3D Particle-in-cell simulations of a pulsar wind interacting with a disk: an application to transitional millisecond pulsars

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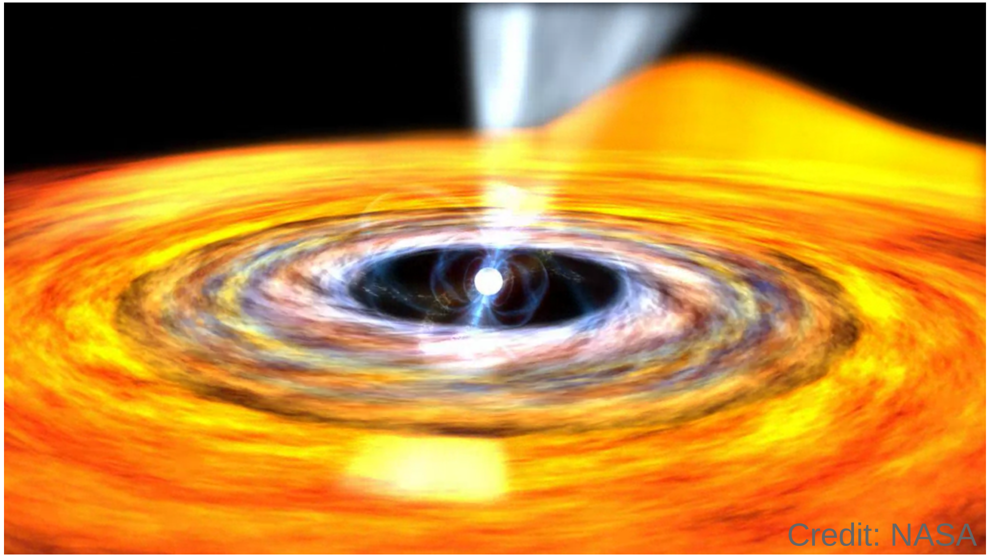
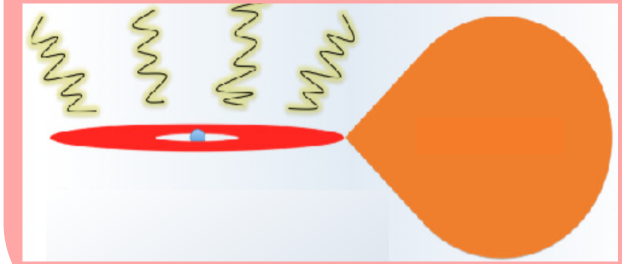


Transitional millisecond pulsars (tMSPs)

- Transitions between 3 possible states, over timescales < 2 weeks

Accretion-powered state

low-mass companion star → accretion disk and accretion columns



Adapted from Tam et al. (2014)

Sub-luminous disk state = intermediate state

- accretion disk but $L_{X,rot}<L_X<L_{X,outburst}$
- X-ray intensity modes (high and low)
- $L_\gamma > L_{\gamma,rot}$
- $L_{opt} > L_{opt,rot}$
- radio continuum, no radio pulses
- flares (X-ray, UV, optical, near-IR)

Rotation-powered state

pulsar behaves as a radio millisecond pulsar

Adapted from Tam et al. (2014)

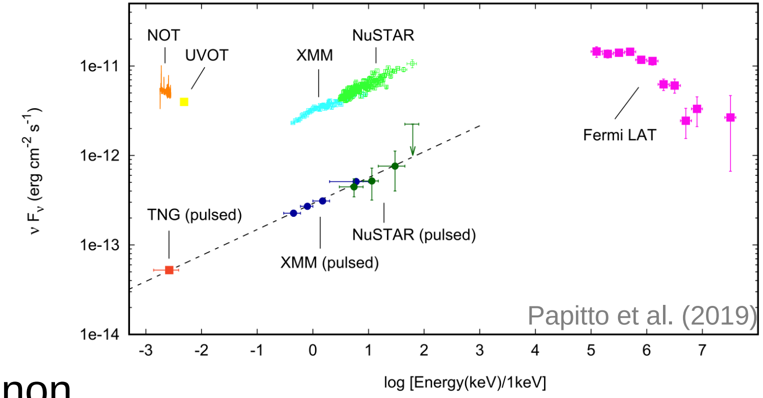
- 3 confirmed systems (PSR J1023+0038, IGR J18245-2452, XSS J12270-4859) + many candidates

Sub-luminous disk state: optical and X-ray pulses from J1023+0038

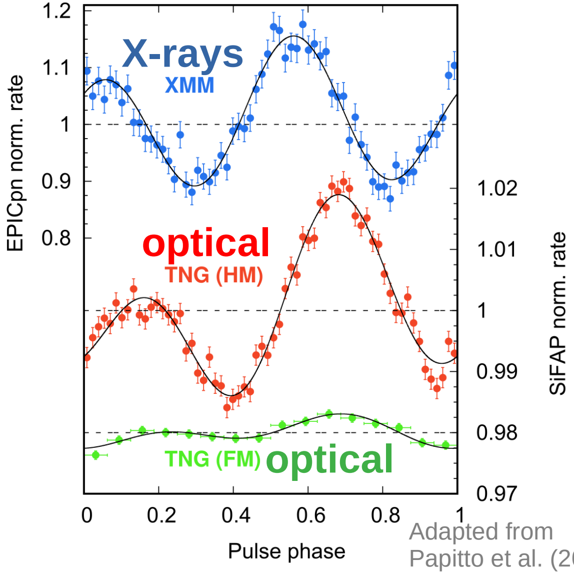
During the X-ray high intensity mode (~70% of the time):

- coherent quasi-simultaneous optical and X-ray pulsations
- similar pulse profiles, two broad peaks 180° apart
- modulation by P_{spin}
- same emitting region (~kms apart)
- both compatible with the same power-law spectrum $F_\nu \propto \nu^{-0.7}$

→ optical and X-ray pulses should originate from the same phenomenon



Papitto et al. (2019)



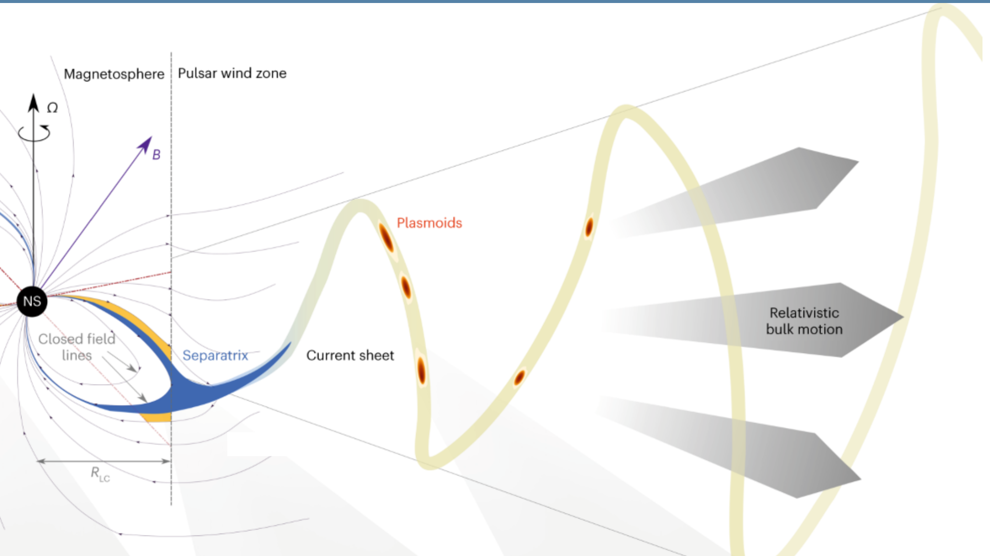
Adapted from Papitto et al. (2019)

Physical origin of theses pulses?

❌ accretion?
pulsed optical luminosity is too high

❌ activity of a rotation-powered pulsar?
pulsed optical and X-ray emission is too high

Pulsar magnetosphere



Credits: the HESS collaboration

3 main zones

→ *closed zone*: closed field lines corotate with the pulsar
plasma is confined, no poloidal current

→ *opened zone*: field lines opened by pulsar rotation
outgoing Poynting flux, relativistic wind
non-zero poloidal current

→ *current sheet*: interface zone between opposite Bfields
non-zero returning poloidal current
energy dissipation zone

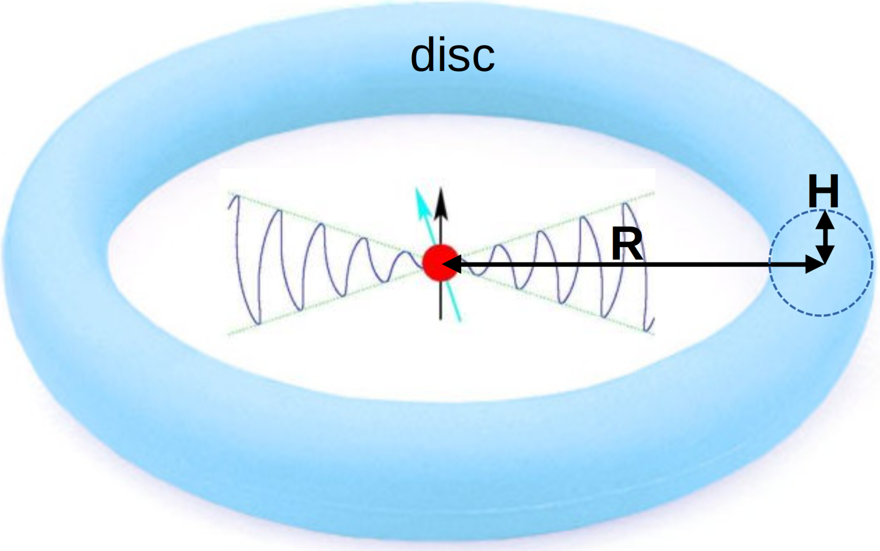
pulsar's spindown power → poynting flux + plasma wind → (magnetic reconnection) particle acceleration → (synchrotron radiation) non-thermal emission

Need of global PIC simulations

3D Particle-in-cell simulations

Grid:

- spherical grid
- number of cells: 1024(r)*128(θ)*256(φ)
- light cylinder radius: $r_{LC}=5\ r_{NS}$
- box size: $r_{max}=5.6r_{LC}$



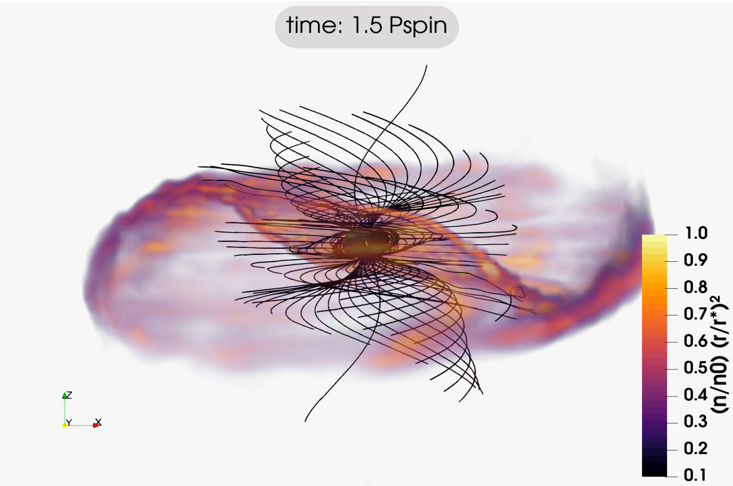
Model:

- central pulsar surrounded by a torus
- no accretion, no disk inflow
- torus: perfectly conducting (and $\mathbf{B}_{in\ torus}$ is neglected), absorbing boundary for particles
- aspect ratio H/R=0.3
- torus inner boundary at 2.5 r_{LC}

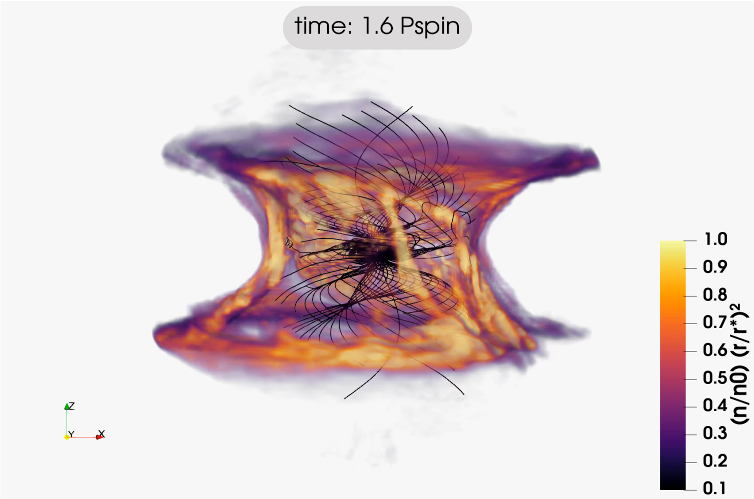
2 different runs for 2 pulsar magnetic obliquities: χ=15° and χ=75°

3D structure of the magnetosphere - χ=15°

isolated pulsar



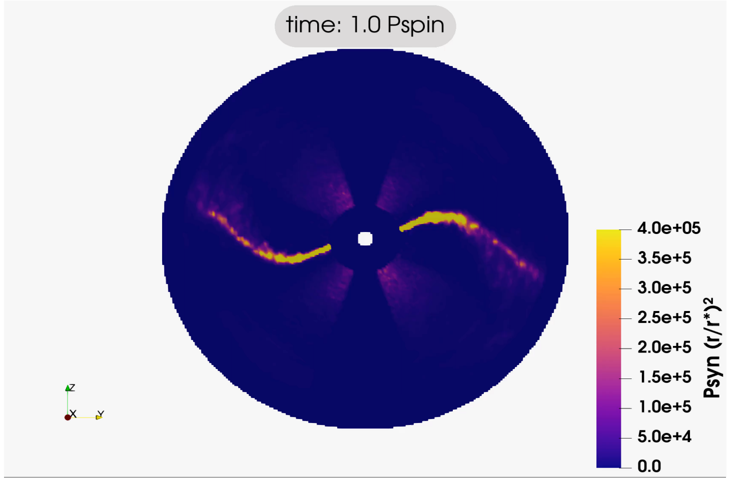
pulsar + disk



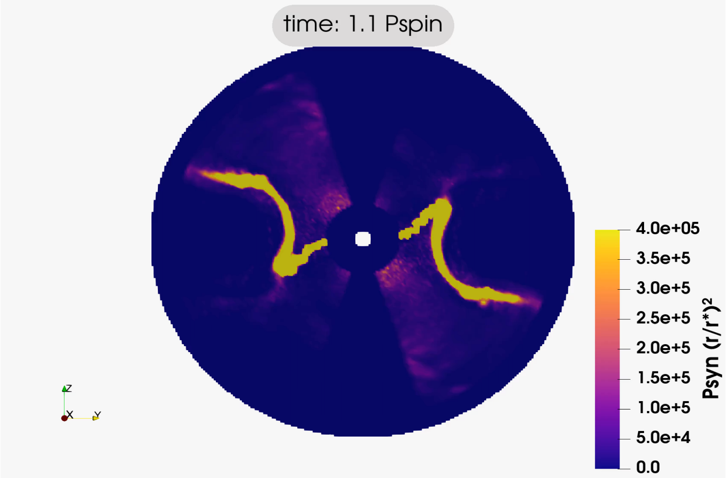
- rearrangement of the magnetosphere around the disk
- plasma from the current sheet is channeled along the disk inner boundary
- isotropization of the plasma

Synchrotron radiation - χ=15°

isolated pulsar



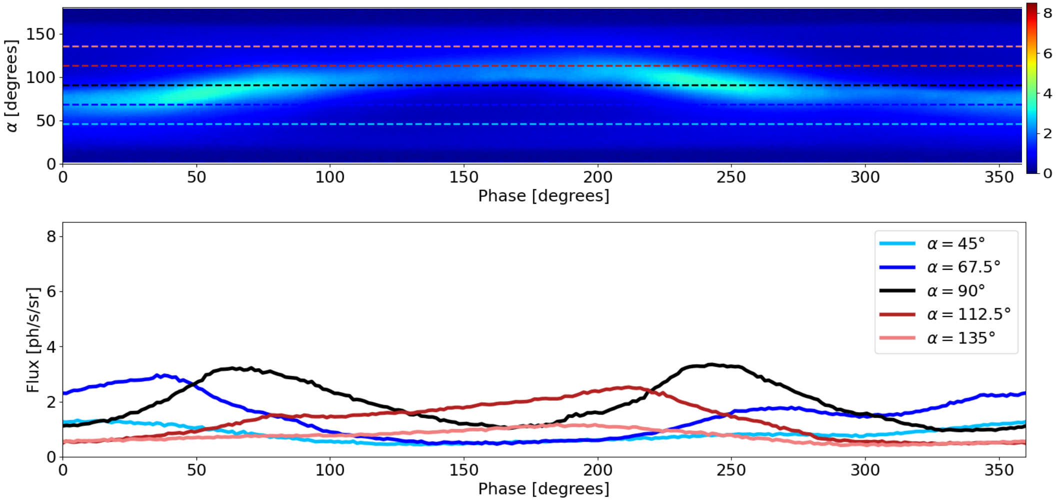
pulsar + disk



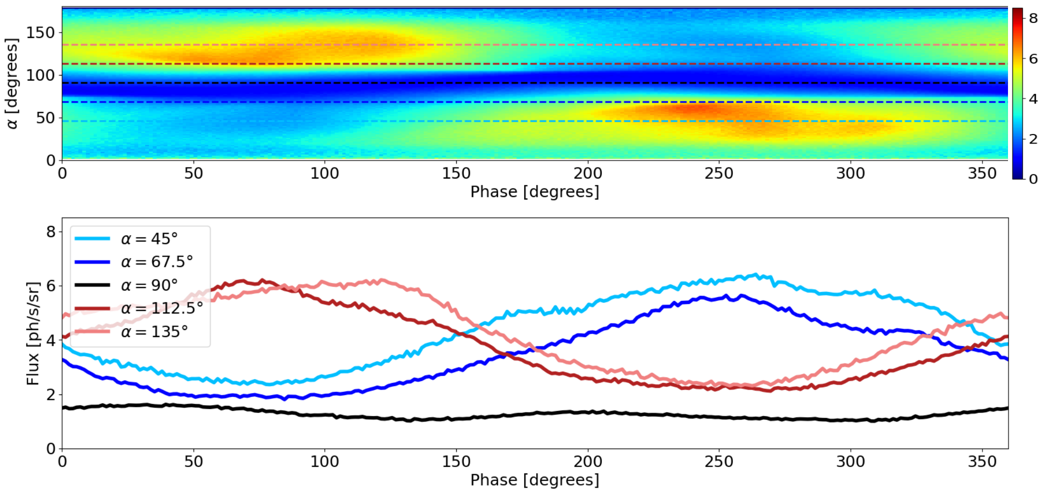
- forced reconnection: the plasma that hits the disk lights up
- significant increase of the synchrotron emission
- concentration of the emission along 2 preferential lines of sight

Lightcurves - χ=15°

isolated pulsar



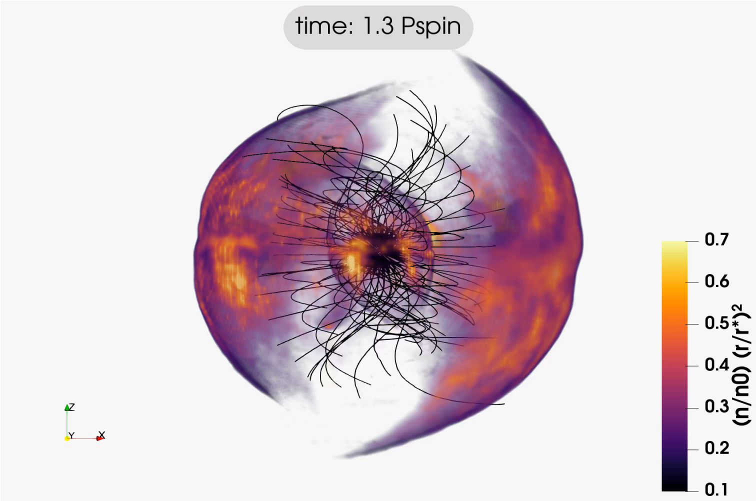
pulsar + disk



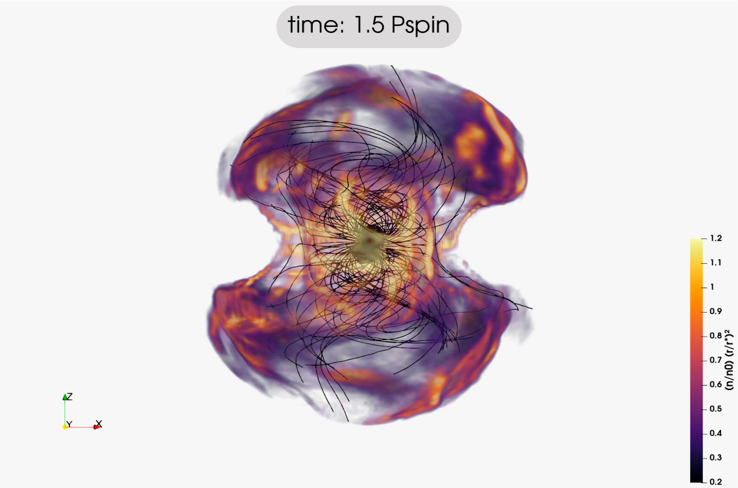
- significant enhancement of the continuum + of the pulsed fraction
- 1 broad pulse per P_{spin}

3D structure of the magnetosphere - χ=75°

isolated pulsar



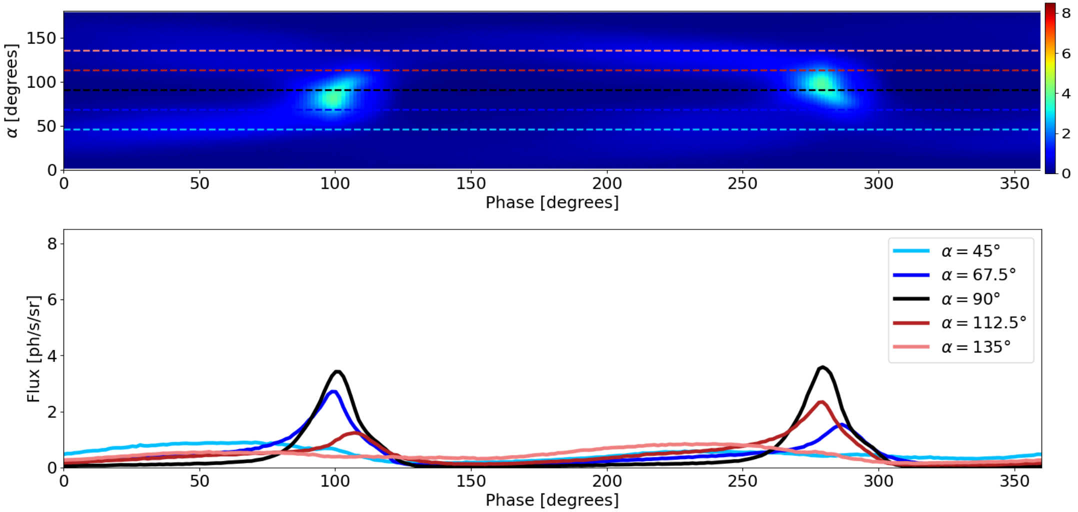
pulsar + disk



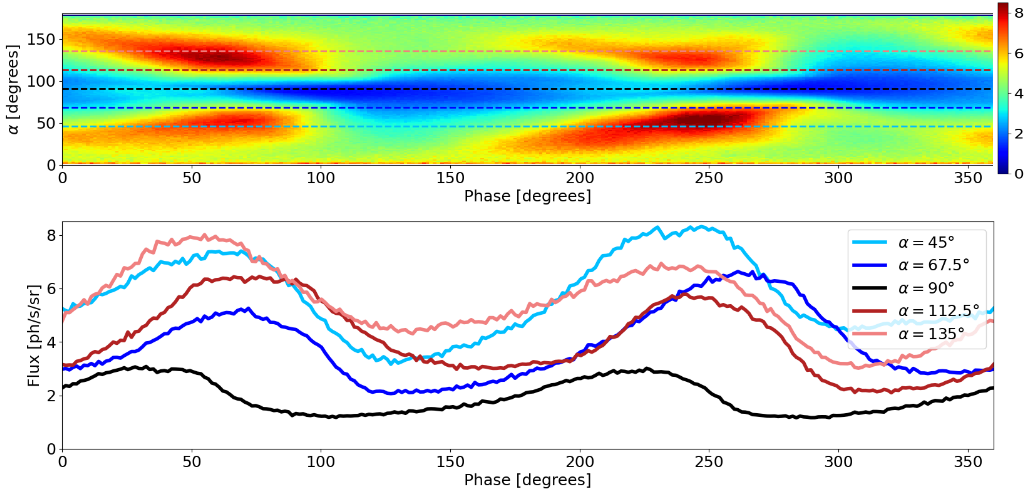
- rearrangement of the magnetosphere around the disk
- deposition of plasma from the current sheet at all latitudes
- isotropization of the plasma

Lightcurves - χ=75°

isolated pulsar



pulsar + disk



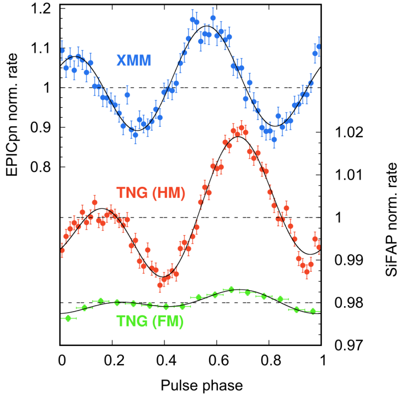
- significant enhancement of the continuum + of the pulsed fraction
- 2 broad pulses per P_{spin}, for any viewing angle
- relative amplitude of the pulses depends on the observers' inclination angle
- observation of J1023: viewing angle ~ 45° (Archibald et al., 2010) → maximum emission

Conclusion

Main results:

- disk → forced reconnection
  - → increase of <γ> and of **B**⊥
  - → significant enhancement of the synchrotron emission (continuum and pulsed fraction)

- lightcurves depend on the pulsar's magnetic obliquity: $\chi < \tan(H/R) \rightarrow$ 1 pic per Pspin
  $\chi > \tan(H/R) \rightarrow$ 2 pics per Pspin



Perspectives:

- probe intermediate magnetic obliquities
- distinguish among energy bands → shift between pulses? different pulsed fractions?
- polarization
- flares for highest magnetic obliquities?
- assess the SSC contribution → Tev emission?