Extra-solar Transients

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S. Corbel, J. Hessels, et al.

most slides stolen from P. Zarka, S. Corbel and J. Hessels

***AIM/IRFU/SAp/CEA-Saclay**

a) **Extrasolar systems**

b) **Other transients**

Transients radio sky

- A glimpse of **physics in extreme environments.**
- Time domain astronomy: a huge discovery potential, recognized in all recent prospective reports. Testing relativity. Cosmic lighthouses for probing the IGM.
- Example of unexpected transients: Discovery of pulsar by J. Bell (Nobel for Hewish), SN1a, GRB, ...
- Even now, **new type of transients are still discovered nowadays**: TDEs and FRBs
- A huge variety of transients on very different timescales: X-ray binaries, pulsars, black holes at cosmological distance, atmospheric **γ**-ray flashes, **exoplanets**, EM signature of GW, the unknown, …

Transients radio sky

Two flavours of transients

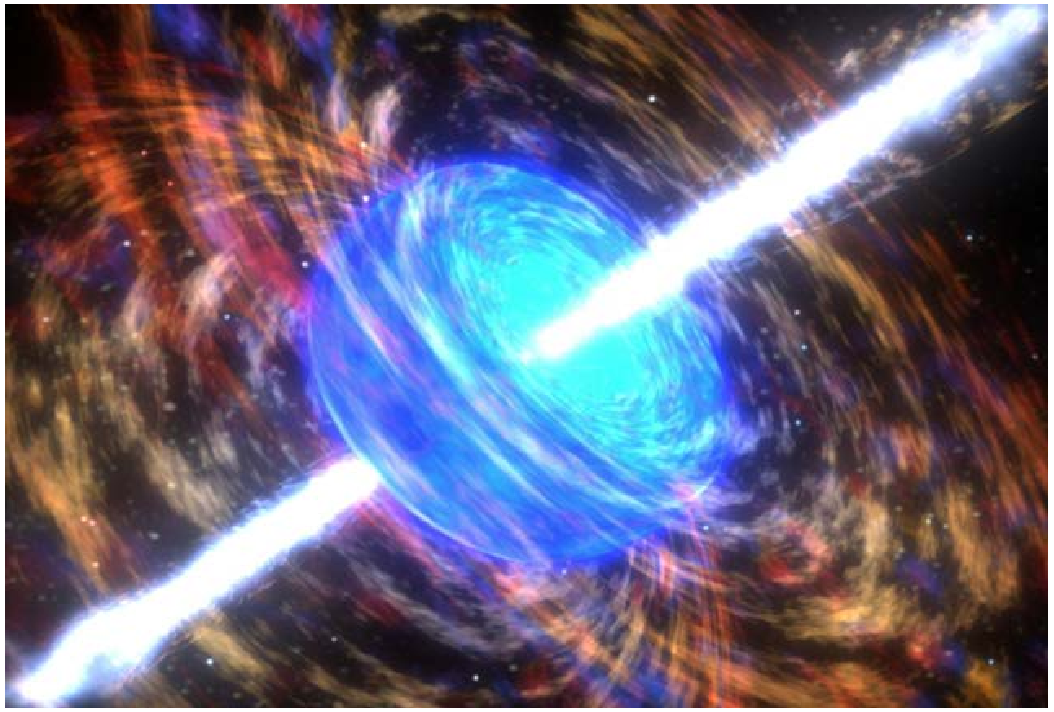
Incoherent synchrotron emission

- Relatively slow variability
- Brightness temperature limited (10^{12} K)
- Associated with all explosive events
- Strong potential for MW astronomy

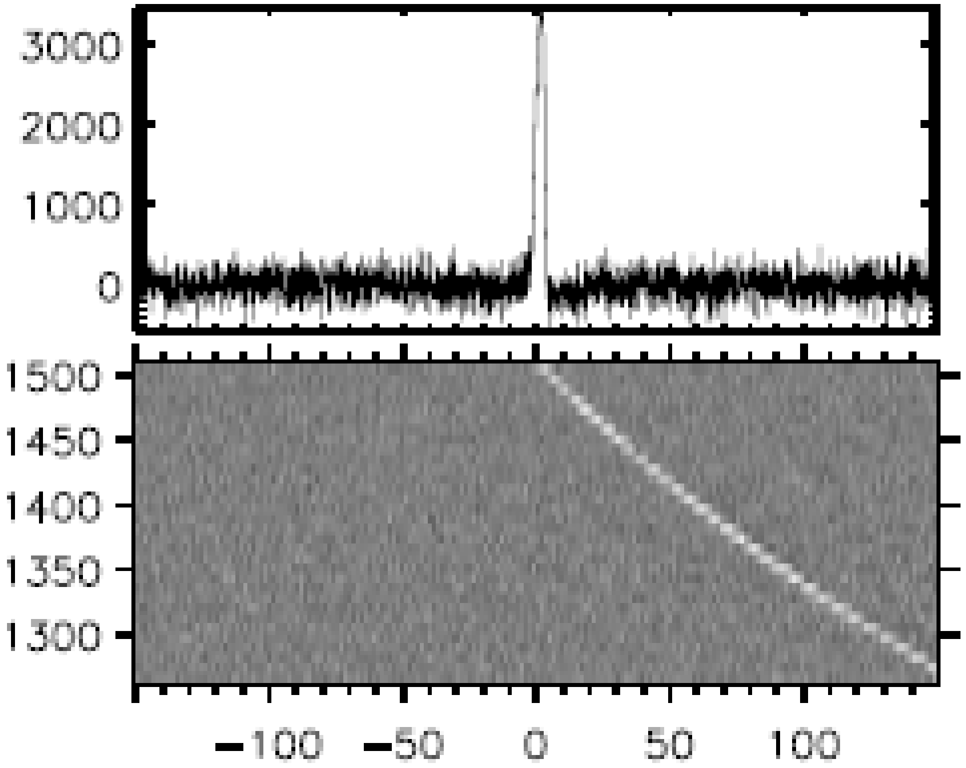
Coherent emission

- Relatively fast variability
- High brightness temperature
- Often highly polarised

Usually associated with pulsars ?

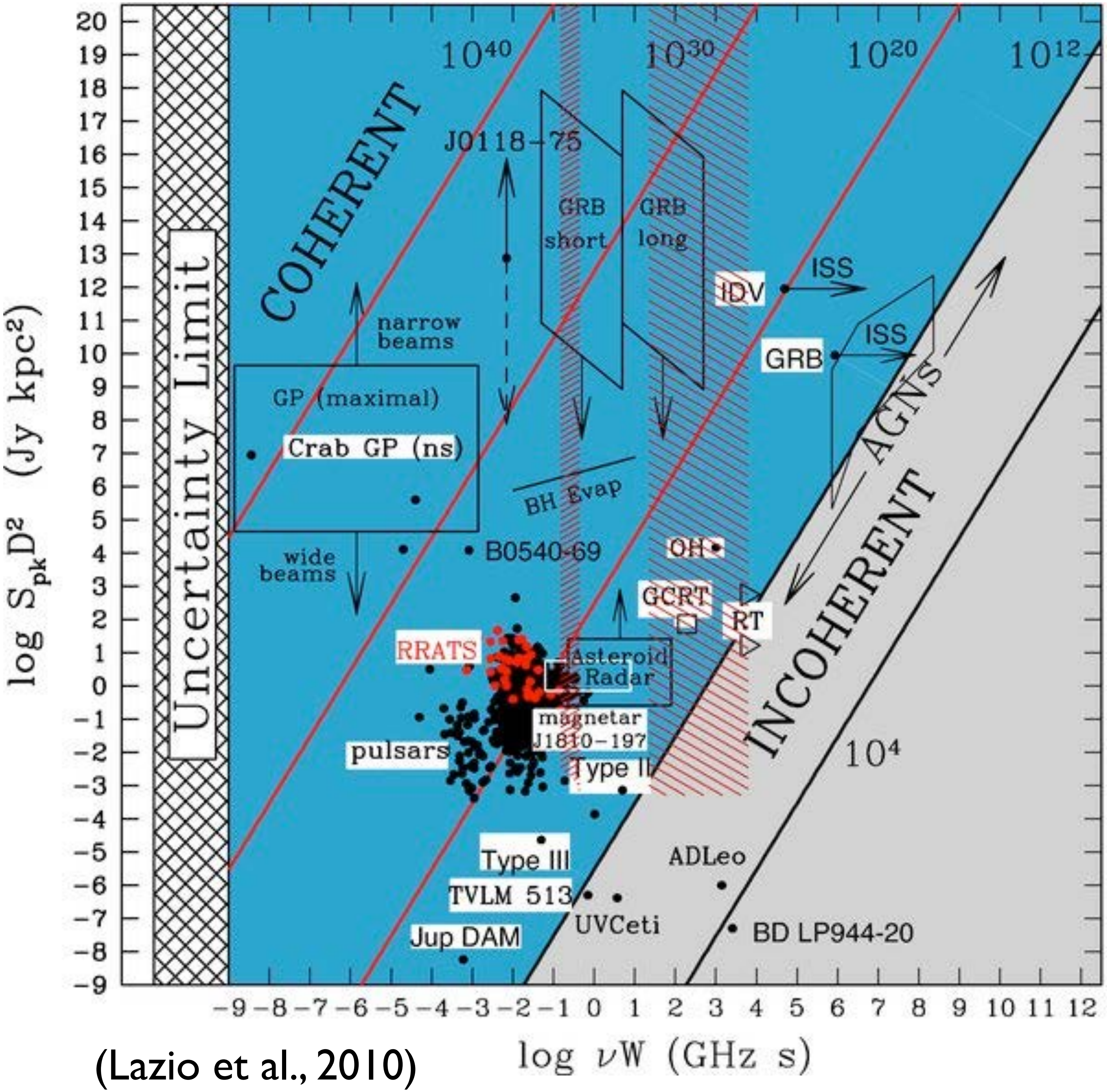


Detection: images



Detection: time series

Transients radio sky

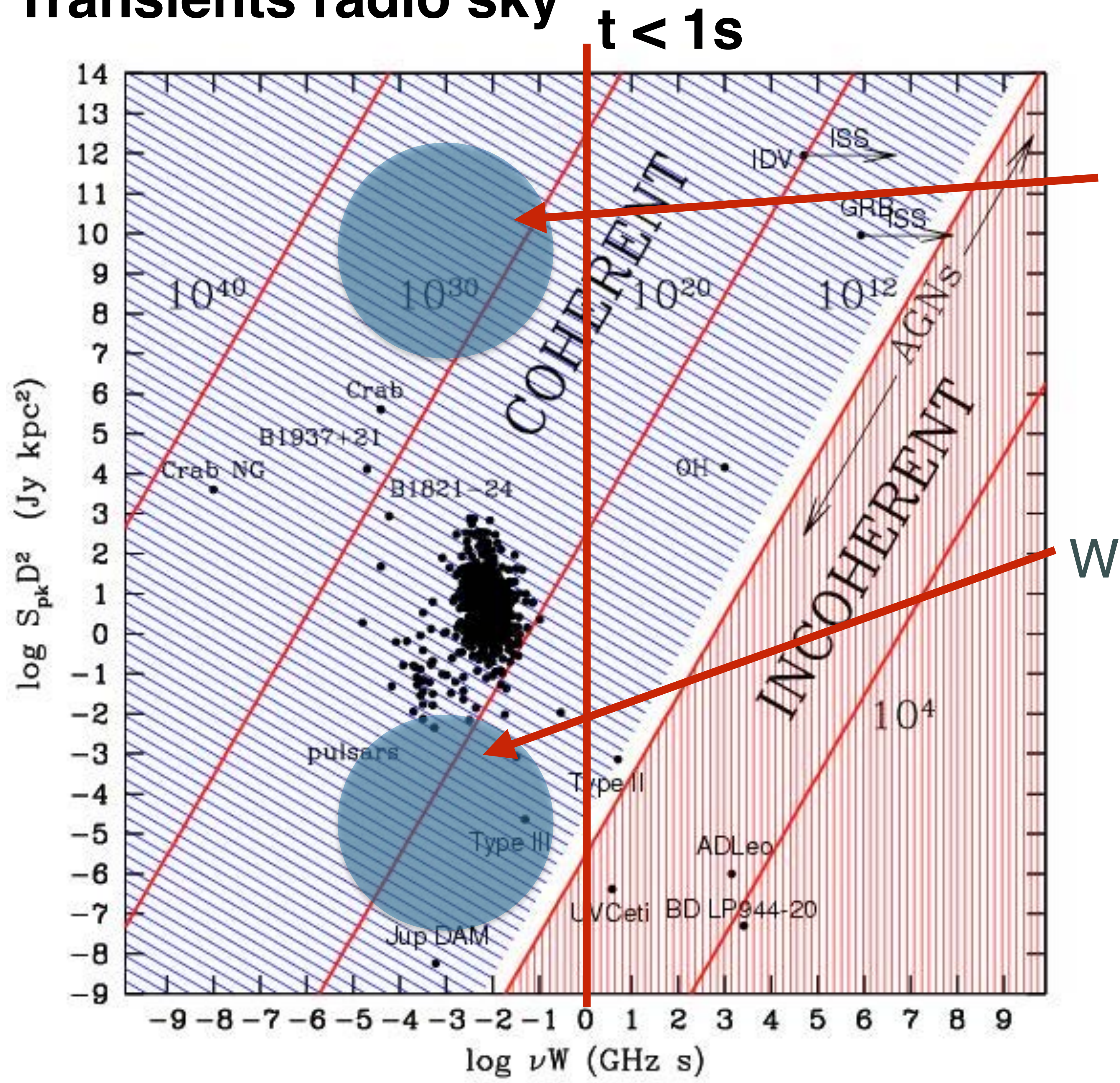


(Lazio et al., 2010)

Parameter space

Parameter space largely empty and unexplored !!!

Transients radio sky



Rare and bright event needs **large FOV**

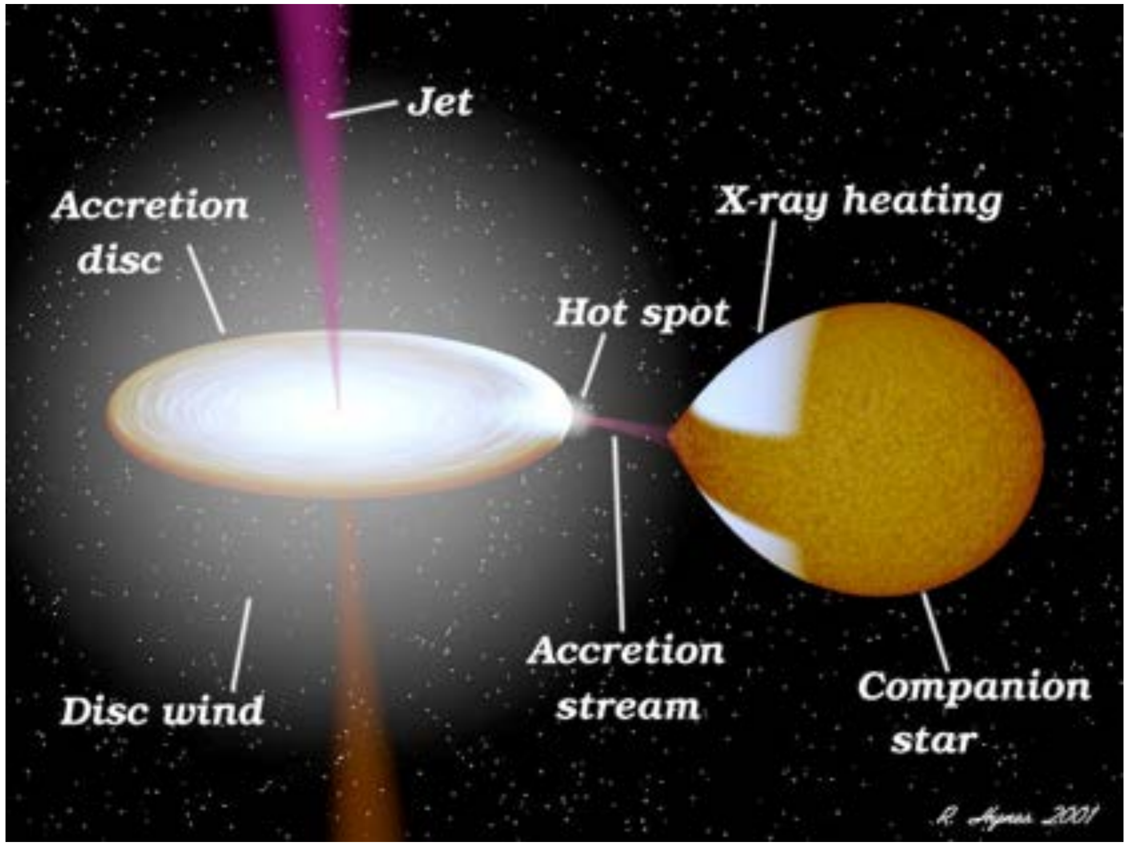
Weak transient event, needs **high sensitivity**

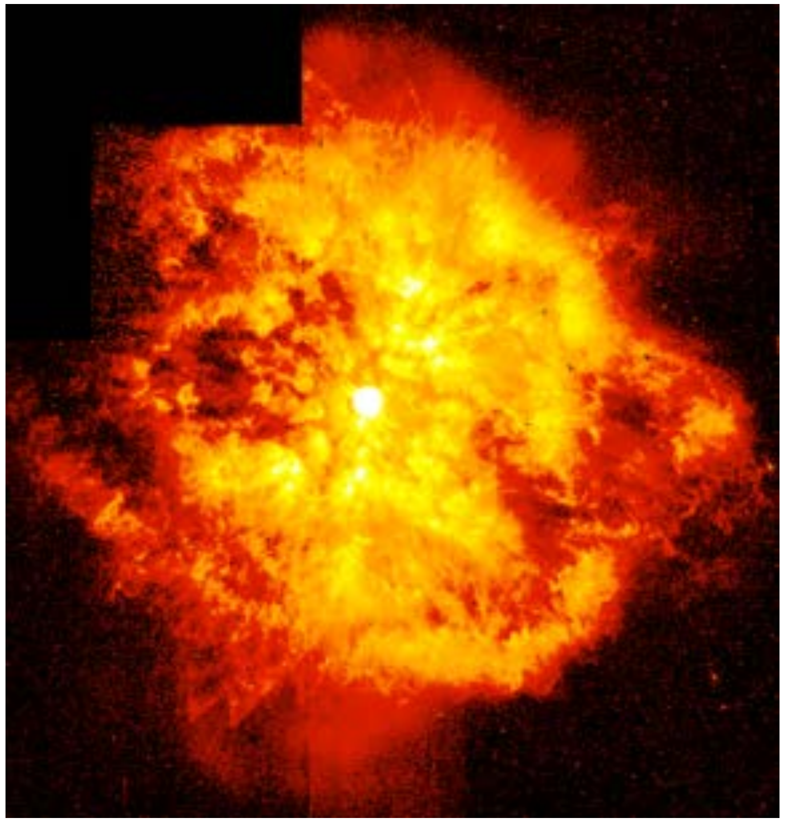
Cordes et al. 2004

Slow synchrotron transients

Primarily explosive events or outflows
Known source classes:

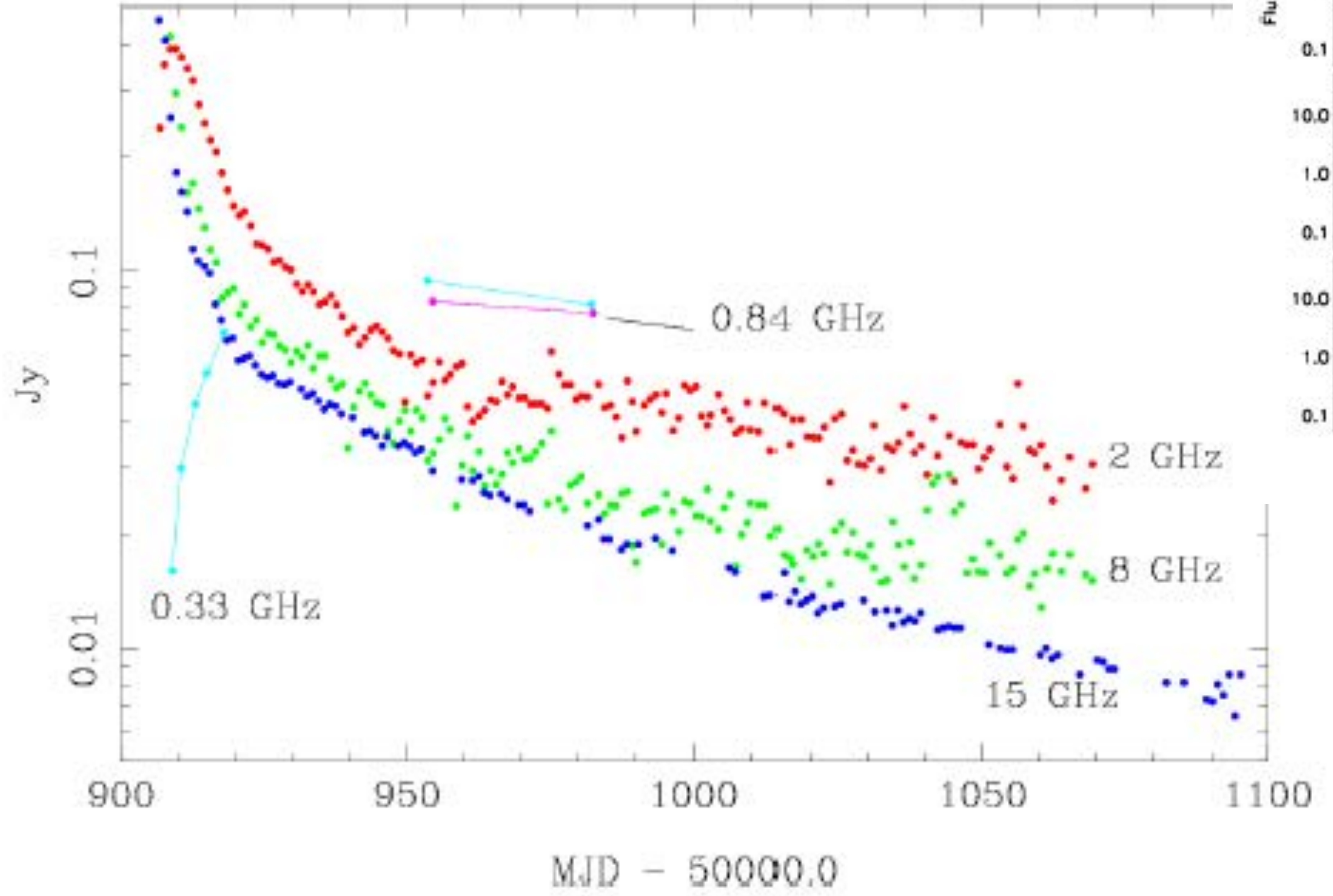
- Cataclysmic Variables (CVs)
- X-ray Binaries (XRBs)
- Magnetar outbursts
- Supernovae (SNe)
- Active Galactic Nuclei (AGN)
- Tidal disruption events (TDEs)
- Gamma-ray bursts (GRBs)
- Some novae (usually thermal)
- but do not forget the unknown !!

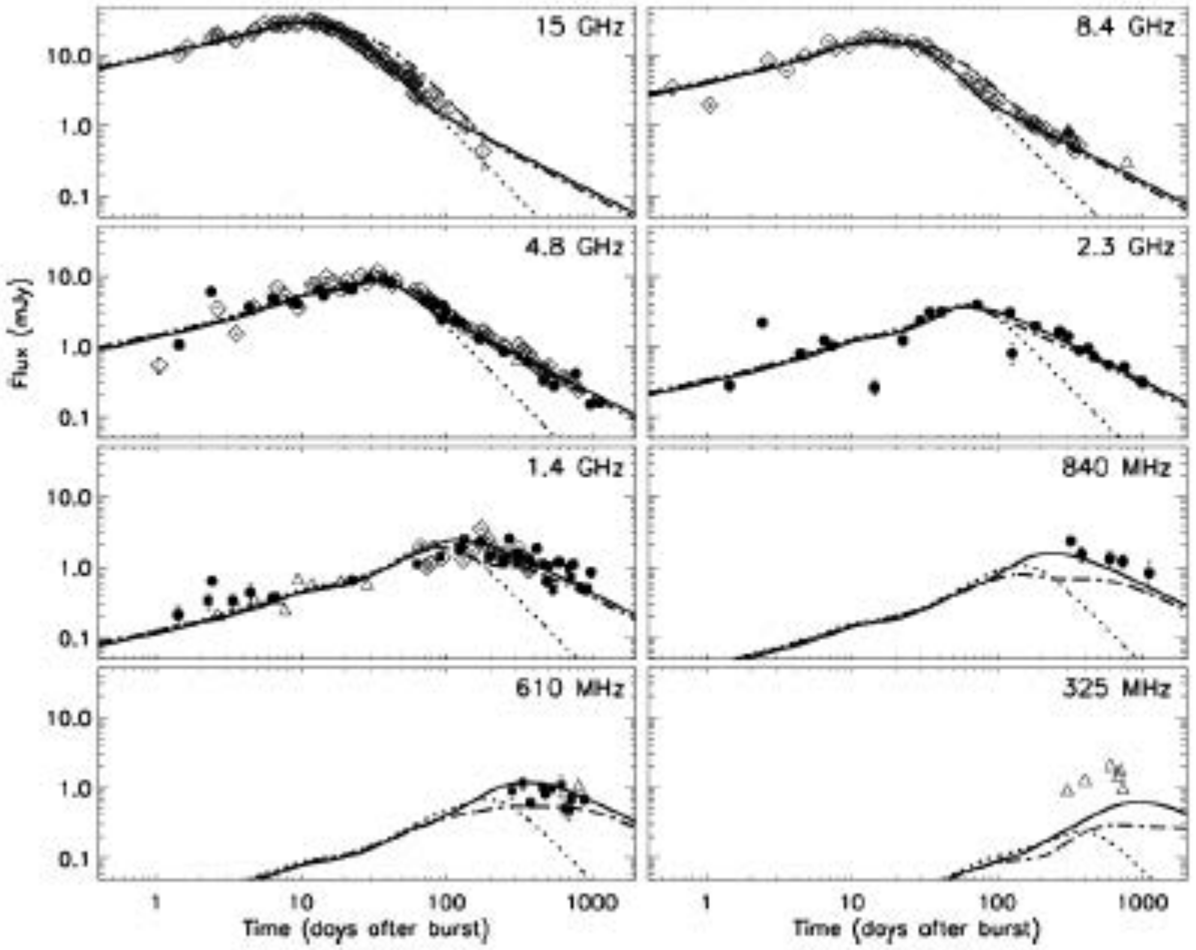




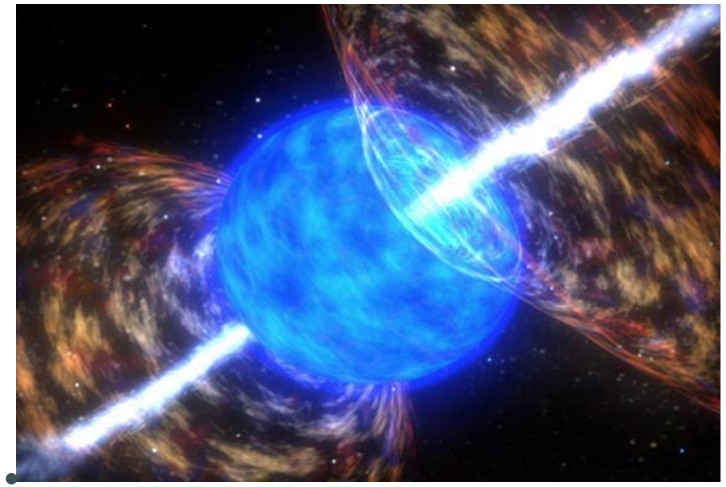
Typical evolution of a slow transient

- Important frequency evolution. Become optically thin later at lower frequencies (+lower flux also).

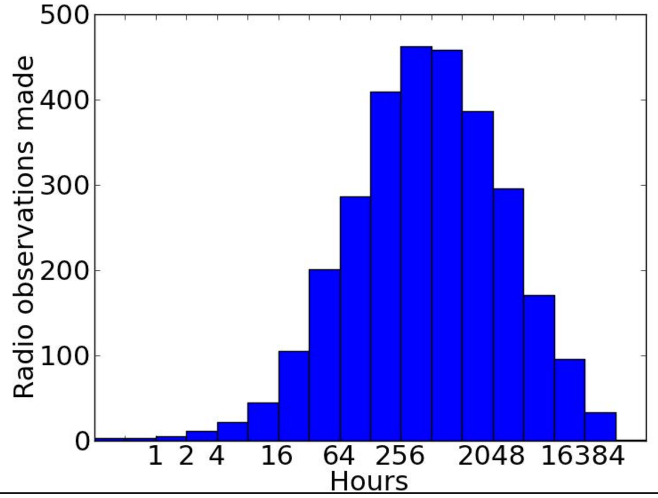




Gamma-ray bursts



- Probes of distant Universe (could be seen to z~25!)
- Estimated rate 10^{-6} year^{-1} galaxy^{-1}
- Radio emission generated by afterglows
- Prompt emission likely self-absorbed at low frequencies



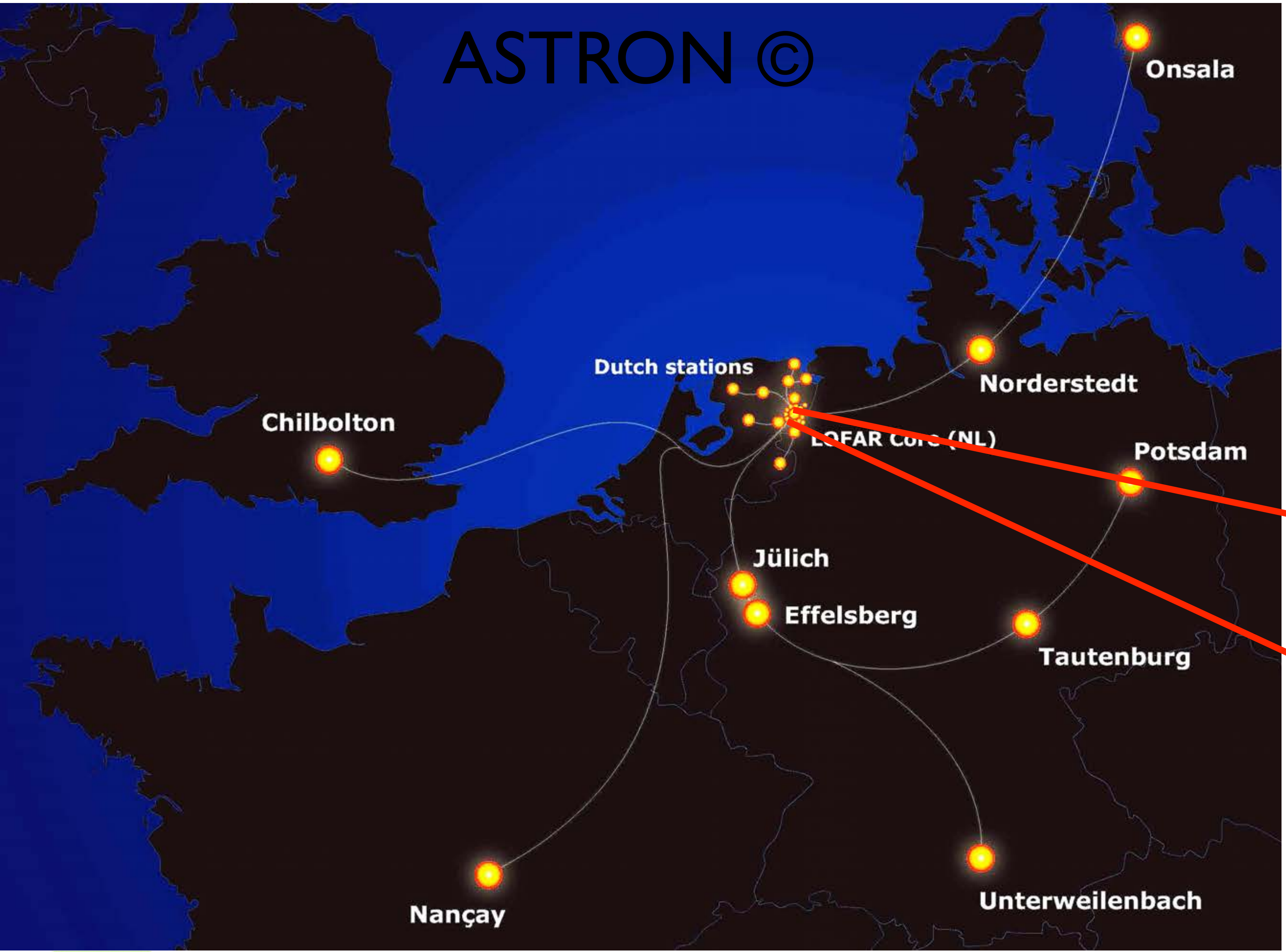
- Key questions:
  - Physical parameters
    - Kinetic energy of explosion
    - Density of circumburst medium
    - Outflow geometry
- Orphan afterglows
  - Beaming fraction and total GRB rate
- Radio loud vs radio quiet populations
  - 70% show radio emission, 30% do not

Tidal disruption events

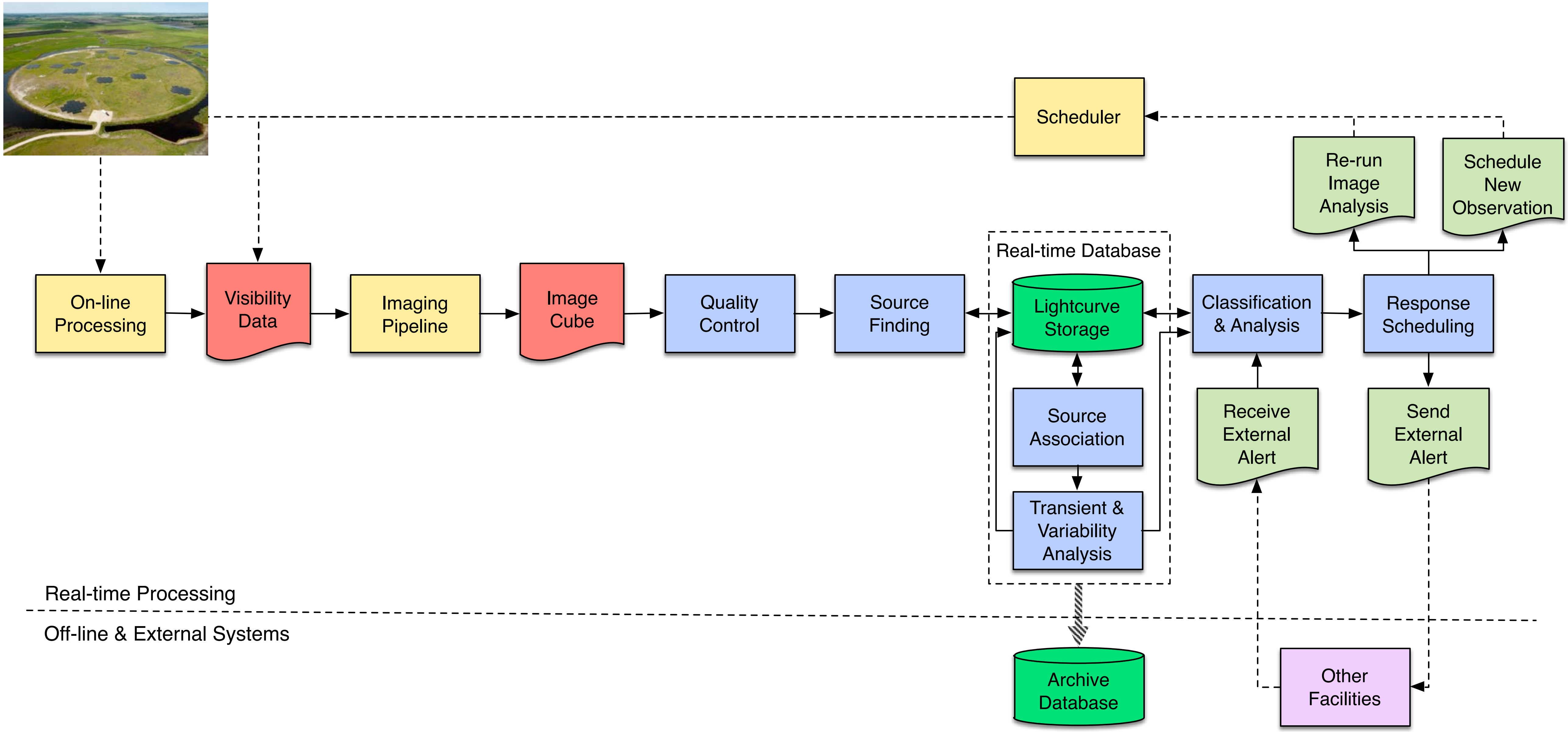
- Star passing too close to a massive black hole
- Estimated rate 10^{-5} year^{-1} galaxy^{-1}
- Probe of jet physics
  - Launching mechanism
  - Super-Eddington accretion rates
  - Dense environments (cf AGN jets)
  - Possibly the most frequent synchr. transients (Frail et al. 2012)

LOFAR: the LOw Frequency ARray

- **Giant digital & multi-purpose radio telescope** distributed across Europe
- **Radio interferometer** composed of ~**48 phased arrays** (stations)
- Working bands: **LBA** 30-80 MHz & **HBA** 120-240 MHz
- **Improved angular** (arcsec), **temporal** (μs), **spectral** (kHz) resolutions
- **High sensitivity** (~mJy) 1 Jy = 10^{-26} W.m^{-2}.Hz^{-1}



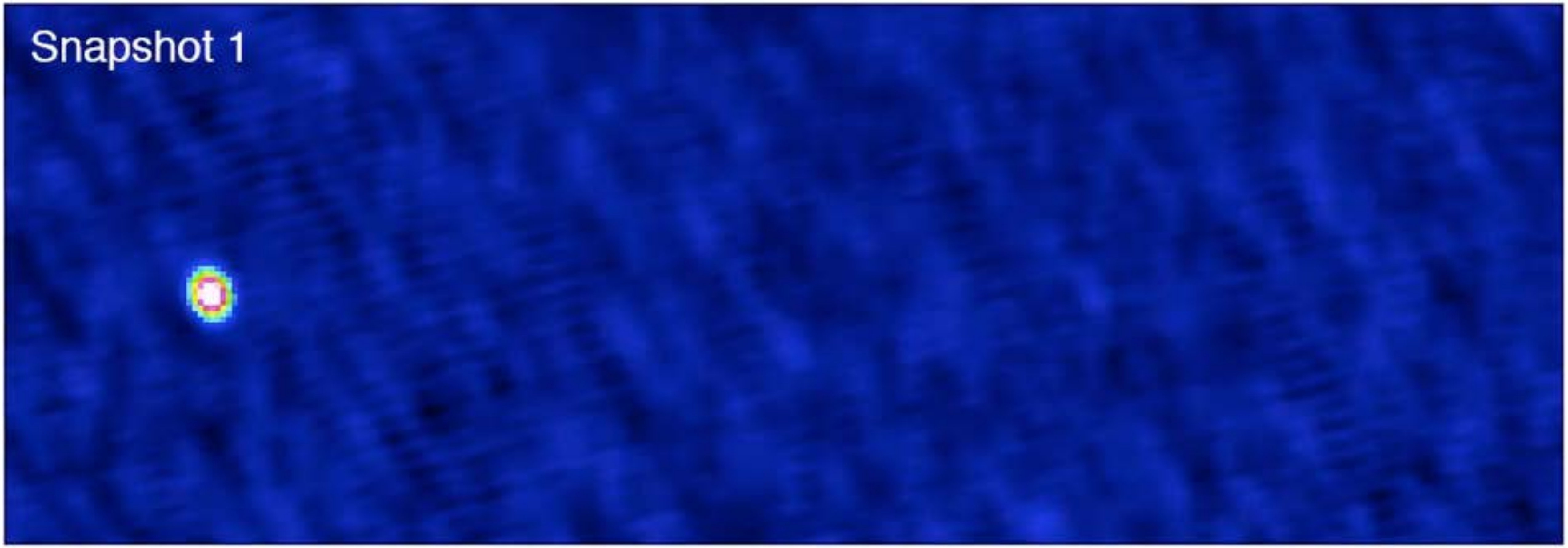
The LOFAR Transients Pipeline



[Swinbank et al., 2011; Scheers, PhD, 2011]

First LOFAR transients detection with MSSS

First MSSS(-LBA) transient candidate (Stewart et al, in prep)



- Appears in one 11-min snapshot, using 10 σ threshold of 4 Jy
- Implied rate for **Δ**t=11min is 1/2537 transients day^{-1} deg^{-2} (~1 transient per square degree per 7 years!)

Type of fast transients ?

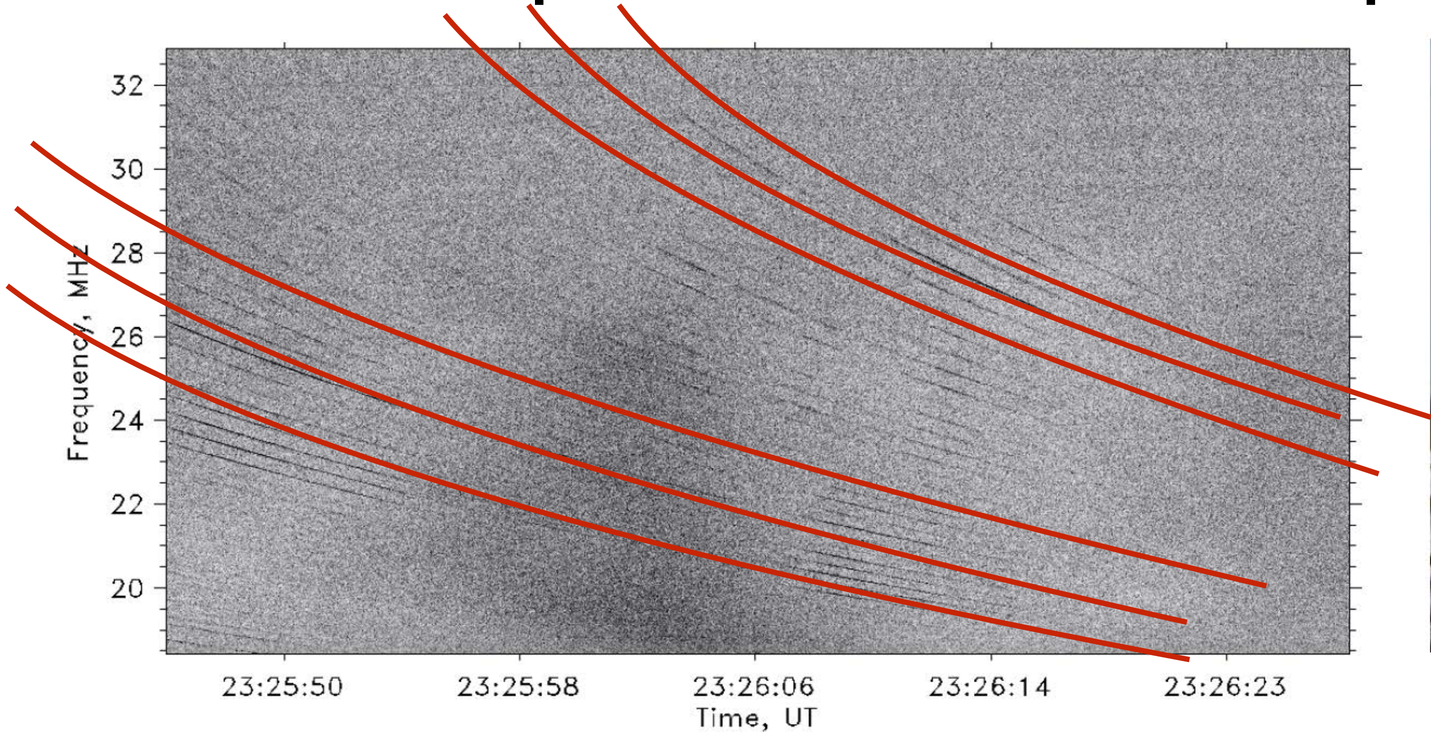
- **Pulsar** giants pulses, RRATs and magnetar
- SETI event
- Electromagnetic counterpart of GW event
- **Exoplanets**, flare stars, solar bursts
- Unknown event ?
- **Fast radio bursts (FRB)**: aka Lorimer type burst

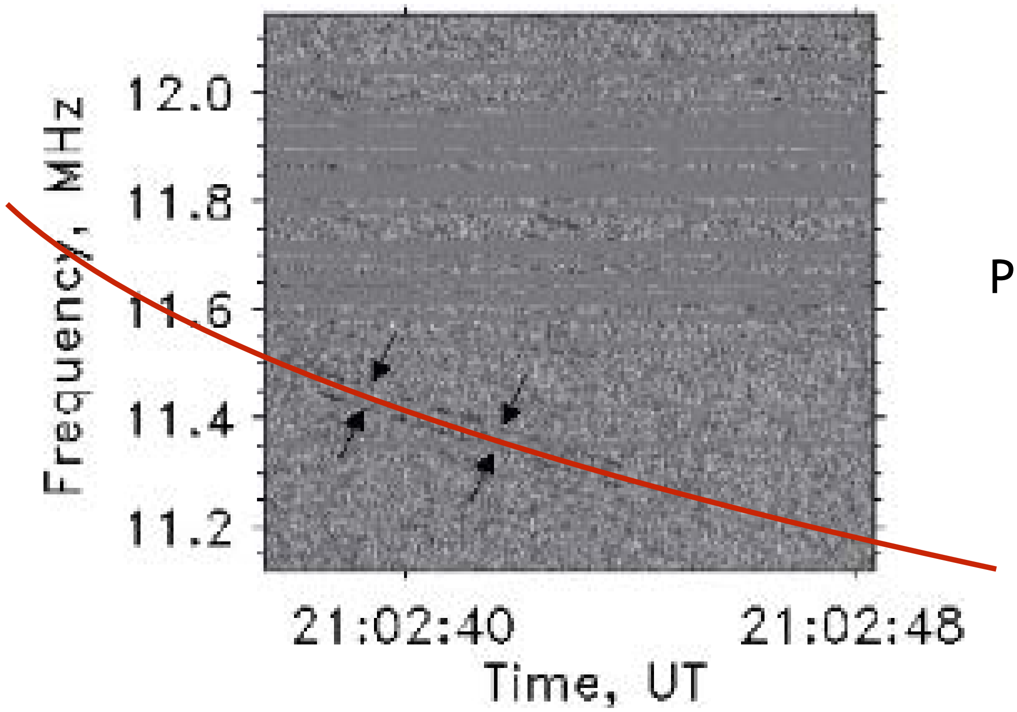
FRB = Good probe of the IGM (missing baryons problem)

FRB as a cosmic rulers (measure dark energy eq of state param. «w» at $z > 2$)

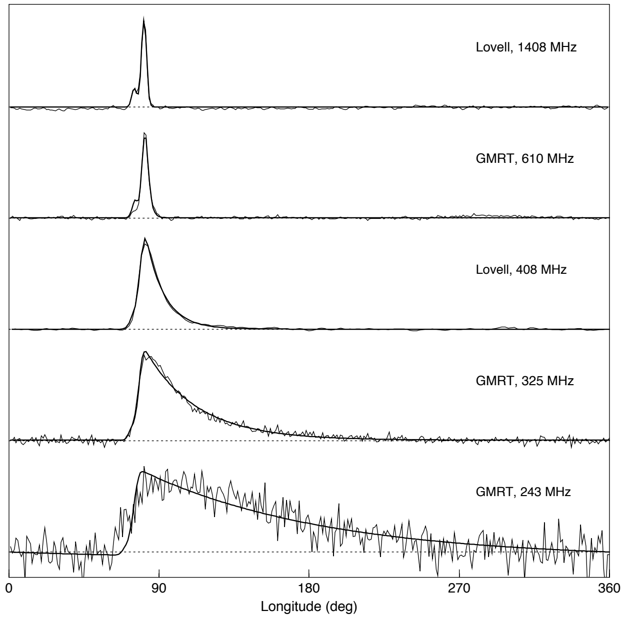
Study of Pulsars

- **LF cutoff of temporal broadening in $1/f^{4.4}$?**
  Study of turbulence ? Limit of transient observations ?
- **Detection of pulsars down to VLF with implication for Interstellar radio propagation**





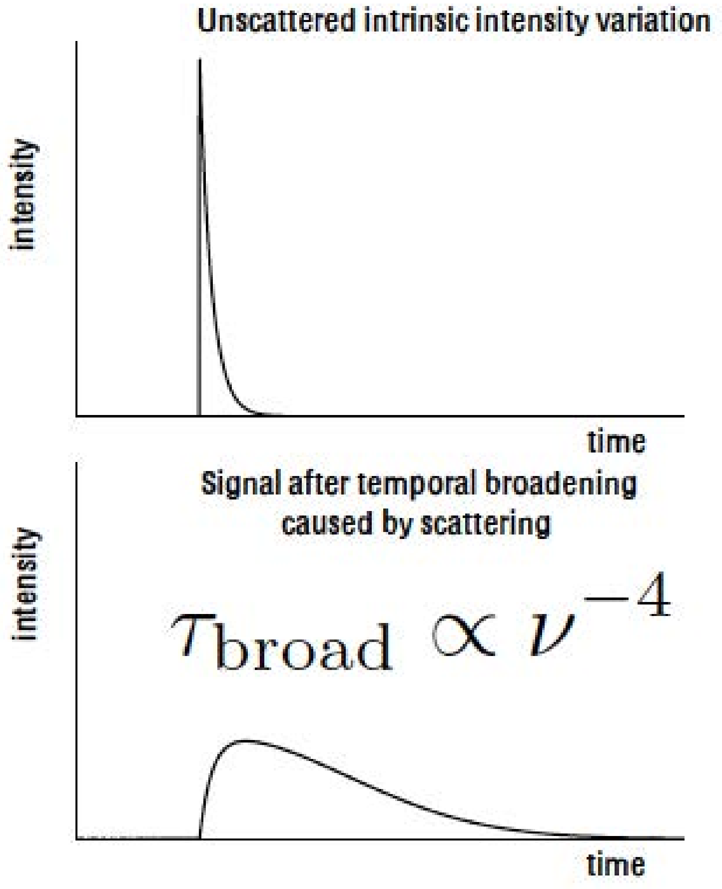
PSR0809+74 at Kharkov UTR2
(Ryabov et al., 2010)



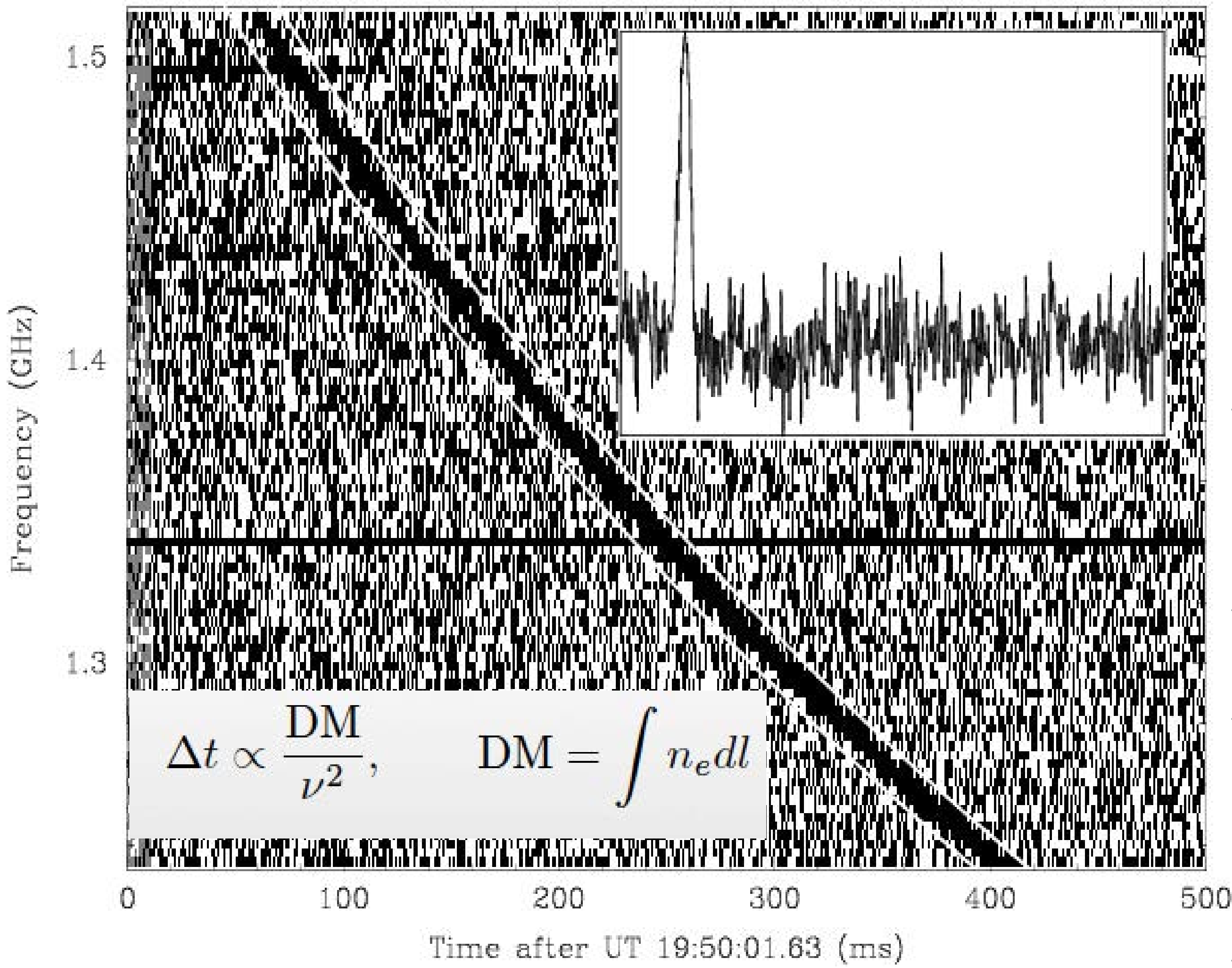
(Löhmer et al., 2004)

- Requires coherent integration over several days

The Lorimer burst



$$\tau_{\text{broad}} \propto \nu^{-4}$$

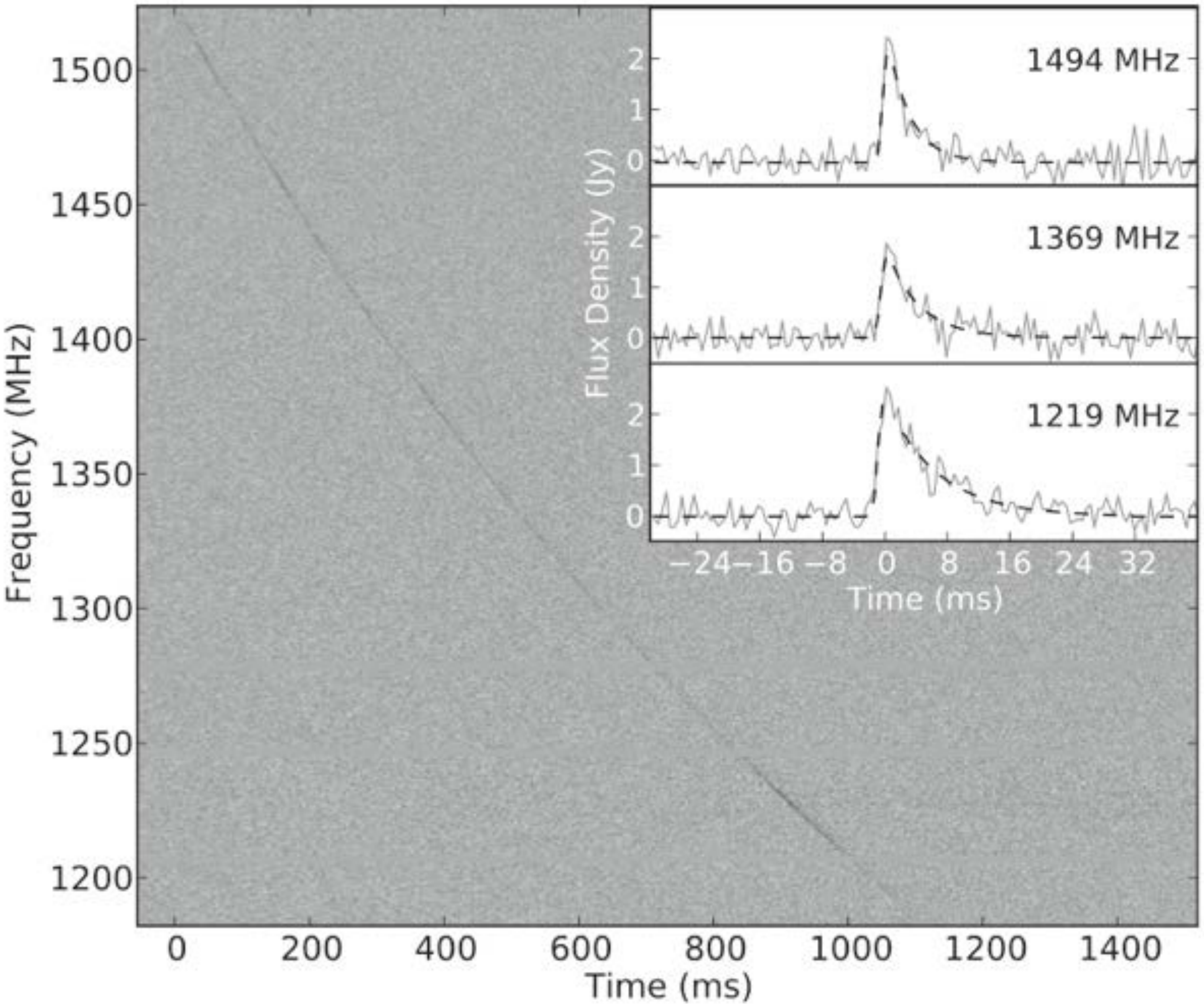


$$\Delta t \propto \frac{\mathrm{DM}}{\nu^2}, \qquad \mathrm{DM} = \int n_e dl$$

Lorimer et al. 2006

- A 30 Jy highly dispersed burst
- Duration ~ms
- High DM > Galactic ⇒ 1 Gpc
- No repetition

New FRBs



FRB 110220

DM = 944 pc cm^{-3}, z~0.8

Pulse width increases as **$\nu^{-4.0}$**, consistent with scattering in a turbulent plasma

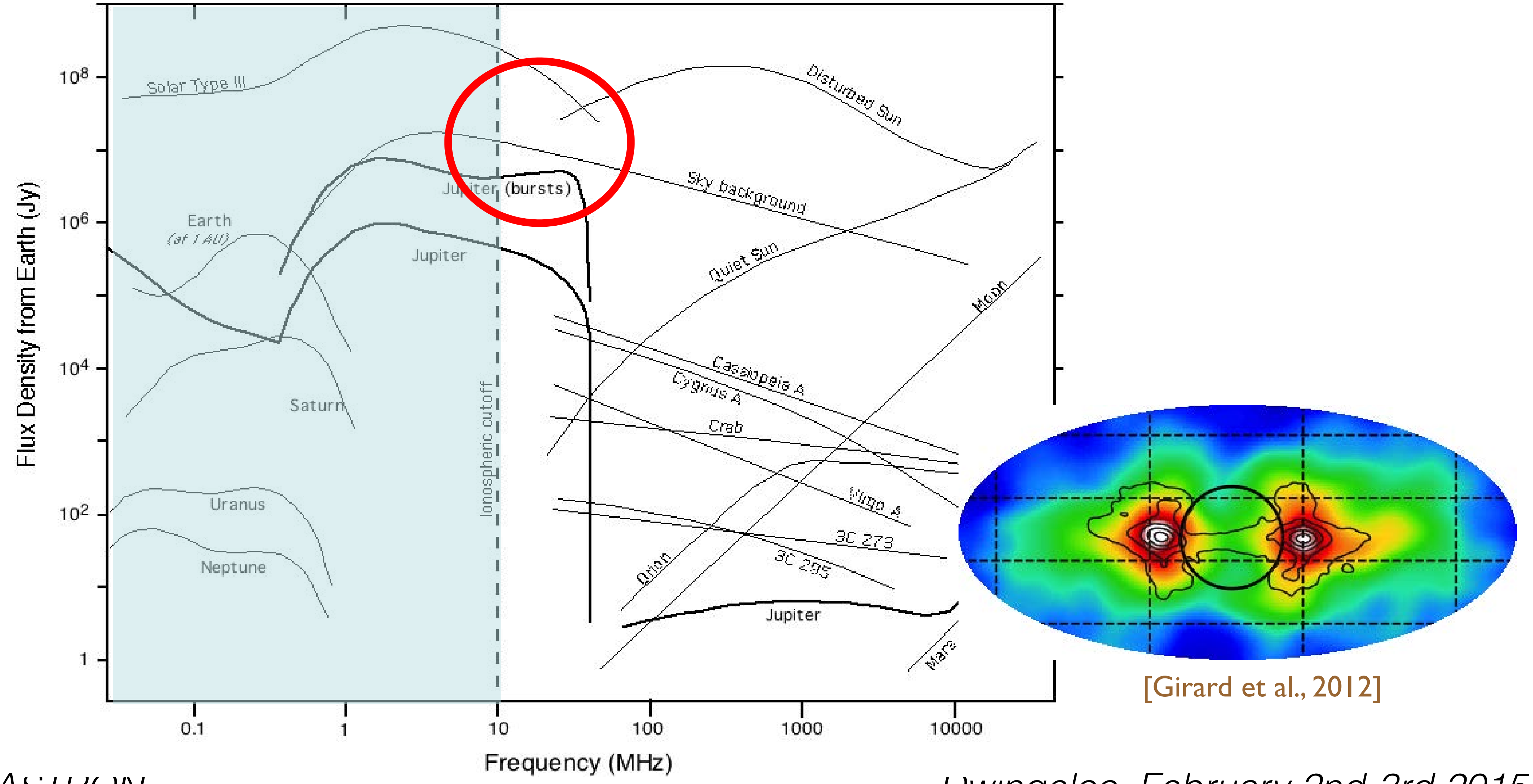
14 such events now

Rate : 10 000 / sky / day !!!

Thornton et al. 2013

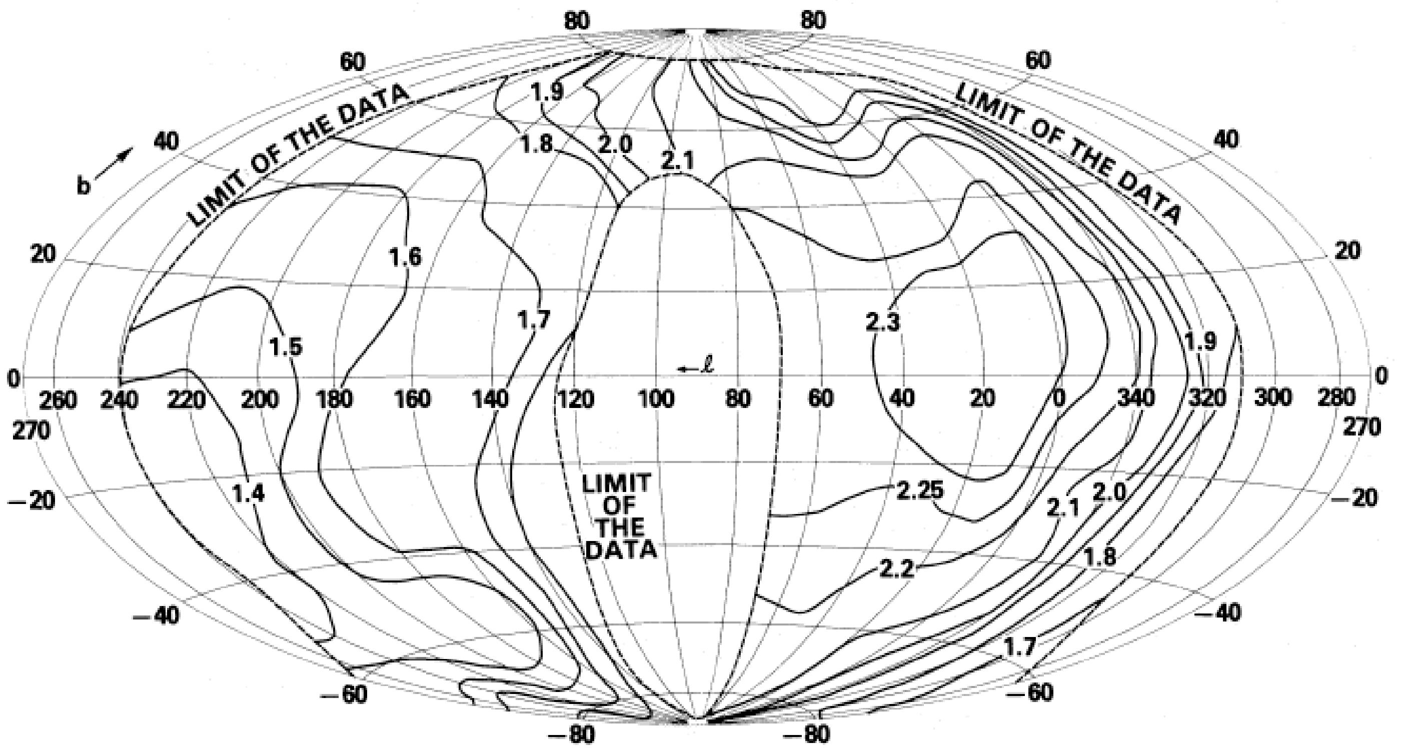
Exoplanetary radio emissions

- Jupiter LF radio emission are intense ⇒ discovery & measure of B field (~10G) and rotation period (~10h)
- ∃ similar Terrestrial emissions, ≤1 MHz (B ~ 0.5G)
- Radiation belts emission = synchrotron
- Auroral emissions = Cyclotron-Maser (CMI) : $f=f_{ce}$, keV e-, high T_B, circular polar., narrow beaming, t-f variability
- Contrast Jupiter - Sun ~ 1 → radio search !



[Girard et al., 2012]

Planetary and exoplanetary radio emissions



CONTOURS ARE IN UNITS OF 10^6K

FIG. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz

RAE-2 observations (Novaco & Brown, 1978) :
→ no individual source identified

Sky temperature

T_{sky}	freq (MHz)	
3.3×10^5	10	galactic synchrotron emission
2.6×10^6	5	
2.0×10^7	1	
2.6×10^7	0.5	free-free absorption
5.2×10^6	0.25	

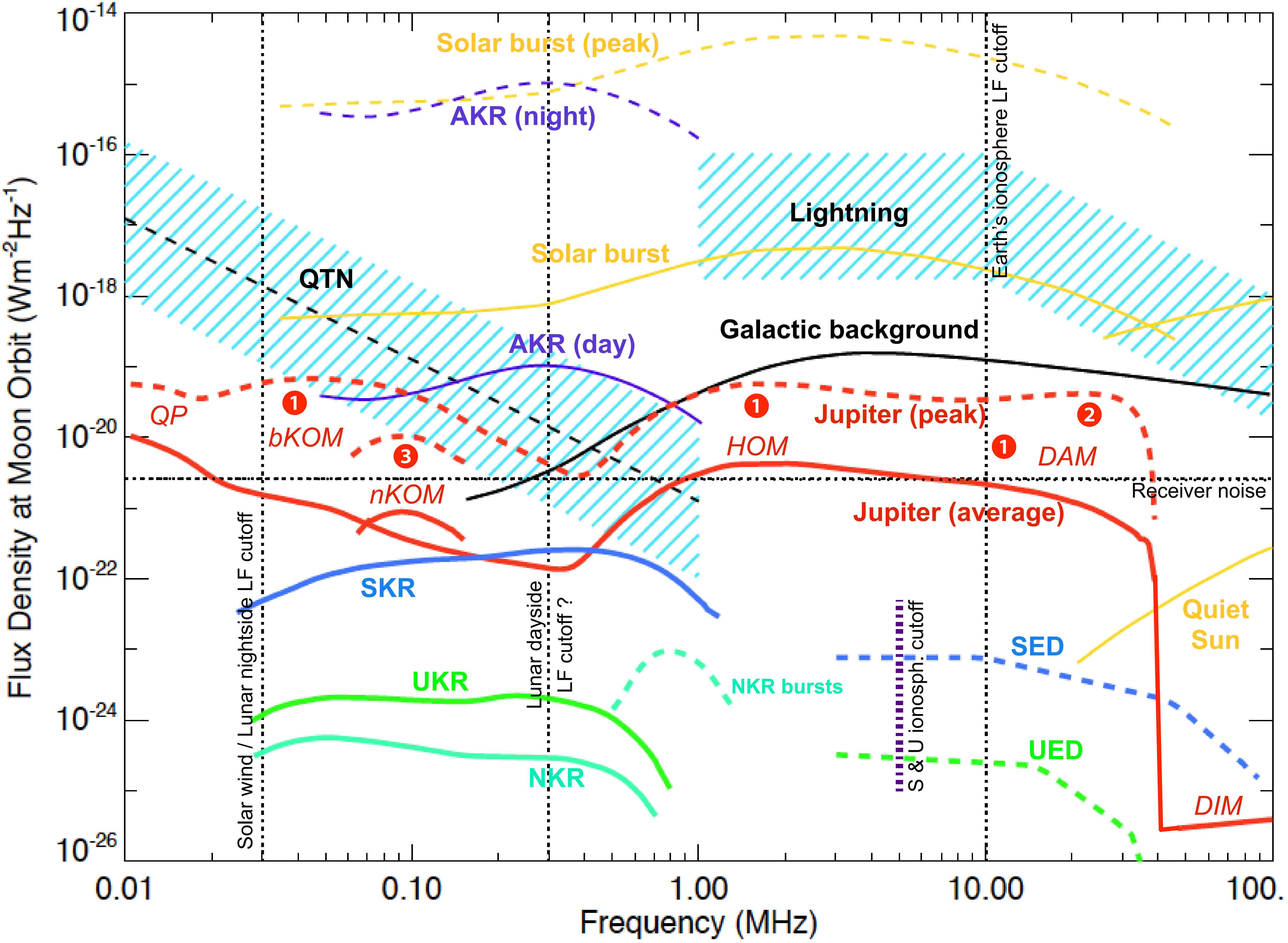
Galactic background flux density detected by a short dipole antenna :

$$S_{sky}^1 \ (\mathrm{Wm^{-2}Hz^{-1}}) = 2kT_{sky}/A_{eff} = 2kT_{sky}\lambda^2/\Omega \qquad \text{with} \qquad \Omega=8\pi/3,\ A_{eff}=3\lambda^2/8\pi$$

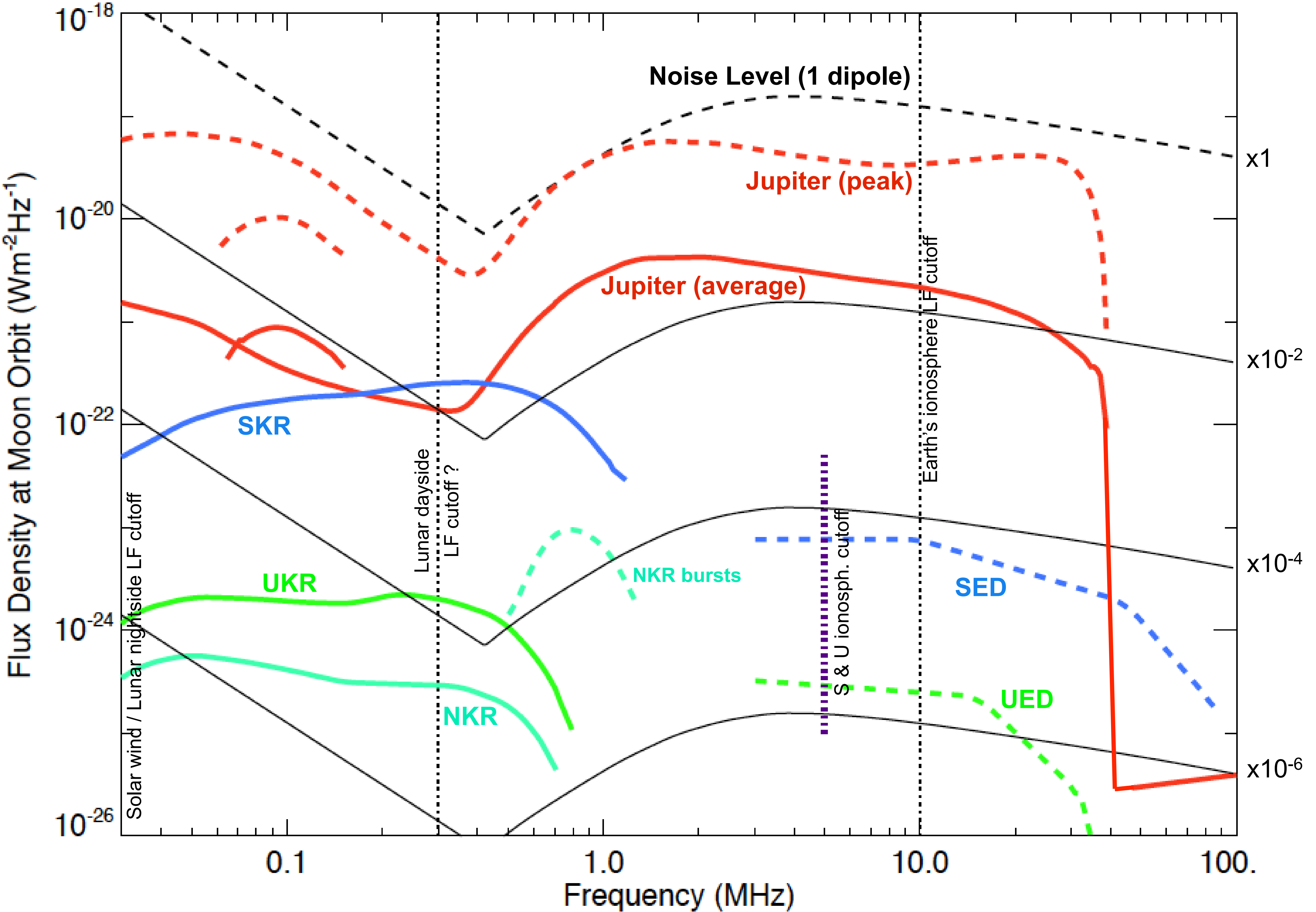
→ sensitivity with N dipoles, bandwidth b, integration time τ :

$$S_{min} = S_{sky}^1/C \qquad \text{with} \qquad C = N(b\tau)^{1/2}$$

Solar system radio emissions at Moon orbit

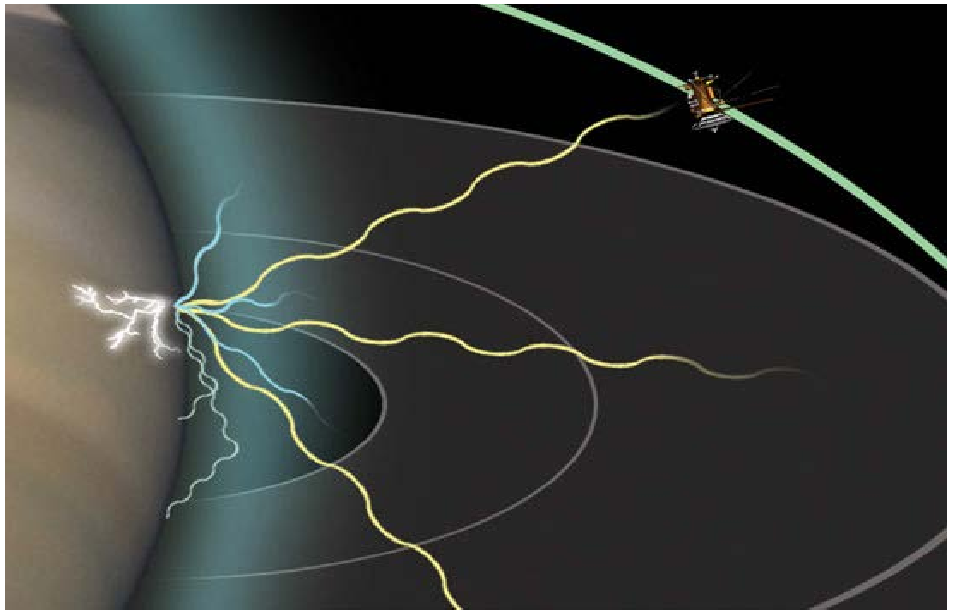


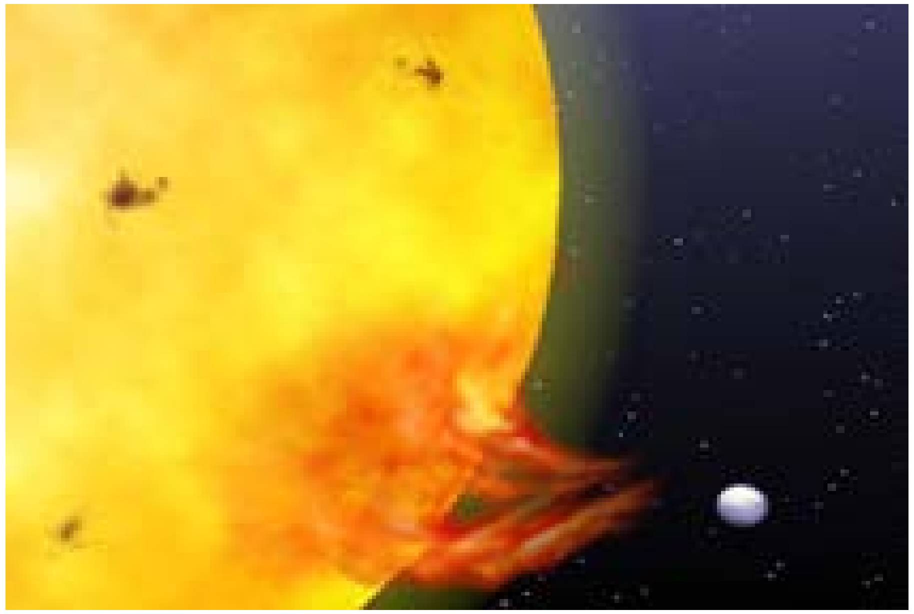
Solar system radio emissions at Moon orbit



Planetary and exoplanetary radio emissions

Radio emission	C	N (dipoles)	b (kHz)	t
Jovian radio components	10^{1}–10^{2}	1	10	1 s
			100	10 ms
SKR	10^{2}–10^{3}	1	100	1–10 s
UKR and NKR	10^{4}–10^{5}	1	200–500	10–60 min
		10^{1}–10^{2}	100	10 s
SED	10^{5}	10^{2}	10^{4}	300 ms
UED	10^{6}	10^{3}	10^{4}	300 ms
Radio-exoplanet	10^{7}	100–500	10^{3}–10^{4}	10–60 min
		~ 10	2×10^{4}	1 day



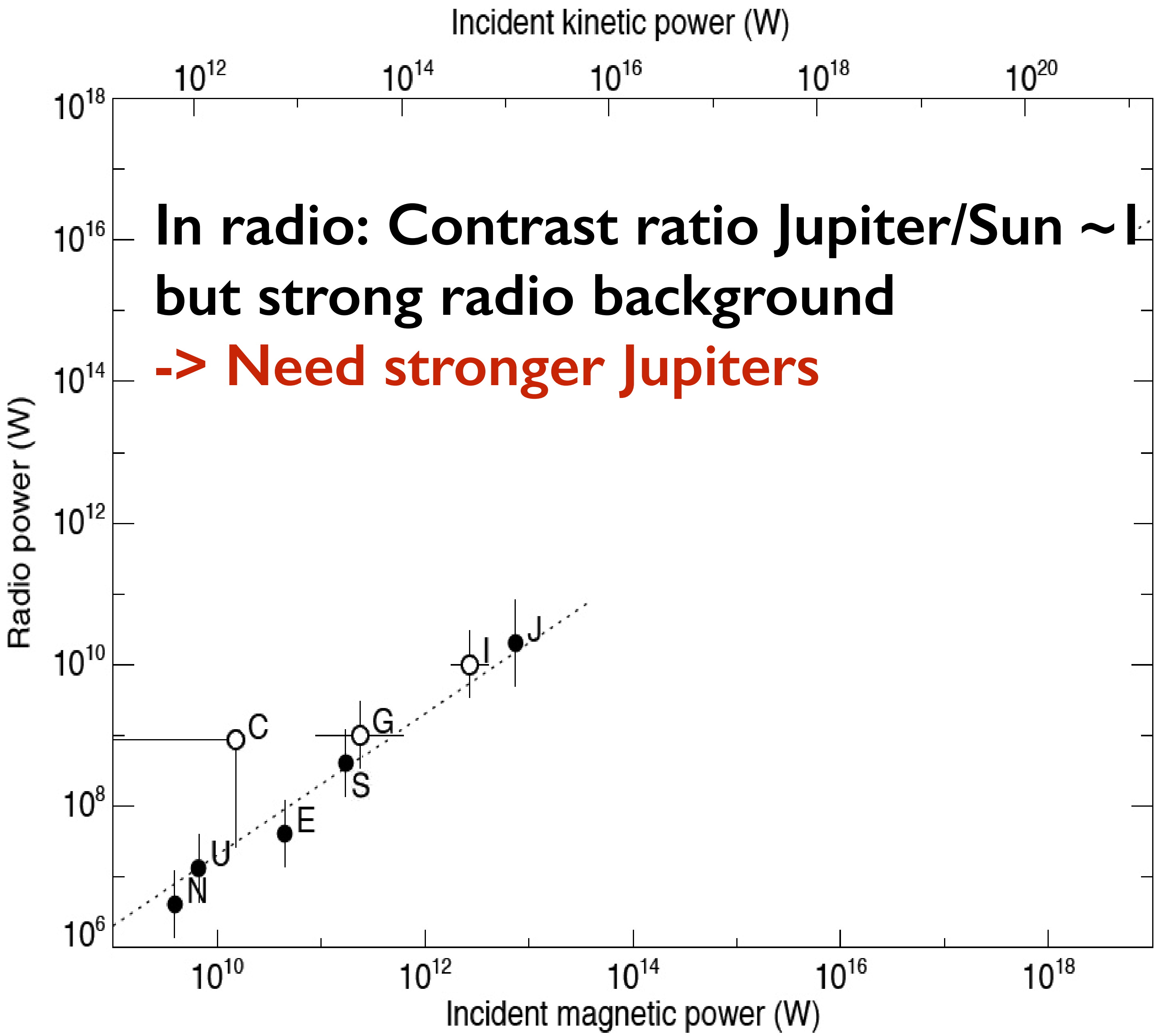


Lightning from Saturn, Uranus, Mars ?

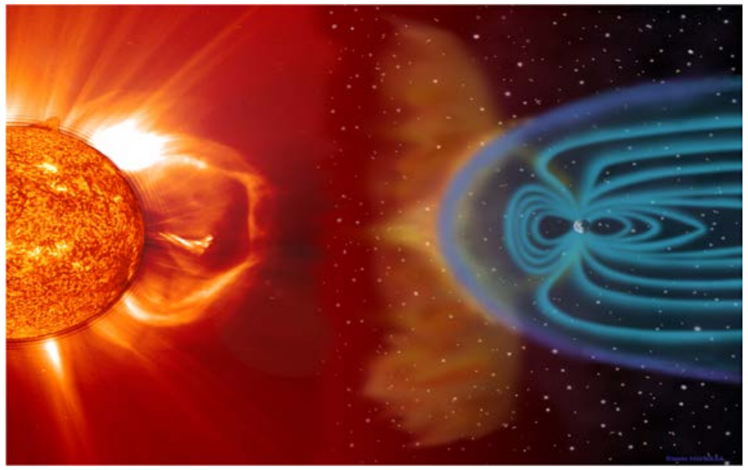
Exoplanets with a large array

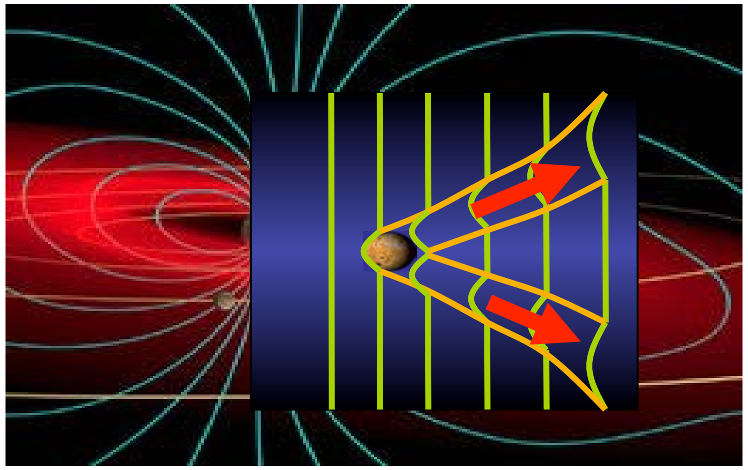
Theoretical background

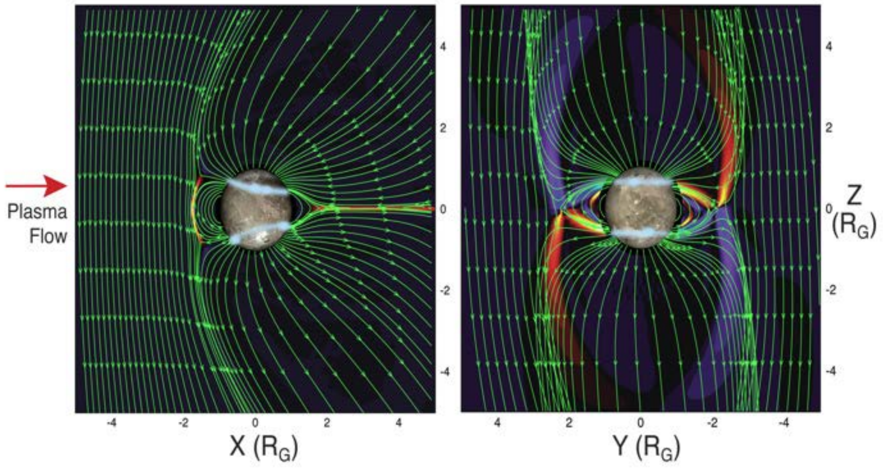
- General theoretical framework of **flow-obstacle interaction** in our SS: *magnetic reconnection, Alfvén waves, Unipolar interaction*
- Empirical radio-magnetic scaling law with ~constant efficiency ε~2-10x10^{-3}



In radio: Contrast ratio Jupiter/Sun ~
but strong radio background
-> Need stronger Jupiters





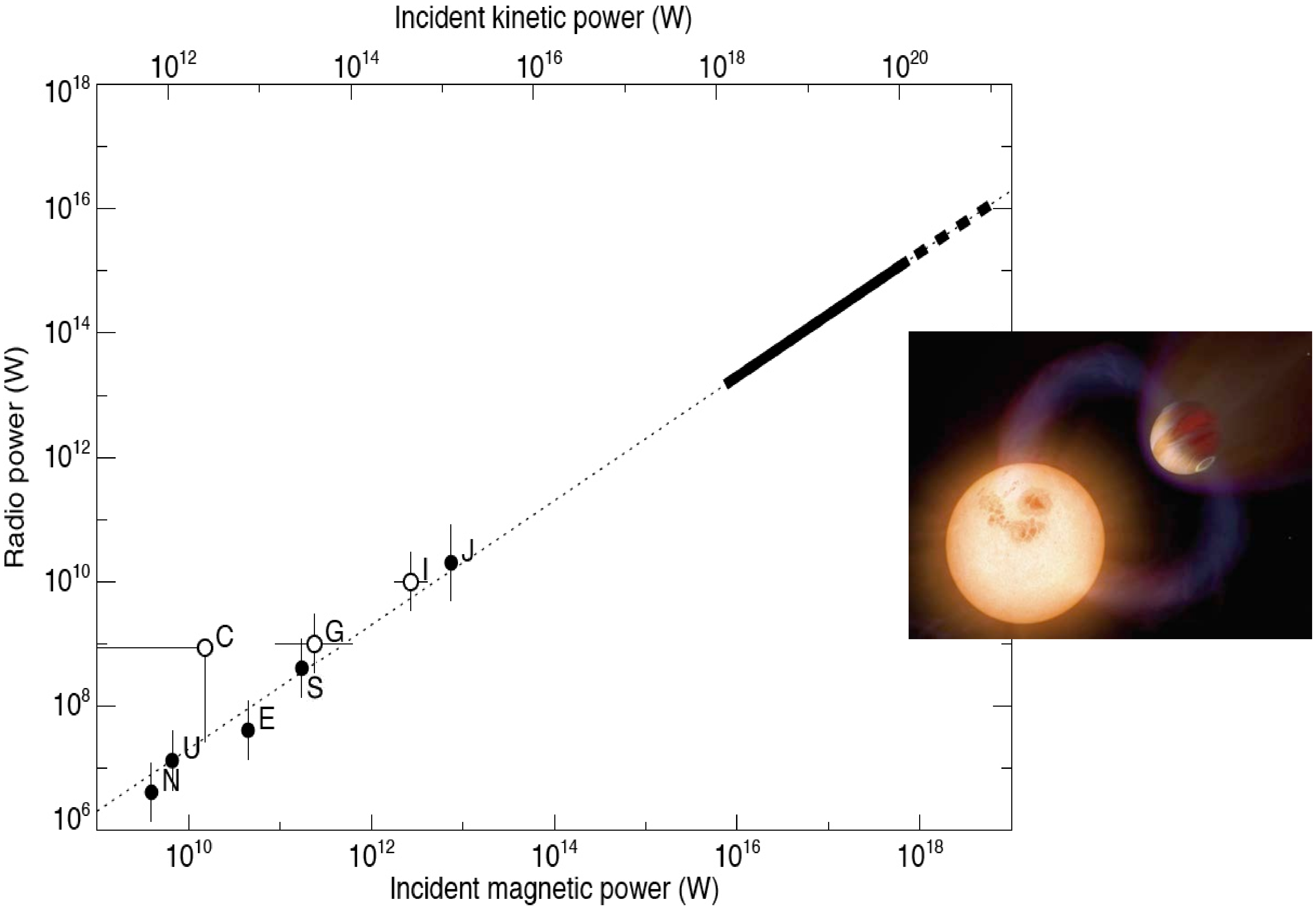


[Zarka et al., 2001, 2007]

Theoretical background

Extrapolation to **hot Jupiters**

- Magnetospheric radio emission up to 10^5 Jupiter
- Unipolar inductor emission up to $>10^6$ Jupiter at > 30-300 MHz but requires $B^* > 10\text{-}100\ B_{jup}$

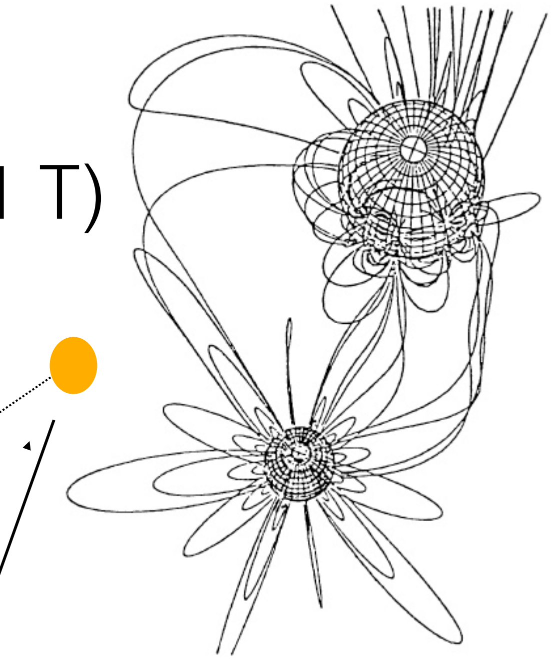


[Zarka et al., 2001, 2007]

Theoretical background

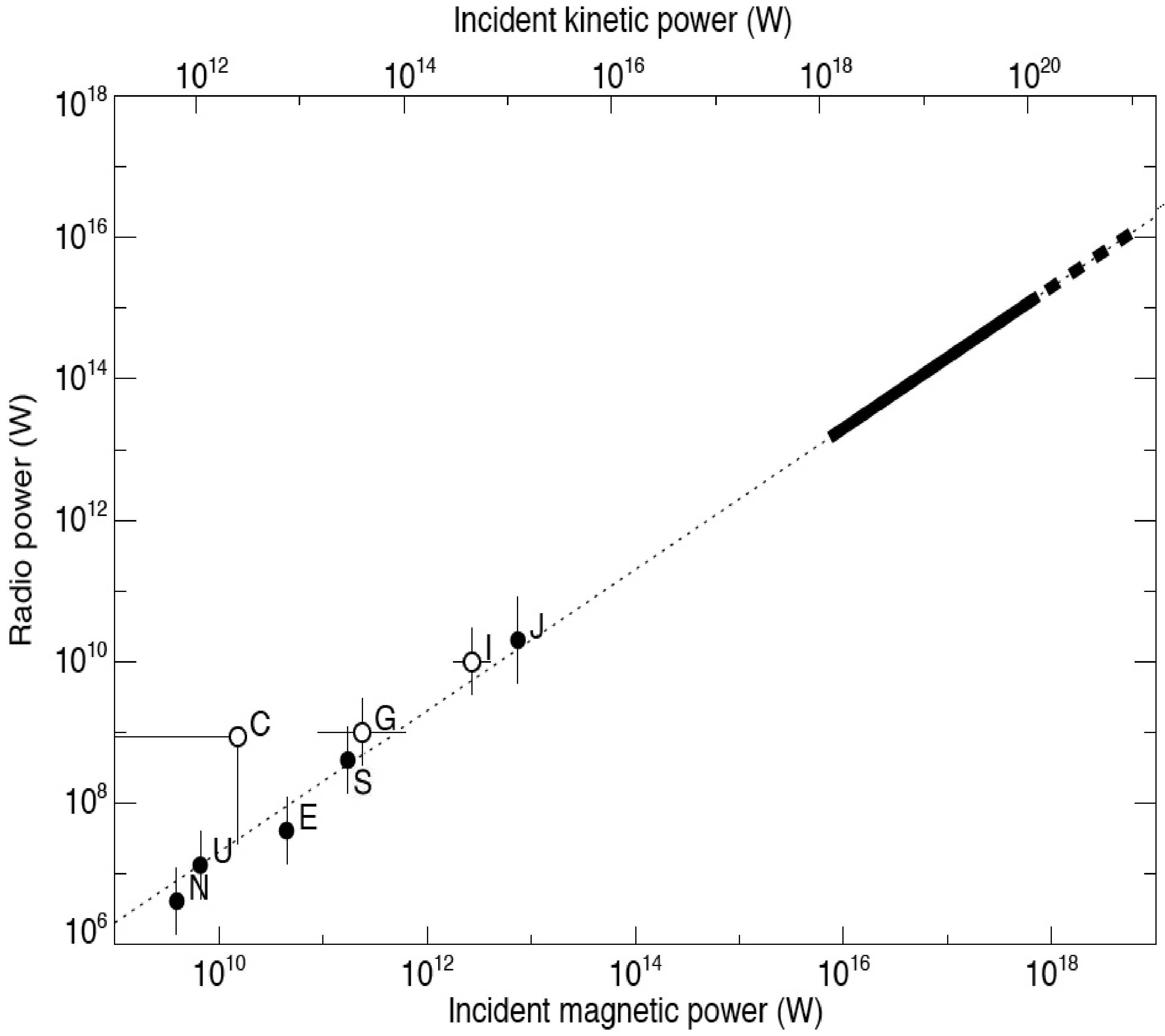
Measurement of an **interacting magnetic binary** (RS CVnV711 T) compatible with extrapolated scaling law

[Zarka et al., 2010]



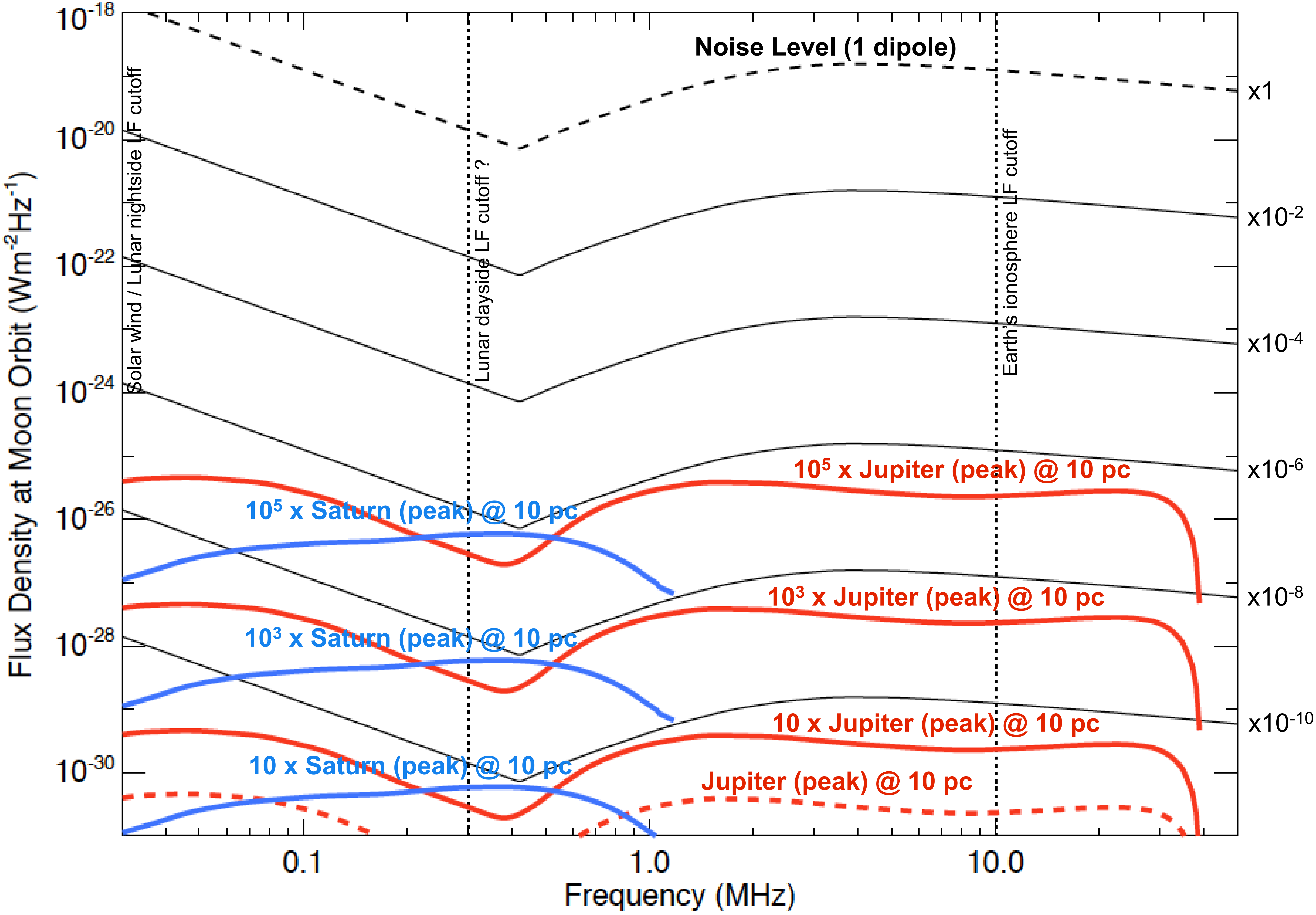
magnetic binary

[Budding et al., 1998]



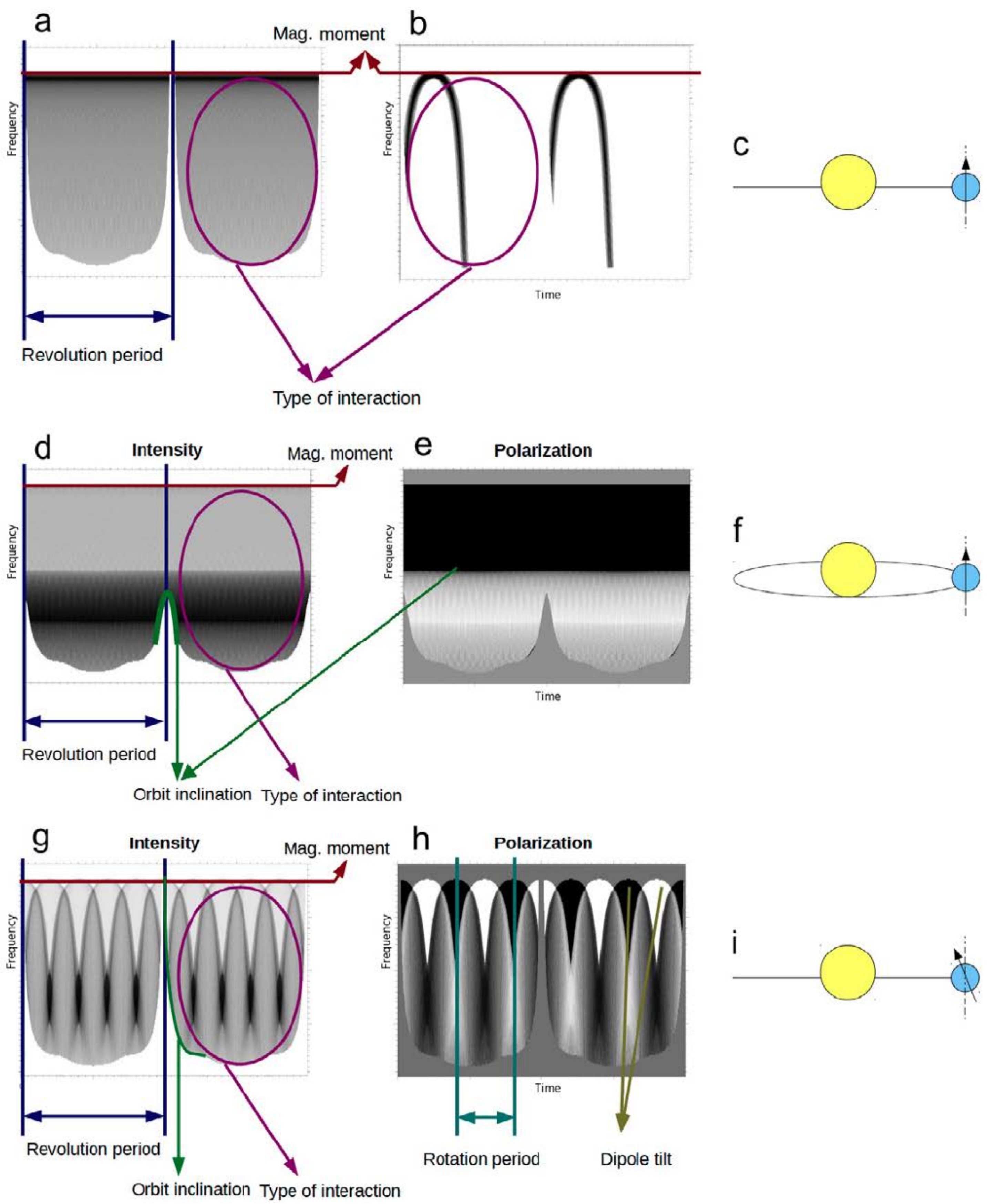
[Zarka et al., 2001, 2007]

Scaling laws for Jupiter-like radio emissions at Moon



- Star-Exoplanet case : parameters (stellar/exoplanet B tilt/offset, orbit inclination), planetary and stellar rotation, planetary orbital period ...

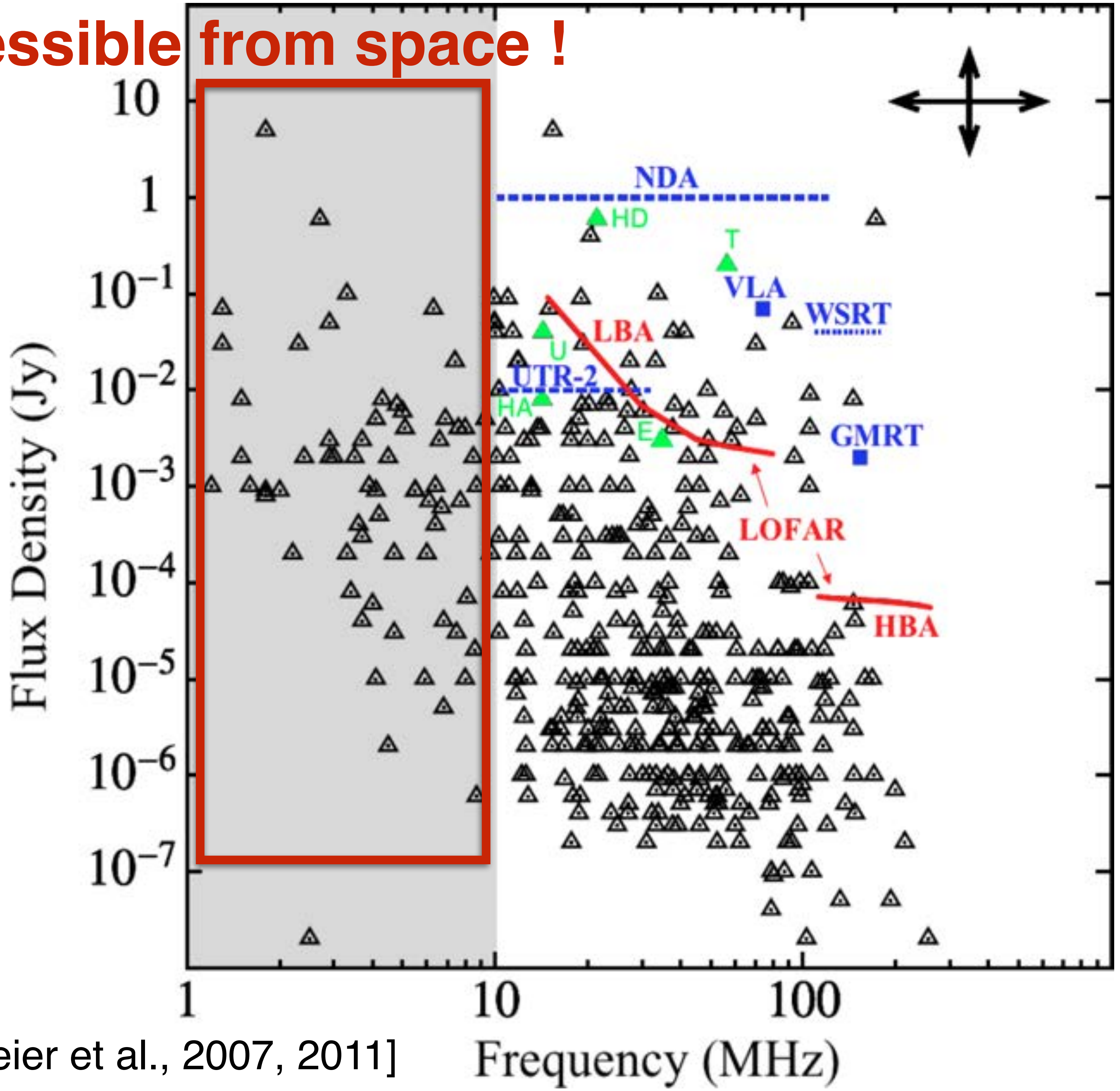
[Hess & Zarka, 2011]



- Study of typical cases (specific modeling post-detection)
- Model predictions scalable to any frequency range (depends on B involved)
- ≥ a few 10's MHz, LF cutoff becomes negligible except very close to the star & at low inclination (~occultation)

Exoplanetary survey

- Candidates were observed with LOFAR in beamformed & interferometer mode
- No detection yet...

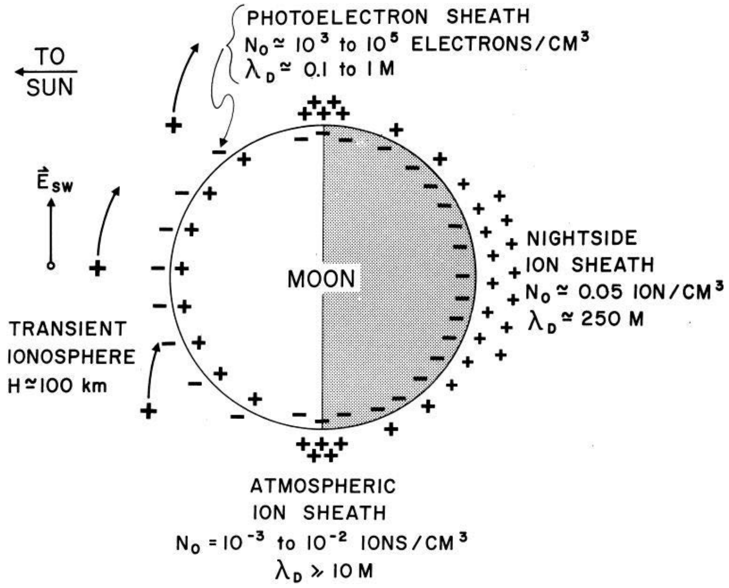


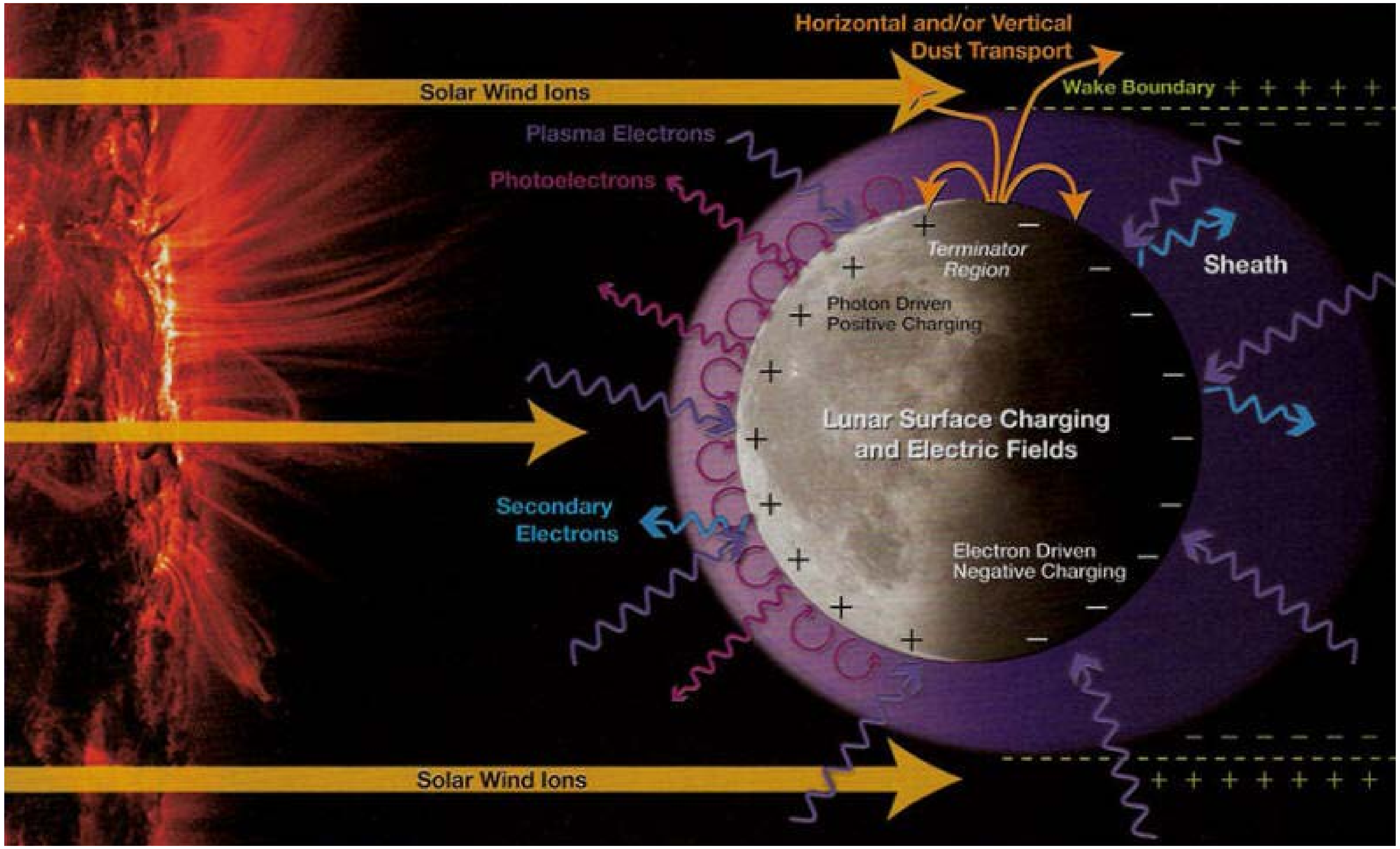
Accessible from space !

[Griessmeier et al., 2007, 2011]

Moon studies

- Automatic by-product of LF radio astronomy measurements = characterization of the (local) lunar electrostatic, electromagnetic and plasma environments, including
  - f_{pe} (LT,solar activity, traversal of Earth's magnetotail)
  - e.s. discharges from regolith charging
  - Properties of lunar subsurface wrt radio waves





Propagation effects in the IPM/ISM affecting transients

- **Angular broadening** **(Rickett and Coles, 2000)**

  (limits the finest resolution of a point source due to scattering)

- **Temporal Broadening**

  (limits the time resolution of transient signals, due to different travel time of the signal, due to scattering)

  Interstellar broadening ~5yr @ 1 MHz **(Woan, 2000)**
  Interplanetary broadening ~0.1s @ 1 MHz

- **Depolarization** *(Faraday rotation* $\propto \lambda^2$*)*

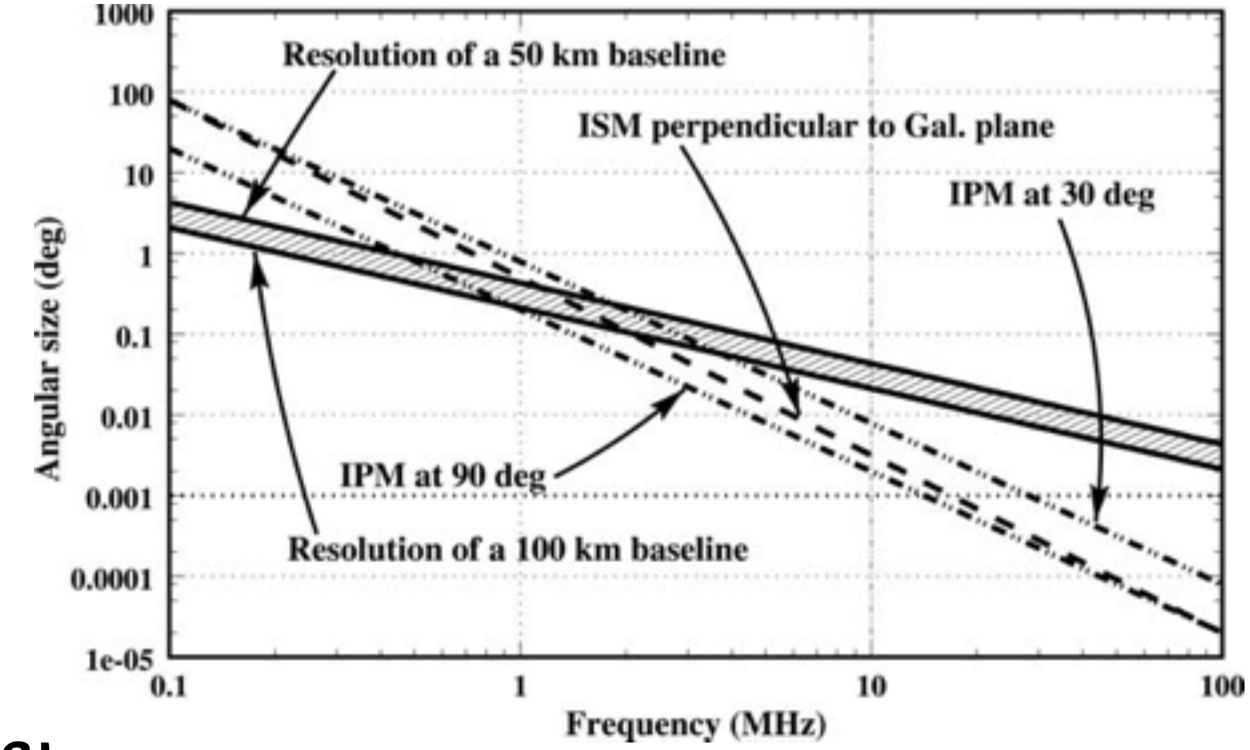
  (Linfield, 1996)

- **Absorption effects** **(Dwarakanath, 2000)**

  (Free-free absorption -> ISM = optically thick)

  (~2kpc @ 3 MHz in ionized medium)

  (Galactic disc ~1kpc thick ==> foggy in all directions)



- **Reflection, refraction, scattering close to the Sun**

  (Bracewell and Preston, 1956)

Additional slides for discussion

Exoplanetary survey (on Earth)

- Intense sky background (+ RFI + ionosphere) → detection difficult
- Maximum distance for $N\sigma$ sky-limited detection of a source ζ x Jupiter :

$$d_{max} = (\zeta S_J A_e/2NkT)^{1/2}(b\tau)^{1/4} = 5\times10^{-8}\,(A_e\,\zeta)^{1/2}\,f^{5/4}\,(b\tau)^{1/4} \quad [\text{pc}]$$

(Zarka et al., 1997)

$\zeta = 1$	$b\,\tau = 10^6$ *(1 MHz, 1 sec)*		$b\,\tau = 2\times10^8$ *(3 MHz, 1 min)*		$b\,\tau = 4\times10^{10}$ *(10 MHz, 1 hour)*	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4$ m^2 (~NDA)	0.003	0.05	0.01	0.2	0.04	0.7
$A_e = 10^5$ m^2 (~UTR-2, LOFAR)	0.01	0.2	0.03	0.6	0.1	2.2
$A_e = 10^6$ m^2 (~SKA)	0.03	0.5	0.1	2.	0.4	7.

(distances in parsecs)

Exoplanetary survey

- Maximum distance for $N\sigma$ sky-limited detection of a source ζ x Jupiter :

$\zeta = 10^5$	$b\,\tau = 10^6$ *(1 MHz, 1 sec)*		$b\,\tau = 2\times10^8$ *(3 MHz, 1 min)*		$b\,\tau = 4\times10^{10}$ *(10 MHz, 1 hour)*	
	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz	f = 10 MHz	f = 100 MHz
$A_e = 10^4\ m^2$ (~NDA))	1	16	3	59	13	220
$A_e = 10^5\ m^2$ (~UTR-2, LOFAR)	3	50	11	190	40	710
$A_e = 10^6\ m^2$ (~SKA)	9	160	33	600	130	2200

(distances in parsecs)

- turbulence → intermittency [Chian et al., 2010]
- scintillations → radio flux x100 ? [Farrell et al., 1999]

Some issues with space-borne interferometry

- **VLF Sky bg** **VERY Strong** **Antenna in a "sky-dominated" noise regime**

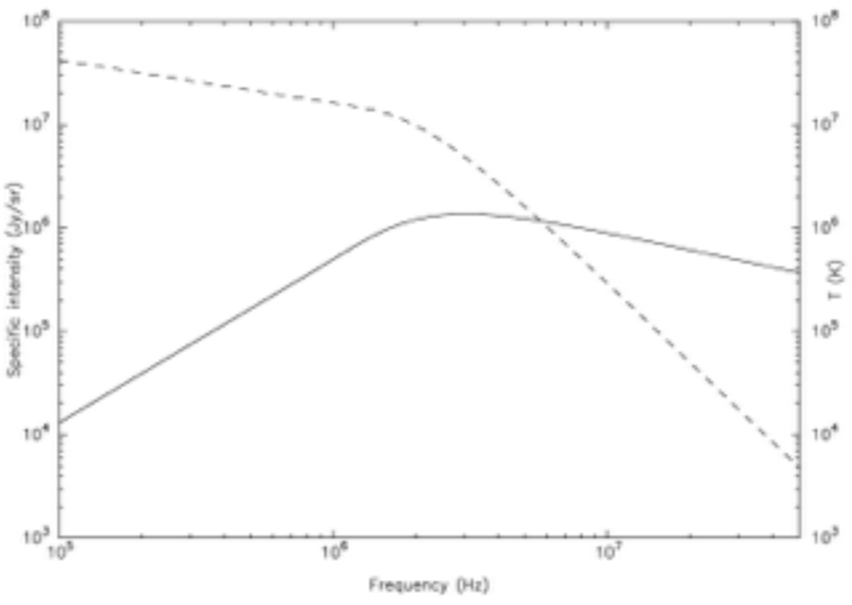
$T \sim 42mK$ **@ 3.8 GHz**

$T \sim 20K$ **@ 408 MHz**

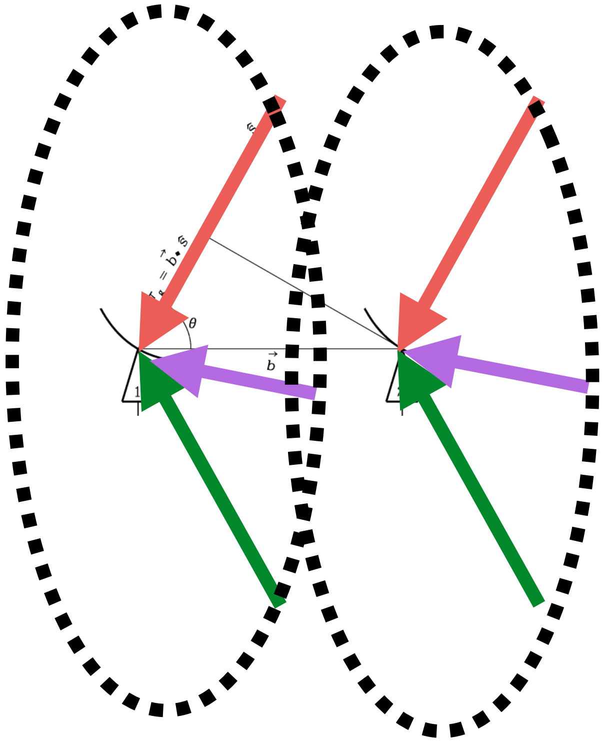
$T \sim 10^4 K$ **@ 30 MHz**

$T \sim 10^7 K$ **@ 3 MHz**

$T \sim 1.3 \times 10^7 K$ **@ 0.3 MHz**



- **Large FoV** $\frac{8\pi}{3} sr$ **for dipole antennas**



- **2pi Delay tracking symmetry**

- **Mapping the full sky**

$$V_\nu(u,v,w) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(l,m)\, I_\nu(l,m) \cdot e^{-2\pi i \left\{ul+vm+w\left(\sqrt{1-l^2-m^2}-1\right)\right\}} \cdot \frac{dl\, dm}{\sqrt{1-l^2-m^2}}, \tag{1}$$

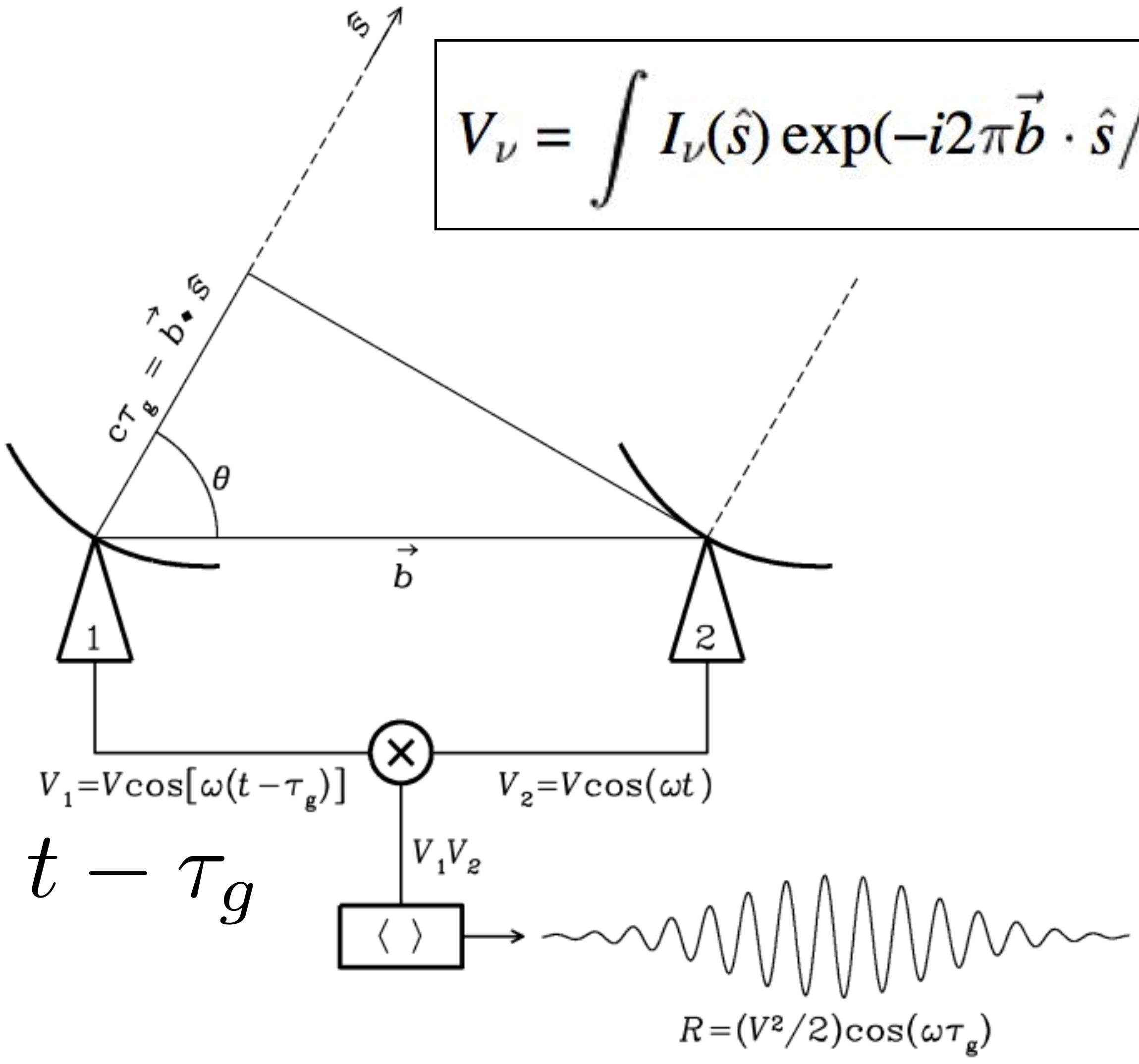
B = 50 km λ **= 15 m** θ_s **= 1' = 6.64.10^-8 sr**

FoV= $4\pi sr$

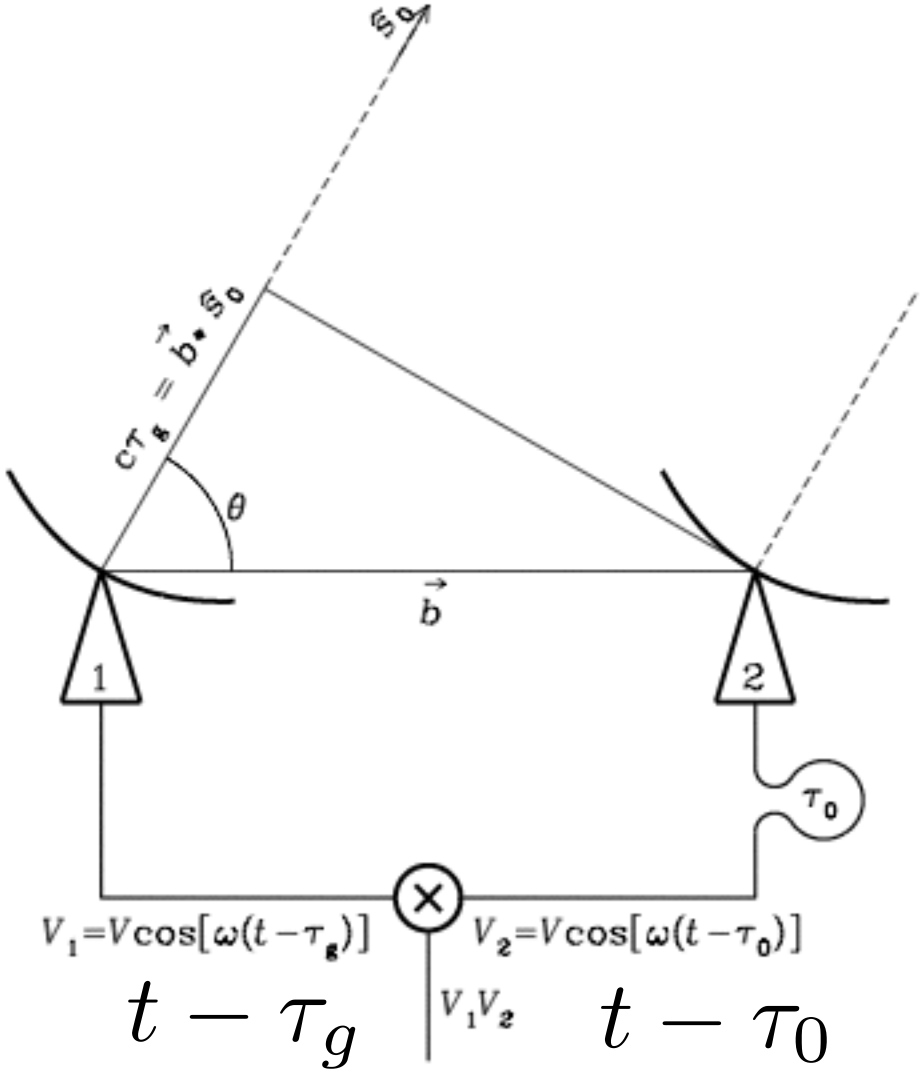
189.10^6 pixels if 1 pixel/beam **13700x13700 px**

657.10^6 pixels if 3 pixels/beam **24000x24000 px**

Monochromatic interferometer



$$V_\nu = \int I_\nu(\hat{s}) \exp(-i2\pi\vec{b}\cdot\hat{s}/\lambda)\, d\Omega$$

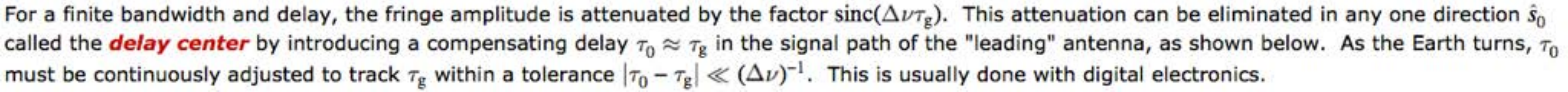


Finite bandwidths and averaging time

$$V = \int I_\nu(\hat{s}) \operatorname{sinc}(\Delta\nu\tau_g) \exp(-i2\pi\nu_c\tau_g)\, d\Omega\ .$$

attenuation

Phase-tracking compensating for ONE direction only



For a finite bandwidth and delay, the fringe amplitude is attenuated by the factor $\operatorname{sinc}(\Delta\nu\tau_g)$. This attenuation can be eliminated in any one direction $\hat{s}_0$ called the ***delay center*** by introducing a compensating delay $\tau_0 \approx \tau_g$ in the signal path of the "leading" antenna, as shown below. As the Earth turns, τ_0 must be continuously adjusted to track τ_g within a tolerance $|\tau_0 - \tau_g| \ll (\Delta\nu)^{-1}$. This is usually done with digital electronics.

Some issues with interferometry

Frequency smearing

put a upper limit to the channel width

$$\Delta\theta\Delta\nu \ll \theta_s\nu$$

Freq

Desired imaging region

channel bw

FWHM

ex:VLA

$$\Delta\nu \ll \frac{\nu\theta_s}{\Delta\theta} = \frac{1.5\times10^9\ \mathrm{Hz}\times4\ \mathrm{arcsec}}{900\ \mathrm{arcsec}\ \textit{(=15')}} \approx 7\ \mathrm{MHz}$$

Time smearing

limits the correlator integration step time

FWHM

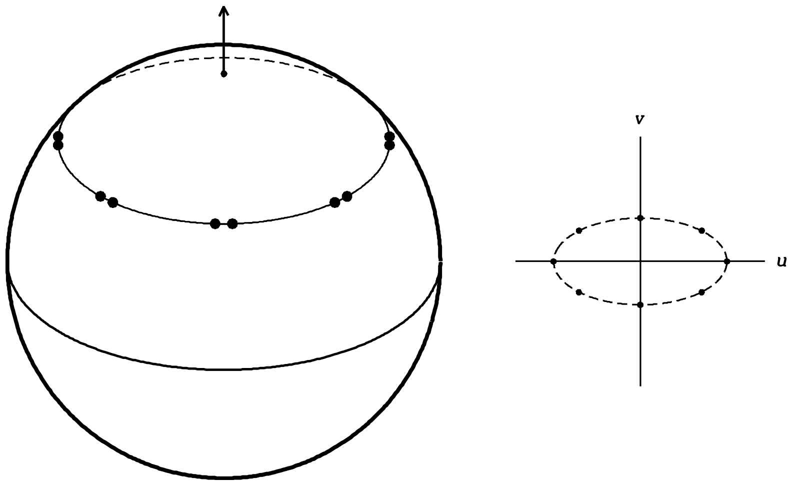
Earth sideral period

$$\Delta\theta\Delta t \ll \frac{\theta_s P}{2\pi}$$

Desired imaging region

correlator avg time

$$\Delta t \ll \frac{\theta_s}{\Delta\theta}\times1.37\times10^4\ \mathrm{s} = \frac{4\ \mathrm{arcsec}}{900\ \mathrm{arcsec}}\times1.37\times10^4\ \mathrm{s}\approx 60\ \mathrm{s}$$



DSL typical bw smearing

$\Delta\theta =$ 90° (angular radius to image half-space)

	$\nu =$ 1 MHz $\lambda =$ 300 m	30 MHz 10 m
$B =$ 10 km	$\theta_s =$ 1.7° $\Delta\nu \ll$ **18 kHz**	$\theta_s =$ 3' $\Delta\nu \ll$ **555 Hz**
$B =$ 100 km	$\theta_s =$ 10' $\Delta\nu \ll$ **1,8 kHz**	$\theta_s =$ 21" $\Delta\nu \ll$ **65 Hz**

$\Delta\theta =$ 5° (10° image)

	$\nu =$ 1 MHz $\lambda =$ 300 m	30 MHz 10 m
$B =$ 10 km	$\theta_s =$ 1.7° $\Delta\nu \ll$ **340 kHz**	$\theta_s =$ 3' $\Delta\nu \ll$ **10 kHz**
$B =$ 100 km	$\theta_s =$ 10' $\Delta\nu \ll$ **33 kHz**	$\theta_s =$ 21" $\Delta\nu \ll$ **1,2 kHz**

DSL typical time averaging

$$\Delta t \Delta\theta \ll \frac{\theta_s P_{orb}}{2\pi}$$

let's assume an orbiting solid array at h=300 km

G=6.67384e-11 m^3.kg^-1.s^-2

r_m+h=2037.10^3 m

M_m=7.3477e22 kg

$$\frac{P_{orb}^2}{(r_m+h)^3} = \frac{4\pi^2}{GM_m} \text{ --> } P_{orb} = 2.3h$$

~8.0e-12

~8249 s

(seleno-stationary orbit h ~ 86000 km)

$\Delta\theta =$ 90° (angular radius to image half-space)

$B =$ 10 km

$\theta_s =$ 1.7° $\Delta t \ll$ **24s**

$\theta_s =$ 3' $\Delta t \ll$ **0.73s**

$B =$ 100 km

$\theta_s =$ 10' $\Delta t \ll$ **2.4s**

$\theta_s =$ 21" $\Delta t \ll$ **80 ms**

$\Delta\theta =$ 5° (10° image)

$B =$ 10 km

$\theta_s =$ 1.7° $\Delta t \ll$ **7min**

$\theta_s =$ 3' $\Delta t \ll$ **13s**

$B =$ 100 km

$\theta_s =$ 10' $\Delta t \ll$ **43s**

$\theta_s =$ 21" $\Delta t \ll$ **1.53s**

Propagation effects in the IPM

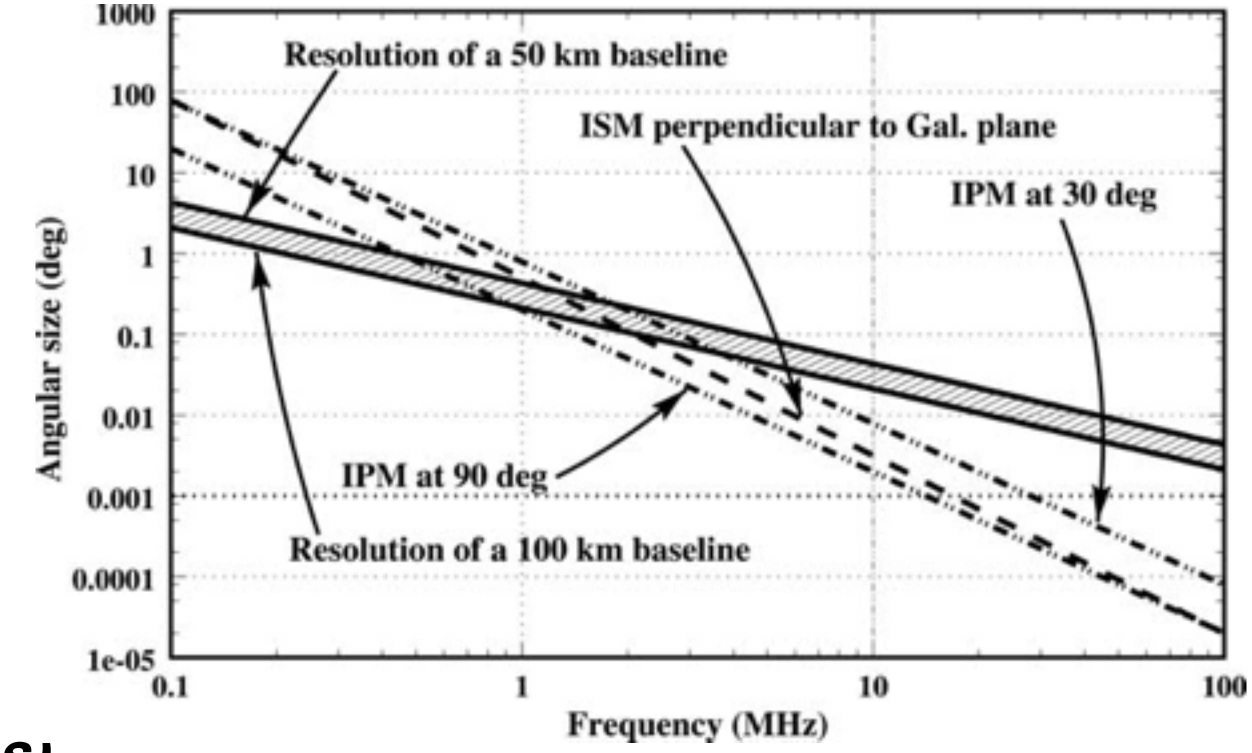
- Angular broadening **(Rickett and Coles, 2000)**

(limits the finest resolution of a point source due to scattering)

- Temporal Broadening

(limits the time resolution of transient signals, due to different travel time of the signal, due to scattering)

Interstellar broadening ~5yr @ 1 MHz **(Woan, 2000)**
Interplanetary broadening ~0.1s @ 1 MHz



- Depolarization *(Faraday rotation* $\propto \lambda^2$*)*

(Linfield, 1996)

- Absorption effects **(Dwarakanath, 2000)**

(Free-free absorption -> ISM = optically thick)

(~2kpc @ 3 MHz in ionized medium)

(Galactic disc ~1kpc thick ==> foggy in all directions)

- Reflection, refraction, scattering close to the Sun

(Bracewell and Preston, 1956)