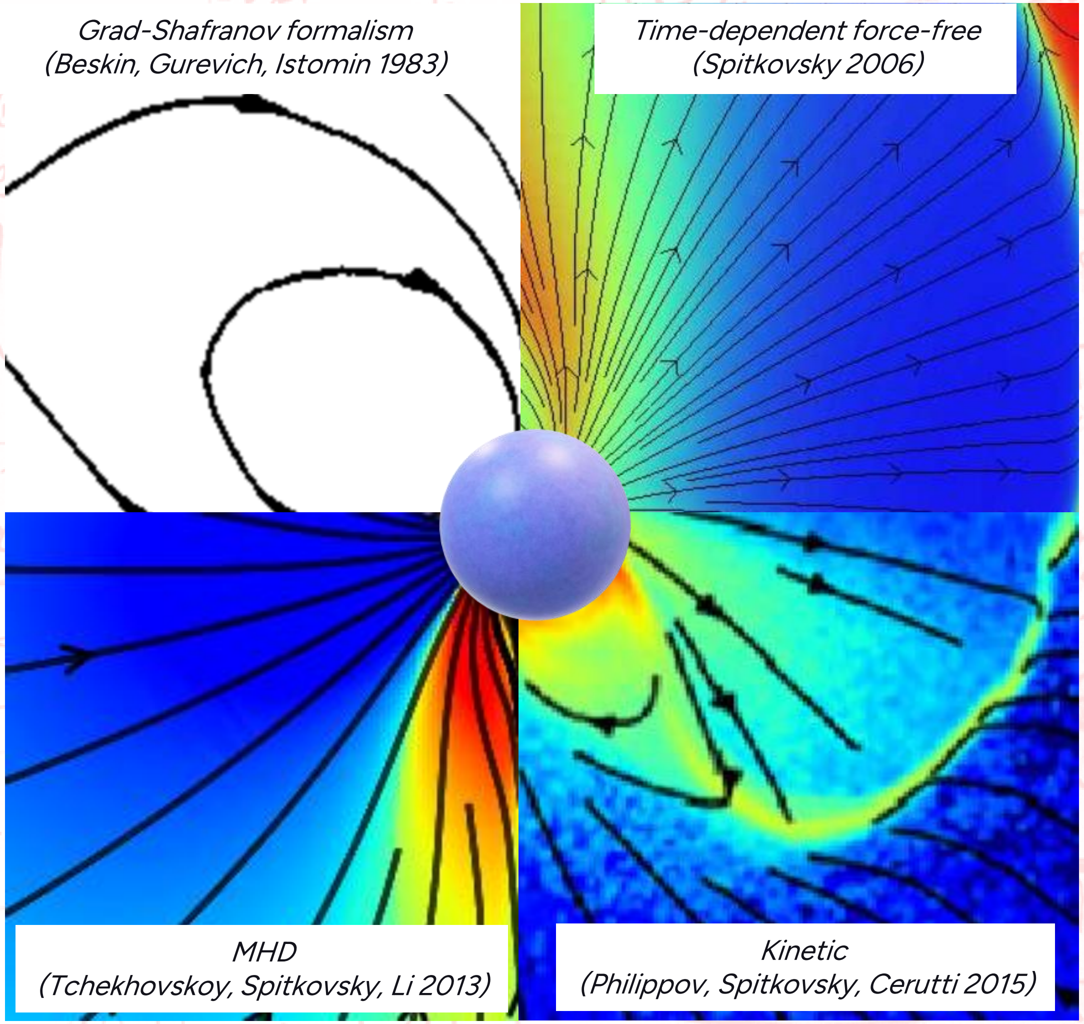
Pulsar

magnetospheres

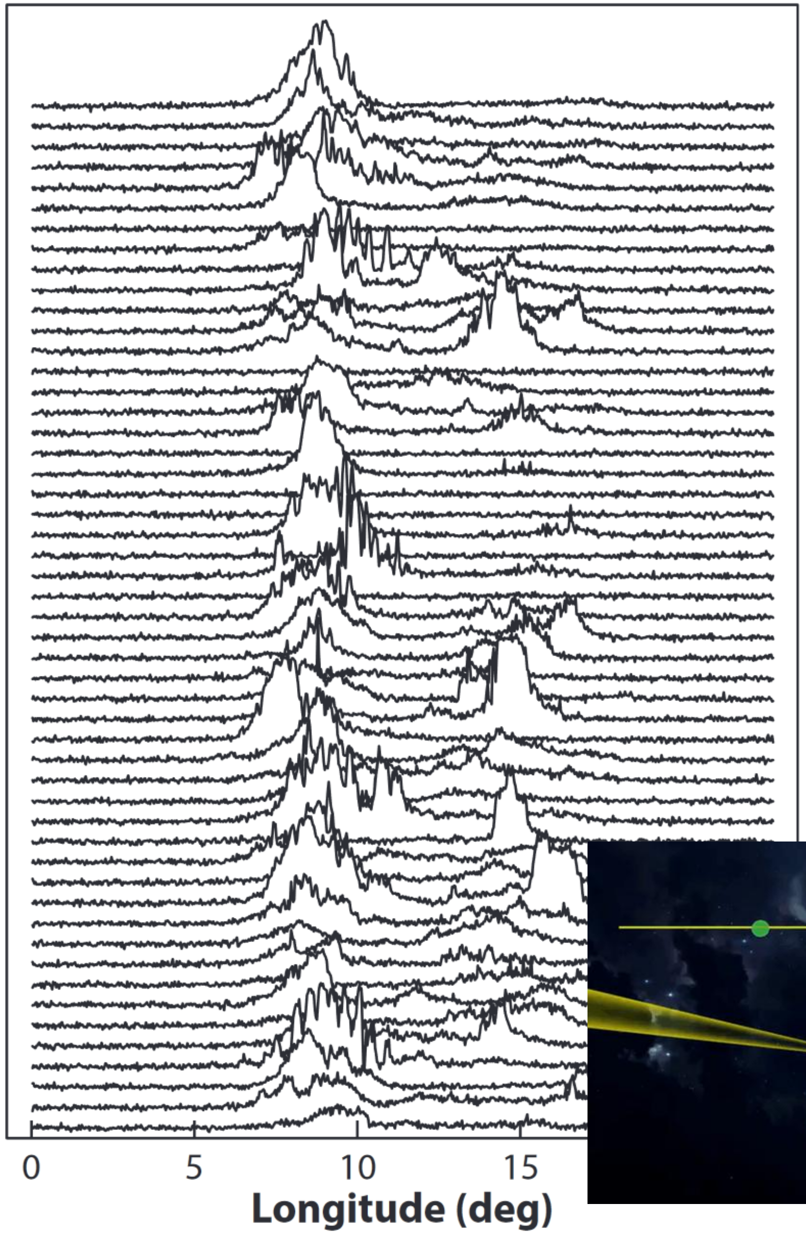
A computational perspective

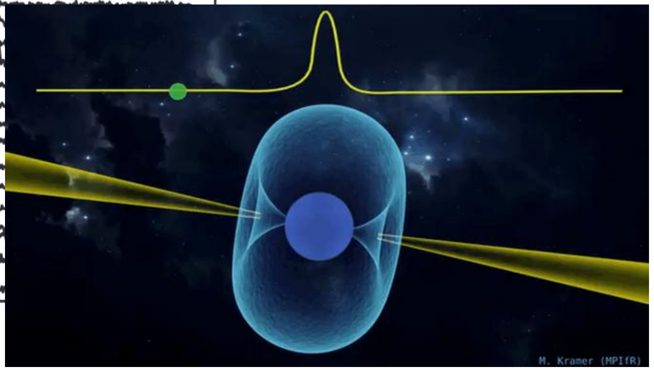
Hayk Hakobyan (Columbia)

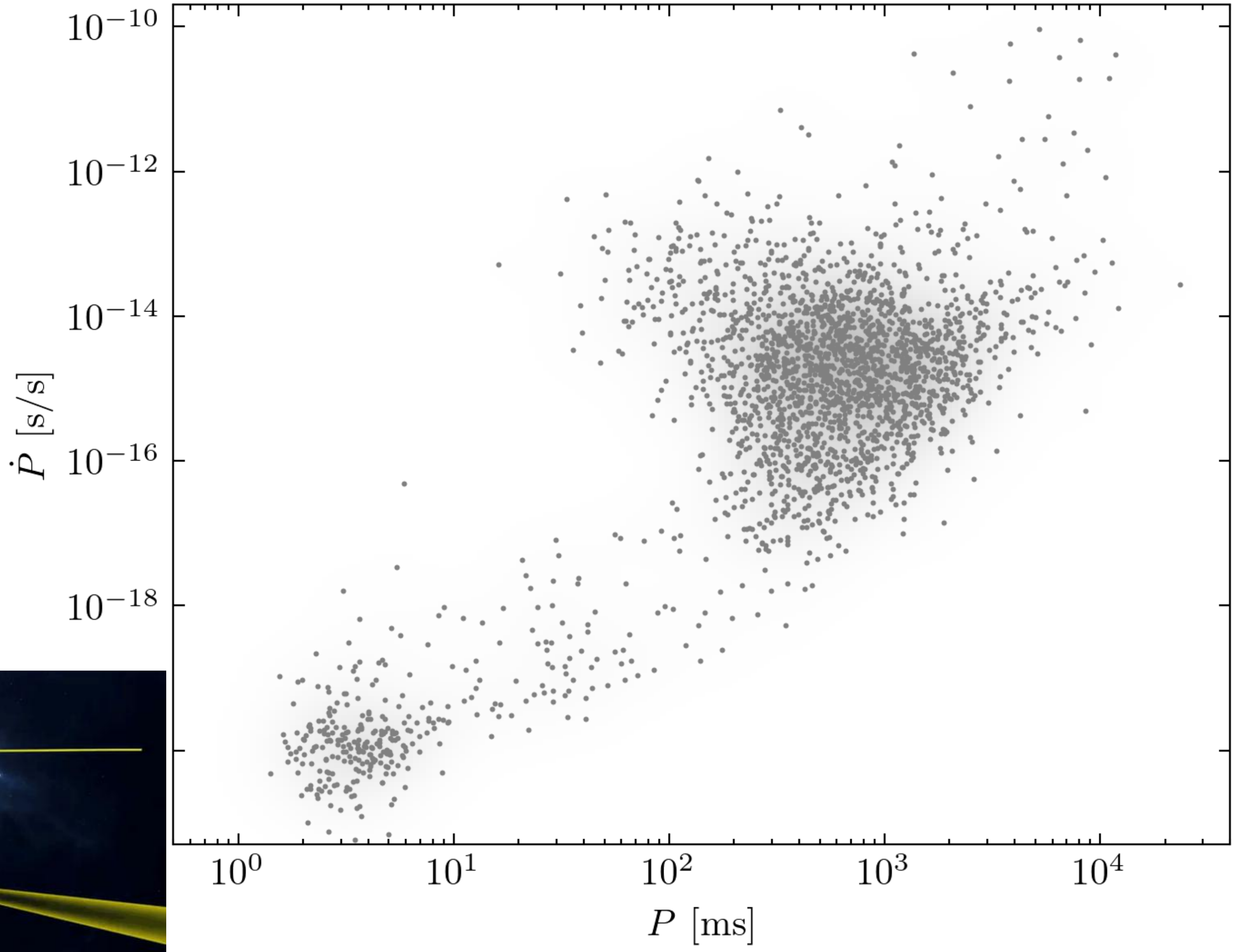
with
Sasha Philippov (UMD)
Sasha Chernoglazov (IAS)
Anatoly Spitkovsky (Princeton)



Pulsars: a complex puzzle with simple premise



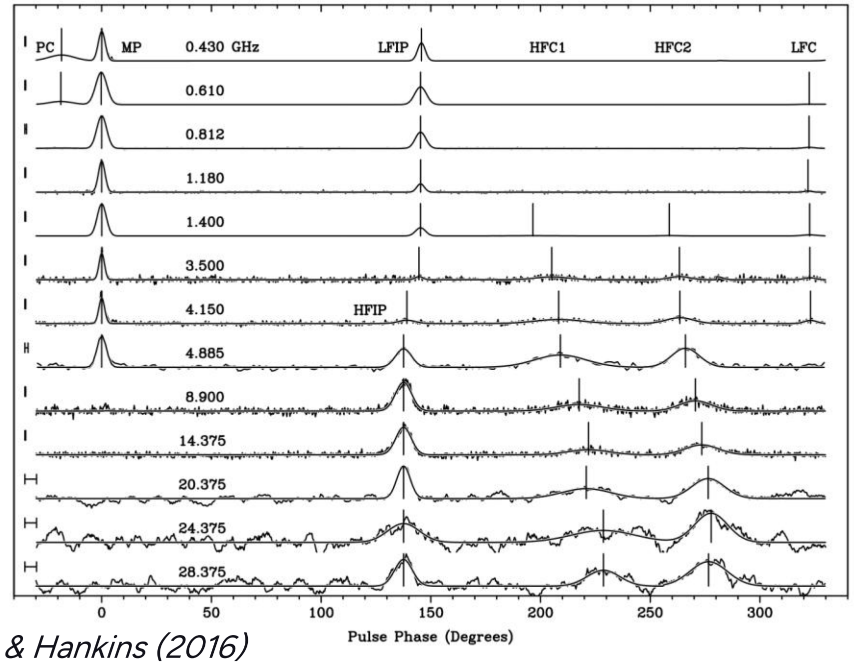




Philippov & Kramer (2022)

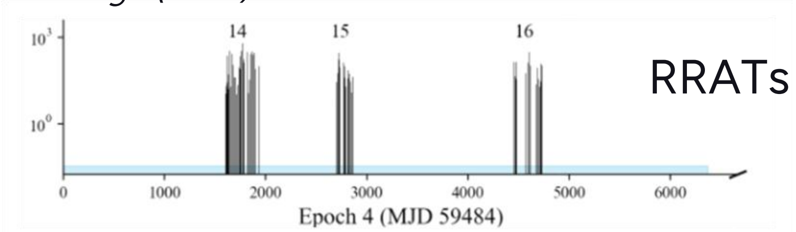
Pulsars: a complex puzzle with simple premise

Complex radio-lightcurve of the Crab

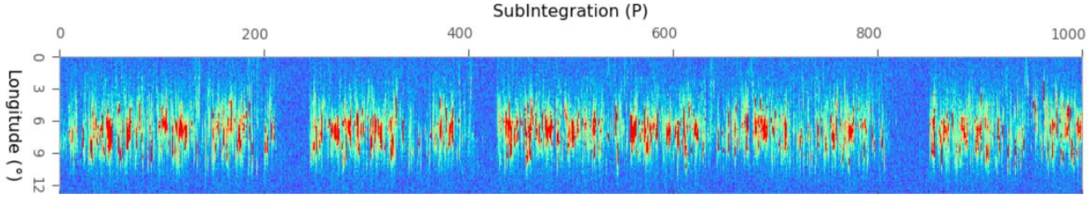


Eilek & Hankins (2016)

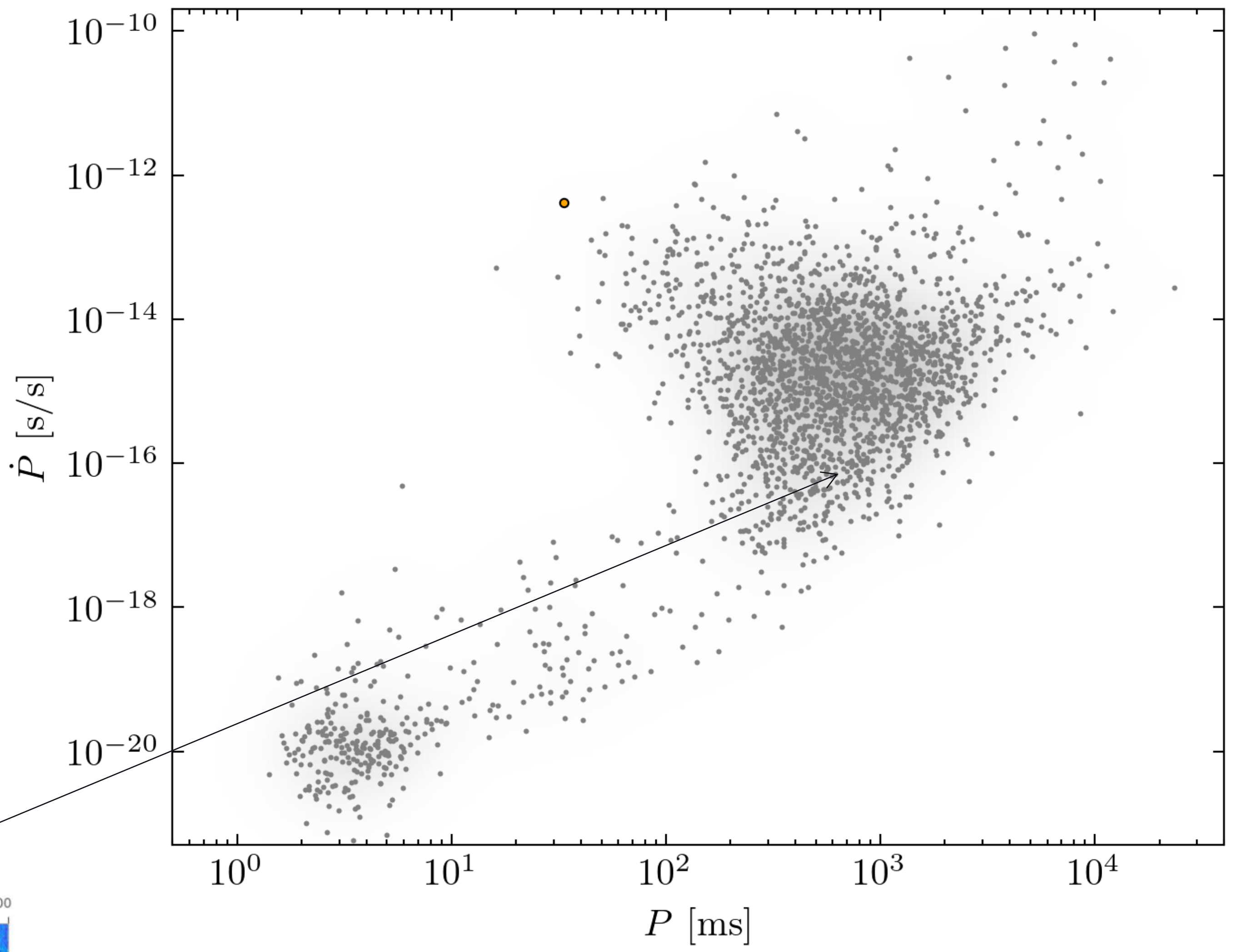
Wang+ (2023)



RRATs & nullings

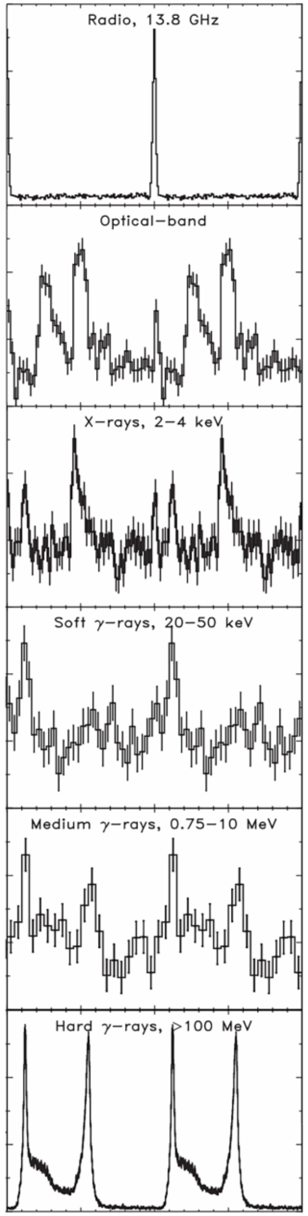


Zhang+ (2020)

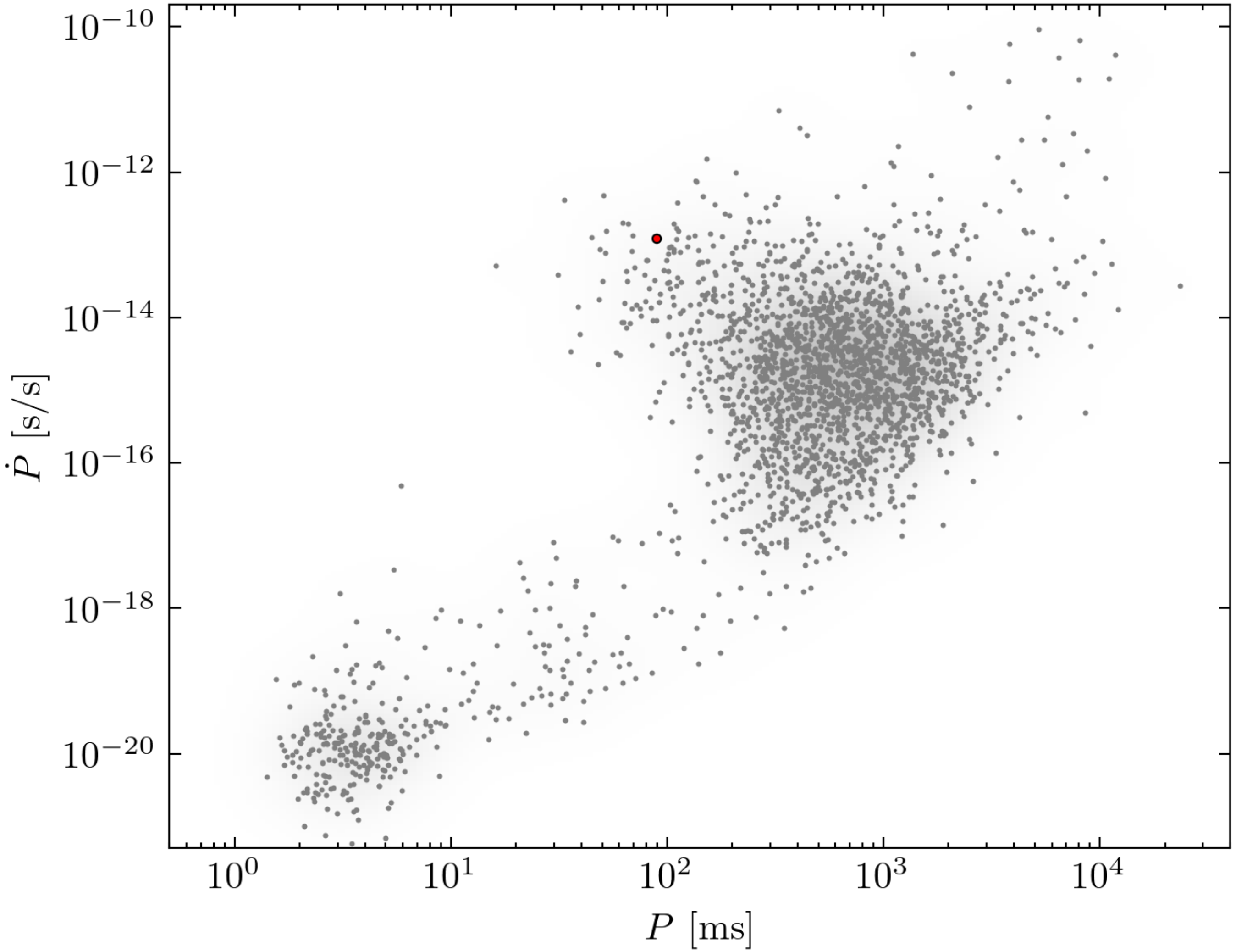


Pulsars: a complex puzzle with simple premise

Vela

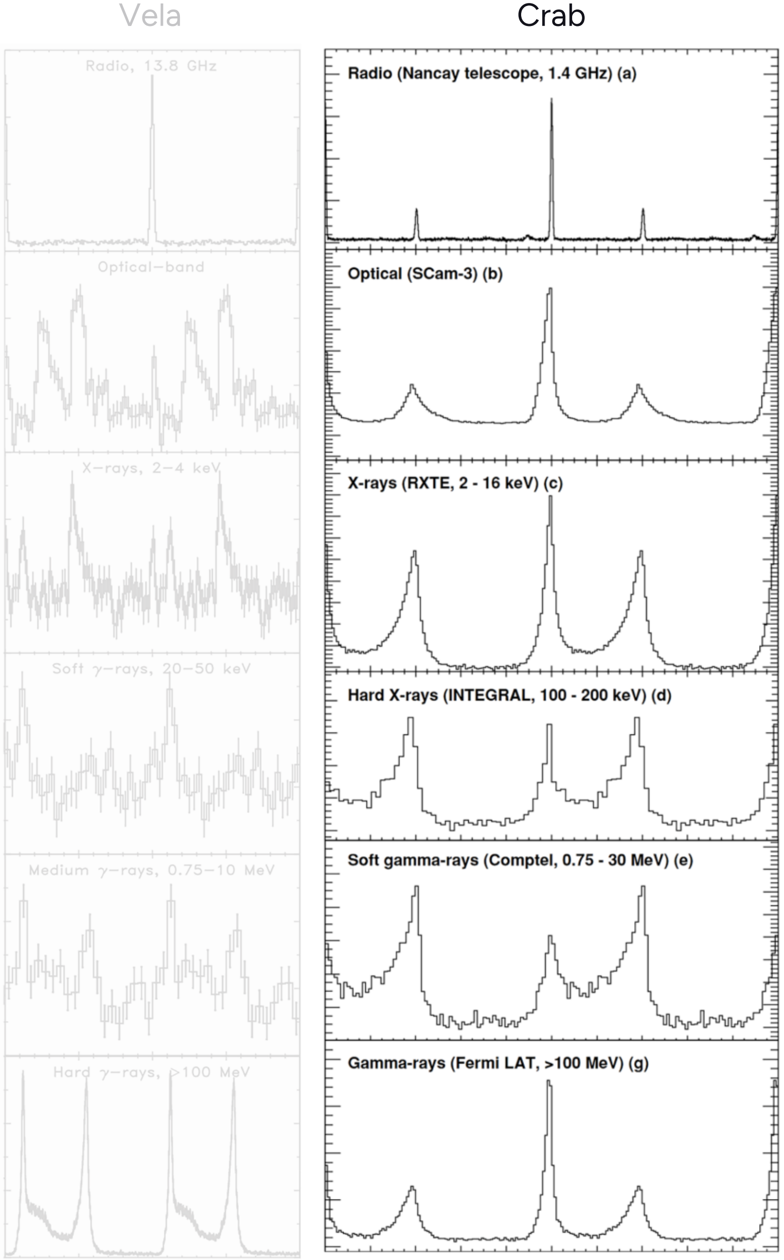


pulsed multiwavelength emission!



← *Abdo+ (2010); Kuiper, & Hermsen (2015)*

Pulsars: a complex puzzle with simple premise



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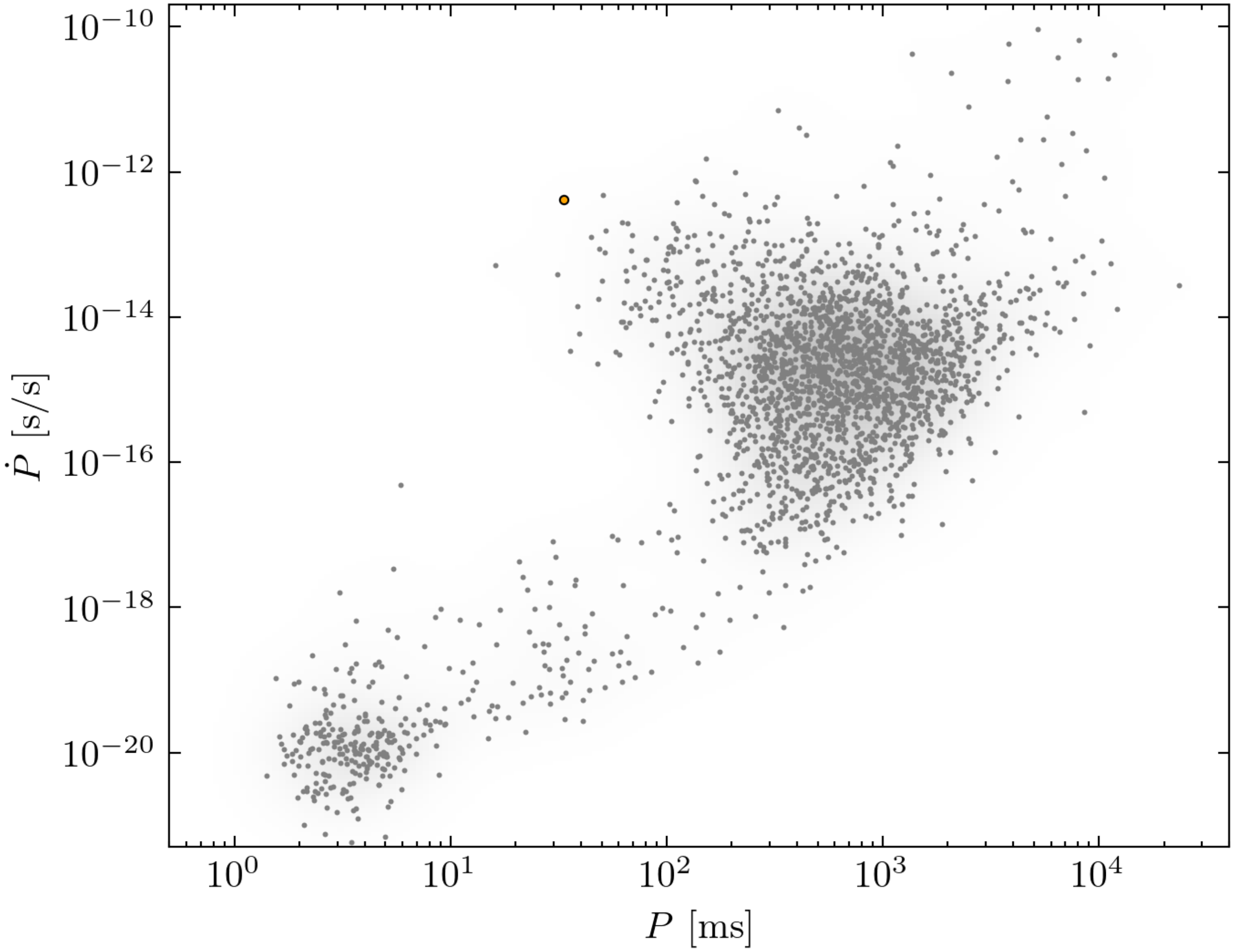
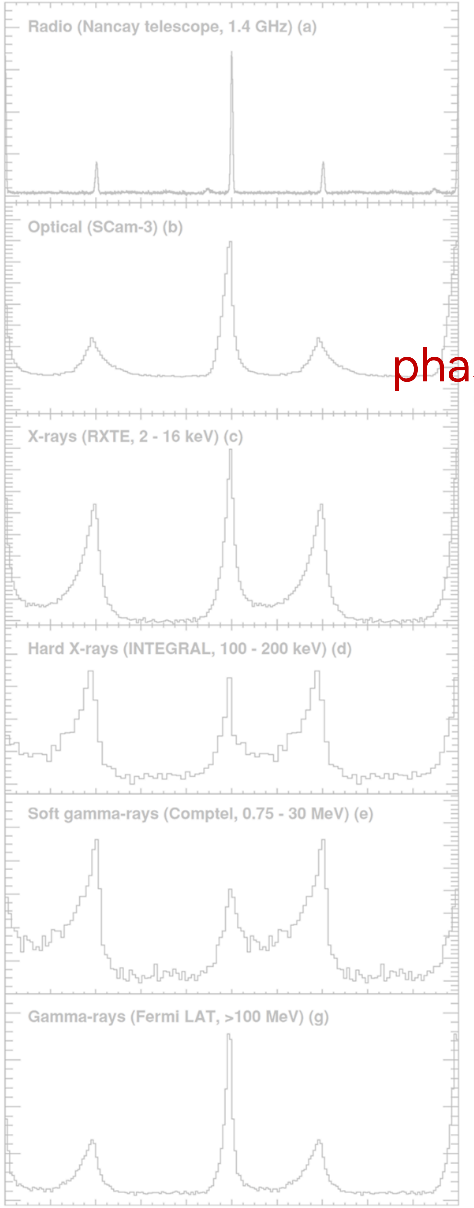


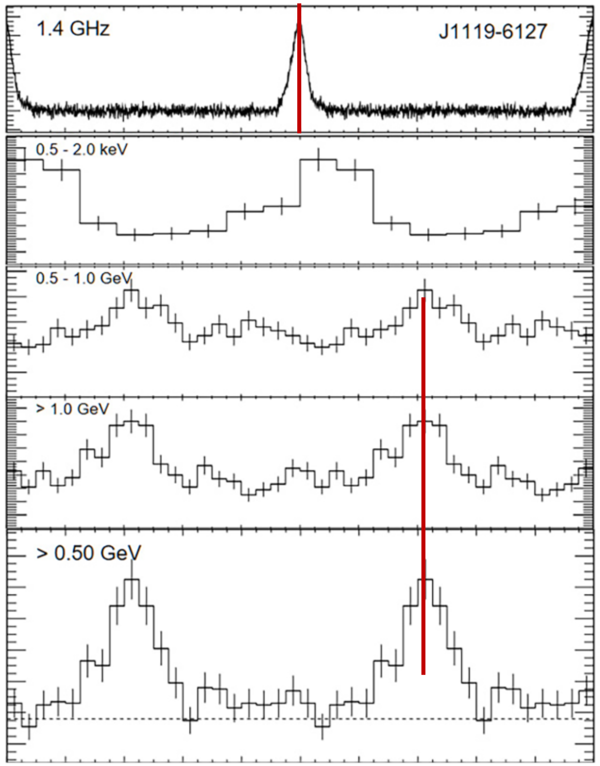
Pulsars: a complex puzzle with simple premise

Vela

Crab



phase-lag w.r.t. radio



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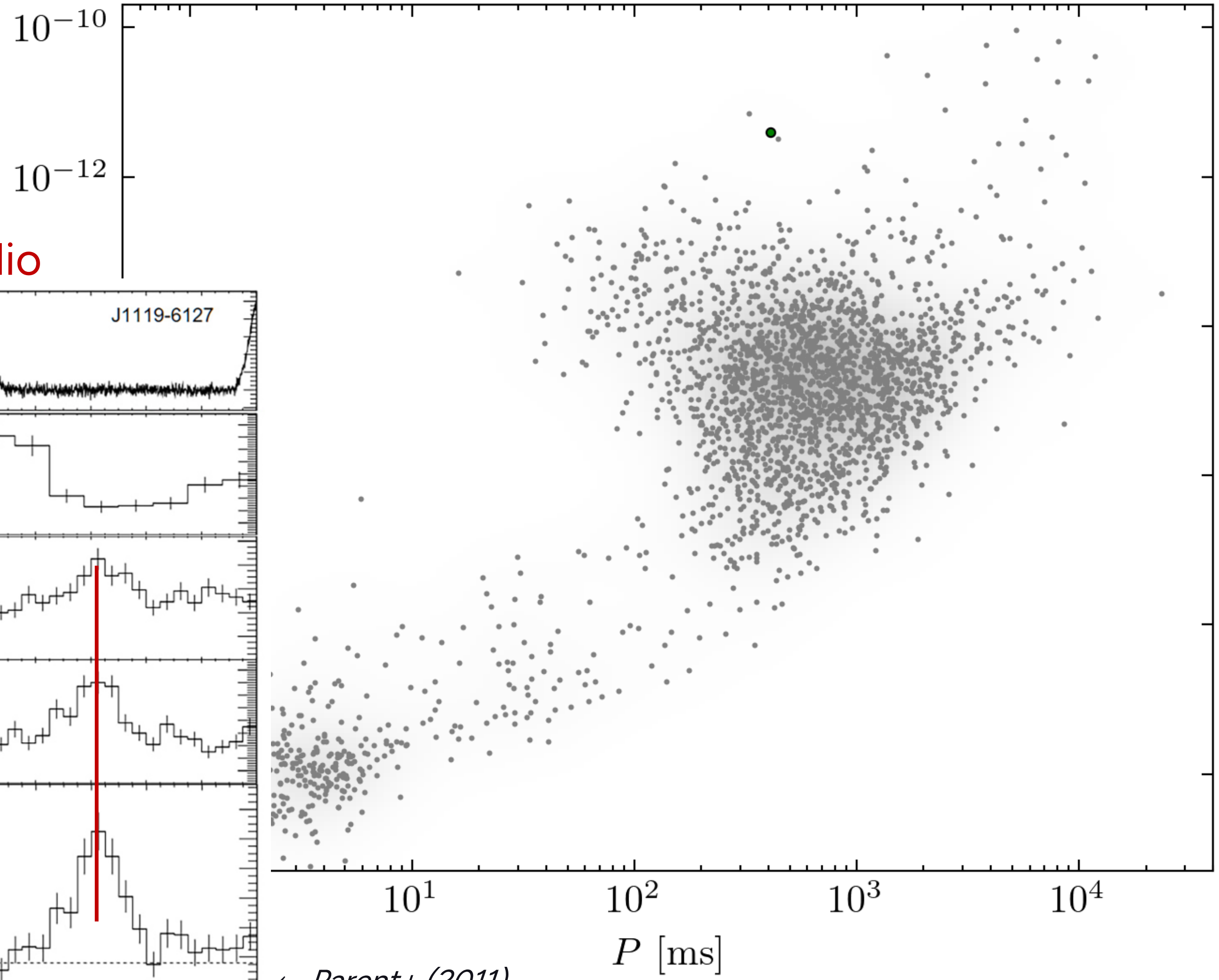
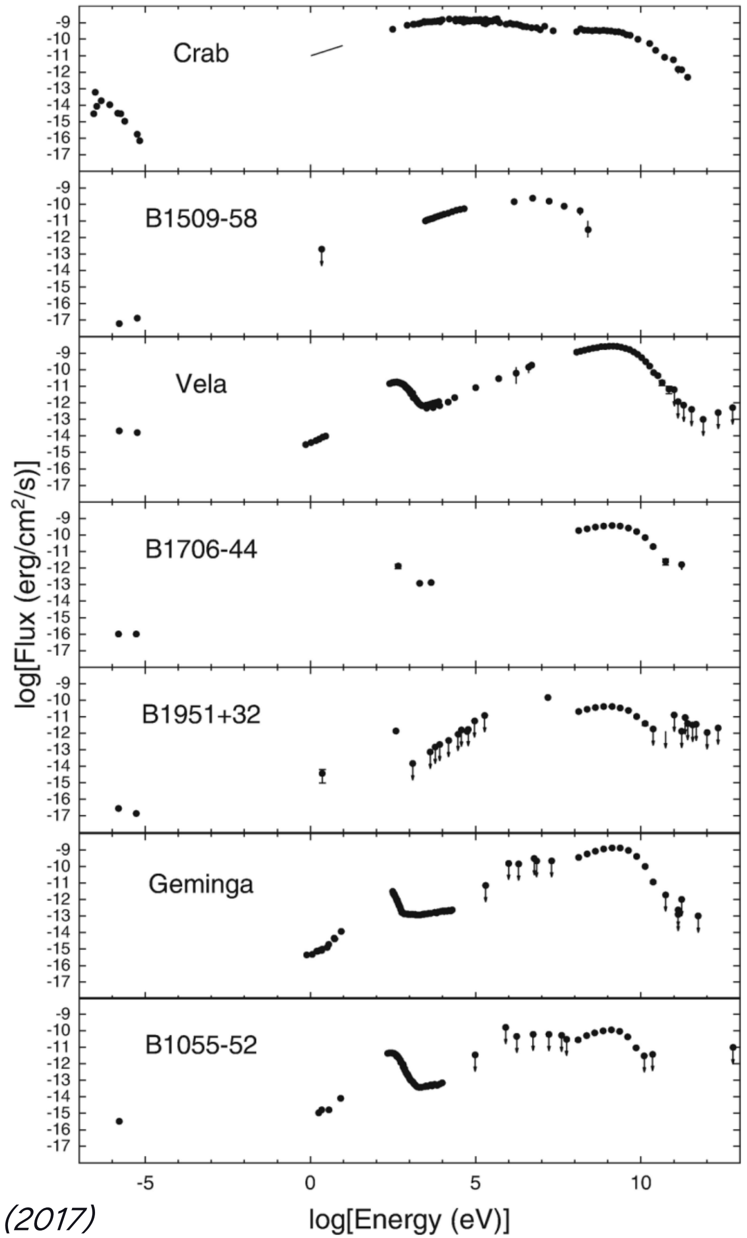
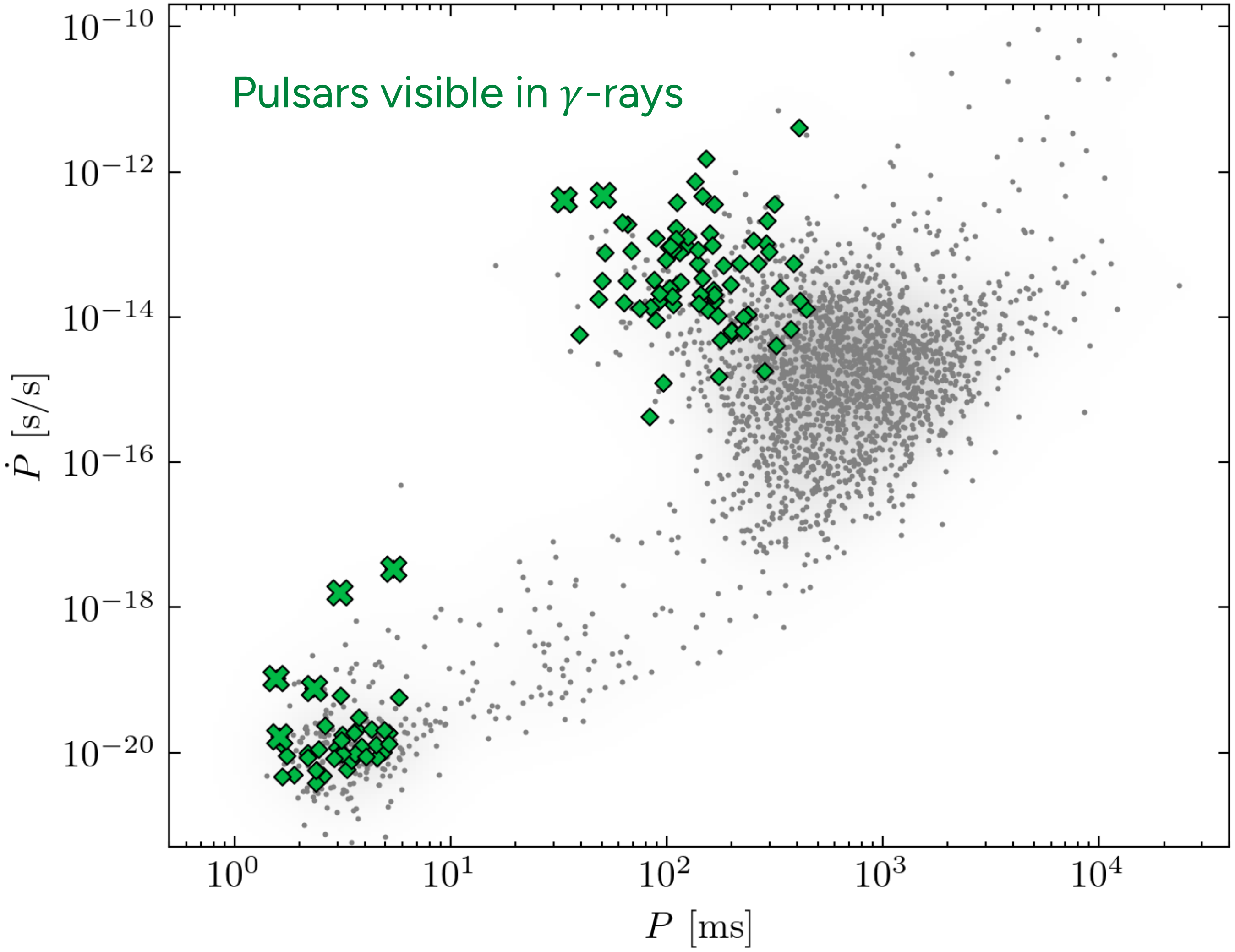


← Parent+ (2011)

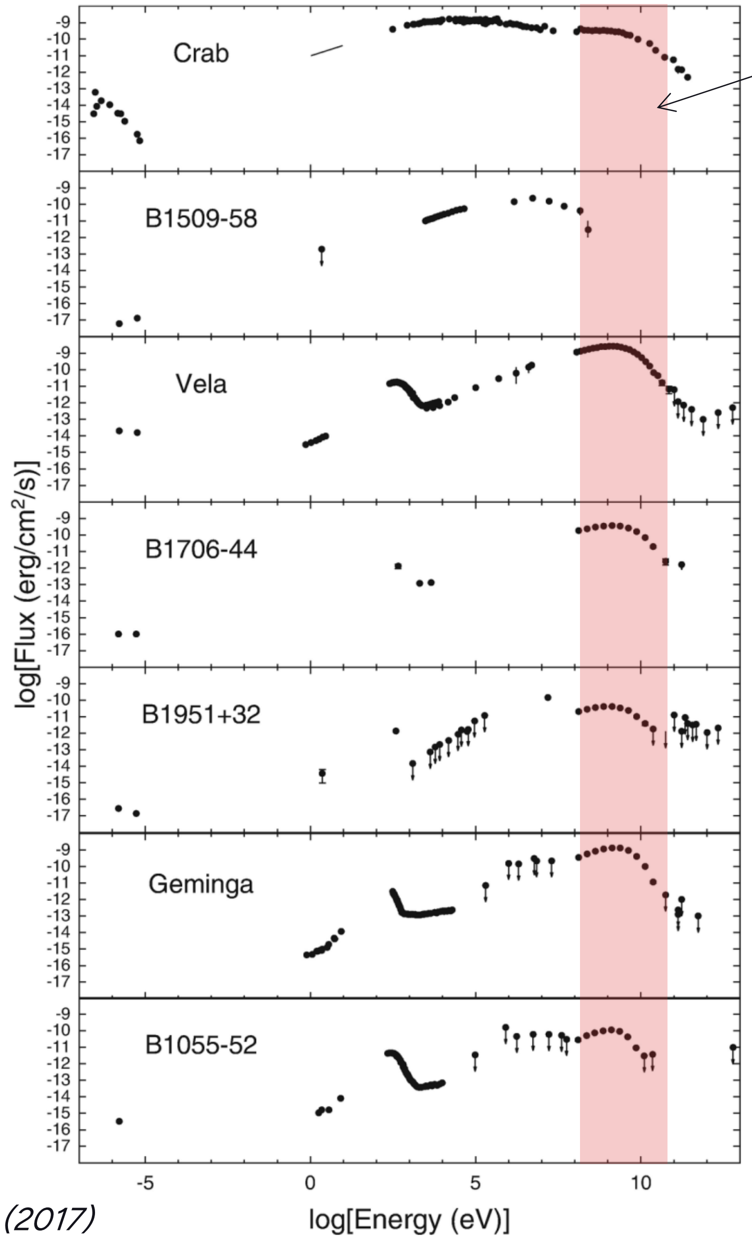
Pulsars: a complex puzzle with a simple premise



Takata (2017)

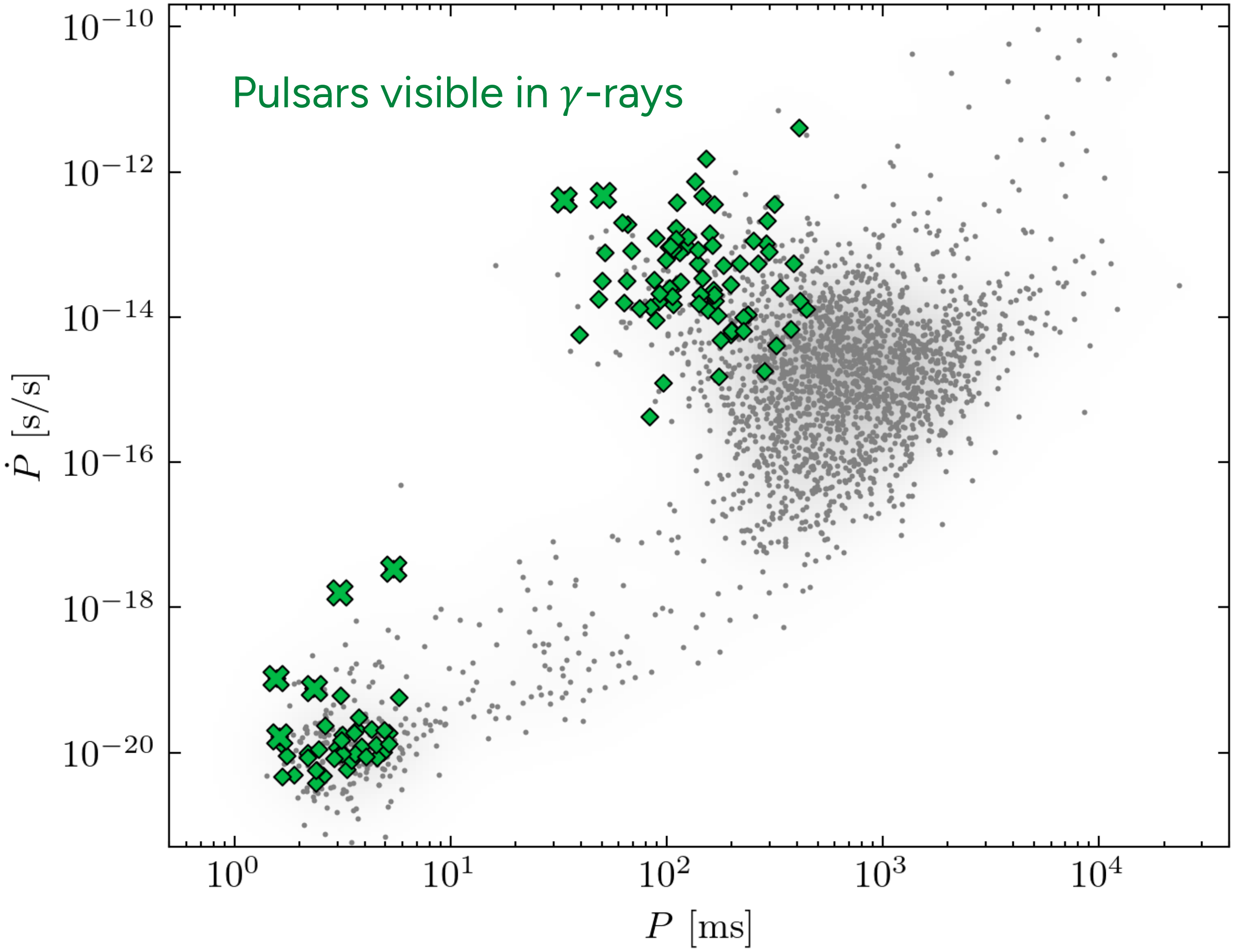


Pulsars: a complex puzzle with a simple premise

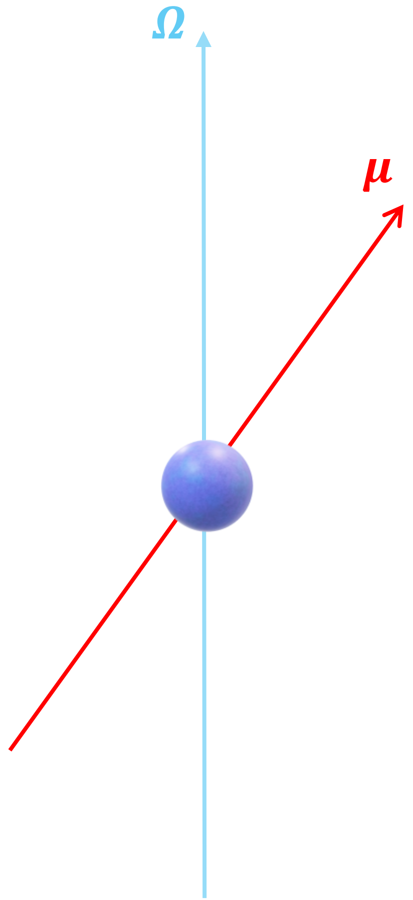


Takata (2017)

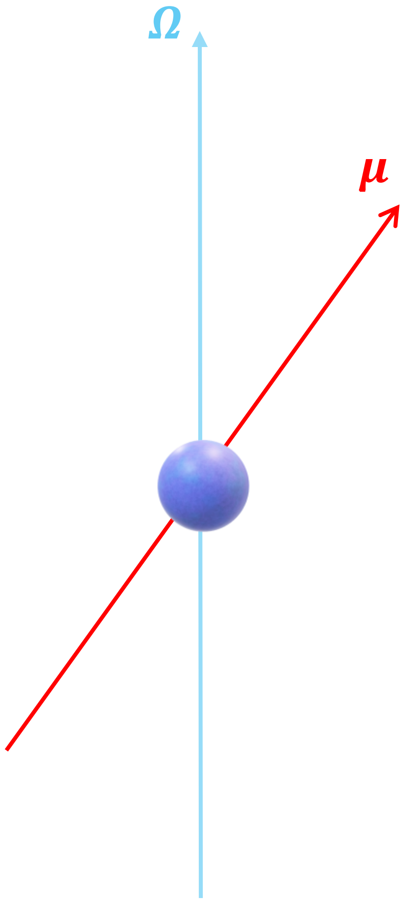
0.1 … 10% of $\dot{E}$ radiated in γ-rays



Pulsar “Tamagotchi”



Pulsar “Tamagotchi”: overfeeding the pulsar



Force-free Solution

- $B^2 \gg \rho_\pm c^2$ (in fact $\rho_\pm = 0$)
- assume $\boldsymbol{E} \cdot \boldsymbol{B} = 0$ (almost) everywhere
- implicit (numerical) dissipation

Time-dependent force-free formulation:

Maxwell’s eqn-s + $\boldsymbol{j}$ closure which satisfies $\partial_t(\nabla \cdot \boldsymbol{E}) + \nabla \cdot \boldsymbol{j} =$

$$\boldsymbol{j} = \nabla \cdot \boldsymbol{E}\,\frac{\boldsymbol{E} \times \boldsymbol{B}}{\boldsymbol{B}^2} + \frac{(\boldsymbol{B} \cdot (\nabla \times \boldsymbol{B}) - \boldsymbol{E} \cdot \boldsymbol{\nabla} \times \boldsymbol{E})\boldsymbol{B}}{\boldsymbol{B}^2}$$

Gruzinov (1999), Blandford (2002)

Pulsar “Tamagotchi”: overfeeding the pulsar

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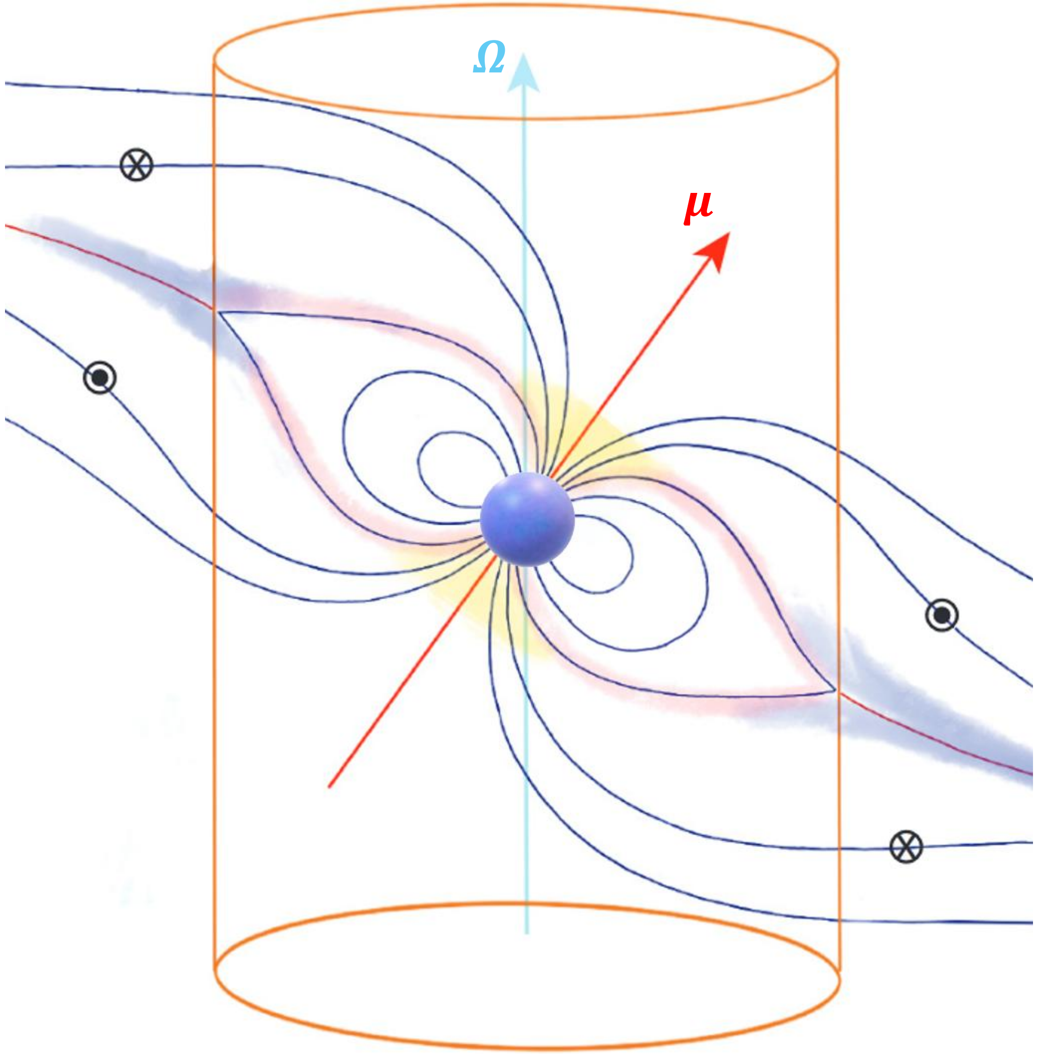
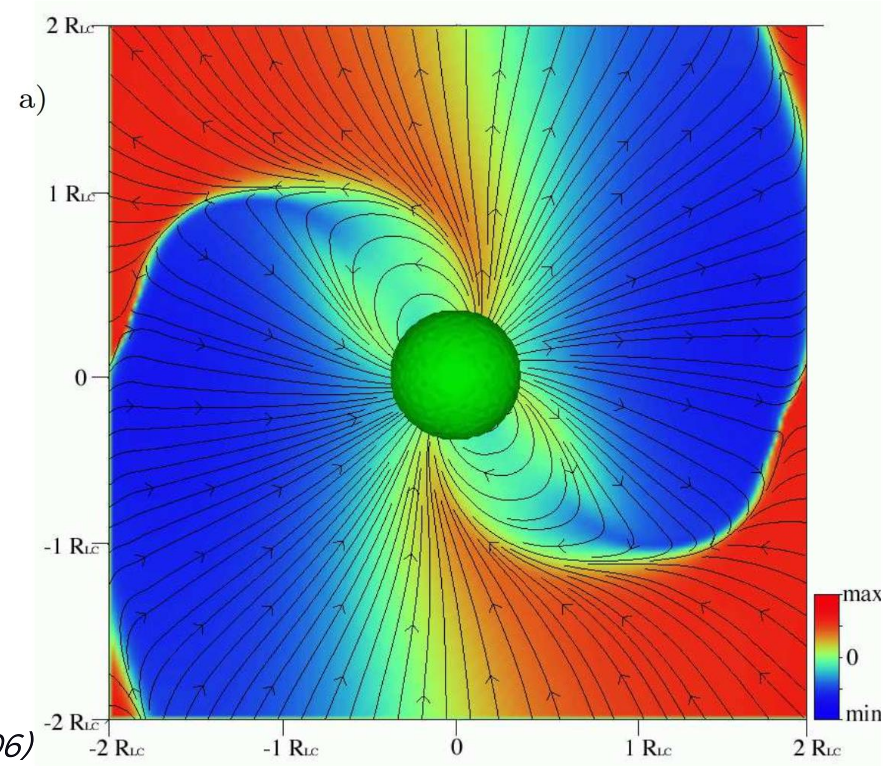


adapted from *Philippov & Kramer (2022)*



Spitkovsky (2006)

also see
Beskin+ (1993), Contopoulos+ (1999), Gruzinov (2005), Timokhin (2005)

Pulsar "Tamagotchi": overfeeding the pulsar

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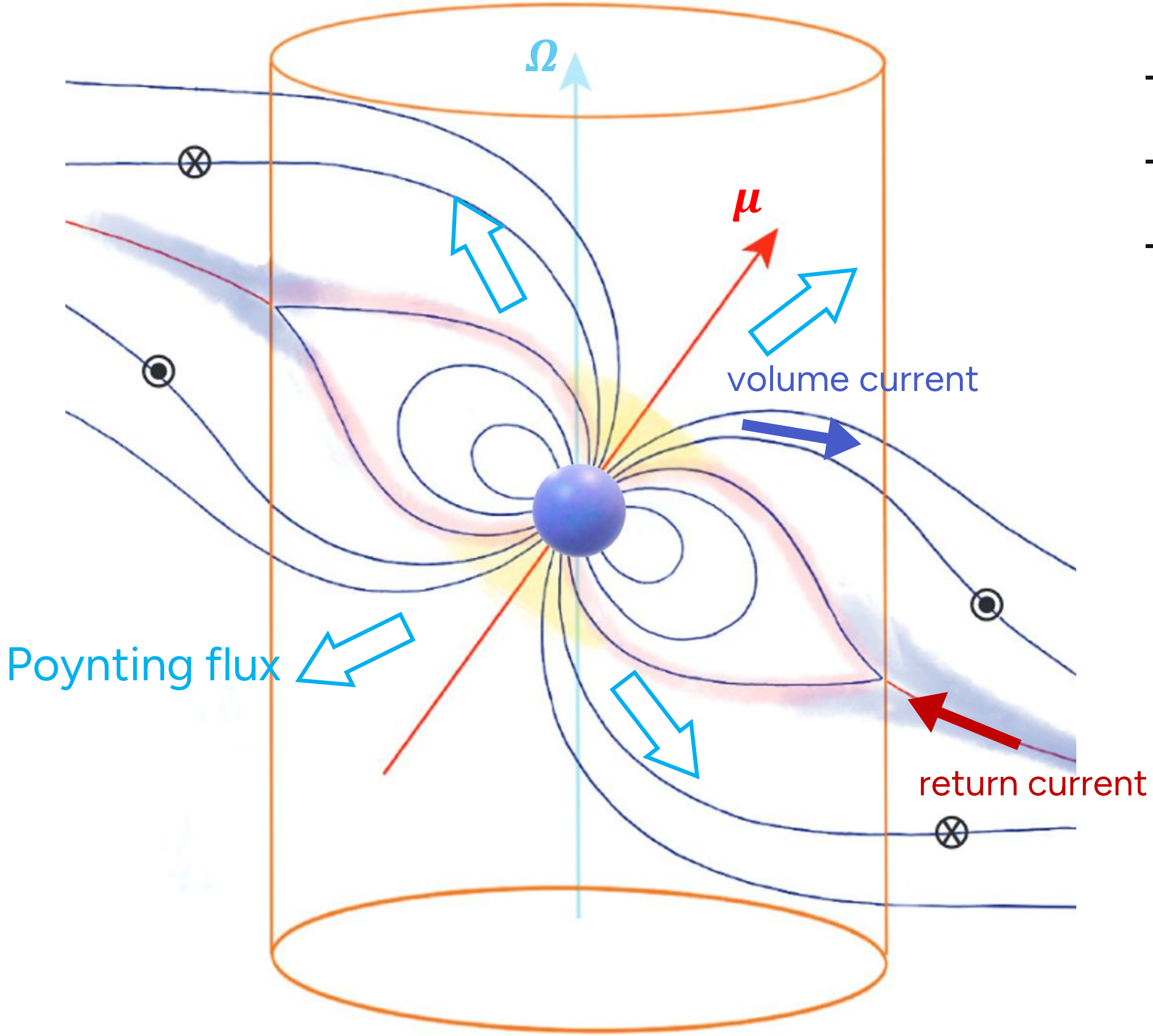

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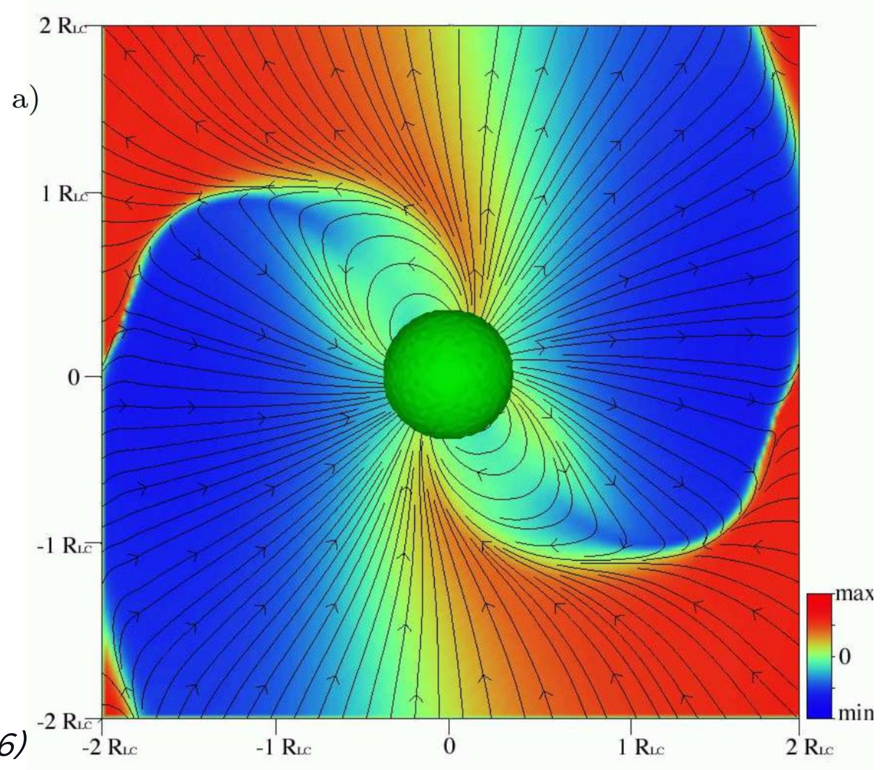

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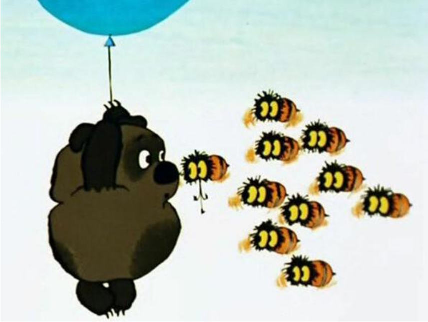
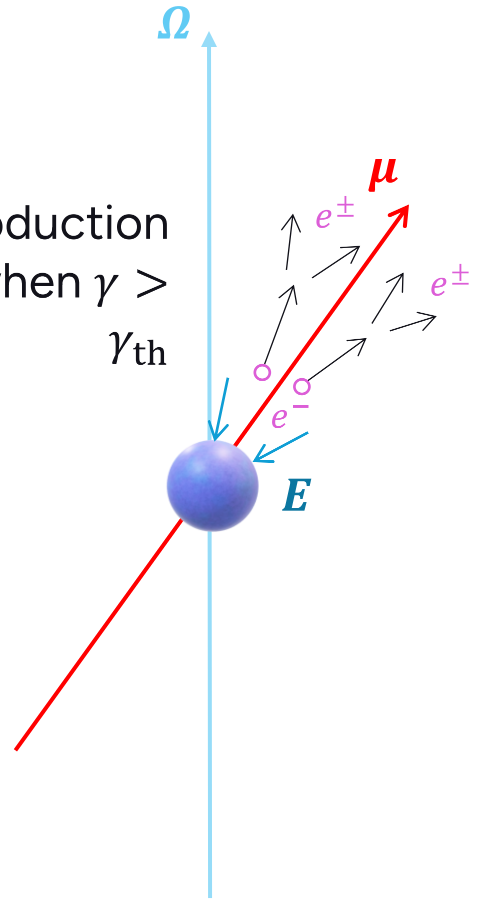
Pulsar "Tamagotchi": feeding just enough



Kinetic Solution

modeling the pair-production cascade: inject $e^{\pm}$ when $\gamma > \gamma_{\mathrm{th}}$



Particle-in-Cell formulation

updating EM fields:

$$\begin{cases} \dfrac{\partial \boldsymbol{E}}{c\partial t} = \nabla \times \boldsymbol{B} - \dfrac{4\pi}{c}\boldsymbol{j} \\ \dfrac{\partial \boldsymbol{B}}{c\partial t} = -\nabla \times \boldsymbol{E} \end{cases}$$

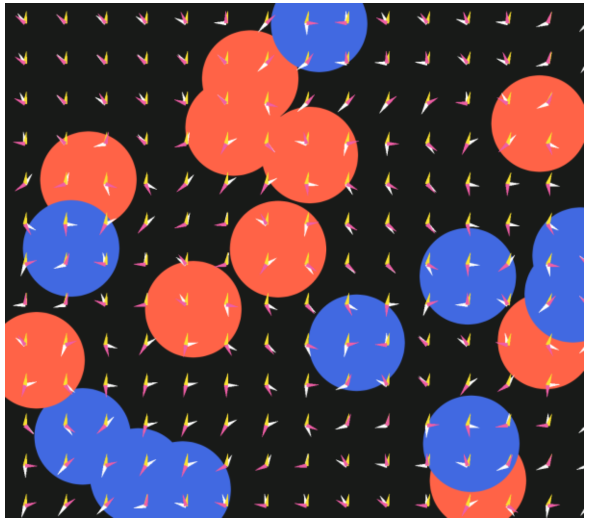
Δt

updating particles:

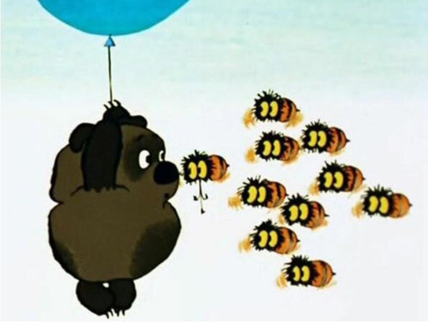
$$\begin{cases} \dfrac{d\boldsymbol{u}}{cdt} = \dfrac{q}{m}\left(\boldsymbol{E} + \dfrac{\boldsymbol{u}}{\gamma} \times \boldsymbol{B}\right) \\ \dfrac{d\boldsymbol{x}}{cdt} = \dfrac{\boldsymbol{u}}{\gamma} \end{cases}$$

depositing currents:

$$\boldsymbol{j} = \sum_{\text{species}} q \frac{\boldsymbol{u}}{\gamma}$$



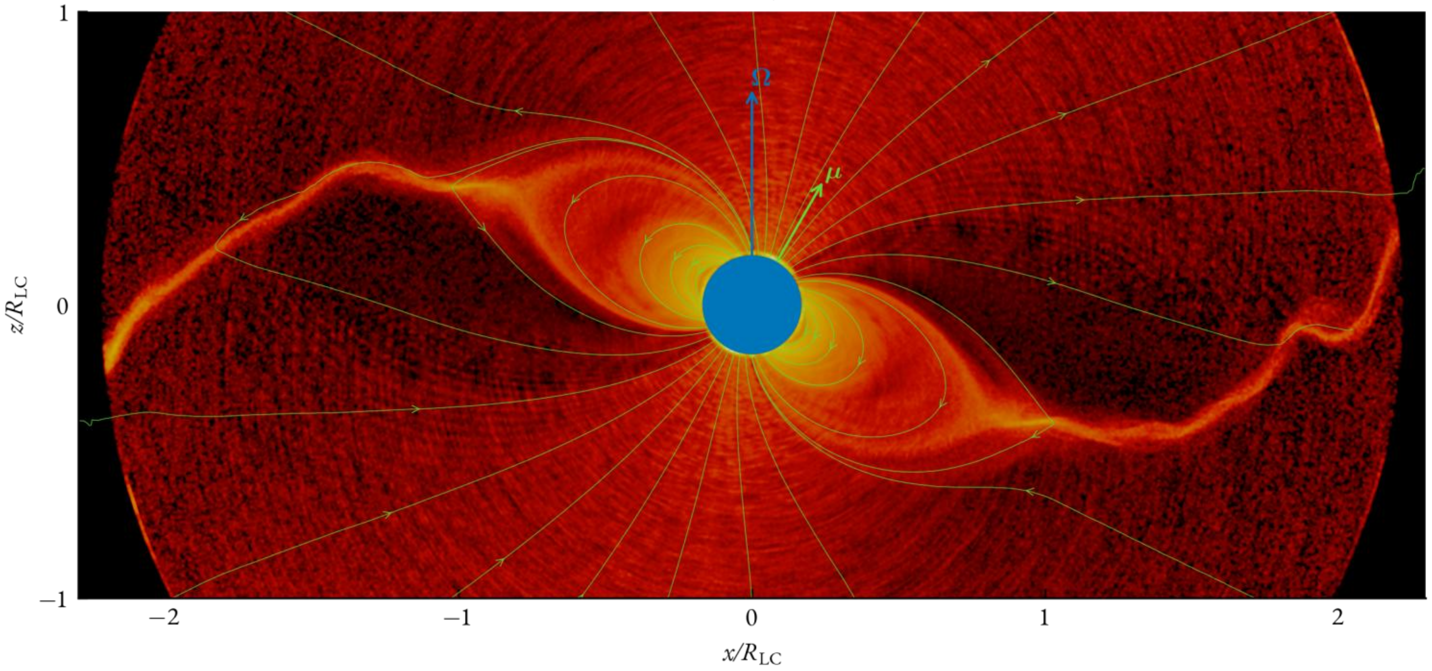
Pulsar "Tamagotchi": feeding just enough



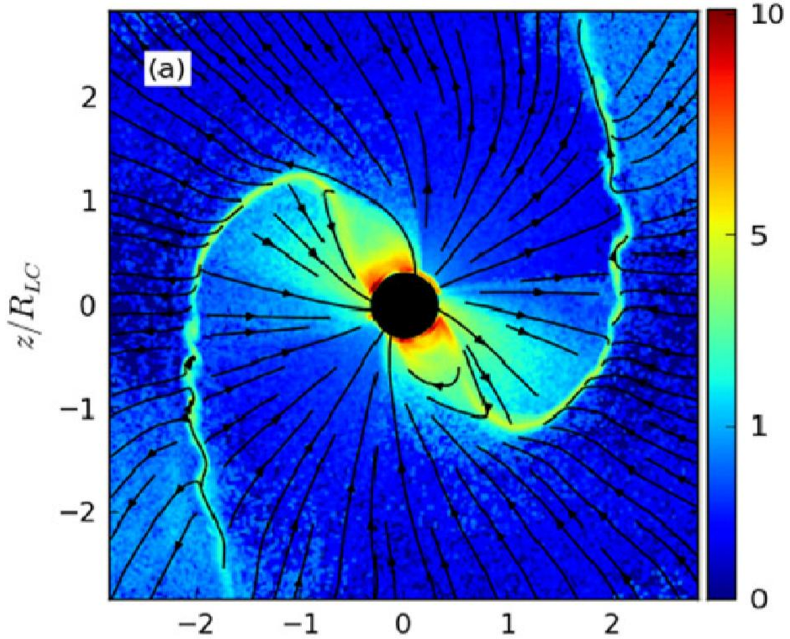
Kinetic Solution

HH, Philippov, Spitkovsky (2023)

density of $e^{\pm}$



density of e^{-}



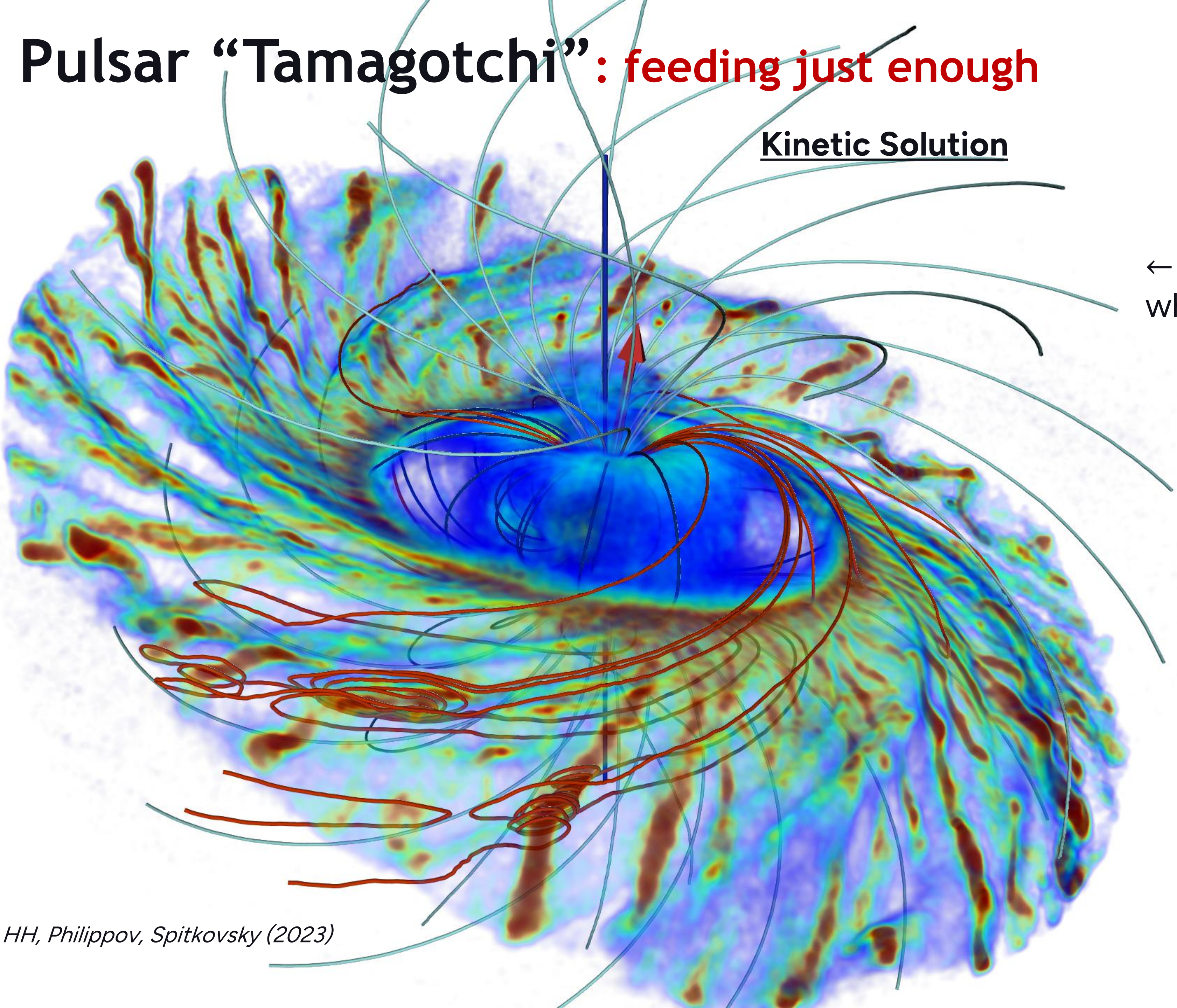
Philippov, Spitkovsky, Cerutti (2015)

the final answer is insensitive on how the cascade is modeled (as long as $n_{\pm} \geq n_{GJ}$)

also see
Chen & Beloborodov (2014), Cerutti+ (2016), Kalapotharakos+ (2018), Bransgrove+ (2023)

Have we learned anything more than with force-free?

Pulsar “Tamagotchi”: feeding just enough



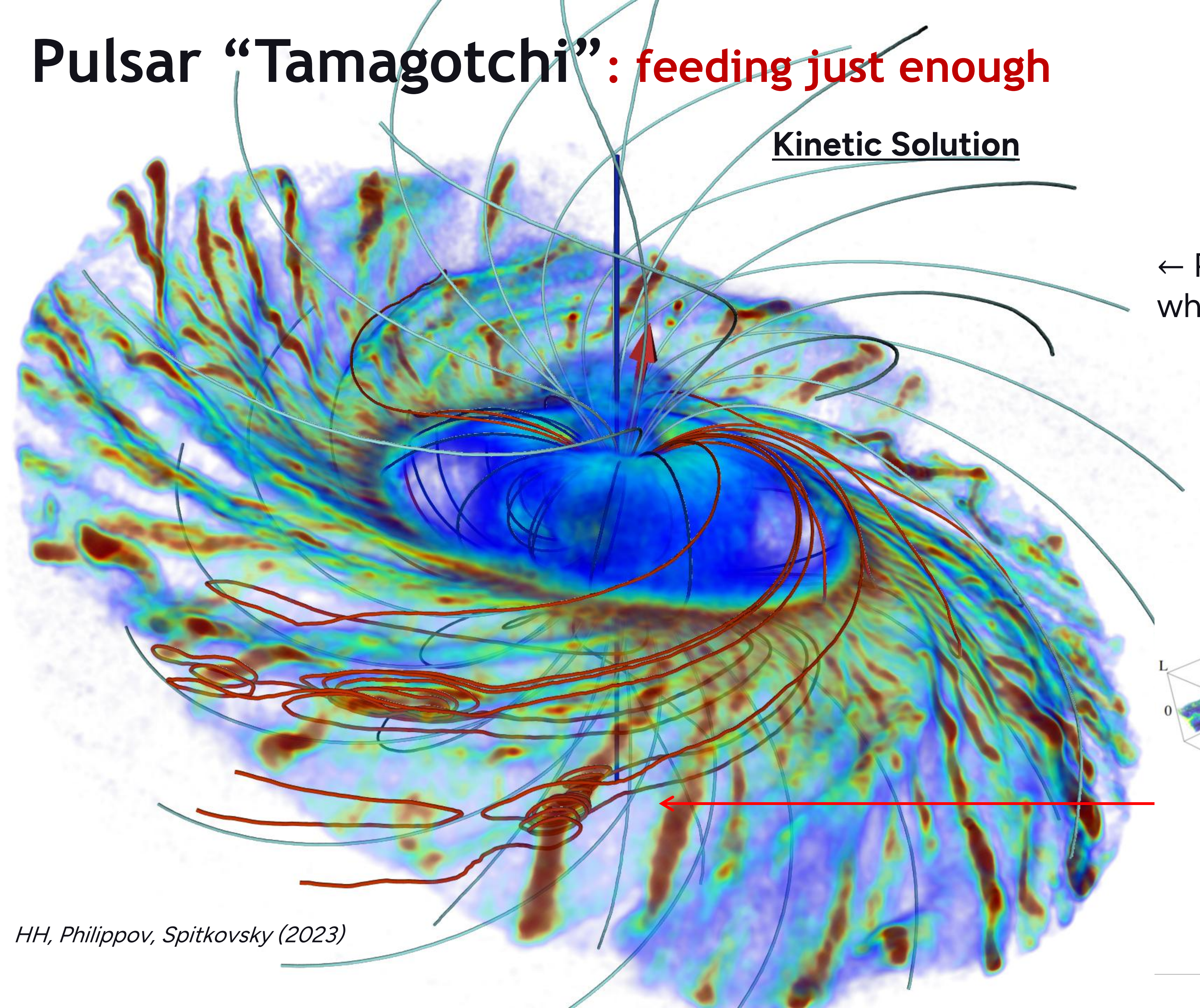
HH, Philippov, Spitkovsky (2023)

← Plasma density in “regions which are ***not*** force-free”

Pulsar “Tamagotchi”: feeding just enough

also see
Cerutti+ (2016, 2017),
Cerutti+ (2020),
Hu & Beloborodov (2022)

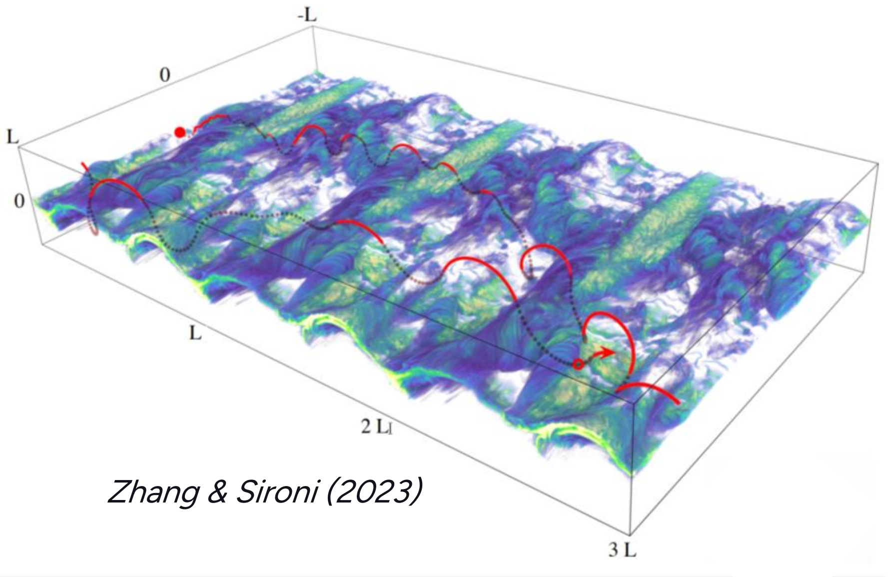
Kinetic Solution



HH, Philippov, Spitkovsky (2023)

← Plasma density in “regions which are ***not*** force-free”

Poynting flux is dissipated via *magnetic reconnection*

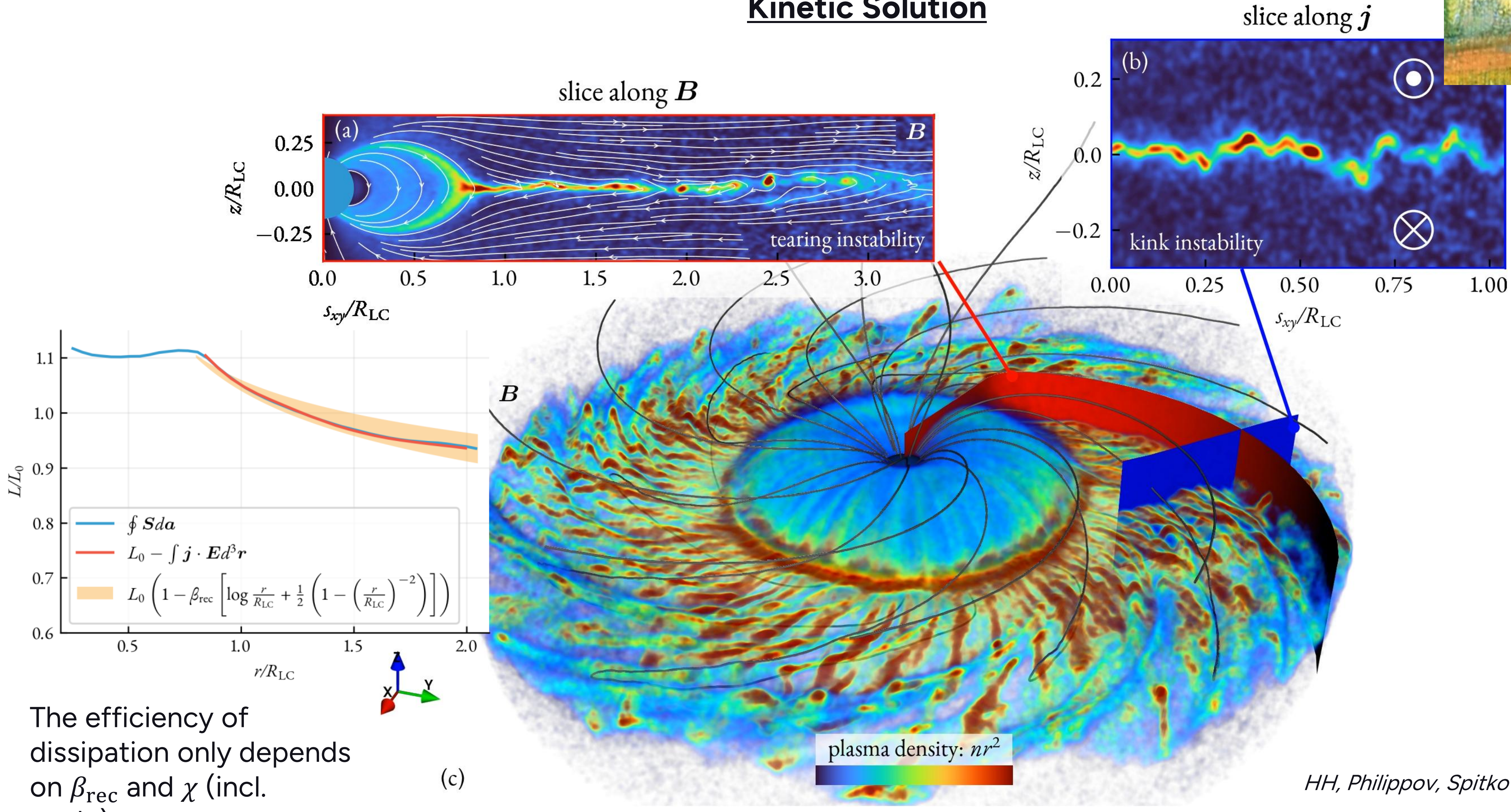


Zhang & Sironi (2023)

Pulsar "Tamagotchi": feeding just enough

also see
Cerutti+ (2016, 2017),
Cerutti+ (2020),
Hu & Beloborodov (2022)

Kinetic Solution

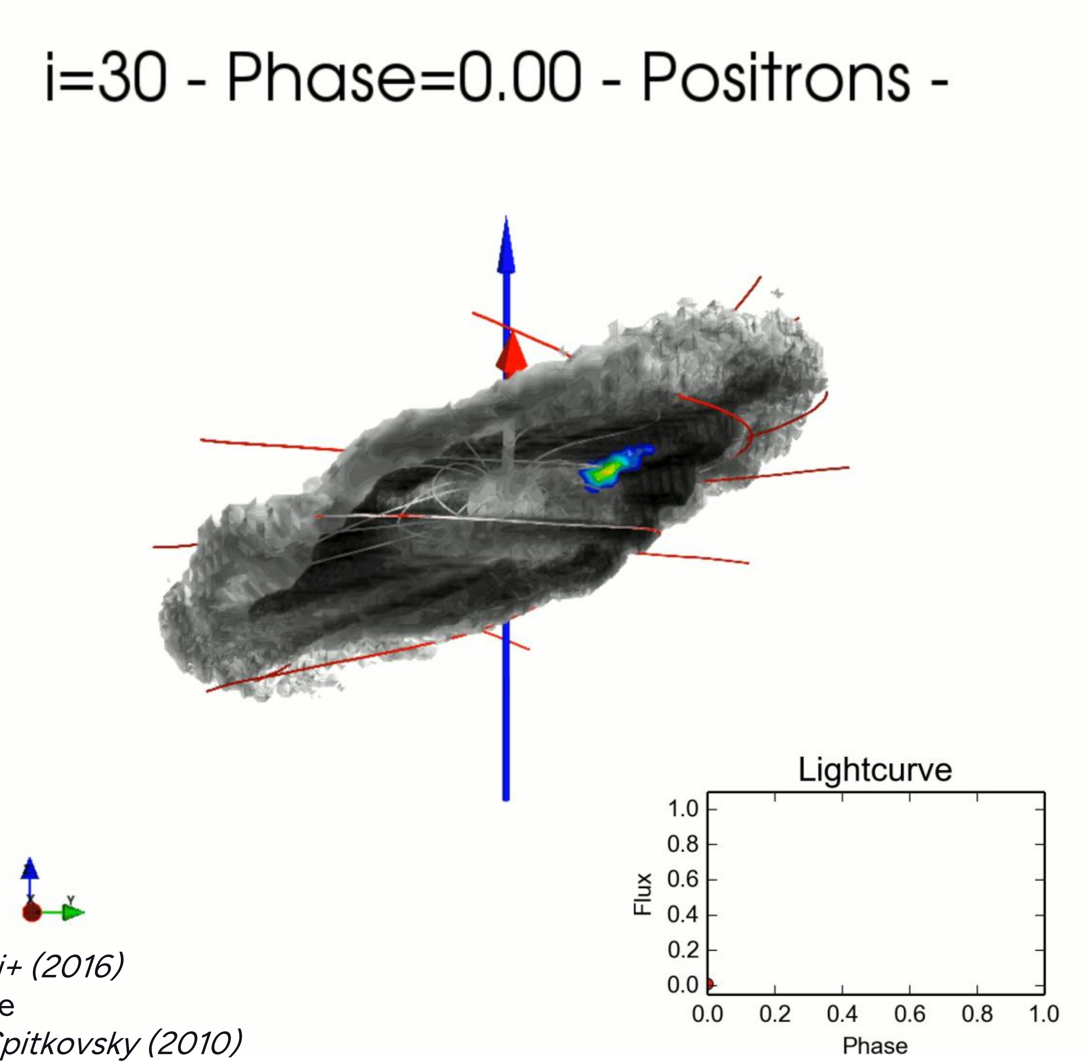


The efficiency of dissipation only depends on $\beta_{\rm rec}$ and χ (incl. angle)

HH, Philippov, Spitkovsky (2023)

Where does the energy go? emission modeling

Emission modeling: lightcurves

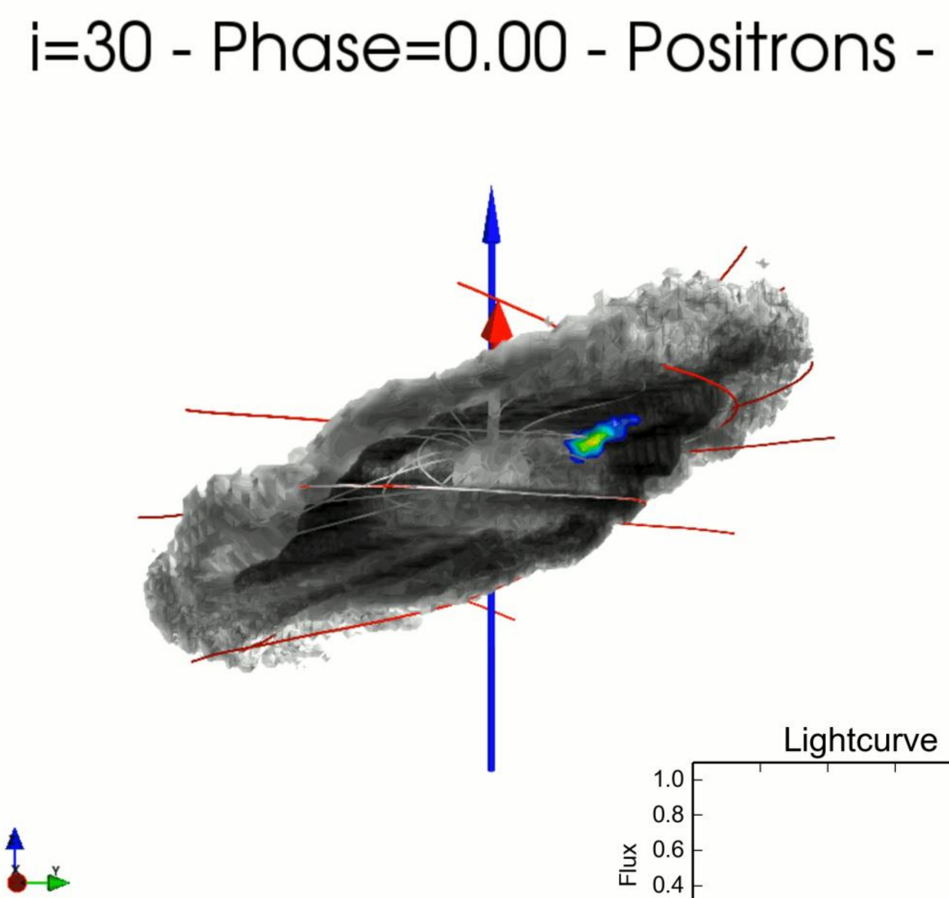


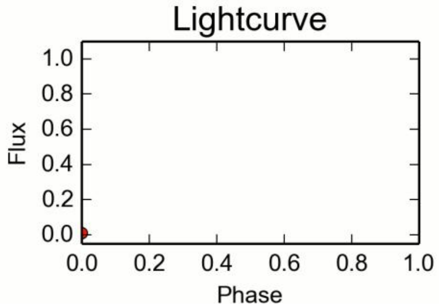
Cerutti+ (2016)
also see
Bai & Spitkovsky (2010)

Lightcurves = caustics
(assuming emission along $\boldsymbol{B}$)

Where does the energy go? emission modeling

Emission modeling: lightcurves





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also see
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Lightcurves = caustics
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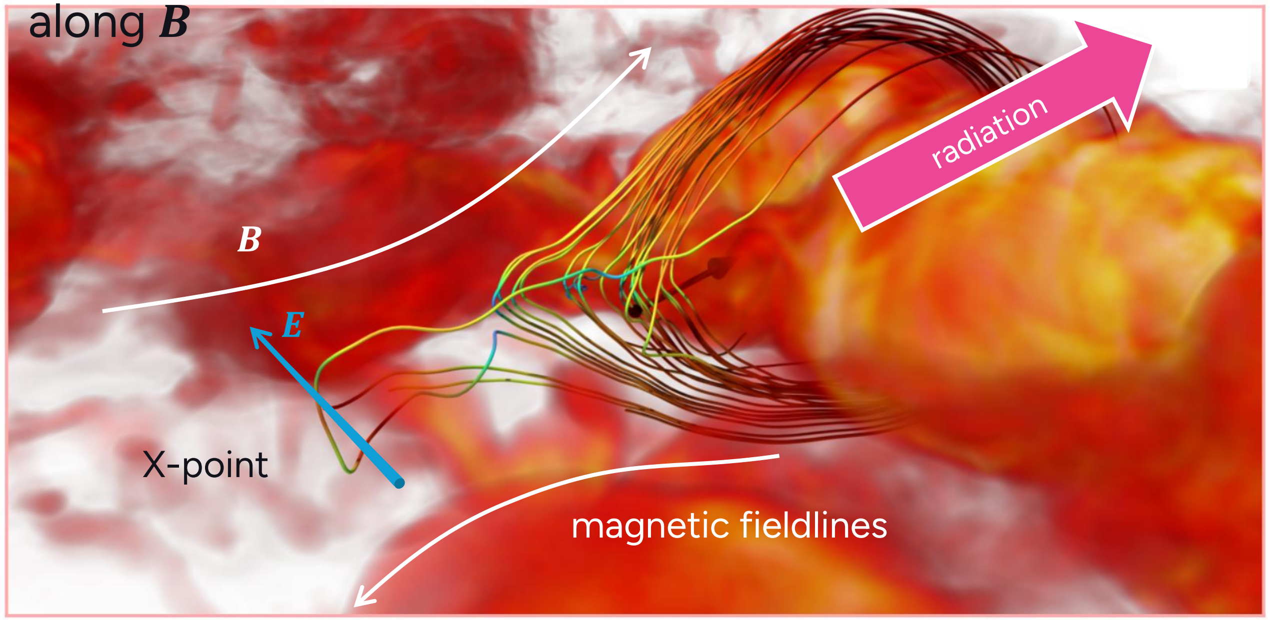
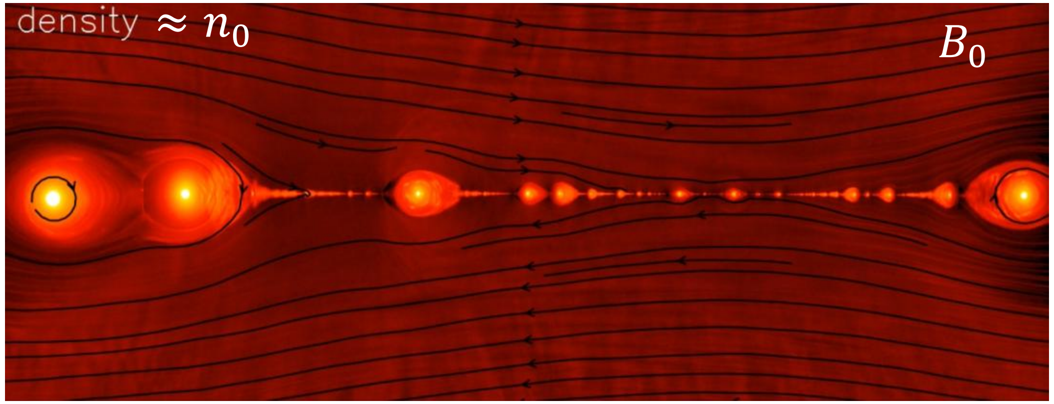
Strong synchrotron cooling leads to emission beaming along $\boldsymbol{B}$



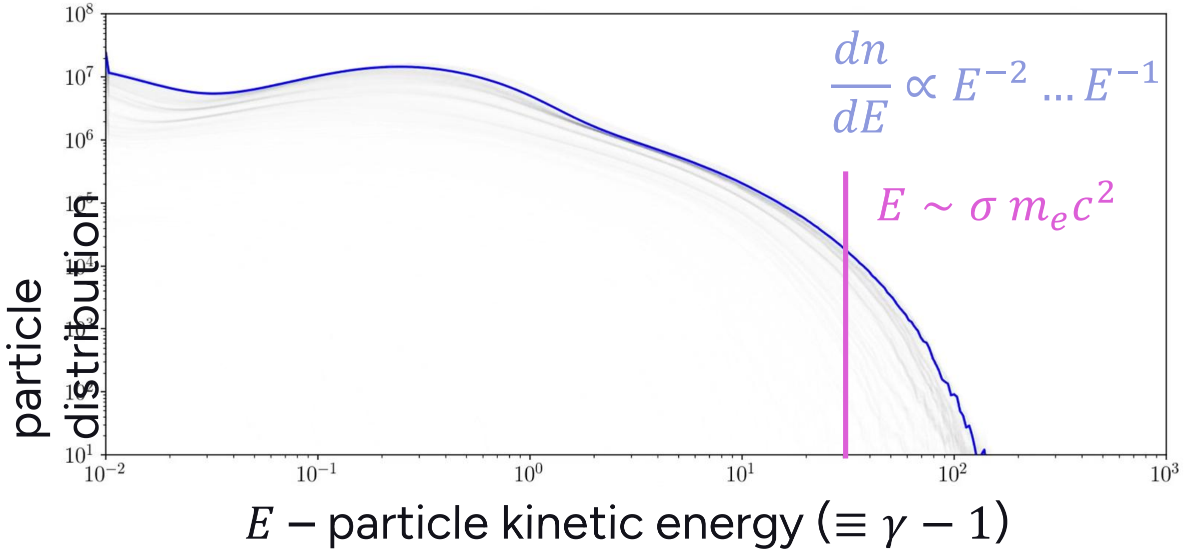
Chernoglazov, HH, Philippov (2023)

Where does the energy go? emission modeling

Emission modeling: γ-ray spectra



HH+ (2021)
also see
Sironi & Spitkovsky (2014), Guo+ (2014), Werner+ (2016), Zhang+ (2021)



magnetization parameter:

$$\sigma = \frac{B_0^2/4\pi}{n_0 m_e c^2} \gg 1$$

for pulsars:

$$\sigma_{LC} = \frac{1}{2}\frac{V_{\rm pc}/m_e c^2}{n_{LC}/n_{GJ}^{LC}} = \frac{1}{2}\frac{\text{voltage}}{\text{multiplicity}}$$

Where does the energy go? emission modeling

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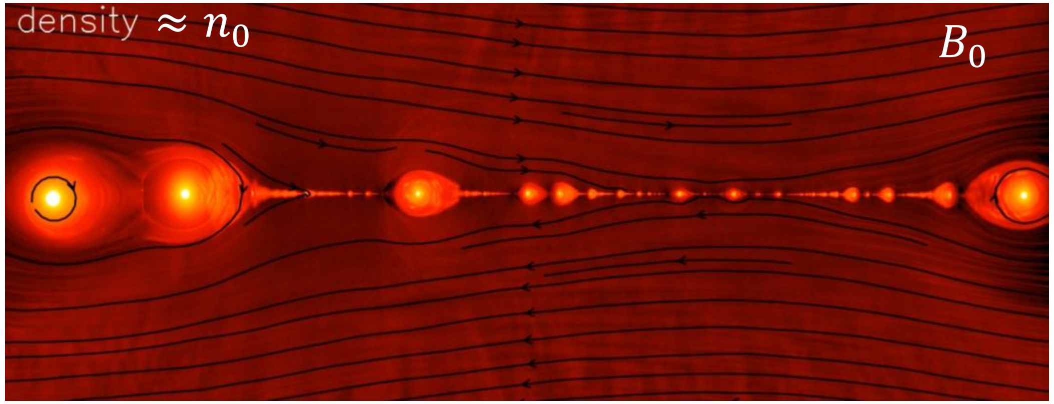

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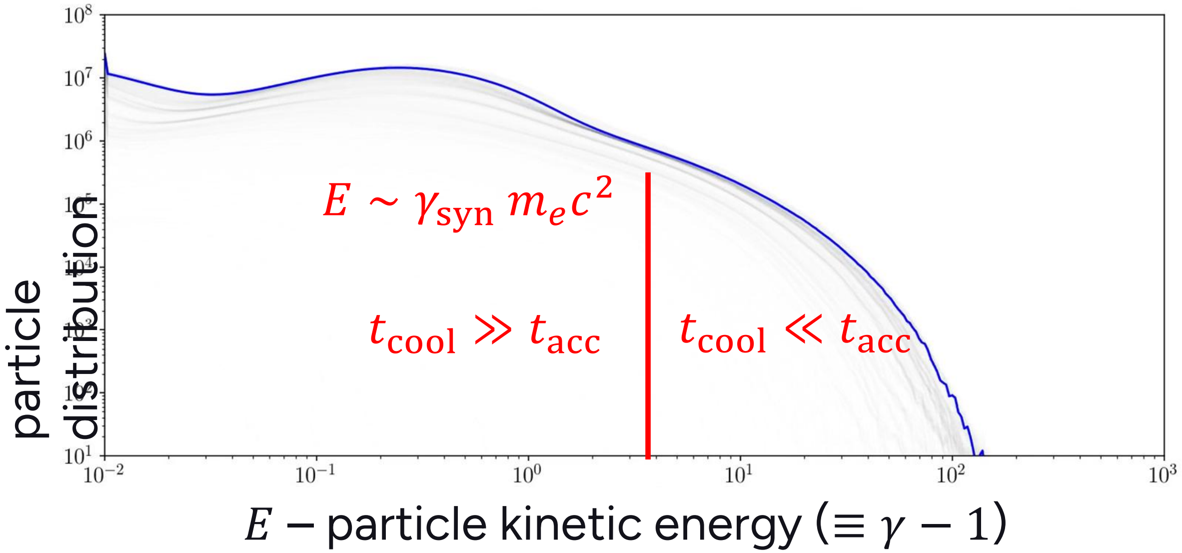

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+ synchrotron cooling

$$\beta_{\rm rec} B_0 |e| = \frac{\sigma_T}{4\pi} B_0^2 \gamma_{\rm syn}^2$$

acceleration force — cooling drag

$$\gamma_{\rm syn}^{LC} \approx 10^5 \left(\frac{B_{LC}}{10^5\ G}\right)^{-1/2}$$

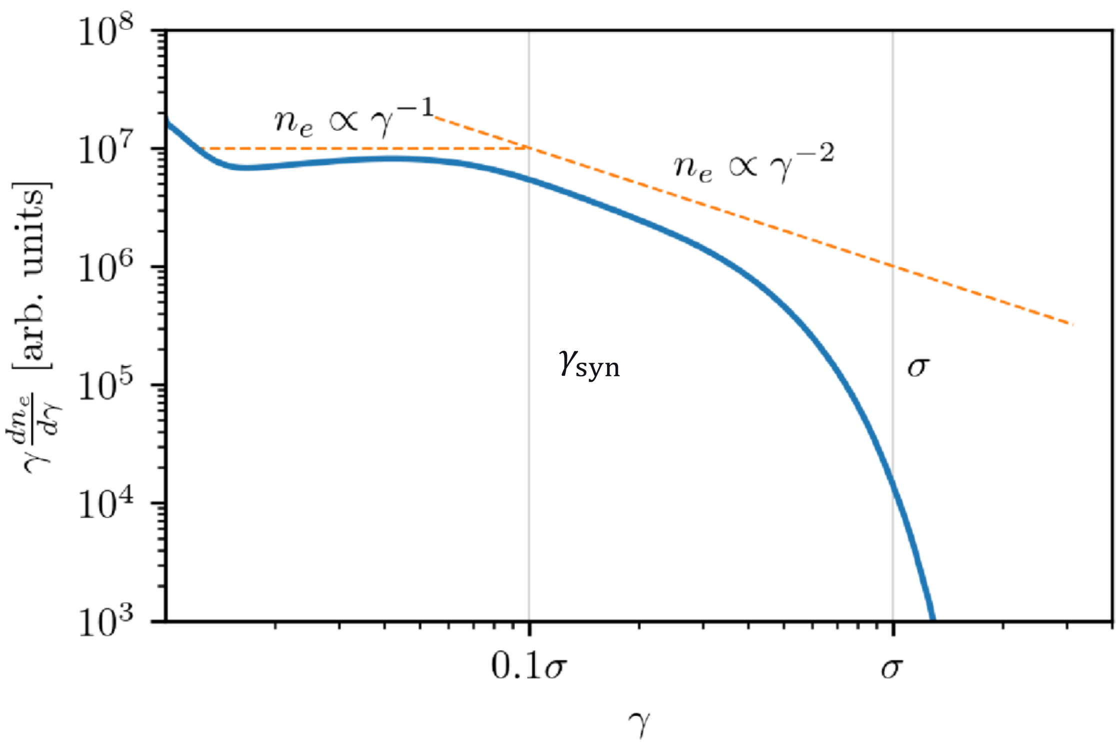
$$E_{\rm syn} \sim \hbar\omega_B \gamma_{\rm syn}^2 = \frac{9}{4}\frac{\beta_{\rm rec}}{\alpha_F} m_e c^2$$

~ 16 MeV

Where does the energy go? emission modeling

Chernoglazov, HH, Philippov (in

Emission modeling: γ-ray spectra

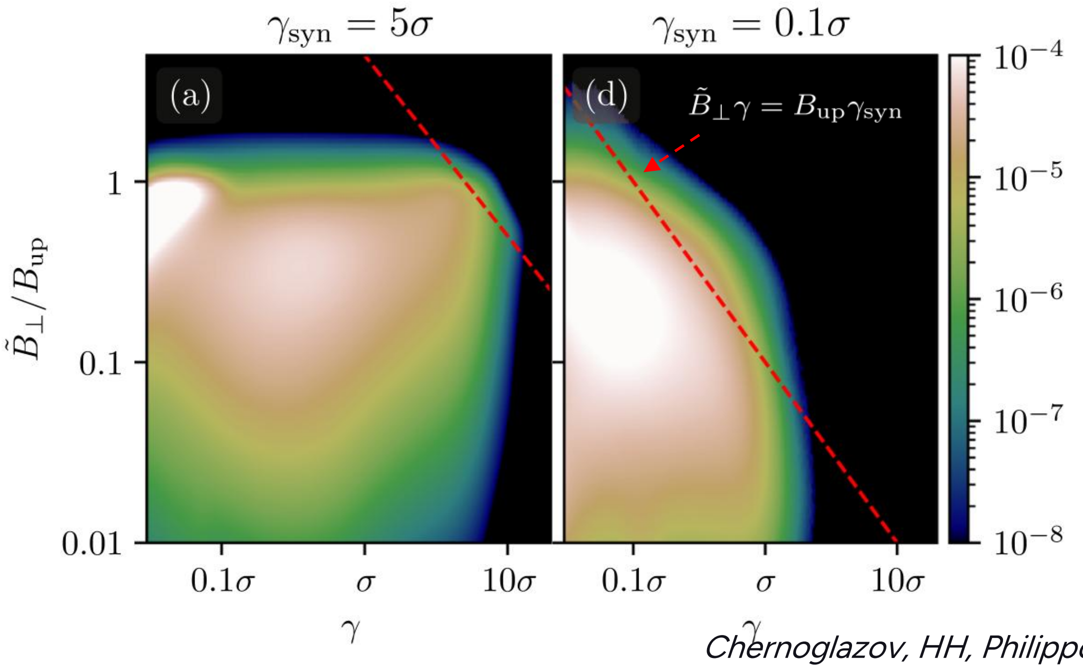


magnetization parameter:

$$\sigma_{LC} = \frac{1}{2}\frac{V_{\rm pc}/m_e c^2}{n_{LC}/n_{GJ}^{LC}} = \frac{1}{2}\frac{\text{voltage}}{\text{multiplicity}}$$

synchrotron burnoff:

$$\gamma_{\rm syn}^{LC} \approx 10^5 \left(\frac{B_{LC}}{10^5\ G}\right)^{-1/2} \qquad E_{\rm syn} \sim \hbar\omega_B \gamma_{\rm syn}^2 = \frac{9}{4}\frac{\beta_{\rm rec}}{\alpha_F} m_e c^2$$



in strong cooling regime ($\gamma_{\rm syn} < \sigma$):

$$\langle B^2 \gamma^2 \sin^2\alpha \rangle \approx \gamma_{\rm syn}^2 B_{\rm up}^2$$

$$\Downarrow$$

$$E_{\max} \sim E_{\rm syn}\left(\frac{B\sin\alpha}{B_{\rm up}}\right)\left(\frac{\gamma_{\max}}{\gamma_{\rm syn}}\right)^2 \sim E_{\rm syn}\left(\frac{\gamma_{\max}}{\gamma_{\rm syn}}\right)$$

Chernoglazov, HH, Philippov (2023)

also see *HH, Ripperda, Philippov (2023)*

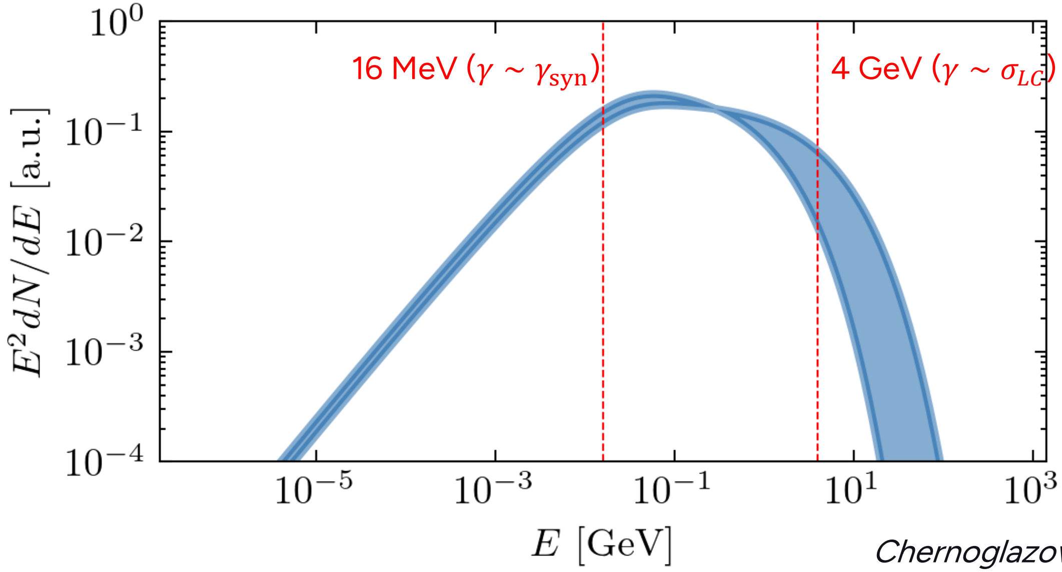
Where does the energy go? emission modeling

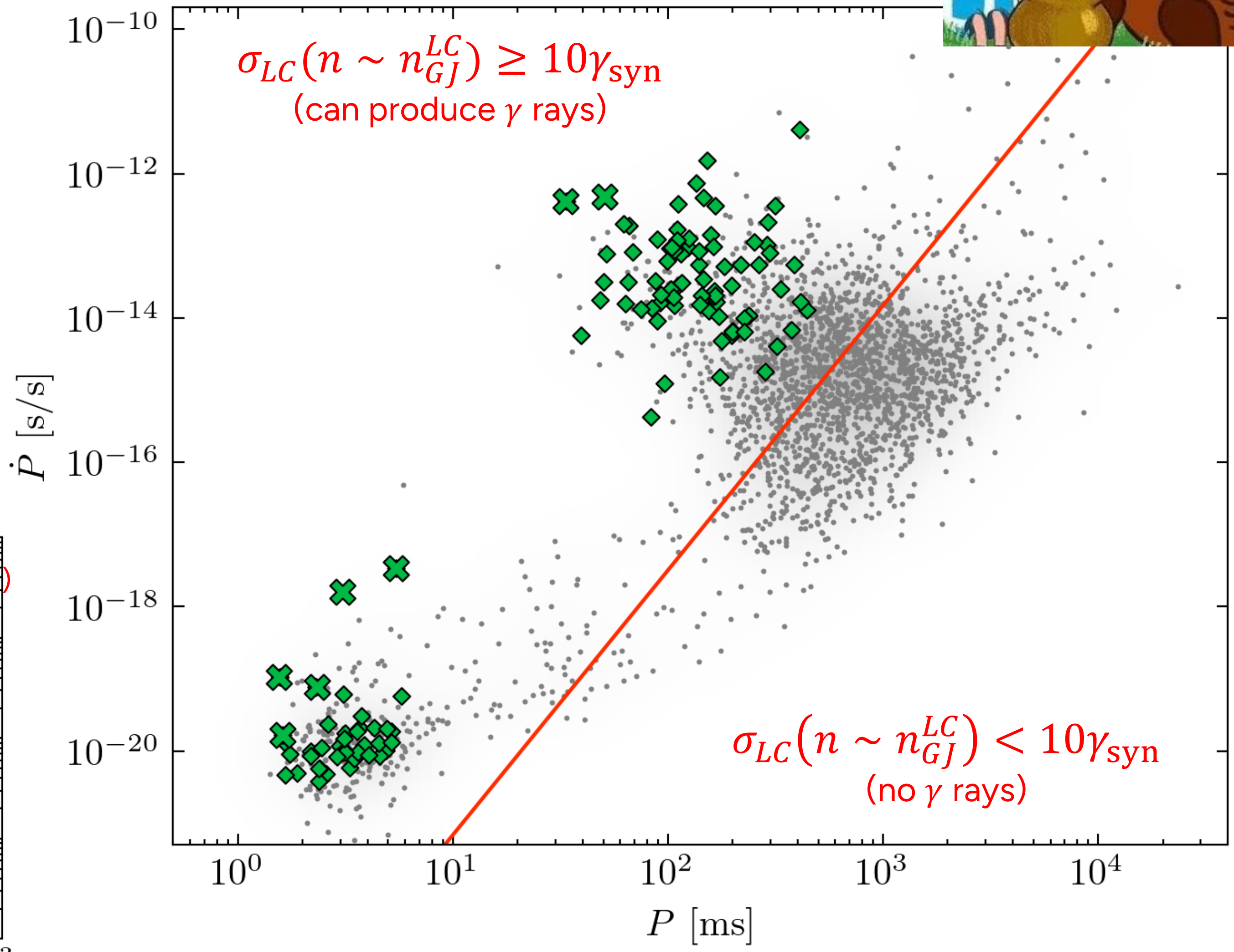
Emission modeling: γ-ray spectra

* Weak cooling regime: $\sigma_{LC} < \gamma_{\rm syn}$
no emission expected around GeV

* Strong cooling regime: $\sigma_{LC} > \gamma_{\rm syn}$
cutoff scales as $E_{\rm cut} \sim 16~\mathrm{MeV} \cdot (\sigma_{LC}/\gamma_{\rm syn})$
(due to pitch-angle anisotropy!)

↓ for Vela parameters
($\gamma_{\rm syn} \sim 10^5$; $\sigma_{LC}/\gamma_{\rm syn} \sim 50 \ldots 250$)

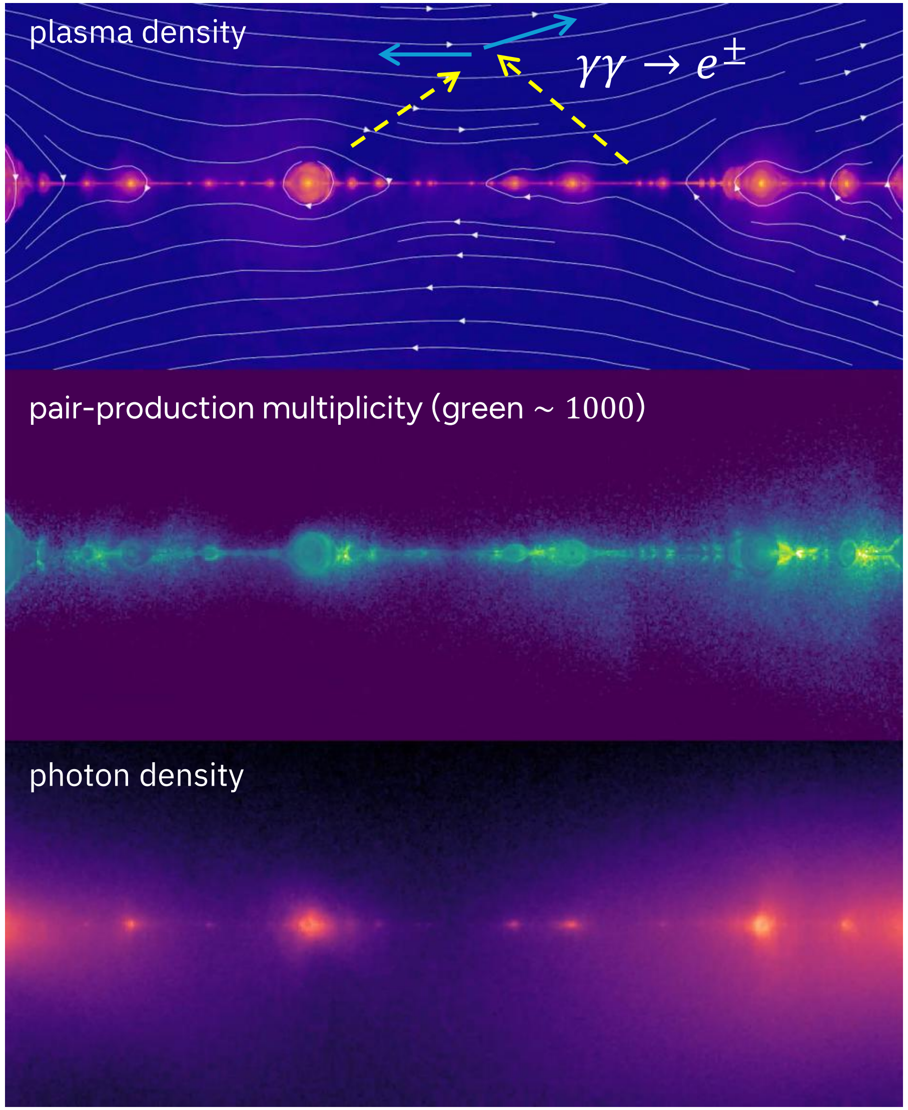




Chernoglazov, HH, Philippov (in prep)

Where does the energy go? emission modeling

Emission modeling: pair-production



$\gamma\gamma \to e^{\pm}$ creates a feedback loop, loading the sheet with plasma and self-regulating σ_{LC}:

$$\gamma_{\max} \sim \sigma_{LC} \quad \& \quad \sigma_{LC} = \frac{1}{2}\frac{\text{voltage}}{\text{multiplicity}}$$

pair production multiplicity:

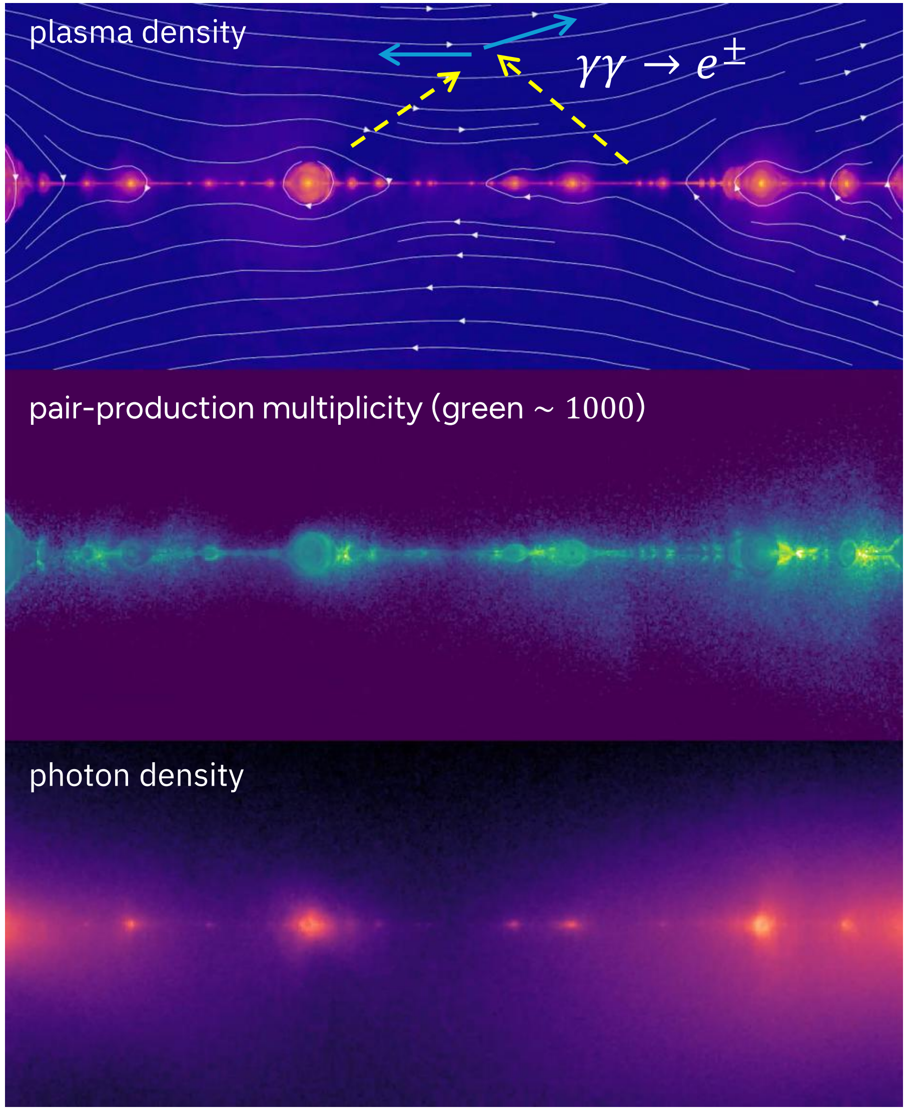
$$\mathcal{M}_{LC} \sim 2 \cdot 10^{6} \left(\frac{\dot{E}}{10^{38}\ \mathrm{erg/s}}\right)^{3/2} \left(\frac{P}{100\ \mathrm{ms}}\right)^{-1} \left(\frac{L_X/\dot{E}}{1\%}\right) \left(\frac{L_\gamma/\dot{E}}{0.1\%}\right)$$

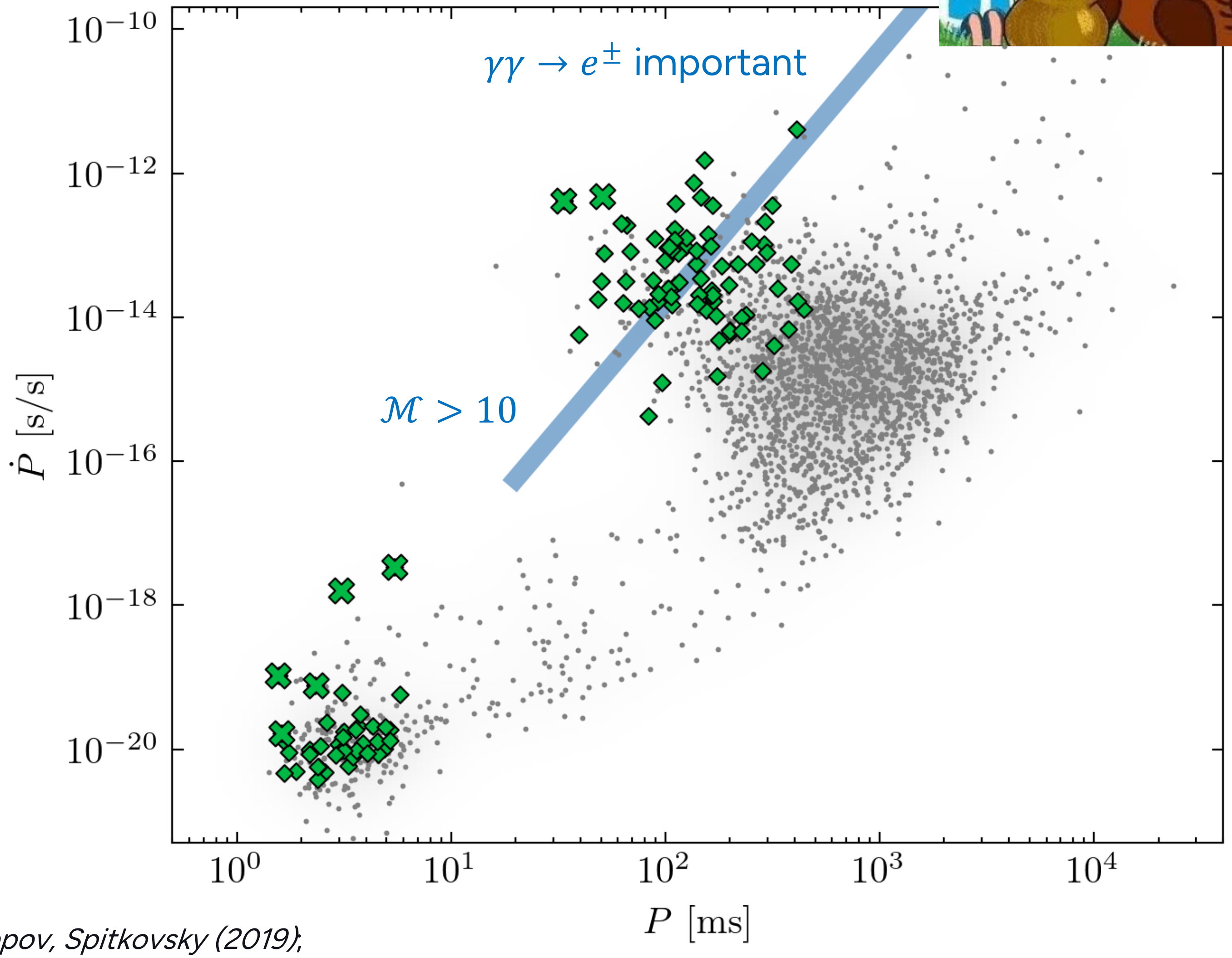
Crab: $\mathcal{M}_{LC} \sim 10^{7}$
Vela: $\mathcal{M}_{LC} \sim 100$

HH, Philippov, Spitkovsky (2019);
also see *Philippov & Kramer (2022)*
mechanism proposed by *Lyubarskii (1996)*

Where does the energy go? emission modeling

Emission modeling: pair-production

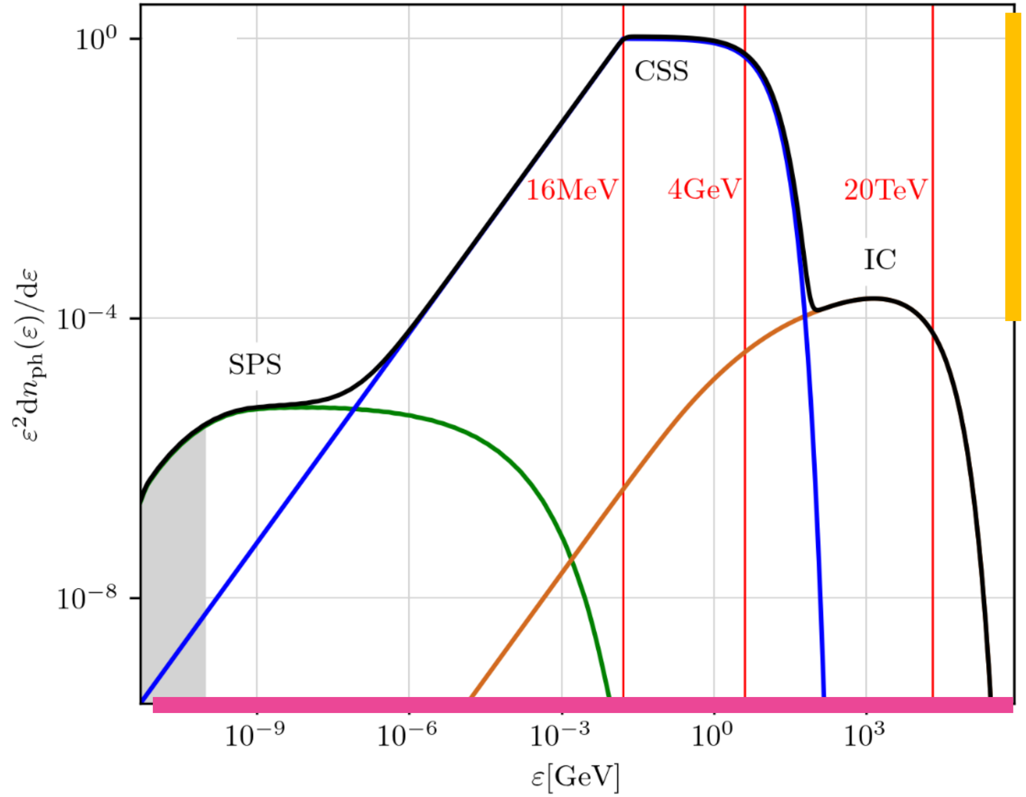




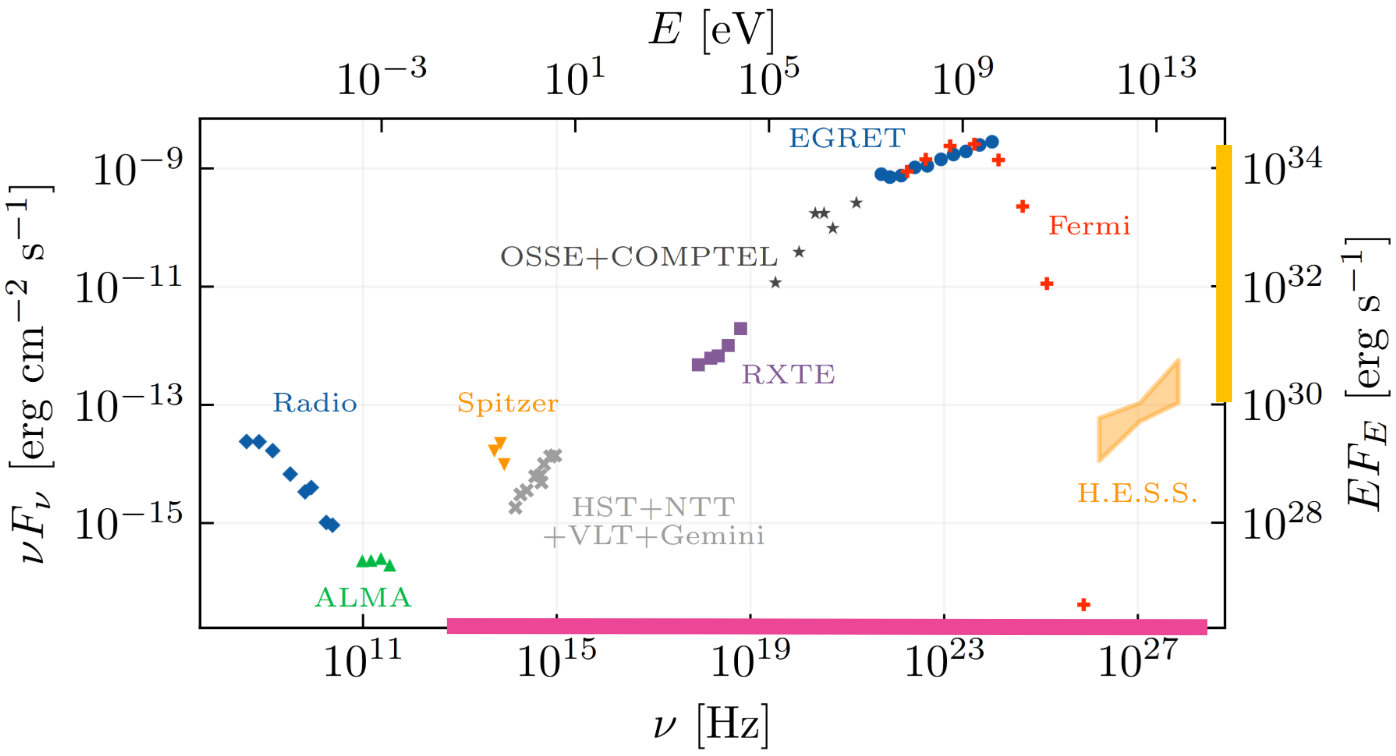
HH, Philippov, Spitkovsky (2019);
also see *Philippov & Kramer (2022)*
mechanism proposed by *Lyubarskii (1996)*

Where does the energy go? emission modeling

Emission modeling: multiwavelength (Vela)



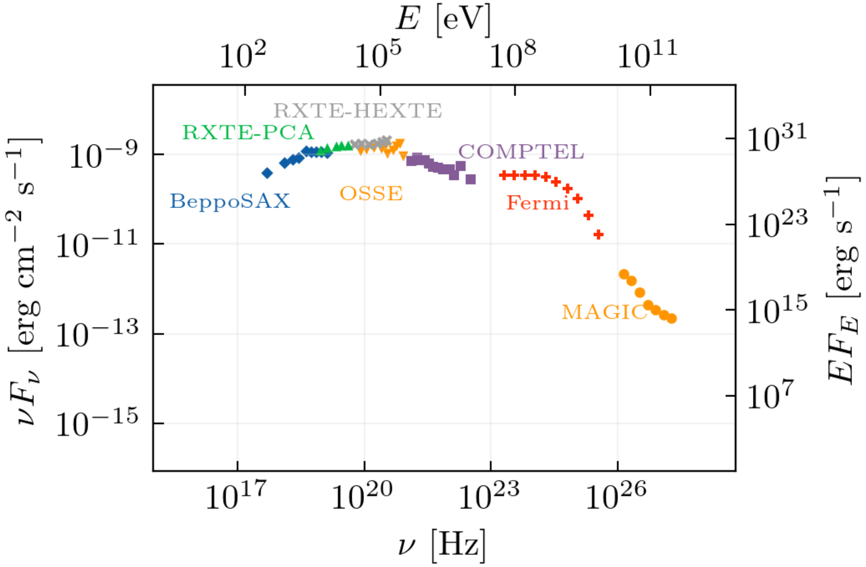
Chernoglazov, HH, Philippov (in prep.)



also see *HH, Ripperda, Philippov (2023 in the context of M87* flares)*

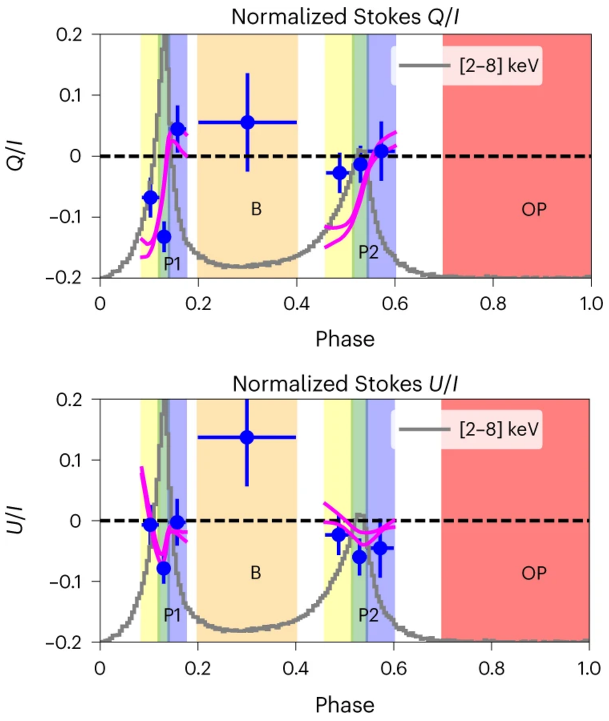
Future challenges: high-energy emission

? Multiwavelength emission of Crab



- no distinct TeV signal
- strong X-ray
- copious $\gamma\gamma \to e^{\pm}$?

? Phase-resolved X-ray polarization in Crab

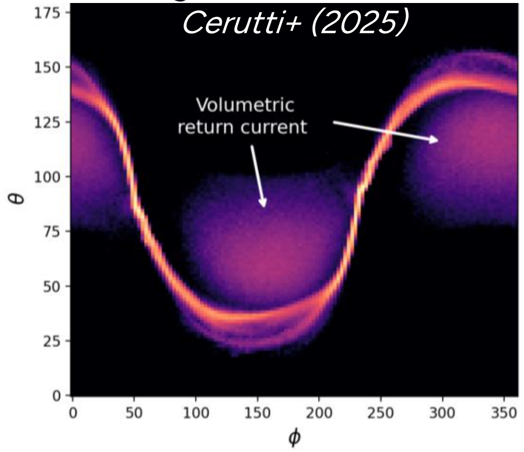


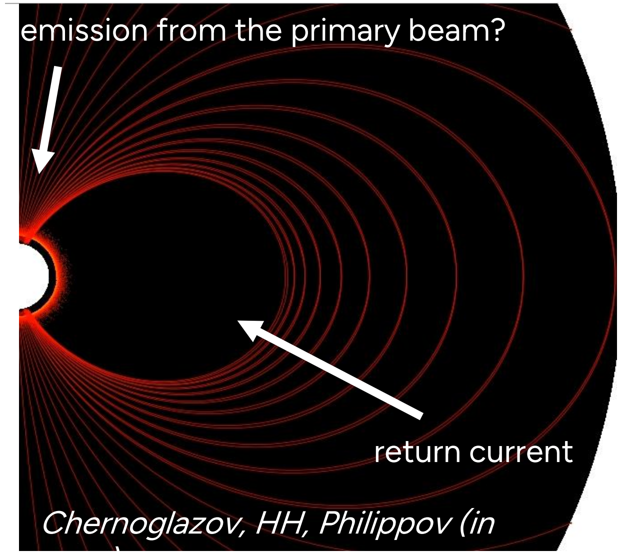
Bucciantini+ (Nature, 2023) with IXPE

dynamics of lower-energy (weakly cooled) pairs

? Alternative sites for high-energy emission

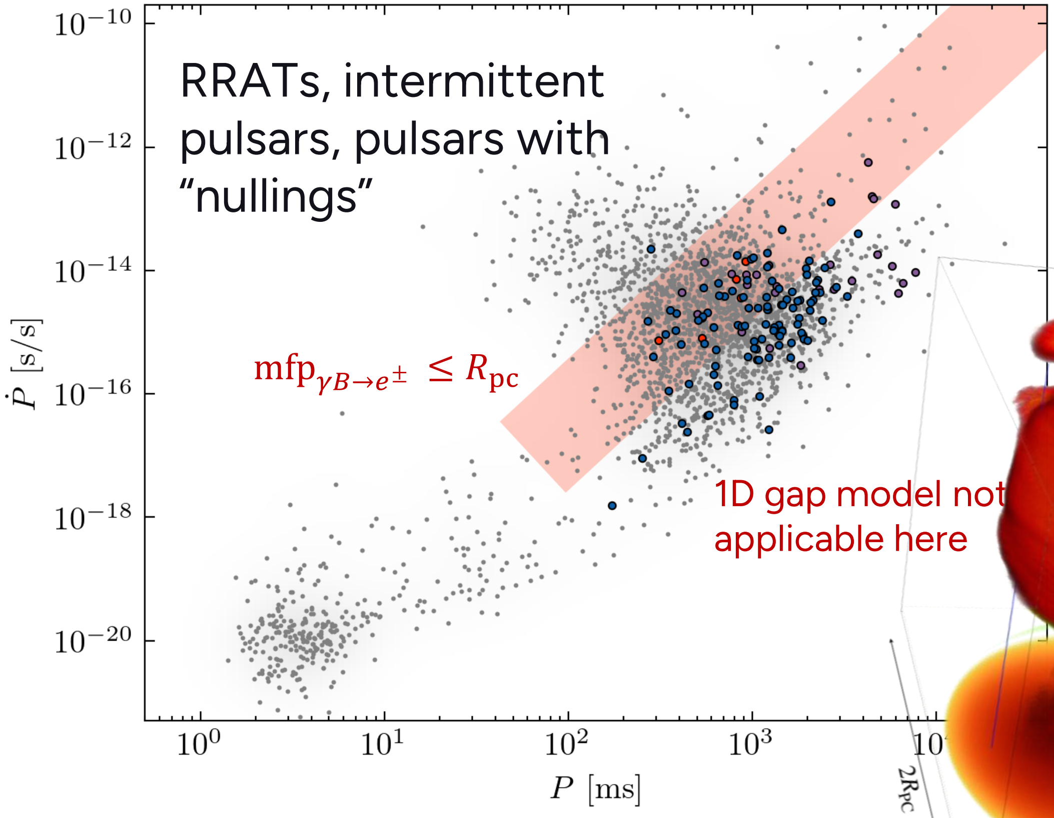
Bridge-emission in Vela?

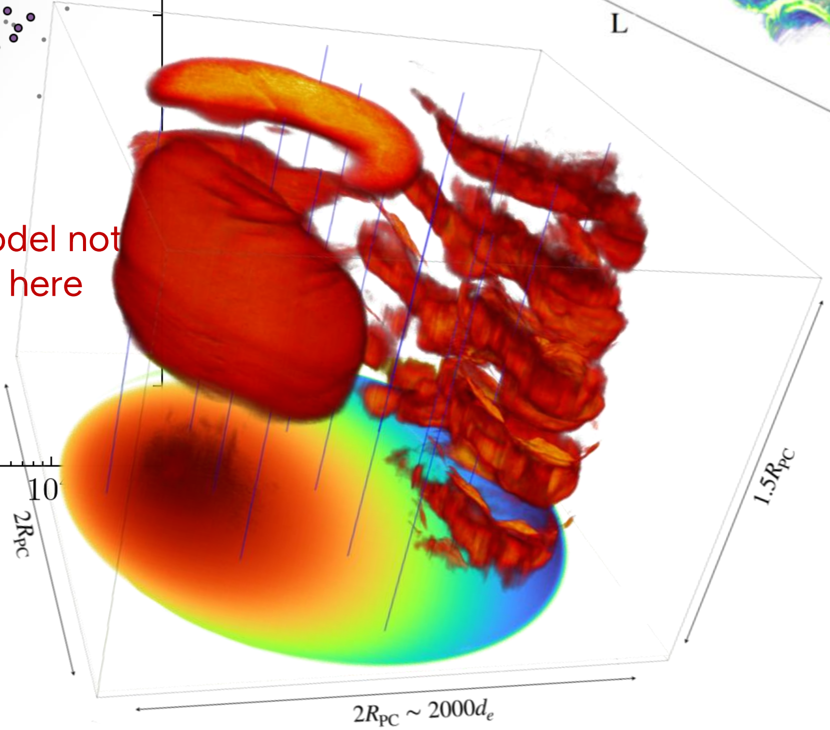




Future challenges: more broadly

? Radio variability & "underfed" pulsars



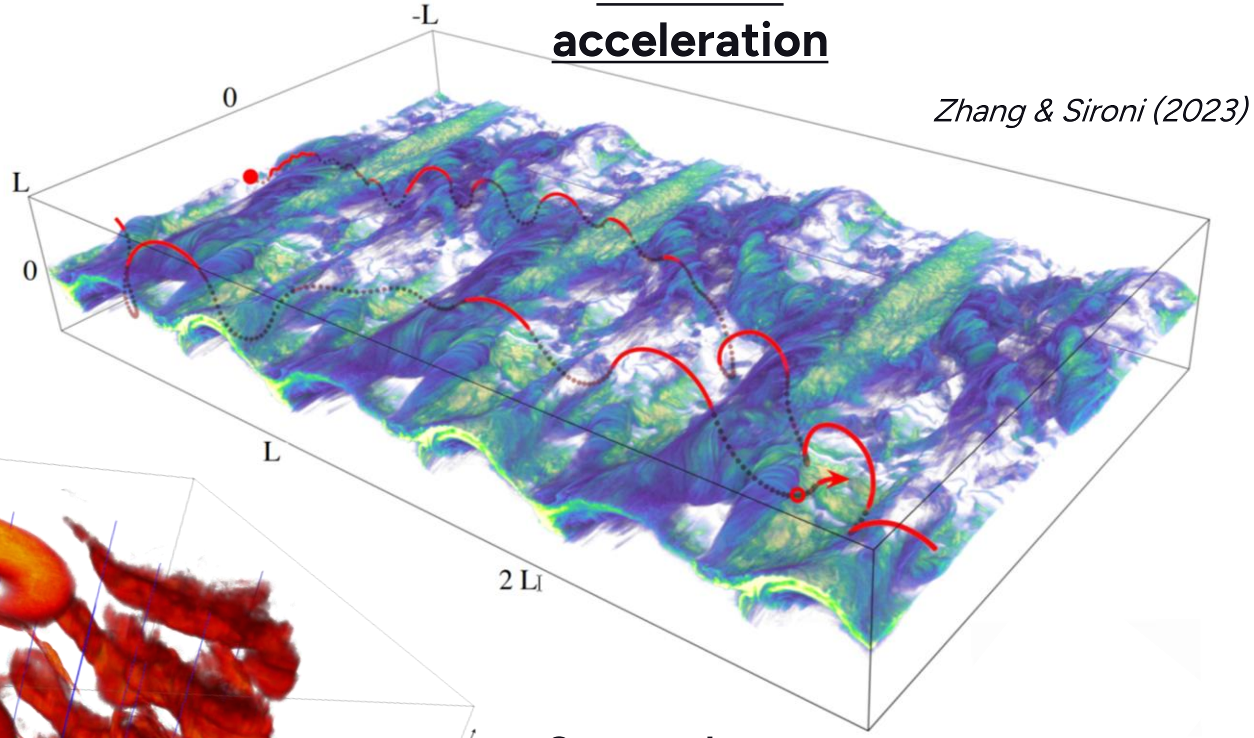


Chernoglazov, Philippov, Timokhin (2024) →

also see *Kalapotharakos+ (2018), Chen+ (2020), Guépin+ (2020), Cruz+ (2024)*

? Proton acceleration

Zhang & Sironi (2023)



Current sheet:

- proton acceleration is not inhibited by synchrotron cooling
- for the youngest pulsars, protons can accelerate to $\gamma \sim 10^7$ ($\sim$ 10 PeV)
- $\mathcal{E}_\pm / \mathcal{E}_i \sim 5\,(n_{GJ}/n_i)(\gamma_{\rm syn}/\sigma_{LC})$

Acceleration In gaps?

How do pulsars shine beyond radio? (the story so far…)

- In well-fed magnetospheres, dissipation occurs only in the equatorial current layer via **magnetic reconnection**
- Current layers emitting synchrotron γ-rays are **strongly cooled** *a-priori*: $\gamma_{\rm syn} \ll \gamma_{\rm max}$
- For the most energetic pulsars ($\dot{E} \geq 10^{35}$ erg/s), most of the **plasma is produced *in-situ*** in the layer via $\gamma\gamma \to e^{\pm}$, potentially producing a lower-energy (opt/UV/keV) counterpart
- Pairs outside the LC are accelerated up to

$$\gamma_{\rm max} \sim \frac{1}{2} \frac{\text{polar cap voltage}}{\text{multiplicity @ LC}}$$

- Emission is beamed along $\boldsymbol{B}$ and cuts off at around

$$\sim 16\ \text{MeV} \cdot (\gamma_{\rm max}/\gamma_{\rm syn})$$

- **Inverse-Compton scattering** of the lower-energy counterpart can produce the observed ~ 20 TeV signal in Vela