Electrodynamics of Gaps: Magnetar and Beyond

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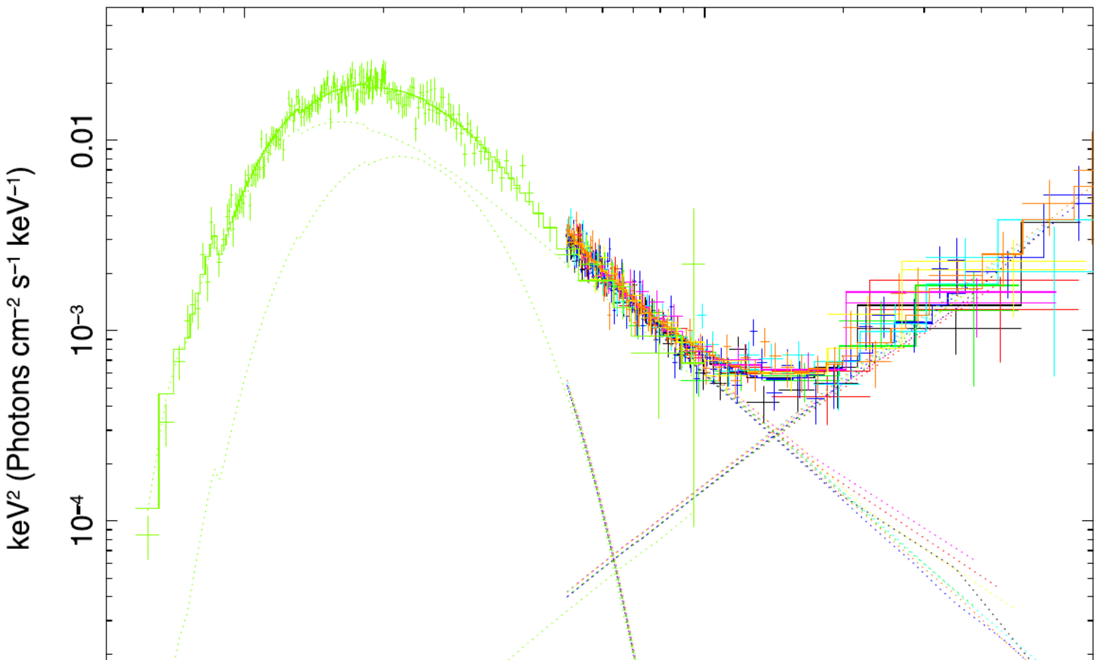
Magnetars: Phenomenology

Magnetars are slowly rotating, isolated neutron stars with extra-strong magnetic field. They are usually bright X-ray sources with luminosity much higher than their spin-down luminosity.

Spin period P and spindown $\dot{P}$ have been measured for most known magnetars. Most have $B > 10^{14}$ G.

Persistent Magnetars

Persistent emission spectrum from 1E 2259+586 (Vogel et. al. 2014)



Persistent Magnetars

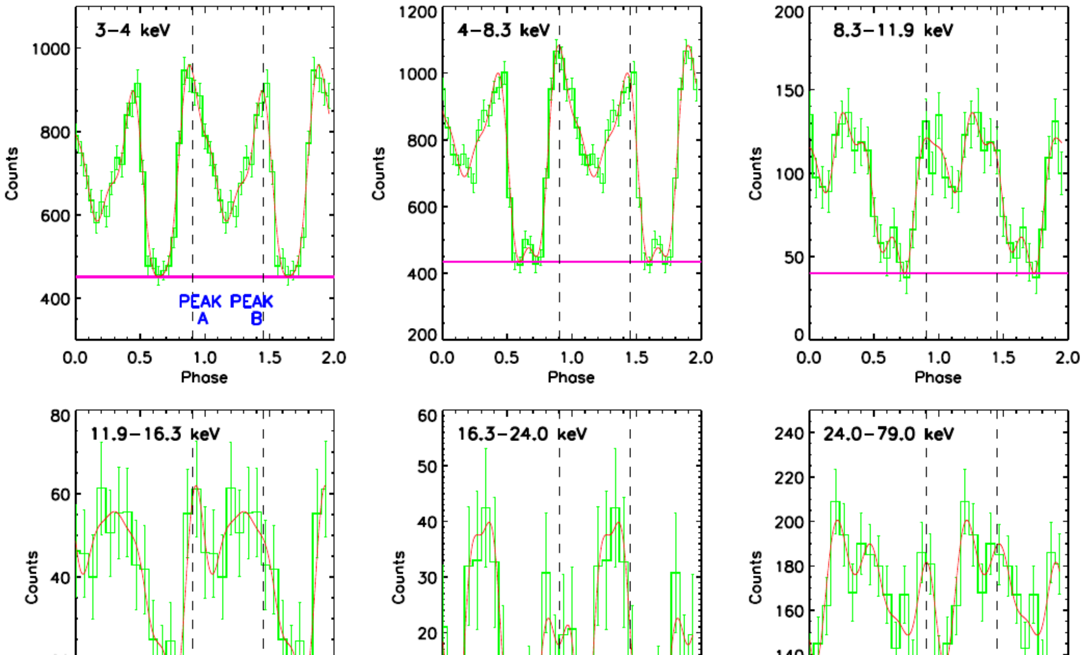
Photon index for several known persistent magnetars with measured hard X-ray spectrum (Olausen & Kaspi 2014)

Name	Pulsed Emission		Total Emission		E_{cut} (keV)
	Γ^p	$F^p_{20-150\text{keV}}$	Γ^t	$F^t_{20-150\text{keV}}$	
4U 0142+61	$0.40(15)$	$2.68(1.34)$	$0.93(6)$	$9.09(35)$	279^{+65}_{-41}
SGR 0501+4516	...	...	$0.79^{+0.20}_{-0.16}$	< 3.5	> 100
1E 1841-045	$0.72(15)$	~ 4.0	$1.32(11)$	~ 6.9	> 140
1E 2259+586	$-1.02(24)$	~ 5.9	$0.4(1)$	< 2.0	...
1RXS J170849.0	$0.86(16)$	$2.60(35)$	$1.13(6)$	$5.2(1.0)$	> 300

Photon index Γ defined by $dN/dE \sim E^{-\Gamma}$. Therefore $\nu F_\nu \sim E^{2-\Gamma}$

Persistent Magnetars

Pulse profiles of 1E 2259+586 at different energy bands look completely different (Vogel et. al. 2014)



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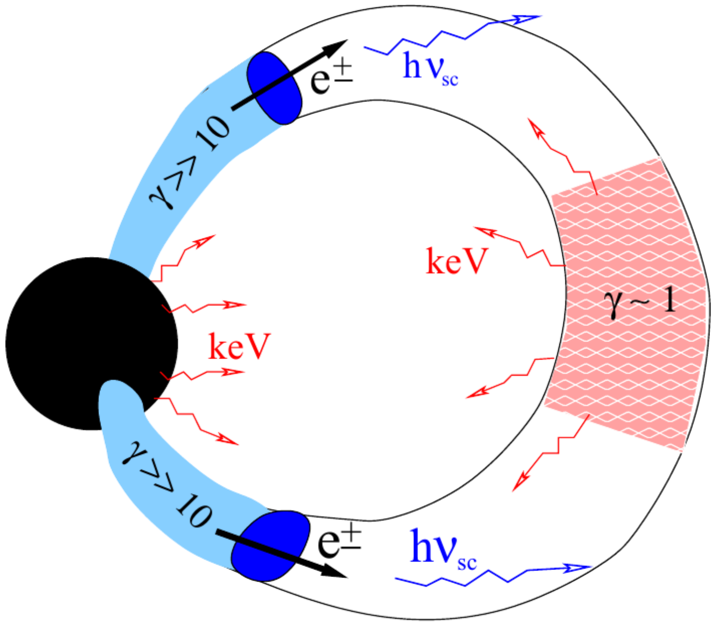
Coronal Outflow Model

Gap near the foot of the corona, creating pair outflow which decelerates due to resonant scattering. (Beloborodov 2013)



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Resonant Scattering

$e^{\pm}$ near the magnetar can absorb thermal X-ray photons resonantly if the photon energy in its rest frame is $\hbar\omega_B$. This process:

- Provides high energy photons for pair production, $\gamma_{\rm thr}$ depends on local B field.
- Applies an effective drag force on the particles
- Produces the observed X-ray spectrum

Resonant Drag on a Single Particle

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Simulation of the Twisted Magnetosphere

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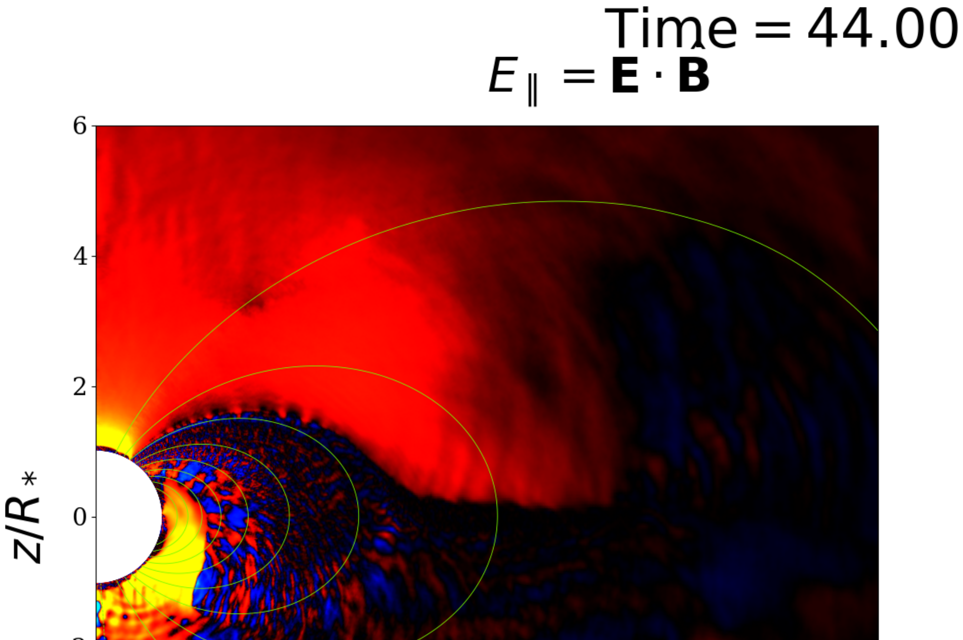
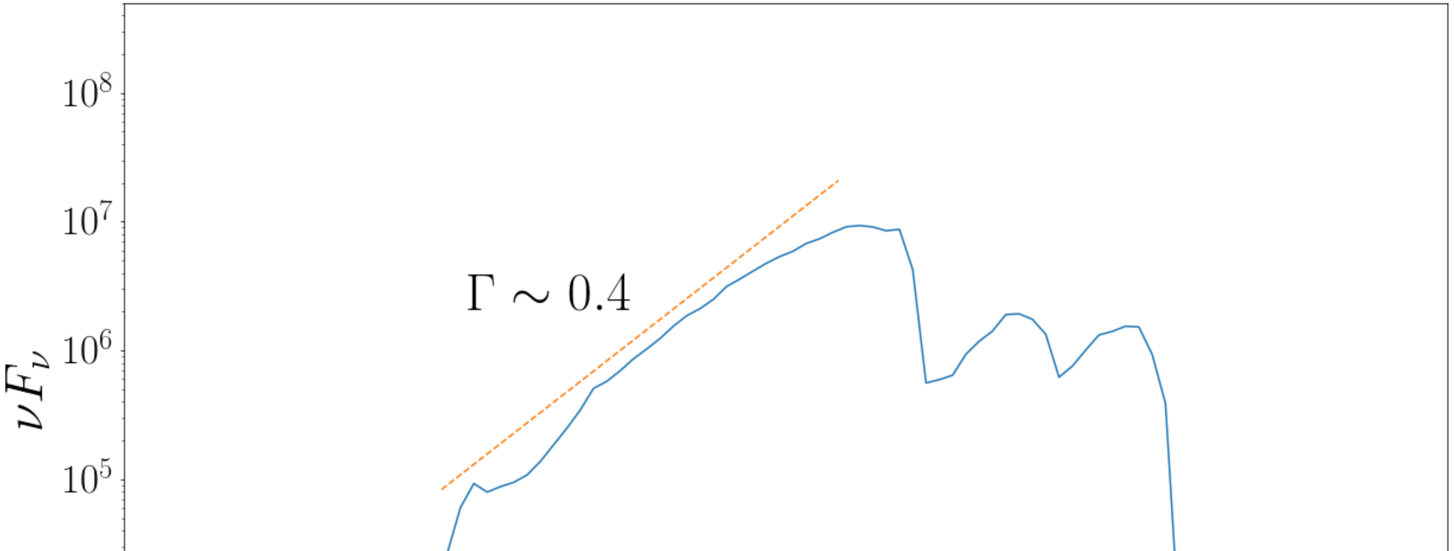
Movie in 3D

Where is the Gap?

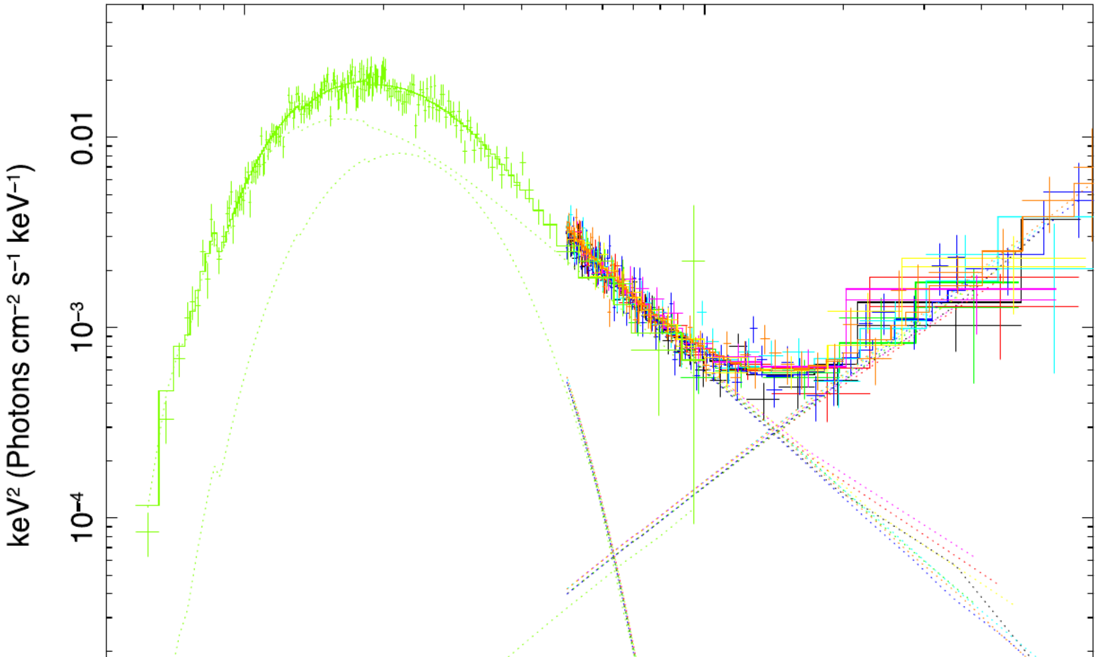


Radiation Spectrum

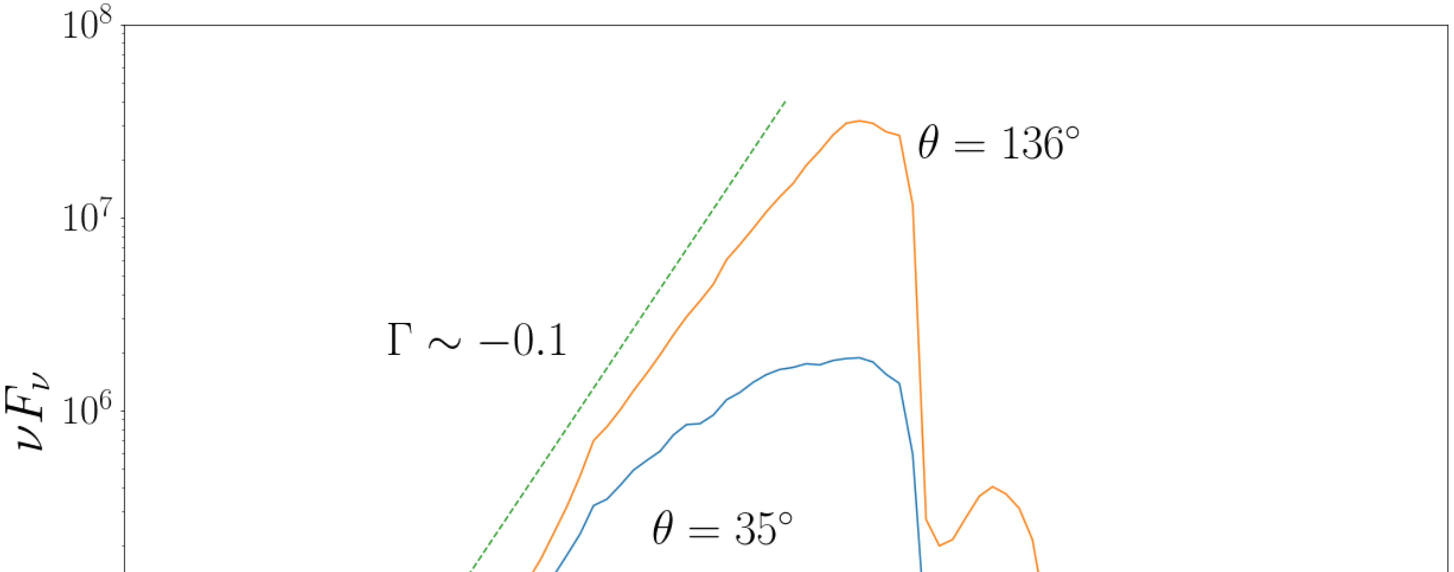


Persistent Magnetars

Persistent emission spectrum from 1E 2259+586 (Vogel et. al. 2014)



Angle-dependent Spectrum



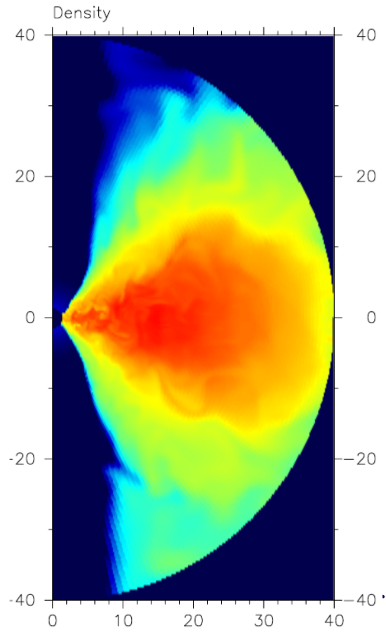
Magnetars, Summary

- Resonant scattering has highly nontrivial effect on the global electrodynamics of the twisted magnetar magnetosphere.
- Electron/Ion asymmetry will lead to two qualitatively different hemispheres.
- We can reproduce hard X-ray spectrum from only resonant scattering in PIC simulations. The spectral index is highly angle dependent.

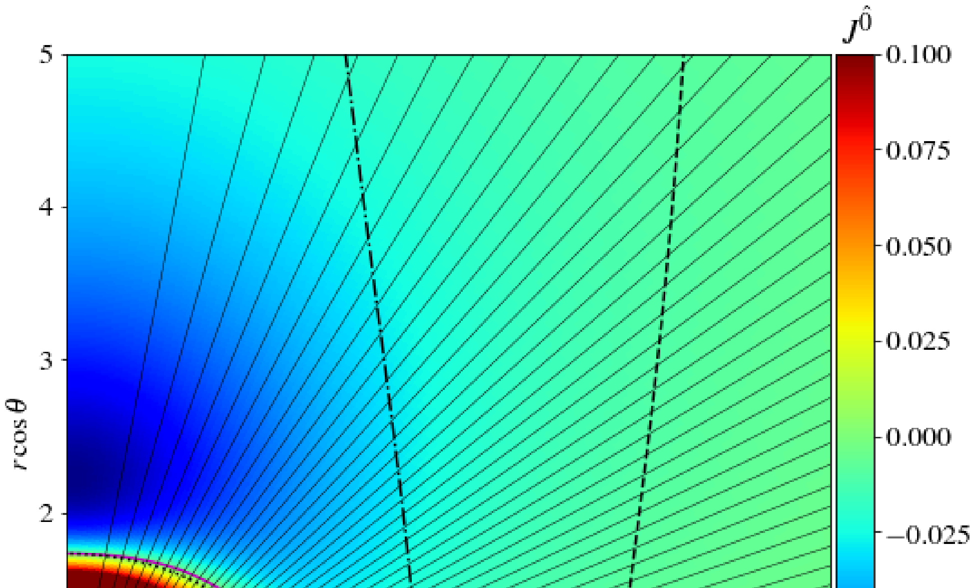
Pair Discharge in BH Magnetosphere

- In black hole jets, the plasma supply in the funnel region has been a long standing problem.

- Centrifugal barrier prevents accretion material to penetrate into the jet. But plasma is required to conduct the BZ current.



Structure of the BH Magnetosphere



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Where is the Gap?

- At null surface?
- At stagnation surface?
- Near light surfaces?
- Is the gap static?

- Is there a limit cycle? If so, what is the period and duty cycle?

1D Simulation

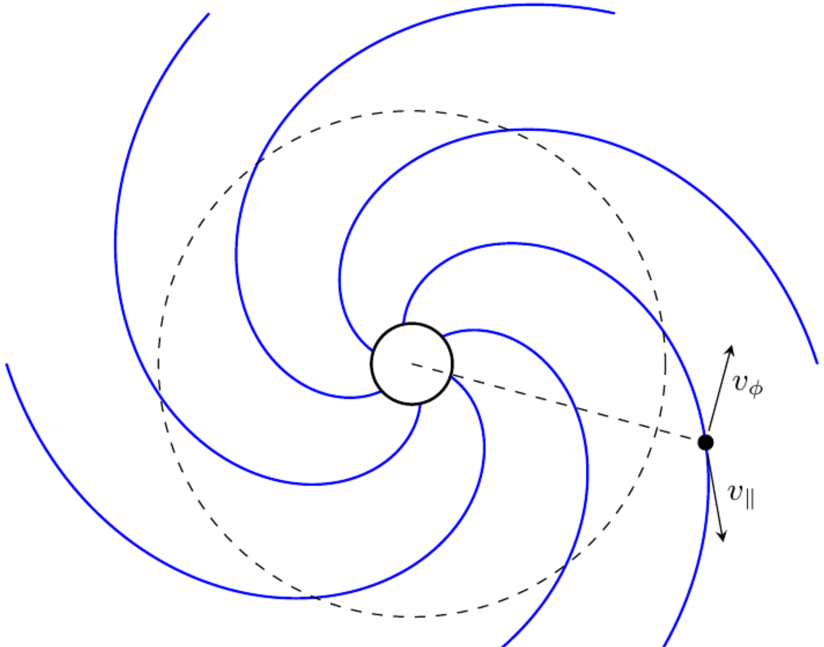
- Constant background current density j_B, varying ρ_{GJ}. $j_B > c|\rho_{\mathrm{GJ}}|$ everywhere.

$$\frac{\partial E_r}{\partial t} = 4\pi(j_B - j), \qquad \frac{\partial E_r}{\partial r} = 4\pi(\rho - \rho_{\mathrm{GJ}})$$

- Both the null surface and the stagnation surface are included.
- Two light surfaces inside the box. Outside the light surfaces particles can only stream one way.

Treatment of Light Surfaces

To capture the effect of light surfaces, we imitate the light cylinders of a rotating pulsar.



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Treatment of Light Surfaces

We consider particle to be "beads on a wire".

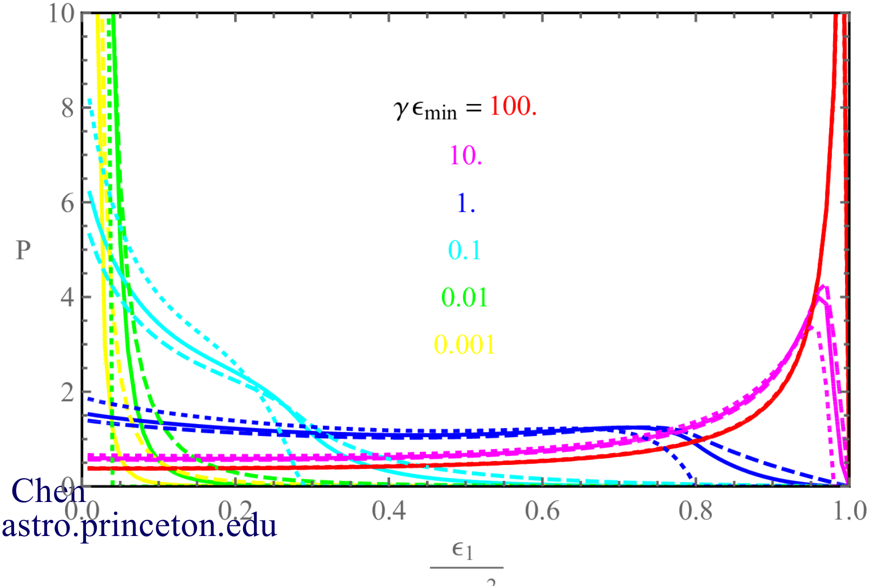
$$\mathbf{v} = v_r \hat{\mathbf{r}} + \left(\Omega r \sin\theta + \beta_\phi v_r\right) \hat{\boldsymbol{\phi}}$$

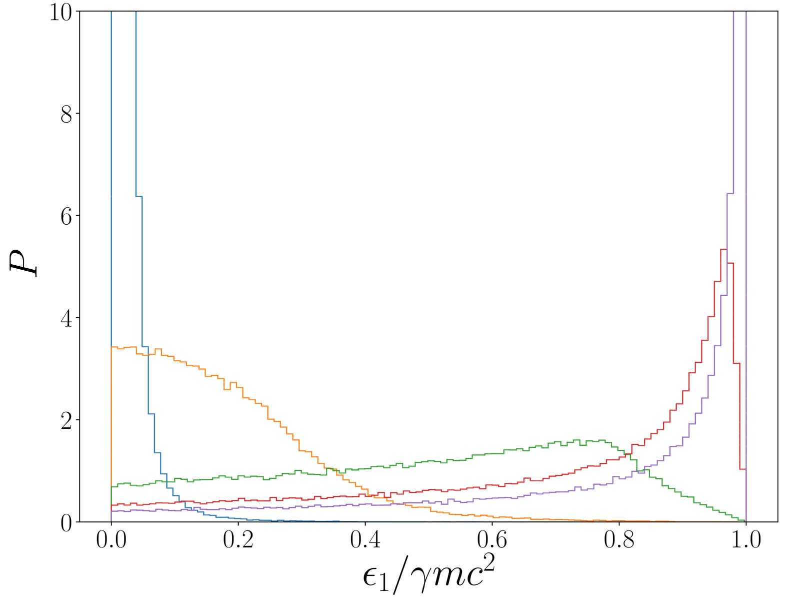
$$\frac{dr}{dt} = v_r = \frac{p_r/\gamma m c + \beta_\phi^2}{1 + \beta_\phi^2}$$

β_ϕ becomes ± 1 at the light surfaces, at which point particles can only move in one direction.

Inverse Compton Scattering

We use Monte Carlo method to sample the IC spectrum, assuming a power law background soft photon distribution $I(\epsilon) \propto (\epsilon/\epsilon_{\min})^{-\alpha}$





1D Simulation

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BH Magnetosphere, summary

- There is never a "vacuum gap". Minimum multiplicity is $\lesssim 1$.
- A gap develops whenever the local multiplicity drops below 1. The null surface is mildly preferred but gap location can be anywhere between the light surfaces.
- The size of the gap is always macroscopic, $h \sim r_g$. However, electric field does not depend on gap size and is purely inductive

BH Gap Mechanism

- What controls the gap size?
  - Global scale of variation of ρ_{GJ}.
- What controls the energy of primary particles?
  - Primary particles are all radiation damping limited. $E_{\|}$ in the gap determines primary Lorentz factor.

BH Gap Mechanism

Scaling of the E field:

$$\frac{E_{\parallel}}{E_0} = \left(\frac{5\kappa \ell_{\mathrm{IC}}^2}{8\pi \lambda_p r_g} \left(\frac{3(\alpha-1)}{4\alpha} \frac{\ell_{\mathrm{IC}}}{\lambda_p} \frac{\epsilon_{\min}}{m_e c^2} \right)^{-\alpha} \right)^{\frac{1}{\alpha+1}}$$

Primary particle Lorentz factor:

$$\gamma_p = \sqrt{\frac{3}{4eE_{\parallel}} \frac{\alpha-1}{\alpha} \frac{\ell_{\mathrm{IC}}}{\epsilon_{\min}}}$$

Scaling to Real Systems

	λ_p/r_g	ℓ_{IC}/r_g	Primary γ_p	Multiplicity	$L_{\mathrm{gap}}/L_{\mathrm{jet}}$
$M87$	2×10^{-8}	5×10^{-5}	4×10^{6}	~ 20	10^{-5}
Sgr A*	2.6×10^{-6}	0.023	3×10^{7}	$\lesssim 10$	0.02

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BH Gap, Future Work

- Most of the dissipation goes into non-thermal radiation. What is the radiation spectrum?
- Nonlinear regime where synchrotron self inverse-Compton is taken into account.
- What happens when the gap electric field grows comparable to B? We need global simulations.