Title: Relativistic turbulence and multi-messenger astrophysics

Date: Nov 08, 2018 01:00 PM

URL: http://pirsa.org/18110067

Abstract: <p>I will discuss recent developments in the theory of relativistic turbulence, from both pure physics and astronomical perspectives. Turbulence in relativistic fluids and plasmas has applicability in high energy density physics, in early-universe cosmology, and in high energy astrophysics. I will focus on its connections with multi-messenger astrophysics, particularly in the context of binary neutron star (BNS) mergers, and the electromagnetic signals that accompany their gravitational wave emission. My talk will include (1) an overview of methods used to simulate and characterize relativistic turbulence, (2) implications of dynamo theory to the dynamics of BNS mergers, (3) new ideas emerging in the theory of "radiation-mediated" relativistic turbulence, and (4) efforts in modeling the prompt and afterglow emission from GW-170817.</p>

Relativistic turbulence and multi-messenger astrophysics

Jonathan Zrake
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Perimeter Gravity Seminar
November 8, 2018

Frederico Fiuza
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Andrew MacFadyen
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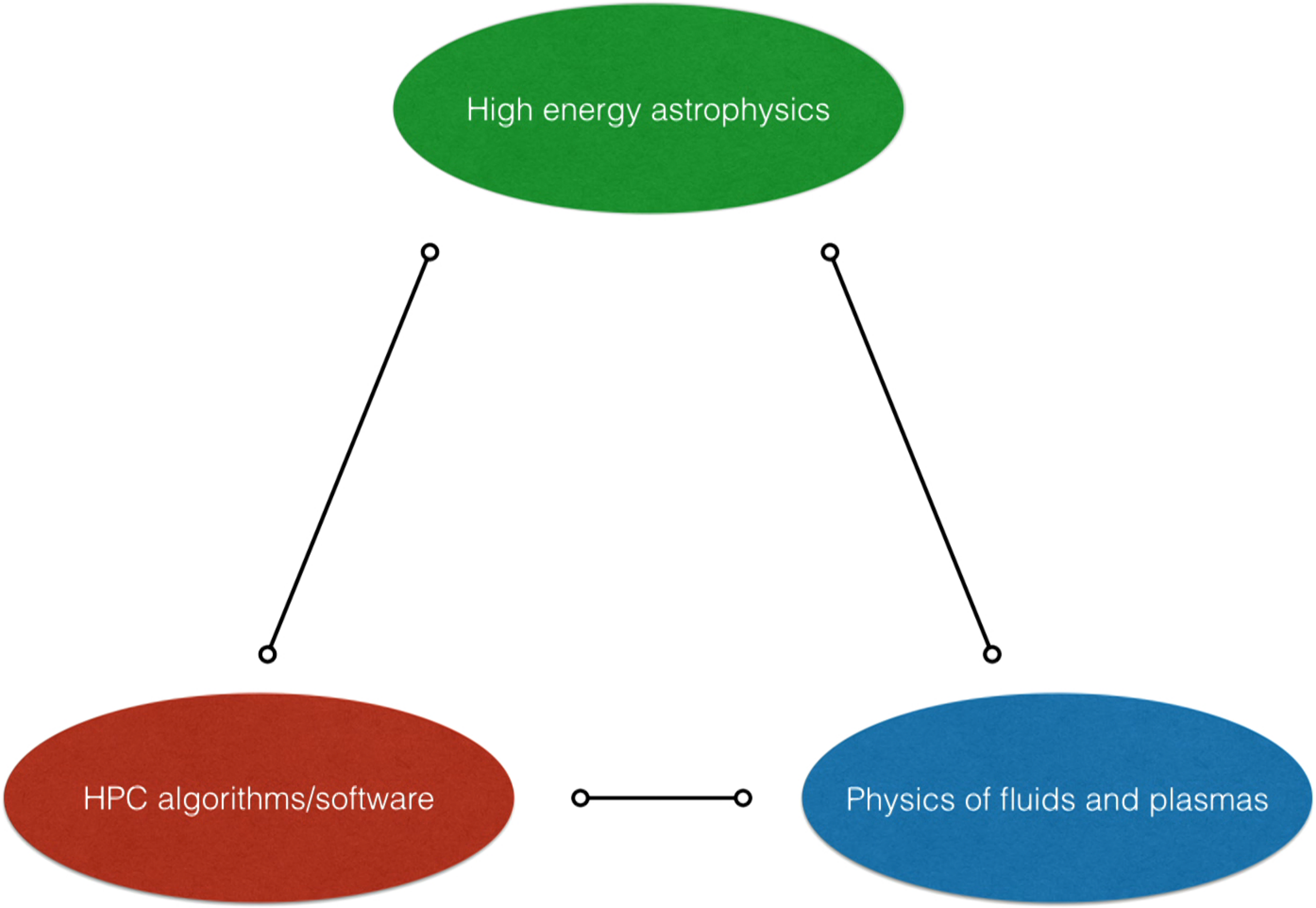

High energy astrophysics

HPC algorithms/software

Physics of fluids and plasmas

High energy astrophysics

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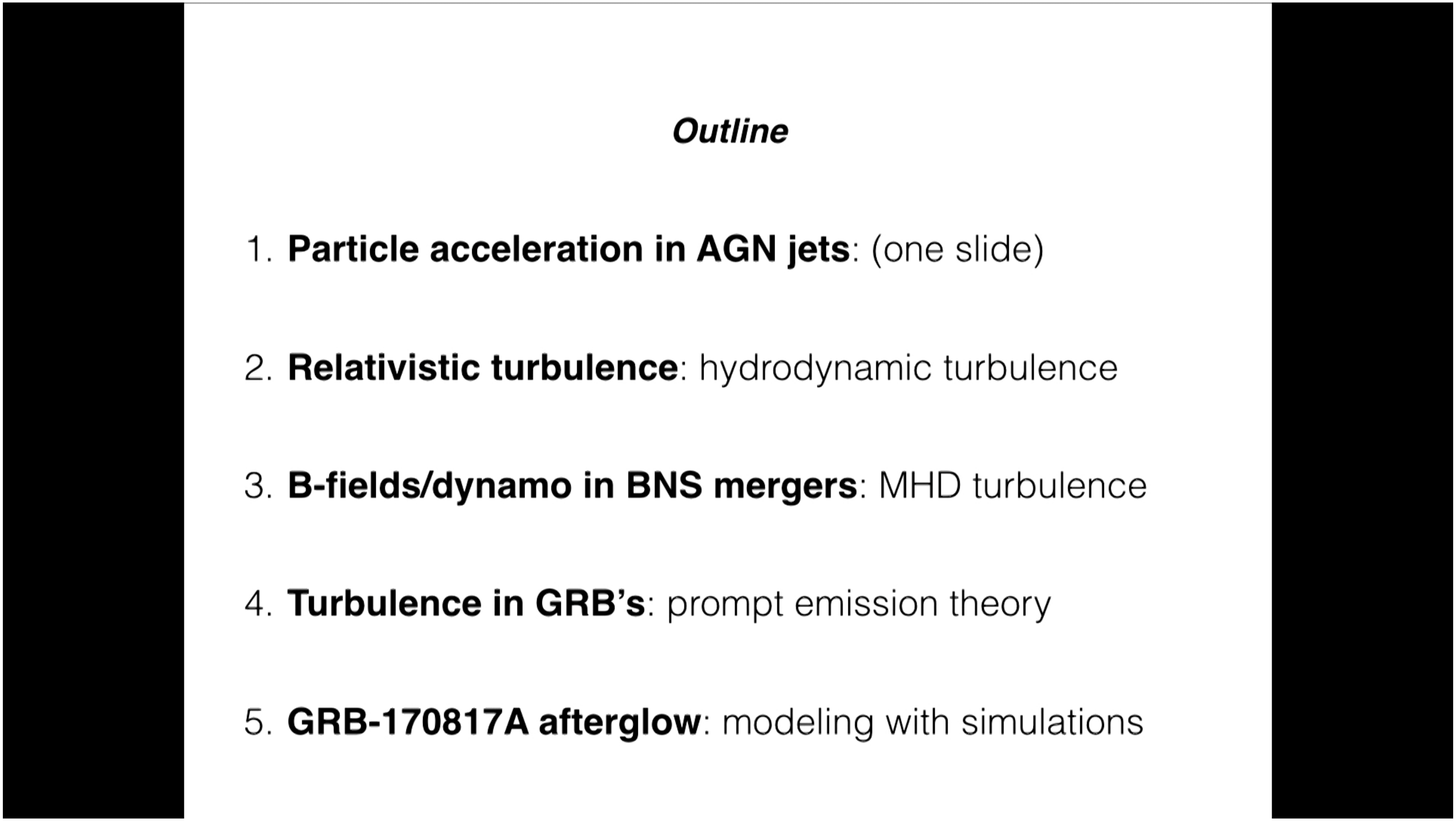


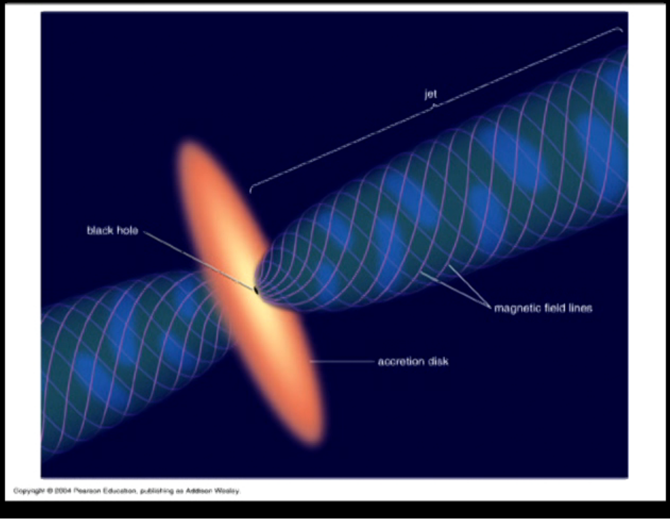
Outline

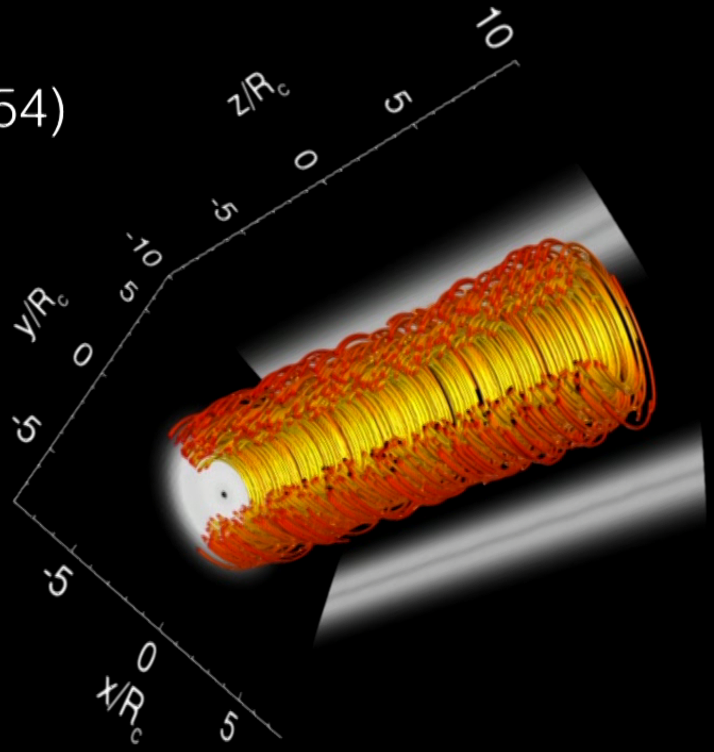
1. **Particle acceleration in AGN jets**: (one slide)
2. **Relativistic turbulence**: hydrodynamic turbulence
3. **B-fields/dynamo in BNS mergers**: MHD turbulence
4. **Turbulence in GRB’s**: prompt emission theory
5. **GRB-170817A afterglow**: modeling with simulations

Efficient nonthermal particle acceleration by the kink instability in AGN jets

Alves, Zrake, Fiuza

Accepted, PRL (arXiv:1810.05154)





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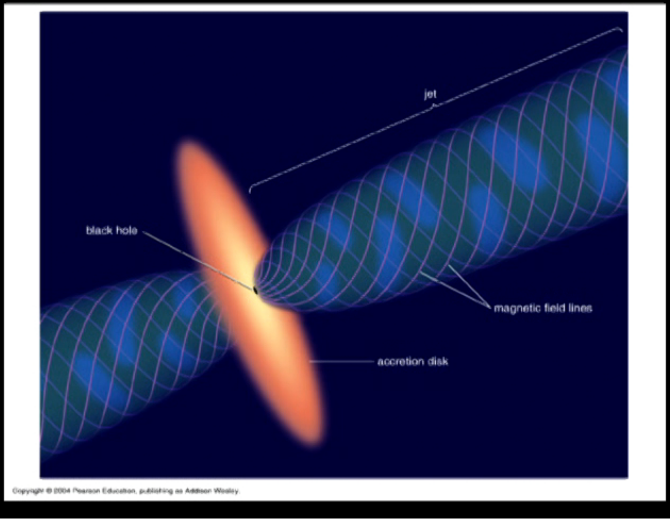
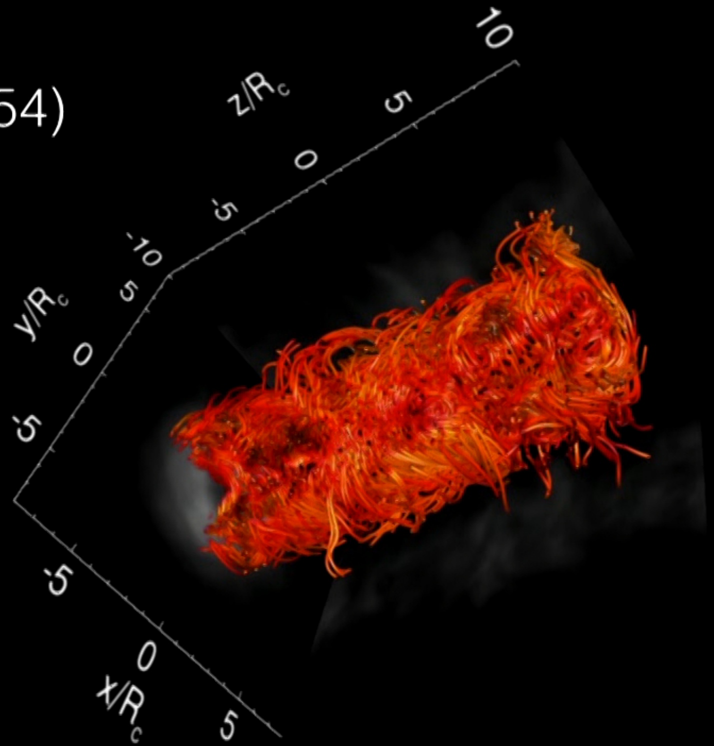




Part I:

Relativistic turbulence: a quick overview

- Turbulence is a building block of fluid dynamics, and an unsolved problem in classical physics
- Relativistic settings include HED, early universe, and high energy astrophysics
- Yet, relativistic turbulence largely unexplored

Some of the questions…

1. Does relativistic turbulence ***exist***?
2. Can it be characterized in terms of known theories (e.g. Kolmogorov)?

Regimes of relativistic turbulence

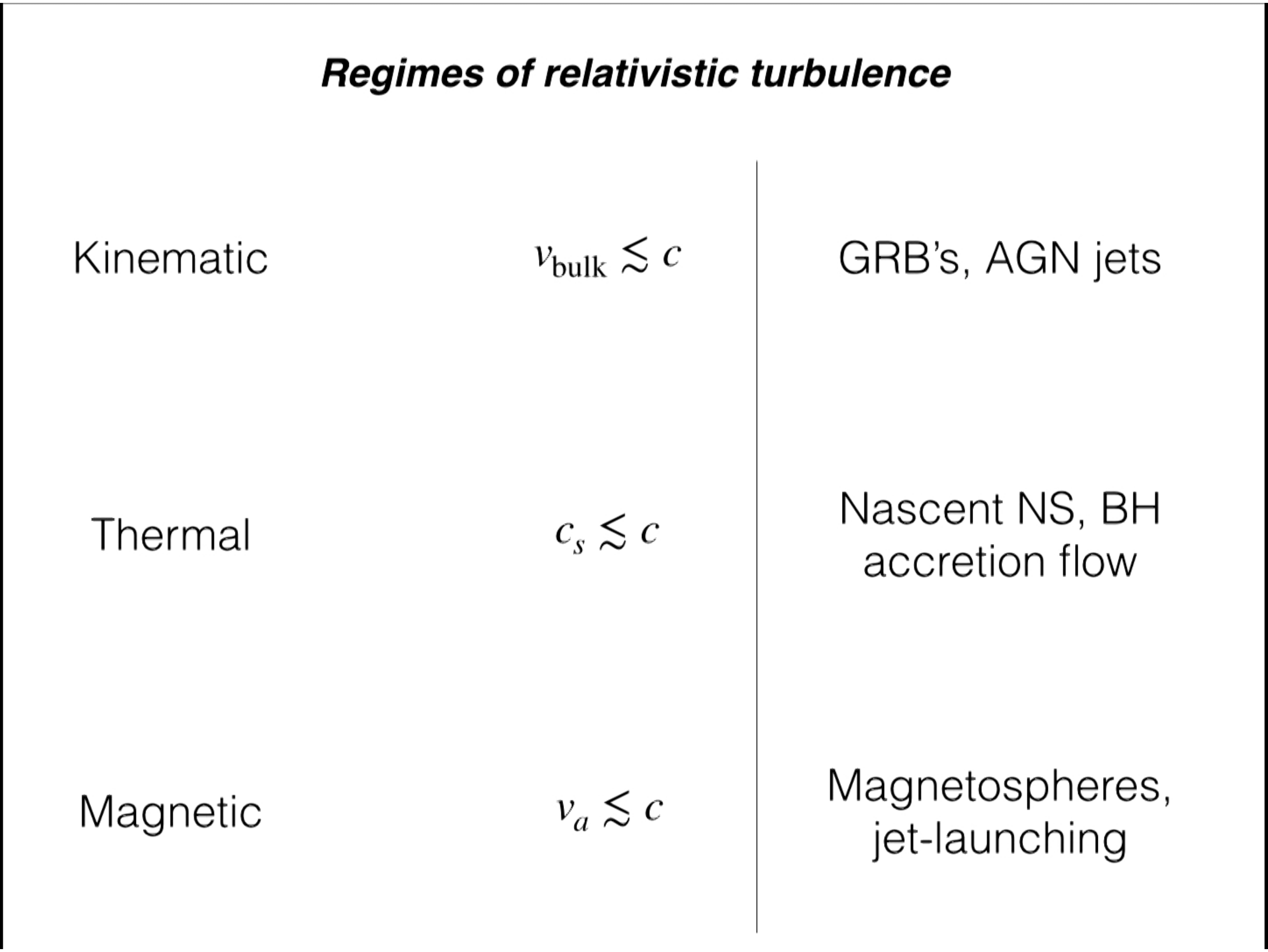
Regimes of relativistic turbulence

Kinematic $v_{\rm bulk} \lesssim c$

GRB's, AGN jets

Regimes of relativistic turbulence

Kinematic	$v_{\mathrm{bulk}} \lesssim c$	GRB's, AGN jets
Thermal	$c_s \lesssim c$	Nascent NS, BH accretion flow



Regimes of relativistic turbulence

Kinematic	$v_{\text{bulk}} \lesssim c$	GRB's, AGN jets
Thermal	$c_s \lesssim c$	Nascent NS, BH accretion flow
Magnetic	$v_a \lesssim c$	Magnetospheres, jet-launching

Formalisms

Hydrodynamic

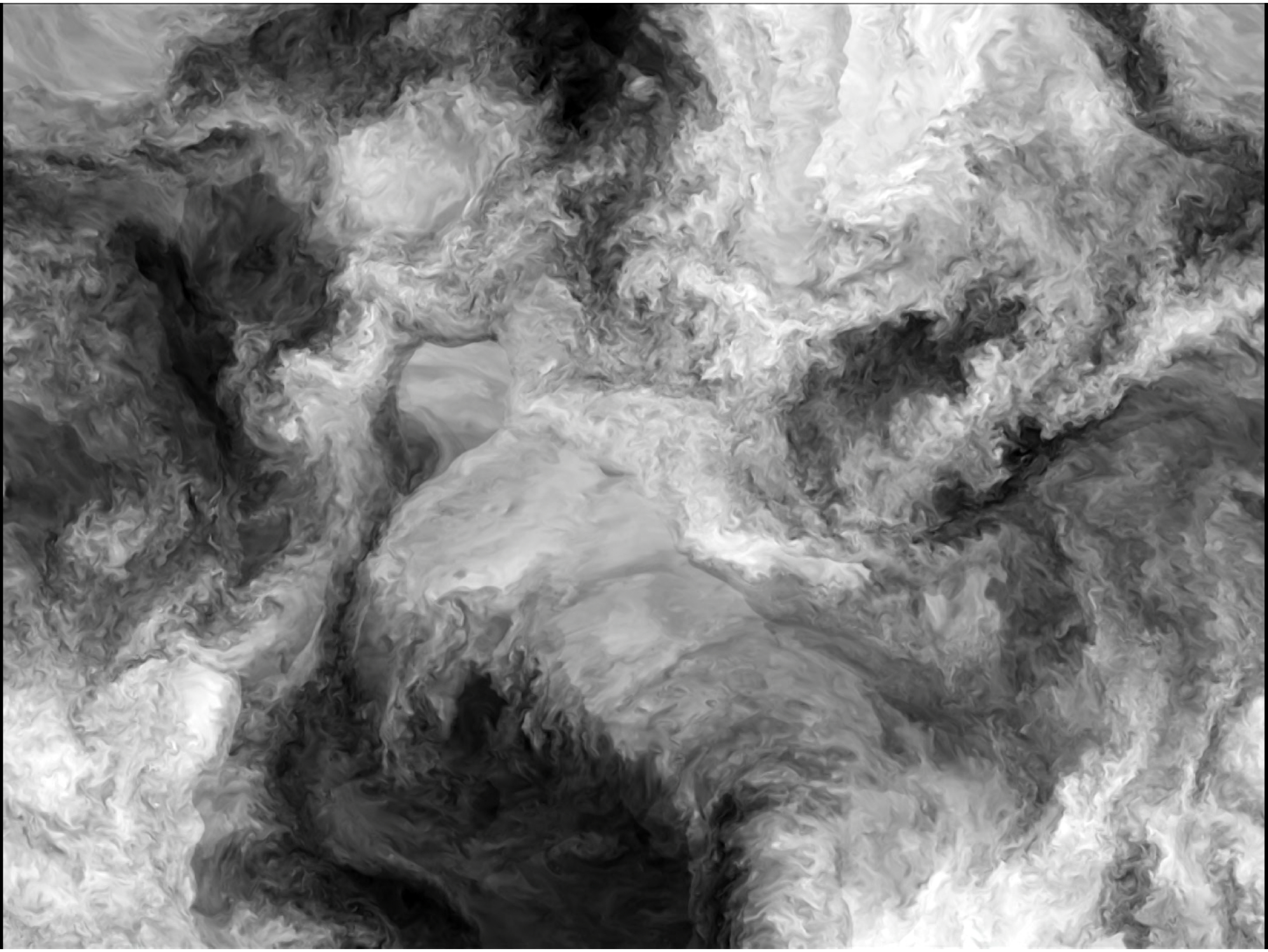
JZ, MacFadyen, Radice, Rezzolla, Lehner

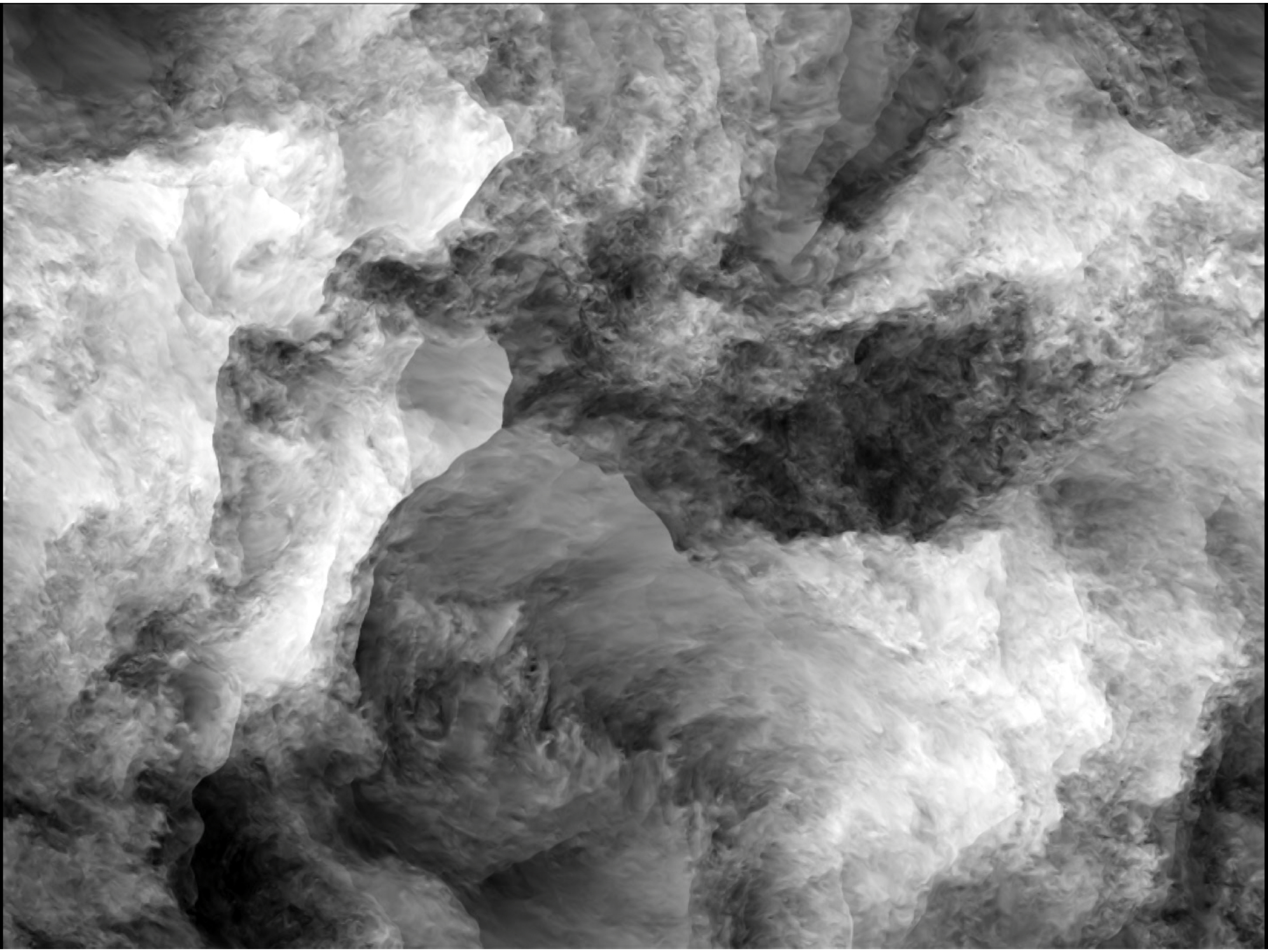
Formalisms

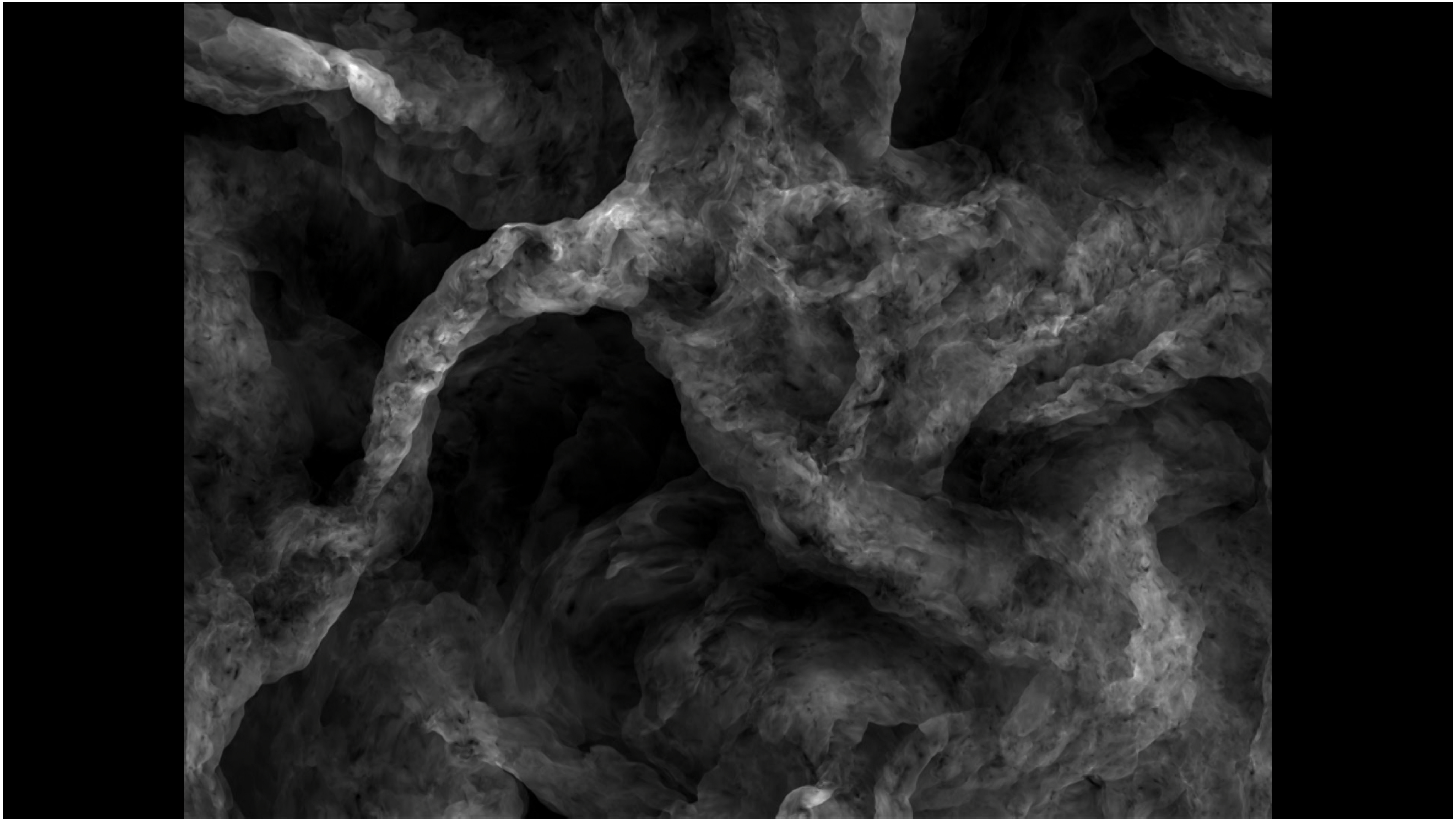
Hydrodynamic	JZ, MacFadyen, Radice, Rezzolla, Lehner
Magnetohydrodynamic	Cho, JZ, MacFadyen, East, Lazarian

Formalisms

Hydrodynamic	JZ, MacFadyen, Radice, Rezzolla, Lehner
Magnetohydrodynamic	Cho, JZ, MacFadyen, East, Lazarian
Fully kinetic	Yuan, Nalewajko, JZ, East, Blandford Zhdanken, Werner, Uzdensky, Begelman Comisso, Sironi

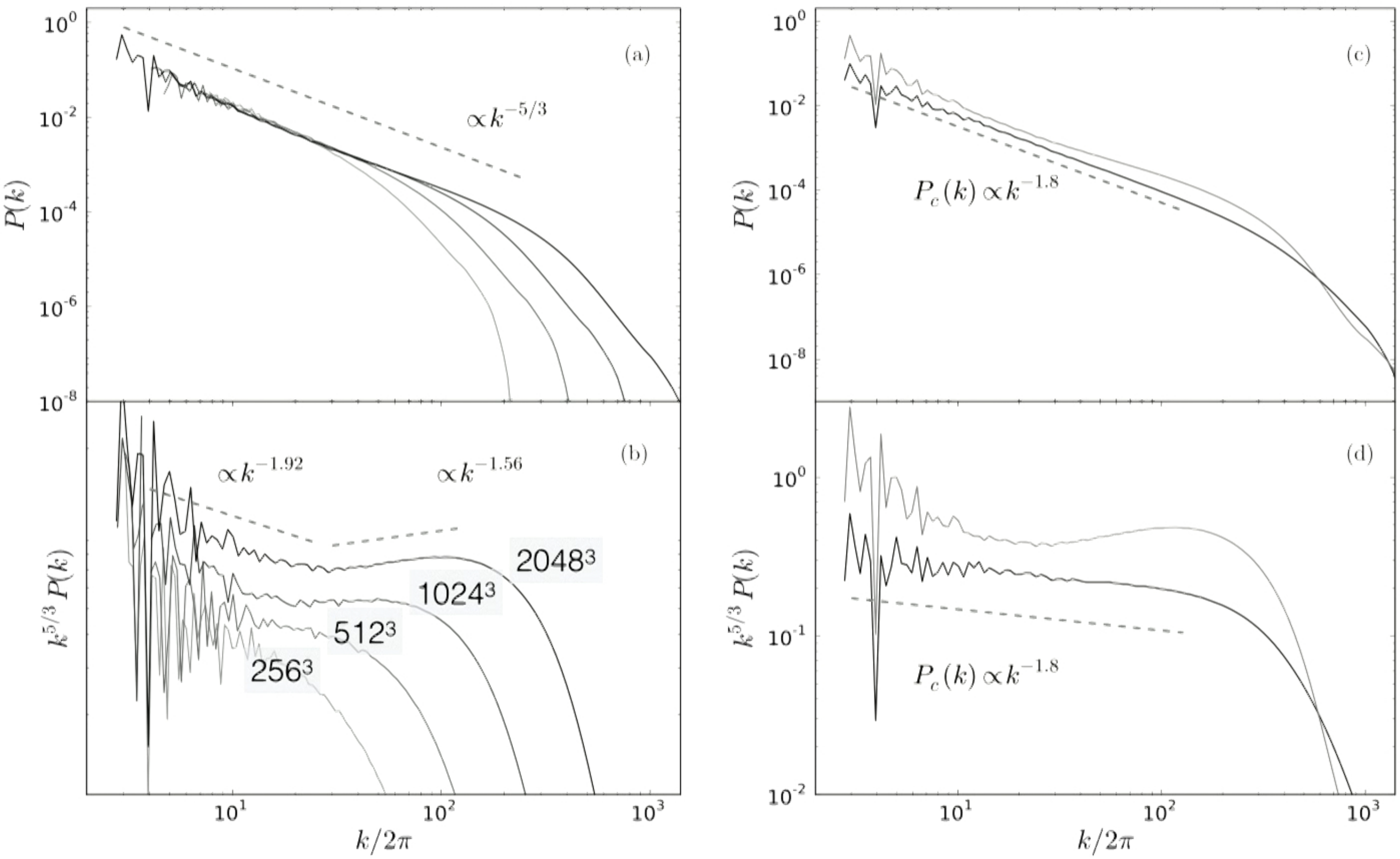






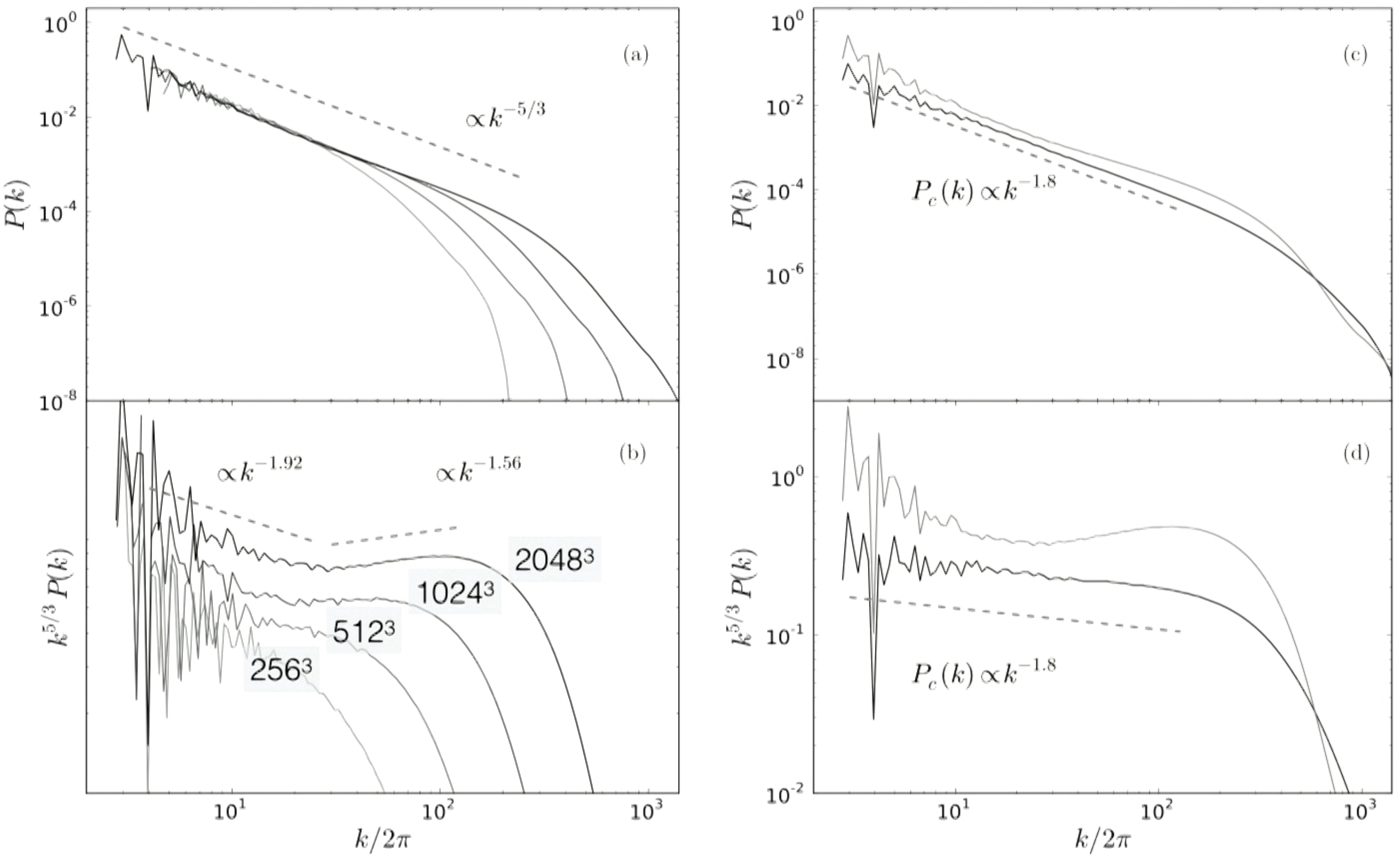
$$P(k)dk = \sum_{\mathbf{k}\in dk} \tilde{\mathbf{u}}_{\mathbf{k}} \cdot \tilde{\mathbf{u}}^{*}_{\mathbf{k}}$$

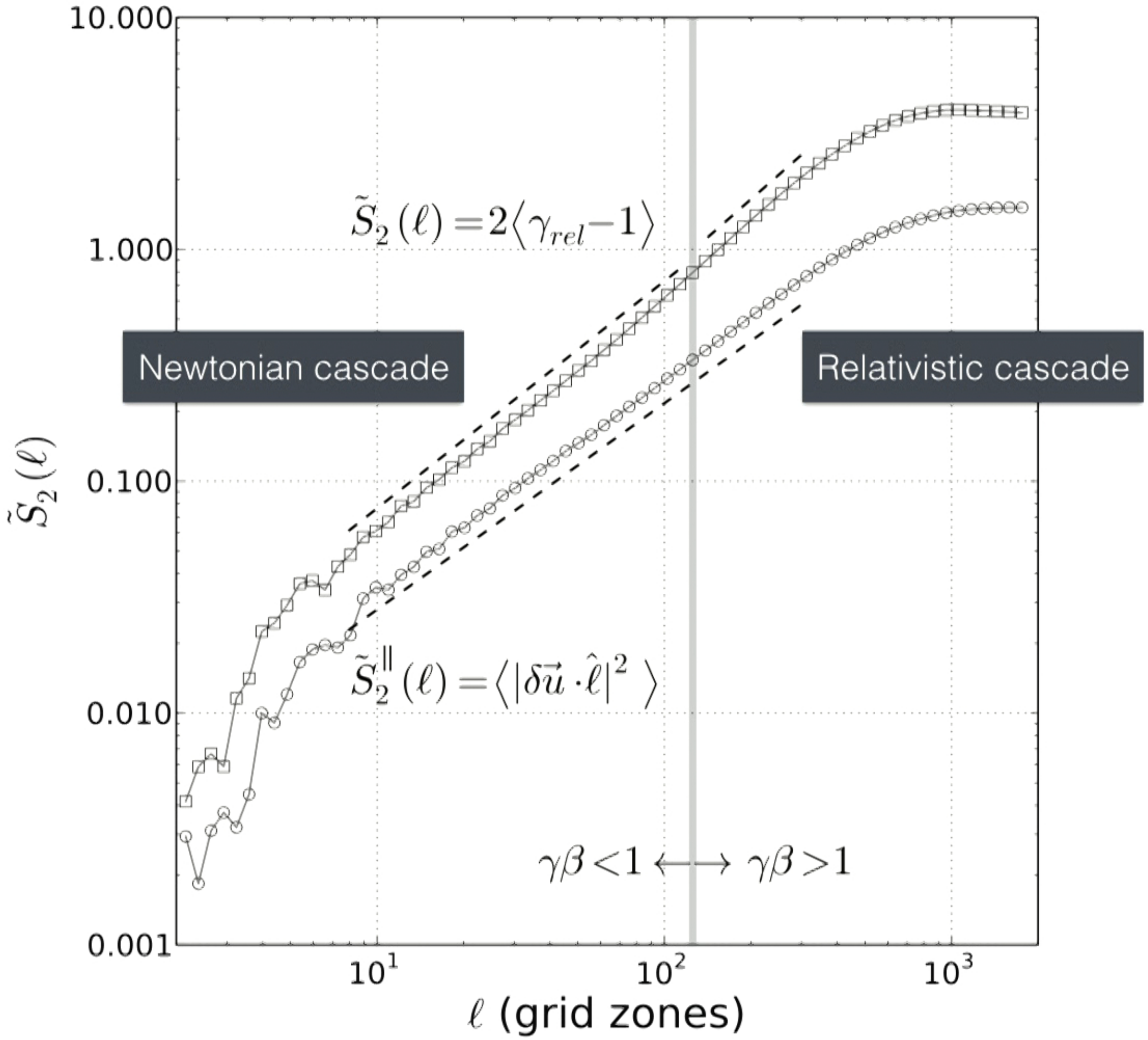
Acoustic/shear modes



$$P(k)dk = \sum_{\mathbf{k}\in dk} \tilde{\mathbf{u}}_{\mathbf{k}} \cdot \tilde{\mathbf{u}}_{\mathbf{k}}^*$$

Acoustic/shear modes





Newtonian cascade

Relativistic cascade

Structure functions

$$S_p(\ell) \equiv \langle\, | \mathbf{v}_2 - \mathbf{v}_1 |^p \,\rangle$$

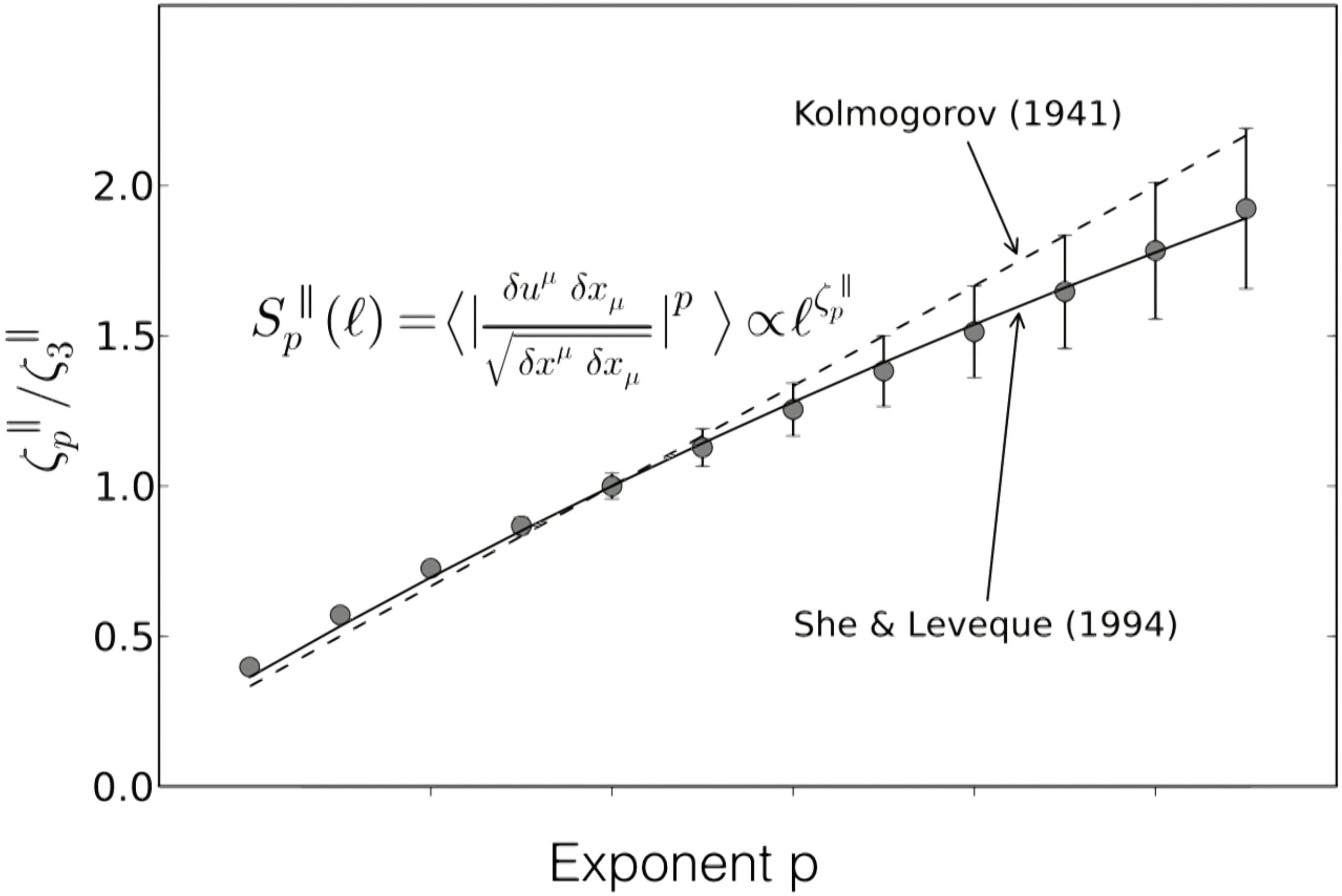
Conventional

$$\tilde{S}_p(\ell) \equiv \langle\, | (u_2 - u_1)^\mu (u_2 - u_1)_\mu |^{p/2} \,\rangle$$

Covariant generalization

Note: $\tilde{S}_2(\ell) = 2\langle \gamma_{\text{rel}} - 1 \rangle$, and we also generalize $S_p^{||}(\ell)$

Non-Gaussianity (intermittency)



$$S_p^{\parallel}(\ell) = \langle \left| \frac{\delta u^{\mu} \; \delta x_{\mu}}{\sqrt{\delta x^{\mu} \; \delta x_{\mu}}} \right|^{p} \rangle \propto \ell^{\zeta_p^{\parallel}}$$

Part II:

MHD turbulent dynamo in BNS mergers

Magnetic fields and BNS mergers

- B-fields may influence all stages of BNS merger

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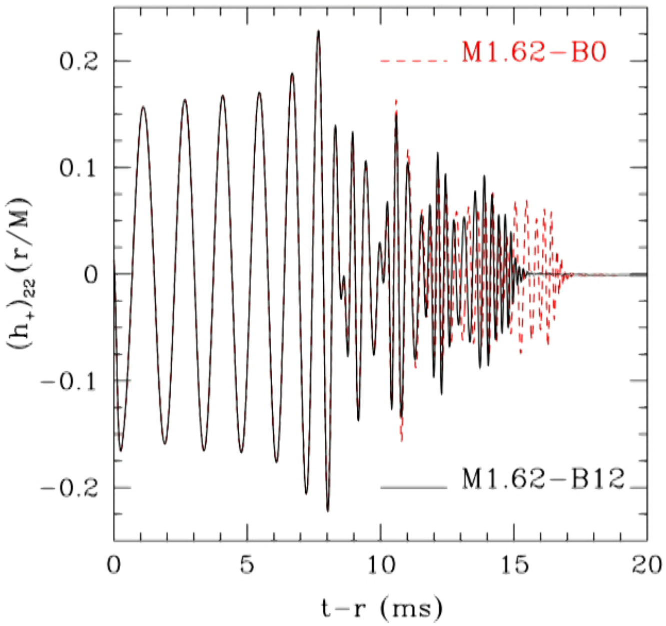
- Involved in non-thermal EM counterparts

Magnetic fields and BNS mergers

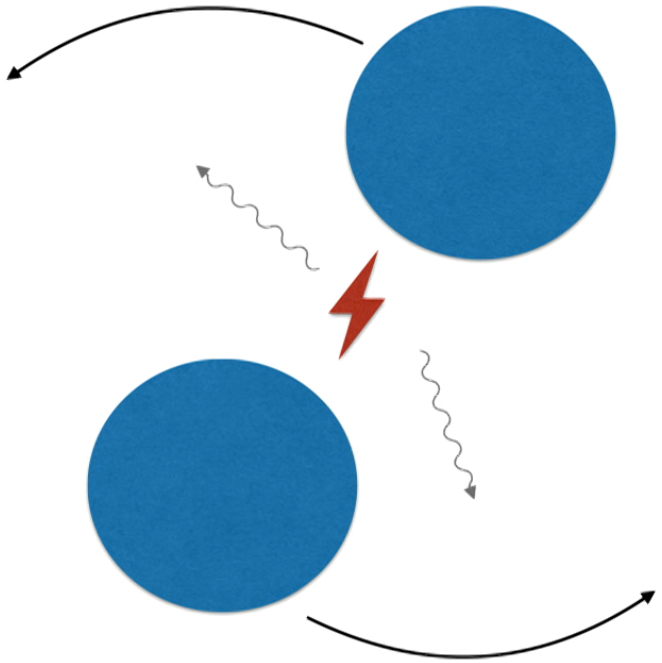
- B-fields may influence all stages of BNS merger
- Involved in non-thermal EM counterparts
- Must understand BNS merger dynamo!

Extreme pre-existing B in component stars may influence GW signature of inspiral and chirp



Giacomazzo (2011) — see also Etienne (2012)

Magnetospheric interactions?

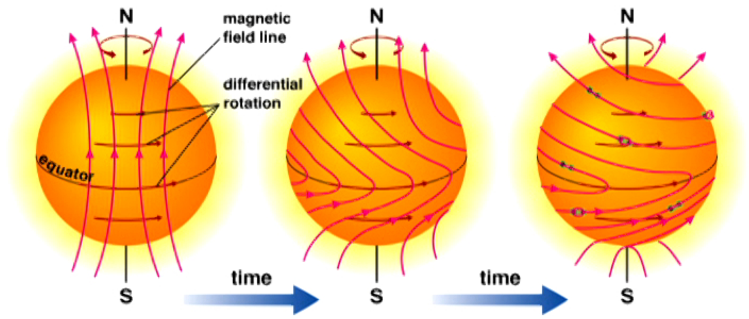


- Lyutikov
- Piro
- Levin (BH-NS)
- Philippov

- May accelerate collapse of HMNS to BH

- B-field redistributes angular momentum via Maxwell stress

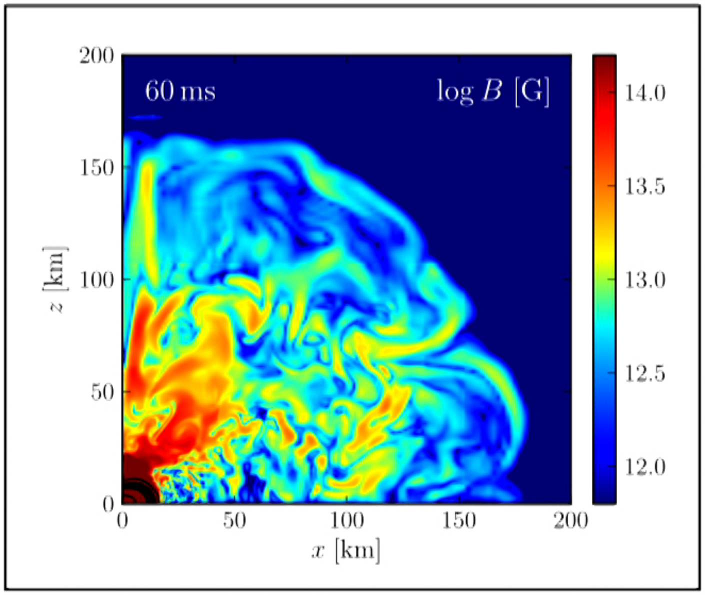
- Tends to drive the star toward rigid rotation



Shibata+ (2005), Duez+ (2006), Stephens+ (2007), Giacomazzo (2011), Kawamura (2016)

1. Winds driven by magnetic pressure

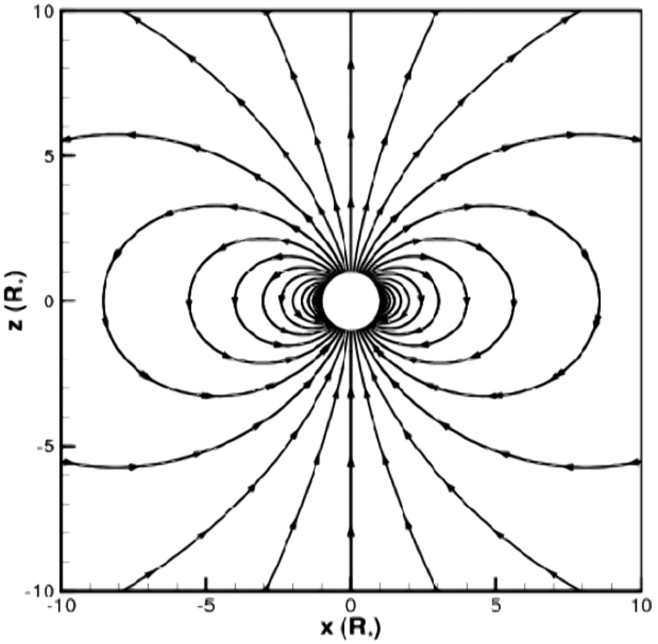
$$L_{\rm EM} \simeq 10^{48}\, \bar{B}_{15}^2\, R_{\rm e,6}^3\, P_{-4}^{-1}\, {\rm erg\, s^{-1}}$$



Siegel & Ciolfi (2015)

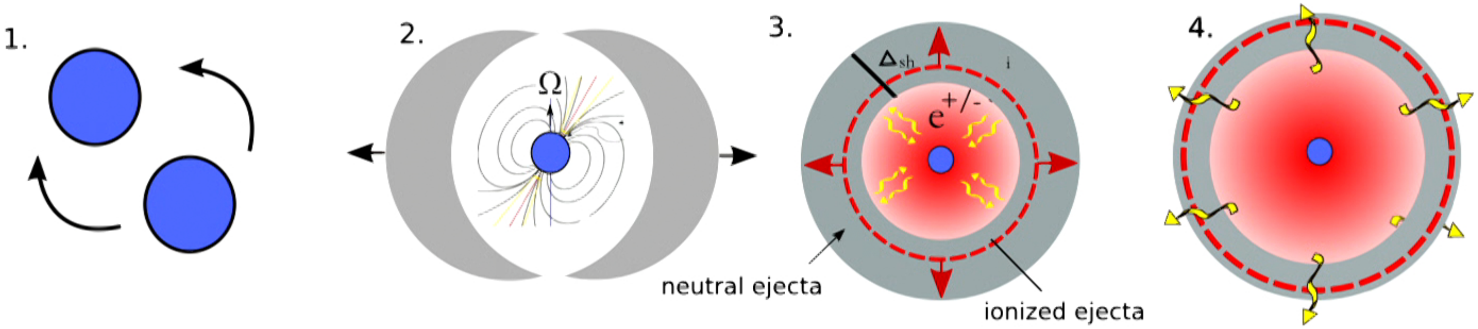
2. Spin-down by electromagnetic torque

$$L_{\rm sd} = \frac{\mu^2 \Omega^4}{c^3} \simeq 6 \times 10^{49} B_{15}^2 P_{-3}^{-4} \left(1 + \frac{t}{t_{\rm sd}}\right)^{-2} {\rm erg\, s^{-1}}$$



EM wind from stable remnant may:

1. Thermalize in merger ejecta, brightening optical emission
2. Ionize the ejecta, emerging as non-thermal X-rays



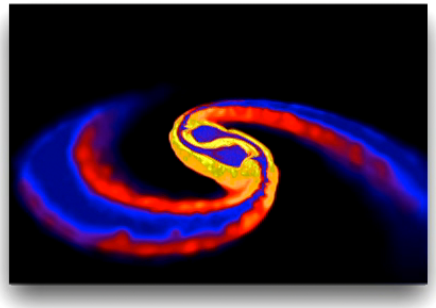
Metzger & Piro (2014)

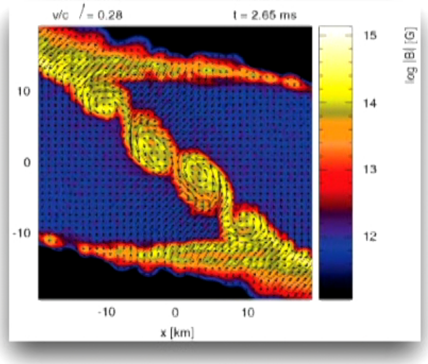
B-fields may be amplified by turbulence during the merger

- Small-scale turbulent dynamo (turbulence)

- Mean-field dynamo (turbulence + differential rotation)

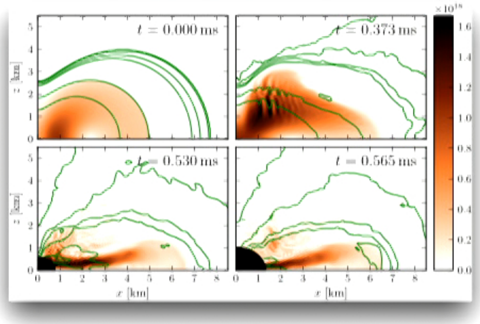
Kelvin-Helmholtz instability





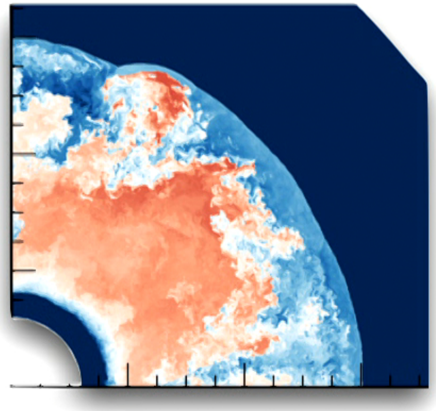
Price & Rosswog (2006)

Siegel+ (2013)



Magneto-rotational instability

Neutrino-driven convection?



Radice+ (2015), CC SN

Turbulent dynamo

- **Small-scale turbulent dynamo**: magnetic field gains energy in a fully developed turbulent medium
- Repeated twisting and folding of magnetic field
- Equipartition-level magnetic fields are magnetar-level, if turbulence is mildly relativistic—

$$B_{\rm RMS} \gtrsim 10^{16}\,{\rm G}\left(\frac{\rho}{10^{13}\,{\rm g\,cm^{-3}}}\right)^{1/2}\left(\frac{v_{\rm eddy}}{0.1c}\right)$$

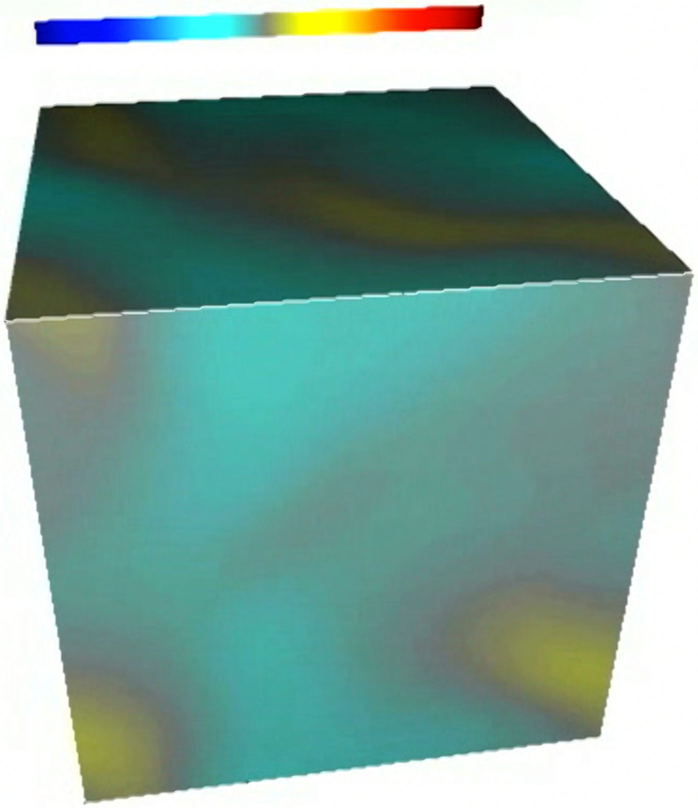
Assuming that mildly relativistic turbulence exists in the BNS merger:

(1) Does B really attain equipartition with turbulence?

(2) If so, how long until equipartition is attained?

Local simulation (Mara)

Zrake & MacFadyen (2013)



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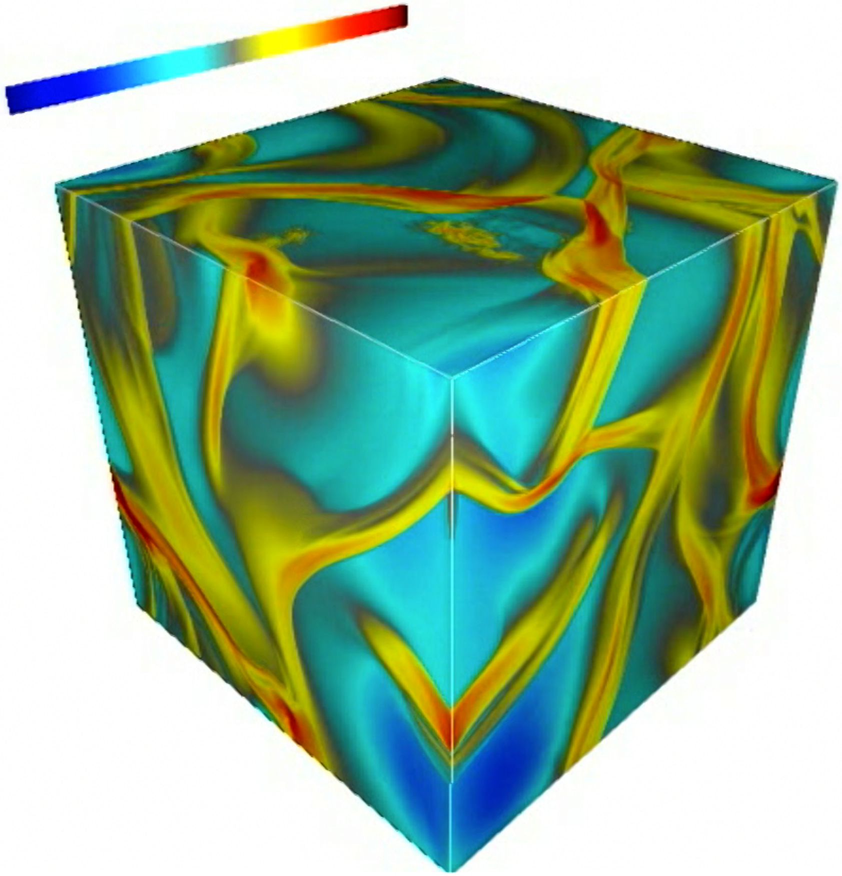

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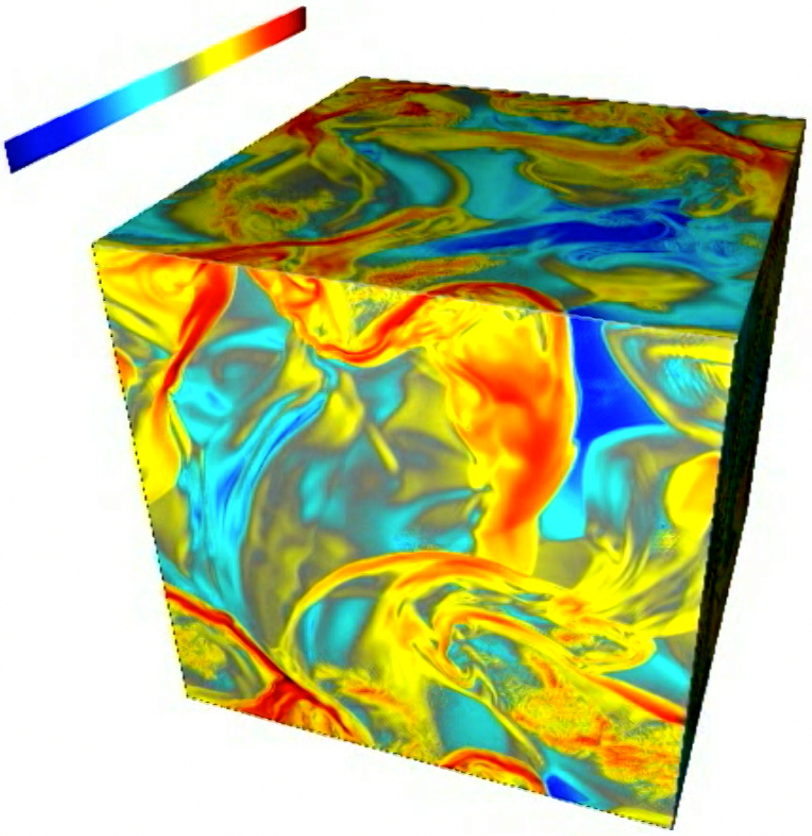

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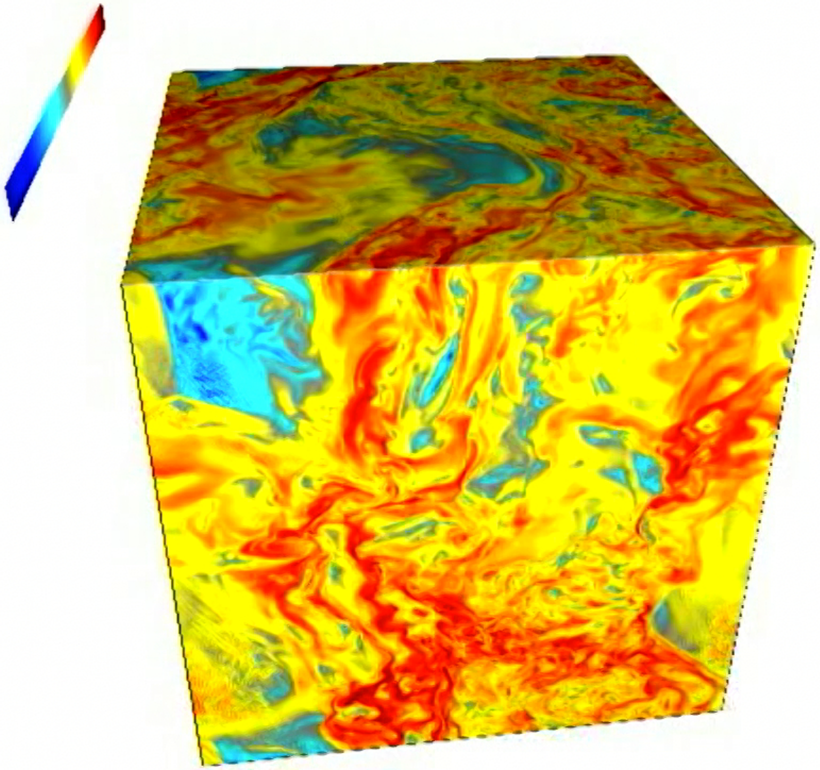

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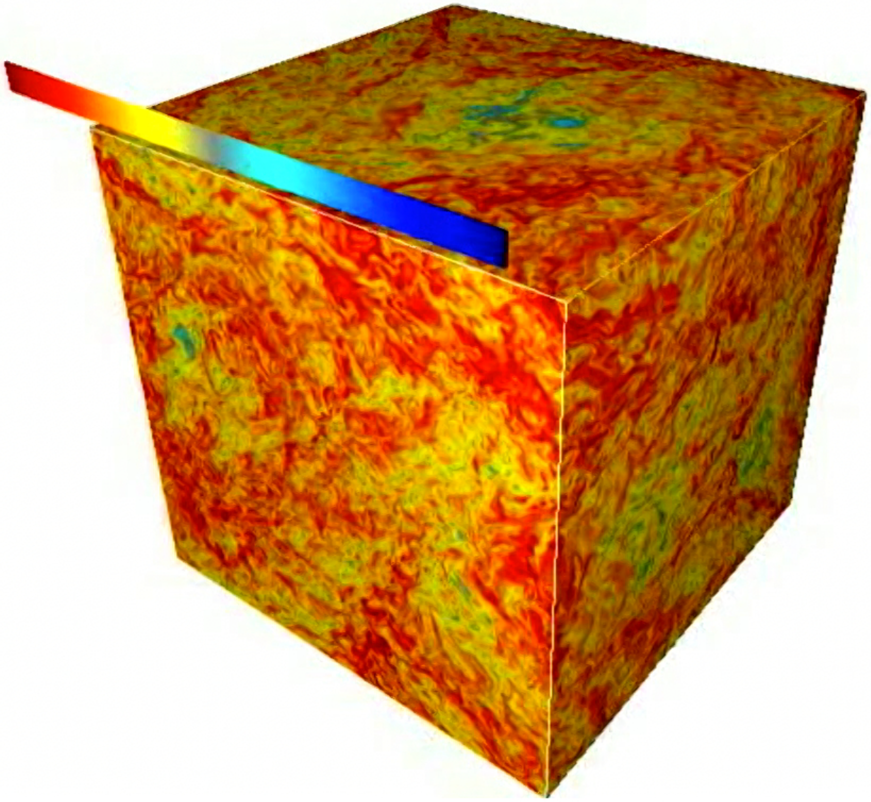

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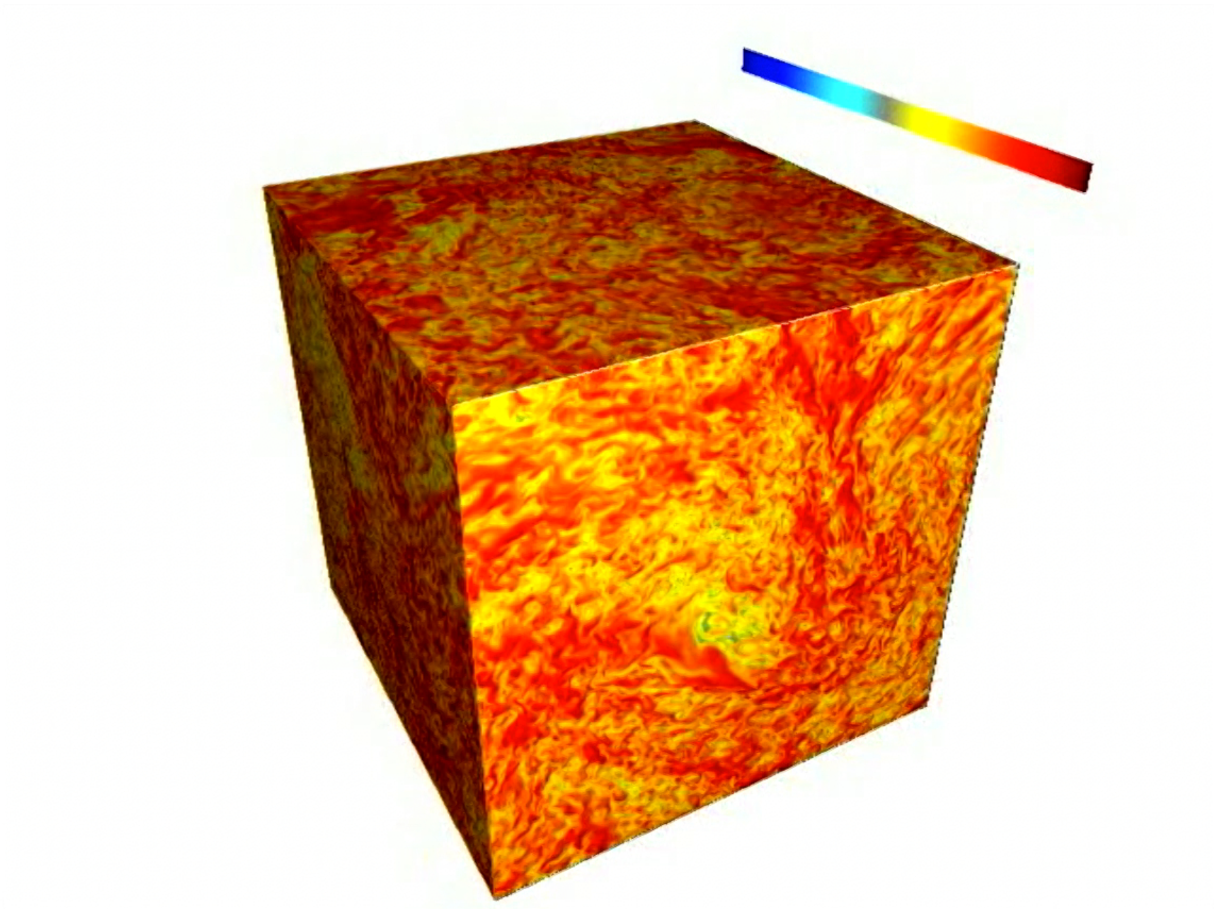

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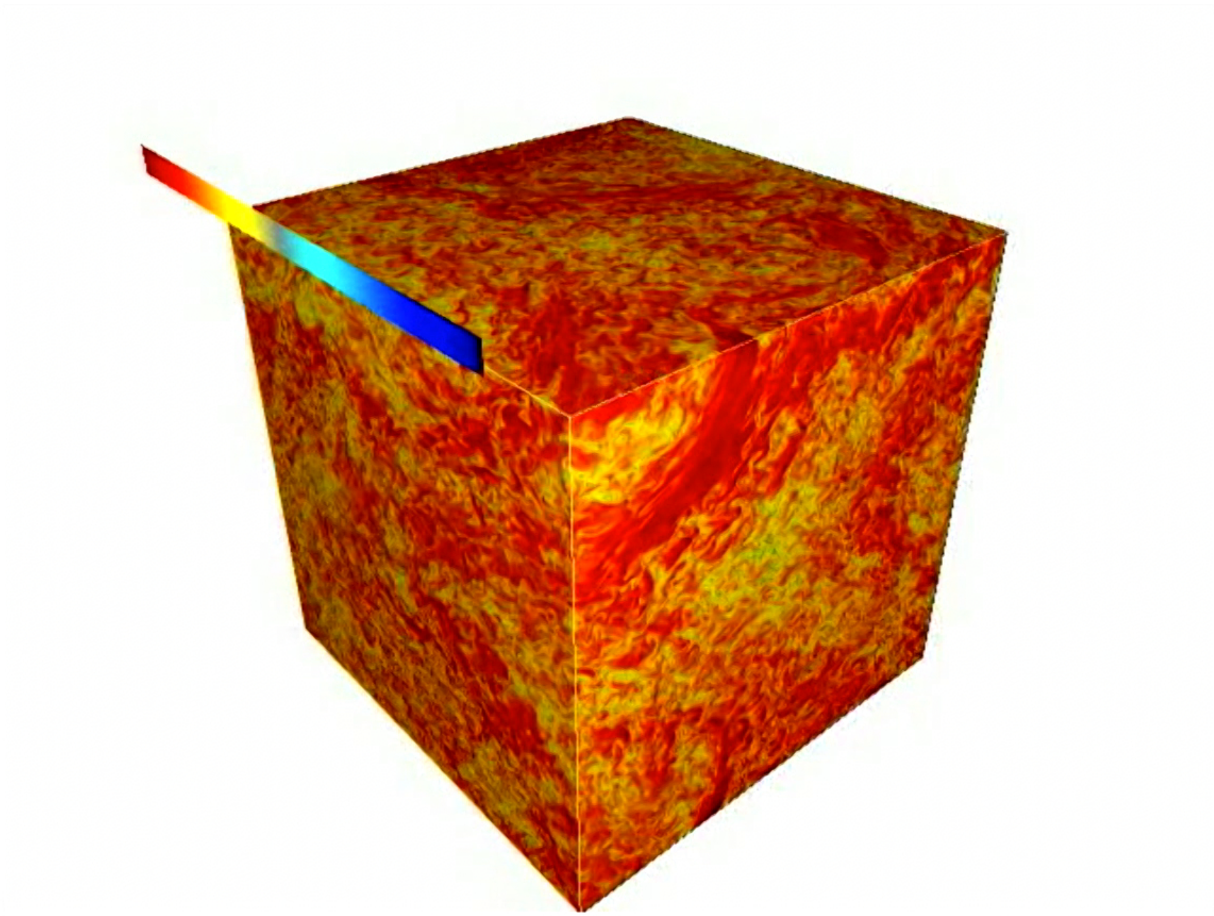
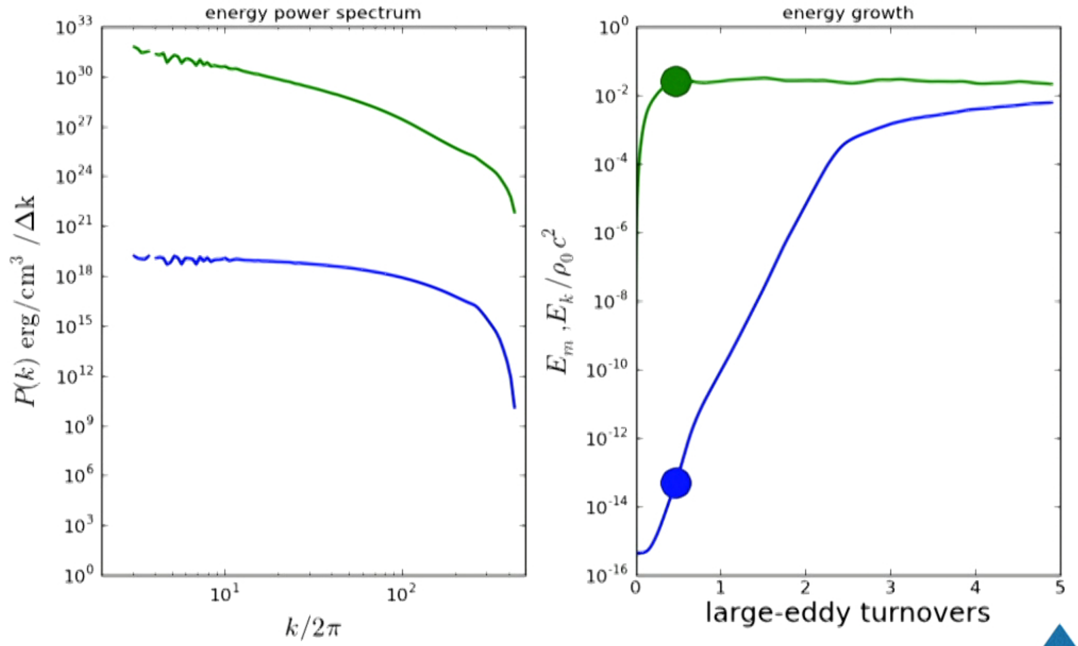


Scale-by-scale equipartition is attained after several dynamical times.



~10^{16} G

~0.5 ms

This indicates magnetic domains on the eddy scale.

Zrake & MacFadyen (2013)

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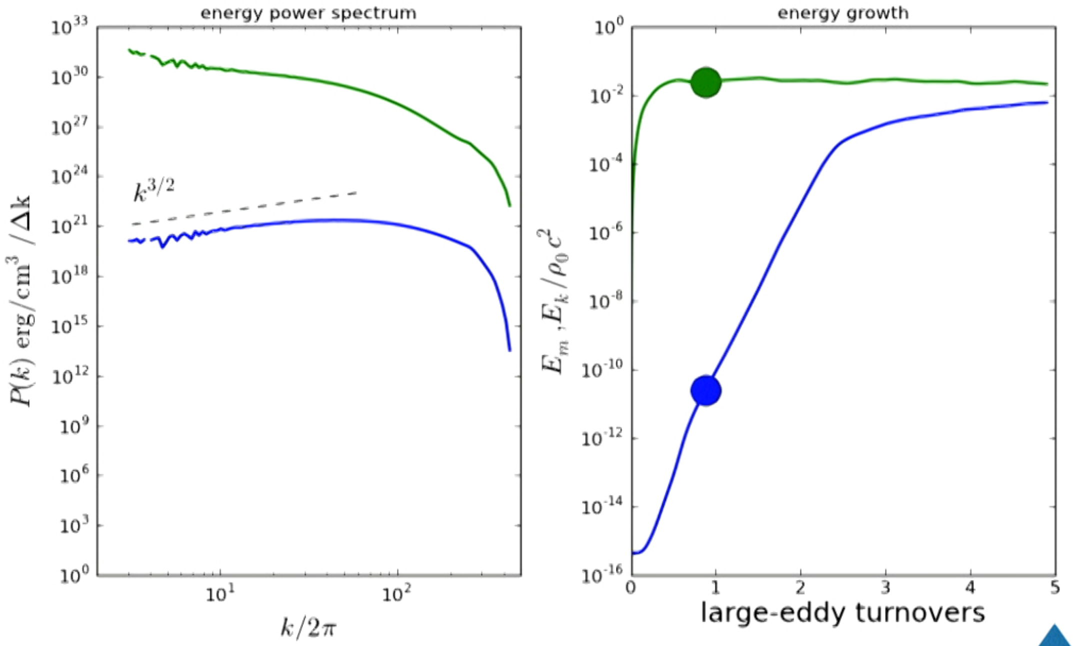

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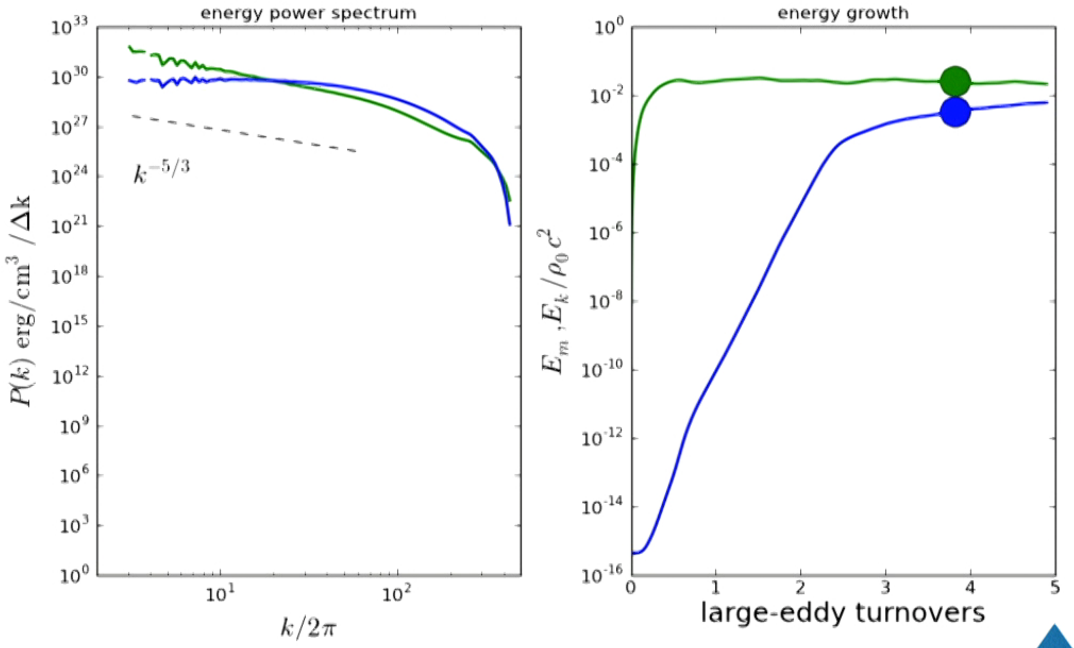

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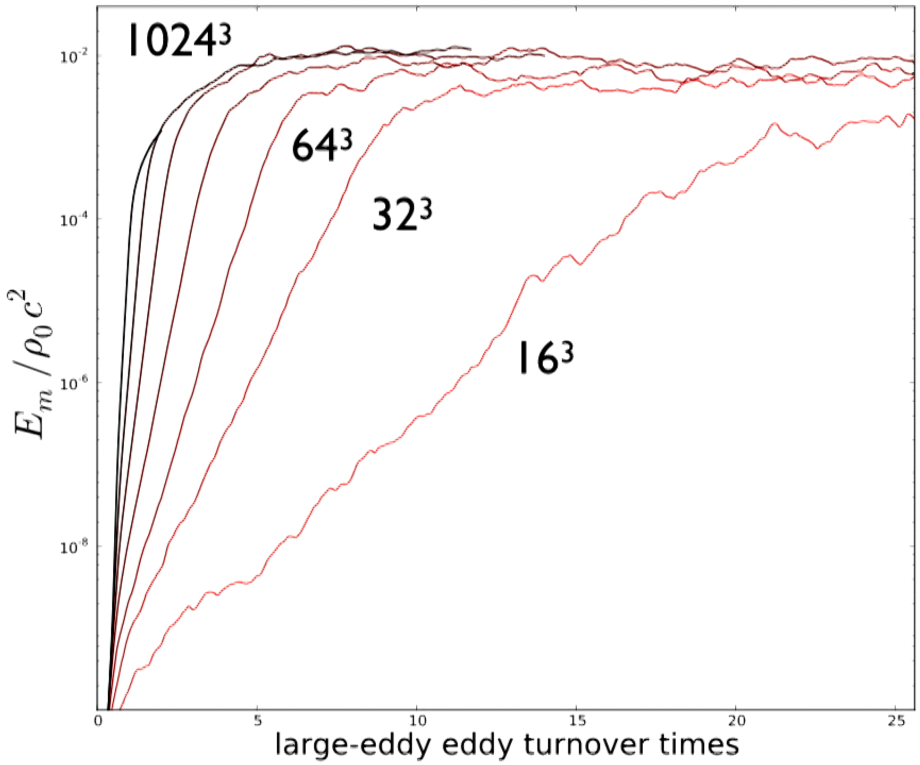
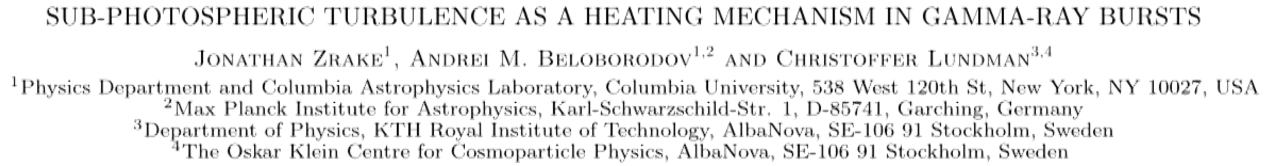


Note: since this work, global simulations can now marginally attain the required resolution, and are generally in agreement with the local simulations.



SUB-PHOTOSPHERIC TURBULENCE AS A HEATING MECHANISM IN GAMMA-RAY BURSTS

Jonathan Zrake[1], Andrei M. Beloborodov[1,2] and Christoffer Lundman[3,4]
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[2]Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85741, Garching, Germany
[3]Department of Physics, KTH Royal Institute of Technology, AlbaNova, SE-106 91 Stockholm, Sweden
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Part III:

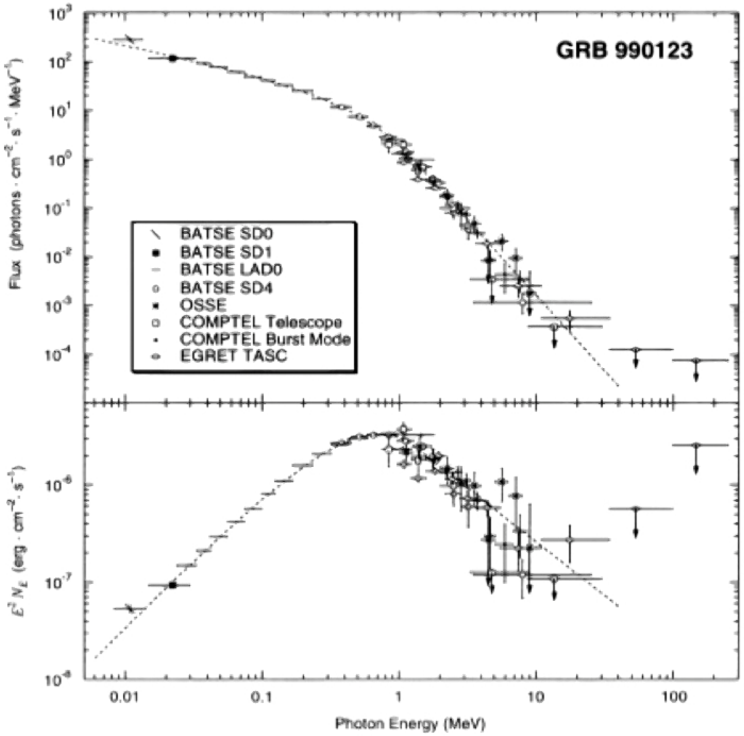
Turbulence in GRB's

- GRB's are produced by a relativistic, collimated plasma outflow

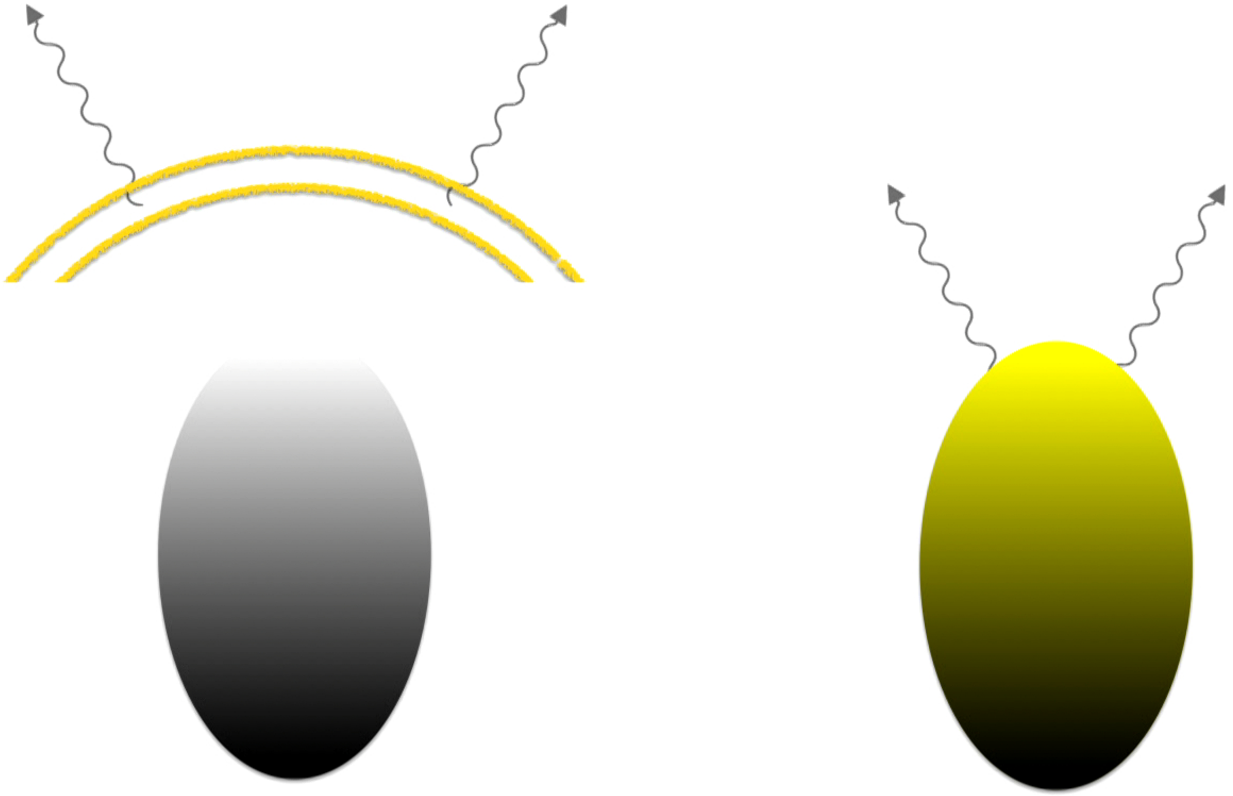
- Prompt (~MeV) emission, long-lived afterglow

- Afterglow well-understood (external shock wave)

- Prompt emission very challenging to model!



Optically thin vs. photospheric emission



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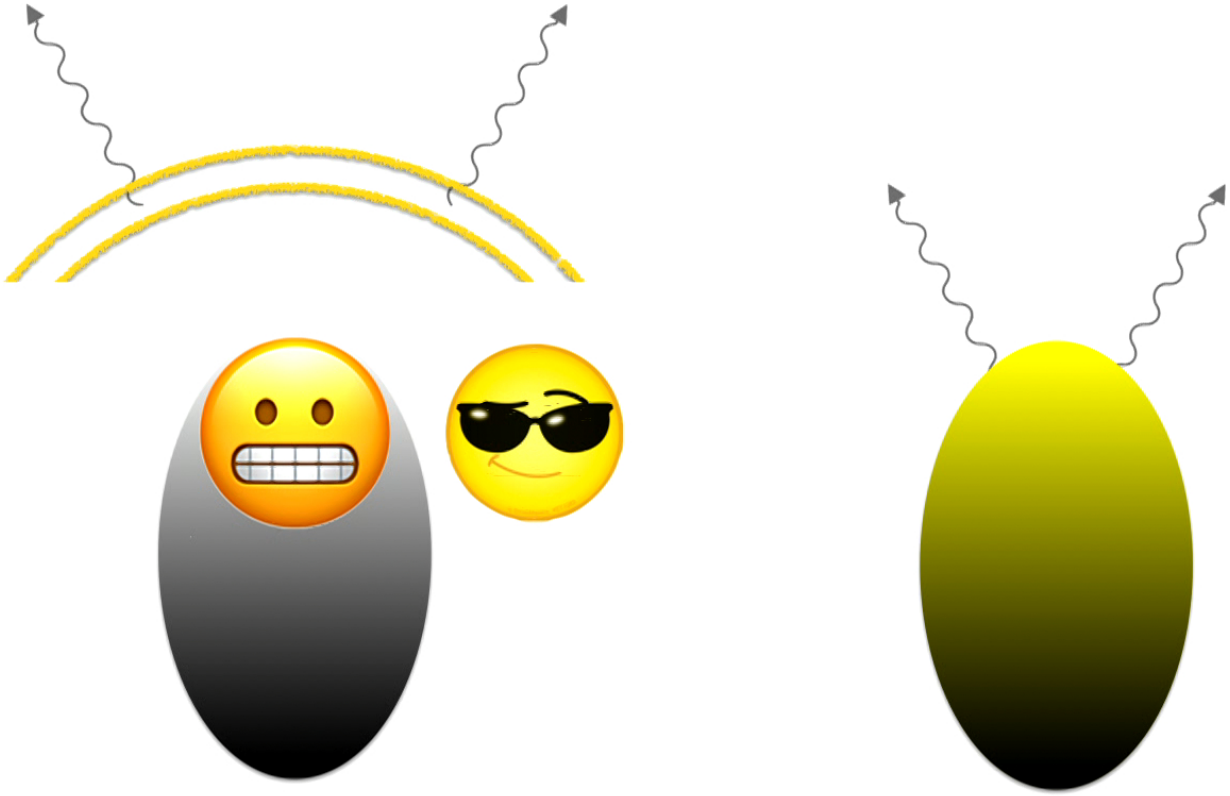

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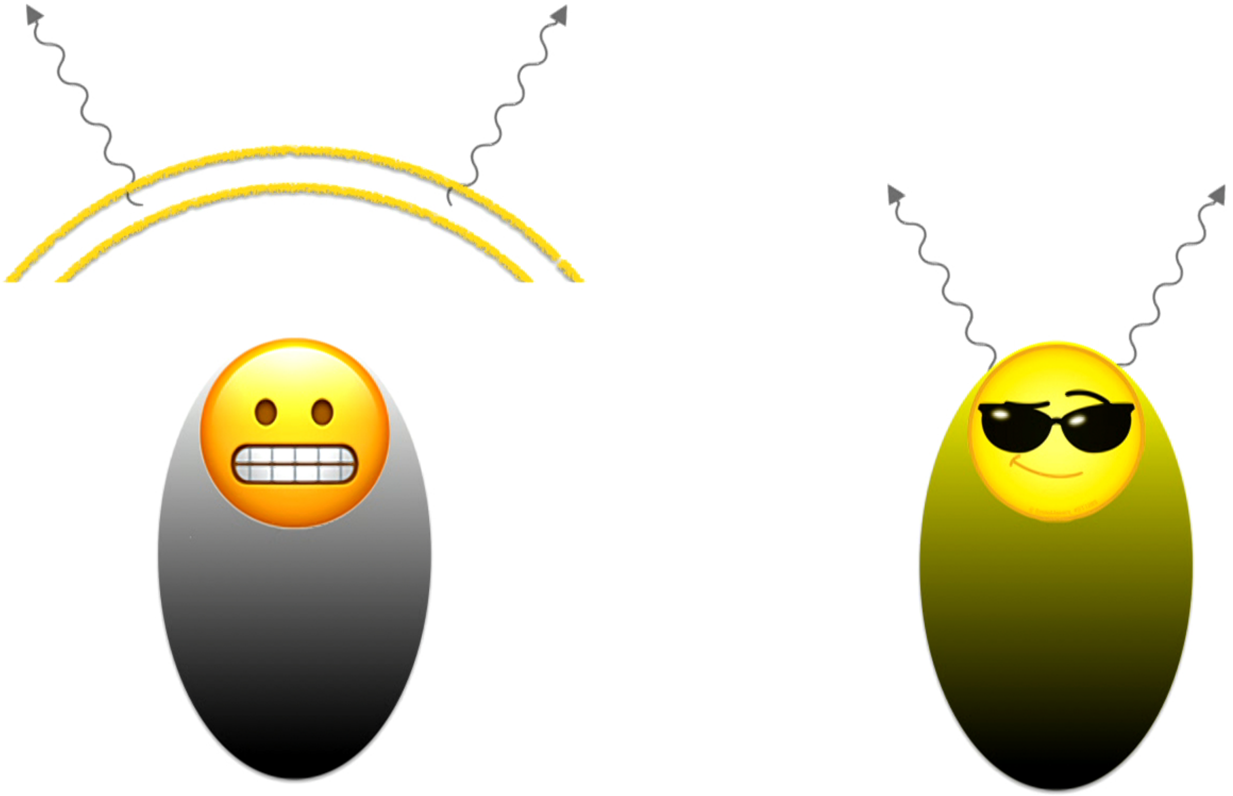
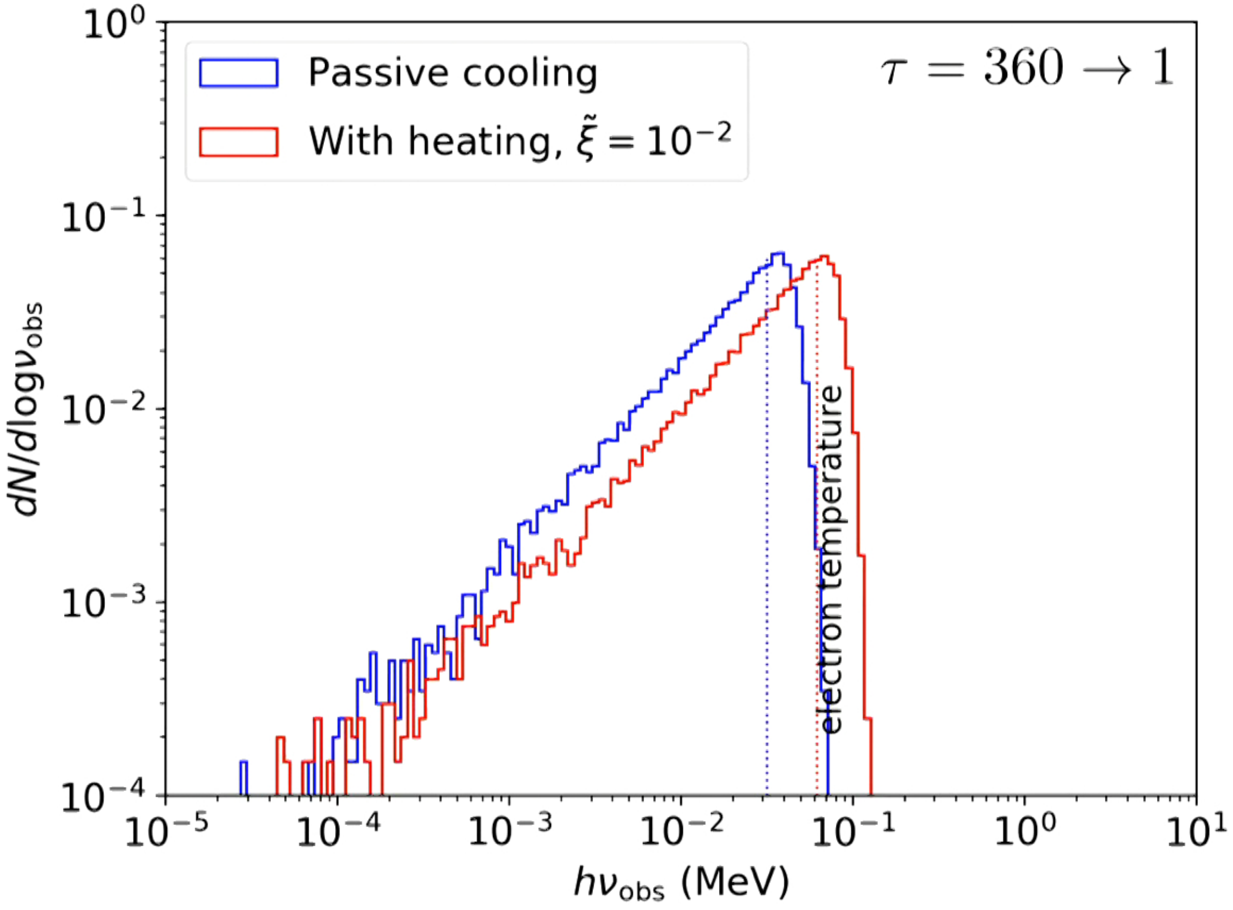


How can photospheric emission be non-thermal?



*Radiative transfer MC

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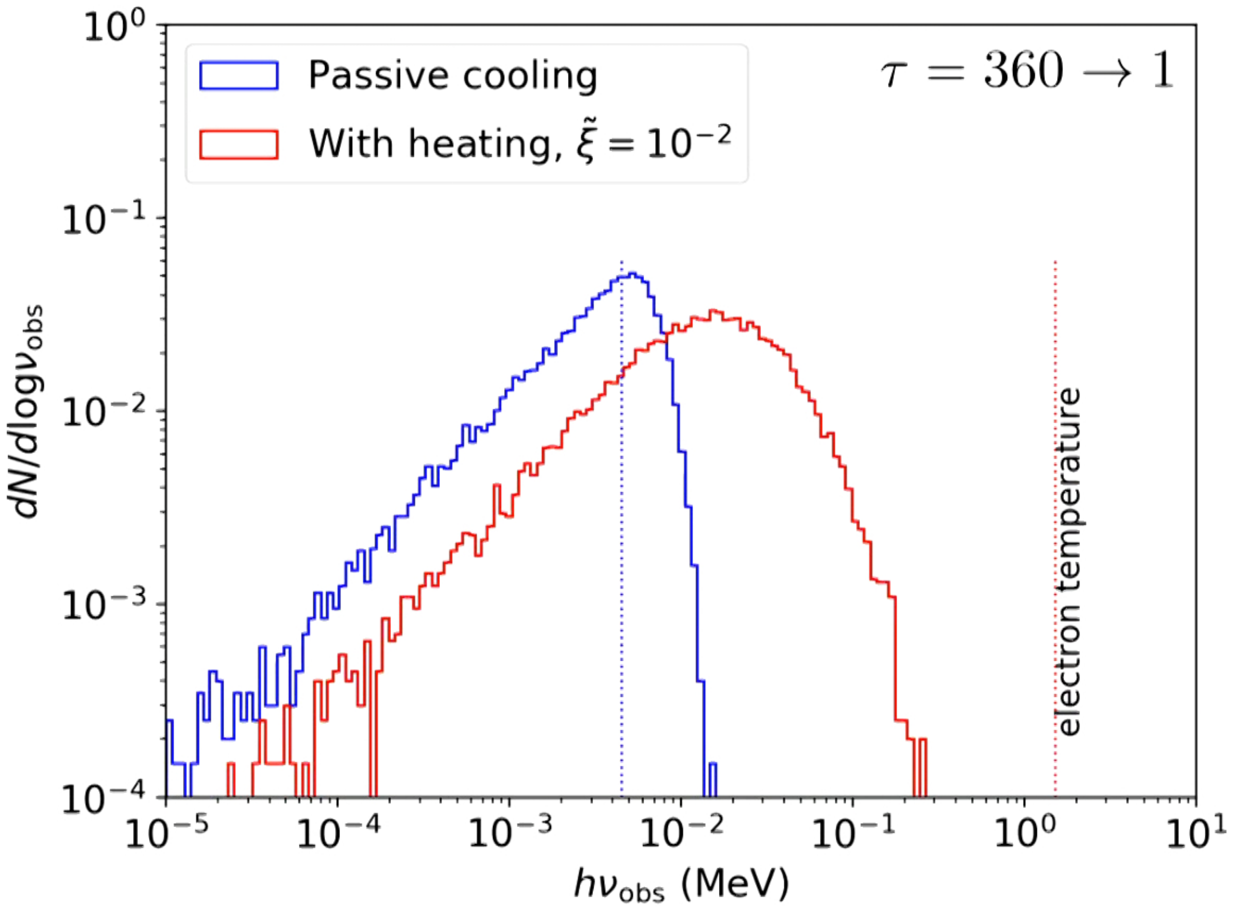

*Radiative transfer MC

What heats the electrons?

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3. Nuclear collisions?

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1. Internal shocks?
2. Magnetic reconnection?
3. Nuclear collisions?
4. Turbulence???

- *Rapid variability (inhomogeneous flow)* + high Reynolds number => **turbulence likely to exist in GRB outflows**

- Any distinct predictions relative to the alternatives?

- *New regime of turbulence!*

Turbulence in GRB's would be *radiative*

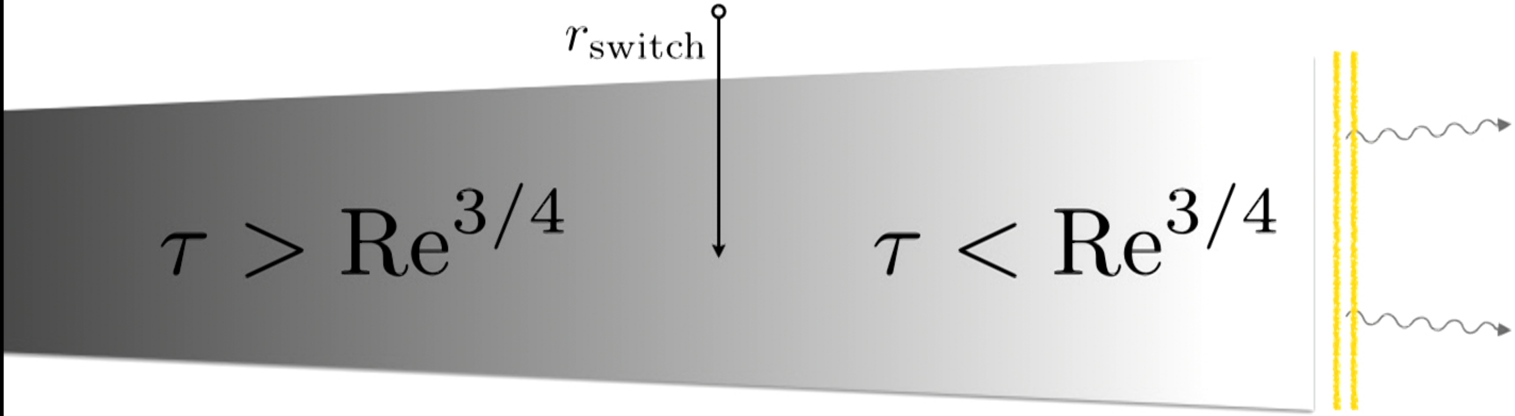
Radiative turbulence can operate in one of two regimes:

Turbulence in GRB's would be *radiative*

Radiative turbulence can operate in one of two regimes:

1. Viscous

2. Collisionless



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Upshot

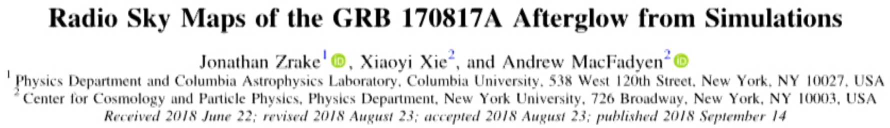
1. Gradual photospheric heating models are promising to account for non-thermal photospheric emission

2. Radiative turbulence has two regimes: (1) viscous and (2) collisionless

3. More work needs to be done in regime (2) to differentiate among various heating modes.

Part IV:

The GRB-170817A afterglow



Radio Sky Maps of the GRB 170817A Afterglow from Simulations

Jonathan Zrake[1], Xiaoyi Xie[2], and Andrew MacFadyen[2]
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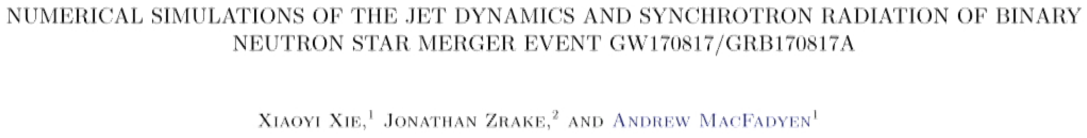
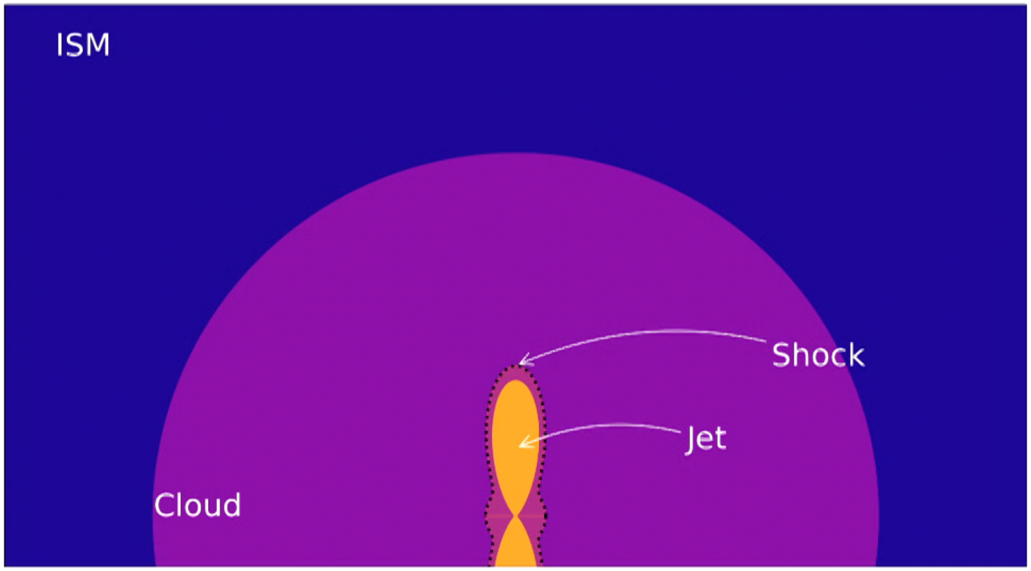
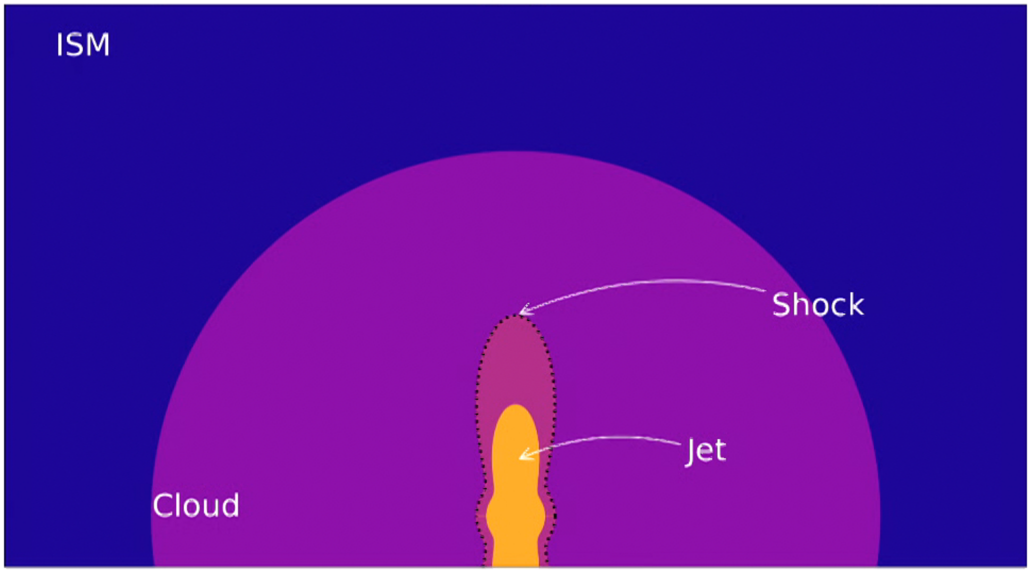


NUMERICAL SIMULATIONS OF THE JET DYNAMICS AND SYNCHROTRON RADIATION OF BINARY NEUTRON STAR MERGER EVENT GW170817/GRB170817A

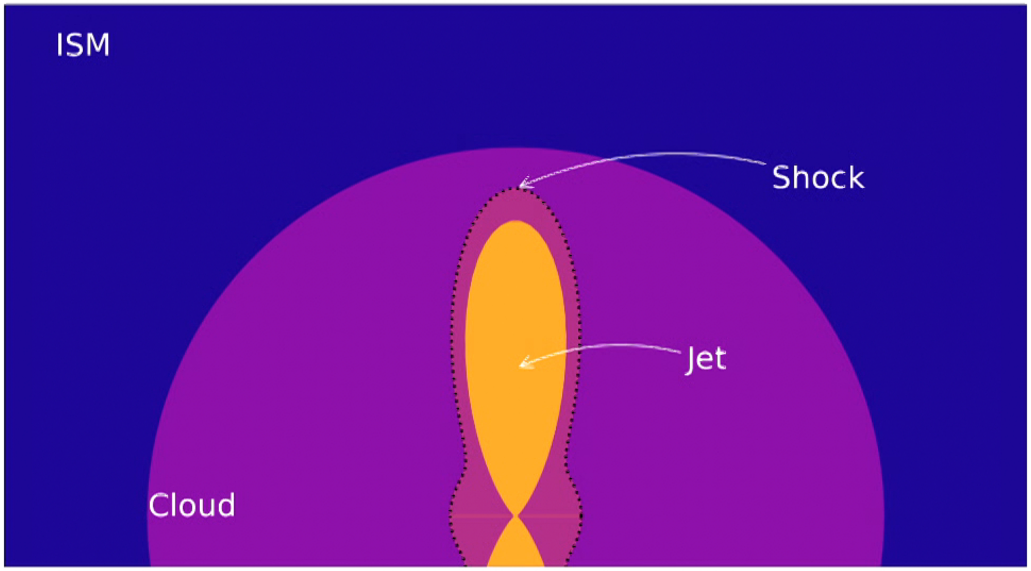
Xiaoyi Xie,[1] Jonathan Zrake,[2] and Andrew MacFadyen[1]



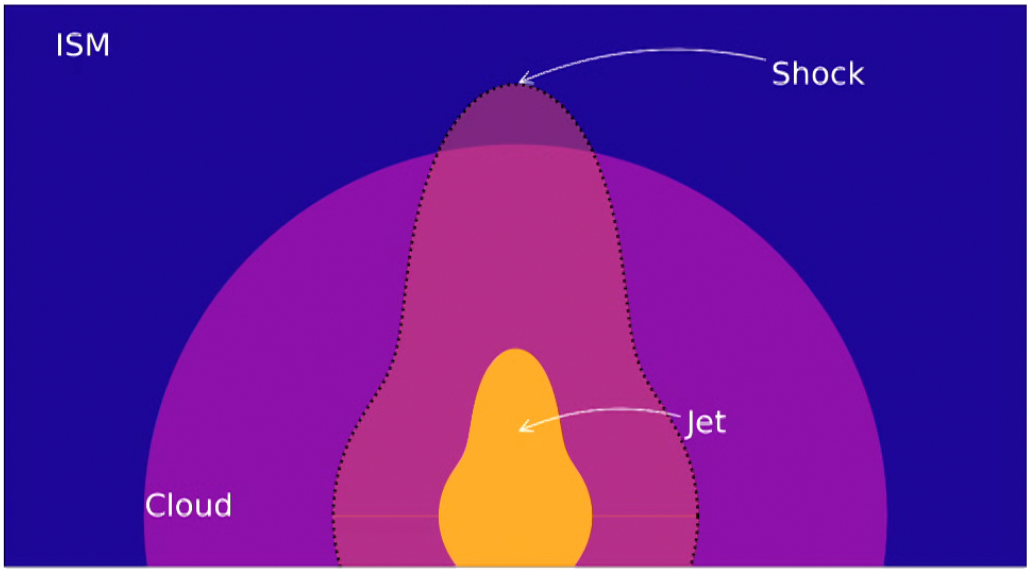
“Successful jet”



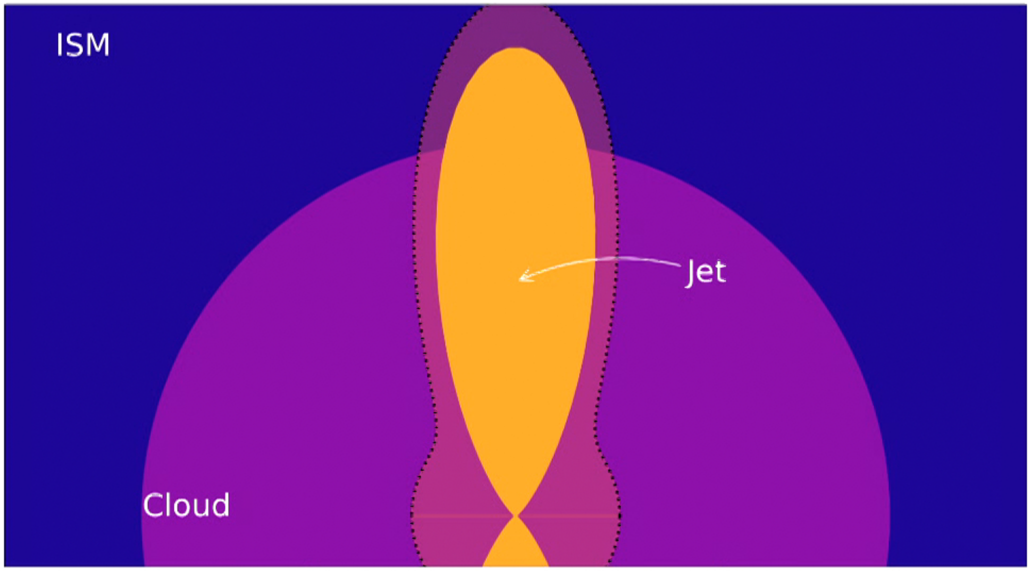
“Failed jet”



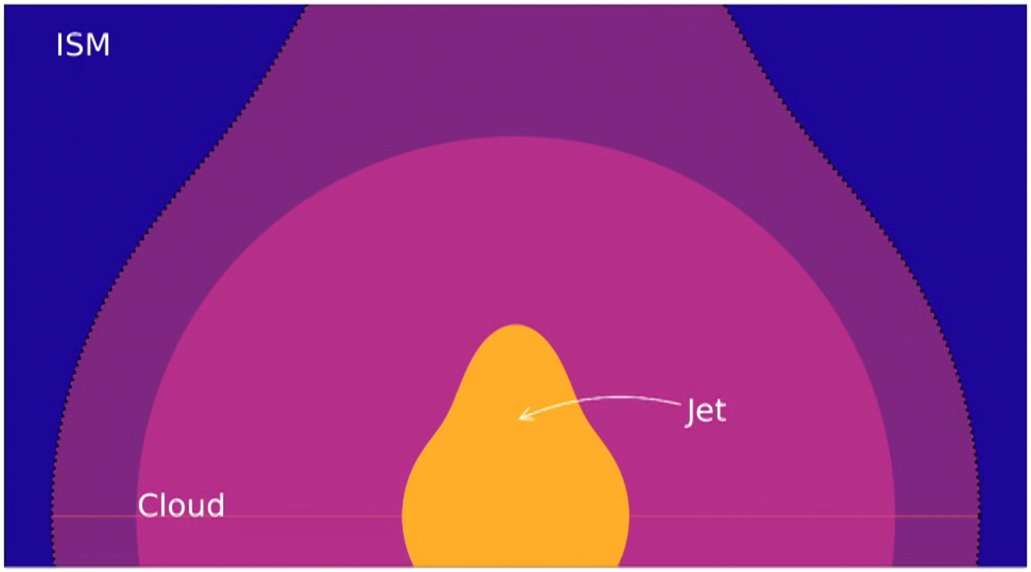
“Successful jet”



“Failed jet”



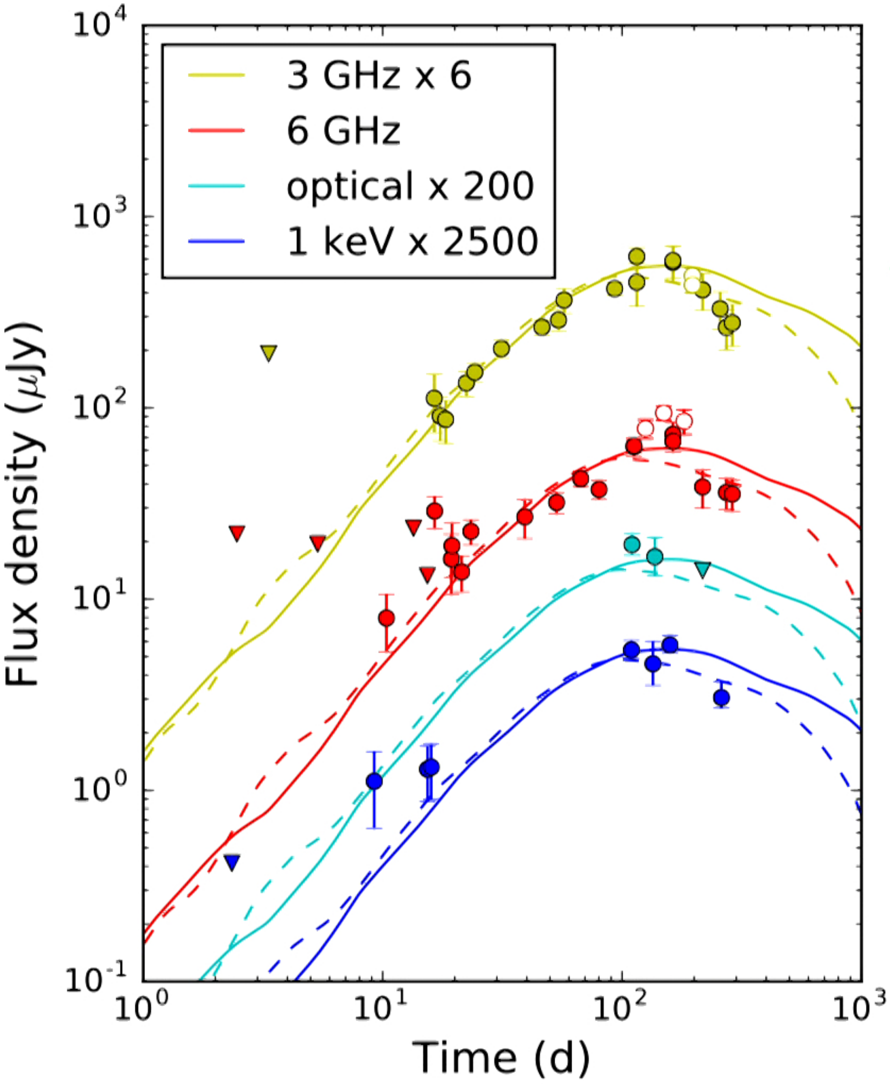
"Successful jet"



"Failed jet"

Why?!

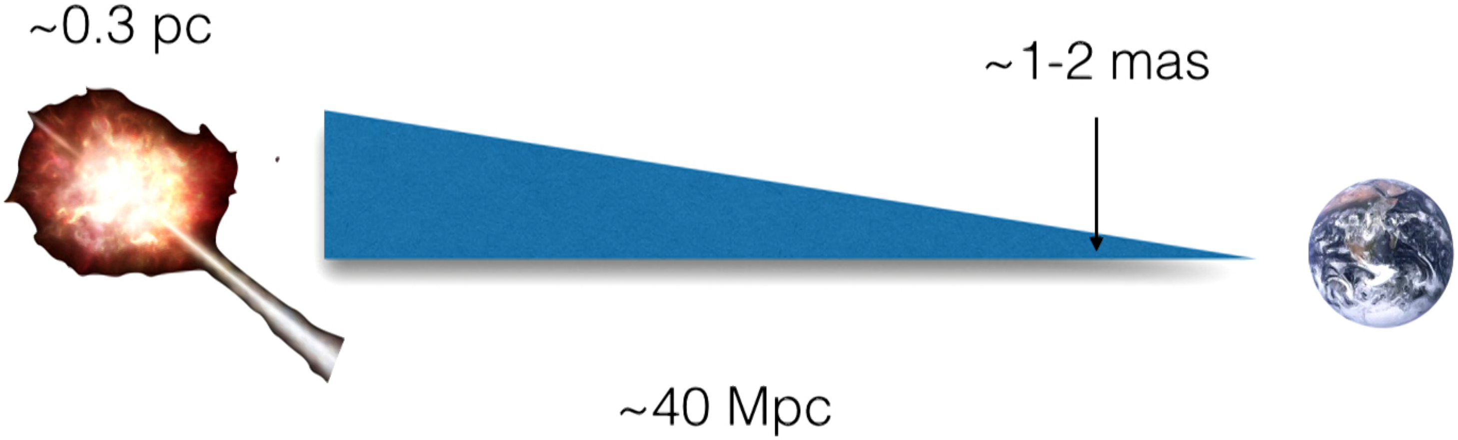
1. BNS merger rate <~> sGRB rate
2. Constraining the Hubble constant via GW standard siren



Margutti+ 18

The afterglow encodes the geometry of the external shock

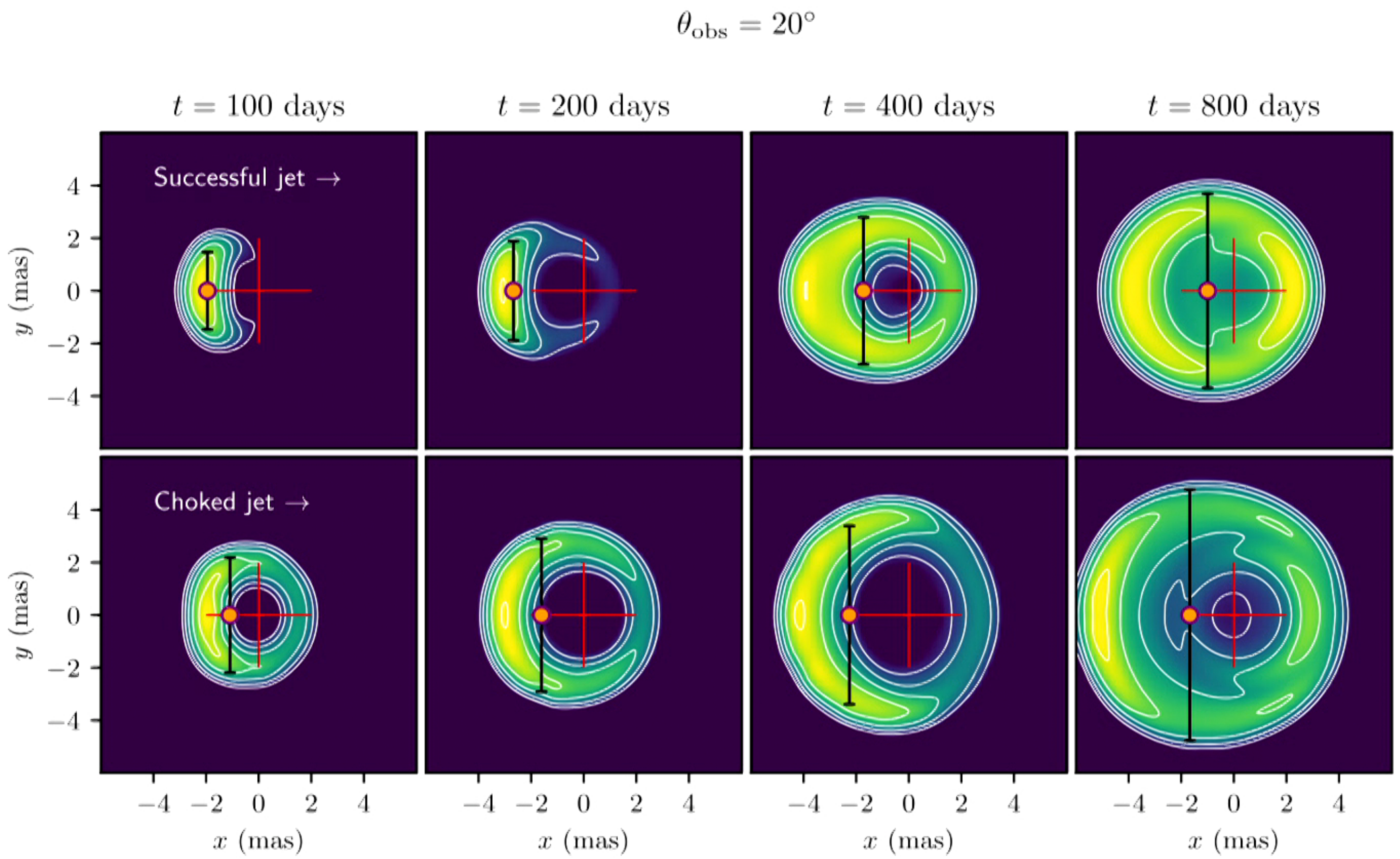
Degeneracy between opening angle and energy ;(

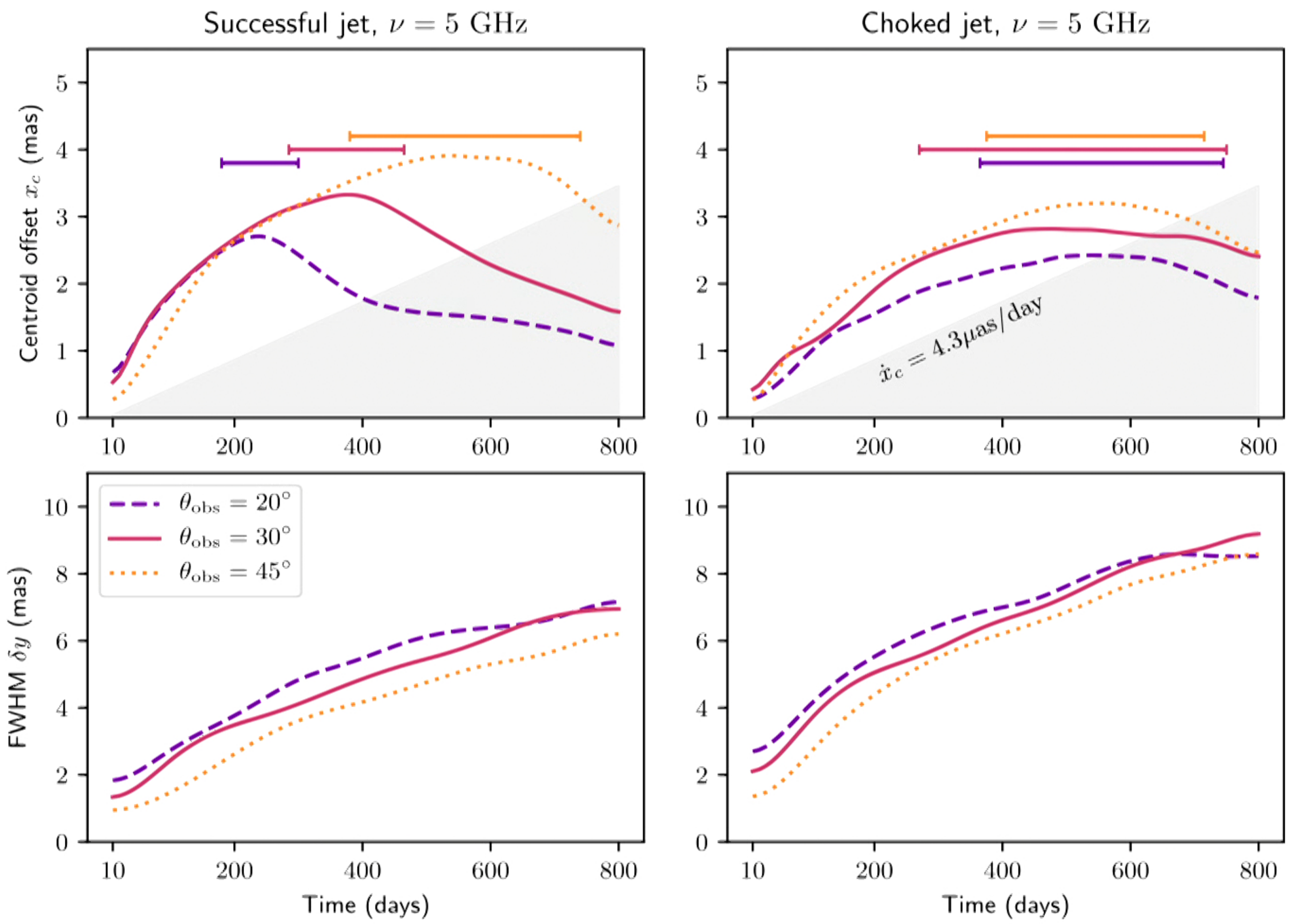


~0.3 pc

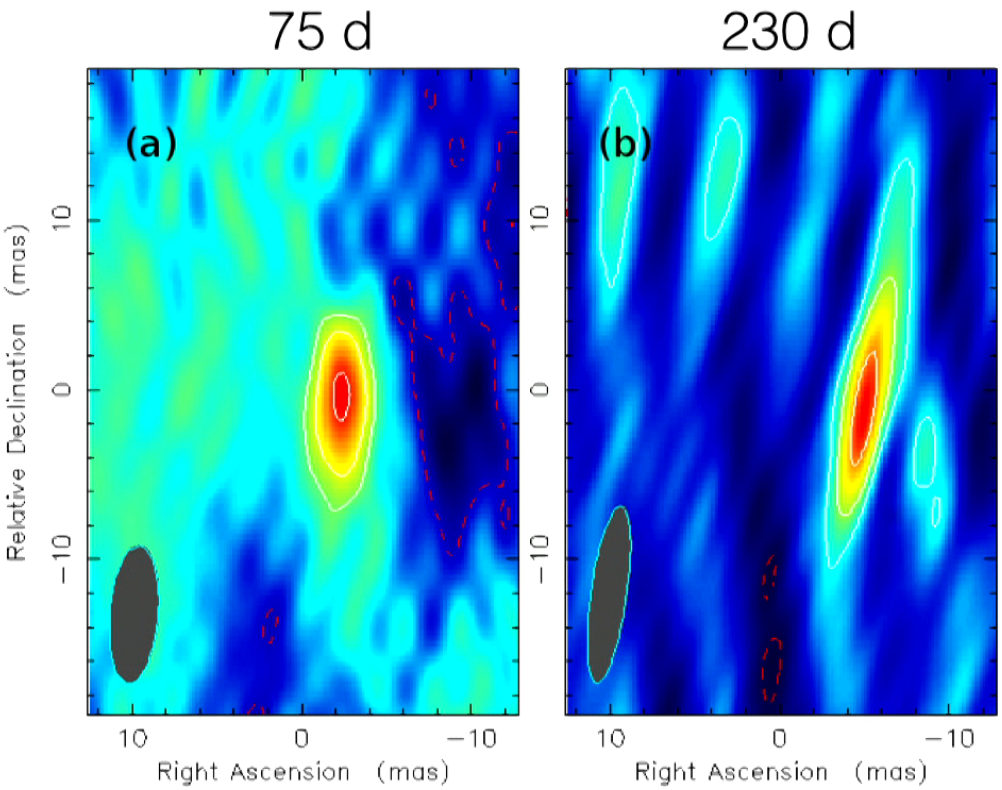
~1-2 mas

~40 Mpc

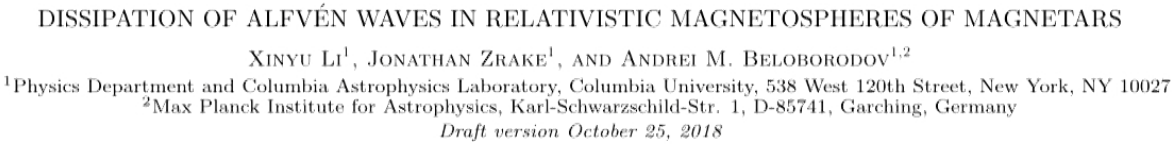

$\theta_{\rm obs} = 20°$
$t = 100$ days
$t = 200$ days
$t = 400$ days
$t = 800$ days
Successful jet →
Choked jet →
y (mas)
x (mas)
4
2
0
−2
−4


Successful jet, $\nu = 5$ GHz
Choked jet, $\nu = 5$ GHz
Centroid offset x_c (mas)
FWHM δy (mas)
$\dot{x}_c = 4.3\mu$as/day
$\theta_{\rm obs} = 20°$
$\theta_{\rm obs} = 30°$
$\theta_{\rm obs} = 45°$
0
1
2
3
4
5
0
2
4
6
8
10
10
200
400
600
800
Time (days)

VLBI observations



Mooley+ 18



DISSIPATION OF ALFVÉN WAVES IN RELATIVISTIC MAGNETOSPHERES OF MAGNETARS

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Xinyu will present the results here @ PI soon

Thank you!

Questions?