2_Mid_Dish

SKA2_AIP_AA

SKA2_Low

	SKA Element	Location	Comment
Low Frequency Aperture Array	SKA2_Low	ANZ	250 stations
Mid Frequency Dish Array	SKA2_Mid_Dish	RSA+	3000 dishes
Mid Frequency Aperture Array	SKA2_Mid_AA	RSA	250 stations

Optimized Transient Programs

SKA_Low and LOFAR, LWA, VLA-low, GMRT?

- extrasolar planets
  - Particularly if extended down to 50 MHz
- GW events?
- Giant pulses?

SKA_Mid and VLA, MeerKAT

- GW events
- Lunar neutrinos
- Giant pulses

SKA1_Survey and ASKAP, WSRT/APERTIF, VLA?

- GW events?
- Lunar neutrinos?
  - Wide field of view probably overkill
- Giant pulses?
  - Can the entire field of view be processed?

The Radio Transient Sky Summary

- **Radio transient sky has been rich source of discovery**
- **Still significant unknowns associated with many source classes**

"Fast" radio transients (coherent emitters)

May require followup at shorter wavelengths, considerable discovery space?

"Slow" radio transients (incoherent emitters)

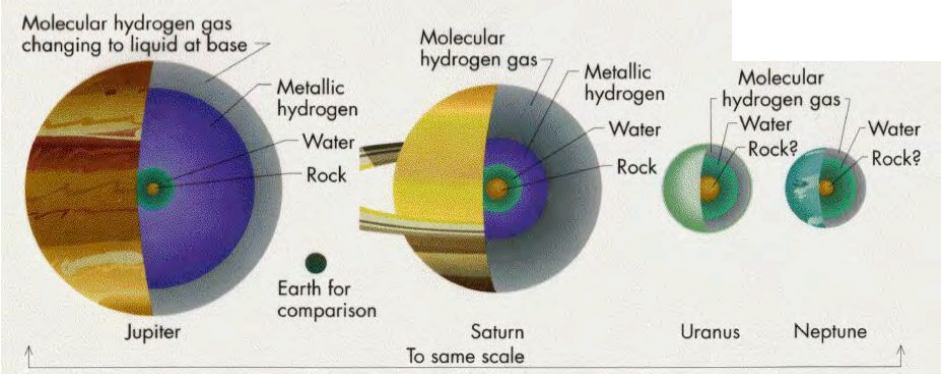
Likely to be important part of followup for transients detected at shorter wavelengths

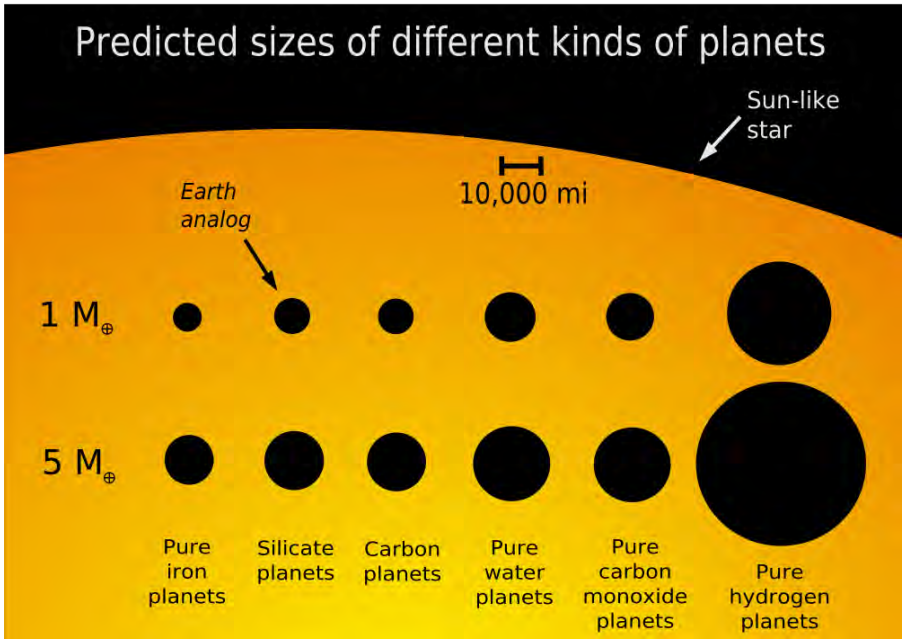
- **Significant new infrastructure becoming available!**

  … but with caveats

BACKUP

(Extrasolar) Planetary Interiors





- **Magnetic field from conducting fluid in interior**
  - **Earth: liquid Fe core**
  - **Jupiter: metallic H_2**
  - **Saturn: metallic H_2**
  - **Uranus: salty H_2O (brine)**
  - **Neptune: salty H_2O (brine)**
- **Extrasolar planetary interiors?**
  - **Fe rich**
  - **Si rich (like Earth)**
  - **C rich**
  - **O (H_2O) rich**
  - **CO rich**
  - **H rich**