The gamma-ray emission of transitional pulsars

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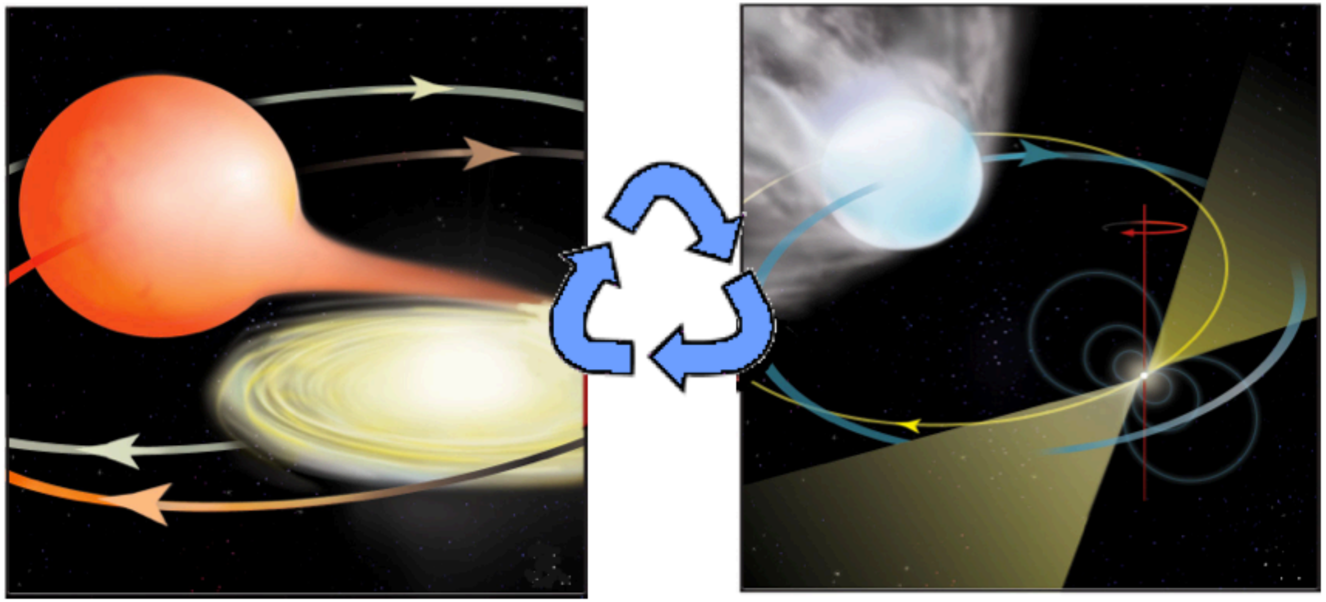
Leading questions

- What powers the emission of the Transitional PSRs?
- How, where, and when are particles accelerated?
- What process(es) yield the highest energy photons?

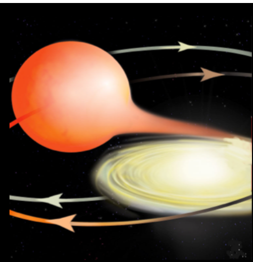
Balance between gravity and field pressure

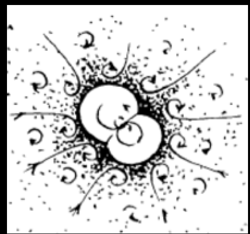


Accretion and rotation power alternate over timescales as short as few weeks

Accretion powered state

Bright X-ray outburst ($\sim 10^{36}$ erg/s)
X-ray pulsations



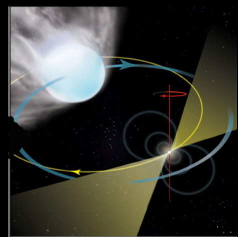


An intermediate (propeller?) state

Sub-luminous accretion ($\sim 10^{34}$ erg/s)
Brighter gamma-ray emission

Rotation powered state

Faint in X-rays ($\sim 10^{32}$ erg/s)
Radio/gamma-ray pulsations



Sub-luminous disk state showed by the transitional PSRs

• **Presence of an accretion disk**, as indicated by Hα broad, sometimes double peaked emission lines observed in the optical spectrum (Wang et al. 2009; Pallanca et al. 2013; Halpern et al. 2013; De Martino et al. 2013)

• **Average X-ray luminosity 10^{33} to 10^{34} erg s^{-1}**, intermediate between the peak of X-ray outbursts (10^{36} erg s^{-1}) and the rotation powered emission ($<10^{32}$ erg s^{-1});

the X-ray emission is variable on timescales of few tens of seconds and has a spectrum described by a power-law with index $\Gamma \simeq 1.5$ and no cut-off below 100 keV (Saitou et al. 2009; De Martino et al. 2010, 2013; Papitto et al. 2013; Linares et al. 2014; Patruno et al. 2014; Tendulkar et al. 2014);

• **Correlated X-ray/UV emission** on timescales of hundreds of seconds (De Martino et al. 2013);

• **0.1-10 GeV luminosity of ≈ 10^{34} erg s^{-1}**, ten times brighter with respect to the level observed during the rotation powered state, and not detected by Fermi/LAT from other accreting NS in low-mass X-ray binaries (De Martino et al. 2010; Hill et al. 2011, Papitto, DFT & Li 2014, Stappers et al. 2014; Takata et al. 2014)

• **No pulsations** in the radio, X-ray and gamma-ray band.

Model build up

$$L_{prop} + L_{disk} + \frac{1}{2}\dot{M}v_{out}^2 = \frac{GM\dot{M}}{R_{in}} + N\Omega_*,$$

Energy conservation

1

The energy available to power the radiative emission from the disk, the propeller (inner disk boundary) and the outflow

=

Gravitational energy liberated by in-fall of matter down to the inner radius, plus the energy release by the magnetosphere through the torque N

2

3

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$$L_{disk} = \xi\frac{GM\dot{M}}{2R_{in}}$$

The disk luminosity assumed as a fraction of the energy emitted by an optically thick, geometrically thin disk. When ξ=1 the disk is radiatively efficient, lower values indicate that part of the disk energy can be advected.

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$$\dot{M}R_{in}v_{out} = N + \dot{M}\Omega_K R_{in}^2$$

Angular momentum conservation at the inner disk boundary

$$\Omega_K = \sqrt{GM/R_{in}^3}$$

Rate of angular momentum in the outflow

=

Torque applied by the magnetic field plus angular momentum carried by disk matter

Model build up

- These equations can be solved to give L_{prop}, once a relation for the velocity of the outflow is assumed.

- Eksi et al. (2005) treated the interaction at the inner disk boundary as a collision of particles, and expressed the outflow velocity as:

$$v_{out} = \Omega_K(R_{in}) R_{in} [1 + (1+\beta)(\omega_* - 1)]$$

$$\omega_* = \frac{\Omega_*}{\Omega_K(R_{in})} = \left(\frac{R_{in}}{R_{co}}\right)^{3/2}$$

Fastness

$R_c = (GM_*/\Omega_*^2)^{1/3}$

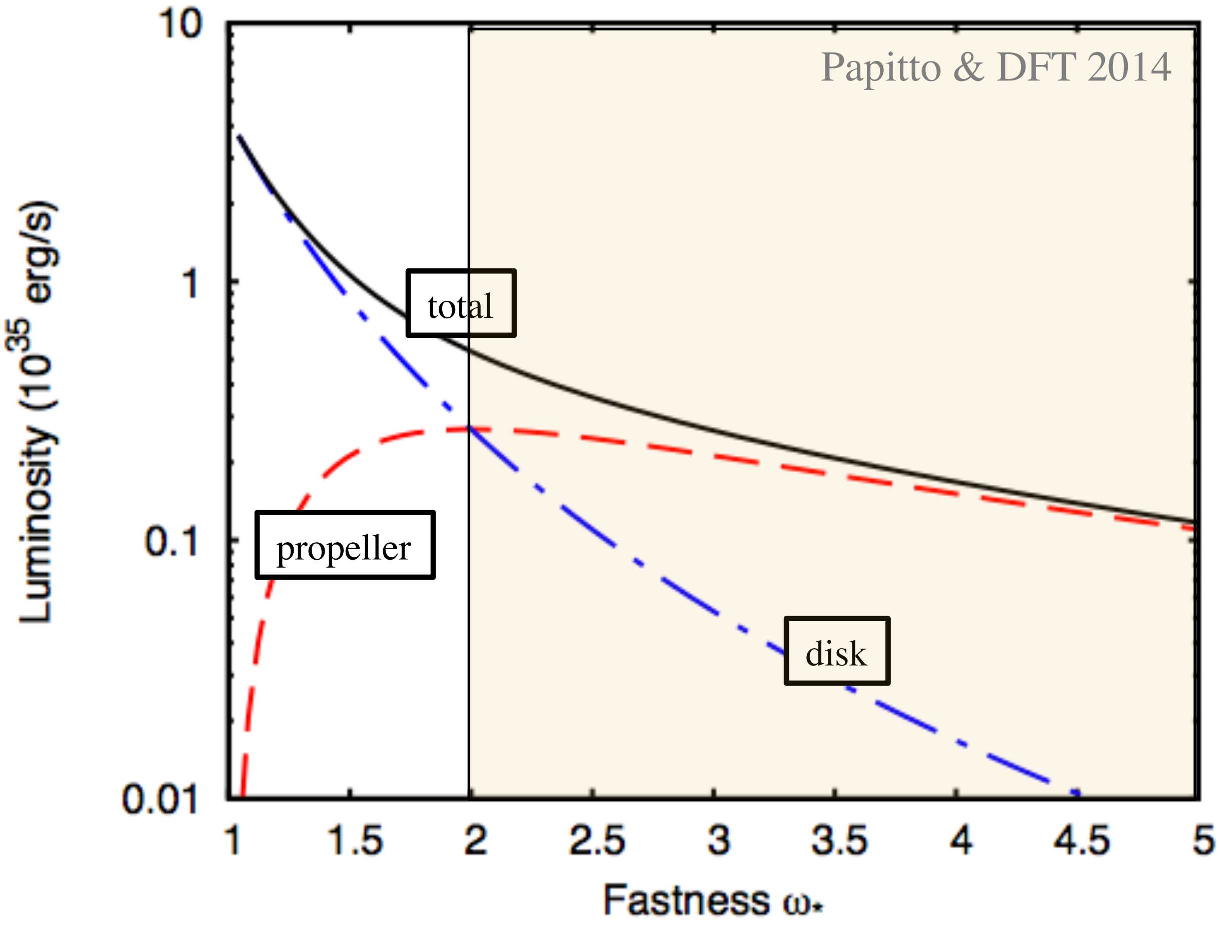
- β is the elasticity parameter. Anelastic collision is given by $\beta = 0$. Elastic case is described by $\beta = 1$.

- The torque is fixed by the one that the magnetosphere exerts on the disk plasma due to the generation of a poloidal component of the B-field thanks to differential rotation

$$N = \left(\frac{\Delta r}{R_{in}}\right) \frac{\mu^2}{R_{in}} \left(1 - \frac{1}{\omega_*}\right)$$

Torque

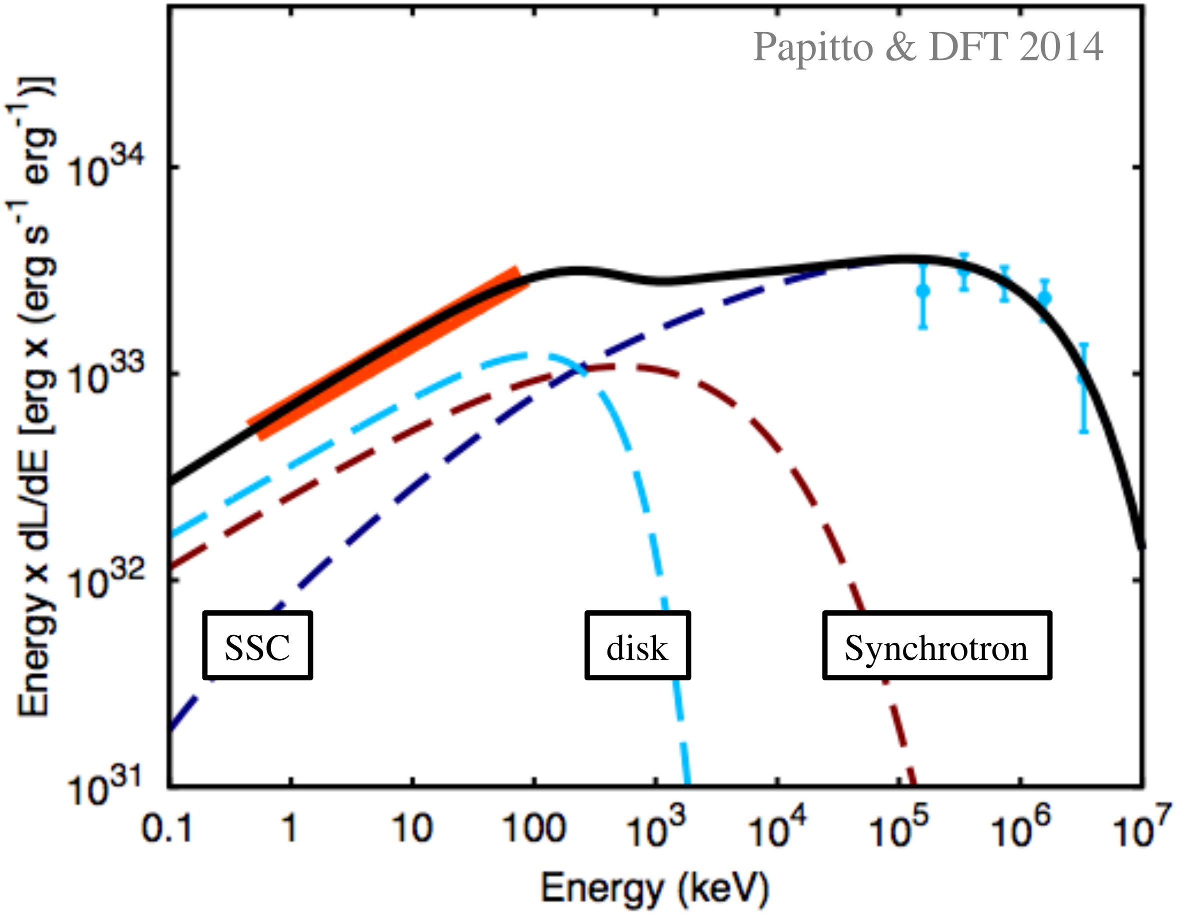
Model in action



Relations evaluated for PSR J1023+0038 ($\mu = 0.79 \times 10^{26}$ G cm^3, $M = 1.4\ M_\odot$, $R_c = 23.8$ km), for the case of an efficiently radiative disk ($\xi = 1$), anelastic collision ($\beta = 0$) at the magnetospheric boundary, and setting the turbulence region size as $\Delta r / R_{in} = 0.5$.

For $\omega_* \geq 2$ the energy liberated by the propelling magnetosphere becomes larger than the disk contribution.

Model results for PSR J1023-0038



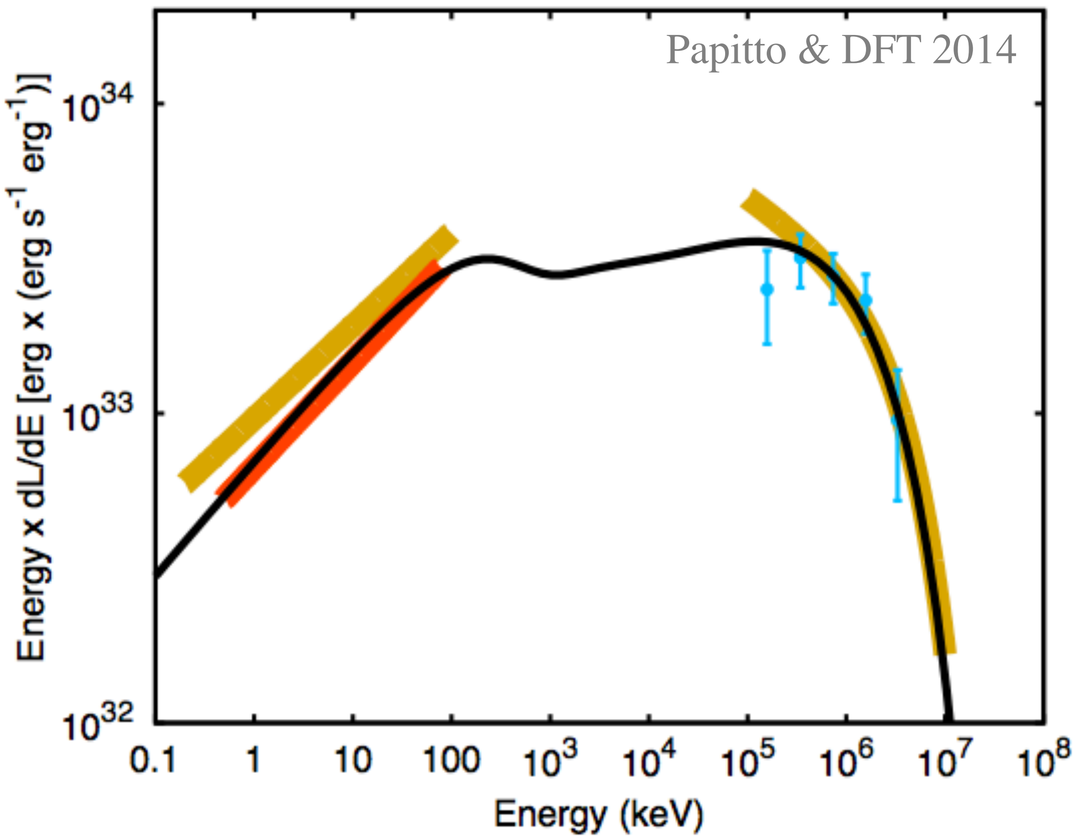
$$\frac{dN_e}{d\gamma} \propto \gamma^{-\alpha} \exp\left(-\frac{\gamma}{\gamma_{max}}\right)$$

$$\bar{B} = \frac{\mu}{R_{in}^3} = \frac{\mu}{R_c^3 \omega_*^2}$$

Gamma-ray emission dominated by self-synchrotron Compton.

- The parameters of the electron distribution (α, γ_{max}, n_e) and the volume V of the region of acceleration are adjusted to model the gamma-ray emission, for a fixed ω_*.
- The contribution of the disk emission in the X-ray band is modelled as a power-law cut-off at an energy outside the energy band (we chose 300 keV).

PSR J1023-0038 model compared with XSS J12270-4859 data



For XSS J12270-4859 we assume a distance of 1.4 kpc.

Its spin period is ~1.7ms, but its period derivative is unknown.

The data similarities suggest that we can also expect a similar magnetic field, and that essentially the same model is a good fit.

Alternatives to propellering? I.: Accreting scenario

If the observed average X-ray luminosity L_X is ascribed to accretion, the implied mass accretion rate:

$$\dot{M}_{accr} = \frac{\epsilon L_X R}{GM} = 6.2 \times 10^{-13} \times$$
$$\epsilon^{-1} \frac{L_X}{7.3 \times 10^{33}\,\mathrm{erg\,s^{-1}}} R_{10}\, m_{1.4}^{-1} \mathrm{M_{\odot}\,yr^{-1}}$$

But then, for a mass inflow rate of the order of 10^{-12} solar yr^{-1}, the inner disk radius ~80 km.

Such value clearly violates the criterion for accretion to proceed ($R_{in} < R_c = 24$ km), making the accretion scenario highly unlikely.

Simultaneous observation of a bright gamma-ray emission would be unexplained by the accretion scenario, considering that the transitonal pulsars PSR J1023+0038 and XSS J12270-4859 are the only LMXB from which a significant emission could be detected by Fermi/LAT, among a population of > 200 known accreting LMXB.

Alternatives to propellering? II.: binary à la LS 5039?

Is a rotation-powered pulsar active even in the presence of an accretion disk, with the radio coherent pulsation being washed out by the enshrouding of the system by intra-binary material? (Stappers et al. 2014, Takata et al. 2014)

Particle acceleration could happen in the shock between the pulsar wind of particles and the mass in-flow (Stappers et al. 2014)

Or directly from interactions of relativistic electrons in the pulsar wind disk photons, with gamma-emission being inverse Compton produced (Takata et al. 2014)

The brightness of PSR J1023+0038 observed in X-rays and gamma-rays requires a spin-down power conversion efficiency of ~40%, much larger than the values observed from rotation-powered pulsars, which typically convert 0.1% (X-rays, Vink et al. 2011) and 10% (gamma-rays, Abdo et al. 2013) of their spin down power.

The SED most likely peaks at 1-10 MeV, i.e. if we believe that the X-rays and gamma-rays in the SED are to be modelled by smooth components, a total luminosity equal to ~1.4 L_{sd} is required.

Flickering in X-rays at hundred-s timescales happens already at 40% spin-down. Unless fully anti-correlated with gamma-rays, flaring happens beyond this limit.

Variability in X-rays?

Propeller models caveats

- Impossibility of observationally separating contributions just at the X-ray domain, partially limiting model predictability/testing.

- This gives a larger phase space of plausible parameters for the disk component, which can accommodate several different elasticities, radiative efficiencies, etc. (This is good and bad depending how you look)

- Best testeable model predictions happen in a range of energies with no sensitive coverage, or at timescales for which Fermi-LAT is not enough sensitive to track them

- Swings of mass accretion by a factor of ~3-4 around average can account for X-ray variability, although the largest mass accretion can formally yield to accretion radius lower than co-rotation. Is there partial accretion at the peak of the flares?

- (Note that this model predicts no detectable TeV counterparts)

...plus general open questions, as a conclusion

What drives variations of the mass in-flow rate?
Tidal interactions? Mass accumulation?

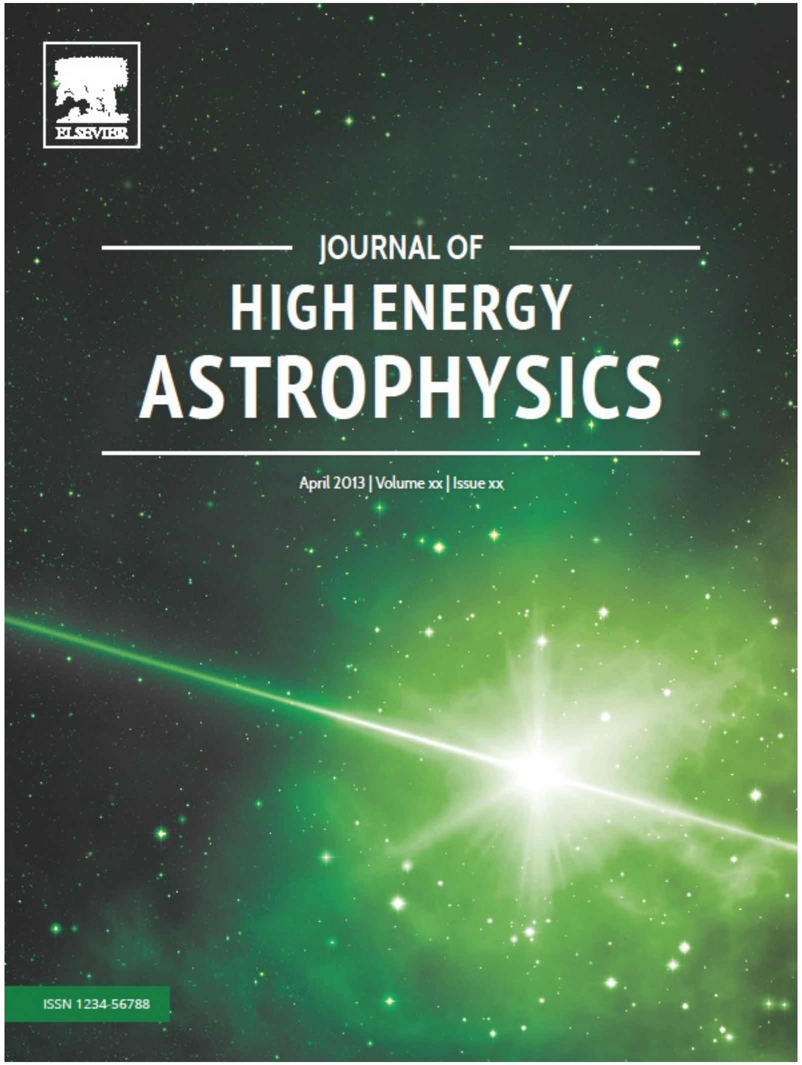
How efficient is the propeller?

Outflows during accretion powered stage
(radio/X-ray correlations)?

Are all millisecond pulsars in close binary systems transitional? Where are the others?
(see Papitto, DFT, Rea, Tauris 2014)

Talk based on:
Papitto, DFT, Li 2014 in MNRAS
Papitto, DFT 2014, in preparation

Announcement of a new journal



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