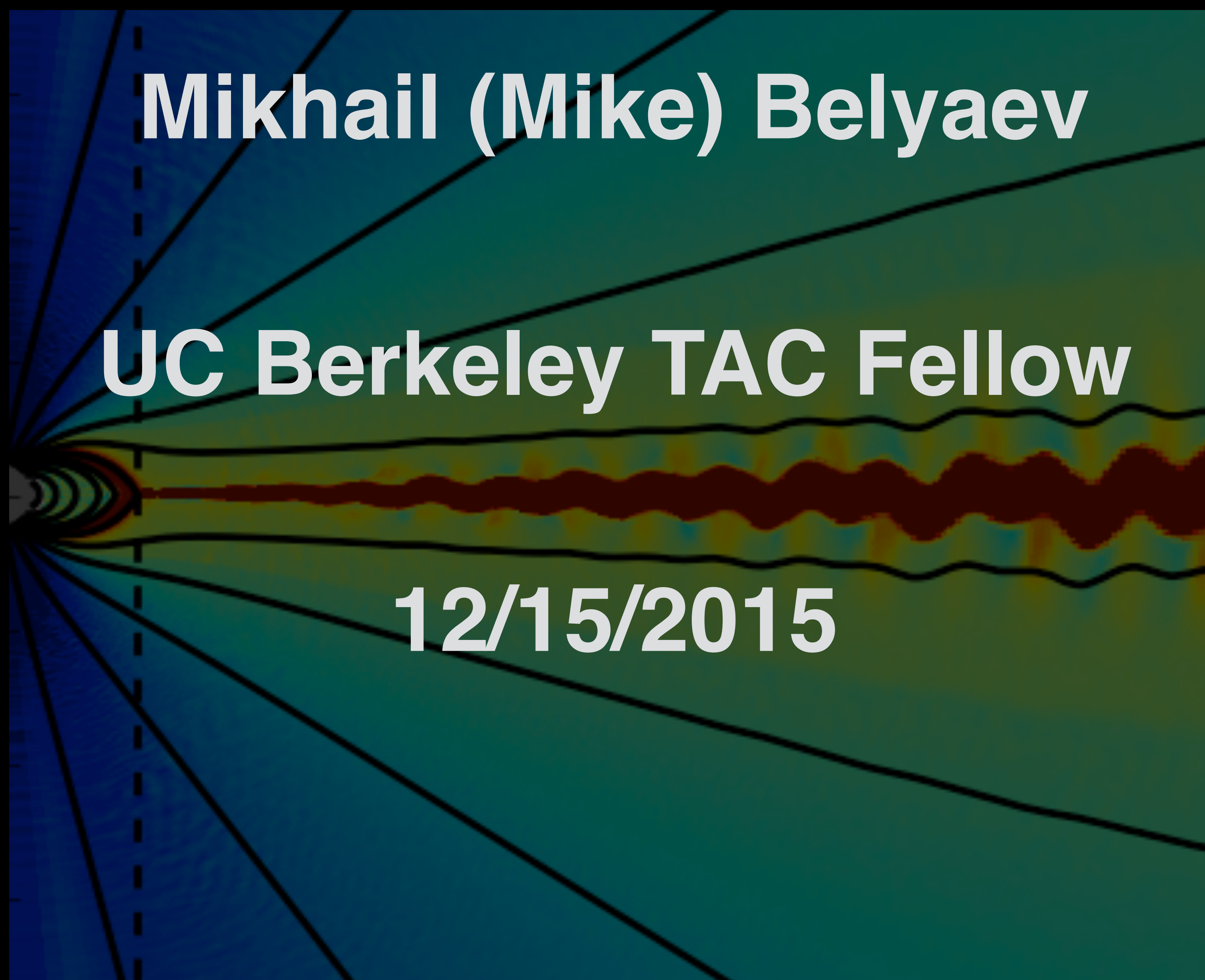
PICsar: Particle in Cell Pulsar Simulations



Mikhail (Mike) Belyaev

UC Berkeley TAC Fellow

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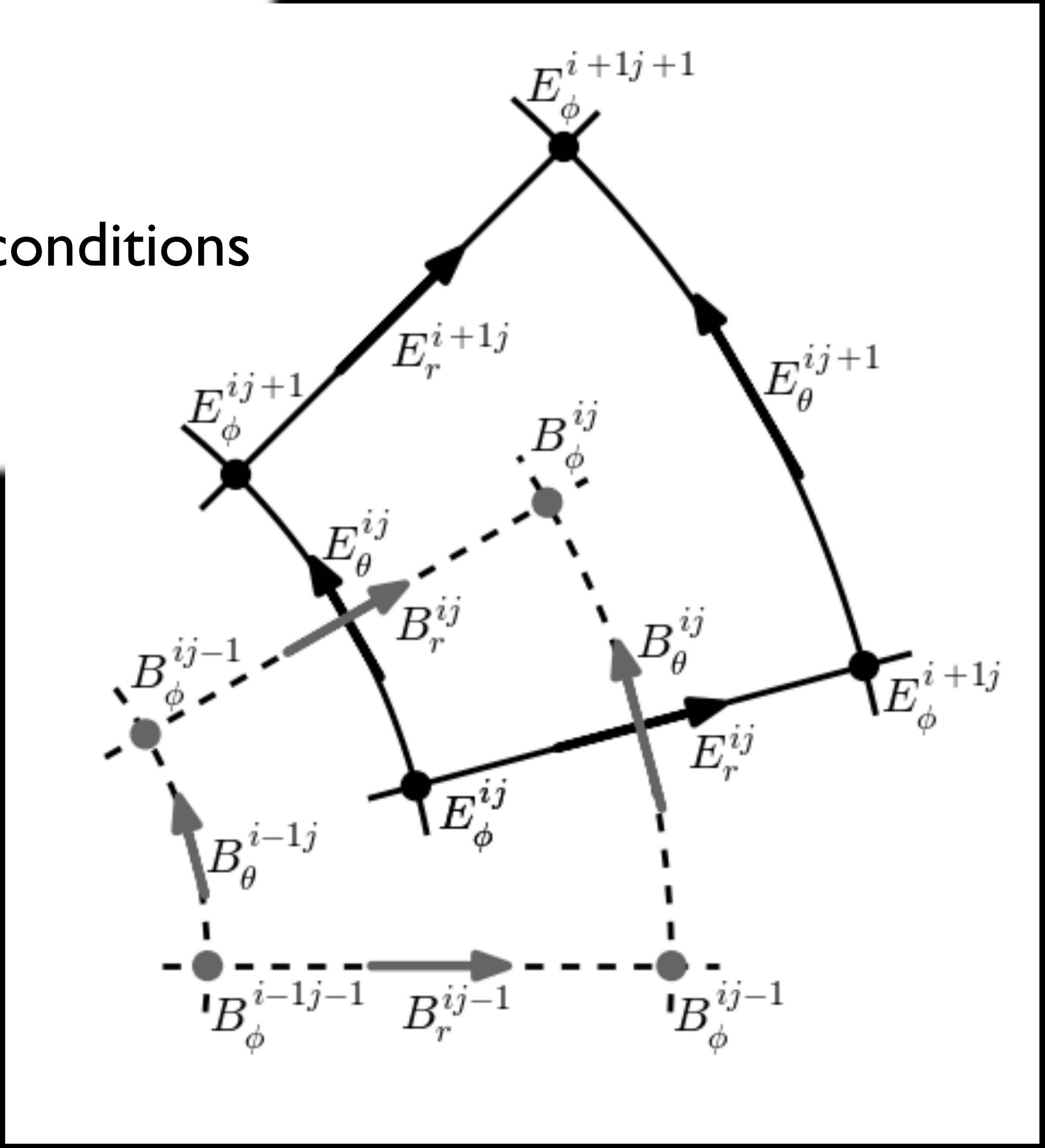
Particle in Cell Method

Computer solves time-dependent Maxwell equations

$$\frac{\partial \mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E} \qquad \frac{\partial \mathbf{E}}{\partial t} = c\nabla \times \mathbf{B} + \mathbf{J}$$

Time-independent Maxwell eqns are initial conditions

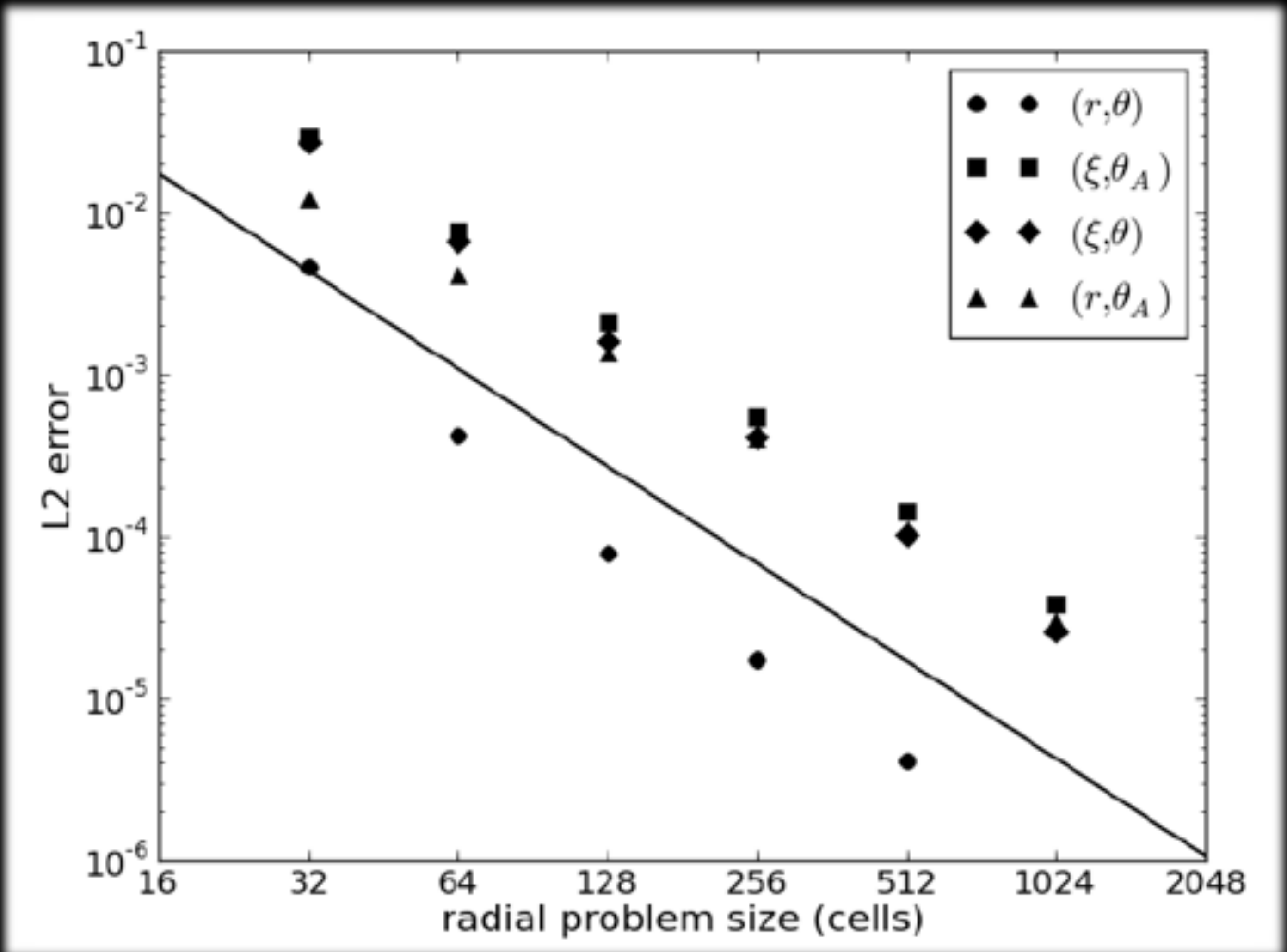
$$\nabla \cdot \mathbf{E} = \rho \quad \nabla \cdot \mathbf{B} = 0$$



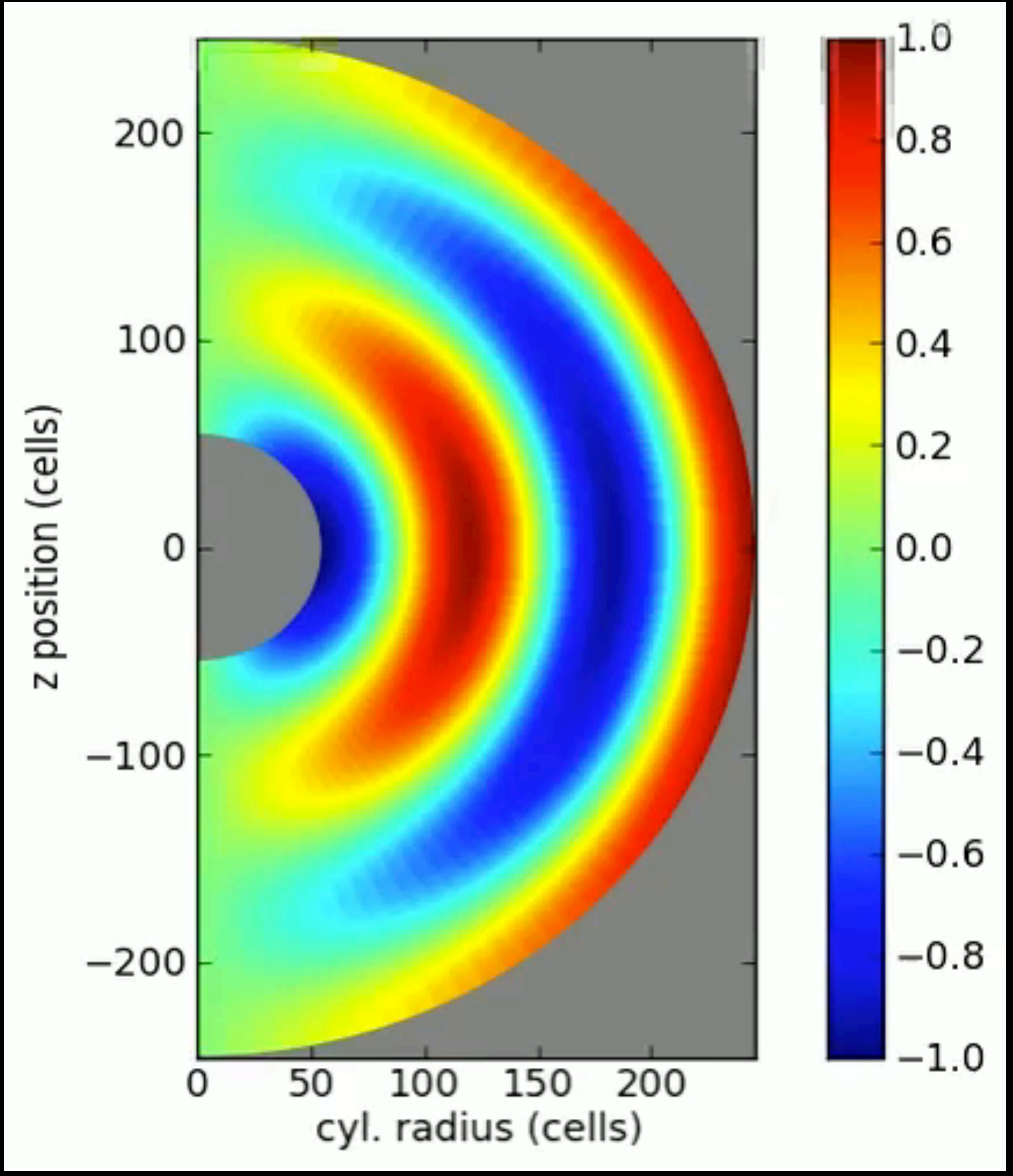
PICsar is an axisymmetric, relativistic, electromagnetic, Particle in Cell code.

Grid: **logarithmic** in radius.

Convergence Test

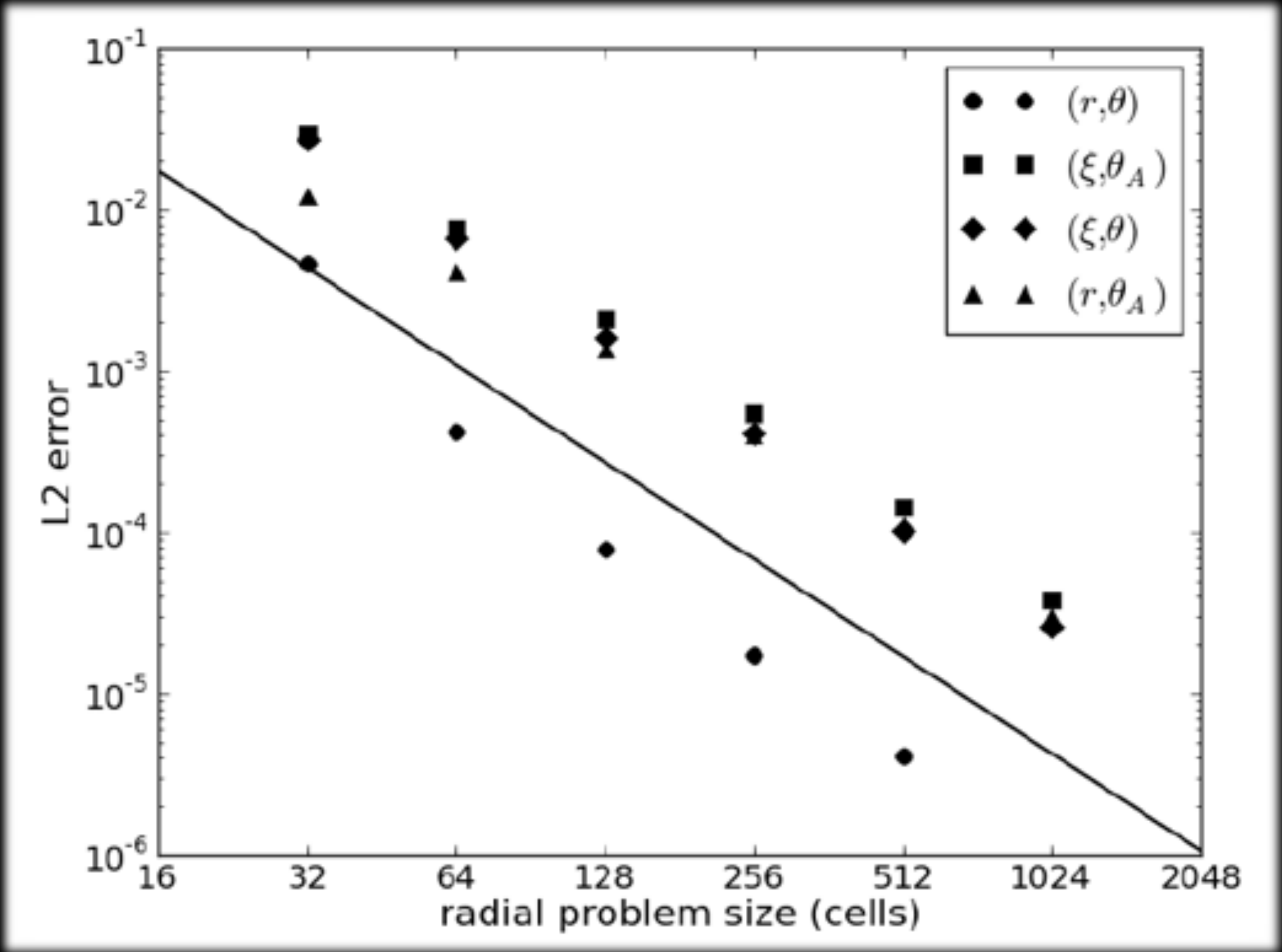


$$B_\phi \propto j_1(kr)\sin(\theta)\cos(kct)$$



Second order convergence in both space and time

Convergence Test



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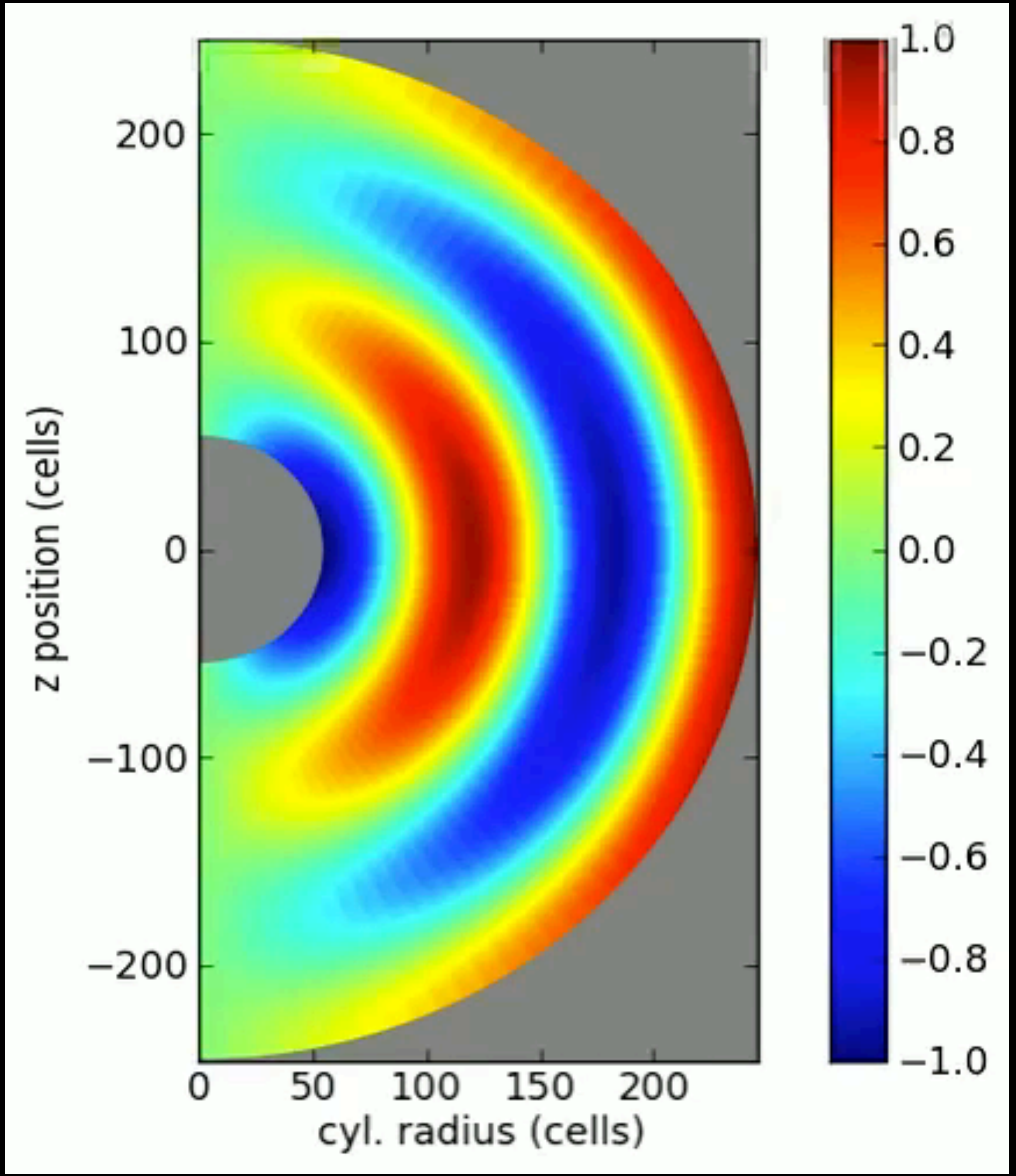
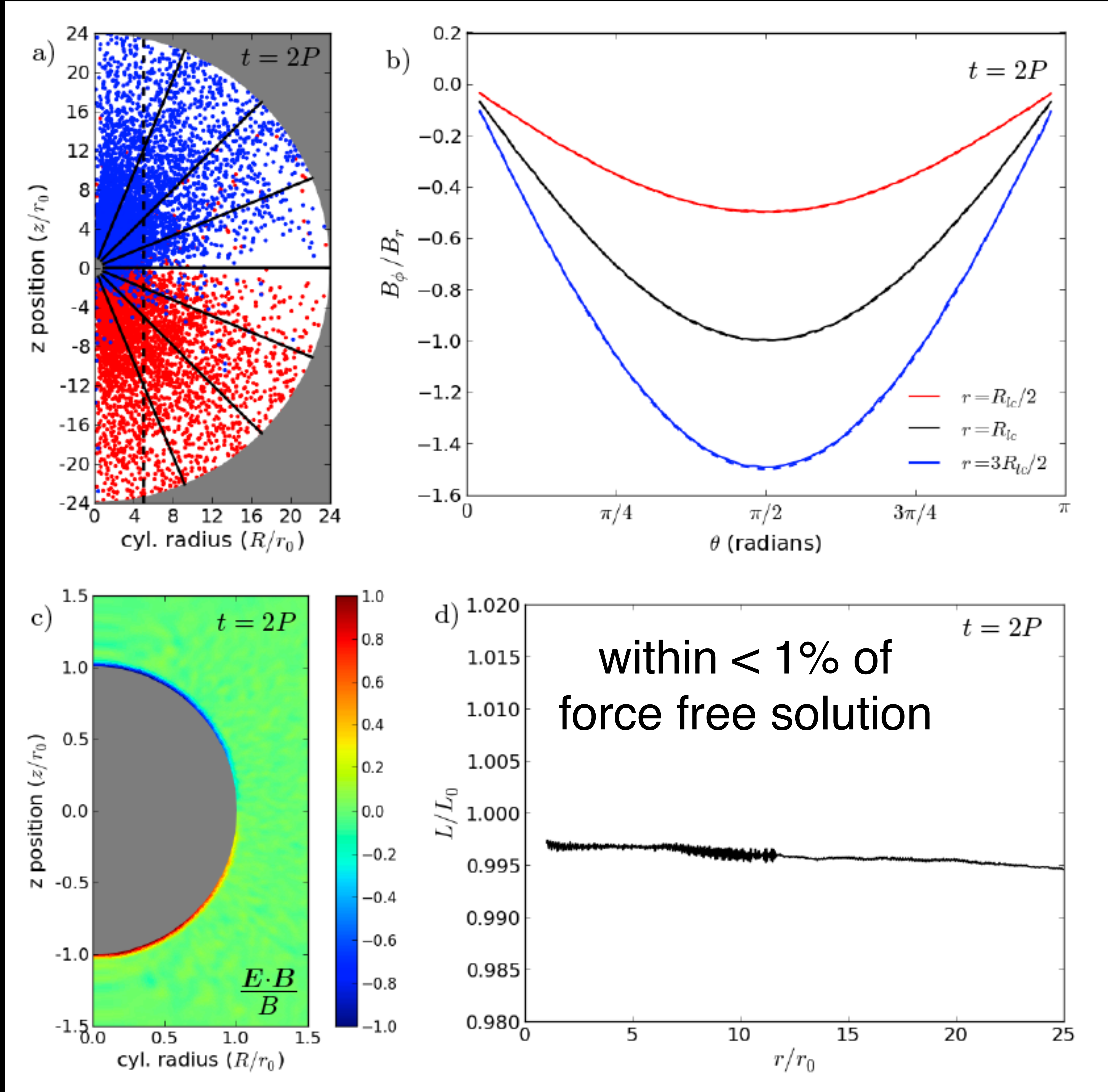


Second order convergence in both space and time

Magnetic Monopole



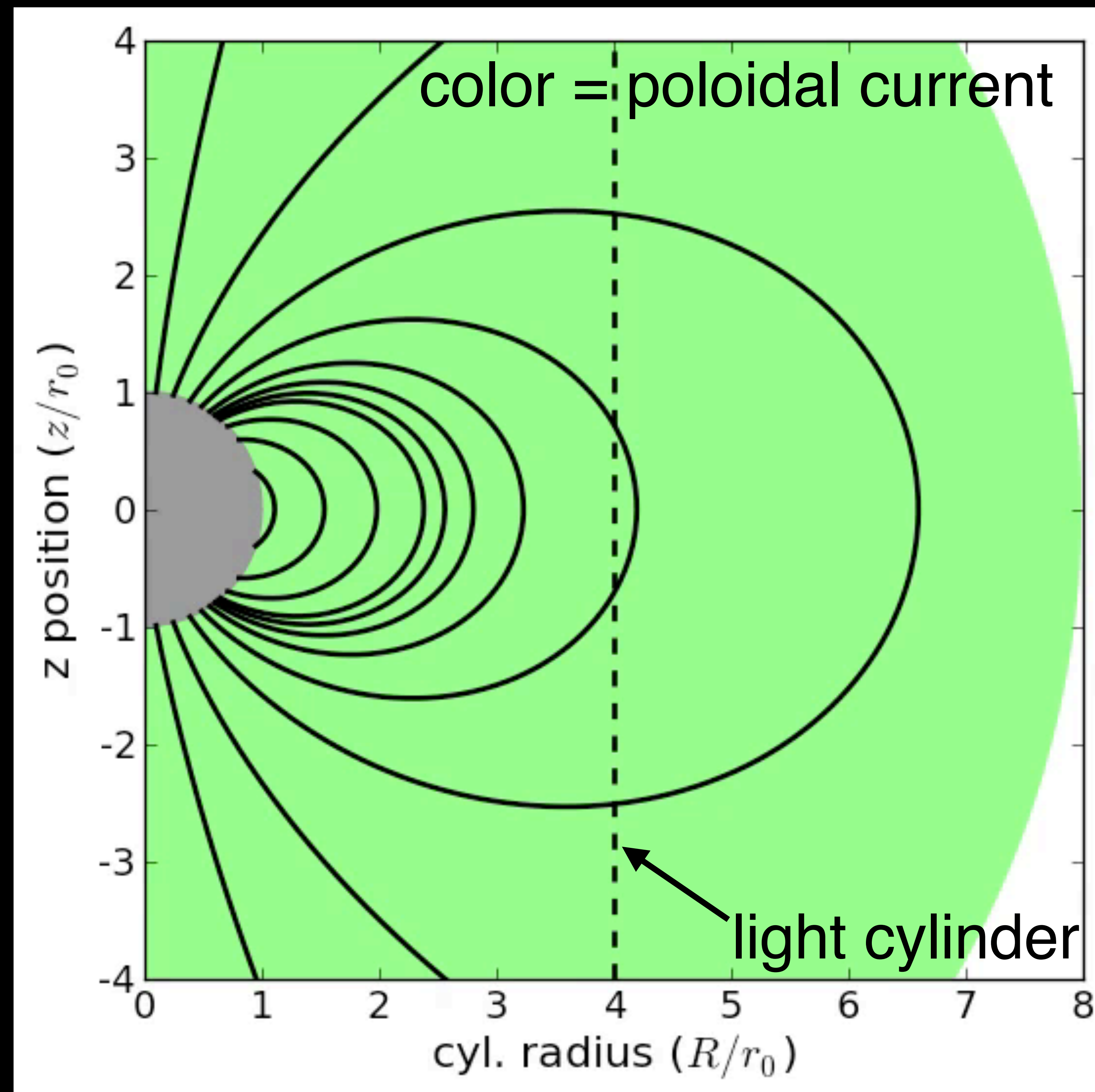
Dipole in Force-Free Limit

Initial conditions:
vacuum dipole fields

Inner boundary:
conducting sphere

Outer boundary:
radiation ($> 100 r_0$)

Charge Injection:
surface charge +
volumetric injection



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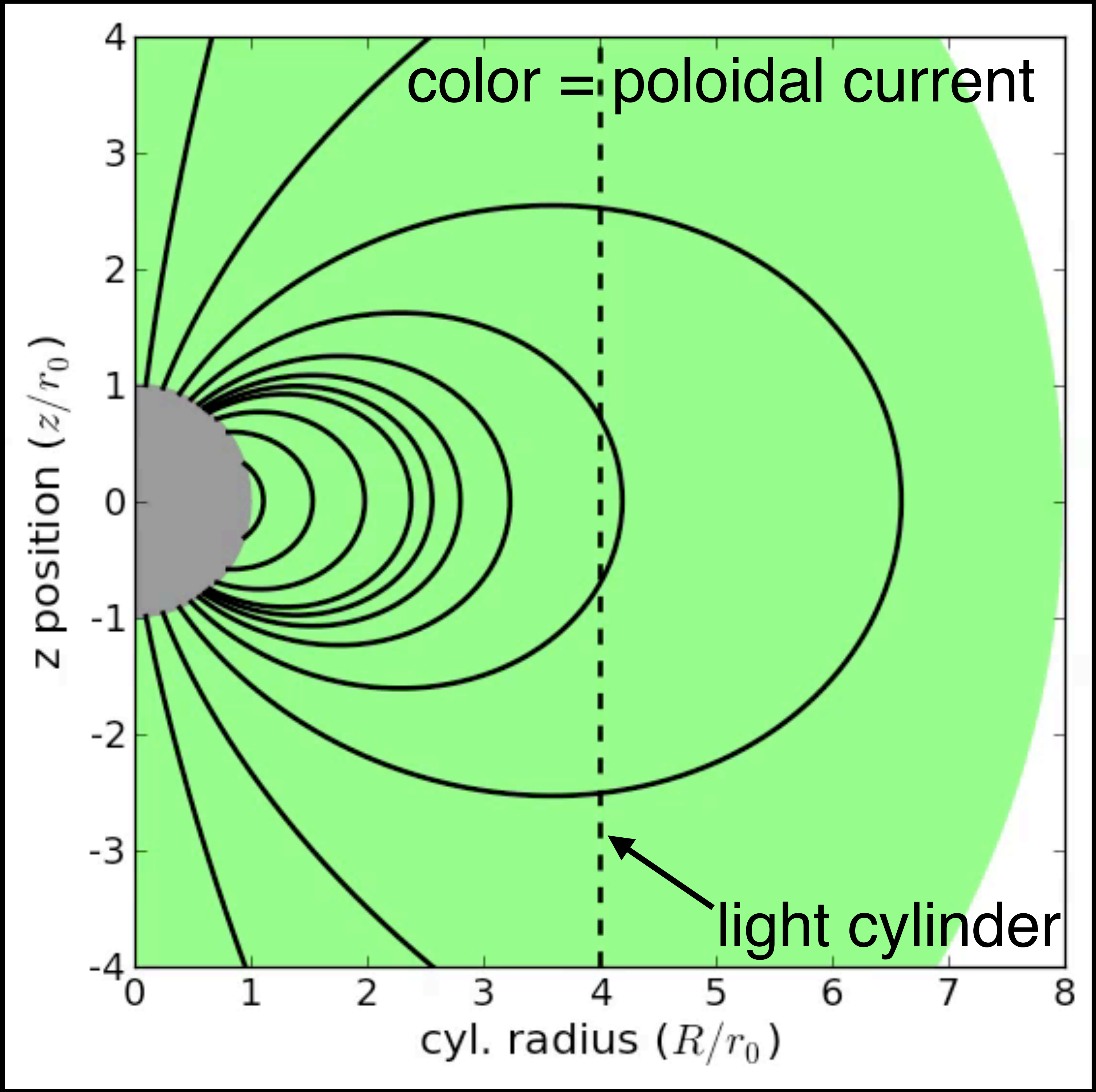
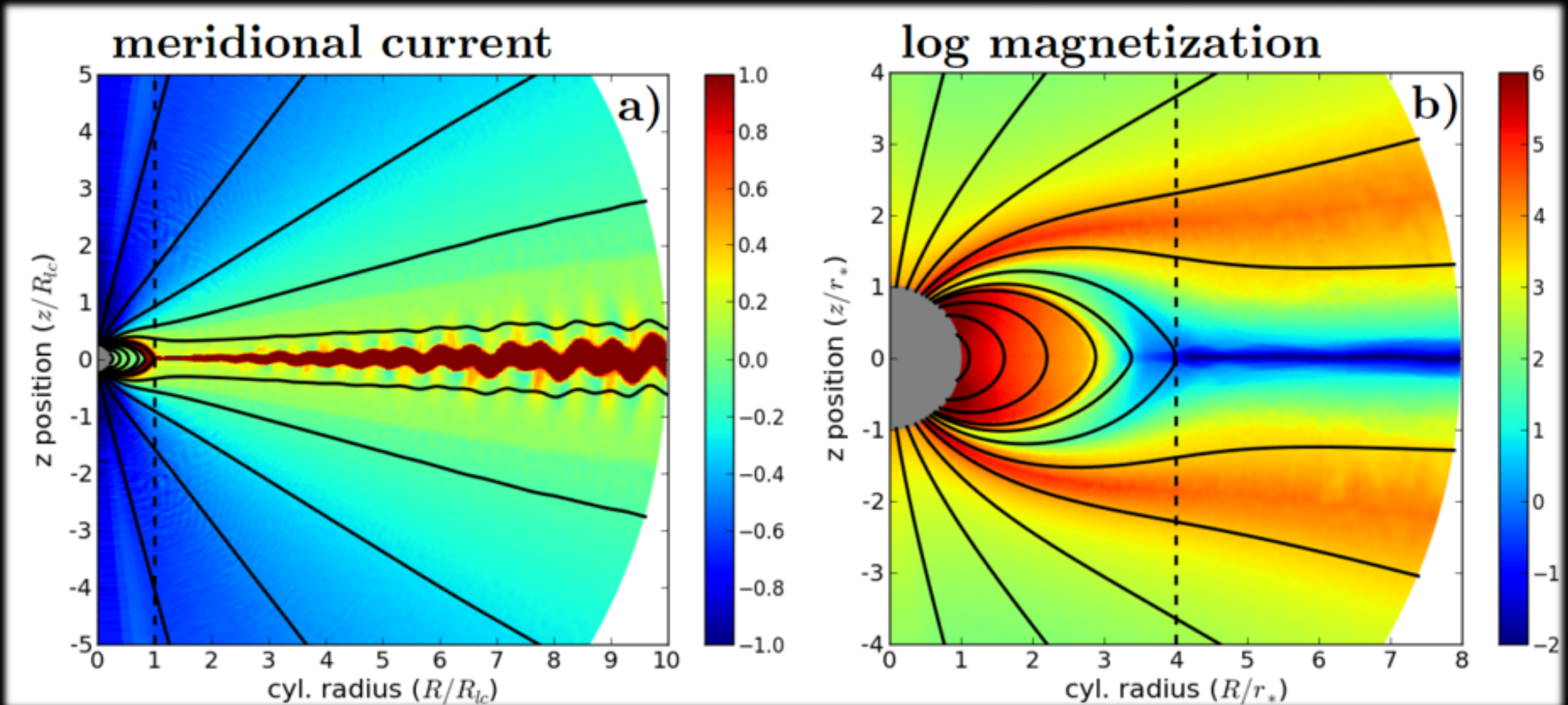


Current Sheet Instabilities



Kink modes in axisymmetry and **kink & tearing** modes in 3D prevalent beyond light cylinder.

Outstanding question: how fast do instabilities dissipate current sheet beyond light cylinder?

Different Approaches to Charge Injection

Belyaev (2015): Each timestep **inject surface charge** just above neutron star surface. Also, inject charge within a radius $r < r_{inj}$ to **relax to force-free field volumetrically**.

Cerutti et al. (2015): Each timestep **inject a multiple of the Goldreich-Julian density** near the surface. Limit pair multiplicity in injection region to a value of ~10 & give particles a “kick”.

Chen & Beloborodov (2014) + Philippov (2015): Directly **simulate pair cascade**. Inject primary particles at surface. Pair production by curvature radiation on B field lines near surface. CB pair production by photon photon collisions in outer gap.

All schemes produce same results in force free limit

Details of Charge Injection

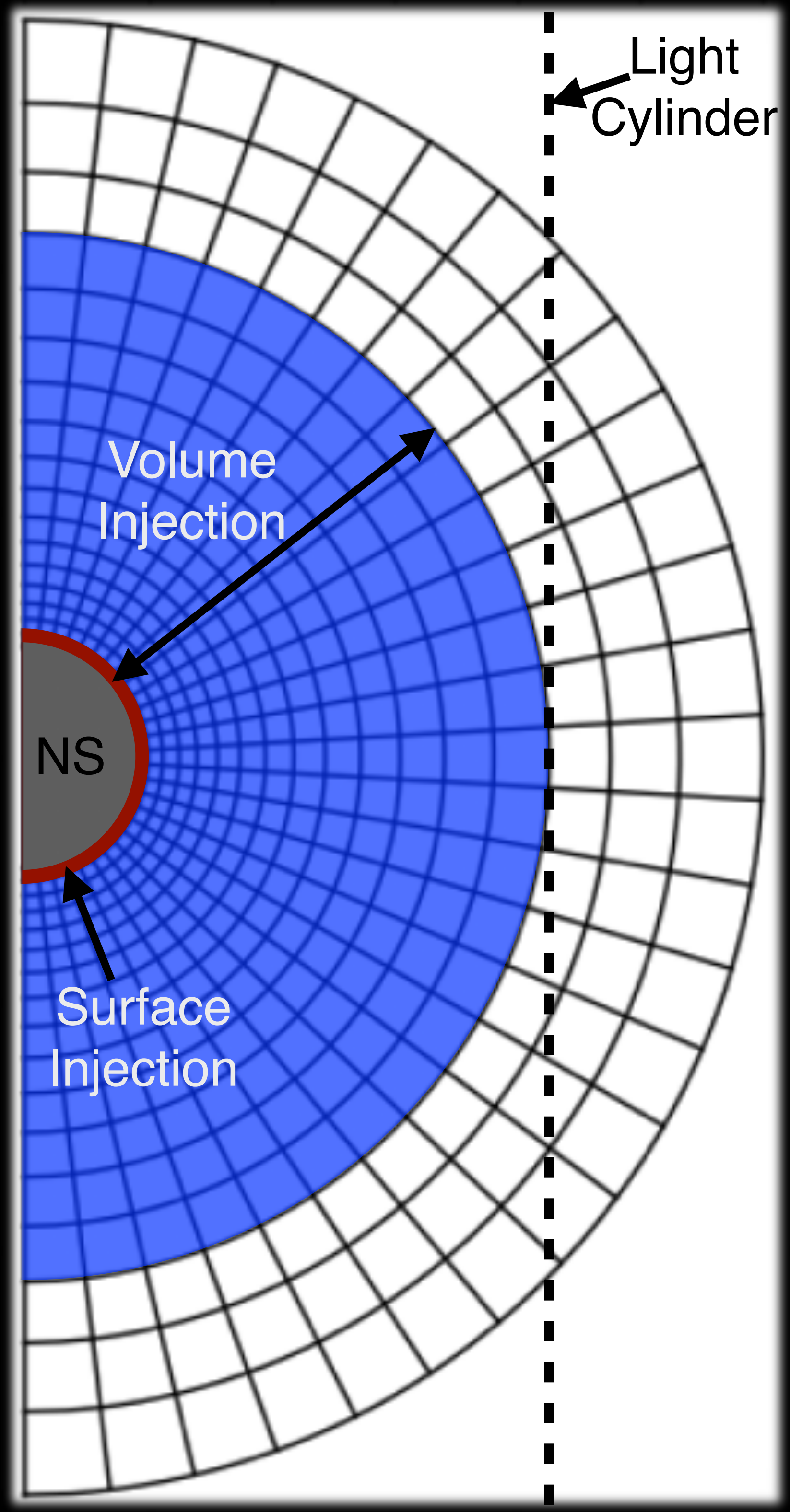
Surface Charge Injection: Inject a fraction of the surface charge each timestep just above NS surface.

Volume Charge Injection: Same basic formula as surface injection but inject throughout a volume. Relaxes $\mathbf{E} \cdot \mathbf{B}$ to zero in time.

$$4\pi q N_{inj}/dA = f_{inj} \frac{\mathbf{E} \cdot \mathbf{B}}{B}$$

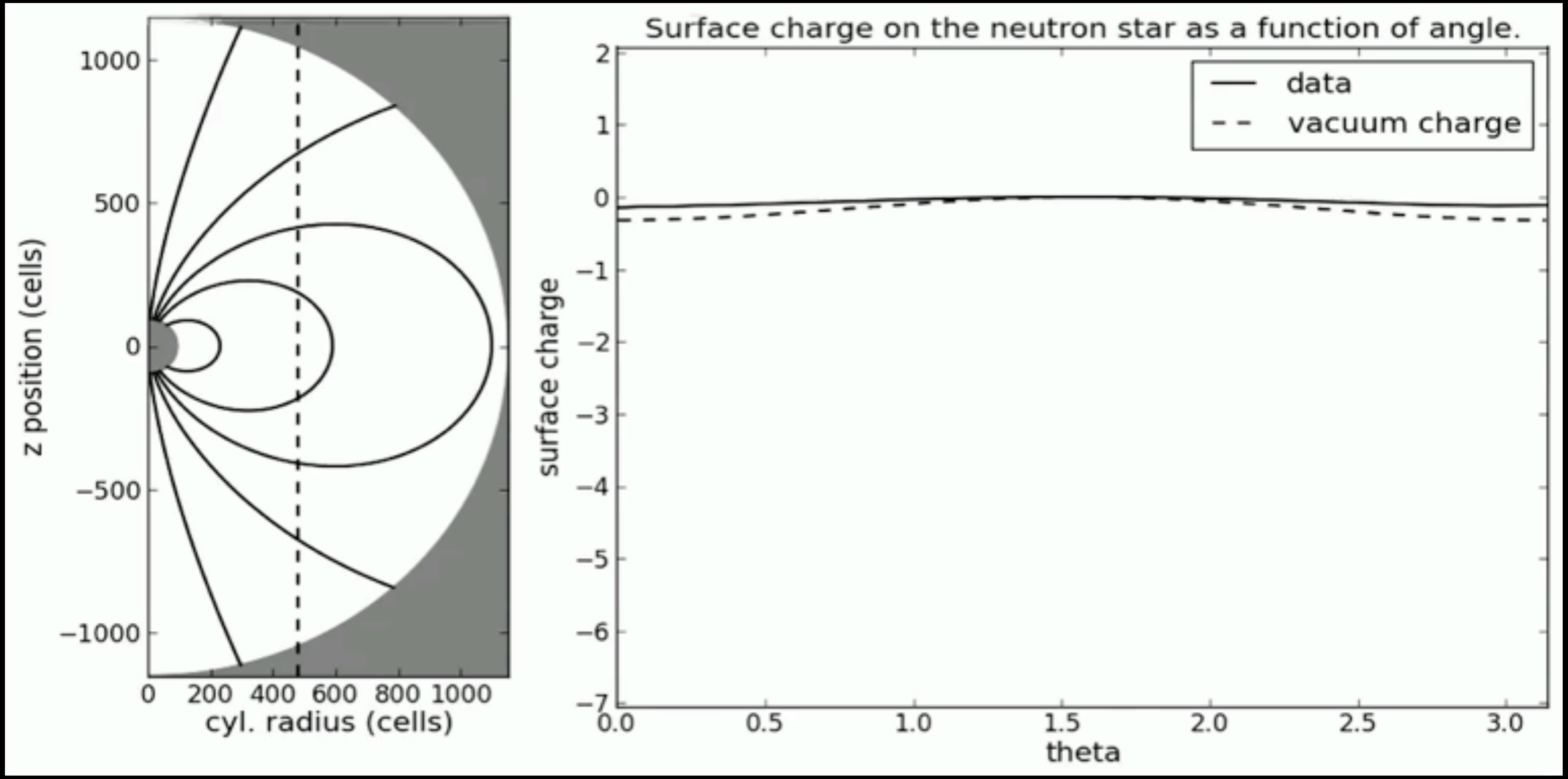
$$f_{inj} \lesssim 1, \quad \text{surface injection}$$

$$f_{inj} \sim c\Delta t/r, \quad \text{vol. injection}$$



Electrosphere

Surface Injection On. Volume Injection Off.



Near-surface pair production could fill the magnetosphere (Cerutti et al. 2015). But, pair production requires spacelike current (Timokhin & Arons 2013). Polar cap currents are timelike in flat spacetime for aligned rotator. GR frame dragging helps (Philippov et al. 2015) but cannot make currents spacelike over entire polar cap (Belyaev in prep).

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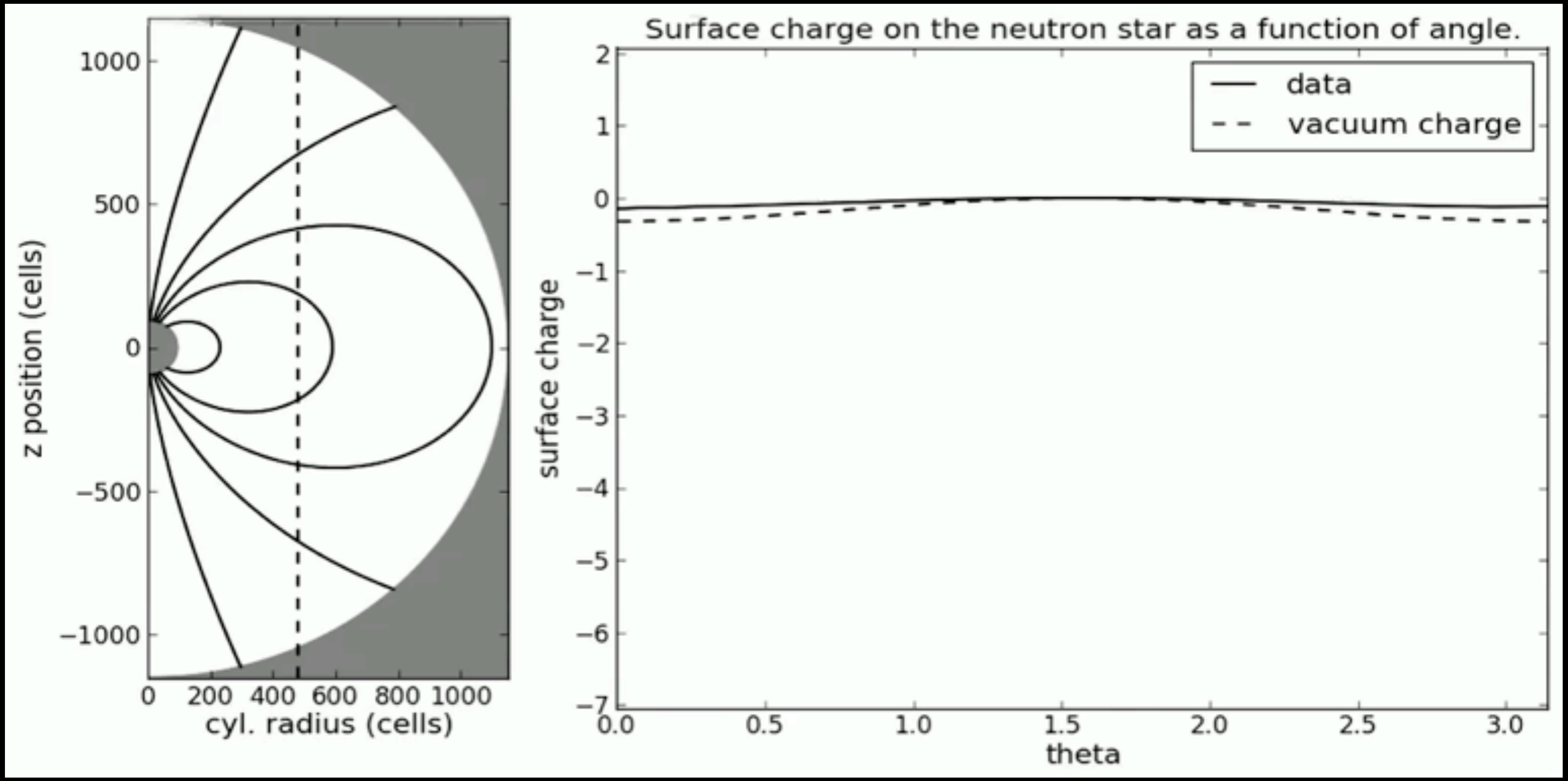

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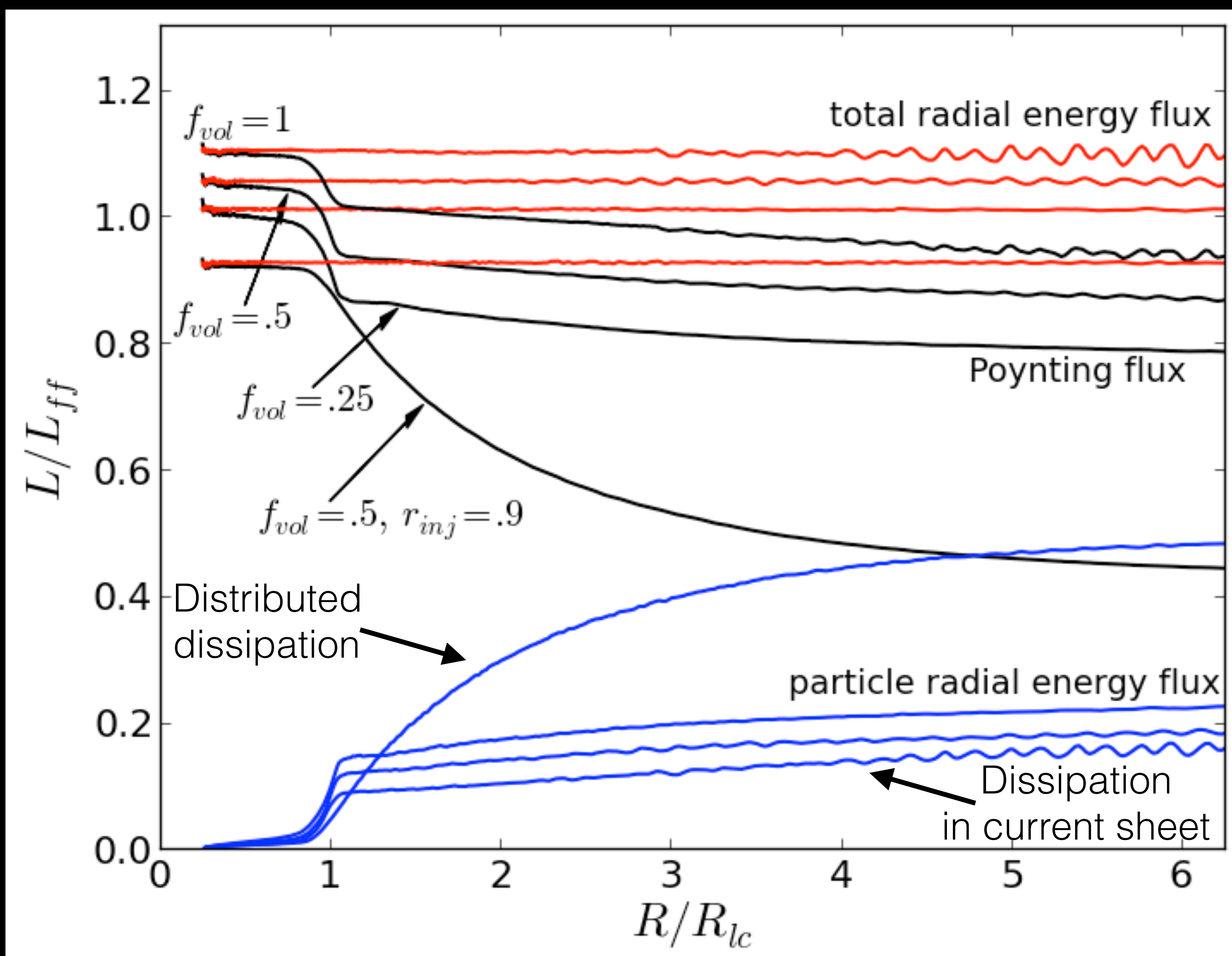
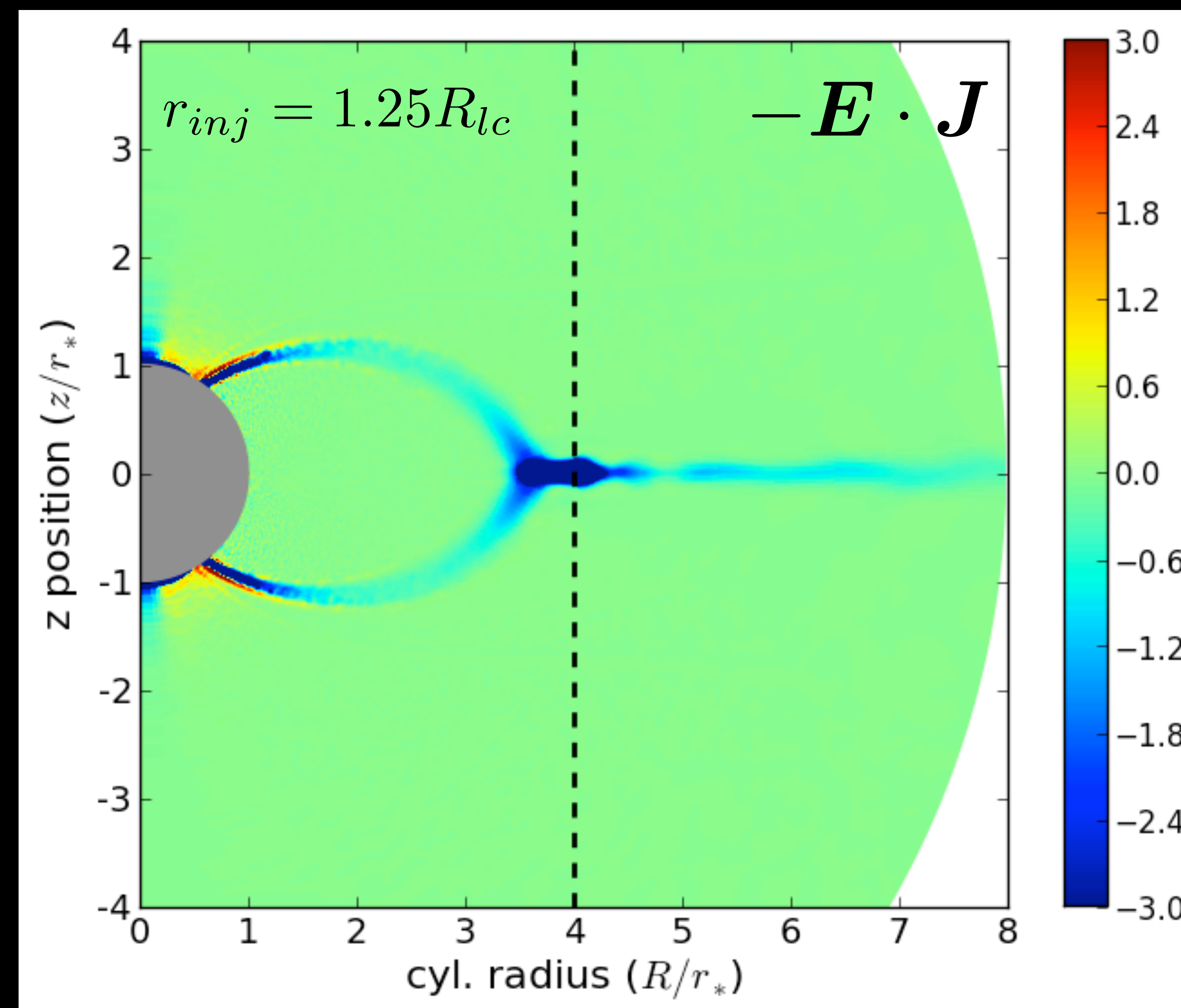
Dissipation & Particle Acceleration

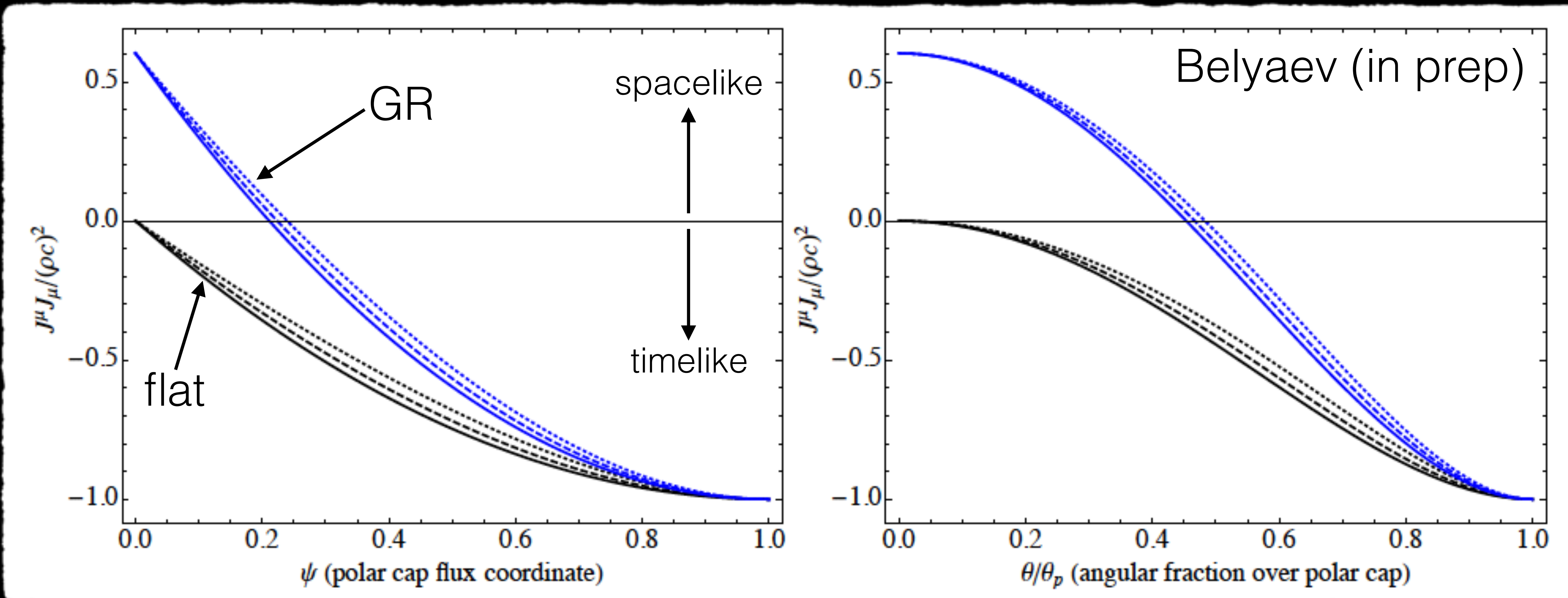
Surface Injection On. Volume Injection On.





Poynting Theorem: $\frac{\partial u}{\partial t} + \nabla \cdot \boldsymbol{S} = -\boldsymbol{E} \cdot \boldsymbol{J}$

Polar Cap Currents with GR



Analytic solutions for polar cap currents in axisymmetry.
Results independent of polar cap B field geometry.
Frame dragging creates spacelike region near pole -> pairs
Timelike region near edge of polar cap -> gaps + dissipation?

Conclusions

1. PIC is a useful tool for numerical experiments of pulsar magnetospheres because PIC is accurate in both force-free and vacuum limits.

2. The largest difference between PIC simulations from different groups is the treatment of charge injection. Although, simulations from different groups agree in the force-free limit.

3. Instabilities in the current sheet set in almost immediately beyond the light cylinder. More research is needed to see whether they can dissipate electromagnetic energy and accelerate particles efficiently.

4. PIC results depend sensitively on if the pair cascade at the polar cap is active. Analytic work on polar cap currents with GR (Belyaev in prep).

5. If pair cascade inefficient over even part of the polar cap and volumetric injection due to e.g. photon-photon pair production is inefficient, there are distributed regions of large dissipation where parallel electric field is not completely screened, near but above the current sheet.