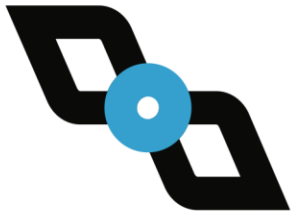
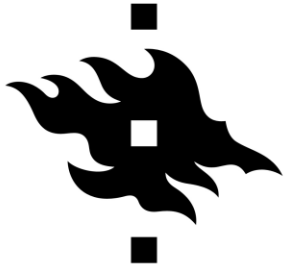


Centre of Excellence neutronstars.fi

Suomen Akatemia
Finlands Akademi
Research Council of Finland

Pair Discharges in Millisecond-Pulsar and White-Dwarf Magnetospheres



UNIVERSITY OF HELSINKI

Tuomo Salmi, University of Helsinki

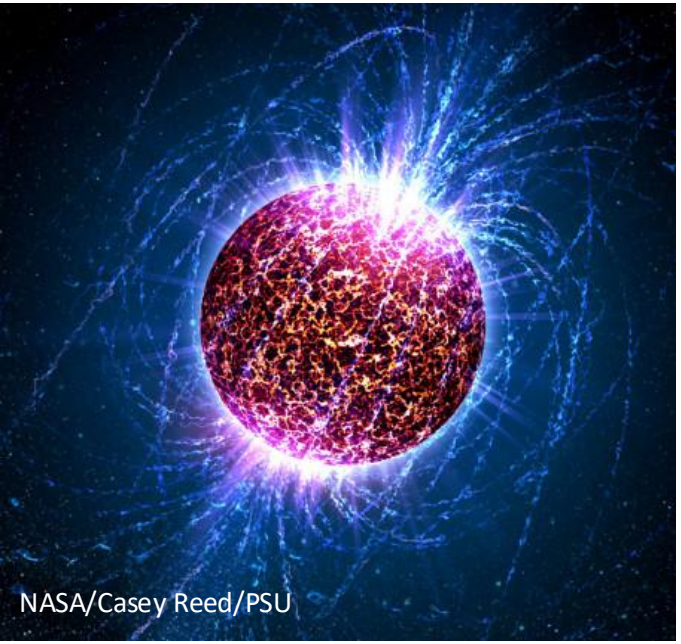
tuomo.salmi@helsinki.fi

In collaboration with: Joonas Nättilä

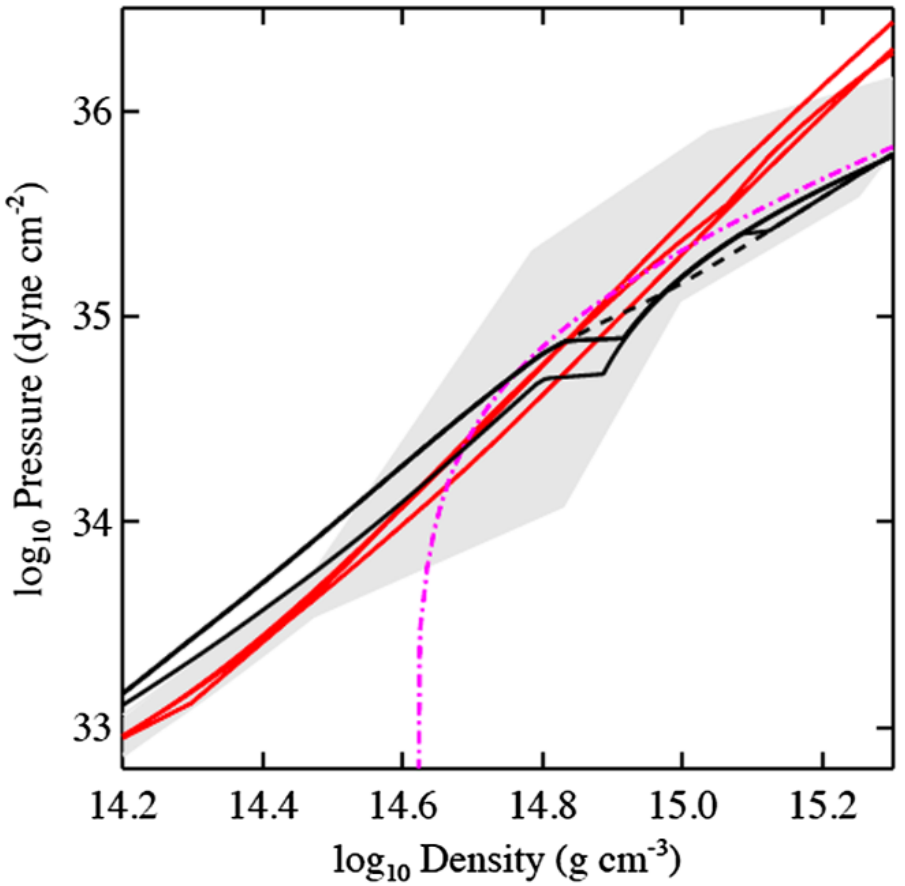
European Research Council

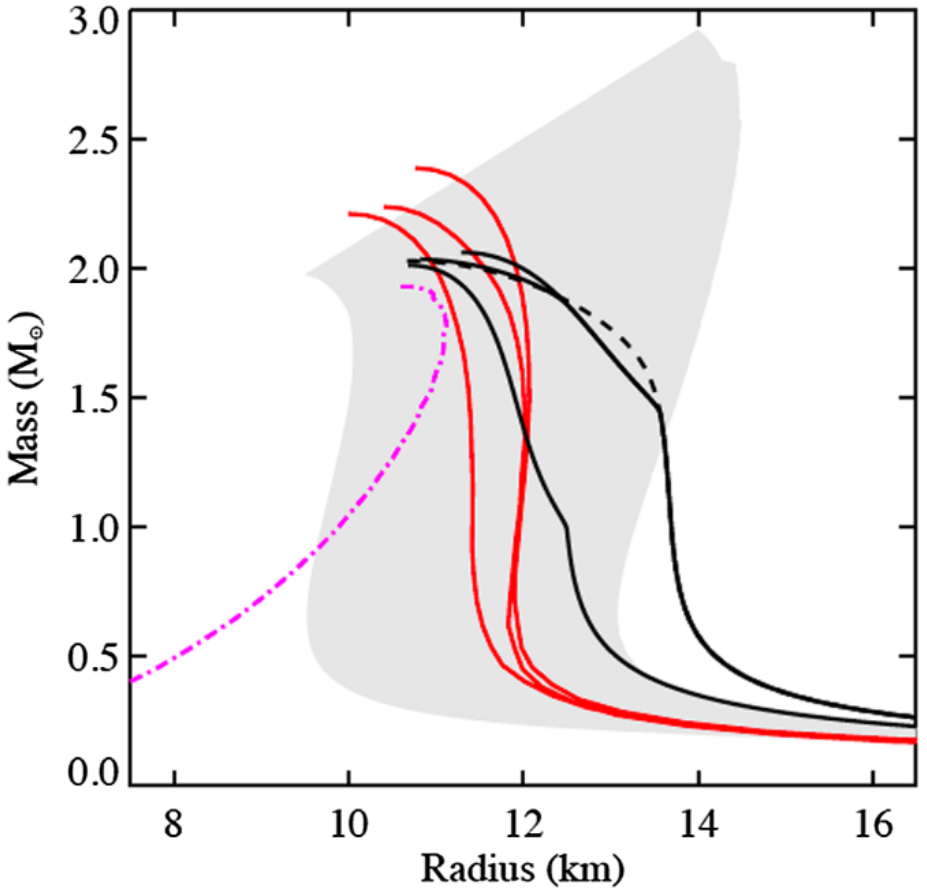
Established by the European Commission

Motivation: Neutron star Equation of State (EOS)



Core:
Nucleonic, quark, hyperonic, hybrid?

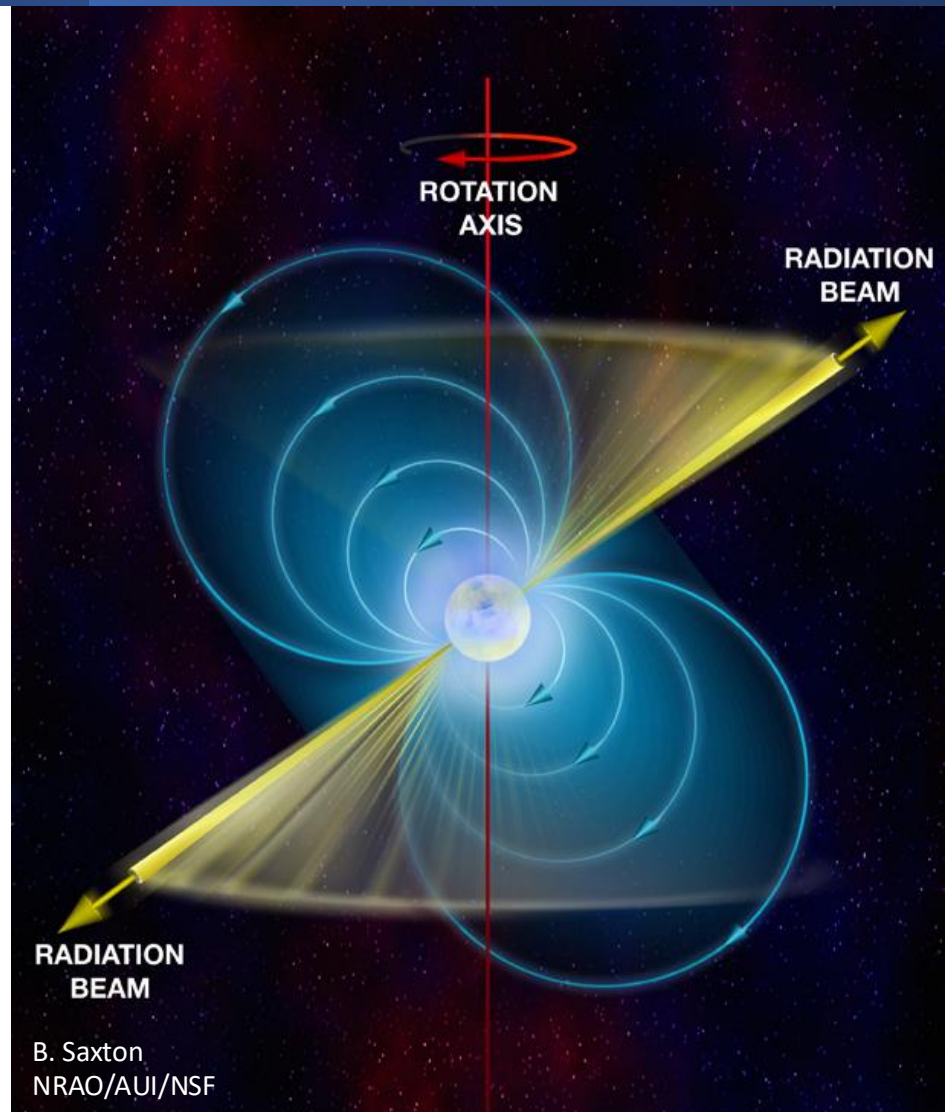




Watts et al. 2016, Rev. Mod. Phys.

Rotation-powered millisecond pulsars (RMPs)

- Primary targets for NICER.
- Mass and radius from X-ray pulse profile modeling.
- Return-current heated polar caps
- Recycled pulsar with no accretion



Recent NICER results

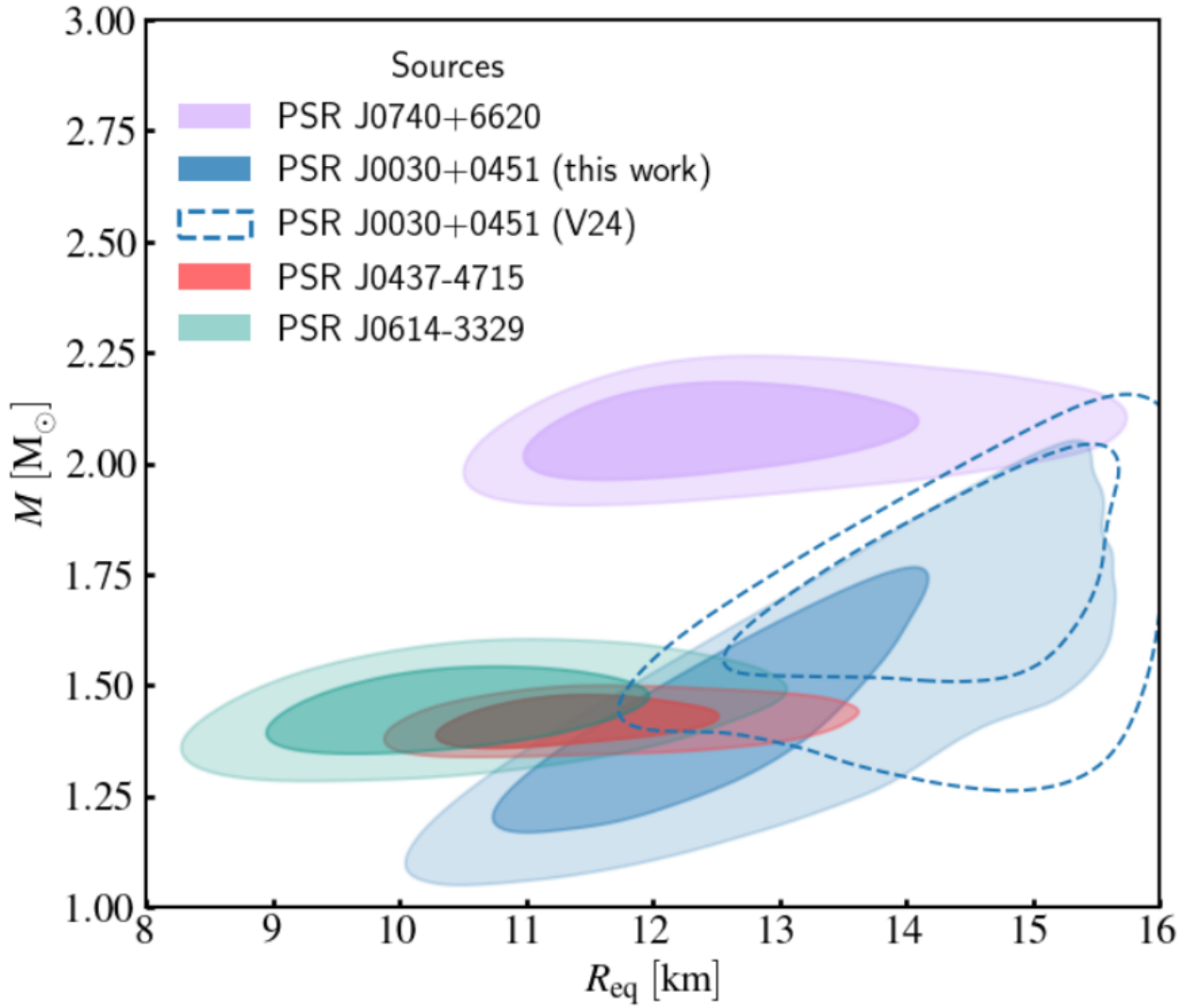
J0030:
Vinciguerra (+Salmi) et al. 2024
Kini (+Salmi) et al. 2026, in press

J0740:
Salmi et al. 2024a

J0437:
Choudhury (+Salmi) et al. 2024

J0614:
Mauviard (+Salmi) et al. 2025

J1231 (not shown):
Low-mass, radius uncertain
Salmi et al. 2024b

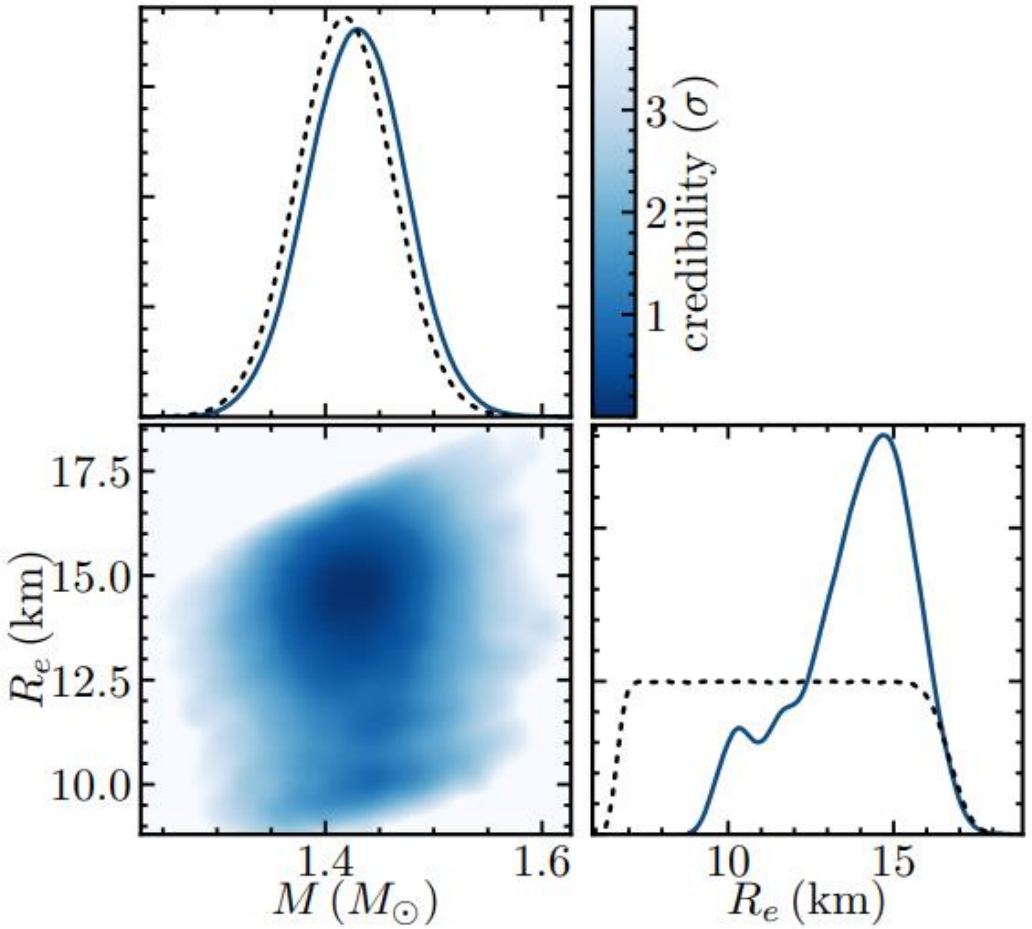


NICER results: J0437

Miller et al. 2026:

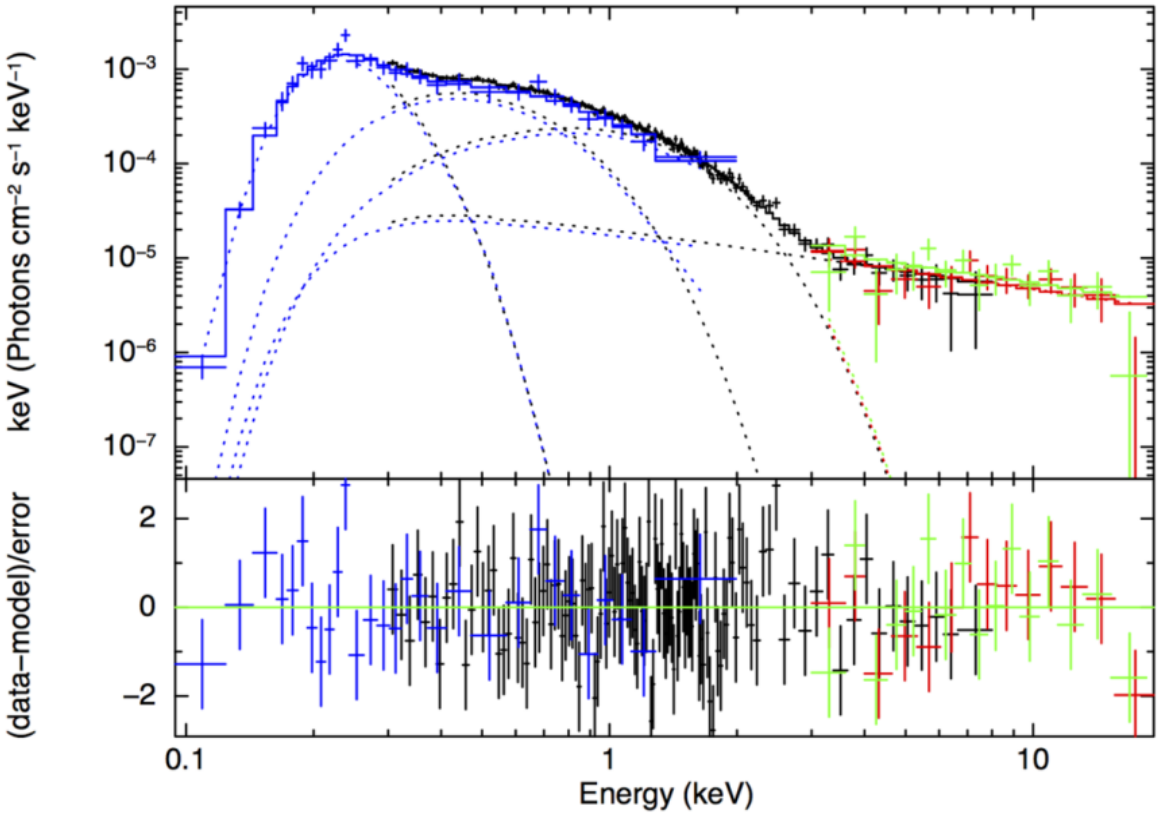
Empirical pulsating power-law model for non-thermal X-rays:

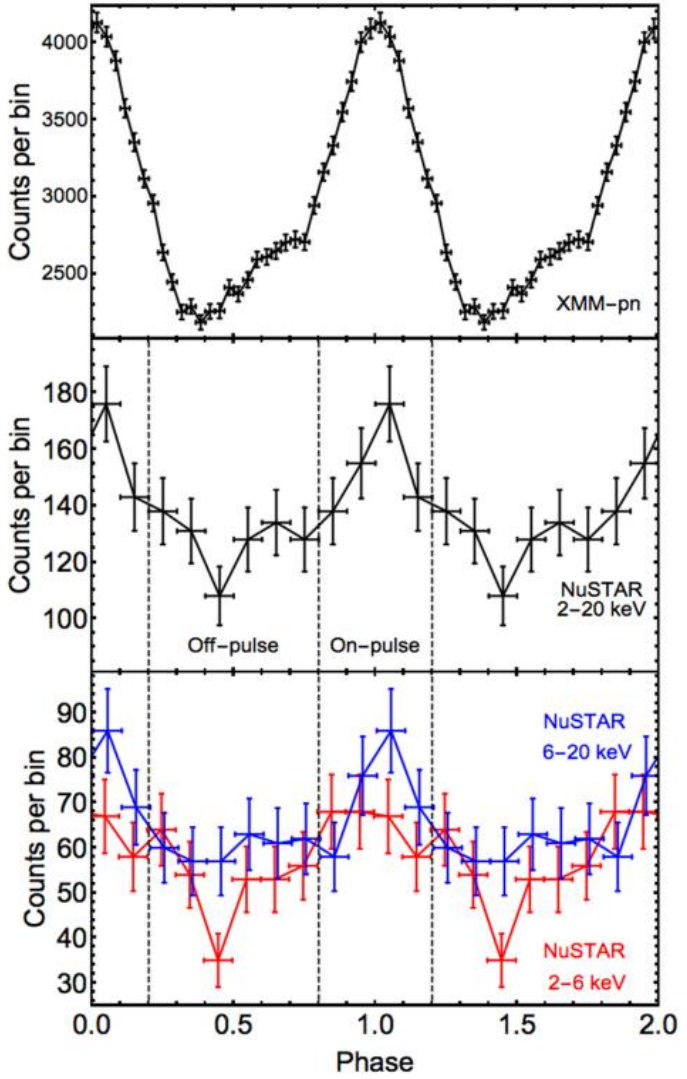
Very broad 68% credible interval:
11.9–15.5 km



J0437: non-thermal pulses

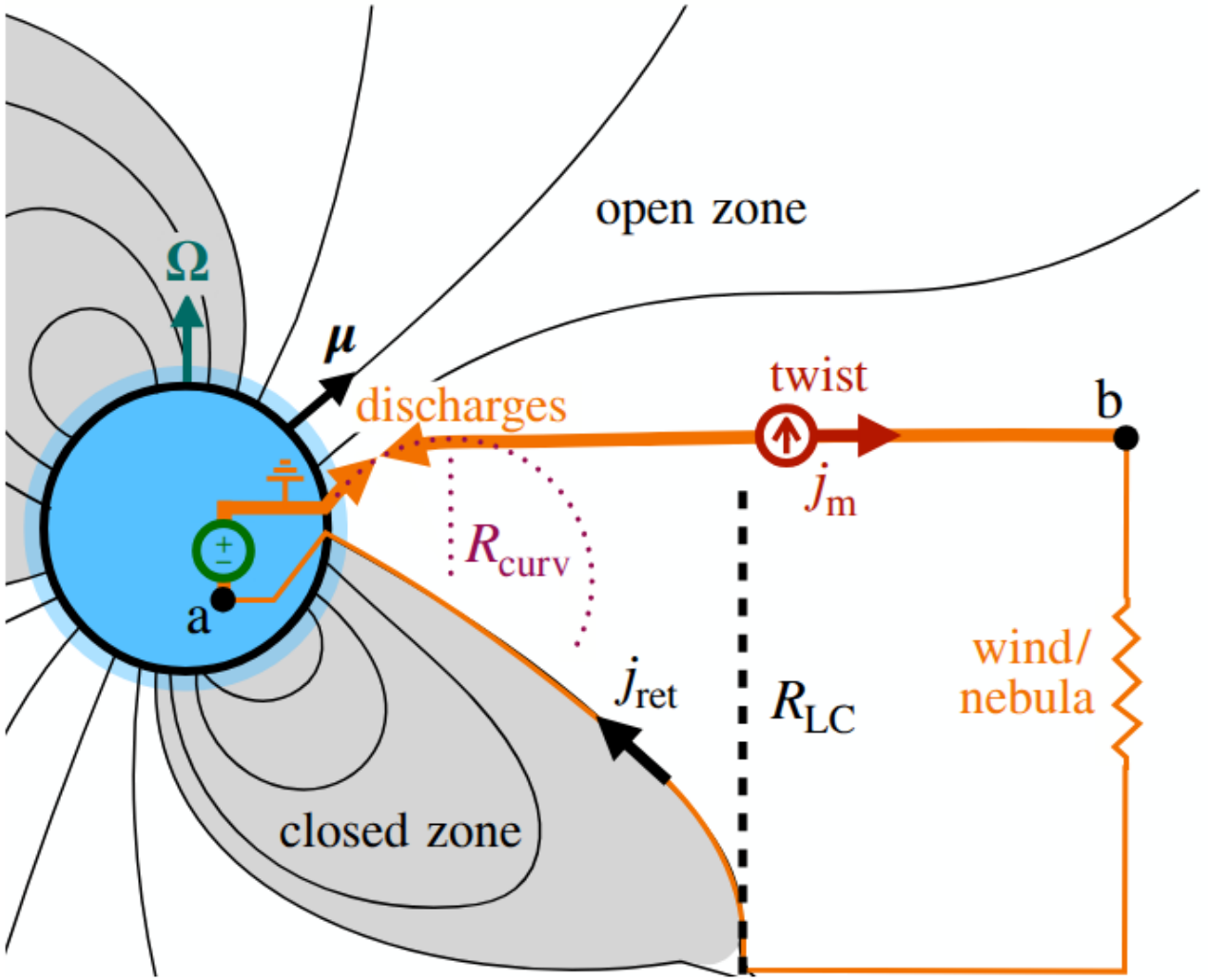
- First observed from NuStar data (Guillot et al. 2016).
- Origin unknown: From magnetosphere/atmosphere?





What happens in the magnetosphere?

- Pair discharges (cascades) occur above pulsar polar caps.



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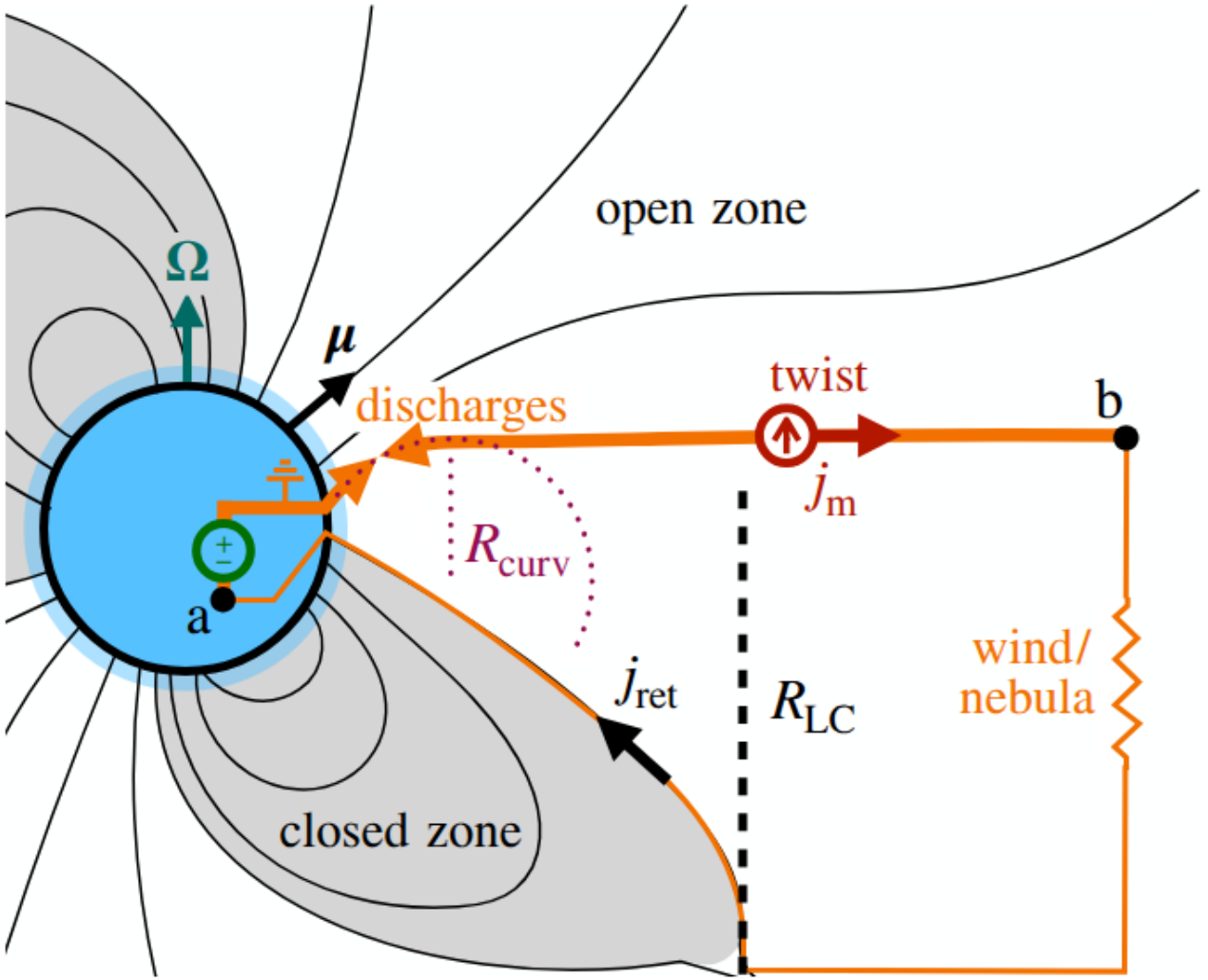

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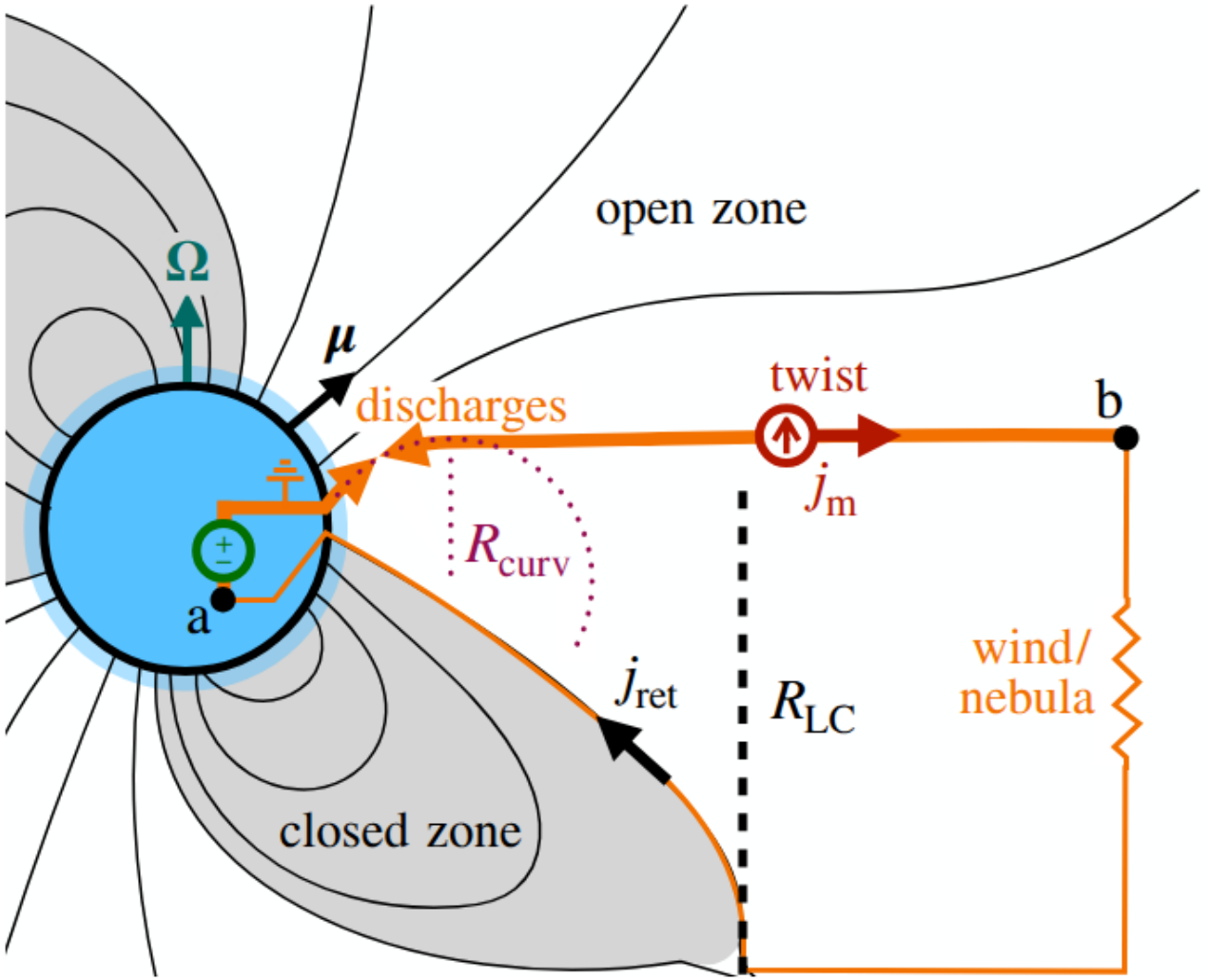
- Oscillating electric field -> observed radio waves (Philippov et al. 2020, Cruz et al. 2021).



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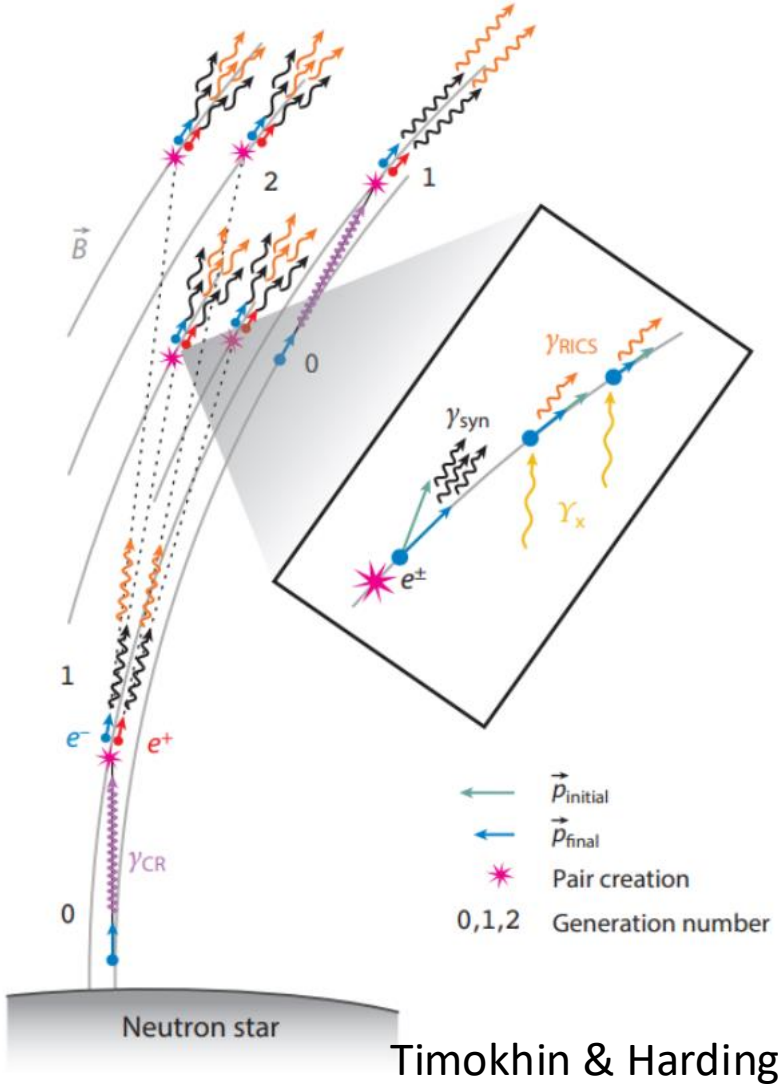
- Standard picture: An accelerated particle emits a curvature photon, which will 1-photon pair create.



Timokhin & Harding 2019

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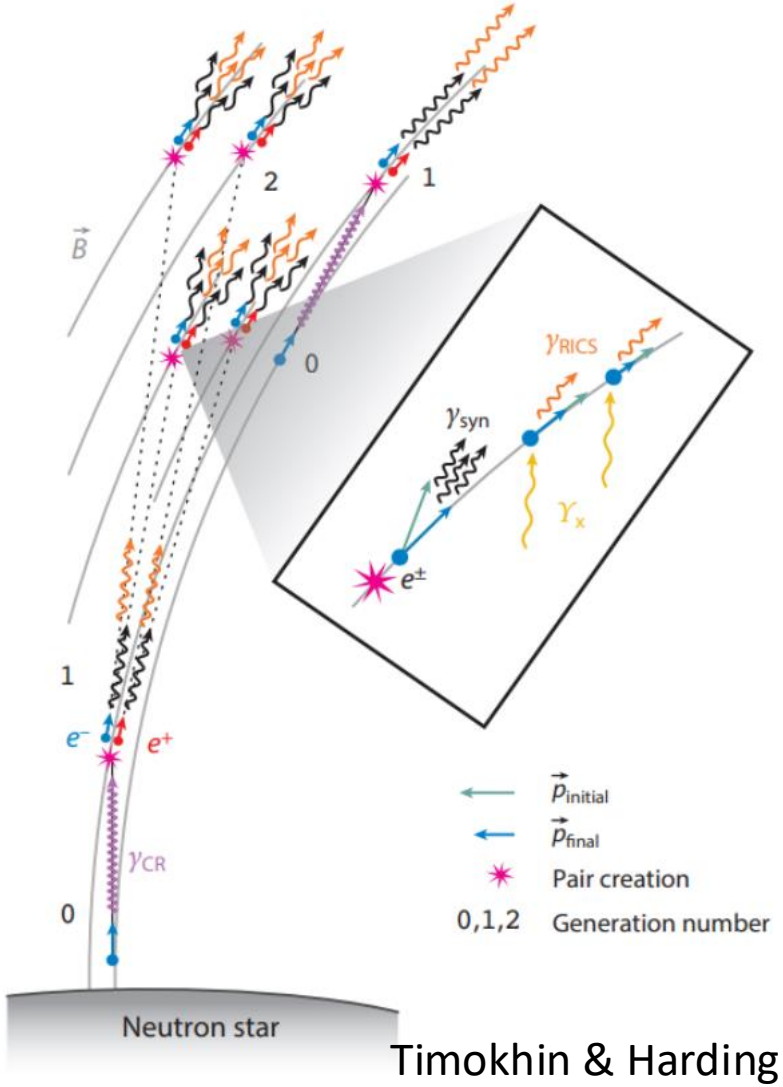

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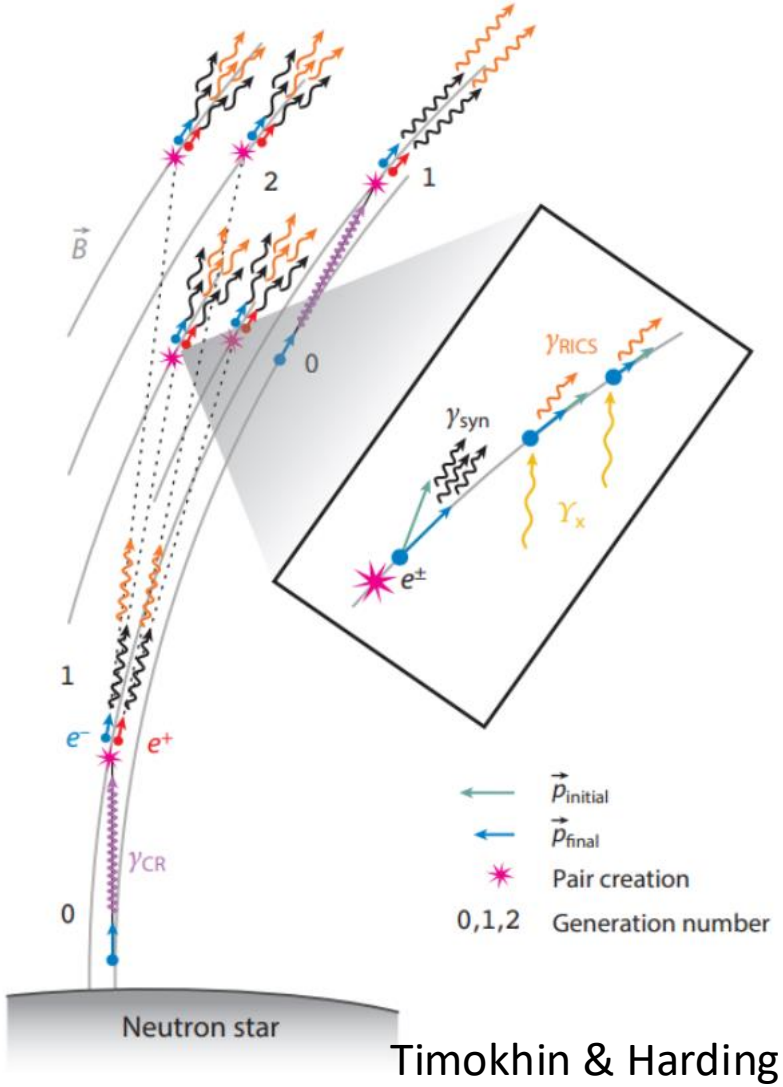

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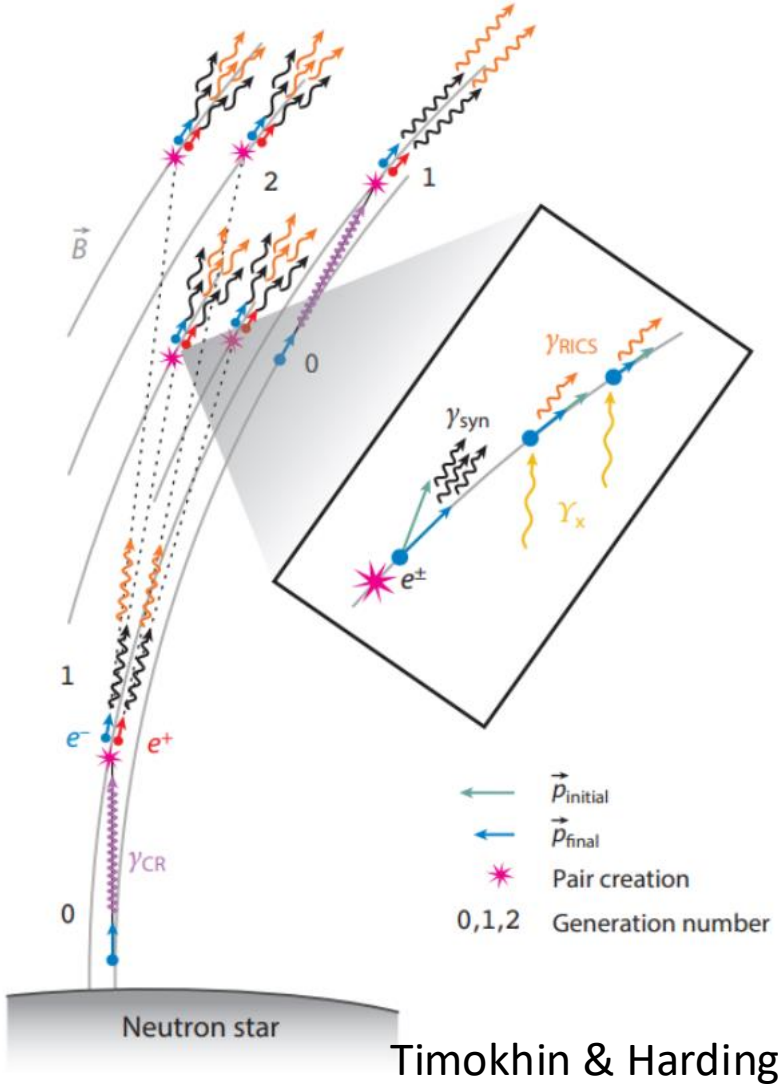

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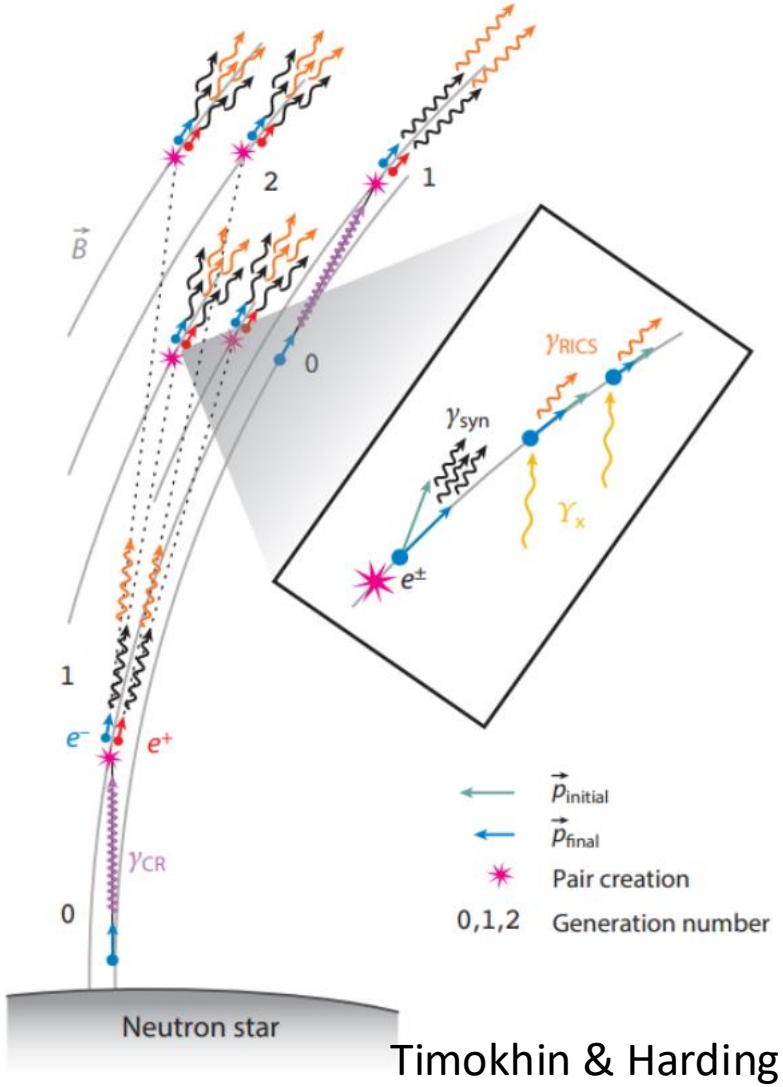
- New pairs screen the E-field -> Acceleration stops -> Particles escape -> E-field grows again.
- **Problem:** RMP magnetic field (B ~ 10^8 G) too low!
- **Alternative**: Inverse Compton scattering of thermal surface photons to higher energies.



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What happens in the magnetosphere?

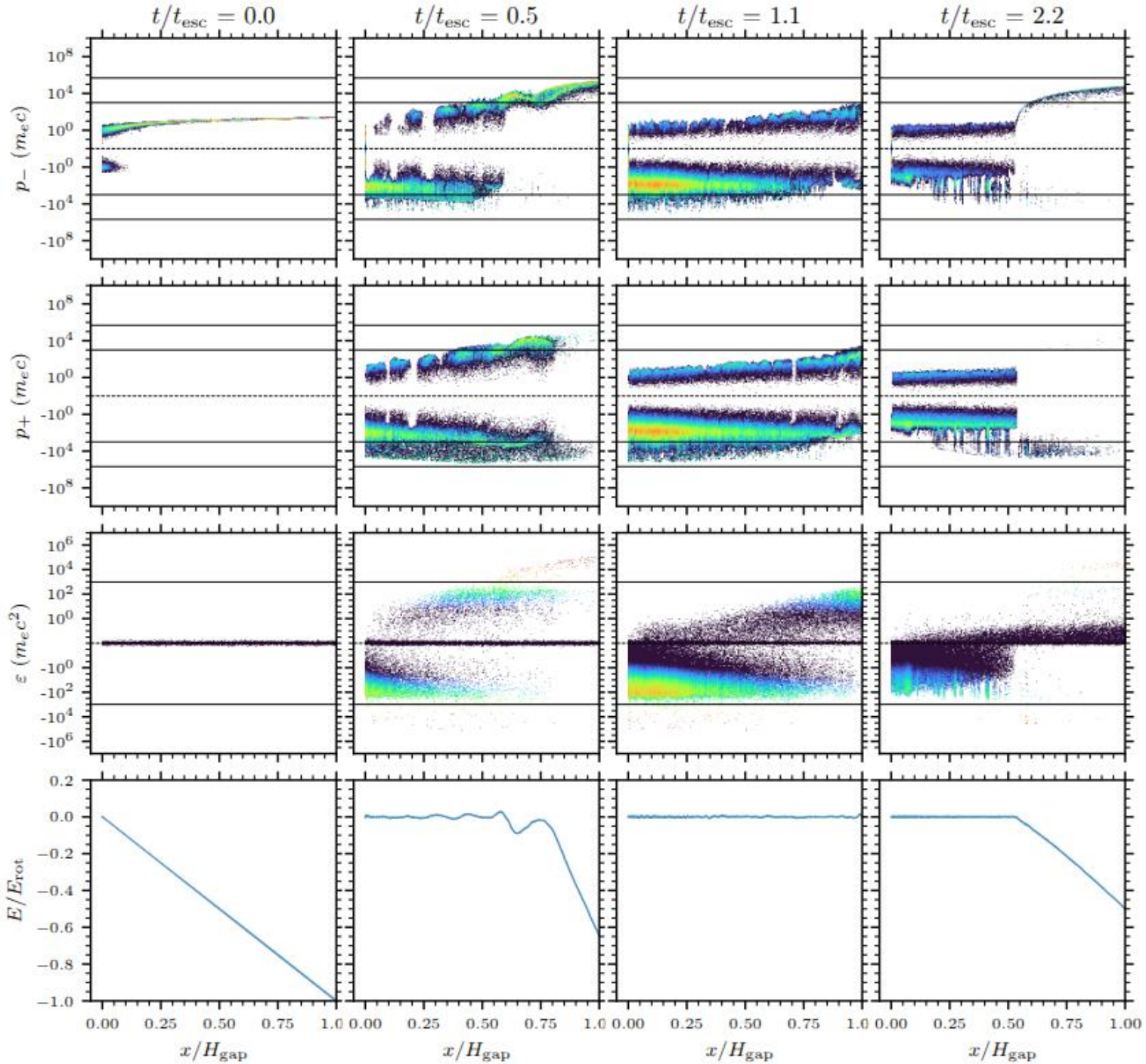
- **Salmi & Nättilä, in prep.**:
  - Particle-in-cell simulations using Runko code.
  - Compton scattering followed by either **2-photon** or **1-photon** pair creation.

$$\gamma + \gamma \rightarrow e^+ + e^- \qquad \gamma + B \rightarrow e^+ + e^-$$

What happens in the magnetosphere?

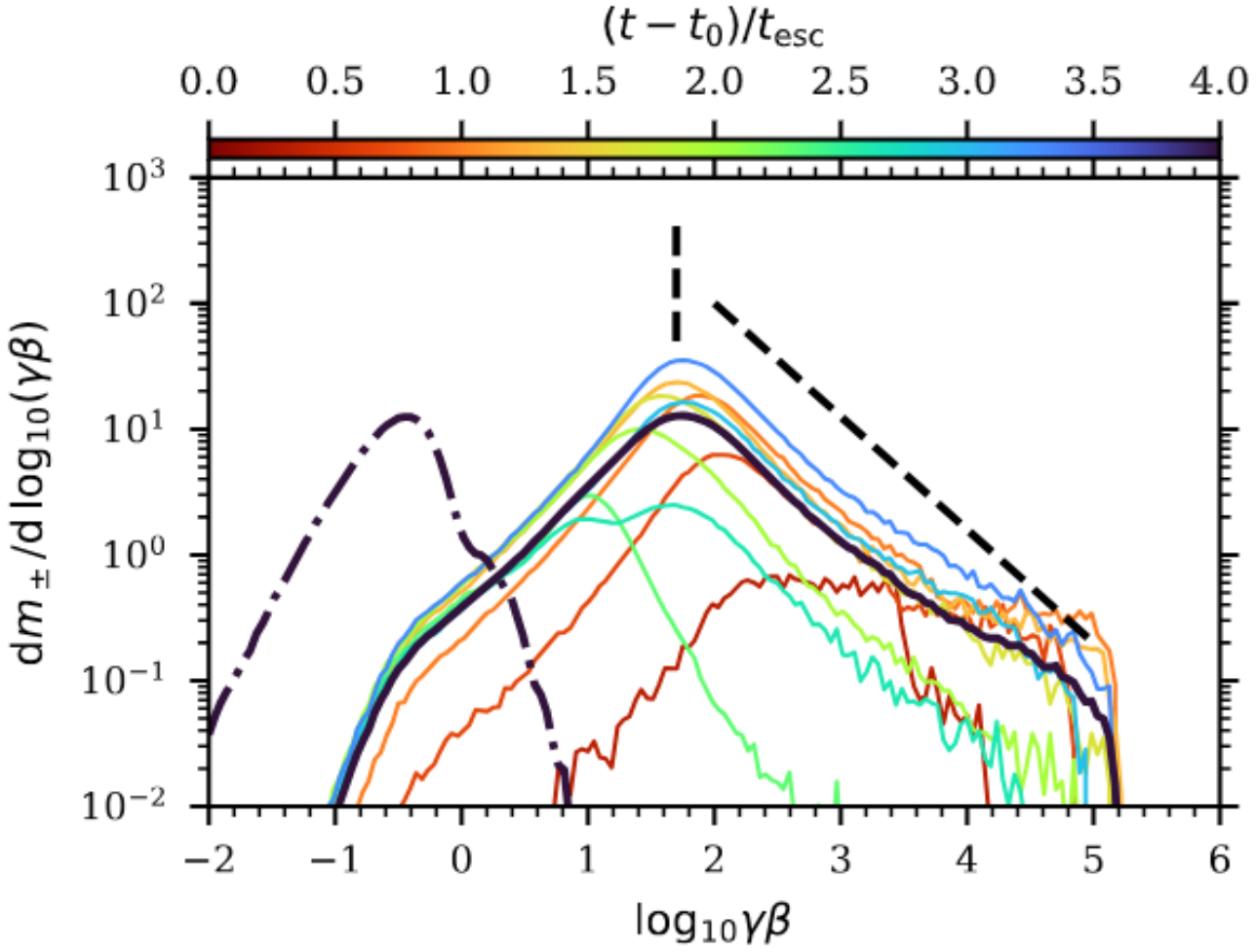
- **Salmi & Nättilä, in prep.**:
  - Particle-in-cell simulations using Runko code.
  - Compton scattering followed by either **2-photon** or **1-photon** pair creation.
  - Results: Intermittent pair cascades form in both cases.
  - 2-photon channel may also explain long-period radio transients (LPTs), likely white dwarfs.

$$\gamma + \gamma \rightarrow e^+ + e^- \qquad \gamma + B \rightarrow e^+ + e^-$$


$t/t_{\rm esc} = 0.0$
$t/t_{\rm esc} = 0.5$
$t/t_{\rm esc} = 1.1$
$t/t_{\rm esc} = 2.2$
p_- $(m_e c)$
p_+ $(m_e c)$
ε $(m_e c^2)$
$E/E_{\rm rot}$
$x/H_{\rm gap}$

Return-current spectra for the 2-photon case

- Return-current particles have rather "low" energies (Lorentz factors of ~100).
- Particles may overheat outer atmospheric layers (**Salmi et al. 2020**): Better models for NICER with non-thermal X-ray pulses.
- However, energies higher for the 1-photon case.



Conclusions and Discussion

PIC simulations show pair cascades are possible for low-B systems and may explain:

- The origin of non-thermal emission in RMPs.
- The origin of radio emission in RMPs and LPTs.

Next steps for Magnetosphere PIC simulations:

- From 1D to multi-D.
- Include all QED processes simultaneously.
- Obtain more robust emission models -> Improved EOS constraints.