Ultrafast variability in AGN jets: Intermittency and lighthouse effect

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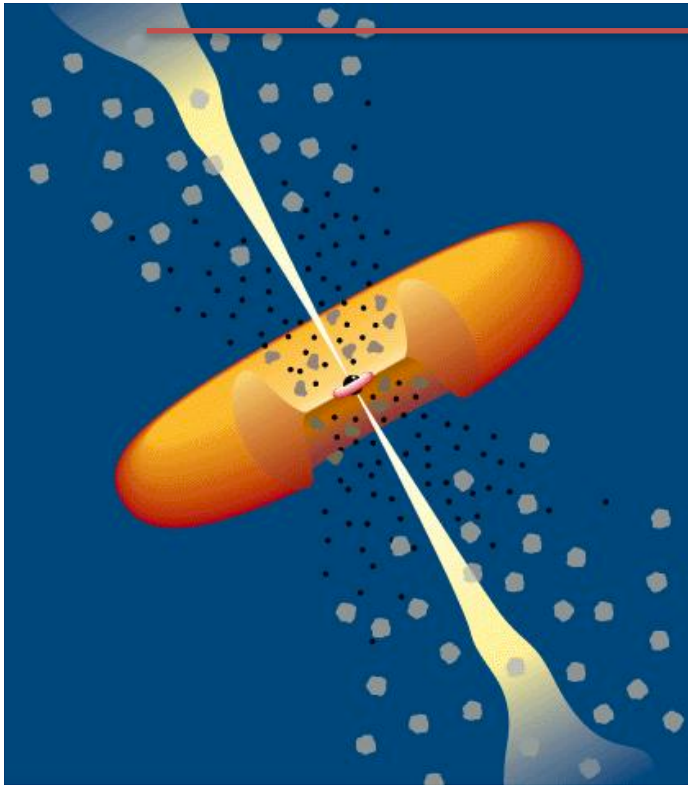
MARIE CURIE ACTIONS

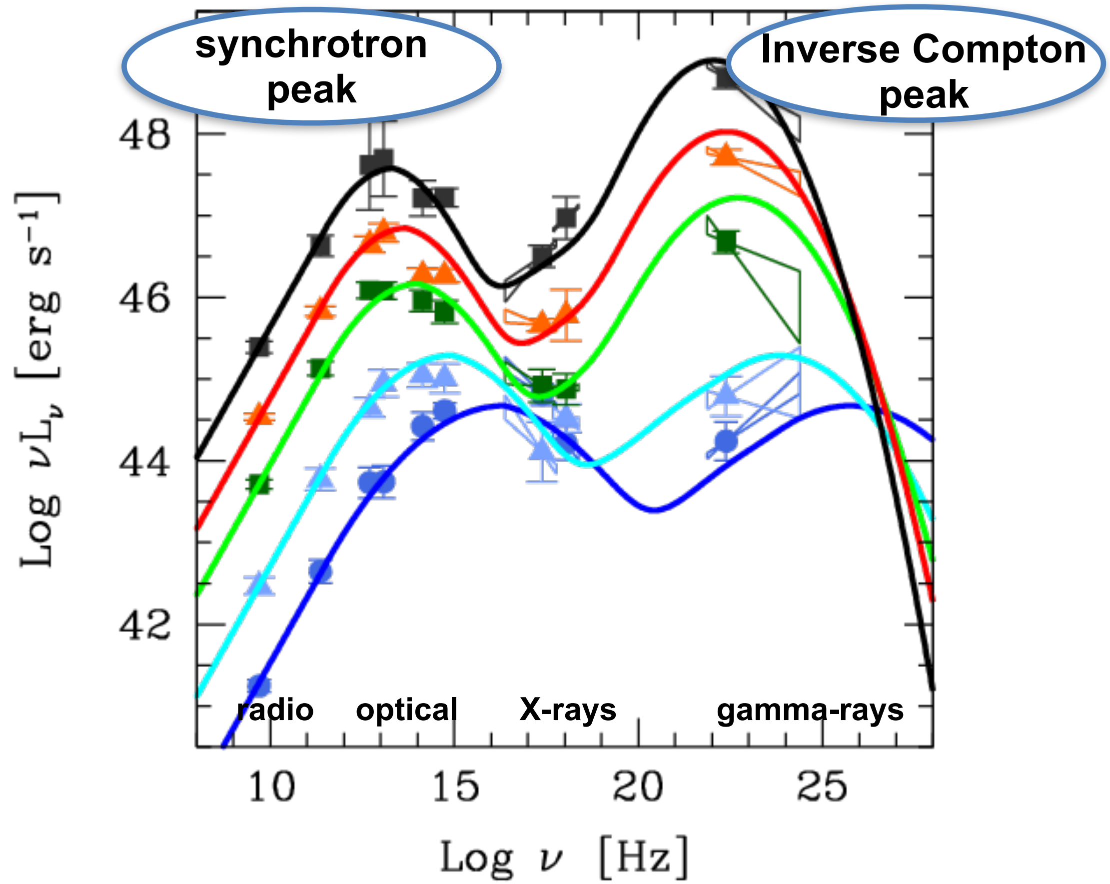
Blazars



(Urry & Padovani 1995)

blazars are AGN with a jet
pointing in the direction of the observer

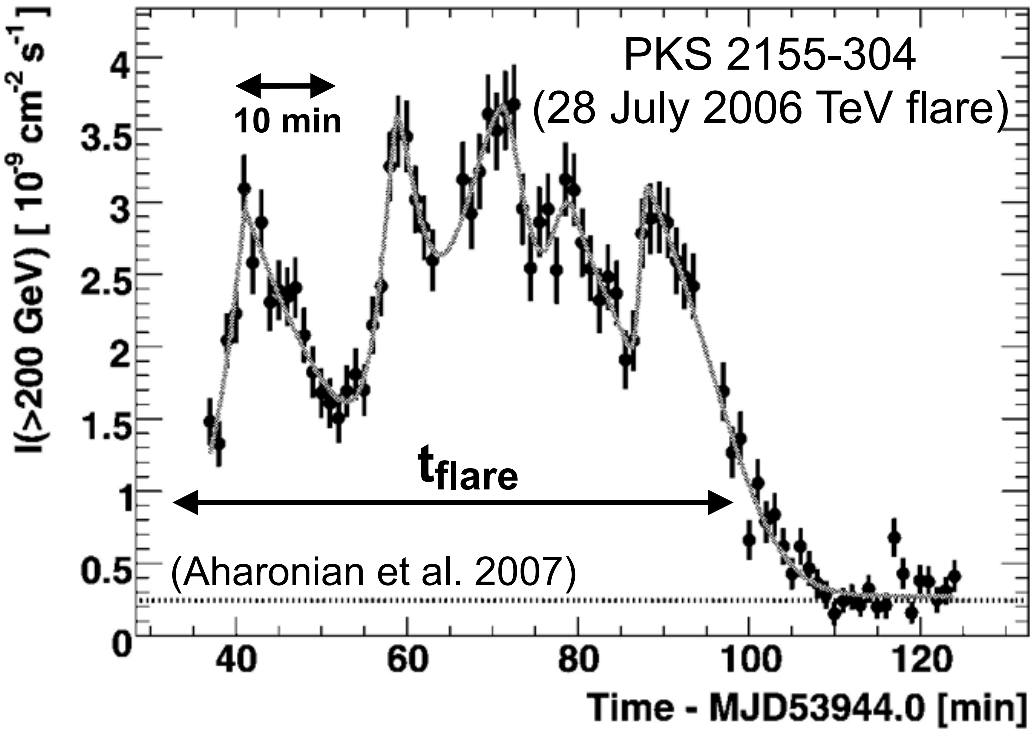
radiation from the jet is strongly beamed



(Fossati et al. 1998; Ghisellini et al. 2017)

synchrotron and IC emission
from the same population
of non-thermal electrons

Ultrafast variability of gamma-ray flares



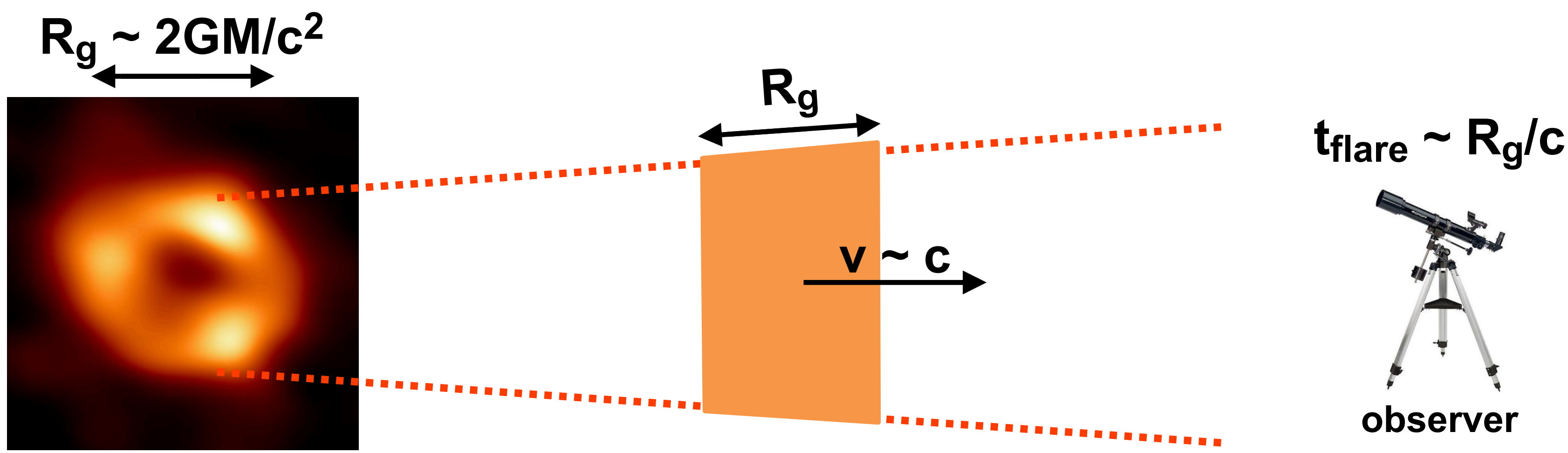
Black hole mass of PKS 2155-304

$$M \sim 10^9 M_\odot$$

(Bettoni et al. 2003)

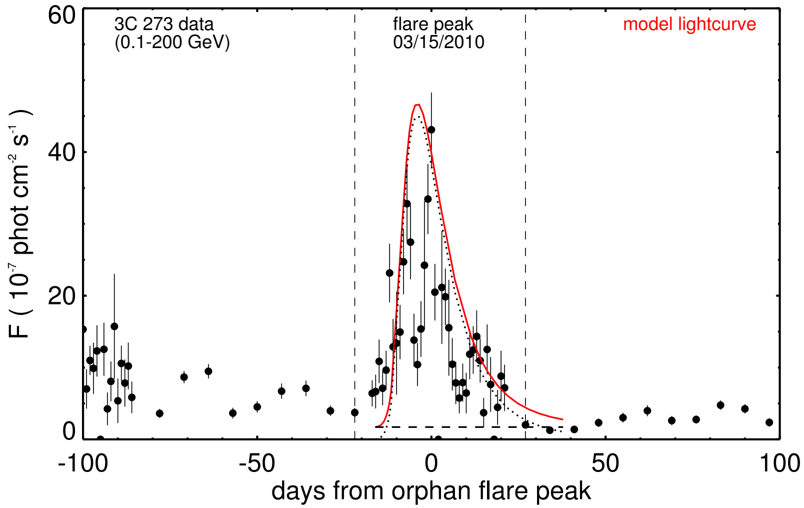
variability timescale
~ a few minutes
<<
light crossing time
of the SMBH event horizon

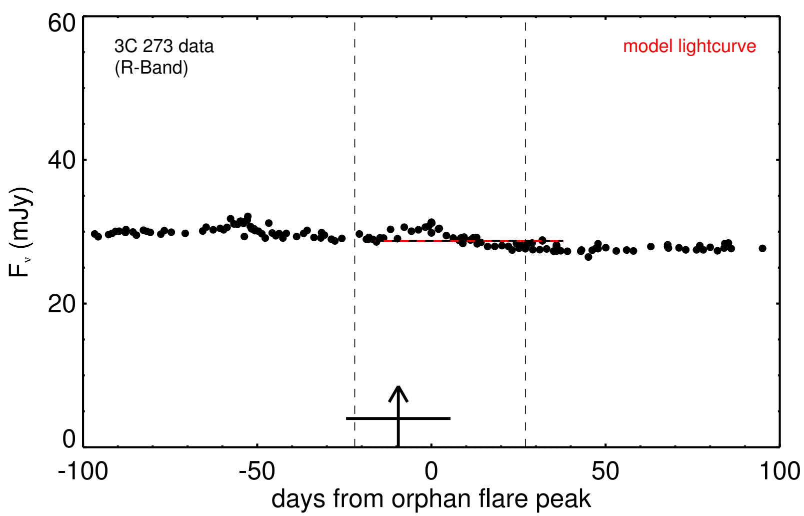
$$t_g = 2GM/c^3 \sim 160 \text{ min}$$



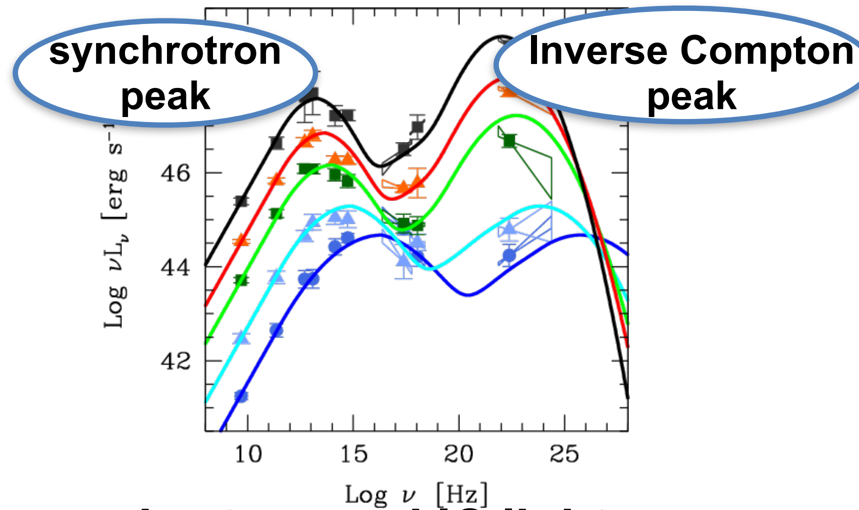
“Orphan” gamma-ray flares

“orphan” gamma-ray flare (no correlation)



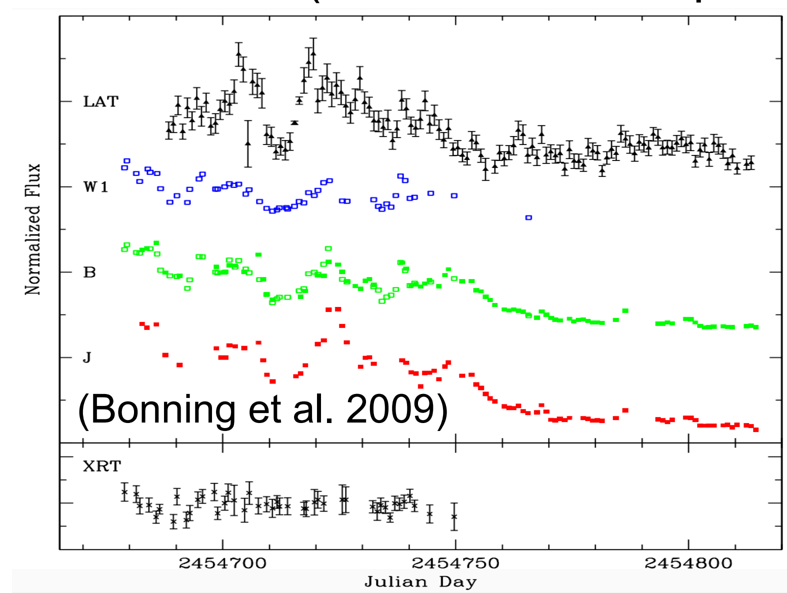


(MacDonald et al. 2017)



synchrotron and IC light curves should be correlated

“standard” flare (correlation as expected)



(Bonning et al. 2009)

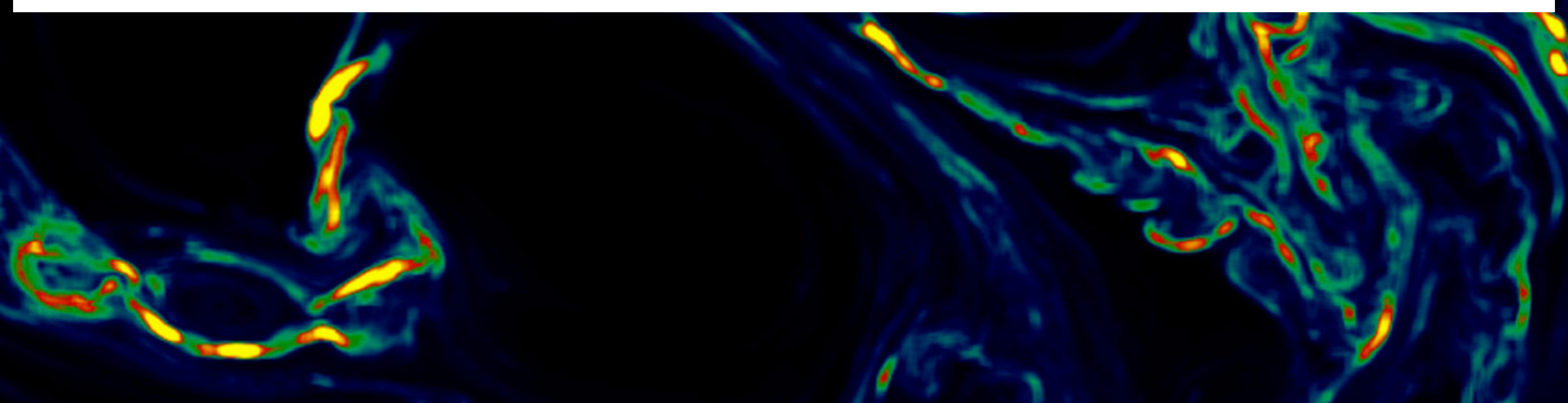
Outline

1. Particles are accelerated by **turbulence**

2. Accelerated particles fill a small fraction of the volume (**intermittency**)
   and move along the local magnetic field (**lighthouse effect**)

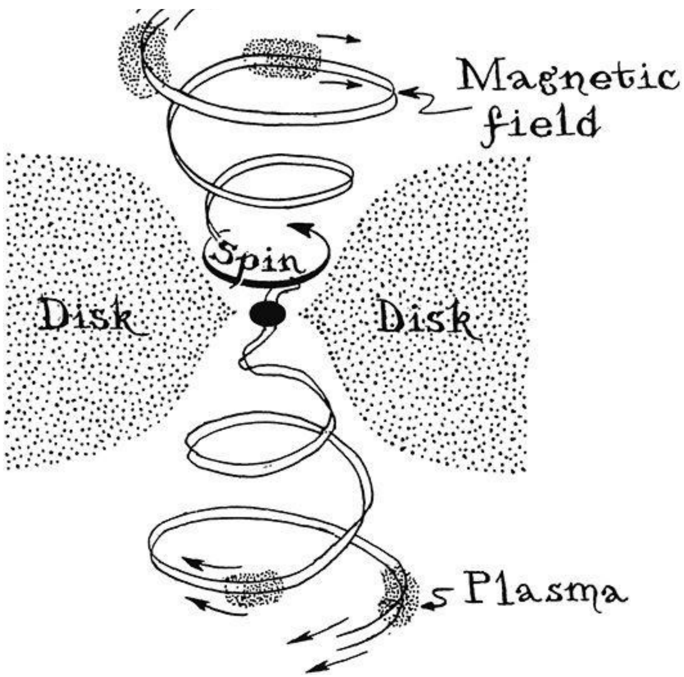
3. Intermittency and lighthouse effect explain:
   - ultrafast variability of gamma-ray flares
   - orphan gamma-ray flares

4. Predictions for observations

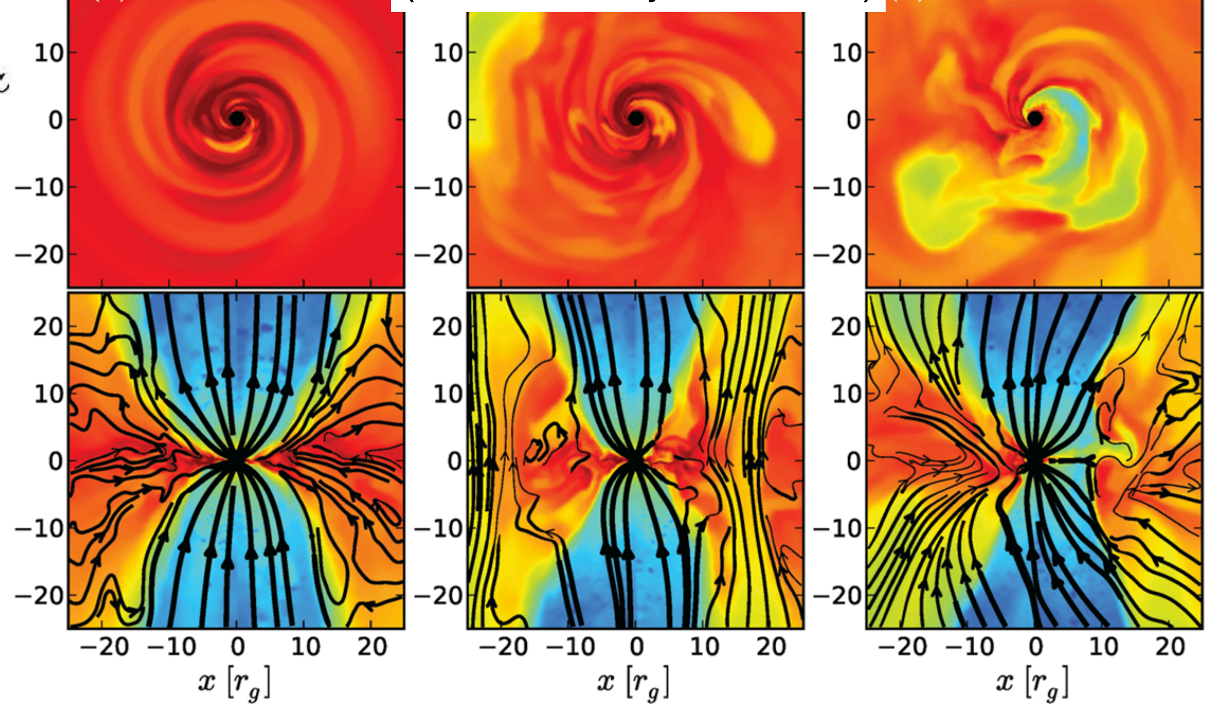


AGN jets are magnetically dominated

(Blandford & Znajek 1977)



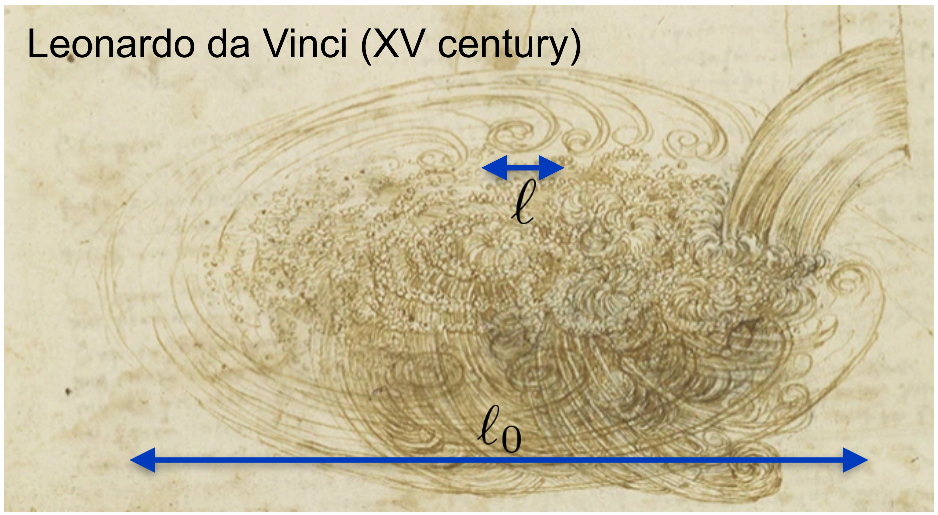
(Tchekhovskoy et al. 2011)

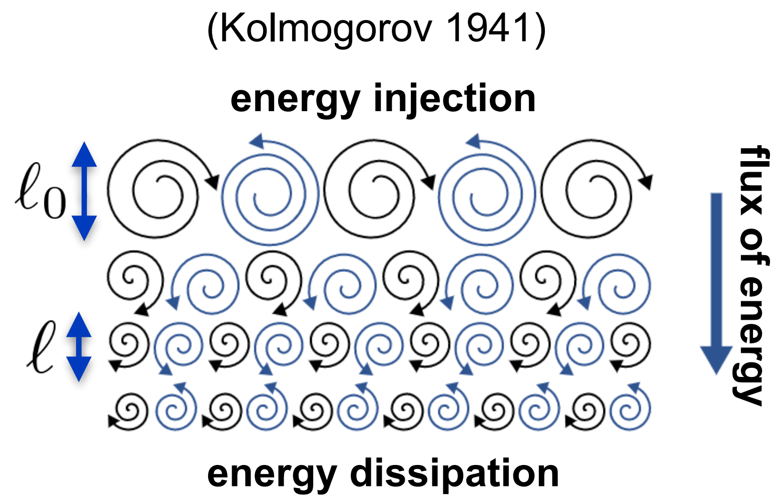


$$\sigma = \frac{B^2}{4\pi n m c^2} \gg 1$$

Turbulence dissipates magnetic energy and accelerates particles

Turbulence is ubiquitous





Separation of scales

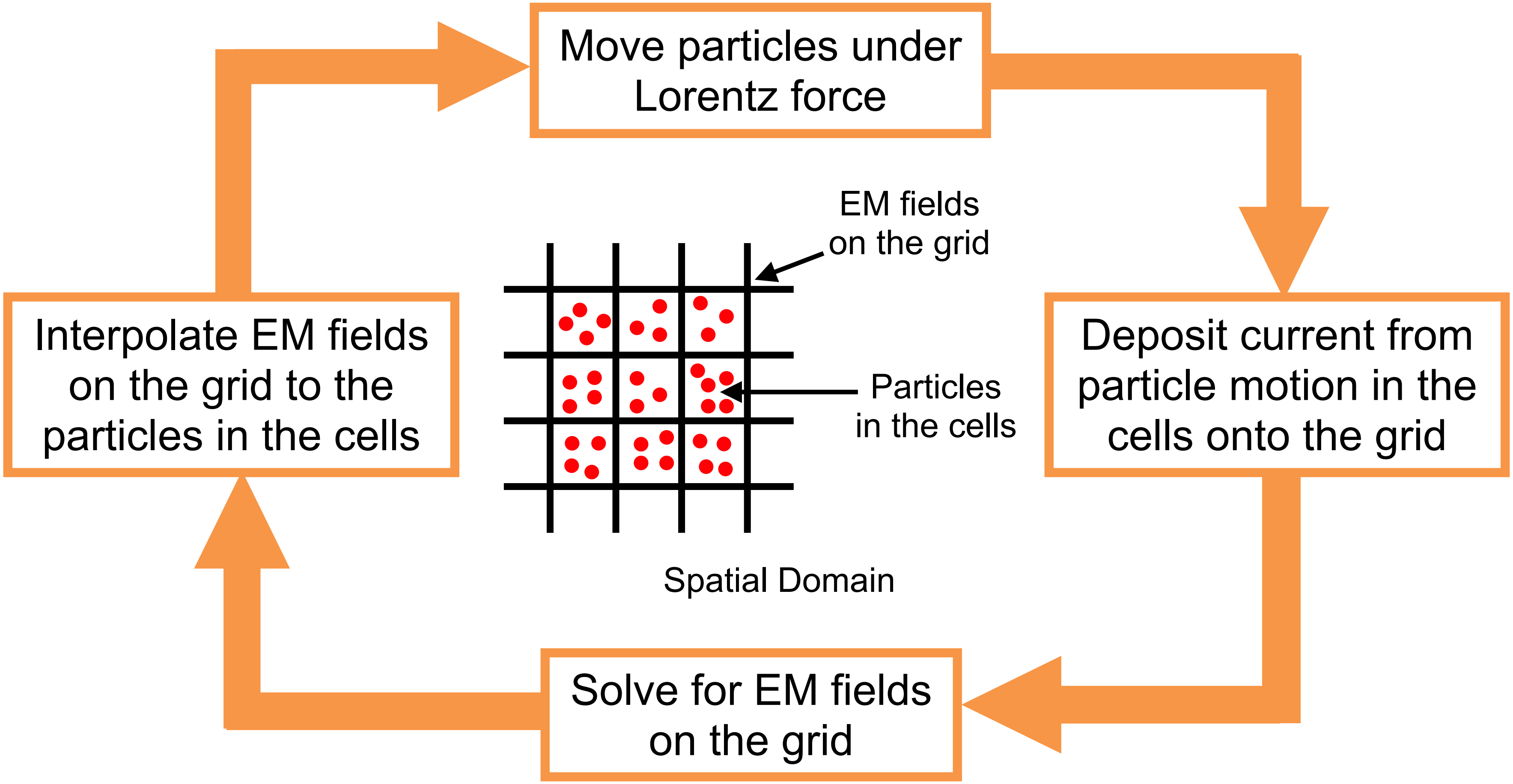
8 orders of magnitude in AGN jets!

$$\ell_0 \gg \ell$$

energy injection
~ transverse size of the jet

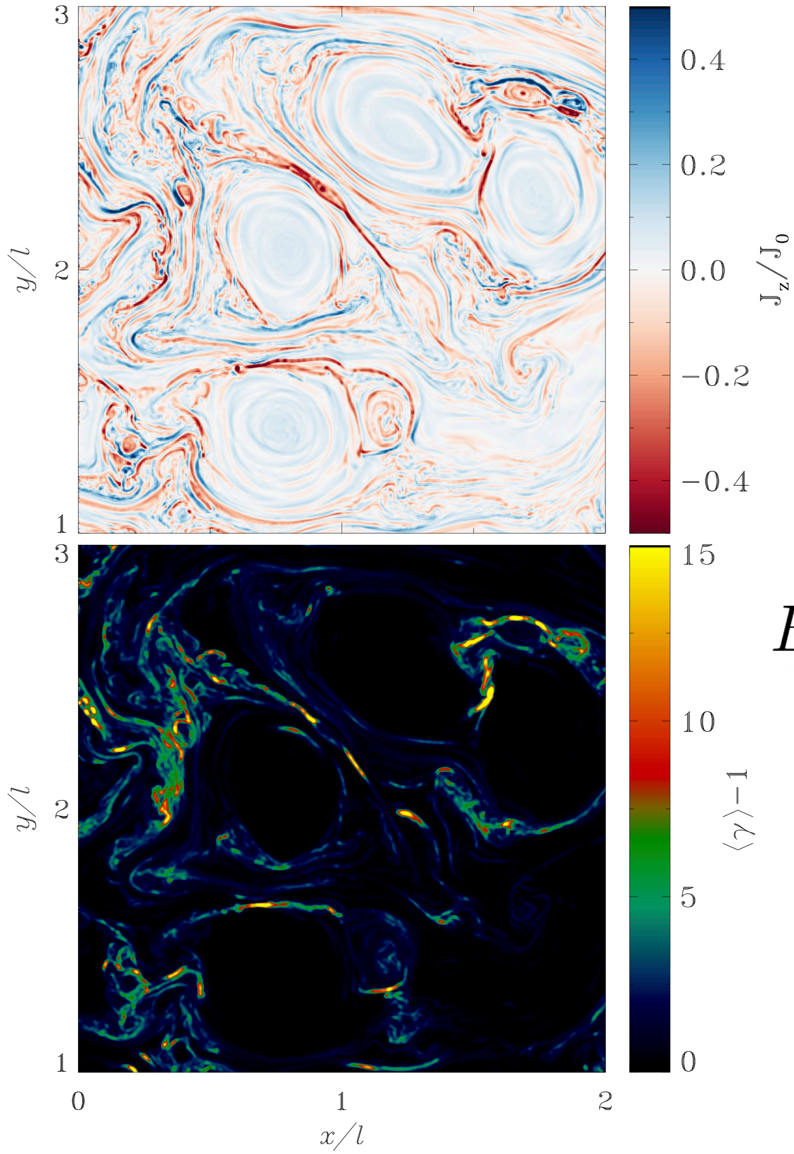
energy dissipation
~ particle Larmor radius

Turbulence is studied with Particle-In-Cell simulations



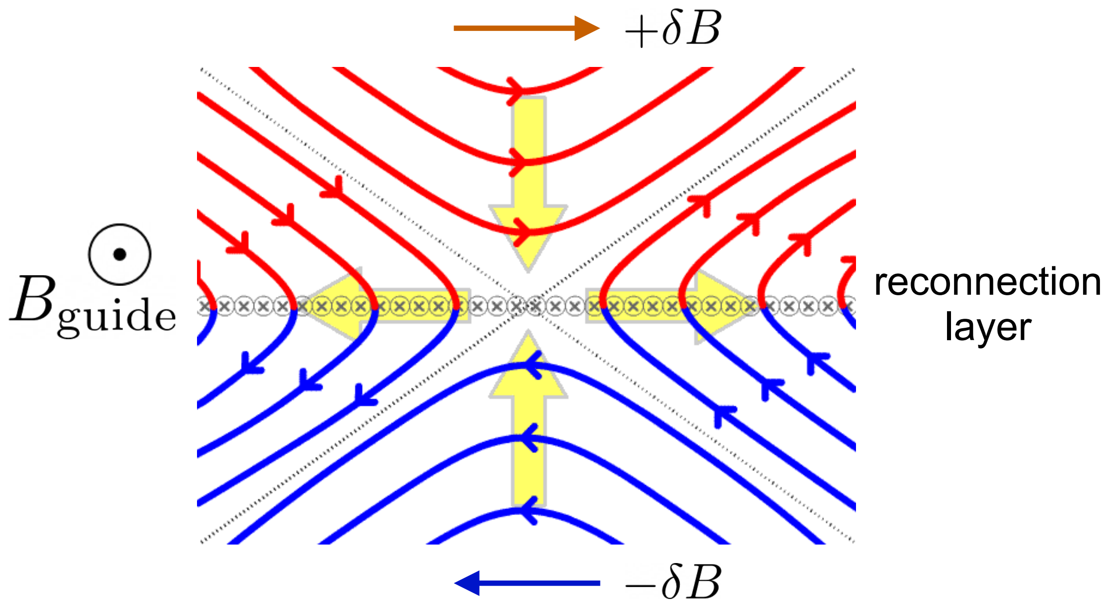
$$\sigma = \frac{B^2}{4\pi n m c^2} \gg 1$$

Accelerated particles fill a small fraction of the volume (intermittency)

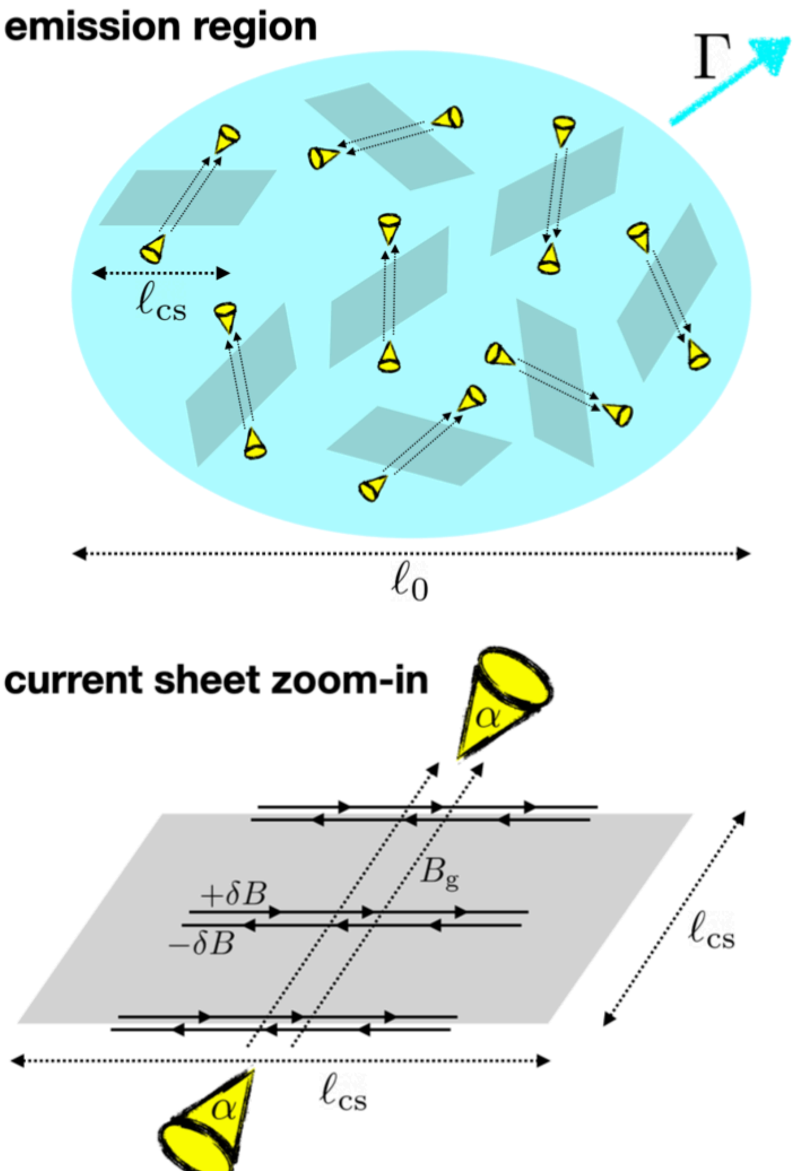


(ES, Nättilä & Sironi 2021)

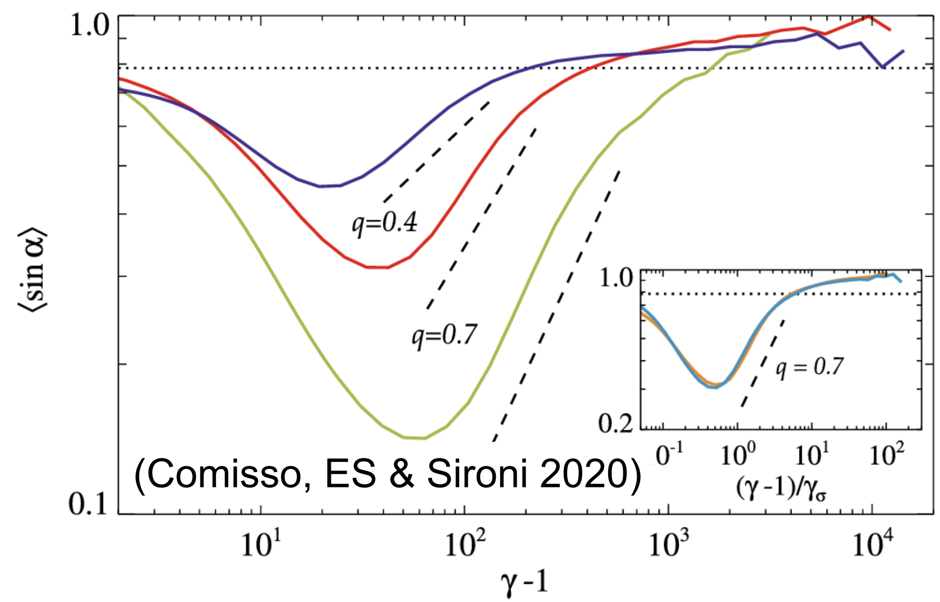
Particles are accelerated by magnetic reconnection



Accelerated particles move along the local B (lighthouse effect)

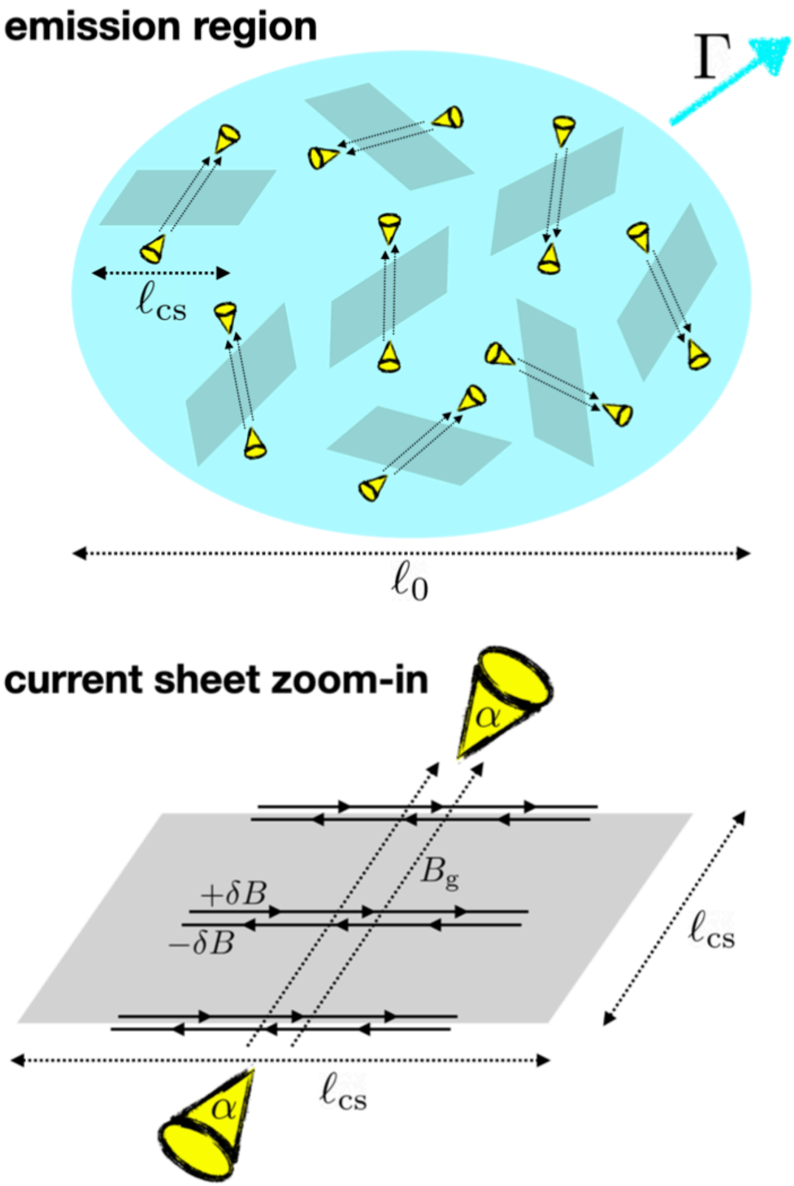


Particles are accelerated along B_{guide}
Strongly anisotropic particle distribution
(pitch angle alpha<<1)

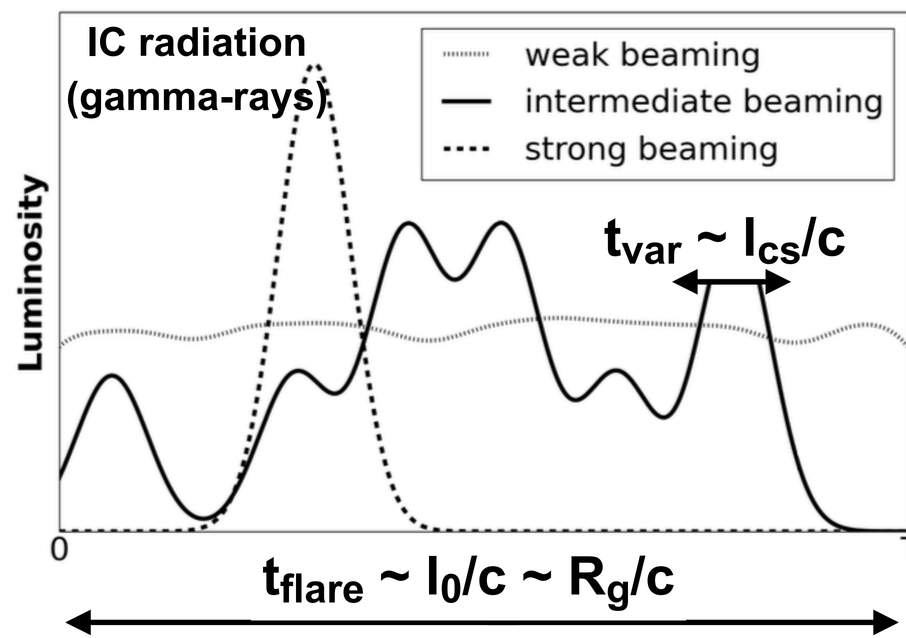


$$\cos\alpha = \frac{\mathbf{v}\cdot\mathbf{B}}{|\mathbf{v}|\,|\mathbf{B}|}$$

Origin of ultrafast gamma-ray flares

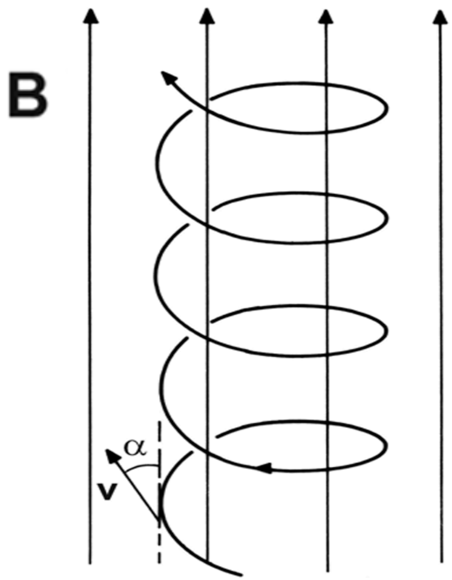


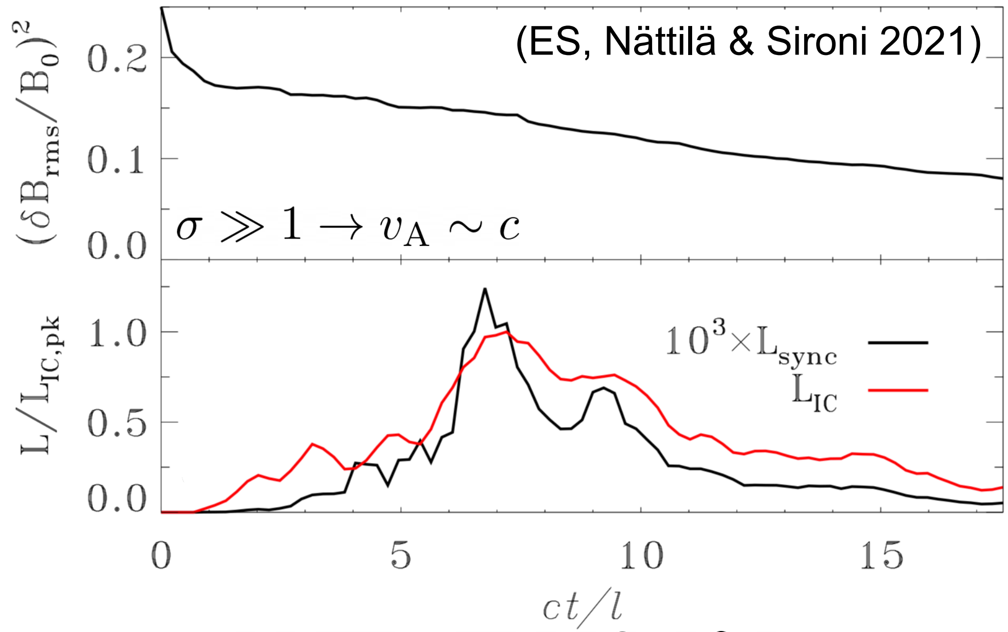
Current sheets produce
radiation pulses of duration l_{cs}/c
Current sheets are visible
when the local B is along the line of sight



(ES, Piran & Comisso 2023)

Origin of orphan gamma-ray flares





$$P_{sync} \sim \sigma_T c U_B \gamma^2 \sin^2 \alpha$$

$$P_{IC} \sim \sigma_T c U_{rad} \gamma^2$$

Accelerated particles move along the local B

$$\frac{P_{sync}}{P_{IC}} = \frac{U_B}{U_{rad}} \sin^2 \alpha \ll \frac{U_B}{U_{rad}}$$

Orphan gamma-ray flares are produced due to small pitch angles

U_B=magnetic energy density
U_{rad}=radiation energy density

Ultrafast gamma-ray flares are orphan

Ultrafast variability and orphan flares are due to pitch angle anisotropy
(accelerated particles move along the local B)

↓

Small amplitude variability of synchrotron radiation (optical, X-rays)
during ultrafast inverse Compton (gamma-ray) flares
Can be tested with multiwavength observations

Summary

Why turbulence?

Huge separation of scales
between the transverse size of AGN jets
and the Larmor radius of the radiating particles

What is new?

Accelerated particles fill a small fraction of the volume (**intermittency**)
Accelerated particles move along the local B (**lighthouse effect**)

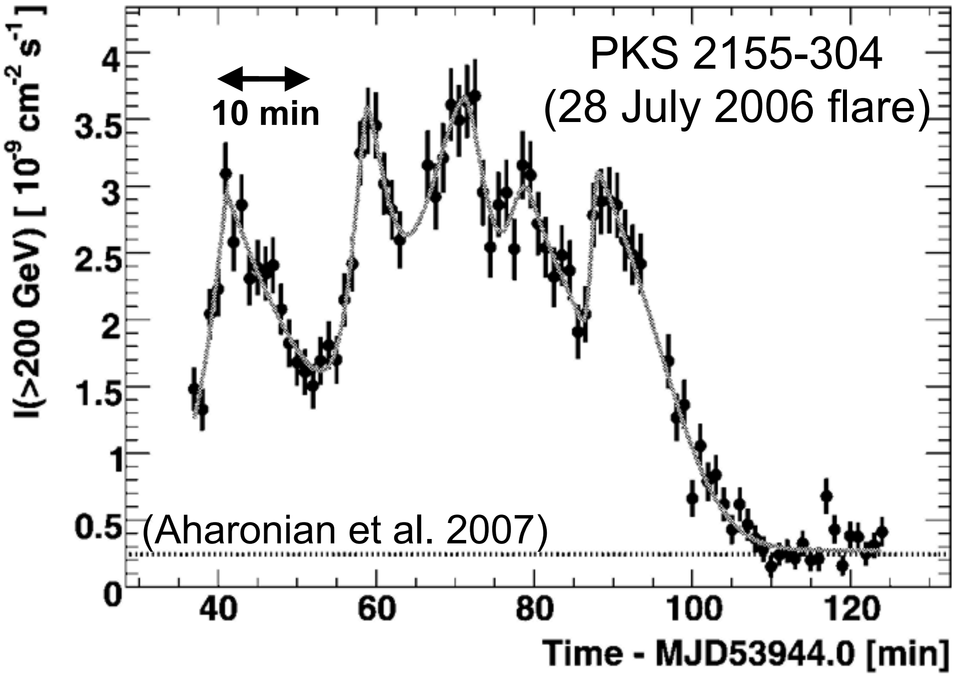
Why is it important?

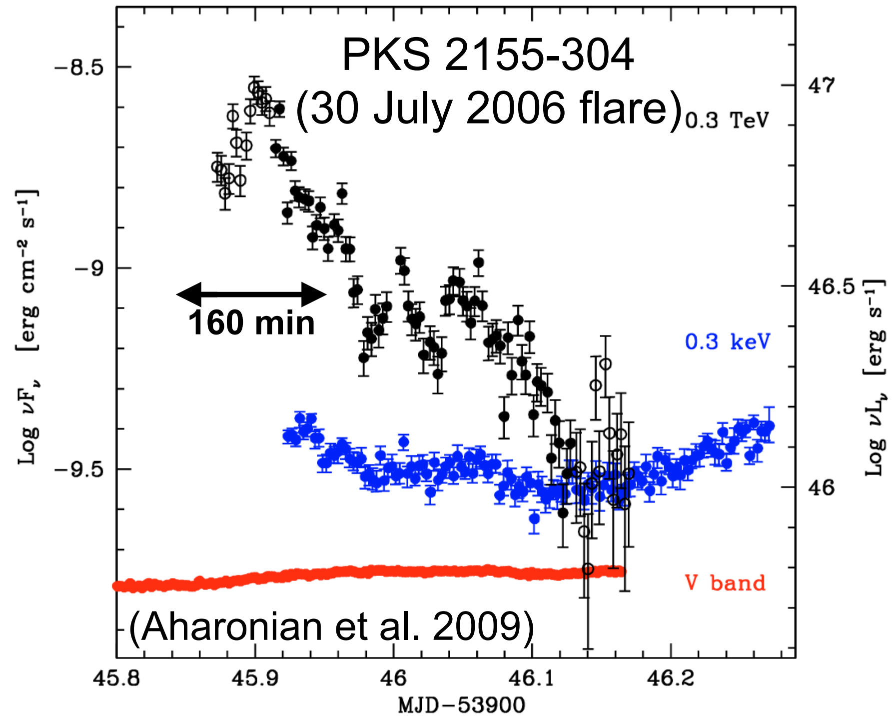
Natural explanation of **ultrafast variability of gamma-ray flares**
Natural explanation of **orphan gamma-ray flares**

Prediction: ultrafast gamma-ray flares are orphan
Can be tested with multiwavelength observations

Extra

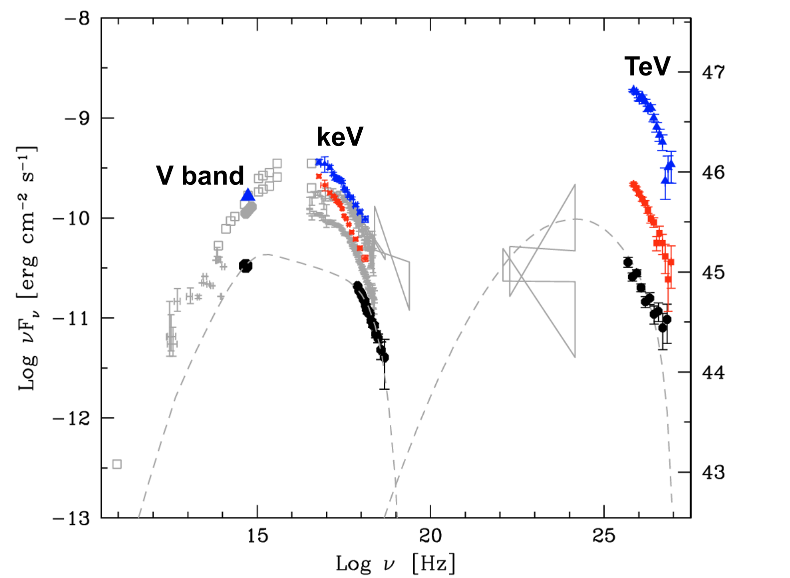
Multiwavelength observations are crucial!





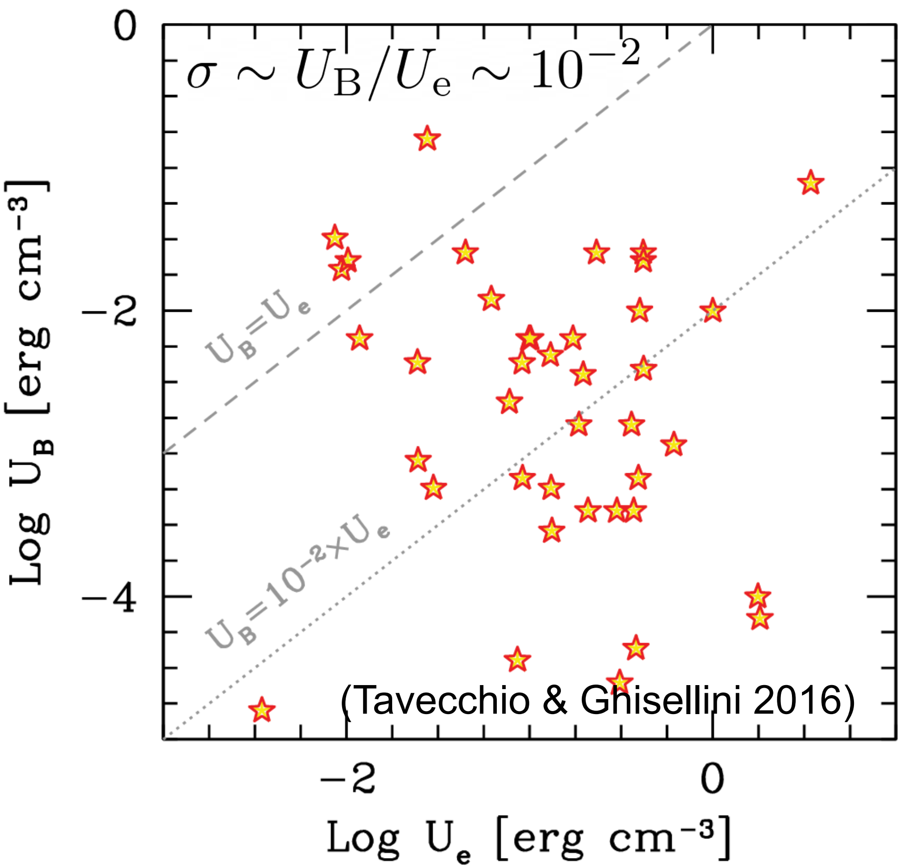
variability timescale ~ a few minutes
<<
light crossing time
of the SMBH event horizon

$$T_g = 2GM/c^3 \sim 160 \left(M/10^9 M_\odot\right) \mathrm{min}$$



Solution of the "sigma-problem" of AGN jets

If particles were **isotropic**, modelling of the spectrum would require that AGN jets are weakly magnetized **magnetization sigma<<1**



If particles are anisotropic, modelling of the spectrum can be consistent with a large magnetization

$$P_{\rm sync} \propto B^2 \sin^2 \alpha$$
$$\nu_{\rm sync} \propto B \sin \alpha$$

what we really measure is

$$(U_{\rm B}/U_{\rm e}) \sin^2 \alpha \sim 10^{-2}$$

$$\sin \alpha \sim 0.1$$
$$U_{\rm B}/U_{\rm e} \sim 1$$

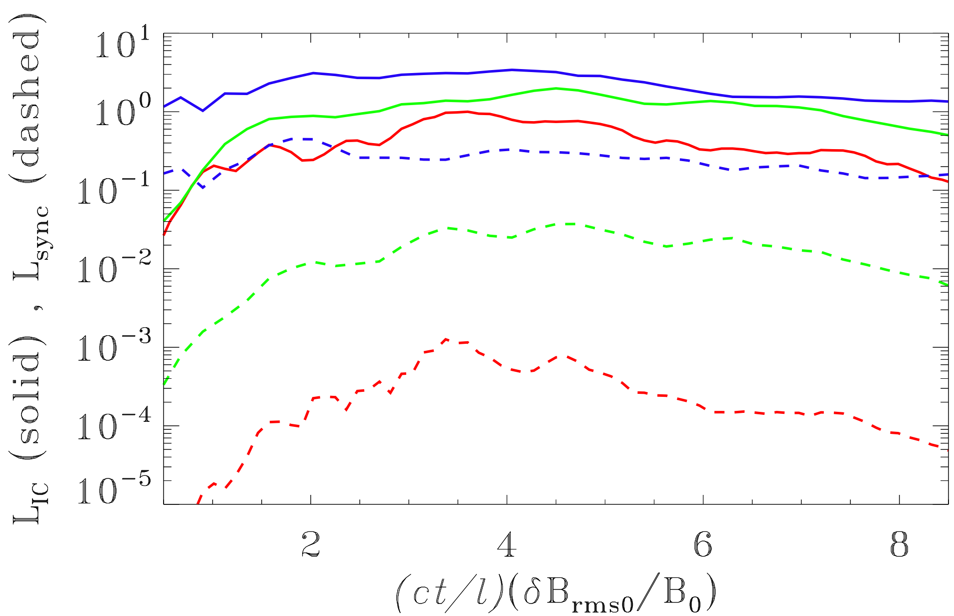
(ES & Lyubarsky 2019;
ES, Sironi & Beloborodov 2021)

“Standard” emission from blazars

synchrotron ~ IC luminosity in the large majority of cases **(orphan gamma-ray flares are the exception!)**

→

need for a mechanism to isotropize the particle distribution



(ES, Nättilä & Sironi 2021)

$$(\delta B/B_0)^2 = 0.25, 1, 4$$

pitch angle of the injected particles depends on the initial conditions

larger initial fluctuations give larger pitch angles