From pulsars to Fast Radio Bursts

Guillaume Voisin
with
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Journée du LUTH , 23/04/2023

Image credit: ESO/L. Calçada (Creative commons)

Transitional Millisecond pulsars :
To be or not to be in a stable state

Corentin Guerra, avec Z. Meliani et G. Voisin

Context : Spider Pulsars

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

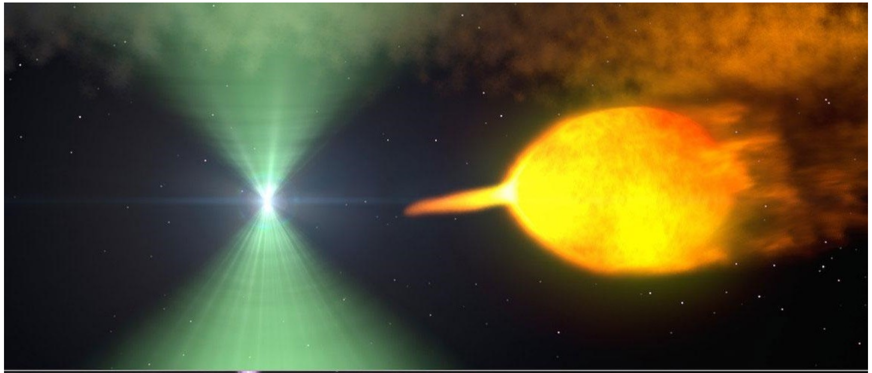
'Black Widow' : with a degenerate evaporating companion ($M_c < 0.1M_☉$)

'Redback' : non or semi-degenerate evaporating companion ($M_c < 0.5M_☉$)

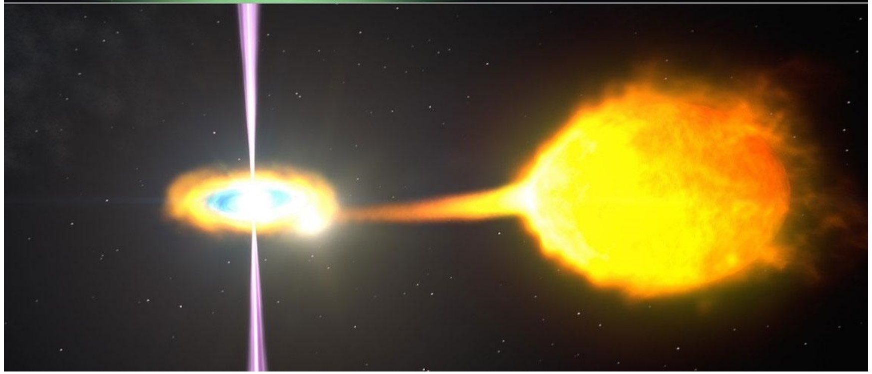
Source of **tMSP** :
transitional millisecond pulsars

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

MSP :



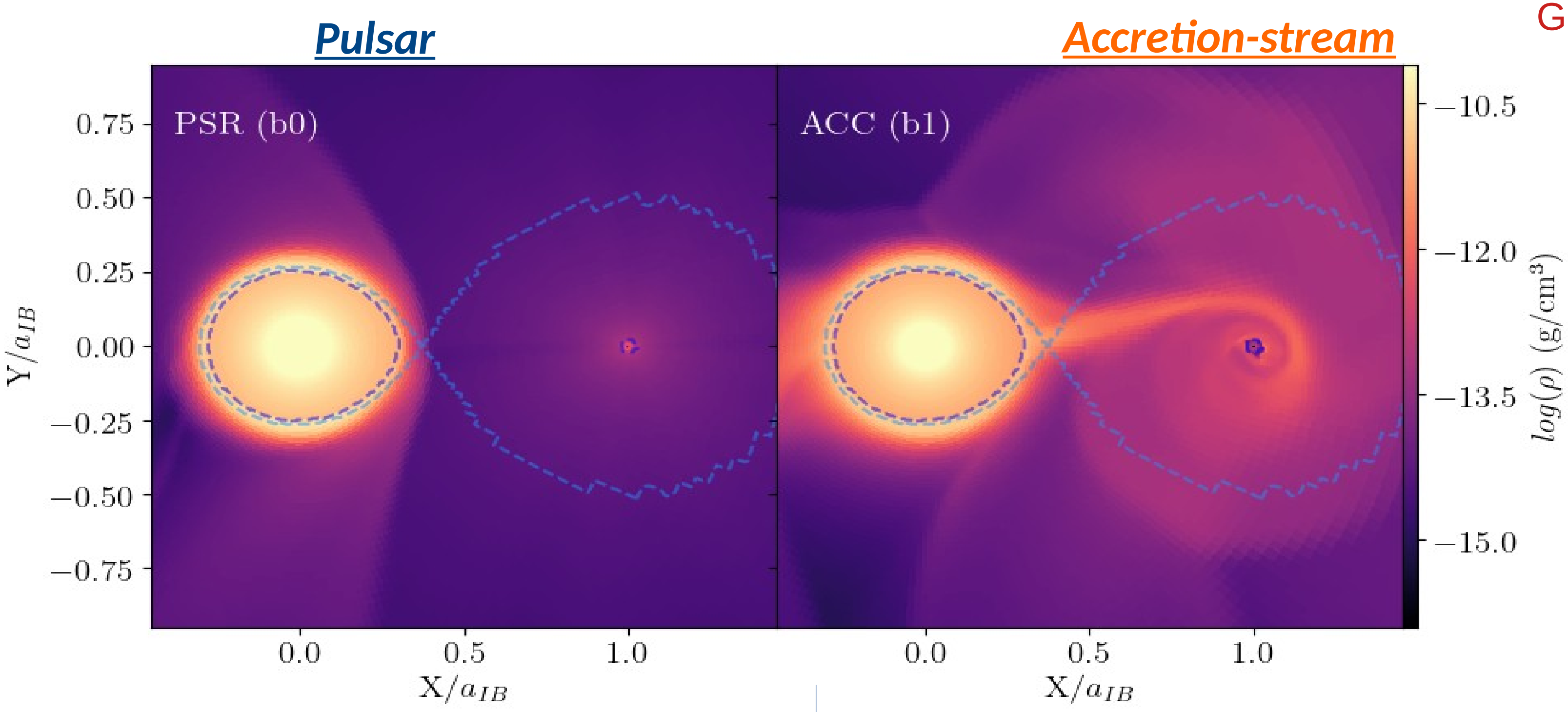
LMXB :



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

Two different outcomes : The two characteristic states of tMSPs

Guerra+, in prep



Intra-binary shock (IBS) formed → **Stationnary**

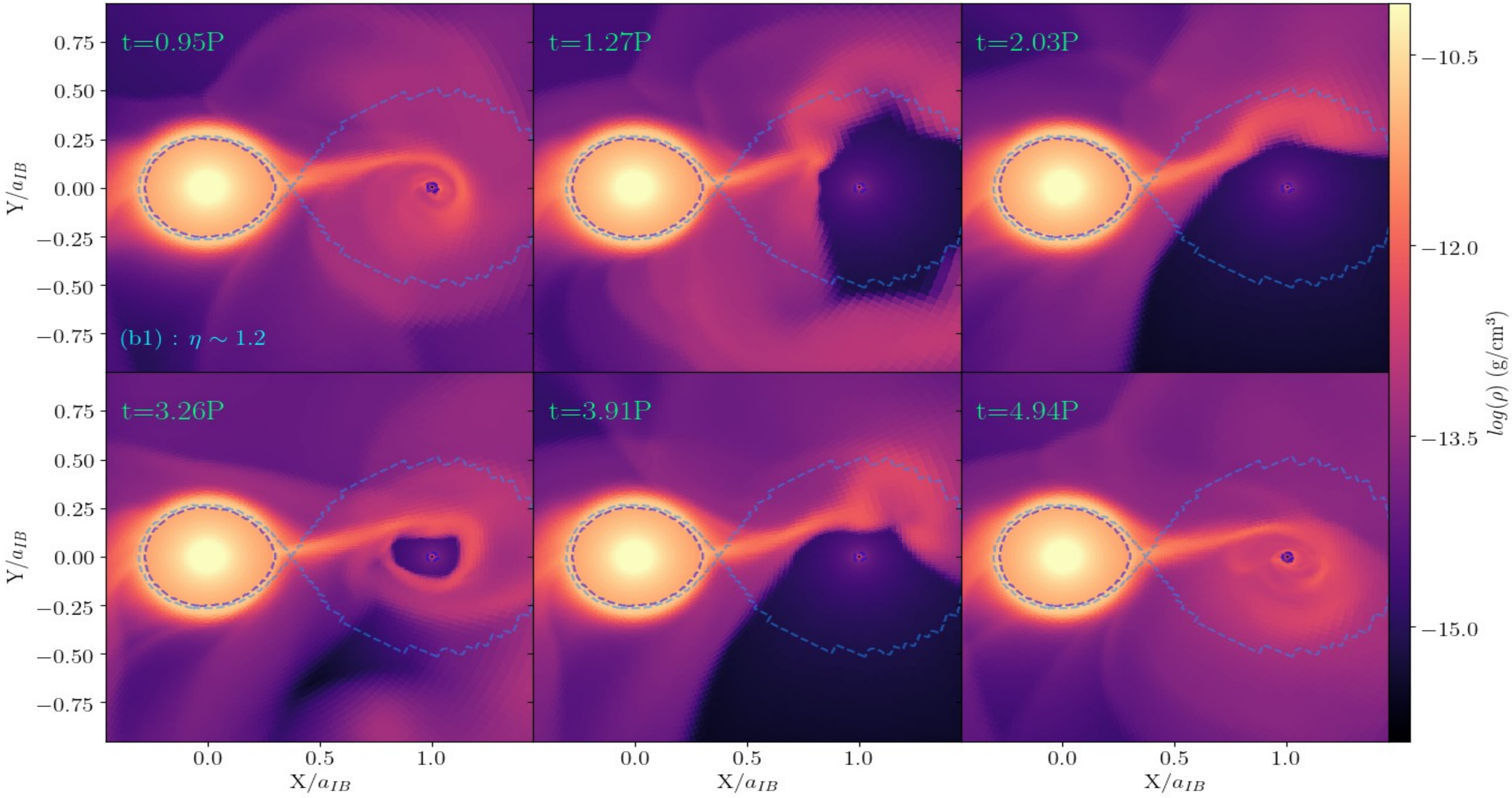
Creation of ***accretion stream*** → **Variability**

Boundary between the two characteristic states is thinner than expected

→ ***Tipping point of transition***

Unstable behavior close to tipping point

Guerra+, in prep

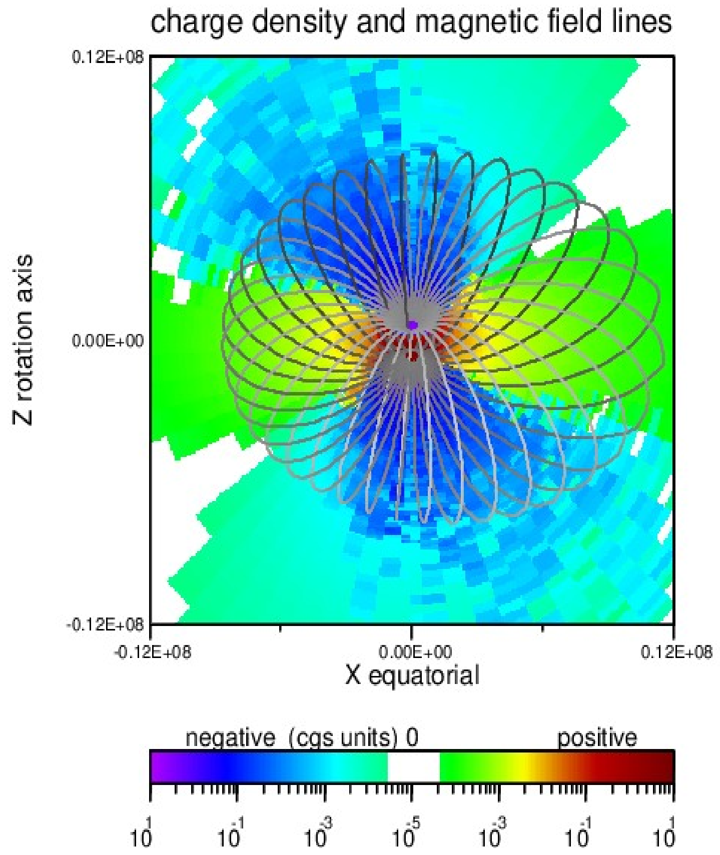


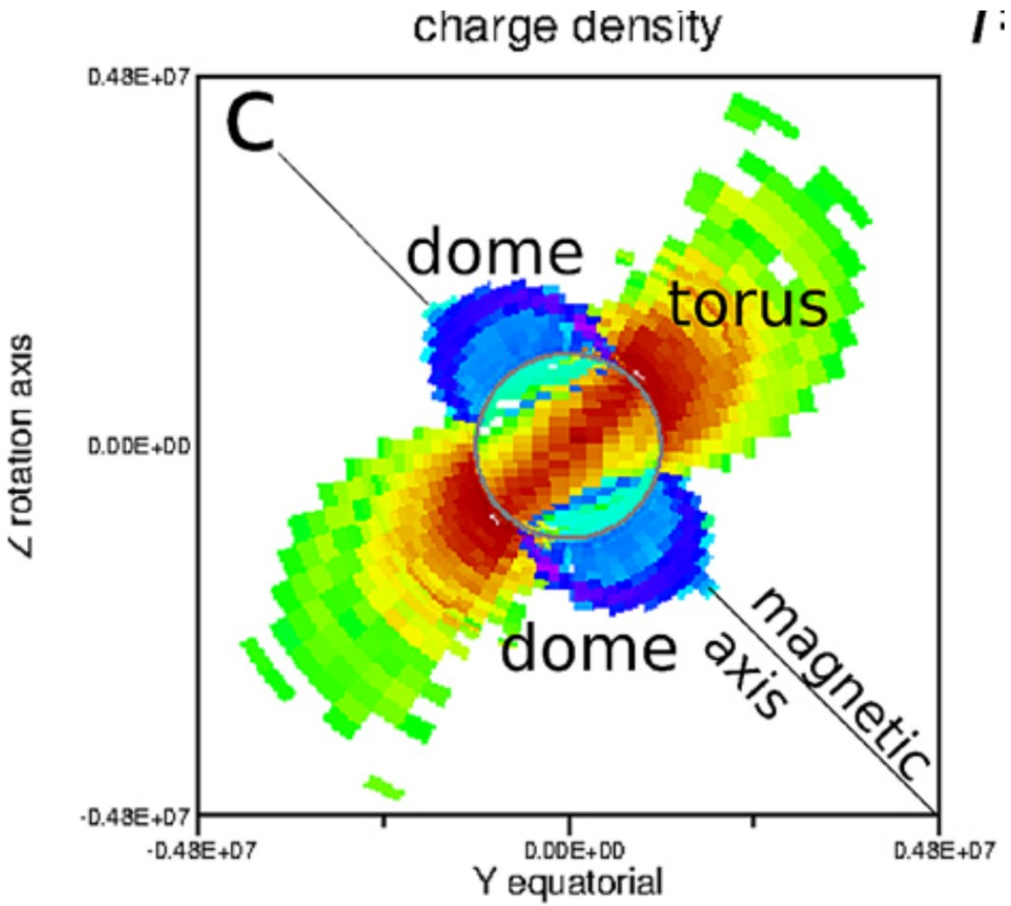
Pulsar electropheres : code Pulsar ARoMa

Théo Francez, F. Mottez, G. Voisin

Proton-electron electrospheres with ARoMa

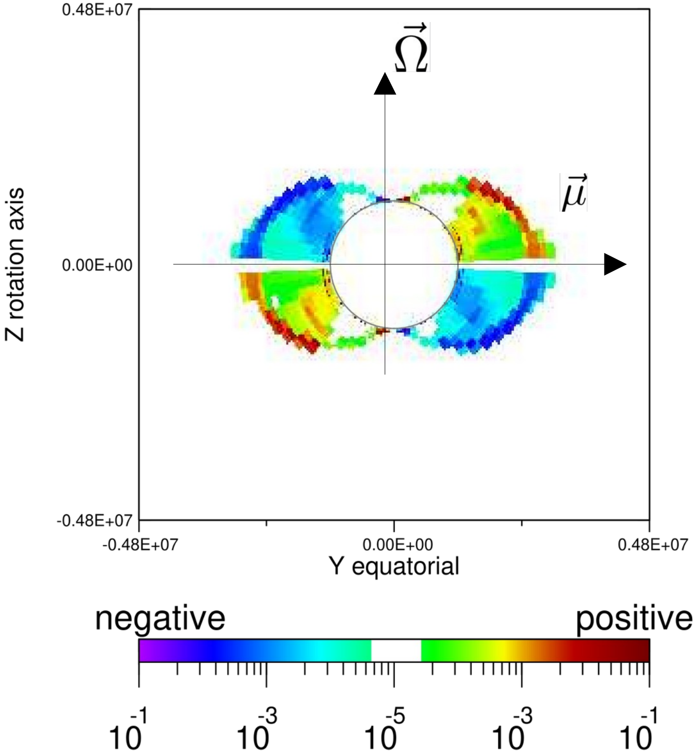
Mottez, A&A 2024

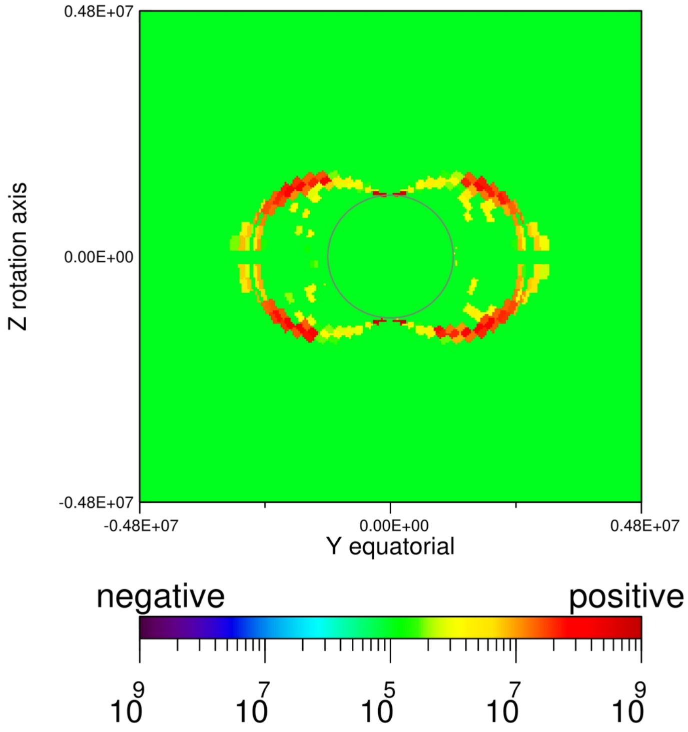




High-energy emissions of an electrosphere

Théo Francez

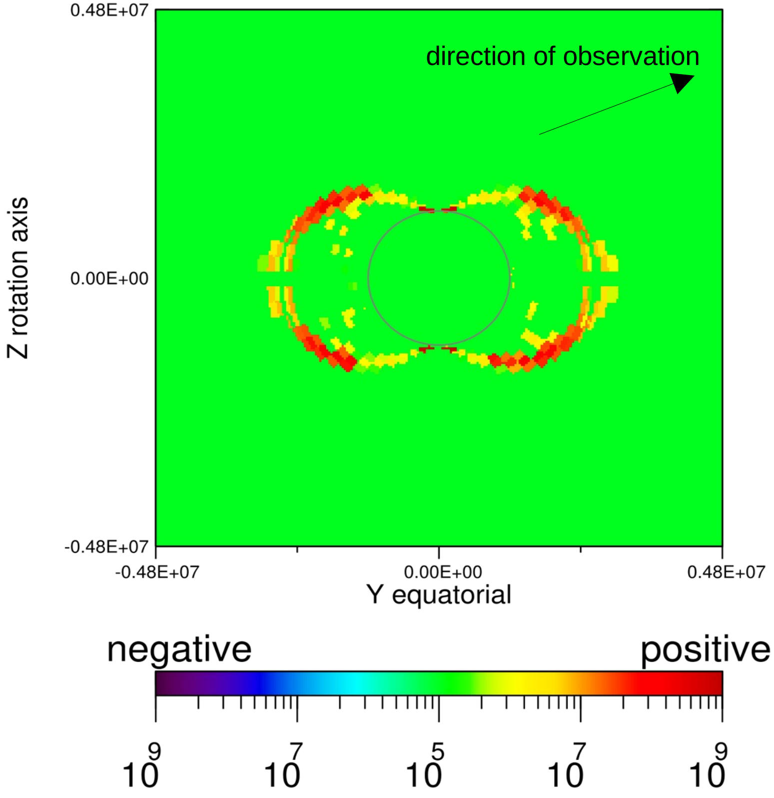




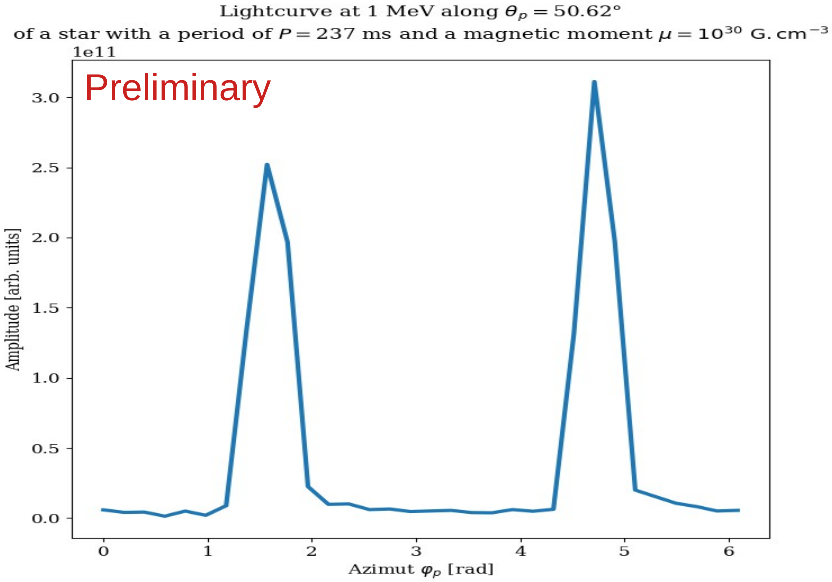
Charge density of a magnetosphere filled with electrons and positrons (left) and the amplitude in arbitrary units of the radiation they emit at 1 MeV in the φ_p=0° plane (right). The star has a period of P=237 ms and a magnetic moment $\mu=10^{30}$ G.cm^{-3}. Its magnetic dipole is orthogonal to its rotation axis.

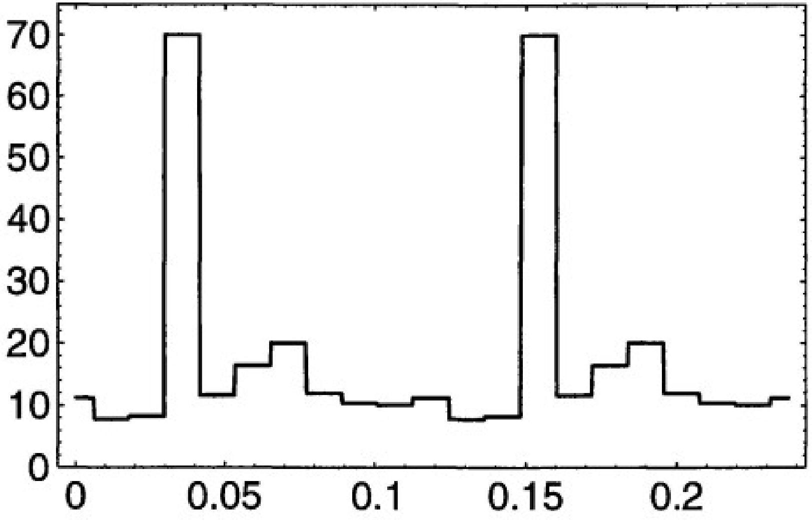
High-energy emissions of an electrosphere

Théo Francez



Radiation emitted at 1 MeV in the φ_p=0° plane.



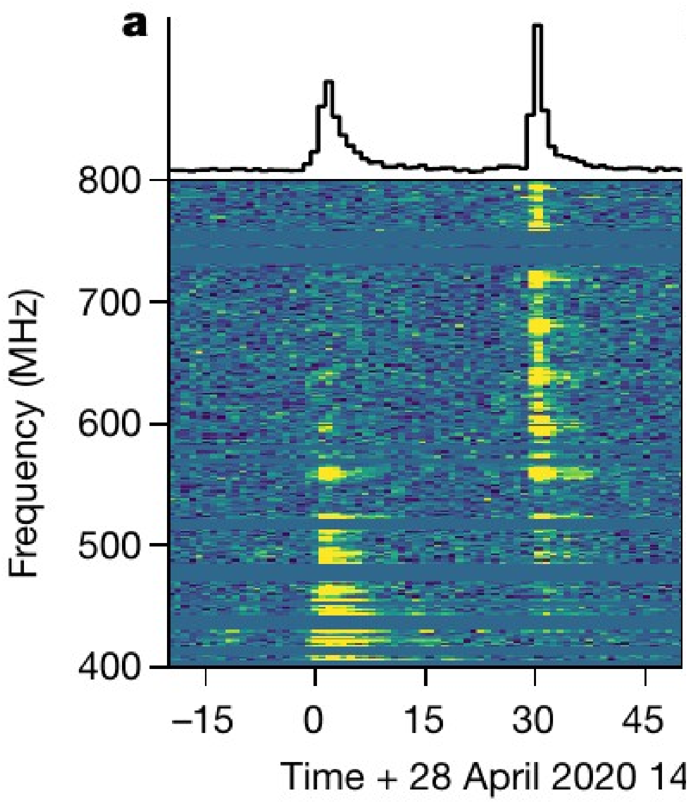


Higgins & Henriksen, 1997

Fast Radio Bursts (FRBs)

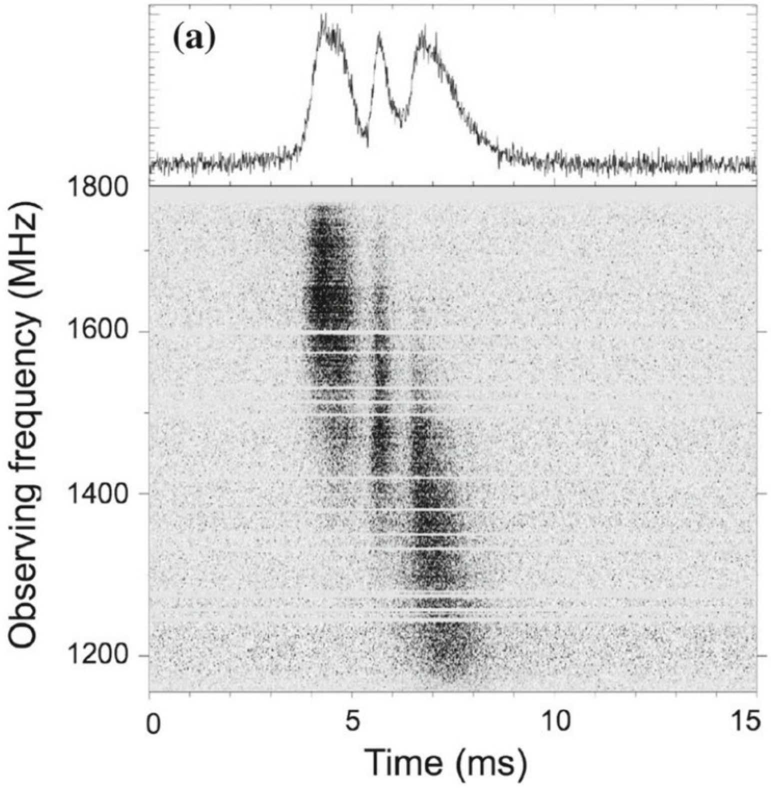
Fast radio bursts

One-off : broad-band and shorter



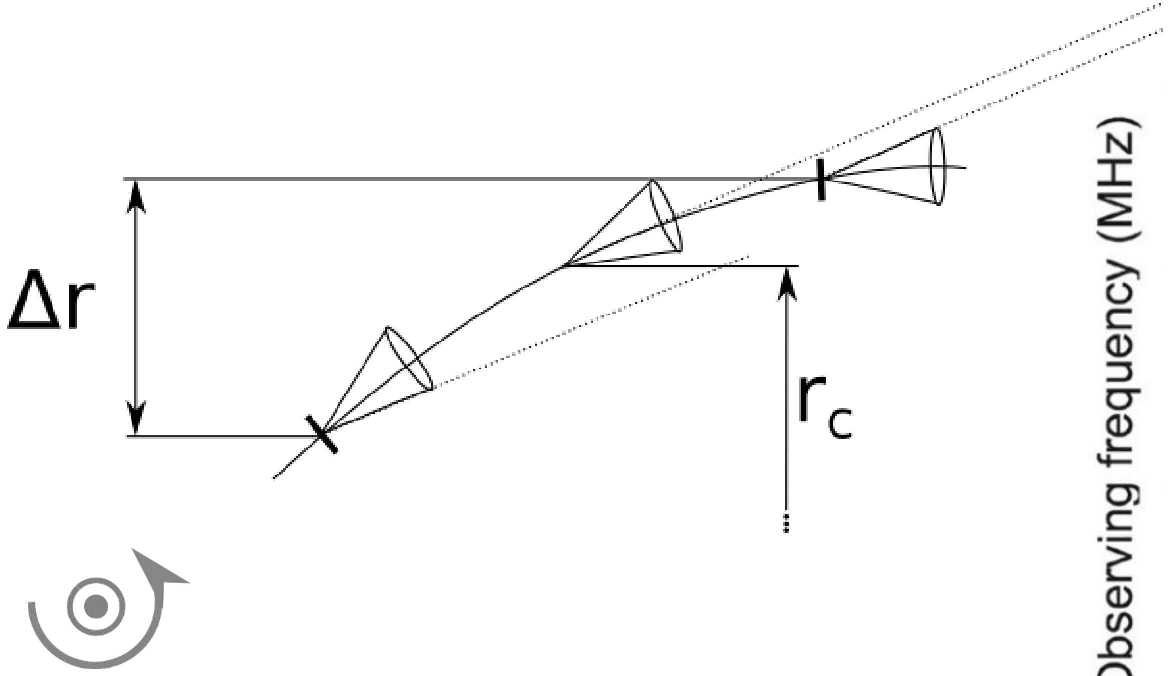
FRB200428, (Chime/FRB 2020b)

Repeaters : narrow-band, longer, downward-drifting sub-bursts

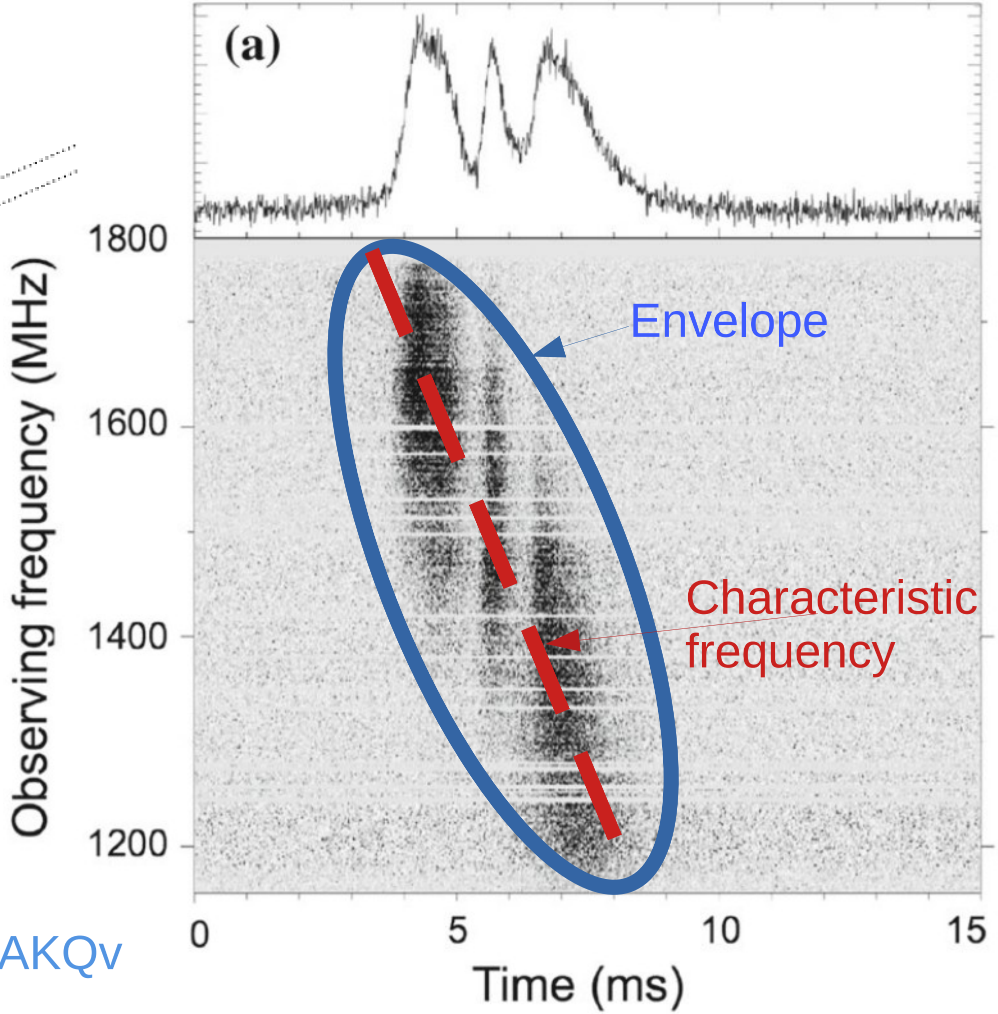


FRB121102, Hessels+18

Geometric envelope



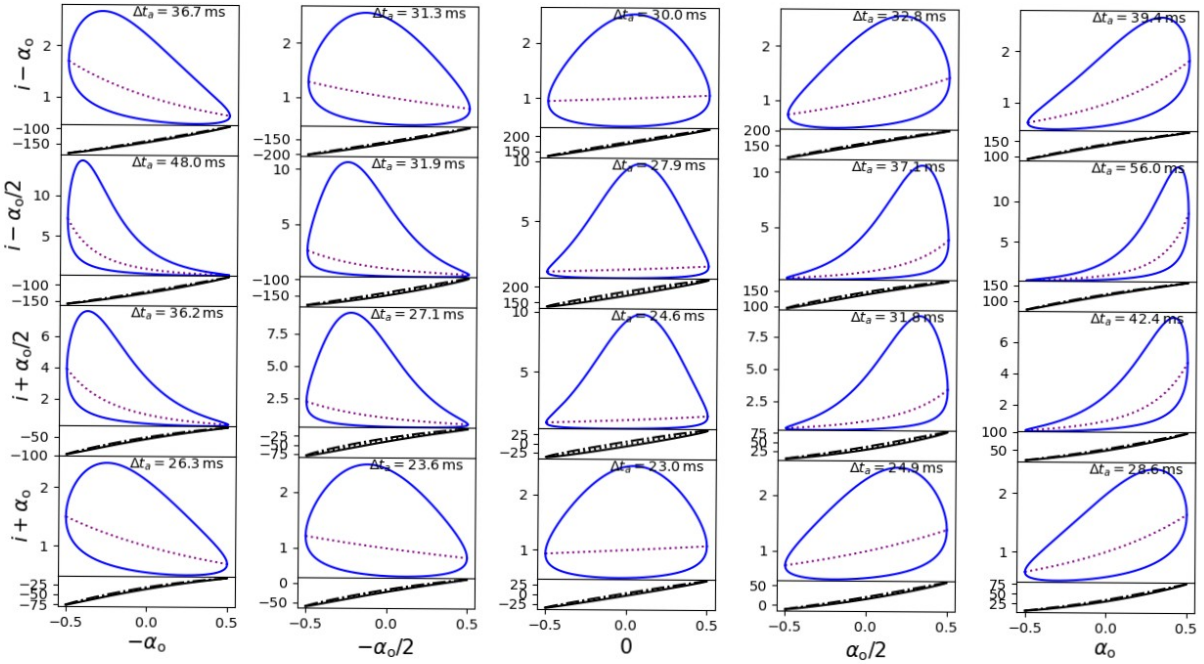
FRB121102, Hessels+18



https://astrotube.obspm.fr/w/f9SxoEzzc2bBvc5KjXAKQv

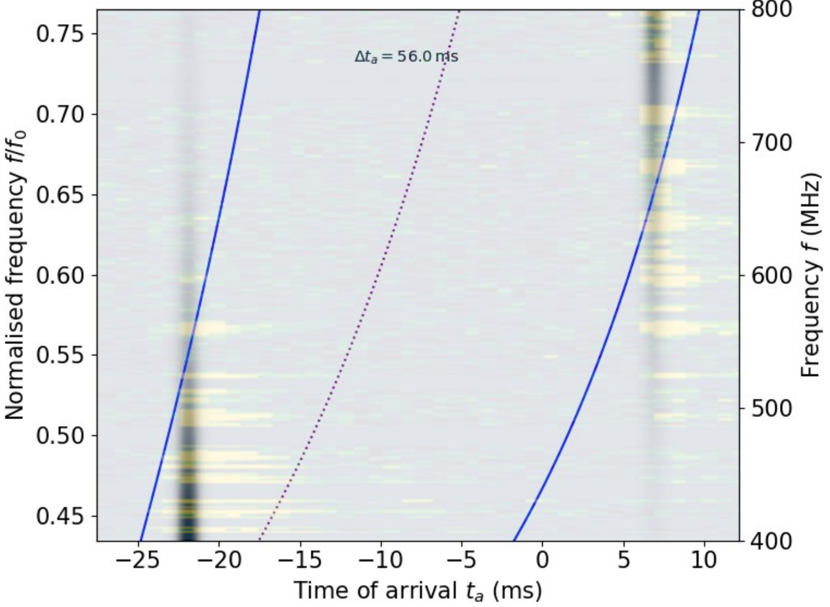
Dipole magnetic field, Pspin=3.2sec

Voisin, A&A 2023



Envelopes in the polar cap region at r = 100R$_{*}$, Voisin2023

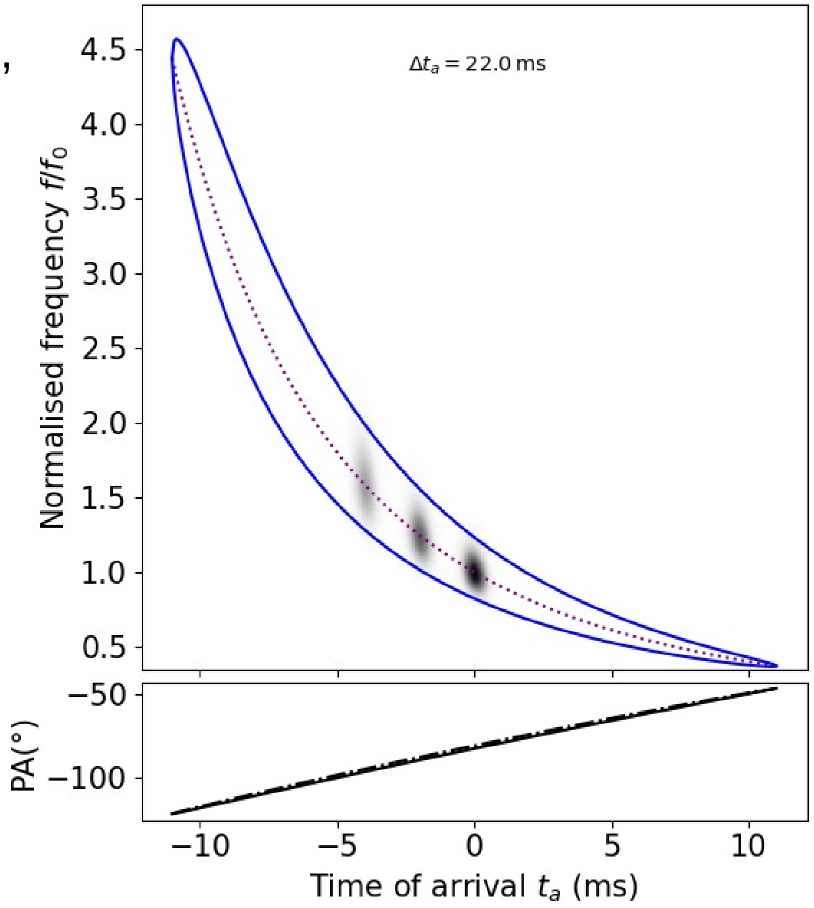
Modelled envelope+bursts overlaid with FRB200428 (Chime/FRB 2020b)



Dipole+toroidal magnetic field : P_*=250ms

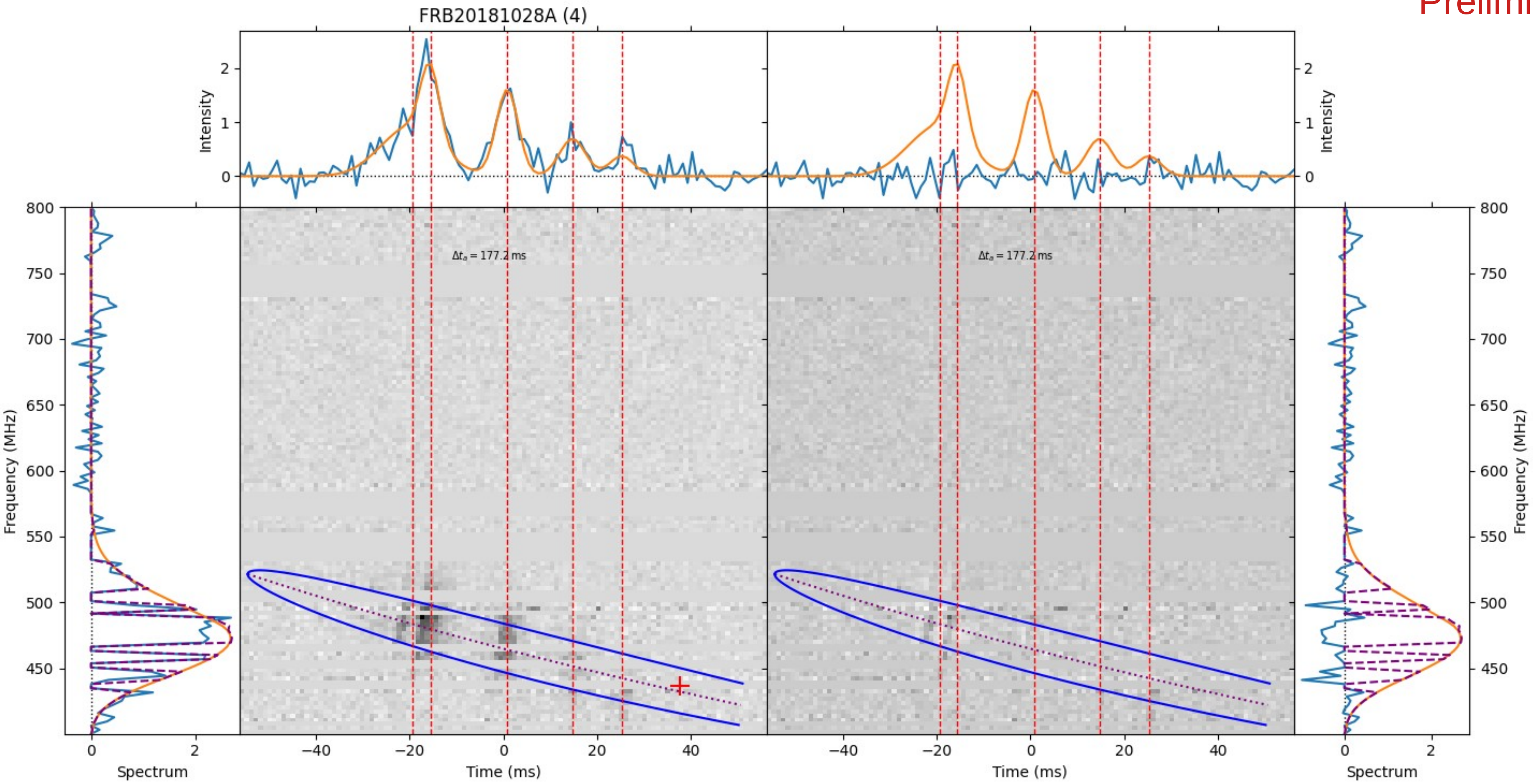
Voisin, A&A 2023

- Three bursts in envelope with Btoro = 0.5 Bdipole, (Voisin2023)
- Relative frequency drift: fdot/f ~ 110s^{-1}
- Toroidal component generically produces downward drifting sub-pulses (if strong enough)



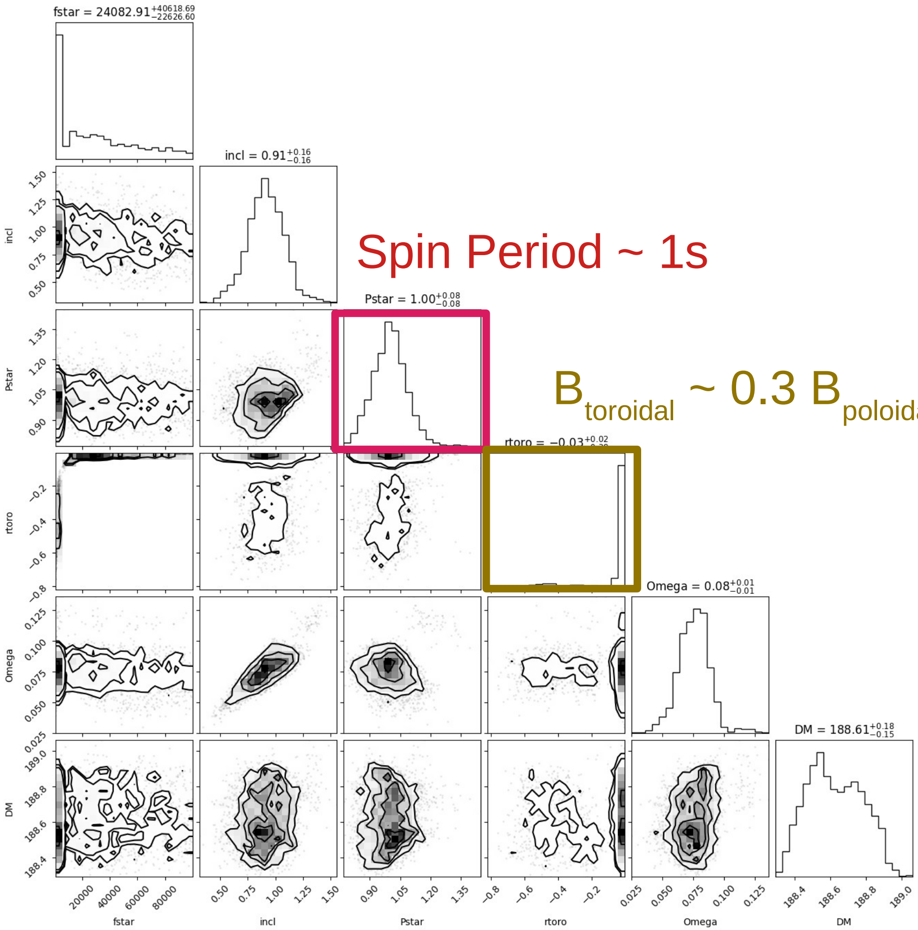
Application to CHIME/FRB data

Preliminary



Moderately fast magnetar with strong toroidal magnetic field

Preliminary



Spin Period ~ 1s

$B_{toroidal}$ ~ 0.3 $B_{poloidal}$ at emission location

Summary

- Transitional Millisecond pulsars :
  - tipping point between accreting and pulsar state (C. Guerra).

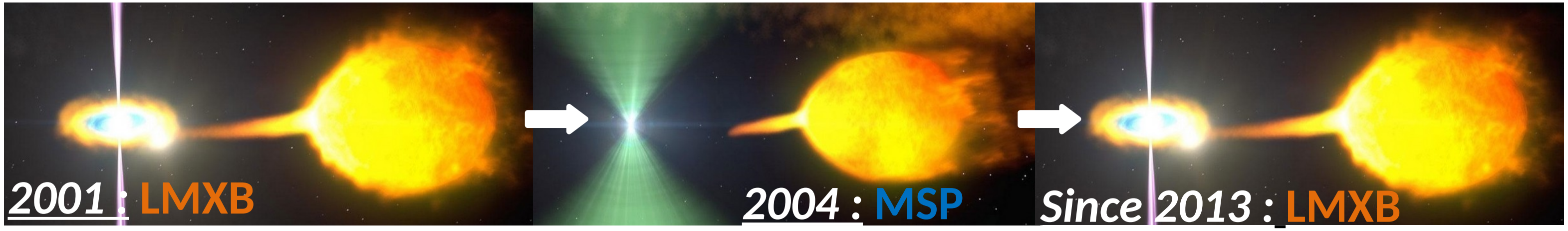
- Pulsar Magnetospheres :
  - Code AroMA published (F. Mottez),
  - High-energy emission underway (T. Francez).

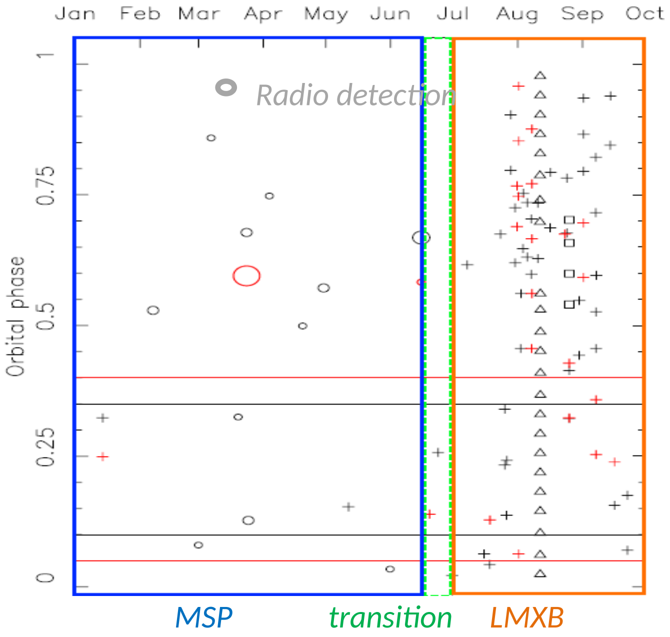
- Fast Radio Bursts :
  - towards characterizing the source thanks to the morphology of the bursts (G. Voisin).

Backup slides

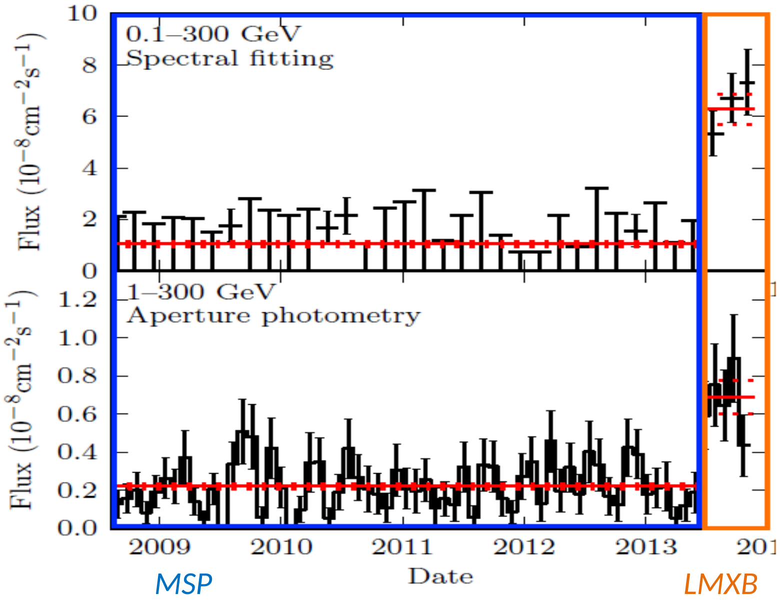
Transitional Millisecond Pulsars (tMSP) :

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



Y-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 :***

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0\,,$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \vec{v} + P) = grav. + rot.\ ,$$

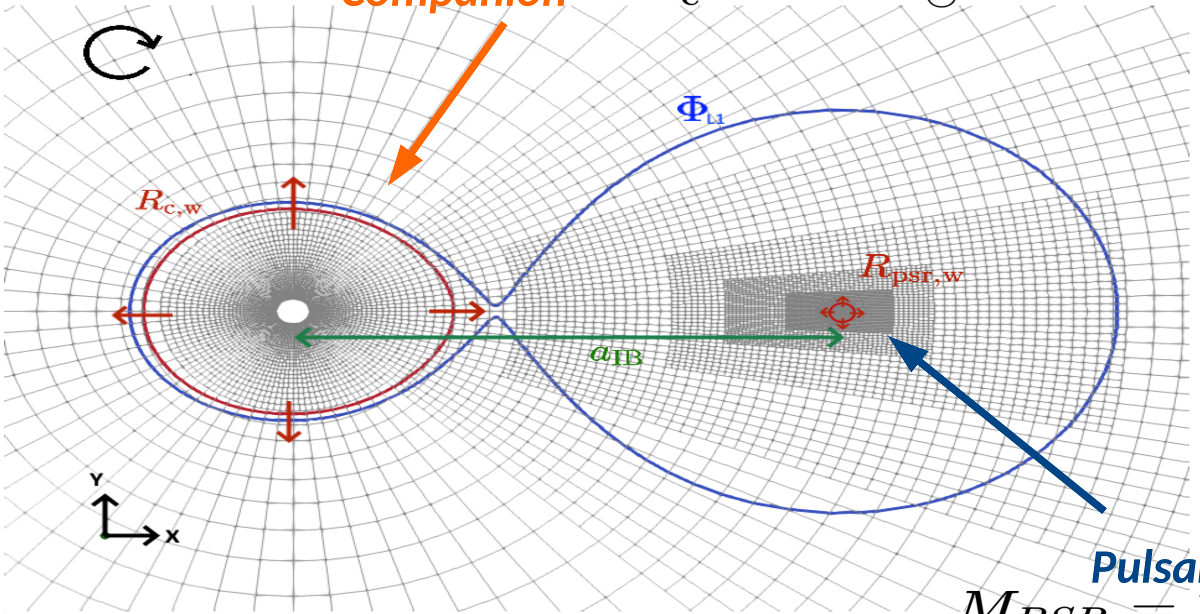
$$\frac{\partial e}{\partial t} + \nabla \cdot [(e + P)\,\vec{v}] = grav. + rot. + heat.$$

Intra binary distance :

$$a_{\rm IB} = 10^{11}\,{\rm cm}$$

→ $P \sim 3.56{\rm h}$

Companion $M_{\rm c} = 0.4 M_{\odot}$

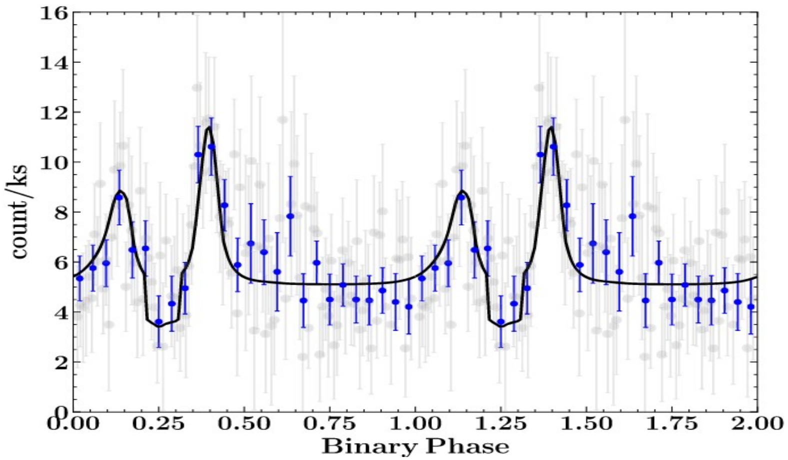


Pulsar $M_{PSR} = 1.4 M_{\odot}$

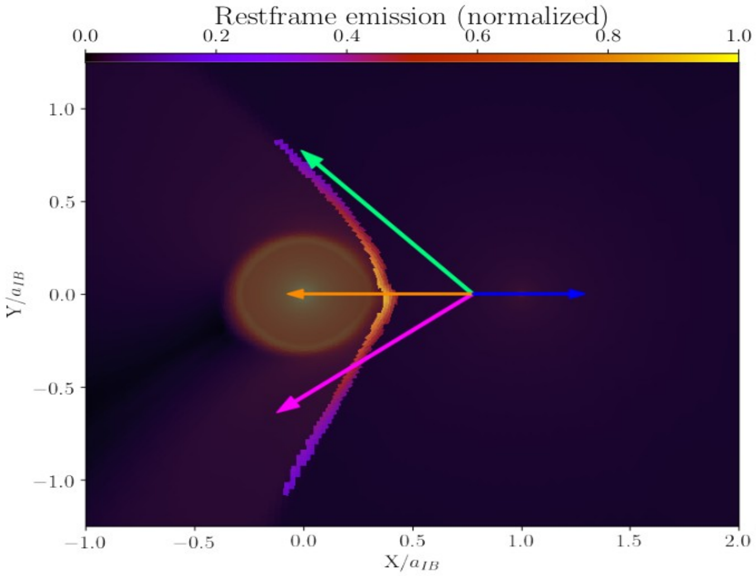
Intra-Binary Shock : Orbital variability of the X-ray flux

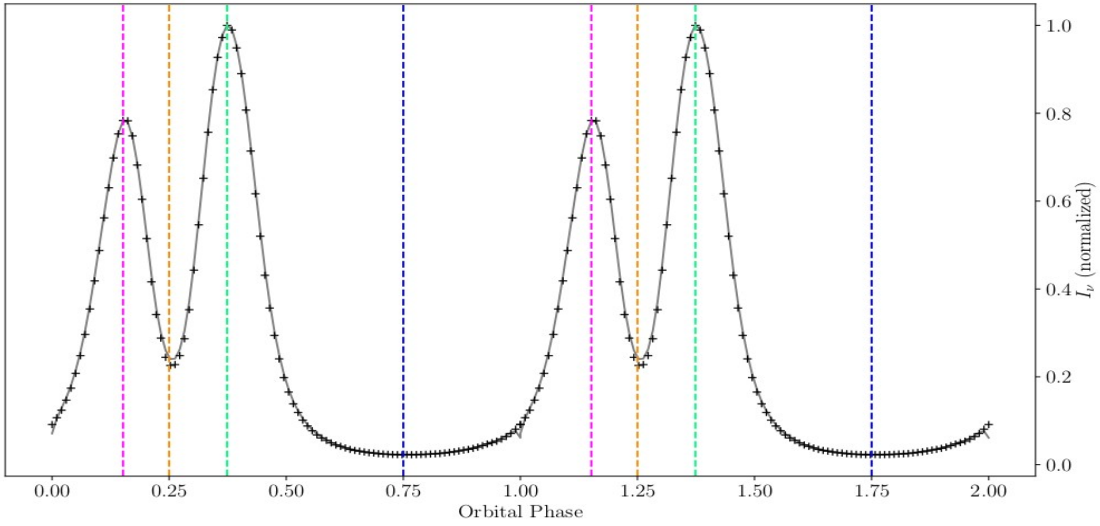
IBS : efficient site of particle acceleration and non-thermal emission due to the SR

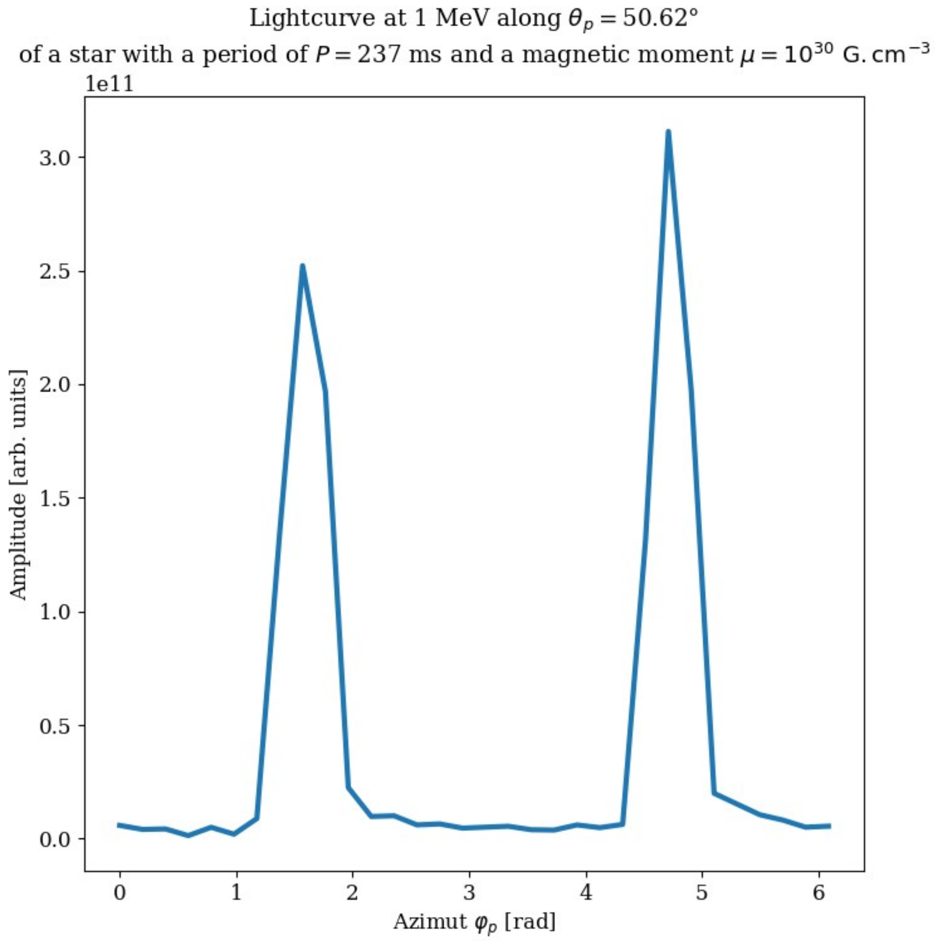
Double peak emission : typical feature due to the two main directions of particles propagation along the IBS

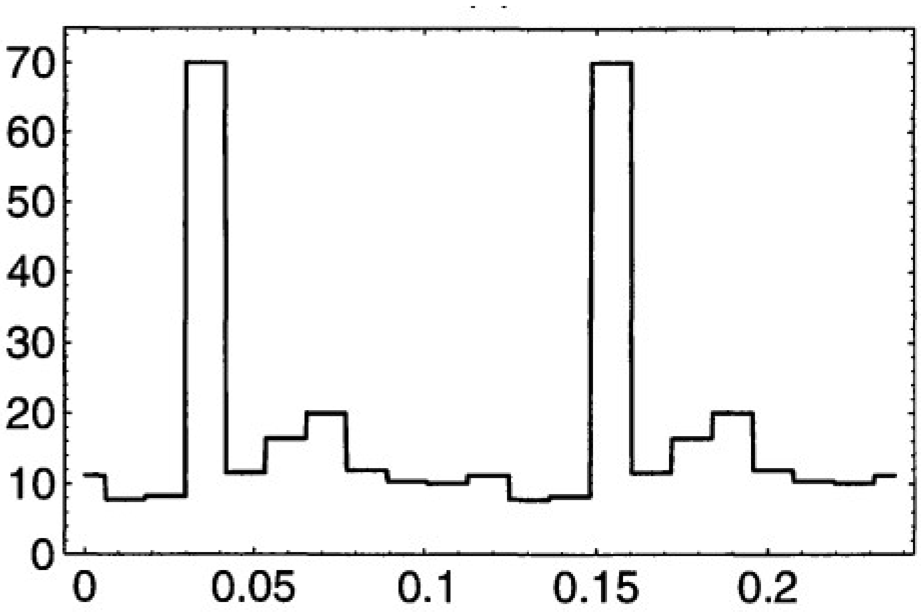


LC of PSR J1959+2048 (Kandel et al. 2021)









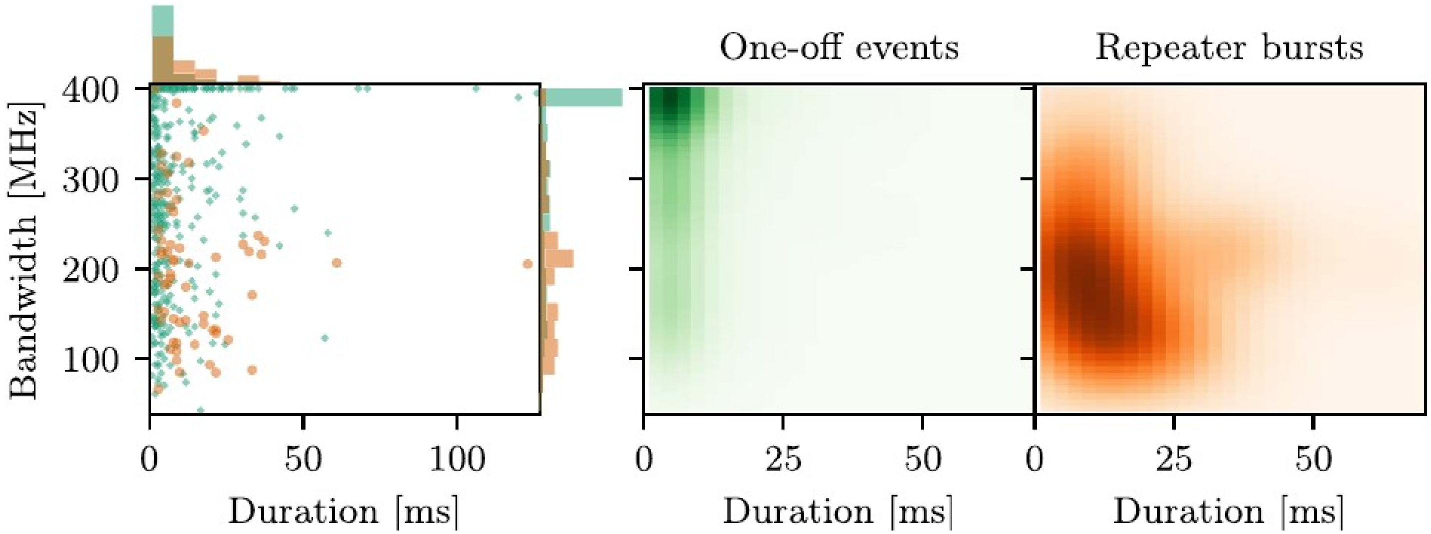
Lightcurve at 1 MeV along θ_p=50.62° of a star with a period of P=237 ms and a magnetic moment $\mu=10^{30}$ G.cm^{-3}. Time is plotted along the horizontal axis and arbitrary intensity along the vertical. Credits: Higgins M. G., Henriksen R. N. (1997).

$$P(t) = fA(t)$$

P(t) total power emitted in the magnetosphere at time t
A(t) : amplitude of the radiation emitted by single particles a time t
f : scaling factor depending of the total power emitted observed

State of the art (more or less)

- Statistical distributions: occurrence times, bandwidth/duration correlations...
- Physical constraints on observables are broadly averaged quantities: flux, duration, bandwidth, frequency drift..
- Burst morphology fitted with empirical functions (e.g. Gaussian).



Pleunis+ 2021