Probing the Most Extreme Environments through Very High Resolution Radio Observations

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Joint Institute for VLBI ERIC (JIVE) & ASTRON

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JIVE30 Joint Institute for VLBI ERIC

ASTRON 75

ASTROFLASH

PANTERA Stars

Hi, I am new here!

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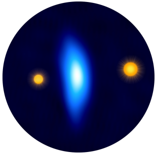
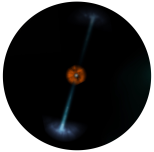
JIVE & ASTRON at Dwingeloo

Radio astronomer
follow up of high-energy transients



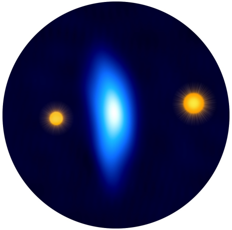
High-Energy Binaries



Gamma-Ray Bursts

Fast Radio Bursts

In this talk…

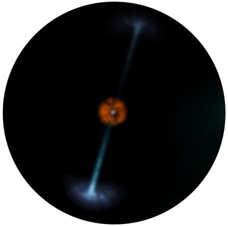


Novae

(Hadrons)

Colliding Wind Binaries

(Cosmic Rays)



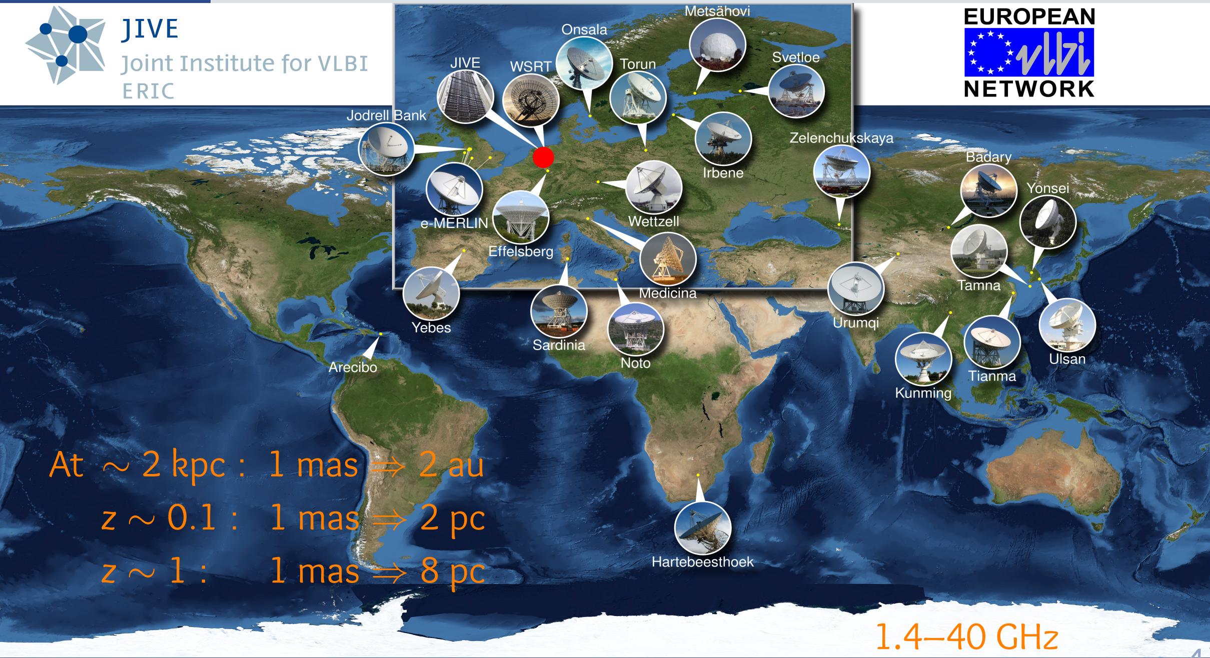
Gamma-Ray Bursts

Fast Radio Bursts

(Photons & Baryons)

JIVE
Joint Institute for VLBI
ERIC

EUROPEAN VLBI NETWORK



At ~ 2 kpc : 1 mas $\Rightarrow$ 2 au

$z \sim 0.1$: 1 mas $\Rightarrow$ 2 pc

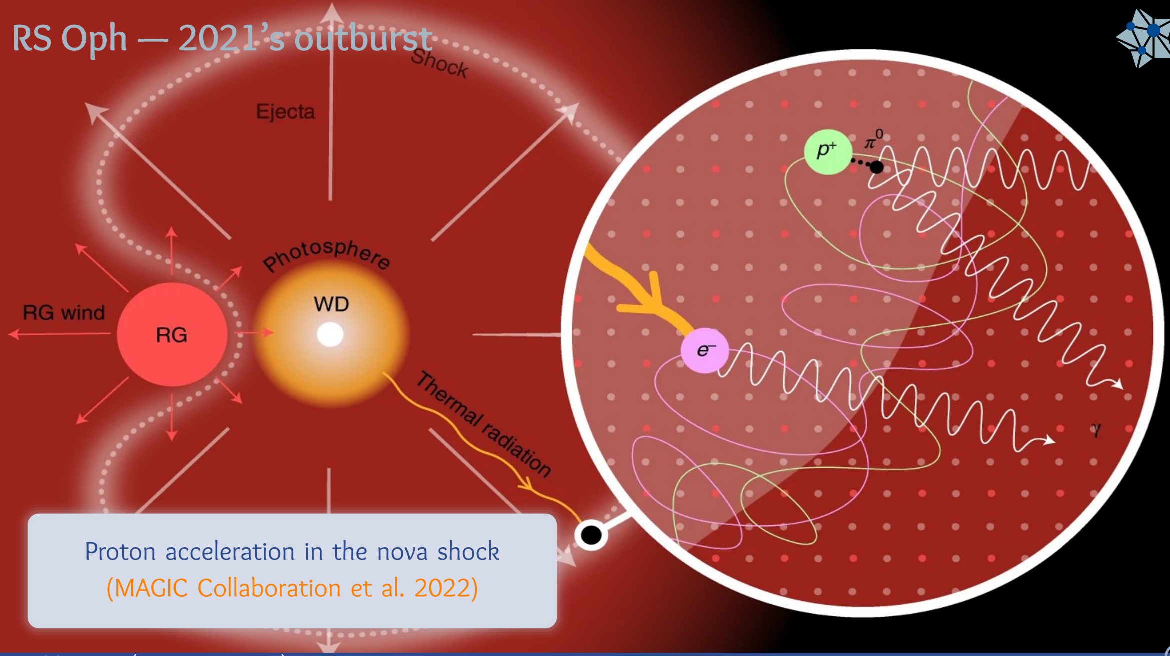
$z \sim 1$: 1 mas $\Rightarrow$ 8 pc

1.4–40 GHz

Novae

Recurrent outbursts from white dwarf/low-mass star systems

RS Oph — 2021's outburst



Proton acceleration in the nova shock
(MAGIC Collaboration et al. 2022)

RS Oph — 2021's outburst

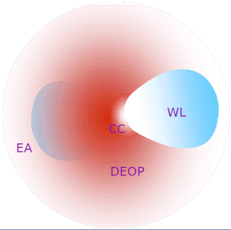
Radio campaign 14–320 d post-outburst.

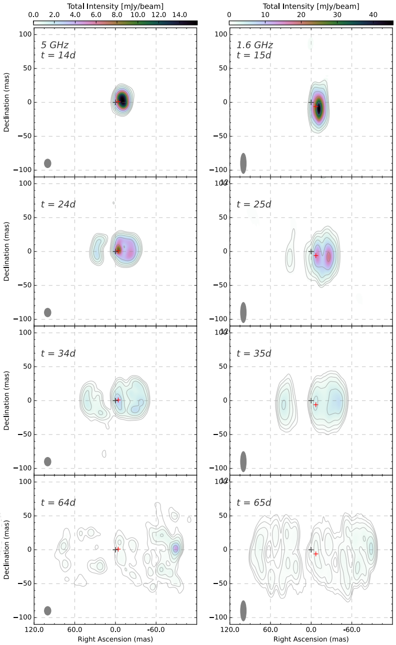
Early results in (Munari, Giroletti, Marcote et al. 2022).
Final results in Rocco et al. (2024, in prep)

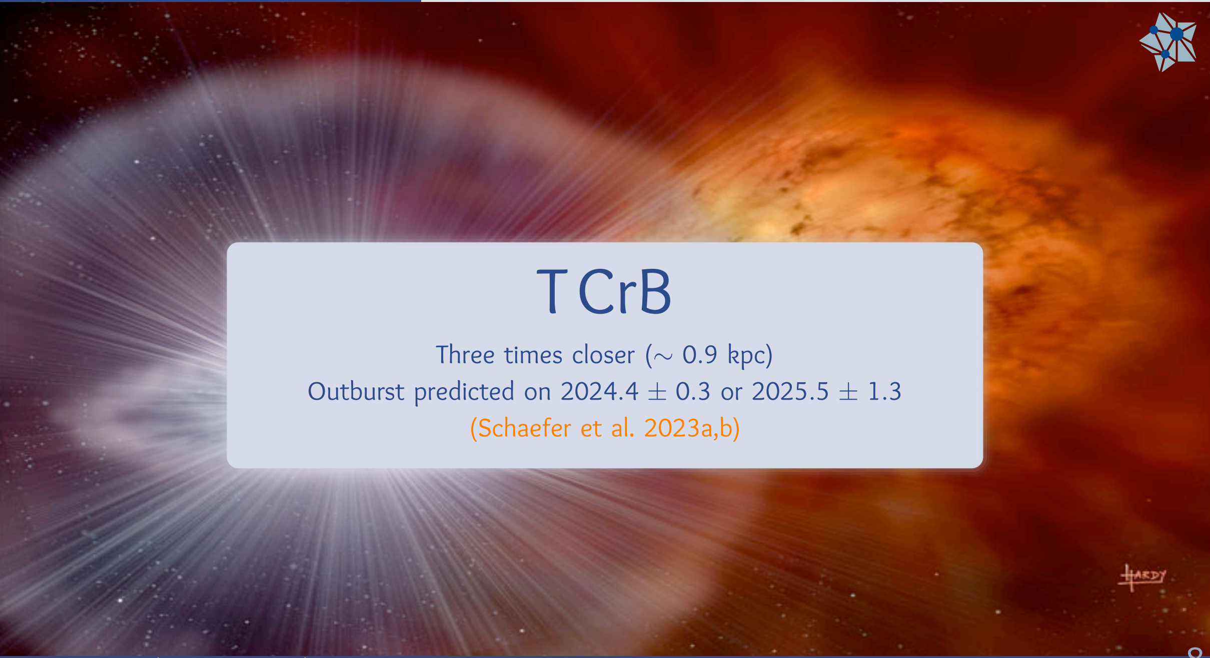
Expansion velocity of $\sim 7\,000$ km s^{-1}

Central and compact core
Bipolar outflow up to ~ 540 AU (+65 d).

$\sim 4.3 \times 10^{-6}\ M_\odot$ at the DEOP,
$\sim 10\%$ accreted by the white dwarf.







T CrB

Three times closer ($\sim$ 0.9 kpc)

Outburst predicted on 2024.4 $\pm$ 0.3 or 2025.5 $\pm$ 1.3

(Schaefer et al. 2023a,b)

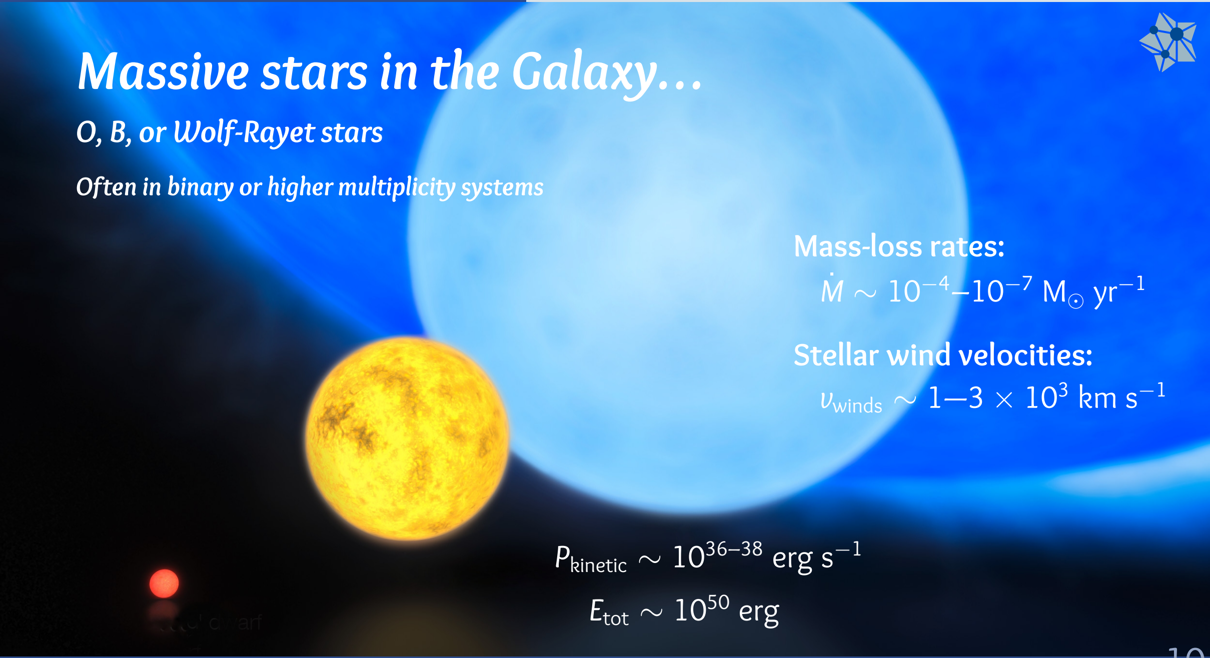
Colliding Wind Binaries

Most massive binary systems in our Galaxy

Massive stars in the Galaxy...

O, B, or Wolf-Rayet stars

Often in binary or higher multiplicity systems



Mass-loss rates:

$$\dot{M} \sim 10^{-4}\text{–}10^{-7}\ \mathrm{M_\odot\ yr^{-1}}$$

Stellar wind velocities:

$$v_{\mathrm{winds}} \sim 1\text{—}3 \times 10^{3}\ \mathrm{km\ s^{-1}}$$

$$P_{\mathrm{kinetic}} \sim 10^{36-38}\ \mathrm{erg\ s^{-1}}$$

$$E_{\mathrm{tot}} \sim 10^{50}\ \mathrm{erg}$$

PACWBs as contributors to the comic ray background?

Most Galactic cosmic rays come from SNe

With an energy injection ~ 0.01–1%:
CWBs convert $\sim 10^{32}$–10^{34} erg s^{-1}
into relativistic particles

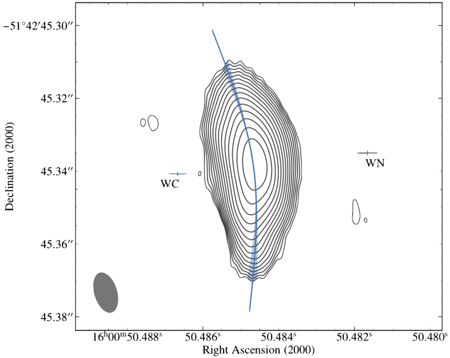
$\sim 10^5$ Galactic massive stars

Energy production rate of cosmic rays:
10^{37}–10^{39} erg s^{-1}

Up to $\sim 1\%$ of the total power in cosmic rays!

(de Becker et al. 2017; Seo et al. 2018
Kalyashova et al. 2019)

The most extreme CWBs in the Galaxy

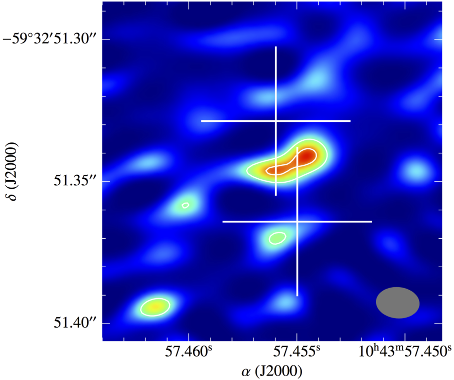


Apep

The first double Wolf-Rayet system

First radio and X-ray non-thermal emitter

(Marcote et al. 2021, MNRAS, 501, 2478)



HD 93129A

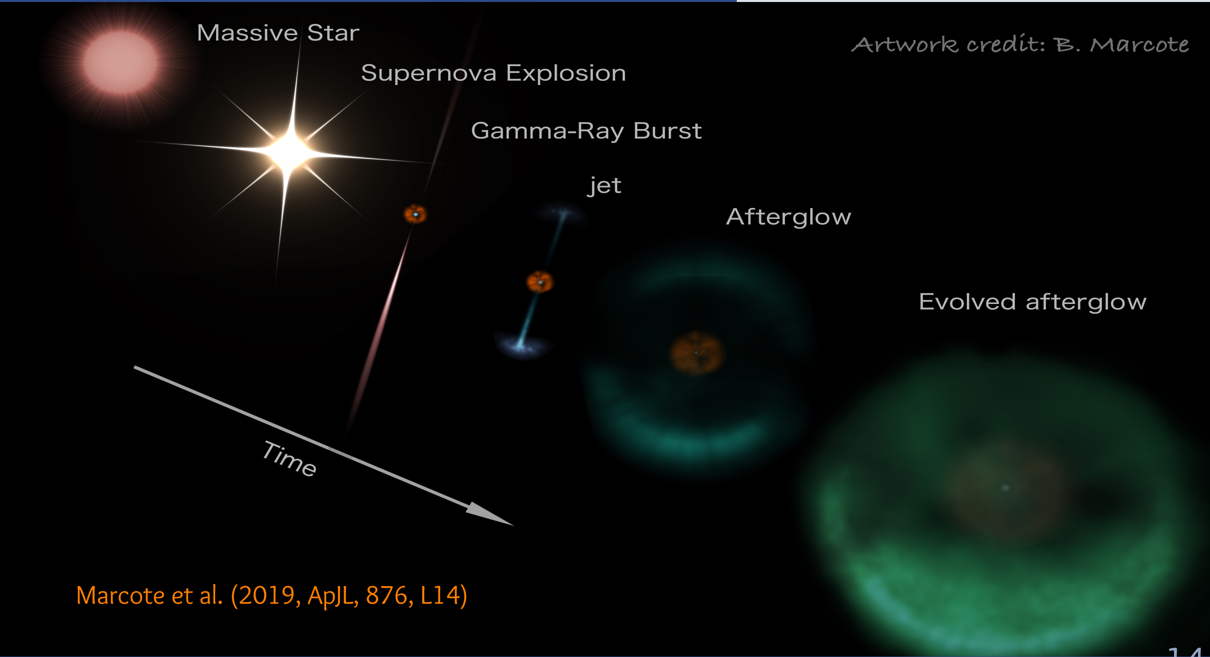
A double O binary system

with a total mass of 200 ± 45 $M_\odot$

(Benaglia, Marcote et al. 2015, A&A, 579, A99)

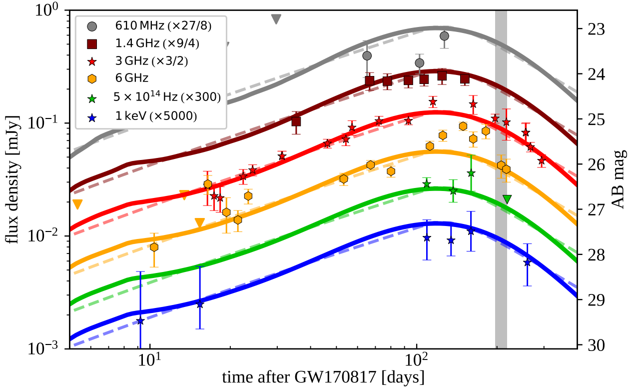
Gamma-Ray Bursts

Decoupling models with the radio afterglow



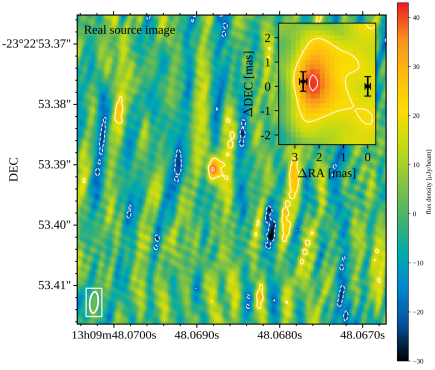
Marcote et al. (2019, ApJL, 876, L14)

The first NSB merger: GW 170817



Ghirlanda et al. (2019, Science, 363, 968)

Structure jet successfully broke through the ejecta



Narrow ($\theta_c = 3.4 \pm 1^\circ$), and energetic ($E_{iso} \approx 2.5 \times 10^{52}$ erg) jet, with a viewing angle of $\sim 15^\circ$.

The BOAT: GRB 221009A

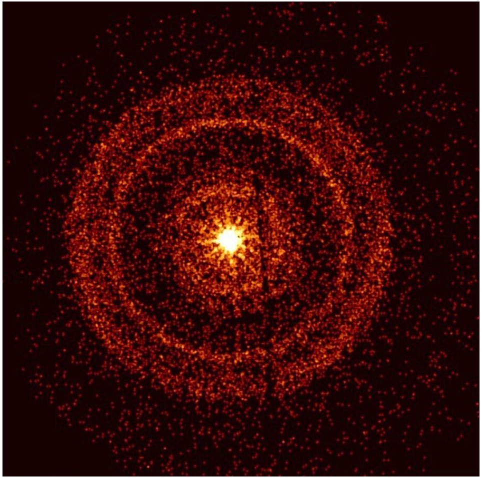
The Brightest Of All Time

Detected > 1 TeV.

First clear evidence for a (IC) component beyond synchrotron emission in the GRB afterglow, with comparable power.

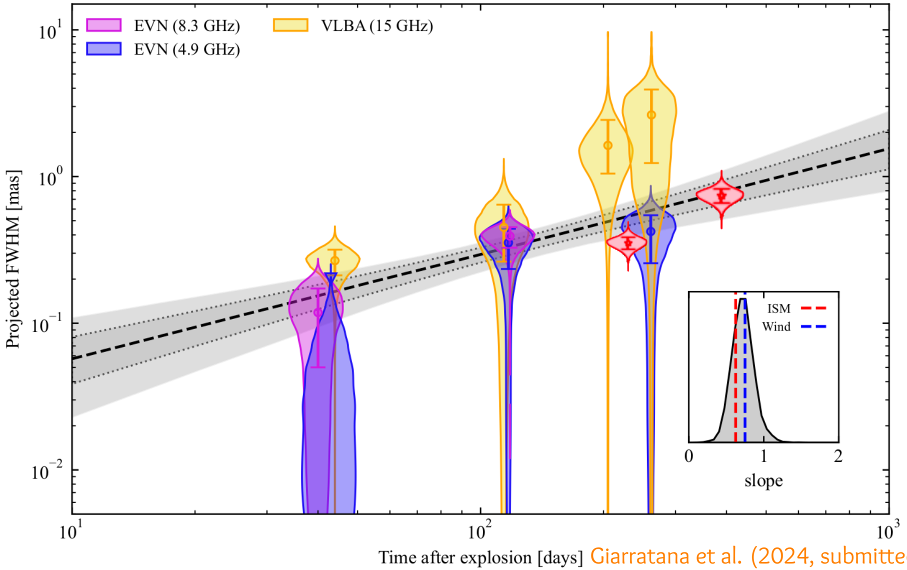
Reverse and forward shock contribution in the early radio afterglow.

We observed 40–261 d post-burst.



Swift's scattered rings (Tiengo et al. 2022)

The BOAT: GRB 221009A



Giarratana et al. (2024, submitted & in prep)

Fast Radio Bursts

Extremely bright ($\sim 10^{40}$ erg s^{-1}) millisecond-duration bursts (magnetars-related?)

What is a Fast Radio Burst (FRB)?

Fast
Duration of $\sim 1\ \mu s$–10 ms

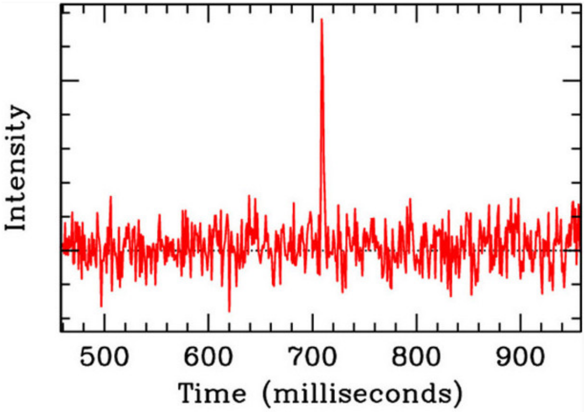
Radio
Observed at 0.2–8 GHz

Burst
Bright $\sim$ 0.1–100 Jy

Discovered by Lorimer et al. (2007)

Thousands FRBs reported
(*frbcat.org*; Petroff et al. 2016)

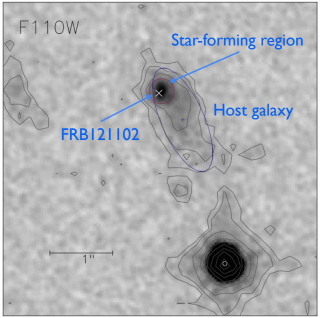
Only $\sim$ 5% exhibit multiple bursts
(so-called “repeaters”)



FRB 140514

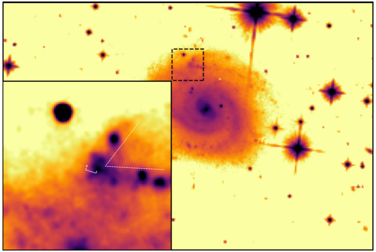
Localizing FRBs to milliarcsecond precision

FRB 20121102A



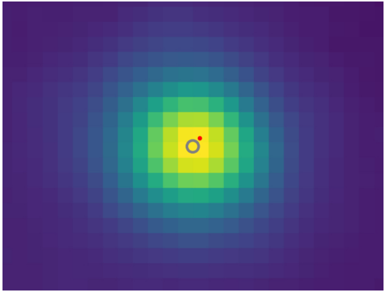
Chatterjee et al. (2017, Nat, 541, 58)
Marcote et al. (2017, ApJL, 834, 8)
Tendulkar et al. (2017, ApJL, 834, 7)
Bassa et al. (2017, ApJL, 843, 8)

FRB 20180916B



Marcote et al. (2020, Nature, 577, 190)
Tendulkar et al. (2021, ApJL, 908, L12)

FRB 20200120E



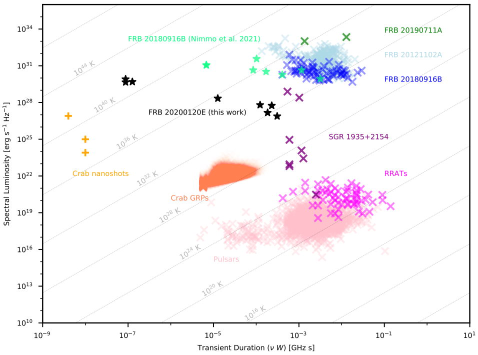
Kirsten, Marcote et al. (2022, Nat, 602, 585)
Nimmo et al. (2022, Nat Astr, 6, 393)

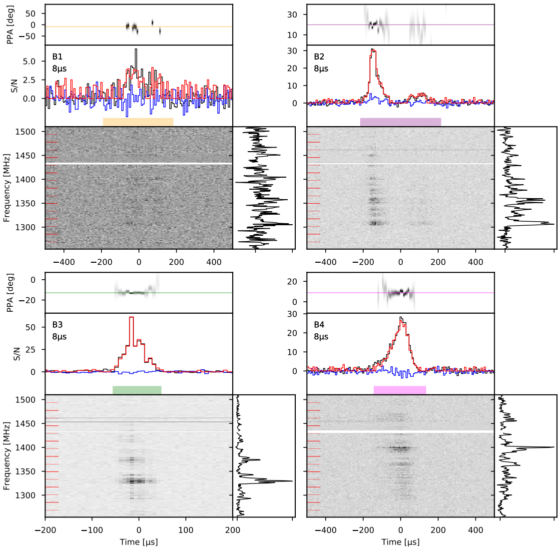
Star-forming dwarf galaxy

Star-forming spiral galaxy

Globular cluster!

FRB 20200120E: narrowest components for a FRB

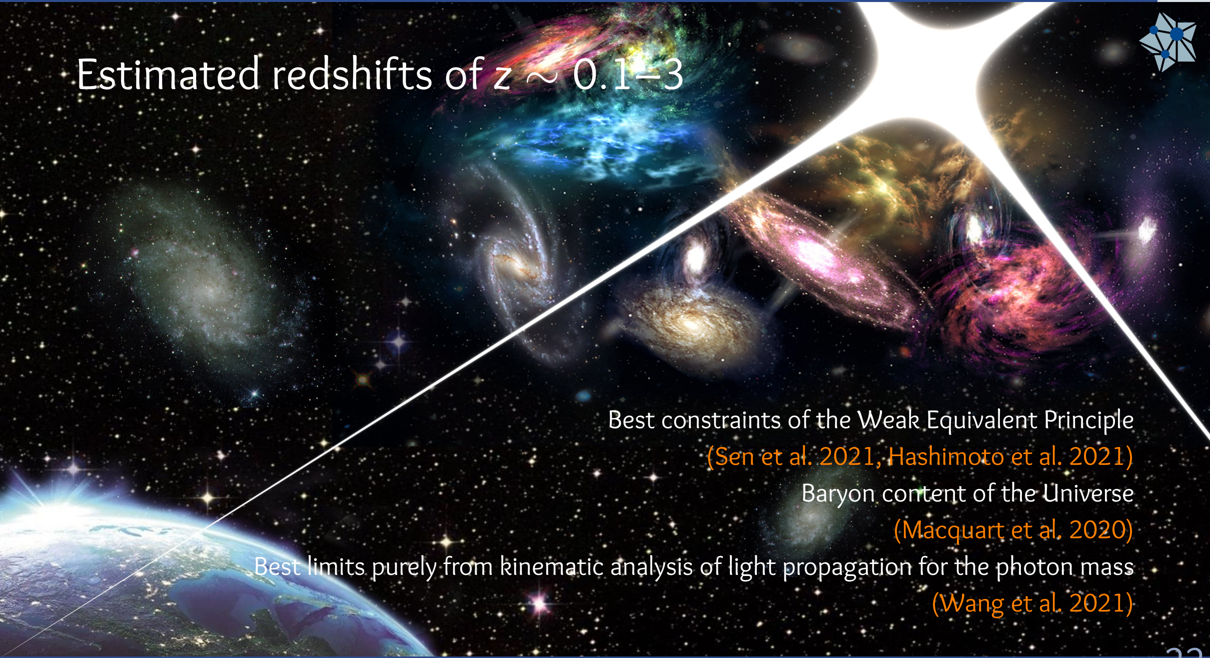




Sub-components as narrow as 60 ns

(Nimmo et al. 2022, Nature Astronomy, 6, 393)

Estimated redshifts of $z \sim 0.1$–3



Best constraints of the Weak Equivalent Principle
(Sen et al. 2021, Hashimoto et al. 2021)

Baryon content of the Universe
(Macquart et al. 2020)

Best limits purely from kinematic analysis of light propagation for the photon mass
(Wang et al. 2021)

Take home messages

The **radio domain** can significantly contribute to the high energies and particle physics!

VLBI at gigahertz frequencies is key to characterize a significant fraction of transient events.

Fast Radio Bursts will become particularly relevant in the coming years outside the radio domain

Plus other topics not discussed here (particle acceleration in gamma-ray binaries or connection between neutrino events and jet launching).

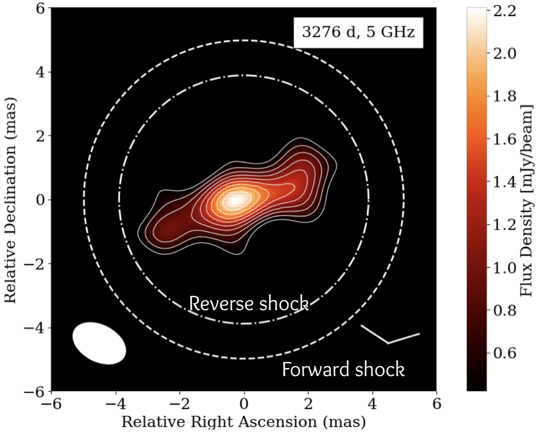
An extragalactic Pulsar Wind Nebula?

A $\sim$10-yr old supernova...

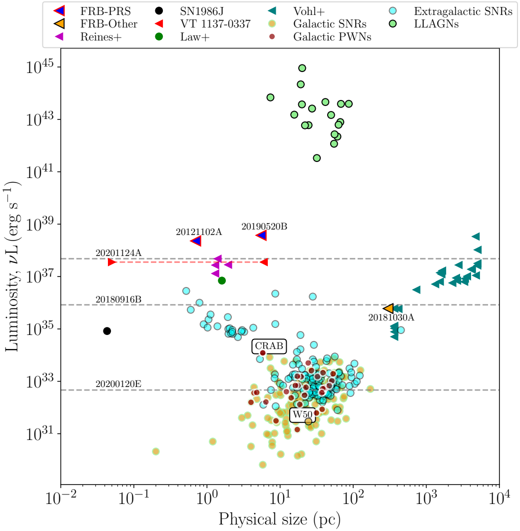
at $\sim$ 30 Mpc and 10^{42} erg release.

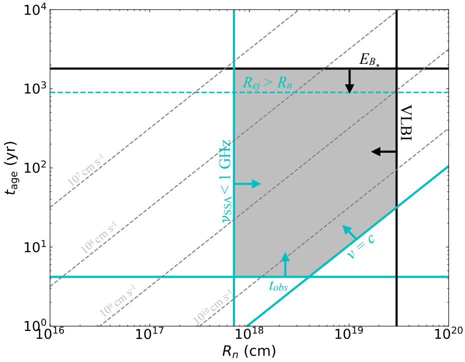
Incompatible with a supernova remnant

First PWN outside our Galaxy?



FRB 20190520B: a twin for the first repeater FRB 20121102A





For a magnetar wind nebula model

(Bhandari, Marcote, et al. 2023, ApJL, 958, L19)