Magnetar models for GRBs

Maxim Lyutikov (Purdue U)

Magnetar models for GRBs, and more

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Galilei to Cosimo II Medici

- It is impossible to obtain wages from a republic [...] without having duties attached. [...] so long as I am capable of lecturing and serving, no one in the republic can exempt me from duty while I receive pay. I can hope to enjoy these benefits only from an absolute ruler.

Galilei, Opere x, 348 ff

GRBMAG14 - The magnetic fields!

Magnetars (Thompson& Duncan)

- Magnetars are powered by **dissipation of ~ 10^{15} G B-field**

$$E_B \sim 10^{47} b_{15}^2 \,\mathrm{erg}$$

- B-field determines the available energy
- Questions:
  - How B-field is generated and evolves in the crust/core
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$$E_{\mathrm{rot}} \sim 5 \times 10^{52} P_{\mathrm{msec}}^{-2} \,\mathrm{erg}$$

- More like **Pulsar - PWN**, just more powerful

$$L_{\mathrm{dipole}} \sim B^2 R^2 c \left(\frac{R\Omega}{c}\right)^4 = I\Omega\dot{\Omega}$$

R ~ 10 km, B ~ 10^{15} G

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Not very high. Can explode a SN (LeBlanc & Wilson)? Probably not: SN explosions are not magnetically-driven (nu-driven), but jet can be.

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B-field determines the rate of energy release, NOT the energy content (rotational)

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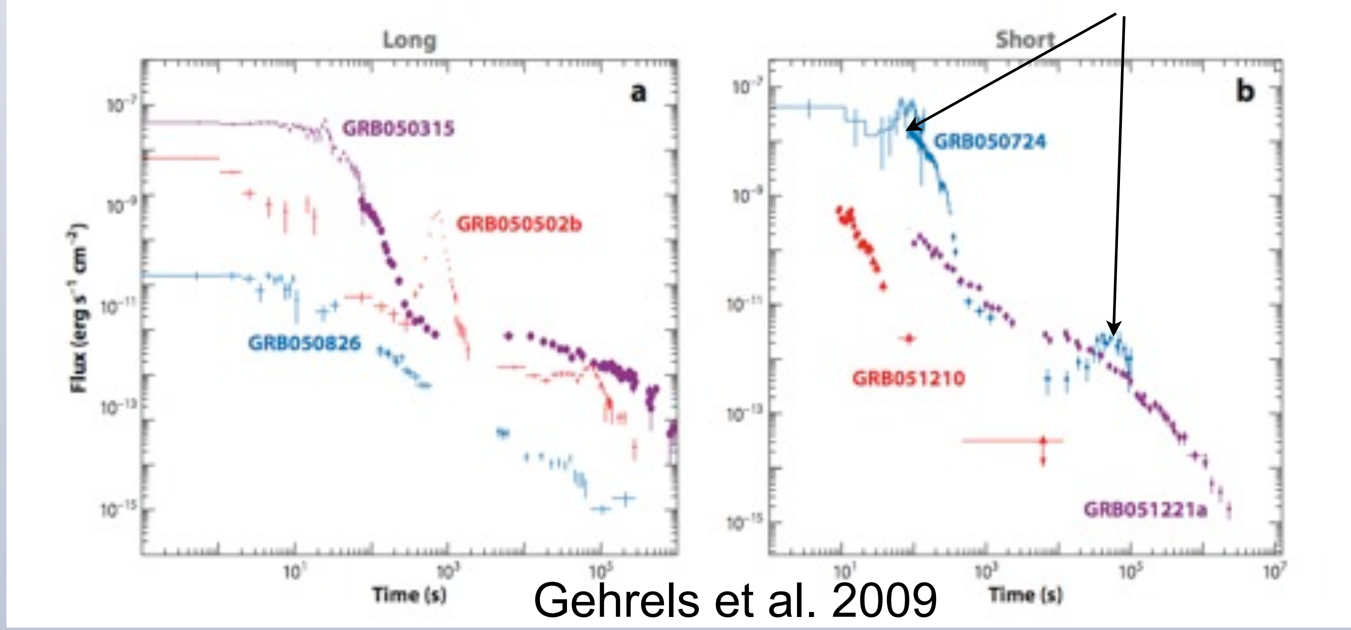
GRBs: magnetically driven

- Long term activity: but nu-fluxes are short lived, ~ seconds
- neutrinos drive baryon contamination
- Colliding shells? - Really fine tuned

Flare @ 100- 10^5 sec in Short!



Gehrels et al. 2009

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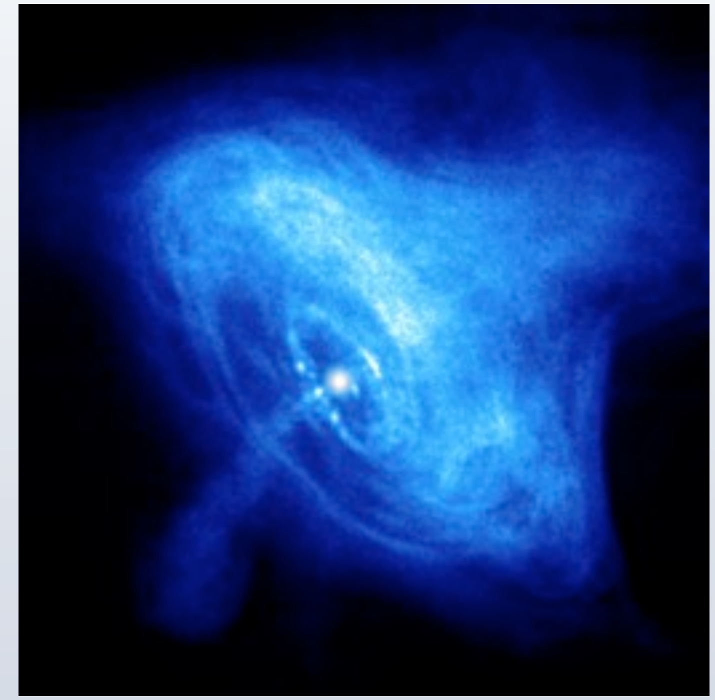

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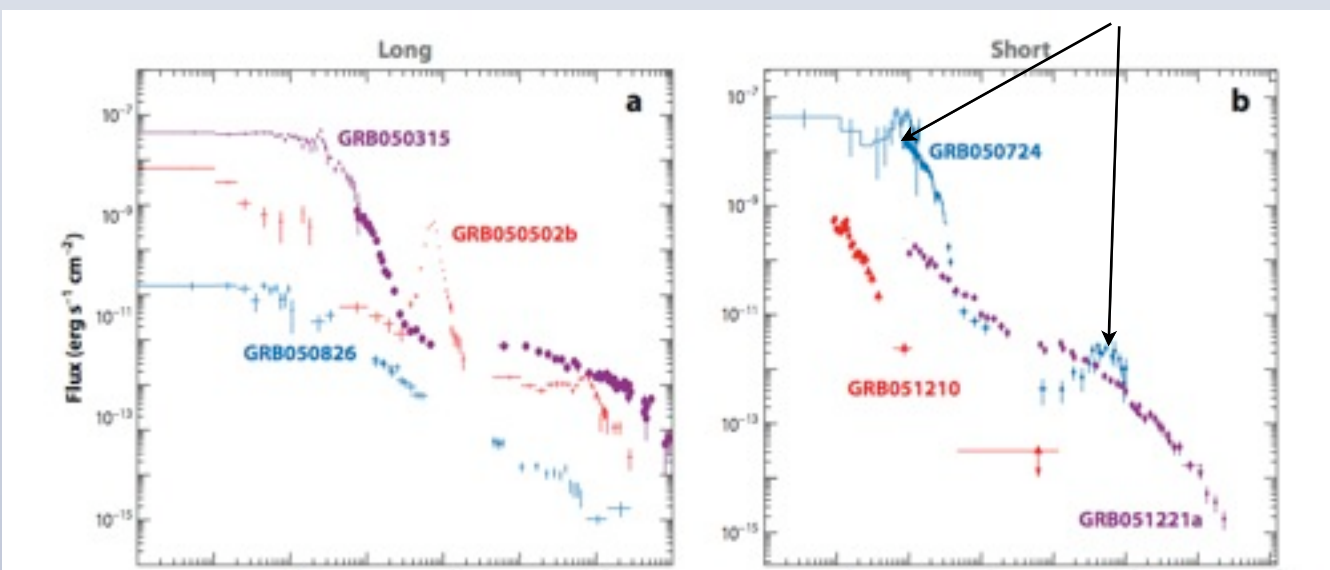

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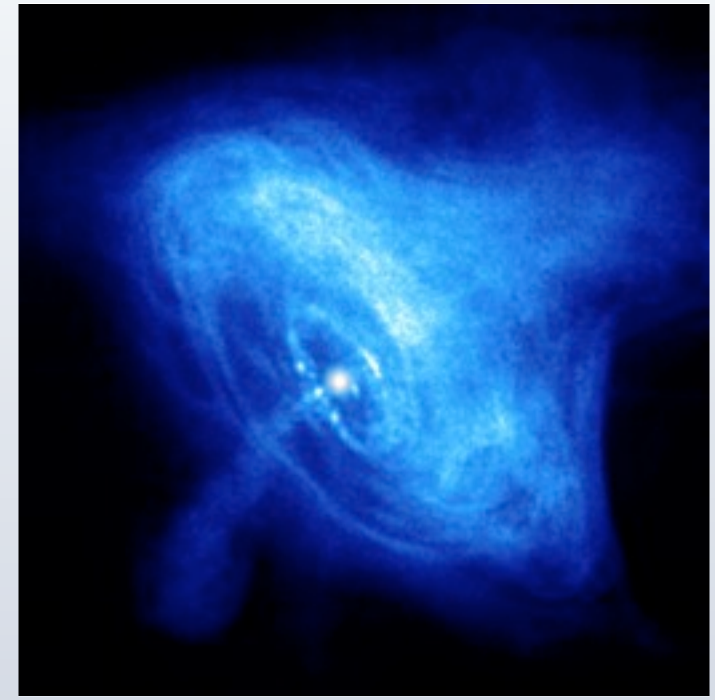

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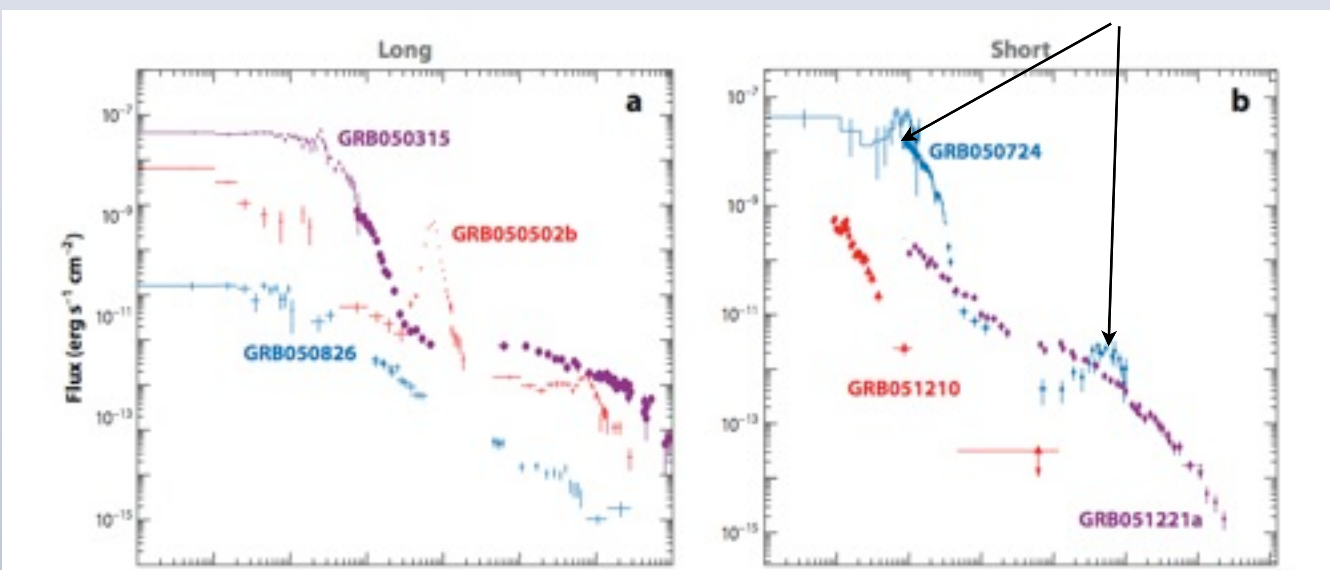

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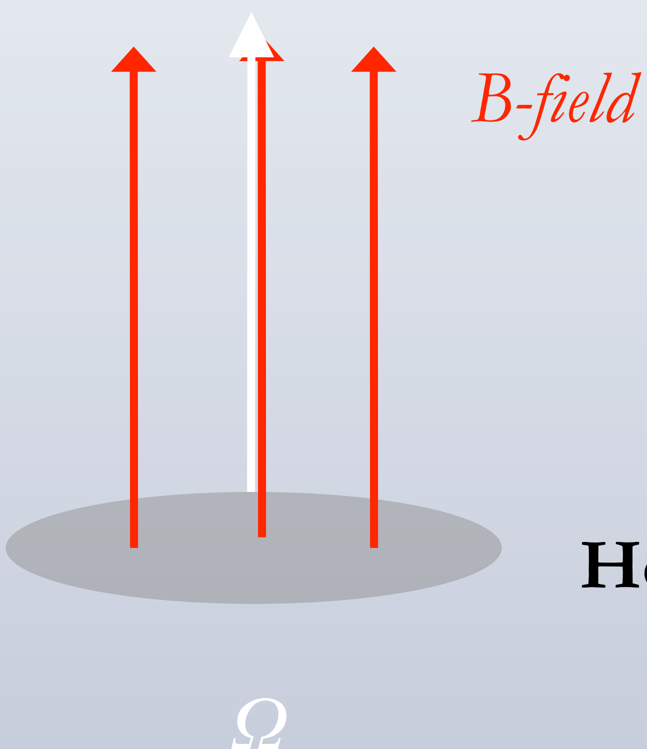
Which flare as well: constant energy supply produces bursts on sub-dynamical scales

Unipolar dynamo (Faraday wheel)

Corona/magnetosphere with σ >> 1

$$\sigma = \frac{B^2}{4\pi\rho c^2}$$



Heavy conducting disk: NS or BH or accretion disk

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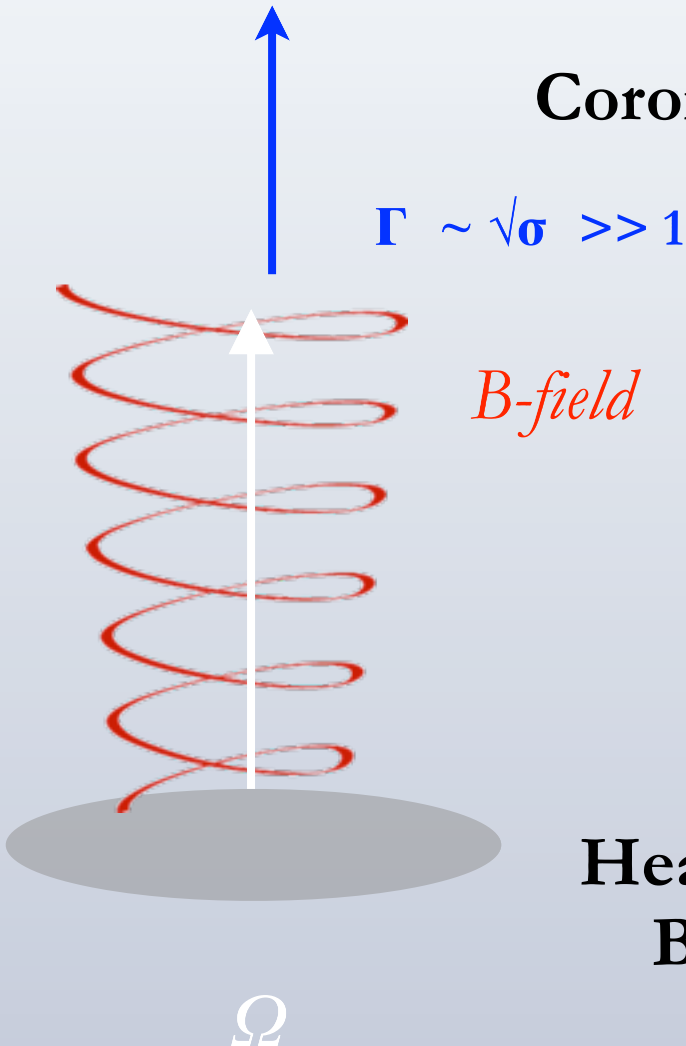


Corona/magnetosphere with σ >> 1

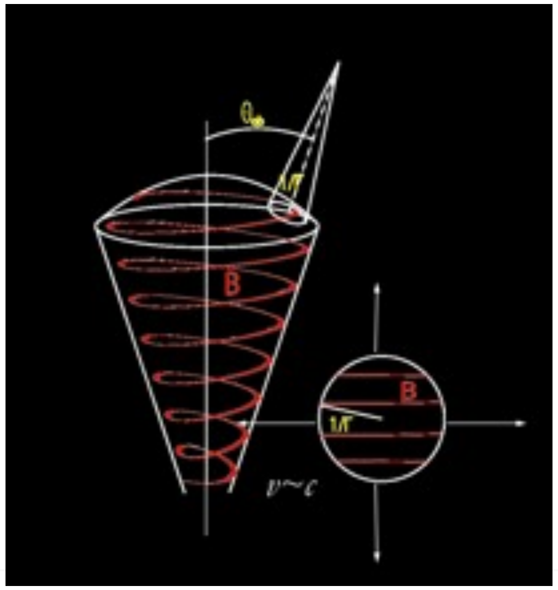
$$\sigma = \frac{B^2}{4\pi\rho c^2}$$

Outflow speed is not related to Keplerian velocity

Heavy conducting disk: NS or BH or accretion disk

Interesting concept... does it work?

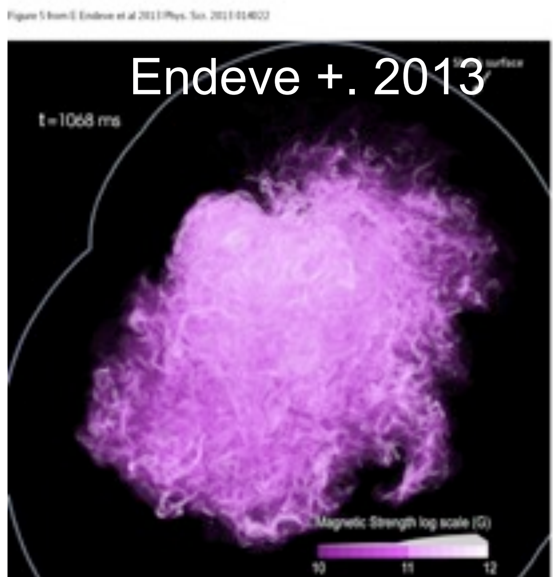
- Can $\sigma >> 1$ magnetosphere be realized?
  - hot plasma (core collapse or NS-NS merger) - nu-driven contamination by baryons, but only for few seconds
  - dissipation inside a star (later in the talk)
  - GRB outflows must be clean - yes, it can.
- How B-fields accelerate and collimate the flow
- Do B-fields continue into the outflow?
  - fireball model: no, but are recreated at matter-dominated shocks
  - EM model (Lyutikov & Blandford 2003): yes, **dissipation & acceleration is magnetic** (not shocks)
- Are there evidence of large-scale B-fields? - Polarization
  - prompt (Coburn & Boggs 2003, others)
  - optical afterglows (e.g., Mundell+ 2013, others)
- How B-field dissipates and accelerates particles



B-field generation (need ~ 10^{15} G)

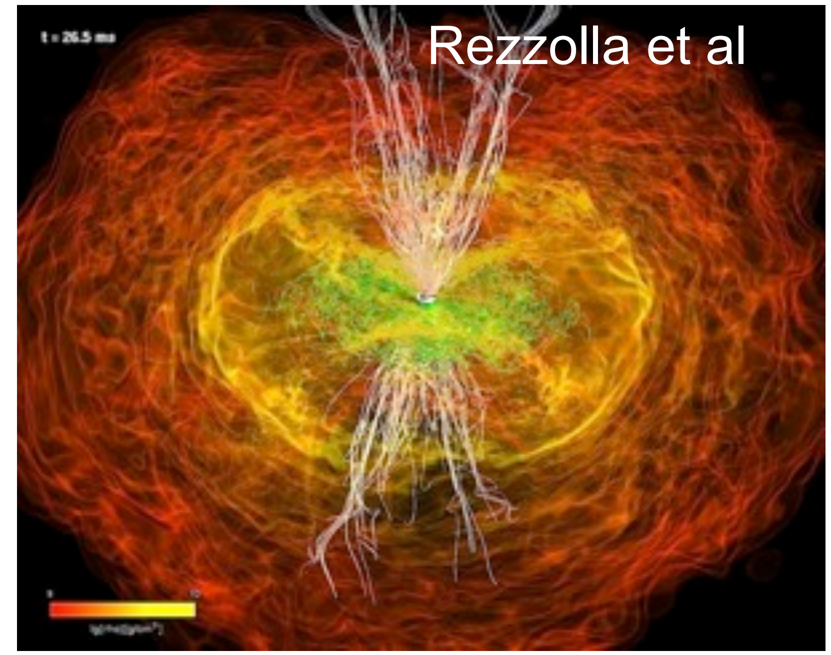
Core-collapse (Long GRBs)

- Compression, shear, turbulent, MRI and/or alpha-Omega dynamo operate during collapse and core bounce



- Most MHD core-collapse simulations do not treat B-field generation, but start with huge magnetic fluxes.
- Even non-magnetic explosions are not settled...

NS-NS mergers (Short GRBs)



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- shear in the torus (Rezzola+)?
- (Both saw amplification to > 10^{15} G)

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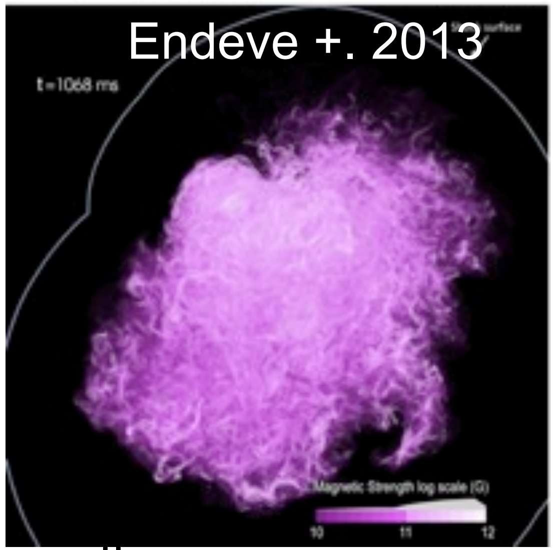

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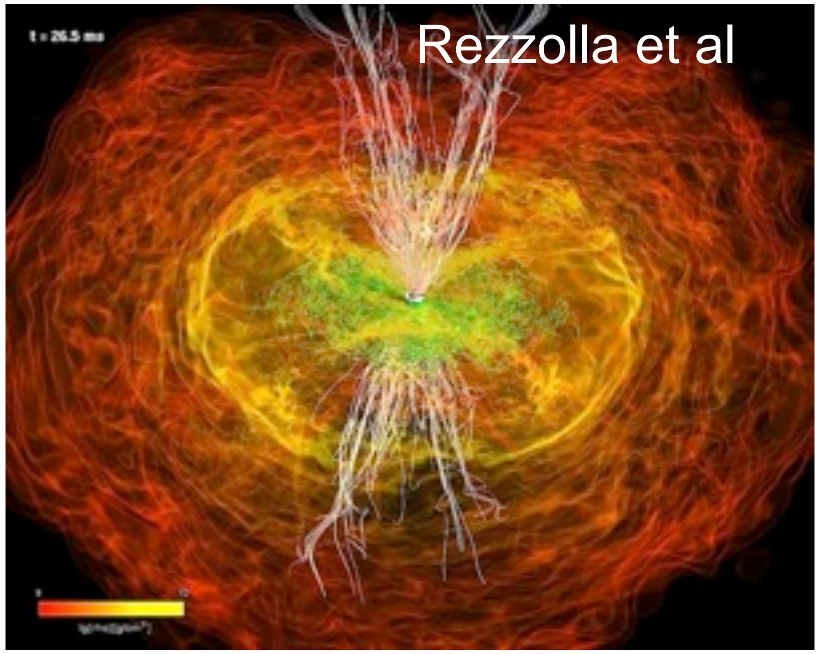

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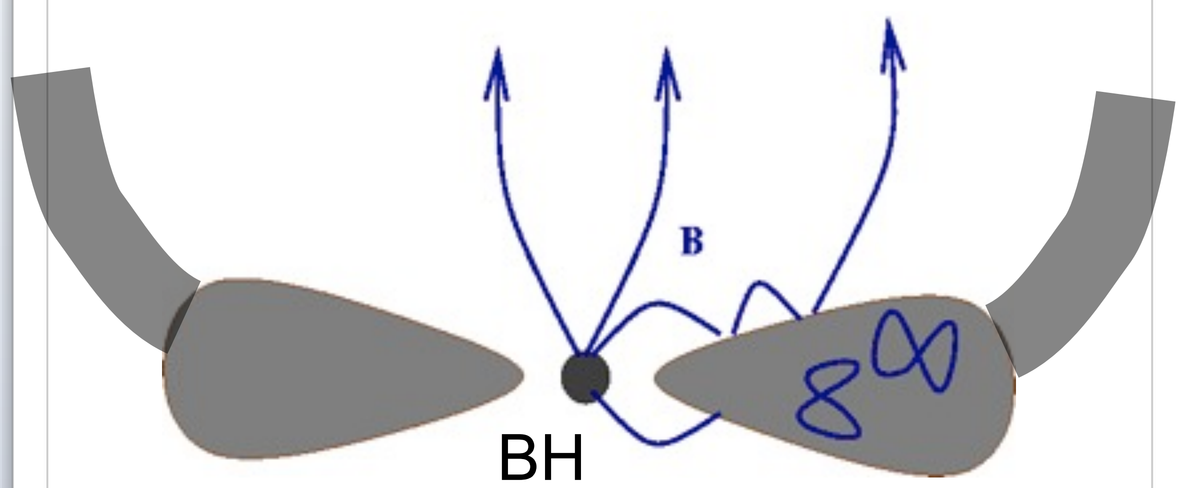
Extremely challenging simulations

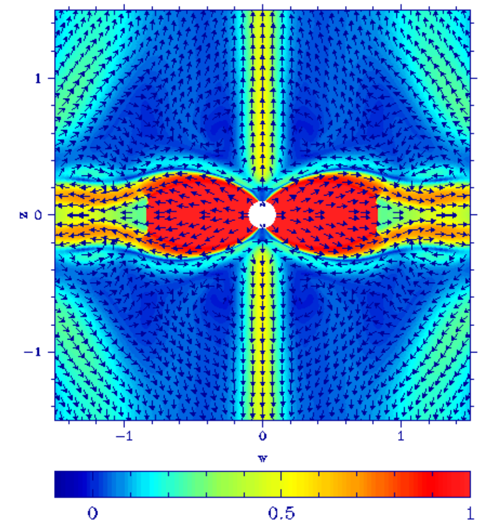
Two types of Faraday wheel in GRBs

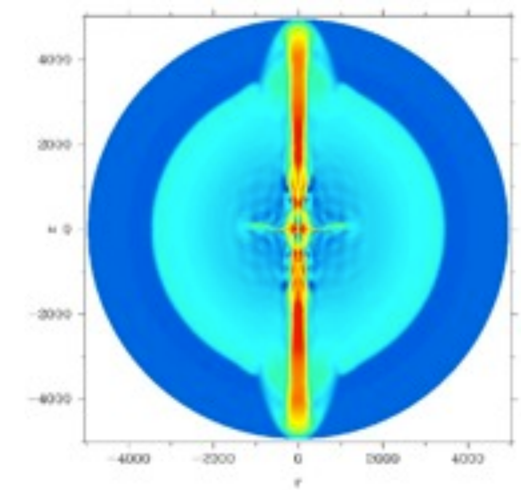
- Collapsar: AGN-like (BZ)



- **B-fields are externally supplied and confined to a BH** (Blandford-Znajek)
- Confining walls (Lynden-Bell, Uzdensky)
- High-Gamma jet, superfast
- Perhaps a weak oblique collimation shock, but mostly continuous nozzle-like acceleration

- Millisecond magnetar: **PWN-like**





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- Equatorially collimated initially

$$L \propto \sin^2 \theta$$

- Strong shock - stop!
- "Slowly" collimated by hoop stresses, sub-fast/super-Alfvenic plume (later nozzles out to super-fast)

Komissarov+, Bucciantini+

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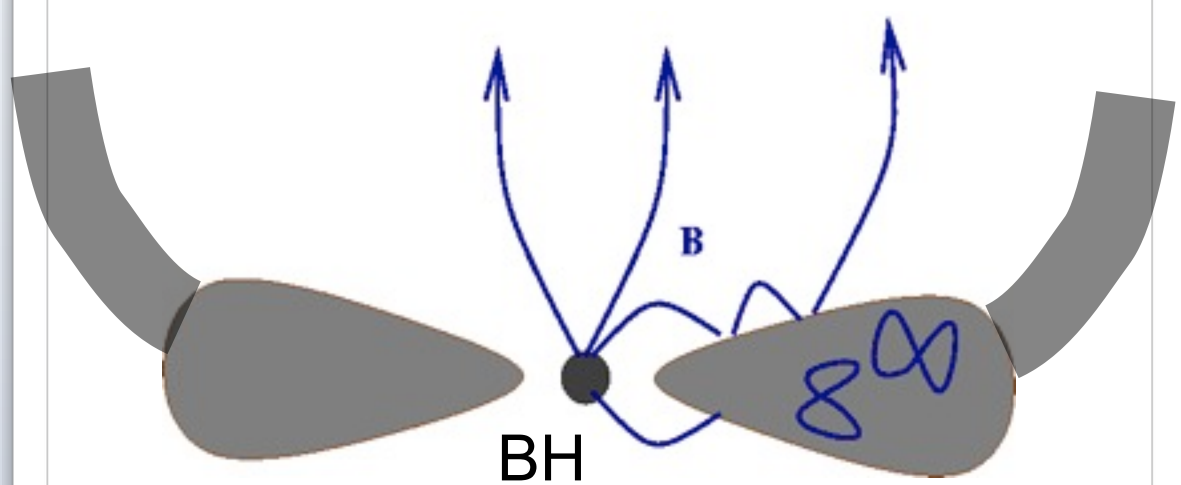

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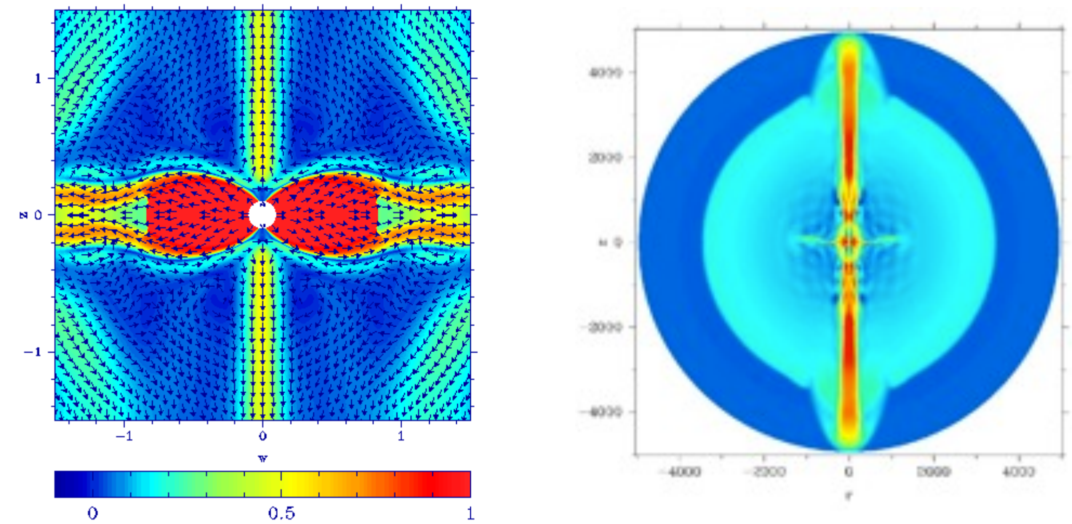

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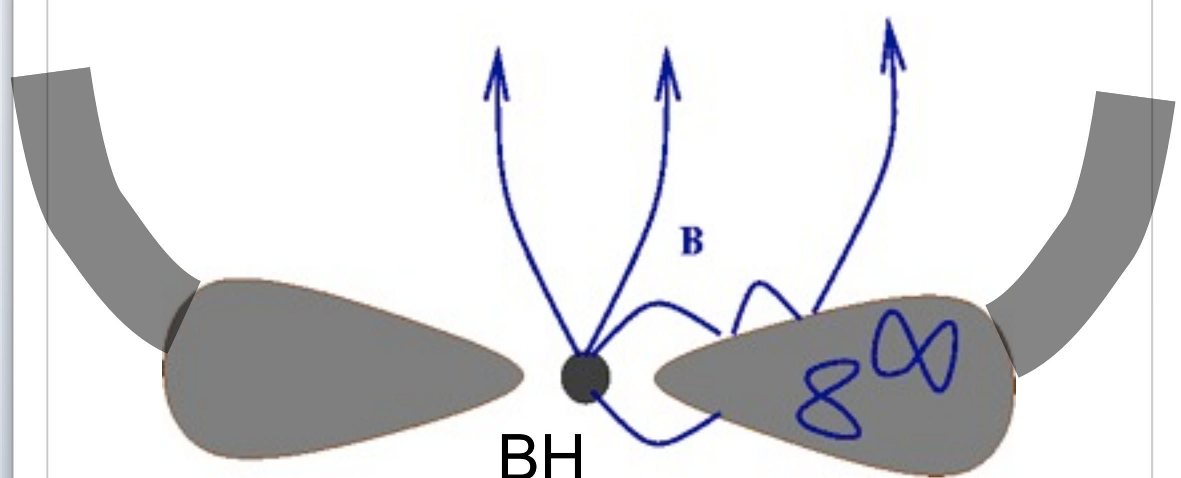

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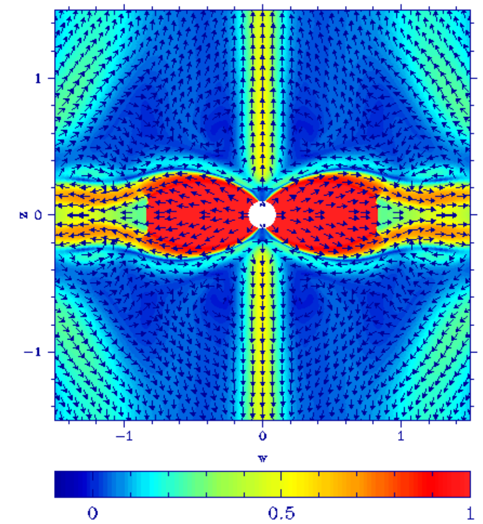

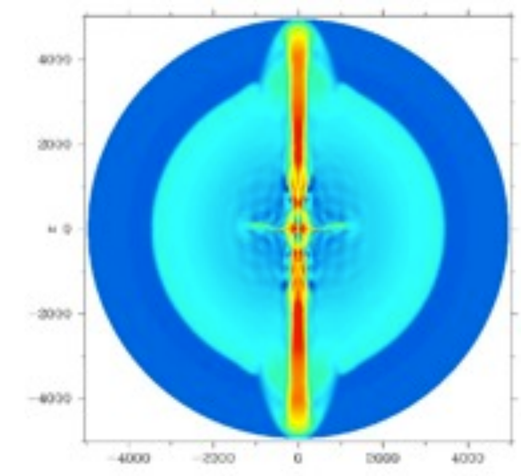

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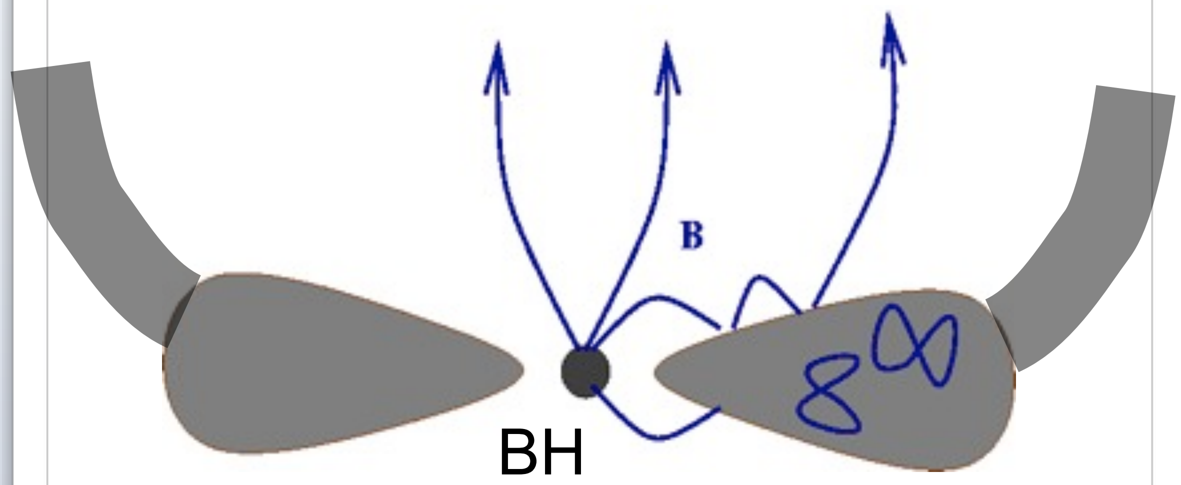

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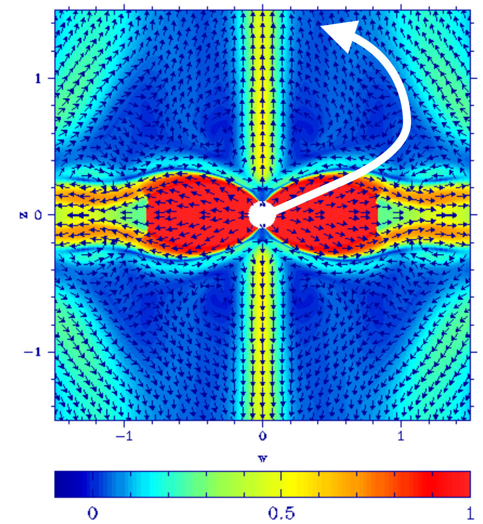

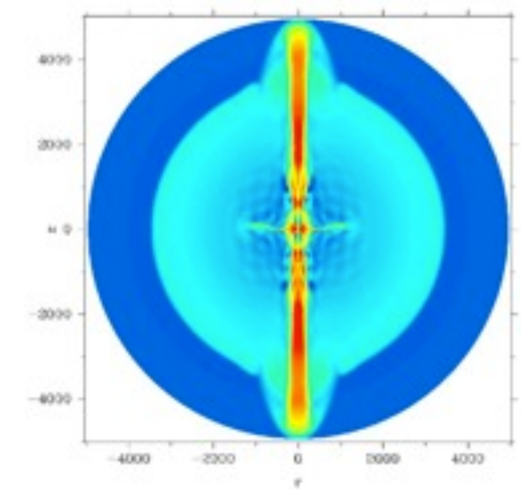

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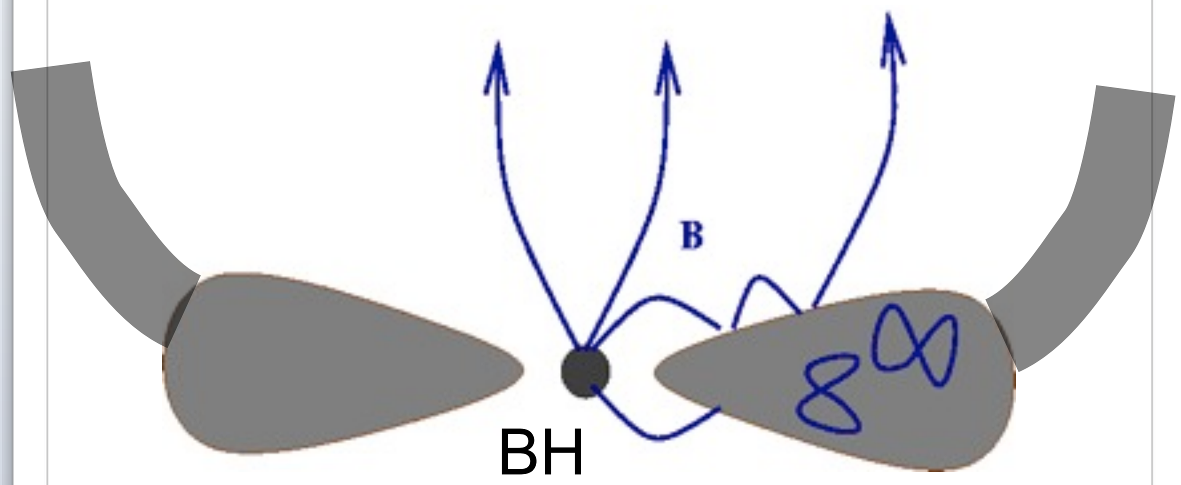

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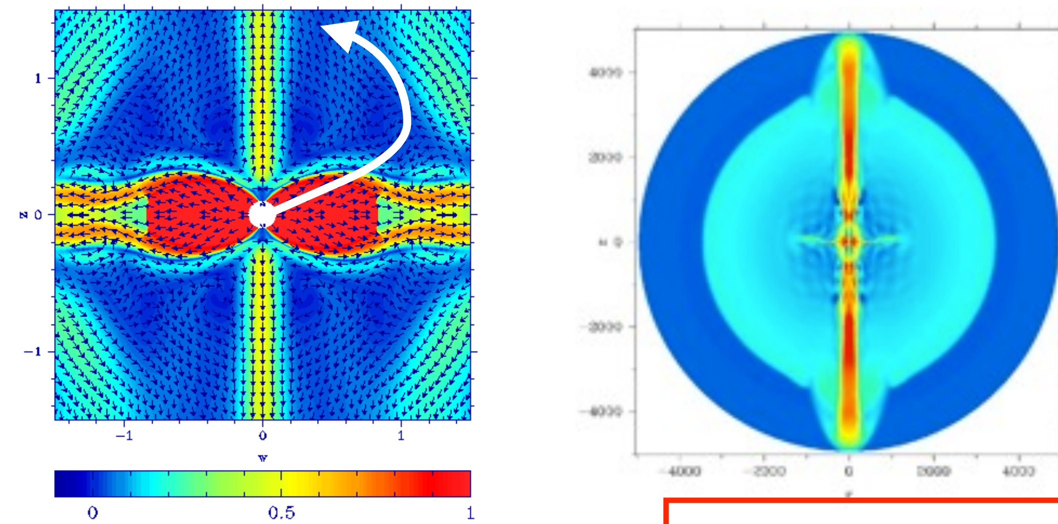

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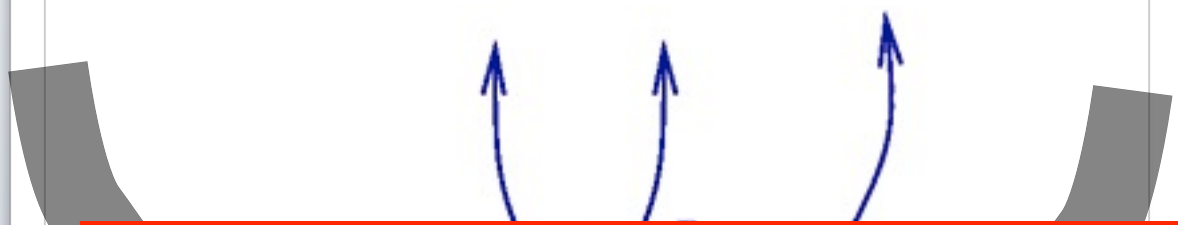

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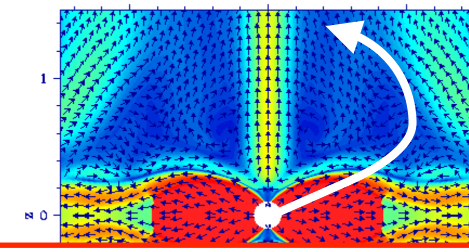

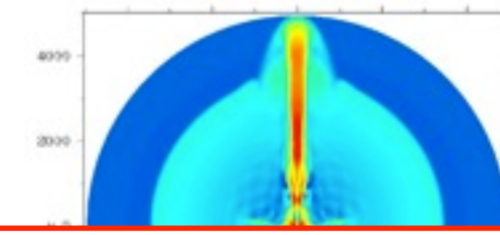

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- In application to Long GRBs central engine, both types of model have two related problems in making a jet
  - the sigma problem
  - stability

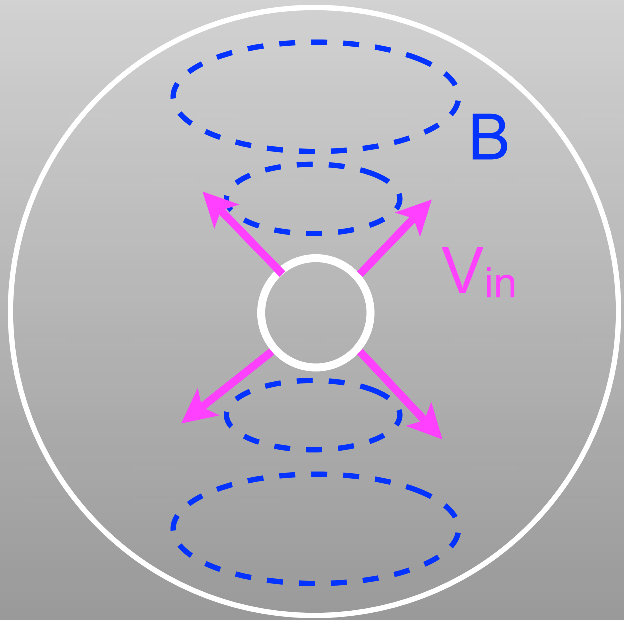
(Lyutikov cir. 2003)

The sigma problem

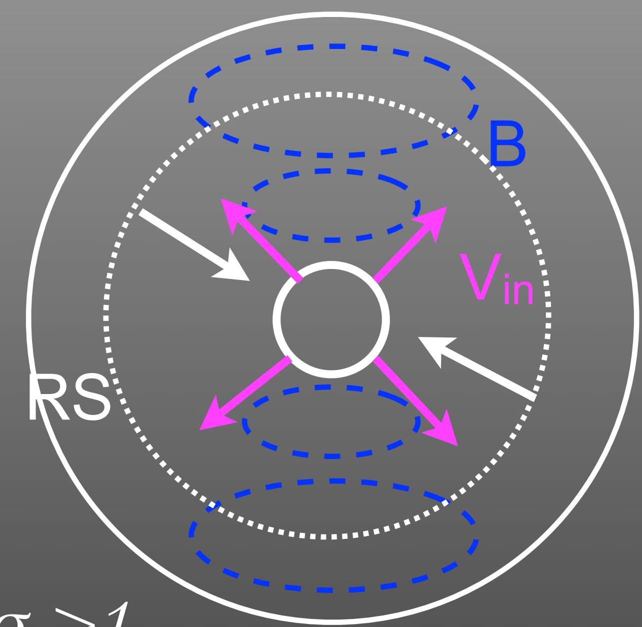
Rees & Gunn
Kennel & Coroniti

Consider a fixed cavity into which a central source injects **energy and magnetic flux** linearly with time. E.g. magnetar cavity is nearly constant on light travel time.

Stored B-flux ~ t, toroidal B-field ~ t, stored energy ~ B^2 ~ t^2 ???



Kennel&Coroniti: in $\sigma > 1$, reverse shock would reach the central engine in light crossing time and model breaks down



V_{RS} ~ c for $\sigma > 1$

(Lyutikov cir. 2003)

Possible resolutions

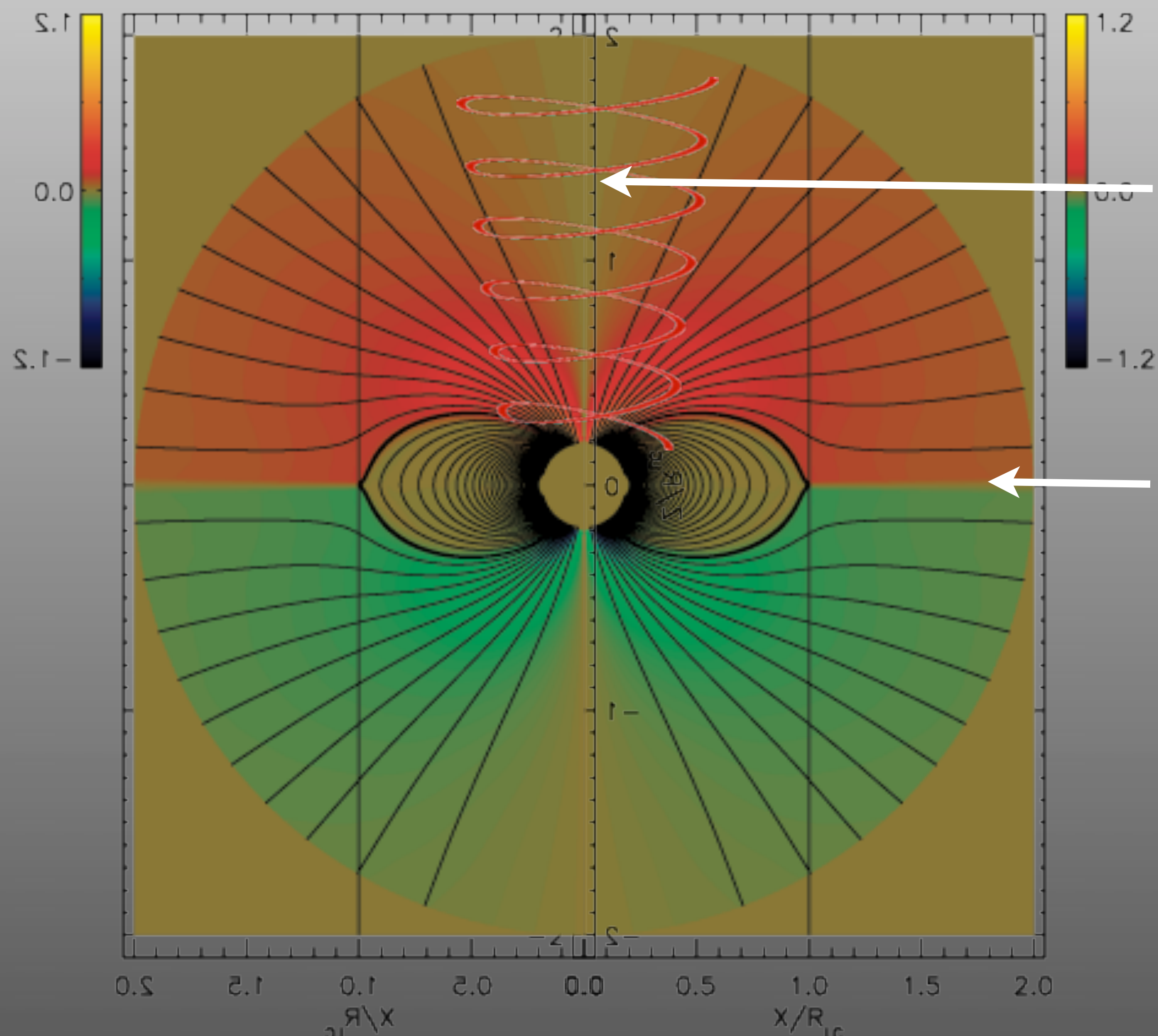
- Kennel & Coroniti: σ must change to << 1 on the way.
(NB: this is a requirement of the self-consistency of the model, not a measured parameter within the model).

- σ remains high, but shock is not MHD (kinetic effects dominate, Lyubarsky). Unlikely in magnetars, too dense.

- **Most of magnetic flux should be destroyed between the source and the boundary. The flow must become dissipative.**

(Lyutikov cir. 2003)

Need to destroy magnetic flux: reconnection.



O-point reconnection

X-point reconnection

Plasma will flow towards reconnection cites

(Lyutikov 2010)

Ideal flow in the bulk, dissipation on the axis & equator

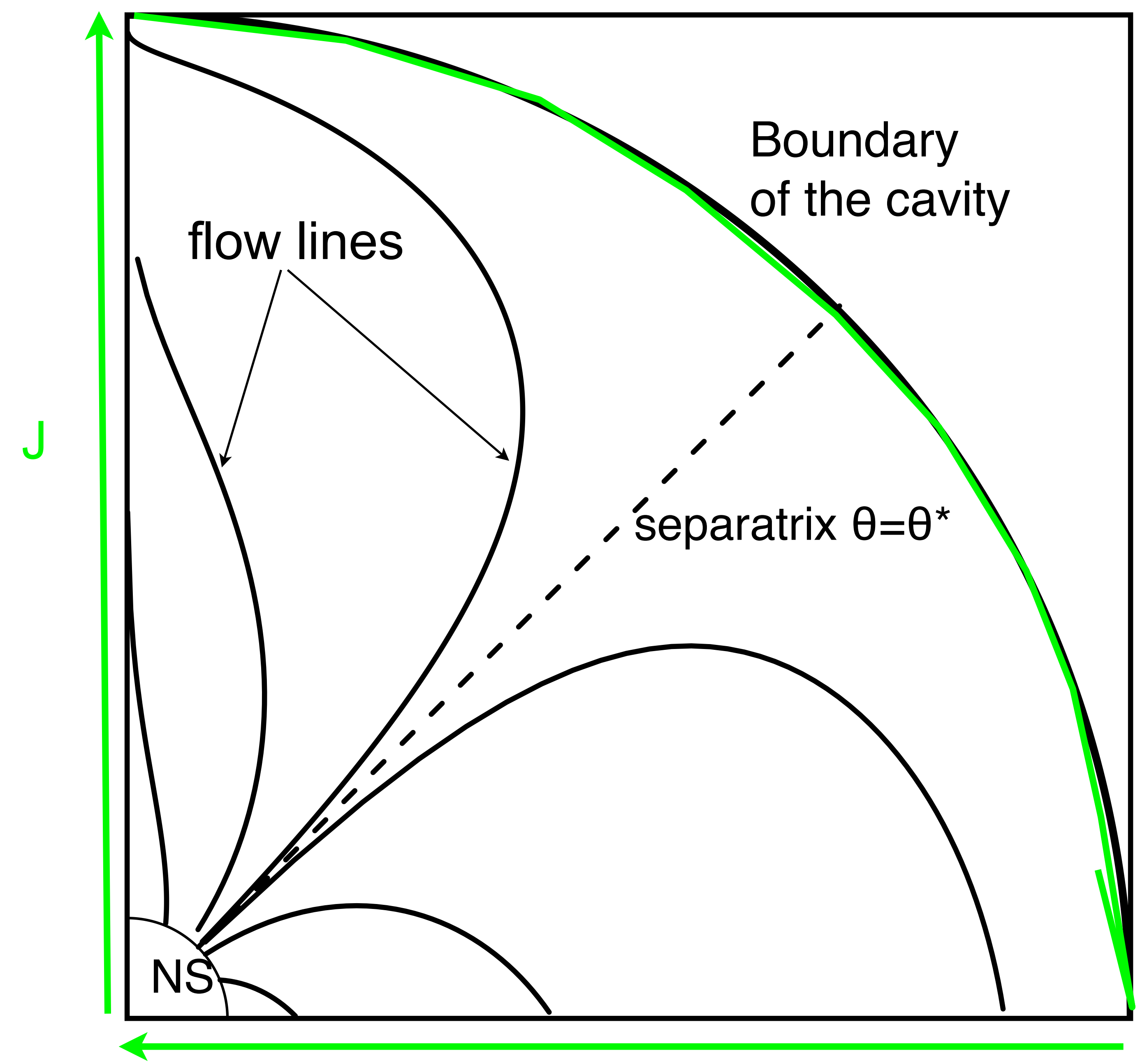
$$2\nabla I^2 = r^2 \sin^2\theta \Delta\Phi\nabla\Phi$$

- Current and charge distributions are related

$$\mathbf{v} = \frac{\mathbf{E}\times\mathbf{B}}{B^2} = \frac{r\sin\theta(\mathbf{e}_\phi \times \nabla\Phi)}{2I}$$

- Vanishing charge and current densities in the bulk.
- I=I0 - current on the axis

$$\Phi = \Phi_0 \left(1 - \frac{R}{r}\right) \ln \frac{\tan\frac{\theta}{2}}{\tan\frac{\theta^*}{2}}$$

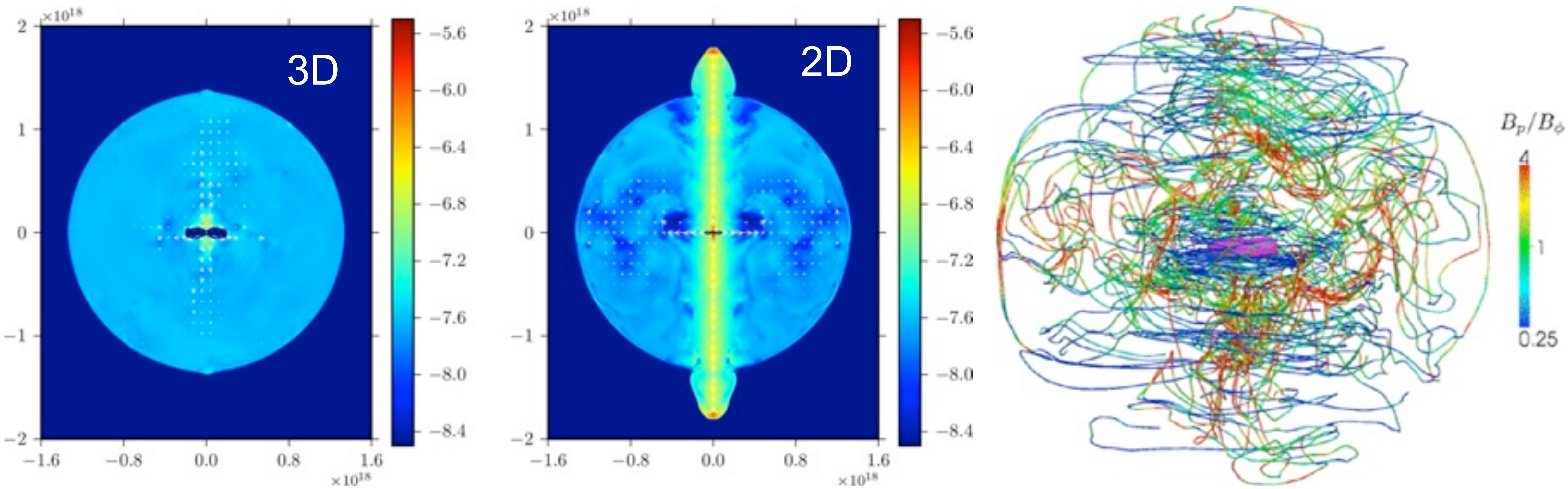


On the axis: toothpaste tube effect

Porth et al .2013

The stability problem

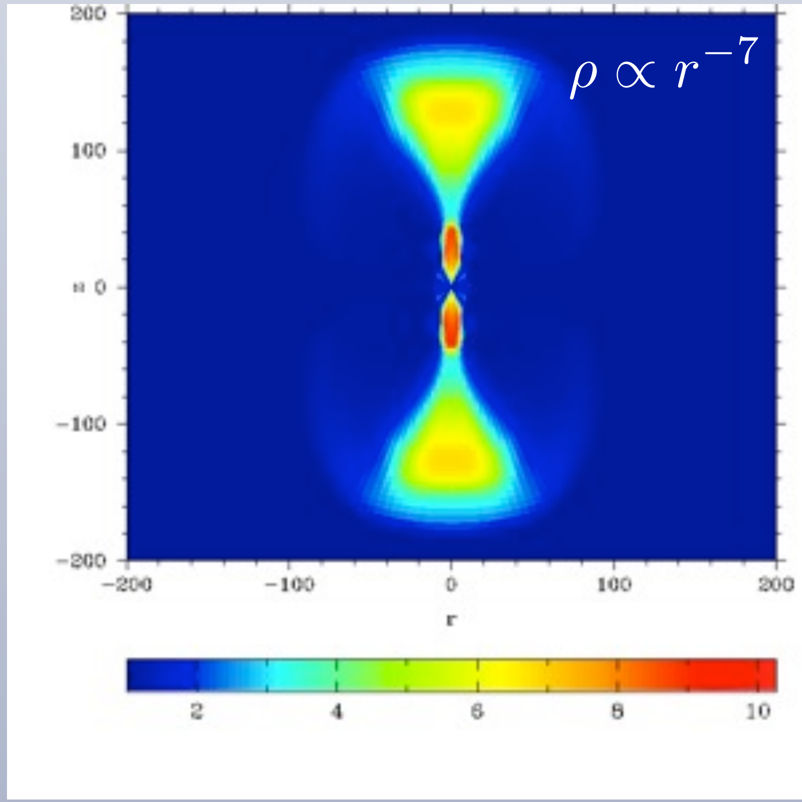
- **How to kill flux: twisted B-field susceptible to kink instabilities**
- First 3D relativistic MHD simulations of PWN, sigma >> 1



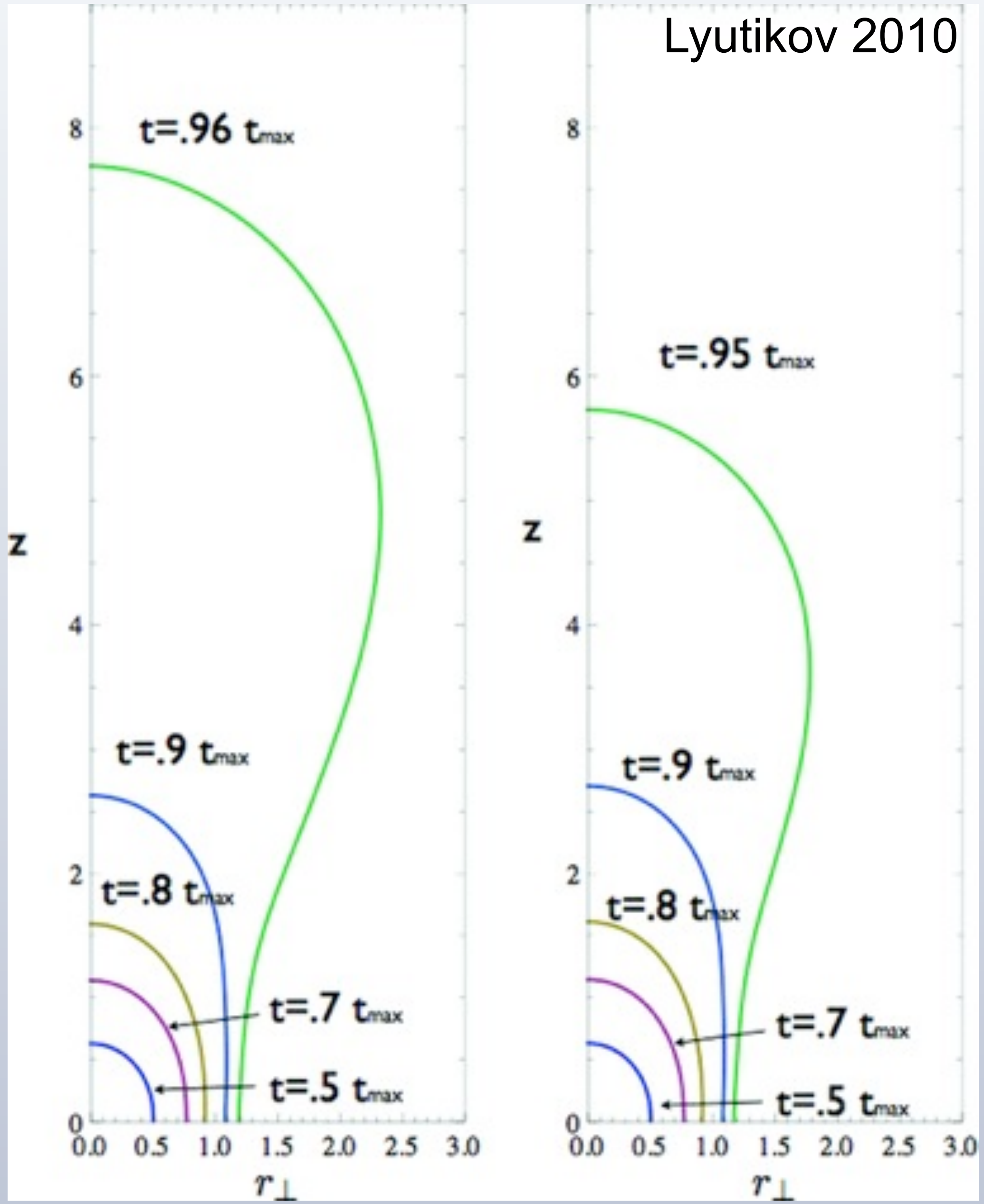
- **Magnetic flux is destroyed. Sigma problem solved.**
- axially-symmetric simulations way overestimated the stability and Lorentz factor of the jets: 3D jets are slow and susceptible to instabilities (in BH-driven jets as well).
- But there is no jet left, only a plume.... Sigma problem became the no-jet problem (~OK for PWNe, not OK for GRBs)

And what to do?... Wait a second

- Wait a few seconds for neutrinos to do the hard part, explode the star.
- B-field is amplified on a contracting proto-NS. Launch a **slightly non-spherical** shock inside a star.
- FS propagates in **expanding envelope (v ~ r), with sharp density gradient** - shock accelerates, makes a key hole (chimney)



Lyutikov & Komissarov, in prep



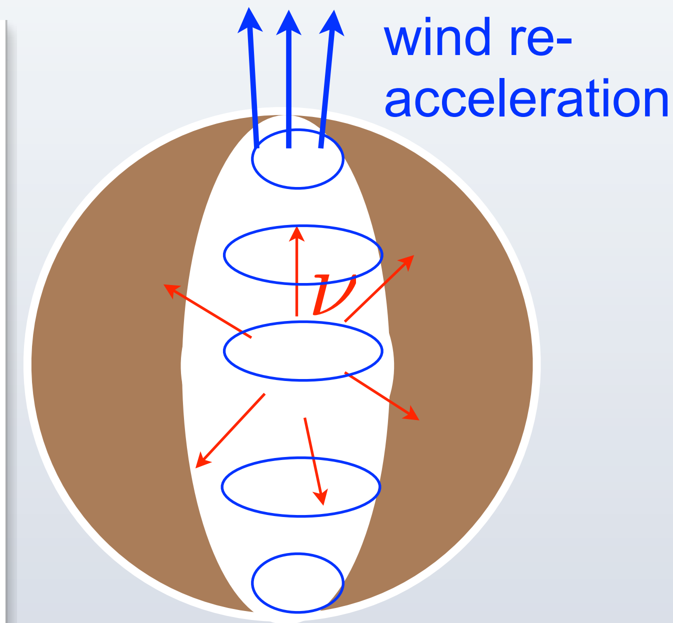
Anisotropic driving

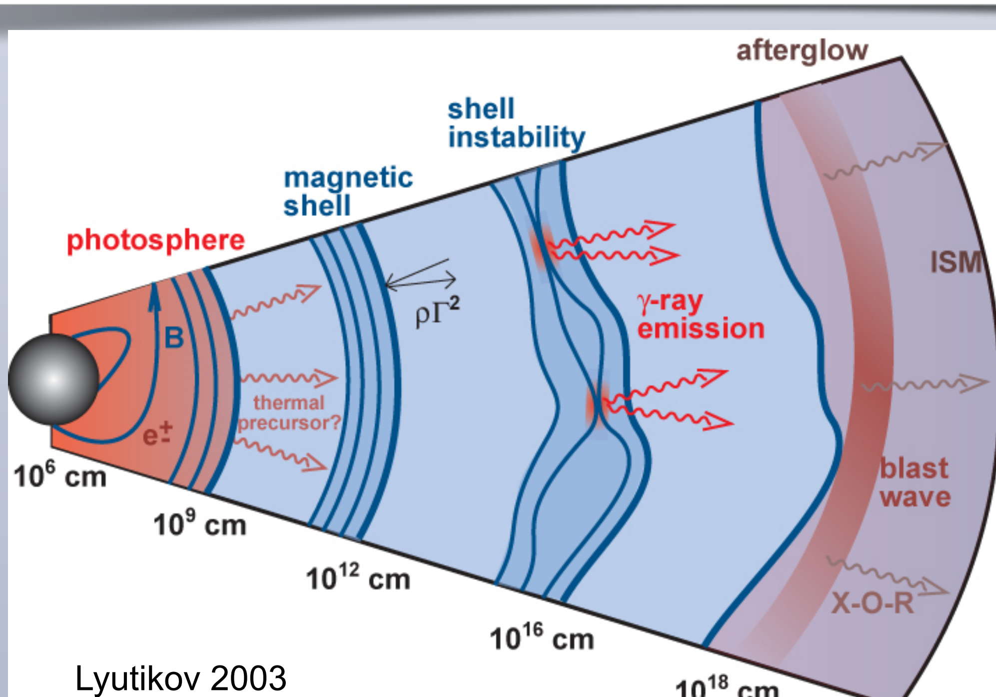
Anisotropic r_0

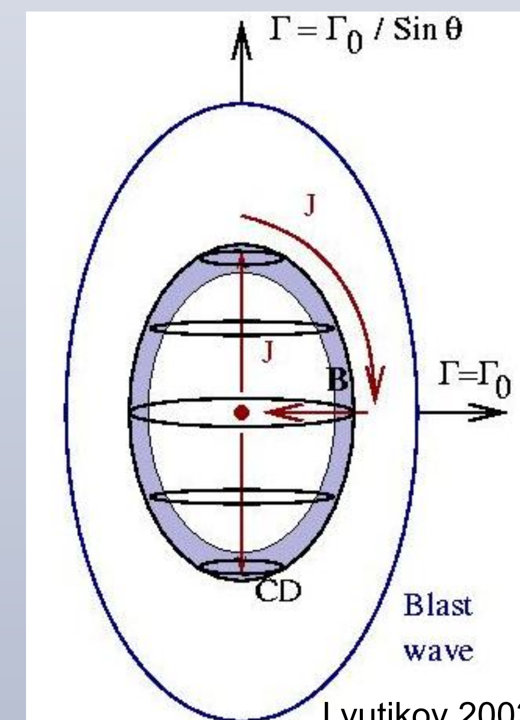
$$1 + \cos^2 \theta$$

After the break-out the wind reaccelerates

- Force balance: $\Gamma \sim \Gamma_0 / \sin\theta$ (but: instabilities?)
- Engine active for 100s secs: magnetars are good for **late activity** (no need for long accretion)
  - not by powering the FS (little energy), but by **internal dissipation** in the long-lasting wind
- But magnetar emission is smooth? - **Peaks in the profile are signatures of the bursty dissipation in the wind, not the central engine activity** (Lyutikov & Blandford 2003, Lyutikov 2006)

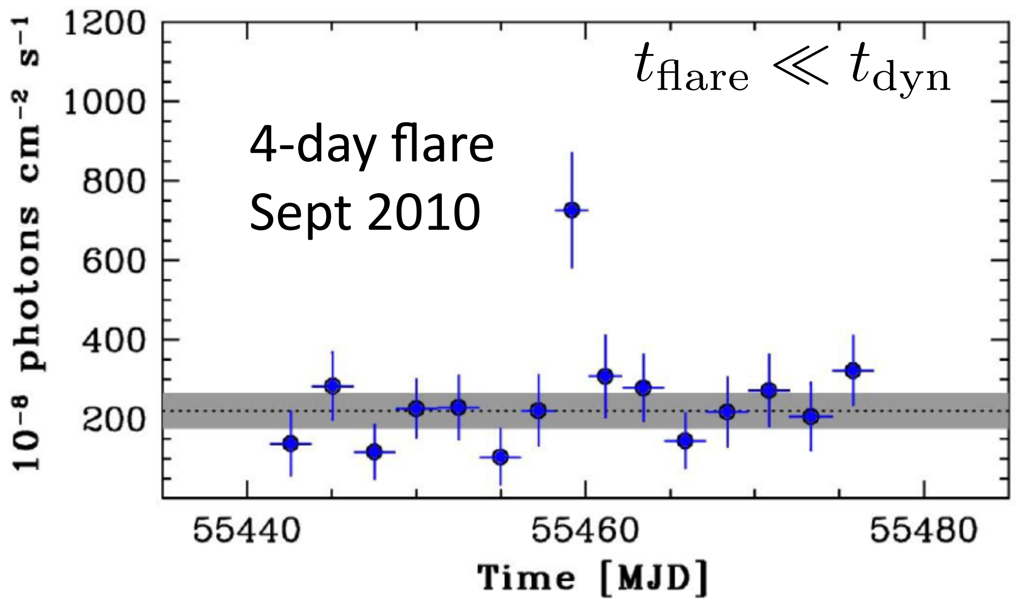




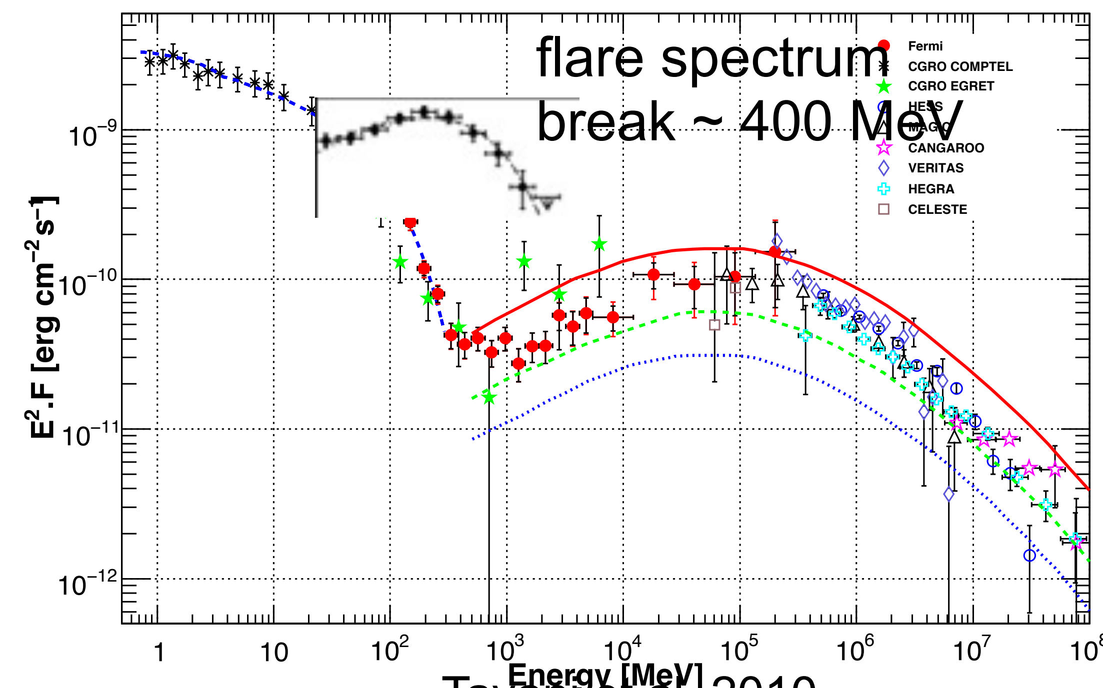


Bursty dissipation in the wind: Crab flares!

Recall: magnetar models of GRBs ~ models of PWNe



Tavani et al. 2011



Tavani et al. 2010
Beuhler et al., 2011

Accelerating E-field < B-field

$$eEc = \eta eBc = \frac{4e^4}{9m^2c^3} B^2 \gamma^2$$

$$E_p = \frac{27}{16\pi} \eta \frac{mhc^3}{e^2} = 236\,\eta\,\mathrm{MeV}.$$

Lyutikov ‘10,
Komissarov & Lyutikov ’11
de Jager ‘98 (for shocks)

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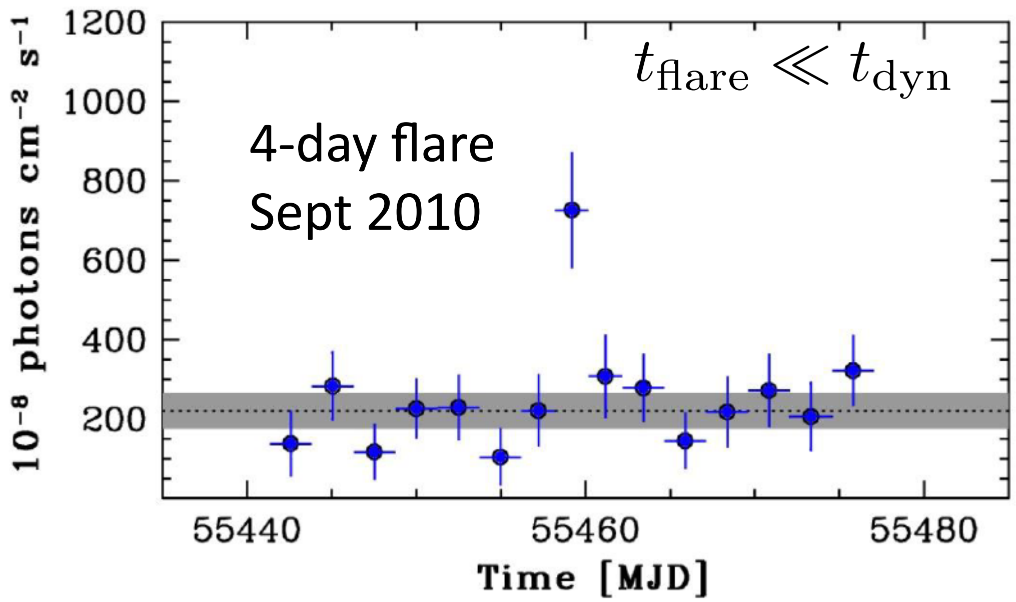

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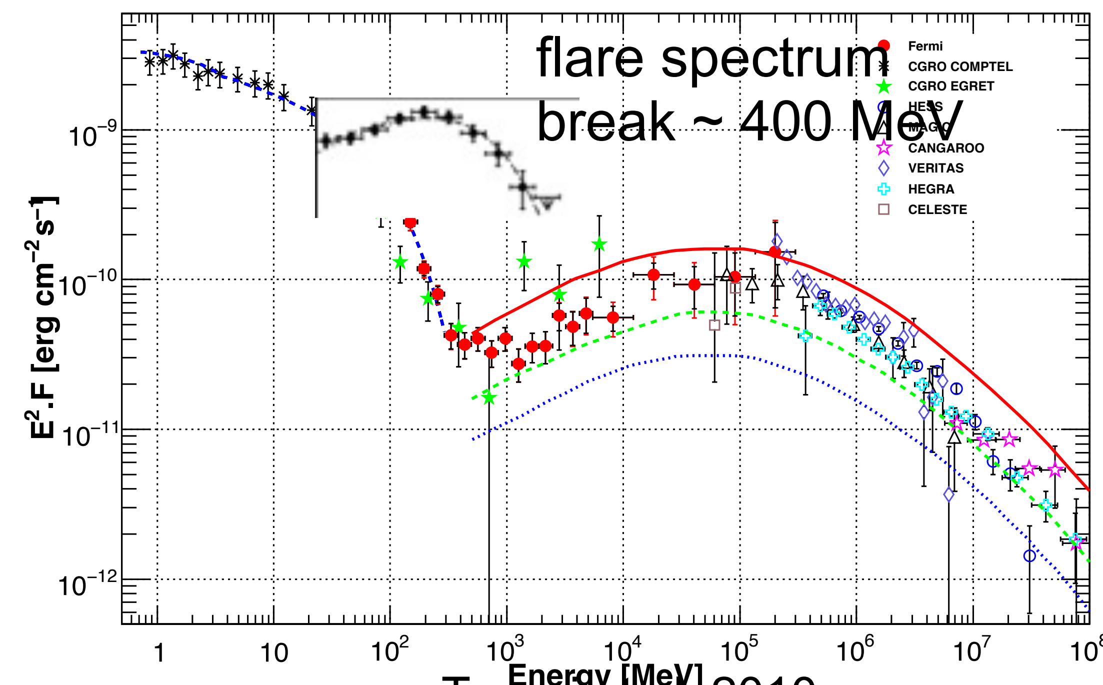

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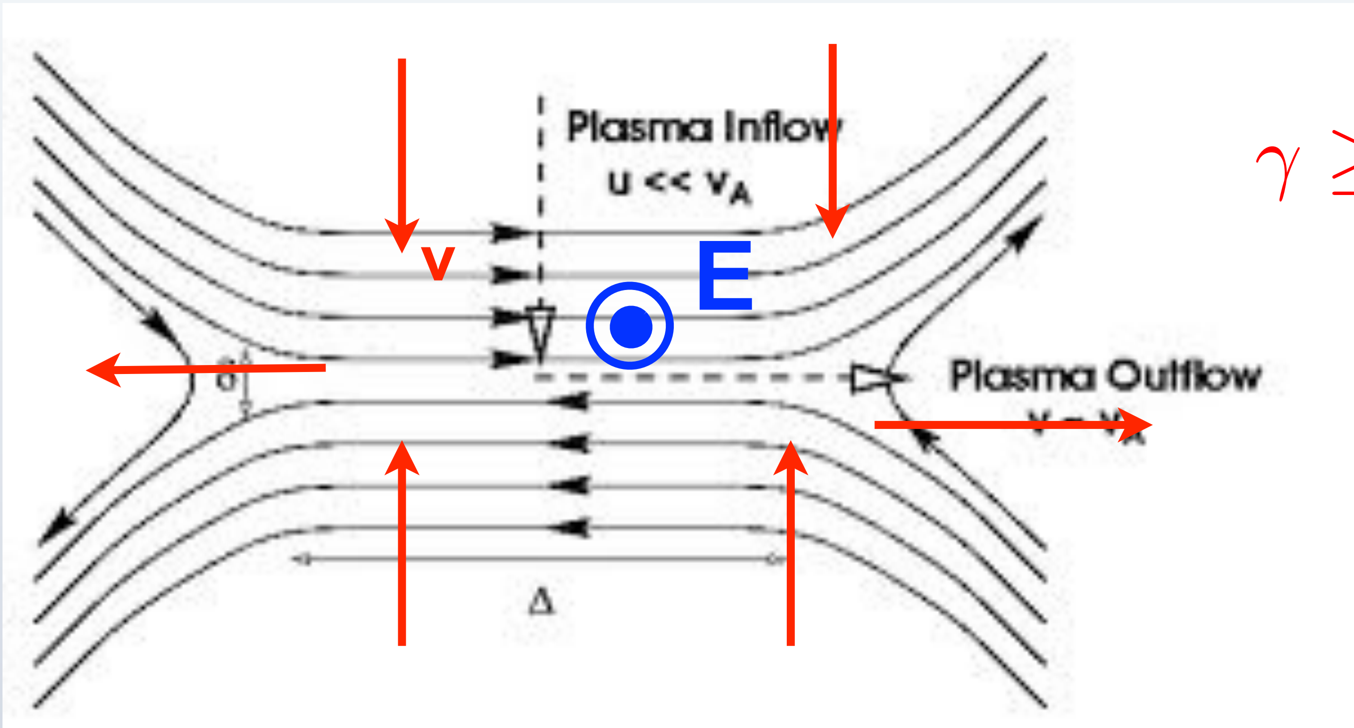
Komissarov & Lyutikov ’11
de Jager ‘98 (for shocks)

- Highly magnetized, sigma >> 1, shocks are weak, not likely to be efficient accelerators.
- All the energy in the B-field: accelerate particles directly via **reconnection.**
- ***Paradigm change (?): some (most?) particles are accelerated by magnetic reconnection (and not shocks)***

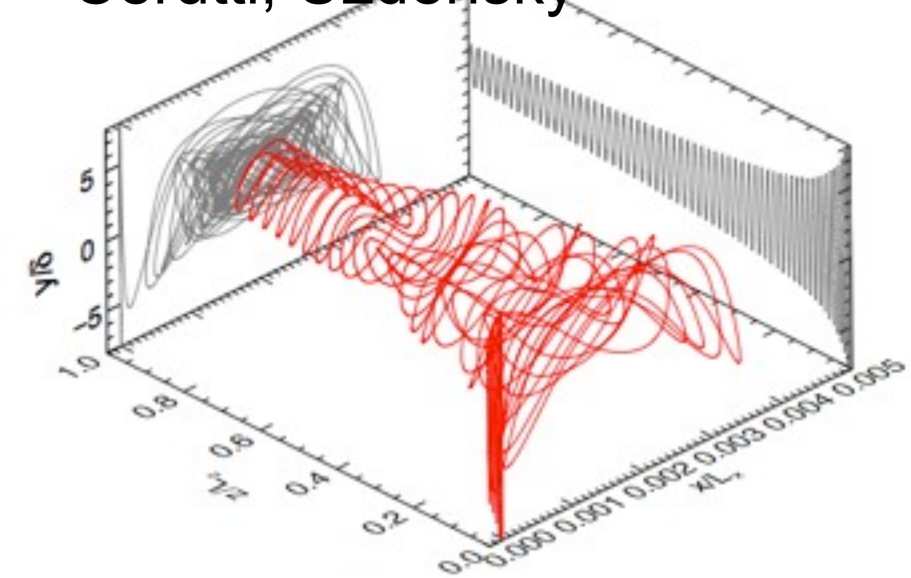
Reconnection: efficient, non-stationary



$\gamma \geq 1$

Reconnection in sigma >> 1 plasma: outflow can be relativistic (Lyutikov & Uzdensky 2002, Lyubarsky)

Cerutti, Uzdensky+



New plasma physics regime: sigma >> 1 plasma.

- **What are dynamic and dissipative properties of such plasmas? - very different from laboratory and space plasmas.**
- Pulsar winds, AGN & GRB jets and magnetospheres of BHs
- Alfven velocity is highly relativistic
  - E-field is dynamically important
  - charge density is important

Reconnection can be bursty from smooth conditions

- Current sheet can be unstable to tearing
-

Lyutikov 2003, Komissarov+ 2007

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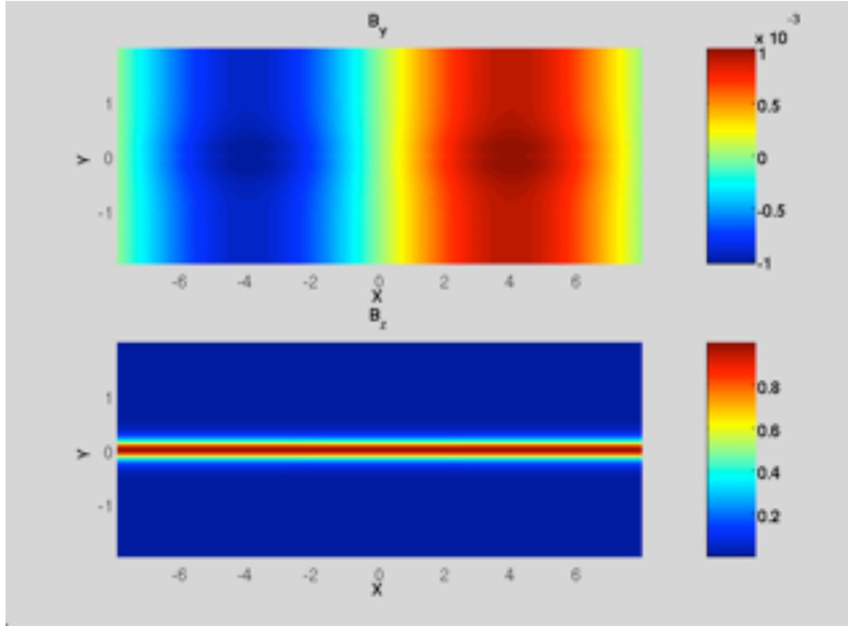

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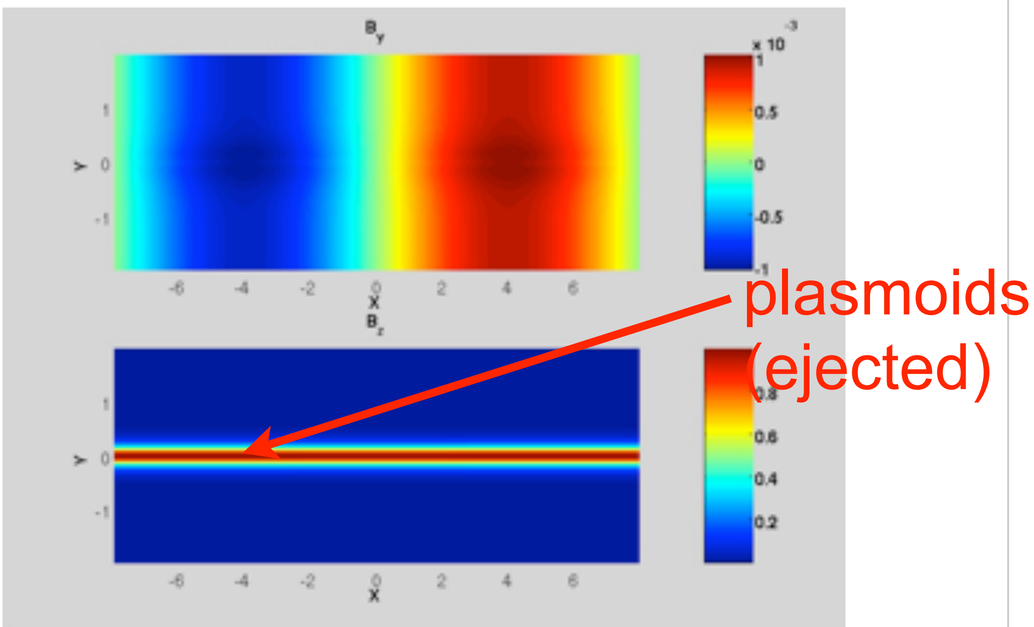

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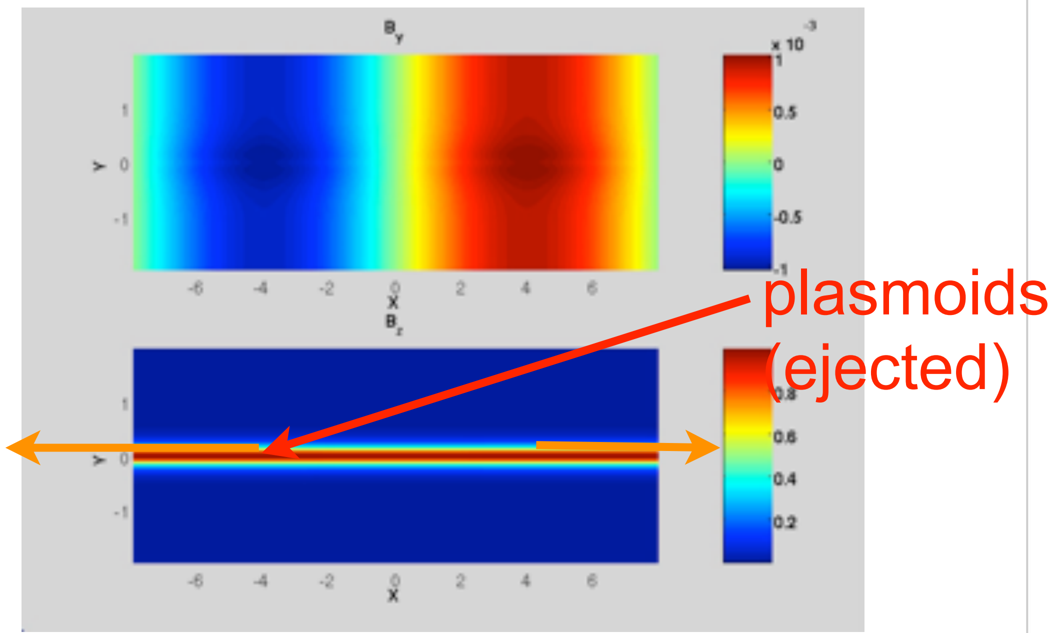

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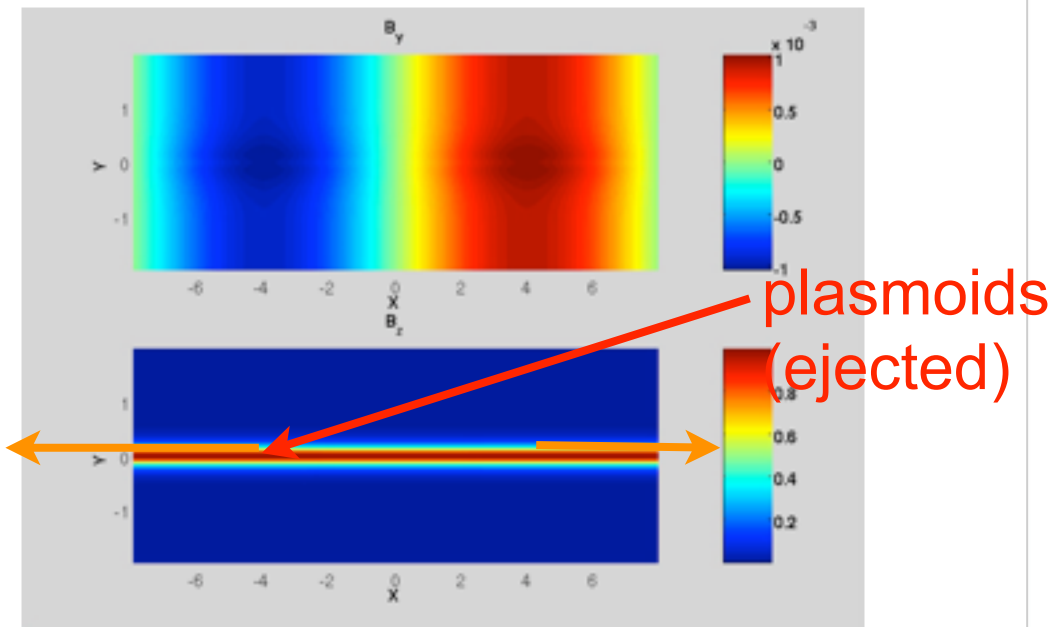
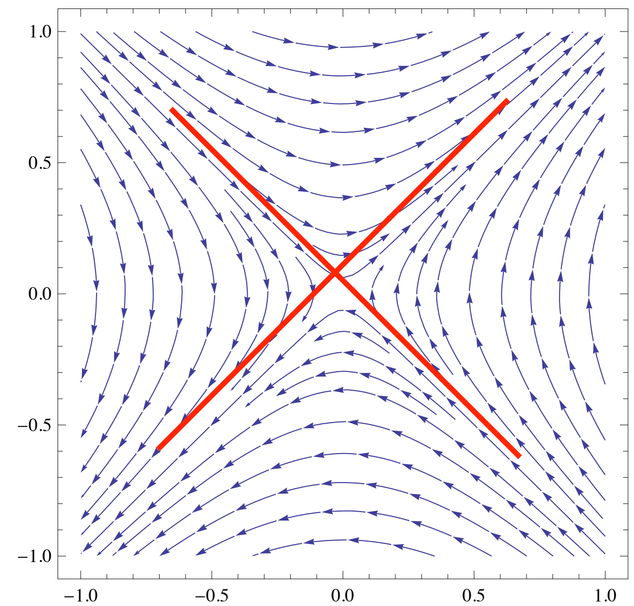


Lyutikov 2003, Komissarov+ 2007

X-point collapse (non-linear tearing?):



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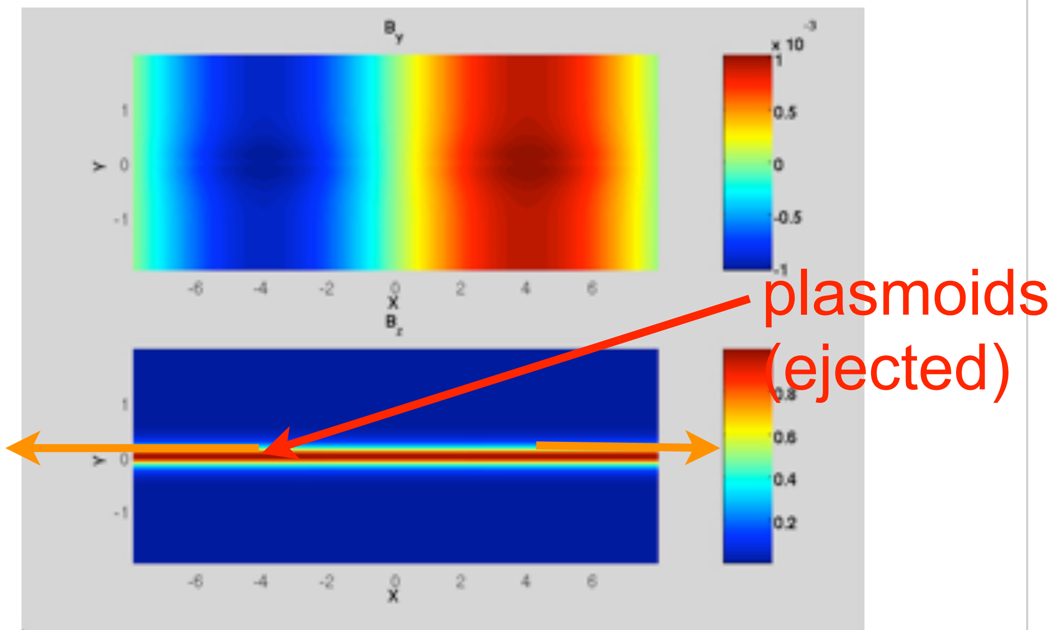

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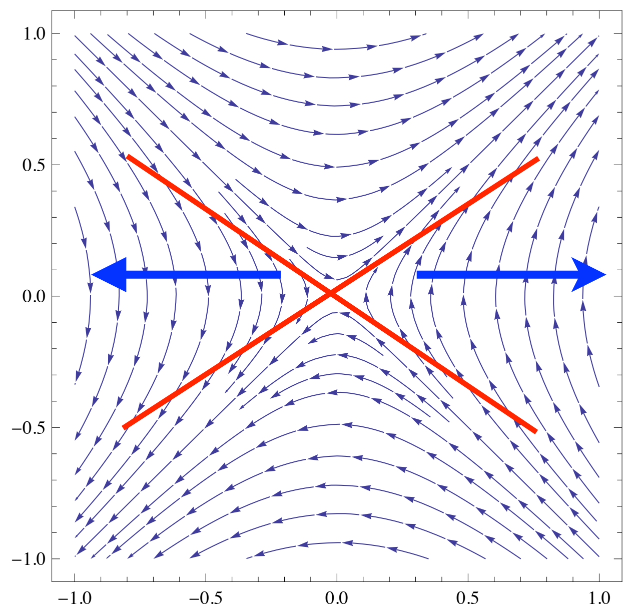

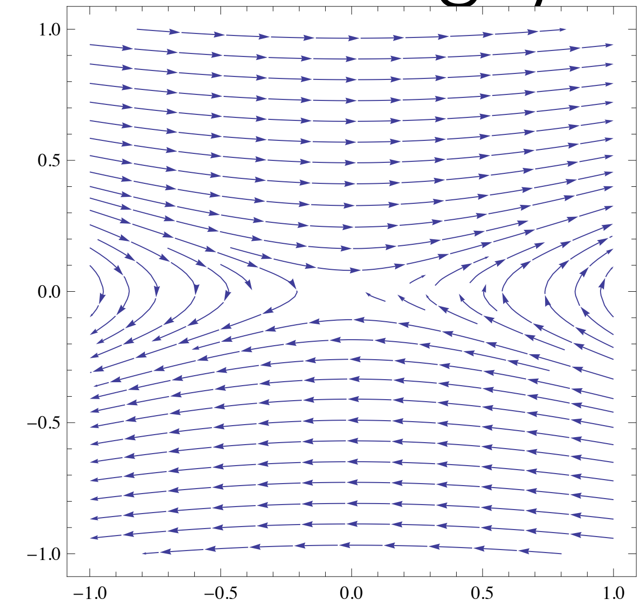

- **explosive** dynamics on Alfven (light) time
- Starting with smooth conditions
- E ~ B_0 (field outside), E>B with resistivity

Reconnection can be bursty from smooth conditions

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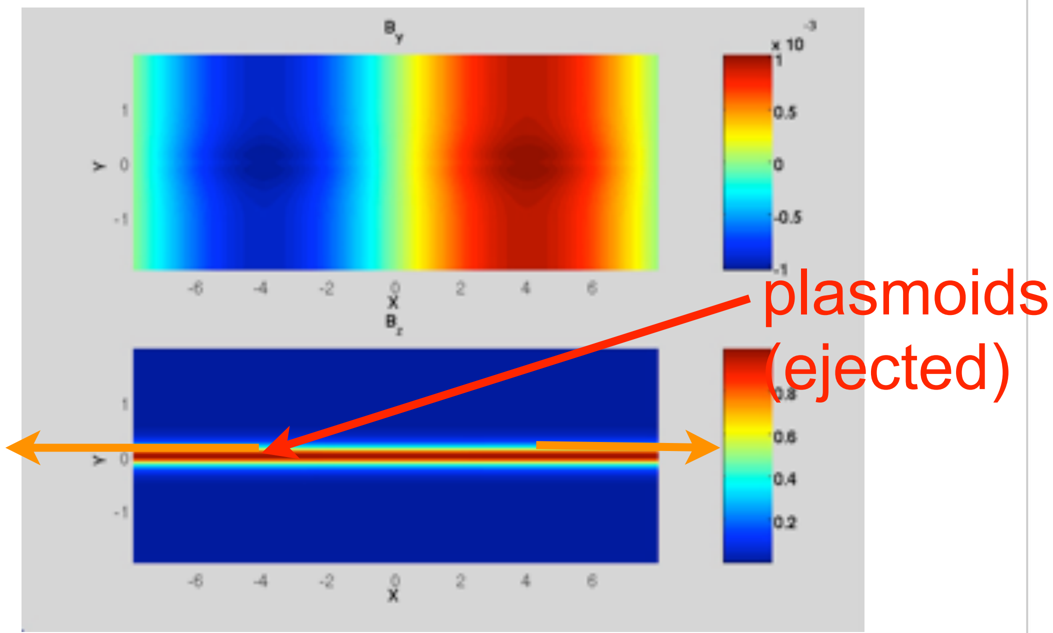

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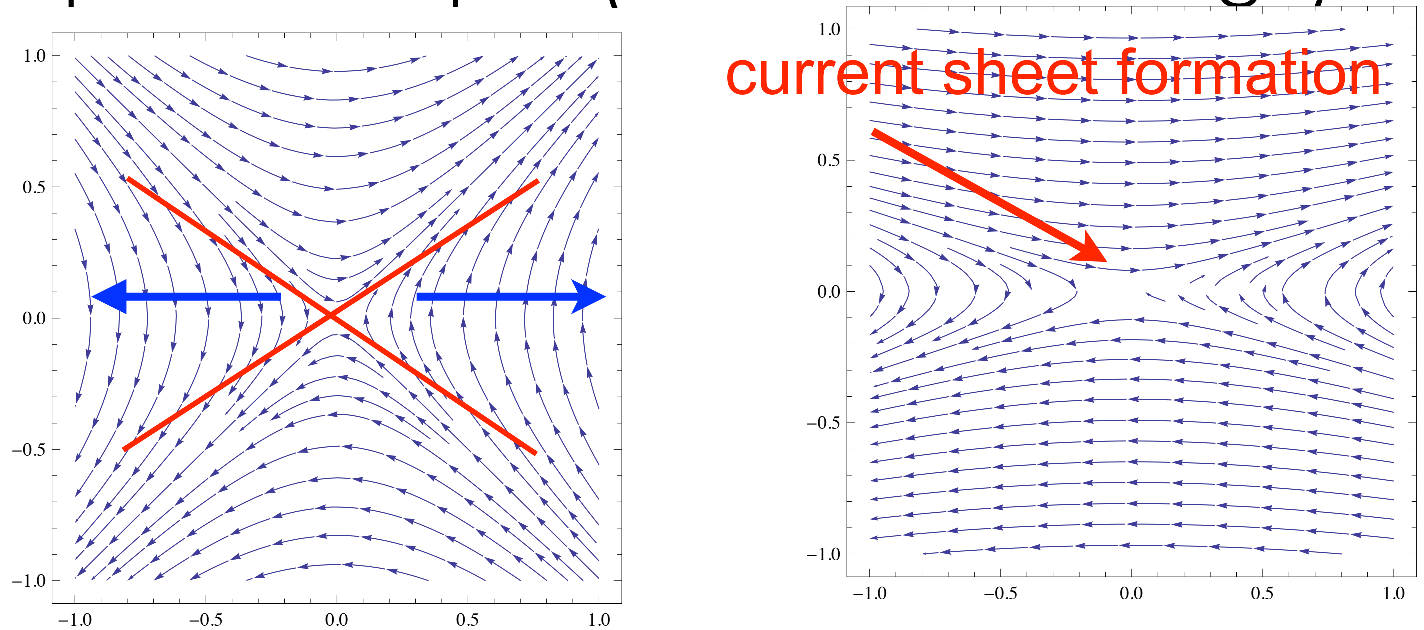

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Monday, January 20, 2014

Reconnection can be bursty from smooth conditions

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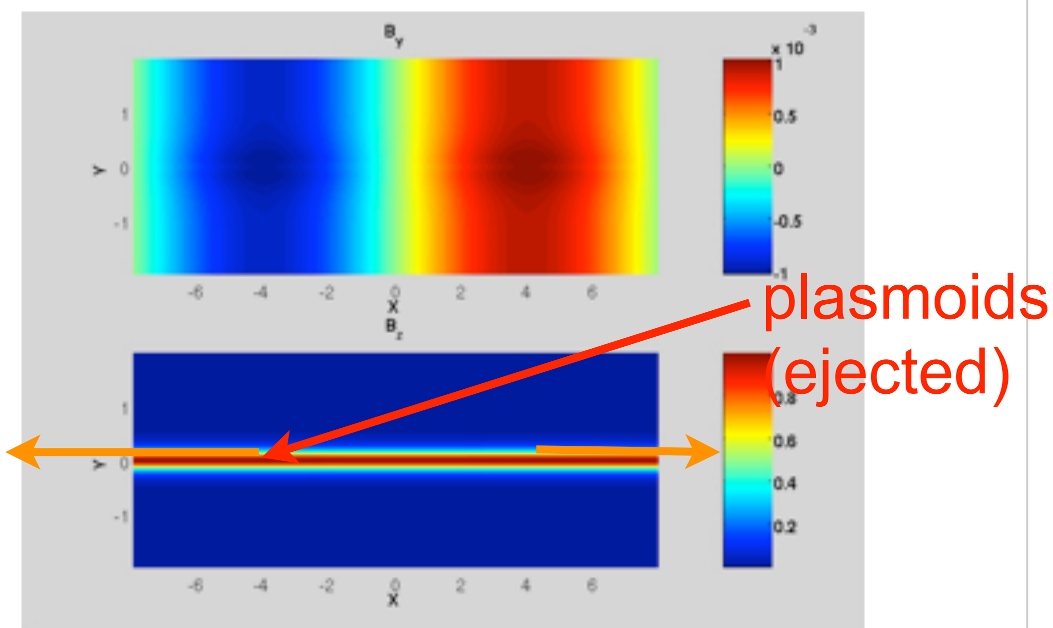

Lyutikov 2003, Komissarov+ 2007

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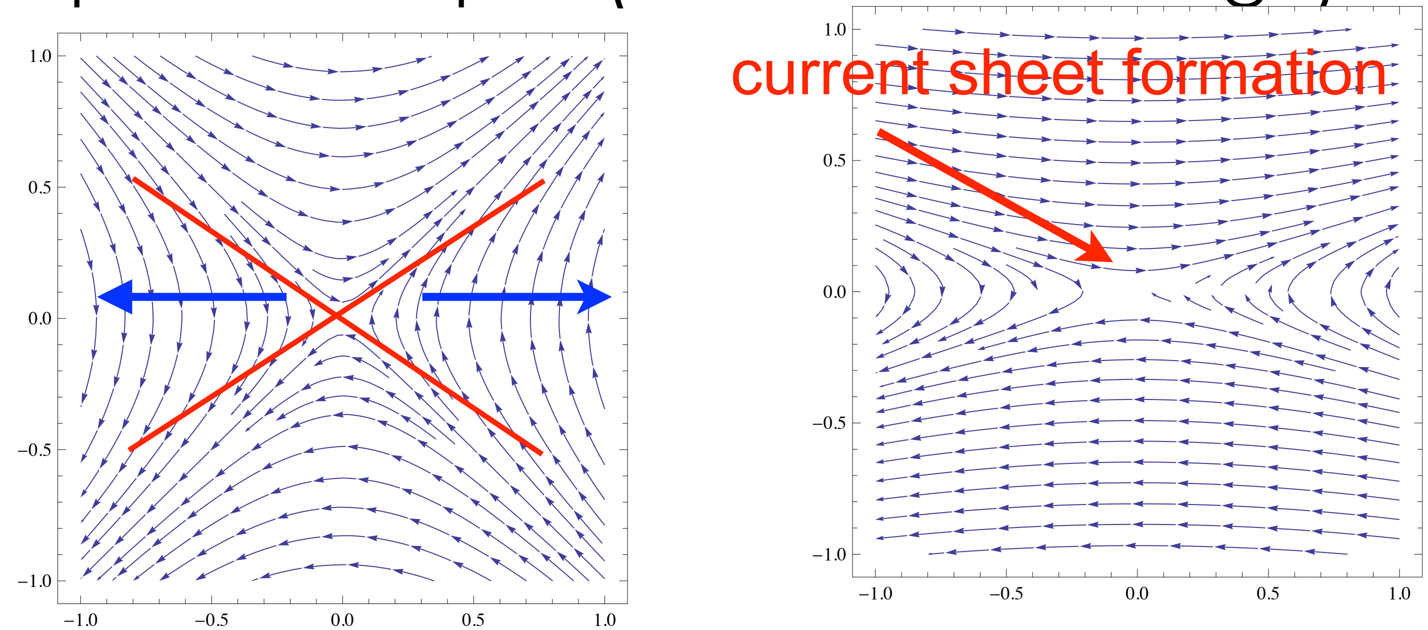

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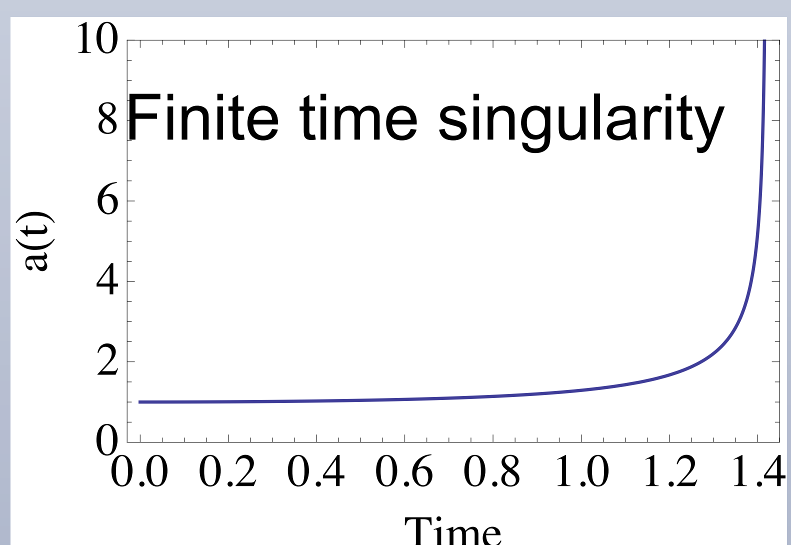
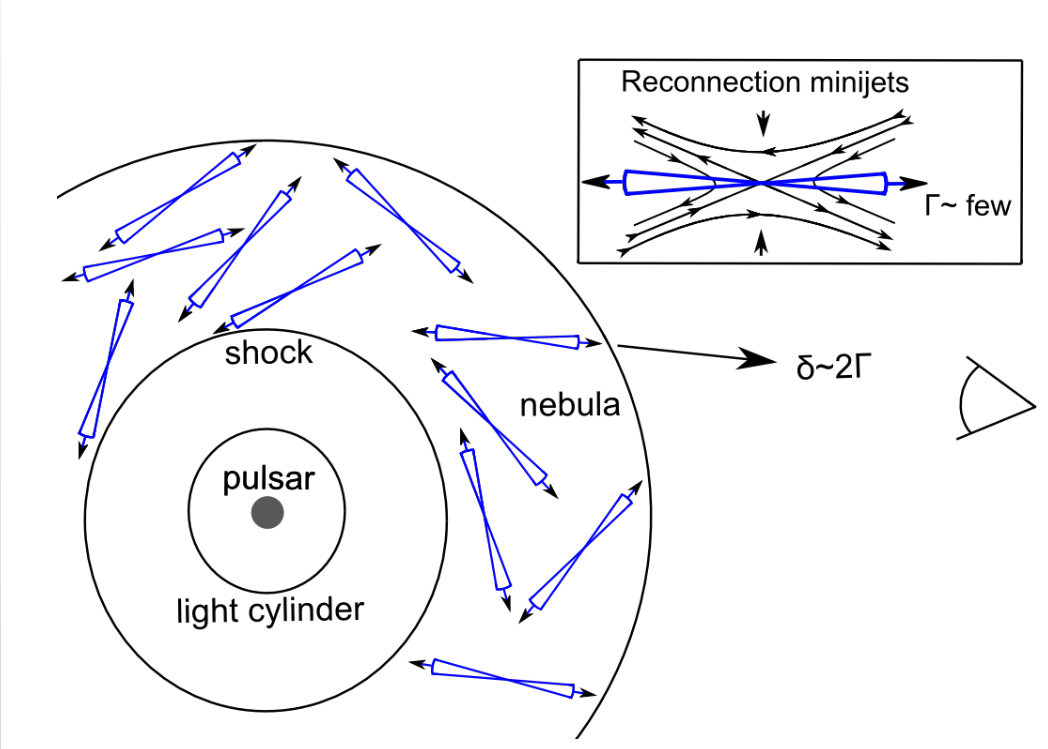


Mini-jets in Crab

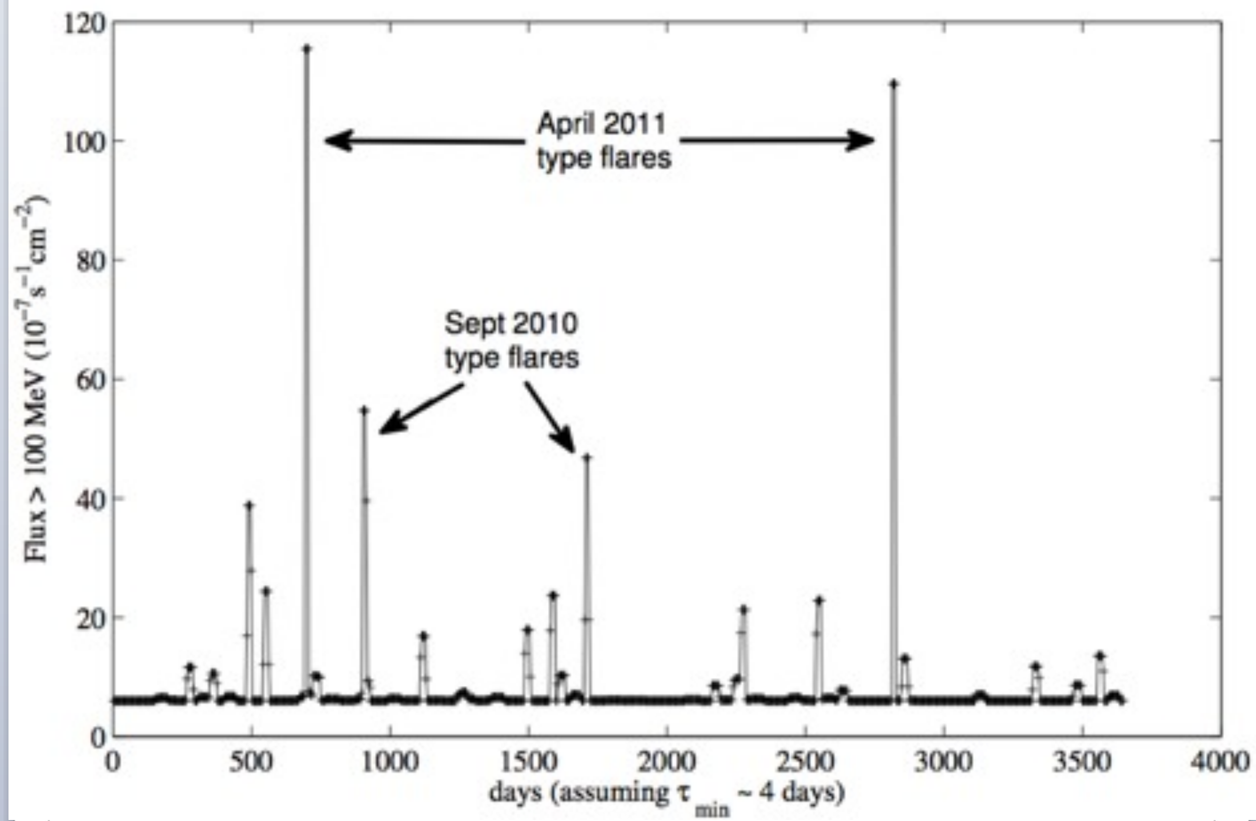
Clausen-Brown, Lyutikov 2012



- probability of flare flux

$$\rho(F)dF \propto F^{-\frac{q+1}{q}} dF \approx \frac{1}{F} dF$$

- average flare flux is dominated by bright rare flares.



Power-law from shot noise!

Mini-jets in Crab

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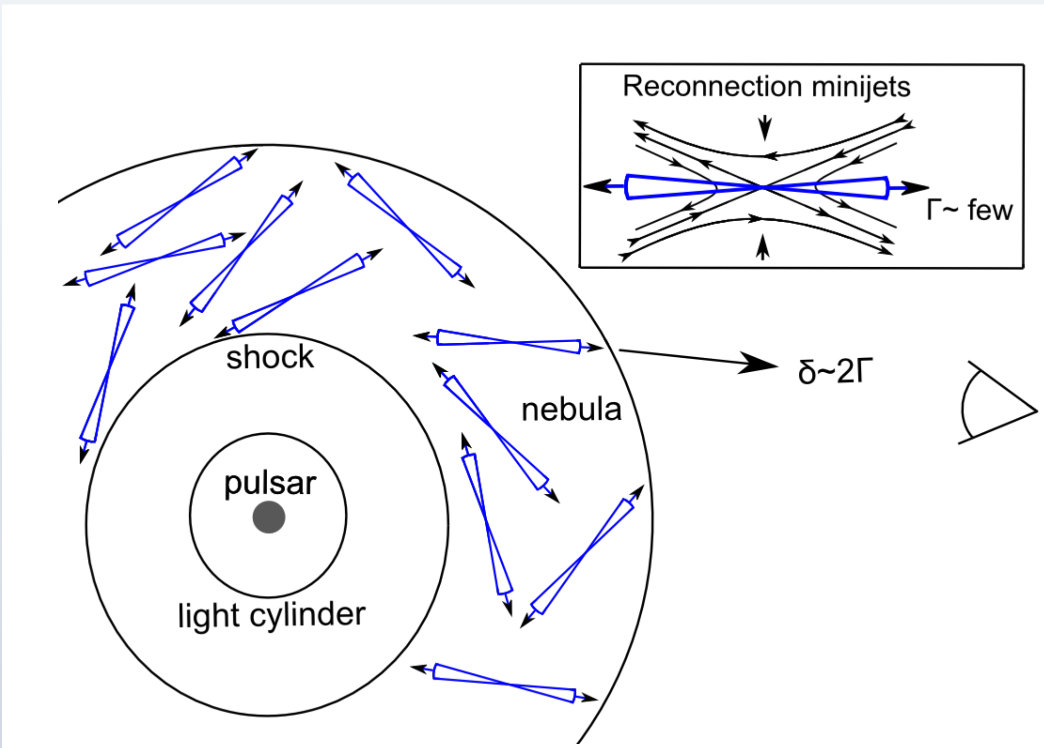
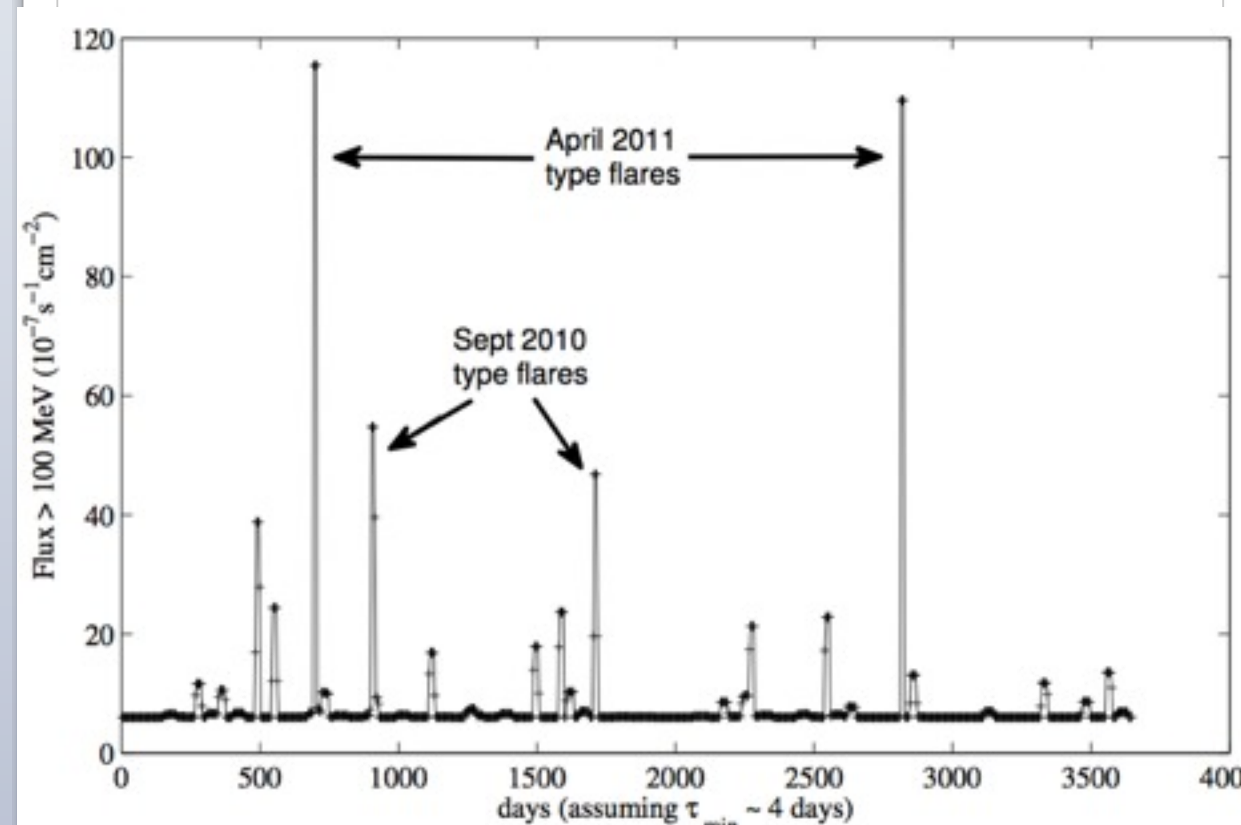


- Crab flares are an example how magnetic reconnection
  - can produce bursty radiation
  - can accelerate particles up to the radiation reaction limit, that radiate efficiently (needed number of leptons produced by Crab in only 1 sec)

•probability of flare flux

$$\rho(F)dF \propto F^{-\frac{q+1}{q}}\, dF \approx \frac{1}{F}\, dF$$

•average flare flux is dominated by bright rare flares.



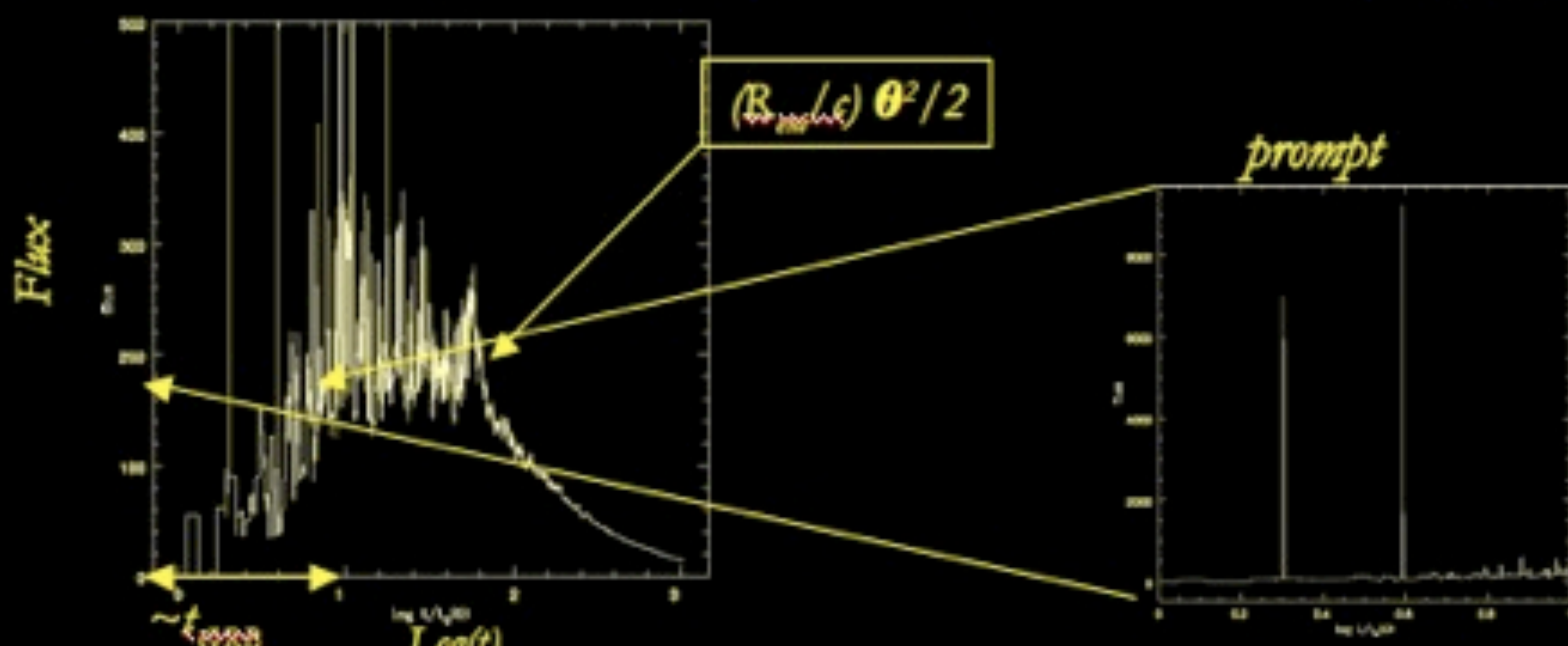
Power-law from shot noise!

Fast variability from large radii, R_{em}~10^{15}-10^{16} cm

(Lyutikov & Blandford 2003)

- *Emission is beamed in outflow frame*
  - *really beamed* $\Delta\theta_{em}$<<1
  - *random internal motion of emitters,* $\Delta\theta_{em} \sim 1/\gamma_{rand}$

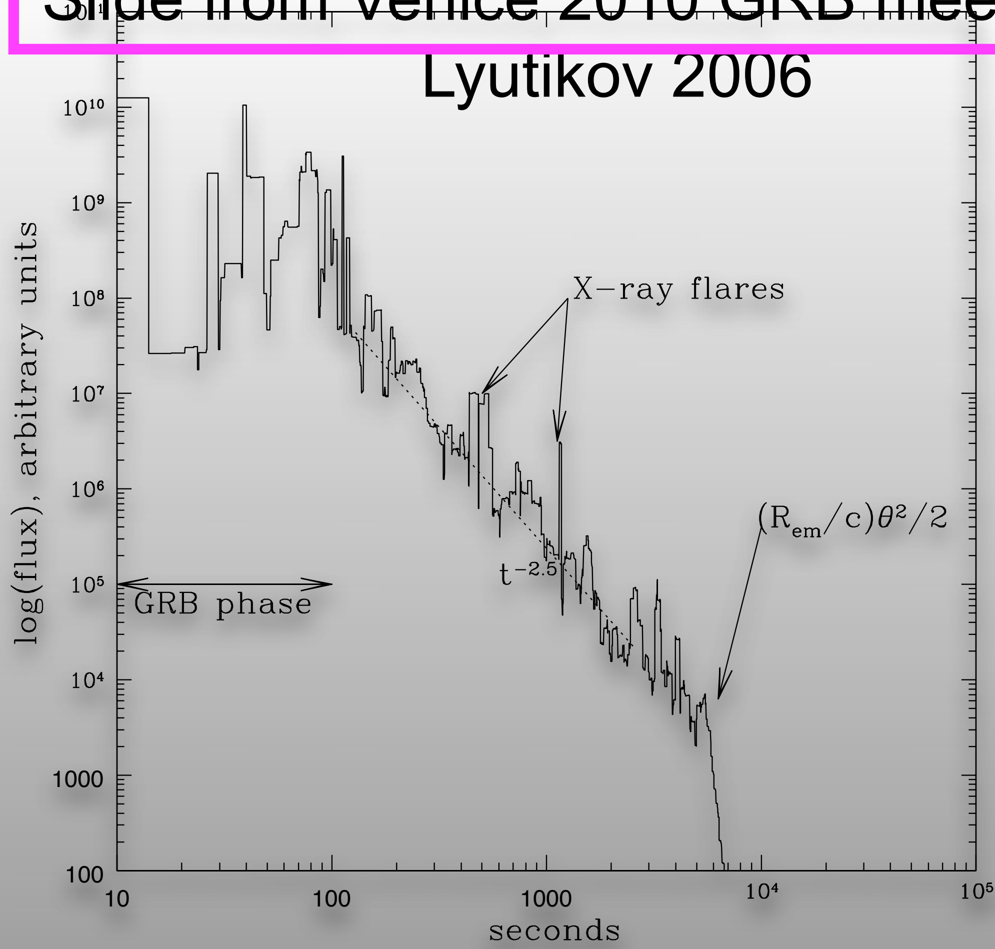
- *X-flares and breaks are tails of prompt*
- *fast varibility*
- *no need for long central engine activity*
- *softening with time, harder spikes*
- *These are preliminary results: alternatives need to be investigated*



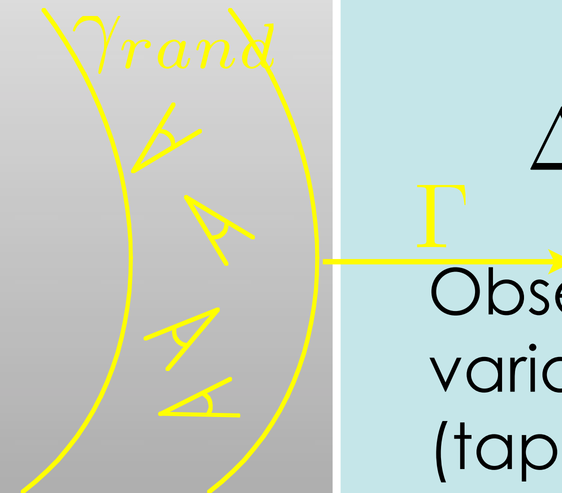
Γ_{bulk}=50, γ_{rand}=5
θ_{ob}=π/10,
θ_{jet}= 3 θ_{ob}
efficiency 10%

(Lyutikov in prog.)

Slide from Venice 2010 GRB meeting



Also: Ghisellini et al. 2008, Lazar et al. 2009, Giannios et al. 2009, Narayan & Kumar 2009



$$\Gamma_{eff} = 2\Gamma\gamma_{rand}$$

$$\Delta t \sim \frac{c}{R}\frac{1}{8\Gamma^2\gamma_{rand}^2}$$

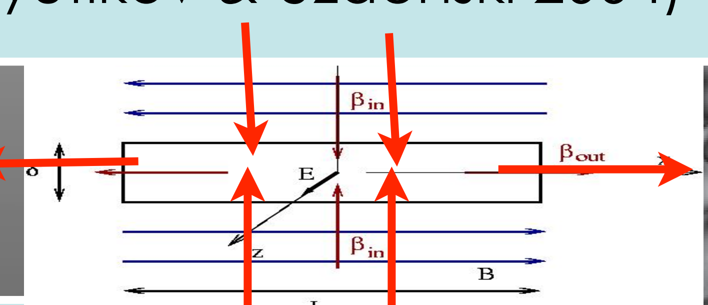
Observed emission can be highly variable and with high efficiency (tapping into most of the proper volume)

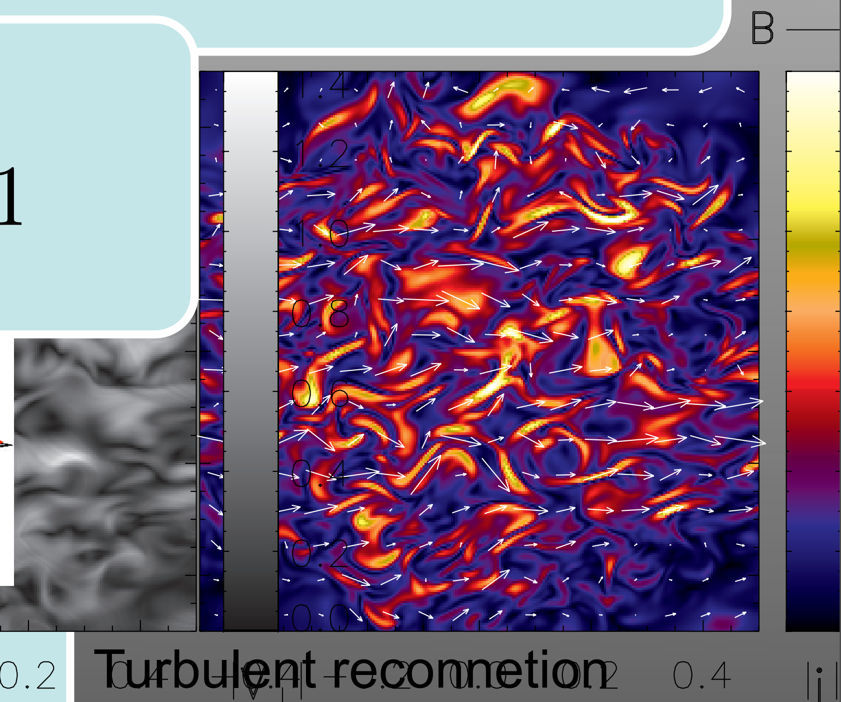
- Not fluid "turbulence",

$$\gamma_{rand} \sim \sqrt{9/8} = 1.06$$

- RM & RT instabilities will produc vT<< c turbulence

- Relativistic reconnection: jets with $\gamma_{out} \sim \sigma \gg 1$ (Lyutikov & Uzdenski 2004)



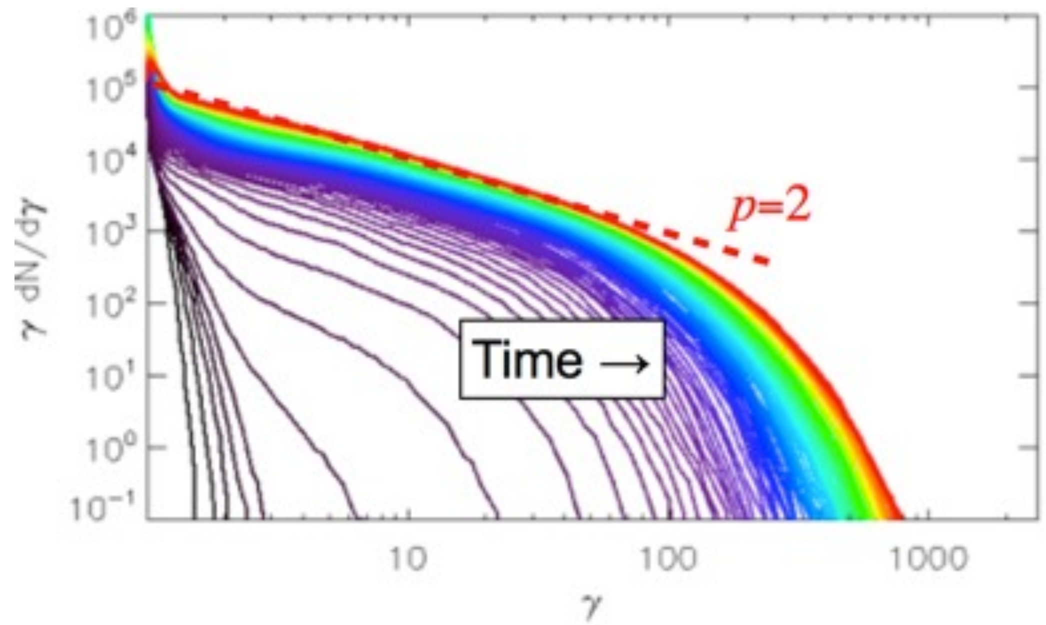


Turbulent reconnection (Lazarian & Vishniac)

- Spectrum is harder during flare (Burrows et al 2005)
- Are flares becoming longer and softer as function of flare time?
- Can some Shorts be "one spike Long"? (failed SN-type)
- Can explain optical -gamma correlations in 080319B? E.g. emitting "blobs" expand, killing both

Particle acceleration in reconnection

- Shock acceleration: correct kinetic spectrum of particles follows from macroscopic jump conditions
- Reconnection - no simple scaling...
- But same result!



Sironi

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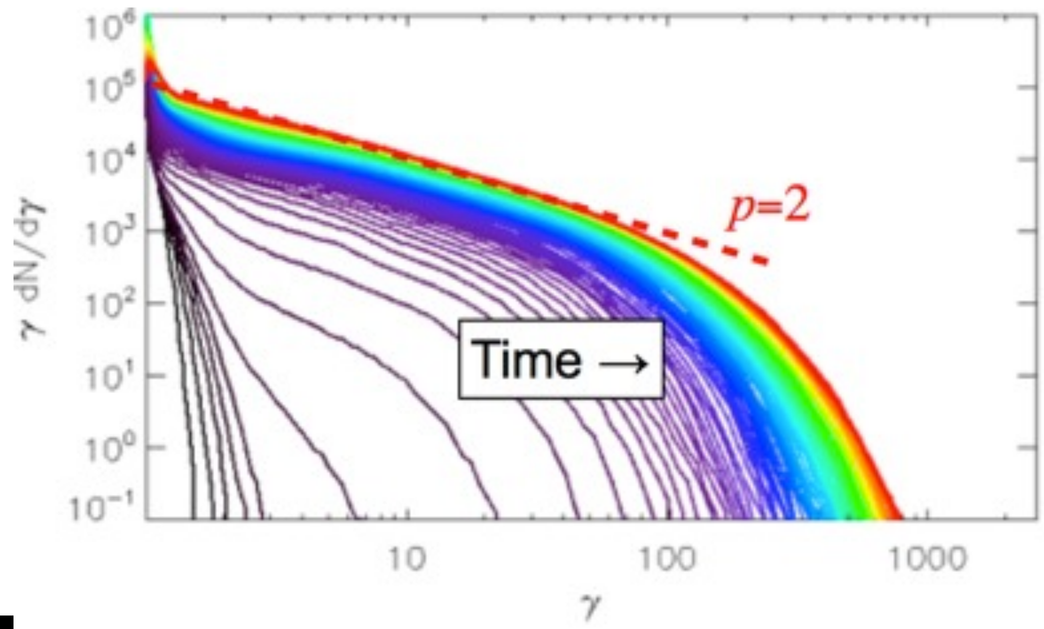
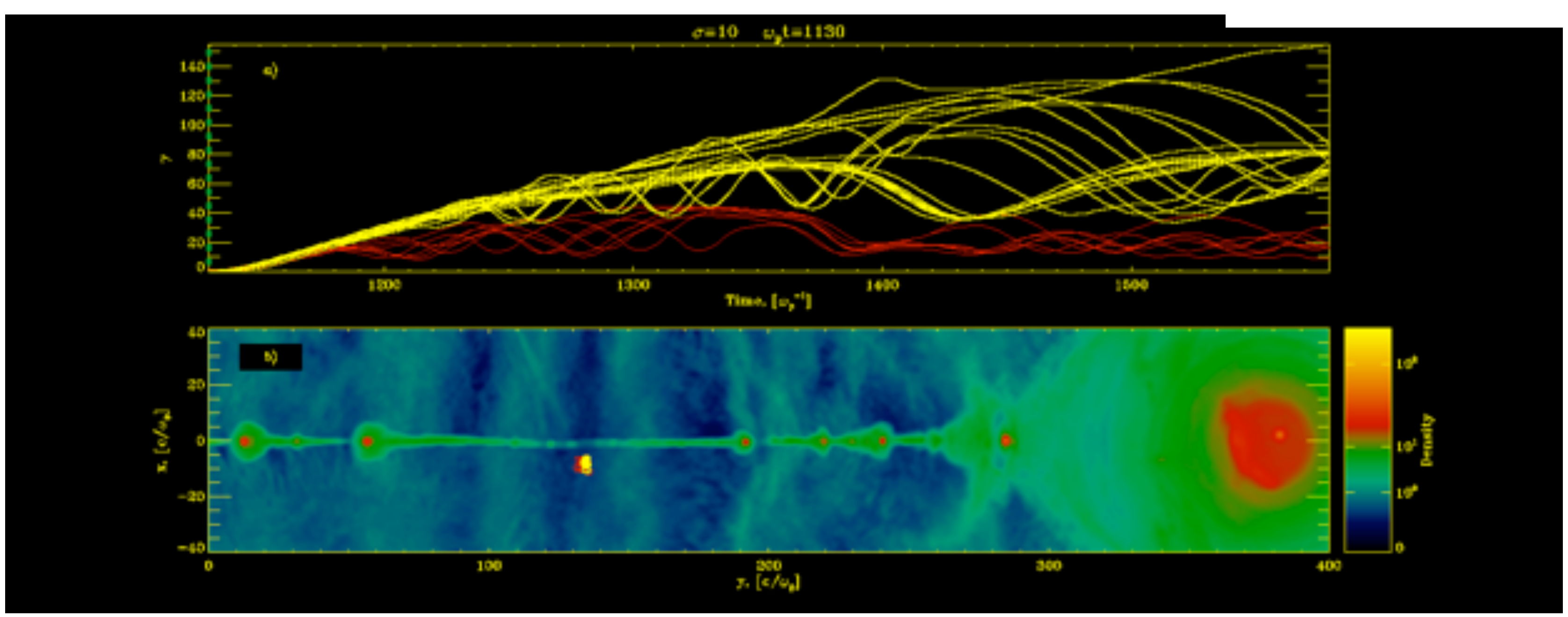




Sironi

Long-lived engines in short GRBs

NS-NS merger as paradigm for Short GRBS

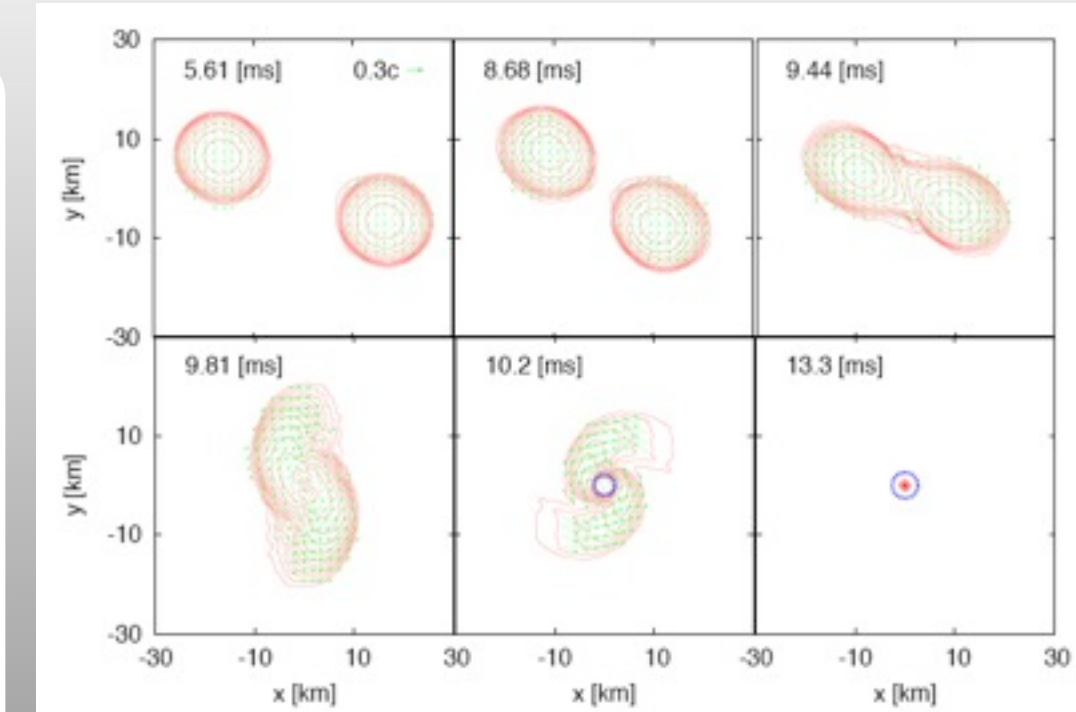
- Active stage of NS-NS merger takes 10-100 msec, then **collapse into BH**

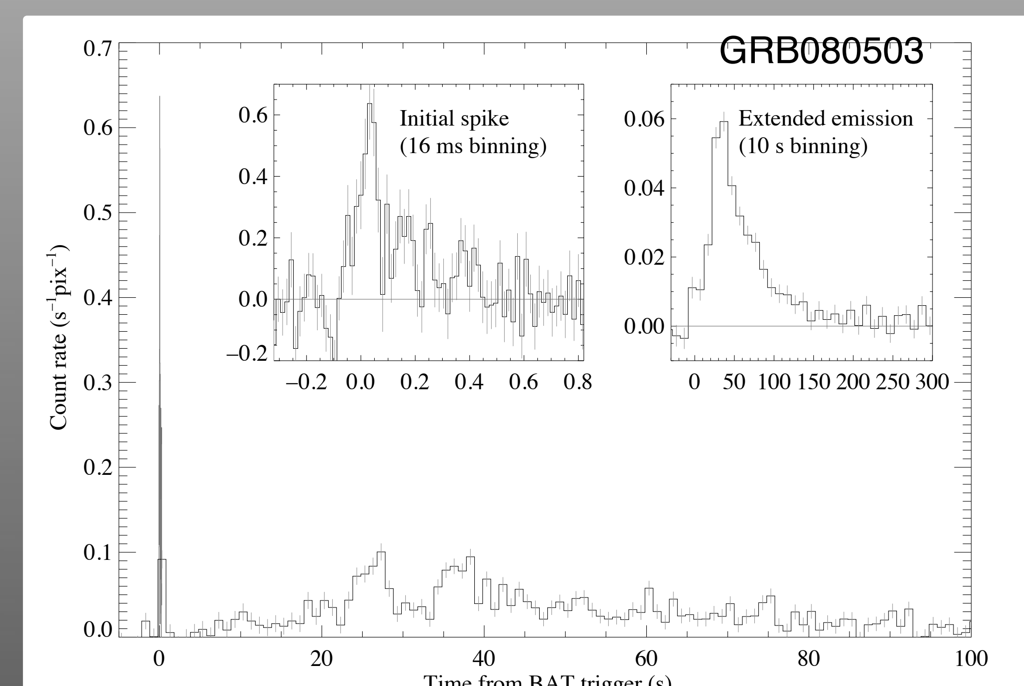
- Transient NS - 100 msec, (**NOT** 100 sec!)

- Very little mass is ejected, drains out quickly

- Many short GRBs have long 100 sec tails, energetically comparable to the prompt spike.

- Many GRBs have late time flares, 10^5 sec





100 sec tail has ~ 30 times more energy than the prompt spike

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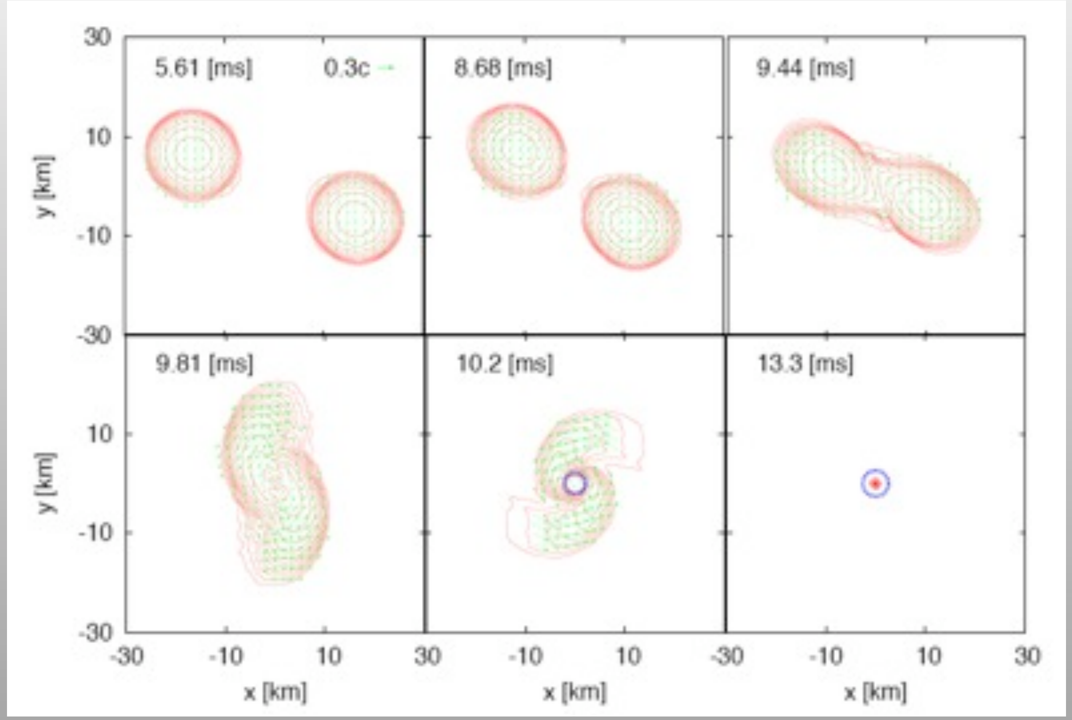
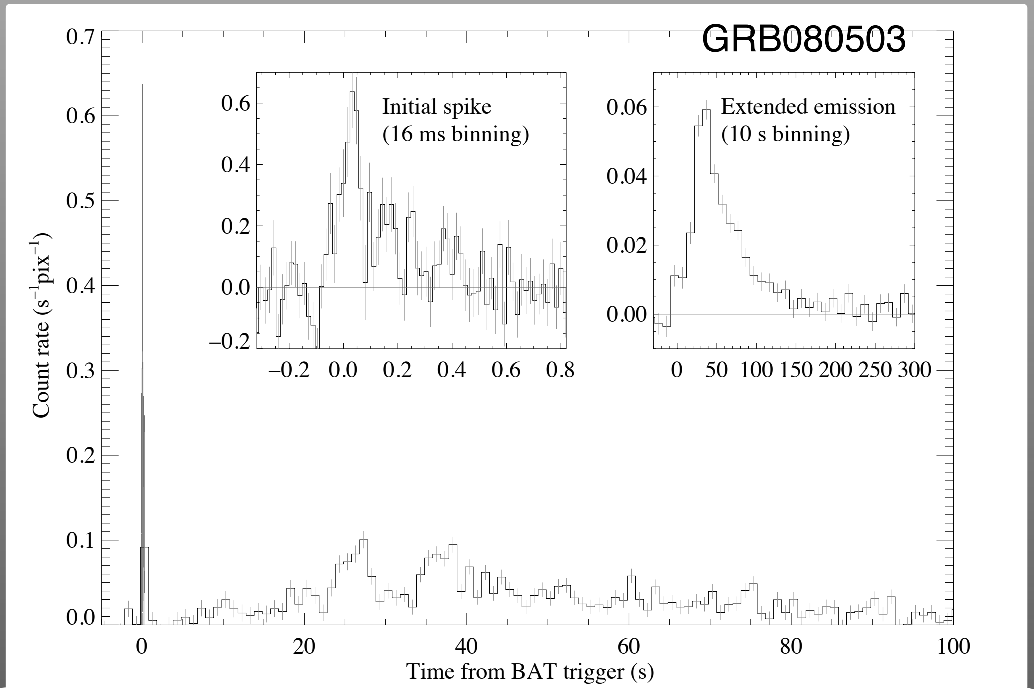


How to explain energetically dominant activity on ~ 100 sec, while the engine lives 10-100 msec?



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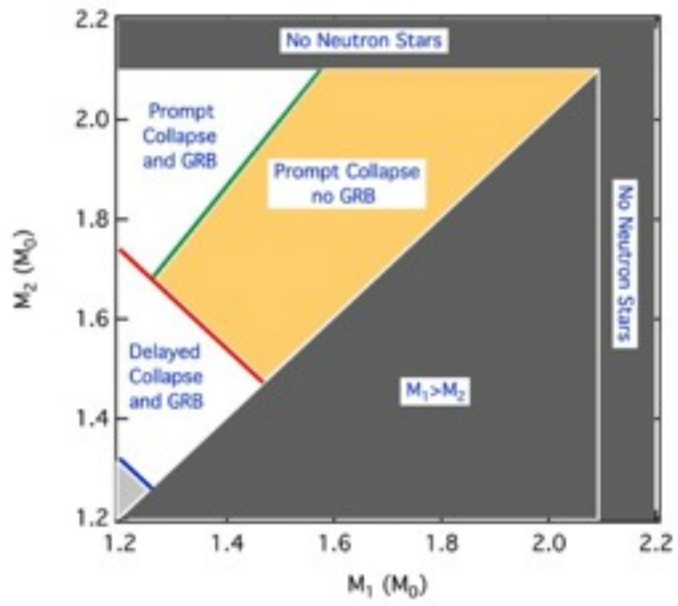
Metzger+,

Can merger of two NSs leave a NS? (millisecond magnetar)

- There is a $2M_{Sun}$ NS
  - Need **both** $M_{NS} < 1.2\ M_{Sun}$
  - And throw out ~ $0.3\ M_{Sun}$
  - And very stiff EoS



Ozel + 2010

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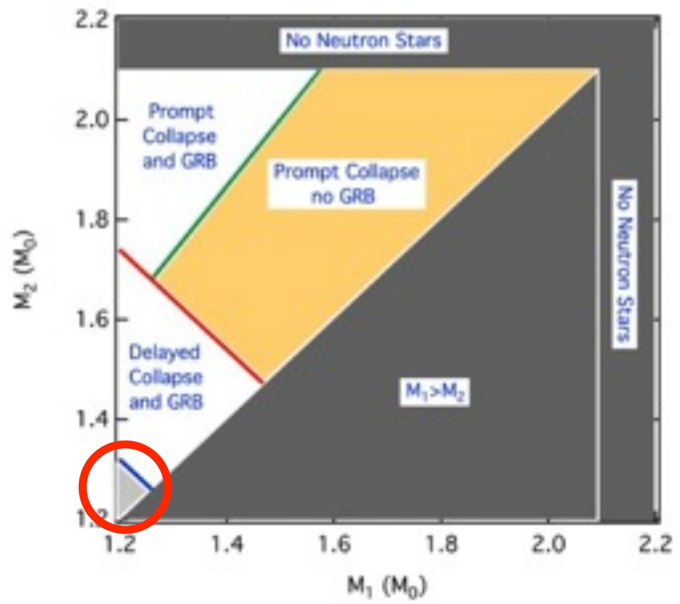

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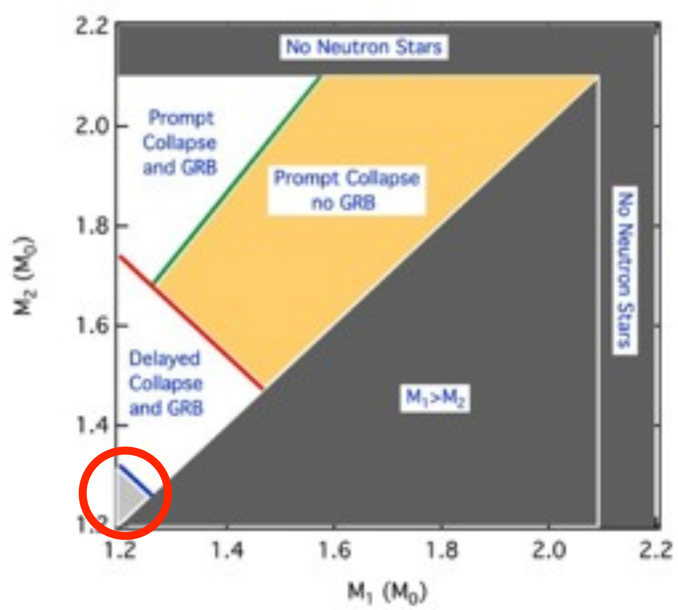
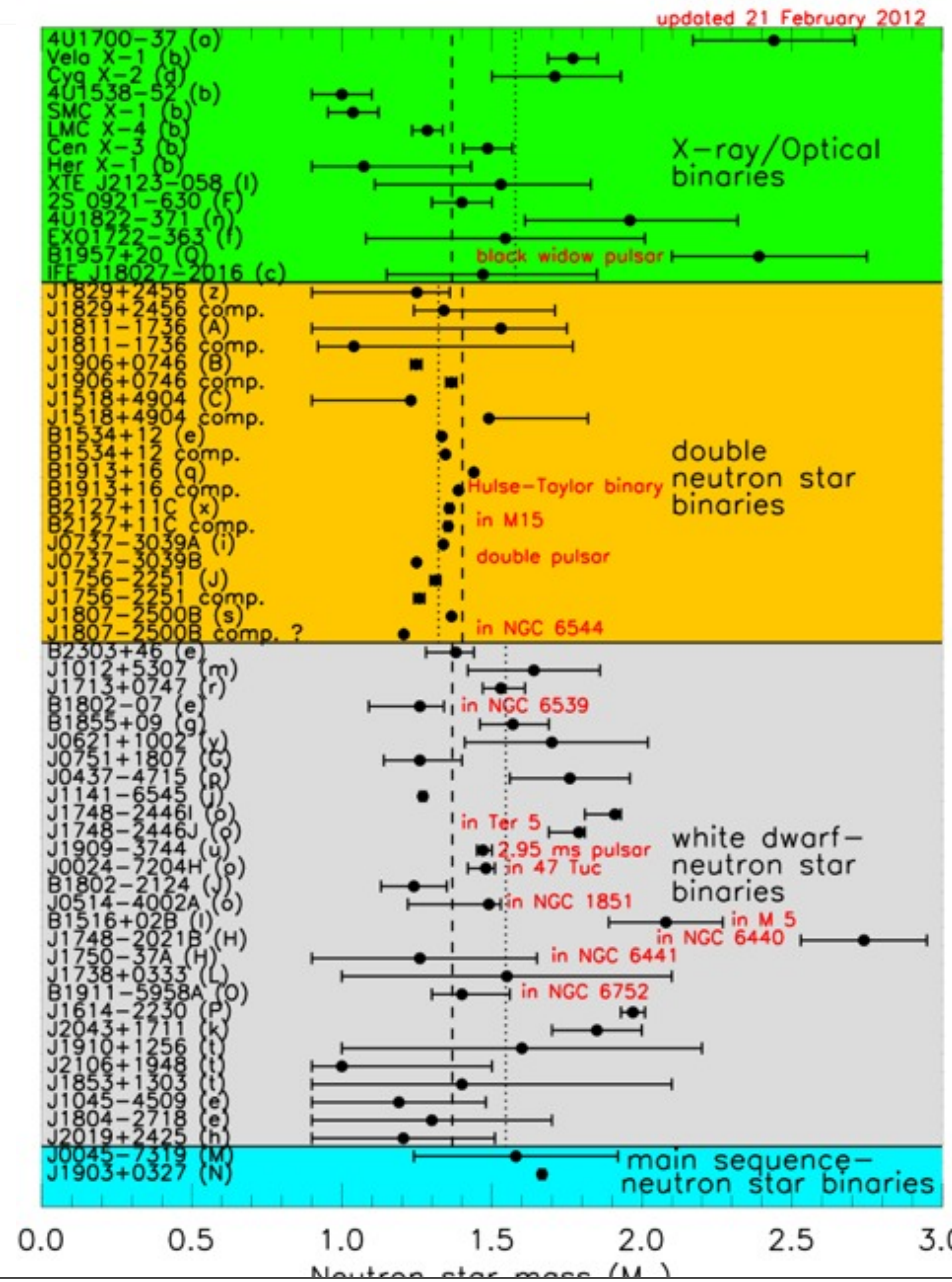


Ozel + 2010



Metzger+,

Can merger of two NSs leave a NS? (millisecond magnetar)

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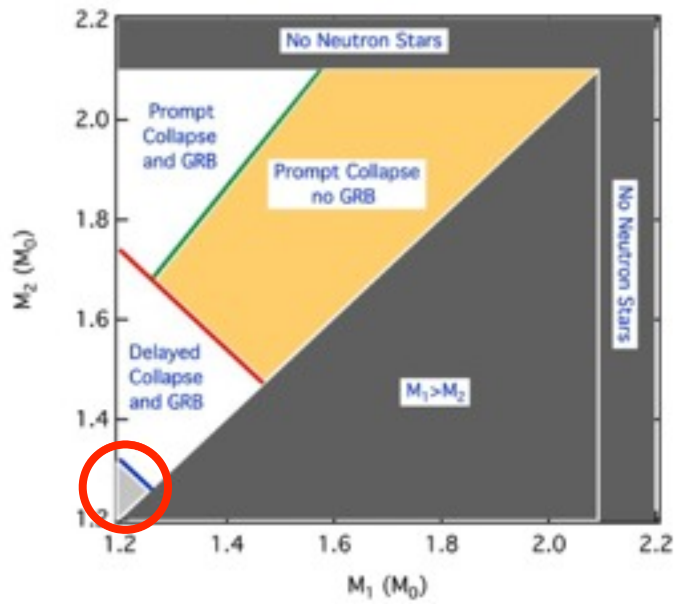

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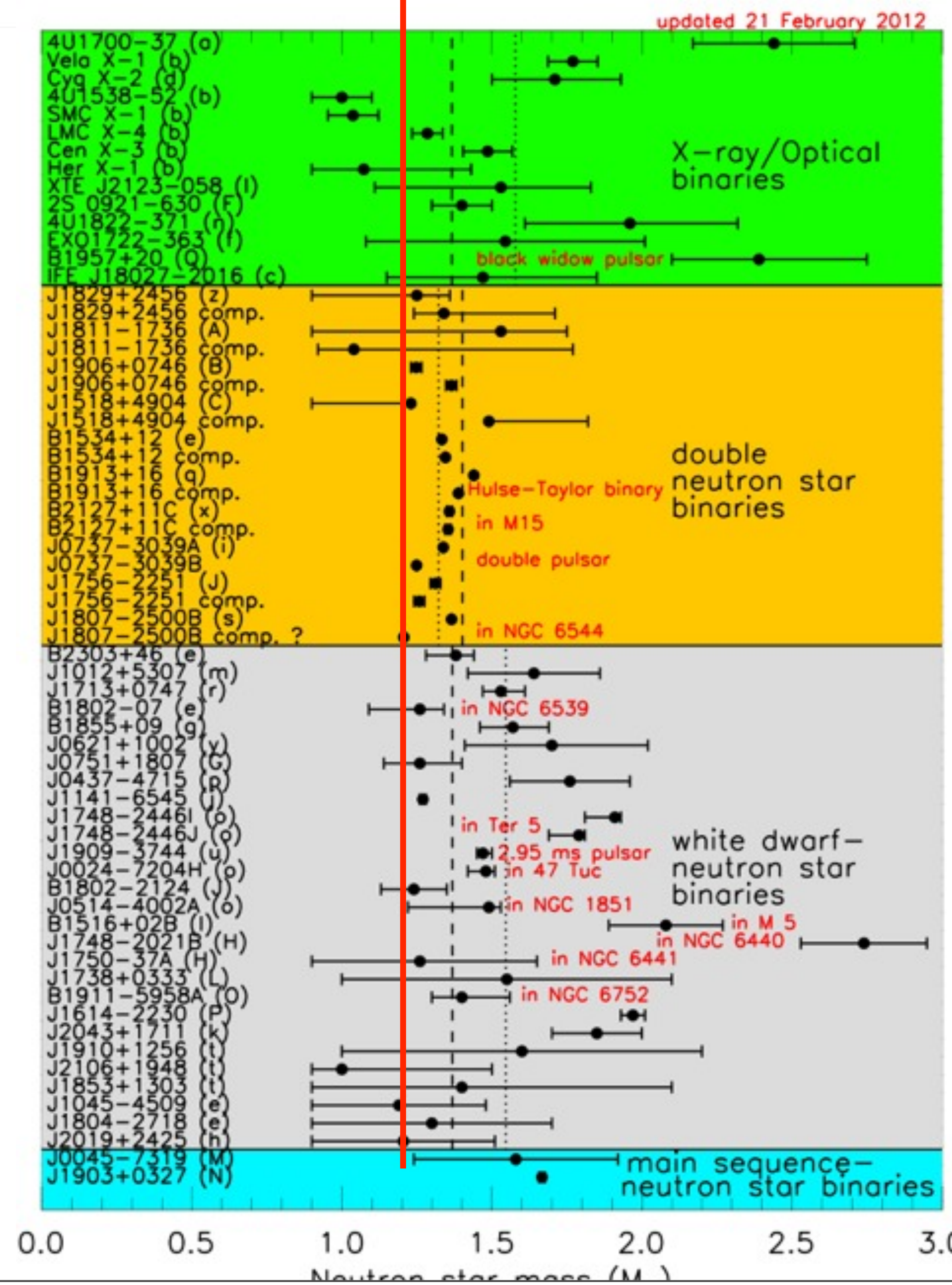

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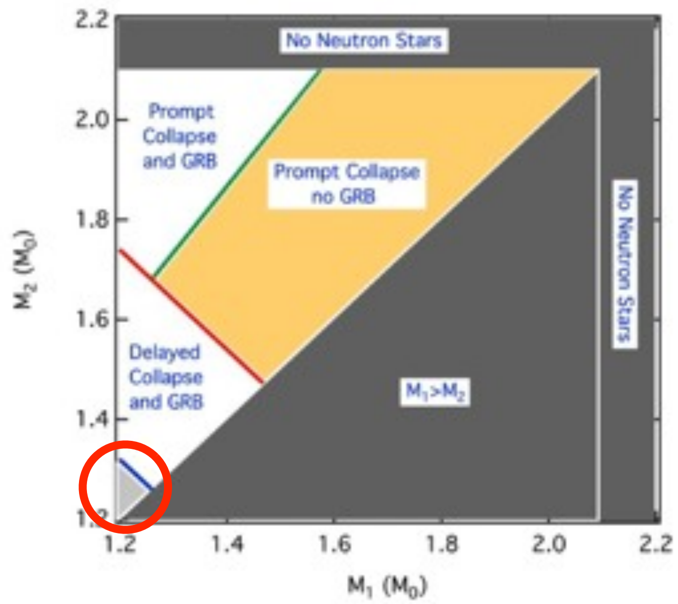

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The best determined masses (down to $10^{-4}\ M_{Sun}$) are in NS-NS binaries,

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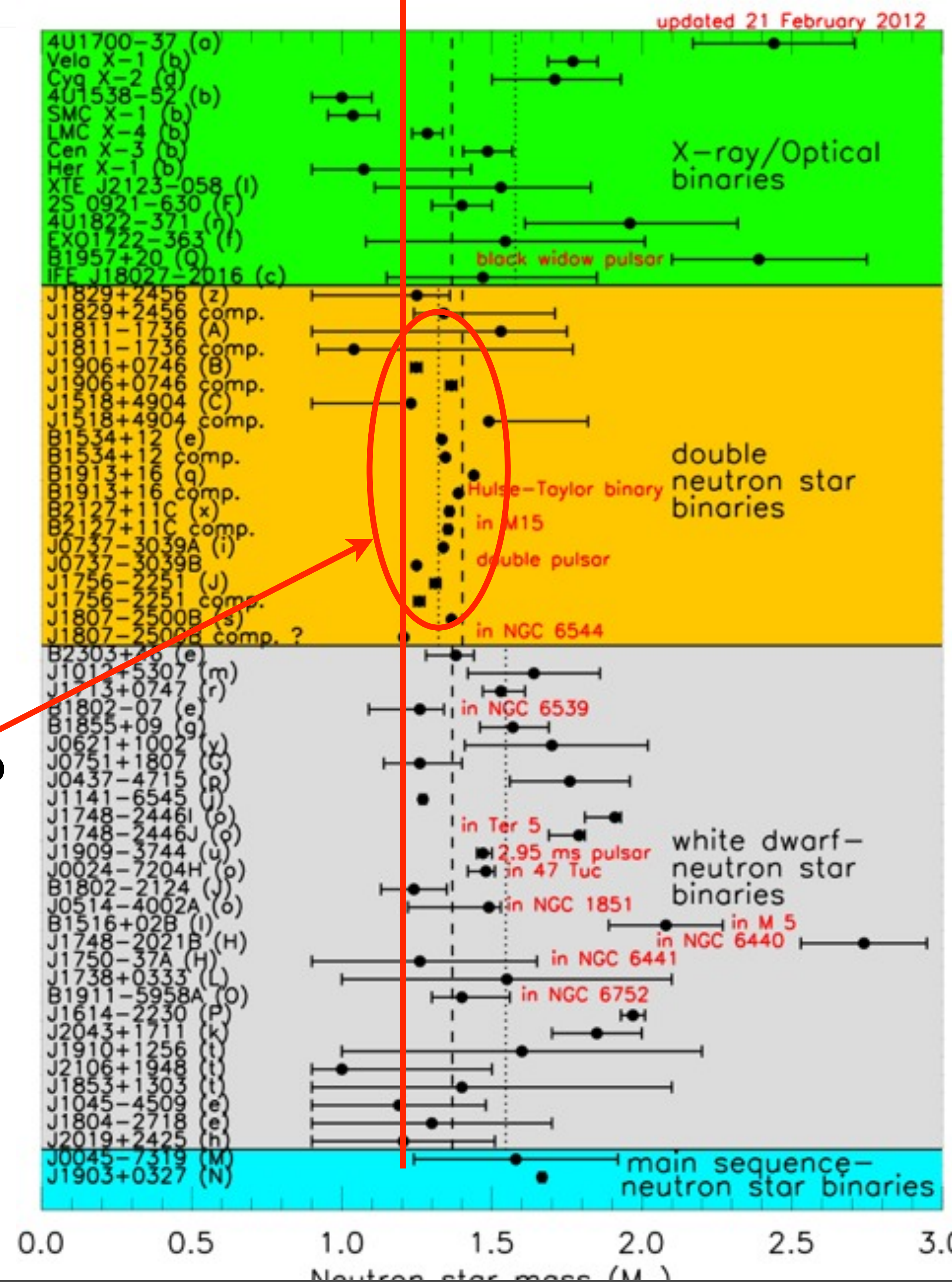

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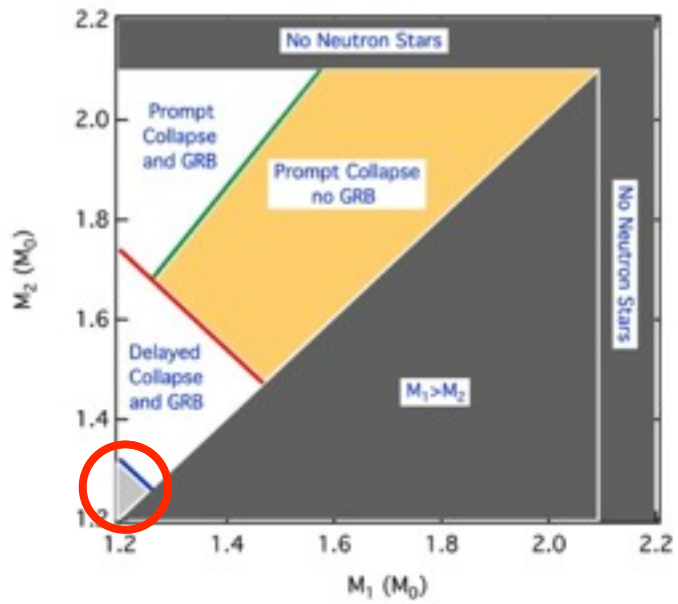

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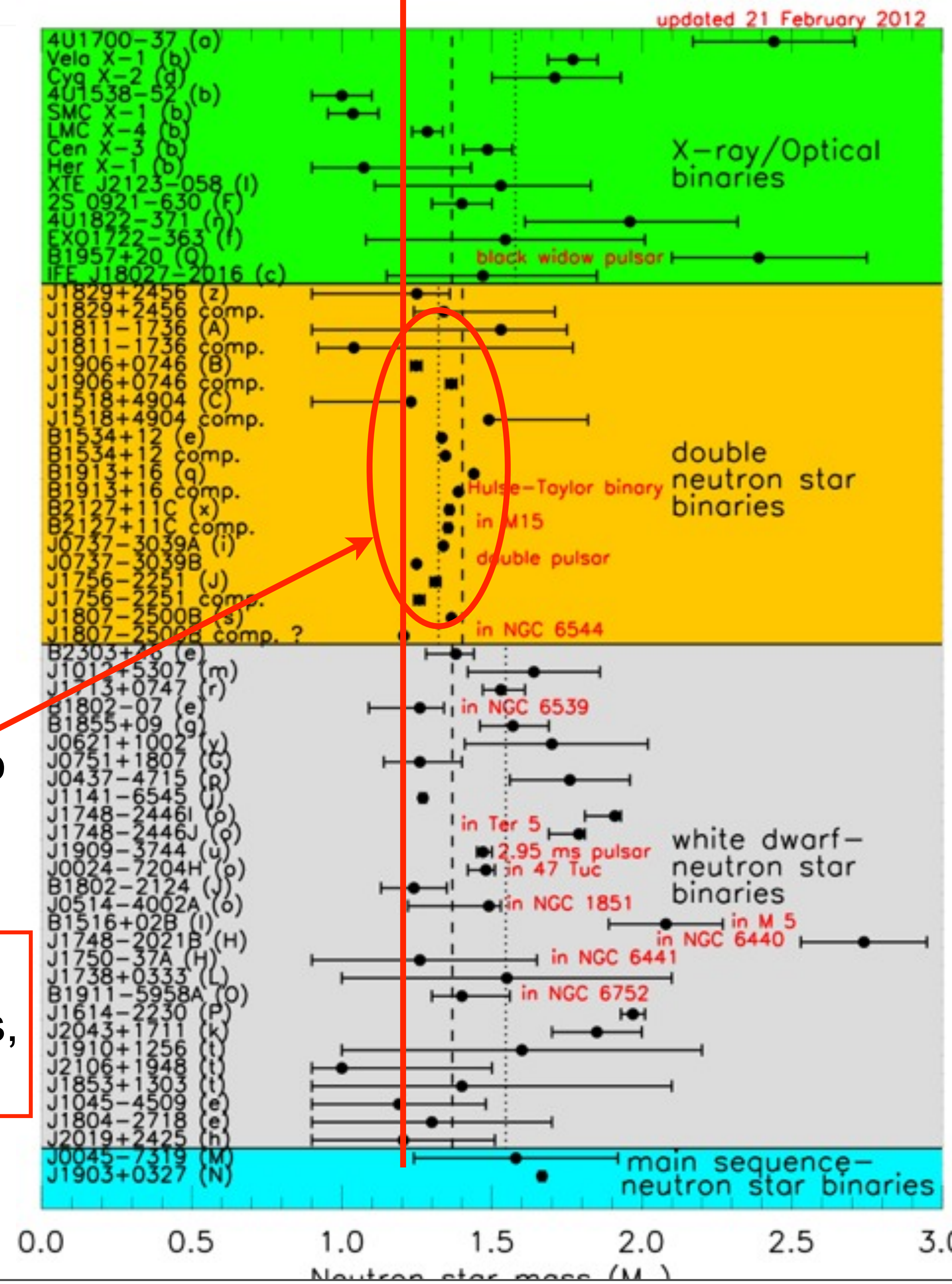
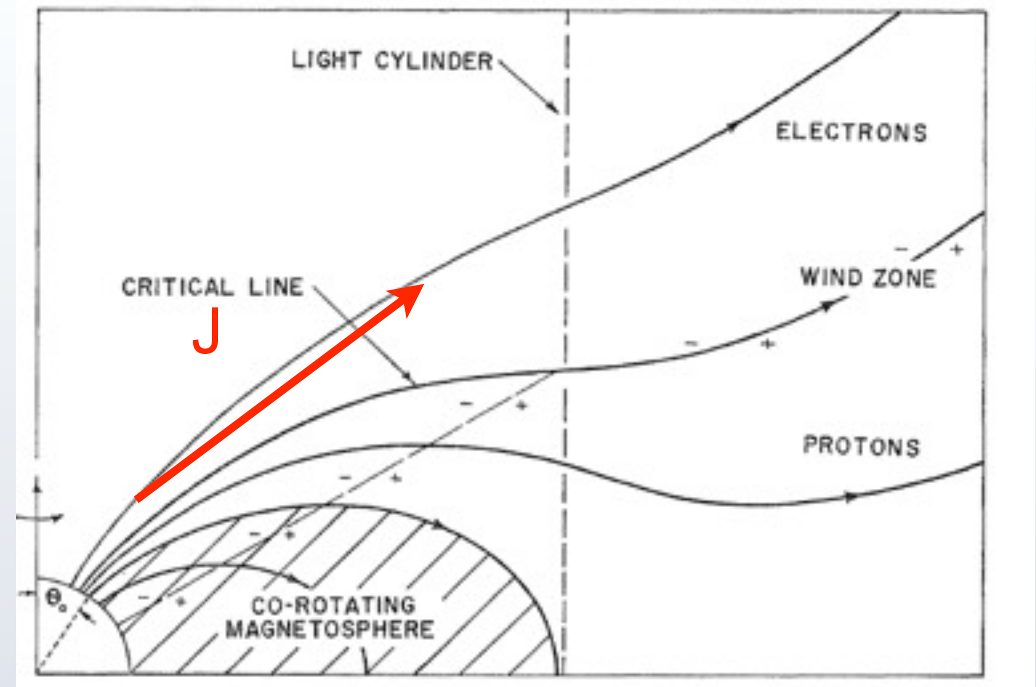
This cannot be the dominant channel of NS-NS mergers and, thus, of short GRBs.



BHs part-timing as magnetars

Newly formed **isolated spinning** astrophysical black holes can keep magnetic fields for times much longer than predicted by the “No hair” theorem, working as ~ millisecond magnetars

- **Rotating** NS - unipolar inductor
  - generate plasma out of vacuum
  - open B-field lines to infinity
- Blandford & Znajek: BHs do the same
- Outside plasma: **E.B** =0 - frozen-in B-field
- If a BH keeps producing plasma, like a NS, B-field cannot slide off**: field lines that connected NS surface to infinity, has to connect horizon to infinity**



Goldreich & Julian, 1969

- **The "no hair" theorem is not applicable to collapse of rotating NSs: high plasma conductivity introduces topological constraint (frozen-in B-field).**

  Conserved number: open magnetic flux:

$$N_B = e\Phi_\infty/(\pi c\hbar)$$

$$\Phi_\infty \approx 2\pi^2 B_{NS} R_{NS}^3/(P_{\rm NS} c)$$

Can be measured at infinity: BH hair

Monday, January 20, 2014

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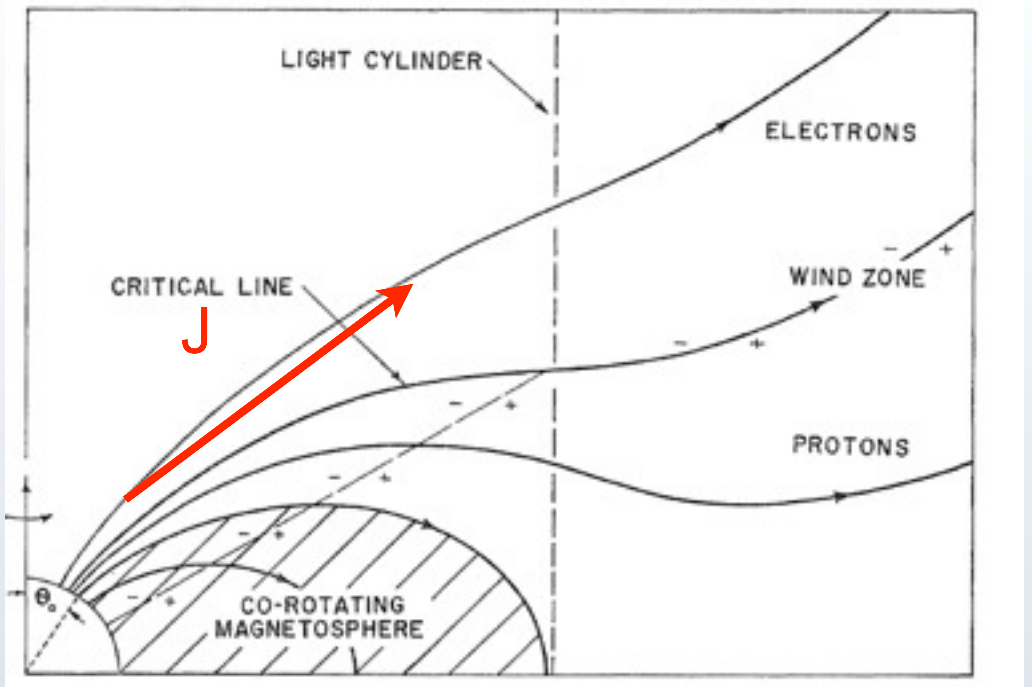

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Countable BH hair!

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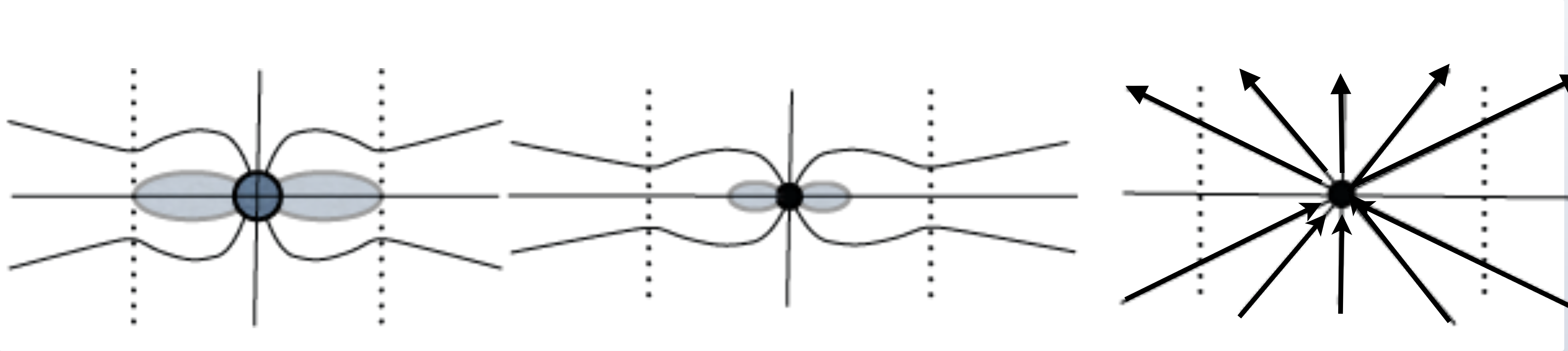
BH can only have open field lines: split monopole magnetosphere



- Analytics: time-dependent force-free B-field in Schwarzschild geom.

$$B_\phi = -\frac{R_s^2 \Omega \sin\theta}{\alpha r} B_s, \quad B_r = \left(\frac{R_s}{r}\right)^2 B_s,$$

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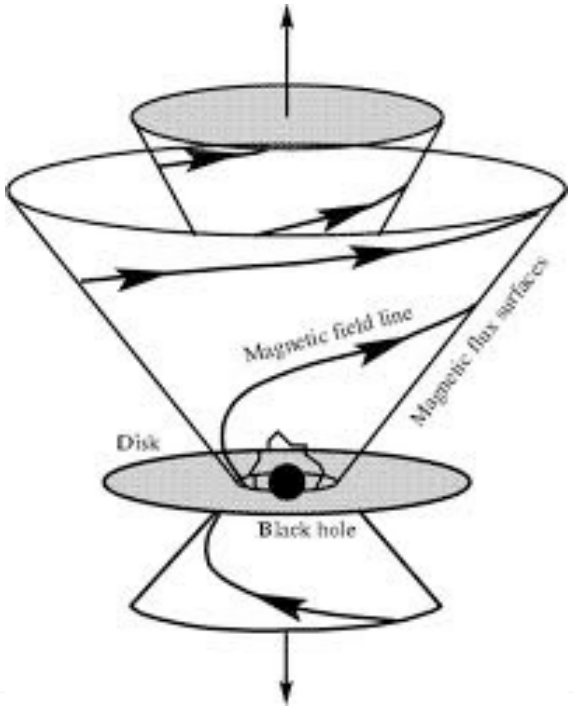

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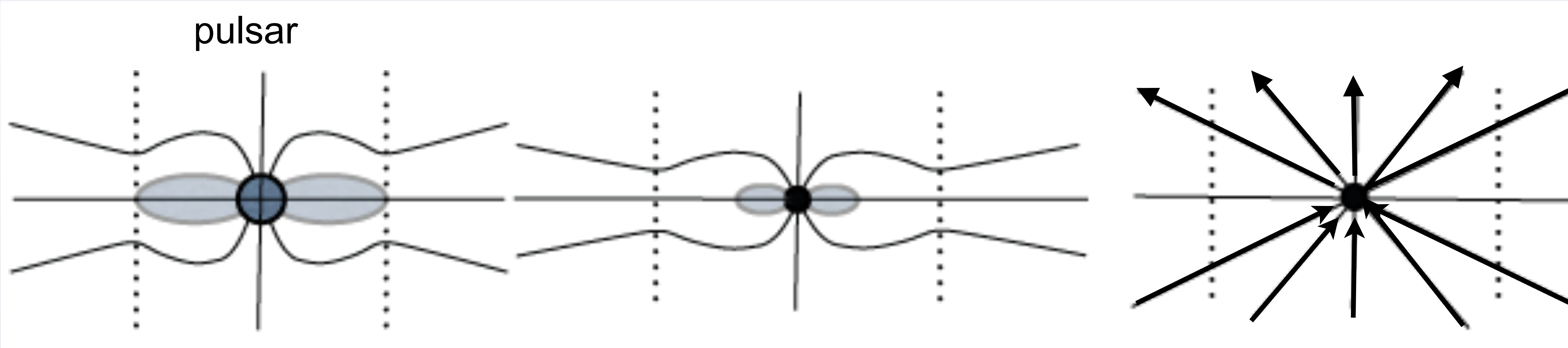

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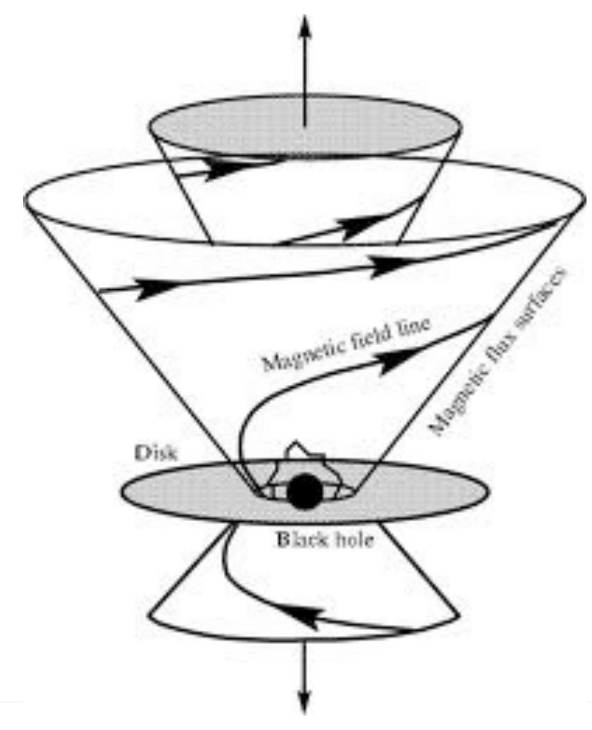

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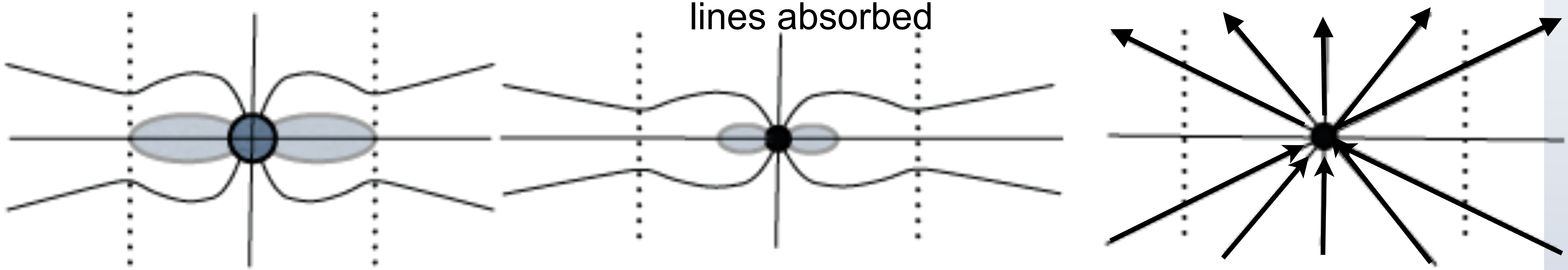

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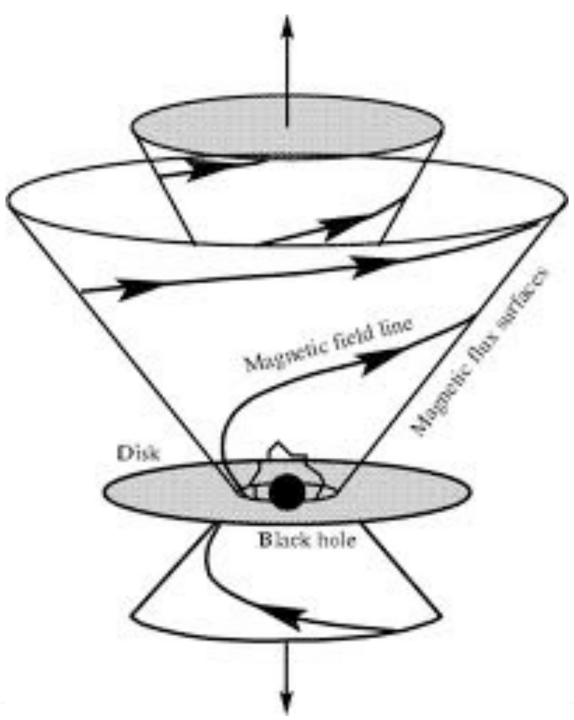

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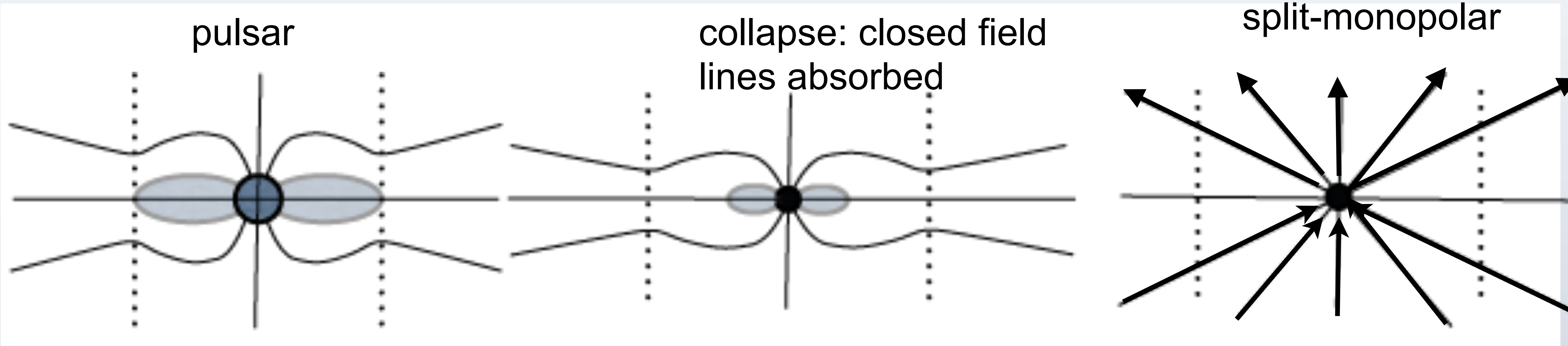

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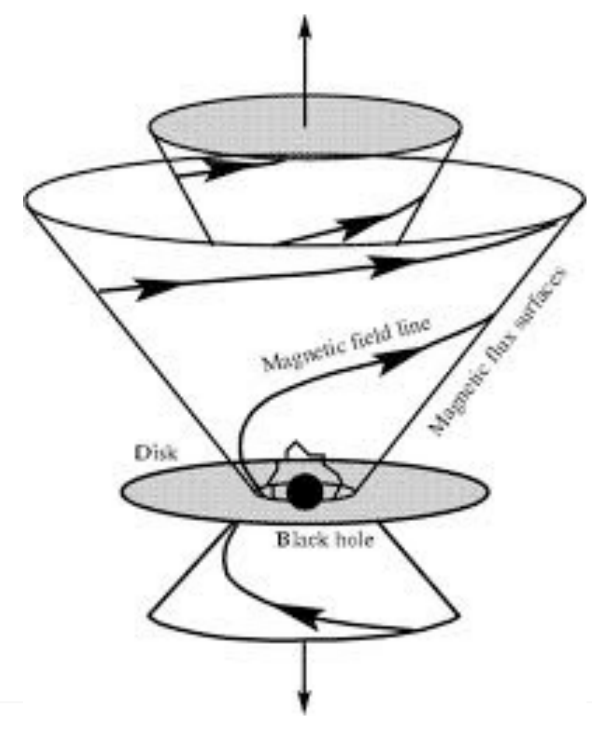

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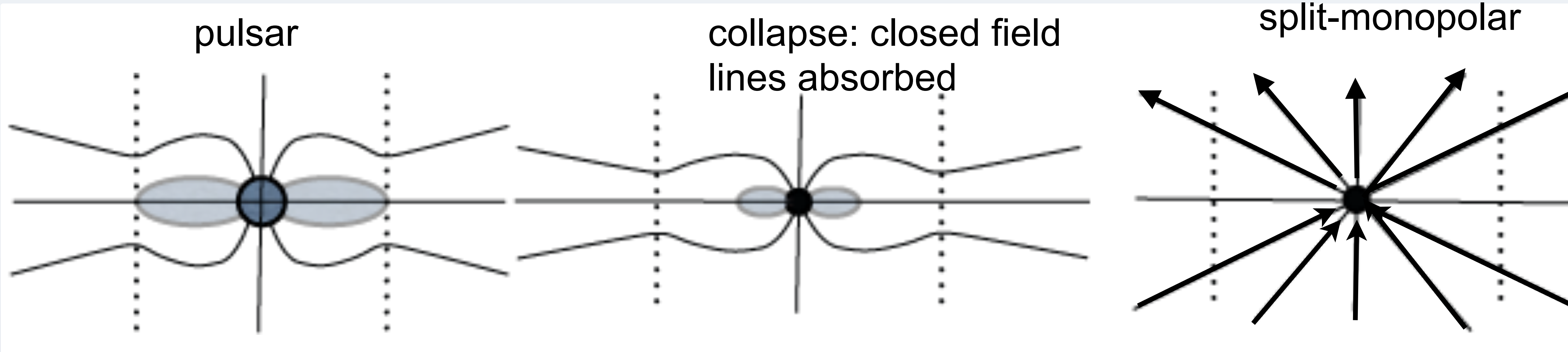

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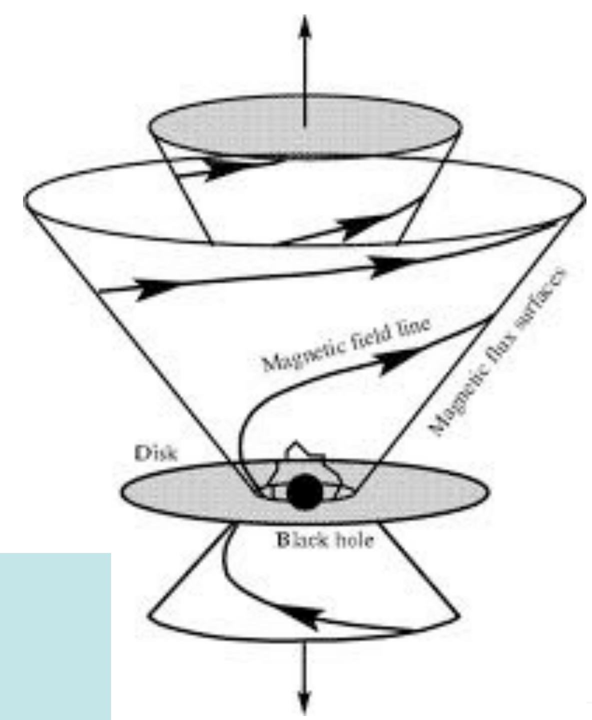
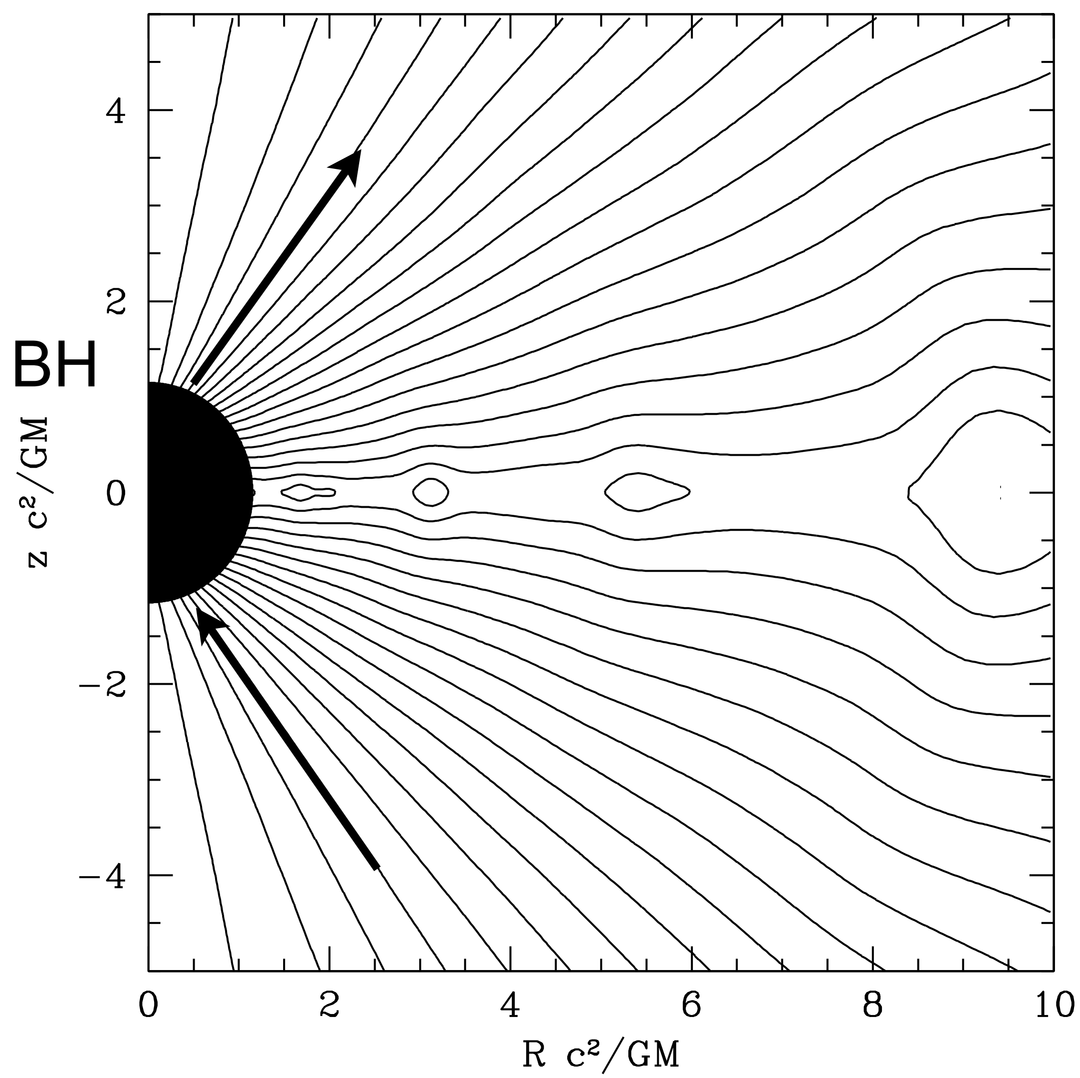


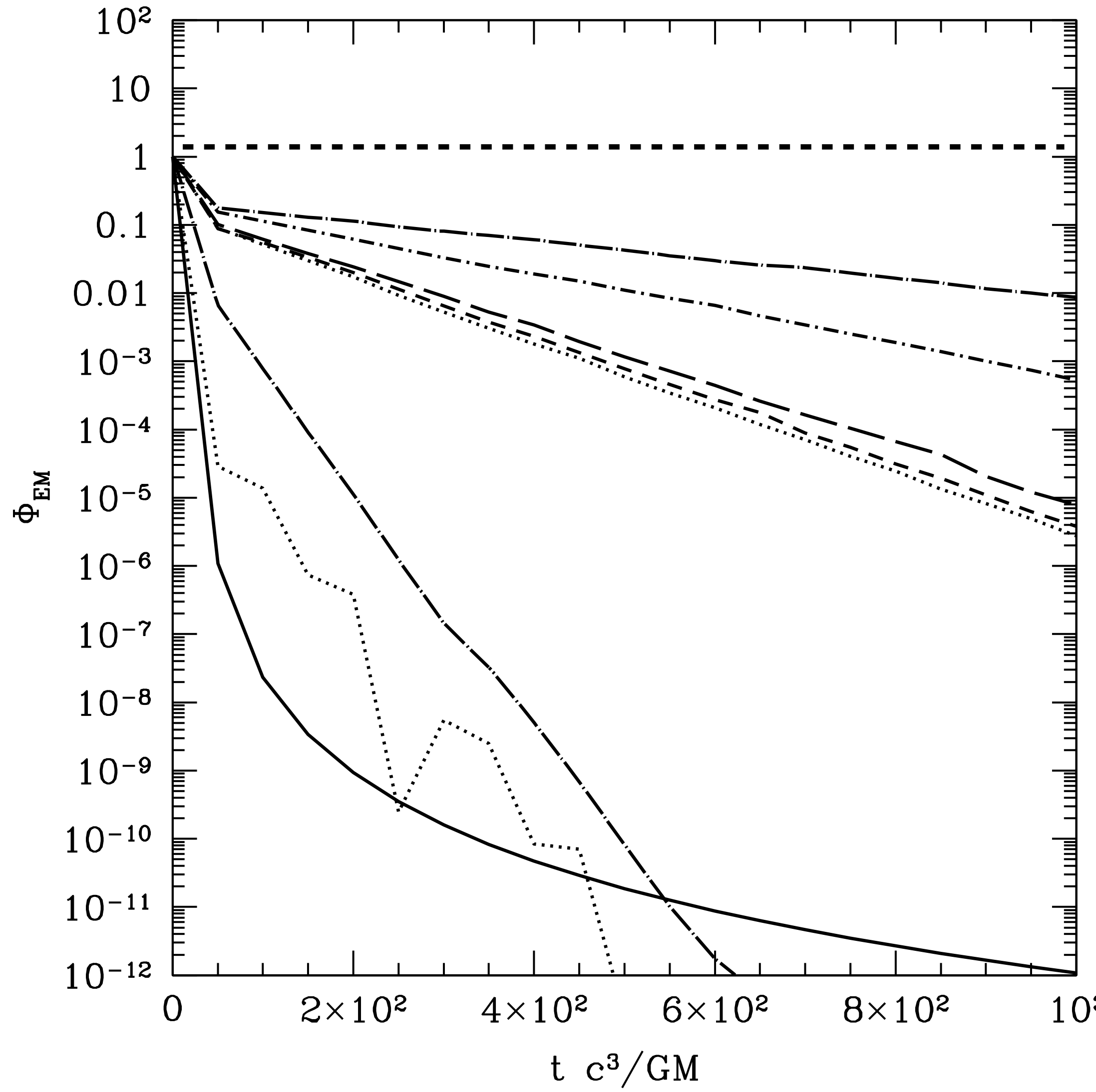
Take a relativistic object with monopolar B-field, rotate it arbitrarily (slowly, a<< 1). The field will remain monopolar

Simulations *(Lyutikov & McKinney, 2011)*

-Split-monopole magnetosphere

- Slow balding





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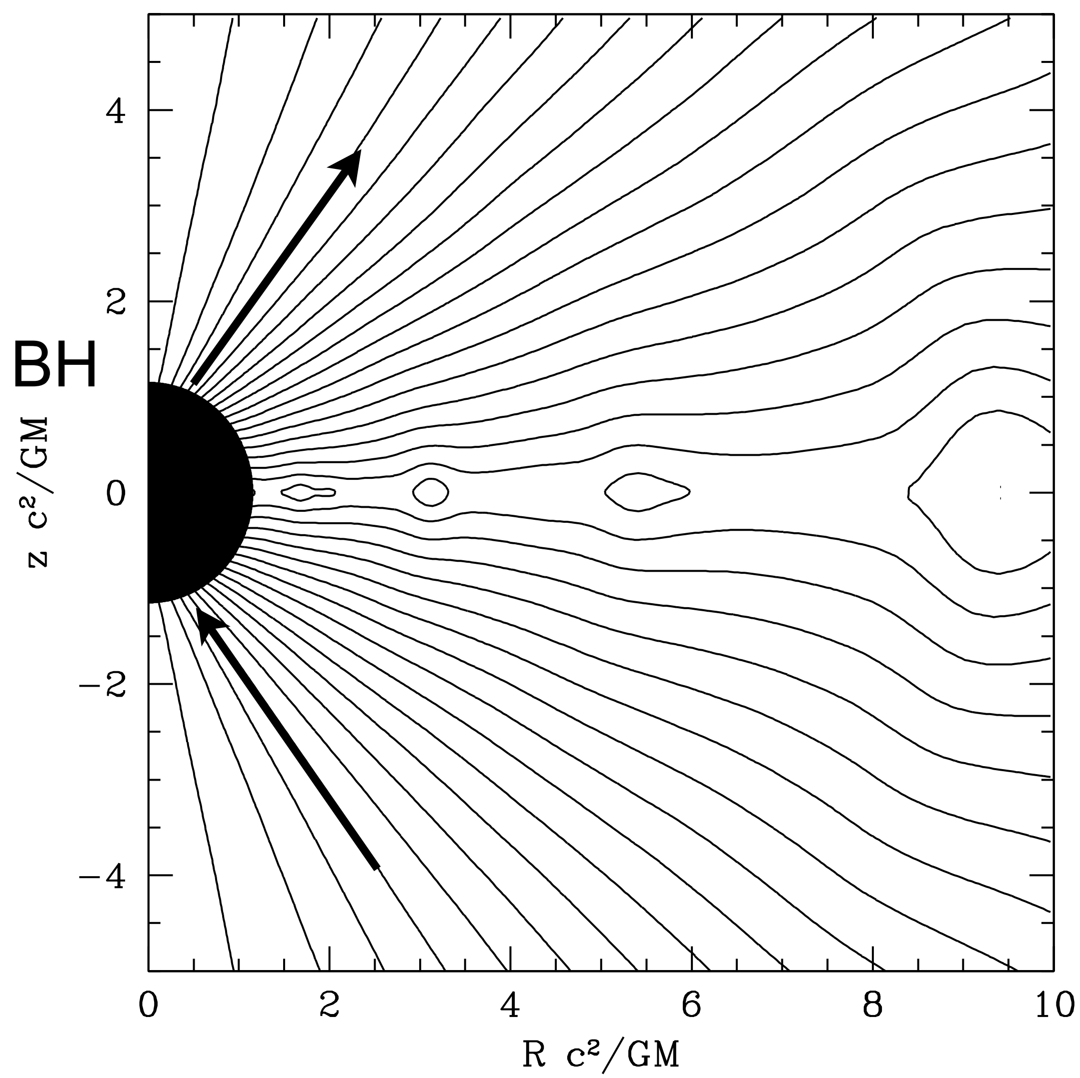

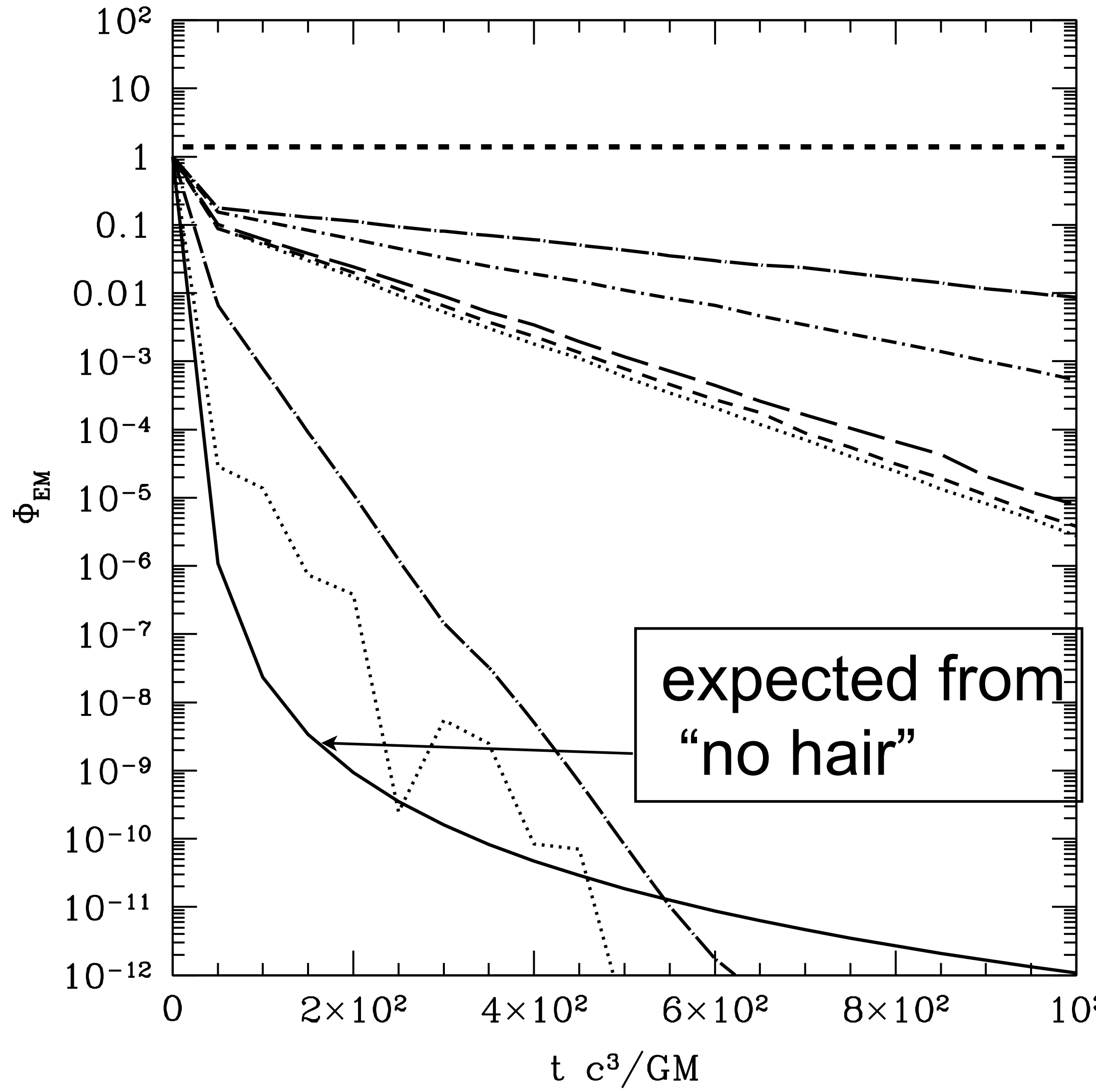

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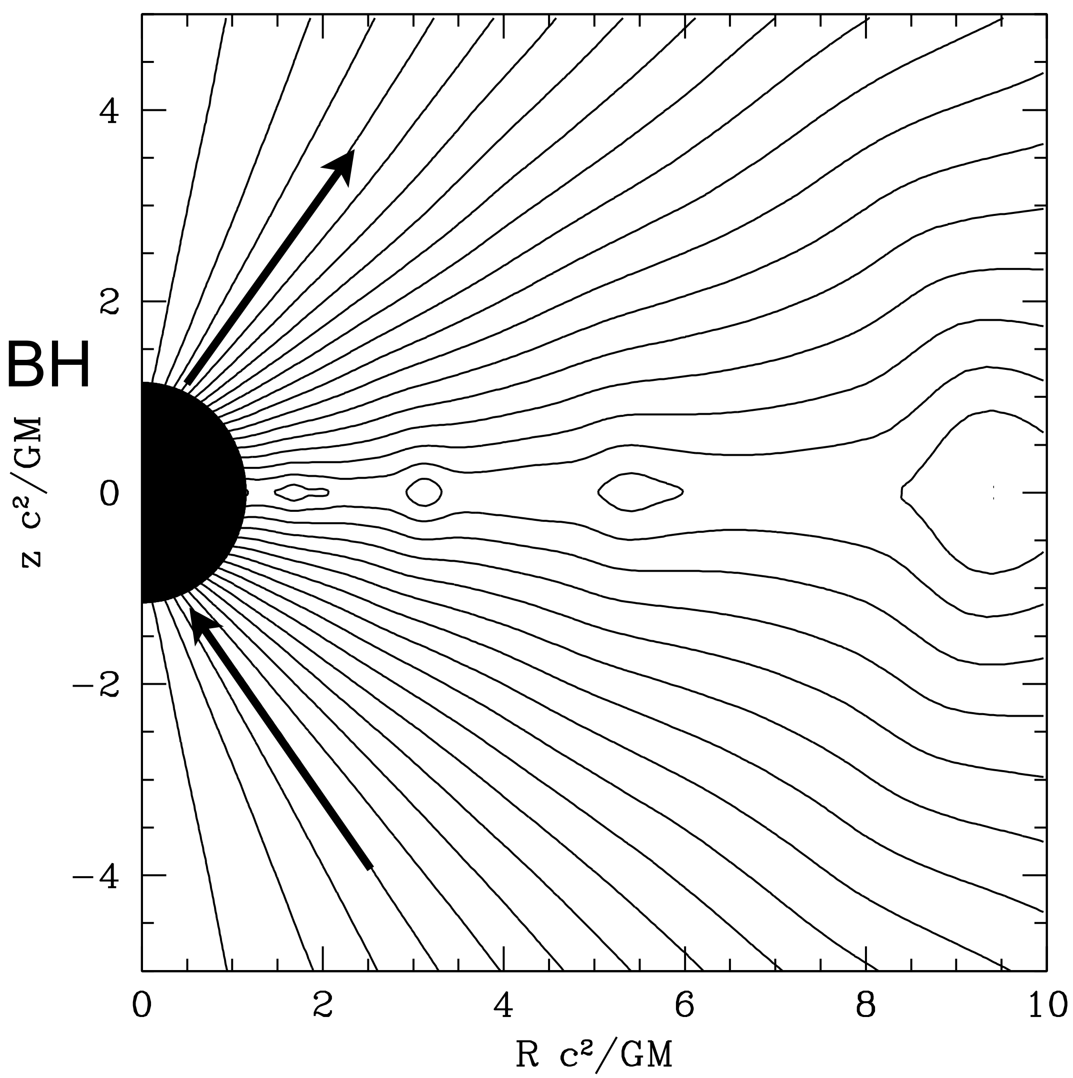

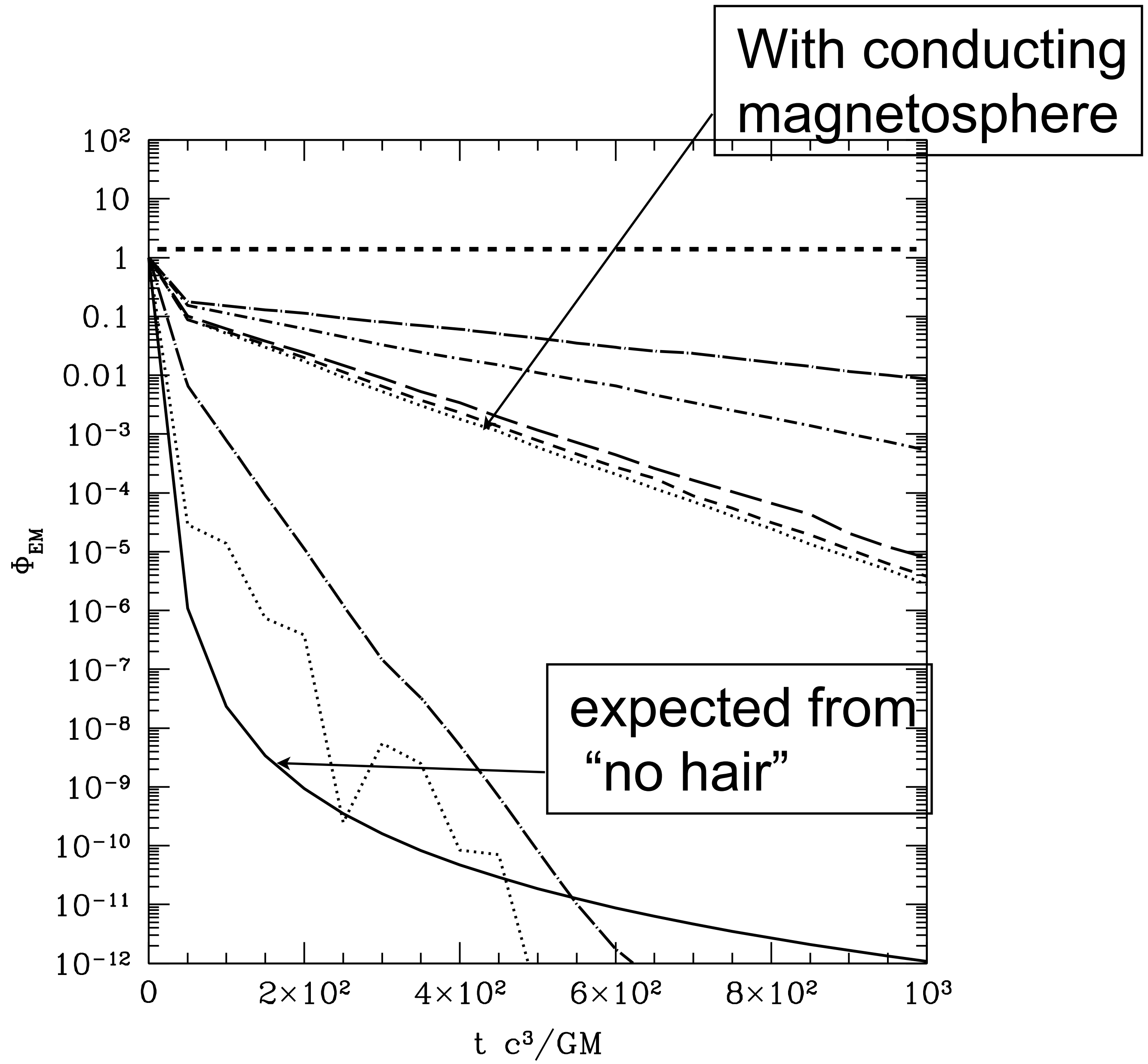

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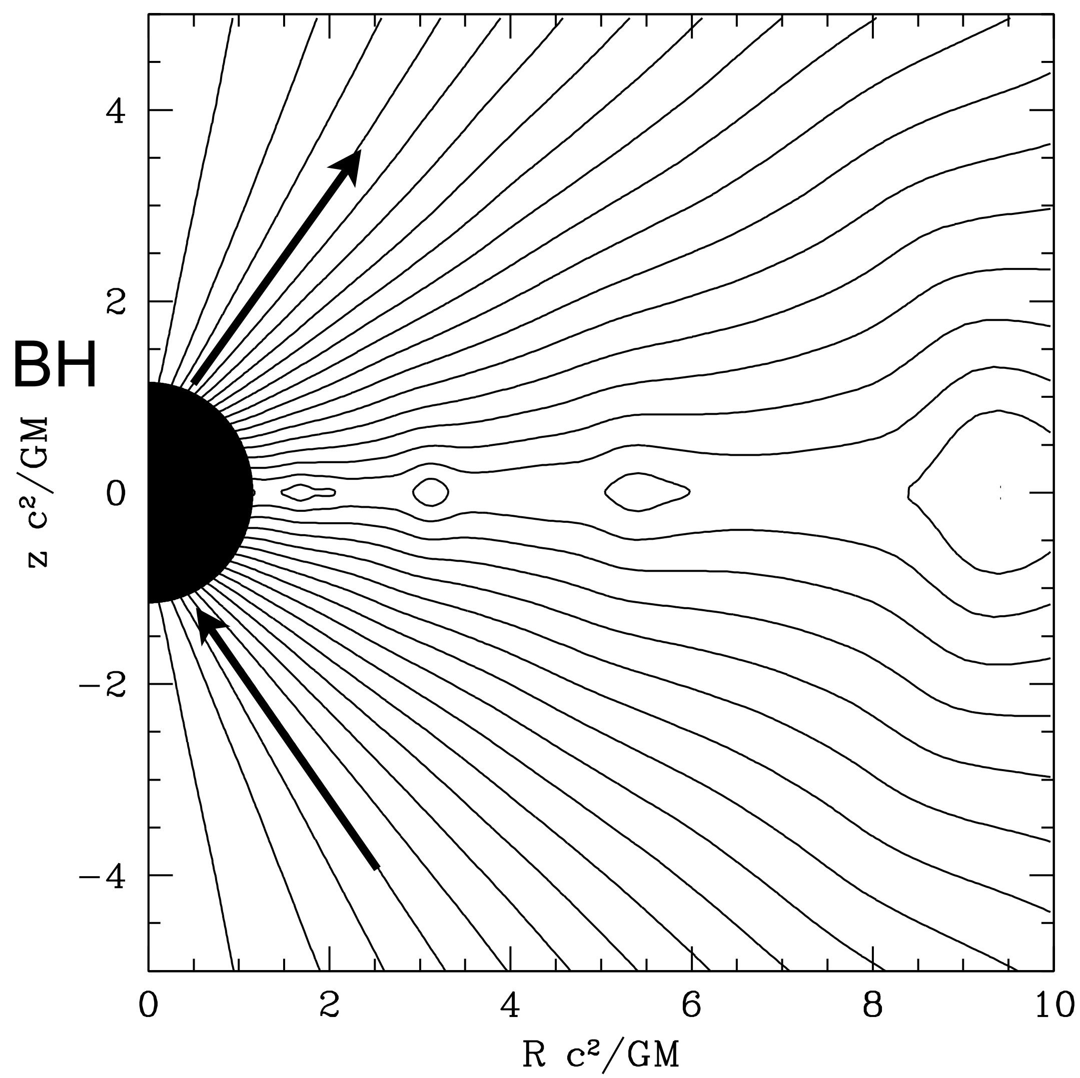

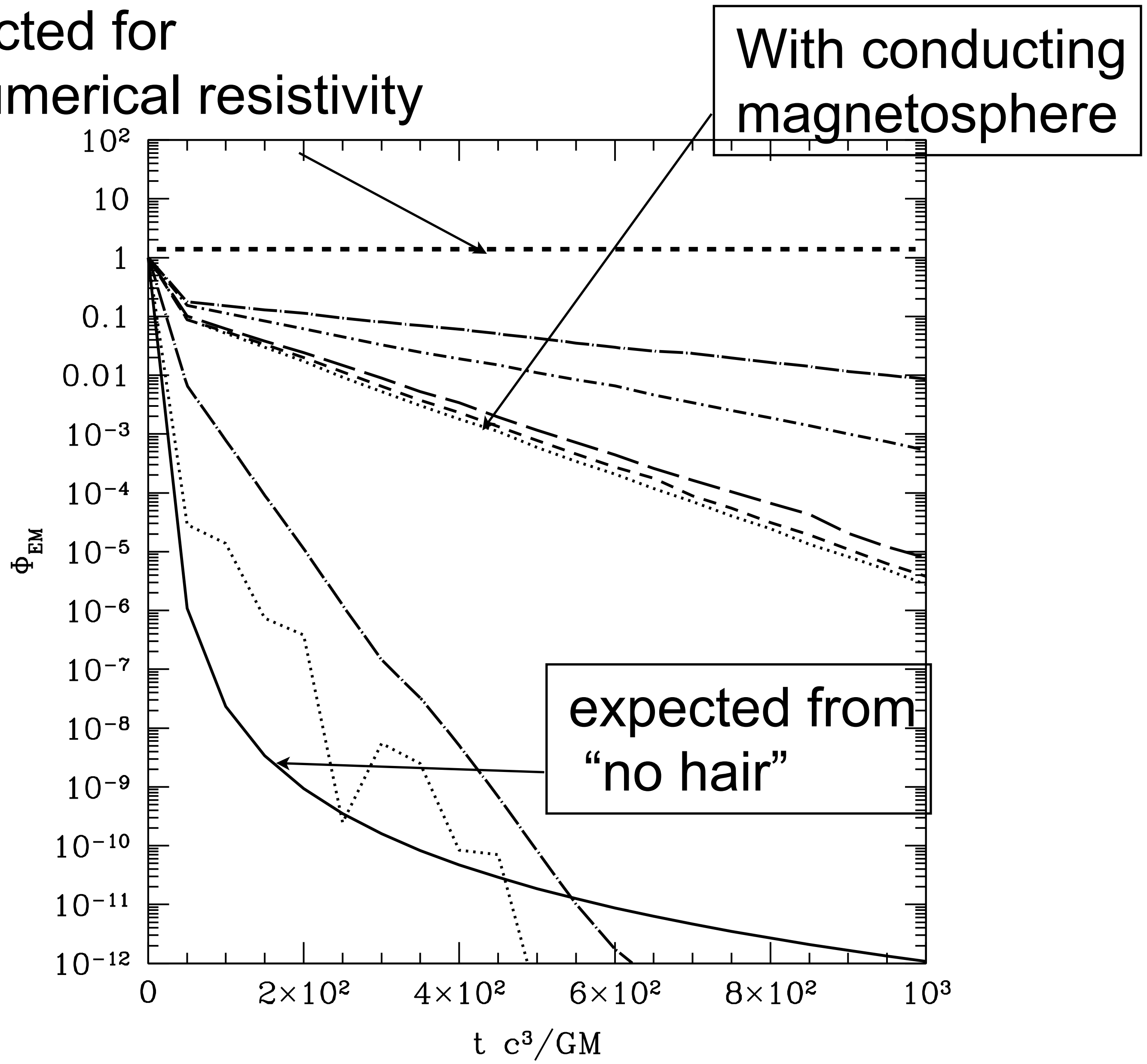

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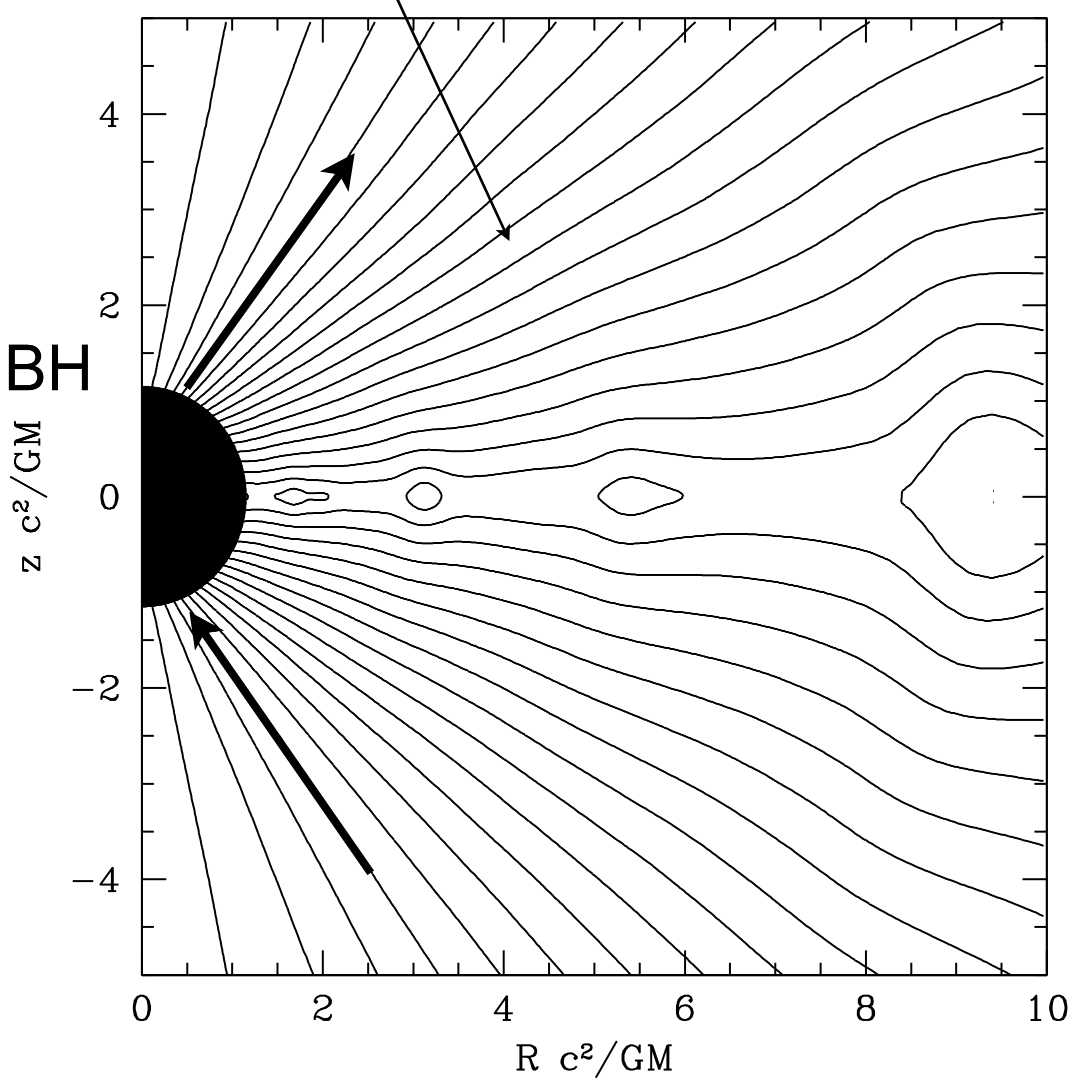
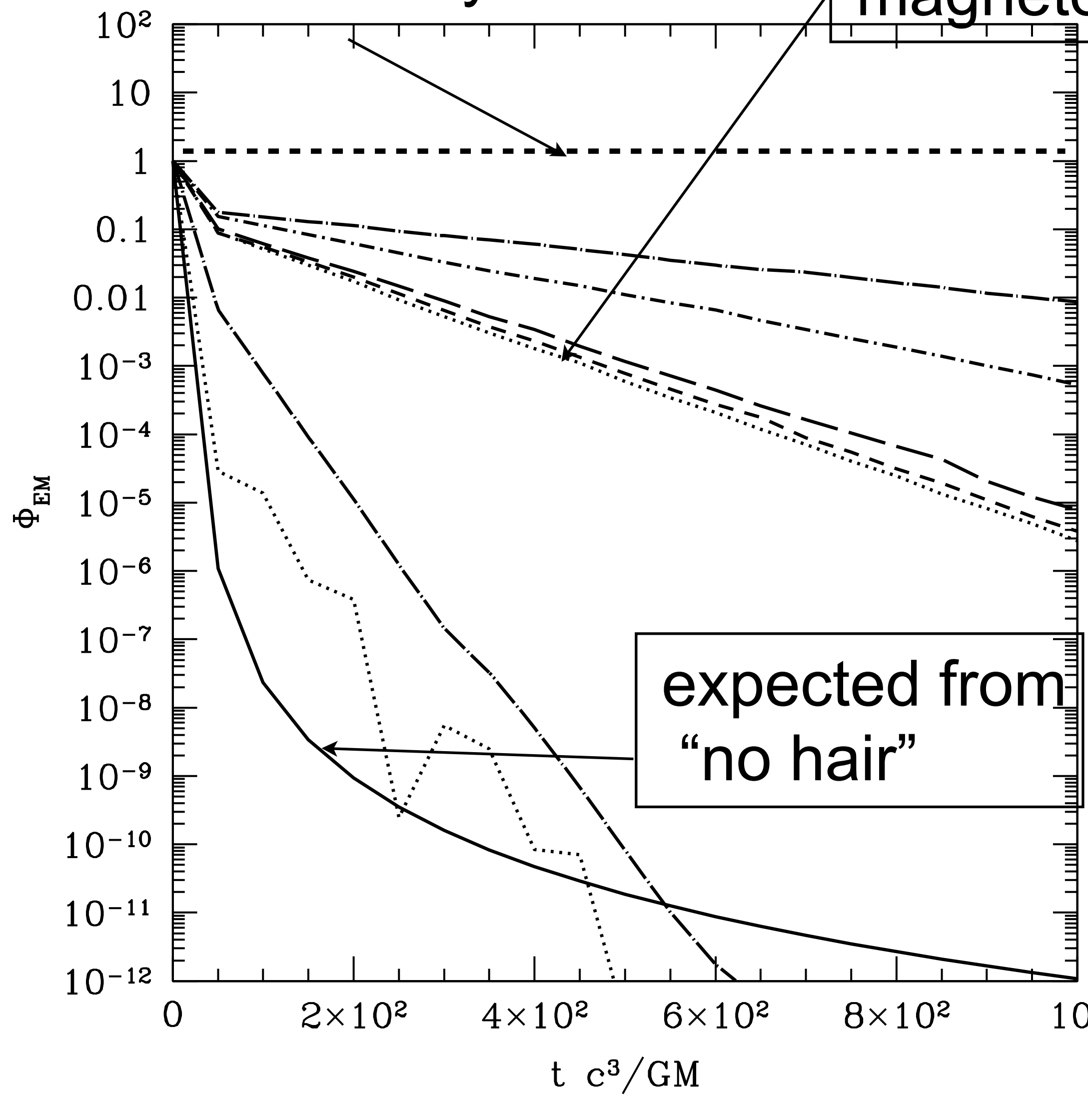


Expected for no numerical resistivity

With conducting magnetosphere



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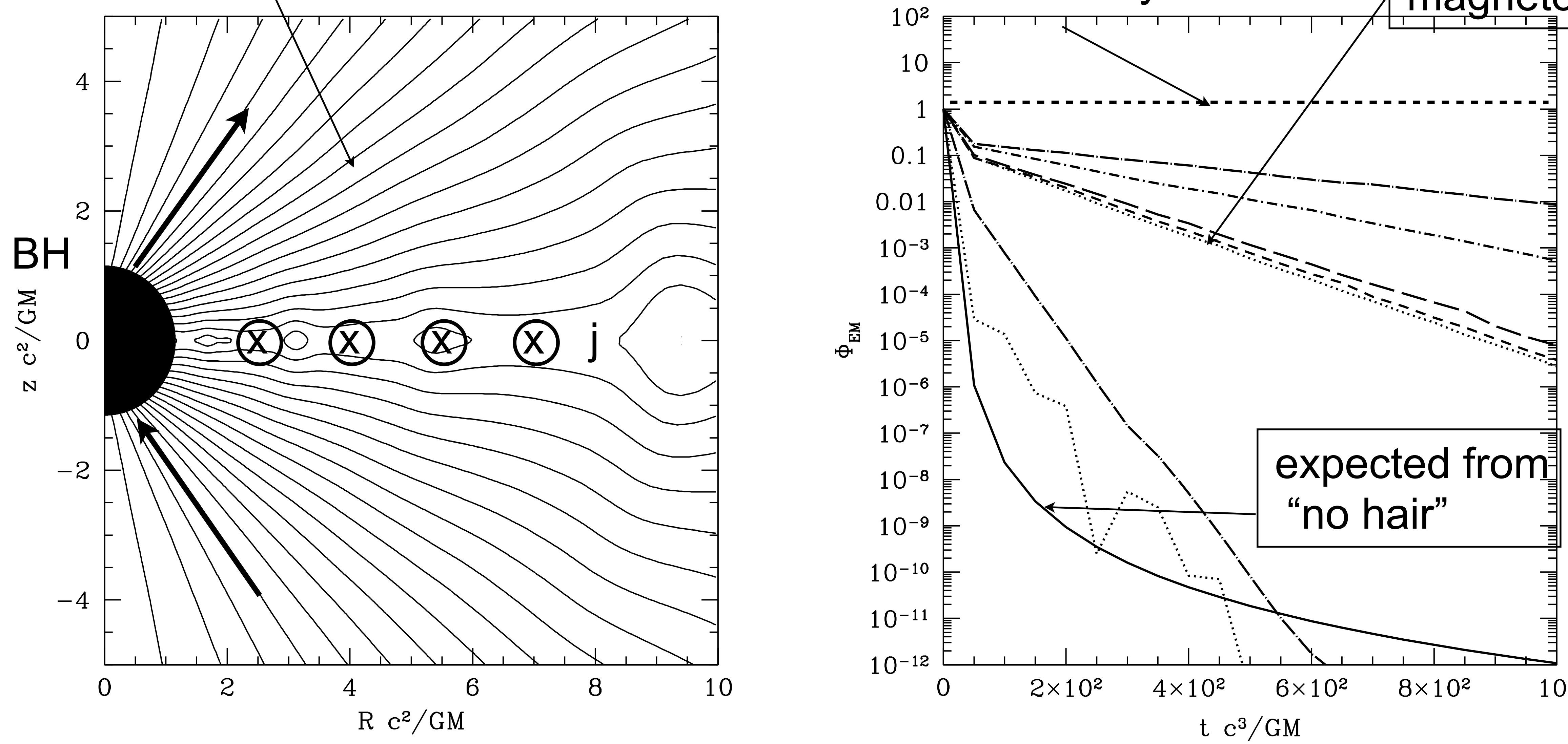

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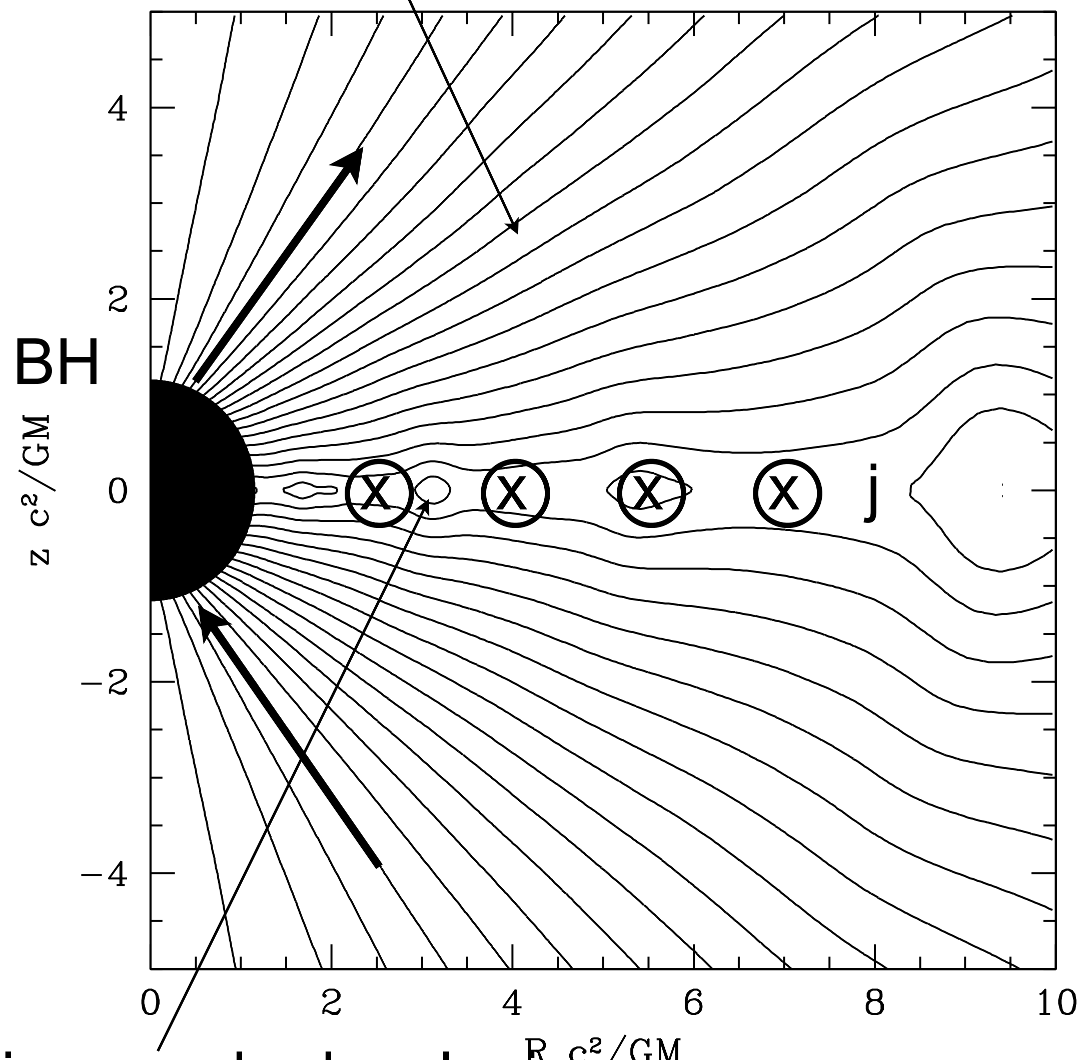

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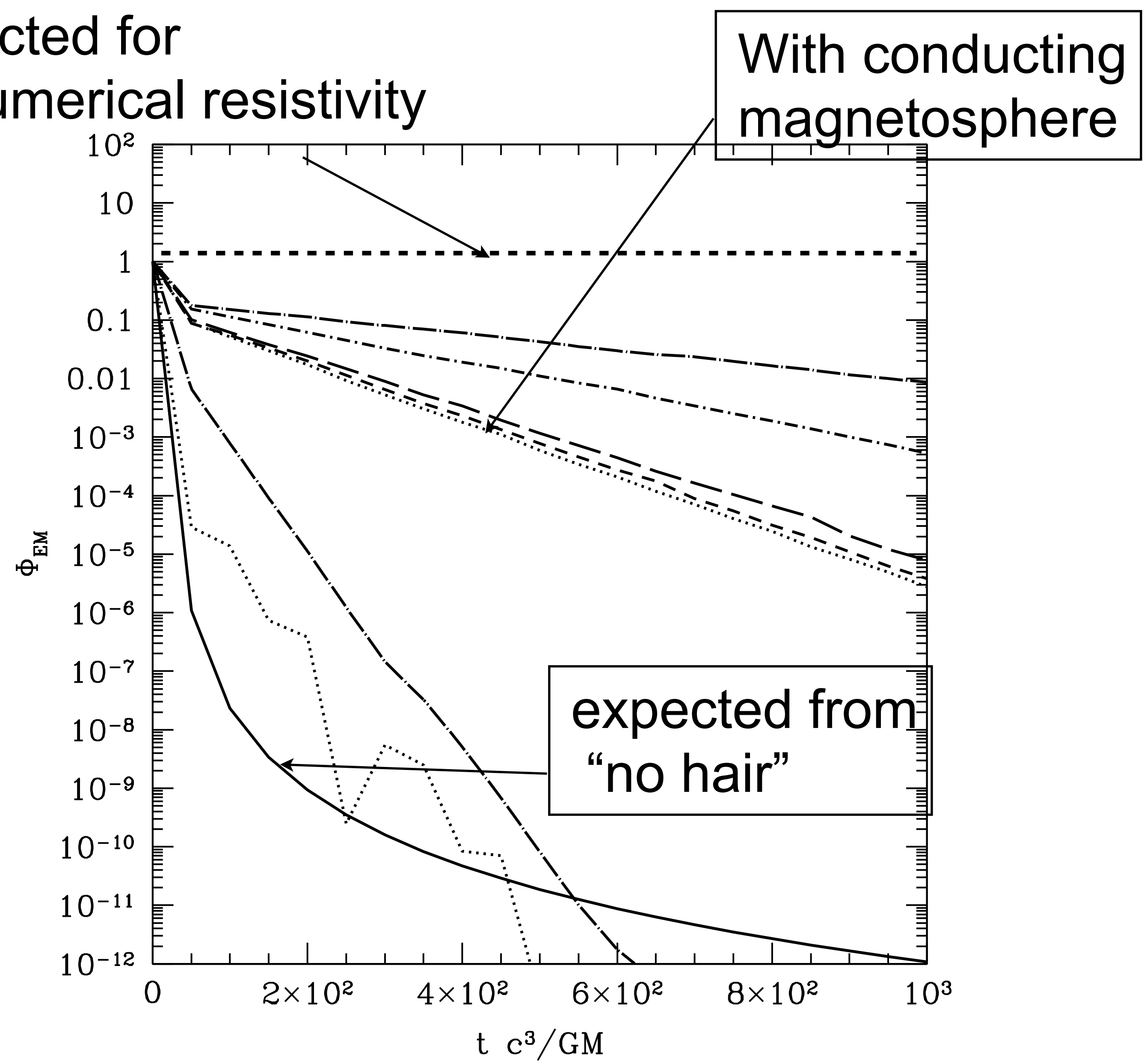

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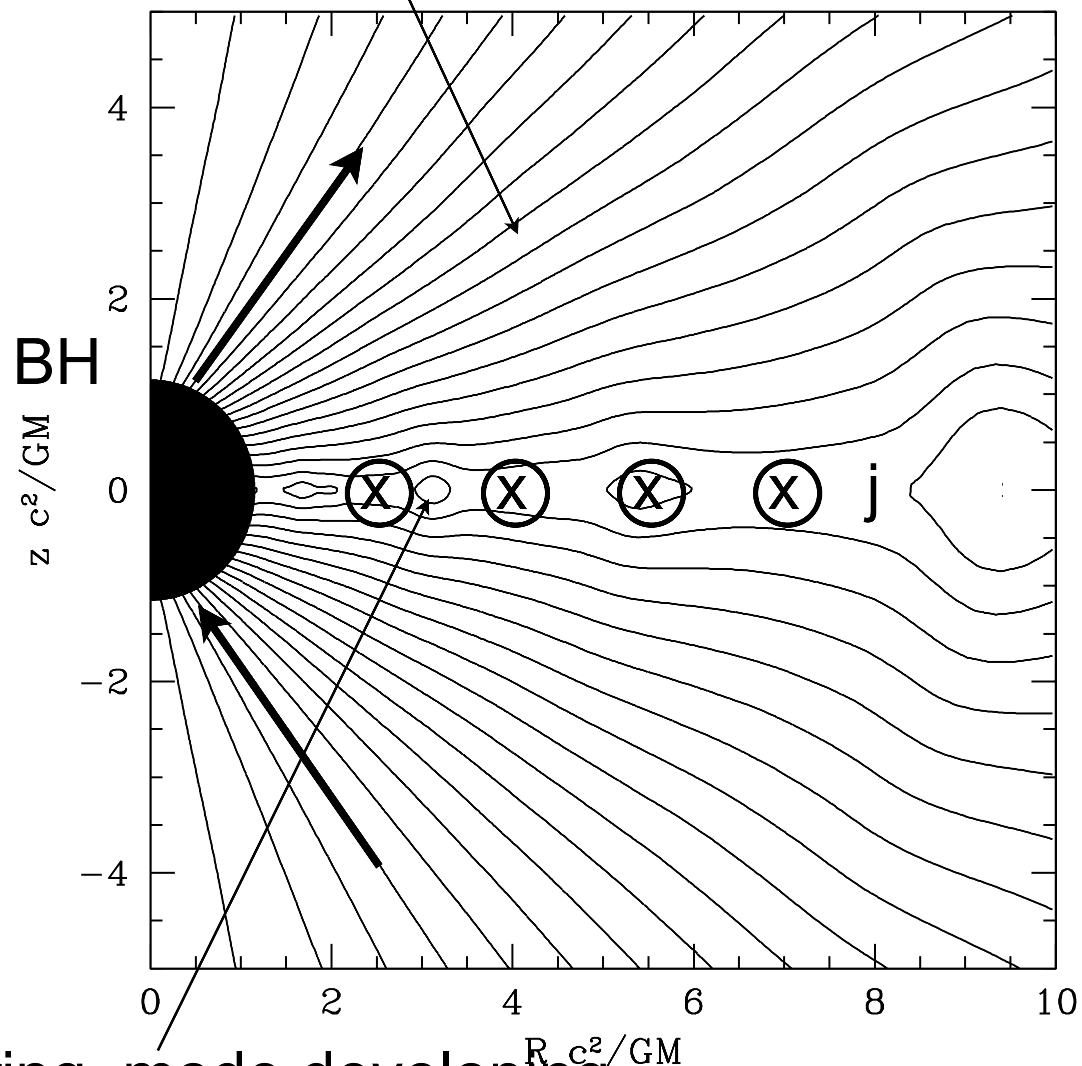

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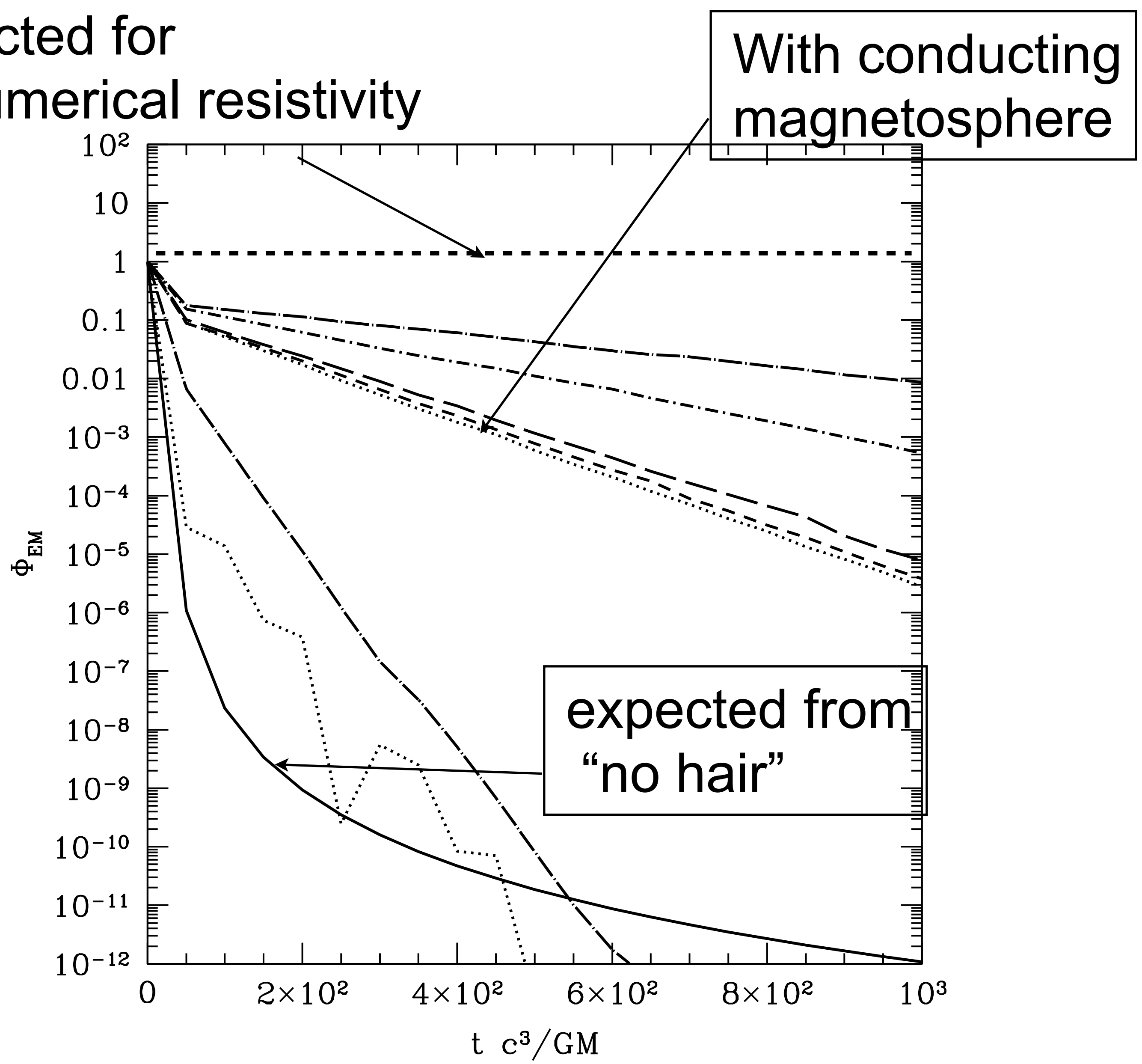

Fields are contained by the equatorial current, just like in BZ, but this current is self-produced

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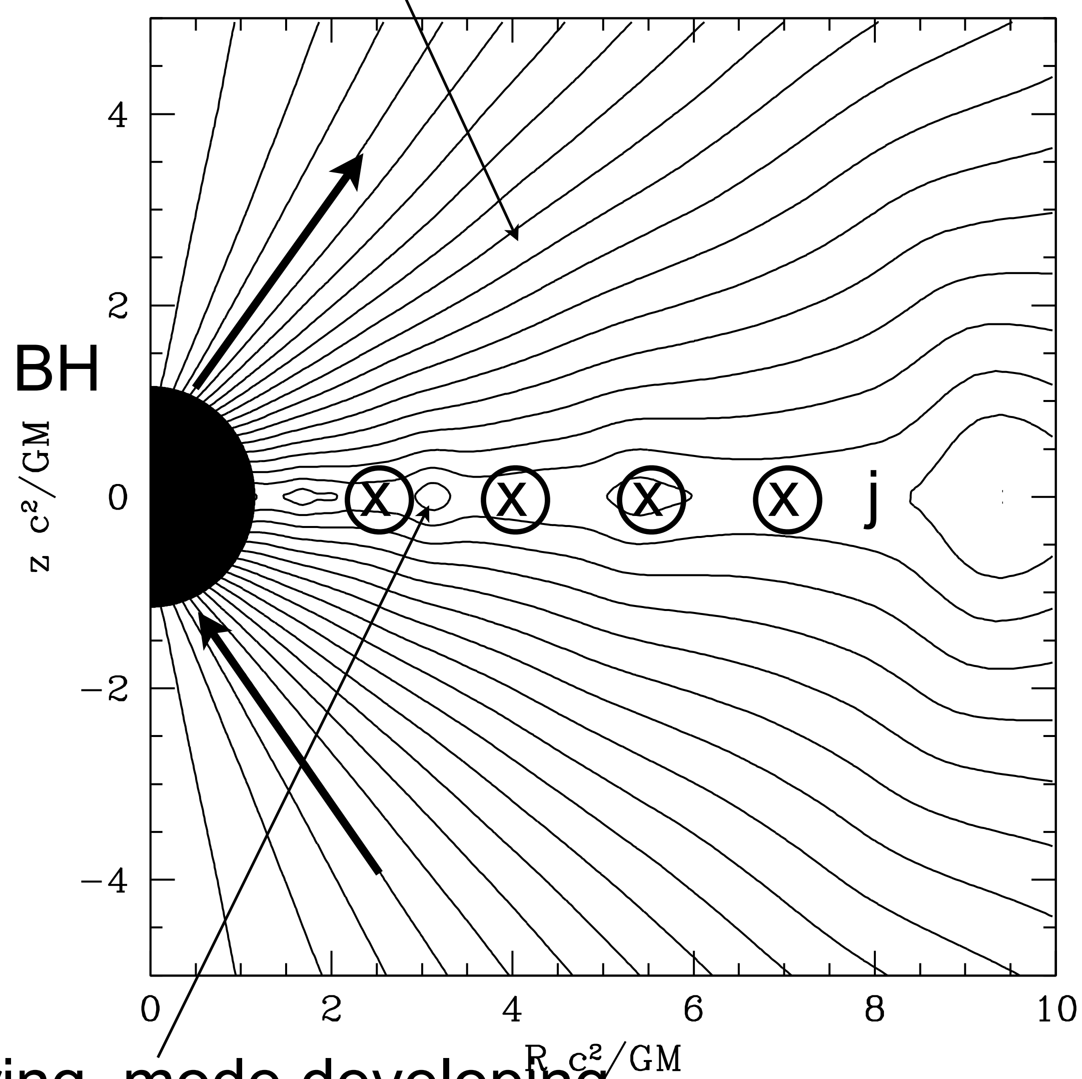

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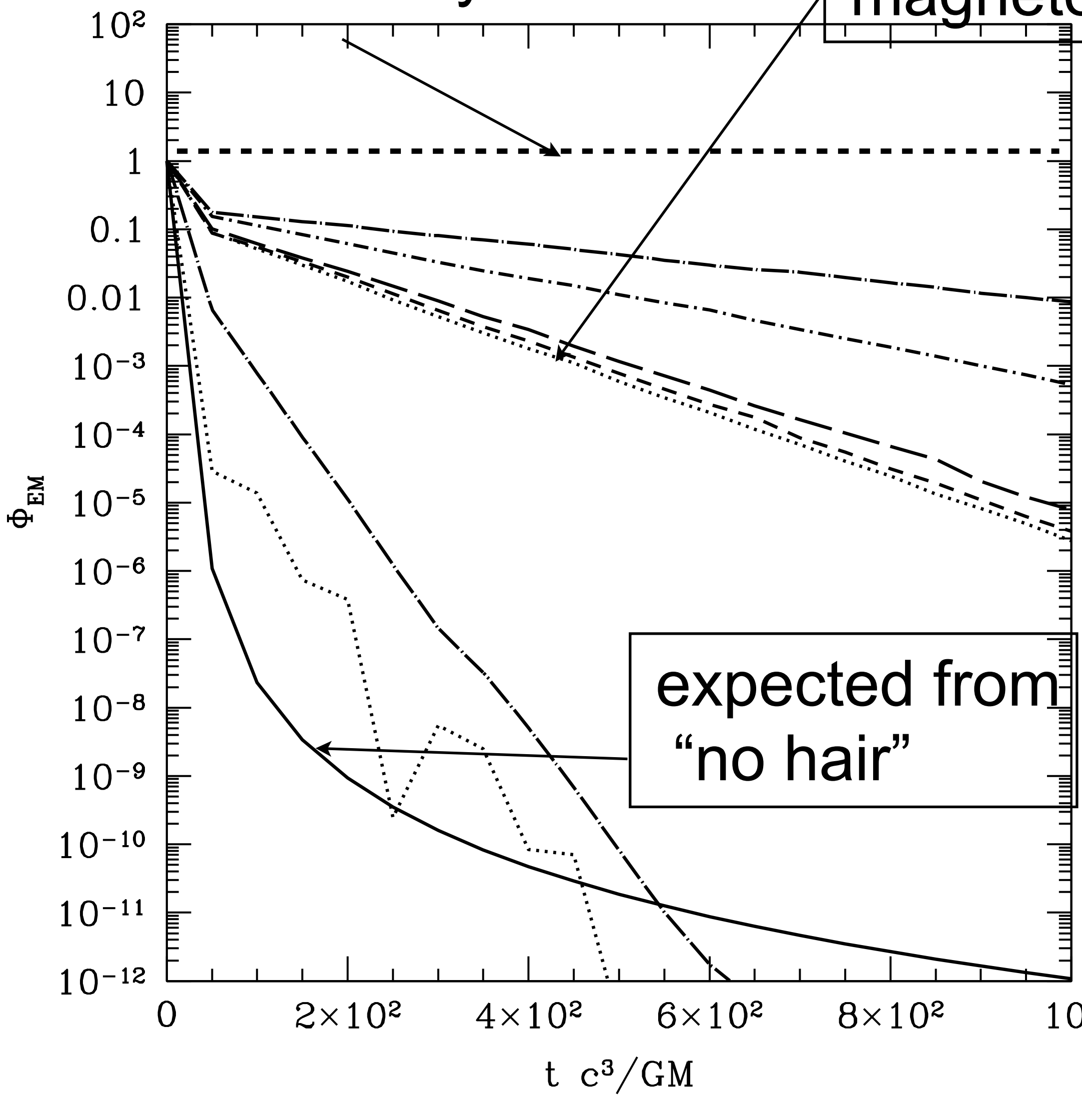

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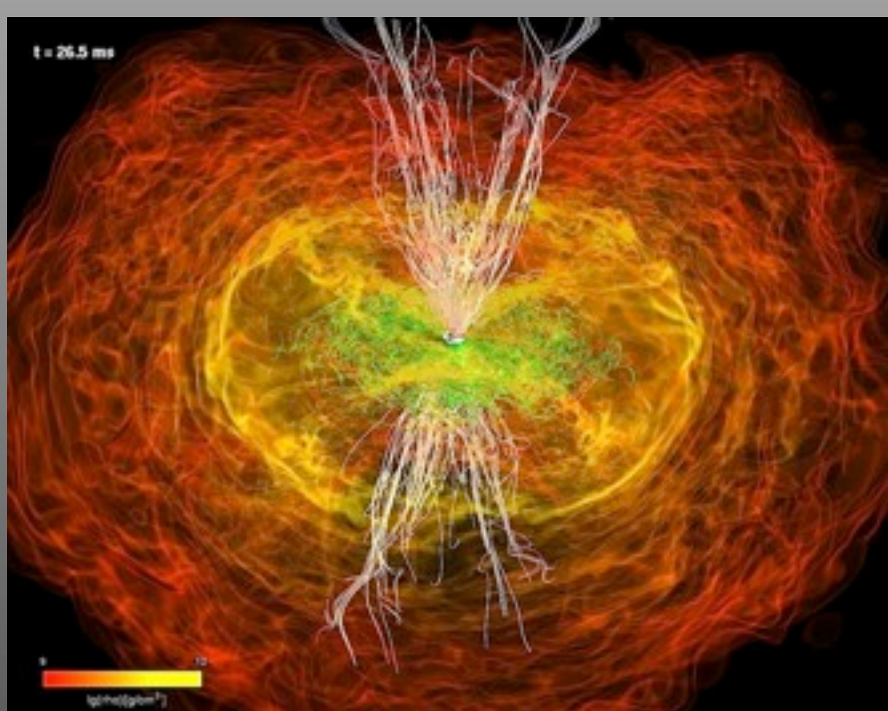
Biggest problem: hard to predict resistive time

The electromagnetic model of short GRBs

- NS-NS merger generates B ~ 10^{15} G in the torus around BH (Rezzolla et al.)
- BH-torus launches a jet along the axis: prompt spike
- After ~ 100 msec torus collapse, isolated BH spins down electromagnetically, produces **equatorially-collimated** flow, $L \propto \sin^2\theta$: prompt tail
- **Tail is more energetic**, but de-boosted for axial observer
- Very late re-brightening of the remnant



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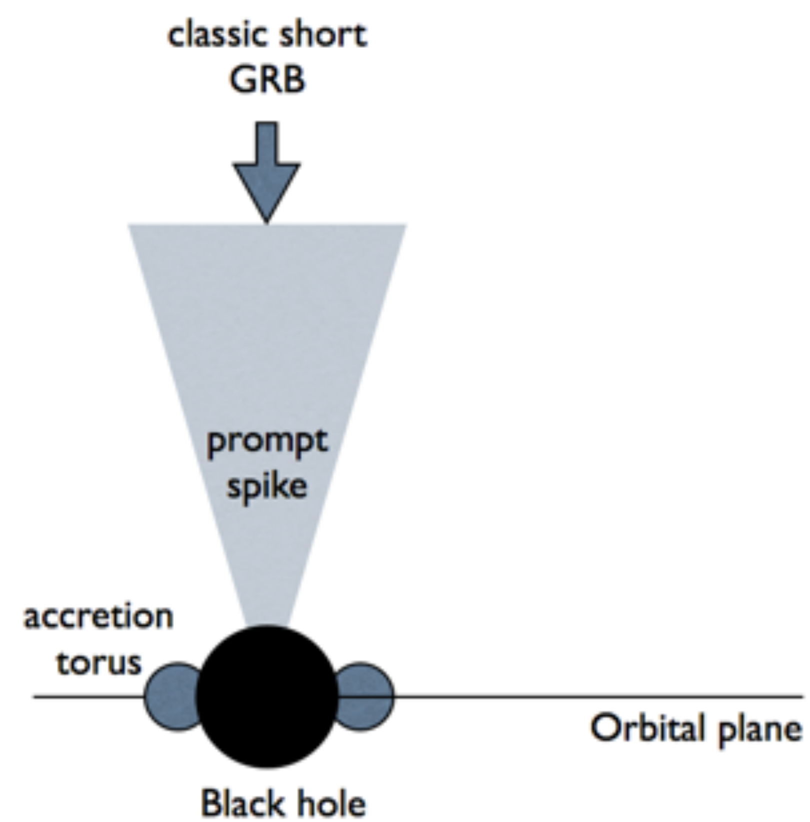

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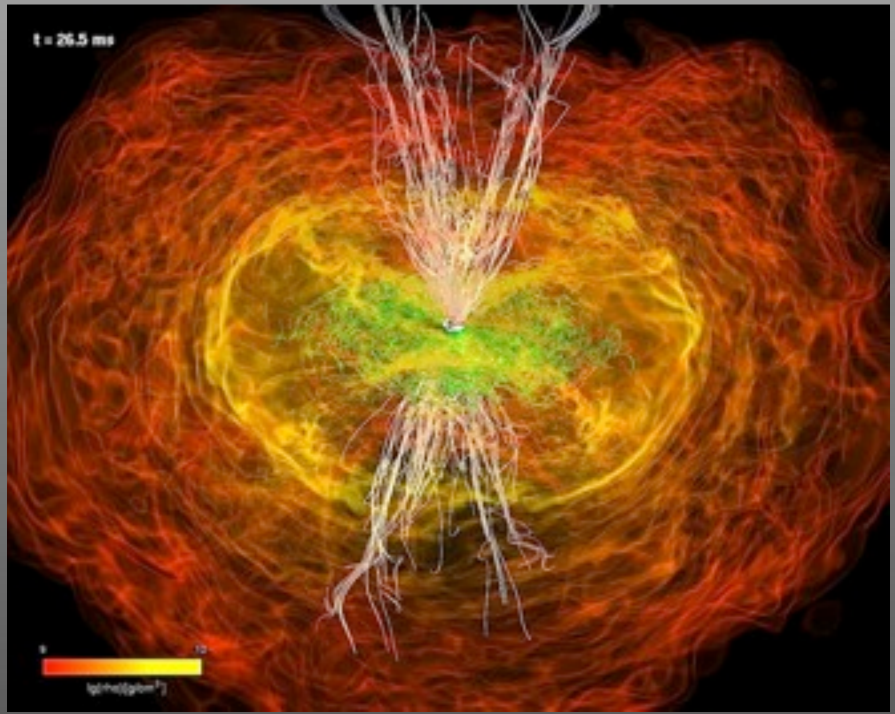

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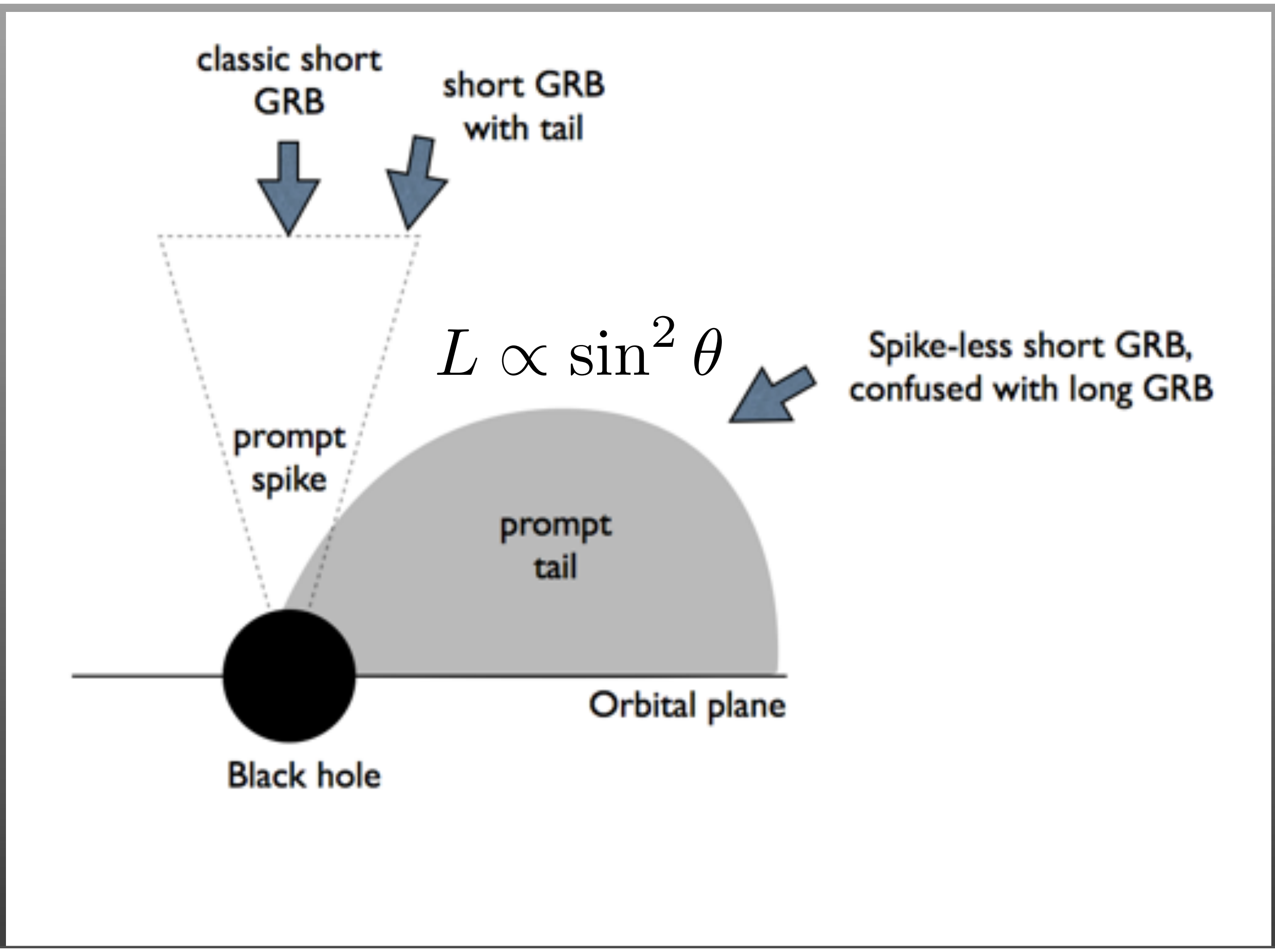

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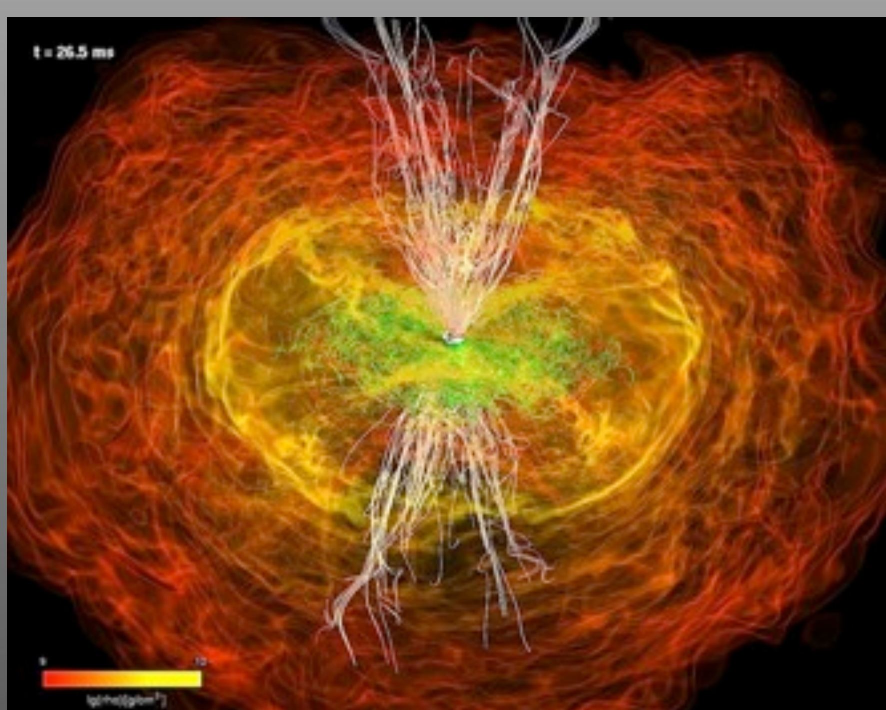

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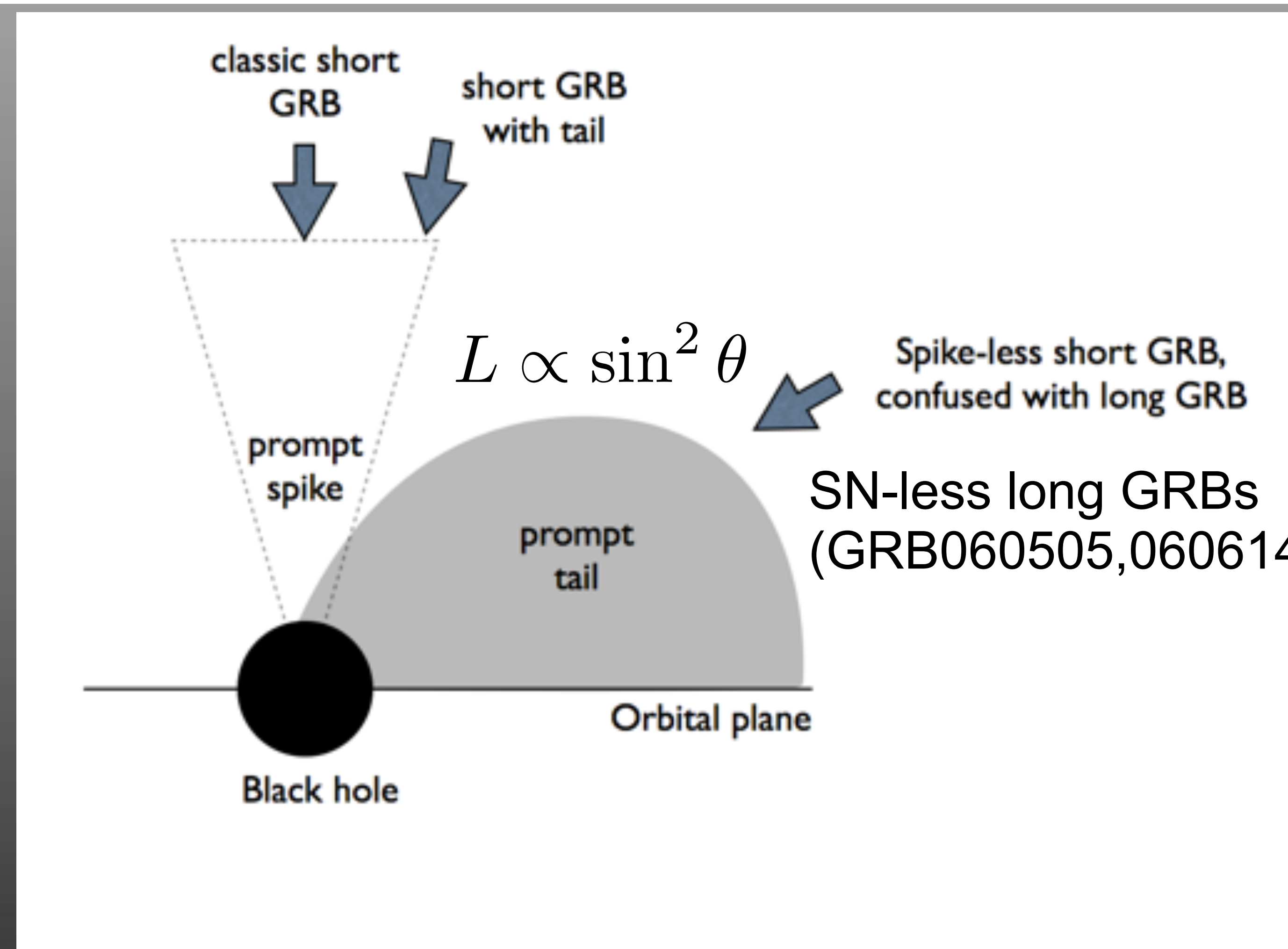

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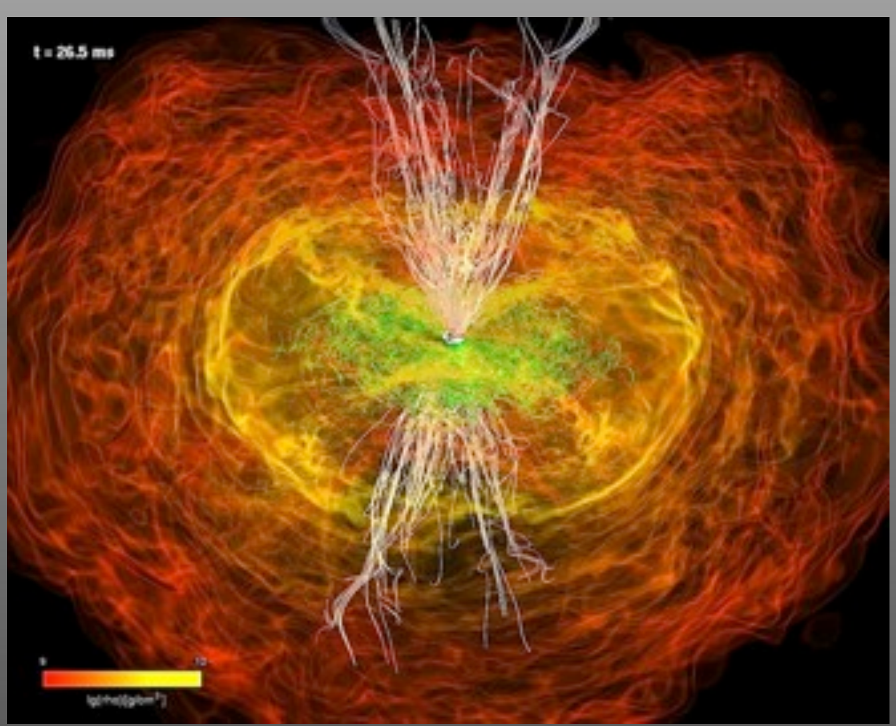

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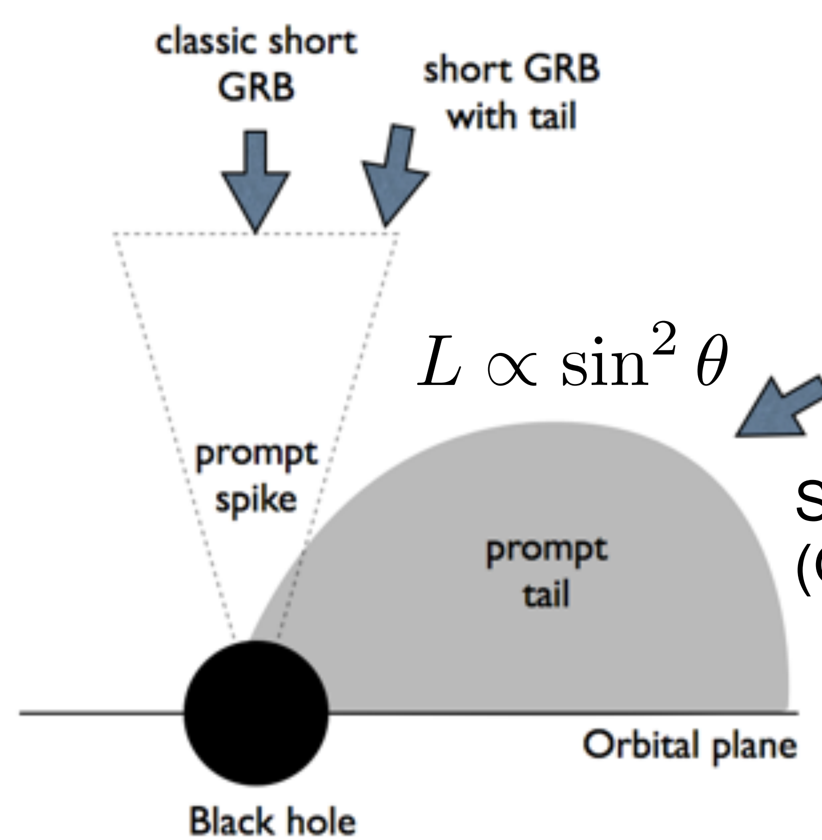

SN-less long GRBs (GRB060505,060614)

like a millisecond magnetar, PWN

Millisecond magnetar as GRB central engine

- Millisecond magnetars is a promising central source
  - can produce clean (after few seconds), highly relativistic outflows
  - can operate on long time scales without external feeding
- Magnetic dissipation/particle acceleration *a la* Crab flares can be important (dominant?) in GRBs
  - Bursty, short time scales from large radii
  - fast efficient acceleration
  - non-thermal tail
- Newly born BHs may work as millisecond magnetars - prompt tails in short GRBs