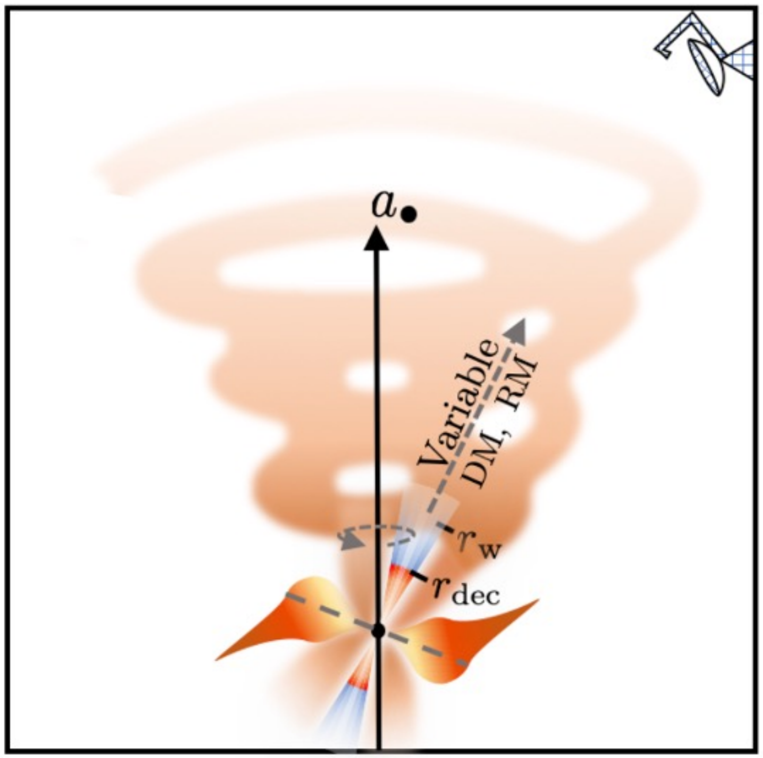
X-ray Binary Jets as FRB Engines

(with Navin Sridhar)

FLATIRON INSTITUTE

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

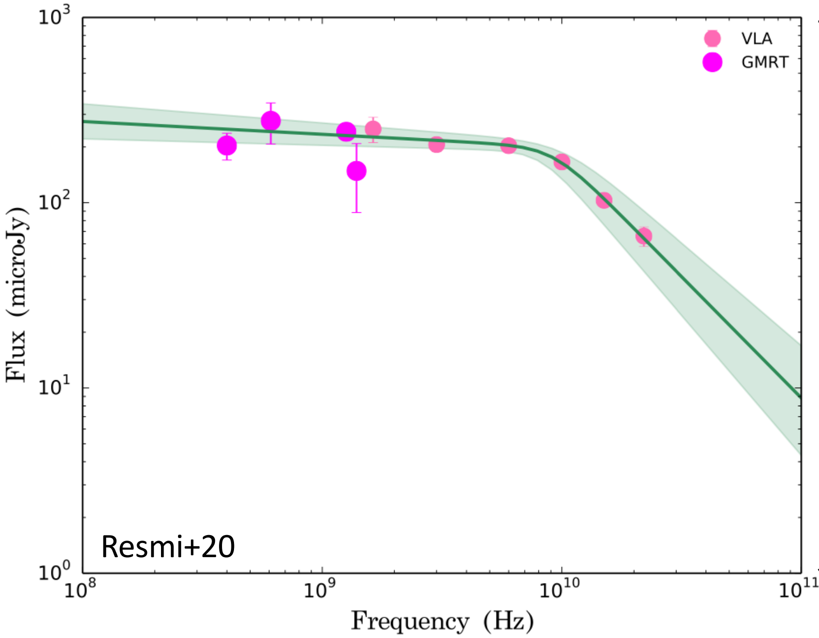


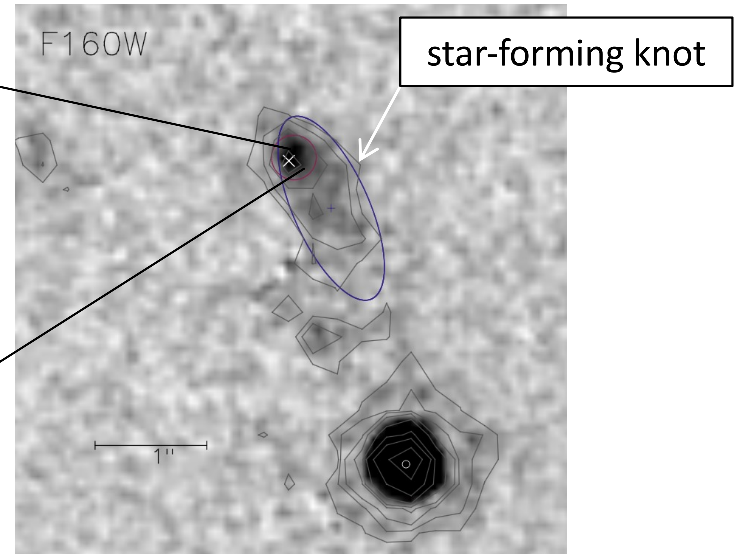
Sridhar, BDM, Beniamini, Margalit, Renzo, Sironi, Kovlakas, 2021, ApJ, 917, 13

Sridhar & BDM, submitted (arXiv: 2206.10486)

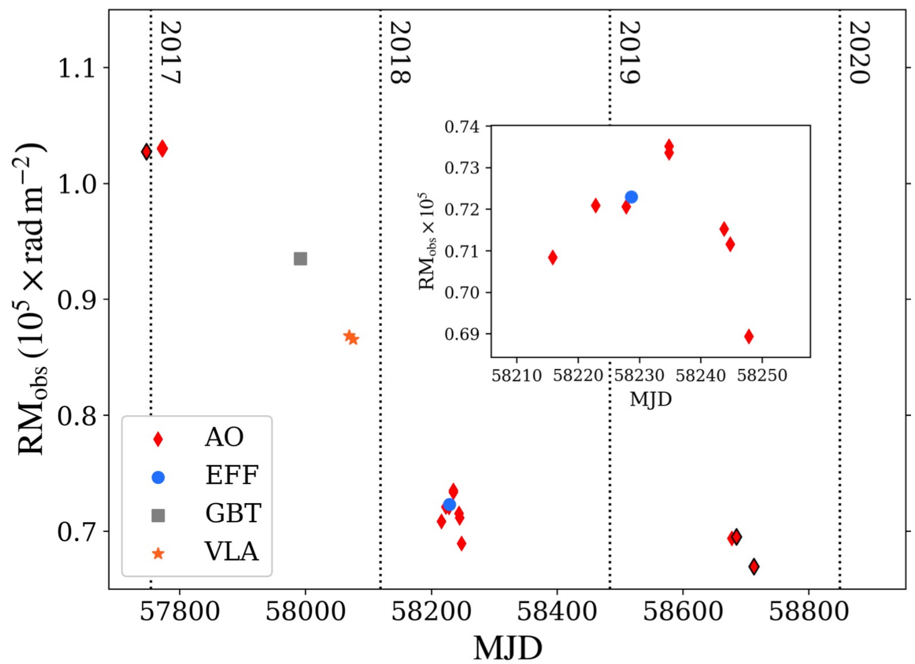
Watershed: FRB121102 Persistent Source

Chatterjee+17, Tendulkar+17, Bassa+17, Michilli+19





Hilmarsson+22, Michilli+18



- Spatially coincident (< 40 pc) luminous $\nu L_\nu \sim 10^{39}$ erg s^{-1} compact (< pc) **synchrotron source**.

- Large time-variable RM => FRB source embedded in active magnetized **nebula**

- RM-generating medium has **electron-ion** composition instead of e^-/e^+ pairs.

Engine-Powered Nebula

Margalit & BDM 18

$$\dot{N}_{\rm e} = (1+\sigma)^{-1}\chi^{-1}\dot{E}$$

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

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

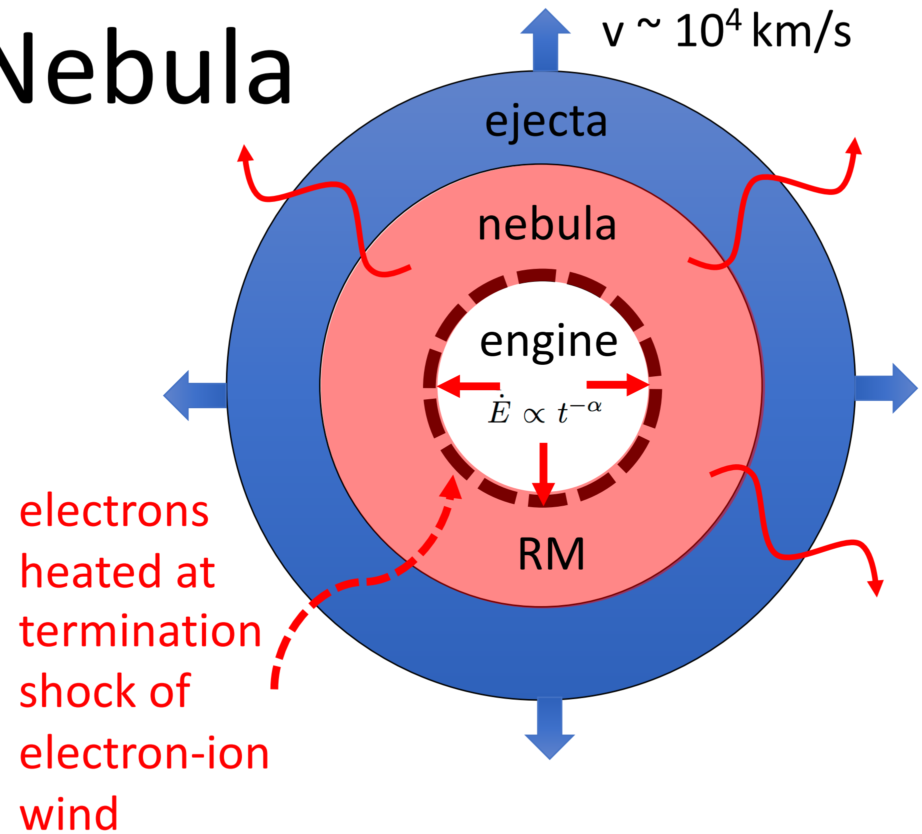
$$\dot{\gamma}_{\rm syn,IC} = -\frac{4}{3}\frac{\sigma_{\rm T}}{m_{\rm e}c}\beta^2\gamma^2\begin{cases} f_{\rm ssa}(\gamma)B_{\rm n}^2/8\pi & \text{, syn} \\ L_{\rm rad}/4\pi c R_{\rm n}^2 & \text{, IC}\end{cases}$$

$$\frac{dE_B}{dt} = -\frac{\dot{R}_{\rm n}}{R_{\rm n}}E_B + \frac{\sigma}{1+\sigma}\dot{E}$$

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

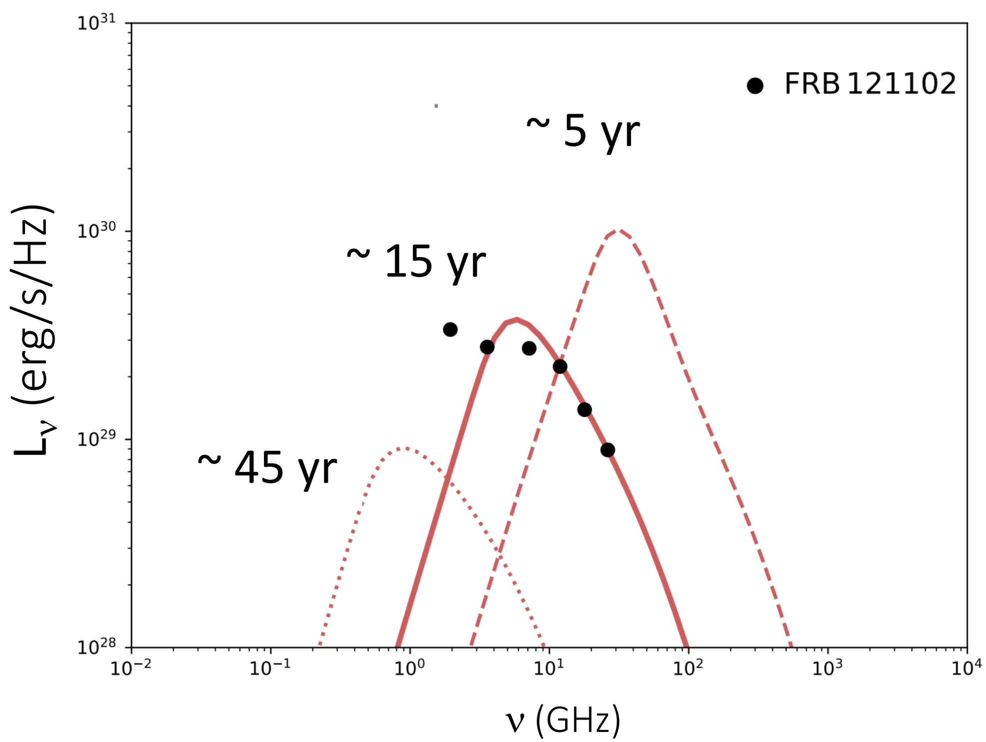
$$j_\nu = \int \frac{N_\gamma P_\nu(\gamma)}{4\pi}d\gamma,\ \ \alpha_\nu = -\int \frac{\gamma^2 P_\nu(\gamma)}{8\pi m_{\rm e}\nu^2}\frac{\partial}{\partial\gamma}\left[\frac{N_\gamma}{\gamma^2}\right]d\gamma$$

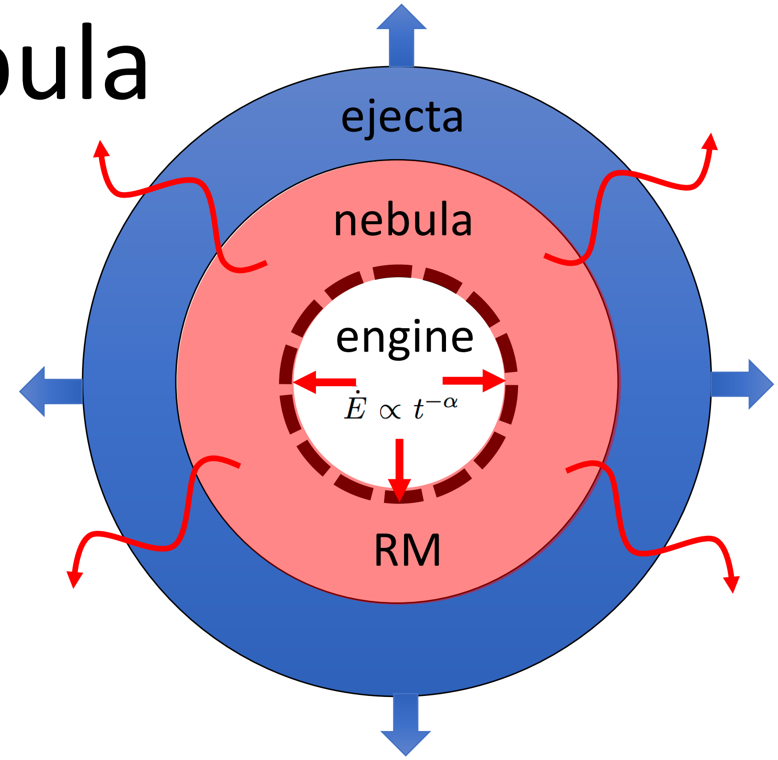
$$\mathrm{RM} \approx \frac{e^3}{2\pi m_e^2 c^4}\left(\frac{\lambda}{R_{\rm n}}\right)^{1/2} R_{\rm n}B_{\rm n}\int N_\gamma\frac{1}{\gamma^2}\,d\gamma$$



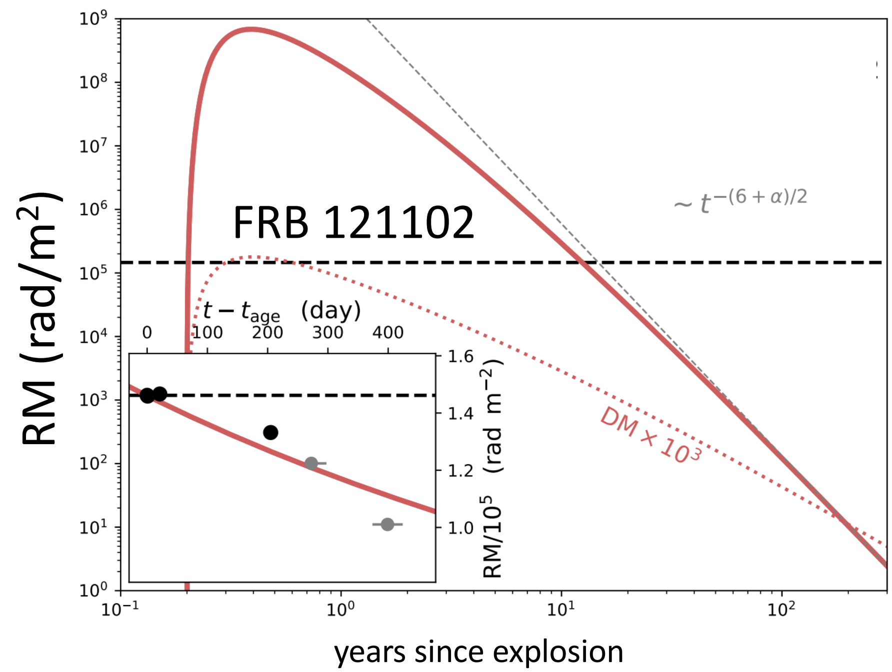
Engine-Powered Nebula

Margalit & BDM 18





=> Source age t ~ 10-100 yr &
total energy E ~ $10^{49\text{-}50}$ erg



$$F_\nu \propto t^{-(\alpha^2+7\alpha-2)/4} \underset{\alpha=0}{\sim} t^{-1/2}$$

$$\left|\mathrm{RM}\right|_{max} \propto t^{-(6+\alpha)/2} \underset{\alpha=0}{\sim} t^{-3}$$

Magnetar Engine?

Energy Reservoir:

$$E_{\rm mag} \sim 3 \times 10^{49} {\rm erg} \left(\frac{B}{10^{16}{\rm G}}\right)^2$$

Engine Lifetime:

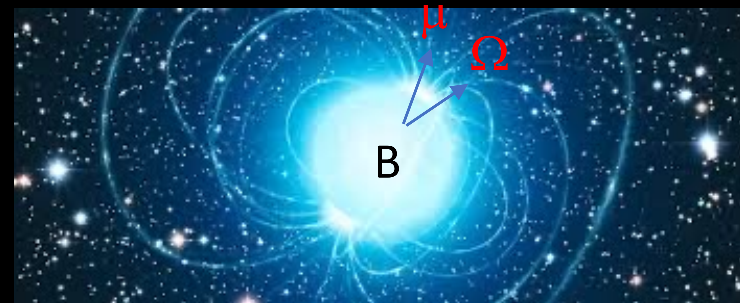
$$t_{\rm mag} \sim (30 - 1000){\rm yr} \left(\frac{B}{10^{16}{\rm G}}\right)^{-1}$$

(e.g. ambipolar diffusion from core)

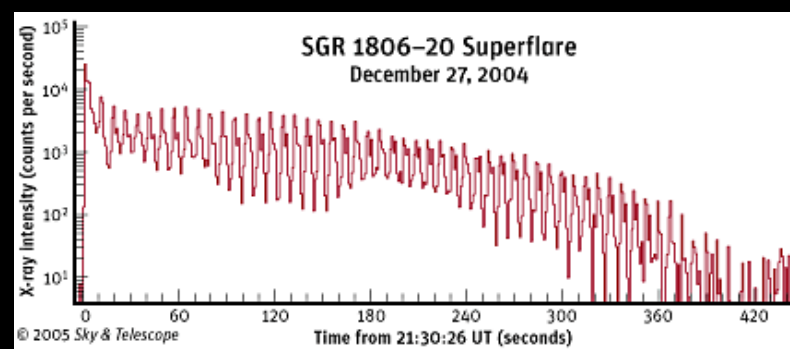
Average Luminosity:

$$\dot{E}_{\rm mag} = \frac{E_{\rm mag}}{t_{\rm mag}} \sim 10^{39} - 10^{41} {\rm erg\,s^{-1}} \left(\frac{B}{10^{16}{\rm G}}\right)^3$$

Outflow Composition:
ions as well as pairs? (e.g. radio afterglows of giant flares)



Giant Flares



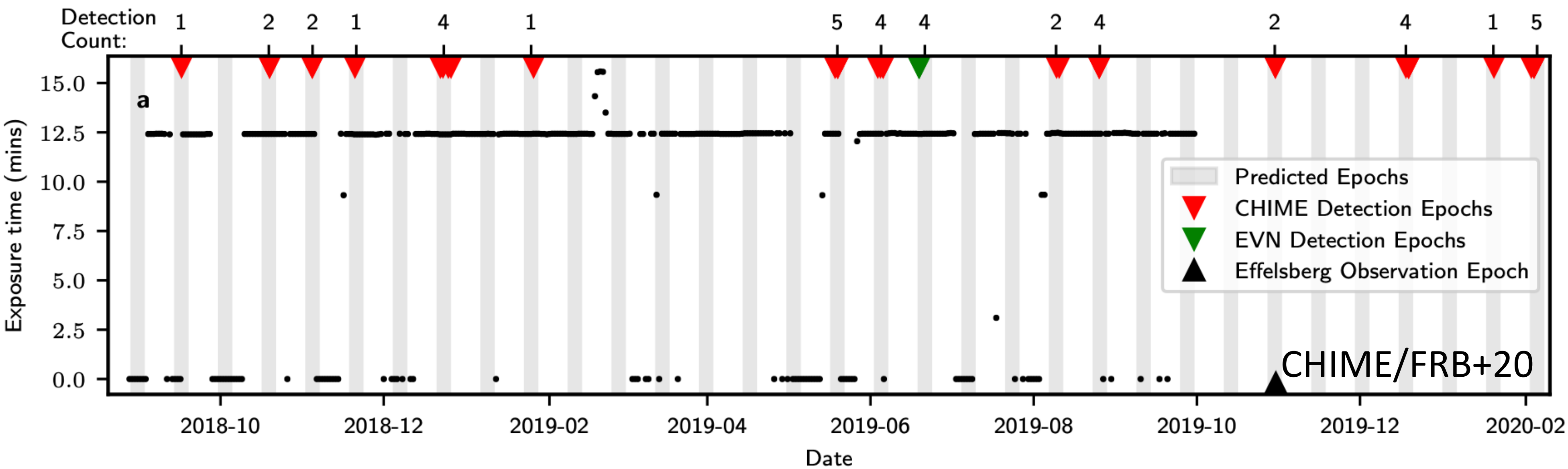
$E_\gamma \sim 10^{44} - 10^{46}$ erg

t_γ ~ 0.2 s

t_{rise} ~ ms

Periodicity in FRB 180916 & 121102

Bursts arrive in "windows" every ~16 d and ~160 d, respectively.



CHIME/FRB+20

see also Rajwade+20

Precessing Magnetar?

(e.g. Levin+20, Zanazzi & Lai 20, Yang & Zou 20)

Very Slowly Rotating Magnetar?

(e.g. Beniamini+20)

Magnetar in a Binary?

(e.g. CHIME+20, Lyutikov+20)

Periodicity in FRB 180916 & 121102

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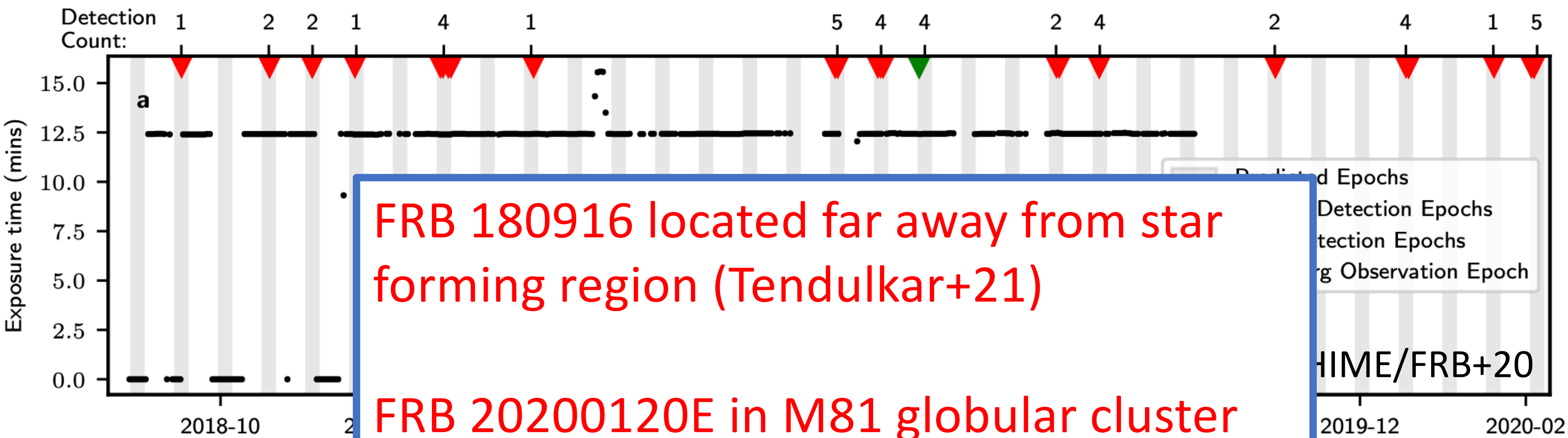


FRB 180916 located far away from star forming region (Tendulkar+21)

FRB 20200120E in M81 globular cluster (Bhardwaj+21, Kirstin+21)

Mechanisms exist to generate magnetars in old stellar populations (AIC, BNS mergers; e.g. Margalit+19), but comparatively rare.

so Rajwade+20

Precessin

(e.g. Levin+20, Zana

Very Slow

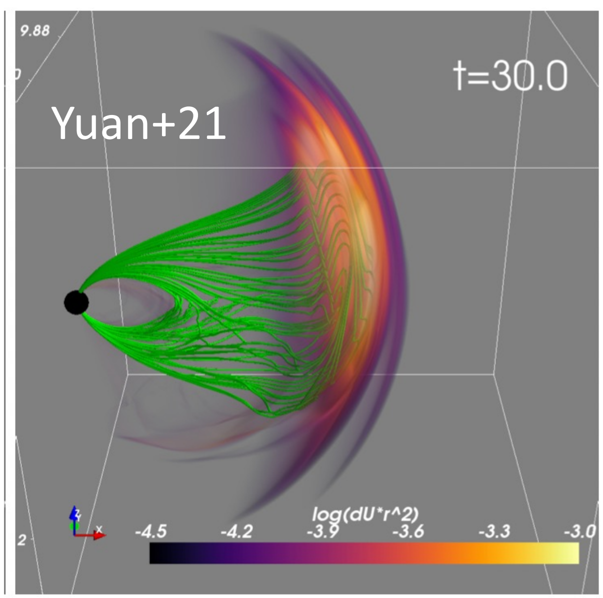
(e.g. Beniamini+20)

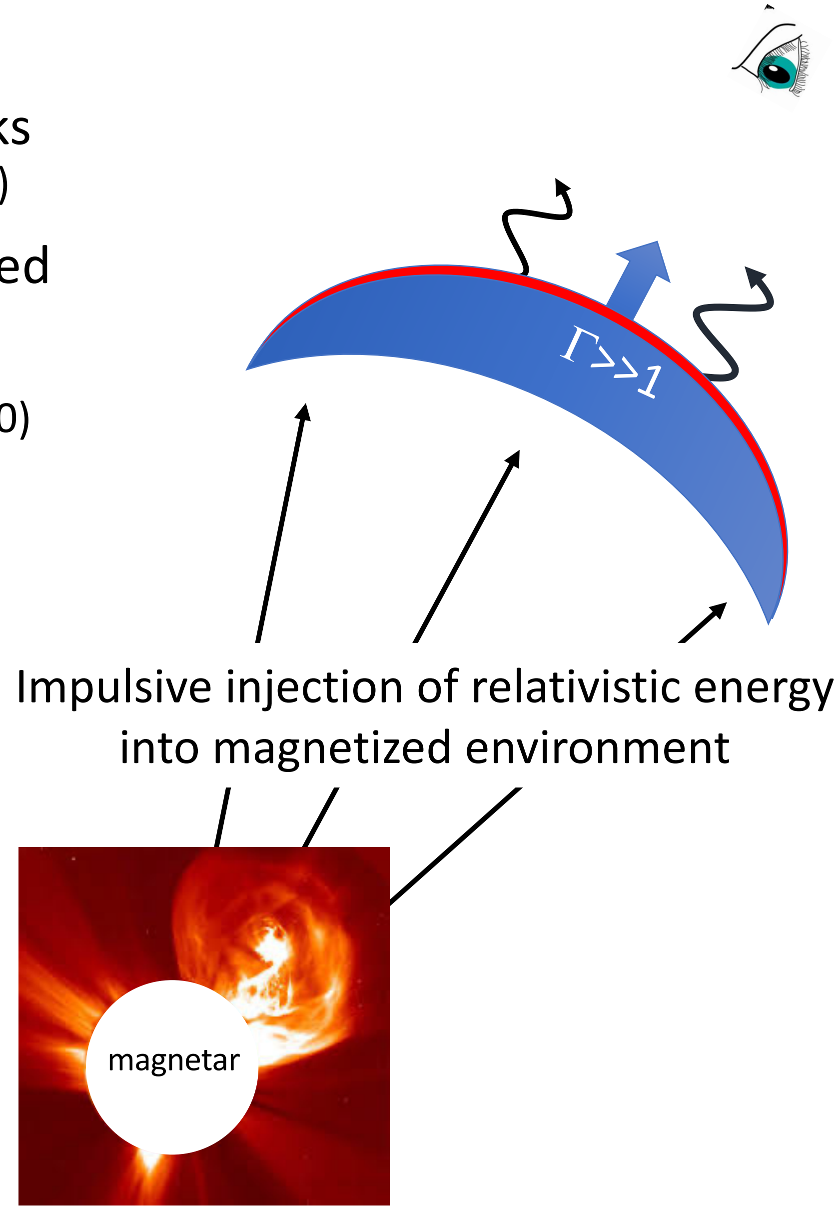
Magnetar in a Binary?

(e.g. CHIME+20, Lyutikov+20)

FRB Emission Mechanisms

- Synchrotron Maser at Relativistic Shocks (e.g. Lyubarsky 14, Beloborodov 17, 19, BDM+19)
- Forced Magnetic Reconnection in Striped Wind (e.g. Lyubarsky 20, Mahlmann+22)
- Alfven Wave Decay (e.g. Kumar & Bosnjak 20)
- Free Electron Laser from Magnetic Reconnection (Lyutikov 20)





Can Accreting BH/NS Jets Make FRBs?

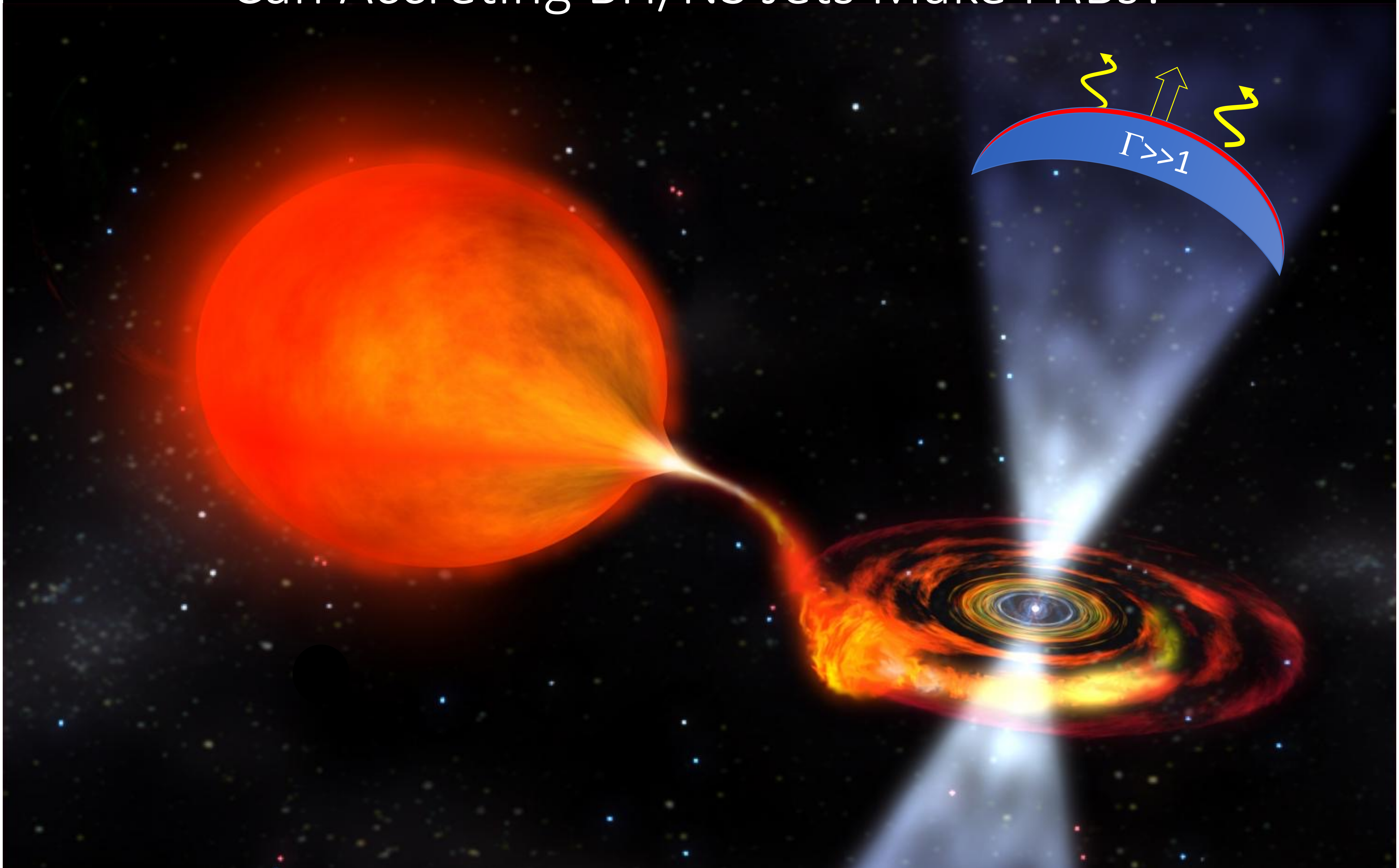
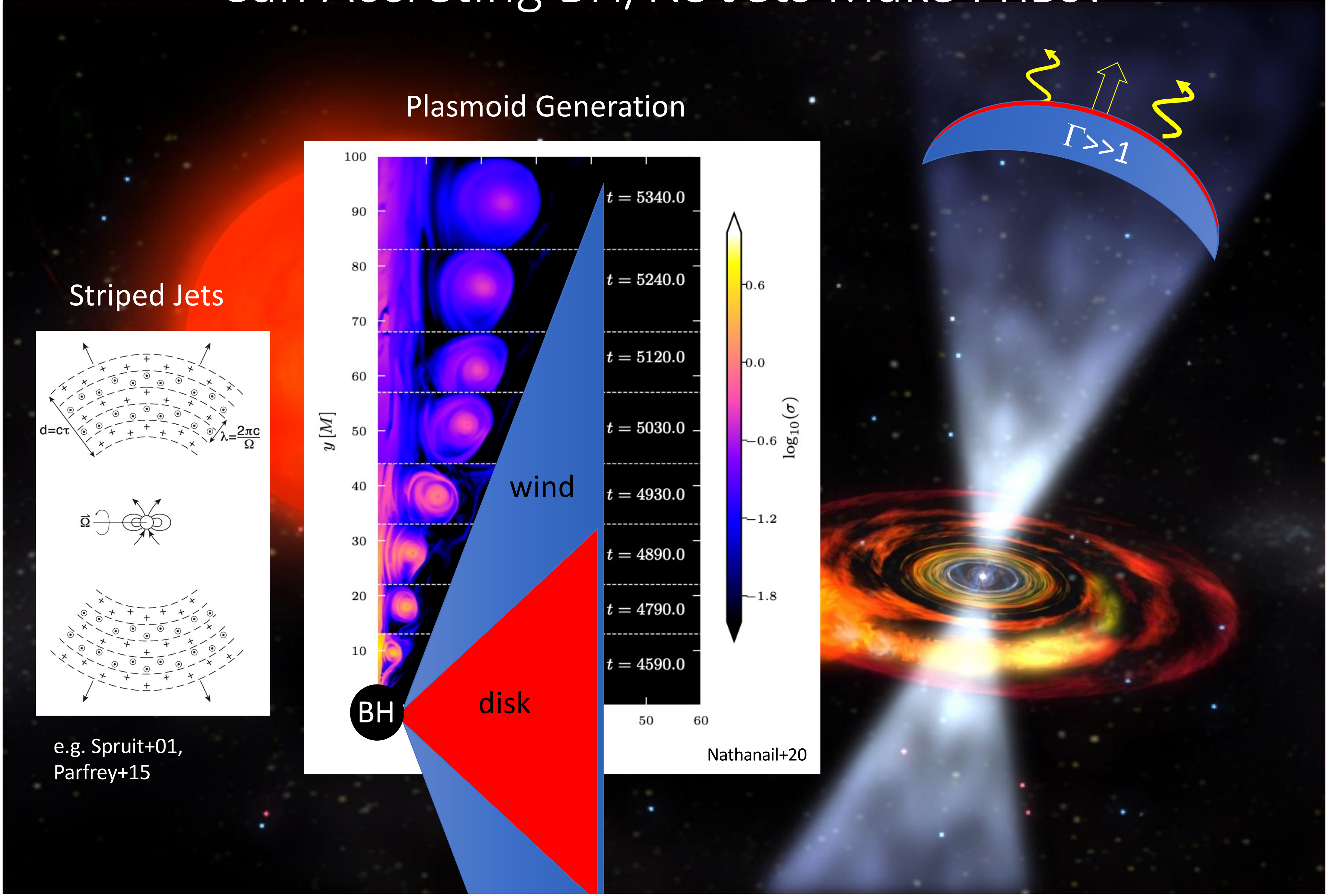


Image Credit: NASA

Can Accreting BH/NS Jets Make FRBs?



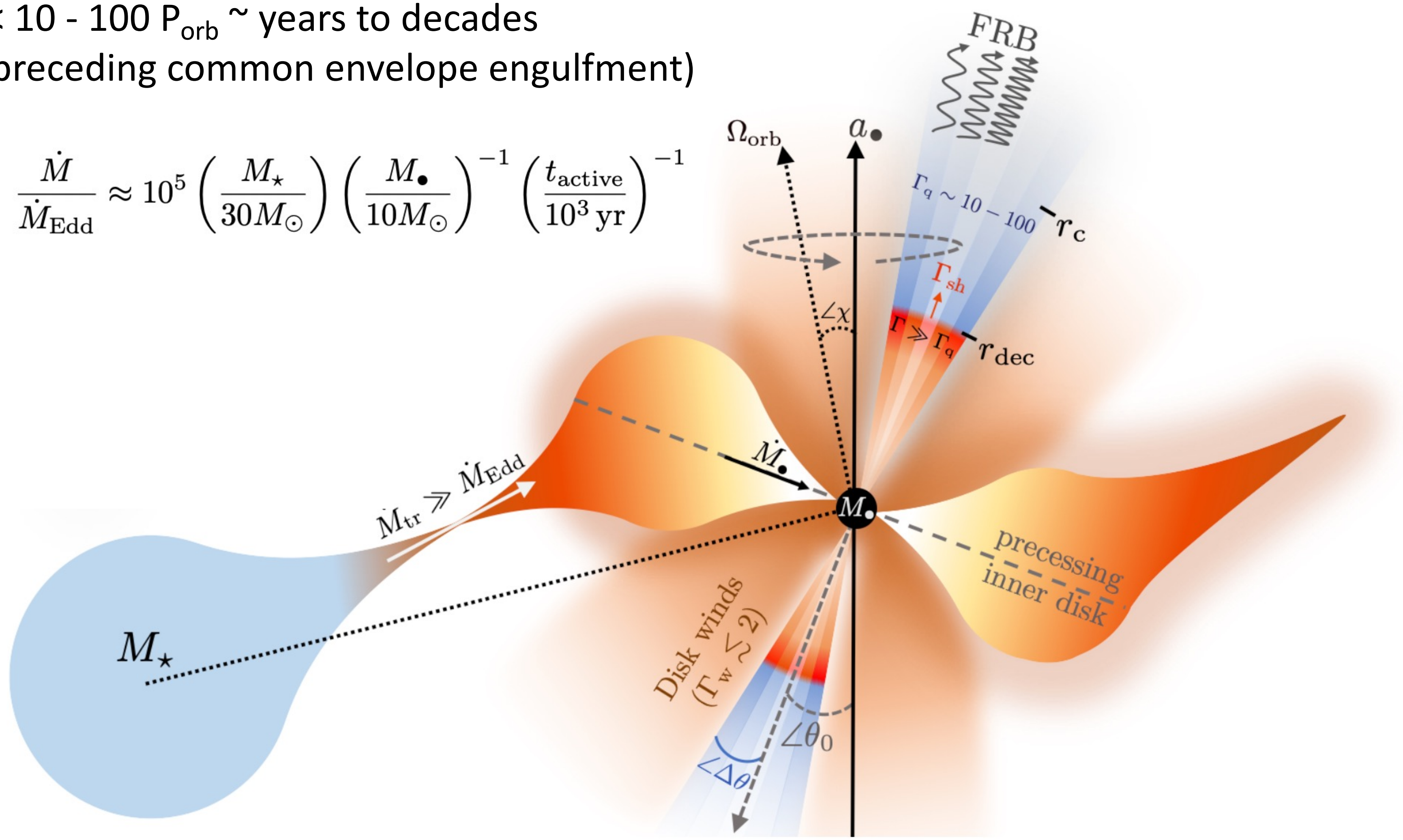
Periodic Fast Radio Bursts from Luminous X-ray Binaries

Navin Sridhar,[1,2] Brian D. Metzger,[3,2] Paz Beniamini,[4,5] Ben Margalit,[6,*] Mathieu Renzo,[2,3]
Lorenzo Sironi,[1,2] and Konstantinos Kovlakas[7,8,9]

t_{active} ~ $10^3 – 10^6$ yr
(stable thermal mass-transfer)

t_{active} < 10 - 100 P_{orb} ~ years to decades
(preceding common envelope engulfment)

$$\dot{M} \approx \frac{M_\star}{t_{active}}; \quad \frac{\dot{M}}{\dot{M}_{Edd}} \approx 10^5 \left(\frac{M_\star}{30 M_\odot}\right)\left(\frac{M_\bullet}{10 M_\odot}\right)^{-1}\left(\frac{t_{active}}{10^3\,\mathrm{yr}}\right)^{-1}$$



Max FRB luminosity set by max jet power

$$L_{\rm FRB}^{\rm max} \approx f_\xi f_{\rm b}^{-1} \eta_{\rm max} \dot{M}_\bullet c^2$$

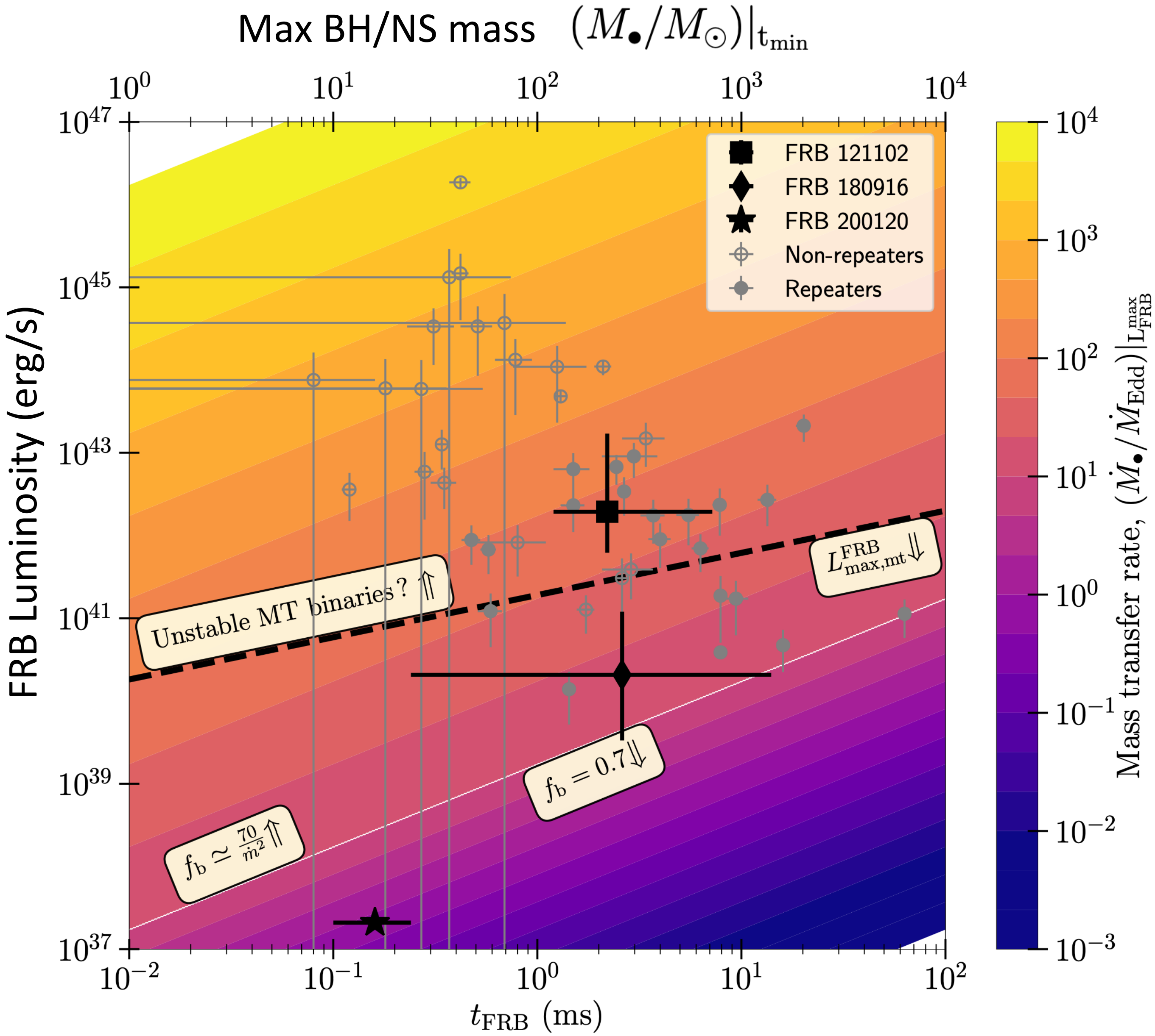
where $\eta_{\rm max}$ ~ 1 (MAD)

f_ξ ~ 10^{-3} (e.g. sync. maser)

beaming set by accretion funnel

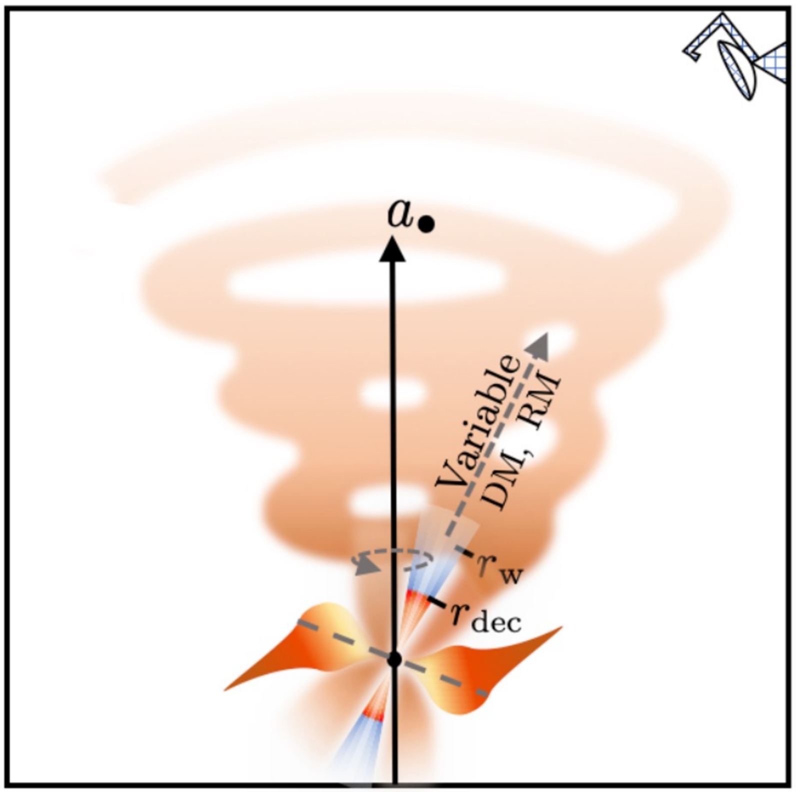
$$f_{b,X} \underset{\dot{m}>>1}{\approx} \frac{73}{\dot{m}^2}$$

(King 09)

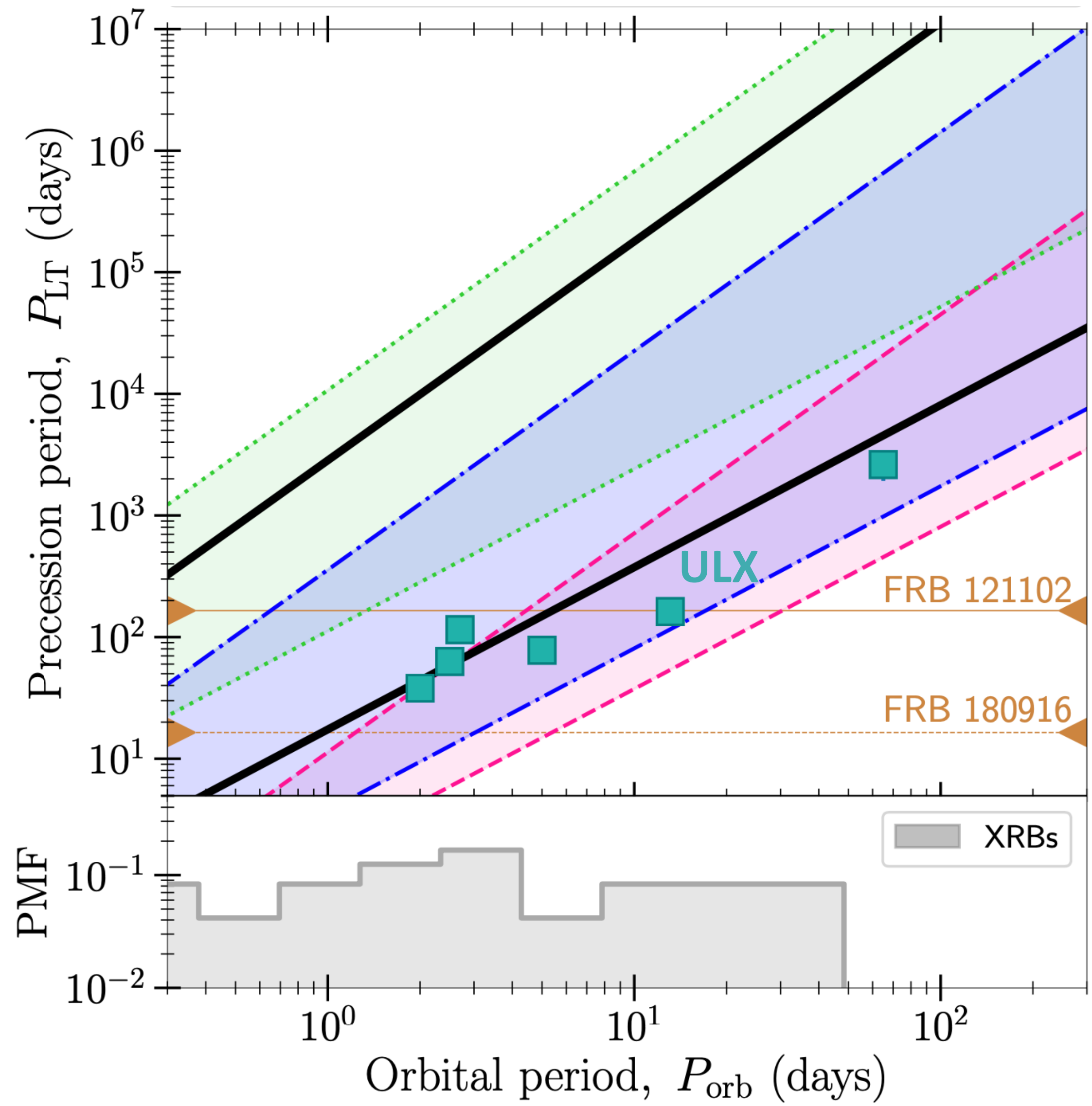


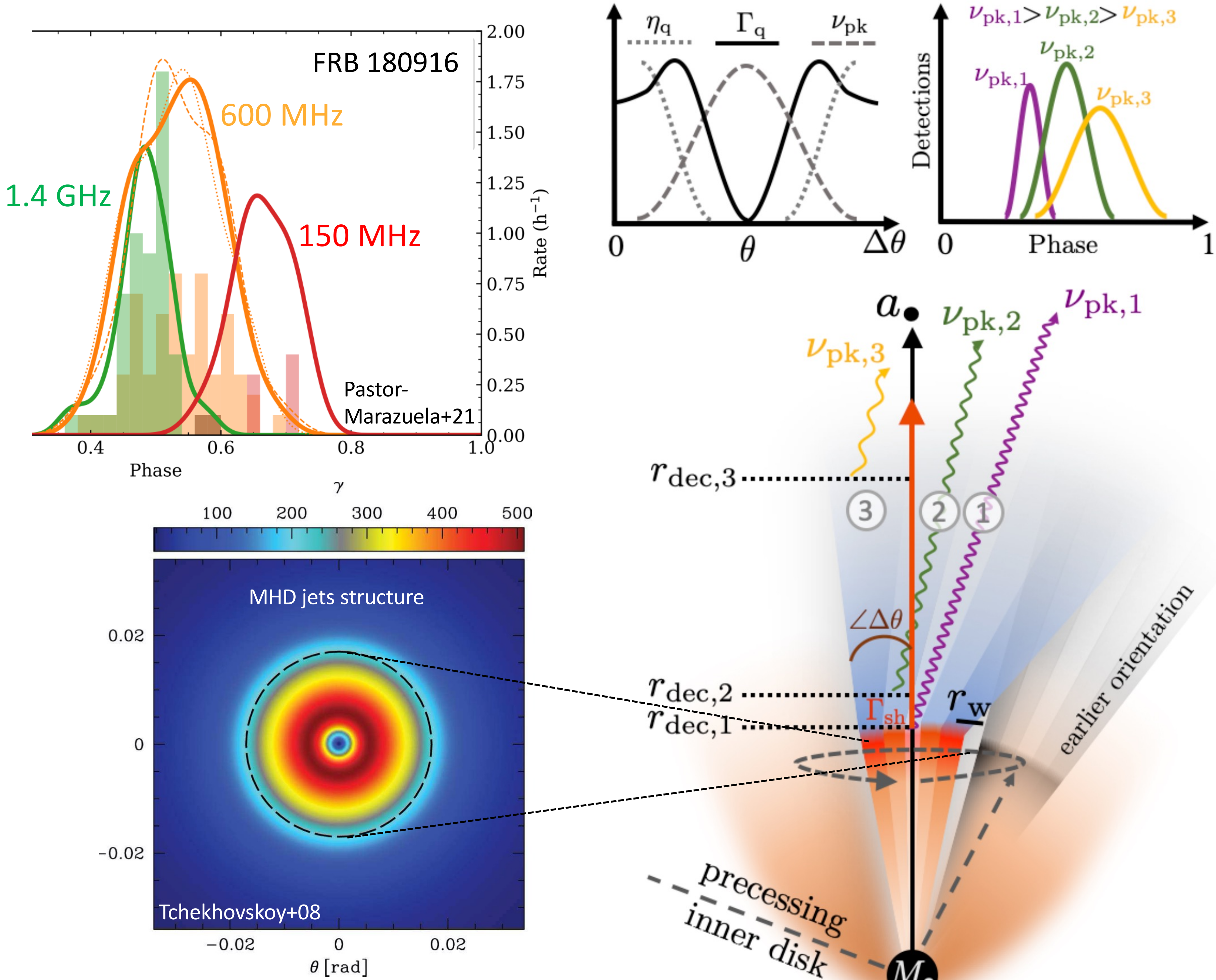
Matching durations & luminosities of most powerful FRBs requires **super-Eddington** accretion onto BHs or NSs => **ULX-like binaries**

Periodicity from Lens-Thirring Precession



Phase-dependent local RM/DM from precessing disk winds?
(related: Katz 17; Ioka & Zhang 20)

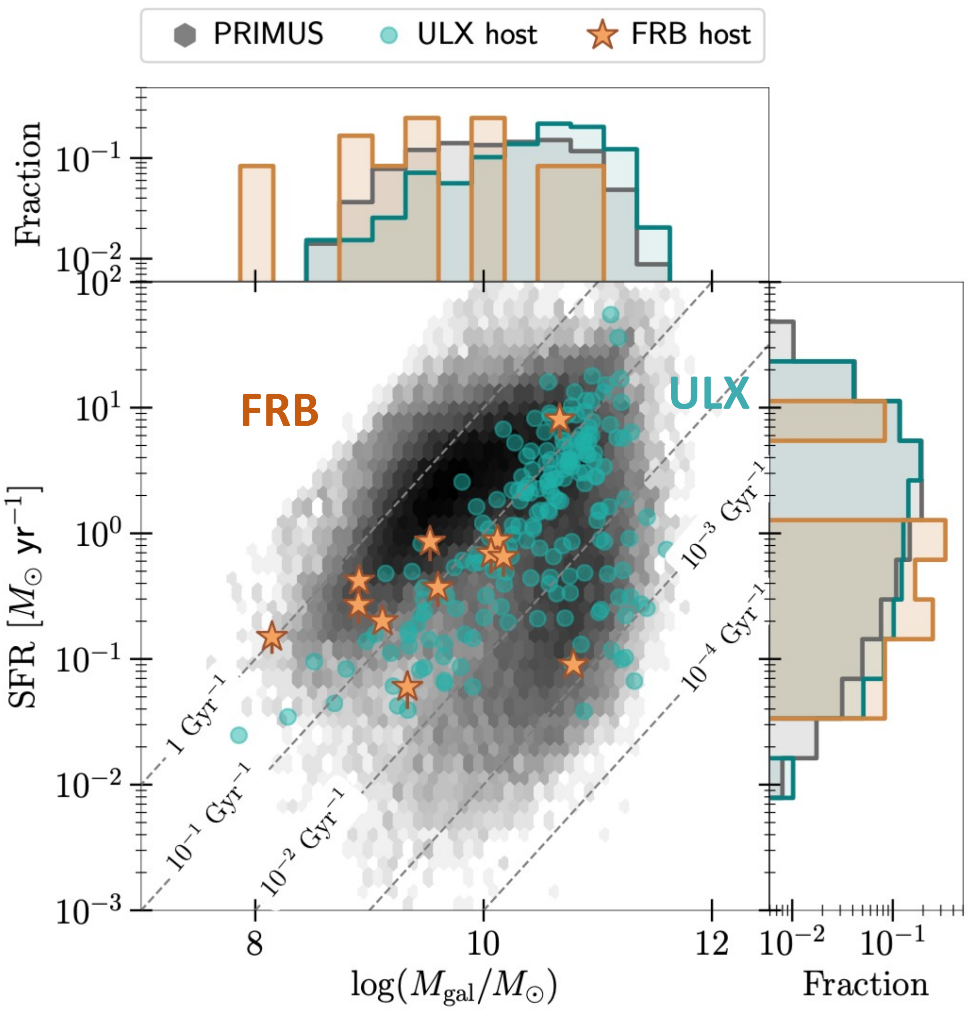




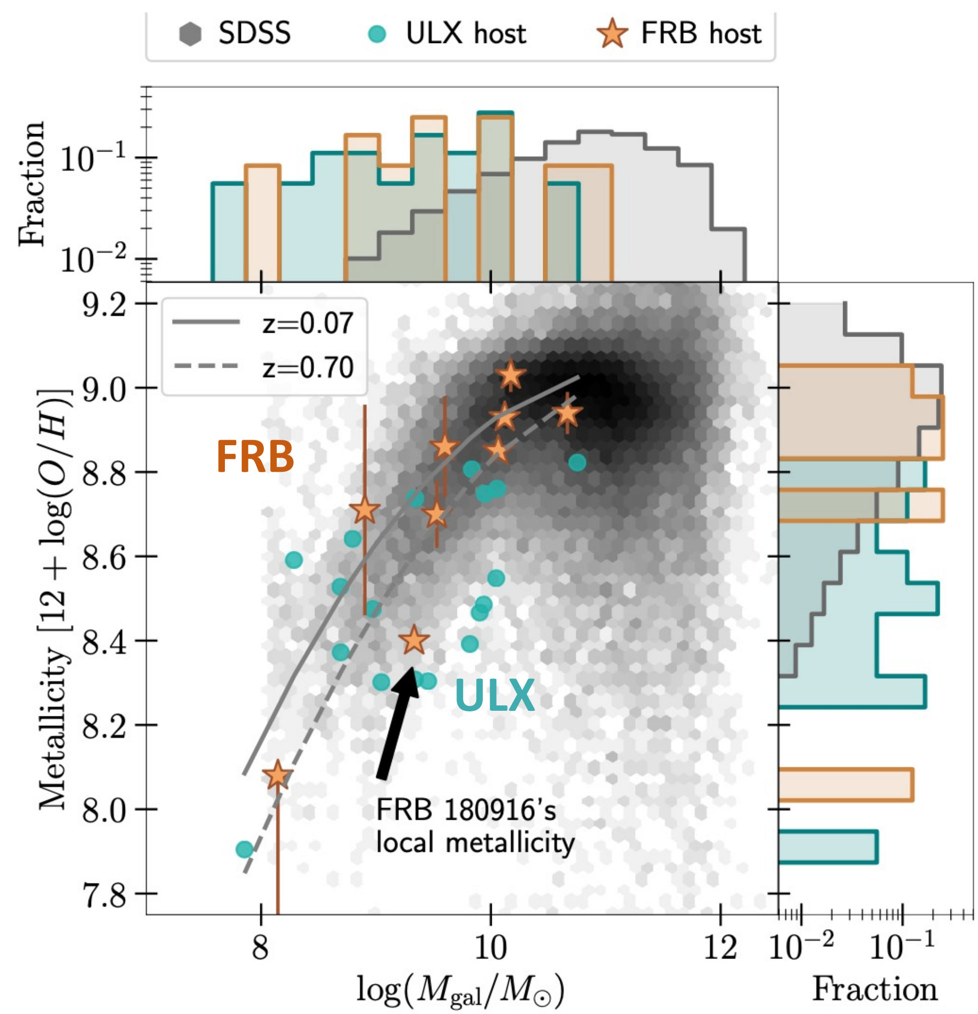
FRB 180916
600 MHz
1.4 GHz
150 MHz
Pastor-
Marazuela+21
Phase
Rate (h^{-1})
η_q
Γ_q
ν_{pk}
θ
$\Delta\theta$
$\nu_{pk,1} > \nu_{pk,2} > \nu_{pk,3}$
Detections
Phase
γ
MHD jets structure
Tchekhovskoy+08
θ [rad]
$a_\bullet$
$r_{dec,3}$
$r_{dec,2}$
$r_{dec,1}$
Γ_{sh}
r_w
$\angle\Delta\theta$
earlier orientation
precessing
inner disk
$M_\bullet$

Host Galaxies of FRB vs. ULX

Star Formation Rate

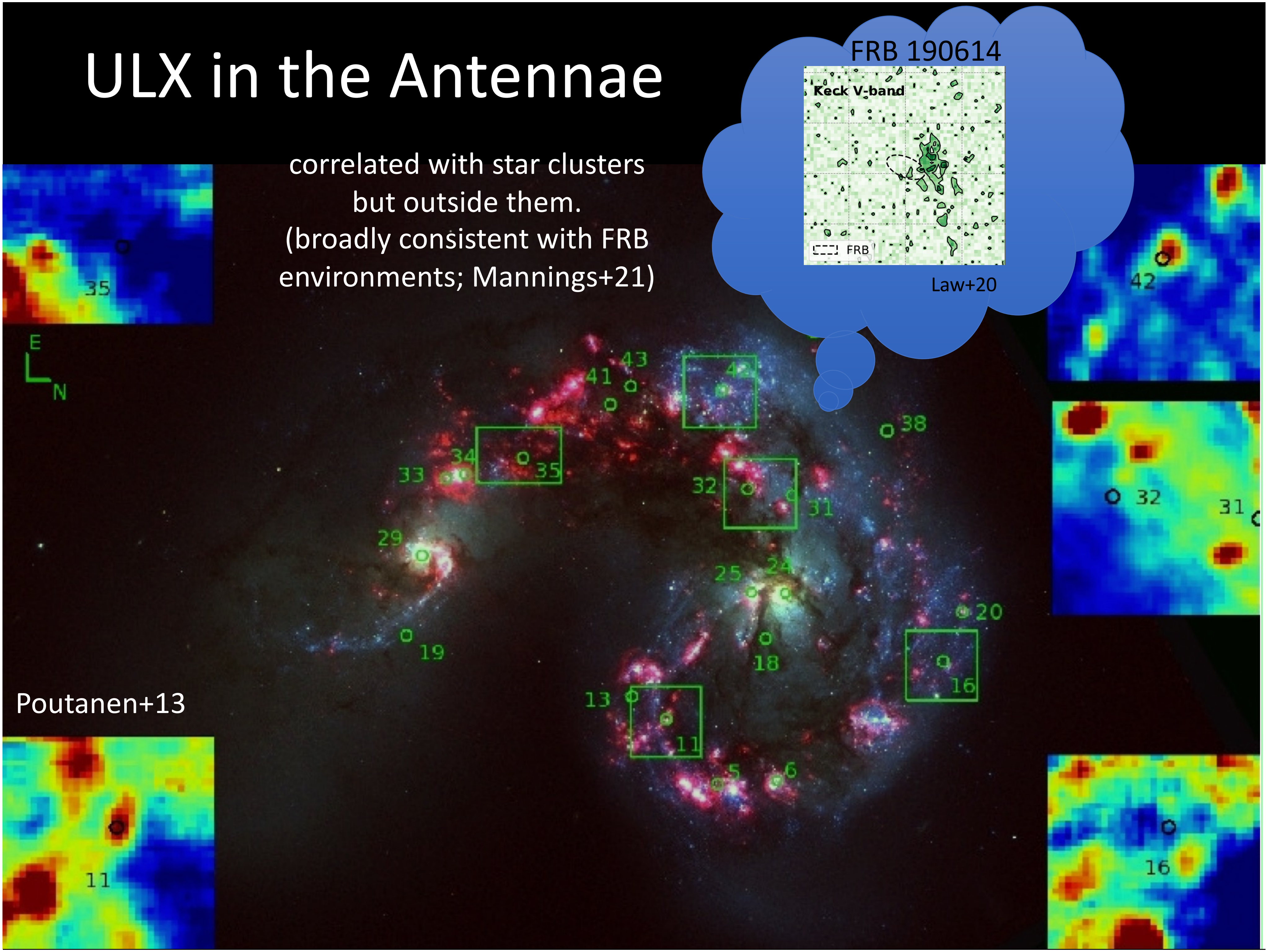


Metallicity



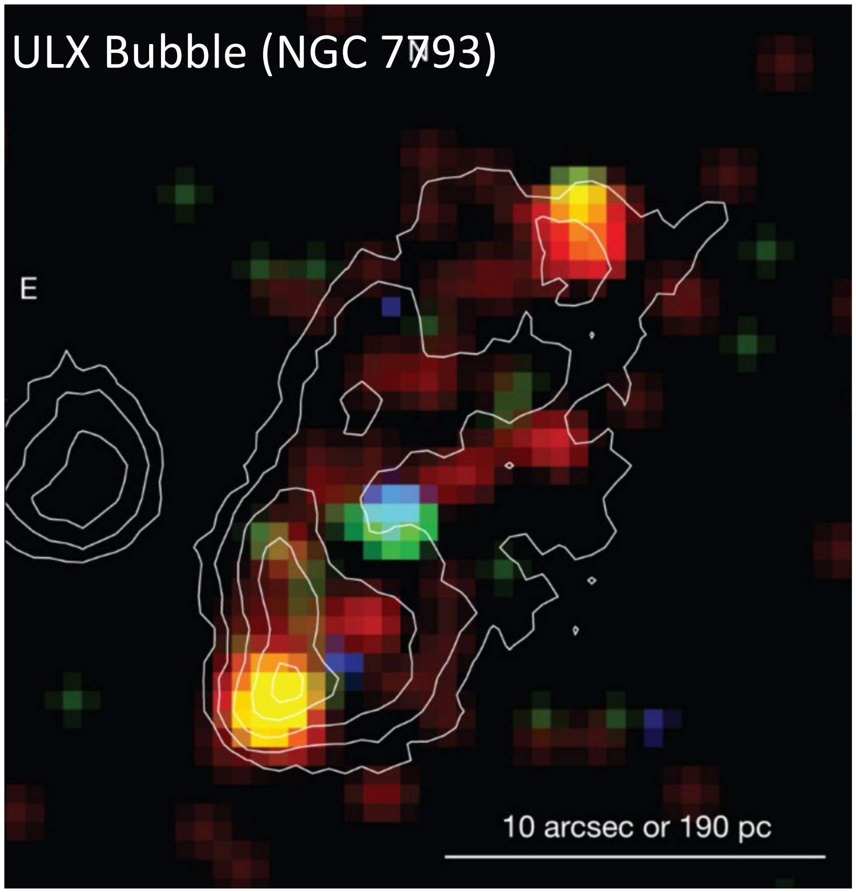
ULX in the Antennae

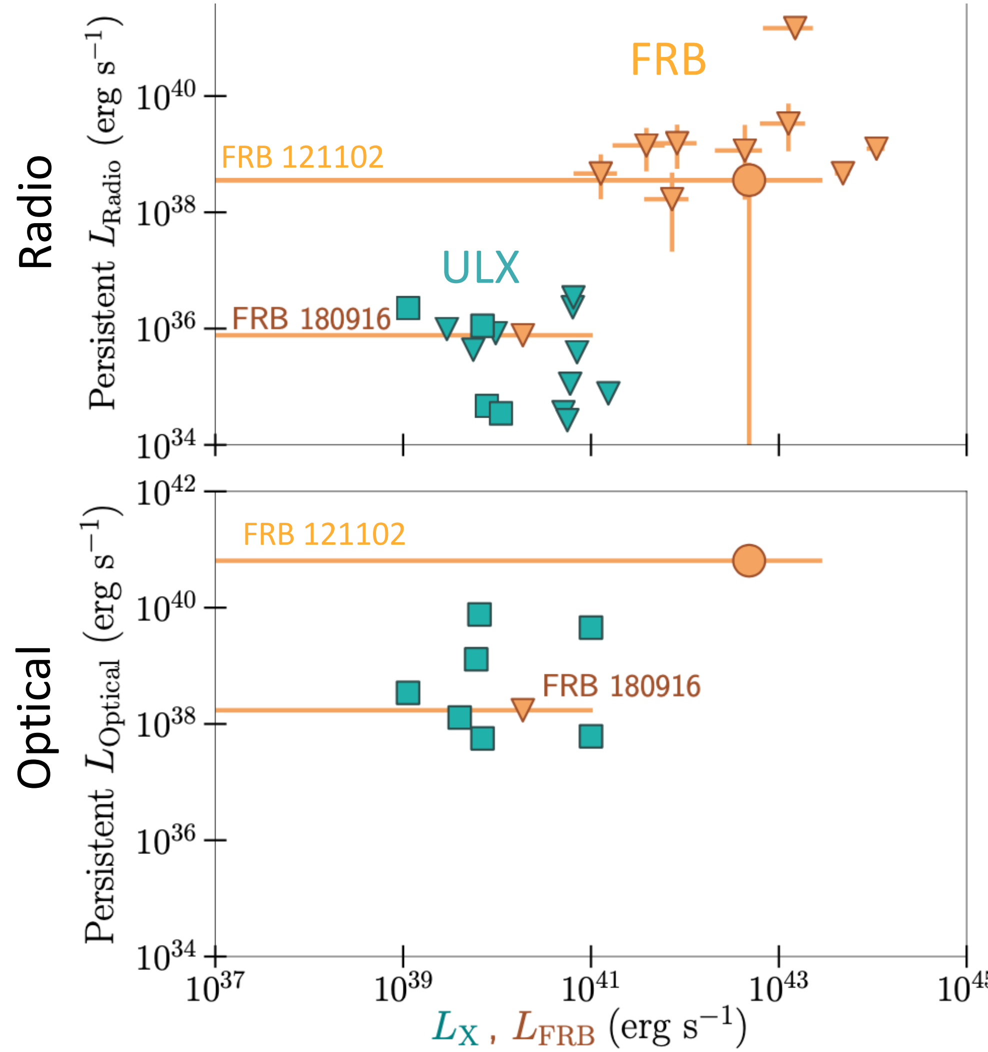
correlated with star clusters
but outside them.
(broadly consistent with FRB
environments; Mannings+21)



ULX Bubbles as Persistent Counterparts

Figure 1: Optical/X-ray image of the 300-pc-diameter jet-inflated bubble S26 in the galaxy NGC 7793.



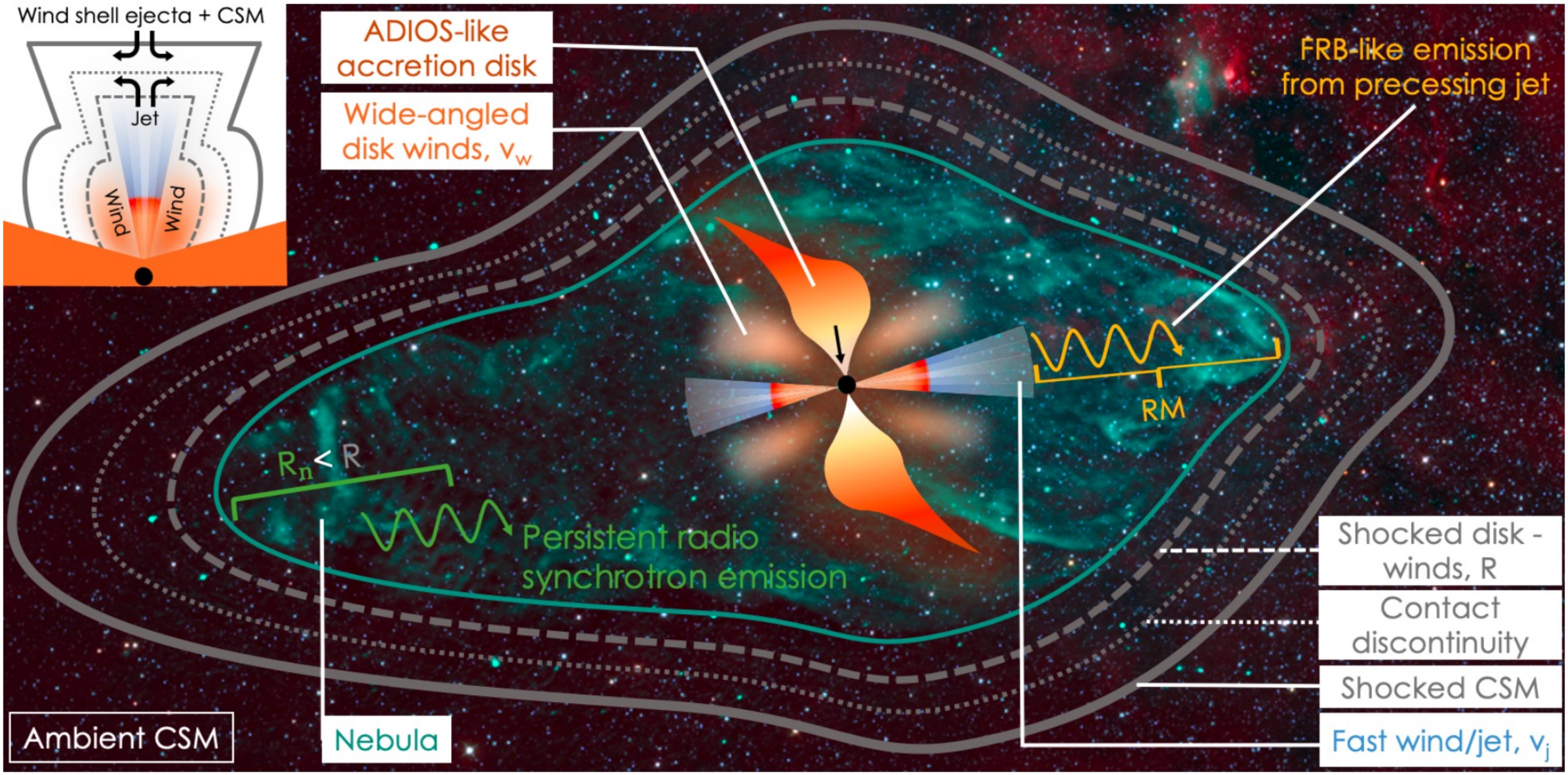


Most known ULX bubbles would not be detectable at the distances of most FRB

However, local XRB/ULX are not the best analogs to powerful cosmological FRB
(which require even higher super-Eddington accretion rates and young source ages)

Radio Nebulæ from Hyper-Accreting X-ray Binaries as Common Envelope Precursors and Persistent Counterparts of Fast Radio Bursts

NAVIN SRIDHAR [1,2] AND BRIAN D. METZGER [3,2,4]



wind-driven bubble evolution (Weaver+77)

$$R(t) \simeq \begin{cases} v_{\rm w} t \approx 0.7\,{\rm pc}\left(\frac{t}{70\,{\rm yr}}\right) & (t < t_{\rm free}) \\ \alpha\left(\frac{L_{\rm w} t^3}{\rho_{\rm csm}}\right)^{1/5} \approx 0.8\,{\rm pc}\left(\frac{L_{\rm w,42}}{n_1}\right)^{1/5}\left(\frac{t}{70\,{\rm yr}}\right)^{3/5} & (t > t_{\rm free}), \end{cases}$$

Relativistic electrons injected at termination shock of fast v_j ~ 0.1-0.3 c wind/jet and evolve under expansion/cooling

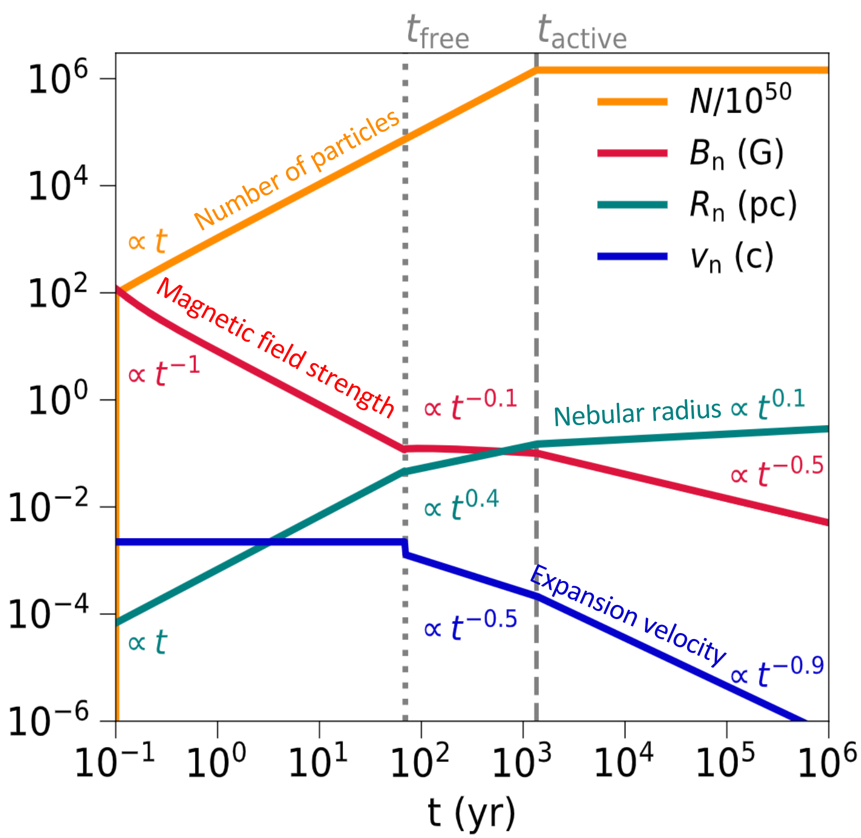
Evolution of Particles in Nebula

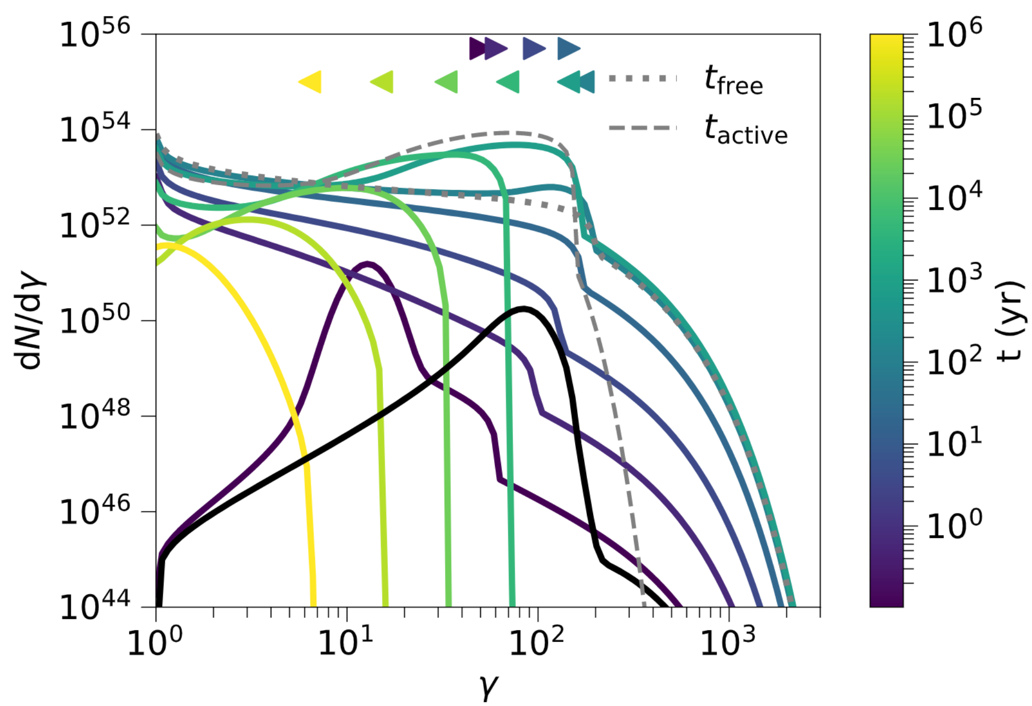
$$\bar{\gamma}_e \simeq \frac{1}{2}\varepsilon_e \frac{m_p}{m_e}\frac{v_j^2}{c^2} \approx 115\left(\frac{\varepsilon_e}{0.5}\right)\left(\frac{v_j}{0.5\,c}\right)^2$$

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

$$\dot{N}_\gamma = \frac{\partial}{\partial t}N_\gamma + \frac{\partial}{\partial \gamma}(\dot{\gamma}N_\gamma) - 3\frac{\dot{R}_n}{R_n}N_\gamma$$

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





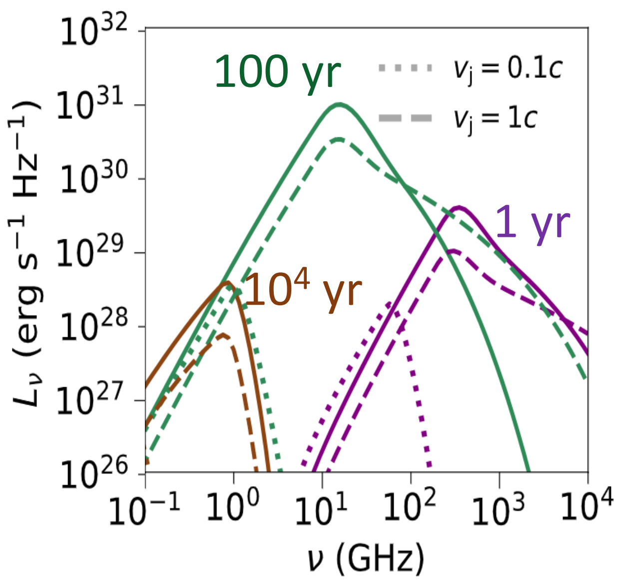
Observables from Expanding Hyper-Nebula

$$L_\nu = 4\pi^2 R_{\rm n}^2 \frac{j_\nu}{\alpha_\nu}(1 - e^{\alpha_\nu R_{\rm n}}) \qquad j_\nu = \int \frac{N_\gamma P_\nu(\gamma)}{4\pi} d\gamma, \quad \alpha_\nu = -\int \frac{\gamma^2 P_\nu(\gamma)}{8\pi m_{\rm e}\nu^2} \frac{\partial}{\partial\gamma}\left[\frac{N_\gamma}{\gamma^2}\right] d\gamma$$

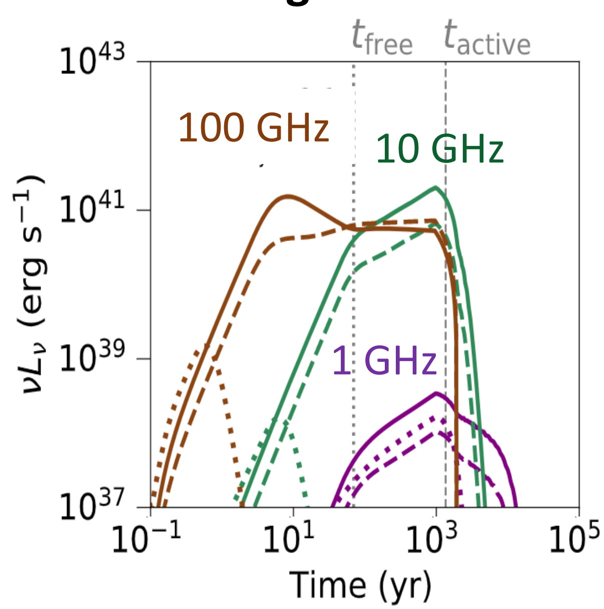
$$|\mathbf{RM}| \simeq \frac{e^3}{2\pi m_{\rm e}^2 c^4}\left(\frac{\lambda}{R_{\rm n}}\right)^{1/2} B_{\rm n} R_{\rm n} \int \frac{N_\gamma}{\gamma^2} d\gamma \qquad \mathbf{DM}_{\rm neb} \simeq R_{\rm n} \int \frac{N_\gamma}{\gamma} d\gamma$$

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

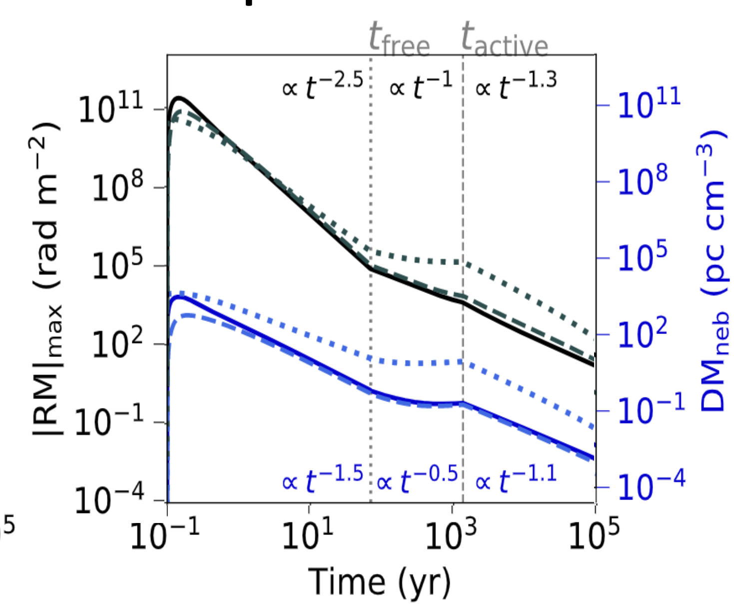
Spectra



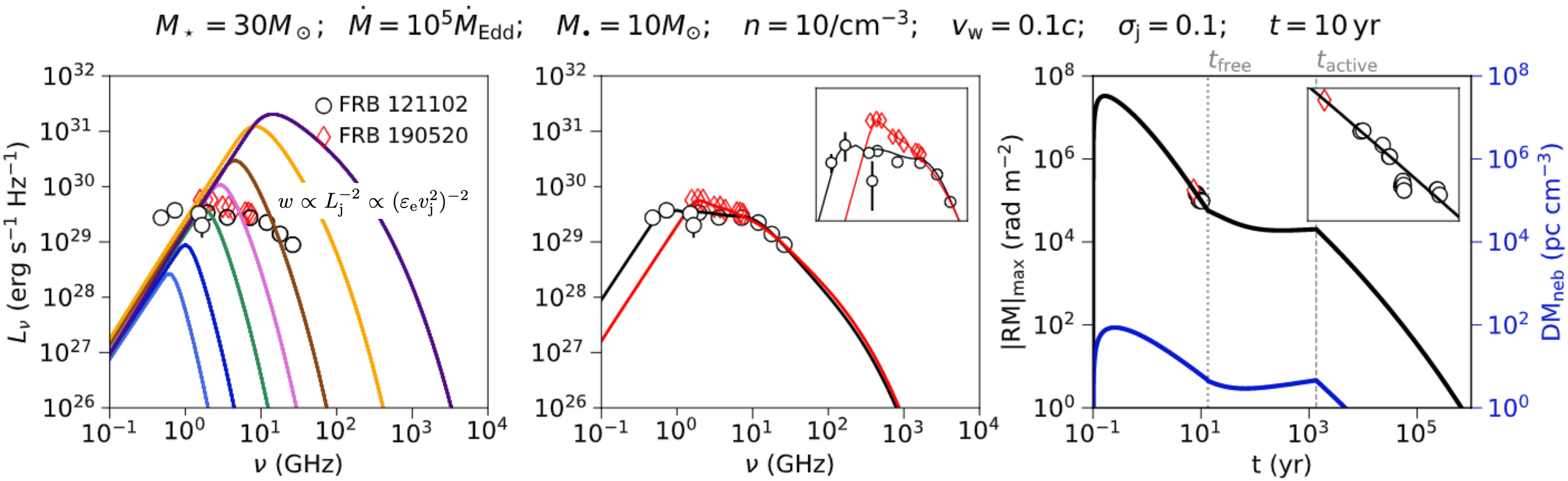
Light curves



Rotation and Dispersion measures

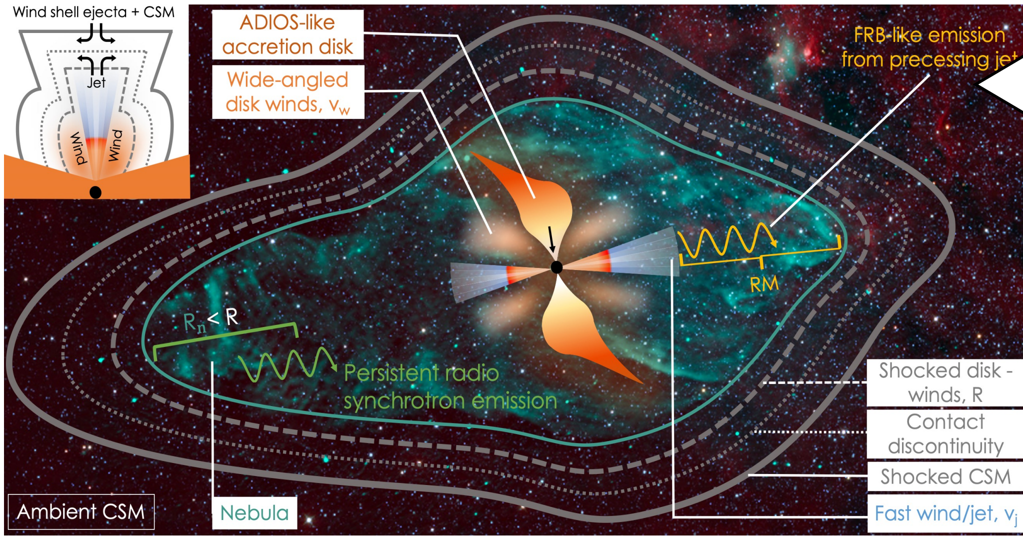


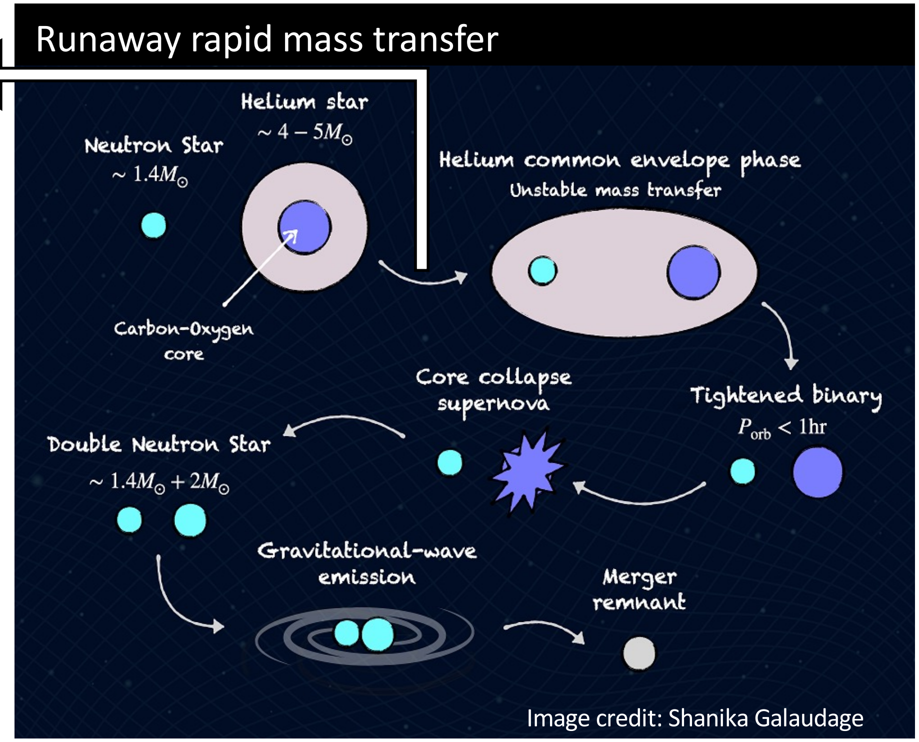
Application to FRB121102 persistent radio source



- ➢ Observed PRS radio spectra are flatter and broader than those predicted by the idealized ‘one-zone’ model with single injected electron luminosity / temperature.
- ➢ Generalizing to allow for a modest spread in the jet luminosity / shock velocity enables a good fit.
- ➢ We constrain the source age of ~10 yr for FRB 1211102, similar to magnetar scenarios. .

Take-away applications of hyper-nebulae





- Accreting engines can potentially explain the properties of FRBs and their associated persistent radio sources.
- They presage energetic transients from *common envelope* mergers (e.g. Luminous Red Novae, FBOTs), and can act as signposts to future LIGO merger events.
- ***Hyper-nebulae* are plentiful in our Universe, even lurking in our samples (e.g., VLASS)… they are just waiting to be discovered.**

Summary

- The luminous persistent radio sources and high time-variable RM of repeating FRBs point to engines embedded in self-powered electron-ion nebulae.
- The engine could be very young and highly-active magnetars which expends a significant amount of its total magnetic energy ejecting baryons from its surface in a trans-relativistic wind.
- However, the discoveries of periodicity in the burst arrival windows and of FRBs from old stellar population may pose a challenge to magnetar scenarios.
- Many of the physical processes that occur in magnetar magnetospheres could also occur in the magnetized accretion funnel of a BH or NS jet.
  Periodicity in the arrival phase arises naturally from precession of the jet funnel.
- The timescale and luminosities of FRBs require binaries with accretion rates near or exceeding Eddington, pointing to short-lived mass-transfer phases (which may not be representative of longer-lived ULX in the local universe).
- Young "hyper"-ULX nebulae offer a new model for FRB persistent radio sources which contribute high and time-variable local RM and DM.