NTNU

Mode switching in transitional millisecond pulsars: insights from GRMHD simulations & radiative transfer

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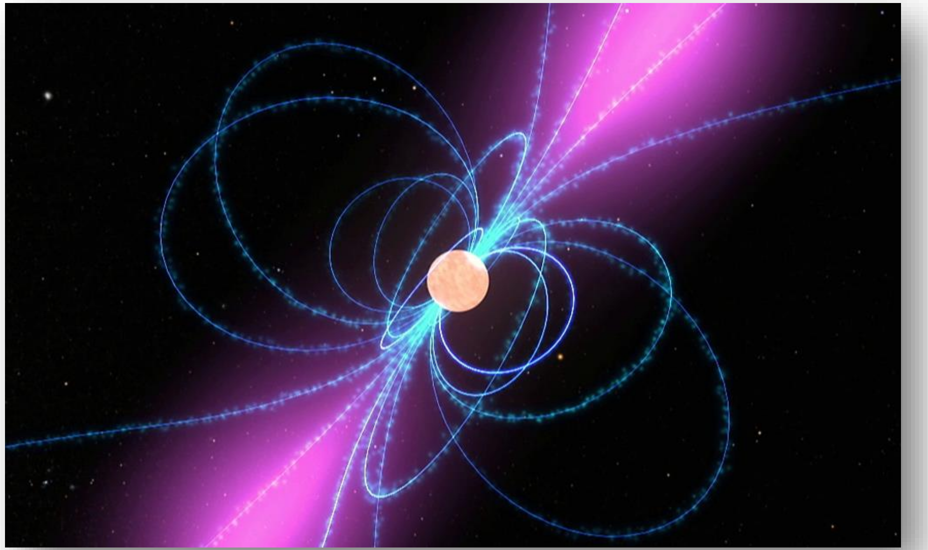
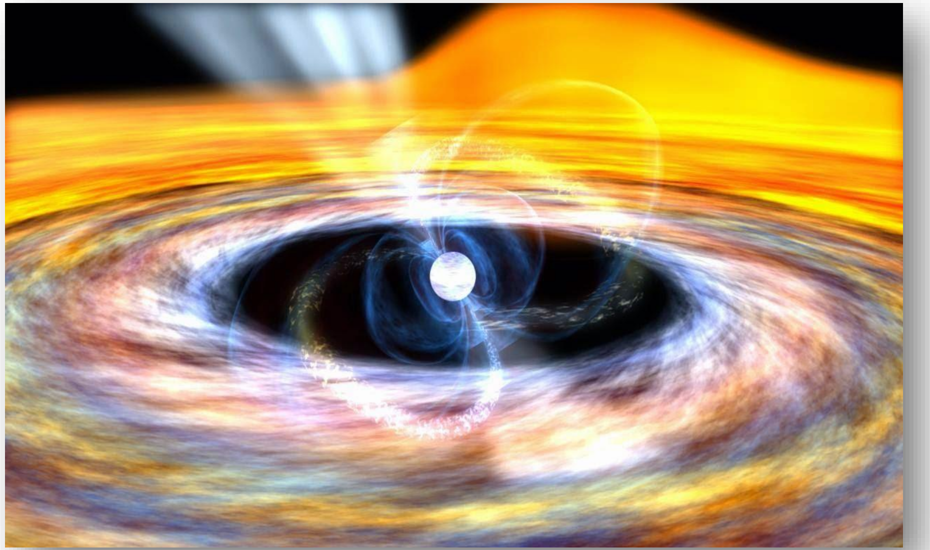
Transitional millisecond pulsars

- Subclass of neutron stars (NS) in binary systems



$\longleftrightarrow$



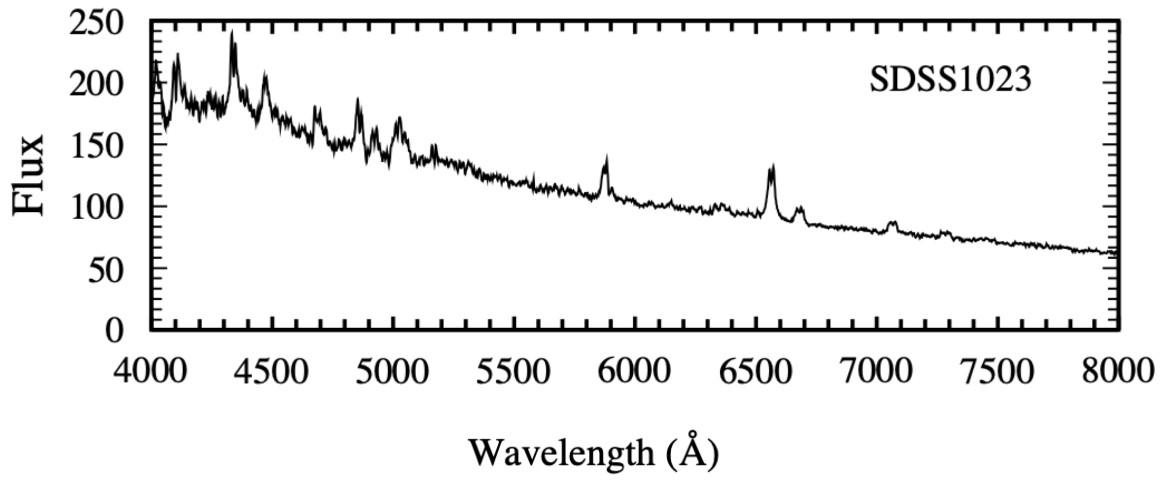
Radio pulsar state

Low-mass X-ray binary state
$M_{\mathrm{NS}} > M_{\mathrm{donor}}$ main-sequence

- « Low » magnetic field $\sim 10^8$G
- Spin period $\gtrsim$ 1 ms
- Clues of the « recycling scenario » ? e.g. Alpar+82
  Gyr-long accretion phase → spin-up

Review: Papitto & De Martino 2022

Transitional millisecond pulsars: 3 sources



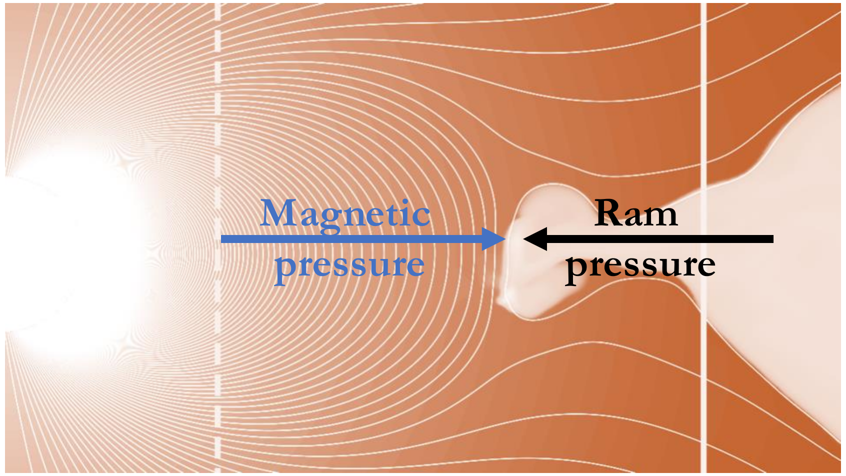
Szkody+03

From X-ray Binary to Pulsar

Pulsars with millisecond rotational periods are thought to originate from neutron stars in low-mass x-ray binaries that had their spin frequencies increased by long-lasting mass transfer from their companion stars. Using data from a radio pulsar survey, **Archibald *et al.*** (p. 1411, published online 21 May; see the Perspective by **Kramer**) found a neutron star in a low-mass X-ray binary that is in the process of turning into a radio millisecond pulsar. The system, which consists of a solar-like star and a 1.69-millisecond radio pulsar, has gone through a recent accretion phase, characteristic of low-mass X-ray binaries, but it shows no accretion disk anymore, confirming the evolutionary connection between millisecond radio pulsars and low-mass X-ray binaries.

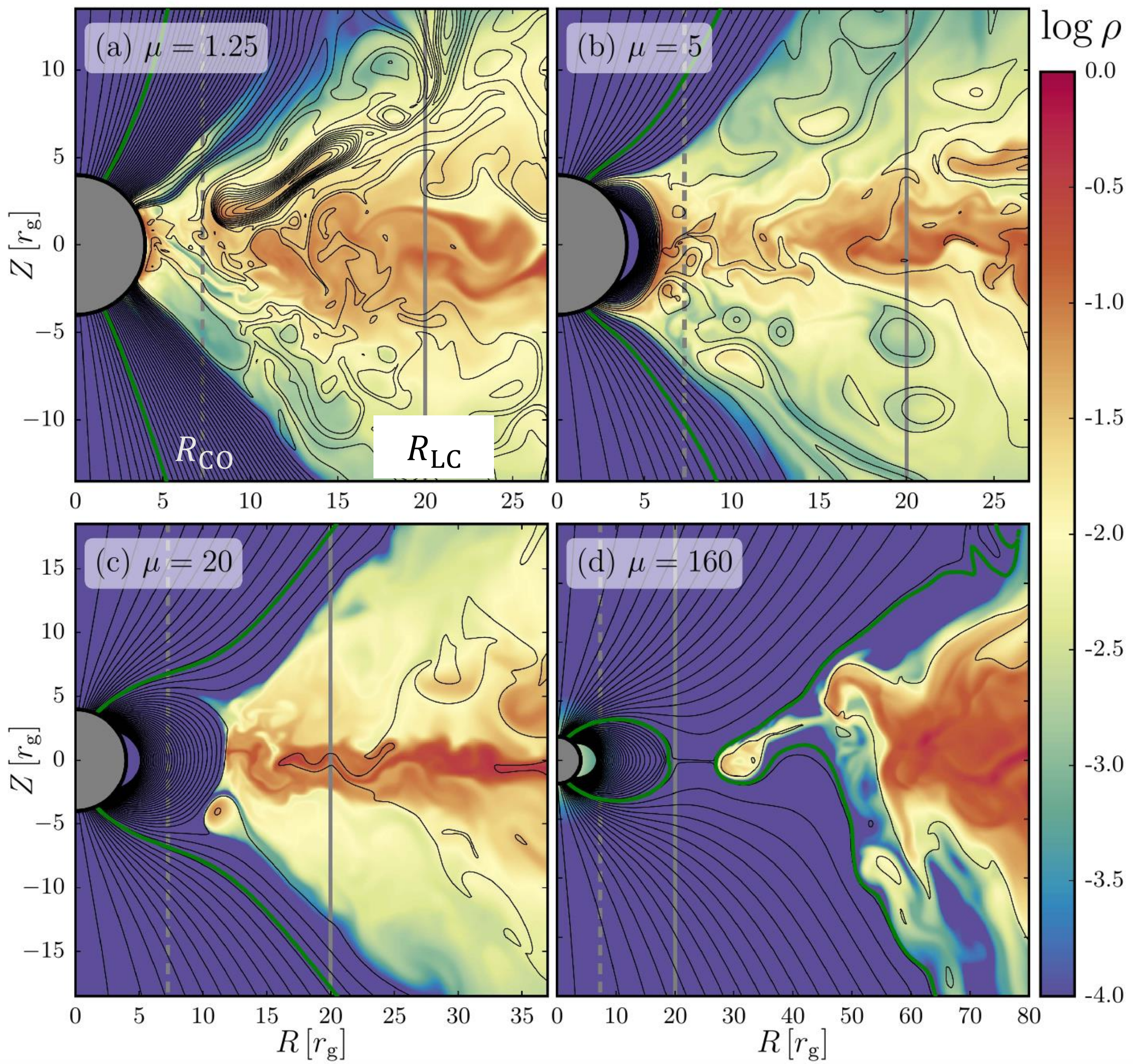
Archibald+09, Science

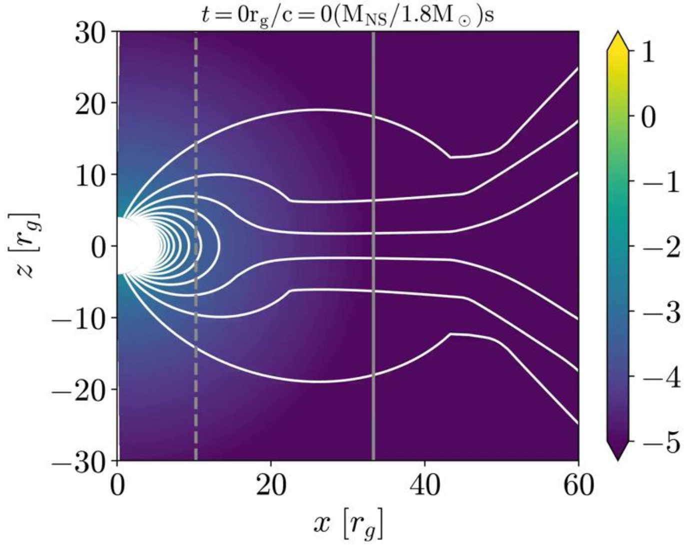
- Three sources so far:
  - PSR J1023+0038, Archibald+09
  - XSS J12270-4859, Bassa+14
  - IGR J18245-2452, Papitto+13
- Plausible scenario: magnetic pressure barrier > accretion



The four states of accretion of transitional millisecond pulsars

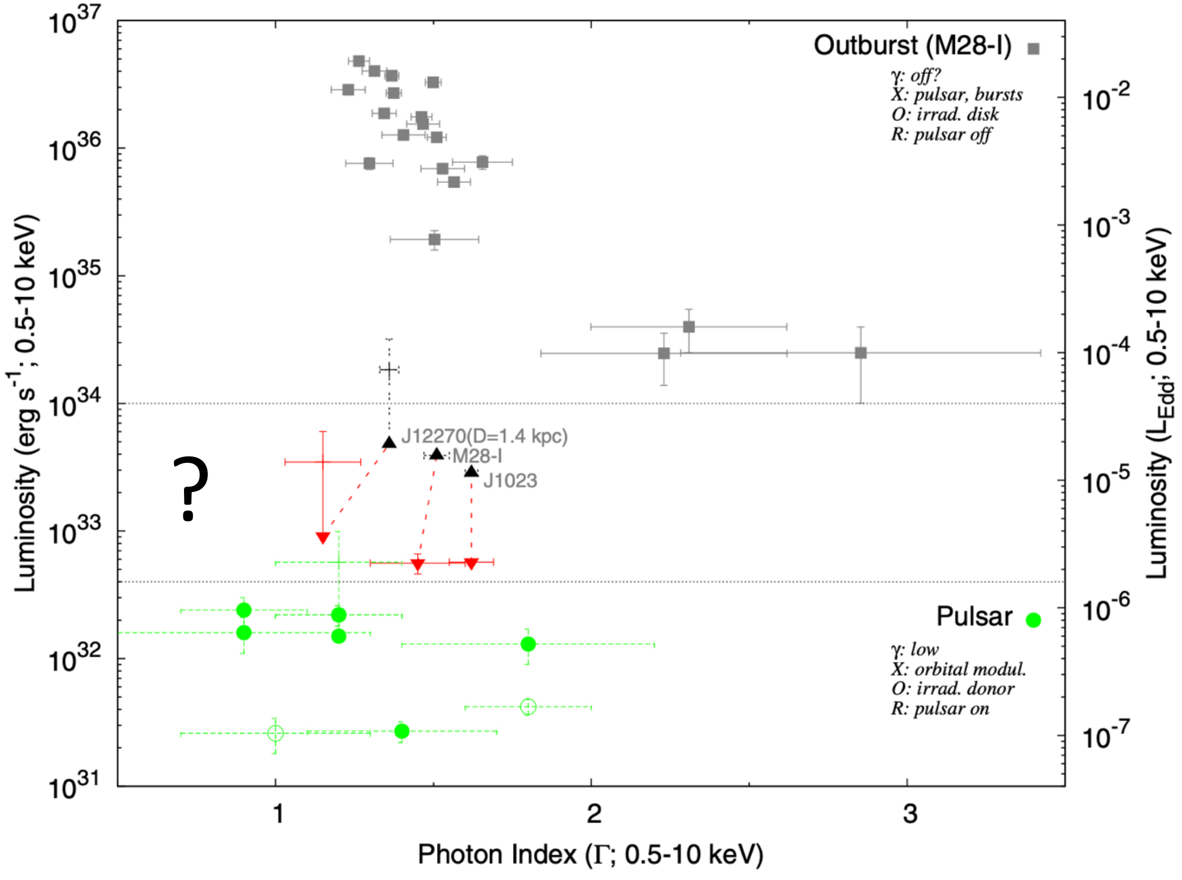
Parfrey & Tchekhovskoy 2017
see also Das+22



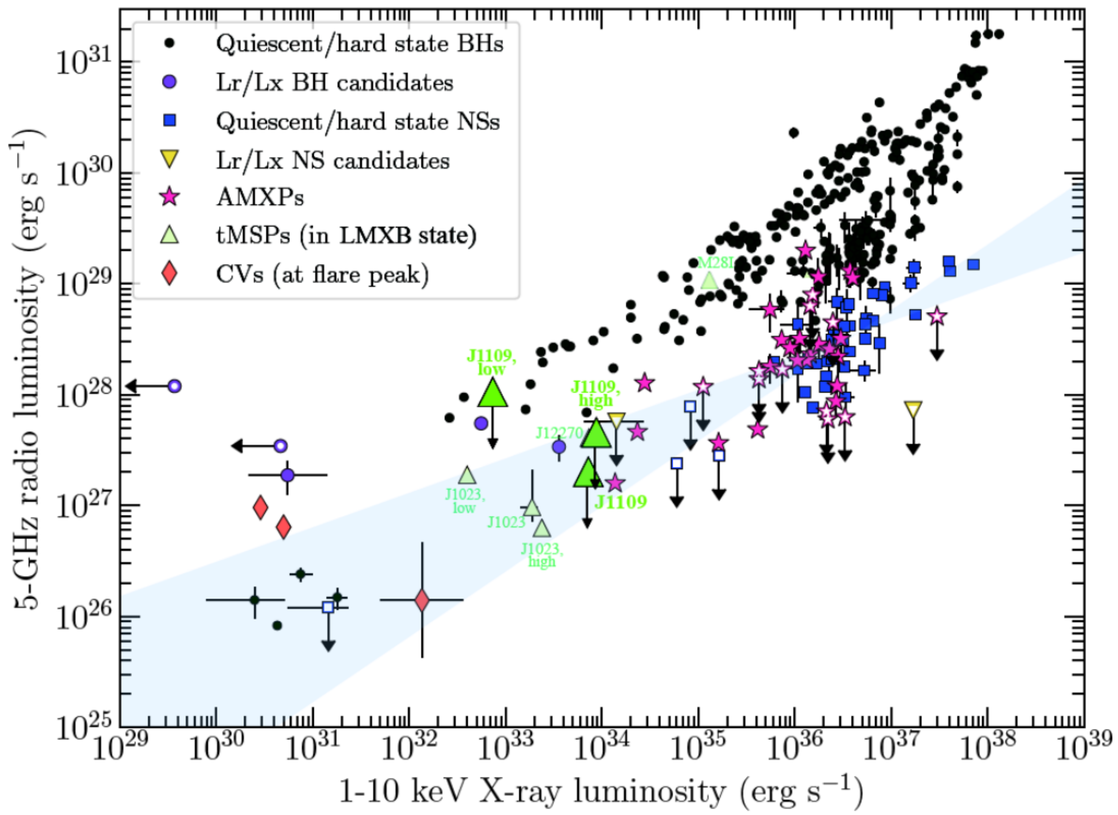


Propeller state

Sub-luminous disk state



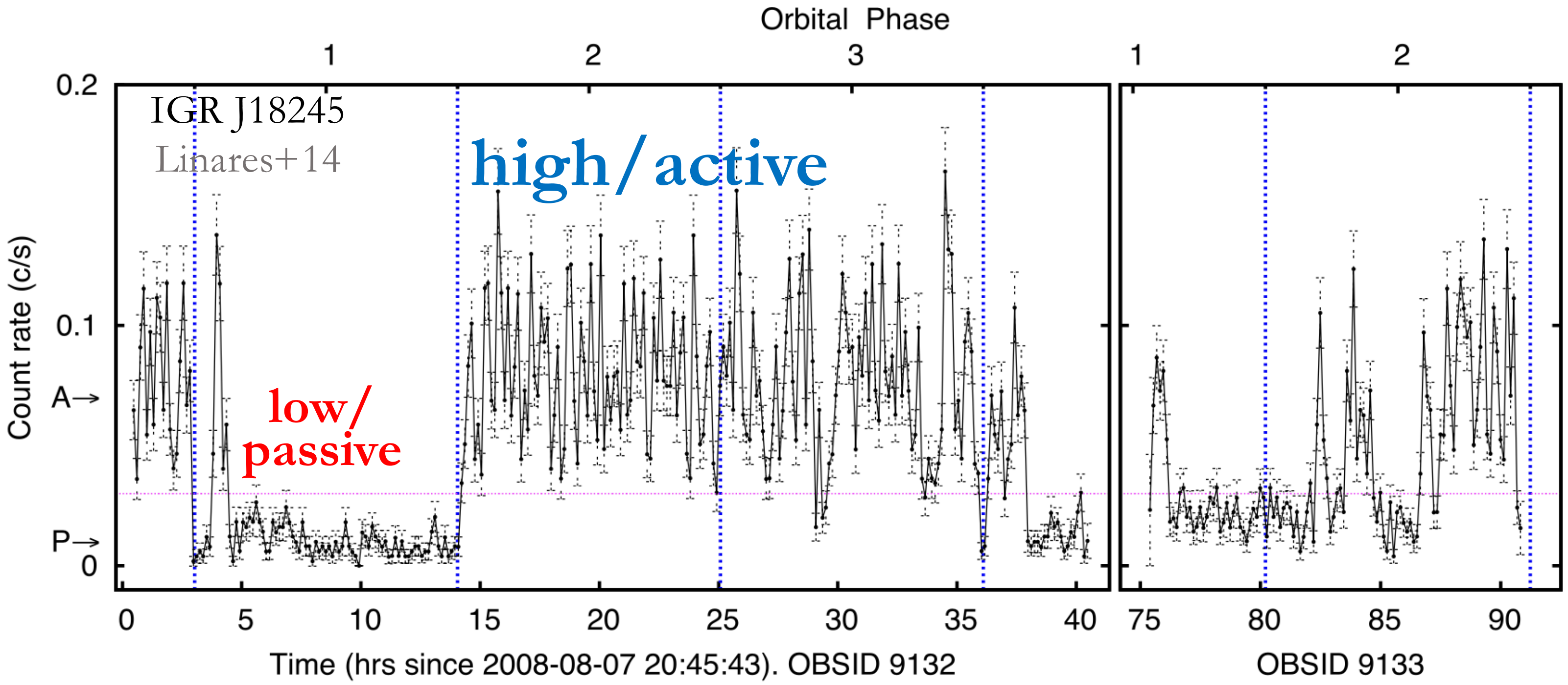
Linares+14



Papitto & De Martino 2022

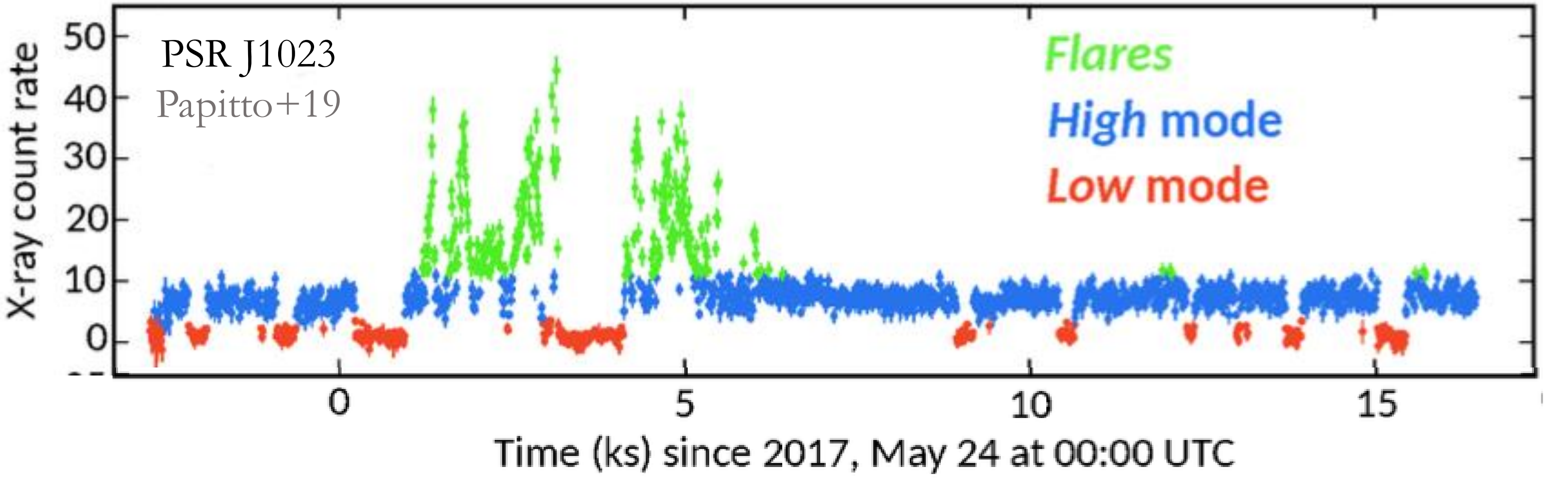
An atypical "disk state". Accretion-powered and/or rotation-powered?

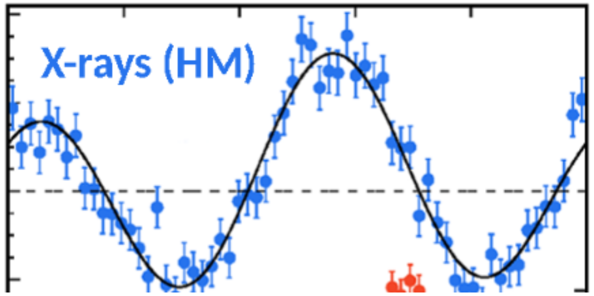
X-ray mode switching behaviour



- L_X (0.5-10keV) $\times\, 5-10$
- randomly
- on timescales ~seconds
- little/no spectral change in X

(Linares+14)



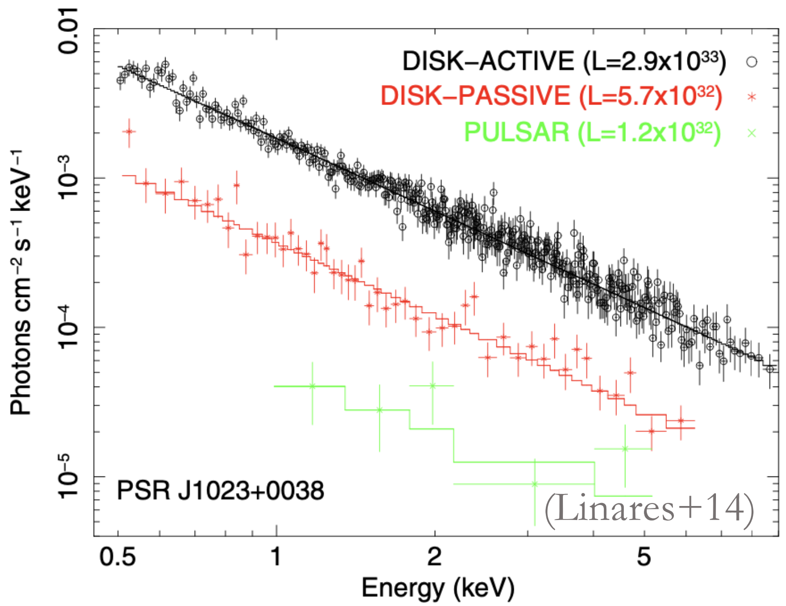


+ spin-period X-ray pulsations

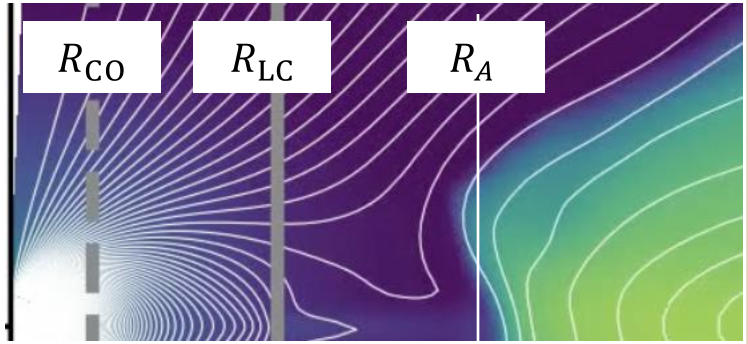
Standard accretion?

- Consistent with the existence of X-ray pulsations but …

- Non-thermal spectrum → not a standard accretion disk spectrum



- $L_X \rightarrow \dot{M} \sim R_{NS} L_X / G M_{NS}$ [assuming accretion onto NS surface] → $R_A = f(\mu, \dot{M})$
  $R_A > R_{\rm LC}$! (J1023, Veledina+19 ; unless high inclination : Bozzo+18)



- **Spin-down rate varies** (increased) by **only** 27% compared to the radio pulsar state (Jaodand+16)

➢ Accretion-only is ruled-out

Open questions

- Energy source: rotation? accretion?

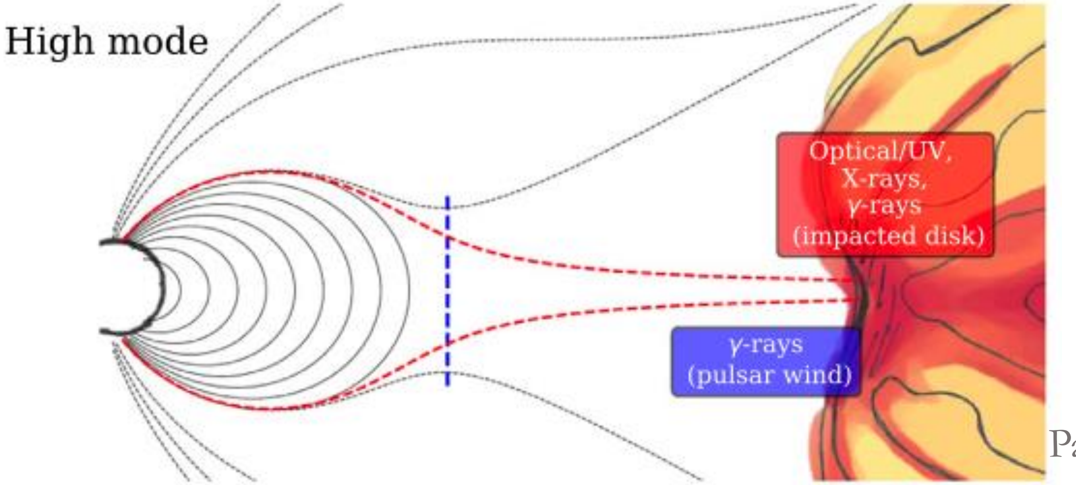
- Emission processes: synchrotron? blackbody?

- Plasma processes: shocks? reconnection?

- Physical/dynamical scenario: accretion rate variation, wind-disk shock, turbulence...?

Two families of scenarios divided by the accretion flow location

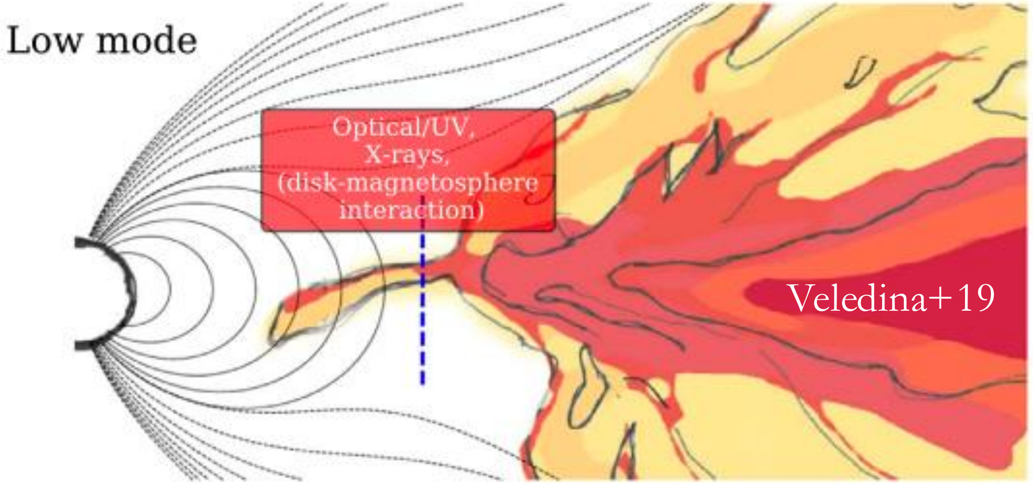
flow outside the light cylinder = high mode



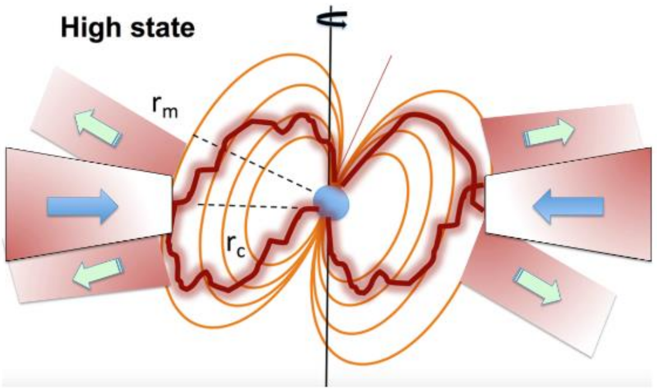
e.g.
Papitto +19

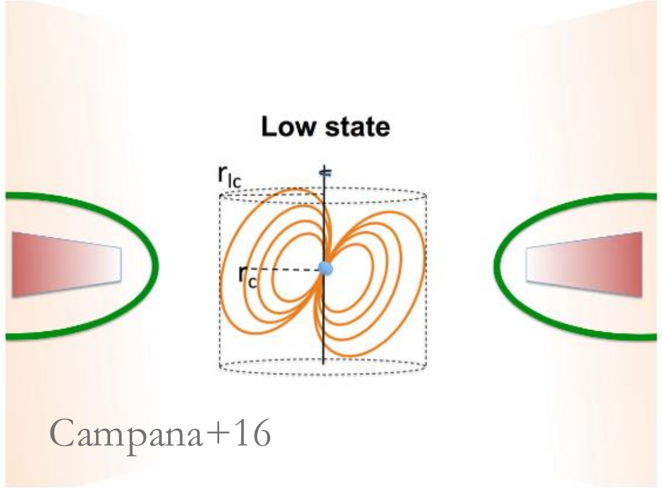
Pulsar wind power maximal at the equator (e.g. Tchekhovskoy+13)

flow inside the light cylindder = low mode



- and the opposite behaviour with slight differences
  Linares+14, Campana+16





see also Baglio+23 for the low mode

Our approach

- Reproduce various accretion states (Parfrey & Tchekhovskoy 2017)

- Methods:

  2D/3D hybrid force-free – general-relativistic magnetohydrodynamical simulations
  Variant of `HARMPI`, Gammie+03

  Post-process with GR radiative transfer code
  `Grmonty`, Dolence+09

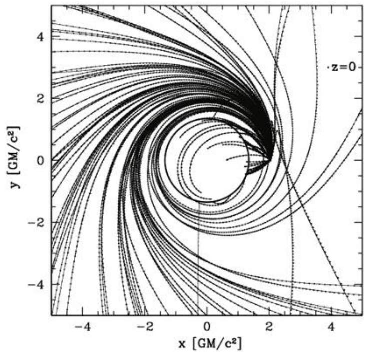
- Objectives:

  See if pulsar wind-disk interaction can

  1. account for the X-ray emission
  2. produce low vs high modes
  3. fit multi-wavelength constraints, i.e. correlations/anti-correlations

Radiative transfer with `Grmonty`

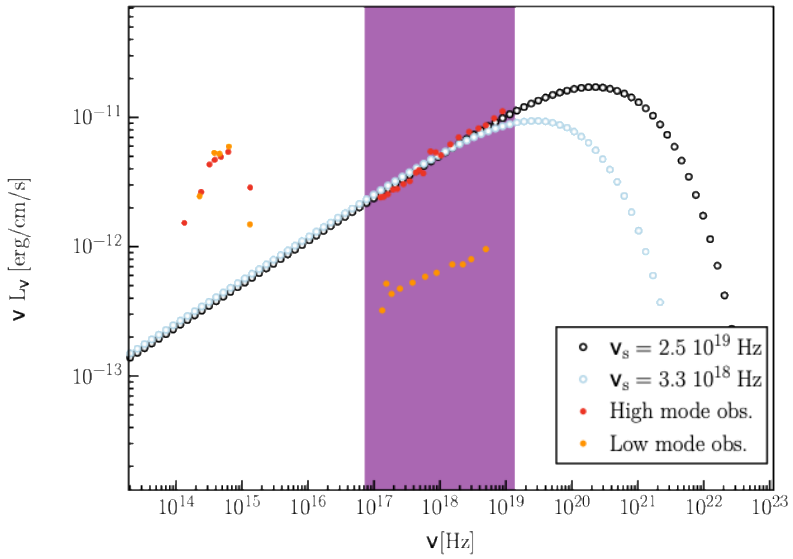
- Takes GRMHD data (= density, velocity, magnetic field)
- Assumes an emission model: thermal synchrotron



$$j_\nu(\nu,\theta) \simeq \frac{\sqrt{2}\pi e^2 n_e \nu_s}{3cK_2(\Theta_e^{-1})}\left(X^{1/2} + 2^{11/12}X^{1/6}\right)^2 \exp(-X^{1/3}) \quad (4a)$$

$$X \equiv \frac{\nu}{\nu_s} \quad (4b)$$

$$\nu_s \equiv \frac{2}{9}\left(\frac{eB}{2\pi m_e c}\right)\Theta_e^2 \sin\theta \quad (4c)$$



- Creates photons and propagate them along (GR → curved) geodesics

- Photon's absorption

$$\frac{1}{C}\frac{d}{d\lambda}\left(\frac{I_\nu}{\nu^3}\right) = \left(\frac{j_\nu}{\nu^2}\right) - (\nu\alpha_{\nu,a})\left(\frac{I_\nu}{\nu^3}\right)$$

- Scattering by electrons (inverse Compton)

  depends on $\beta_m \equiv$ **the particle speed in the plasma frame**

  - ➢ we don't have "particles" (e- or p+) in the fluid code but a thermal fluid at a given temperature

    → provides the electron thermal velocity

In summary : thermal synchrotron emission + absorption + inverse Compton scattering

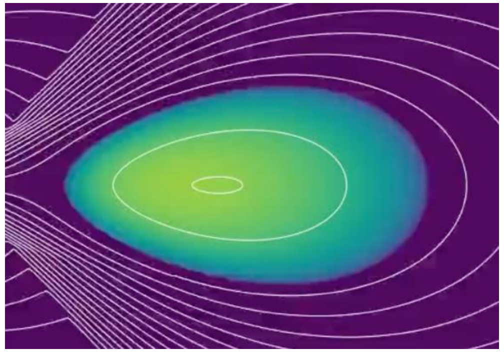
Fluid/dynamical setup:

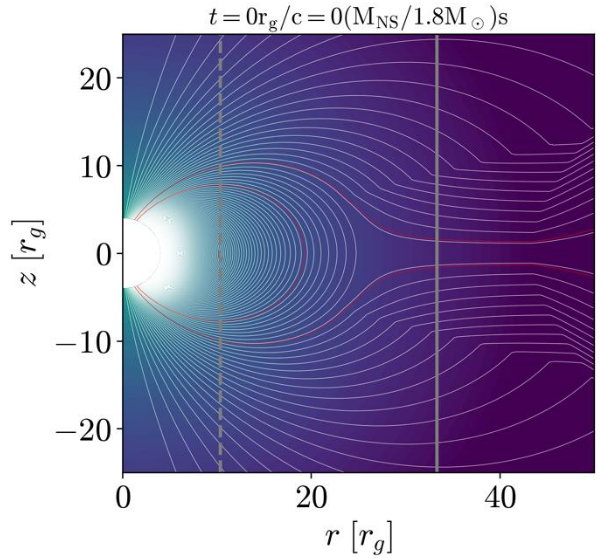
- Matter:
  Magneto-rotationally (Balbus & Hawley 1991) unstable torus at $85 r_g > r_{LC}$, $\rho_{max} = 1$
  One magnetic poloidal loop ; angular momentum $\propto r^{1/3}$

- Numerics: resolution $N_r \times N_\varphi = 1024 \times 512$

- Neutron star:
  Spin period $P_* = 1.88$ ms $\rightarrow R_{LC} = 89$ km
  Mass $M_* = 1.8\ M_\odot$; radius $R_* = 10.8$ km
  Dipolar field, magnetic moment μ in units of $r_g^3 \sqrt{4\pi\rho_{max}c^2}$
  Kerr metric, spin $a_* = 0.2$

❖ **Physical free parameter: μ → accretion state**



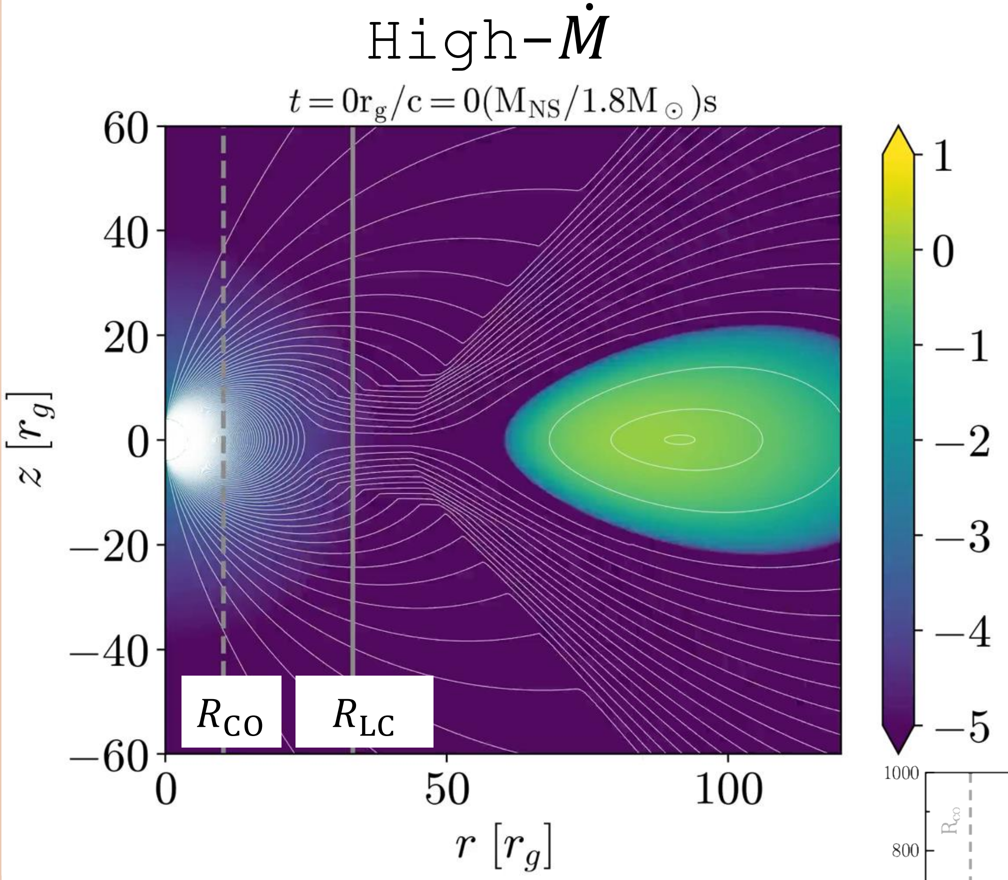


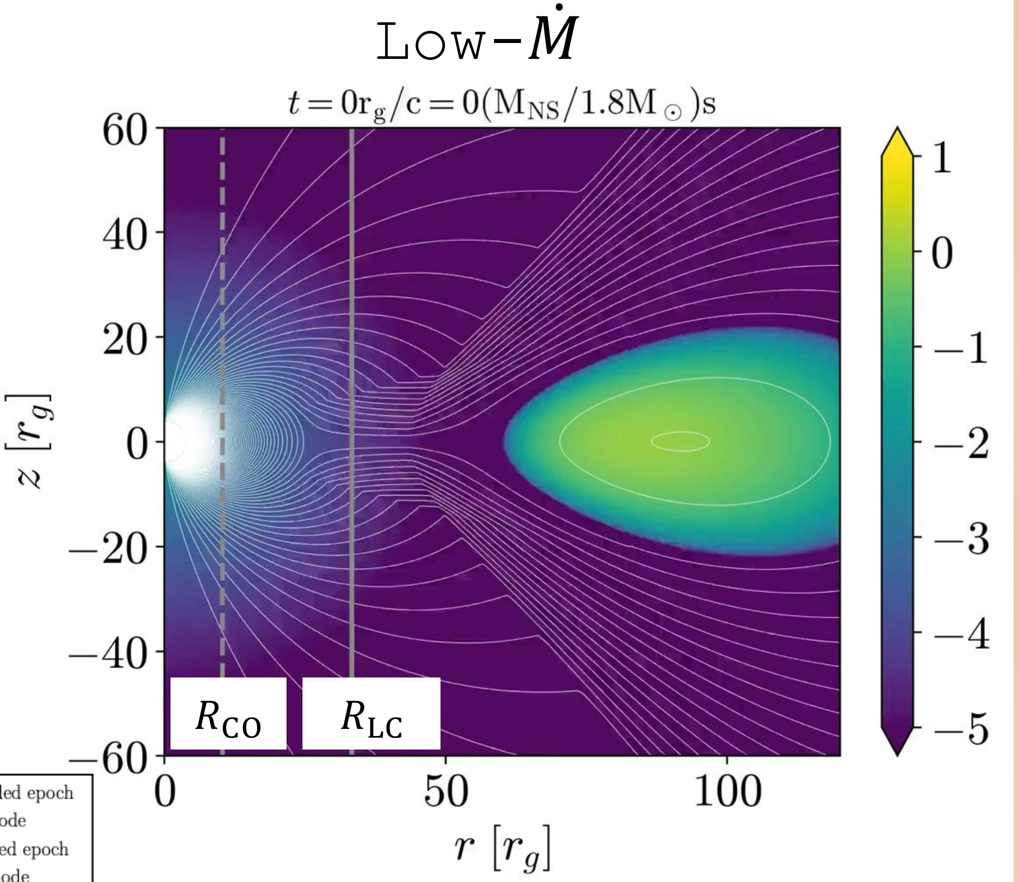
Radiation setup

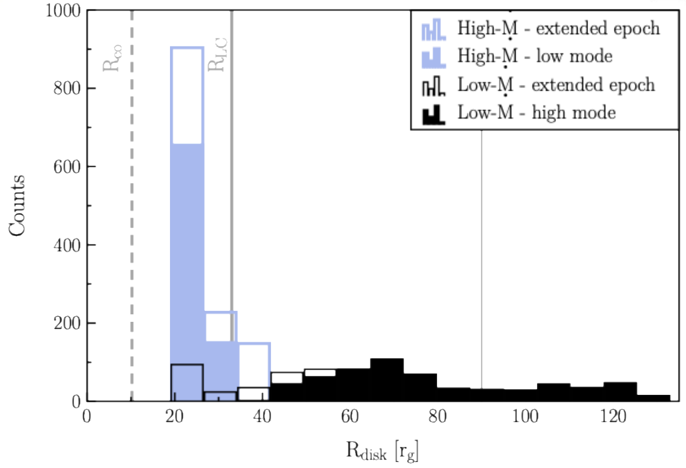
- Restrict the post-processing to non-force-free regions (magnetization $\sigma < 10$)

❖ **Physical free parameter: gas mass unit → observed X-ray flux as calibration**

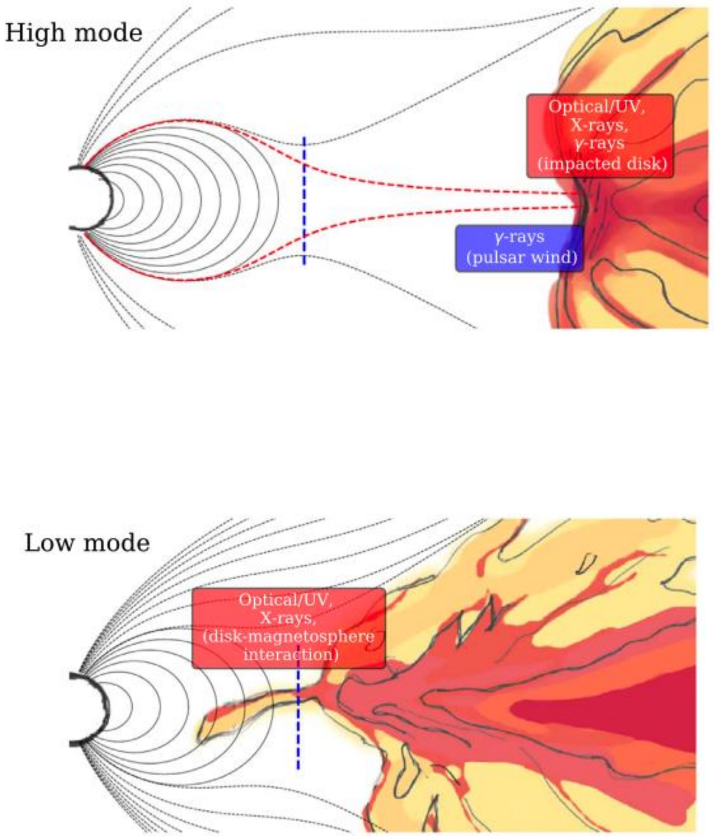
Low vs high accretion rate simulations



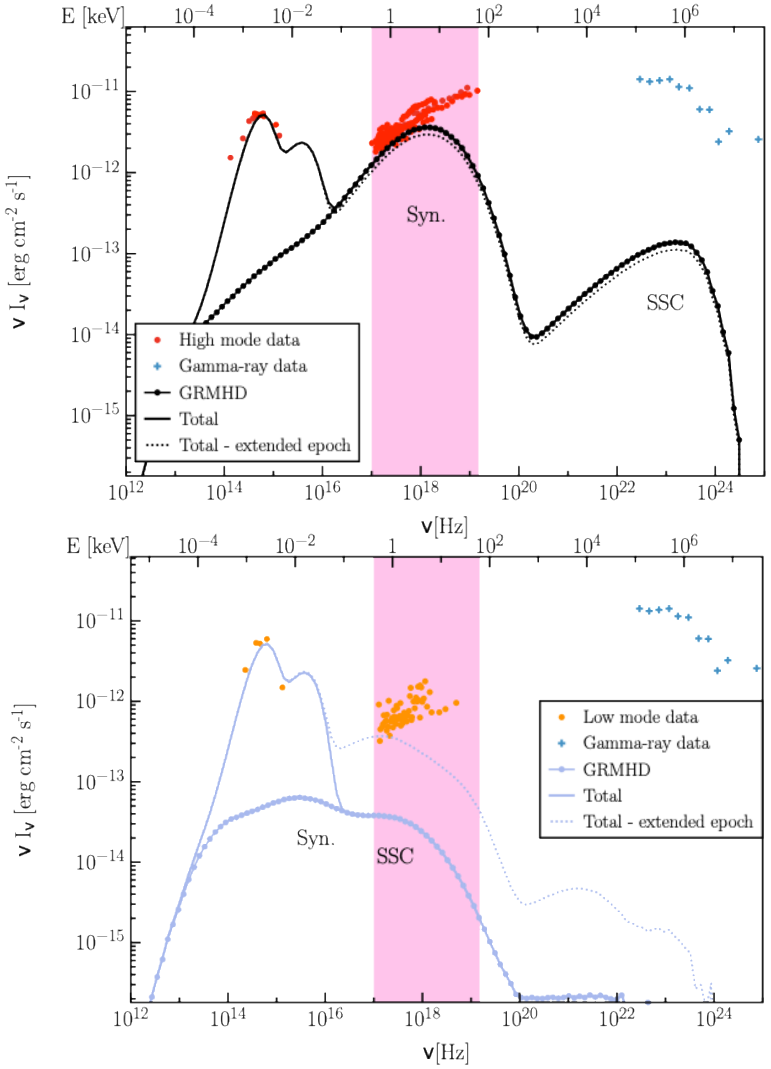


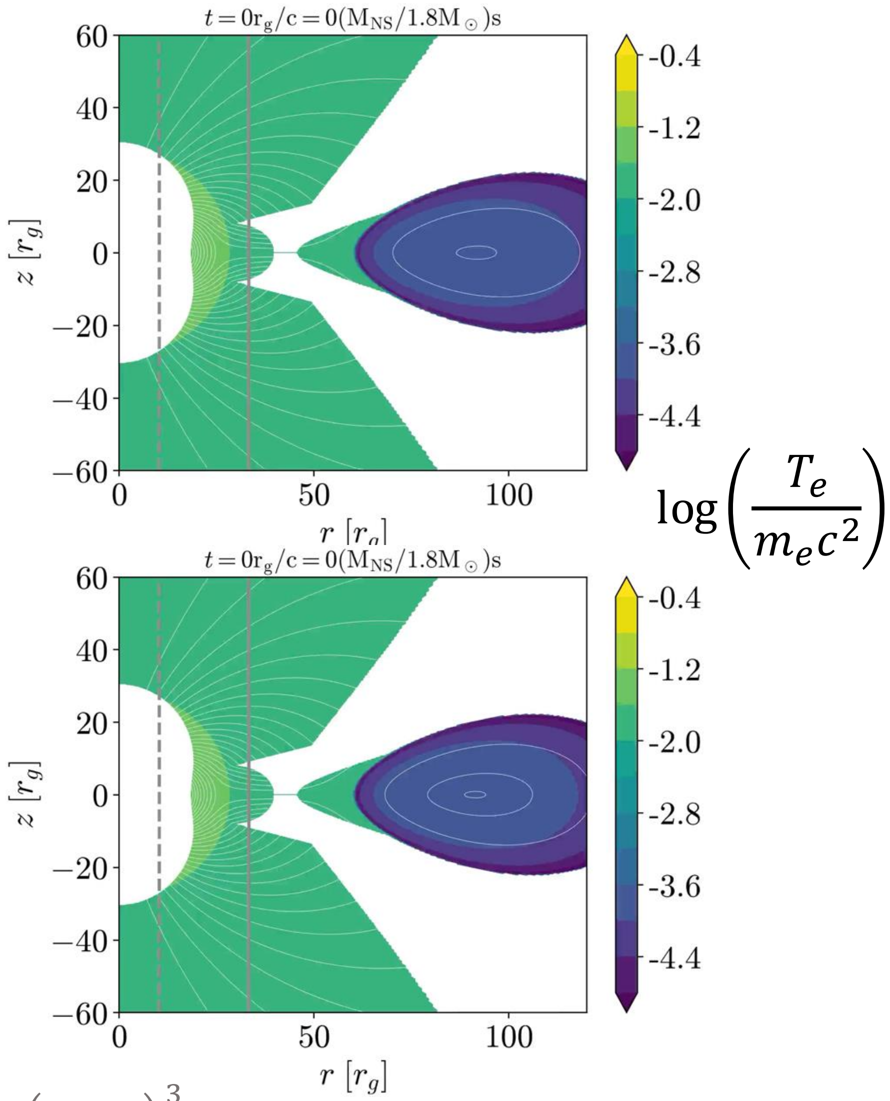


Test the scenarios in 2D



Veledina+19





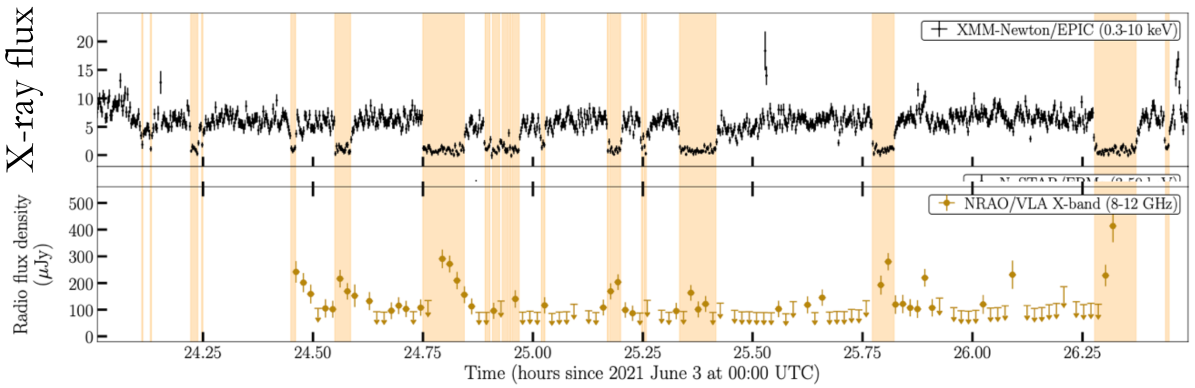
- Reproduces X-ray modes
  - high mode power-law slope
  - too less heating in the low mode?

$$\mu_{*,\mathrm{obs}} = 8\times10^{25}\ \frac{B_*}{4\ 10^8\mathrm{G}}\left(\frac{M_*}{1.8\ M_\odot}\right)^3\ \mathrm{G\ cm^3}\ \text{vs}\ \ \mu_{*,\mathrm{num}}\sim 8\times10^{25}\ \mathrm{G\ cm^3}$$

Mignon-Risse, Linares, Parfrey, Tchekhovskoy, Ressler, to be subm.

On the X-ray - radio anti-correlation

Obs : X-ray/radio anti-correlation



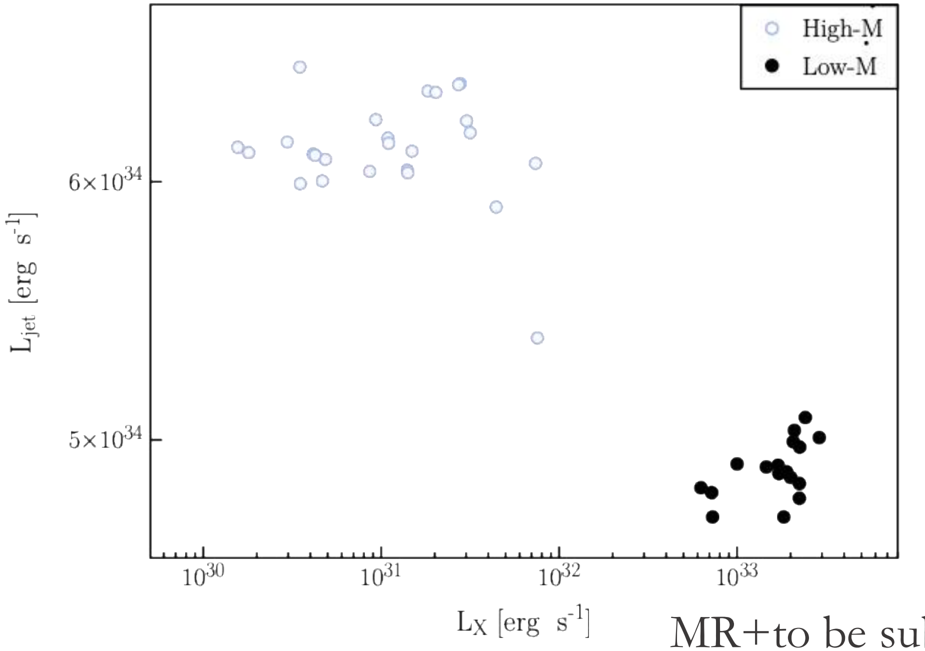
J1023 Baglio+23

Our sims : jet luminosity increases when flow inside LC opens field lines (e.g. Parfrey+16)

$$L_{\rm jet} = -\int\int \left(b^2 u^r u_t - b^r b_t\right) \sqrt{-g}\, d\theta\, d\phi.$$

- **Produces an X-ray – jet luminosity anti-correlation**
- **~7-9% enhanced spin-down through EM torque**

  (vs 27%, Jaodand+16)

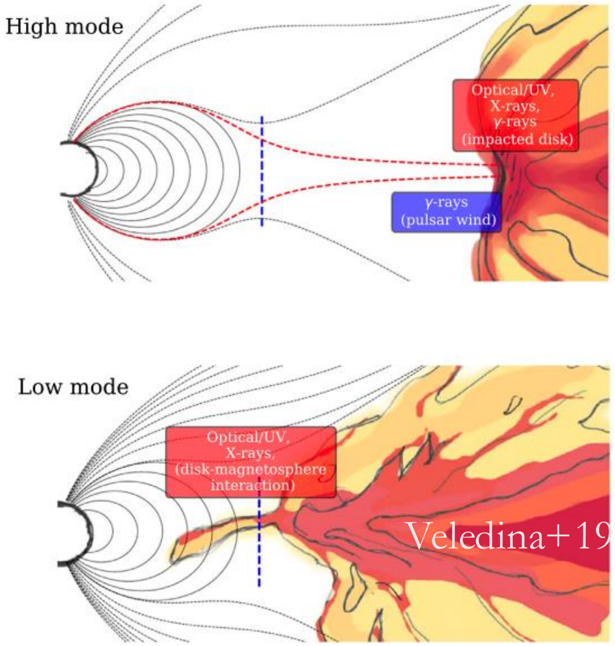


MR+to be subm.

Conclusions

Results (Mignon-Risse, Linares, Parfrey, Tchekhovskoy, Ressler, to be subm.)

- **Thermal synchrotron from pulsar wind heating** can account for **observed X-ray flux** (vs e.g. Linares+14)
- **Variations in the accretion rate** can produce low vs high X-ray mode
- Non-negligible **optical** (e.g. Ambrosino+17) **UV** (e.g. Baglio+23) **gamma flux** (e.g. Papitto+19)
- If $L_{\rm jet} \sim L_{\rm radio}$: then **X-ray – radio anti-correlation** (vs e.g. Bogdanov+18)
- Scenario consistent with Veledina+19. Just a proof-of-concept so far
- Spin-down torque enhanced by ~7-9% (vs 27%, Jaodand+16)

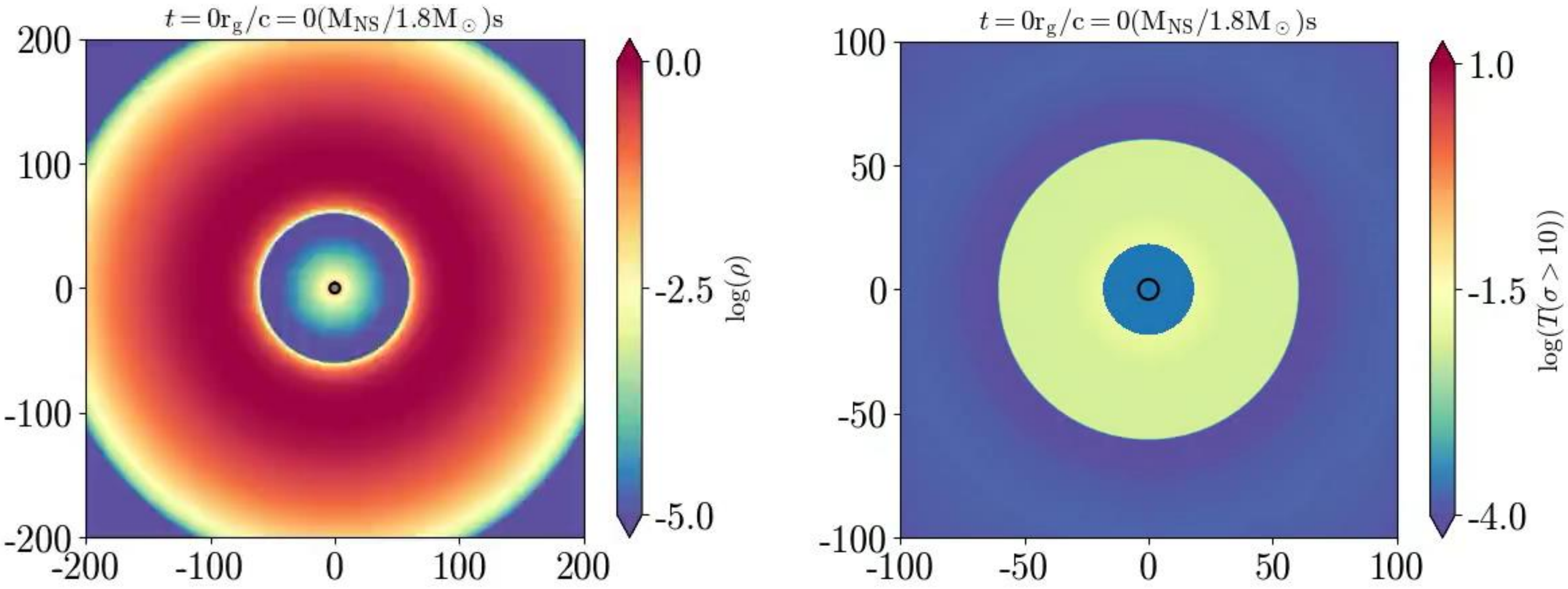


Limitations

- Time integration < 1s vs mode transitions ~10 s (e.g. Baglio+23)
- Thermal distribution of electrons
- 2D: axisymmetric accretion (Parfrey & Tchekhovkoy 2023), no obliquity (e.g. Das & Porth 2023, Murguia-Berthier+23)

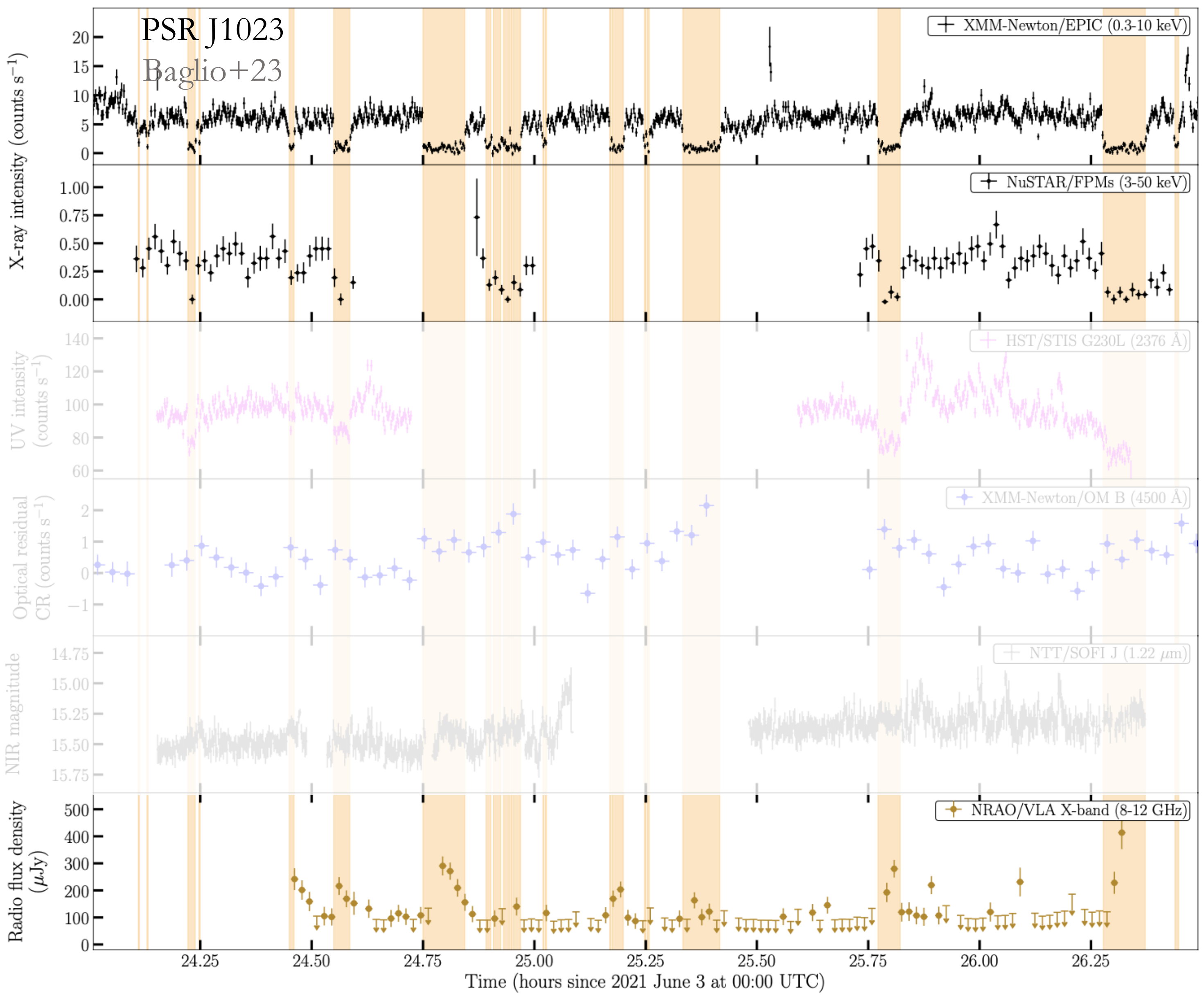
2D → 3D

Q: can we reproduce the in-and-out dynamics in 3D?
Q: and the heating process?



Yes, if longer-term simulations

More recent constraints: multi-wavelength observations



X-ray anti-correlated to radio

Bogdanov+18

+Detectable gamma-ray flux

Fixing the mass unit

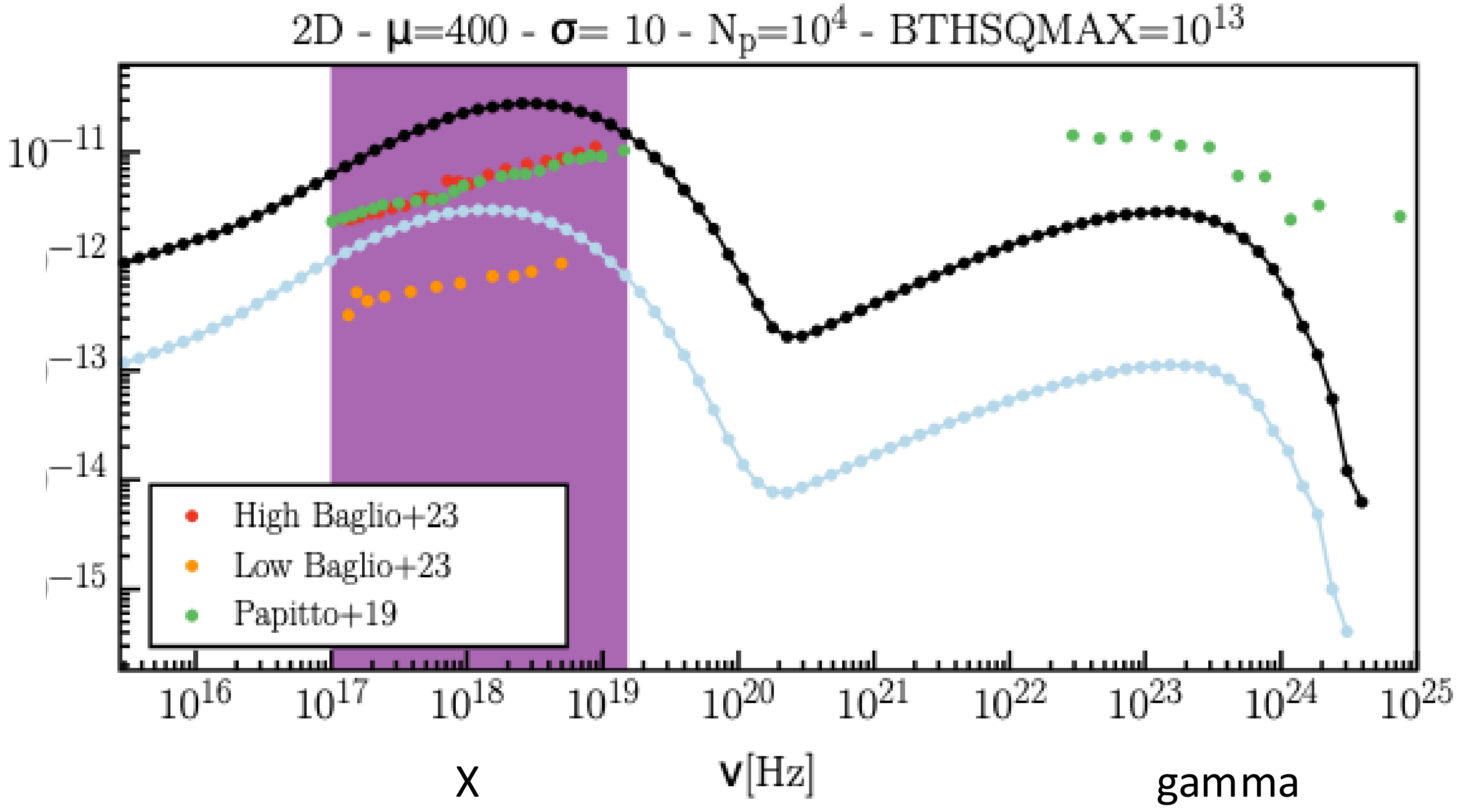
- **Physical free parameter: mass unit**
  - → flux magnitude
  - → peak frequency

$$j_\nu(\nu,\theta) \simeq \frac{\sqrt{2}\pi e^2 n_e \nu_s}{3cK_2(\Theta_e^{-1})}(X^{1/2} + 2^{11/12}X^{1/6})^2 \exp(-X^{1/3}) \tag{4a}$$

$$X \equiv \frac{\nu}{\nu_s} \tag{4b}$$

$$\nu_s \equiv \frac{2}{9}\left(\frac{eB}{2\pi m_e c}\right)\Theta_e^2 \sin\theta \tag{4c}$$

→ fixes the magnetic energy unit

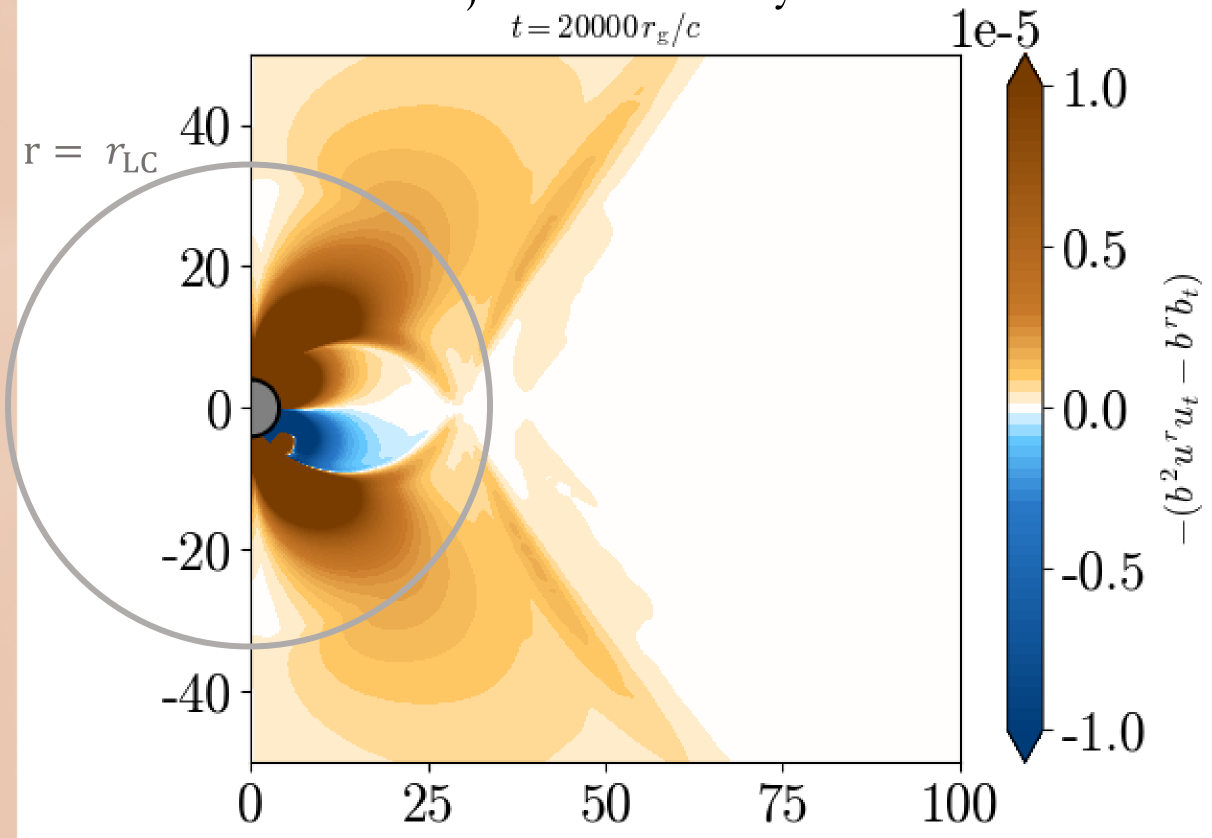


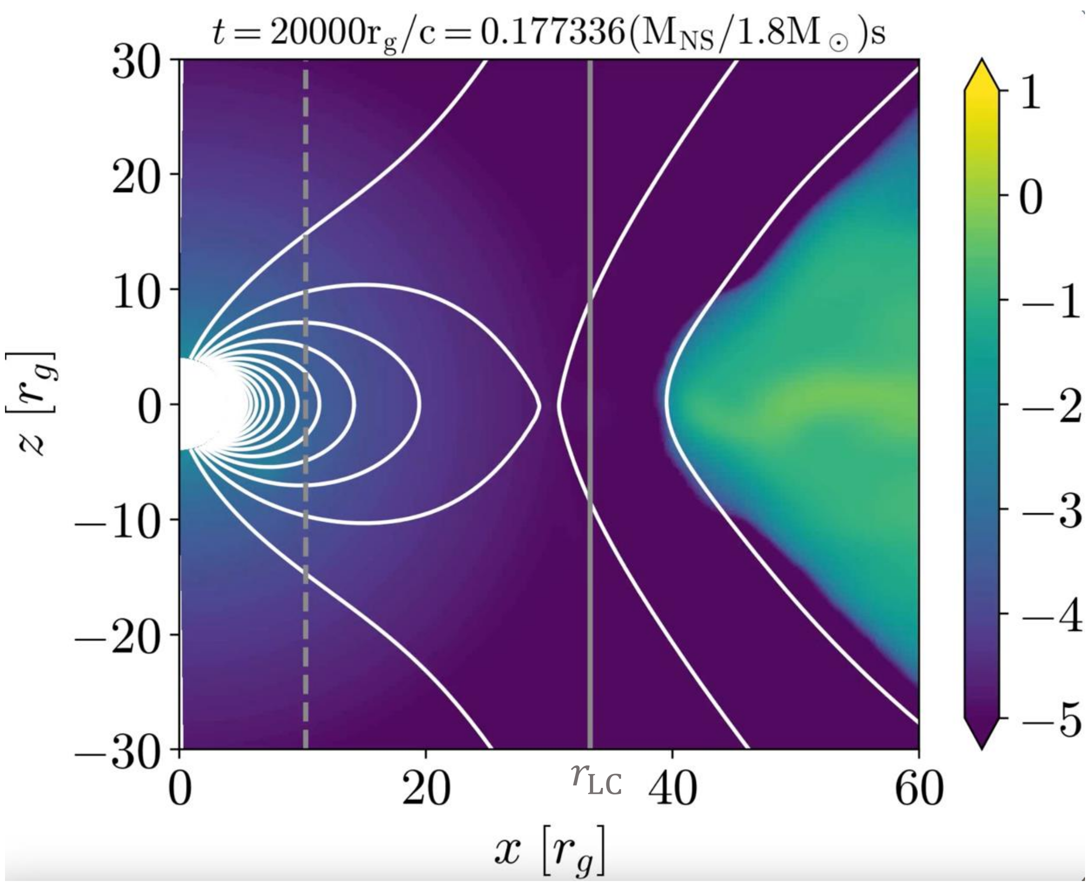
- **Observational constraint:**
  - ~~Accretion rate~~
  - Neutron star magnetic moment:

$$\mu_* = 2\times 10^{25}\,\frac{B_*}{10^8\mathrm{G}}\left(\frac{M_*}{1.8\,M_\odot}\right)^3 G\ \mathrm{cm}^3$$

Proxy for radio flux

Radio flux ~ jet luminosity ?



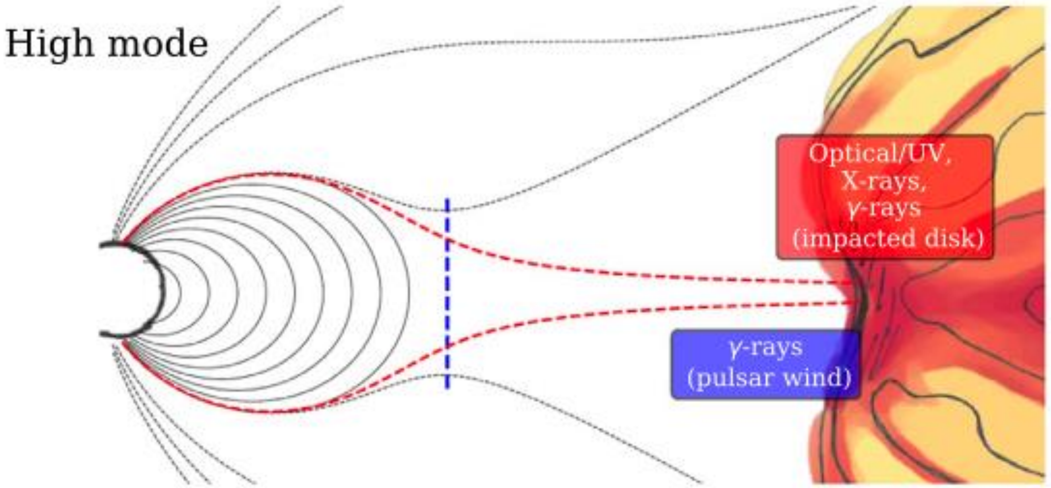


$$L_{jet} = -\int\int \left(b^2 u^r u_t - b^r b_t\right) \underbrace{\sqrt{-g}\, d\theta\, d\phi}_{\text{surface element in GR}}.$$

surface element in GR

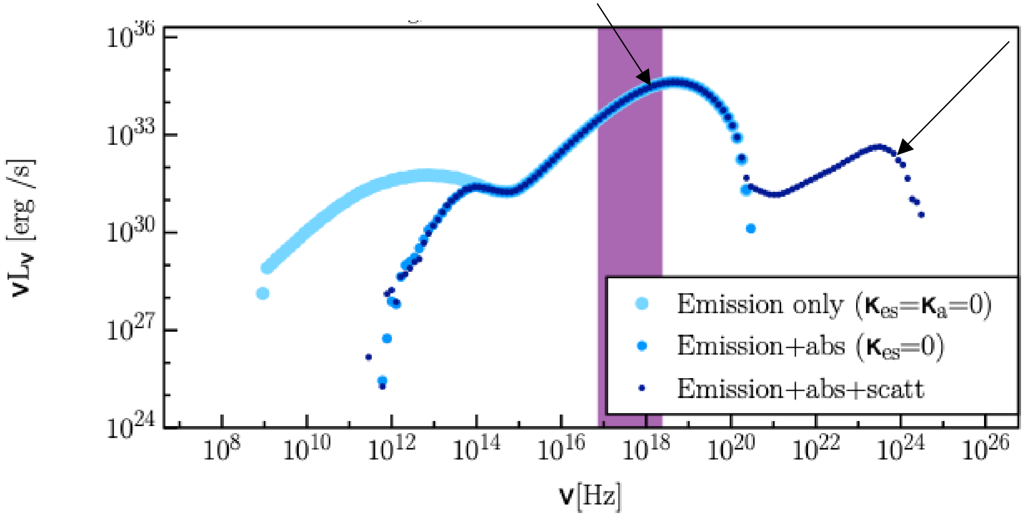
Electromagnetic energy = energy budget for the jet luminosity in radio

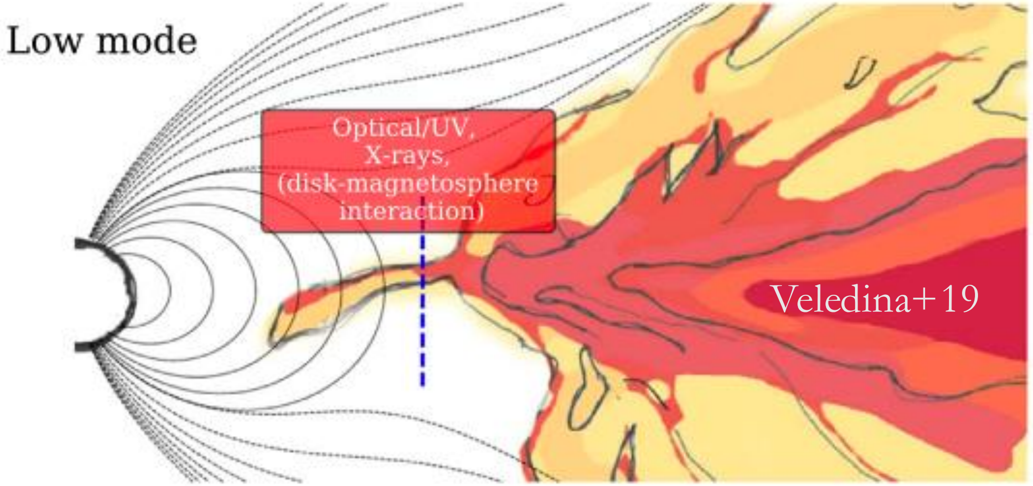
Contributions to the spectrum



X-ray from synchrotron

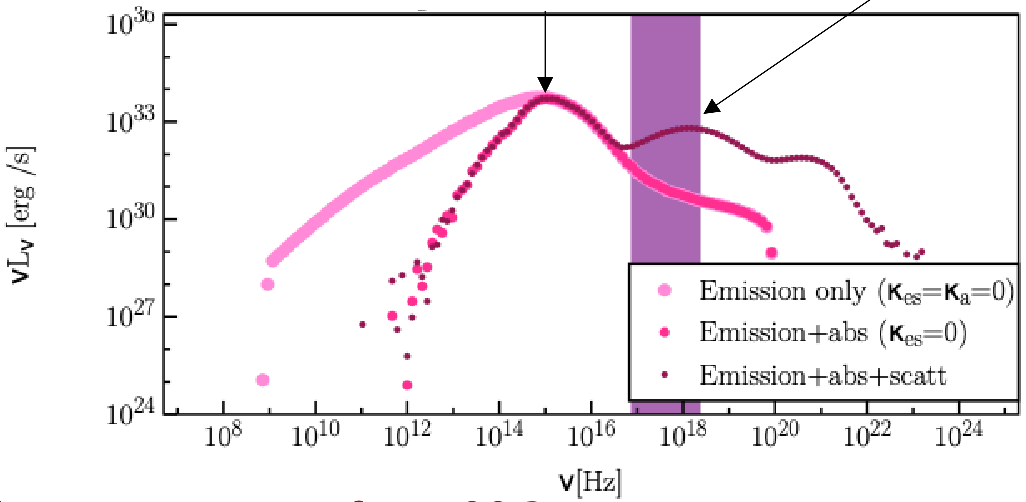
gamma from SSC





UV/optical from synchrotron

X from SSC



MR+to be subm.

- X-ray from thermal synchrotron, gamma from SSC

Pulsar wind power distribution