Probing Pulsar Winds and Particle Acceleration from High Energy Emission in Spider Pulsars

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Feeling the pull and the pulse of relativistic magnetospheres
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Work with Roger Romani (Stanford), Roger Blandford (Stanford), Lorenzo Sironi (Columbia/CCA)

Spider Pulsars

- MSP in binaries with orbital periods $\mathrm{P_b} < 1$ day
  - Low mass companion $M_c < 1\ M_{\odot}$
- Pulsar irradiates the companion via high energy EM emission
- Intrabinary shock may form between pulsar and companion

Kluzniak et al. (1988)
van Paradijs et al. (1988)
Roberts (2013)
Wadiasingh et al. (2017)
Kandel et al. (2019)
Hui & Li (2019)

Spider Bifurcation

Black Widows

- $M_c \ll 0.1\ M_\odot$

- Shock wraps around companion

Redbacks

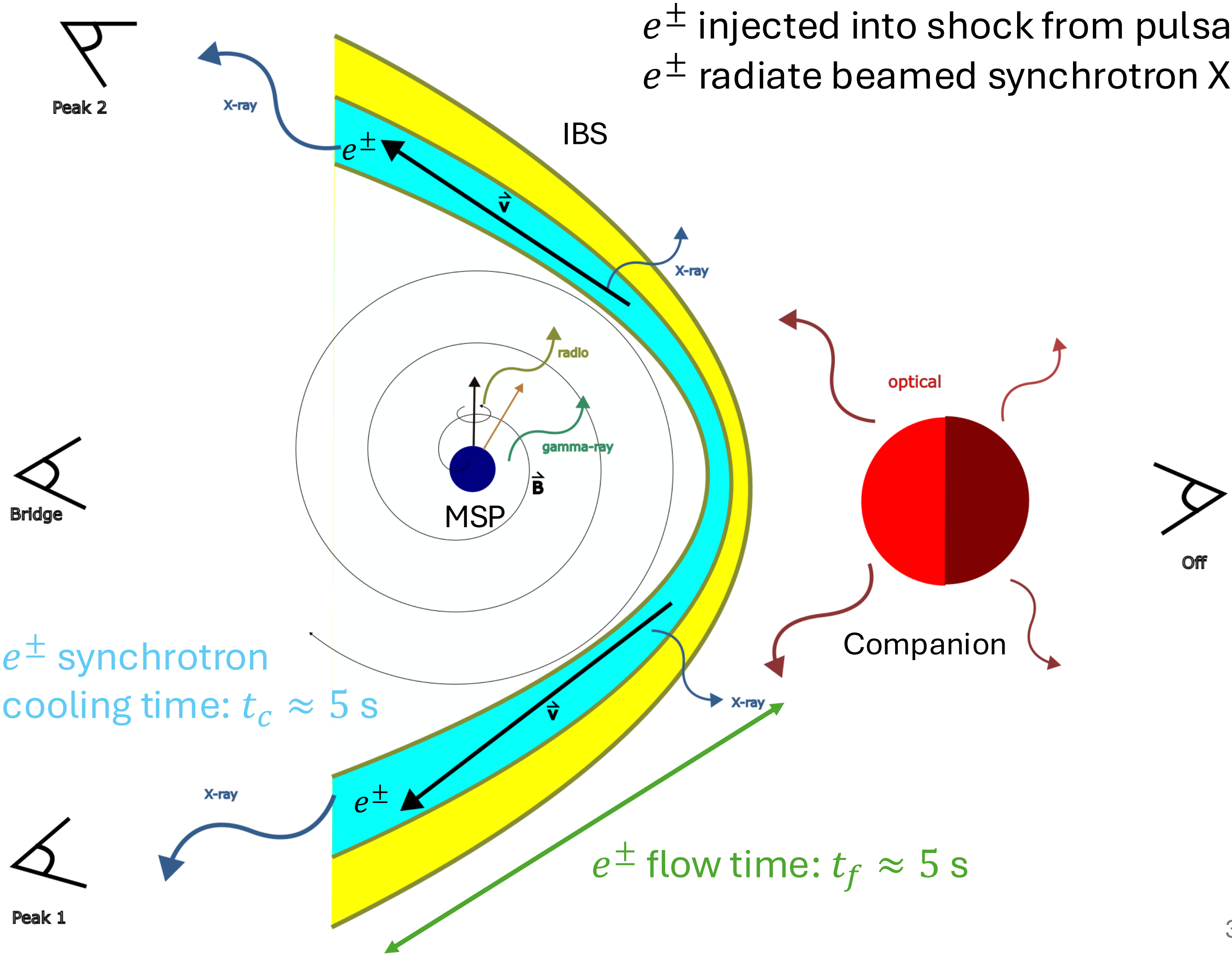
- $M_c \sim 0.1 - 0.4\ M_\odot$

- Shock wraps around pulsar

Wadiasingh et al. (2017)
Kandel et al. (2019)

Global Picture

$e^{\pm}$ injected into shock from pulsar wind
$e^{\pm}$ radiate beamed synchrotron X-rays



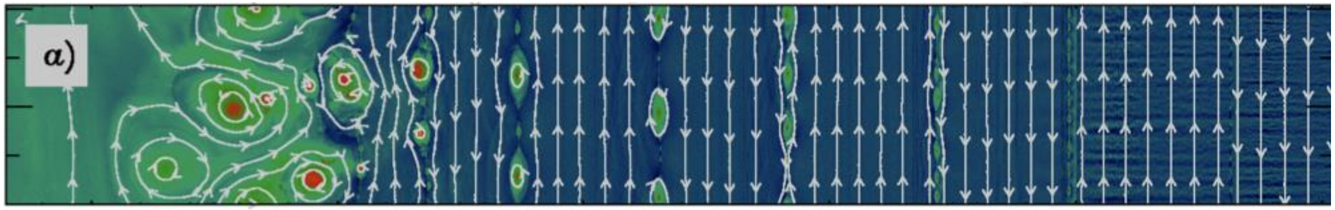
Outline

- **Part I** – Intrabinary shocks as a pulsar wind probe
- **Part II** –Numerical modeling of black widow intrabinary shocks in 3D
- **Part III** – Pulsar wind properties from redback X-ray observations

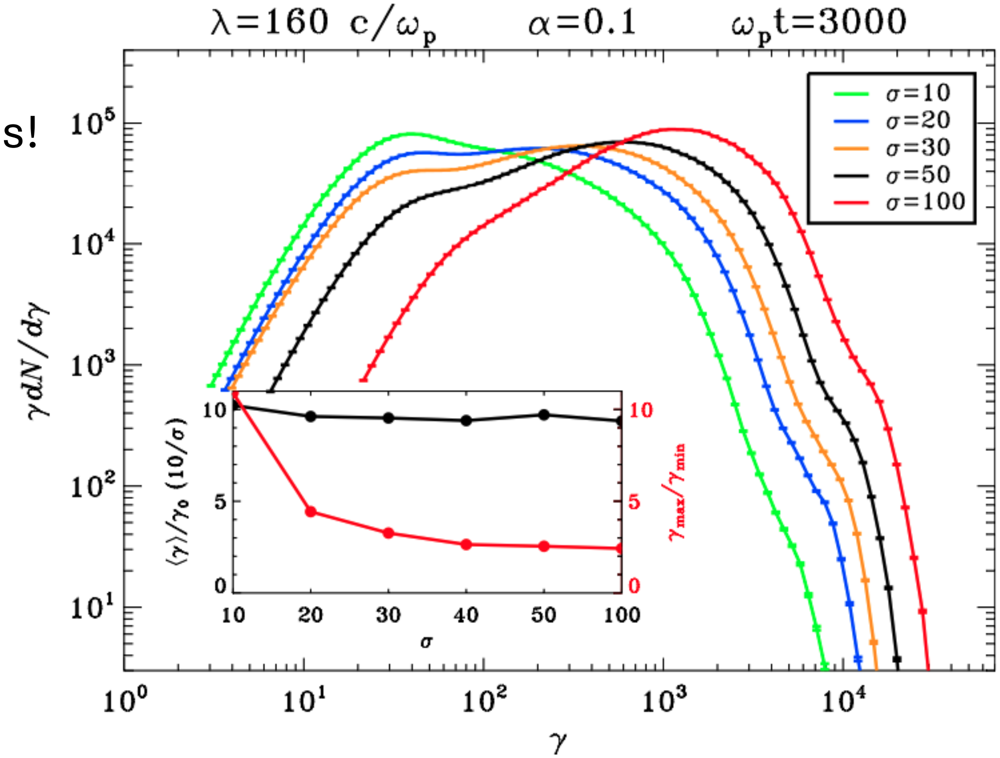
Part I

Intrabinary shocks as a pulsar wind probe

Local shock particle acceleration

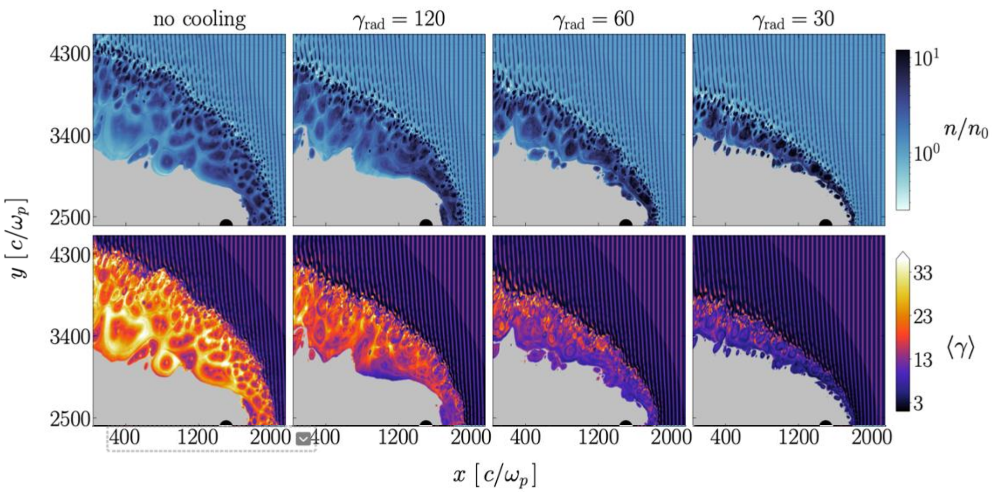


- Striped wind B reconnects!
- Efficient particle acceleration up to $\gamma \sim \sigma$



Sironi & Spitkovsky (2011)

Global intrabinary shock models

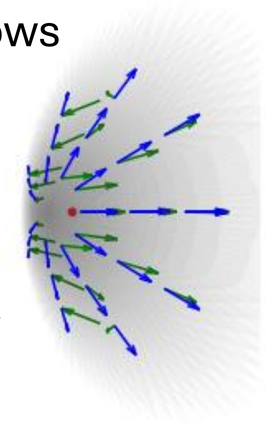


PIC for Black Widows in 2D

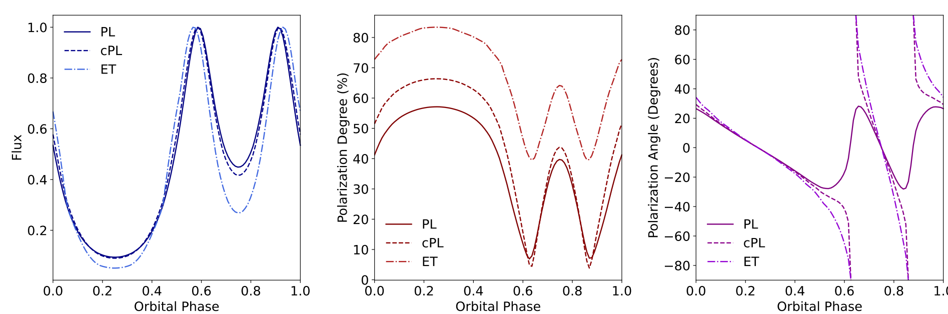
Cortés & Sironi (2022)
Cortés & Sironi (2024)
Cortés & Sironi (2025)

Semi-analytic 3D geometry

for Redbacks and Black Widows



Predict synchrotron X-ray flux and polarization patterns



Kandel et al. (2019)
Sullivan & Romani (2023)

Part II

Numerical modeling of black widow intrabinary shocks in 3D

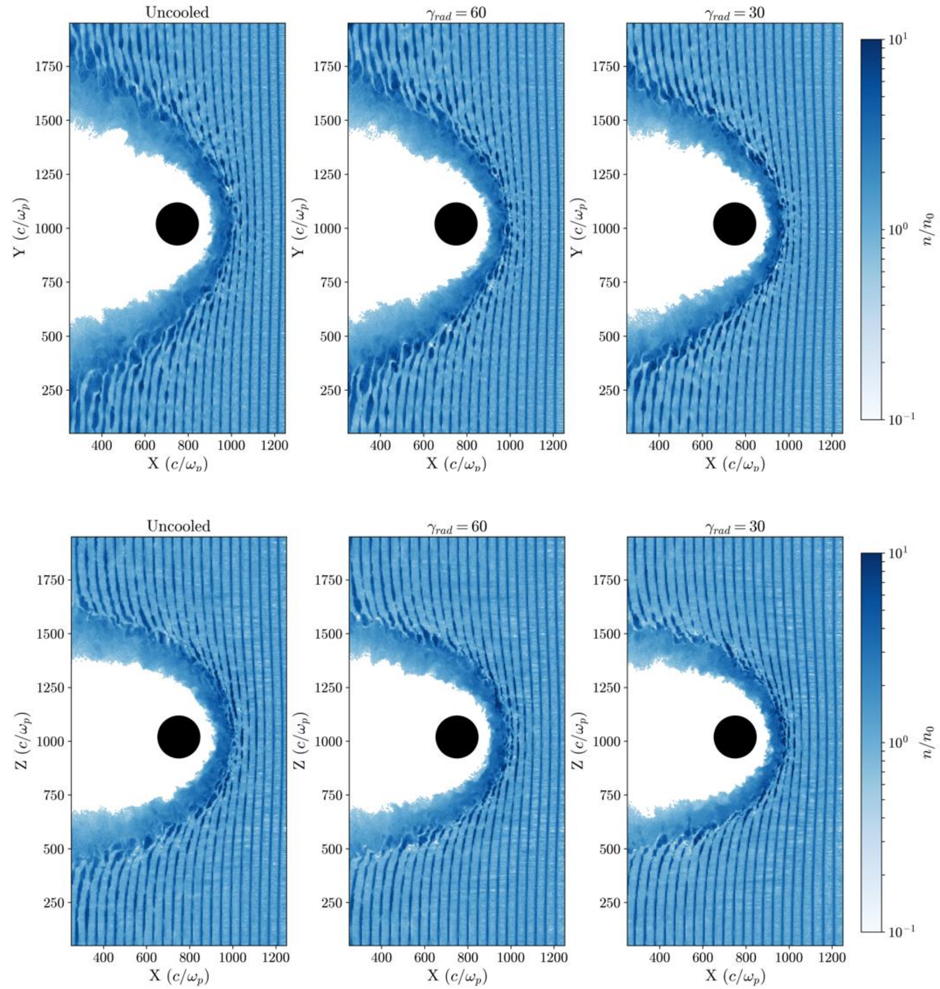
3D Shock Modeling in PIC

$t = 3262.5\ \omega_p$

$$B_y(x,t) = B_0 \tanh\left\{\frac{1}{\Delta}\left(\alpha + \cos\left(\frac{2\pi(x+\beta_0 ct)}{\lambda}\right)\right)\right\}$$

$$\sigma = \frac{B^2}{4\pi n_0 \gamma_0 m_e c^2} = 10$$

Radiative cooling with reduced Landau-Lifshitz formalism



Sullivan, Sironi, & Cortés (in prep.)

Particle and Emission Spectra

$$\frac{dN_e}{d\log(\gamma - 1)} \propto \gamma^{-p}; p \approx 1.6$$

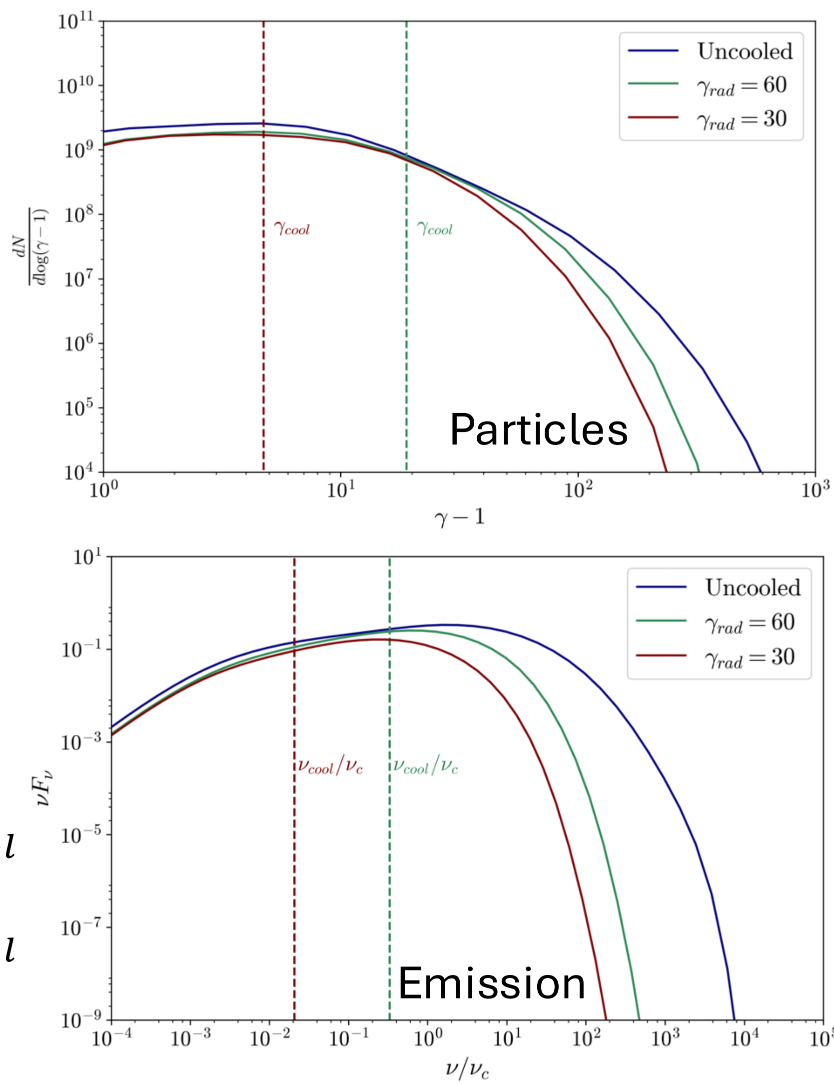
$$\frac{\nu_{cool}}{\nu_c} = \frac{1}{\eta^2}\frac{c/\omega_p}{R_c}\frac{\gamma_{rad}^4}{(1+\sigma)^2\sigma\,\gamma_0^4}$$

$$\frac{dN_\gamma}{d\nu} \propto \frac{F_\nu}{\nu} \propto \nu^{-\Gamma}$$

$\Gamma \approx 1.7, \nu < \nu_{cool}$

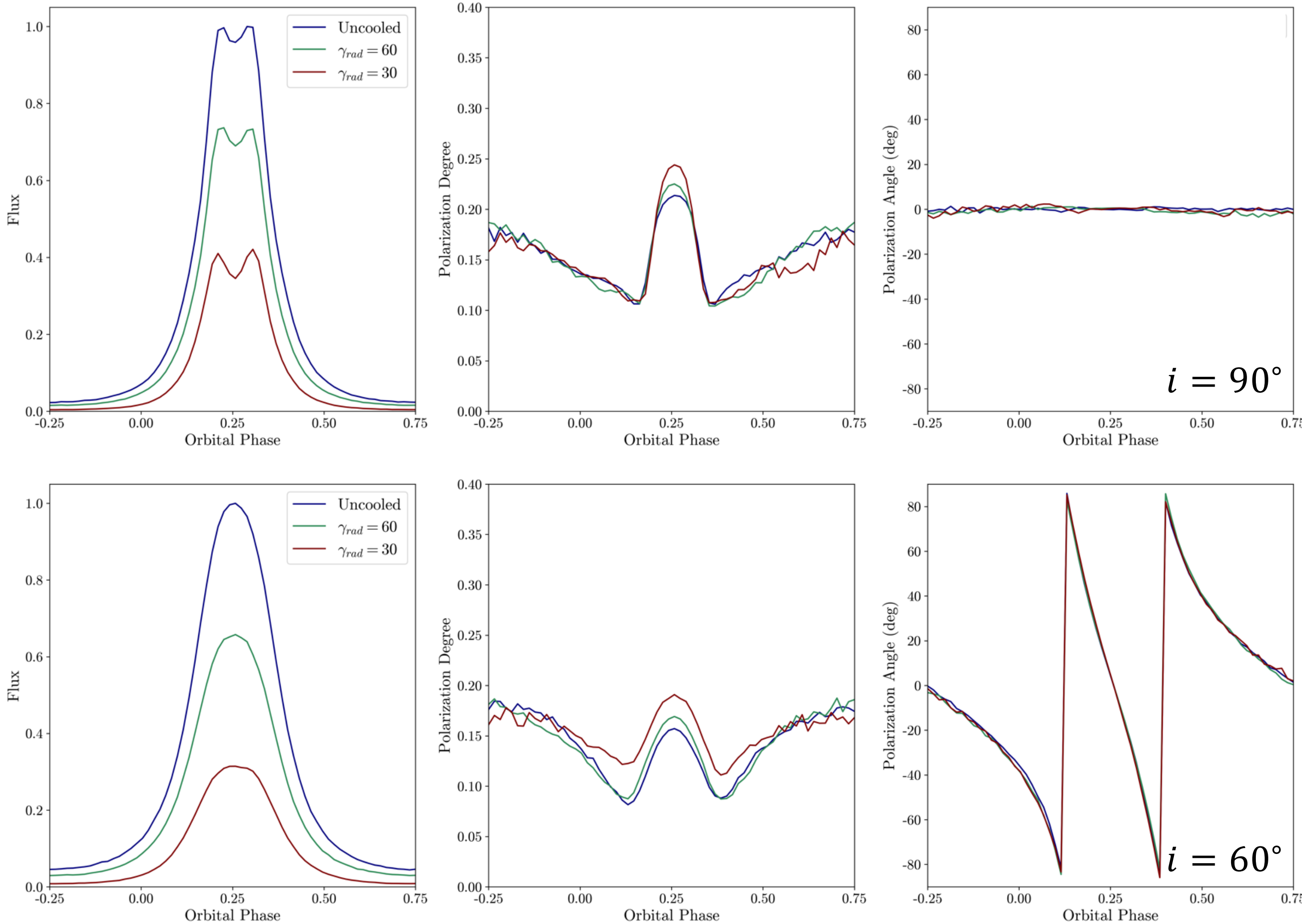
$\Gamma \approx 2.0, \nu > \nu_{cool}$

$t = 3262.5\ \omega_p$



Sullivan, Sironi, & Cortés (in prep.)

Polarized Emission Patterns

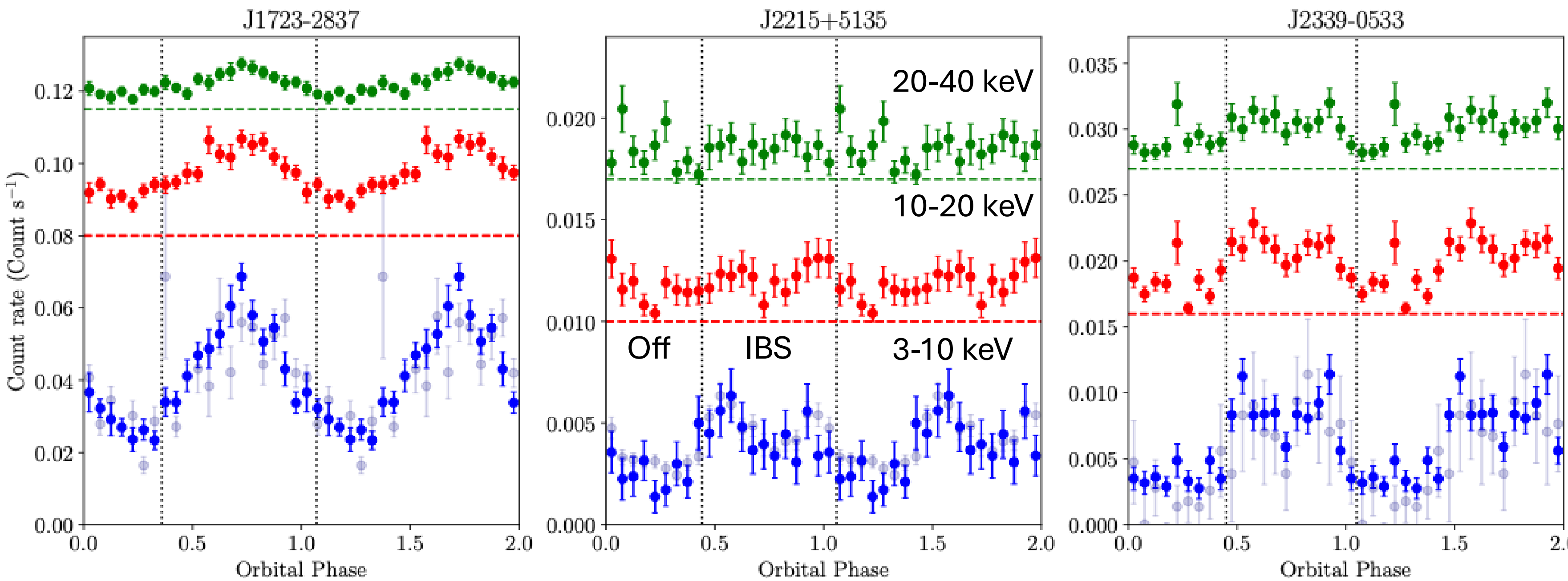


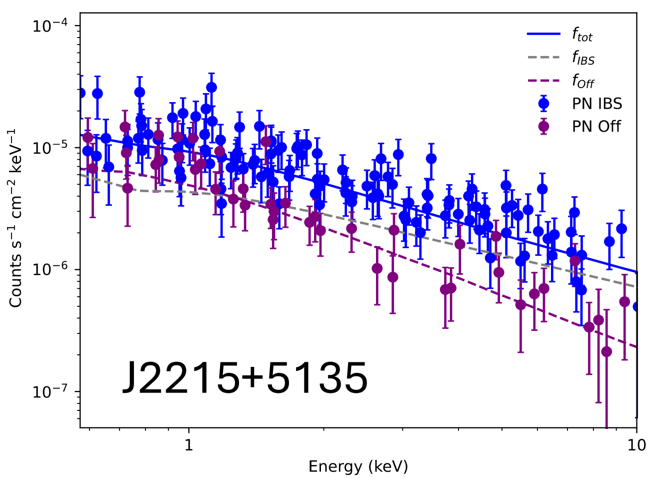
Sullivan, Sironi, & Cortés (in prep.)

Part III

Pulsar wind properties from redback X-ray observations

Orbital Phase Modulated Emission





Hard IBS component

$$f(E) = \begin{cases} e^{-N_H\sigma(E)}\left(K_{IBS}E^{-\Gamma_{IBS}} + K_0E^{-\Gamma_0}\right) & \text{IBS} \\ e^{-N_H\sigma(E)}K_0E^{-\Gamma_0} & \text{Off} \end{cases},$$

Soft phase independent component

Sullivan & Romani (2024)
Sullivan & Romani (2025)

High energy spectral features

- Synchrotron cooling break at energy E_b
  - Spectral index increases by $\Delta\Gamma = +0.5$

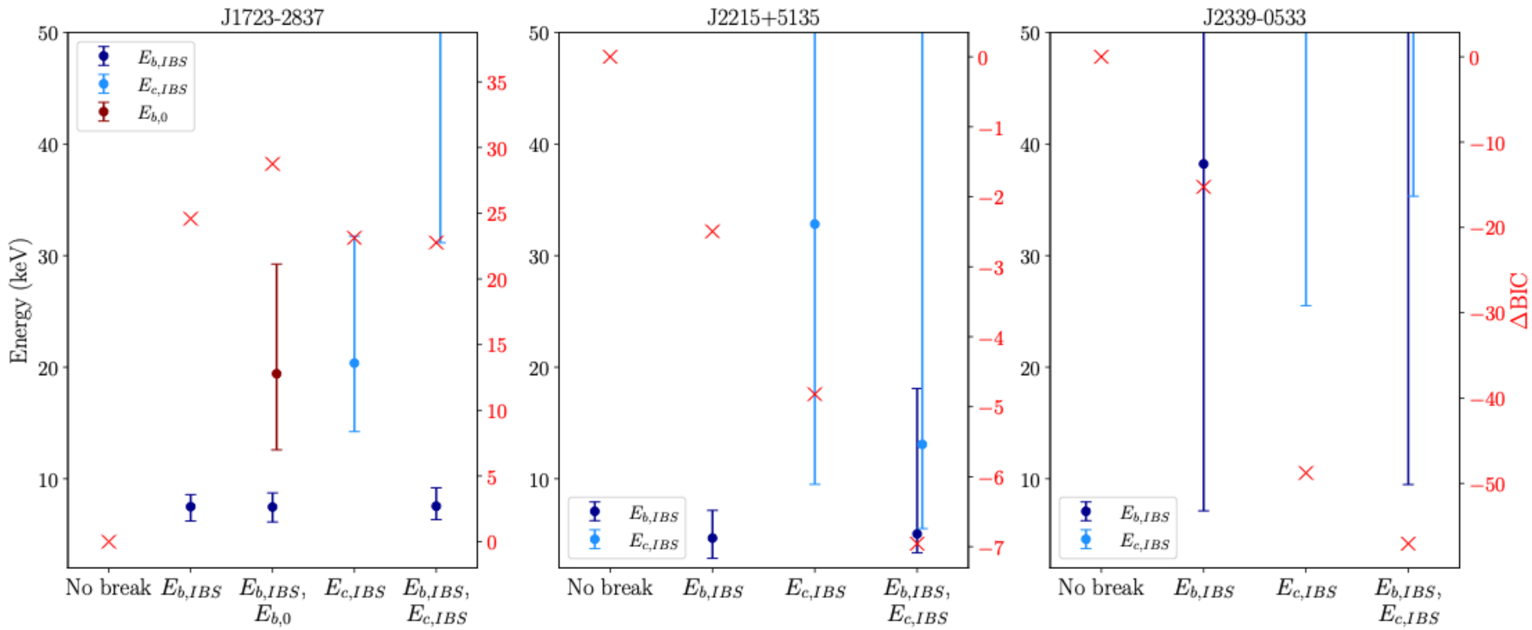
$$B_{IBS,\perp} = \frac{3}{2}\left(\frac{m_e^5 c^9 \hbar}{e^7 E_b t_f^2}\right)^{\frac{1}{3}} \approx 65\,\mathrm{G}\left(\frac{E_b}{10\,\mathrm{keV}}\right)^{-\frac{1}{3}}\left(\frac{t_f}{3\,\mathrm{s}}\right)^{-\frac{2}{3}}$$

- Exponential cutoff at energy E_c
  - Scale spectra by $\exp(-E/E_c)$

$$\gamma_{max} = 2 \times 10^5 \left(\frac{E_c}{100\,\mathrm{keV}}\right)^{-\frac{1}{2}} \left(\frac{B}{65\,\mathrm{G}}\right)^{-\frac{1}{2}}$$

Sullivan & Romani (2025)

Models with high spectral features



Object	B_{LC} (10^5 G)	Γ_{IBS}	Γ_0	$E_{b,IBS}$ (keV)	$E_{c,IBS}$ (keV)	B_{IBS} (G)	γ_{max} (10^5)
J1723−2837	1.6	$0.85^{+0.13}_{-0.12}$	$1.21^{+0.06}_{-0.06}$	$7.5^{+1.3\dagger}_{-1.3}$	> 32	38^{+2}_{-2}	> 2.2
J2215+5135	1.2	$0.84^{+0.13}_{-0.12}$	$1.29^{+0.16}_{-0.15}$		> 9.5		> 1.0
J2339−0533	0.73	$0.94^{+0.18}_{-0.20}$	$1.71^{+0.42}_{-0.15}$		> 35		> 1.9

Sullivan & Romani (2025)

Magnetosphere constraints

$$\sigma_{pw} \approx 3 \times 10^5 \left(\frac{\lambda}{10^3}\right)^{-1} \left(\frac{P}{2\text{ ms}}\right)^{-1} \left(\frac{B_{LC}}{10^5\text{ G}}\right) \sim \gamma_{max}$$

Pair multiplicity

J1723-2837

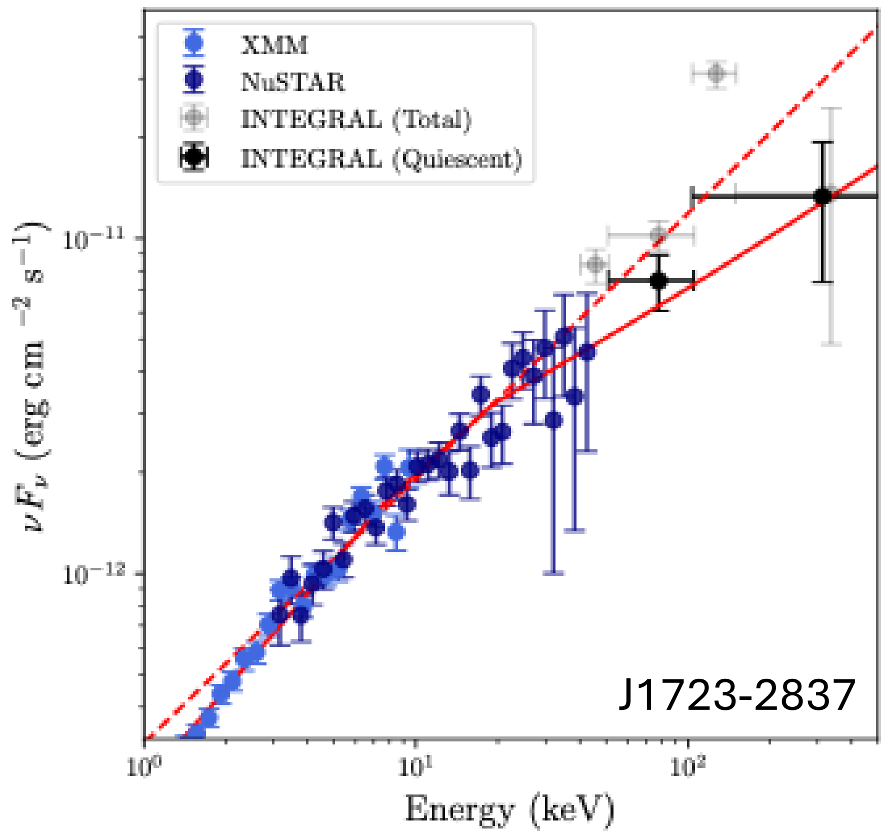
Synchrotron cooling break: $B_{IBS} \approx 40$ G
Spectral cutoff: $\gamma_{max} > 2.2 \times 10^5$
Reconnection: $\lambda < 2.3 \times 10^3$

J2215+5135

$B_{IBS} \approx 70$ G
$\gamma_{max} > 1.0 \times 10^5$
$\lambda < 2.8 \times 10^3$

J2239-0533

$B_{IBS} < 60$ G
$\gamma_{max} > 1.9 \times 10^5$
$\lambda < 8.0 \times 10^2$



Sullivan & Romani (2025)

Summary

- Global 3D modeling provides testable predictions for intrabinary shock emission
  - Spectral features $\Gamma < 1.7$
  - Polarization patterns – PD > 20%

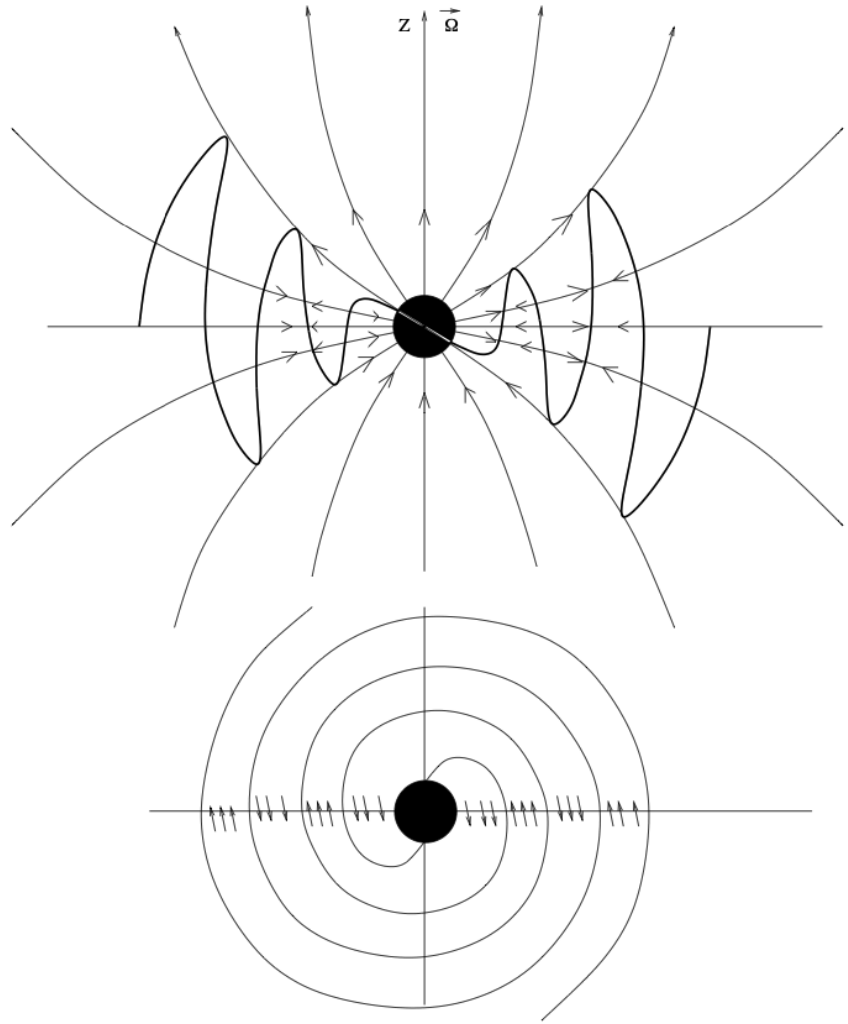
- High energy X-ray observations probe physics of shocked pulsar wind
  - Emission spectral indices $\Gamma_{IBS} \sim 0.8 - 0.9$ → $p \sim 0.6 - 0.8$
  - Cooling breaks $E_b \approx 5 - 8$ keV → $B_{IBS} \approx 40 - 70$ G
  - Exponential cutoffs $\mathrm{E_c} > 10$ keV → $\gamma_{max} > 10^5$

- Observations constrain MSP magnetospheric properties:
  - Pulsar wind magnetization: $\sigma > 10^5$
  - Pair multiplicity: $\lambda < 2 \times 10^3$

Extra Slides

Pulsar Wind

- Wind region at $r > R_{LC}$
- Magnetically dominated $\sigma \gg 1$
- $B_\phi \propto \frac{1}{r}$
- “Striped” for oblique rotator



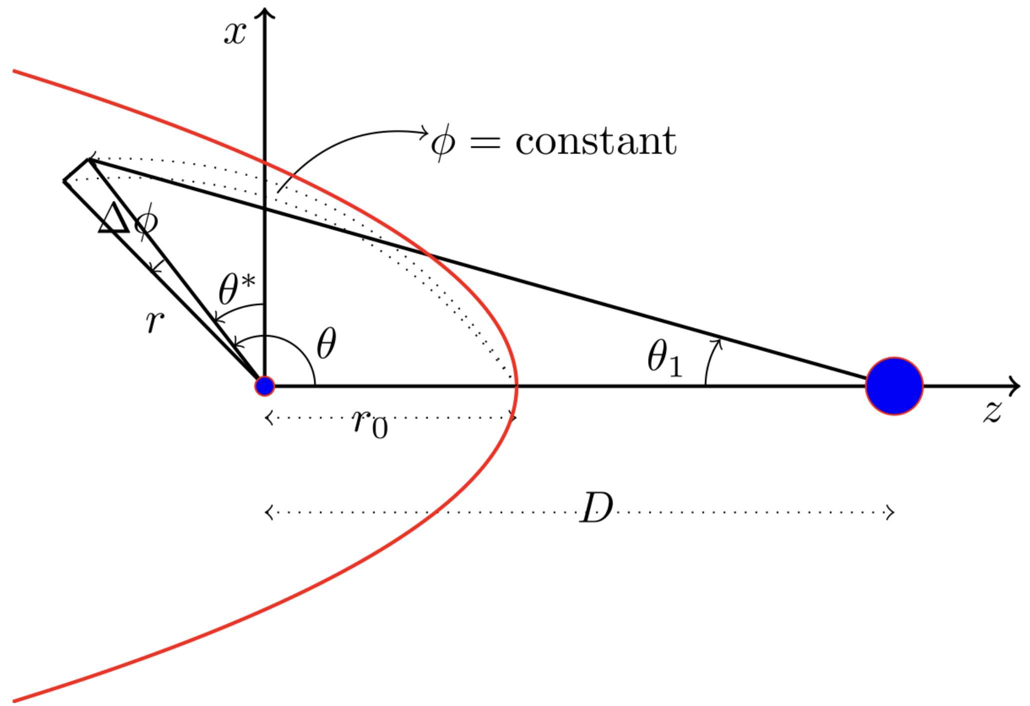
Bogovalov (1999)

Intrabinary Shock Geometry

- $d\dot{E}_p = \frac{\dot{E}_{PSR}}{4\pi} \sin^{2n}\theta_\star \sin\theta' d\theta'$

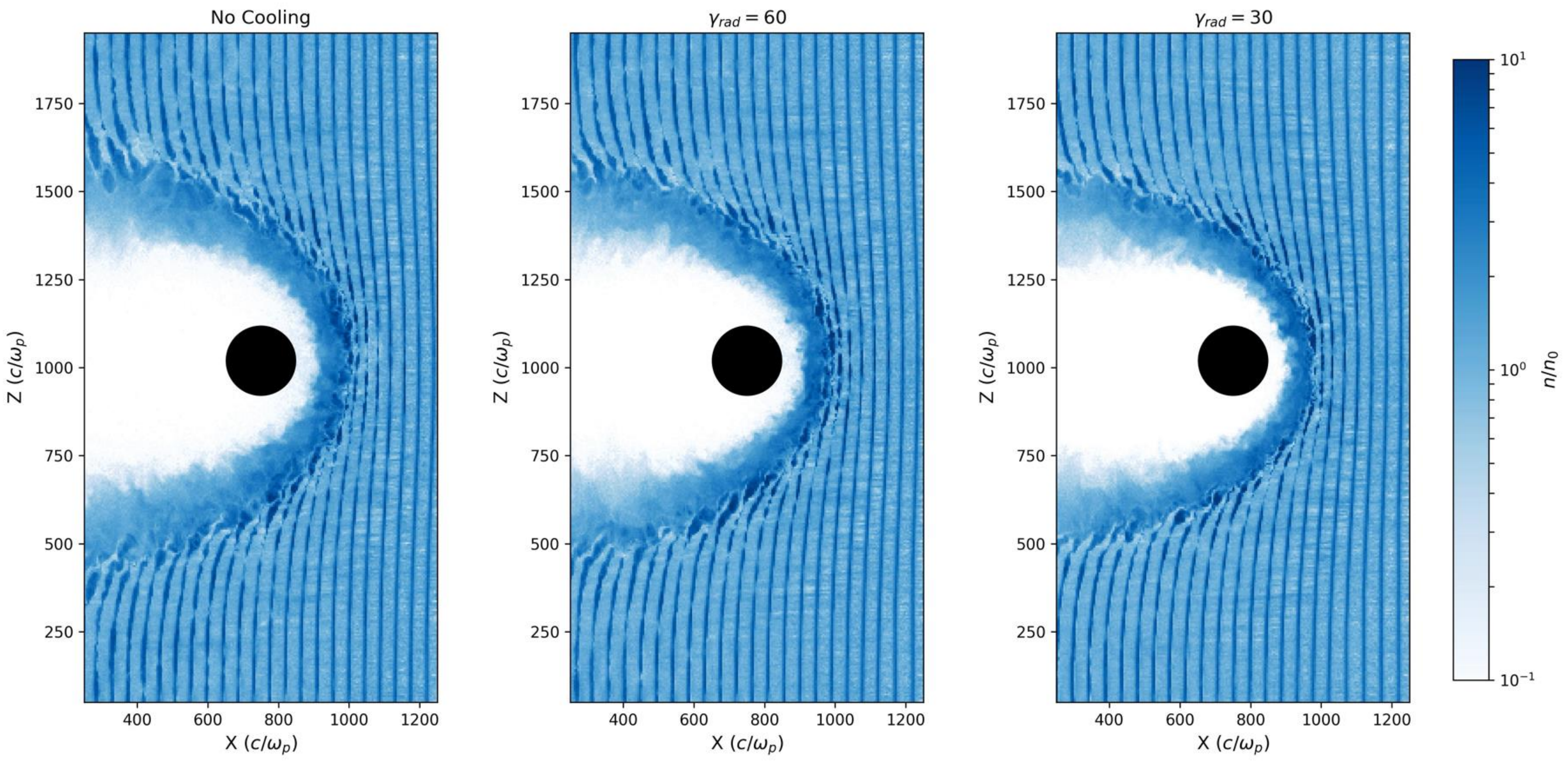
- Assume momentum flux $\Pi = \int d\dot{E}_p$ balances companion wind $f_c(r)$

- $f_c(r) = \frac{\dot{M} v_w}{4\pi r^2}$



Romani & Sanchez (2016)
Kandel et al. (2019)

3D PIC Movie



No Cooling
$\gamma_{rad} = 60$
$\gamma_{rad} = 30$
1750
1500
1250
1000
750
500
250
Z (c/ω_p)
400
600
800
1000
1200
X (c/ω_p)
10^1
10^0
10^{-1}
n/n_0

Polarized Emission

- Compute Stokes Parameters
  - $Q = \left(L_{\perp} - L_{||}\right)\left[\left(\vec{e} \cdot \hat{l}_{proj}\right)^2 - \left(\vec{e} \cdot \left(\vec{n} \times \hat{l}_{proj}\right)\right)^2\right]$
  - $U = \left(L_{\perp} - L_{||}\right)\left[\left(\vec{e} \cdot \hat{l}_{proj,45^\circ}\right)^2 - \left(\vec{e} \cdot \left(\vec{n} \times \hat{l}_{proj,45^\circ}\right)\right)^2\right]$
- Polarization degree and Polarization Angle
  - $\Pi = \frac{\sqrt{Q^2+U^2}}{L}$
  - $\chi = \arctan_2\left(\frac{U}{Q}\right)$

$\alpha = 0.0$ vs. $\alpha = 0.1$