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Pulsars, Magnetars and Fast Transients with AtLAST

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Introduction

- The science covered in this talk is **Time Domain Science**
- Time domain science ↔ **extreme events**:
  - Rapid changes (intrinsic or in intervening medium)
  - High energies / High densities
  - Exotic emission mechanisms (e.g., coherency)

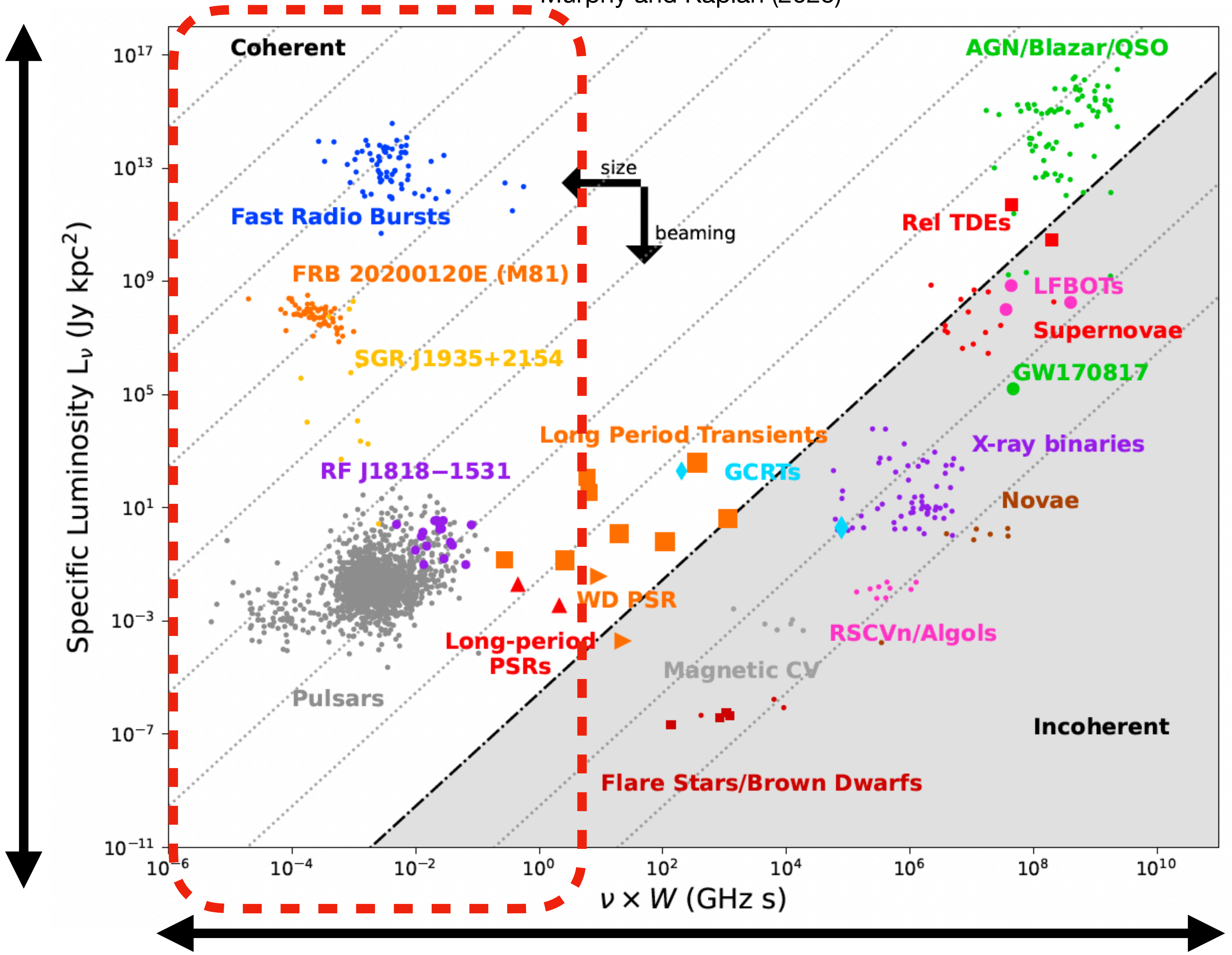
For a review, see e.g., Murphy and Kaplan (2025) and references therein

- Enables experiments for **fundamental physics**, e.g.: B-field creation, emission processes, strong-field gravity, star formation history across cosmic time
- Information on **intervening media on all scales**: interplanetary, interstellar, intergalactic

Introduction

Brightest events

Murphy and Kaplan (2025)

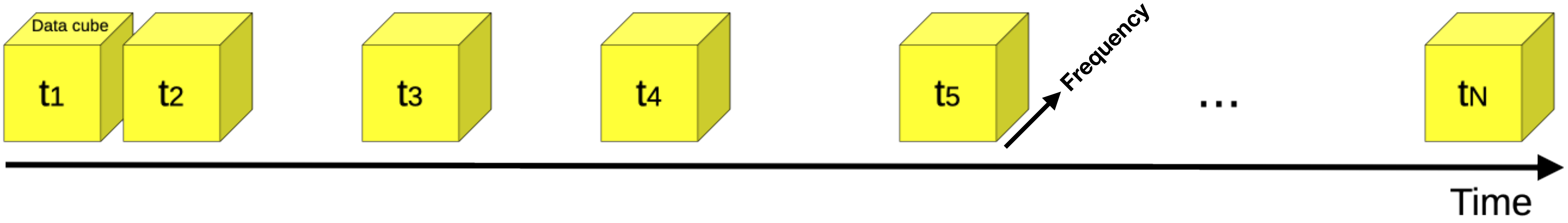


Fast (+ low frequency) **Slow (+ high frequency)**

- Time Domain Science is a very broad topic
- **<u>Goal of this talk</u>**:
  - General overview of Time Domain Science w/ *focus on (sub)mm- regime & "fast" transients*
  - How-to enable it + Why AtLAST is important

Introduction

- **Requires control on an extra dimension for science: TIME**
  - ➡ **When to observe**, **how often**, (**time resolution** of data)



- Some examples:
  - Monitoring of variable sources (change in properties, variability in intervening medium)
  - Astrometry (track movement)
  - Time-critical observations (e.g., coordinated with other telescopes, multi-messenger)
  - Target-of-Opportunity (rapid response)
  - Pulsars, Magnetars, Fast Transients (high-resolution time domain) ⬅ **More in next slides**

Definitions for clarity

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- **(Sub)Millimeter** = *For us in practice* ***~30 to 950 GHz*** [Note: IR/Optical also interesting]
- **Transient** includes "Long-lived" (~months), "Short-lived" (~days), and "One-Off" events.
- **What is "Fast" ?**
  - Not everyone understands the same by "fast transients"

In (sub)millimetre-wavelength field
"fast" usually mean minutes to days/weeks

Key classes of 'typical' mm- transients:

- Luminous Fast Blue Optical Transients
- Gamma-Ray Burst afterglows
- Tidal Disruption Events
- BH accretion / Jets
- Stellar flares
- Sun's activity

OK with time sampling of seconds to hours /days

Usually enabled with "typical" technical specifications (time samplings ~seconds) + human coordination

Other very interesting sources exist in the second to nanosecond regime:

Key classes of 'ultra-fast' mm- transients:

- Normal Pulsars
- Magnetars
- Fast Radio Burts*
- **New discoveries**

* Not yet detected at (sub)mm-λ

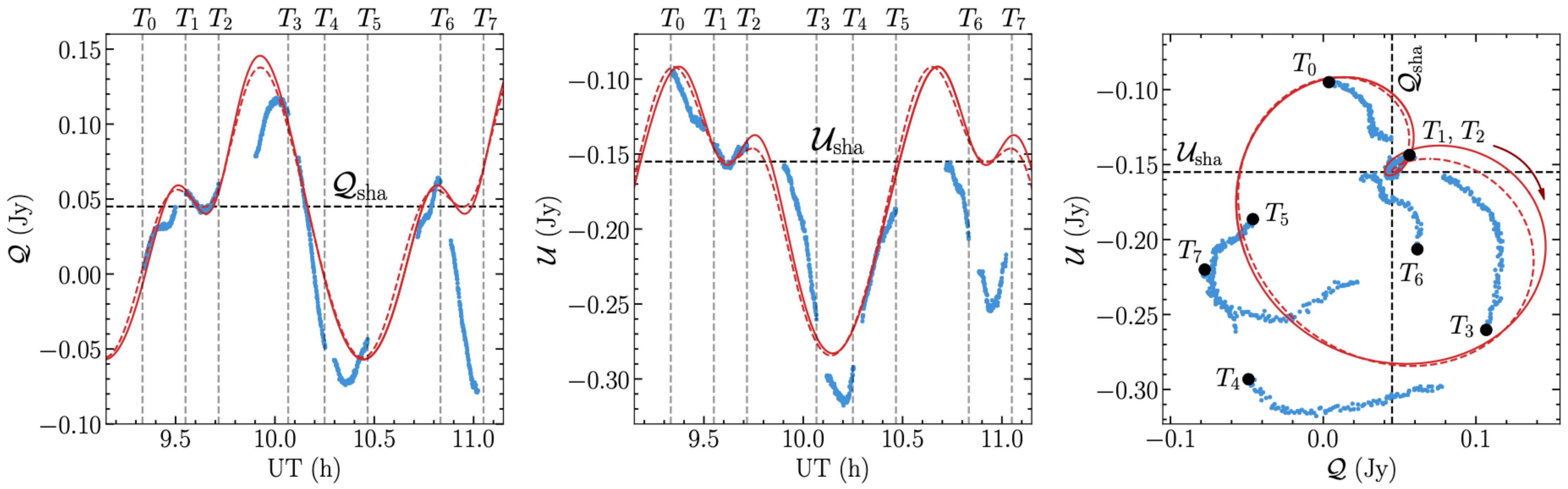
Need ~nanosecond to millisecond time resolution!

Requires very high time resolution often not contemplated in sub(mm-) instrumental design

(Sub)mm- Time Domain Science — A few examples

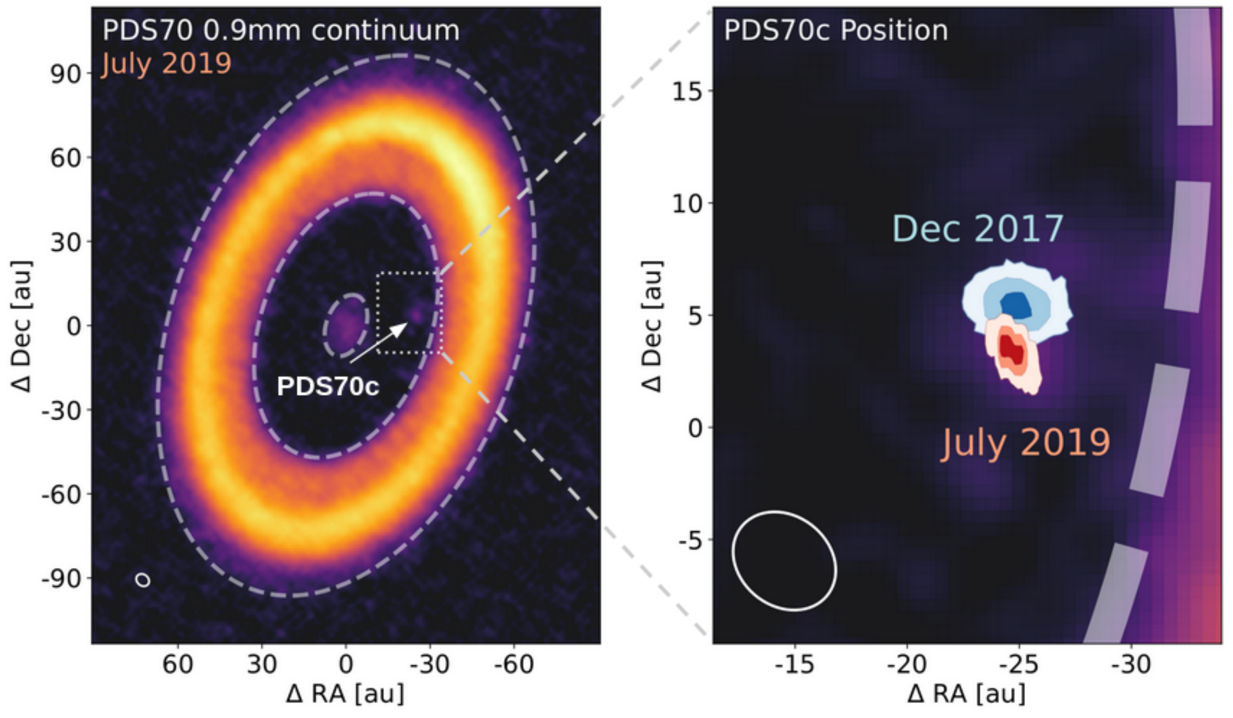
ALMA

Sgr A* Polarisation of a an orbiting Hot Spot in mm- wavelengths



Wielgus et al. (2022)

VLT
ALMA

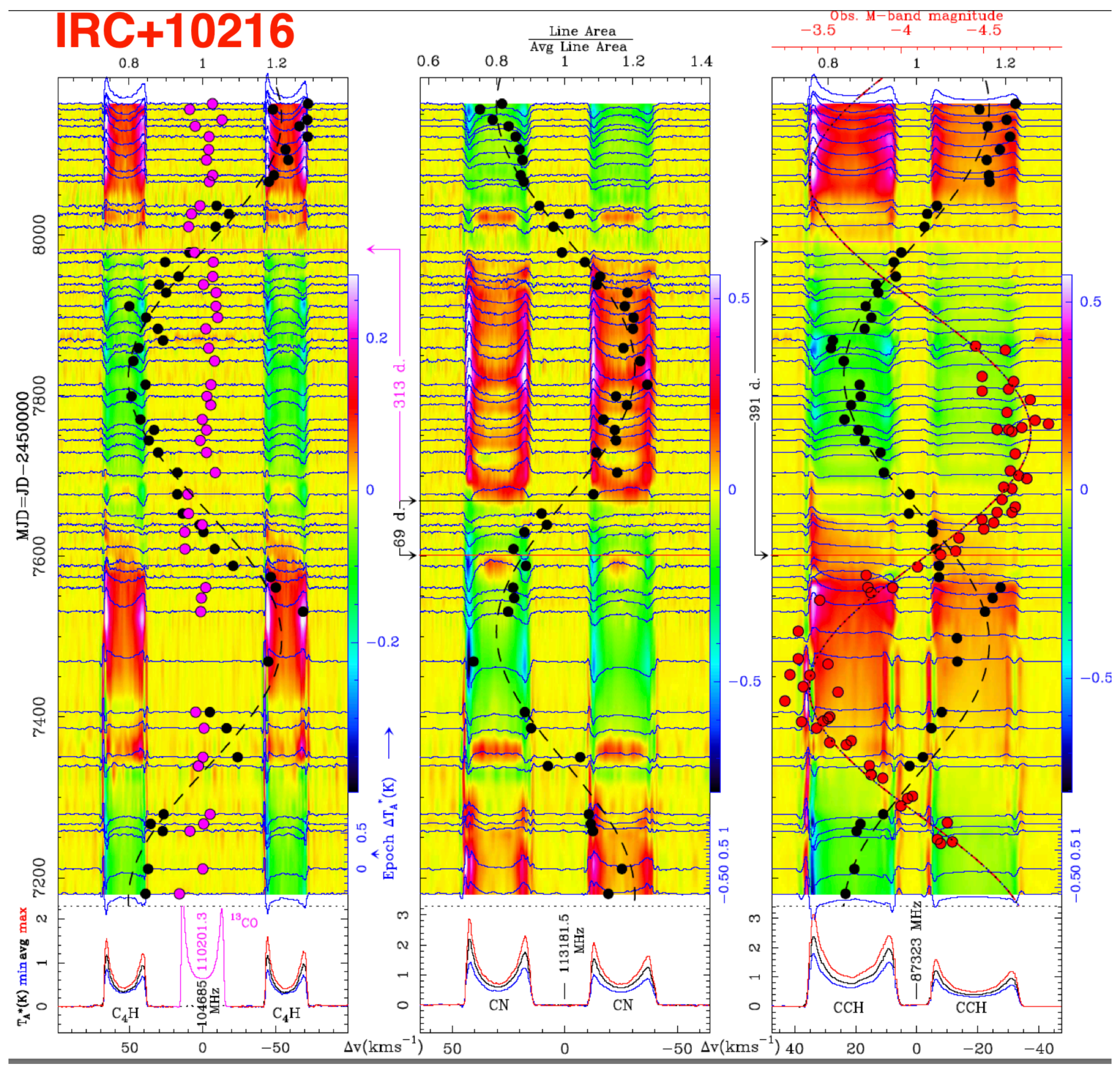


Protoplanetary disks and planetary bodies Keplerian movement

Keppler et al. (VLT/SPHERE, 2018)
Benisty et al. (incl. Kurtovic 2021)
For binaries: Kurtovic et al. (submitted)

IRAM 30m

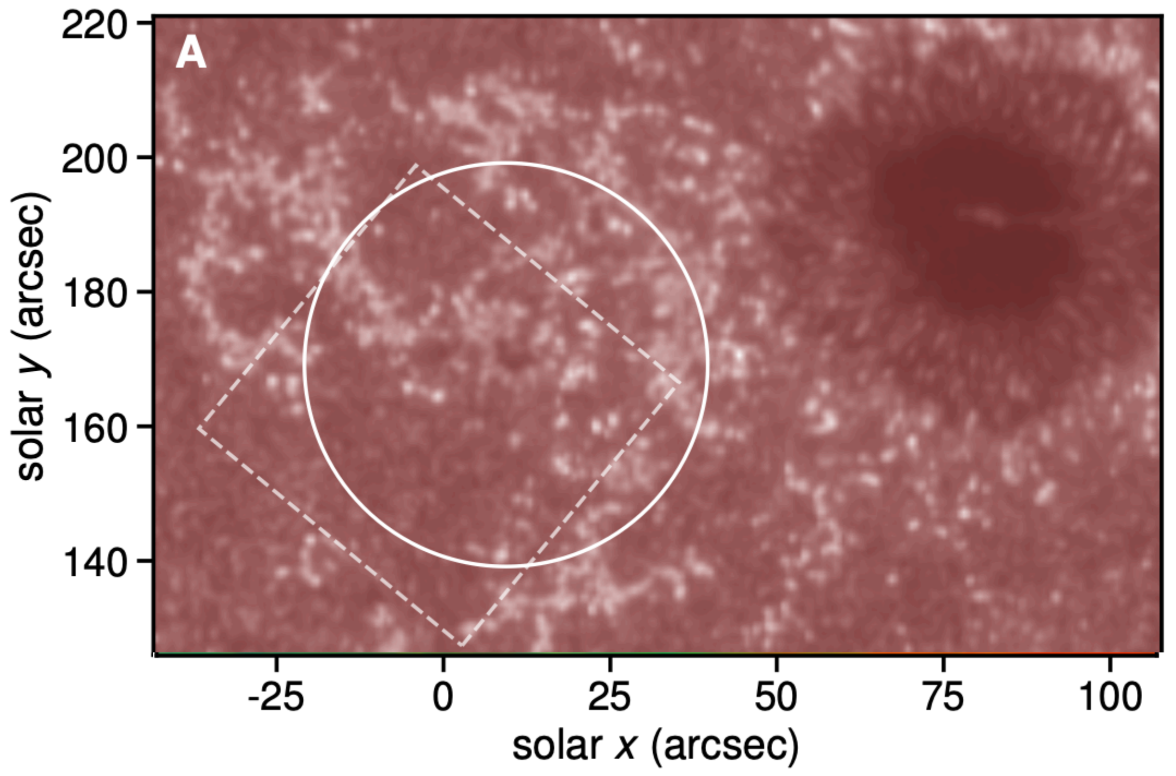
Time dependent (periodic) molecular emission
Period = 635 days



Pardo et al. (2018)

ALMA

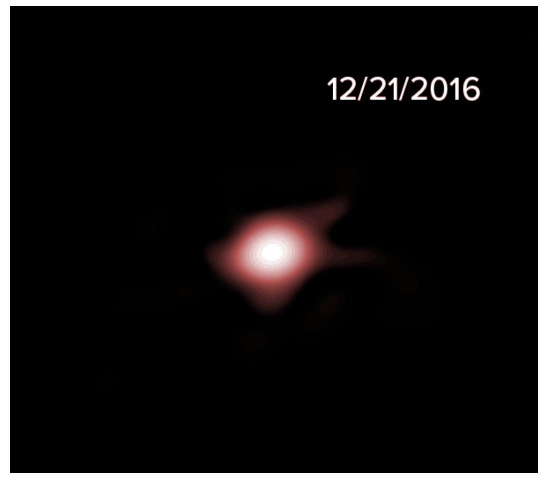
Sun's multi-λ simultaneous observations



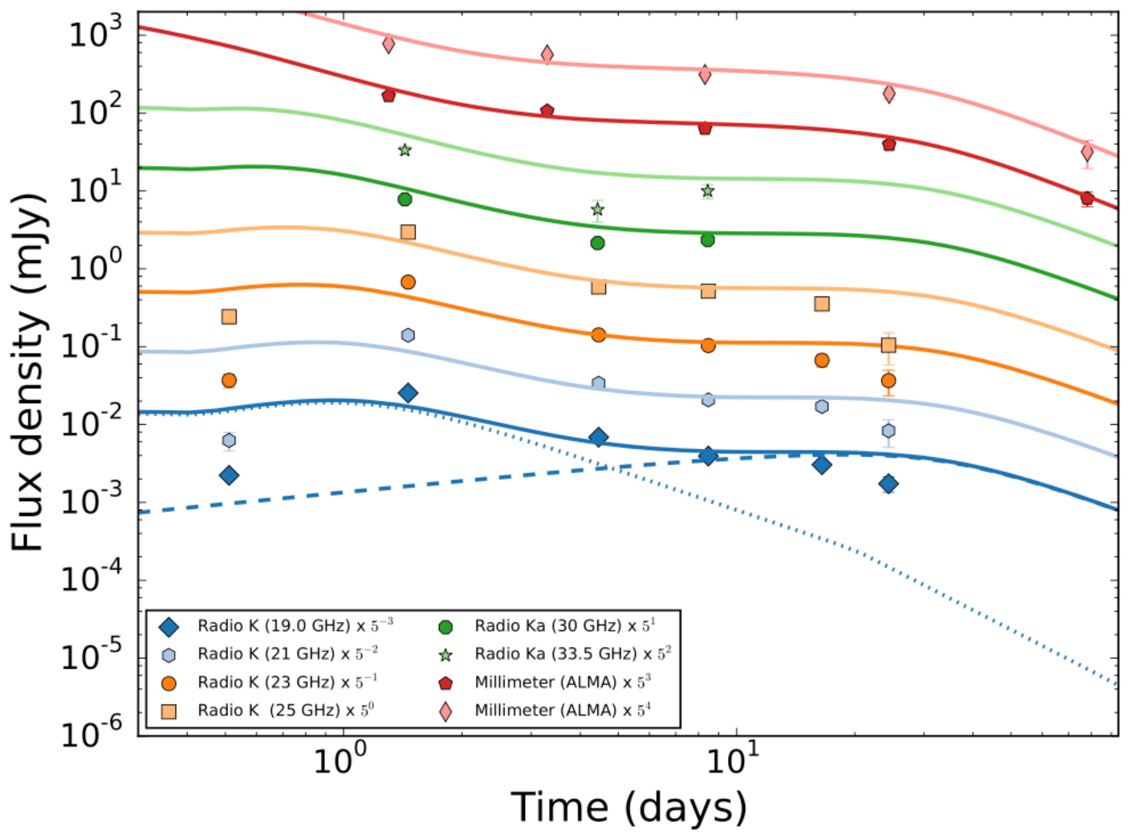
da Silva Santos et al. (2022)

GRB Afterglow and multi-λ light curve

ALMA



ALMA (ESO/NAOJ/NRAO), T. Laskar; NRAO/AUI/NSF, B. Saxton



Laskar et al. (2018)

Pulsars & Magnetars

- **Pulsars = Neutron stars = Compact remnants after supernova explosions**

The Crab Nebula

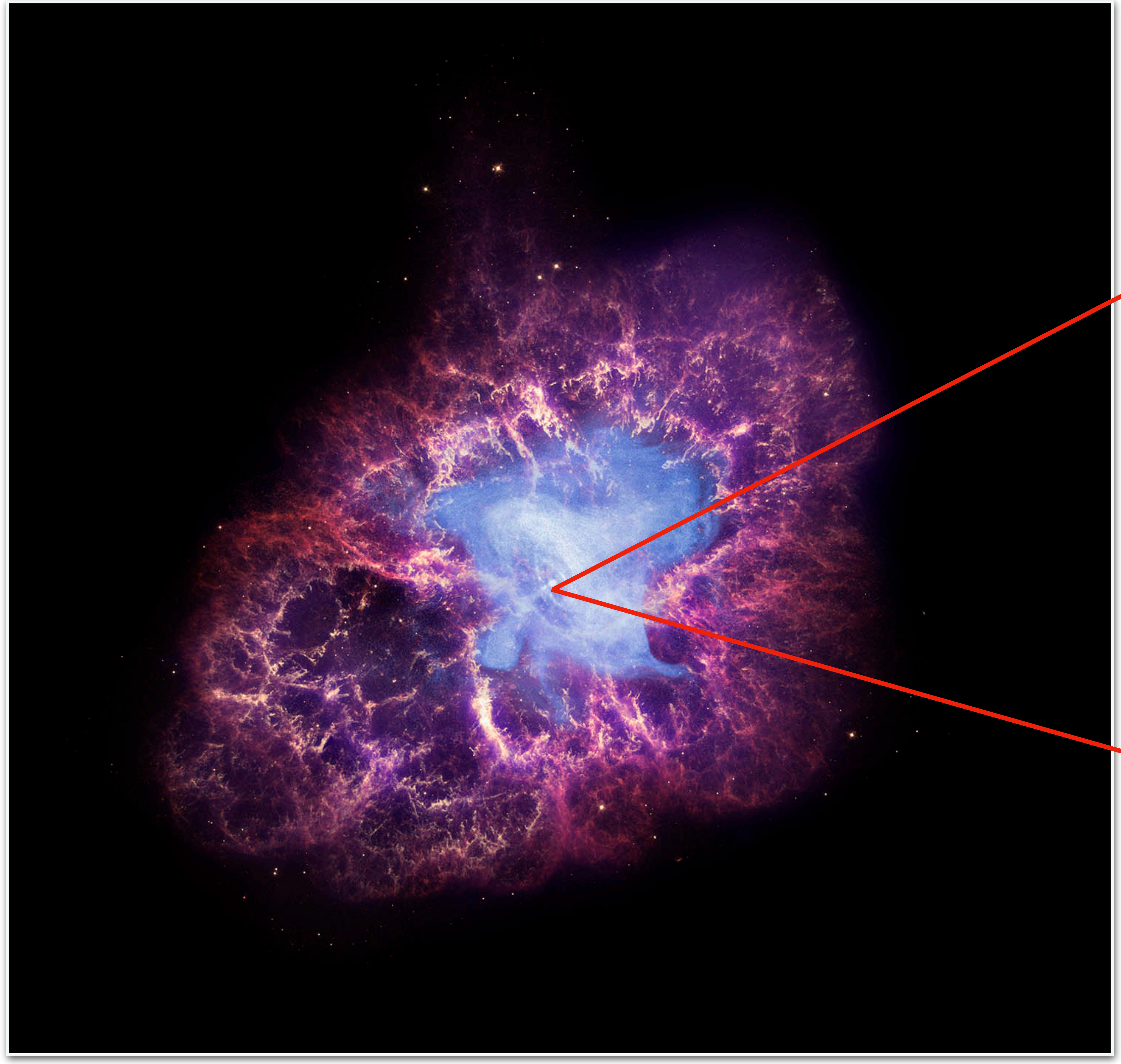
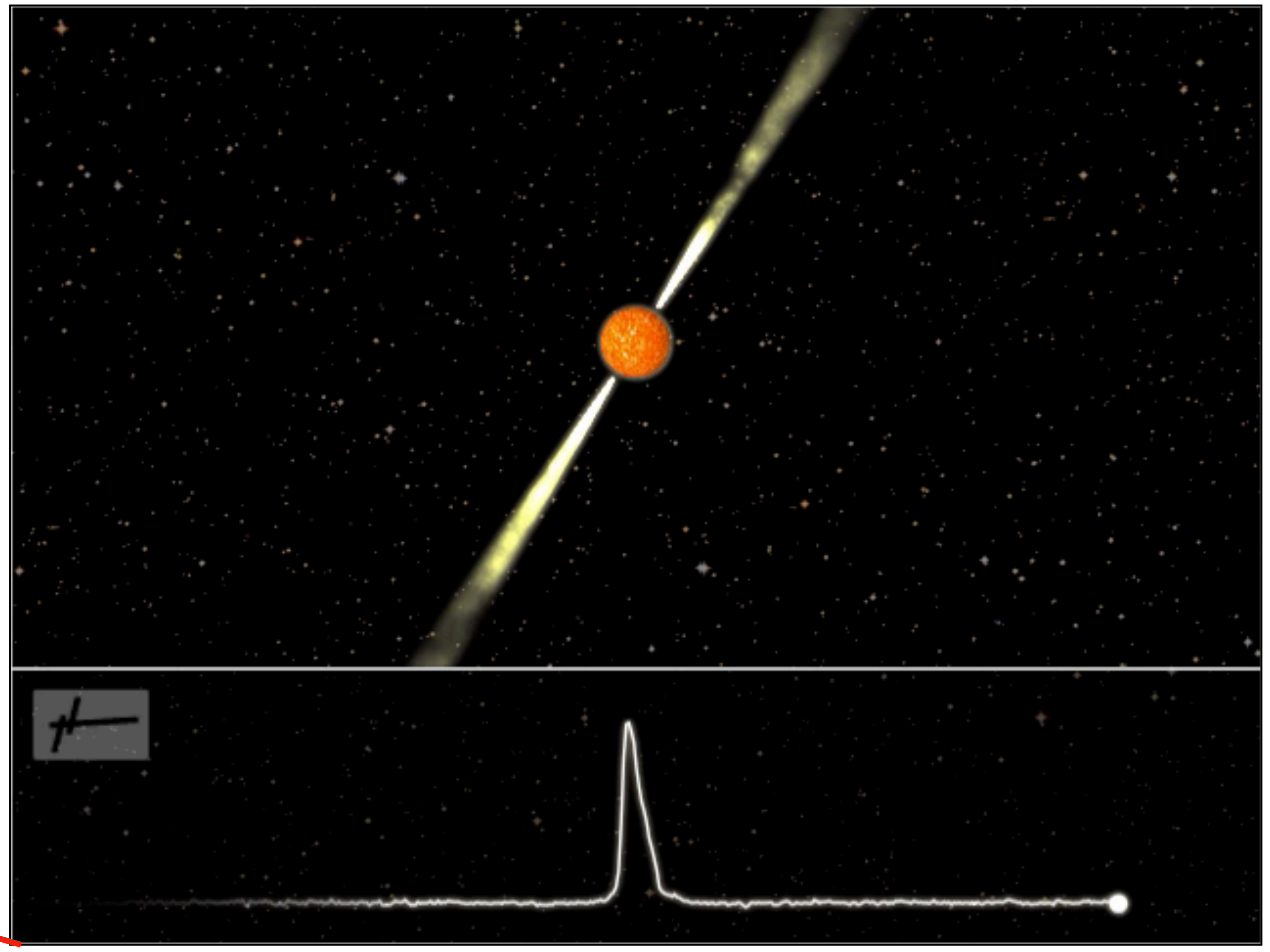


Image credit: X-ray: NASA/Chandra; Optical: Nasa/Hubble; Infrared: NASA/Spitzer.



Credit: J. van Leeuwen

Pulsars & Magnetars

- **Pulsars = Neutron stars = Compact remnants after supernova explosions**
- Magnetars = Subfamily of neutron stars with the highest magnetic fields [also: X-ray luminosity > spin-down energy]

- 4300+ pulsars known (as of June 2026)
- Different ways of classifying pulsars: B-field strength, Age, Energy, Binary/Isolated, Period, Period derivative, …
- **Extremely weak (uJy — mJy) → <u>need big collecting areas</u>**
- Three main subdivisions
  - Canonical / Normal, Millisecond, Magnetars

Canonical and millisecond pulsars usually *steep* radio spectrum
⇒ Become weak at (sub)mm- wavelengths

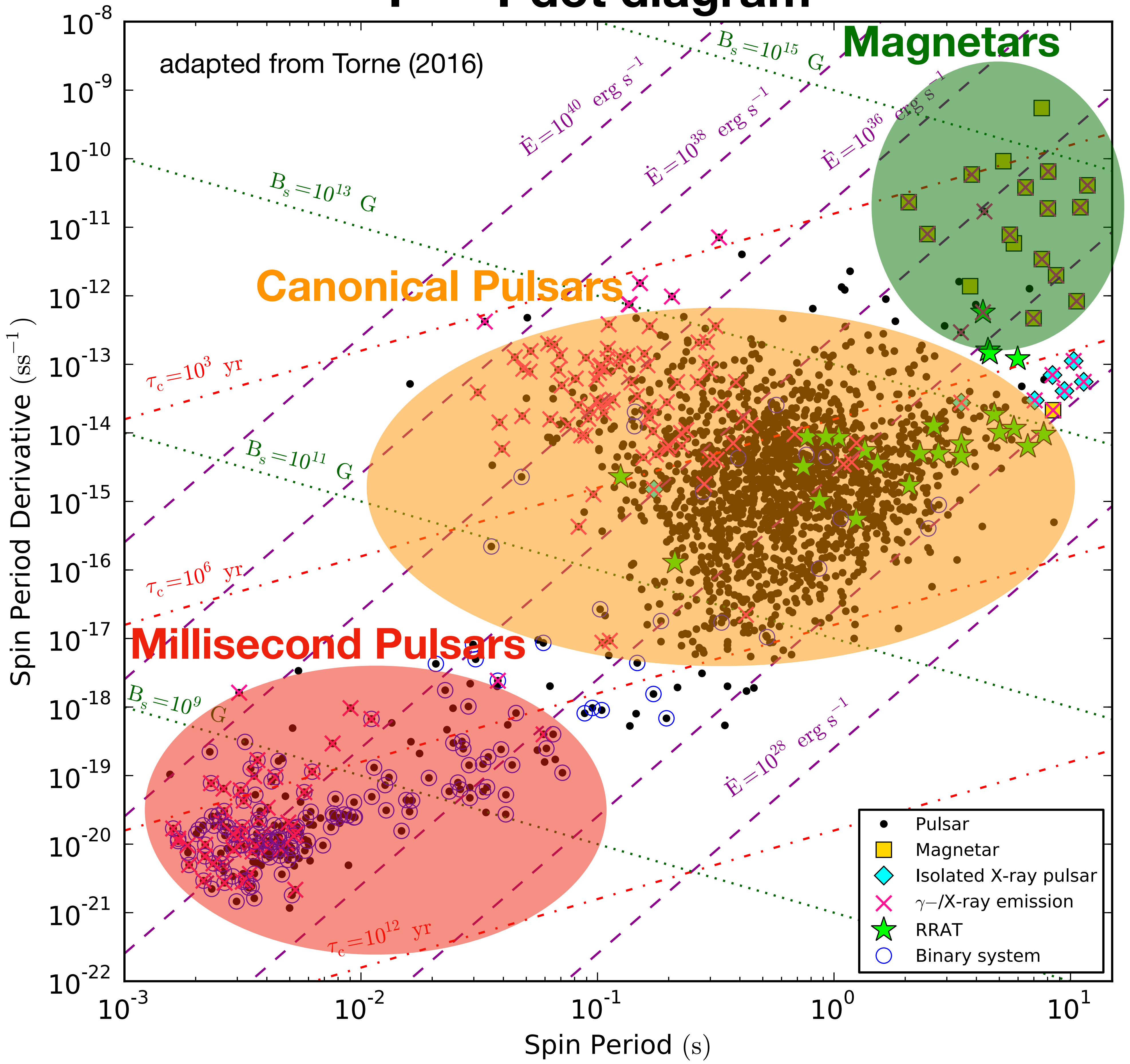
AtLAST

Magnetars usually *flat* (or inverted) spectrum in radio
⇒ <u>Can be detected at (sub)mm- wavelengths</u>

AtLAST

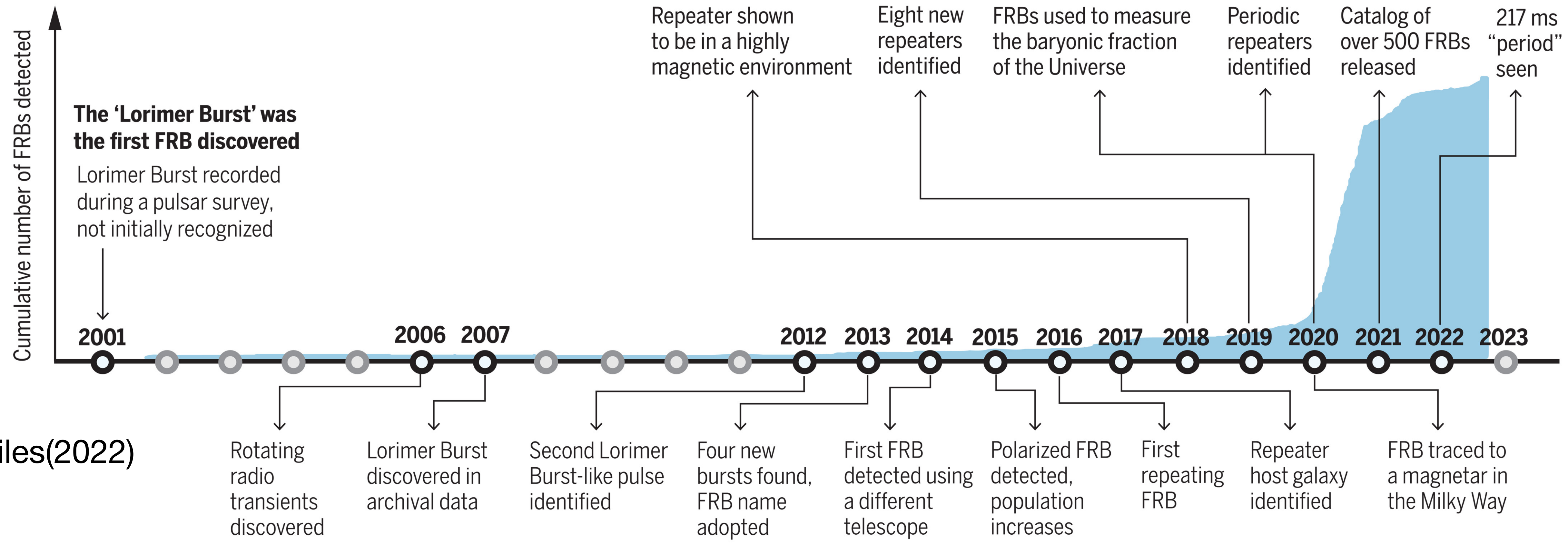
see e.g., Camilo et al. (2007), Torne et al. (2015, 2017)

P — Pdot diagram



Fast Transients

- Within scope of this presentation: Fast Radio Bursts (but also check Long-period pulsars and Long-period transients)
- "Recent" discovery, **rapidly evolving fields**, hot topics: New sources / emission mechanisms, challenging established models
- Most FRBs are at cosmological distances → probe Milky Way + host galaxy and intergalactic medium. Unique astrophysical tools.
- Unknown origin (but some are magnetars) → **(sub)mm- detections would help identifying the emitting sources and mechanisms**
- Some repeat, most do not → **Need large FoV to "catch" them**
- Weak (~mJy) → **Need large collecting area to detected them**

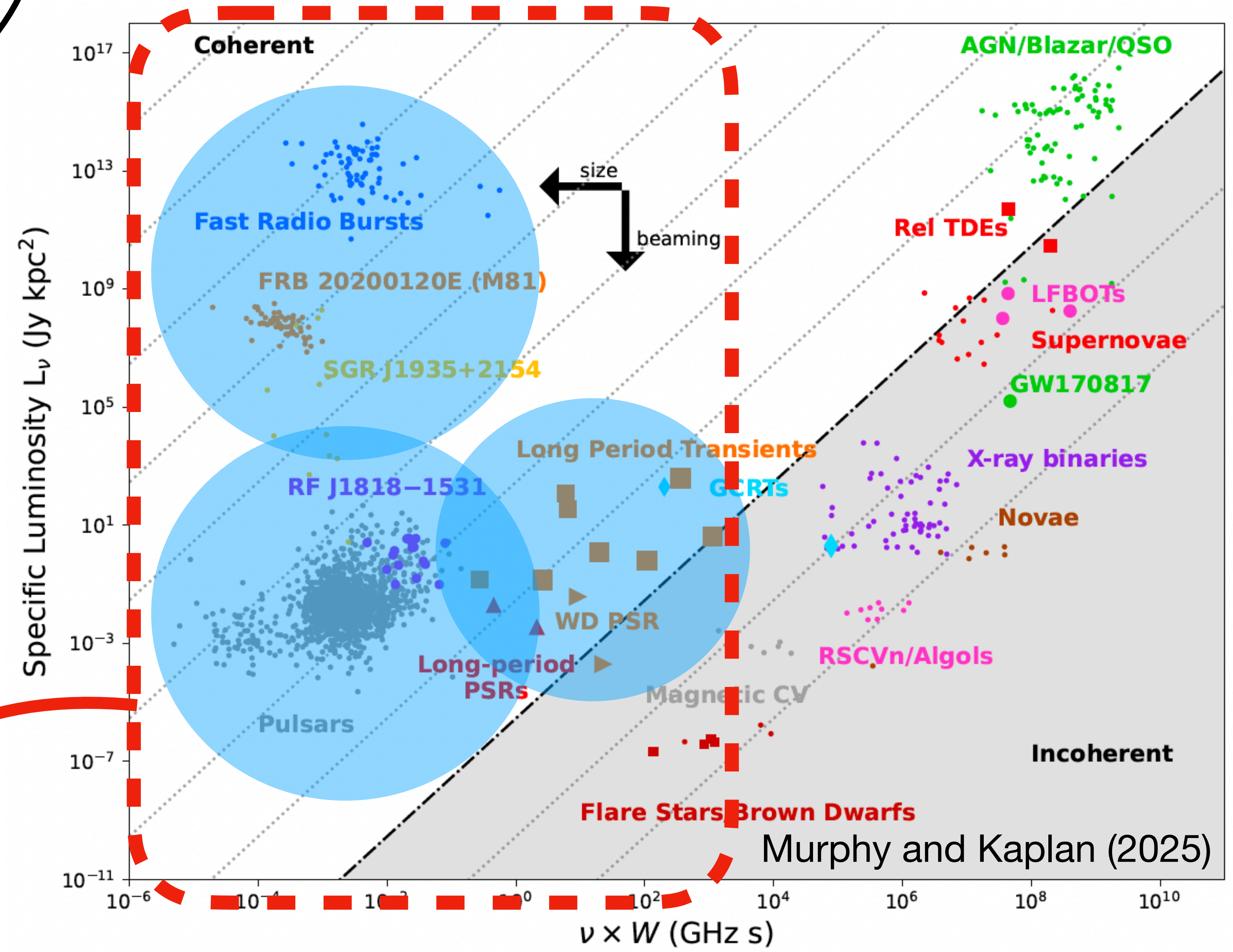


Bailes(2022)

First FRB discovery 2007. Second FRB in 2013. Today 4500+.
Rate of few 1000s per sky per day
See Lorimer, McLaughlin & Bailes (2024) for a review

AtLAST

Space largely unexplored above ν_{obs} = 10 GHz



Murphy and Kaplan (2025)

First long period transient / pulsar discovery 2022
Today 20. Very new population of sources!

Pulsars, Magnetars & Fast Transients at (sub)mm-λ

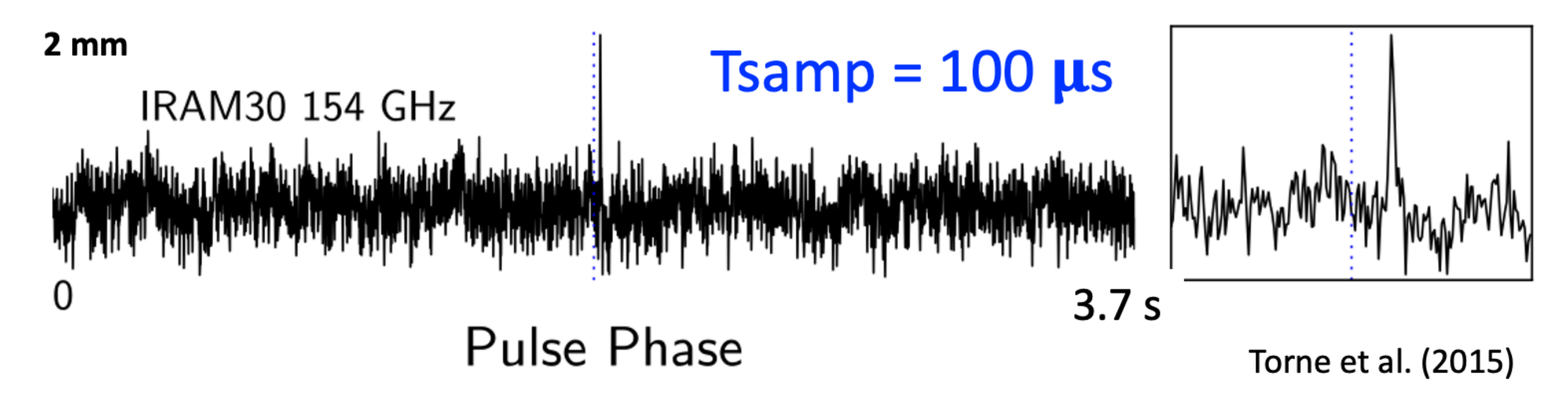
Can we observe pulsars, magnetars & (fast) transients at (sub)mm- wavelengths?

YES! - Currently "Enabled" Facilities

- **A few mm- radio telescopes can already do fast time sampling modes (<< 1 second)**
  - ➡ Usually non-standard modes. Require experts for setup and data reduction.
  - ➡ Tested in different receiver technology: SiS, KID, TES

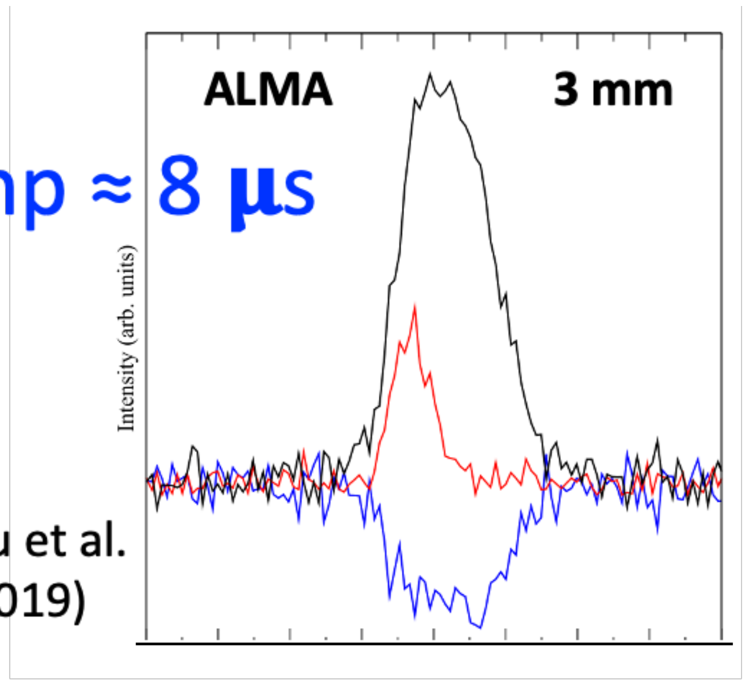
Some examples:

PSR J1745-2900



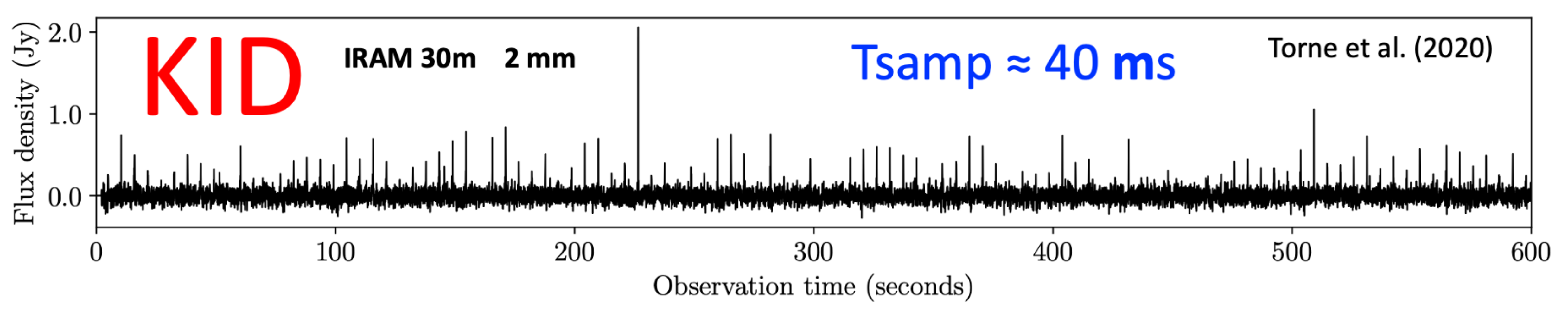
SiS

Tsamp ≈ 8 µs

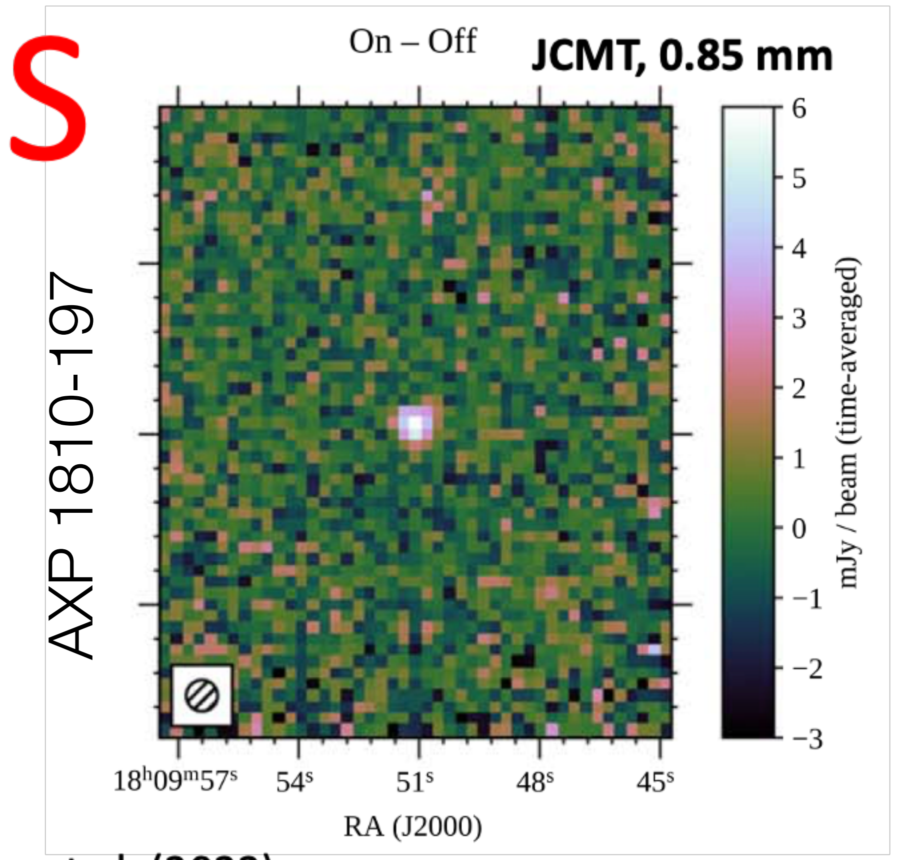


Vela pulsar

AXP 1810-197



TES



Torne, Bell, Bintley et al. (2022)

Tsamp ≈ 5 ms

IRAM 30m Telescope

James Clerk Maxwell Telescope

ALMA

Pulsars, Magnetars & Fast Transients at (sub)mm-λ

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Why / How can AtLAST play a major role in this field of astrophysics?

The Main Requirements

For persistent sources:

see e.g., Lorimer & Kramer (2004)

Minimum detectable flux density at S/N level

Good (sub)mm- site

$$S_{\rm min} = \beta \frac{(S/N_{\rm min})\, T_{\rm sys}}{G \sqrt{n_{\rm p}\, t_{\rm obs}\, \Delta\nu}} \quad \text{[Jy]}$$

Large collecting Area

Radiometer-like noise to integrate long

Large instantaneous bandwidths

For blind transient surveys:

from Cordes (2004)

Solid angle on sky

Observing time

$$A\Omega \left(\frac{T}{\Delta t} \right) \rightarrow \text{“large”}$$

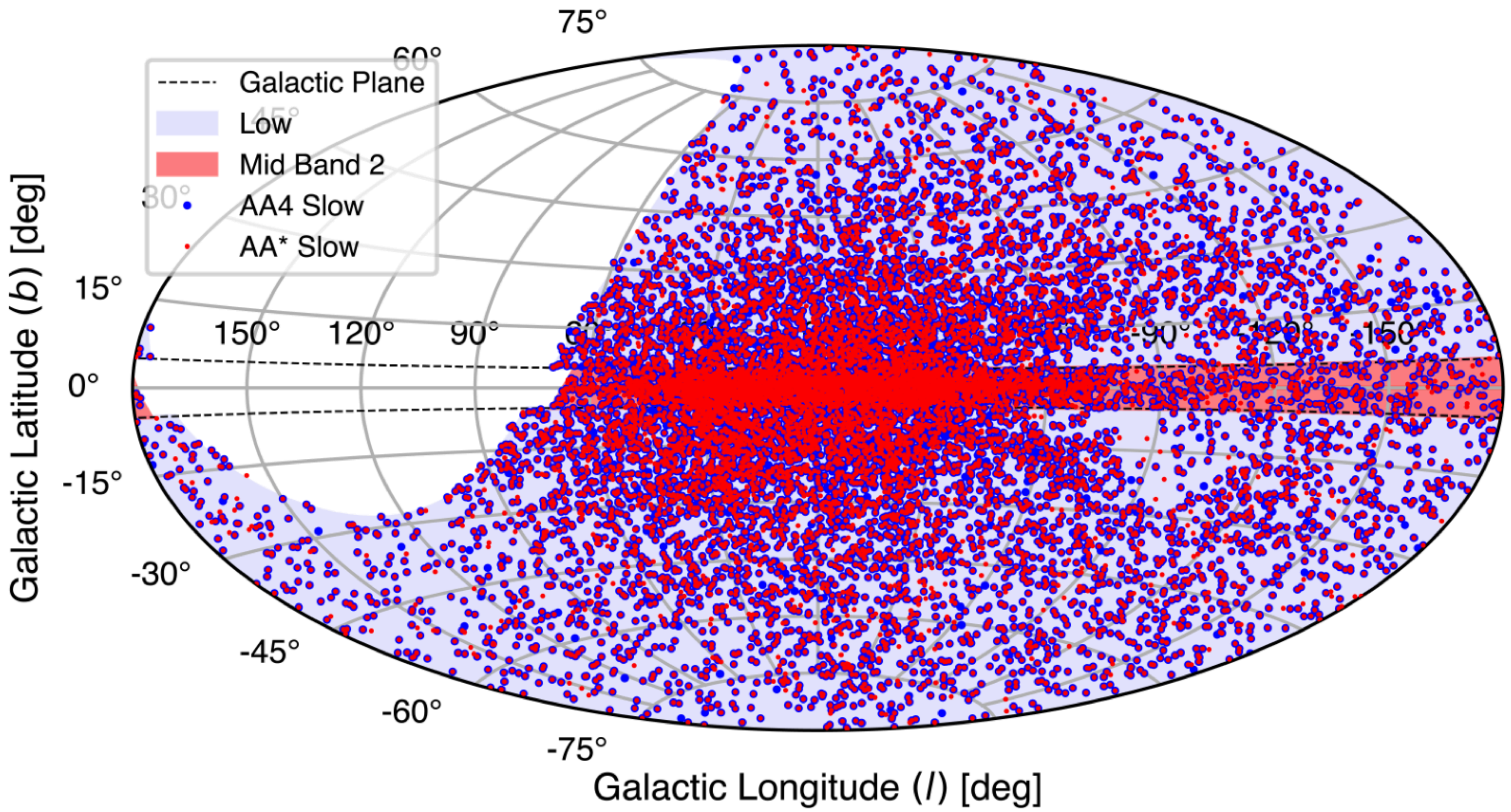
Collecting Area

Data time resolution

- **AtLAST superb in many of these parameters: Gain (Area), Tsys, Field-of-View**
- But do not forget: radiometer-like noise and data time resolution
  Note: some frequency resolution & polarisation information also highly desirable
- High time resolution ***and*** large Field-of-View? (The great combo: but data rate issues)
- Observing time for transient surveys → Be commensal (e.g, MeerTRAP, Bezuidenhout *et al.* 2022)

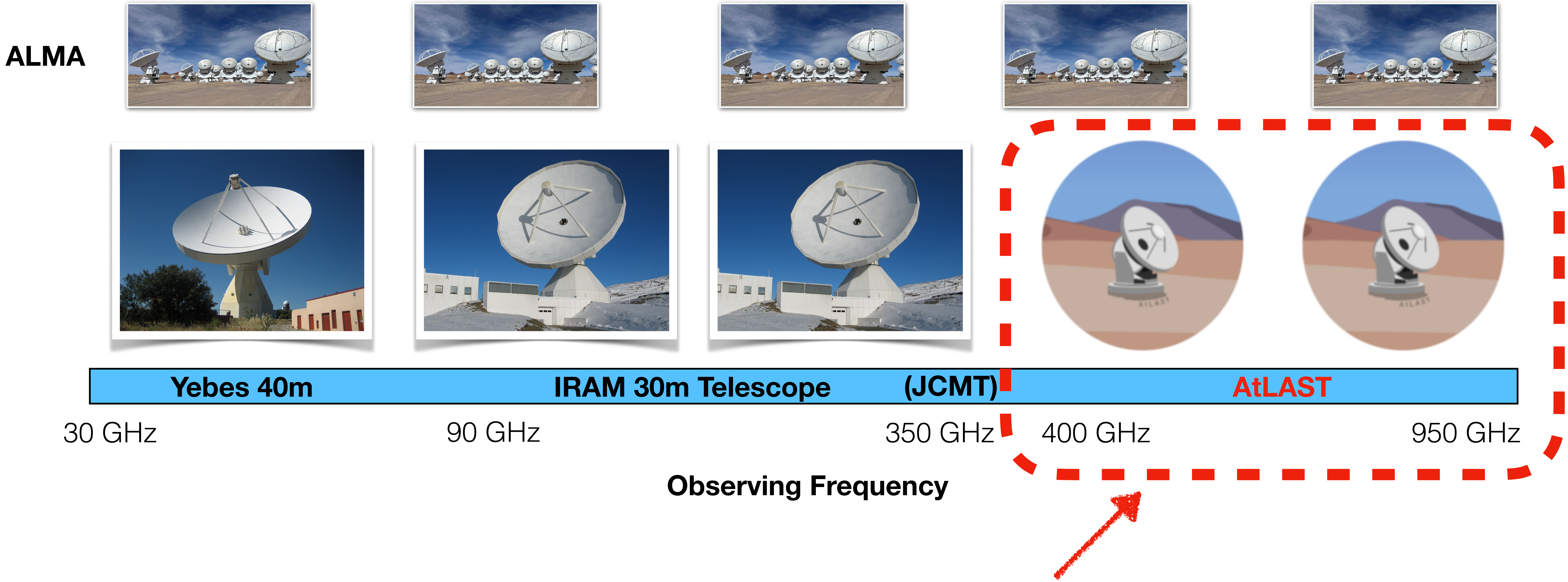
Access to the Southern Sky

- **AtLAST covers the southern sky!**
- About 1400 known pulsars with Dec < -30 deg are not visible from the IRAM 30m Telescope (nor NOEMA or JCMT)
- About 30 pulsars with ~flat spectral index lie in this range of Dec < -30 deg [Great targets for AtLAST]
- Note: Square Kilometre Array (SKA) expected to detect another ~10000 pulsars



Keane *et al.* (2025)

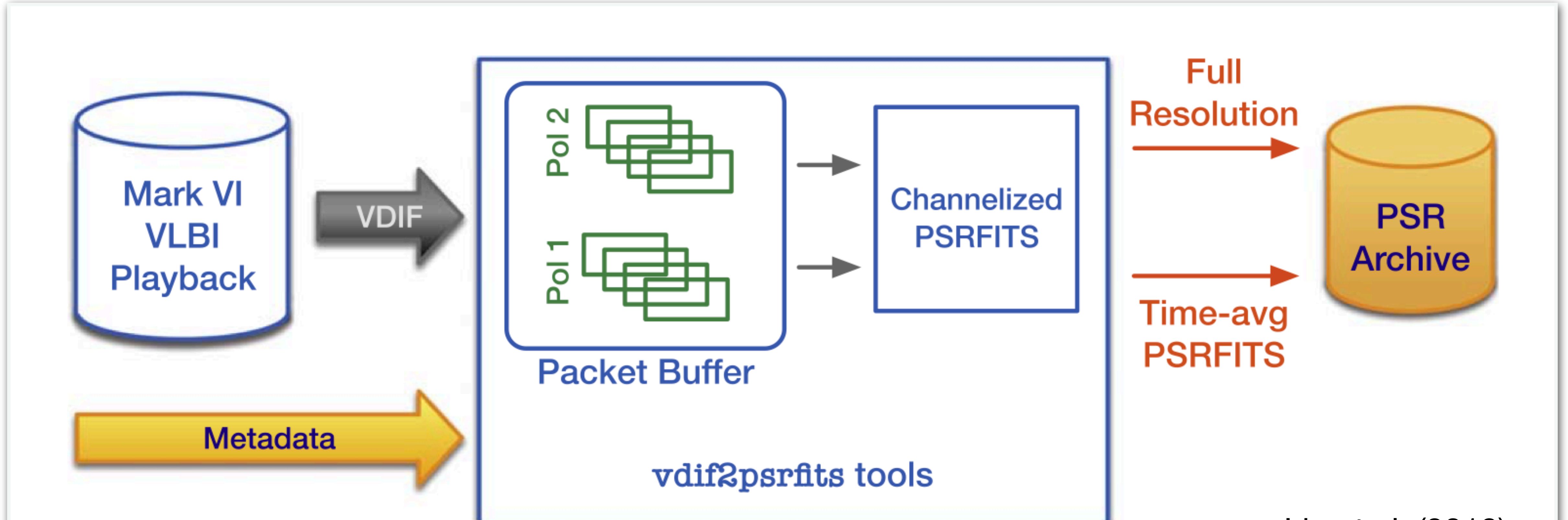
Access to extended frequency range > 350 GHz



- **Above ~350 GHz, we need AtLAST to really enable the pulsars, magnetars & fast transients science case**
- Current facilities not efficient enough above ~350 GHz, or collecting area small (e.g., JCMT)
- ALMA phasing mode not yet enabled above 350 GHz, and its Field-of-View is tiny

Initial Ultra-Fast Time-Domain System

- Very Long Baseline Interferometry (VLBI) system
- Records data in baseband → Enables high resolution data → Pulsars, Magnetars are FRBs ✅
- Overkill, limited bandwidth, and only one beam, but “free” if AtLAST joins VLBI
- Mode successfully used in IRAM 30m, ALMA and Large Millimeter Telescope



Liu et al. (2019)

Matthews et al. (2018)

A Mark6 recorder. Credit: MIT/Haystack

Summary

* **Time Domain Science expanding into (sub)mm- regime**
  - Under-researched field, mainly by lack of enough sensitivity and FoV → exactly what AtLAST offers

* **Do not forget technical and operational requirements to fully enable it**
  - They are sometimes not included in design stages and it is difficult to adapt later

* **"Ultra-Fast" time domain (<< 1 second)**
  - Often not contemplated in (sub)mm- instrumental designs, but sometimes required

* **AtLAST excellent for Pulsars, Magnetars & Fast Transients science at sub(mm)-λ**
  - Large sensitivity key for all cases
  - Large FoV key for transient surveys → Unexplored parameter space = *big discovery potential!*

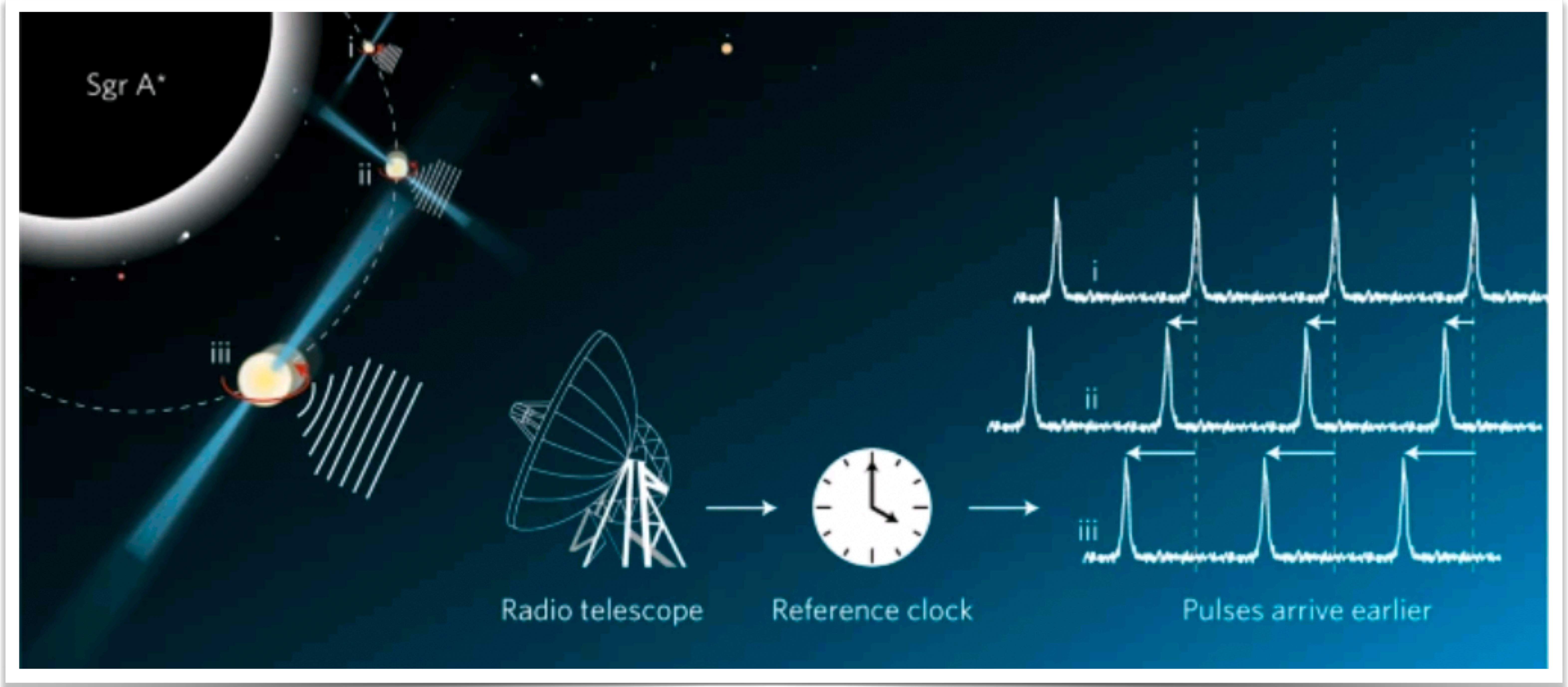
Questions? Thank you.

Pulsars, Magnetars & Fast Transients at (sub)mm-λ

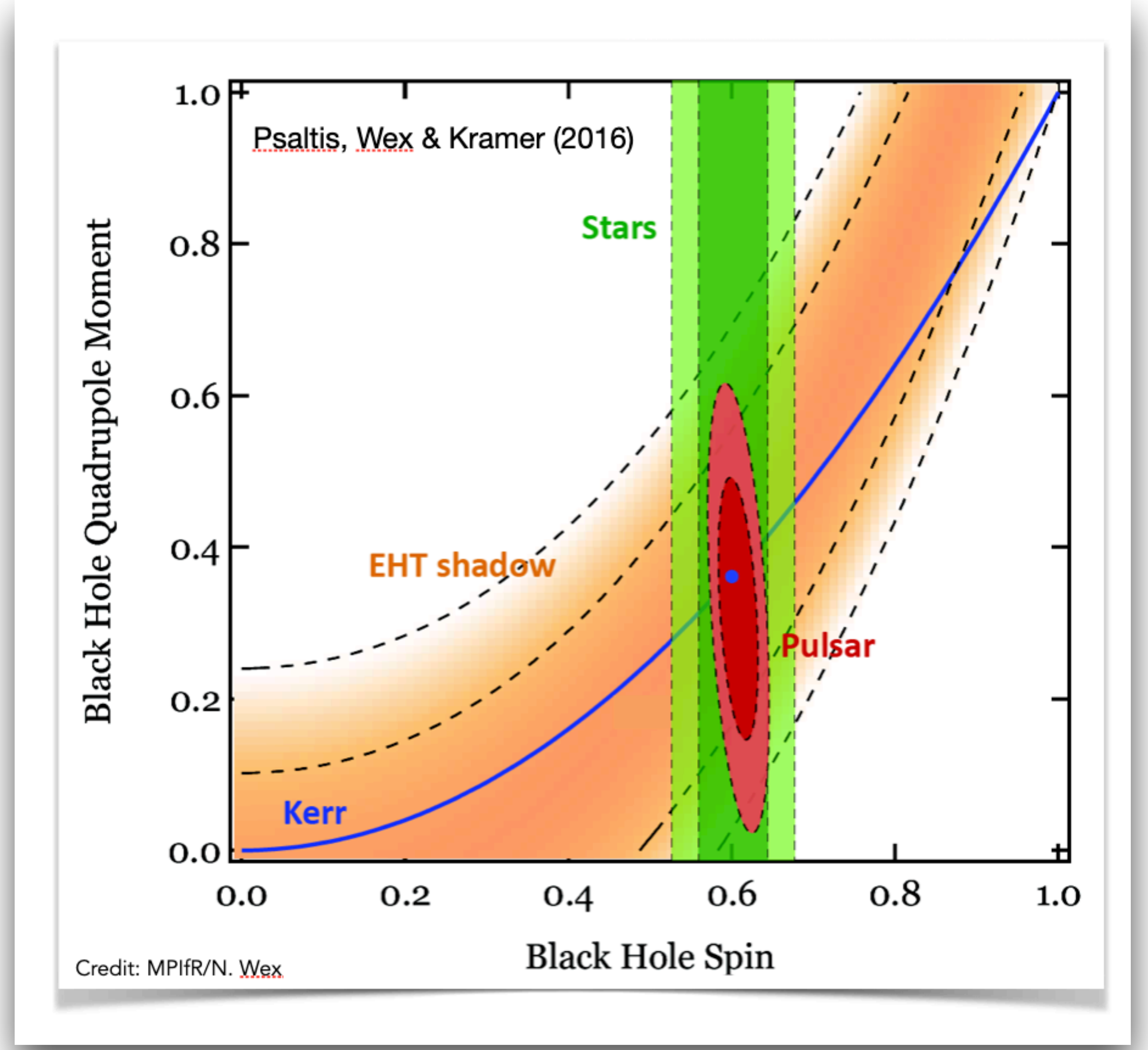
Backup Slides

A Word on Clock Accuracy

- Some time domain experiments require high accuracy in absolute time stamping
- Pulsar timing: absolute data time stamping needs 10–100 ns
- High time resolution systems should be able to provide absolute timing accuracy (≤ 100 ns)



Liu and Eatough (2017)



Advantages and Challenges of Sub(mm) Observations

- **Focusing on "Ultra-Fast" targets: Pulsars, Magnetars, FRBs, etc.**

- **Advantages**:
  - Submm- wavelengths (much) **less affected by ISM** (dispersion, scattering, RM)
    - ➡ Cheap (computationally speaking) data reduction in blind searches [good for real-time pipelines]
    - ➡ Emission from regions were lower frequencies are washed-out (e.g., by scattering)
  - Unexplored spectral regime: opportunities for science (e.g., emission mechanisms, **new discoveries**)

- **Challenges**:
  - Typically **very weak emission** and instruments' sensitivity low* (**hard to make detections**)
  - **Instruments and data reduction pipelines** at mm-wave typically **not designed for ultra-fast time sampling**
  - ISM imprints is what allows for a **celestial identification** of signal **versus RFI**
    - ➡ *Hint: Polarisation is your friend (need if possible pol. info)*
    - ➡ *Hint: Pulse morphology is your other friend (need high time resolution)*

* compared to low-frequency radio facilities (Gain, Tsys)

Ultra-Fast Transients at (sub)mm- Wavelengths

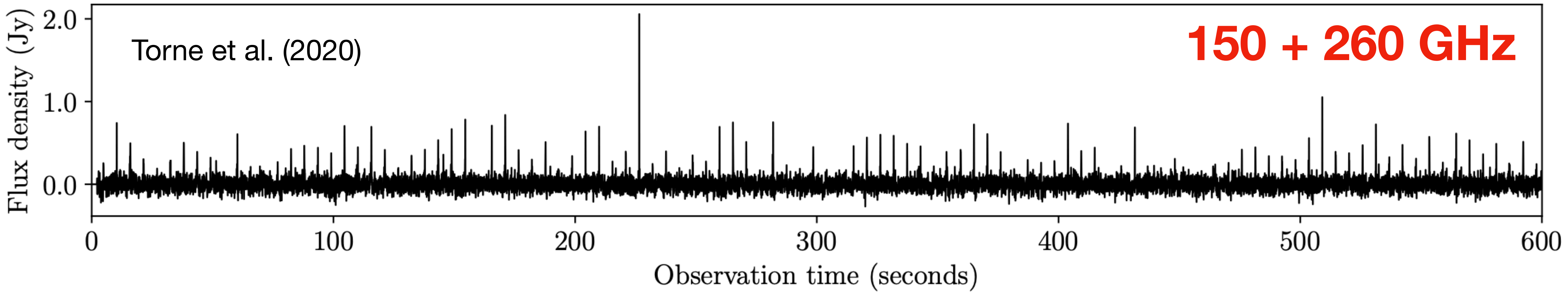
- **Active Radio Magnetars** see e.g., Camilo et al. (2007), Torne et al. (2015, 2017, 2020, 2022)
  - Flat (or inverted) radio spectra → can be bright at mm- waves
  - Best for testing instruments or methods due to brightness

- **Normal pulsars** see e.g., Liu et al. (2019)
  - Weak, but steady (unlike magnetars). Giant pulse regime unexplored.
  - Good for calibration purposes

- **Fast Radio Bursts** see e.g., Wharton et al. (2025)
  - Potential breakthrough (link with magnetars, FRB emission physics, …)
  - mm- wave perhaps the way to detected FRBs that are ultra-scattered at lower wavelengths
  - No FRB detection above 8 GHz to date (Did we try enough?)

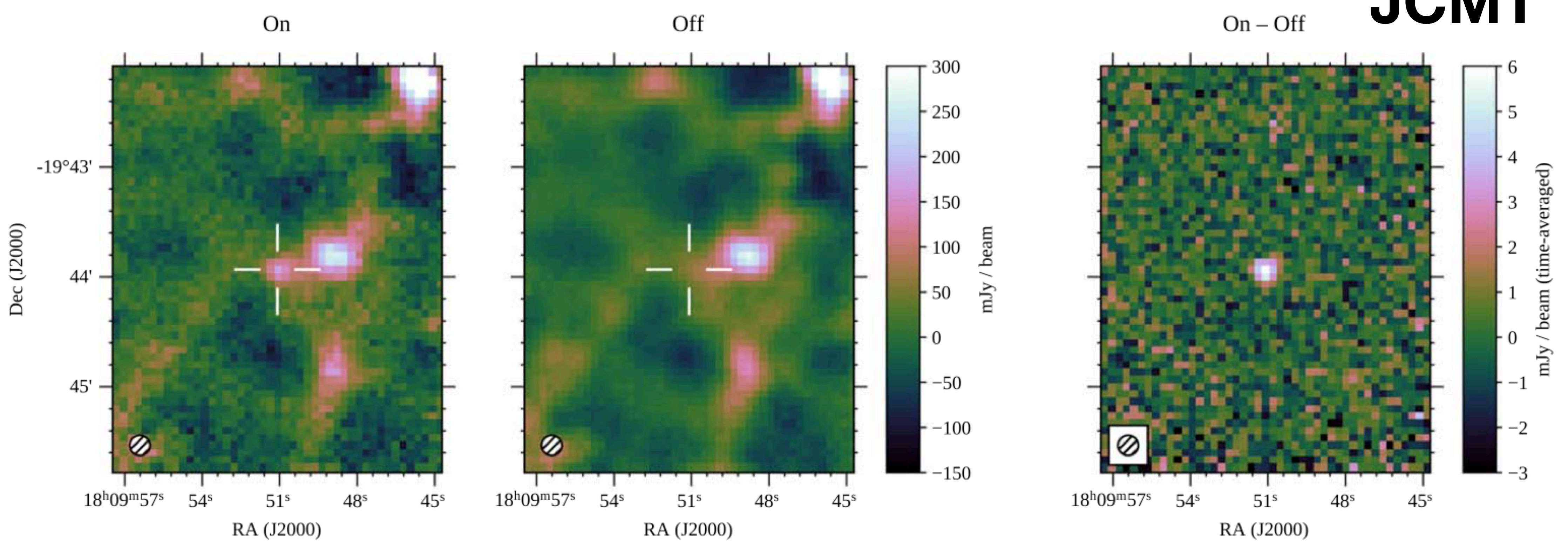
- **Blind Surveys for the Unknown**

(Sub)mm- Time Domain Science — A few examples II



IRAM 30m

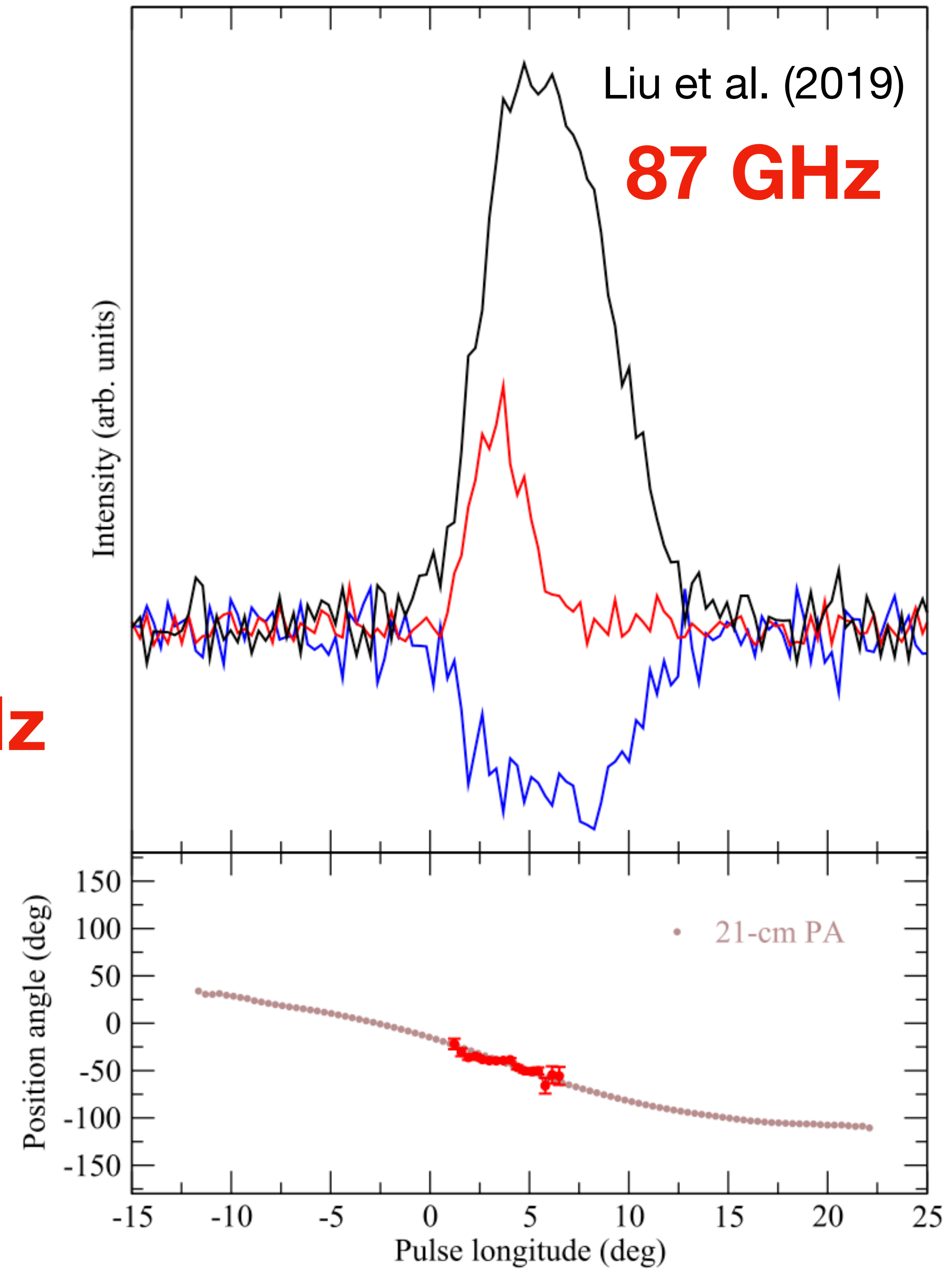
JCMT



5.54 s

Torne et al. (2022) **350 to 660 GHz**

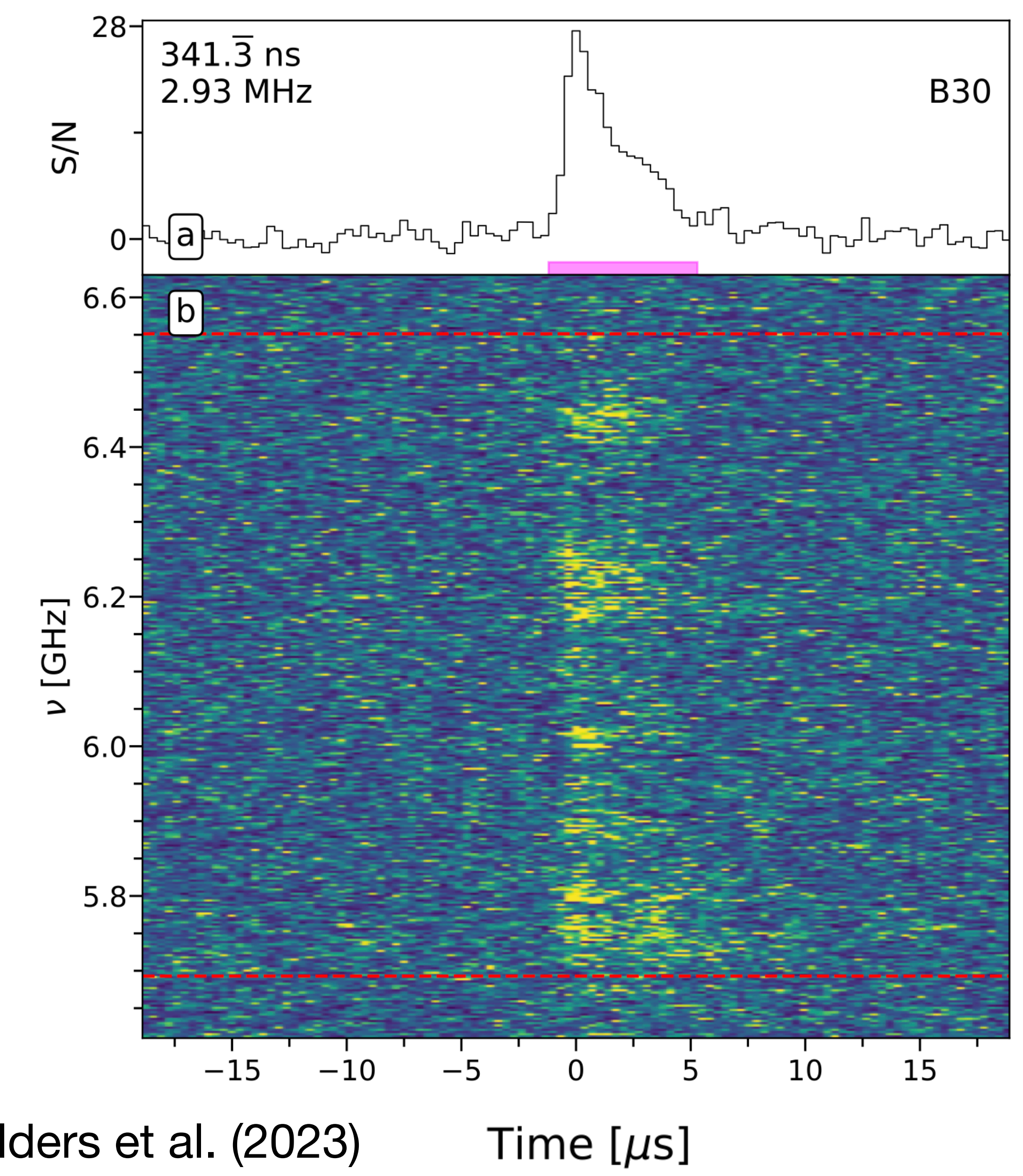
ALMA



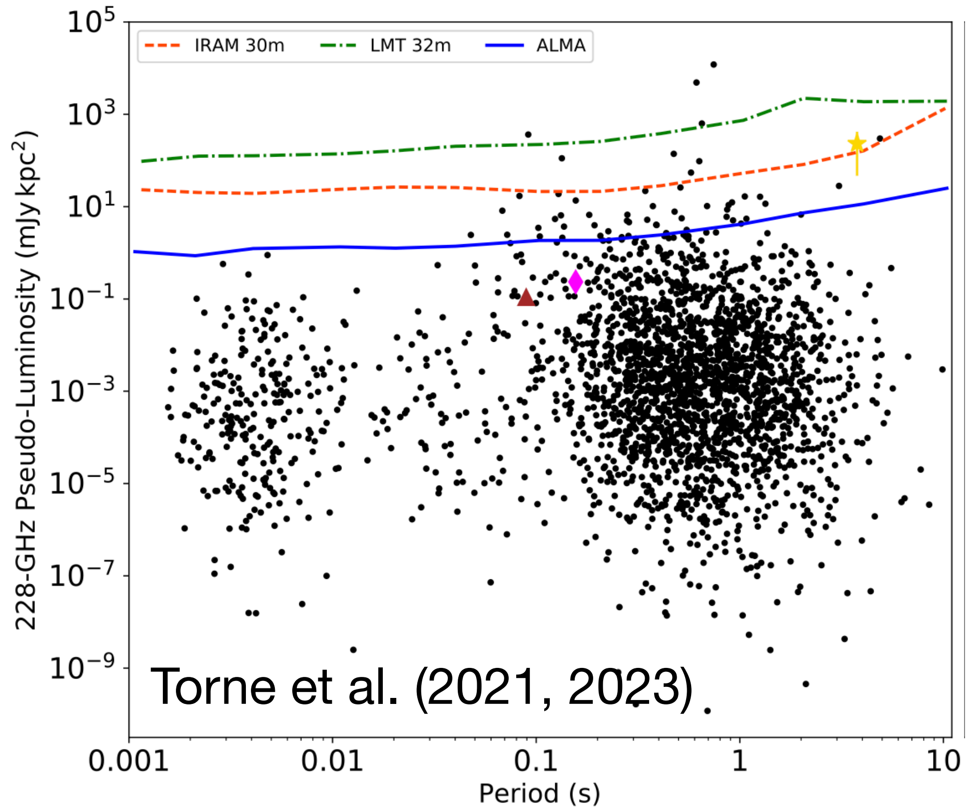
10 ms

GBT

Fast Radio Bursts
(Ultra-fast bursts from FRB20121002A)



Snelders et al. (2023)



Pulsar and Magnetar emission studies at (sub)mm- wavelengths (XTE J1810-197 and Vela)

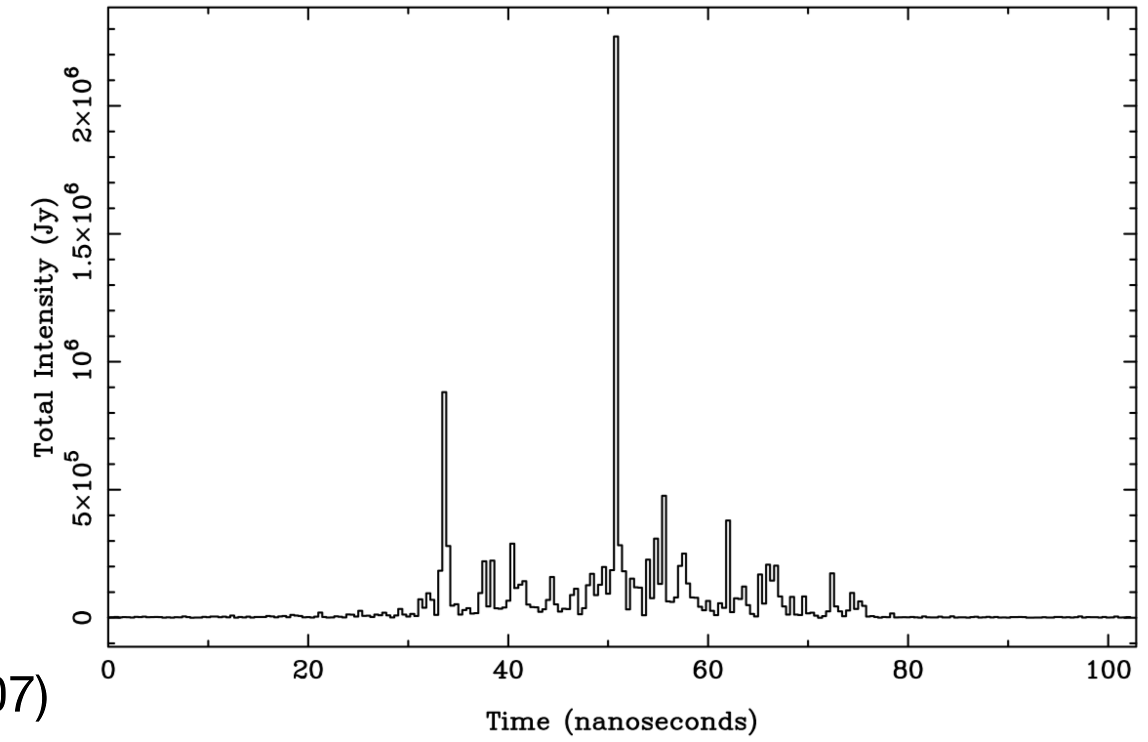
87 GHz to 230 GHz

Searches for pulsars around Sgr A* at mm-λ

ALMA, IRAM 30m, LMT

Arecibo

Crab Pulsar Nanoshots



Hankins & Eilek (2007)