Hydrodynamical simulations of wind interaction in spider systems

a step towards understanding transitional millisecond pulsars

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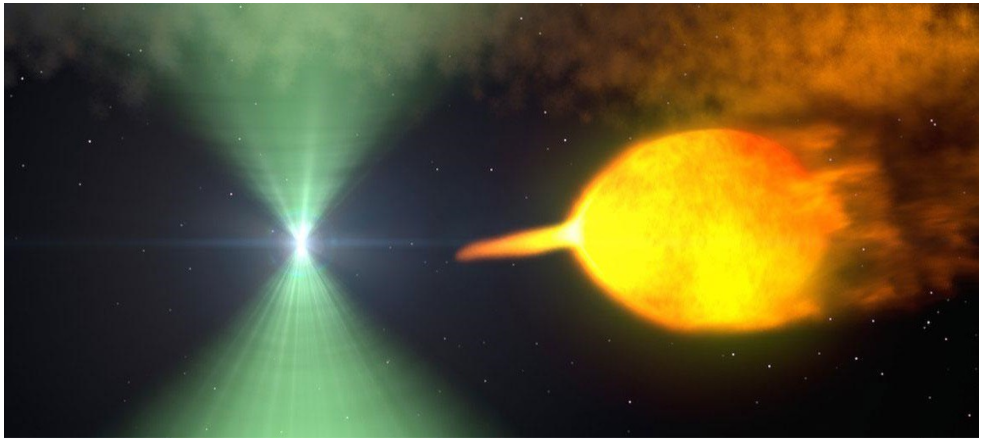
Context : Spider Pulsars

Millisecond pulsars (MSP) in tight binary orbit (~hours)
with a low-mass stellar companion

90+ spiders systems discovered over the last decade thanks to MWL Fermi followup



- *'Black Widow' : with a degenerate evaporating companion* ($M_c < 0.1 M_\odot$)
- *'Redback' : non or semi-degenerate evaporating companion* ($M_c < 0.5 M_\odot$)

The ***possible ablation of the companion from the impact with the pulsar wind*** explain the evocative name of cannibal spider species

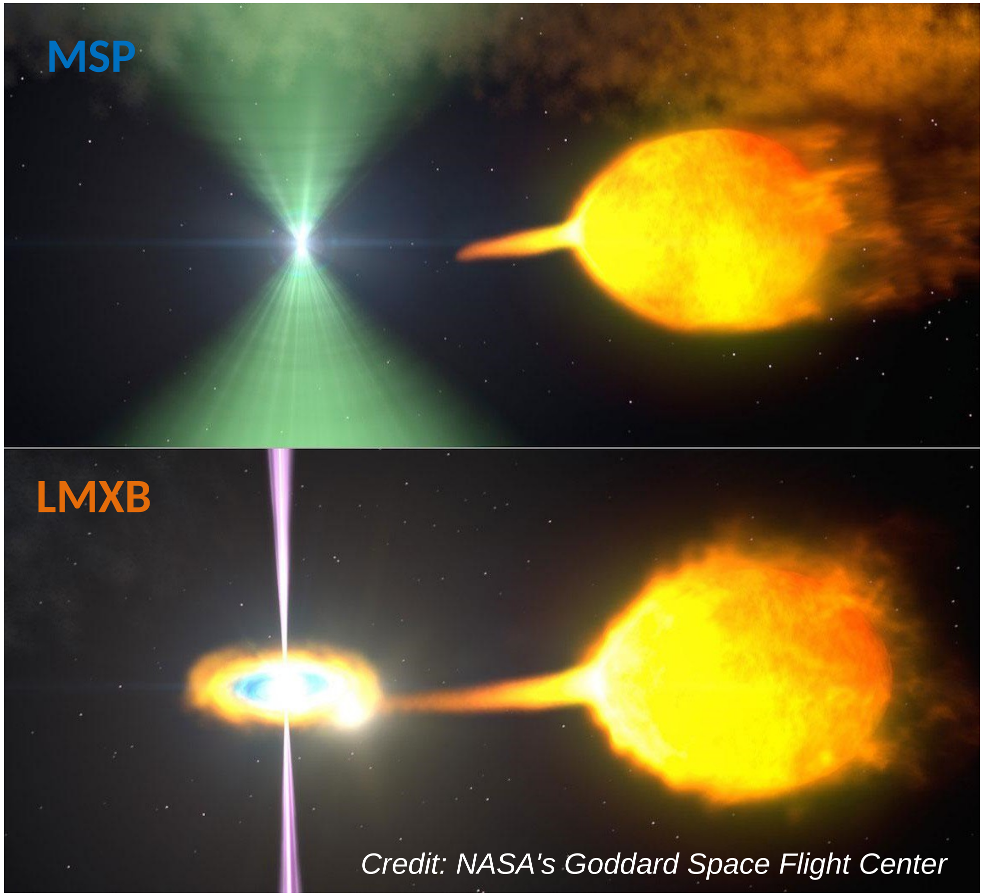
could be the missing link between binary pulsar systems and isolated millisecond pulsars

Context : Spider Pulsars transitions

Source of **tMSP** :
transitional millisecond pulsars

Systems where the *neutron star can swing* between the radio-pulsar and accretion states on a *timescale of a few years*

Papitto, Torres, 2015



'Redbacks' et 'Black Widows' :
closest link between
Low Mass X-ray Binary & **MSP**

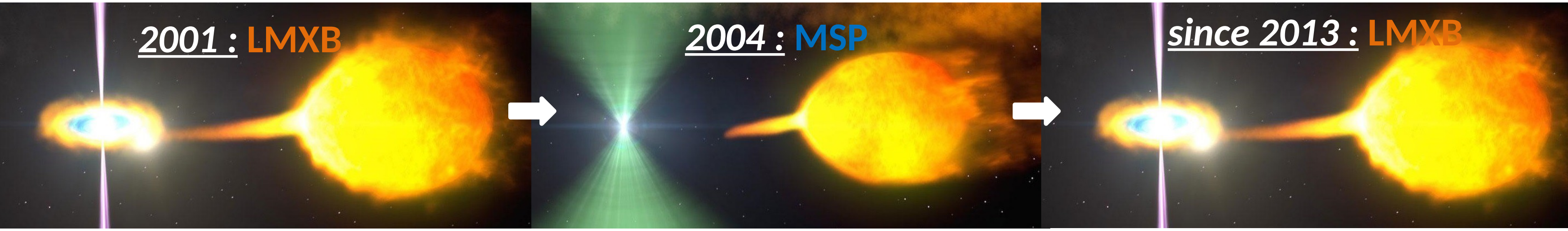
➡ offers a rare opportunity to understand the recycling scenario

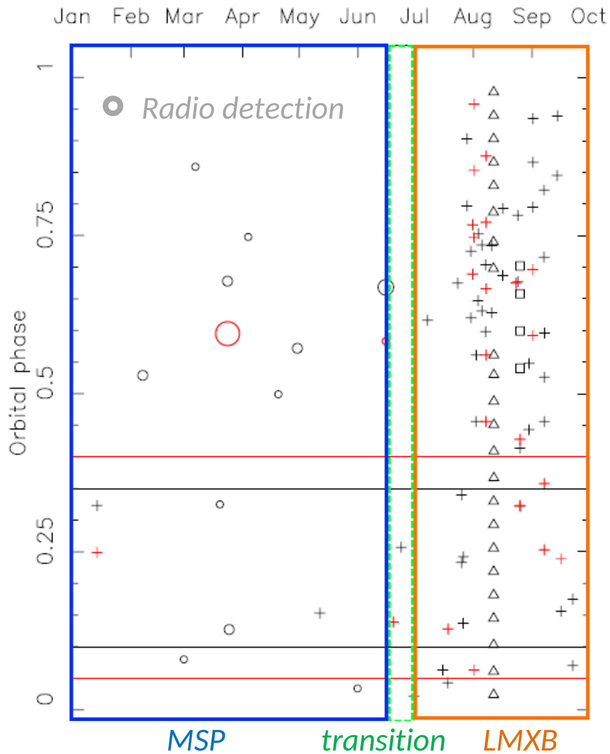
MSPs formation : ('*recycling scenario*')

LMXB ⟶ **MSP**

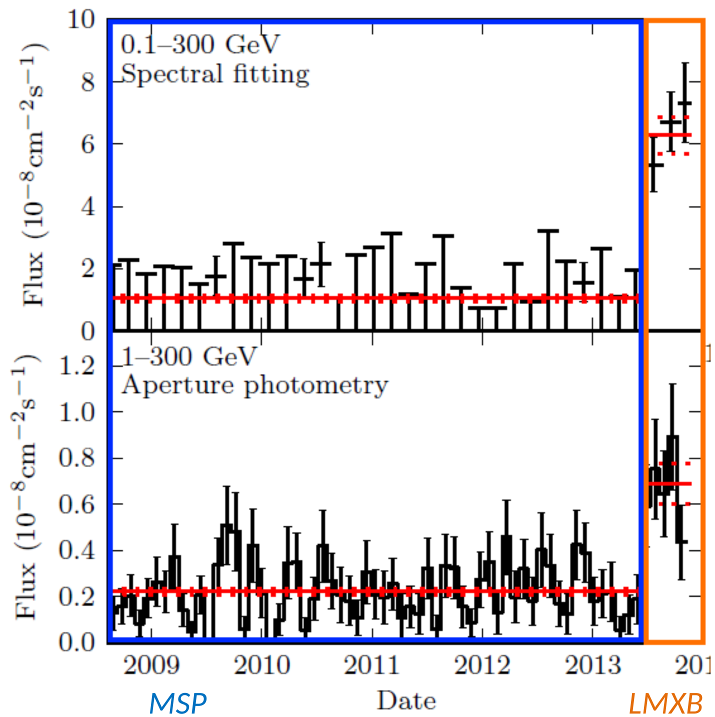
Transitional Millisecond Pulsars (tMSP)

Example of PSR J1023+0038





Radio observations of J1023+0038 with the LT at 1500MHz and WSRT at 1380MHz (black symbols), WSRT at 350MHz (red symbols), GBT at 2 GHz (triangles) and Arecibo at 4.5 GHz (squares) , Stappers et al. 2014



Ɣ-ray photon flux from J1023+0038 in June 2013, Stappers et al. 2014

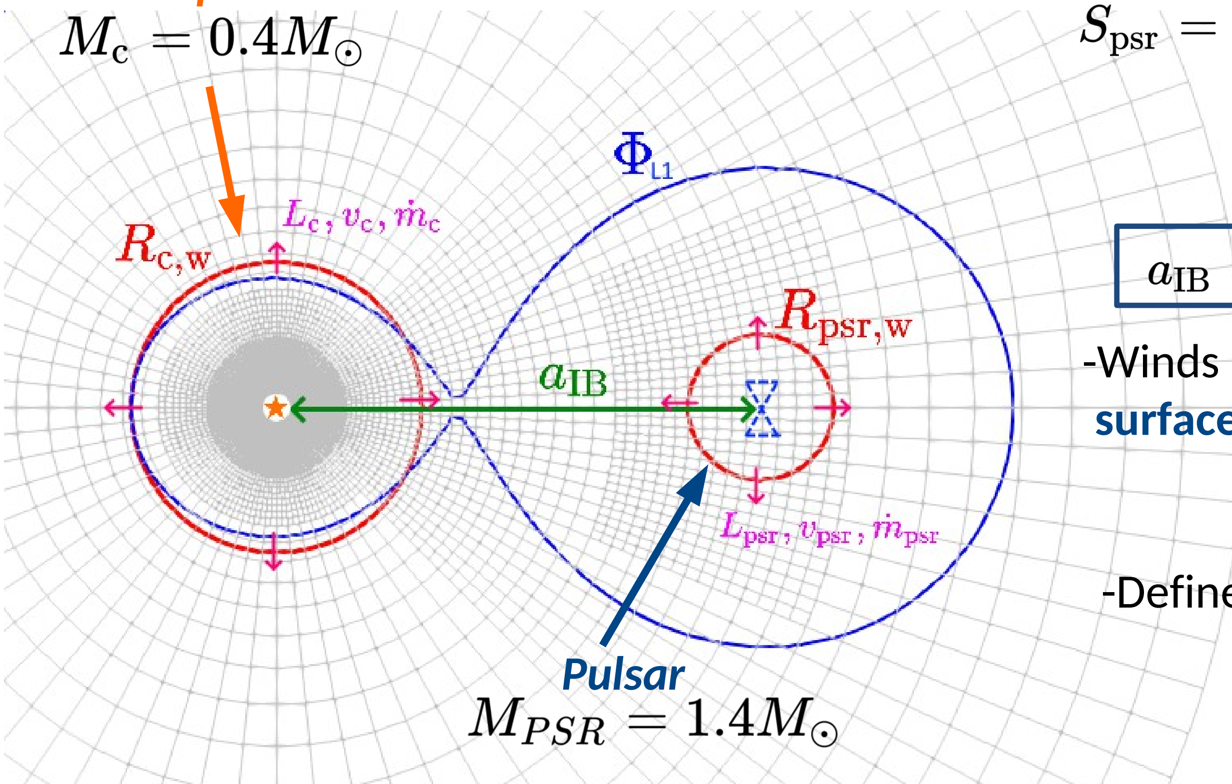
2D Hydrodynamical simulations : *Redback case*

Using Adaptative Mesh Refinement (AMR) code **AMRVAC 2.0 :**

$$\begin{cases} \dfrac{\partial \rho}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}) = 0\,, \\ \dfrac{\partial \rho\vec{v}}{\partial t} + \vec{\nabla}\cdot(\rho\vec{v}\vec{v} + P) = grav. + rot.\ , \\ \dfrac{\partial e}{\partial t} + \nabla\cdot[(e+P)\,\vec{v}] = grav. + rot. + S_{\rm psr}\ , \end{cases}$$

$$S_{\rm psr} = \rho \frac{L_{\rm sd}}{4\pi a_{\rm IB}^2 \hat{\sigma_T}} \left[\Upsilon_\gamma \left(1 - \frac{T}{T_c} \right) \right]$$

(Tavani and London, 1993)



-**Intra binary** distance :

$a_{\rm IB} = 10^{11}\,{\rm cm}$ ➞ $T \sim 3.47h$

-Winds are **isotropic**, originate **from the surface** of a sphere **surrounding each object**

-Defined by **luminosity, mass flux** and **velocity**

$$L_{\rm c} = \dot{m}_{\rm c} v_{\rm c}^2/2$$

Pulsar wind

Spider systems :

$$L_{\rm sd} = L_{\rm psr} + L_\gamma = bL_{\rm sd} + (1-b)L_{\rm sd}$$

Mechanical ($L_{\rm psr}$) — *Radiated in γ* (L_γ)

$$L_{\rm sd} = 10^{35}\,{\rm erg/s}$$

$$\rm b = 0.9$$

Non relativistic simulation : $v_{\rm psr} = 10^{-2}\,{\rm c}$

Momentum fluxes ratio :

analogue

$$\beta = \frac{\dot{m}_{\rm c} v_{\rm c}}{\dot{m}_{\rm psr} v_{\rm psr}} = \frac{\dot{m}_{\rm c} v_{\rm c}}{bL_{\rm sd}/c} = \frac{\dot{m}_{\rm c} v_{\rm c}}{L_{\rm psr}/c}$$

→ $L_{\rm psr,w} = \dot{m}_{\rm psr} v_{\rm psr}^2/2$

Companion wind

Constraints :

-Correct **hierachy of velocities** between the two winds :

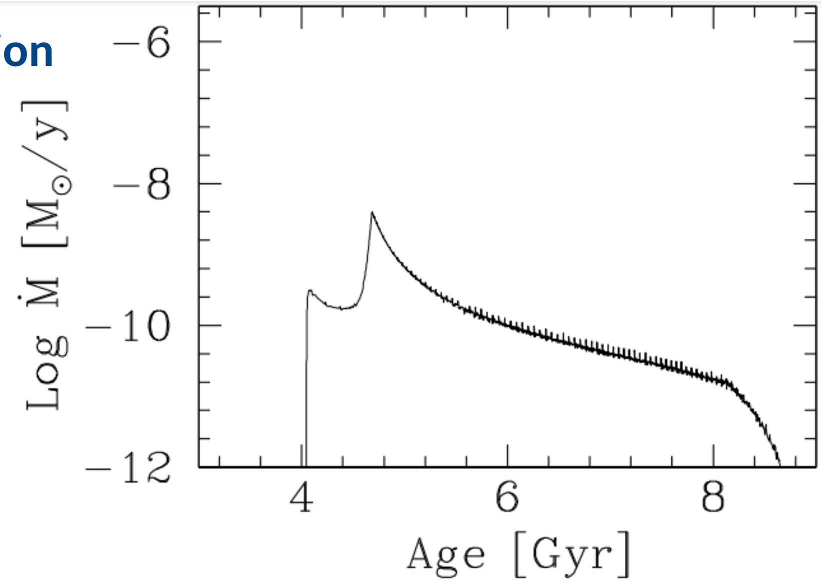
$$v_{c,\max} = 0.1 v_{psr} = 3 \times 10^7 \mathrm{cm/s}$$

-Mass-loss rate constrained by **stellar evolution**

$$\dot{m}_{c,\max} = 1 \times 10^{-8} \mathrm{M}_\odot/\mathrm{yr}$$

Simulation settings :

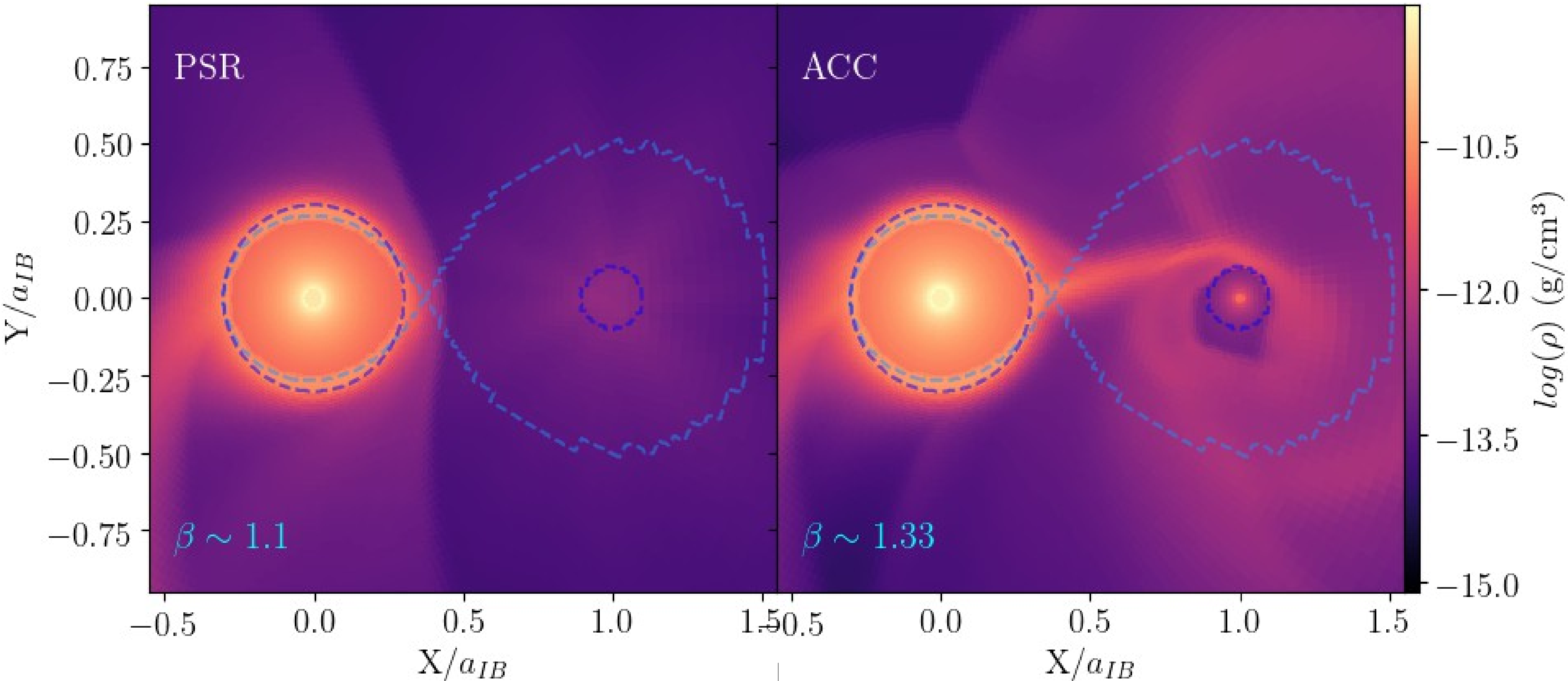
→ ***Accretion through Roche Lobe Over-Flow (RLOF)***



Mass-transfer rate for a solar composition donor star of 1.25 $M_\odot$, evolving on a CBS together with a 1.4 $M_\odot$ NS on an 0.75 day orbit.
Benvenuto et al. 2015

Two different outcomes
The two characteristic states of tMSPs

Pulsar | **Accretion-like (arm)**



Intra binary shock (IBS) formed

Radio pulsation not blocked

→ **Stationnary**

Creation of ***accretion arm***

Accretion disk perturbed by pulsar wind

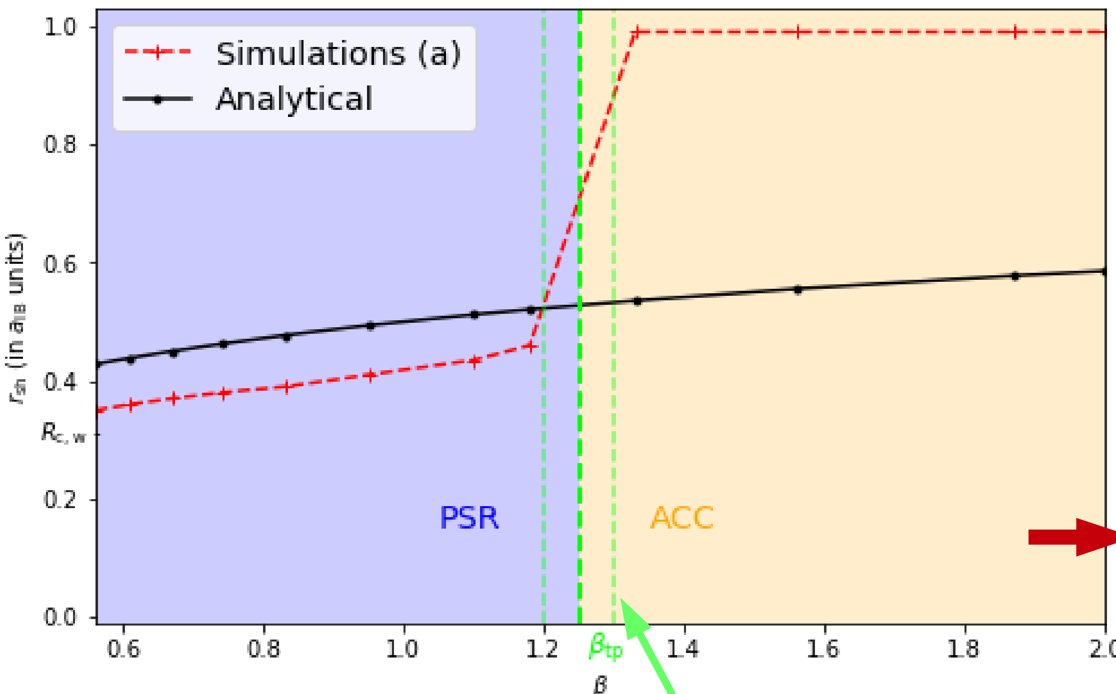
→ **Variability**

Influence of β on outcome of system : Tipping Point of transition

L_c (erg/s) \ $\dot{m}_c$ ($M_\odot$/yr)	1.75×10^{-9}	2.5×10^{-9}	3.5×10^{-9}	4.8×10^{-9}
2.5×10^{31}	$\beta = 0.81$, PSR	$\beta = 0.96$, PSR	$\beta = 1.14$, PSR	$\beta = 1.33$, ACC
3.6×10^{31}	$\beta = 0.97$, PSR	$\beta = 1.16$, PSR	$\beta = 1.37$, ACC	$\beta = 1.60$, ACC
5.0×10^{31}	$\beta = 1.14$, PSR	$\beta = 1.36$, ACC	$\beta = 1.61$, ACC	$\beta = 1.89$, ACC

$\beta_{tp} \sim 1.25$

$$\beta = \frac{\dot{m}_c v_c}{\dot{m}_{psr} v_{psr}}$$



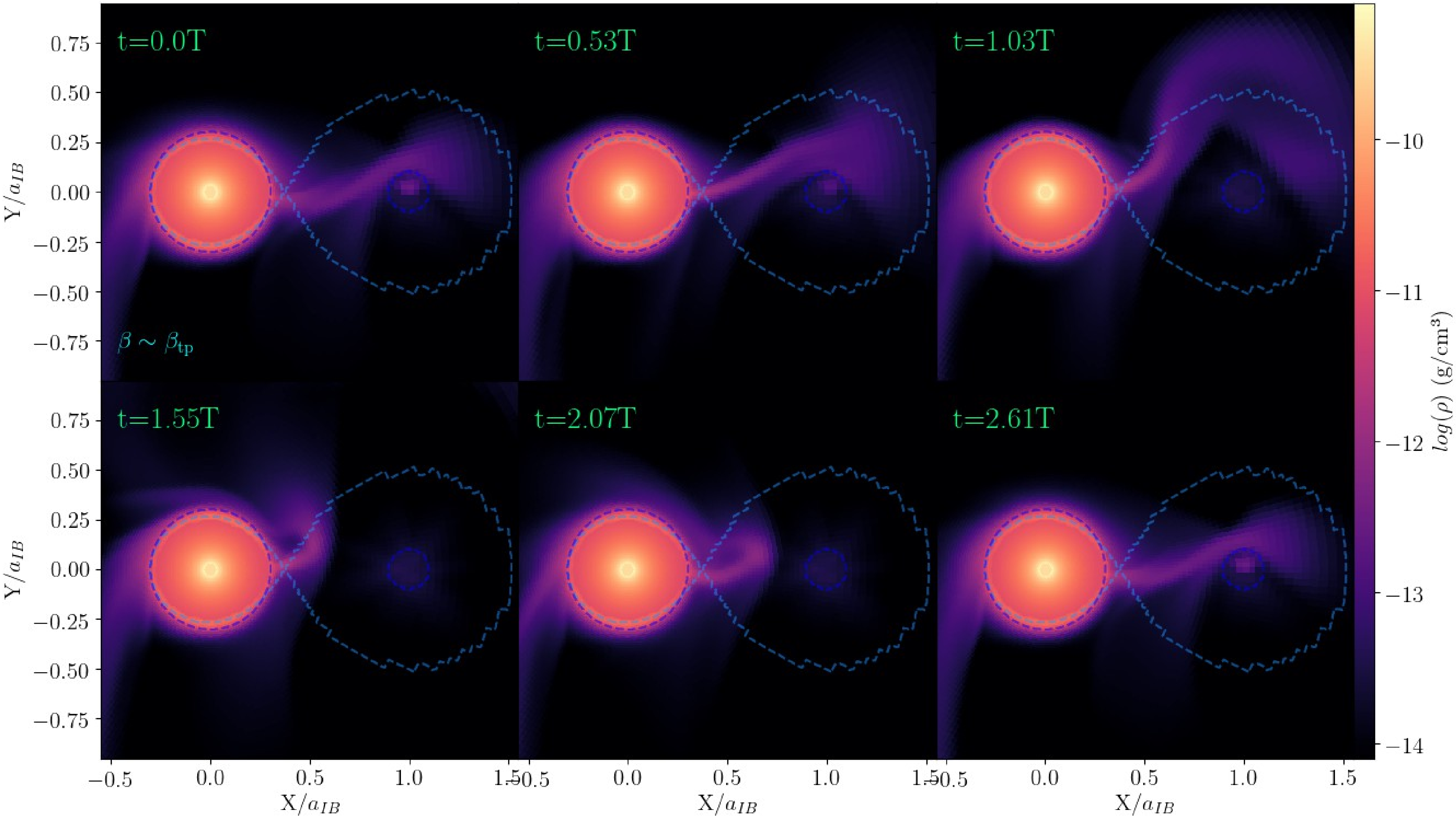
Unstable

Analytical equation of **stagnation point radius**
(not taking into account gravity)

$$r_{sh} = \frac{\beta^{1/2} a_{IB}}{1 + \beta^{1/2}}$$

Tipping point of transition due to presence of an accretion arm

Unstable state close to Tipping Point



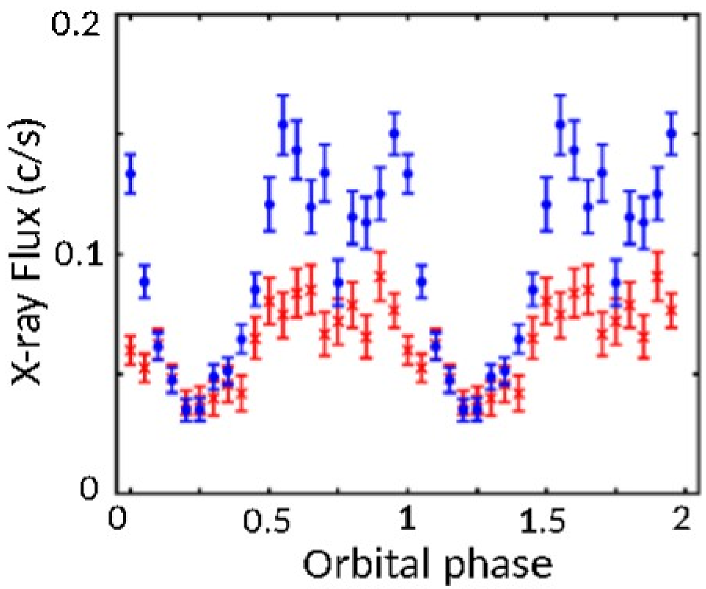
TMSPs ➡ Spider systems near this potentially existing tipping point ?

Intra-Binary Shock : Orbital variability of the X-ray flux

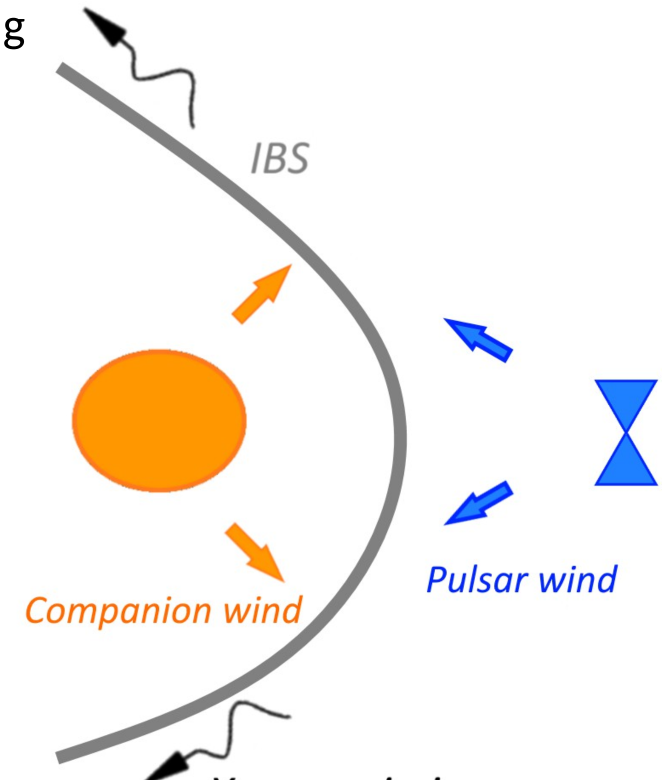
IBS : **efficient site of particle acceleration** and **non-thermal emission** due to the Doppler boosting, SR and IC

Double peak emission : typical feature due to the *two main directions of particles propagation* along the IBS

➡ **Shock orientation** and **opening angle** determining the shape of the X-ray orbital light curve.



X-ray orbital modulation observed from PSR J1227−4853 (RB) on 2013, Dec 29 (red points) and 2014, Jun 27 (blue points), Papitto and de Martino, 2020
Phase 0 corresponds to the passage of the NS at the orbit ascending node



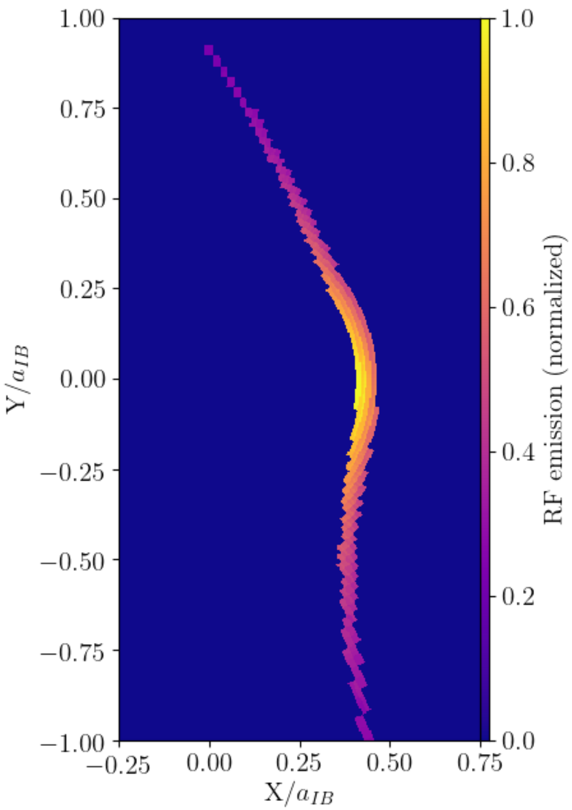
Modelling shock X-ray light curve

Solve radiative transfer equation for multiple lines of sight :

$$I_\nu = I_{\nu,0} \exp\left(-\tau_\nu\right) + \int_0^{\tau_\nu} \delta_i^3 \frac{j_\nu}{\alpha_\nu} \exp -(\tau_\nu - \tau_{\nu'}) d\tau_{\nu'}$$

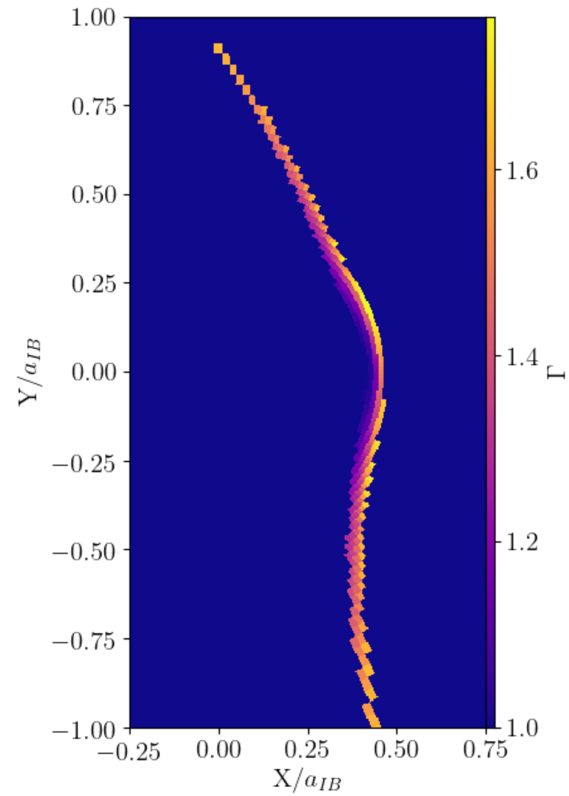
Restframe emission

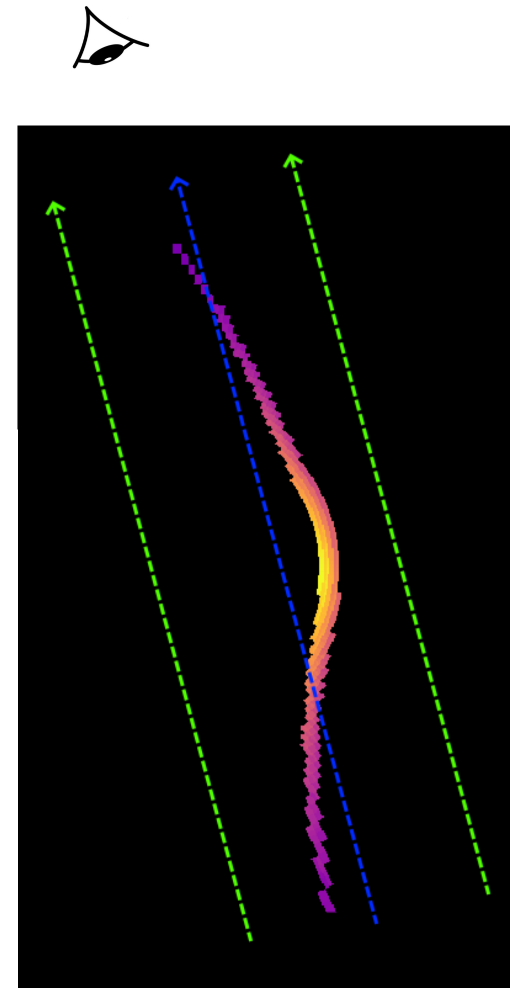
$$j_\gamma(\nu) = \frac{\sqrt{3} e^3 B sin(\alpha)}{4\pi m_e c^2} \left(\frac{\nu}{\nu_c}\right) \int_{\nu/\nu_c}^{\infty} K_{5/3}(x) dx$$



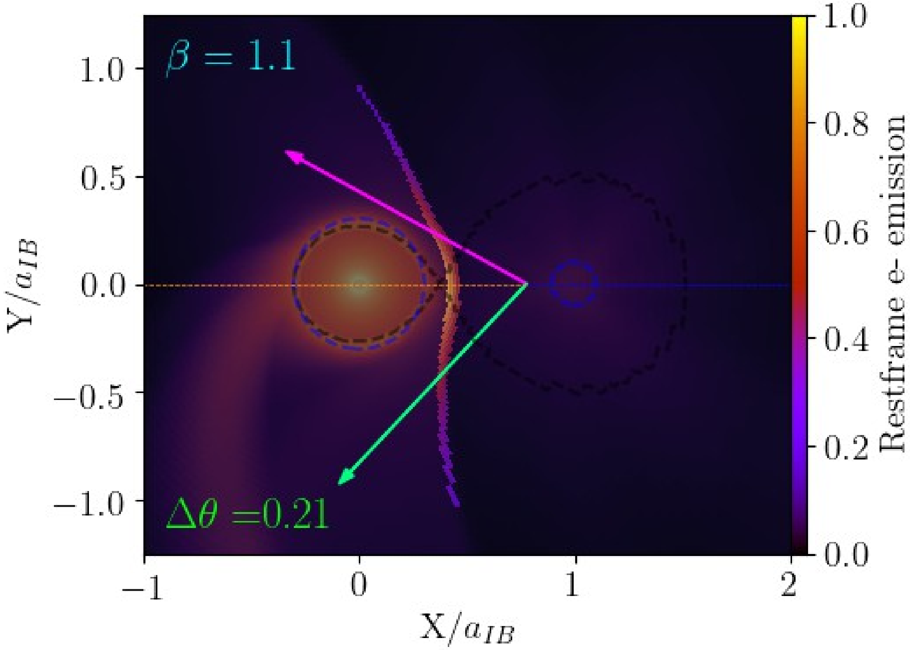
Beaming effect

$$\delta_i = \frac{1}{\Gamma_i (1 - \sqrt{1 - 1/\Gamma_i^2} \cos(\theta_i))}$$





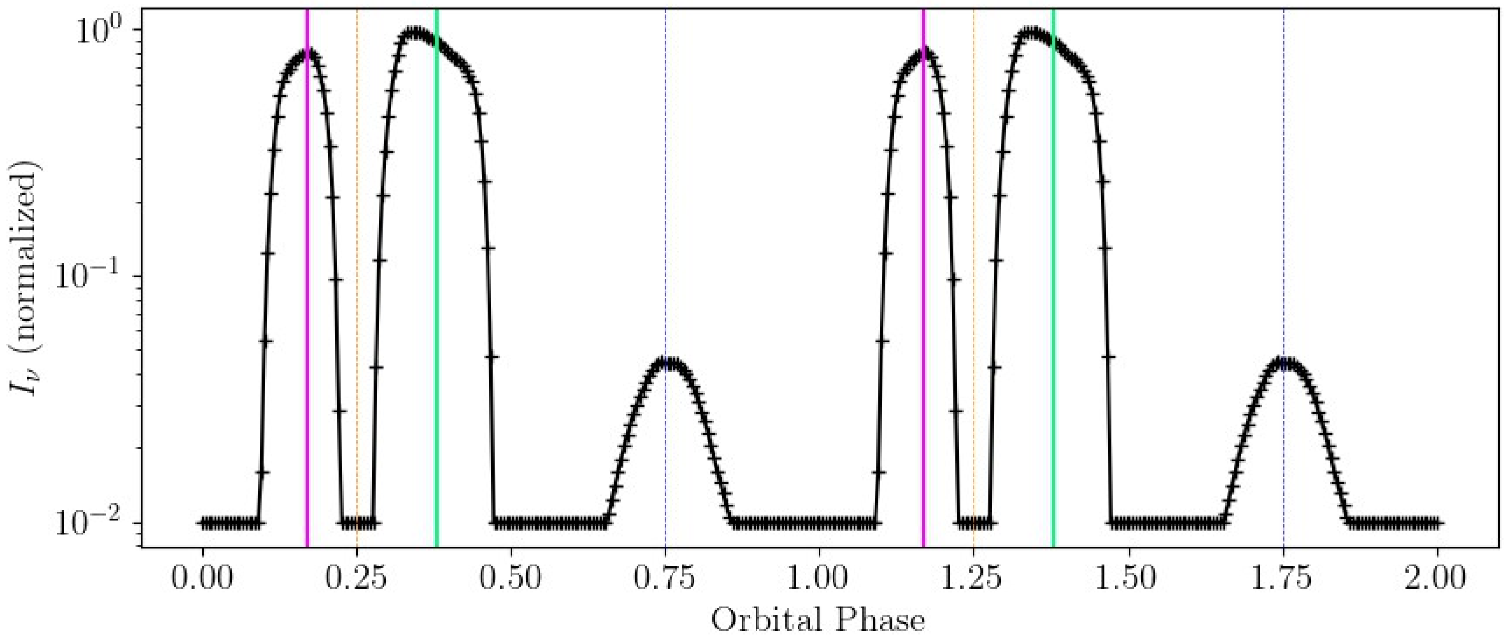
Modelling shock X-ray light curve



- ***Double peak feature*** at star's inferior conjunction

- ***Non symmetrical*** due to ***rotating frame***

- ***Not aligning*** with ***asymptotic direction*** of shock



Variability of system and eclipses in Radio

Long duration radio eclipses observed from spider systems

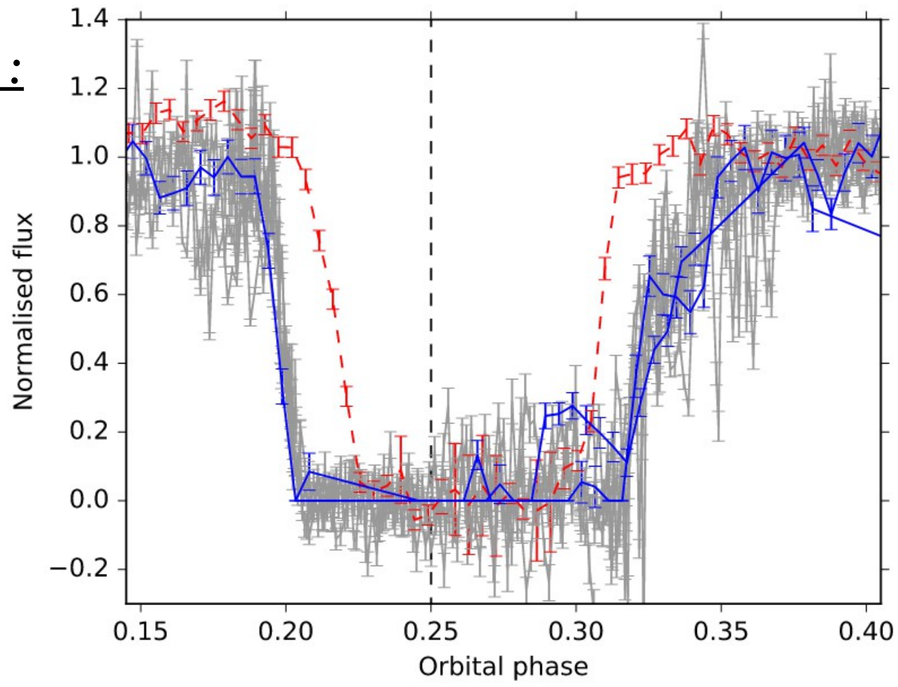
Differents eclipses processes : refraction /absorption / scattering

→ still things not well understood…

Influence of accretion arm on radio eclipses :

- **Asymmetry** of flux around star's inferior conjunction

- **Variability** of eclipses between different periods



Measured flux density (345 and 149 MHz) as a function of orbital phase of PSR J1810+1744 (BW)
Using LOFAR & Westerbork Synthesis Radio Telescope observations between 2011 and 2015
(Polzin et al. 2018)

Conclusion

Simulations :

- Model of companion and pulsar based on **characteristics spider systems values**

- Simulation of both **characteristics state of tMSPs** depending on **momentum fluxes ratio β**

- **Gravity** in model : **Tipping point of transition** and **unstable behaviour**

Observables :

- Construction of ***X-rays LC of IBS emission***

- ***Unstable system*** can be linked to ***variability observed in radio eclipses***

Follow up **:** More precise numerical model 3D, relativist, MHD …

(Guerra et al. in prep.)

Thank you for your attention