Magnetic effects in the propagatation of collapsar jets ~~and in the afterglow ejecta~~

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Relativistic Jets: Creation, Dynamics and Internal Physics

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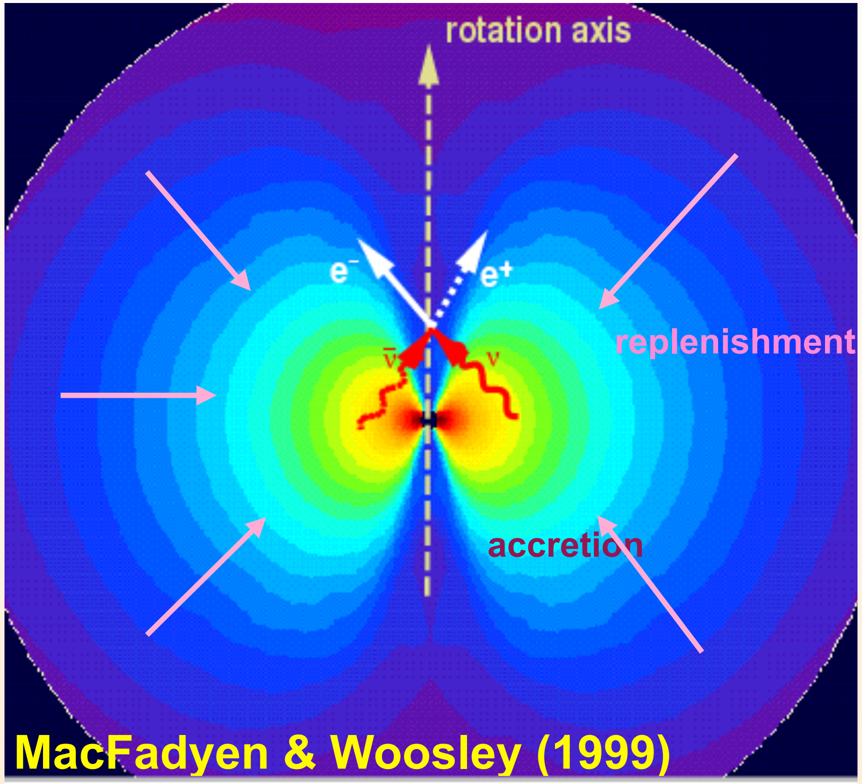
LGRB Progenitors: Collapsars



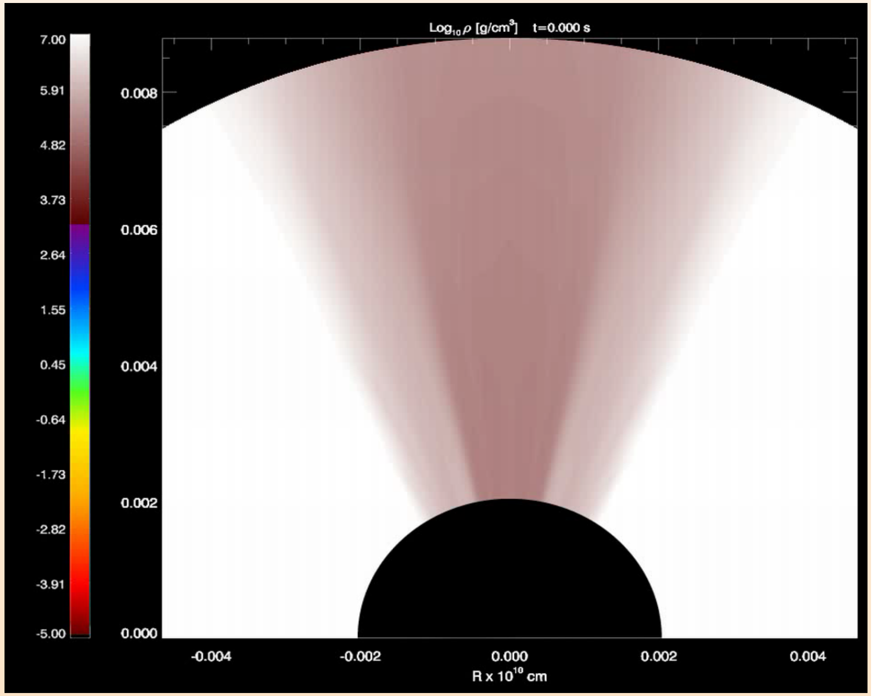
MacFadyen & Woosley (1999)

Woosley (1993):

- Collapse of a massive ($M_* \sim 30M_\odot$, WR) rotating star that does not form a successful SN but collapses to a BH ($M_{BH} \sim 3M_\odot$) surrounded by a thick accretion disk. The hydrogen envelope is lost by stellar winds, interaction with a companion, etc.

- The viscous accretion onto the BH ⇒ strong heating ⇒ thermal $\nu\nu$-annihilating preferentially around the axis ⇒ formation of a relativistic jet ($\Gamma=[1-(v/c)^2]^{-1/2}$).
- However, **the ability of producing thermally driven outflows with $\Gamma \gtrsim 100$ is limited**
- Alternative generation: ***hydromagnetic*** (Blandford-Payne mechanism) or ***electromagnetic*** (Blandford-Znajek mechanism).

⇒ **the resulting outflow will be magnetized.**



Aloy et al. (2000)

Numerical set up

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- Two steps:
    1. ***RMHD models*** (this talk).

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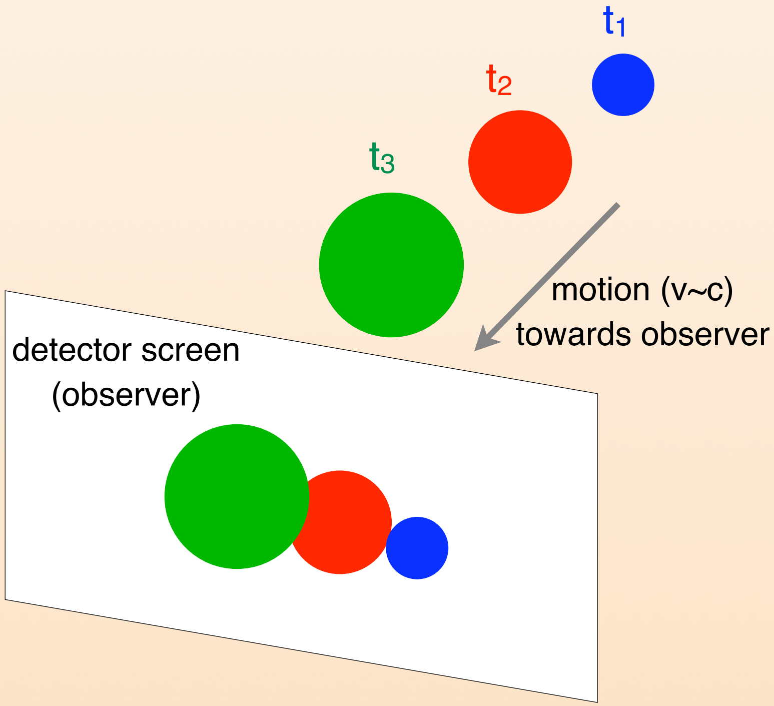

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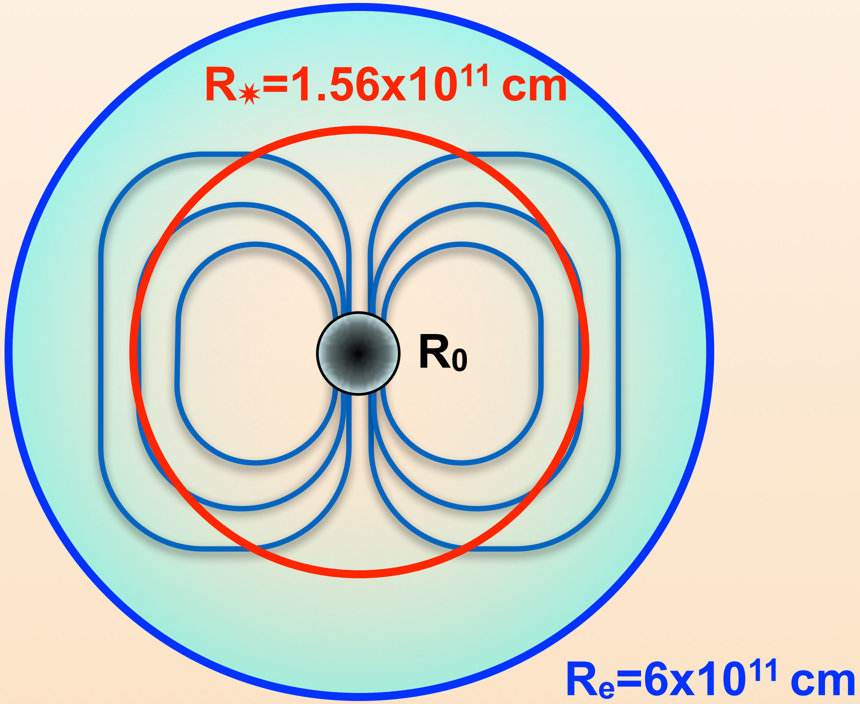


1. Stellar Model: **35OC** (Woosley & Heger 2006). **$R^* = 1.56\times10^{11}$ cm**
2. RMHD code (MP5, CT, Self-gravity): finite-volume, Eulerian formulation.
3. EoS Table:
   - $\rho>10^{-4}$ gr/cm^3: Helmholtz EoS (leptonic table + baryons)
   - $\rho<10^{-4}$ gr/cm^3: baryons + Boltzmann e-gas +radiation.
4. Injection nozzle @ $R_0 = 10^9$ cm.
5. Domain: **[R_0, 6x10^{11} cm] x [0º,90º]** with standard resolution 2560 x 360.
6. Progenitor magnetic field (if any): dipole with a generating current at 2x10^8 cm

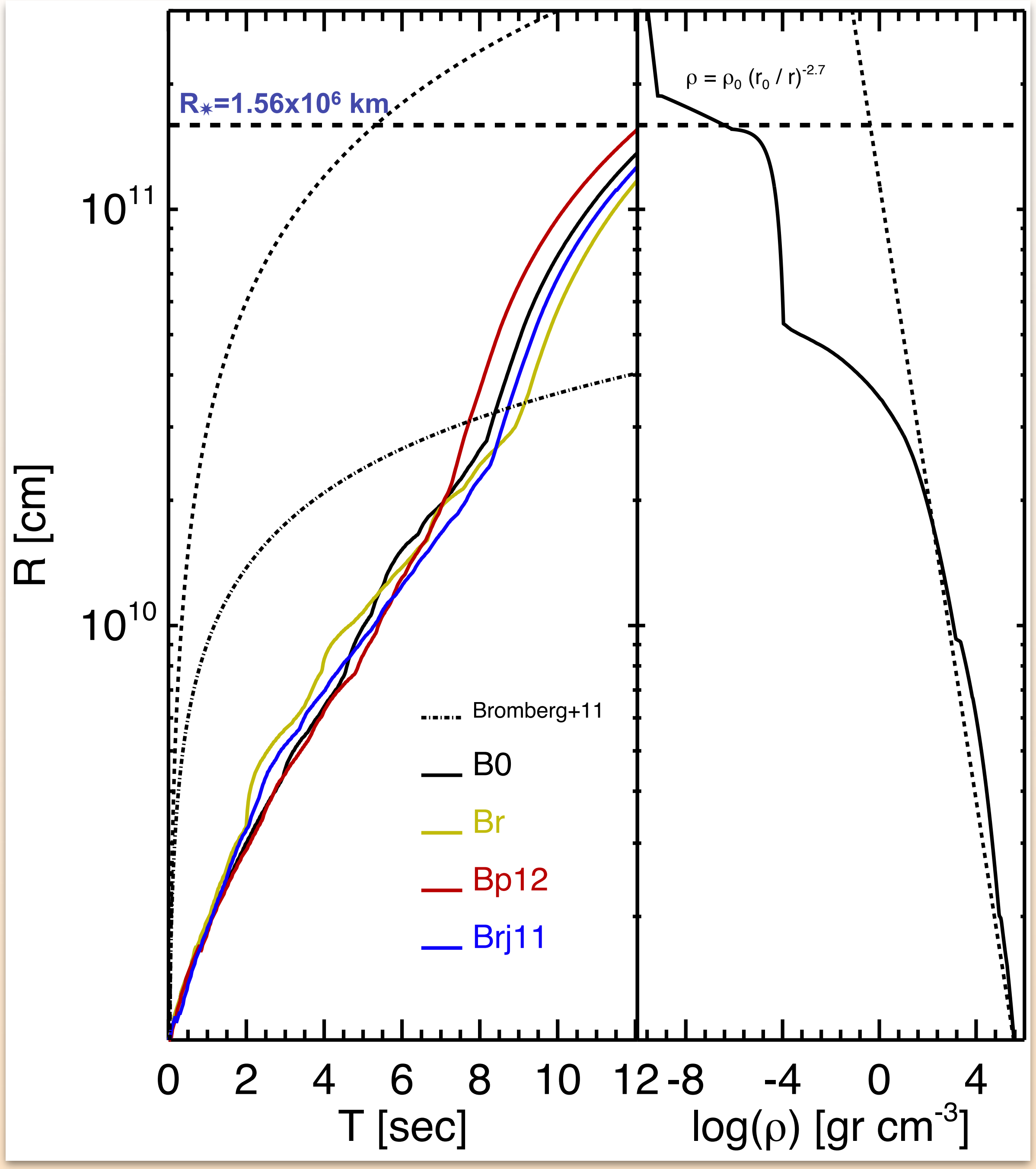
Models

Model	B	B	σ	L
B0	0	0	0	6.65
Bp	0	2x10	0,18	6.66
Br	10	0	111	13.7
Brp	10	10	111	13.7

Common jet parameters (nozzle):

- $\theta = 10^{\circ}$ $\theta\Gamma = 0.87 < 1$ (causally connected)
- $\Gamma = 5$ $(\Gamma_\infty \sim 500)$
- $\varepsilon = 80\ c^2$
- $\rho = 0.1$ gr/cm^3
- $p = 2.23 \times 10^{22}$ erg/cm^3

Jet dynamics



There is not a clear trend for the propagation speed:

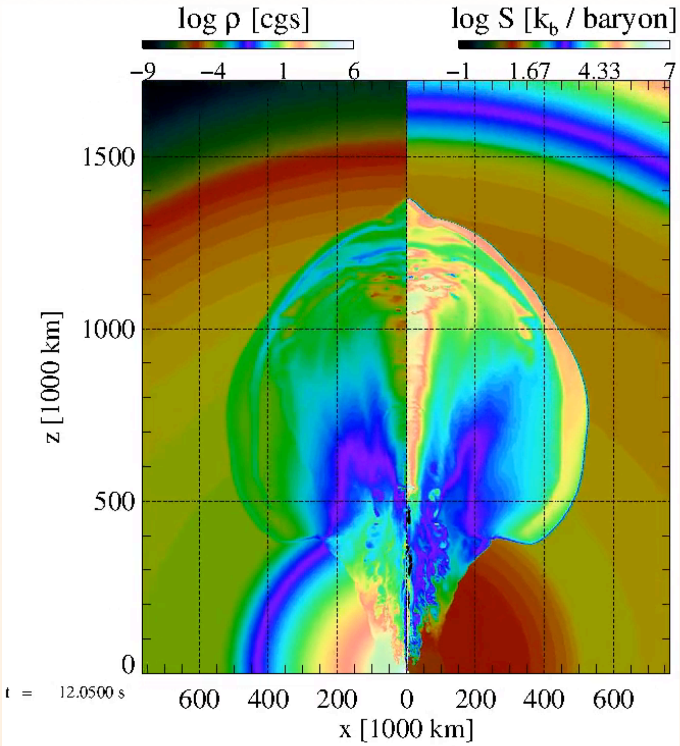
- Faster: model with dominant Bϕ (v~0.43c)
- Slower: model without Bϕ (v~0.33c)
- Unmagnetized model: v~0.38c

Bromberg et al. (2011) estimate (unmagnetized model):

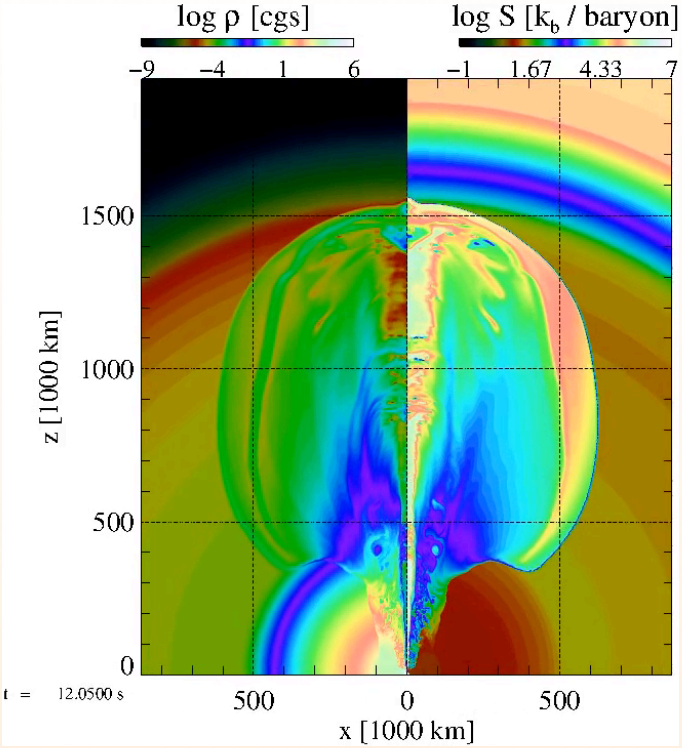
- **Falls short by 25% close to the stellar surface (β ~ 0.3c).**
- **Too large close to the jet nozzle.**

Jet dynamics

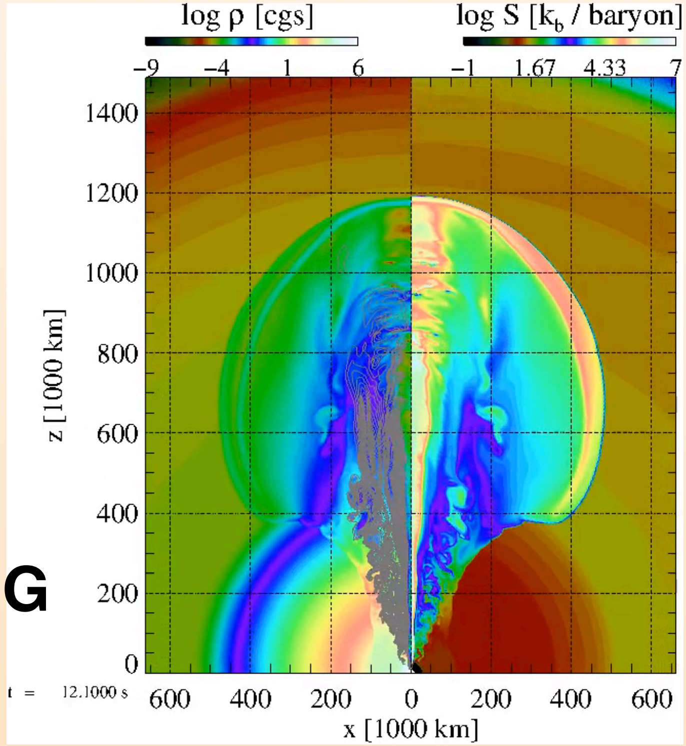
B=0



$B_{\phi} = 2x10^{10}$ G
$B_{ext} = 0$
$\sigma = 0.18$



$B_{\phi} = 0$
$B_r = 10^{11}$ G
$\sigma = 111$



$B_{\phi} = 10^{10}$ G
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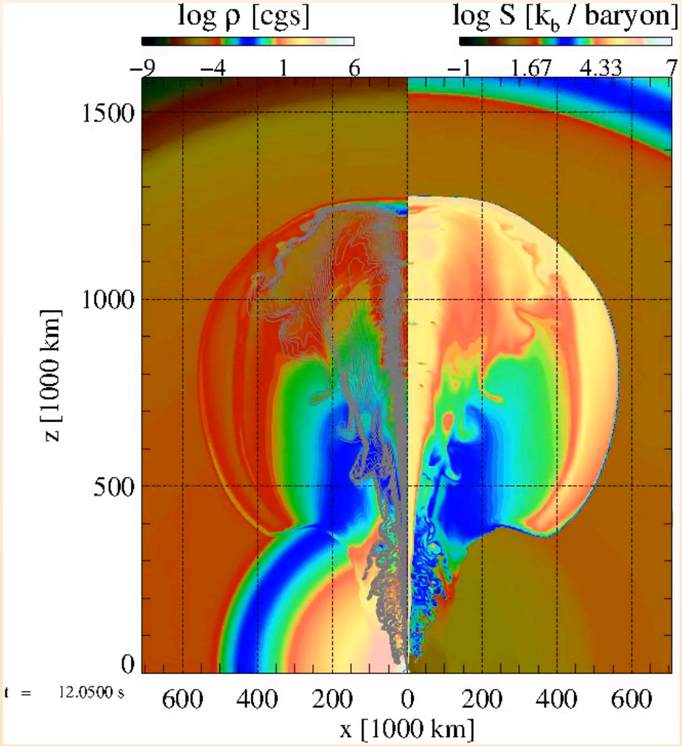
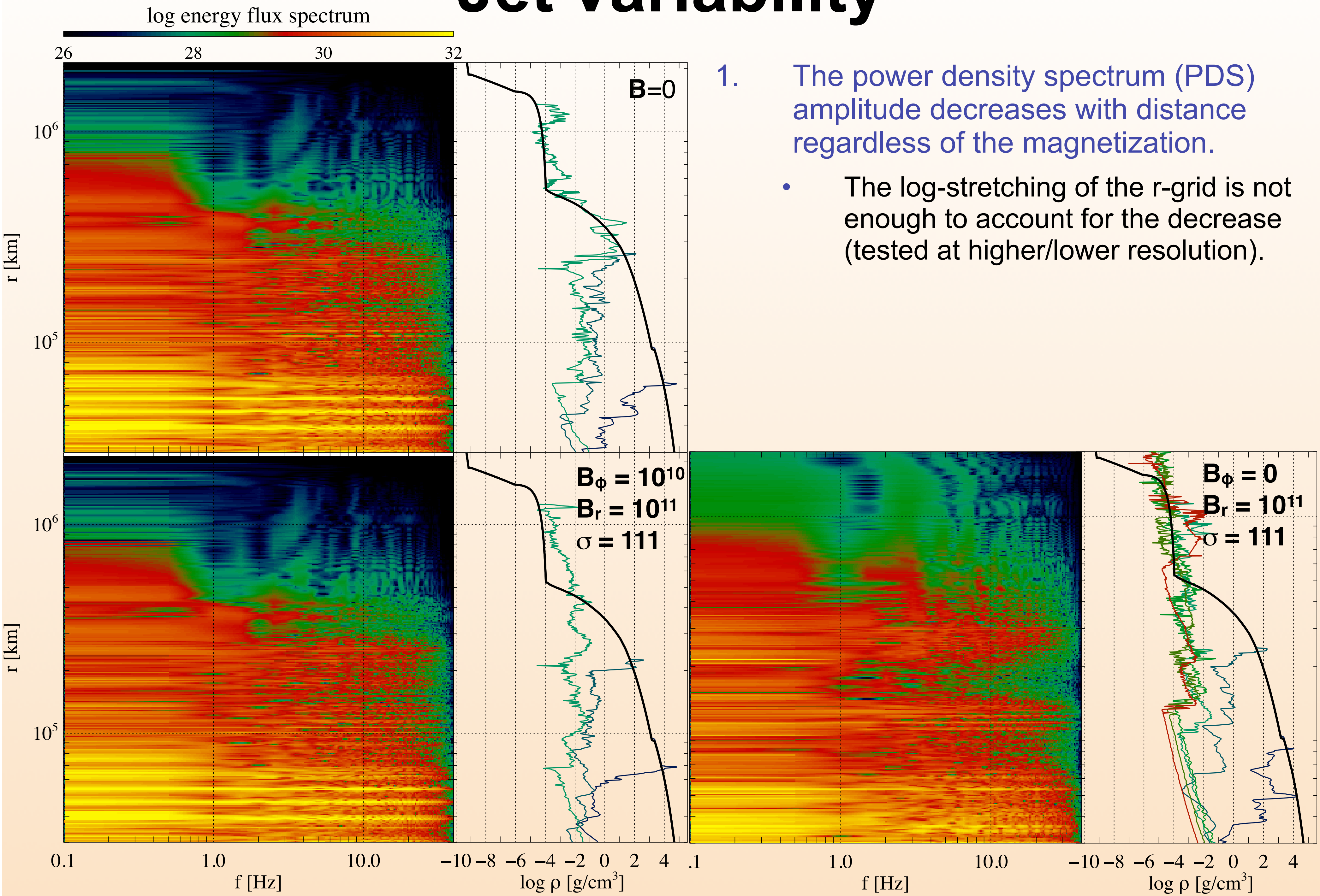
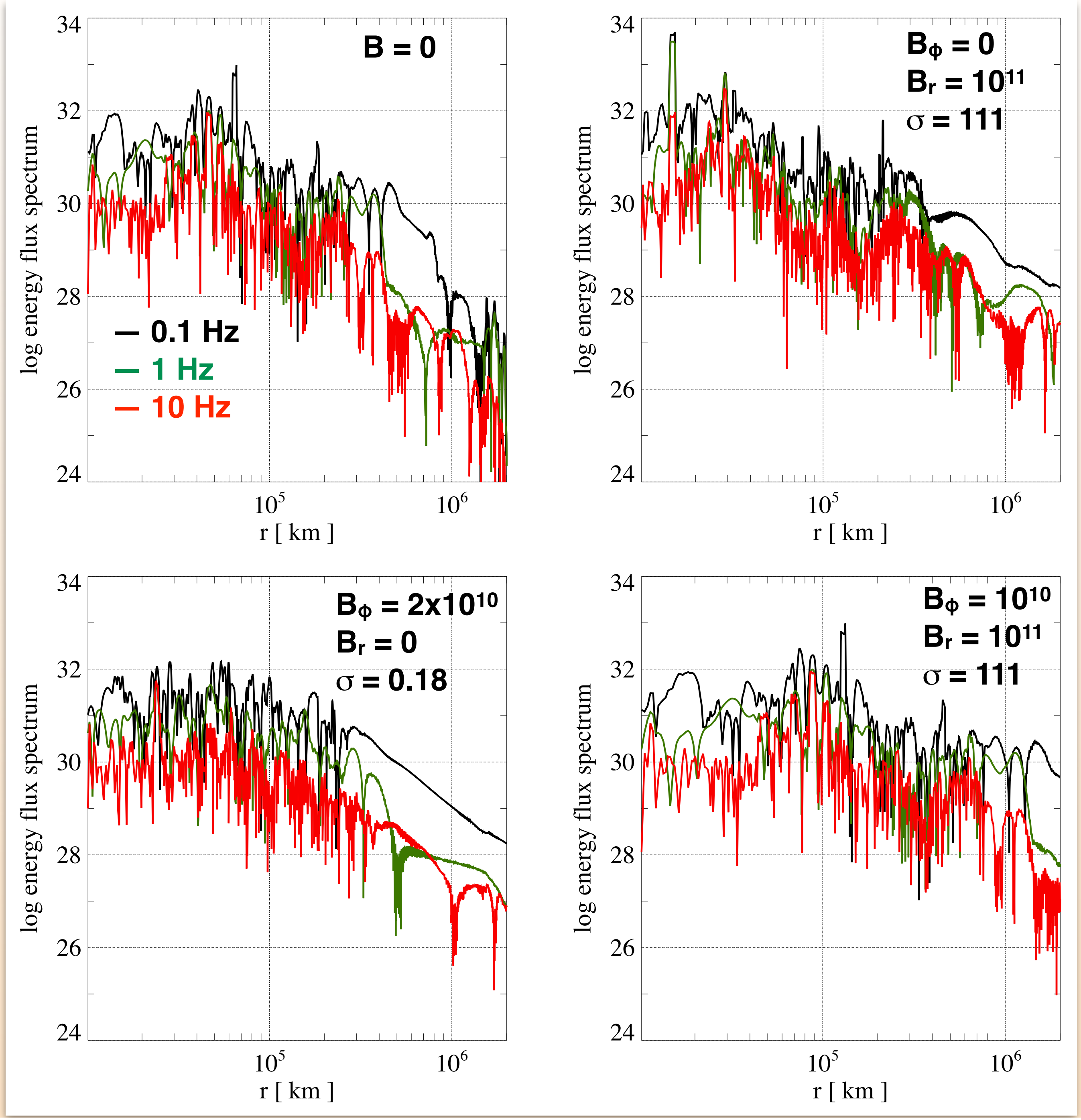


Jet variability



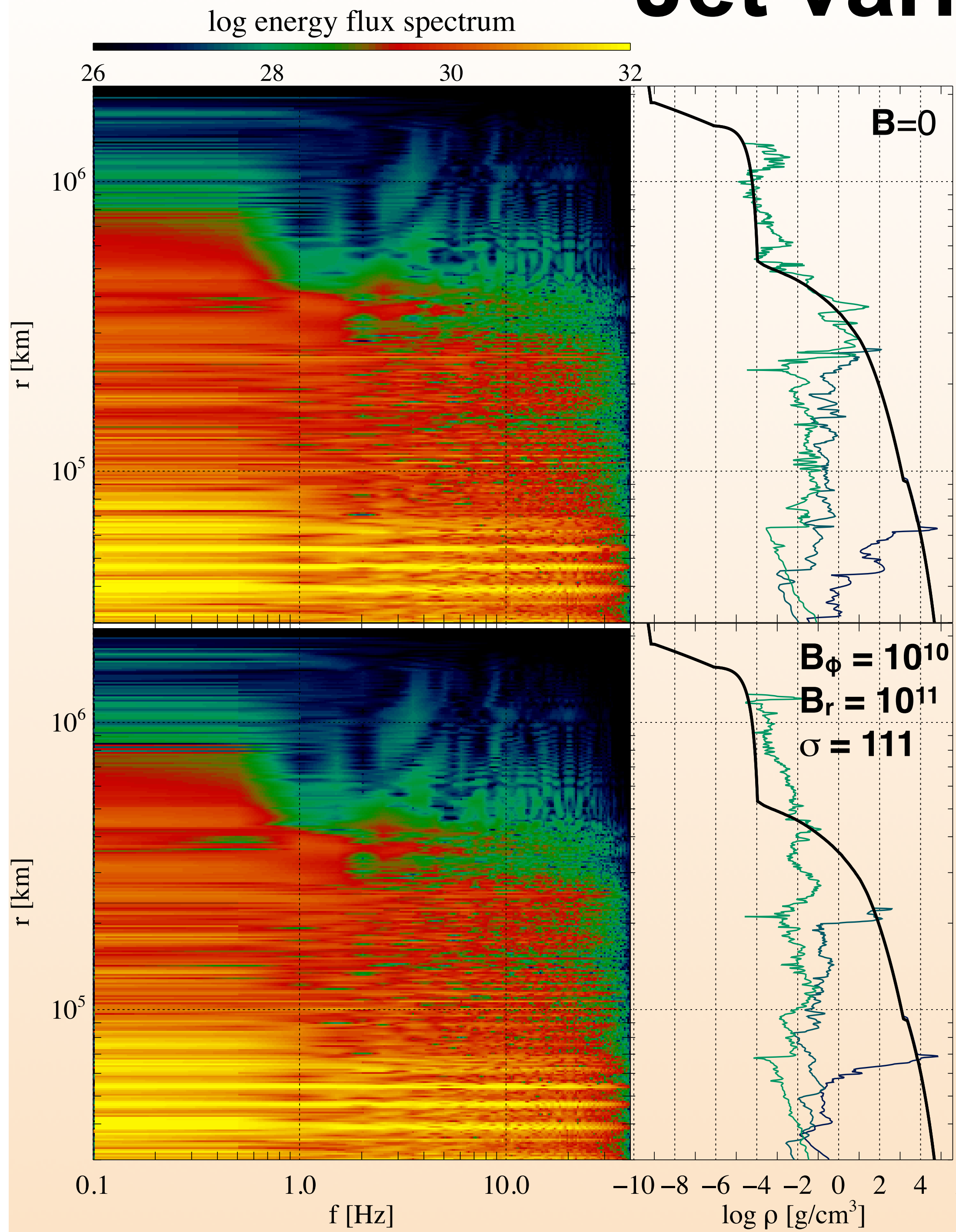
1. The power density spectrum (PDS) amplitude decreases with distance regardless of the magnetization.
    - The log-stretching of the r-grid is not enough to account for the decrease (tested at higher/lower resolution).

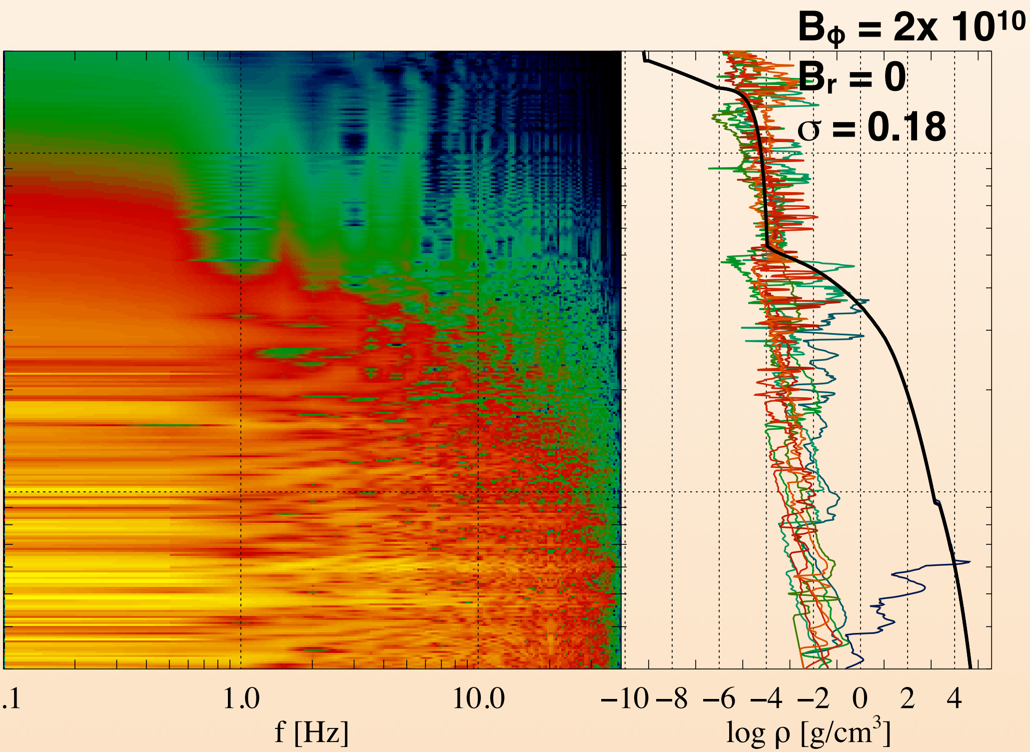
Jet variability



2. **In magnetized models the PDS decrease with distance is smaller.**
   - Models with toroidal field, show the smaller variability decrease with distance.
   - The most magnetized model with mixed poloidal +toroidal field is the one less affected by the stellar density gradient.
     - signature of self-collimation.
3. **Models with purely toroidal and strong fields show smaller power at high frequencies** (>5 Hz).

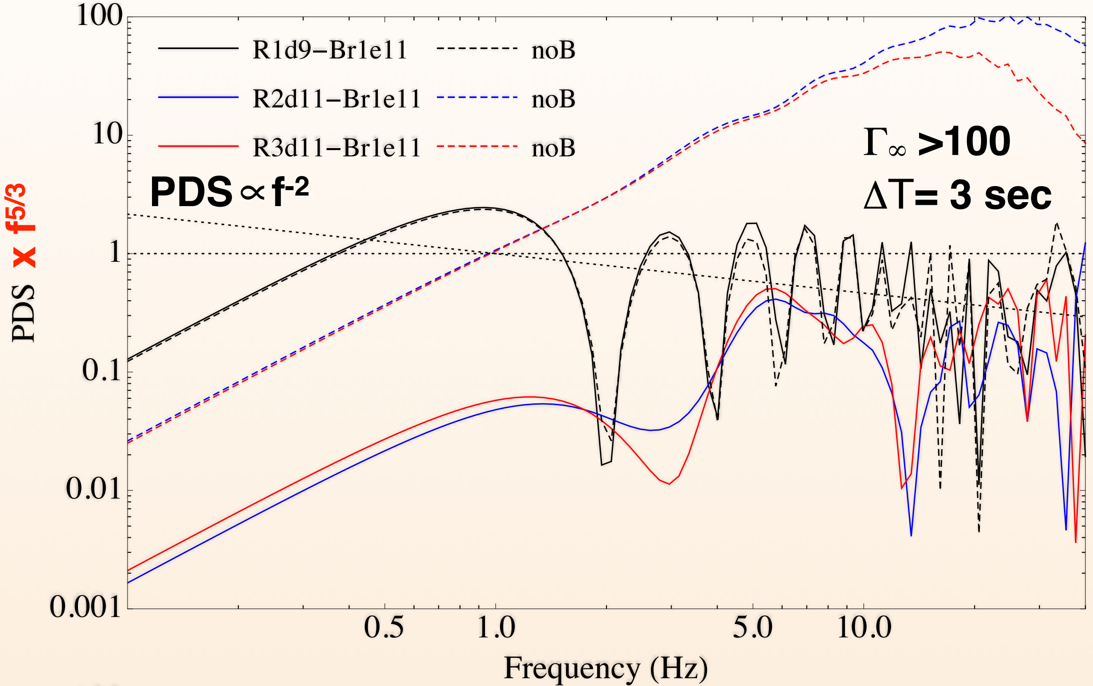
Jet variability

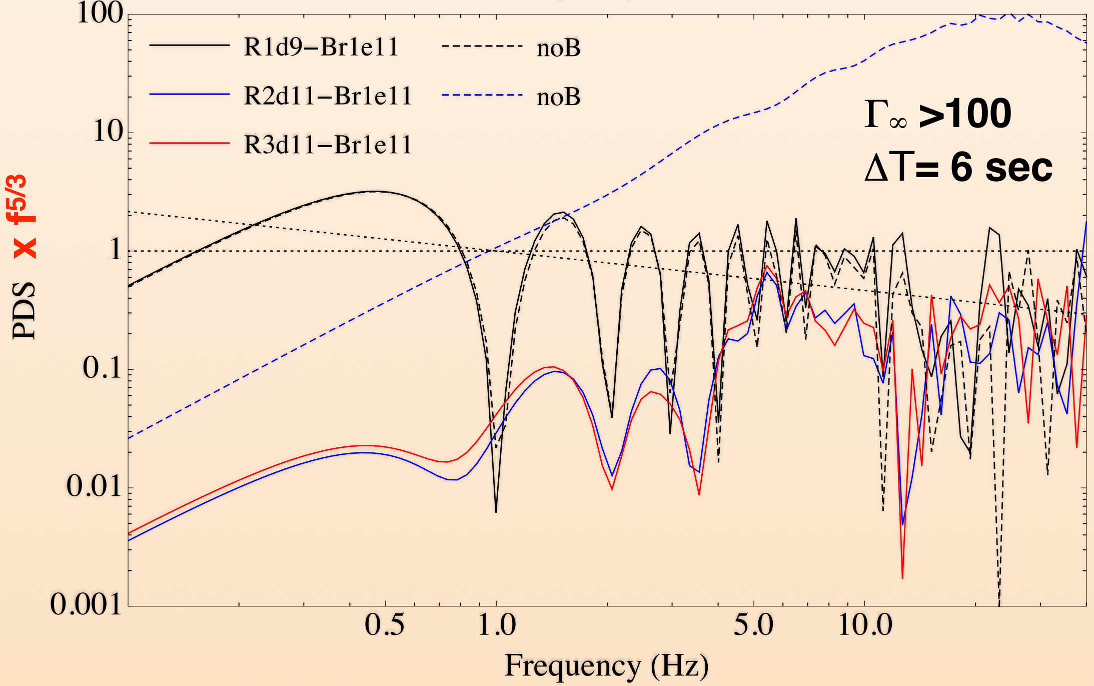




4. The PDS damping occurs chiefly close to the stellar surface, where the steepest density gradient is found.
5. *Provisional:* The acceleration post-break out might damp the high-frequency PDS.
   - Note: We consider in the spectrograms ALL matter regardless its Γ_∞.

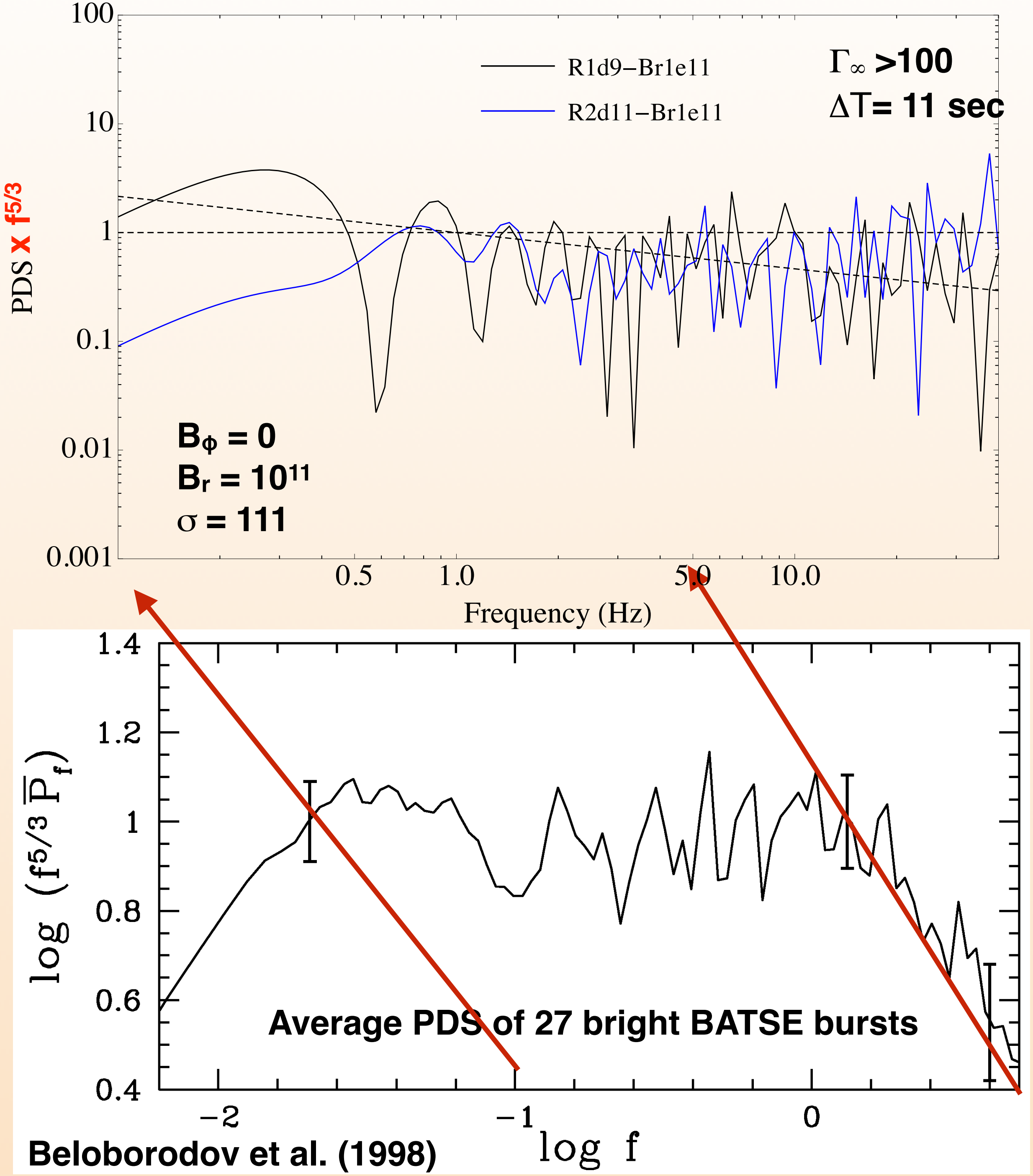
Jet variability





6. Restricting the analysis to matter with Γ_∞>100, magnetized models display smaller PDS at low frequencies than non-magnetized ones.
   - Need to redo analysis for finer time sampling (currently: Δt=0.025 s) to confirm the trend.
7. Including in the PDS longer sampling times (ΔT=6 s), obviously raises the low frequency strength, and a minor increase of the power at high frequencies.

Jet variability



Average PDS of 27 bright BATSE bursts

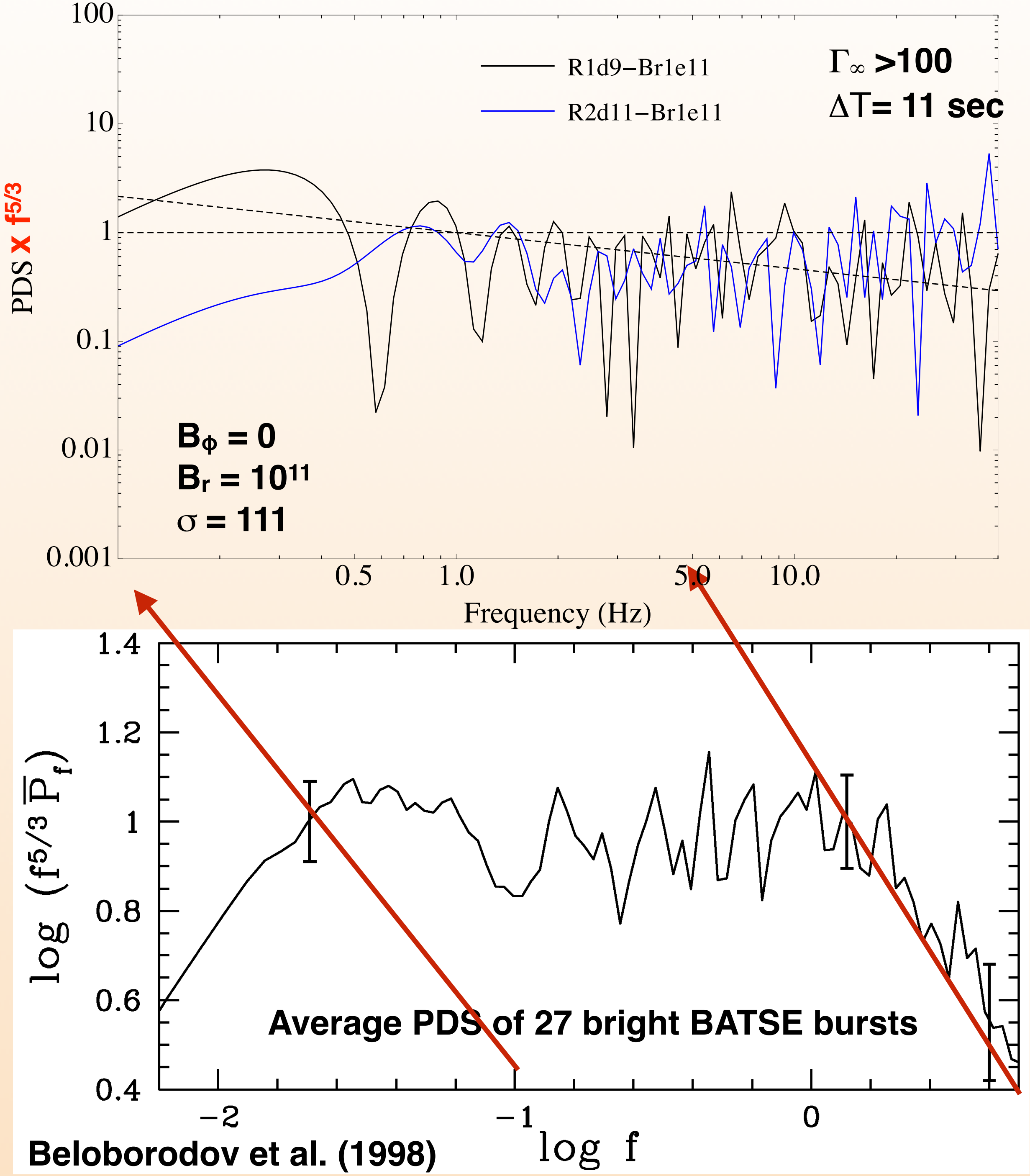
Beloborodov et al. (1998)

8. In the model with purely poloidal field, we have considered a longer sampling interval (ΔT=12 s). We observe that the PDS at 2×10^{11} cm tends to match the PDS close to the nozzle ($R=10^9$ cm).

9. *Provisional:* The PDS obtained after the jet breaks out of the surface of the star ($R_\ast=1.56\times10^{11}$ cm), does not match that of the sample of bright BATSE bursts (Beloborodov et al. 1998, 2000).

   - *We do not expect a one-to-one matching, because the GRB variability may result from a complicated interplay between the variability properties of the flow + emission model.*

Jet variability



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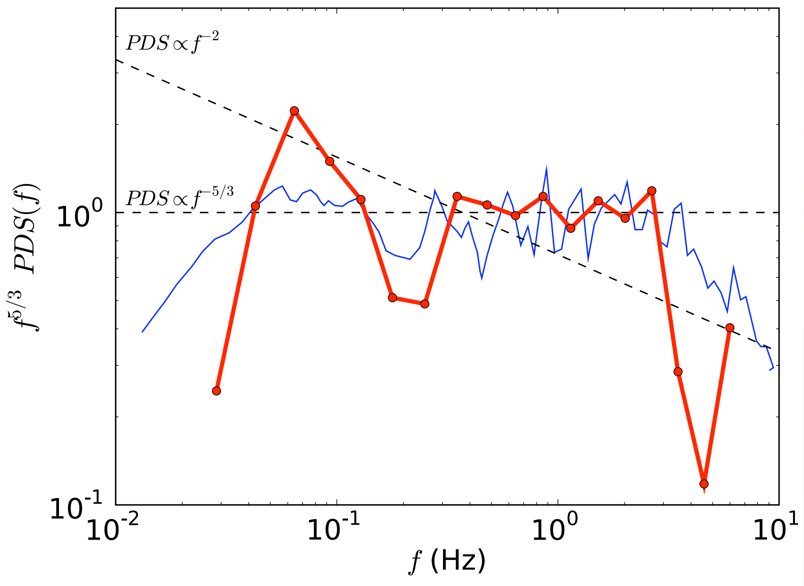

- *We do not expect a one-to-one matching, because the GRB variability may result from a complicated interplay between the variability properties of the flow + emission model.*
- *See, however, Morsony, Lazzati & Begelman (2010)*

Summary and conclusions

- We are exploring the properties of relativistic magnetized jets propagating in collapsars, and (obviously) found that the magnetic field strength and topology can be key to shape both the dynamics of relativistic outflows and its observational signature.

- The jet / star interaction produces a highly variable jet, and the variability PDS depends, in a non-trivial way, on the progenitor structure, as well as on the magnetic field.

- Regardless of the magnetization, there is a decrease of the PDS at high frequencies that we (tentatively) relate to the stellar density gradient.

    - The initial (<5 sec) jet variability may be used as a probe of the structure of the final edge of the star assuming that the LC of a GRB is produced by photospheric emission.

- Provisional: variability at low frequencies (<~ 5 Hz) can be used as proxy for magnetization.