ms-Millenia-Long Transients from Wind-Inflated ‘Hypernebulae’

Navin Sridhar

JSI Winds Throughout the Universe

12th Oct 2023

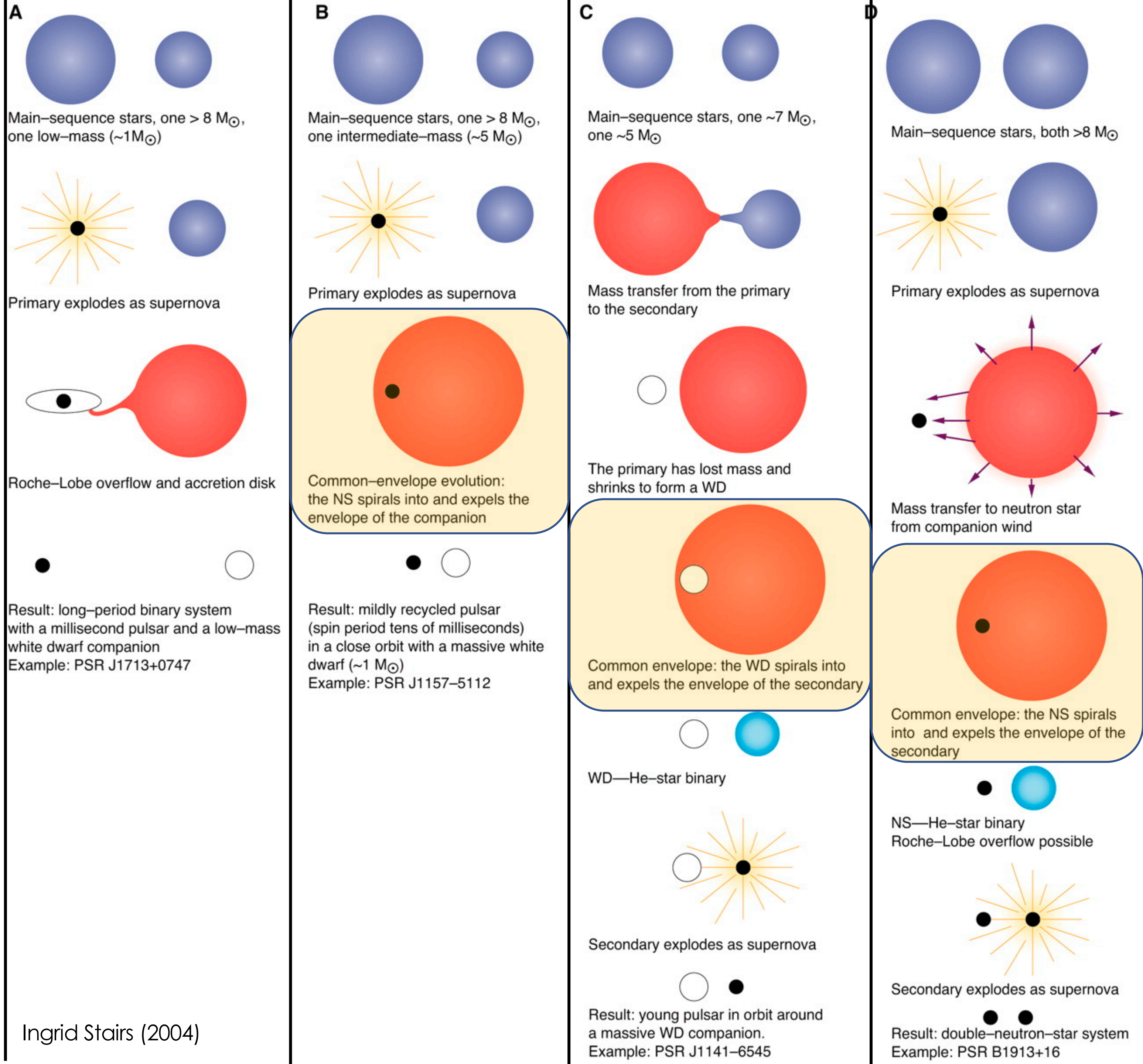
NASA
FINESST

THEORETICAL HIGH ENERGY ASTROPHYSICS

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

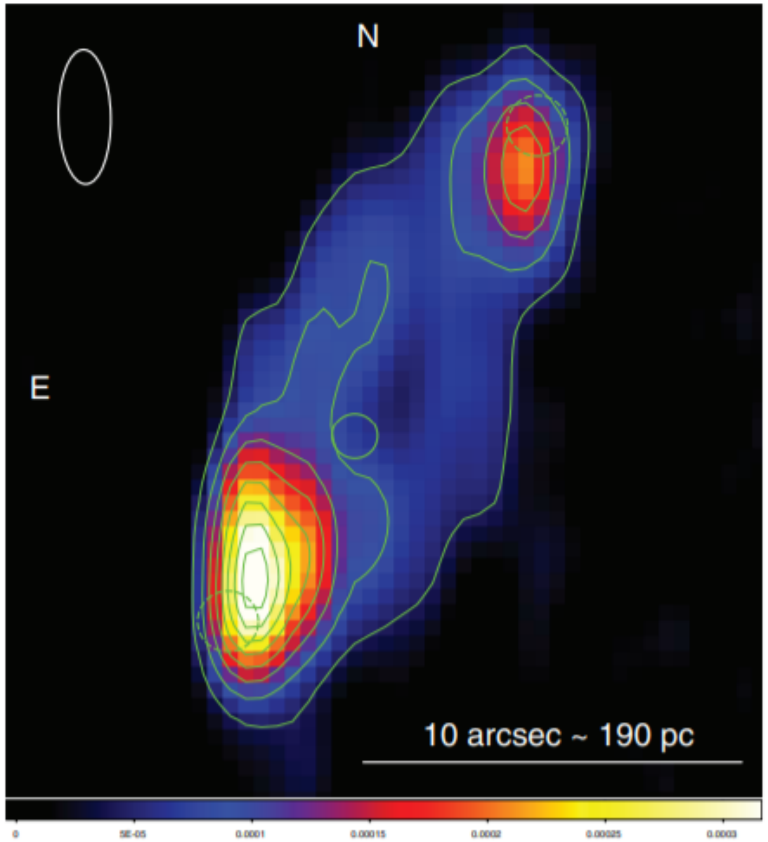
Common envelope

- Least understood phase of binary stellar evolution.
  - R ~O(10^4) Gpc^{-3} yr^{-1}.
  - R ~O(10^3) Gpc^{-3} yr^{-1} (w/compact object).
- Believed to give rise to transients such as:
  - Luminous Red Novae
  - Fast Blue Optical Transients
- Preceded by: XRBs → ULXs → thermal timescale → rapid runaway mass transfer → CE.
- Physics of hyper-Eddington accretion, disk wind outflows, CSM-shock interactions, etc.



Ingrid Stairs (2004)

ULXs are surrounded by wind-inflated "bubbles"



ULX in NGC 7793; S26 nebula (Soria+10)

Galactic microquasar SS 433; W50 "Manatee" nebula

c.f. Jon Miller's talk

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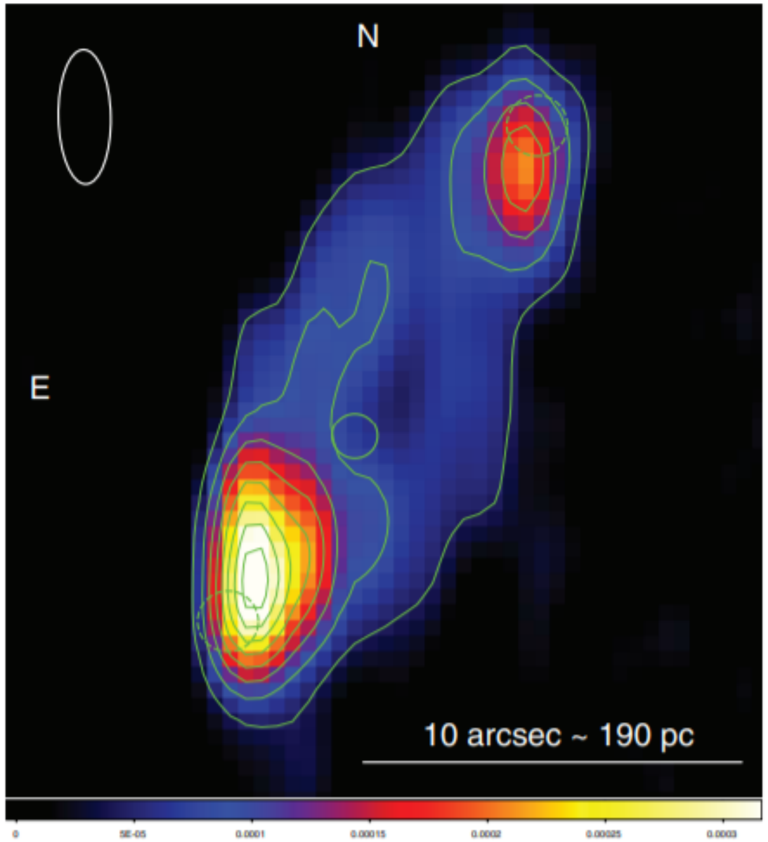

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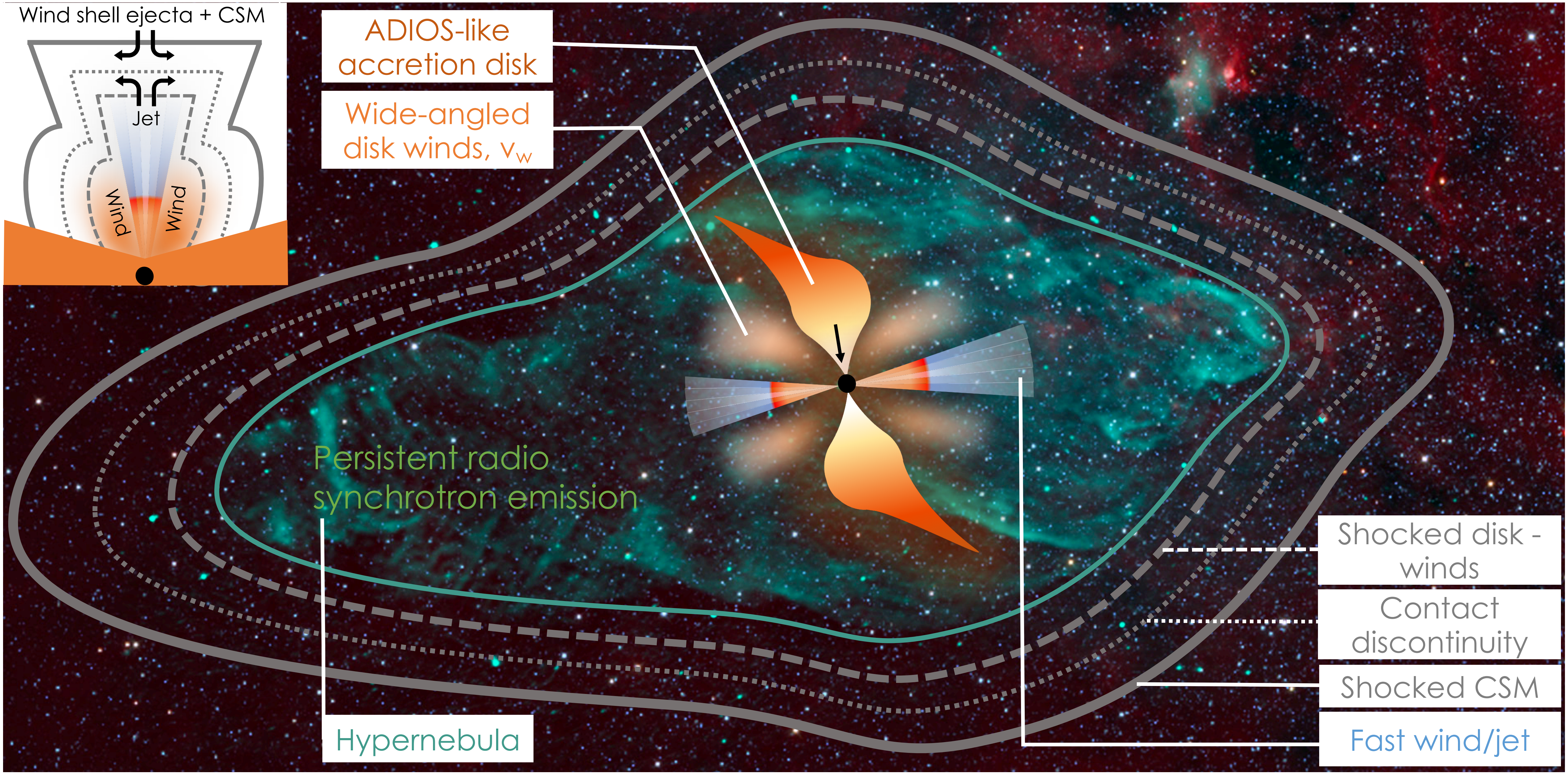
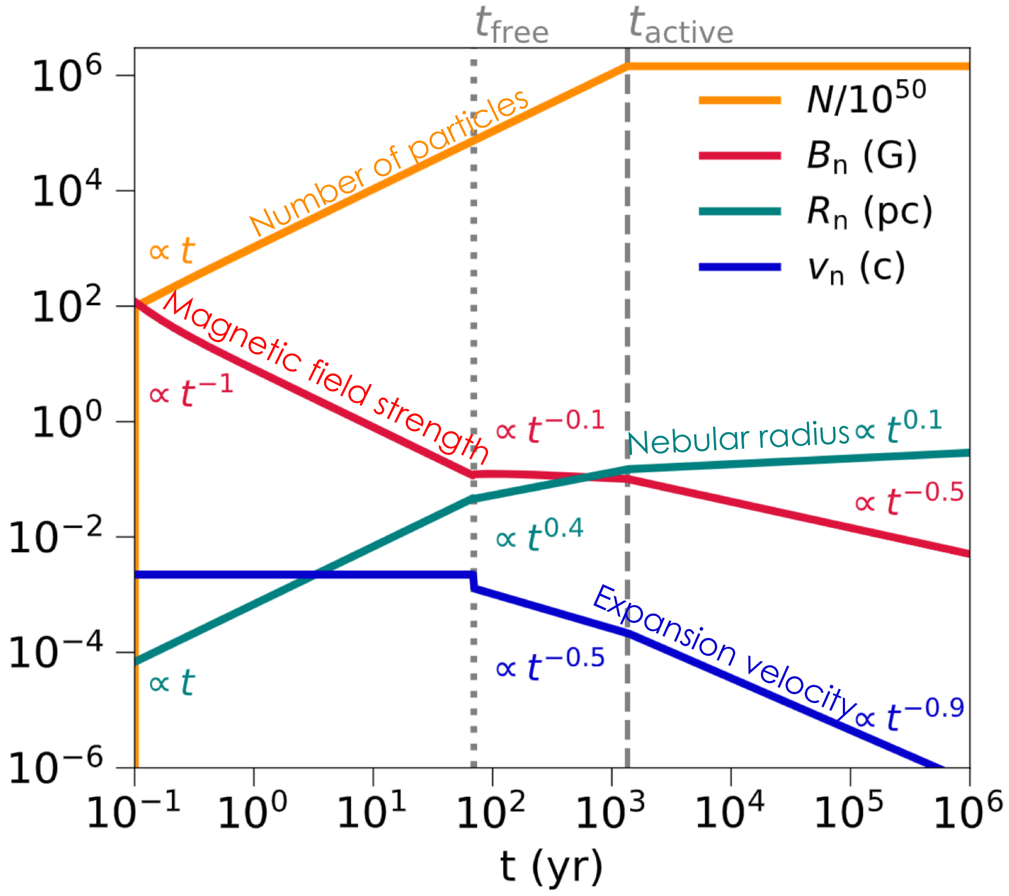


Radio '**hypernebulae**' from hyper-accreting XRBs presaging <u>common envelope mergers</u>
(Sridhar & Metzger 2022)

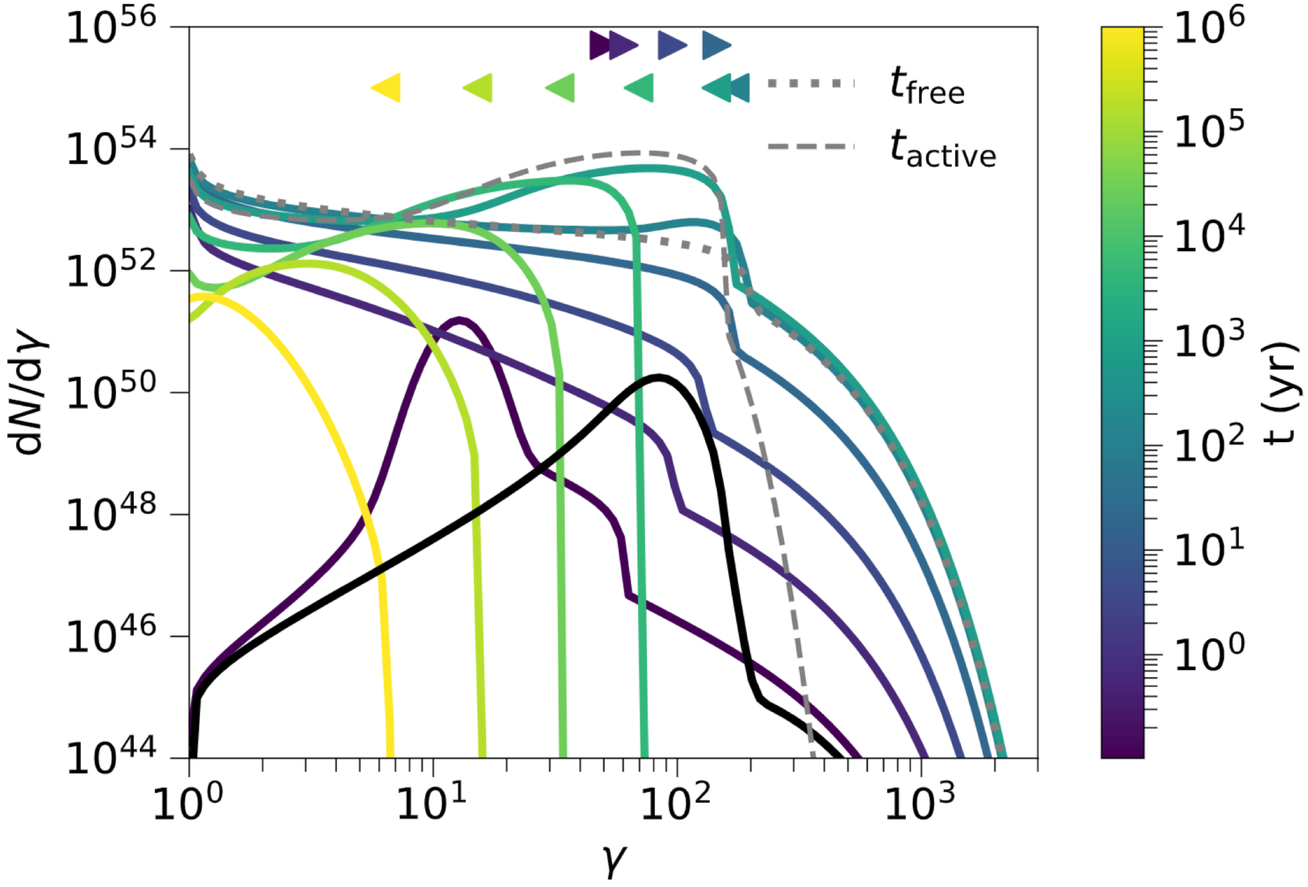
Evolving particle/field energy distribution given various cooling losses

$$\frac{dE_{\rm B}}{dt} = \frac{\sigma_{\rm j}}{1+\sigma_{\rm j}}L_{\rm j} - \frac{\dot{R}_{\rm n}}{R_{\rm n}}E_{\rm B}$$



$$\dot{N}_\gamma = \frac{\partial}{\partial t}N_\gamma + \frac{\partial}{\partial \gamma}(\dot{\gamma}N_\gamma) - 3\frac{\dot{R}_{\rm n}}{R_{\rm n}}N_\gamma$$

$$(\dot{\gamma} = \dot{\gamma}_{\rm ad} + \dot{\gamma}_{\rm brem} + \dot{\gamma}_{\rm IC} + \dot{\gamma}_{\rm syn})$$



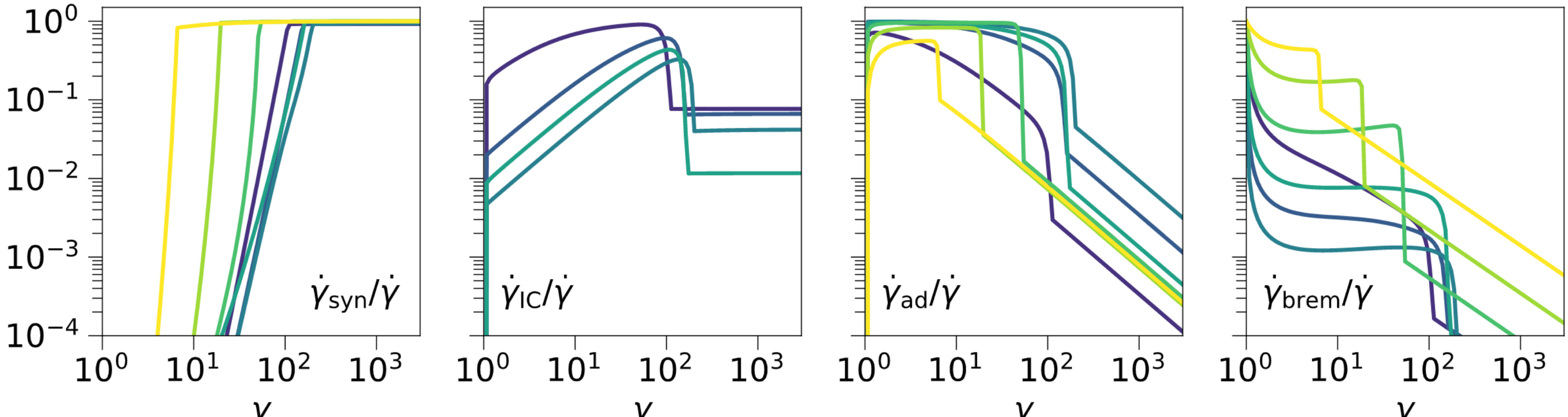
- ➢ Non-unity aspect ratio differentiates it morphologically from e.g., PWNe.
- ➢ Need **ngVLA** (0.1 mas resolution) to resolve ~0.1 pc hyper-nebulae, at 100 Mpc.

Contribution of various cooling losses

$$\dot{\gamma}_{\rm syn,IC} = -\frac{4}{3}\frac{\sigma_{\rm T}}{m_{\rm e}c}\beta^2\gamma^2 \begin{cases} f_{\rm ssa}B_{\rm n}^2/8\pi & \text{(synchrotron)} \\ L_{\rm tot}/4\pi c R_{\rm n}^2 & \text{(inverse−Compton)} \end{cases}$$

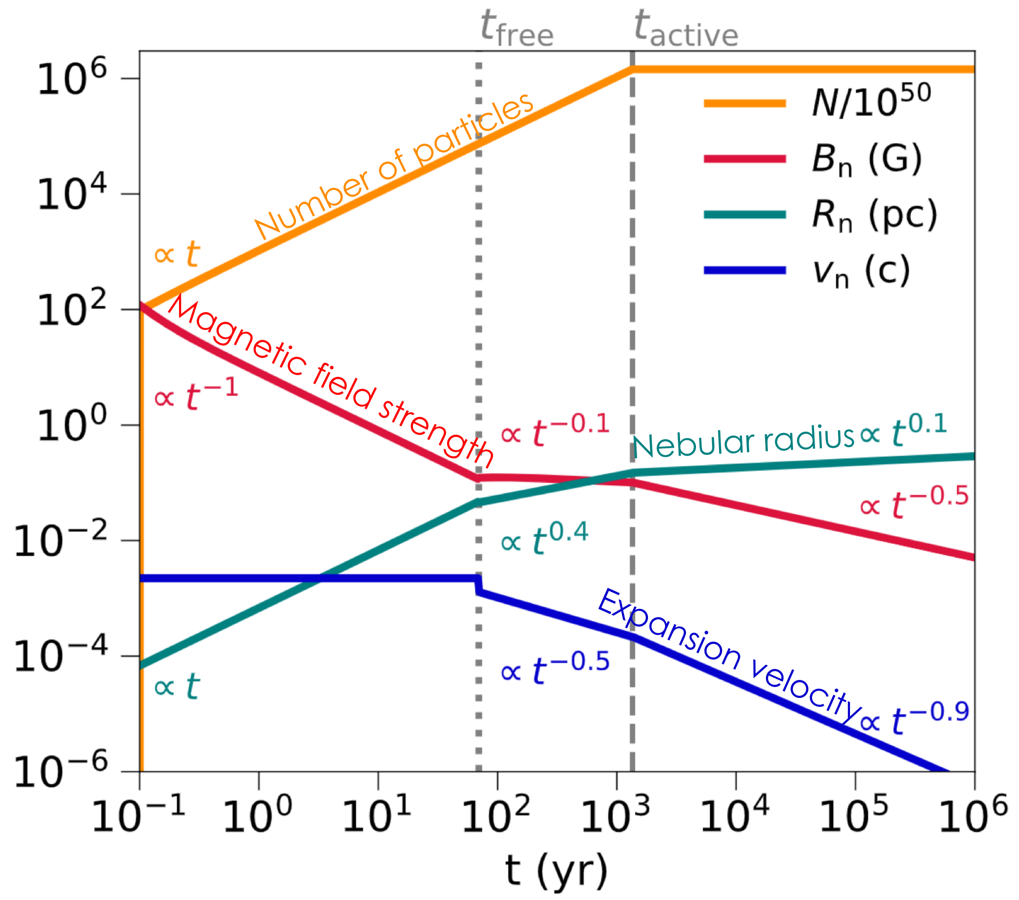
$$\dot{\gamma}_{\rm ad} = -\frac{1}{3}\gamma\beta^2\frac{{\rm d}\ln V_{\rm n}}{{\rm d}t} = -\gamma\beta^2\frac{\dot{R}_{\rm n}}{R_{\rm n}}$$

$$\dot{\gamma}_{\rm brem} = -\frac{5}{3}c\sigma_{\rm T}\alpha_{\rm fs}n_{\rm e}\gamma^{1.2}$$



Evolving particle/field energy distribution given various cooling losses

$$\frac{dE_B}{dt} = \frac{\sigma_j}{1+\sigma_j} L_j - \frac{\dot{R}_n}{R_n} E_B$$



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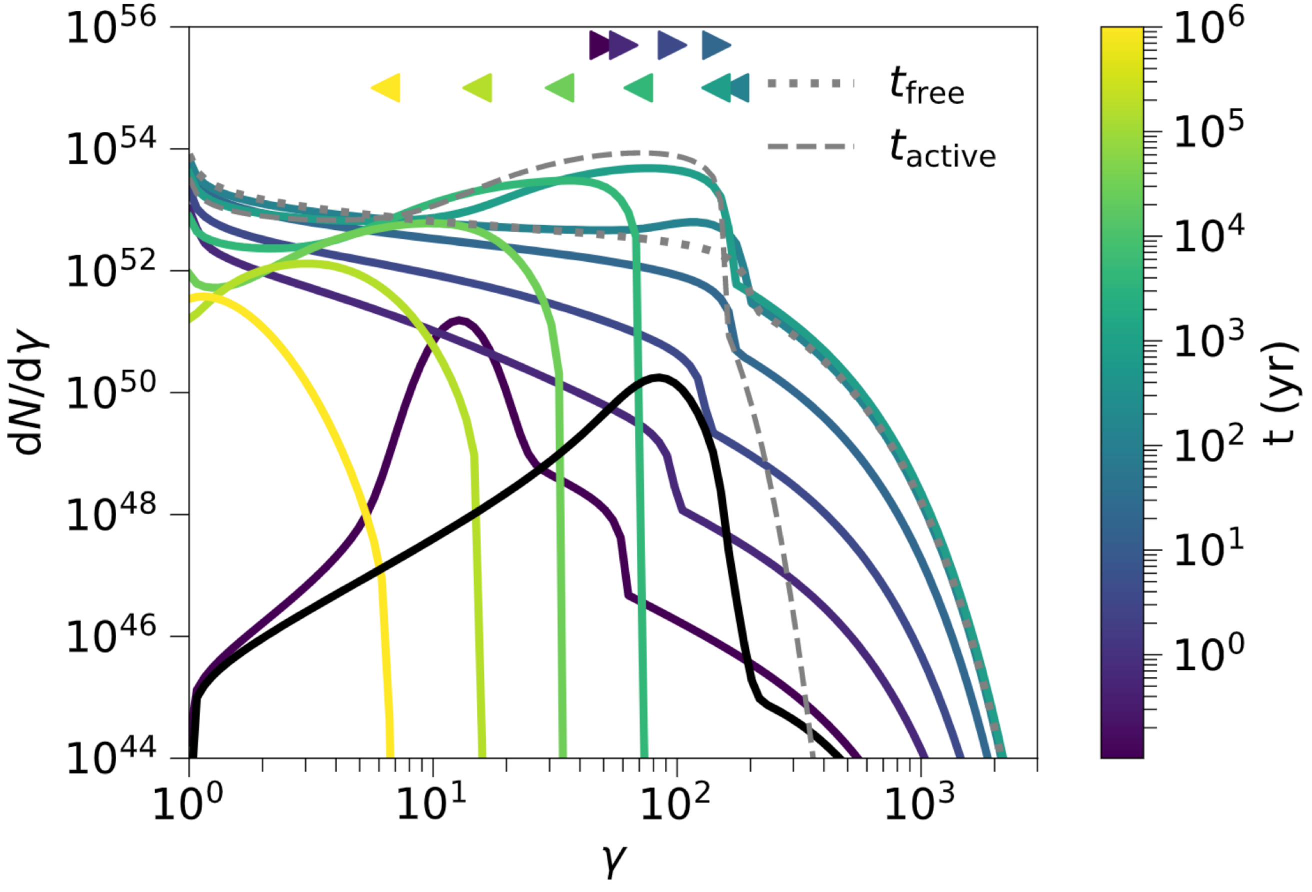


- ➢ Non-unity aspect ratio differentiates it morphologically from e.g., PWNe.
- ➢ Need **ngVLA** (0.1 mas resolution) to resolve ~0.1 pc hyper-nebulae, at 100 Mpc.

Observables from the expanding hyper-nebula

$$L_\nu = 4\pi^2 R_\mathrm{n}^2 \frac{j_\nu}{\alpha_\nu}(1 - e^{\alpha_\nu R_\mathrm{n}})$$

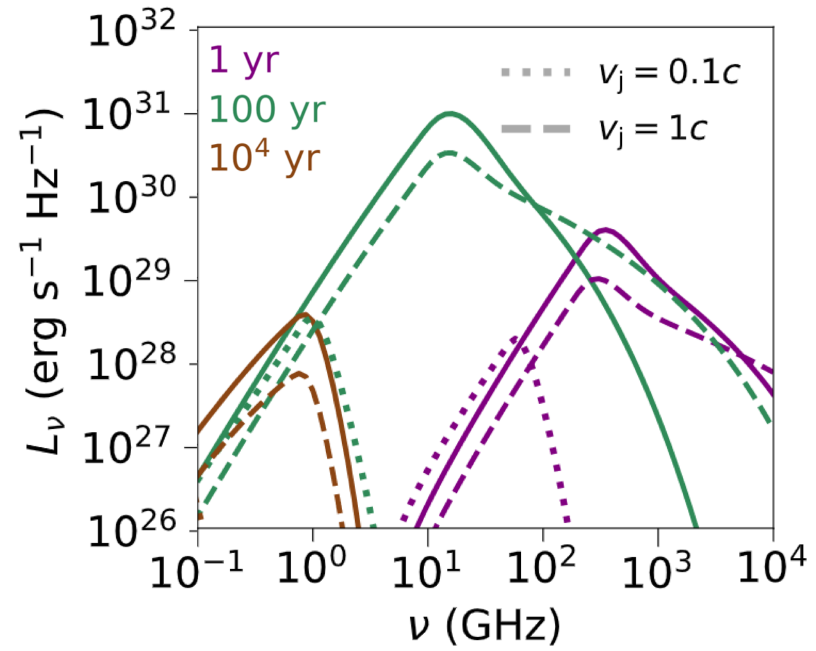
$$j_\nu = \int \frac{N_\gamma P_\nu(\gamma)}{4\pi} d\gamma, \quad \alpha_\nu = -\int \frac{\gamma^2 P_\nu(\gamma)}{8\pi m_\mathrm{e} \nu^2} \frac{\partial}{\partial \gamma}\left[\frac{N_\gamma}{\gamma^2}\right] d\gamma$$

$$|\mathrm{RM}| \simeq \frac{e^3}{2\pi m_\mathrm{e}^2 c^4}\left(\frac{\lambda}{R_\mathrm{n}}\right)^{1/2} B_\mathrm{n} R_\mathrm{n} \int \frac{N_\gamma}{\gamma^2} d\gamma$$

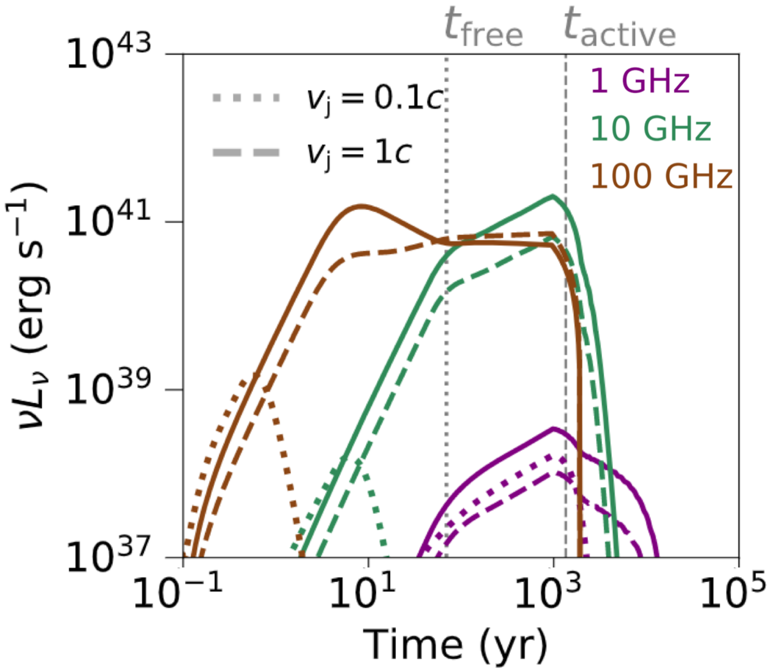
$$\mathrm{DM}_\mathrm{neb} \simeq R_\mathrm{n} \int \frac{N_\gamma}{\gamma} d\gamma$$

$M_\star = 30 M_\odot$; $\dot{M} = 10^5 \dot{M}_\mathrm{Edd}$; $M_\bullet = 10 M_\odot$; $n = 10/\mathrm{cm}^{-3}$; $v_\mathrm{w} = 0.03c$; $v_\mathrm{j} = 0.5c$; $\sigma_\mathrm{j} = 0.1$; $\eta = 0.1$; $\varepsilon_\mathrm{e} = 0.5$

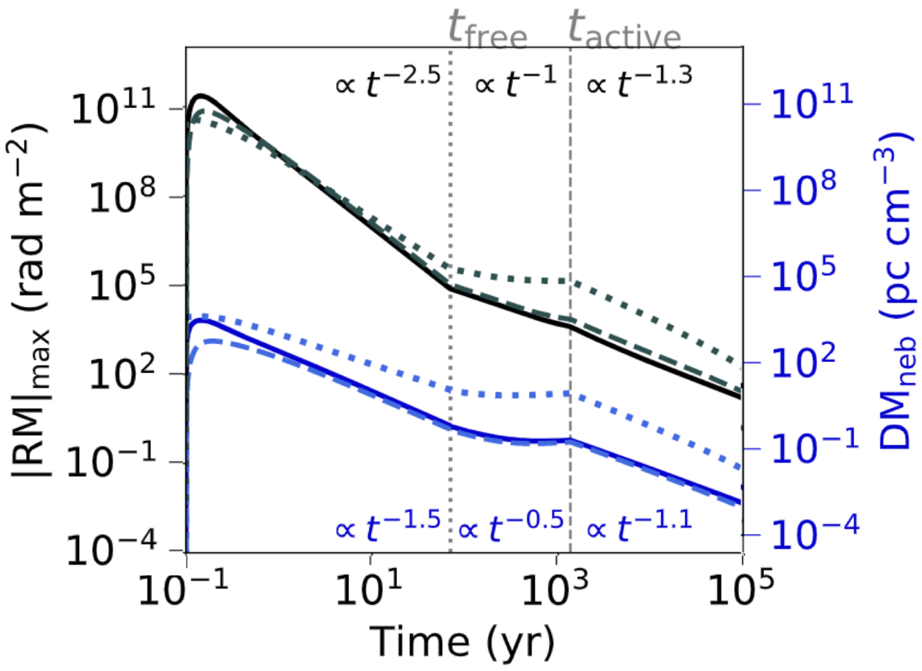
Spectra



Light curves

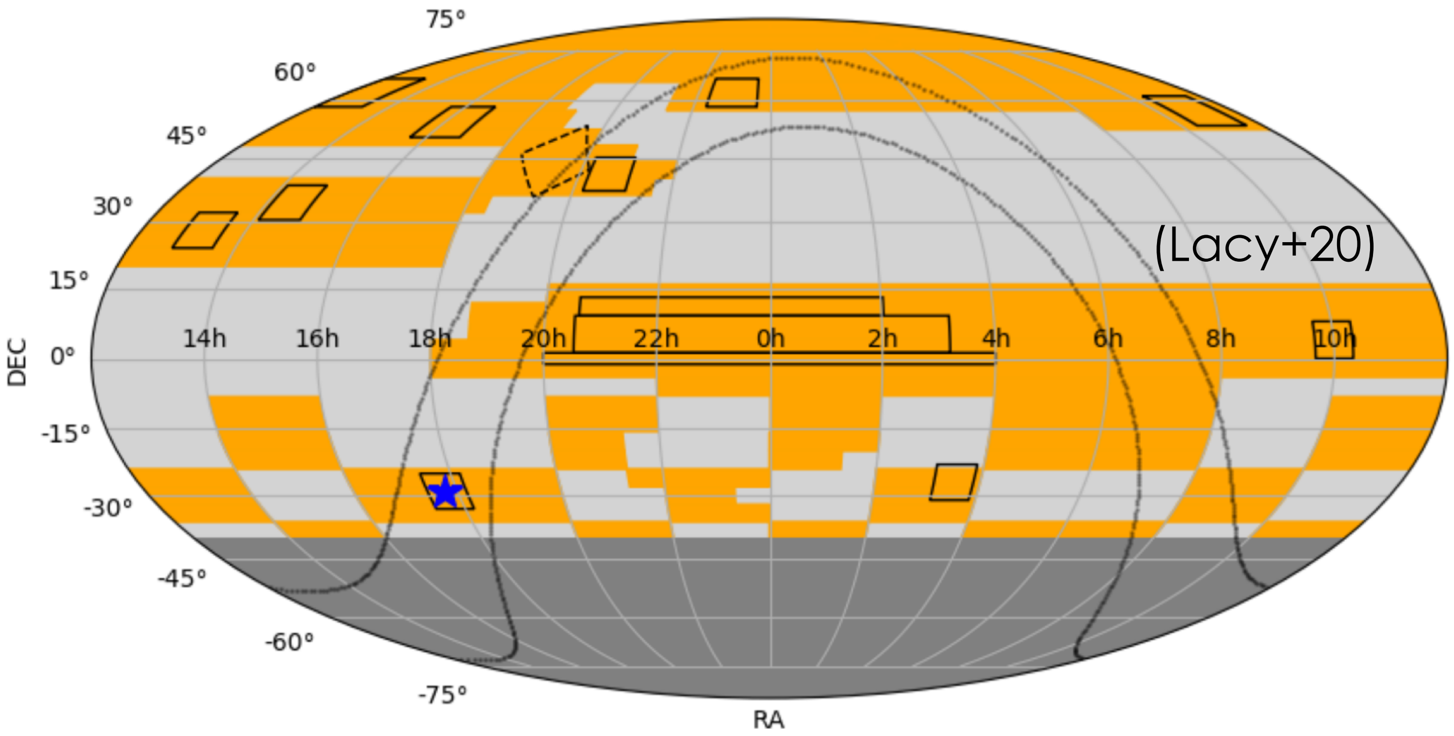


Rotation and Dispersion measures



Detection in blind radio surveys (VLASS)

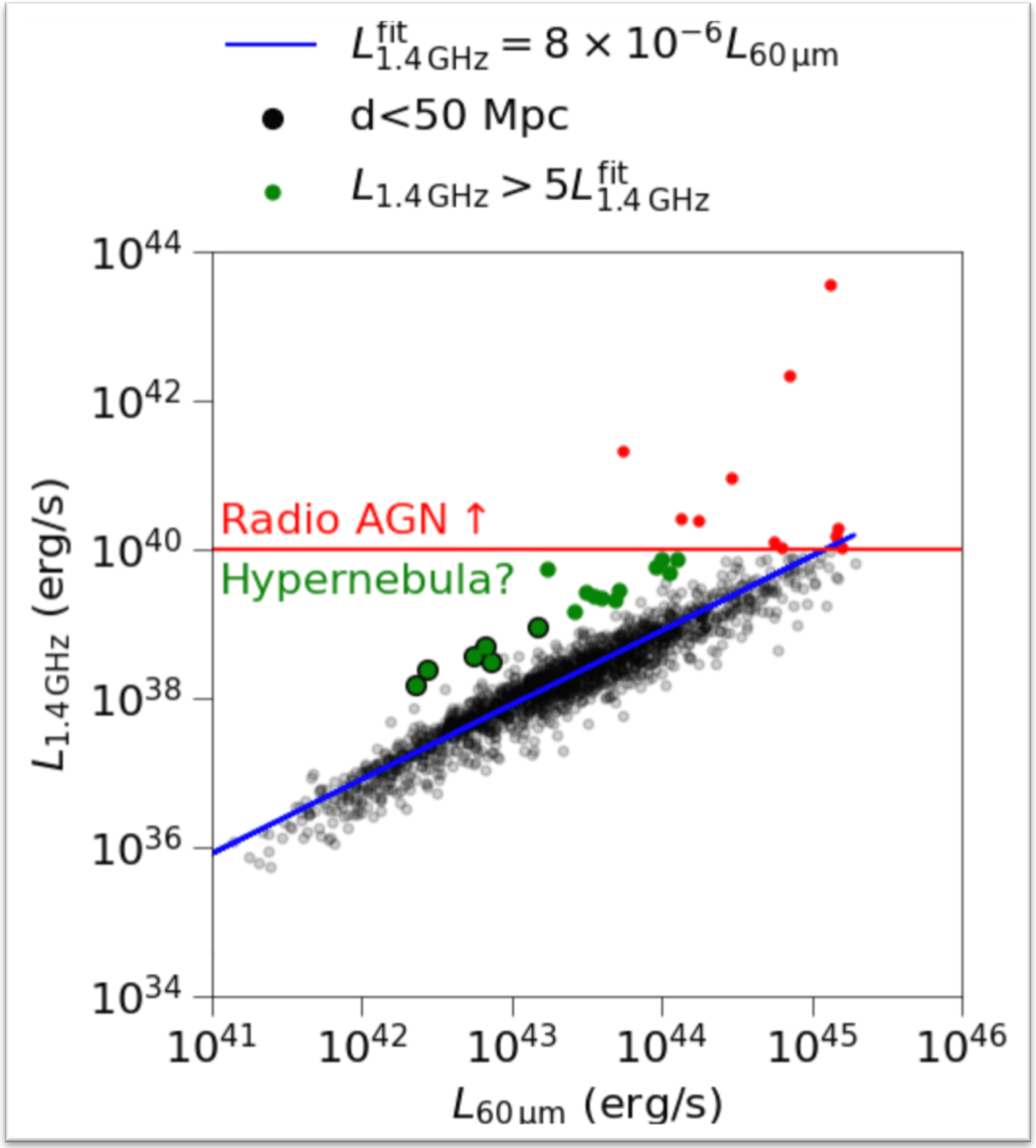
- 34,000 deg^2 coverage
- 5σ sensitivity at 0.7 mJy
- 10^6 radio point sources
- ~1000 transients in each epoch (32 months)



- Hypernebulae count in VLASS (assuming a common envelope volumetric rate of R~100 yr^{-1} Gpc^{-3}):
  - **Total: ~10^4 (~1%)**
  - **Decades-long radio transients: ~10** (between FIRST and VLASS epochs).

Multi-wavelength surveys

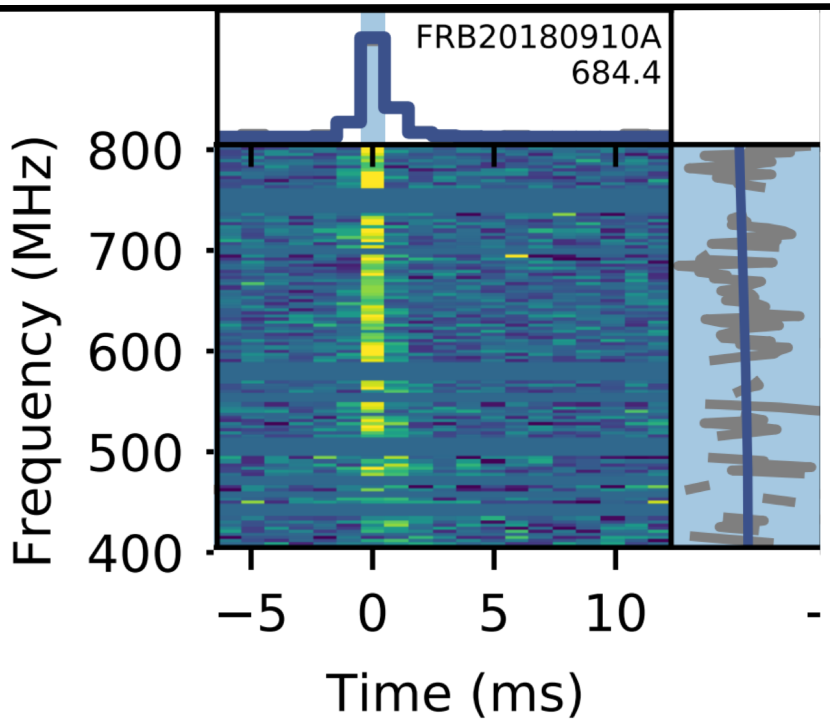
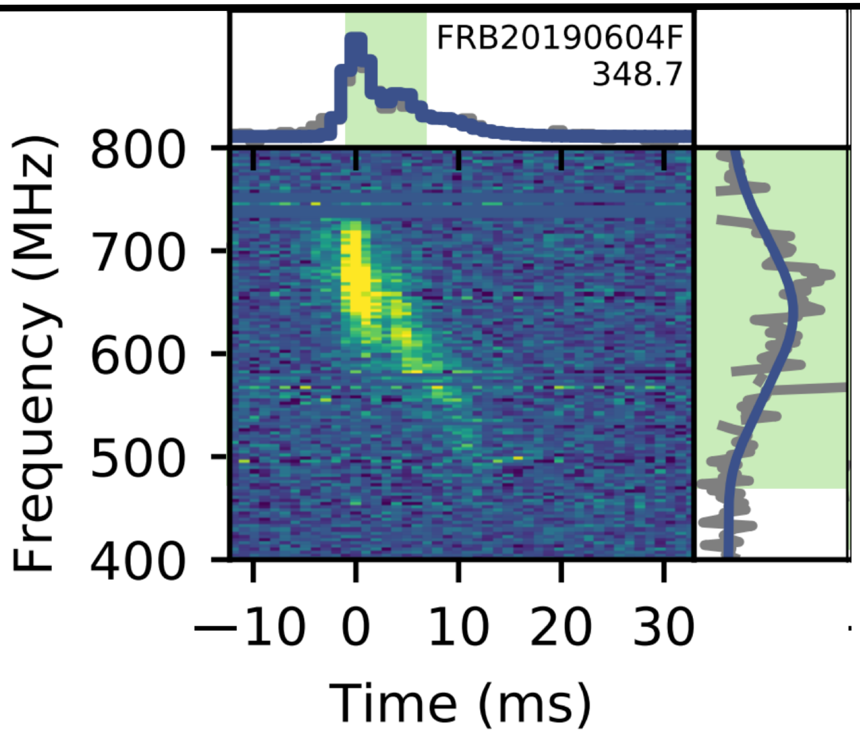
- Far IR-radio correlation →
  (Yun, Reddy, and Condon 2001)
- Hypernebulae peak at ~1e40 erg/s at GHz band: >1e40 erg/s sources => AGN
- Radio – IR correlation (blue line) due to star formation: anything above => hypernebulae?
- NIR broad H-recombination lines (JWST)



Applications

FRB spectro-temporal dichotomy:

*Metzger, **NS**, Beniamini, et al. (2022) for a toy-model of the dichotomy: arXiv:2110.10738*

Non-repeater	Repeater
	
• Short duration • Broadband (powerlaw) energy spectrum. • Drifts down faster.	• Longer duration • Narrowband (Gaussian) energy spectrum. • Drifts down slower.

First CHIME/FRB catalog (2021)

Suggestive of more than just a single (magnetar-based) engine.

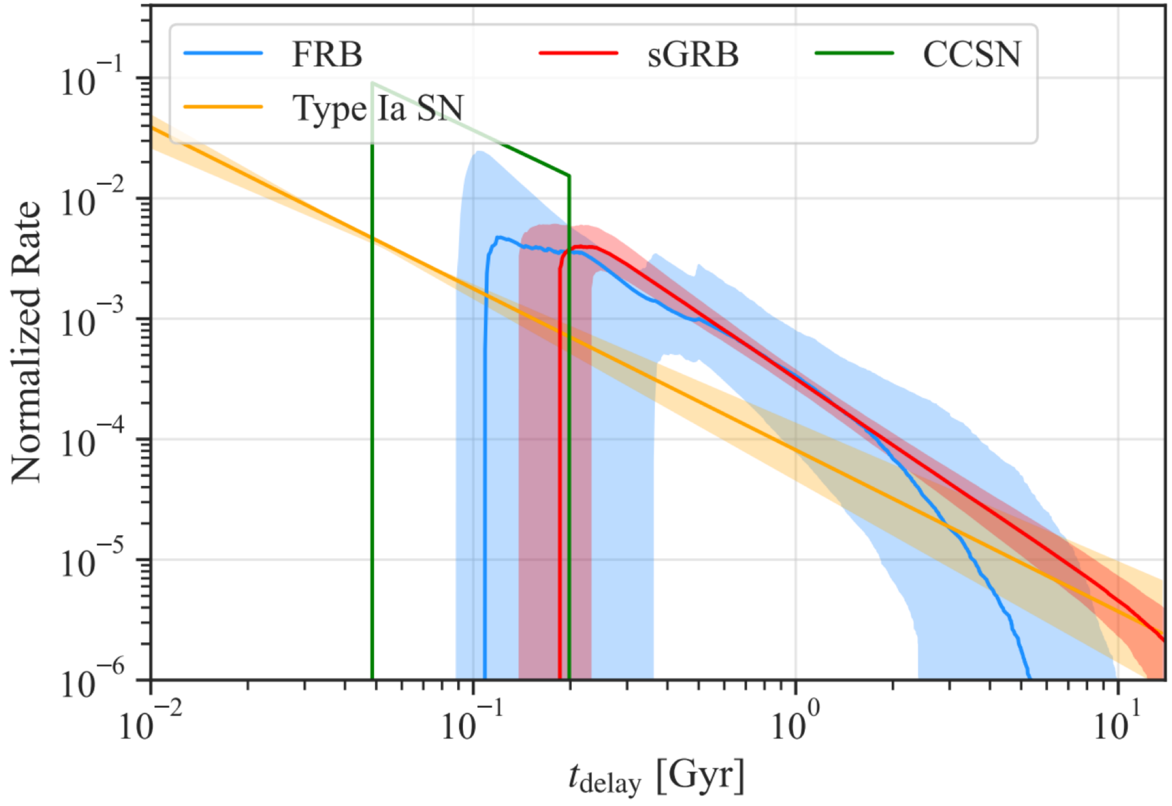
FRB hosts

- The sources of FRBs are formed over a wide range of times relative to star formation.

- **Requires more than one progenitor formation channel** associated with old stellar populations, such as the binary evolution of compact objects.

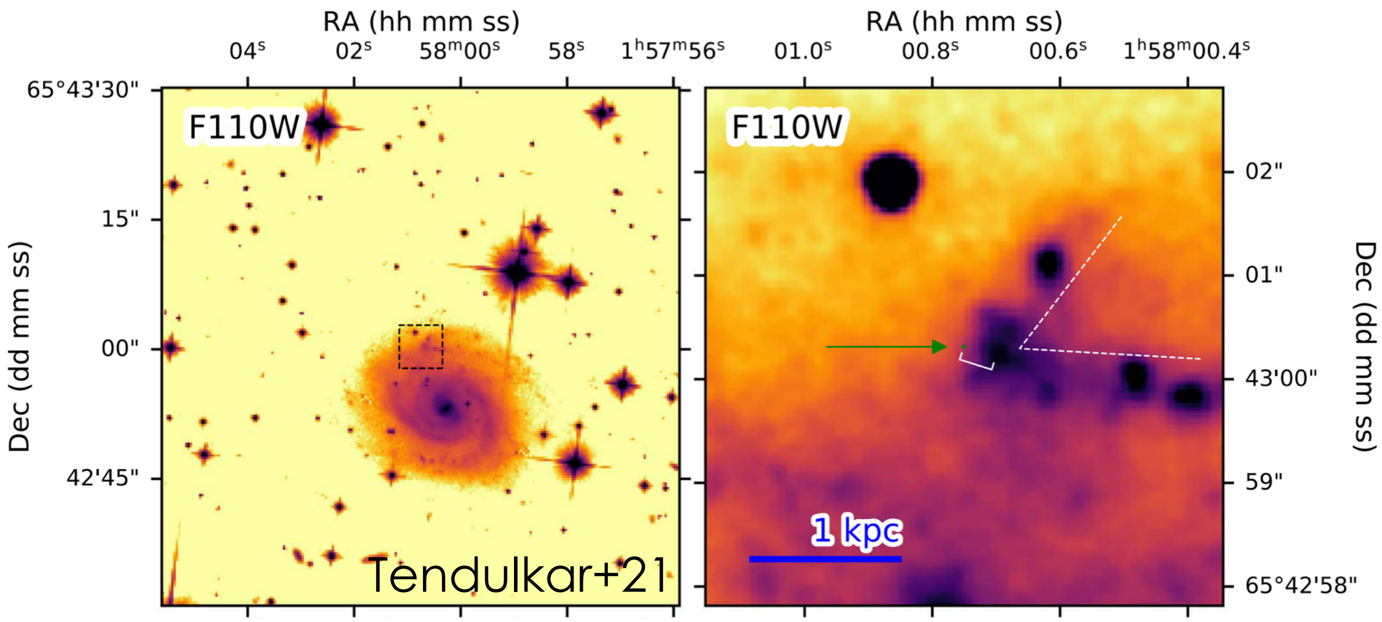
DSA-110 FRB Sample

Law+23



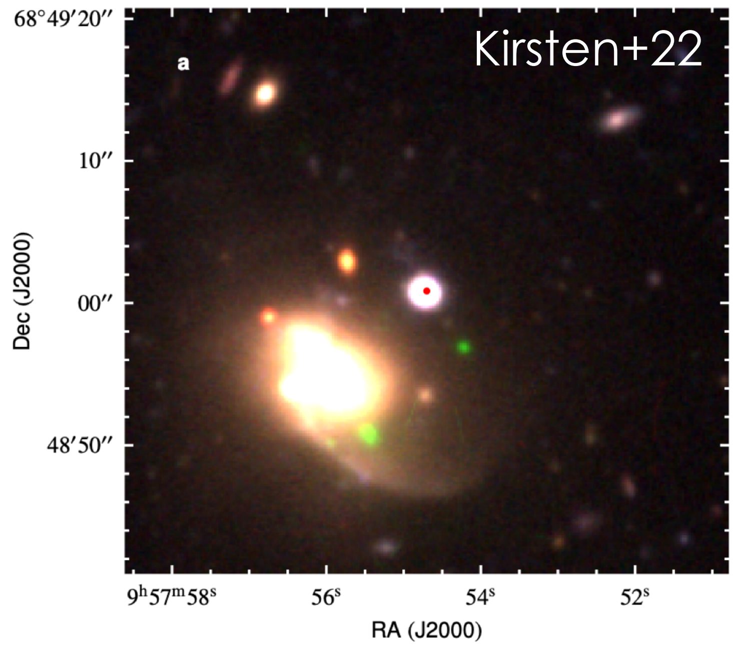
FRB hosts

FRB 180916



~250 pc offset from SFR. A young magnetar (few decades old) born in a star-forming region could not have traveled this far.

FRB 200120

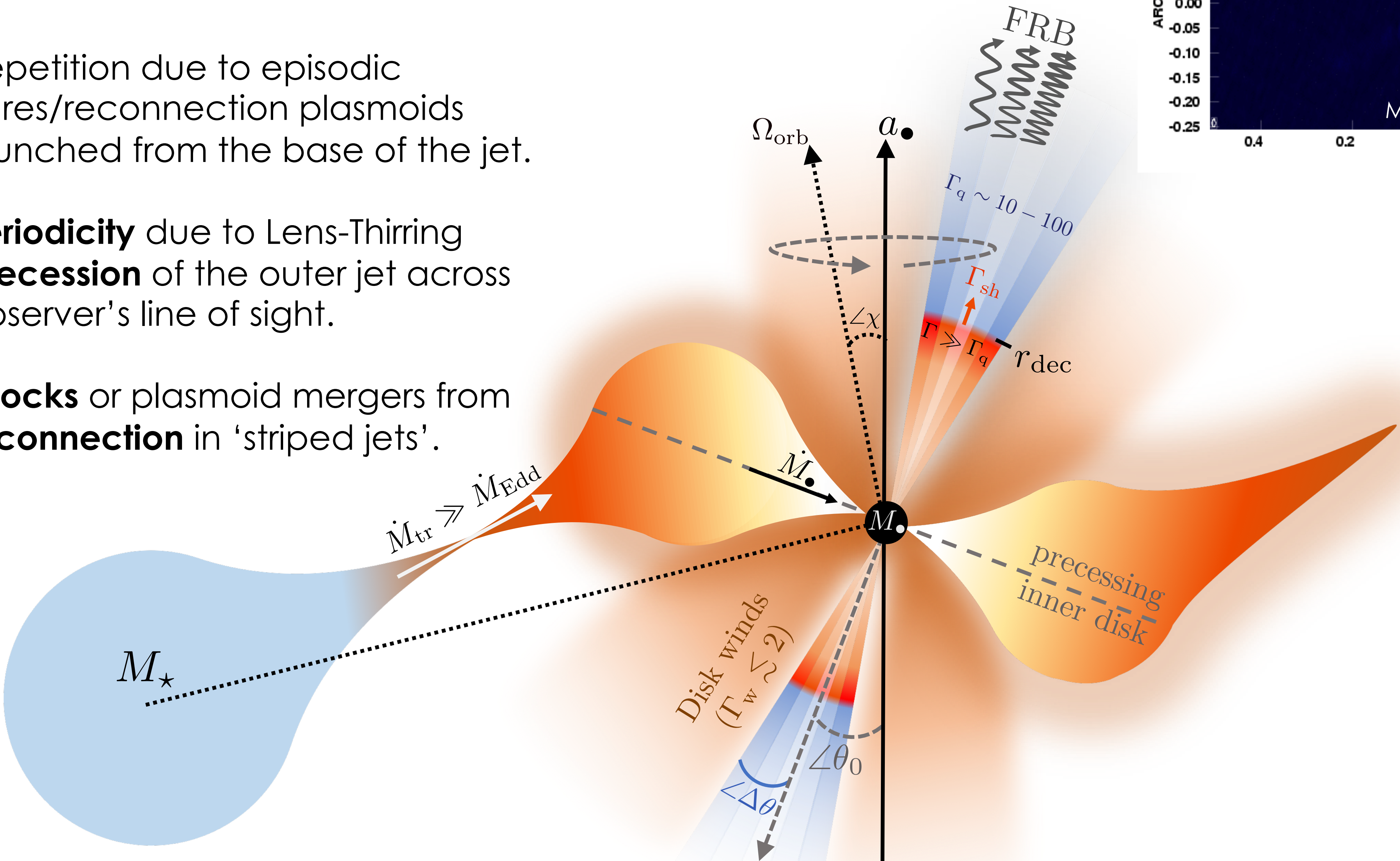


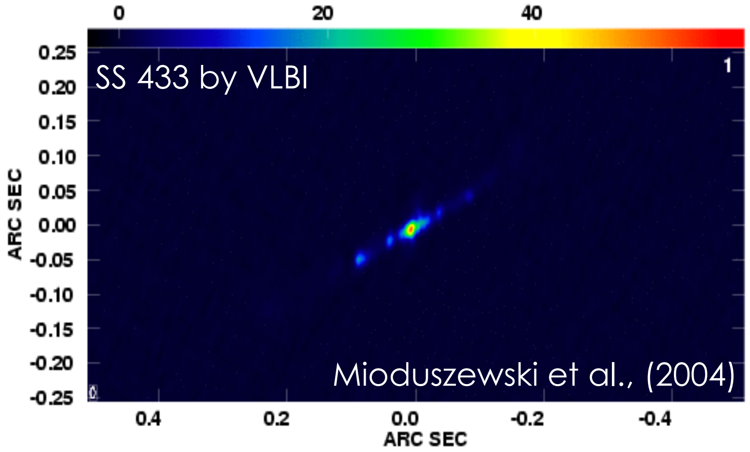
Localized to a globular cluster. Indicative of old stellar population.

Typical of older population: accreting (BH/NS) X-ray binaries.

Accreting engine (‘*microblazars*’?)

- Repetition due to episodic flares/reconnection plasmoids launched from the base of the jet.
- **Periodicity** due to Lens-Thirring **precession** of the outer jet across observer’s line of sight.
- **Shocks** or plasmoid mergers from **reconnection** in ‘striped jets’.



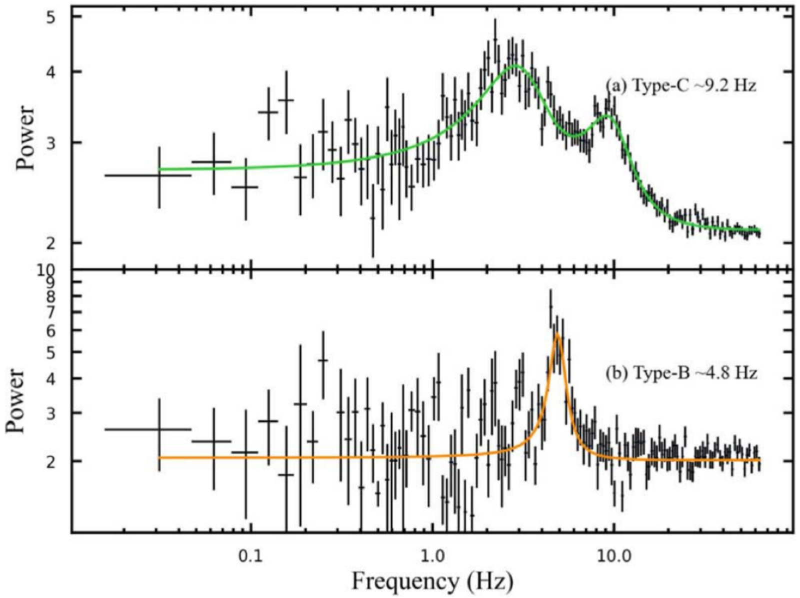


Sridhar+21b

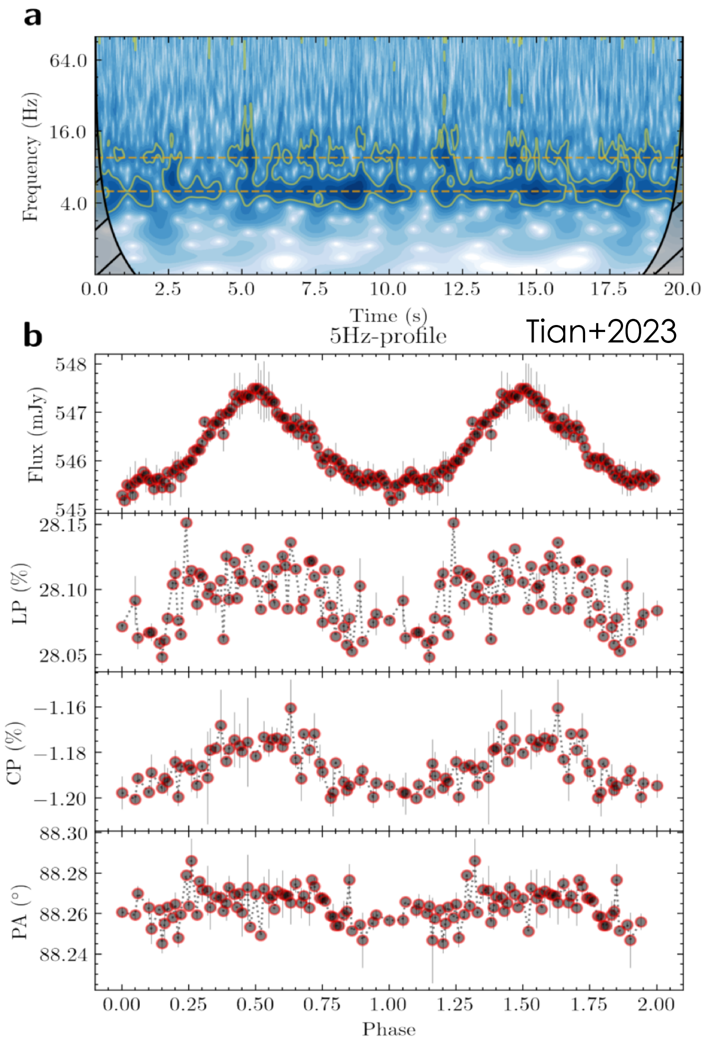
X-ray binaries

- 5 Hz ‘Type-B’ X-ray QPOs

Liu et al.



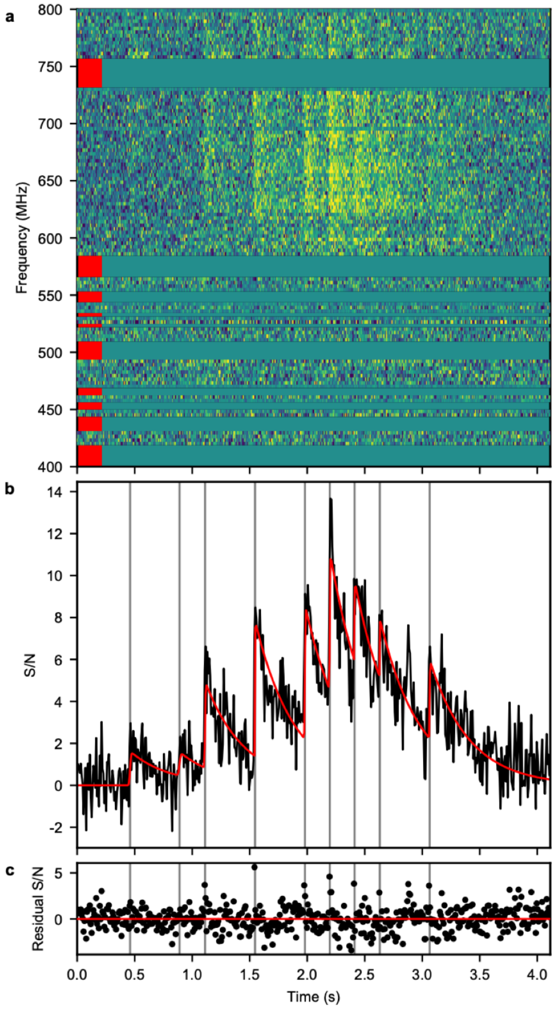
- Evidence for radio jets precessing at 5 Hz from GRS 1915+105 →
- Cycles last for few second.



Tian+2023

FRB 20191221A:

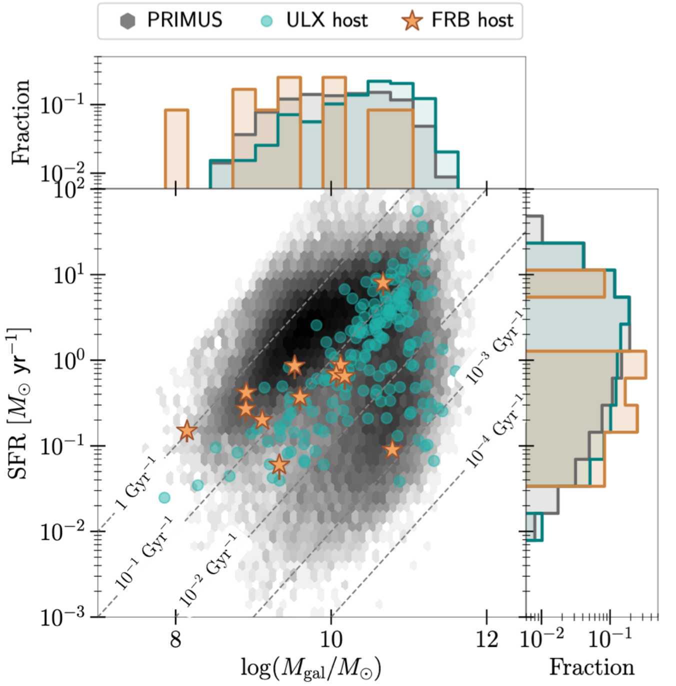
- ~3 second duration
- 5 Hz periodicity

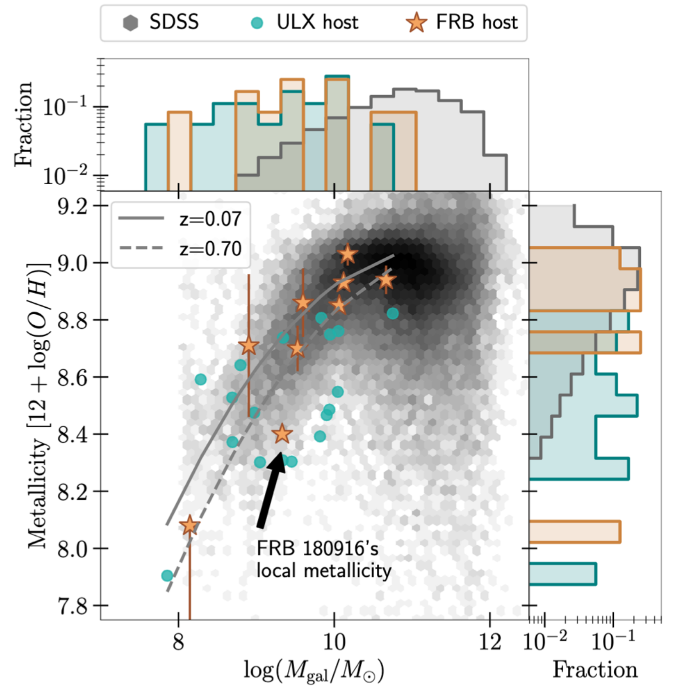


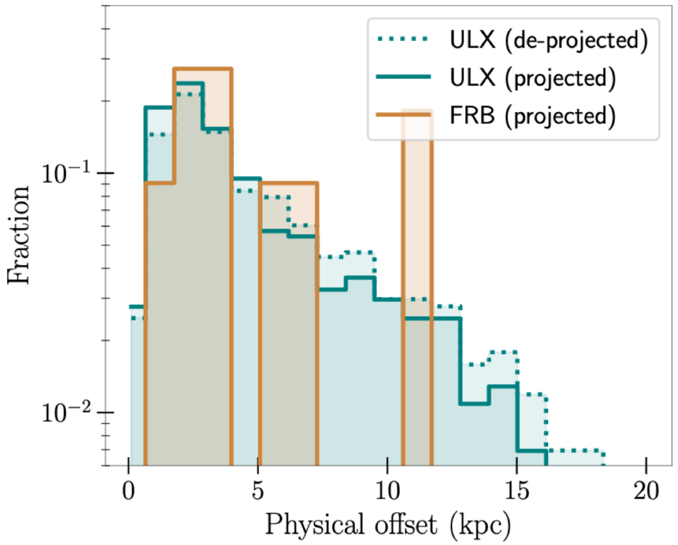
CHIME/FRB collaboration+22

Host (galaxy) properties

- **SFR:** Both FRB and ULX hosts form stars at similarly lower rates. ✓
- **Mass:** The FRB hosts are slightly less massive than ULX hosts. ?
- **Metallicity:** FRB and ULX hosts prefer low-metallicity hosts. ✓
- **Offset:** The distributions (peaks) overlap. ✓ ?



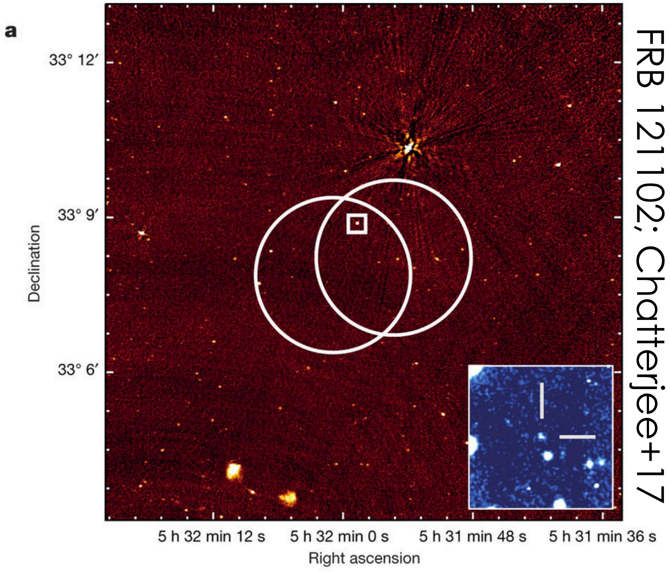




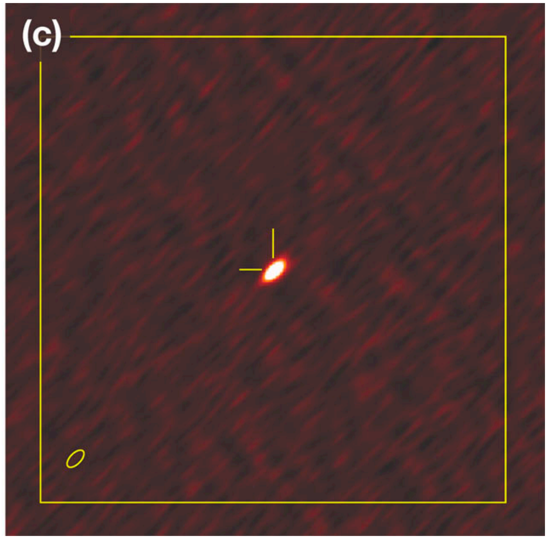
Not all FRBs from accreting engines, a fraction of them may.

Sridhar+21b

Persistent radio counterpart to FRBs



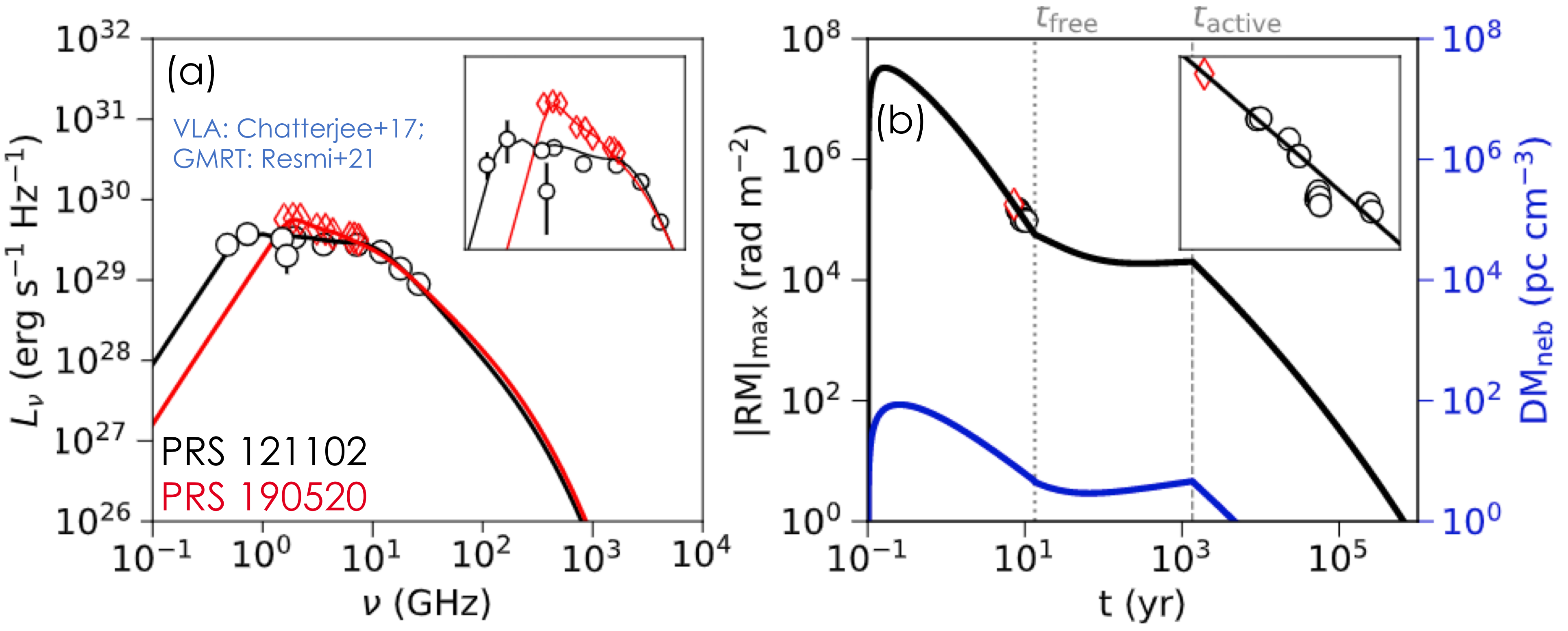
FRB 121102; Chatterjee+17



FRB 190520B; Niu+22

- Optically thin (synchrotron) with a luminosity $\nu L_\nu \sim 10^{39}$ erg s^{-1}; more luminous than:
  - Supernova remnant
  - Local star formation activity
- Large Faraday Rotation Measure ~10^5 rad m^{-2}: requires the persistent nebula to be baryon rich.
- Oddity?

Hypernebula model to FRB persistent radio sources



(a) Jet-speed-weighted-average of the one-zone model spectra of hypernebula radio synchrotron emission `fits' the observed PRS spectra.

(b) The model also explains the RM evolution; constrain a source age of ~10 yr.

(Sridhar & Metzger 2022)

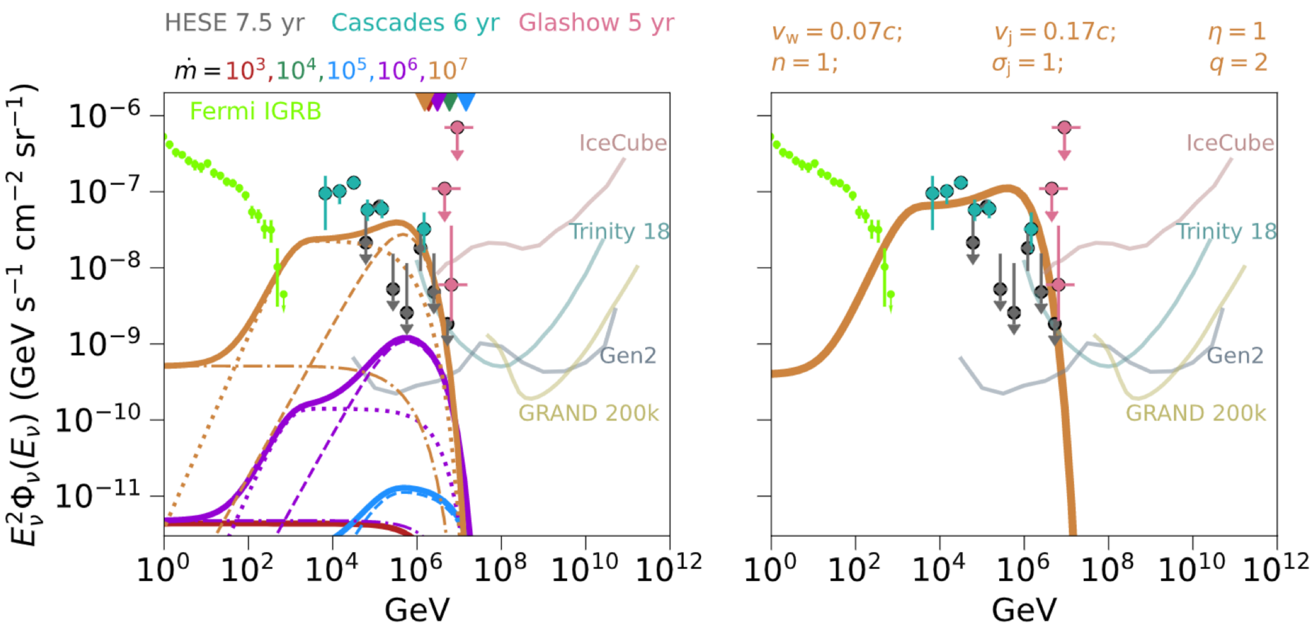
Sridhar+23: arXiv: 2212.11236

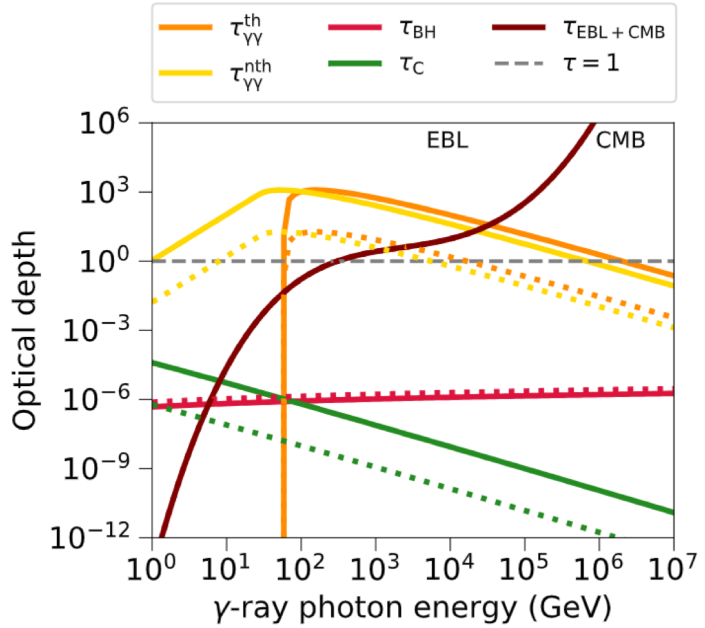
HE neutrino emission

- Diffuse (extragalactic) high energy (1 TeV ~ 1 PeV) background neutrinos seen by IceCube (~3e-8 GeV s^{-1} cm^{-2} sr^{-1}).
- Known transients (SNe, GRBs, FBOTs, TDEs, etc.) **not enough**: supply O(1%) of the flux.

- Jet termination shock of hypernebulae: Accelerate protons → interact with disk (thermal+Comptonized) photons → **photomesonic** reaction p+γ → Δ^+ → p + π^0 + $\pi^\pm$ → $\mu^\pm$ + $e^\pm$ + ν_μ + ν_e.

- High optical depth of disk photons → γ-rays won't escape (satisfies Fermi constraints).

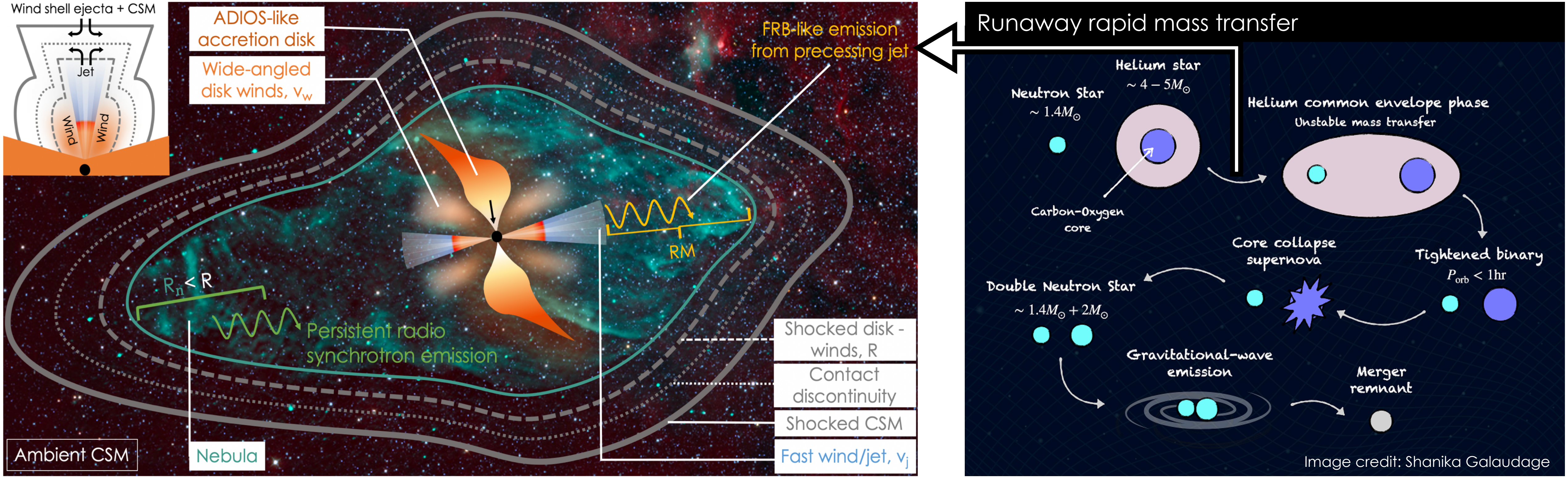




Persistent neutrino counterparts (**PNC**) from individual hypernebulae* could be detected with a 10-yr integration with IceCube-Gen2.

*sources within a few Mpc with a PRS counterpart as bright as FRB 121102's.

Take-aways of hyper-accretion wind-powered Hypernebulae



- Laboratories to study the extreme wind outflow properties from stellar-mass compact objects.
- **Probes of binary stellar evolution**: presage energetic transients from **common envelope** mergers, and can act as signposts to future LVK/LISA events.
- They can potentially explain the observations of **FRBs** and diffuse **extragalactic HE neutrino** flux.
- ***Hypernebulae* are plentiful in our Universe, even lurking in our sample (e.g., VLASS)… They are just waiting to be identified.**