Jet Gravitational Waves

Tsvi Piran

Ofek Birnholtz, Eli Leiderschneider, Dimitry Ofengeim

erc
GRB
TReX
MultiJets

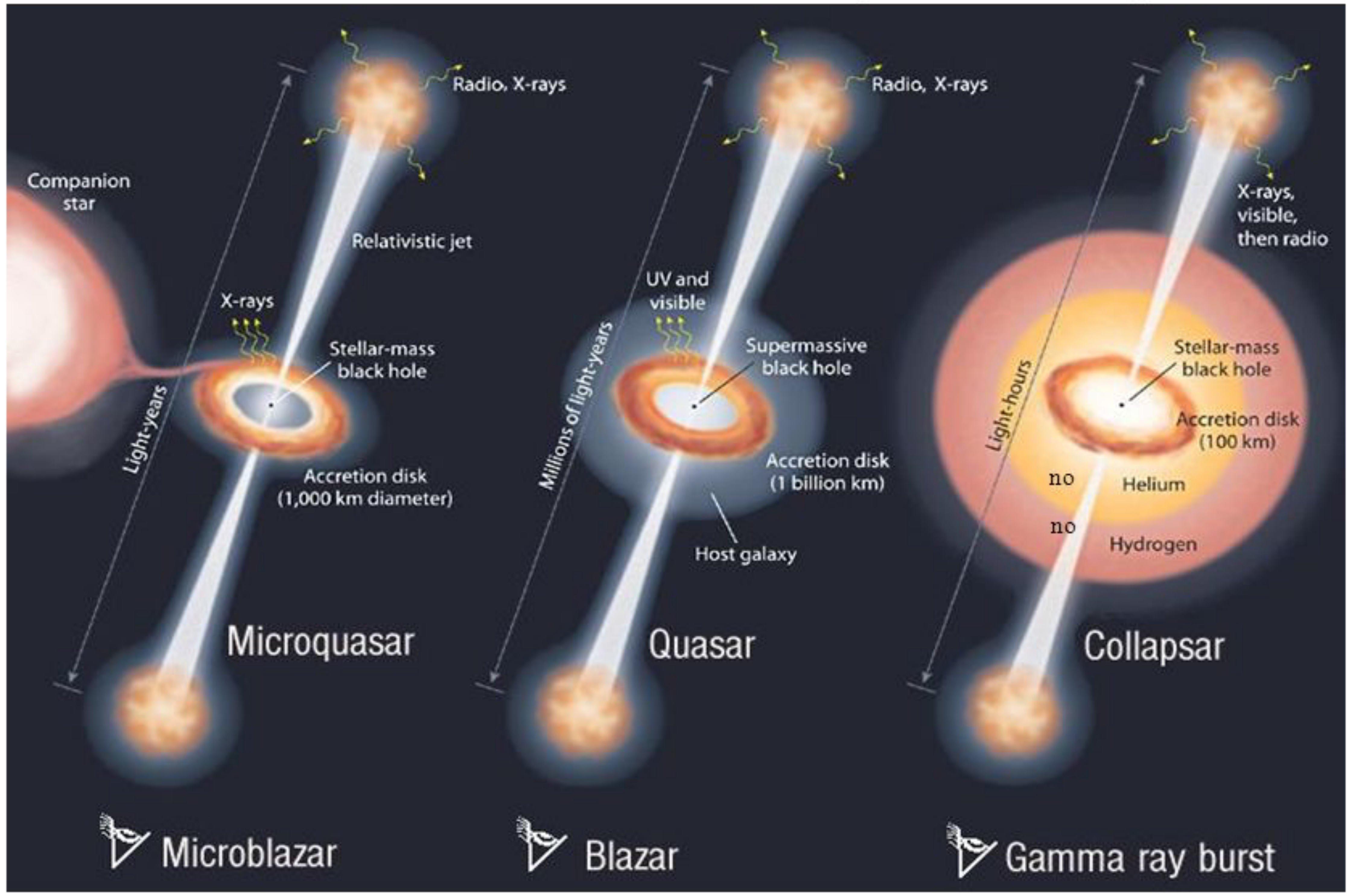
Nishinomiya-Yukawa Symposium February 2024, Kyoto Japan

Outline

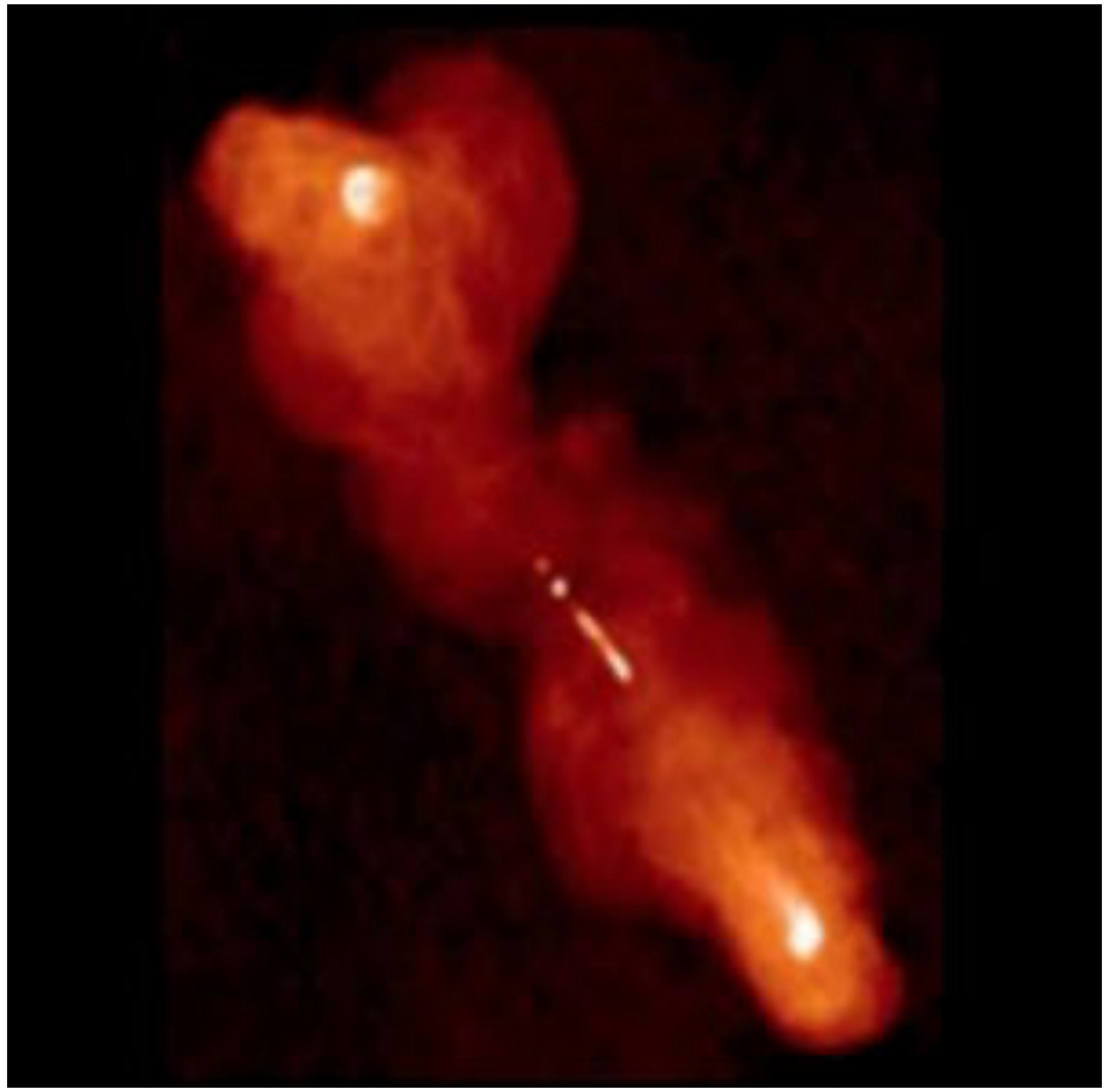
- Jets are everywhere
- GW from jet acceleration (and deceleration)
- Astrophysical sources and Limits
- Lunar Detectors
- (Lorentz Invariance Violation and 221009A)

Relativistic Jets are Everywhere

Many jets are transients



From: Mirabel and Rodriguez 2002

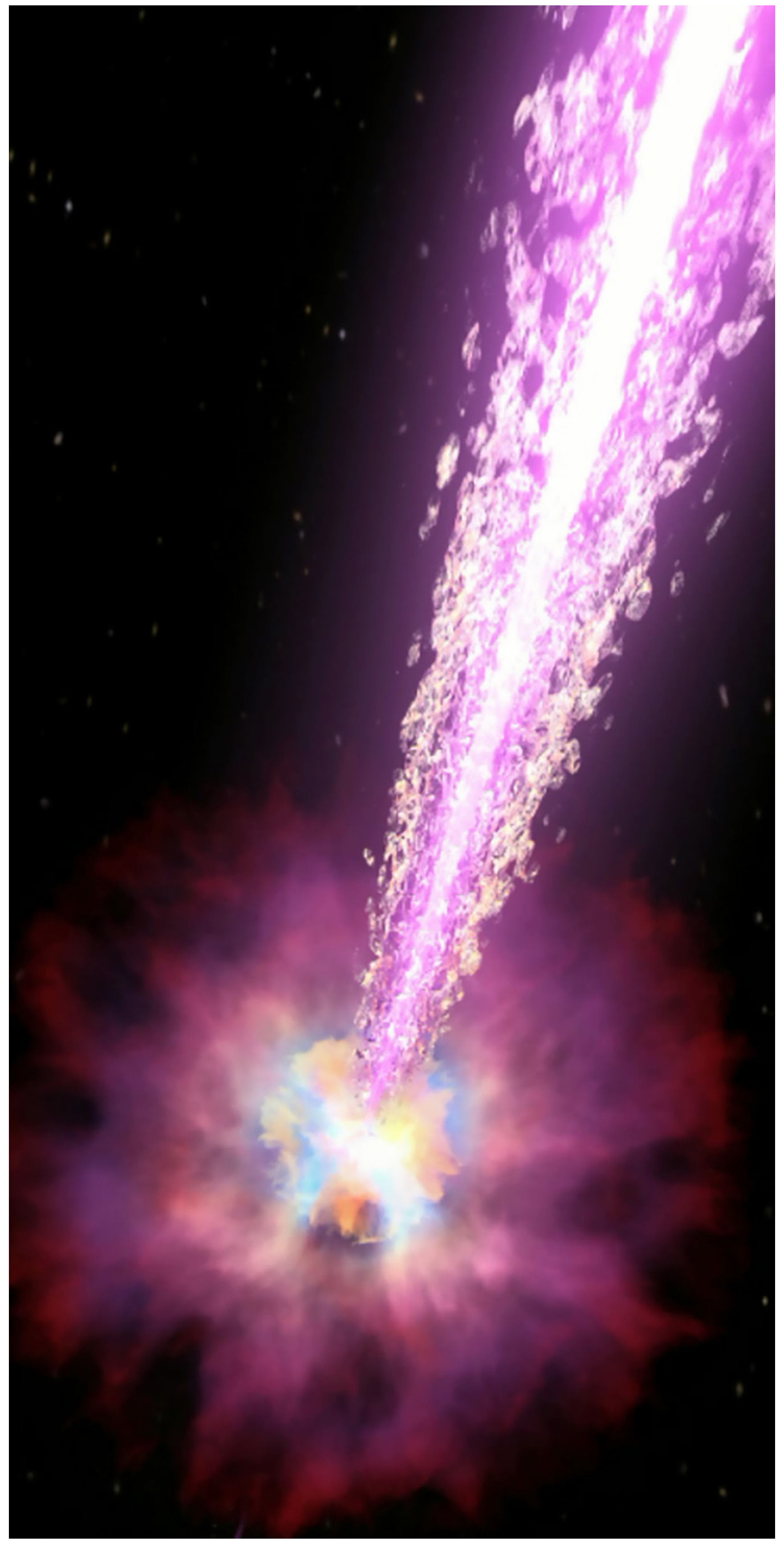


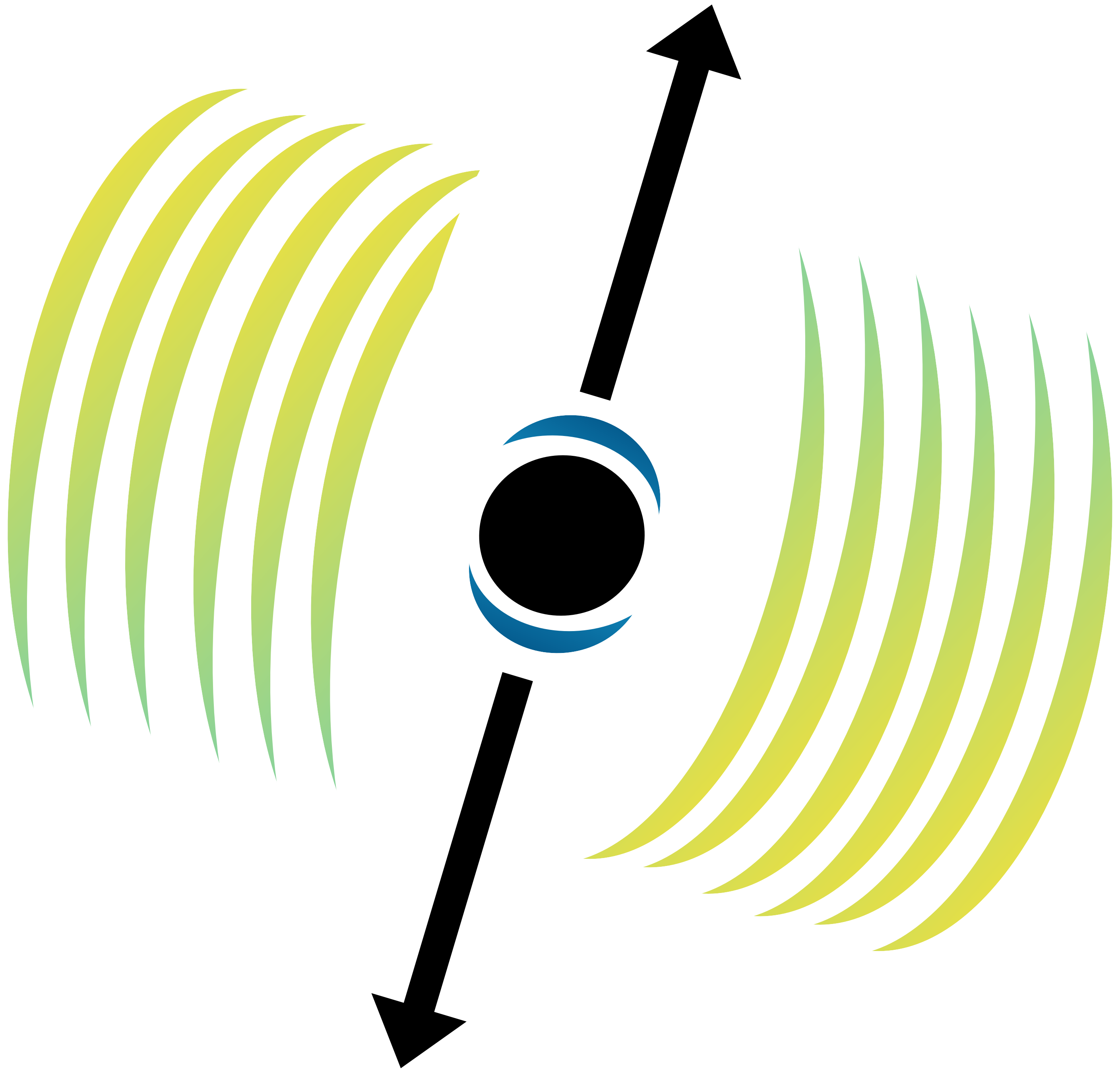
AGN 3C219 in Radio

The EM or even neutrino signals arrive from large distances form the black hole. The acceleration regions are hidden.

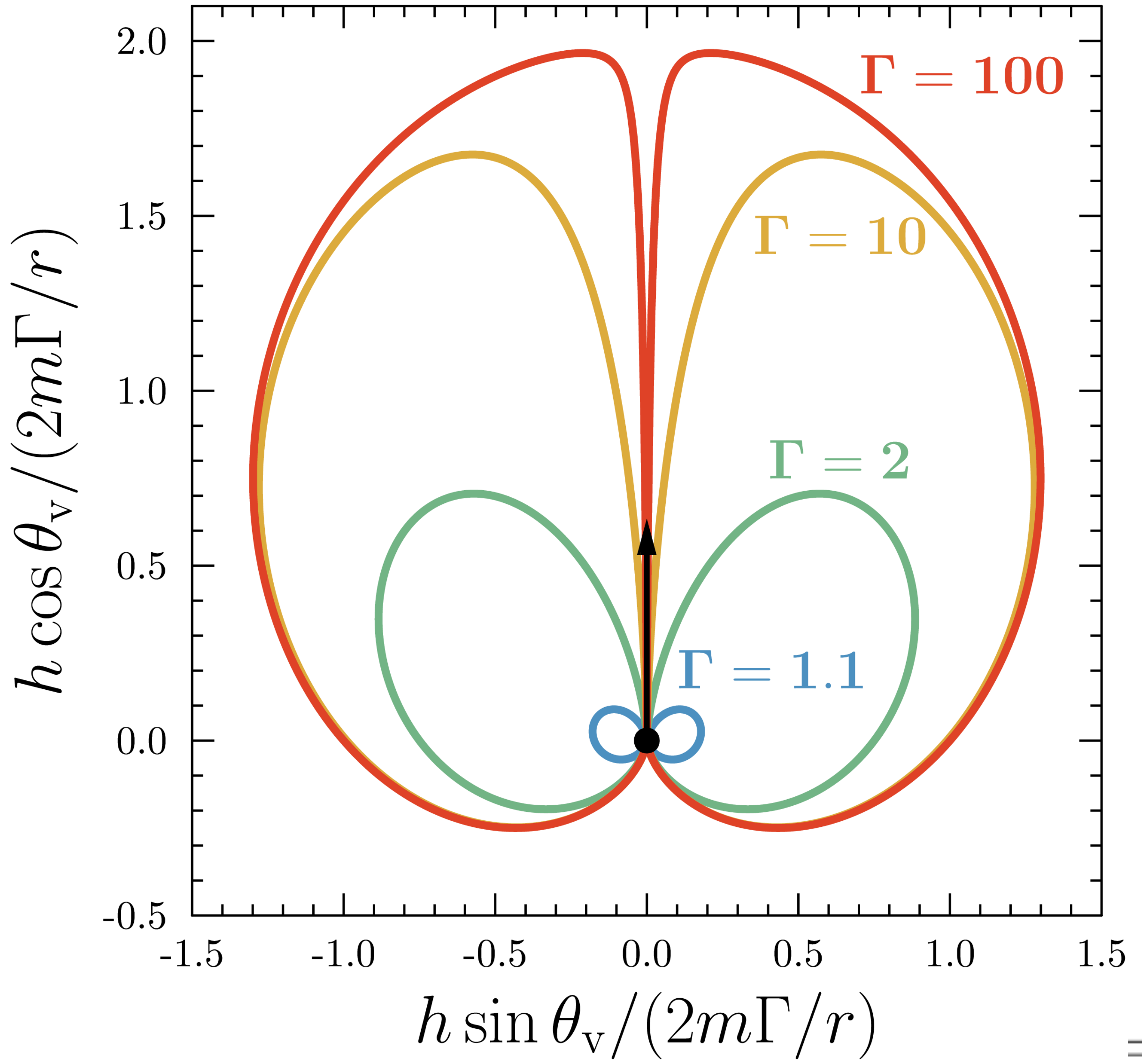
We *CAN* see directly jet acceleration

Acceleration of $\sim 10^{50}$ erg from rest to c $\rightarrow$ Jet-GW

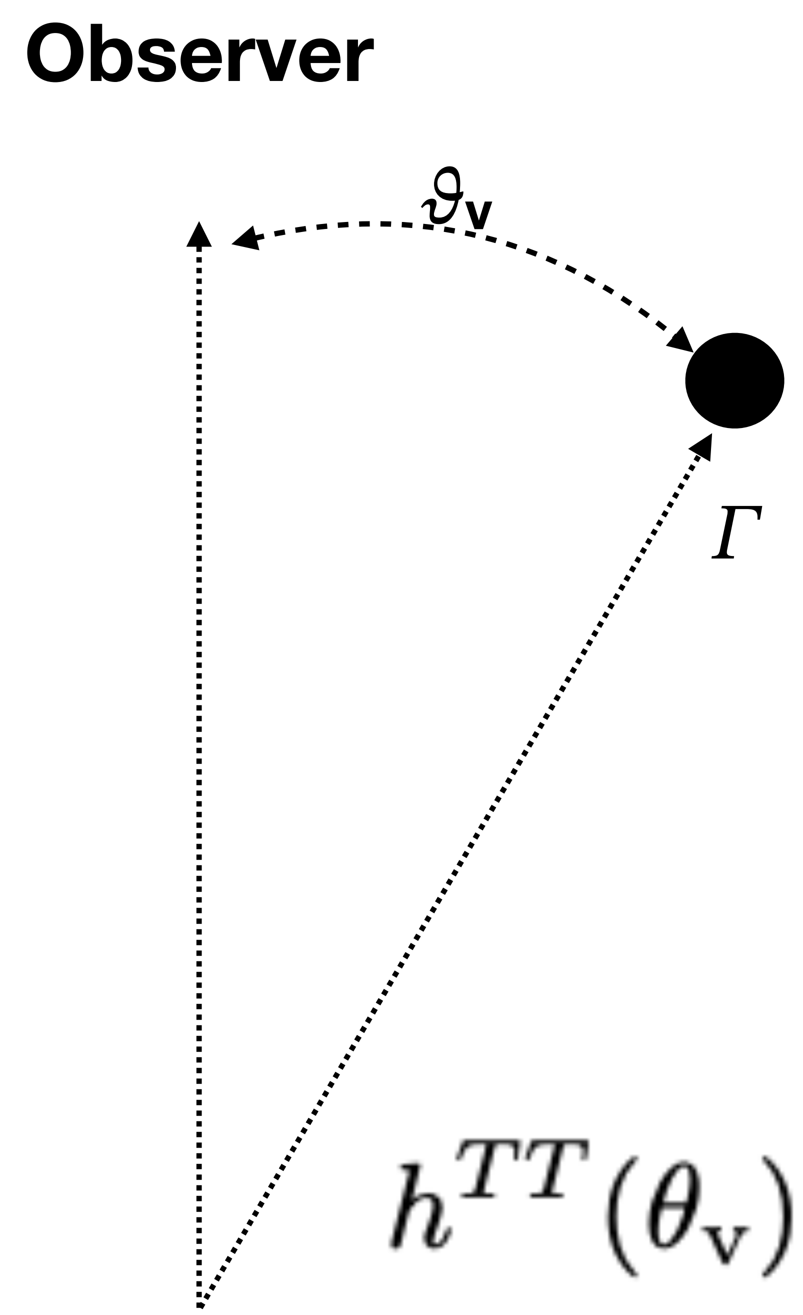




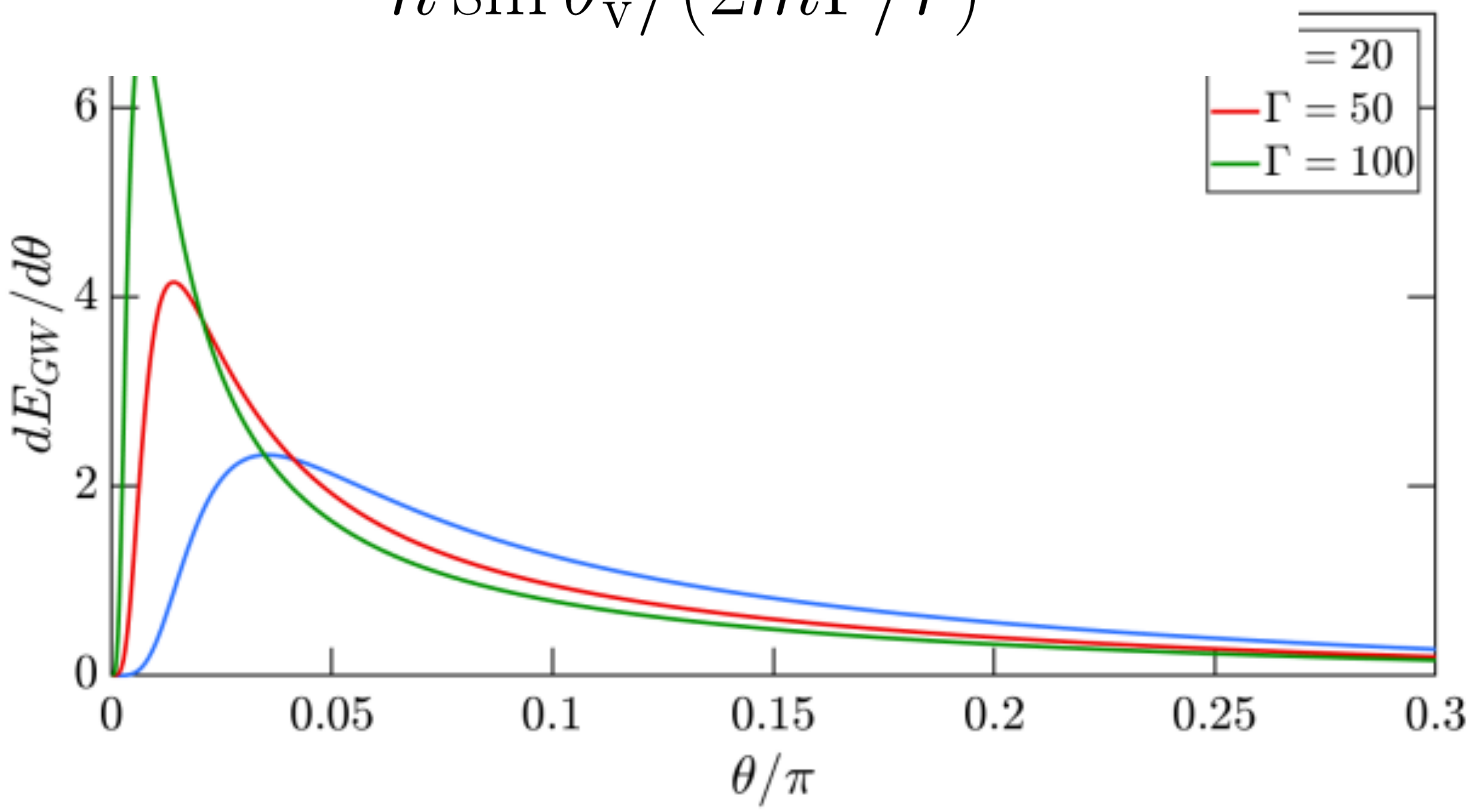
A point source



Segalis & Ori 2001; Piran 2002



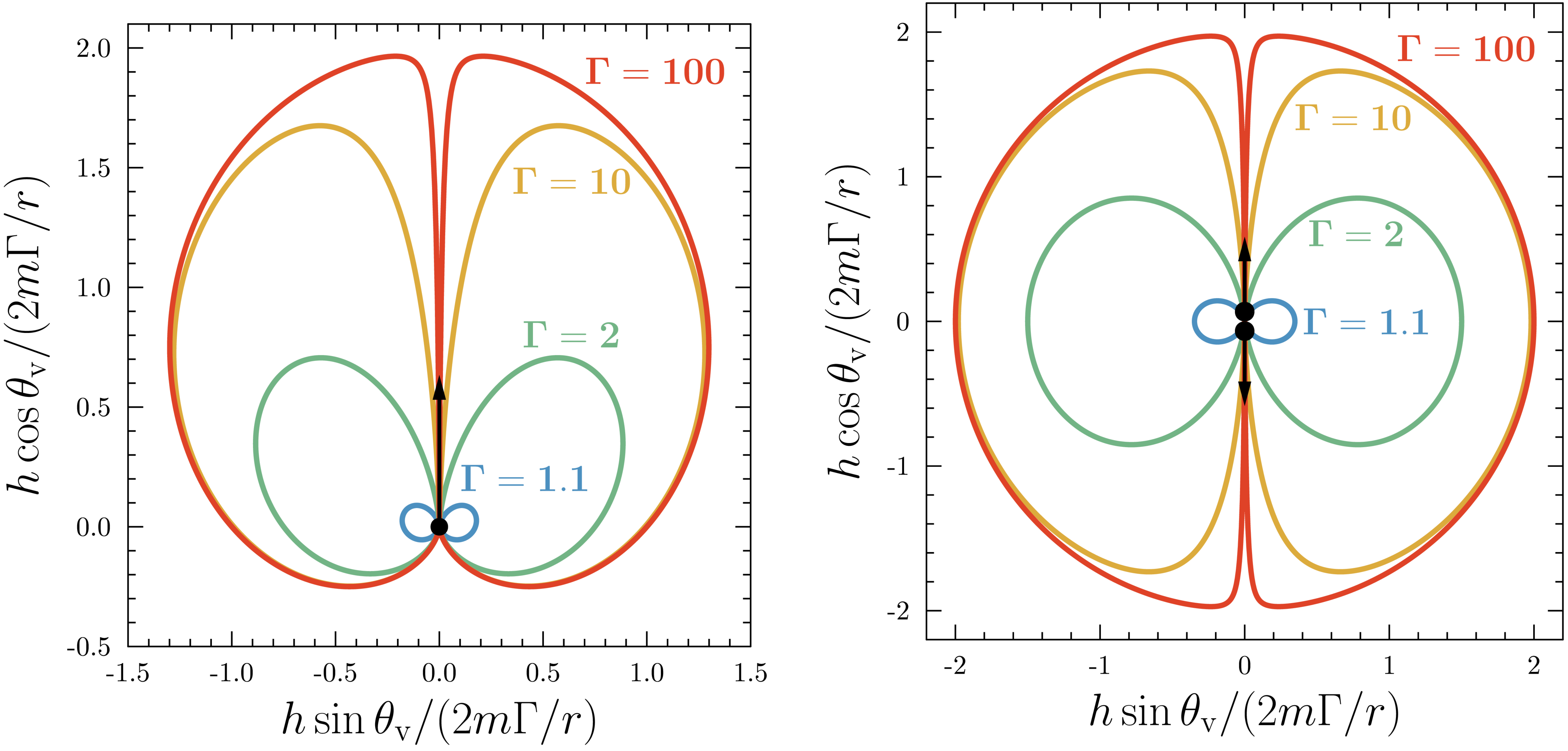
$$h^{TT}(\theta_v) = h_+ + ih_x = \frac{2\mathcal{E}\beta^2}{r}\frac{\sin^2\theta_v}{1-\beta\cos\theta_v}e^{2i\phi}$$



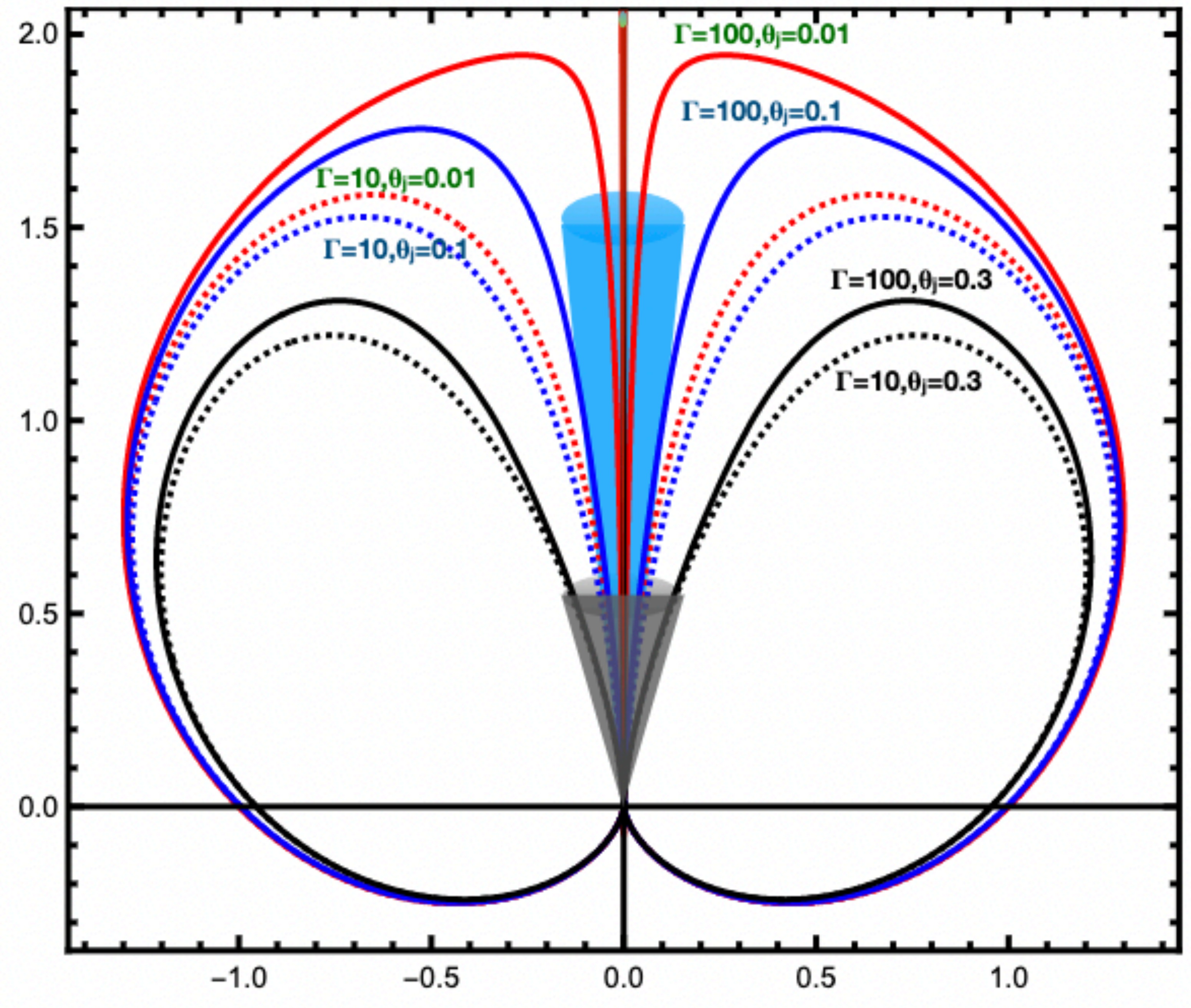
$$h_{\max} = \frac{4G\mathcal{E}}{c^4 r}\frac{\Gamma}{\Gamma+1}, \quad \text{at} \quad \theta_{\max} = \cos^{-1}[\frac{1+\Gamma}{\beta\Gamma}] \approx \sqrt{\frac{2}{\Gamma}}$$

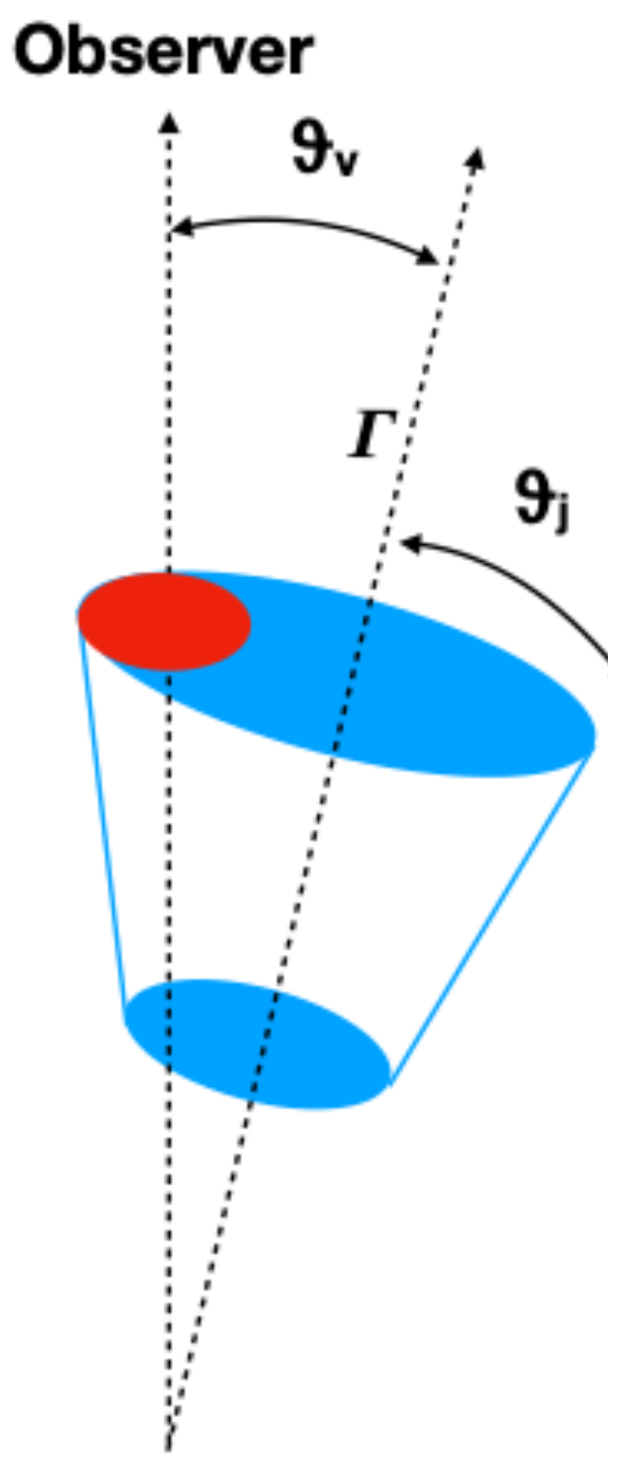
$$E_{GW} = F(\Gamma)[G\mathcal{E}/c^5 t_c]\mathcal{E}$$

One and two point source



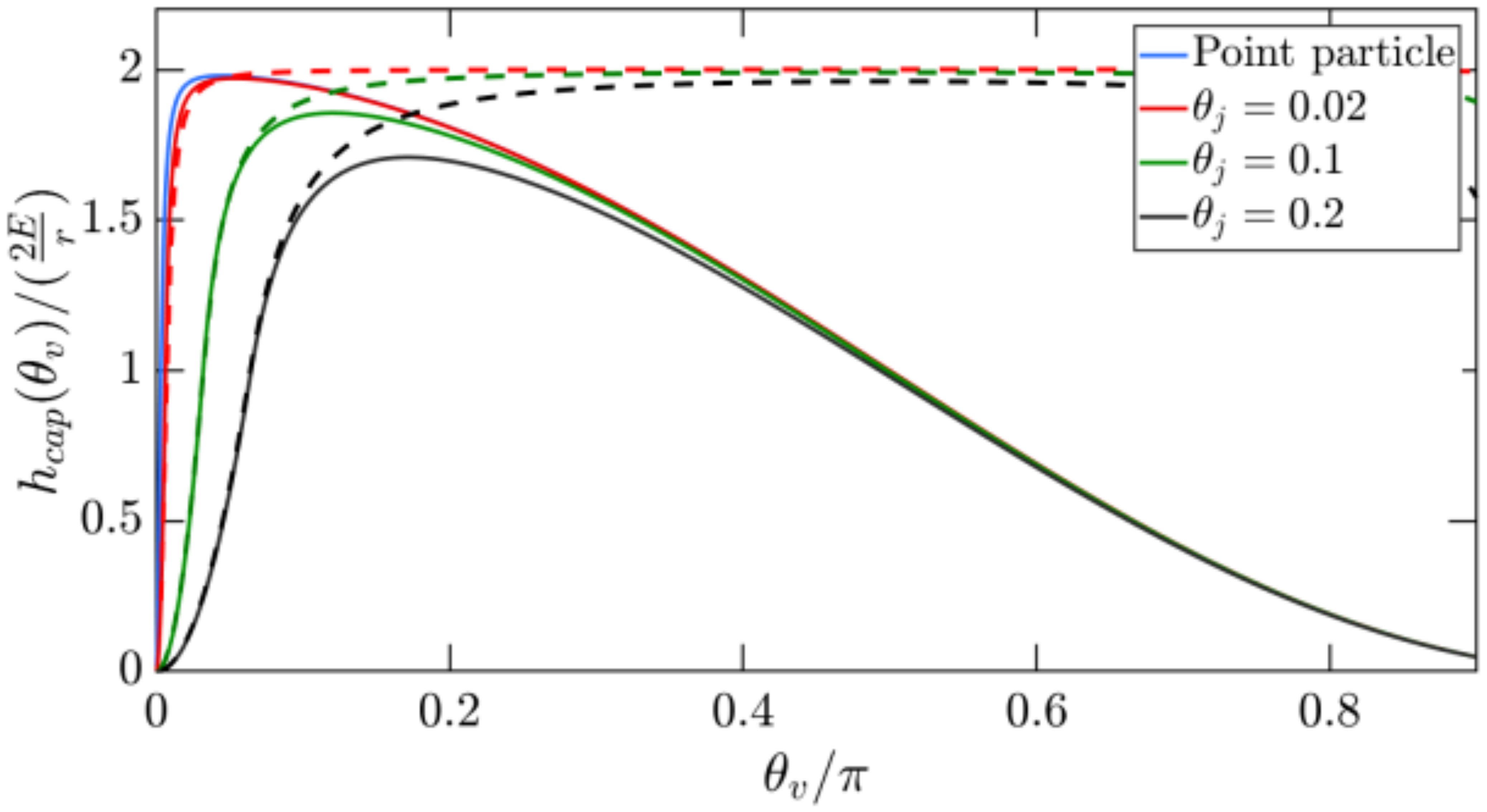
One sided jet

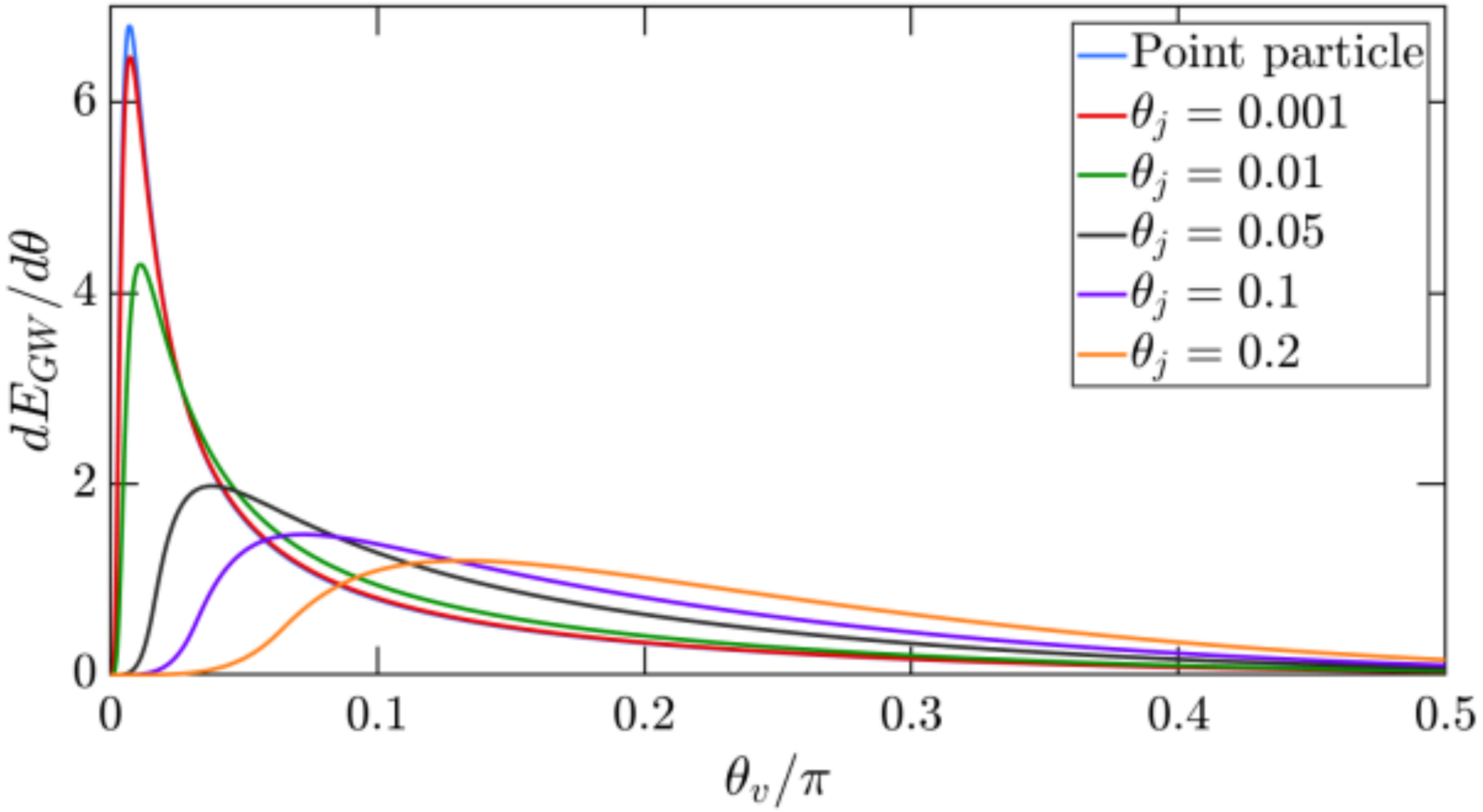




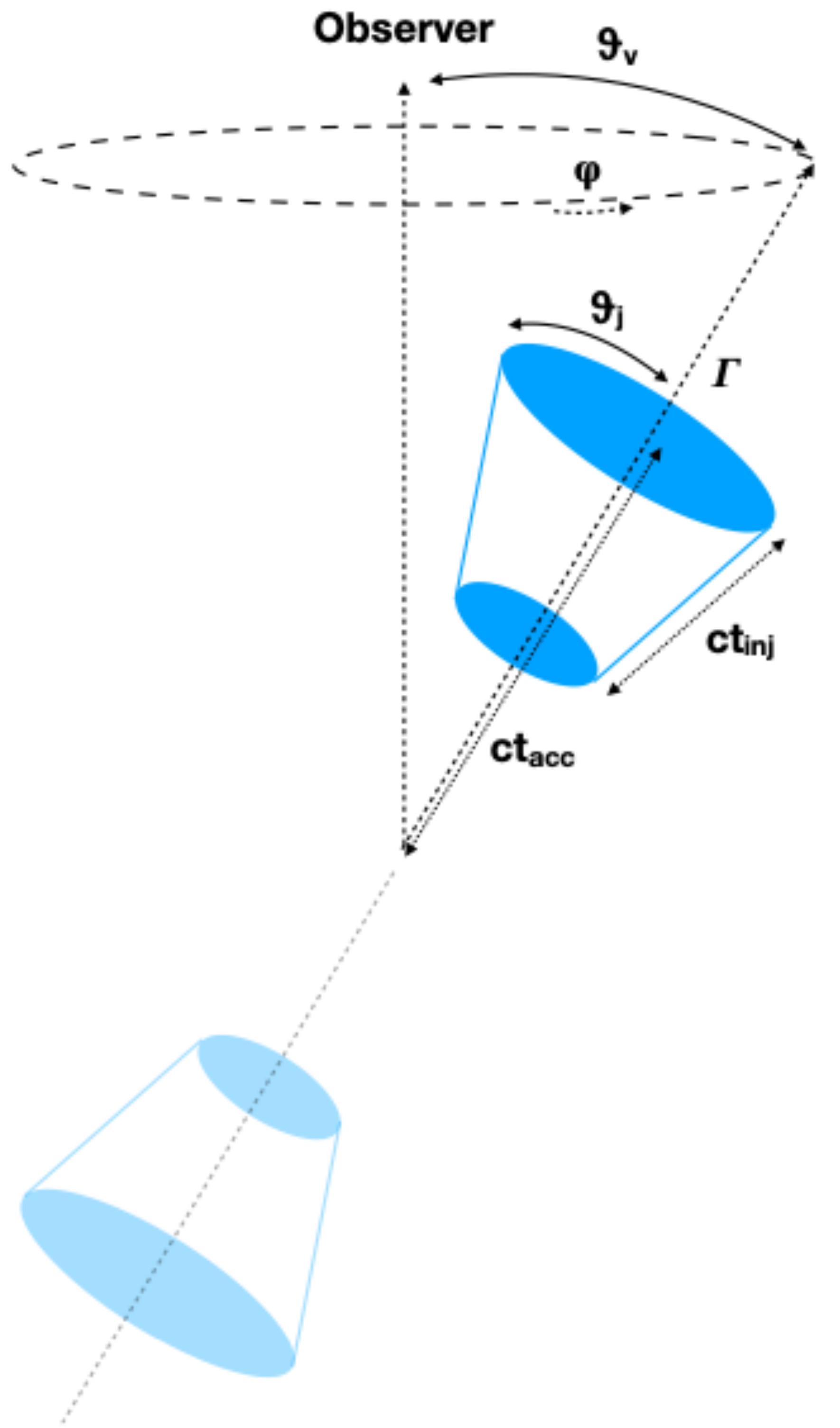
The amplitude from one sided jet

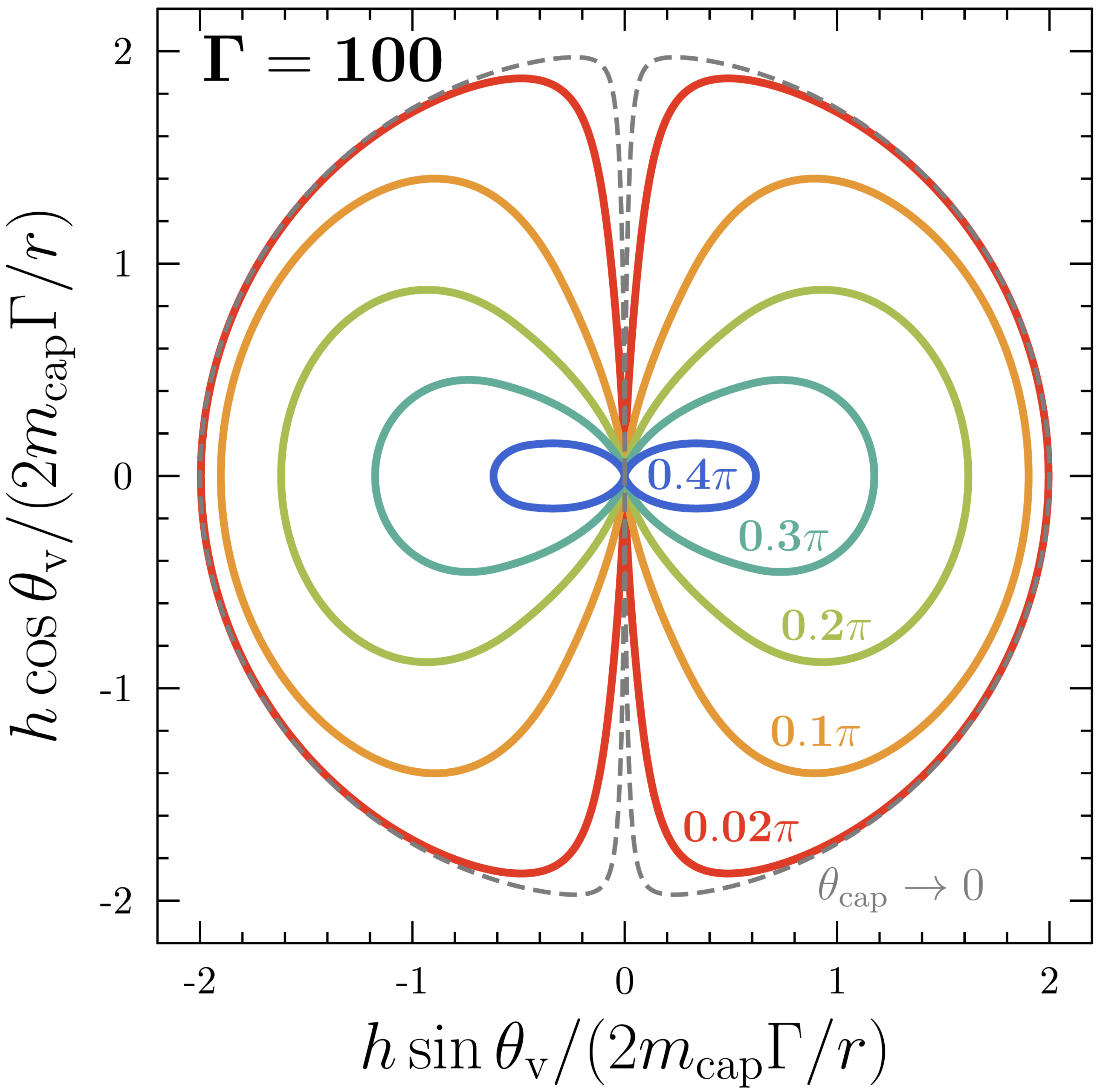
One sided jet



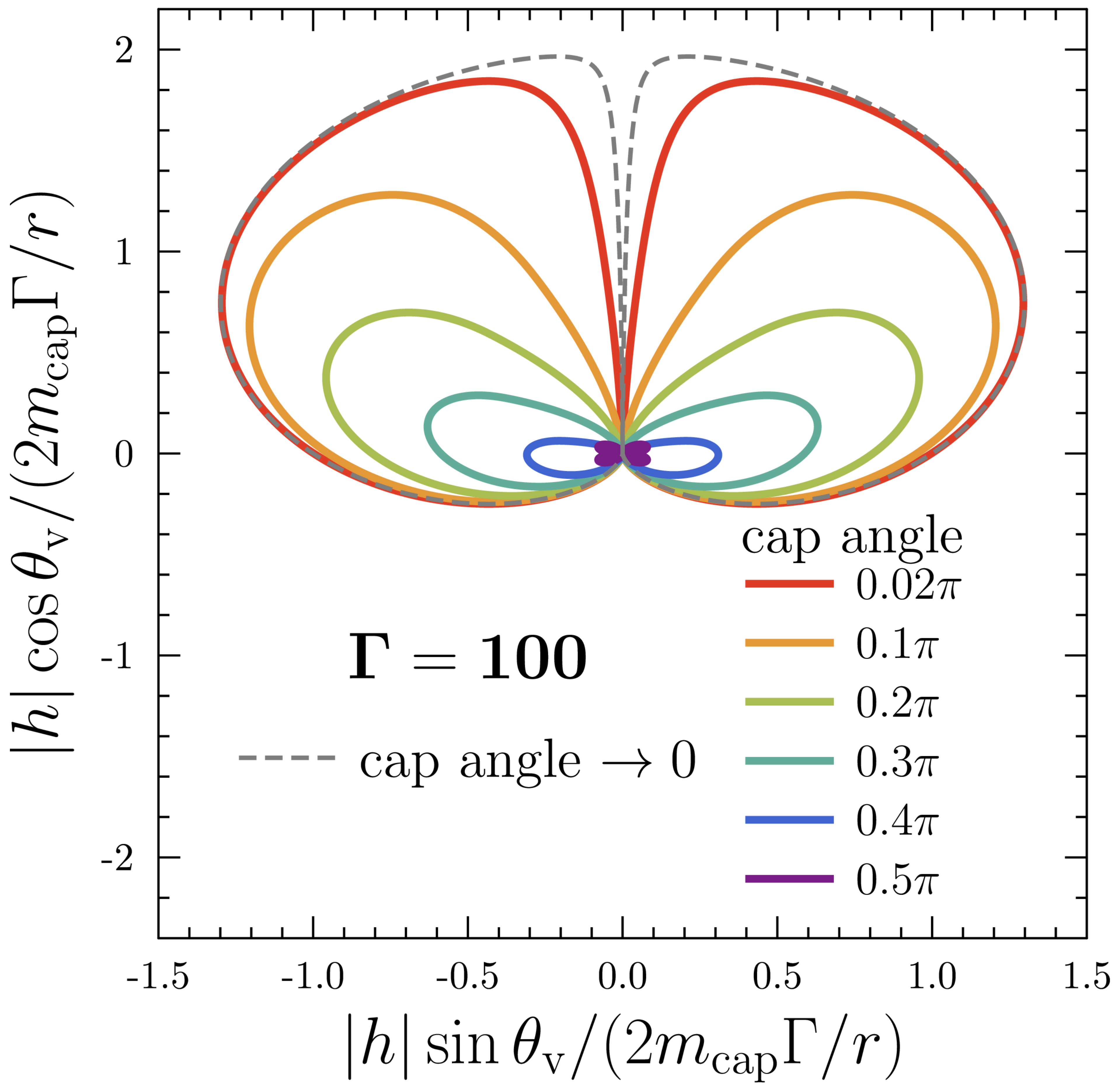


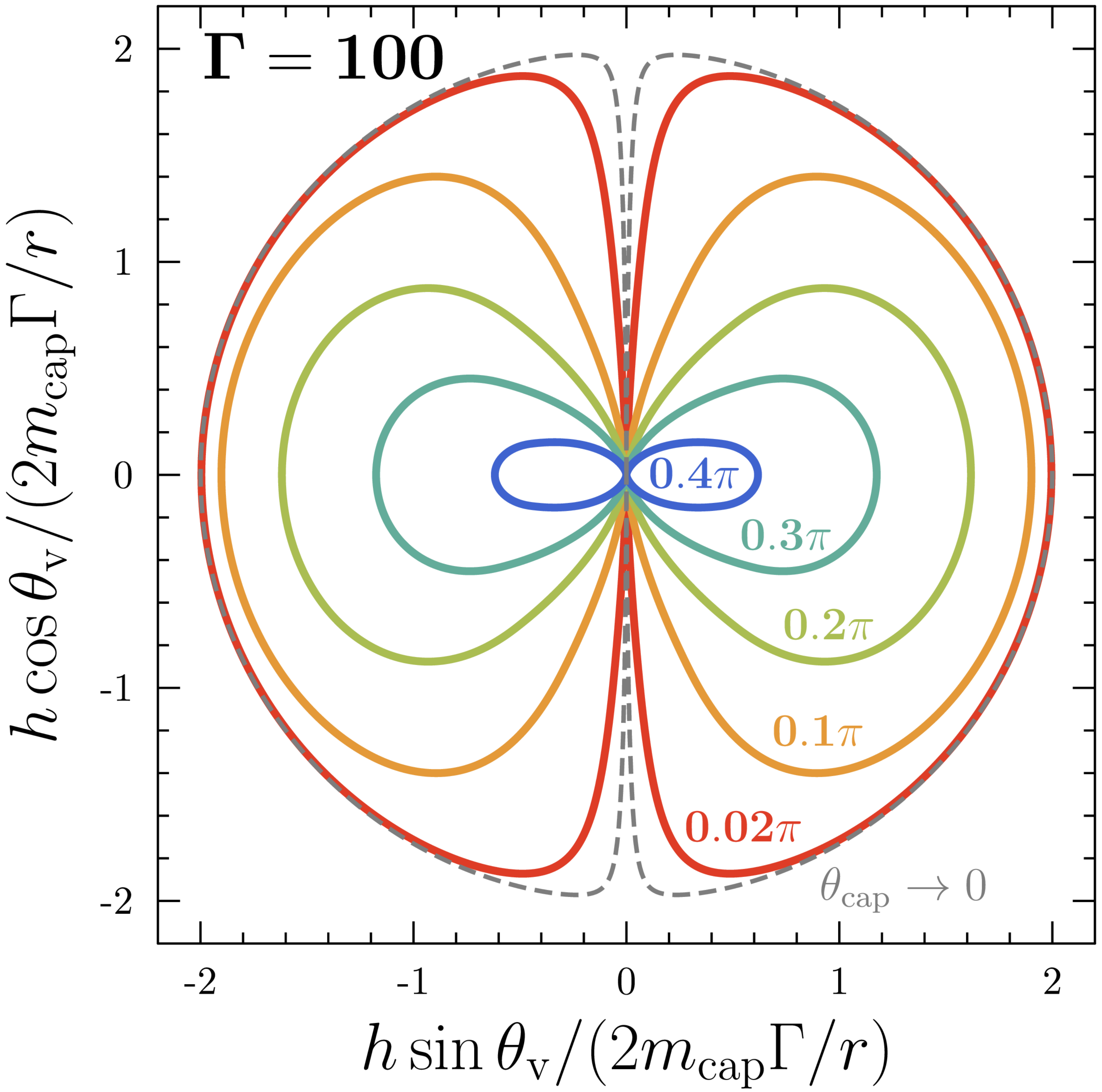
Two sided jets



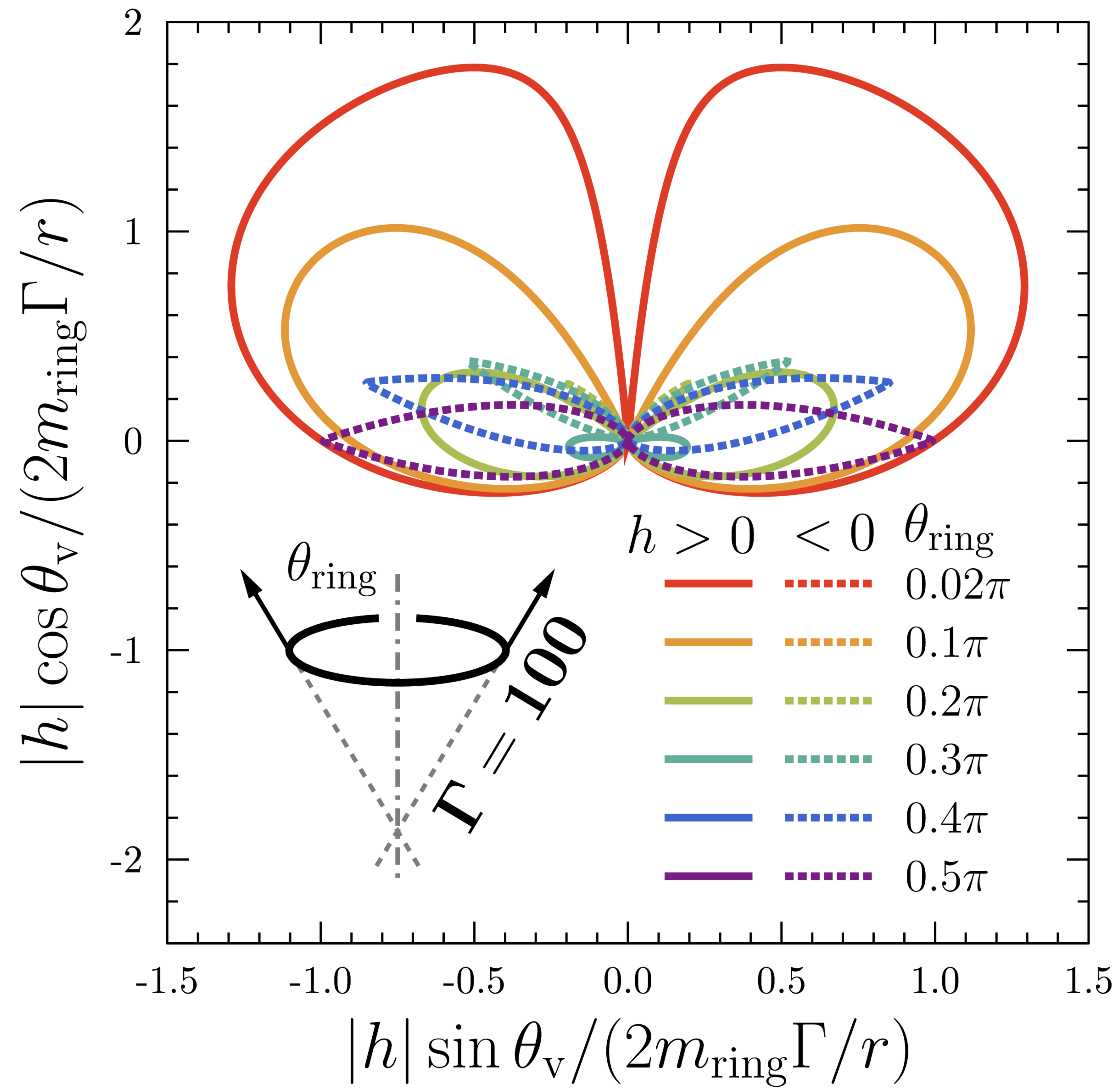


One or two jets

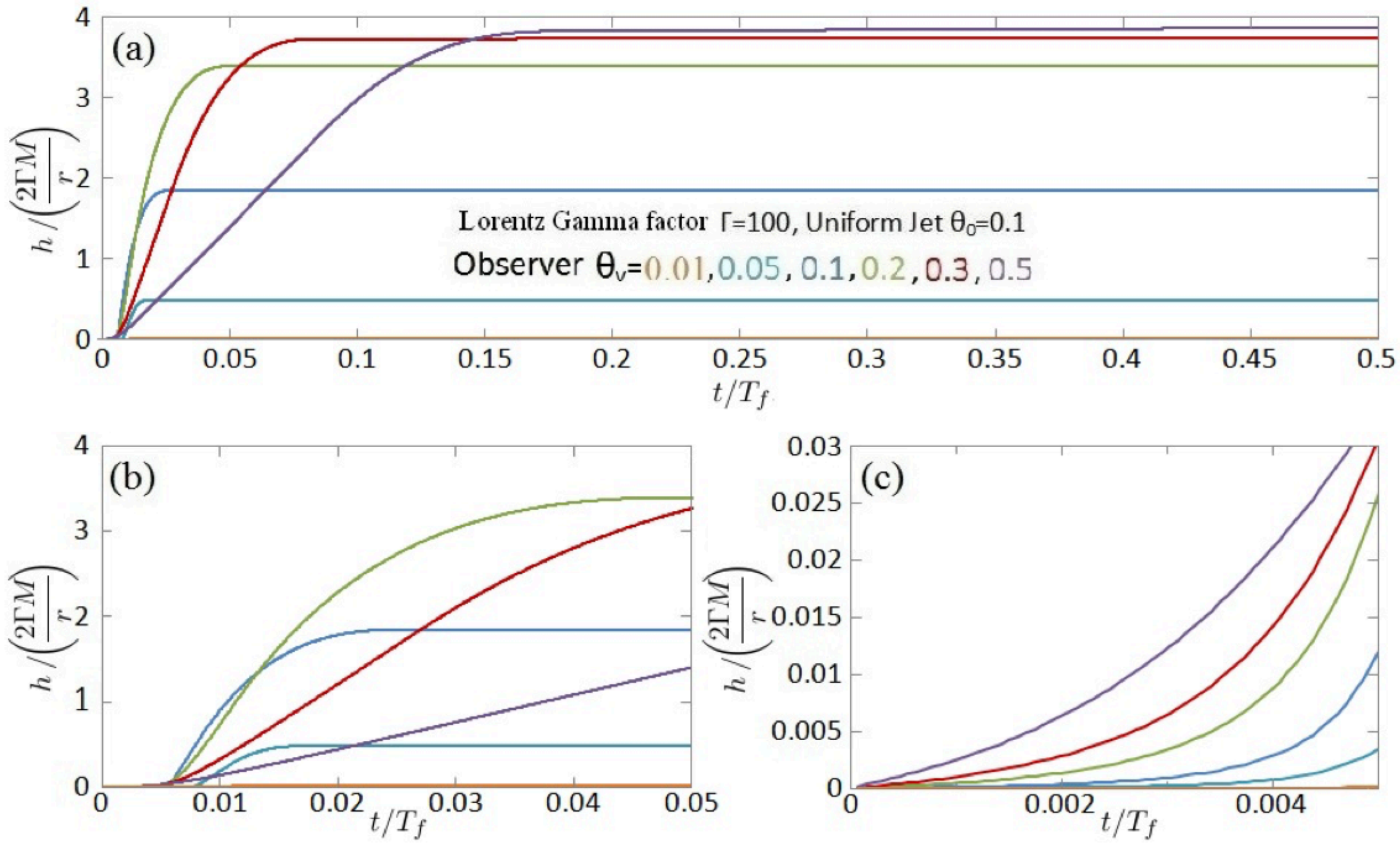




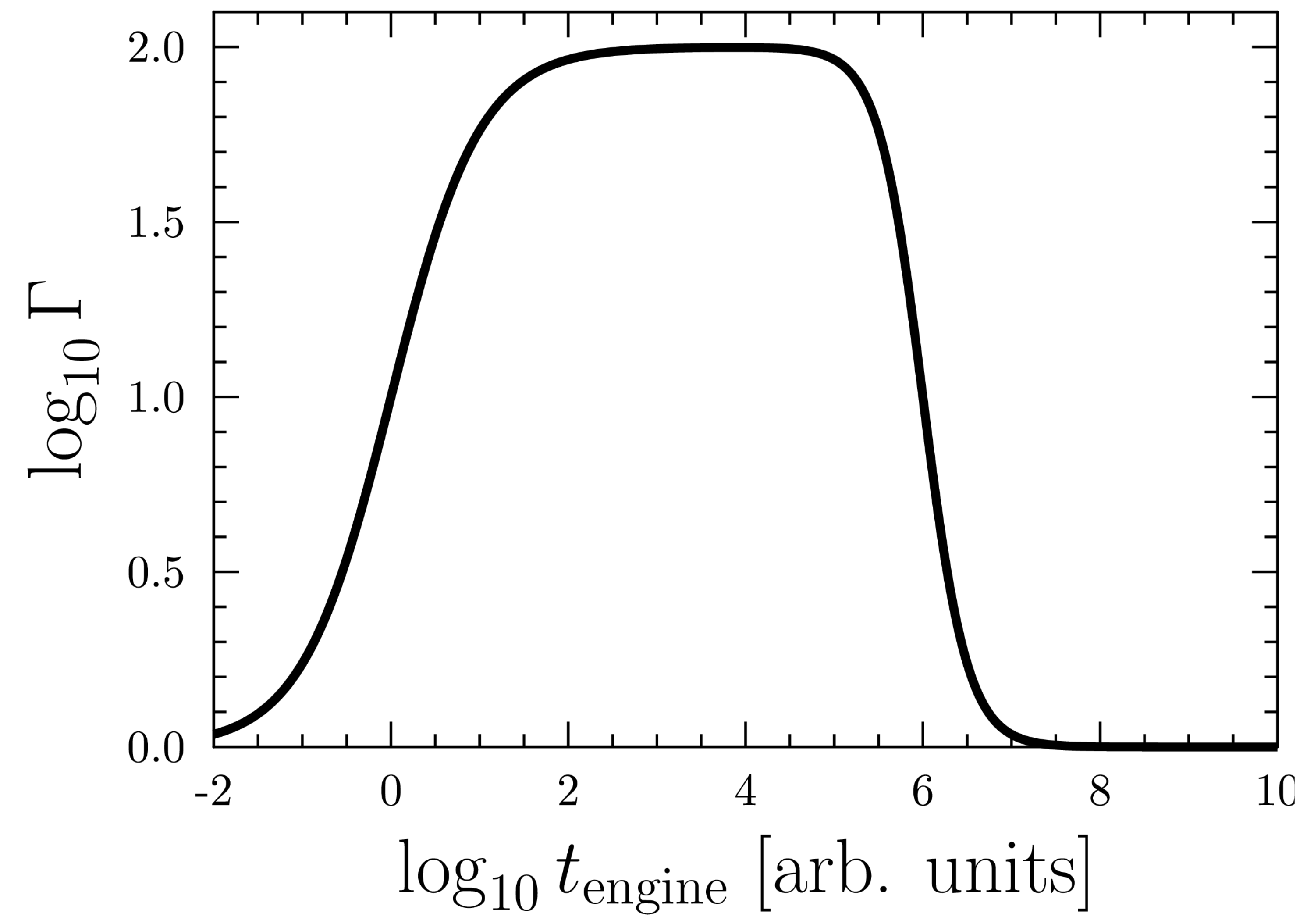
A single Accelerated Ring

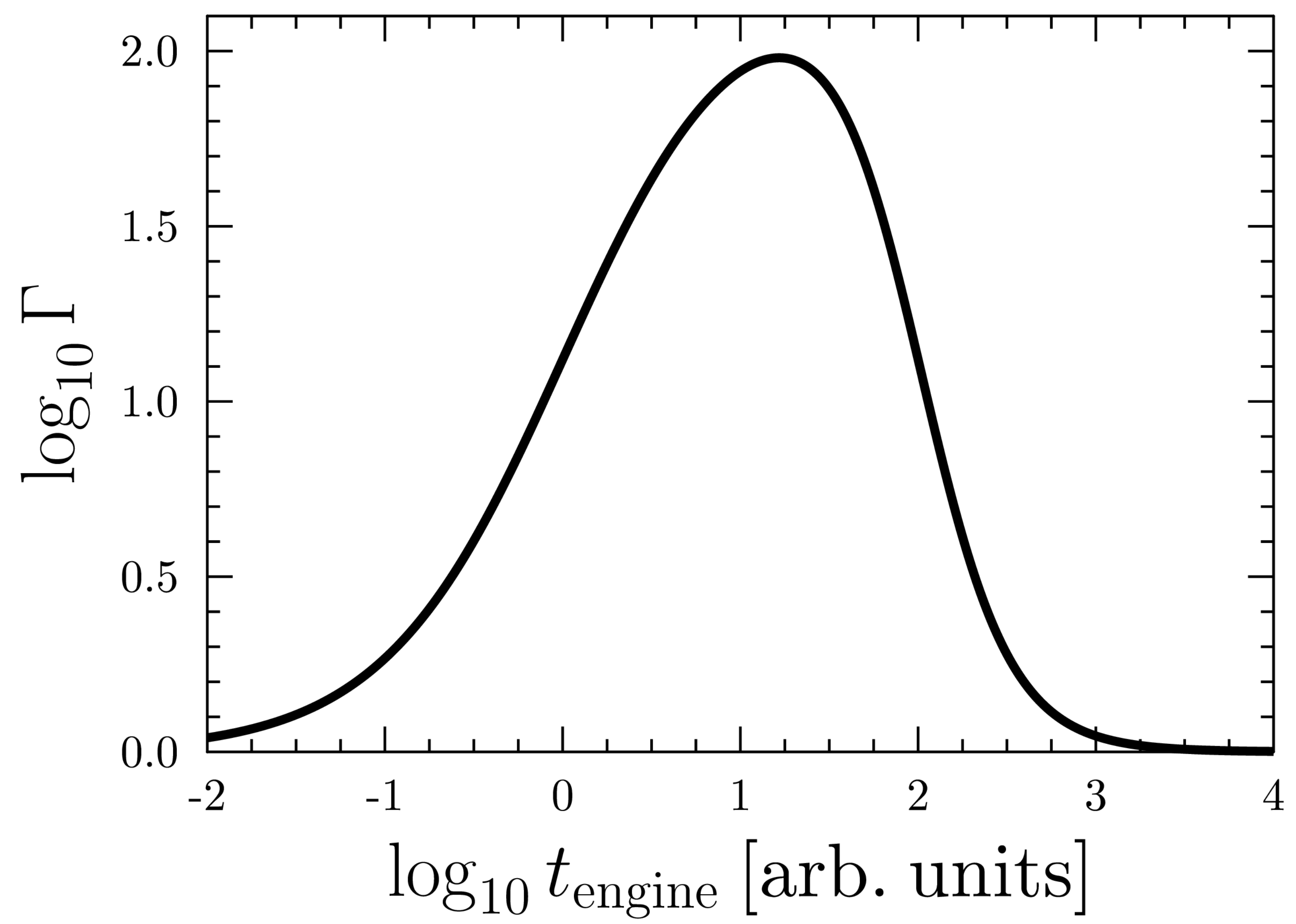


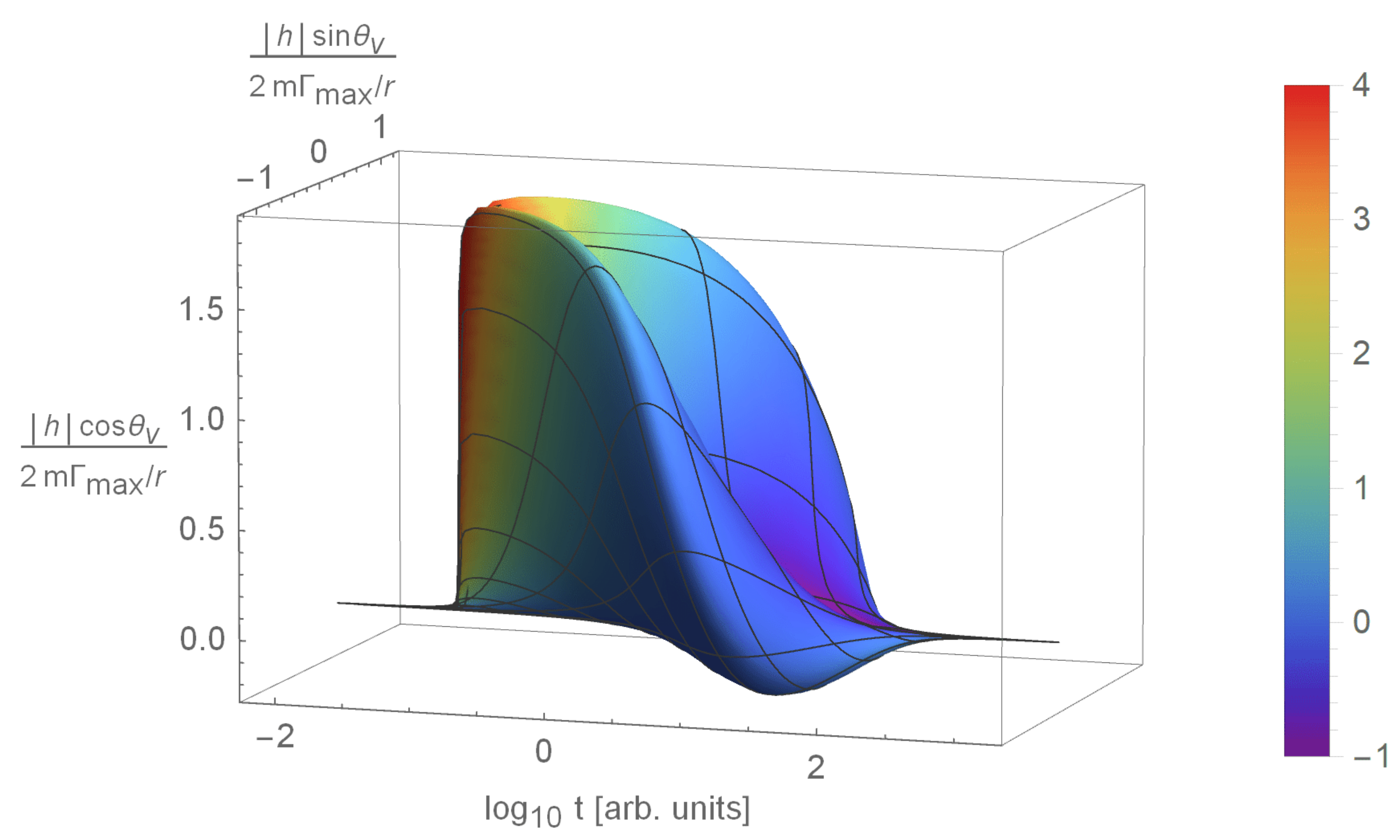
The temporal structure

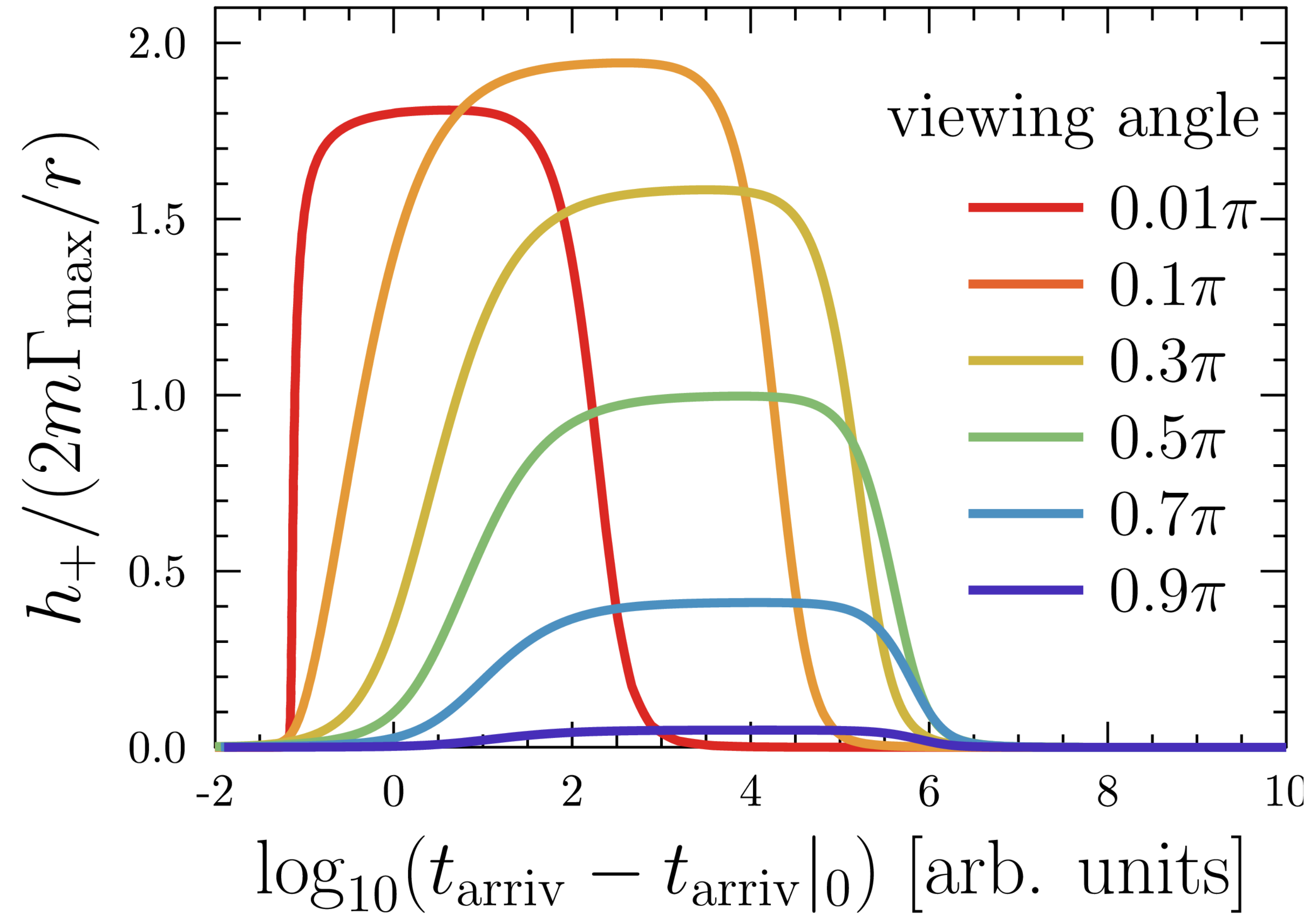


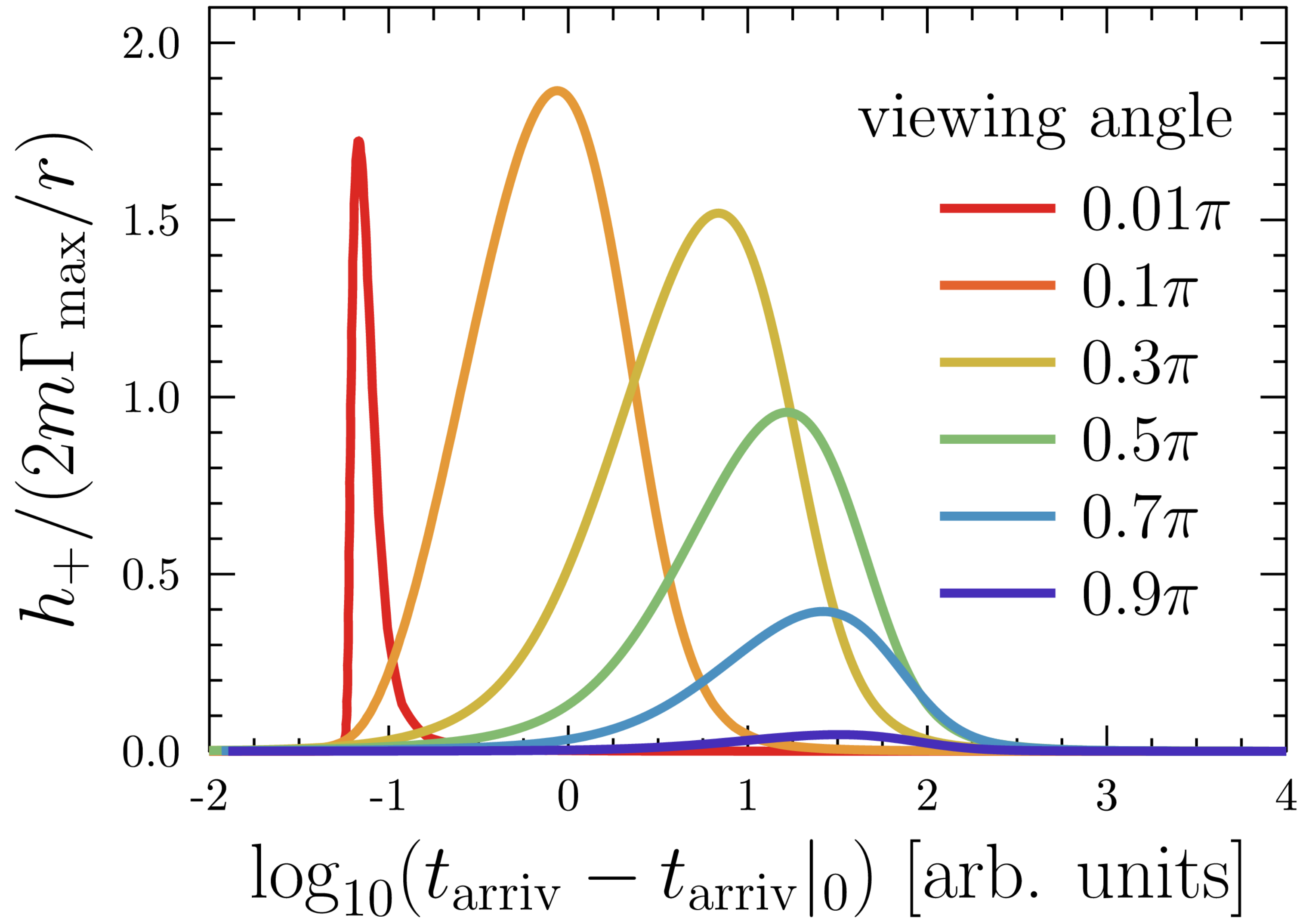
Decceleration



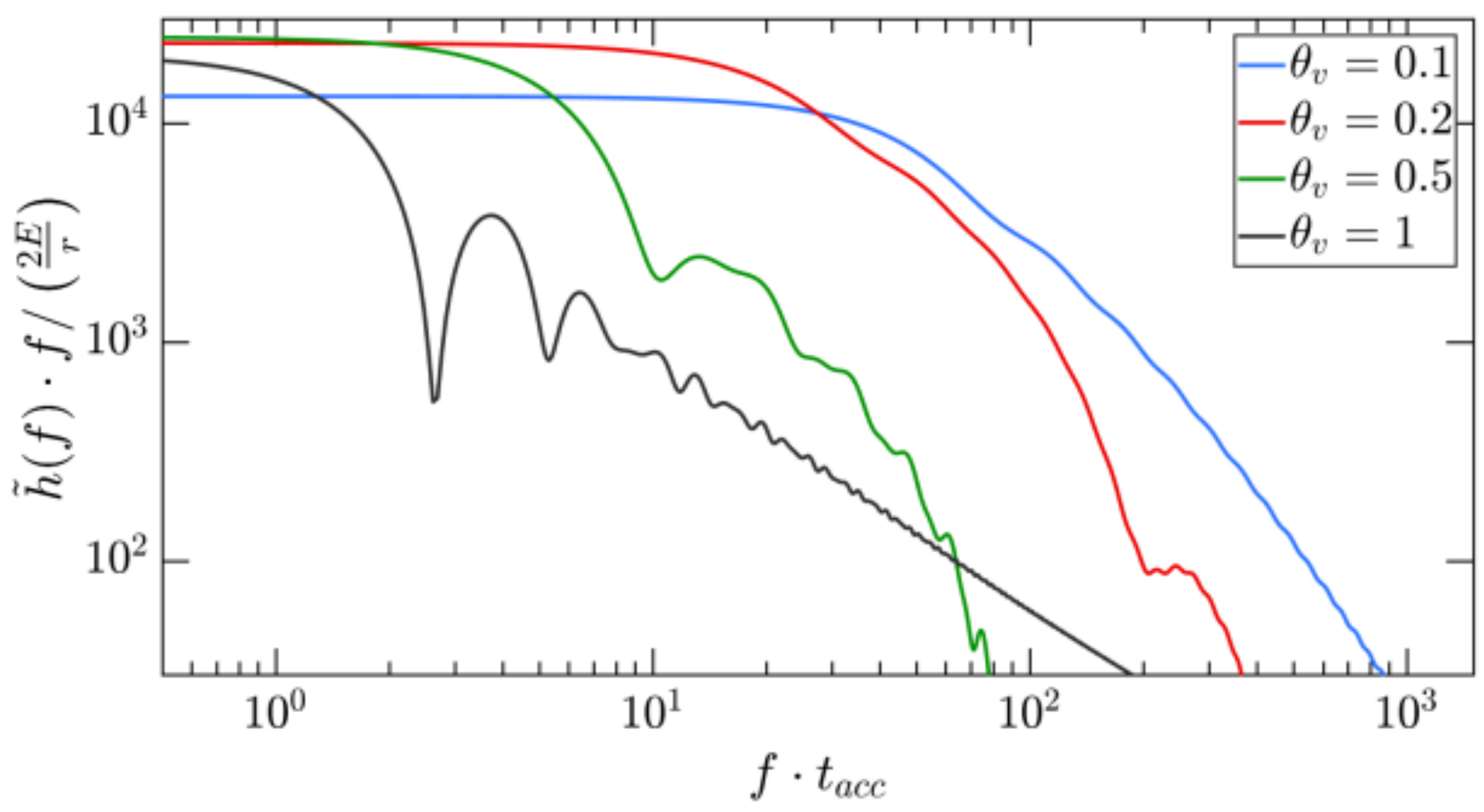


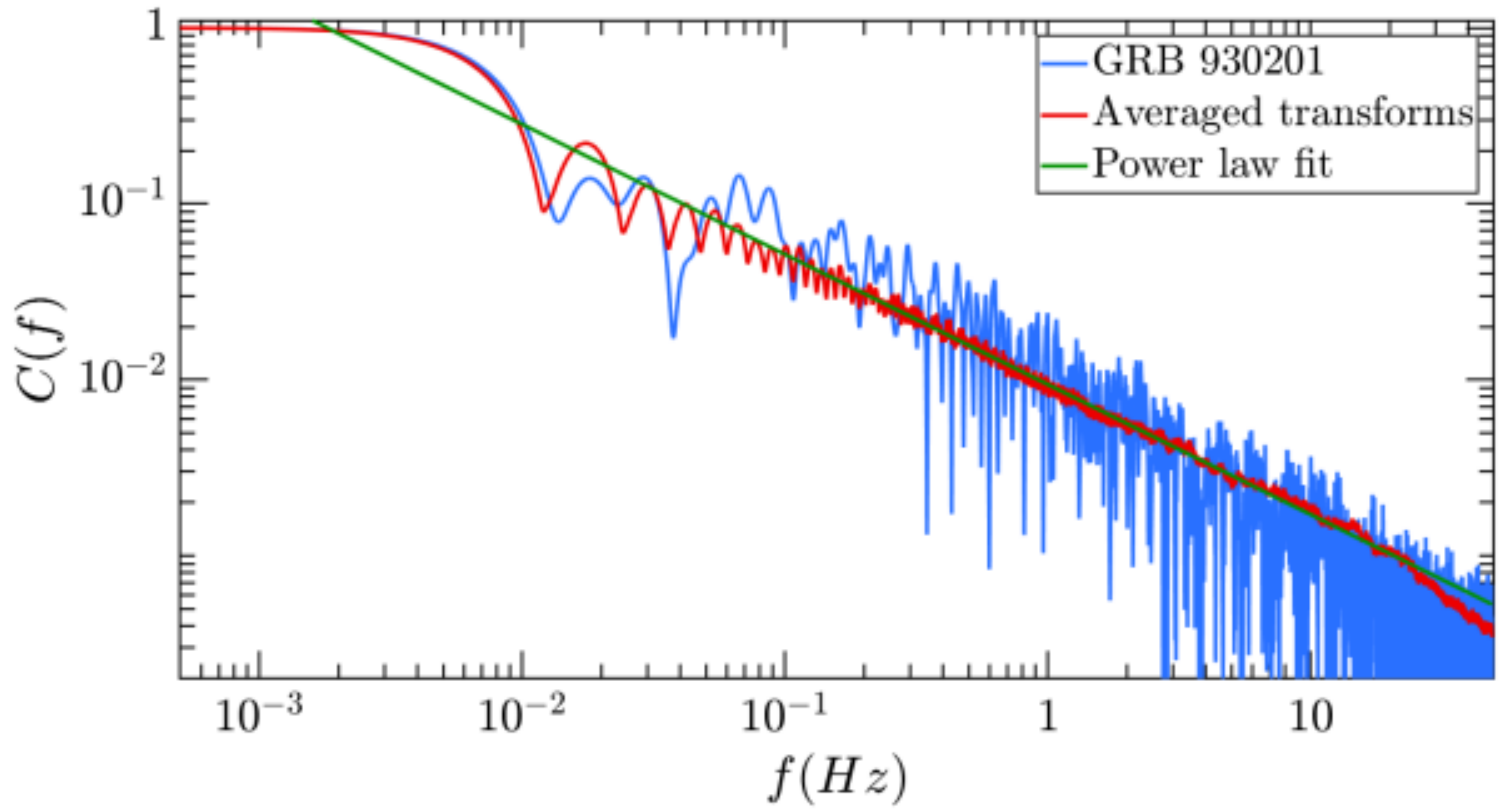






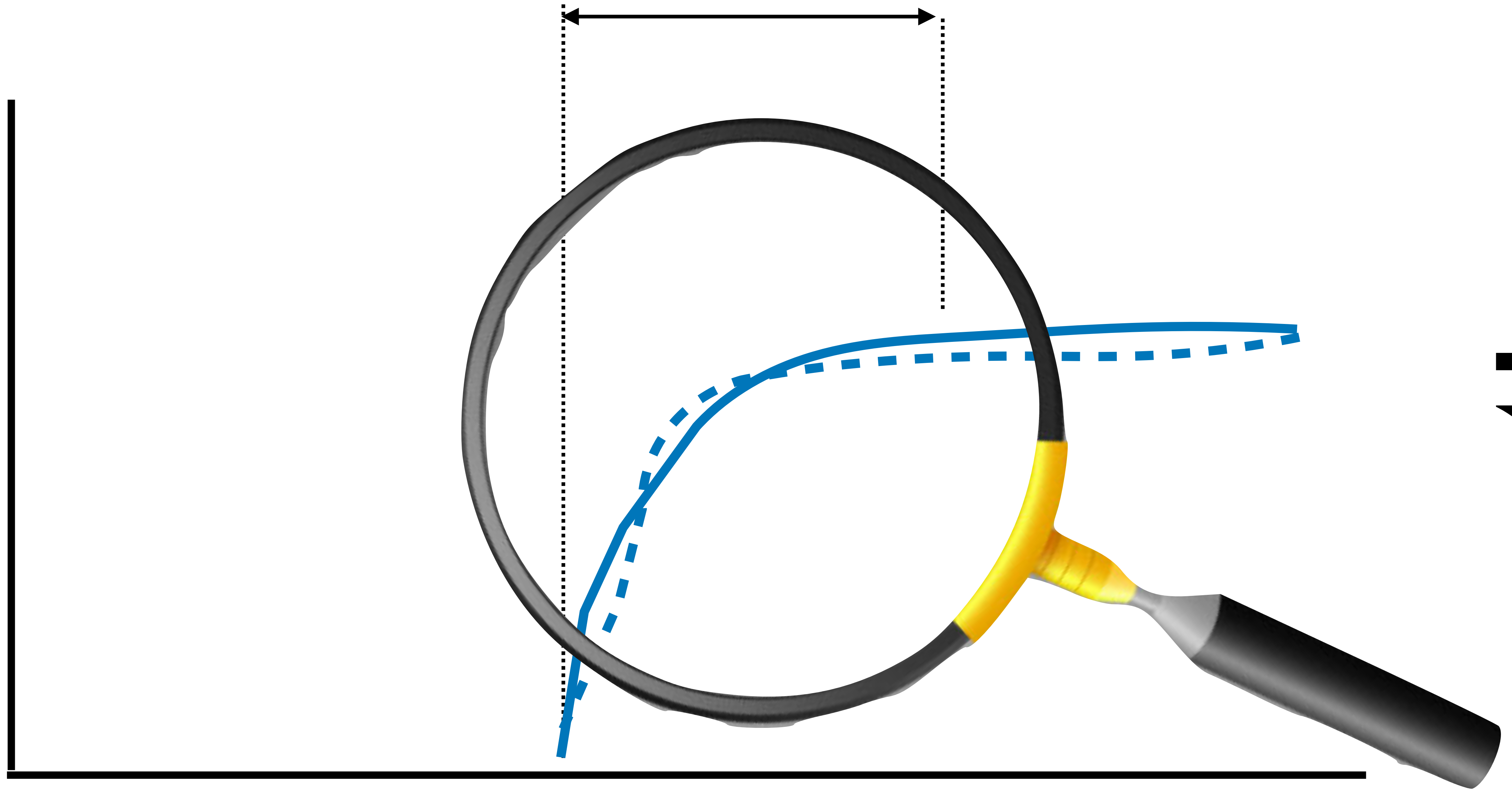
The temporal structure



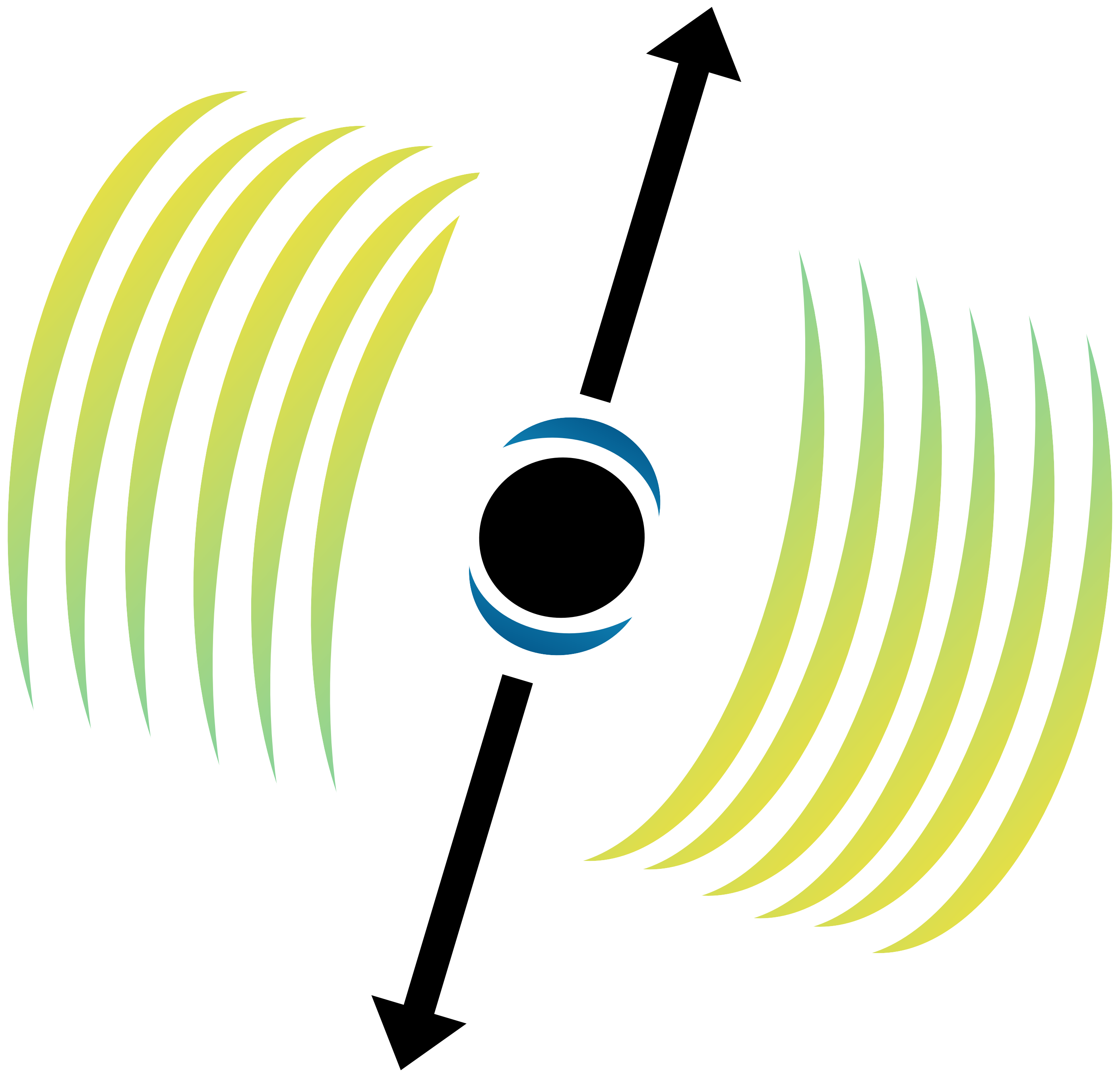


We *CAN* measure Acceleration, Collimation, Composition

$$0.1 - 10\ sec \rightleftharpoons 0.1 - 10\ Hz$$



$\rightleftharpoons$



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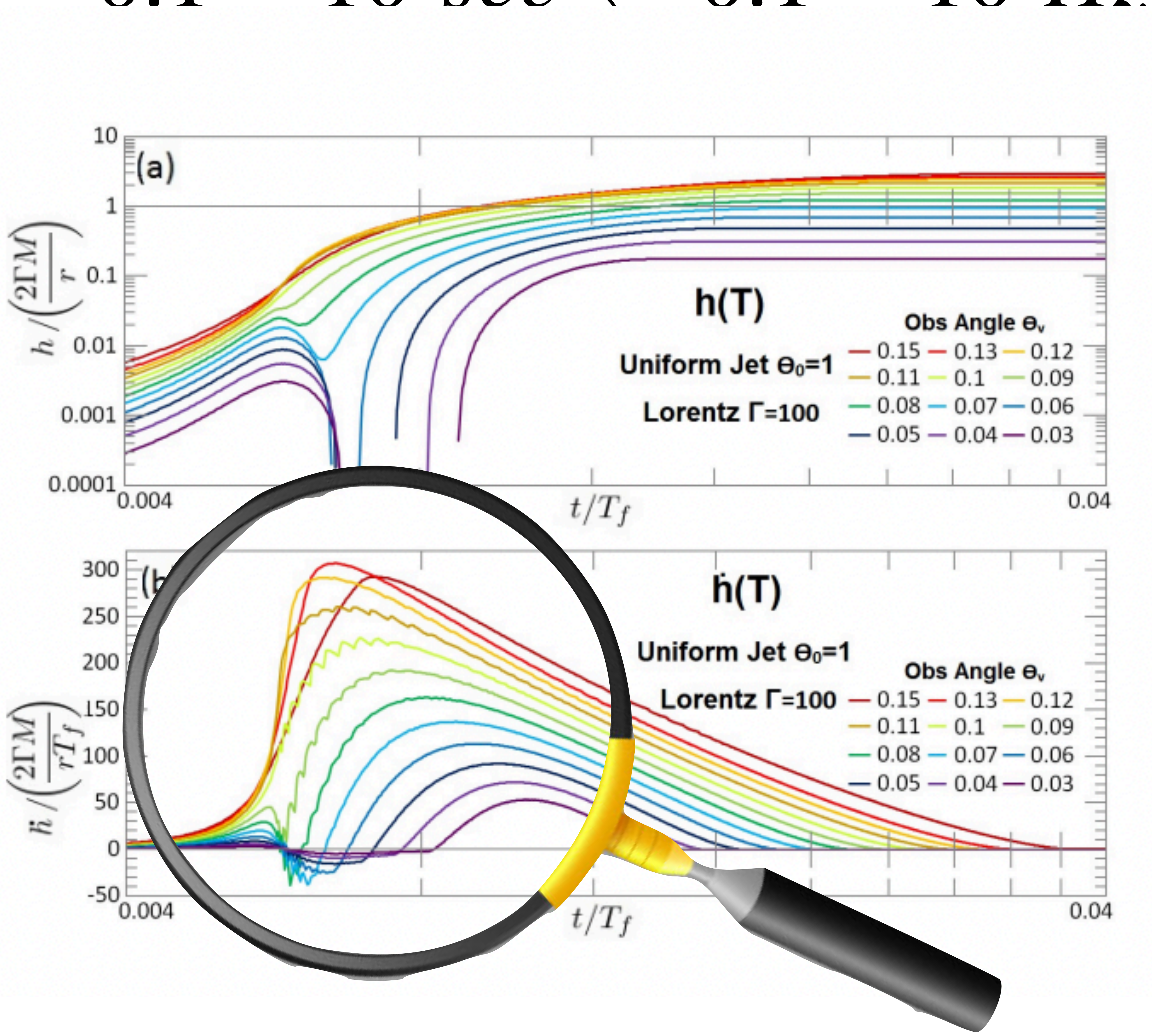
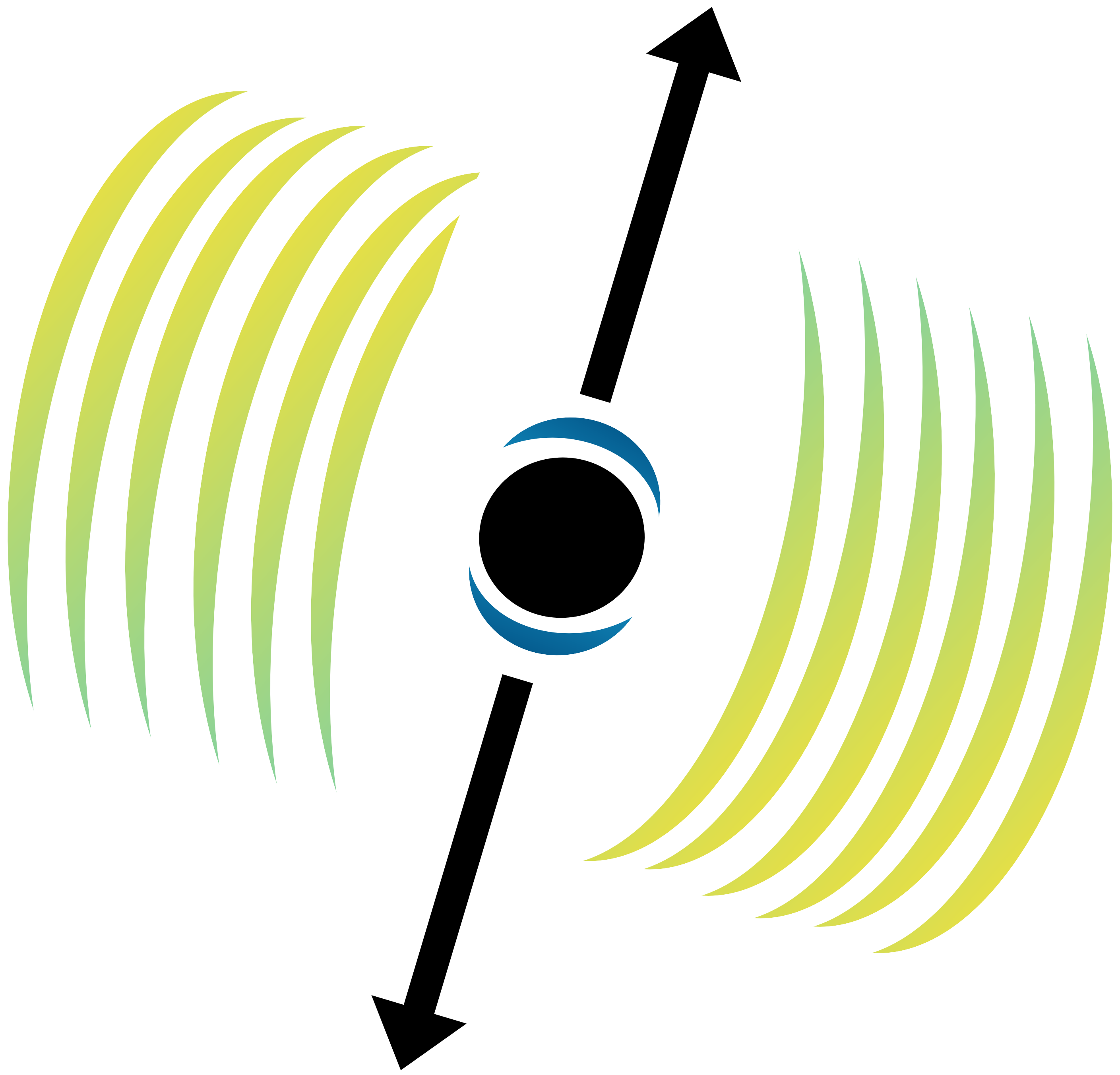


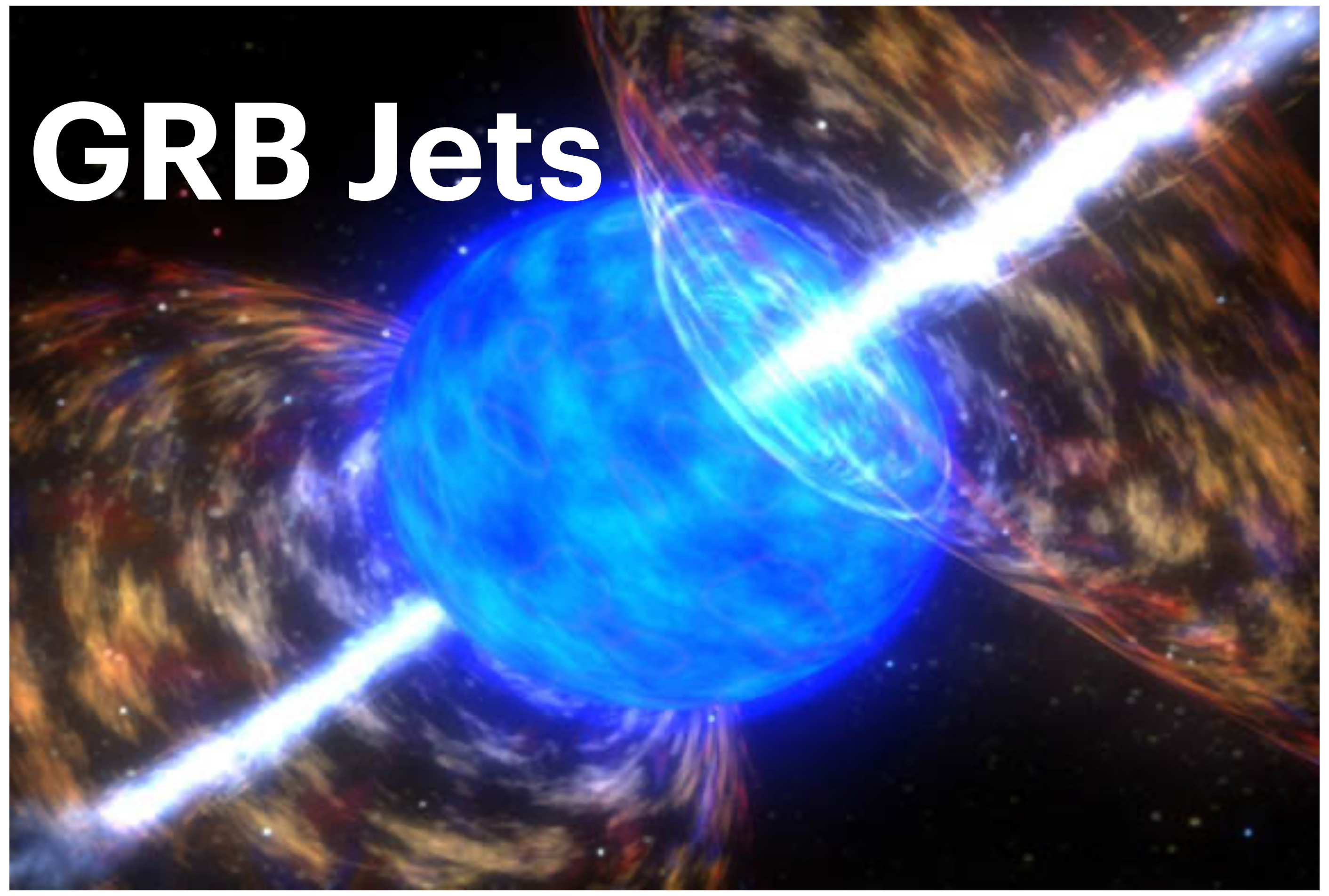
$\rightleftharpoons$



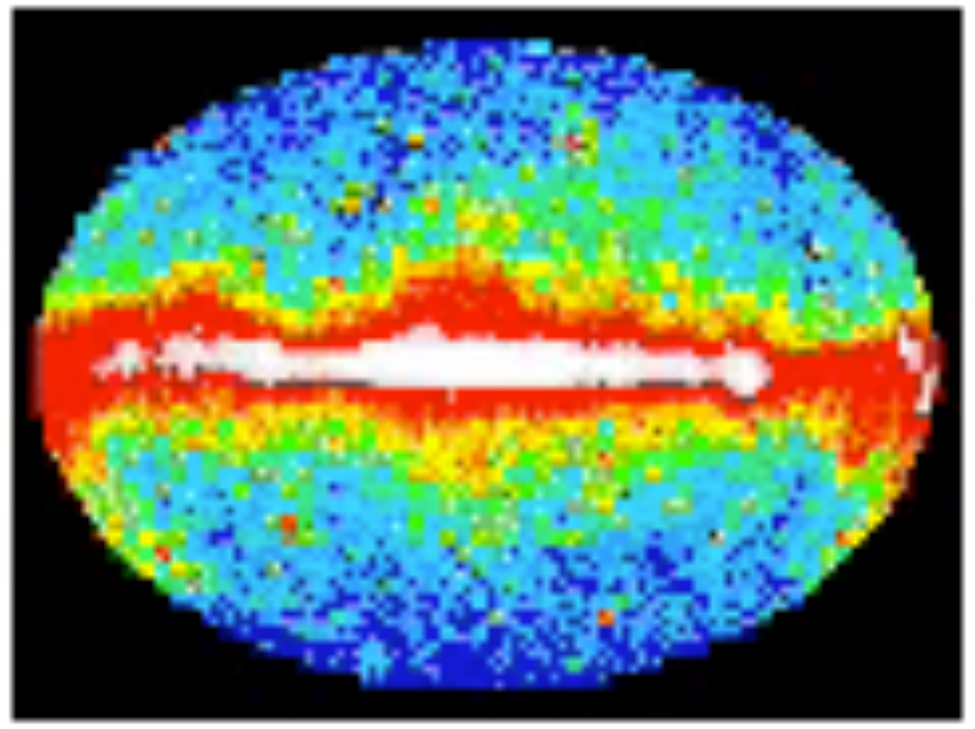
Birnholtz & TP 2013

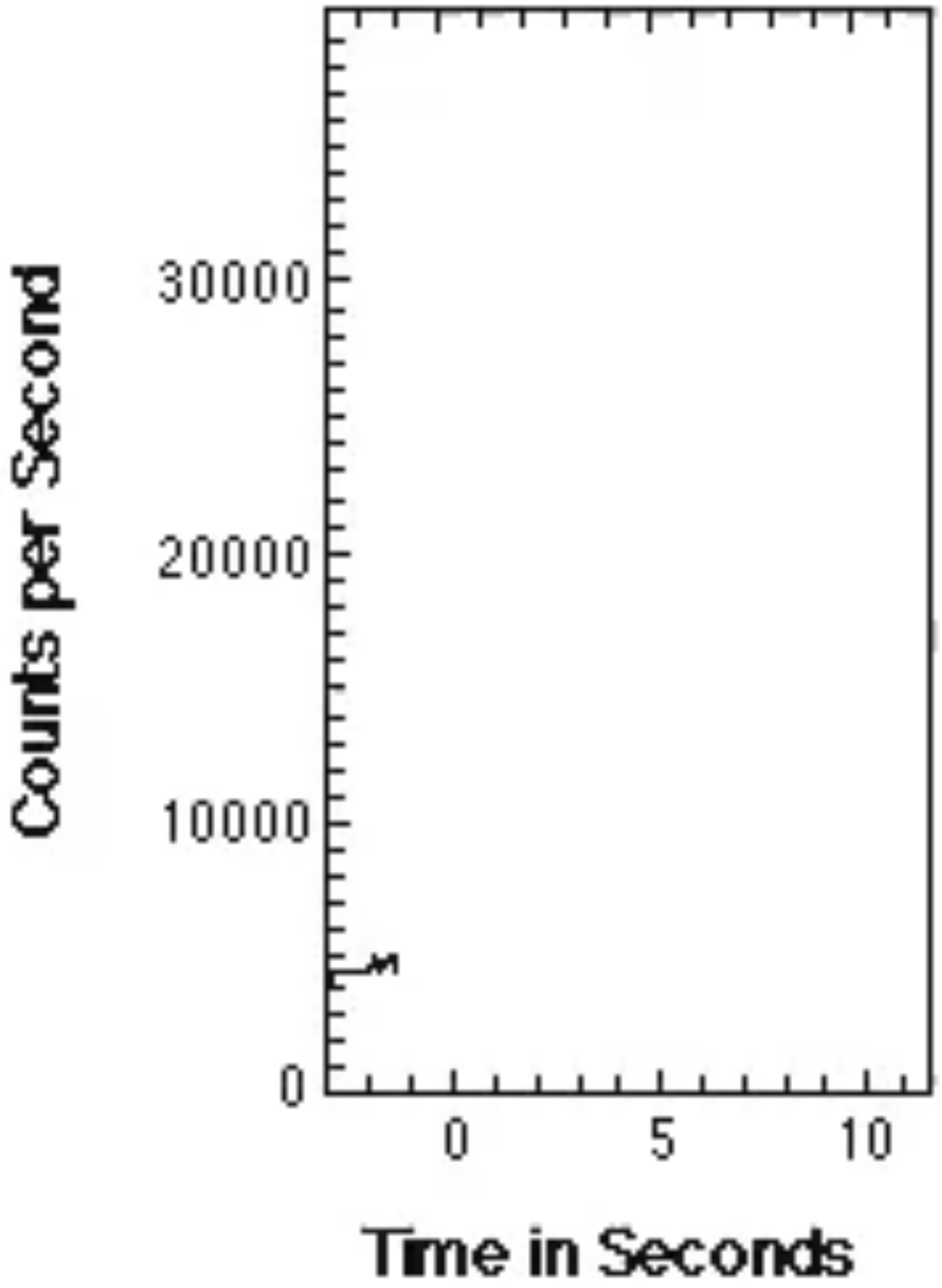
Jet-GW Sources

$$h \approx \frac{GE}{c^4 d}$$

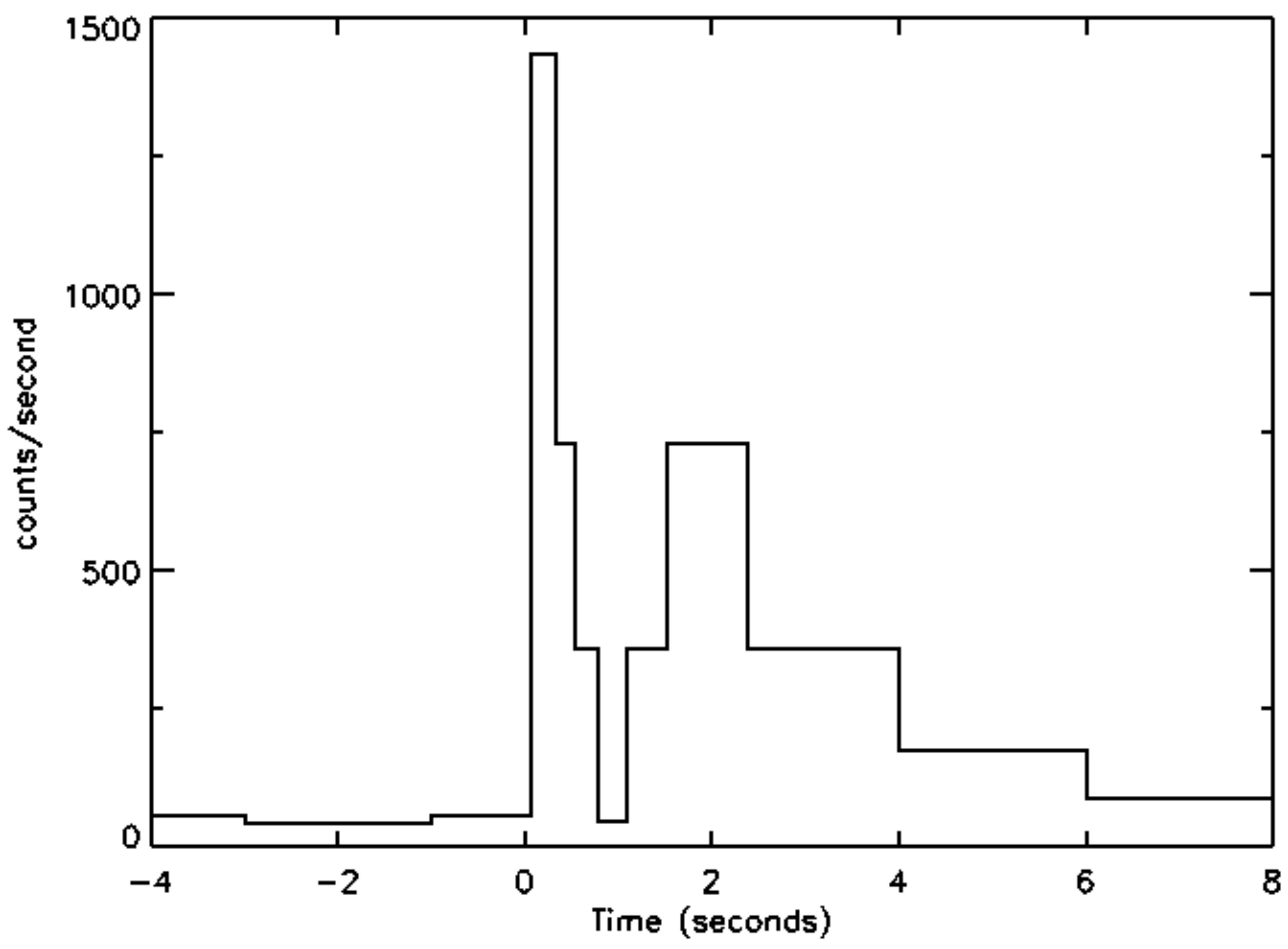


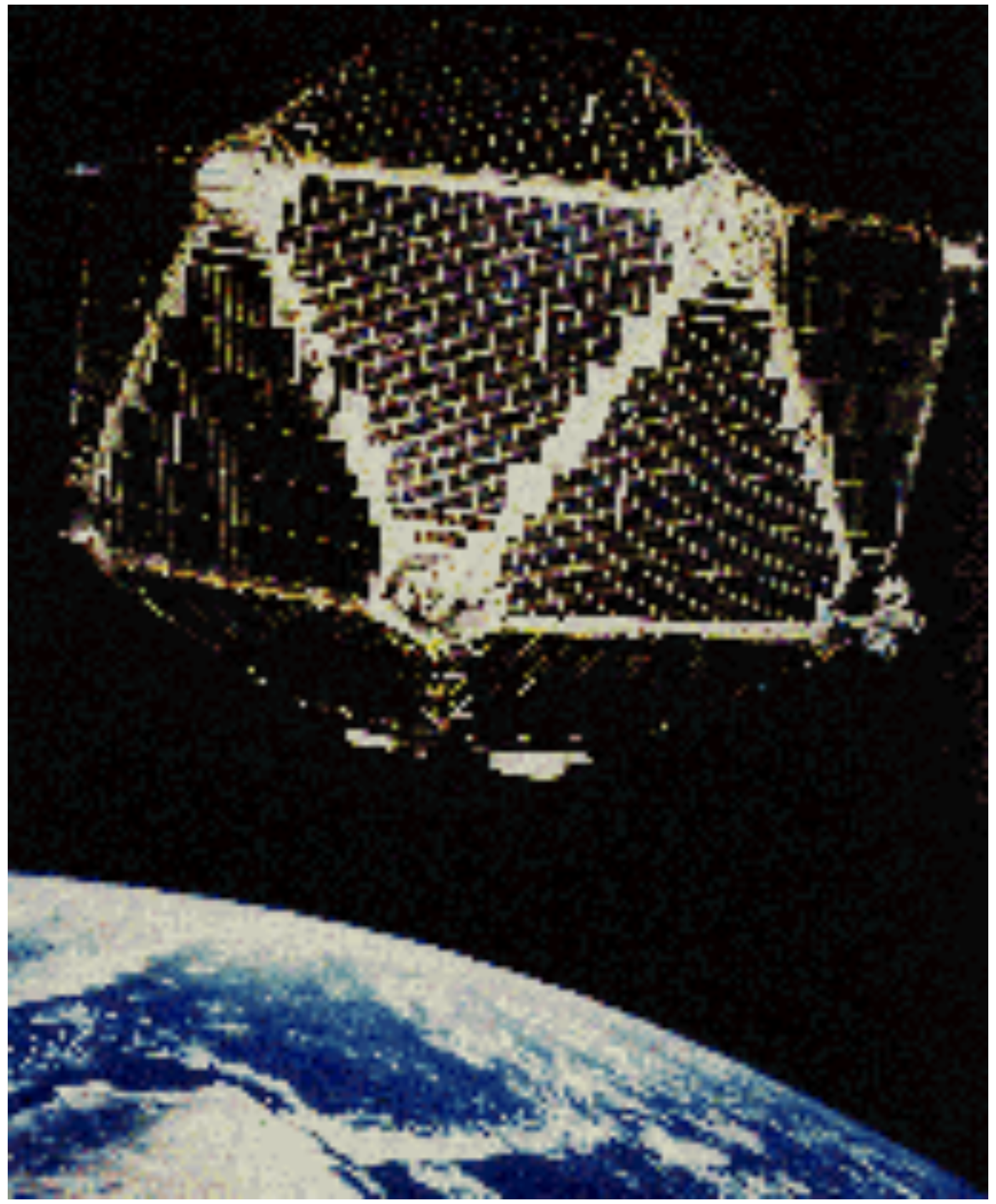
10^{51}erg; $z \gtrsim 0.05$ h~10^{-24}





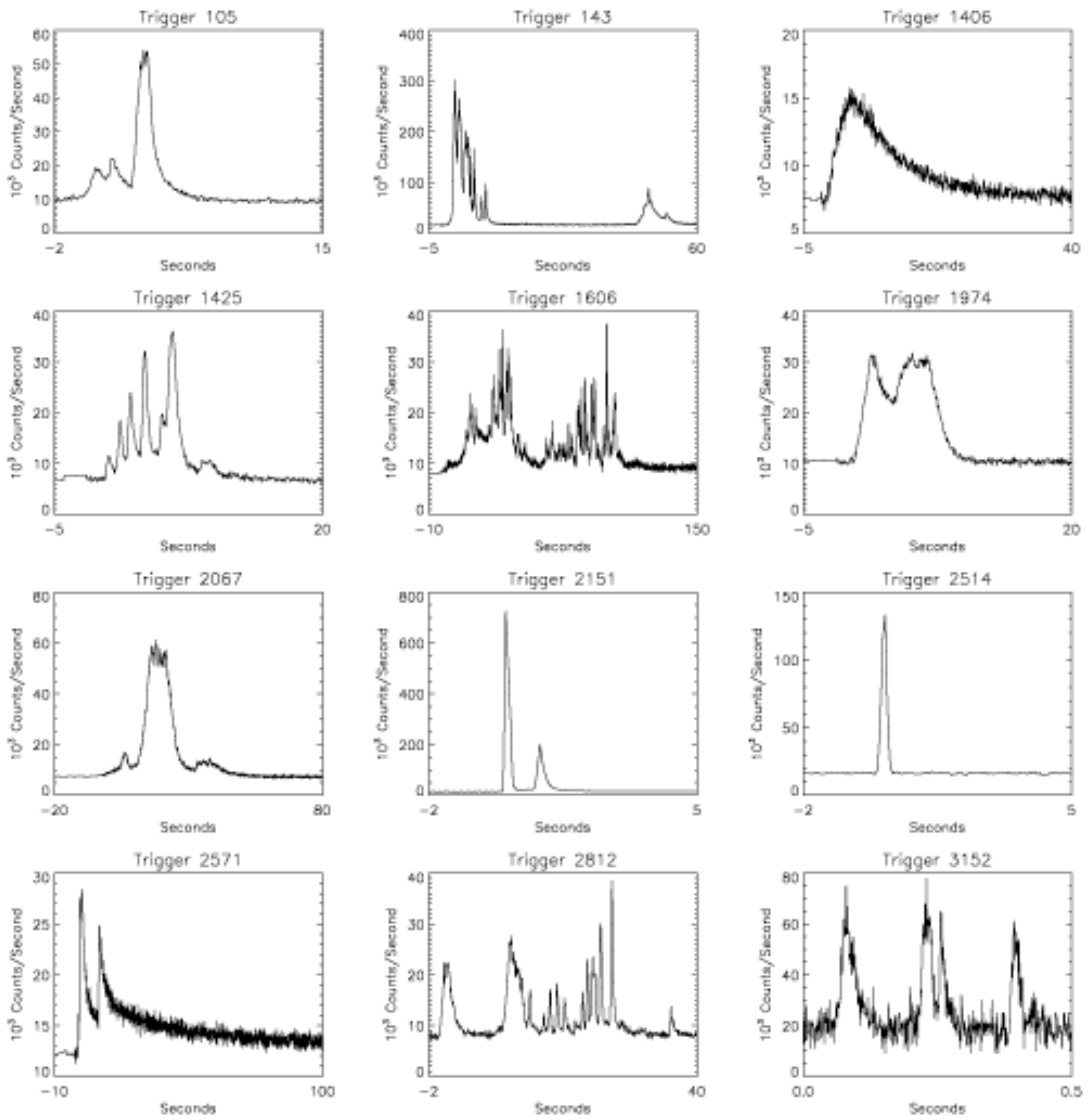
The first GRB





July 2nd 1967 by Vela 4a (noticed only in 1969)
Published Klebsadel, Strong & Olson 1973

GRBs' light curves



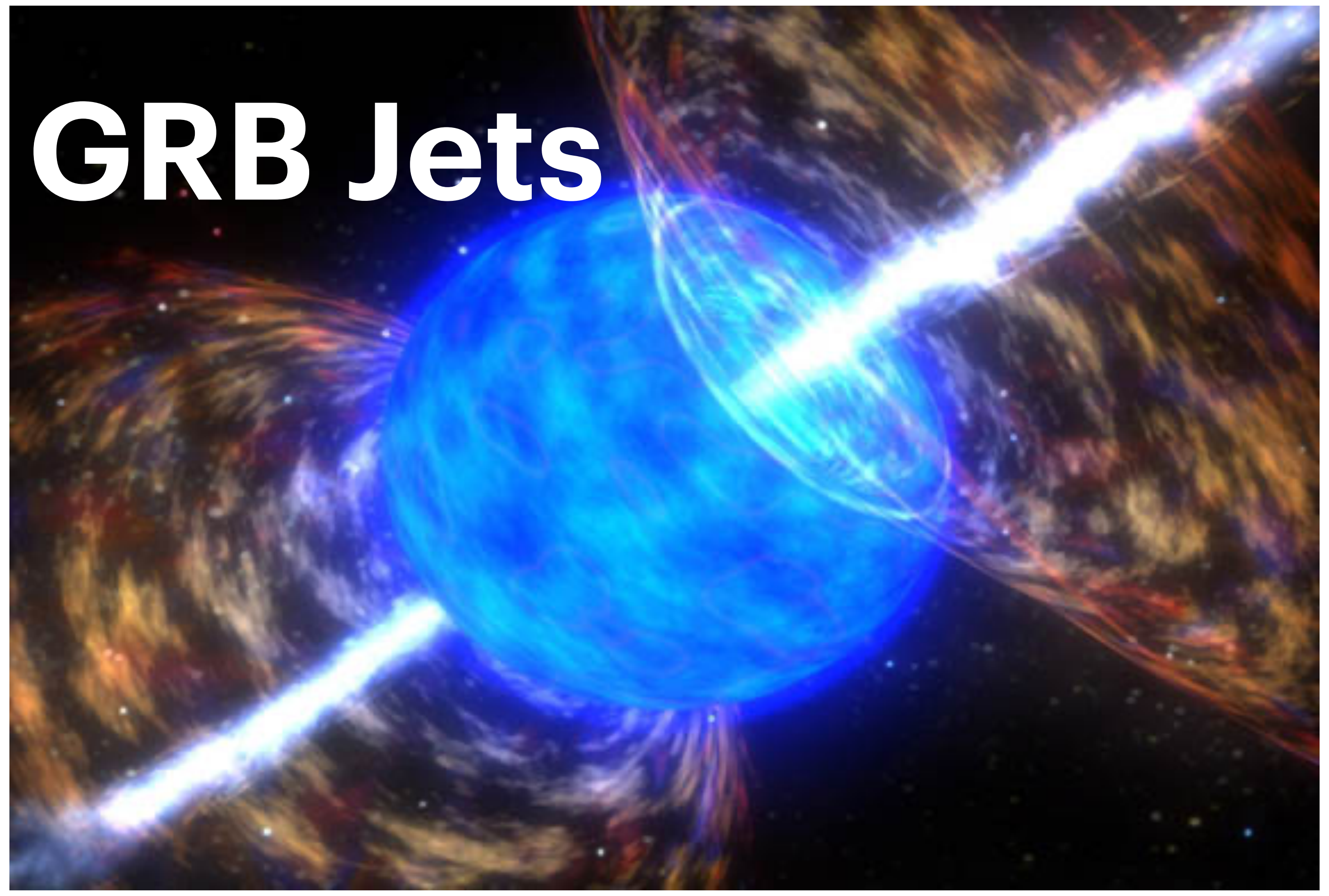
Variable - very different light curves

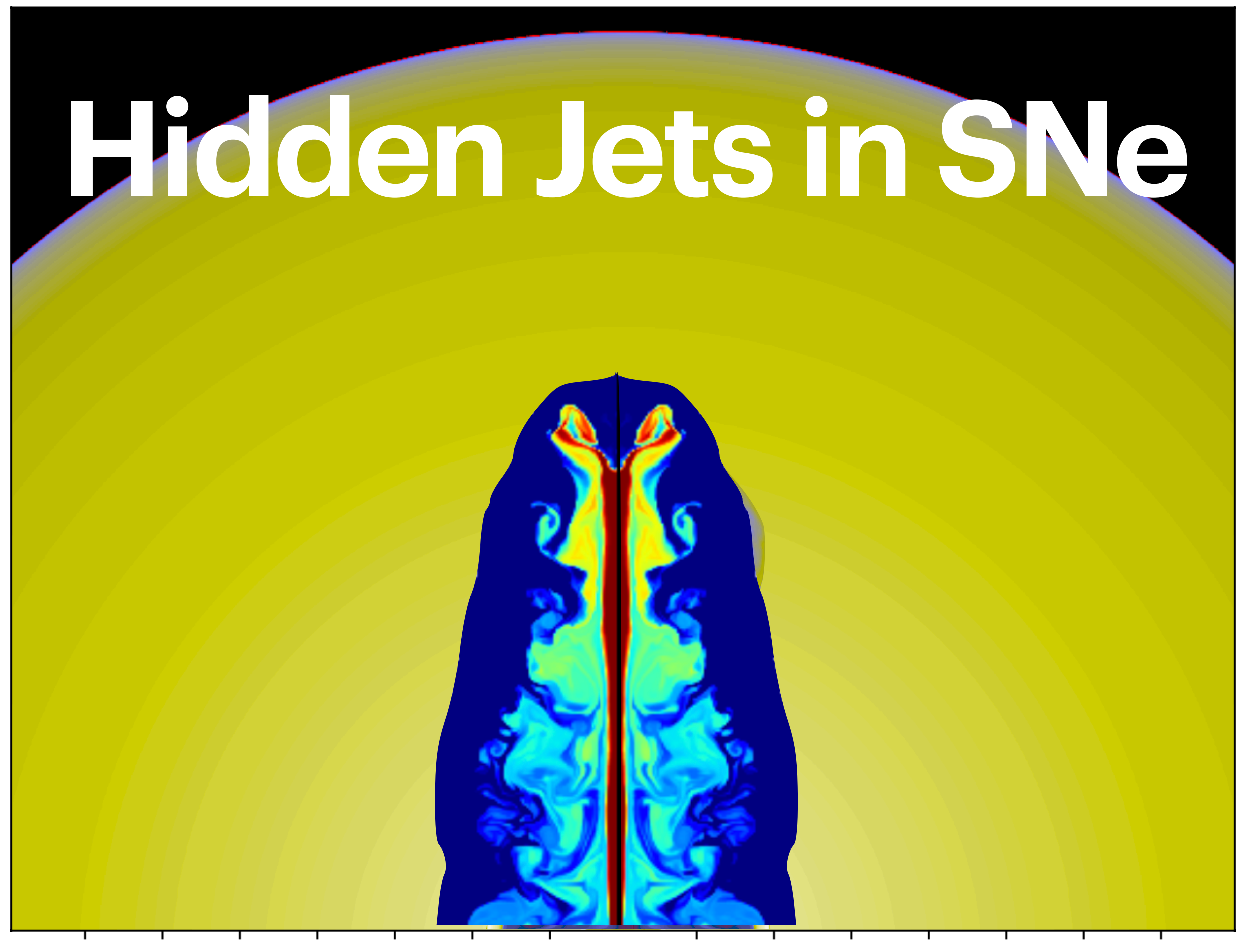
Time scale for a long GRB a few dozen se, for a short GRB 1-2 sec

Jet-GW Sources

$$h \approx \frac{GE}{c^4 d}$$

Might be stronger than the GW from the collapse itself





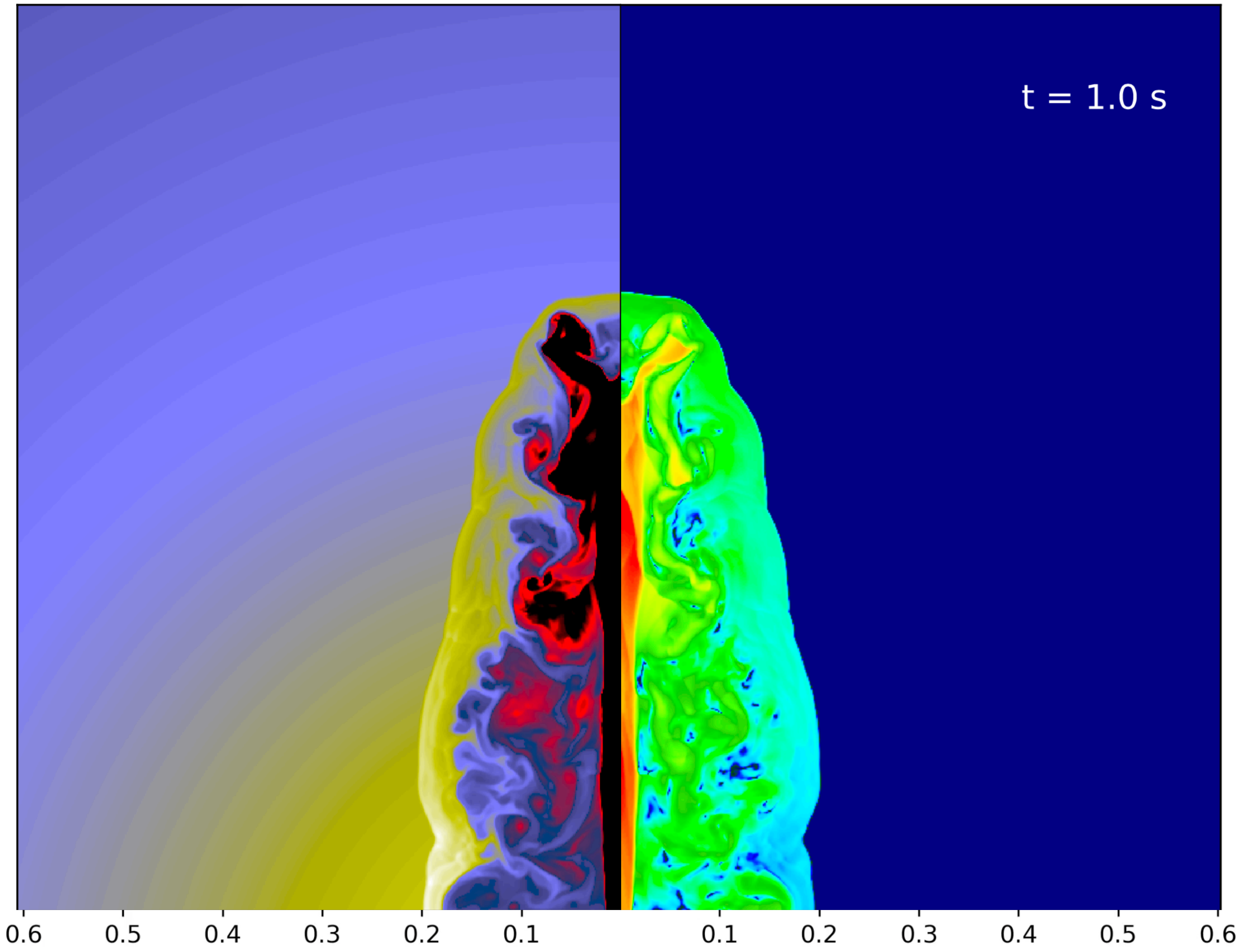
10^{51}erg; $z \gtrsim 0.05$

10^{51}erg; $d \approx 20Mpc$

h~10^{-24} @0.1Hz

h~10^{-22} @0.1Hz

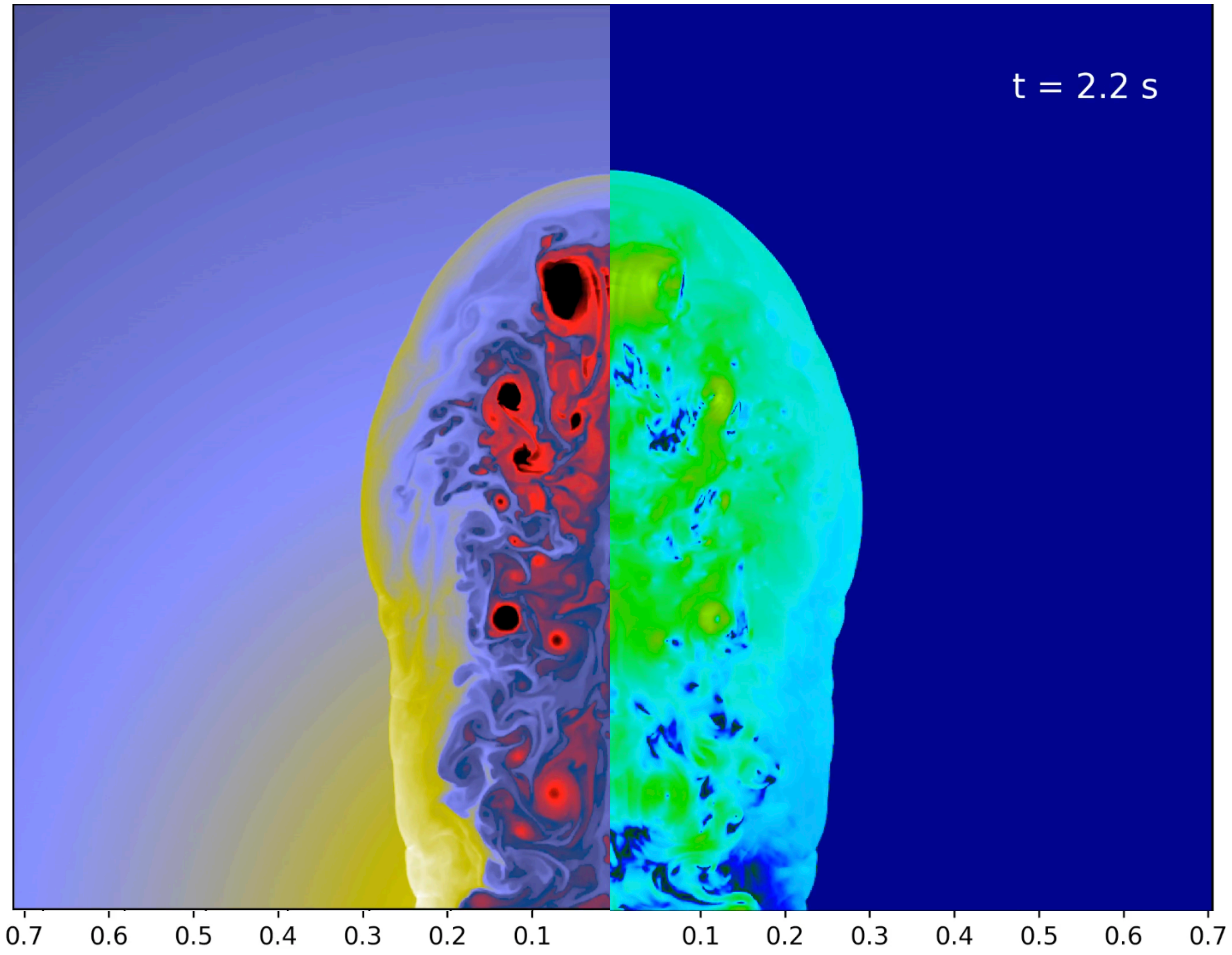
A Relativistic jet inside a star



Density Velocity

Pais & TP, 2022

The Jet is choked leaving a cocoon



Density Velocity

Pais & TP, 2022

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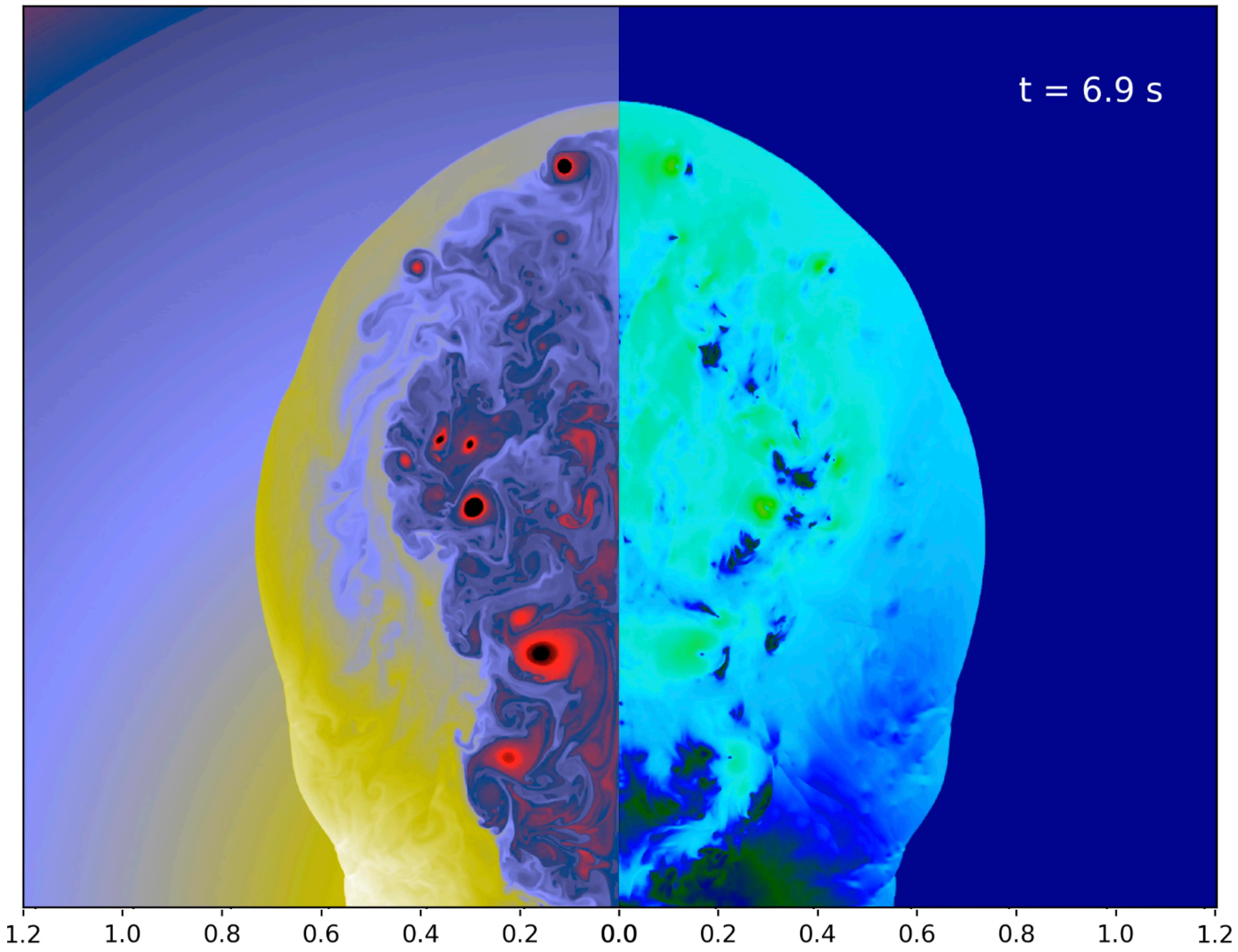
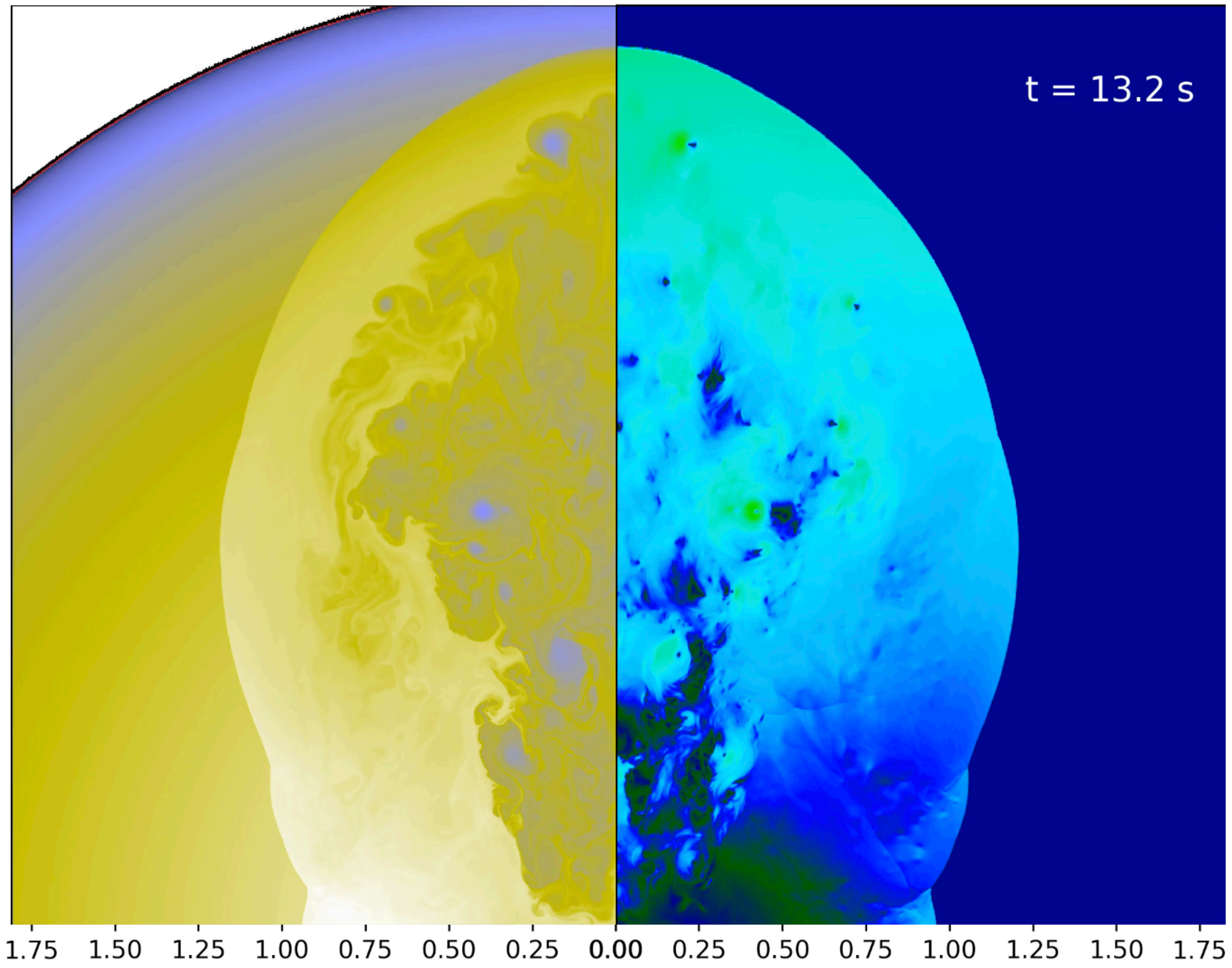


Density

Velocity

Pais & TP, 2022

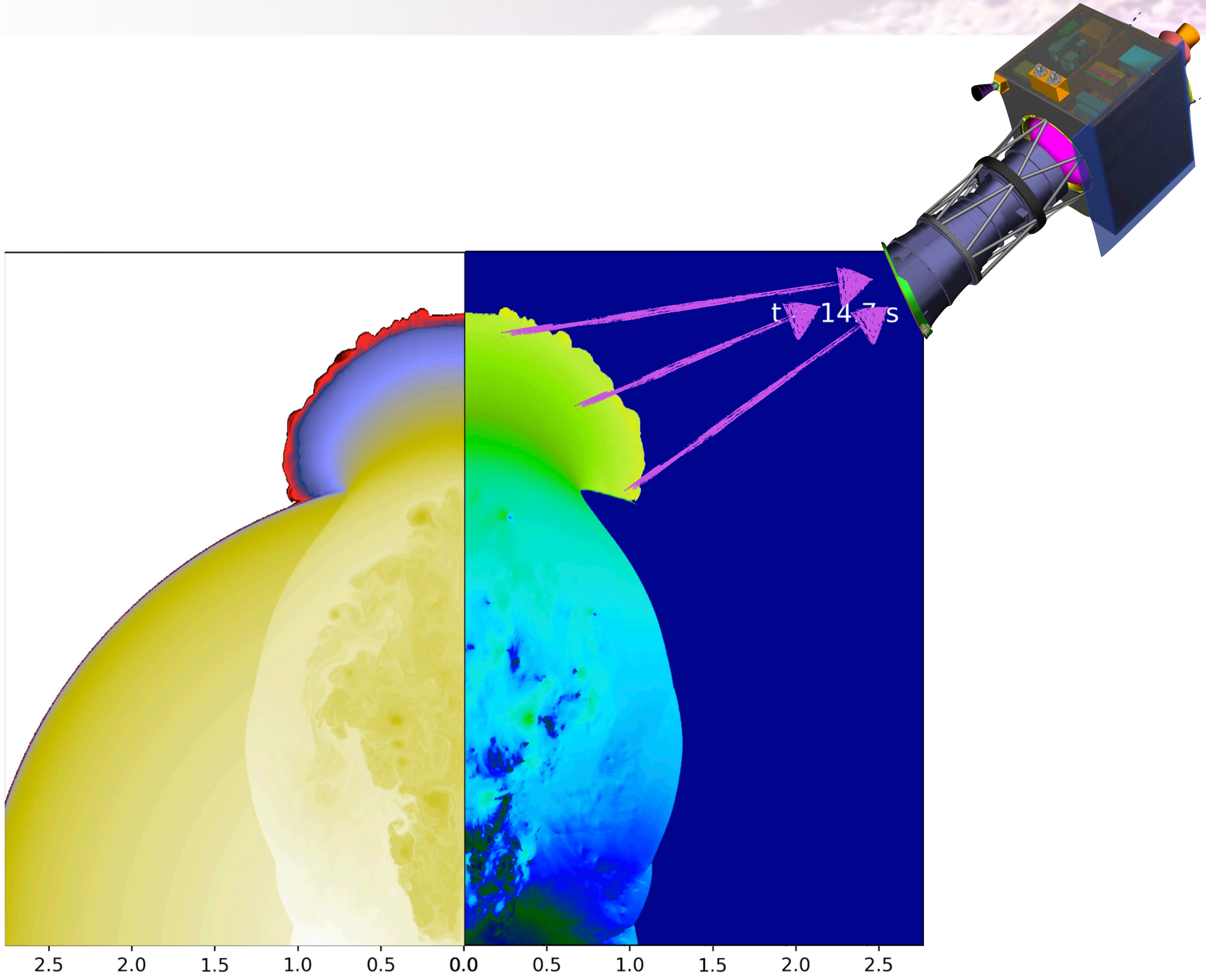
The Jet is choked leaving a cocoon



Density Velocity

Pais & TP, 2022

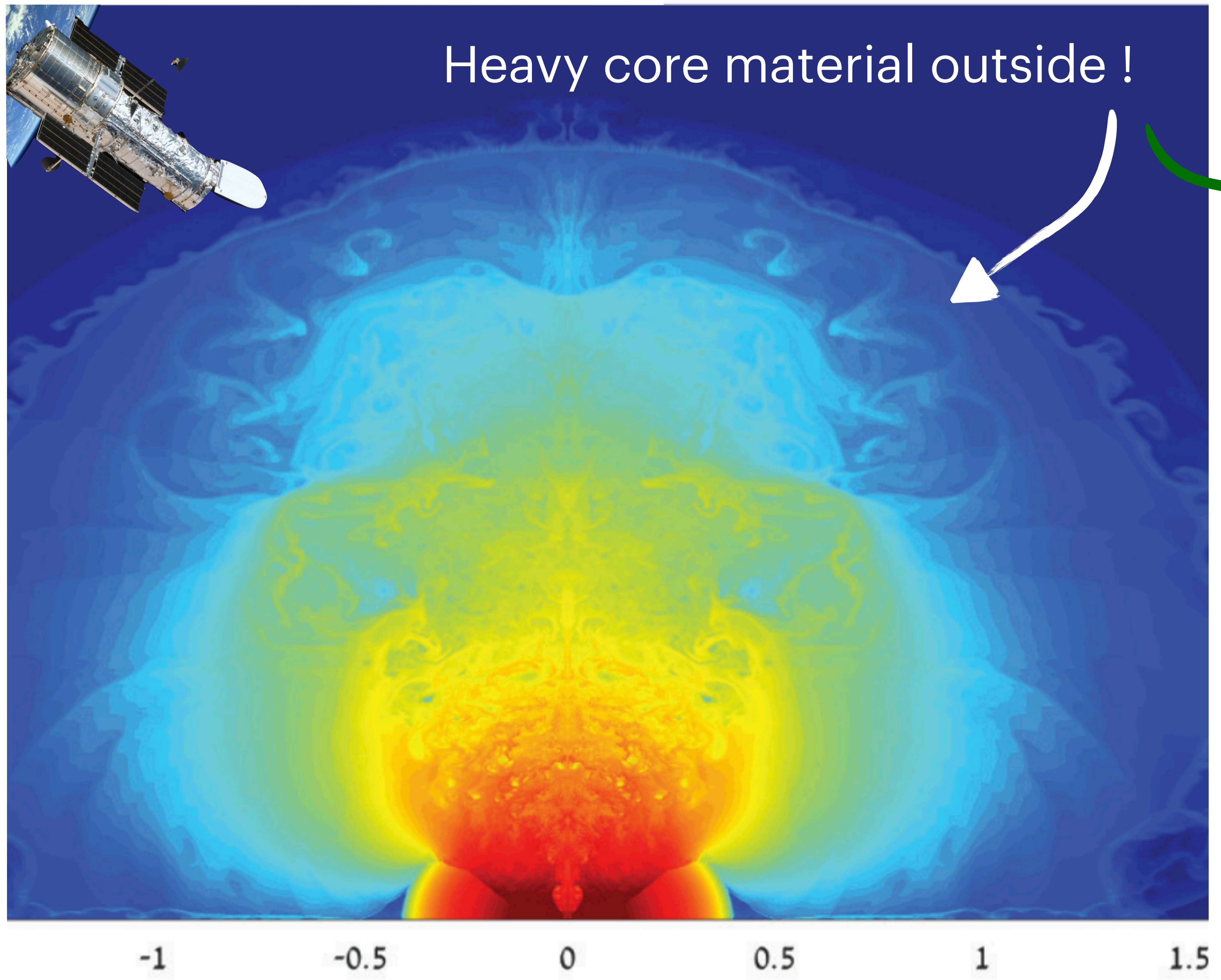
Shock breakout



Density Velocity

Pais & TP, 2022

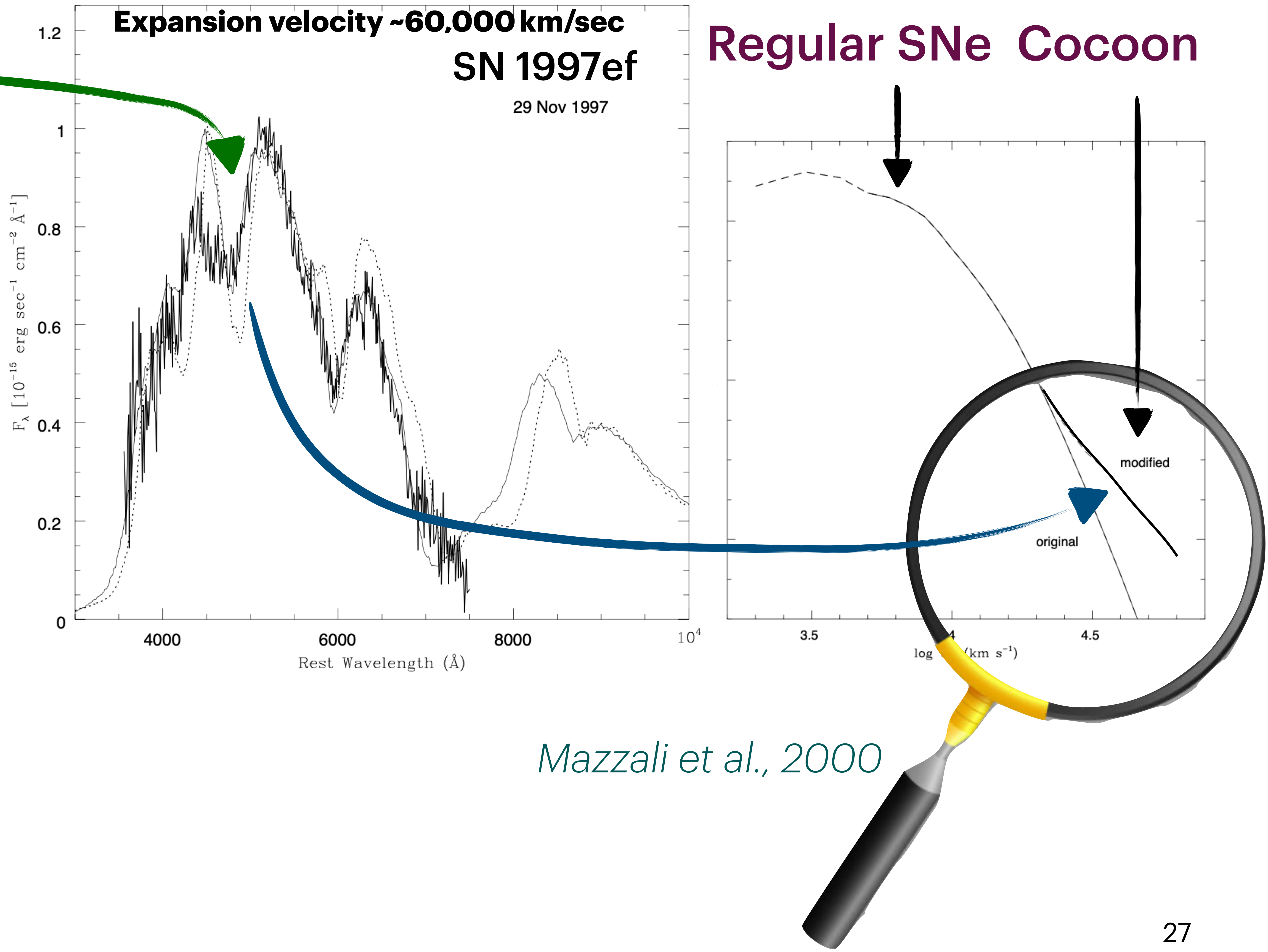
Evidence for Jets in SNe



TP et al., 2017, 2019

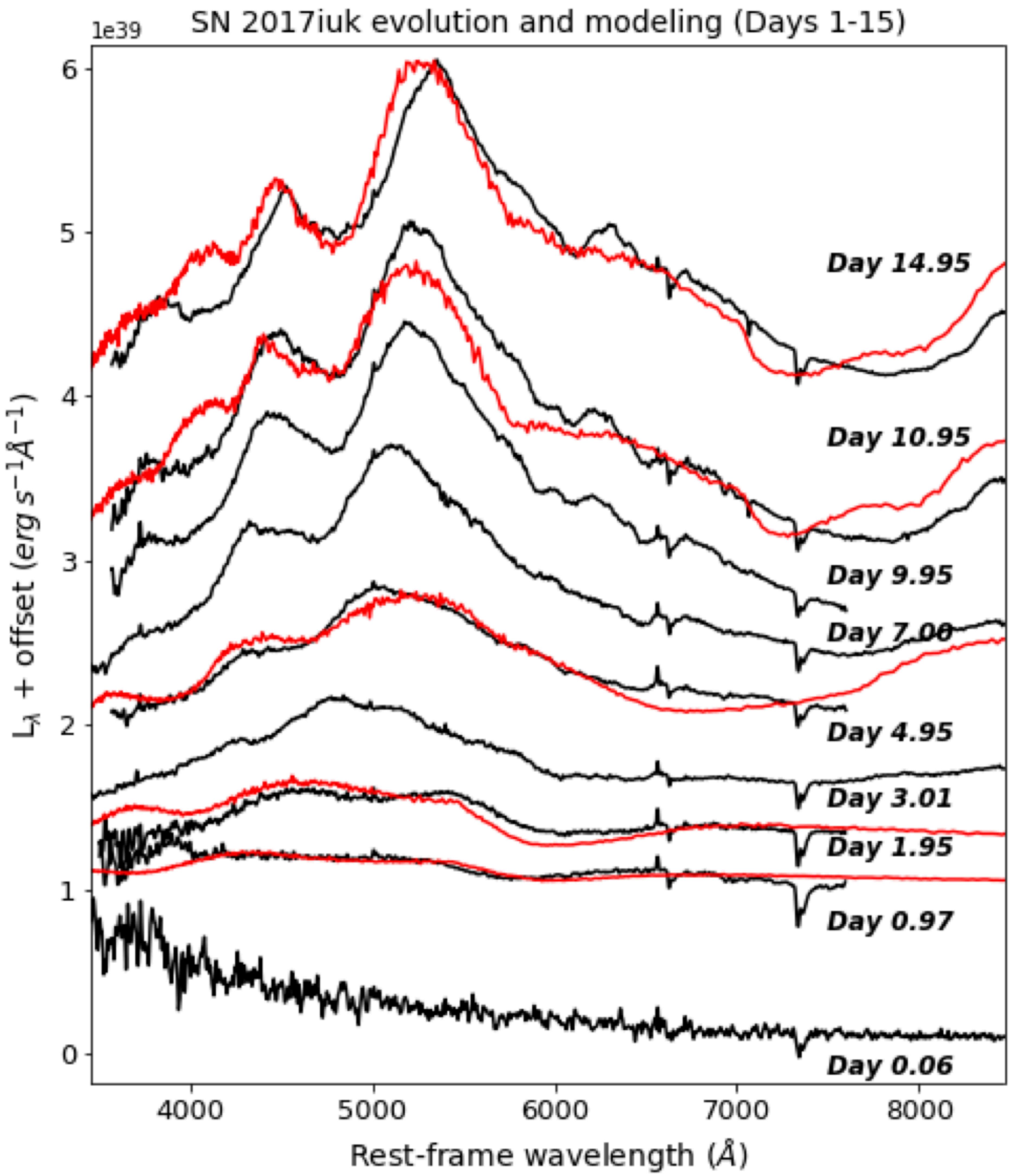
Spectrum

Density distribution



Mazzali et al., 2000

SN2017iuk - 100,000 km/sec

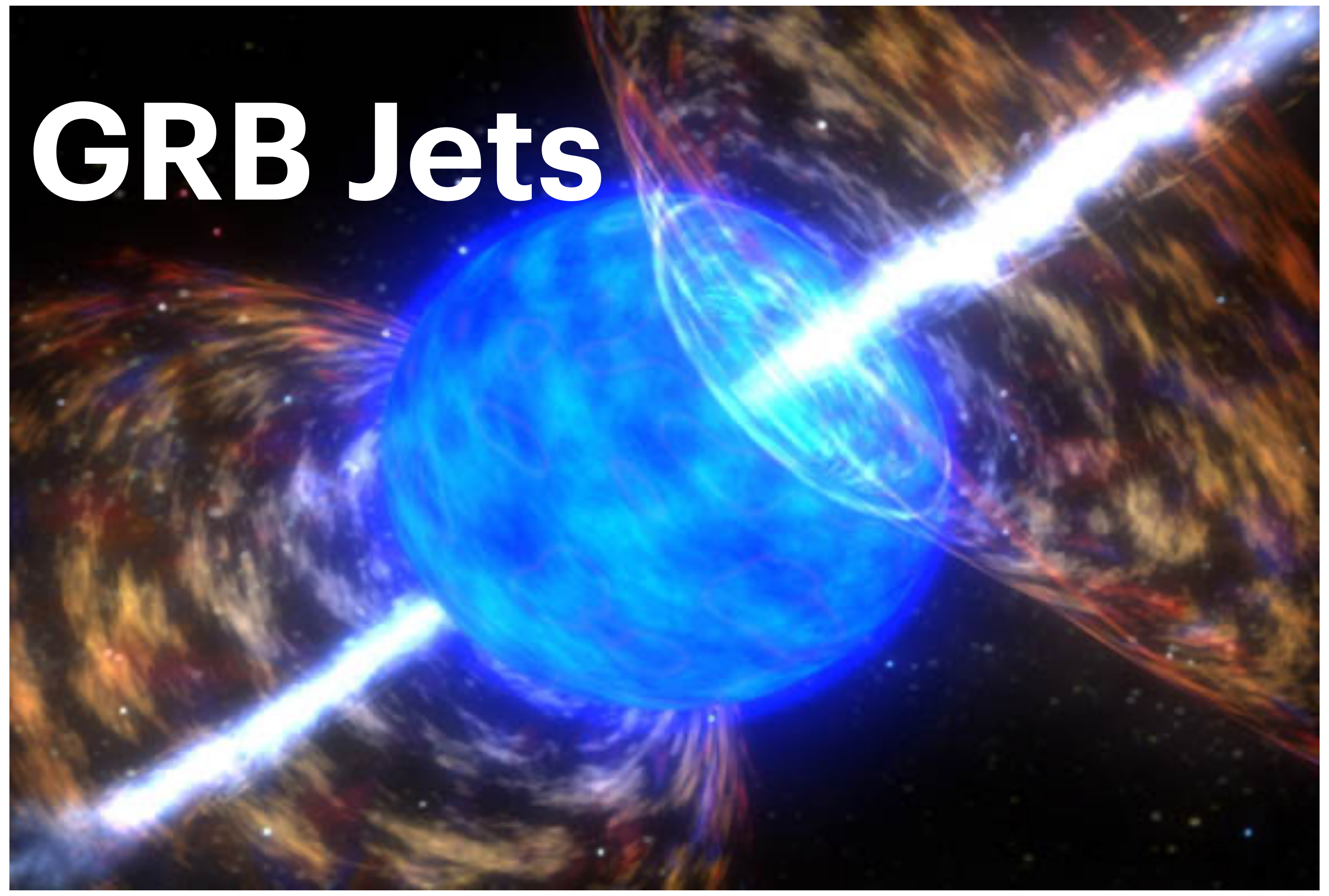


Izzo et al, 2019

Jet-GW Sources

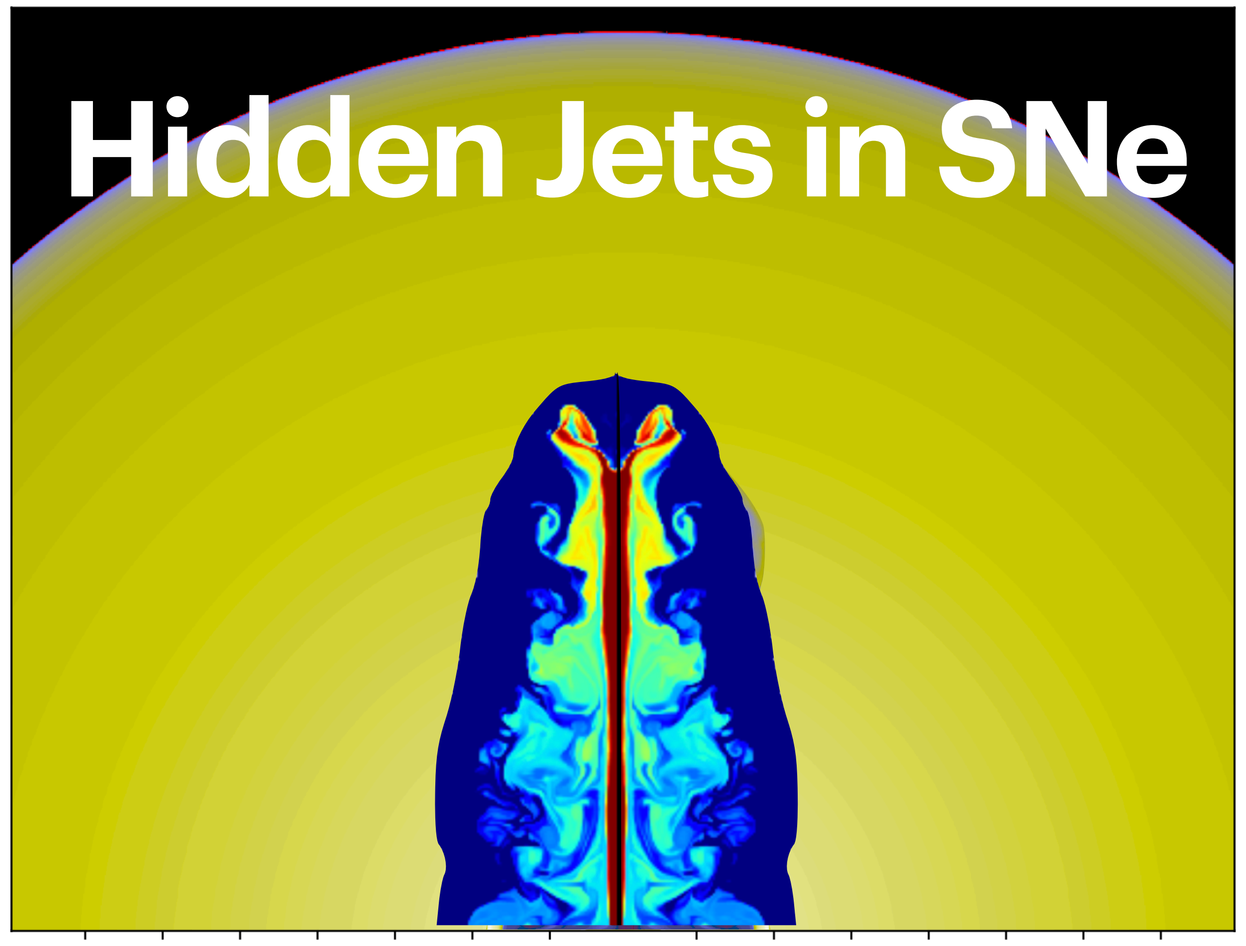
$$h \approx \frac{GE}{c^4 d}$$

Might be stronger than the GW from the collapse itself



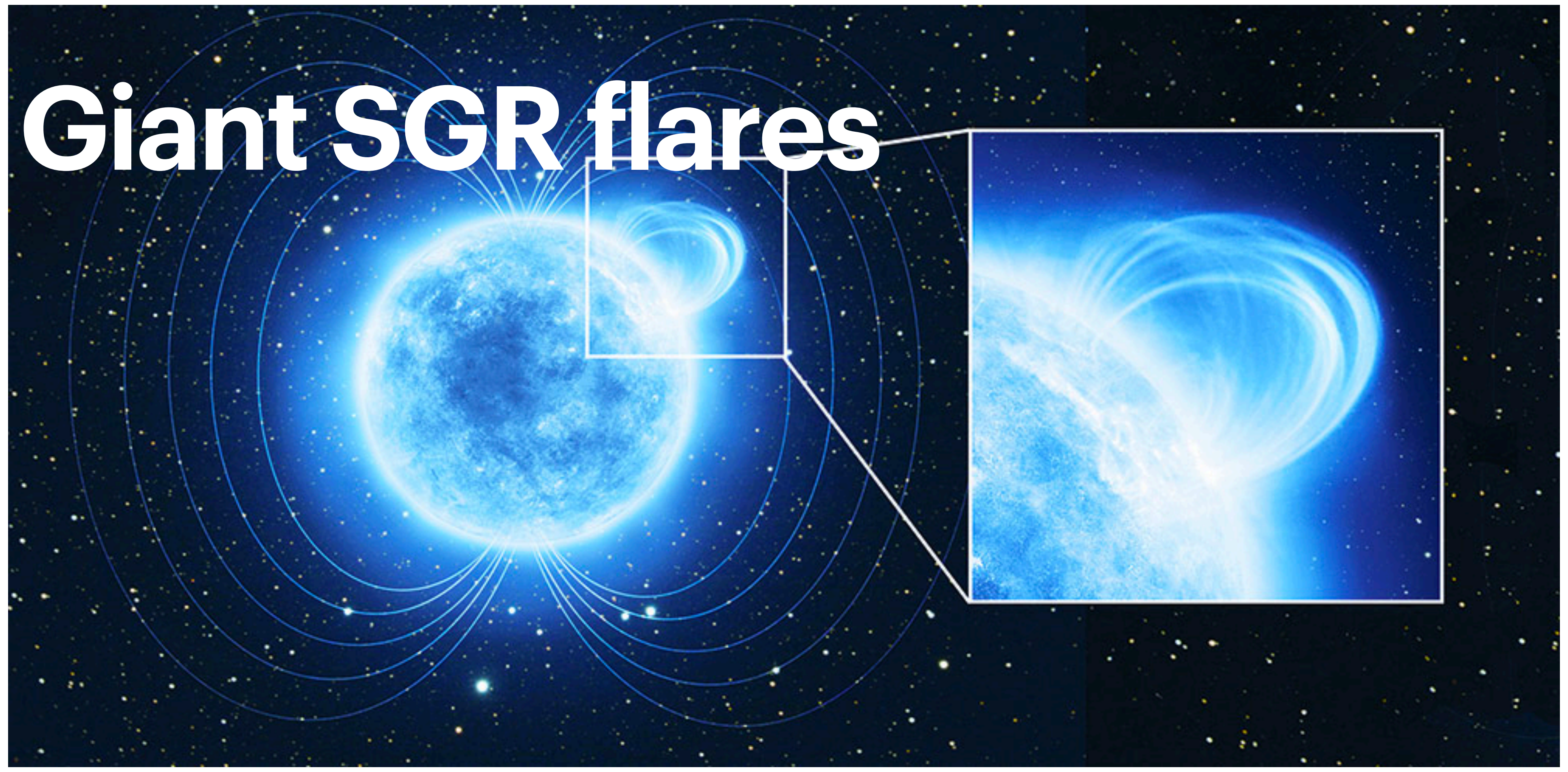
10^{51}erg; $z \gtrsim 0.05$

h~10^{-24} @0.1Hz



10^{51}erg; $d \approx 20 Mpc$

h~10^{-22} @0.1Hz

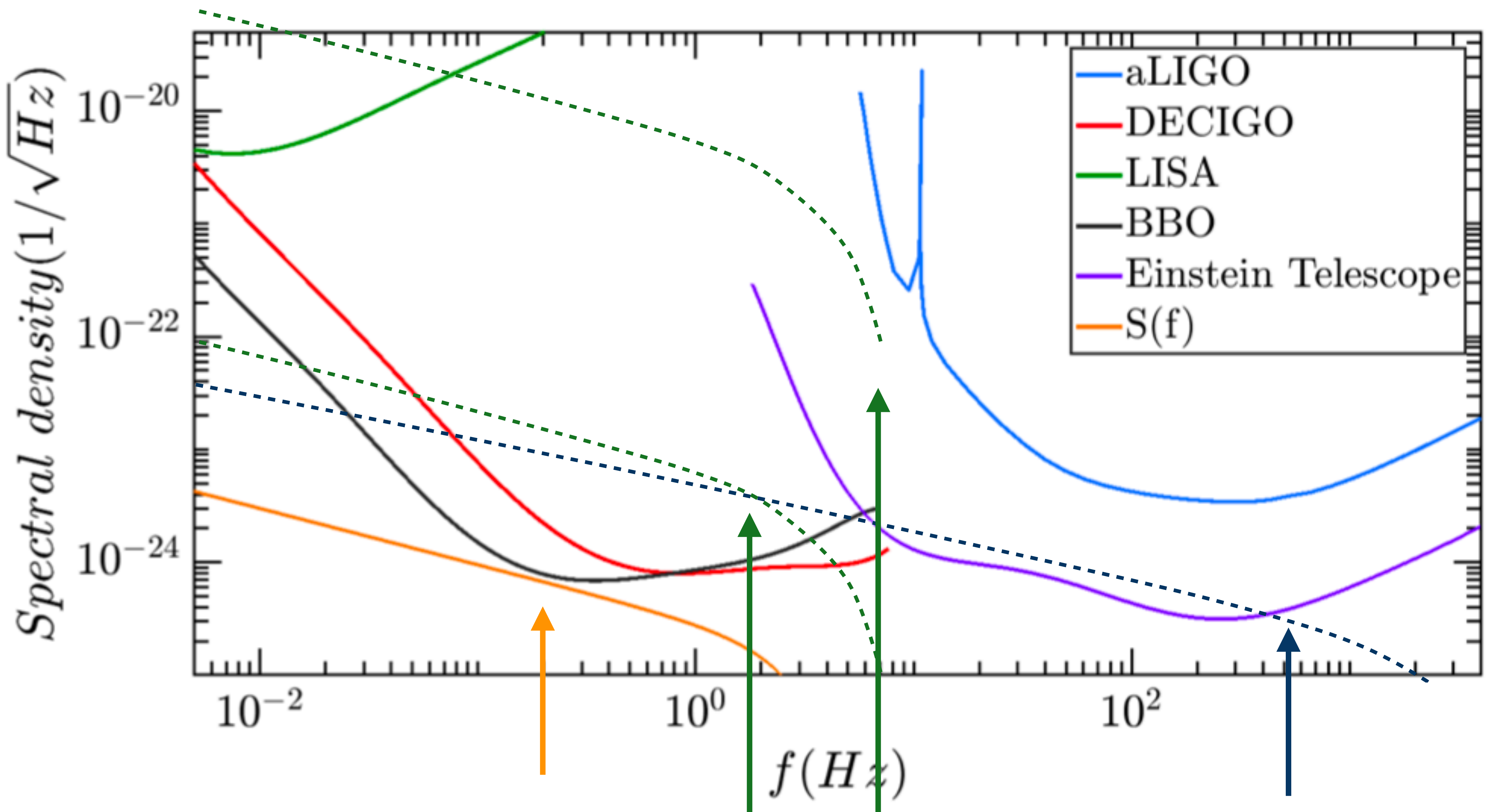


10^{47}erg; Galactic, L-V-K frequency

h~10^{-22} @ kHz

Preparation for this GW detection

If we don't know how it looks, we won't know how to look.
Once detected - it will be a revolution.



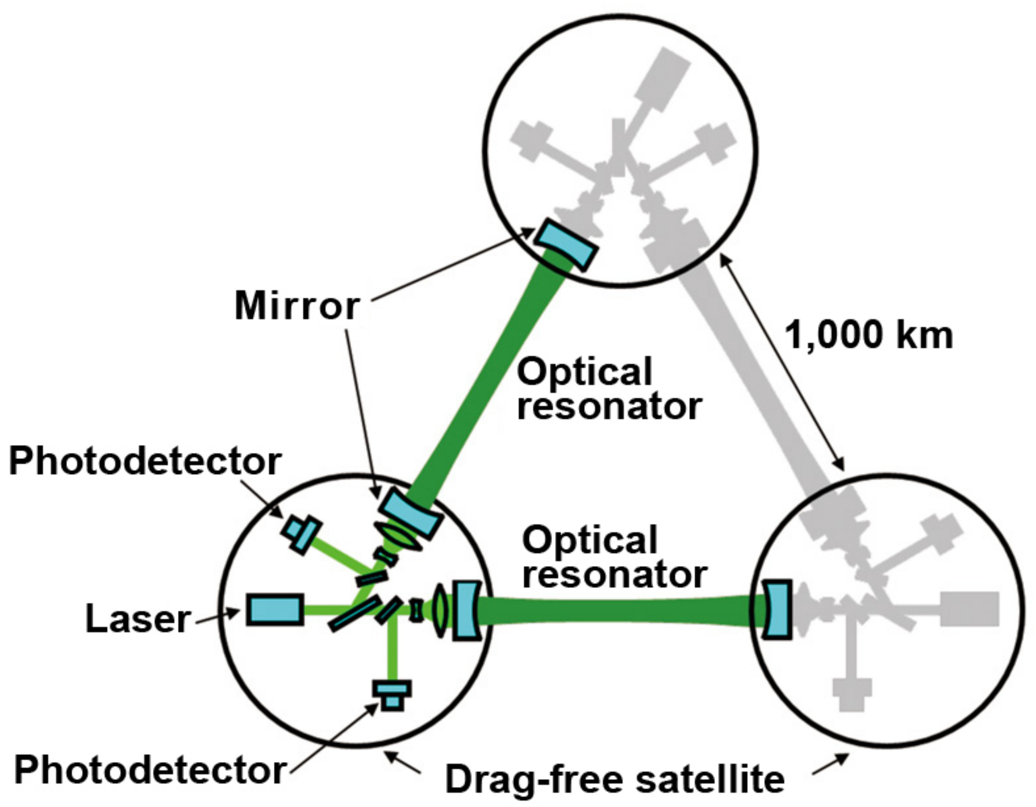
GW 170817 $10^{49.5}$ erg @ 40 Mpc

Magnetar flare 10^{47} erg @ 10 kpc

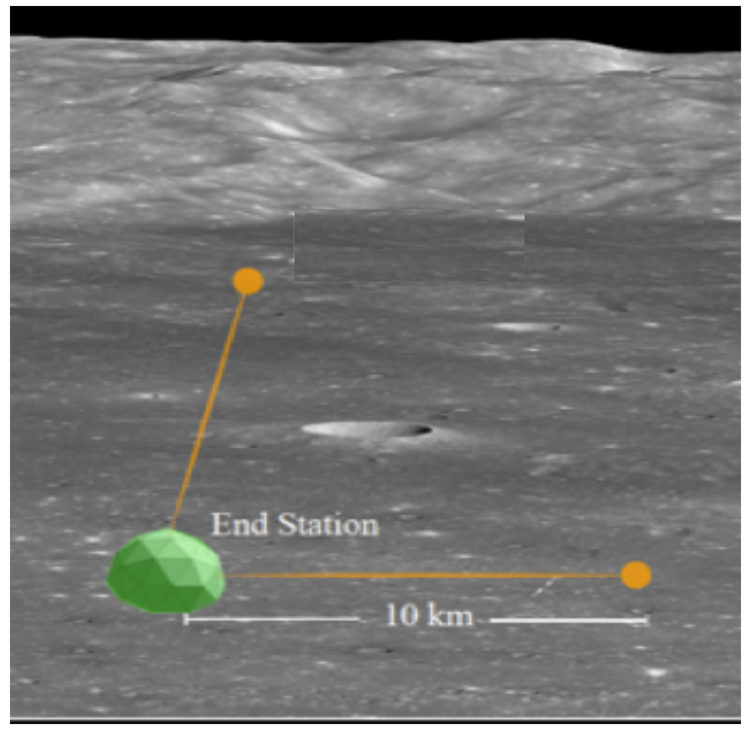
SN 10^{51} erg @ 20 Mpc

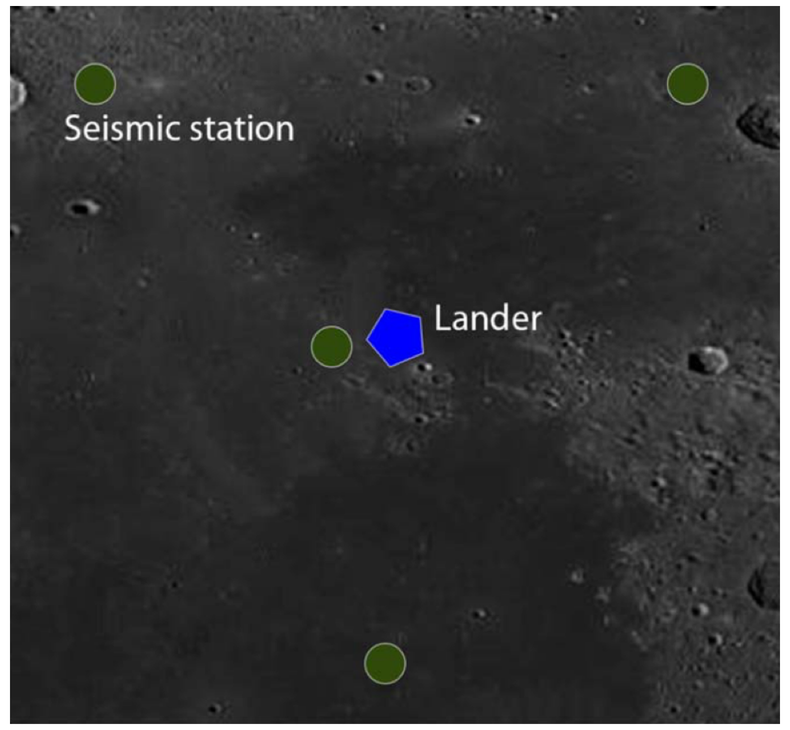
SN 10^{51} erg @ 20 kpc

DECIGO



Lunar Gravitational Antenna

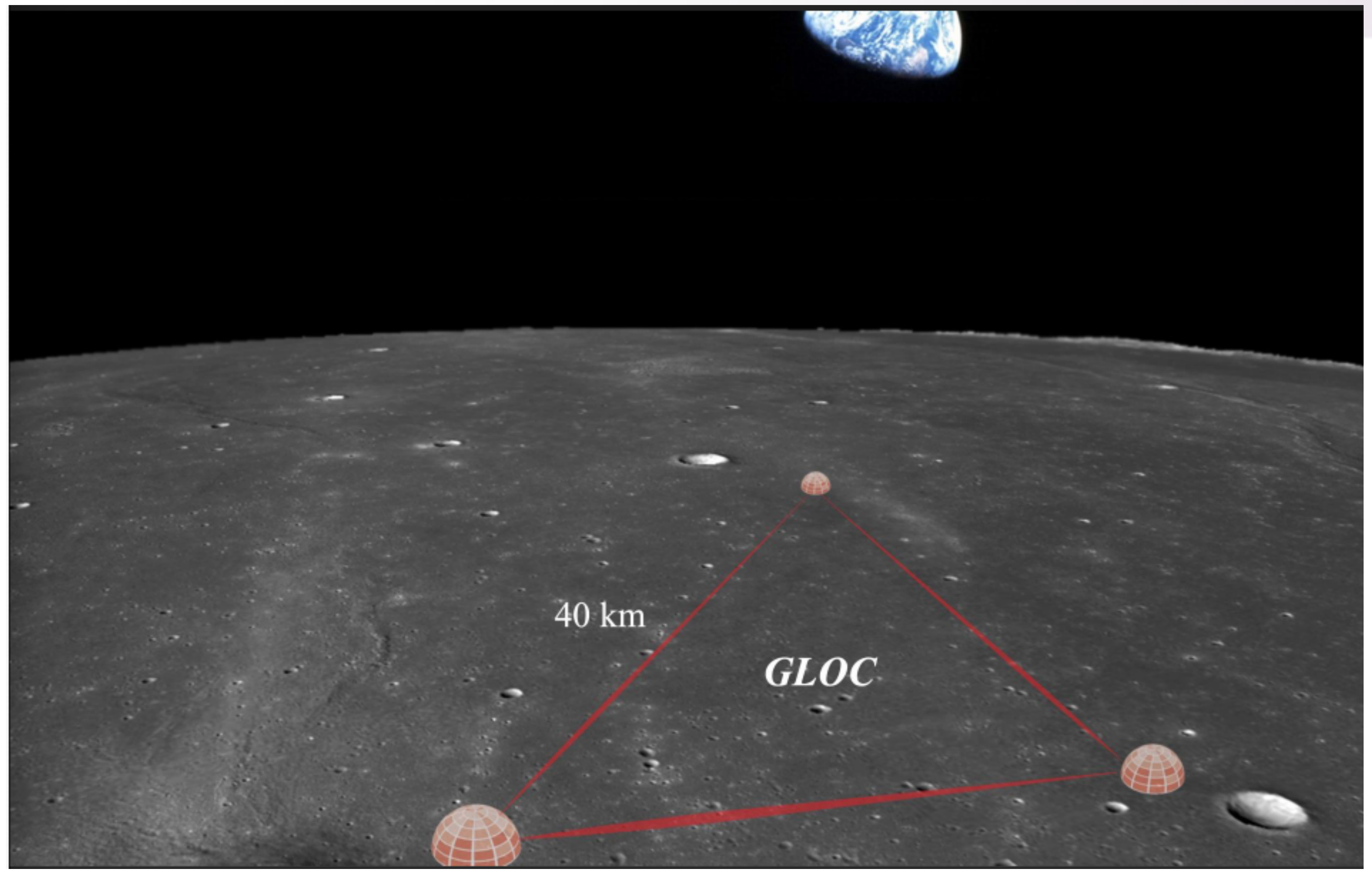




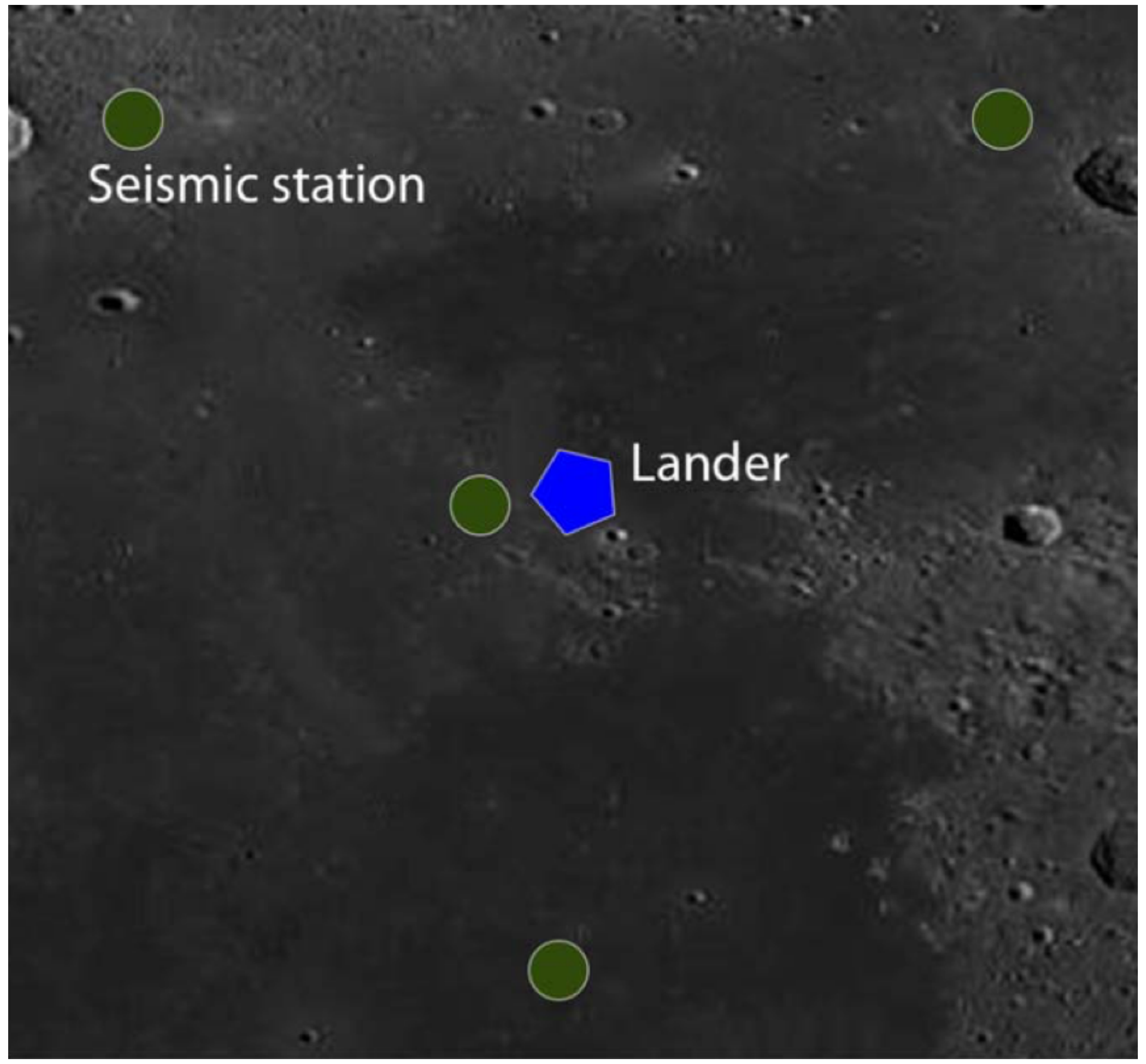
DECIHz detectors

Leiderschneider & TP, 2021

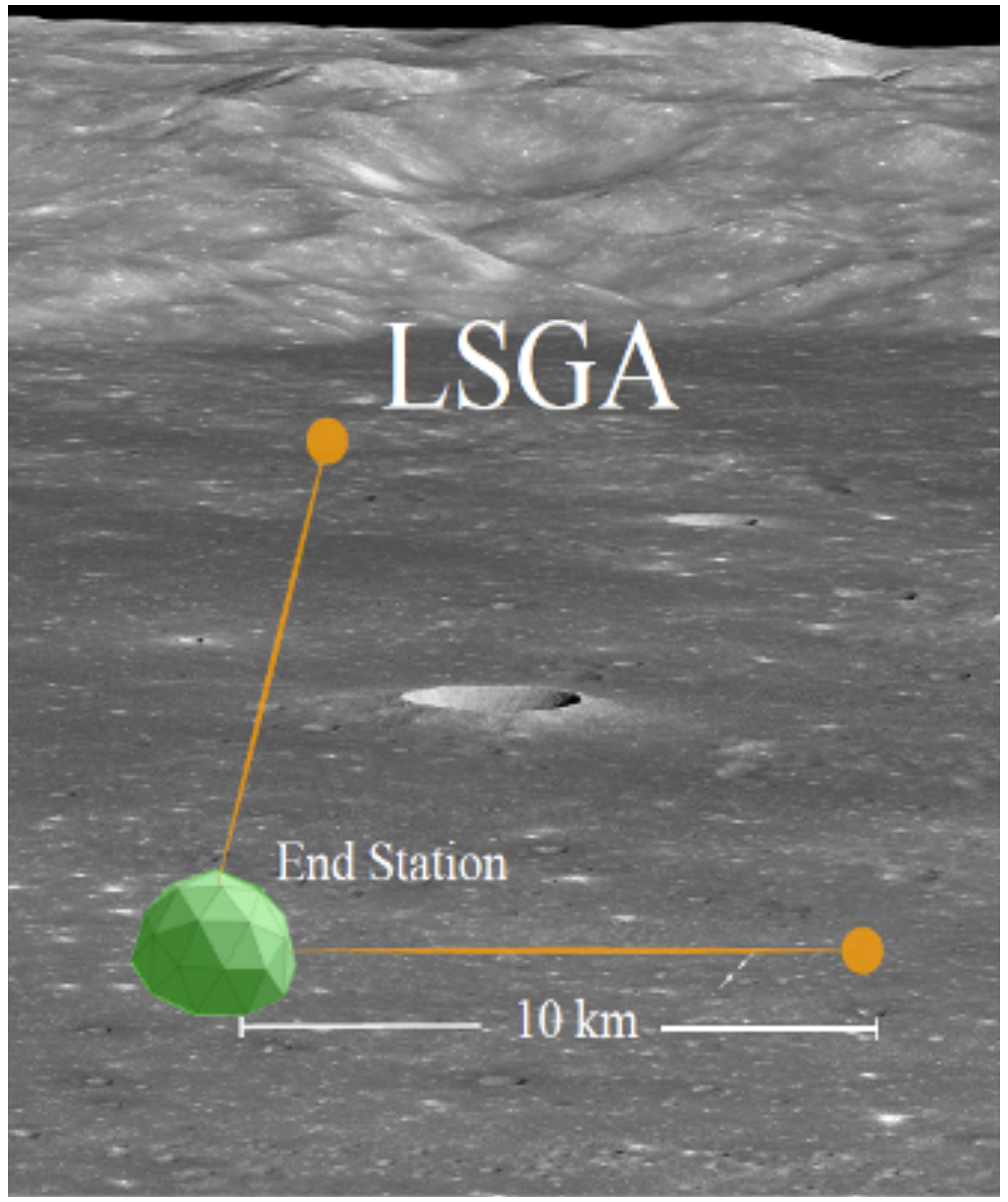
Lunar GW Detectors



Gravitational-wave Lunar Observatory for Cosmology GLOC

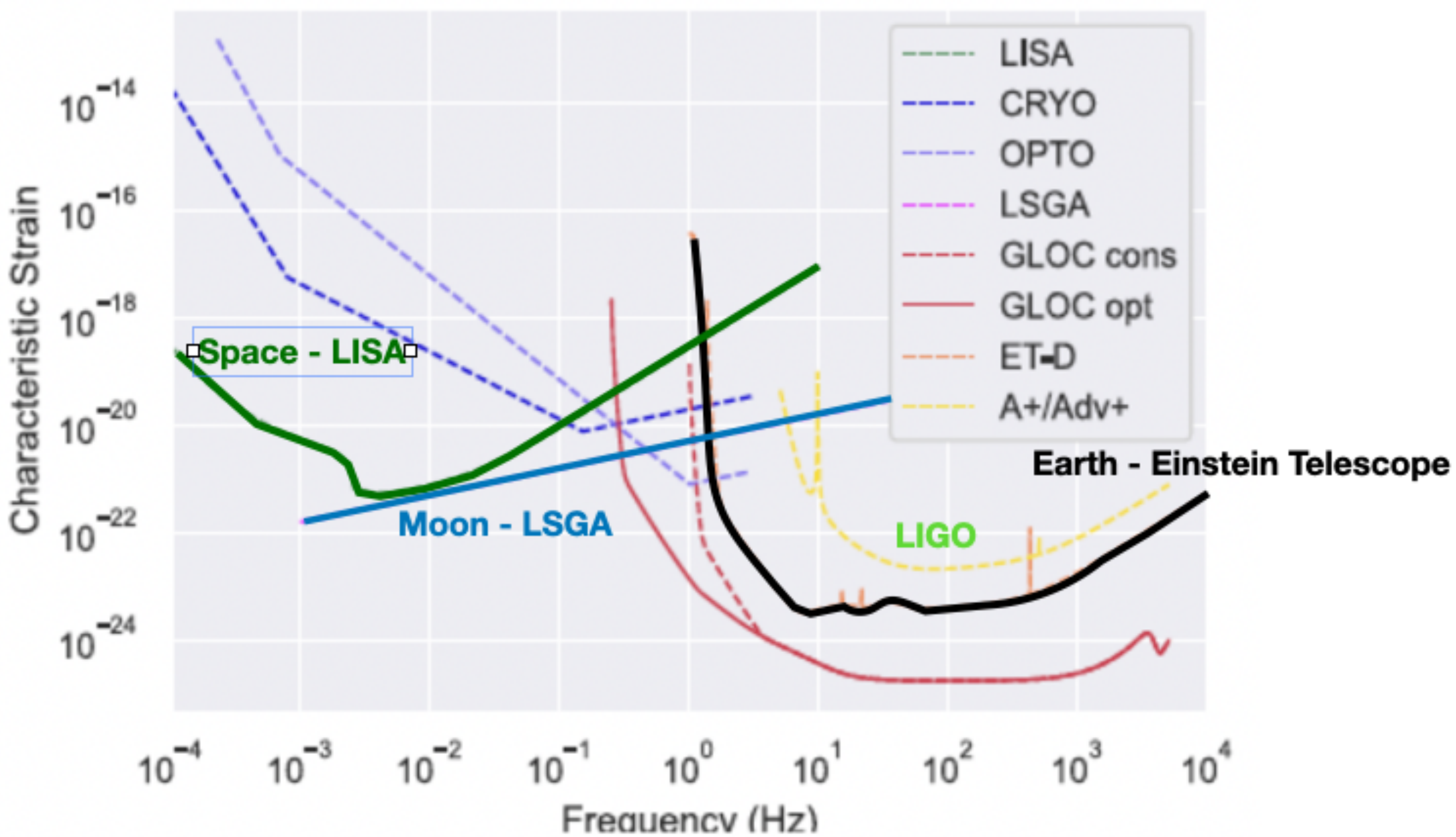


Lunar Gravitational Waves Antenna LGWA

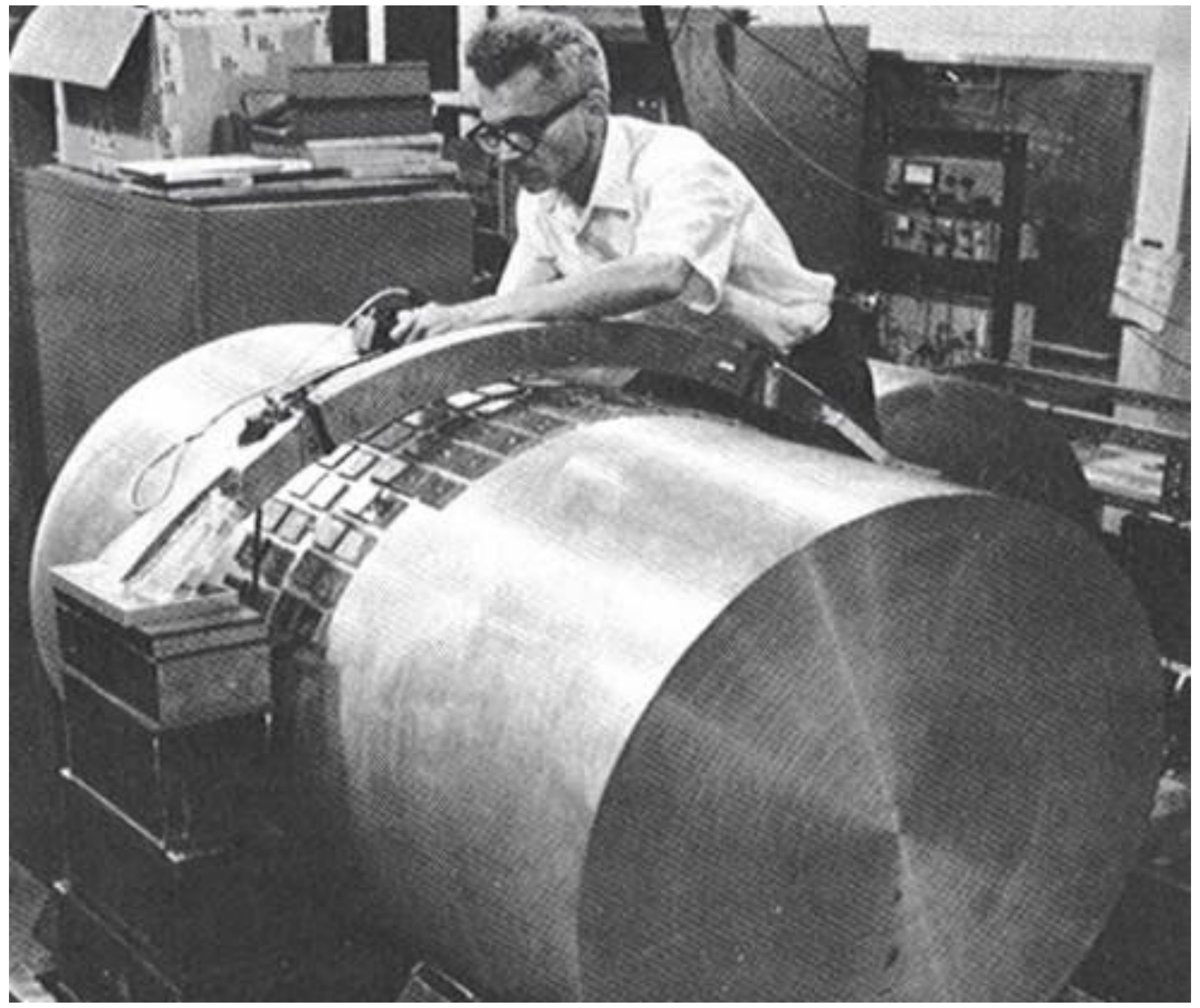


Lunar Seismic and Gravitational Antenna LSGA

Lunar GW Detectors



The Idea



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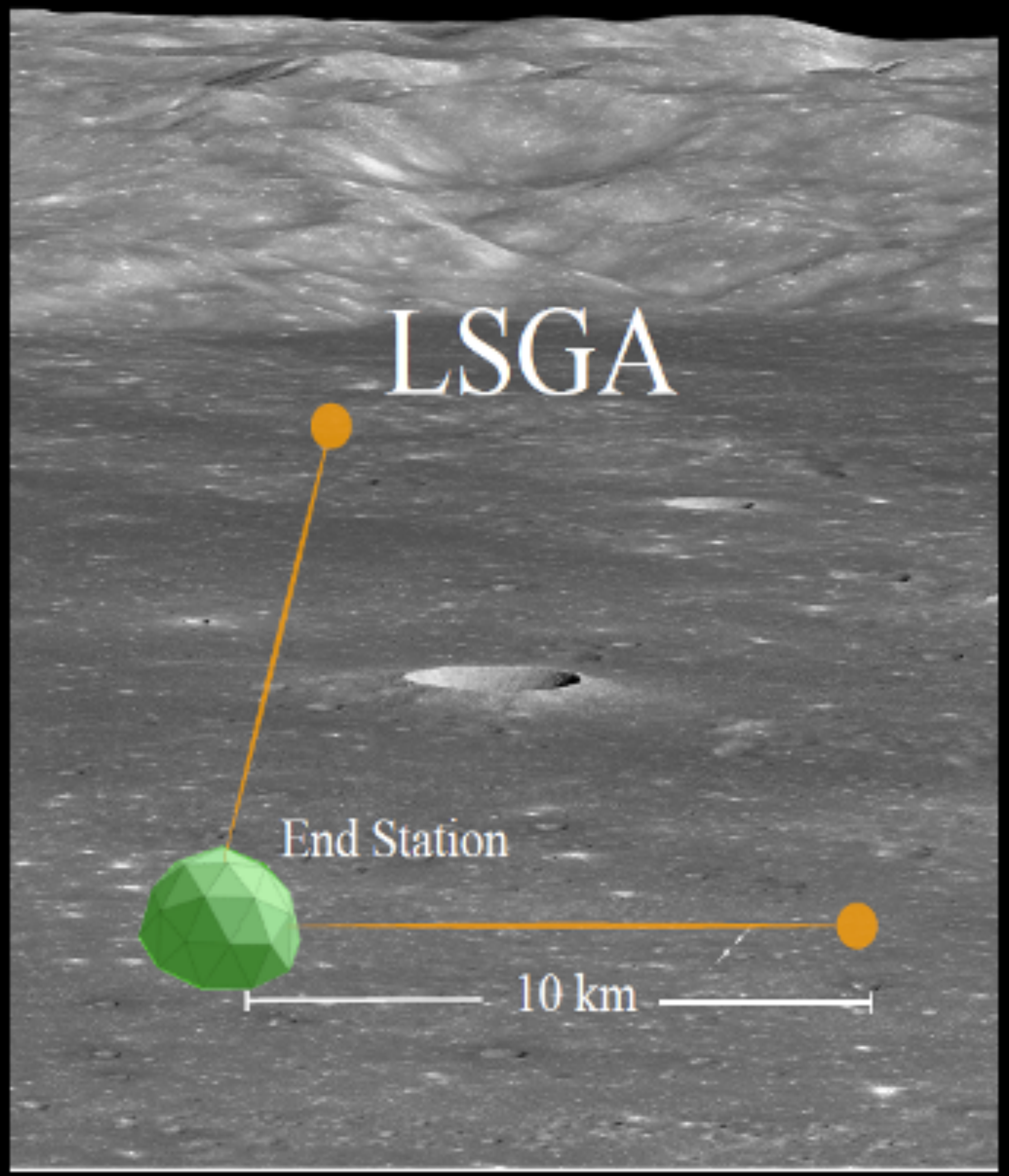
Lunar Seismic and Gravitational Antenna

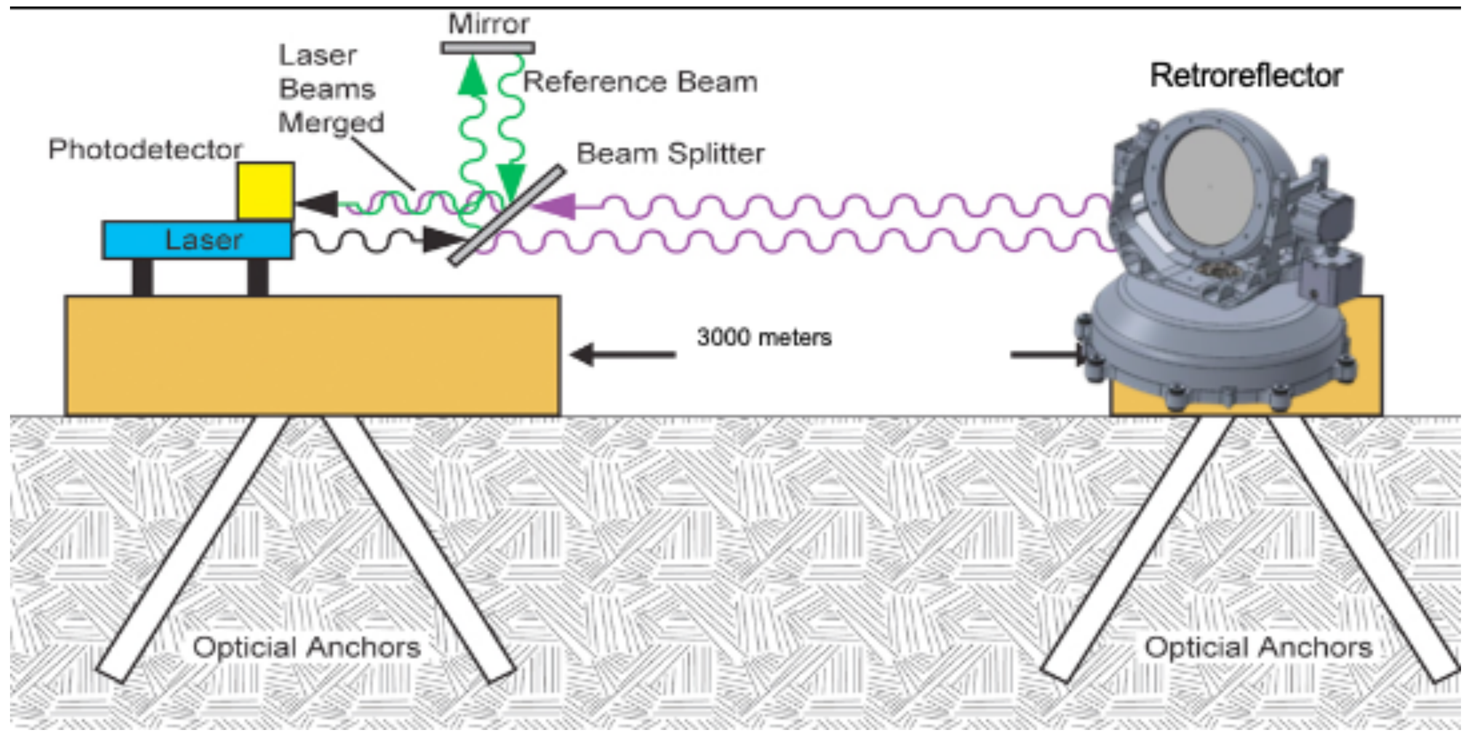
Lunar Seismic and Gravitational Antenna (LSGA)

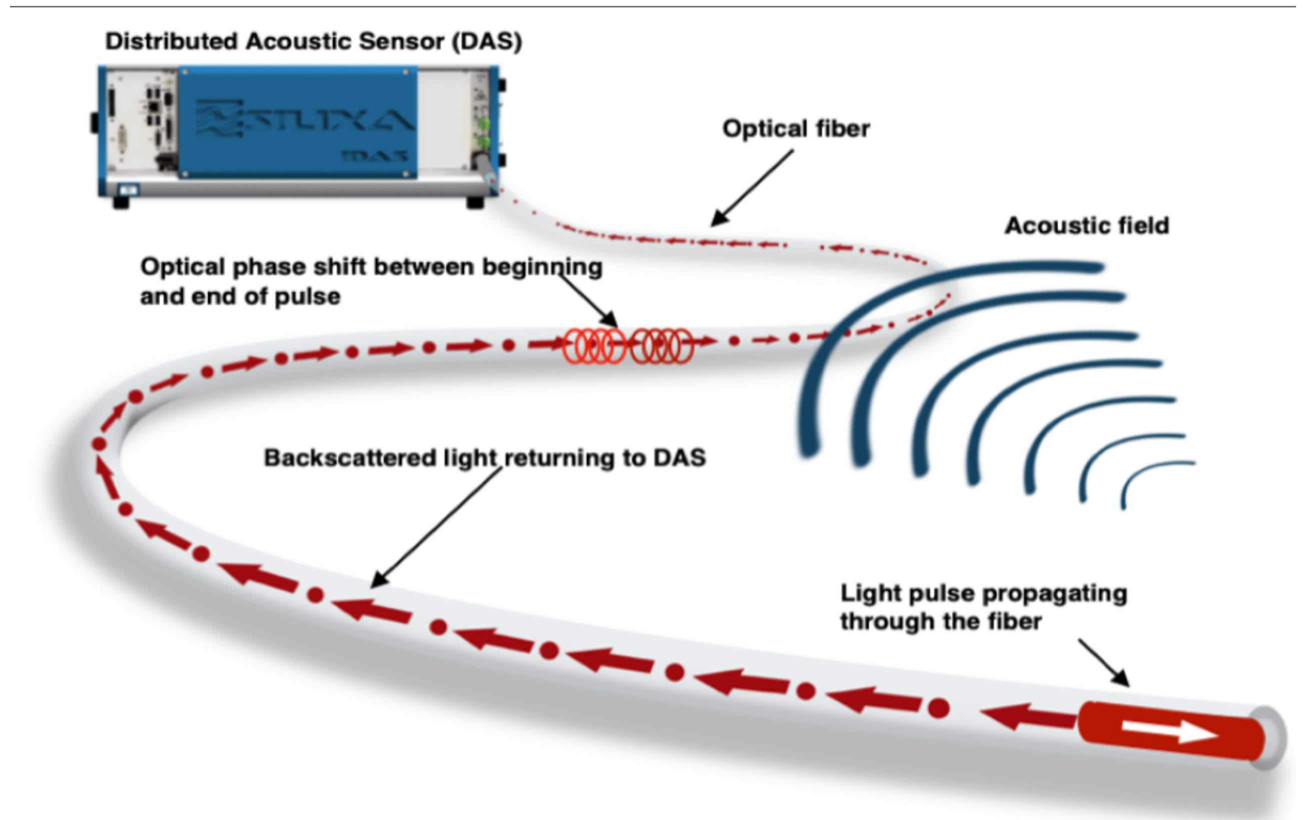
PI's S. Katsanevas EGO/UPC/APC, Co-PIs: P. Lognonné UPC/IPGP, S. DellAgnello INFN



S. Katsanevas
European Gravitational Observatory
Director
Presentation to ELS2022, 25 May 2022

France: Stavros Katsanevas, Prof. Univ. Paris Cité (UPC) and director European Gravitational Observatory (EGO), Antoine Kouchner, Michael Punch Aline Aloni, (UPC) and CNRS/IN2P3, Philippe Lognonné Prof. UPC and Institut de la Physique du Globe de Paris (IPGP), Taichi Kawamura, Sebastien de Raucourt, Eléonore Stutzmann, Pascal Bernard, Nobuaki Fuji, Jean-Philippe, Métaxian (UPC and IPGP), Raphael Garcia, Institut Supérieur de l'Aéronautique et de l'Espace, Supaéro, Toulouse, Anne-Amy Klein, Christian Chardonnet, CNRS/Univ. Paris 13, Paul-Eric Pottie, Observatoire de Paris, Josipa Majstorovic, Univ. de Grenoble, Vincent Bertin, Univ. de Marseille, Phd Students: T. Colin, Y. EL Kadeiri, Michel Chevalier, S. Harer **Italy:** Simone Dell'Agnello, National Institute of Nuclear Physics (INFN), Marco Muccino, Luca Porcelli, Mattia Tibuzzi, Giovanni Delle Monache, Lorenzo Salvatori, INFN, Elena Pian, INAF, Valerio Boschi INFN/University of Pisa, Akis Gkaitkatzis EGO **U.K.** Paolo Mazzali, Univ. of Liverpool, M.Farhadiroushan Sergey Shatalin, Athena Chalari, Silixa **Germany:** Philippe Jousset, Deutsches GeoForschung Zentrum(GFZ), Andreas Haungs, Andreas Rietbrock, Karlsruhe Institute of Technology (KIT) Helmholtz Centres **Israel:** Tsvi Piran, Hebrew University, Oded Aharonson, Weizmann Institute **Greece:** Manolis Plionis, National Observatory of Athens (NOA), Theoharis Apostolatos, Univ. of Athens **Poland:** Tomek Bulik, Leszek Rozkowski, Astronomical Centre M. Copernikus (CAMK)/Astrocent **US:** Saul Perlmutter, Laurence Berkeley Laboratory, Karan Jani, Vanderbilt University, **Norway** M. Landro, L. Amundsen, B. Arntsen Norwegian University of Science and TEchnology





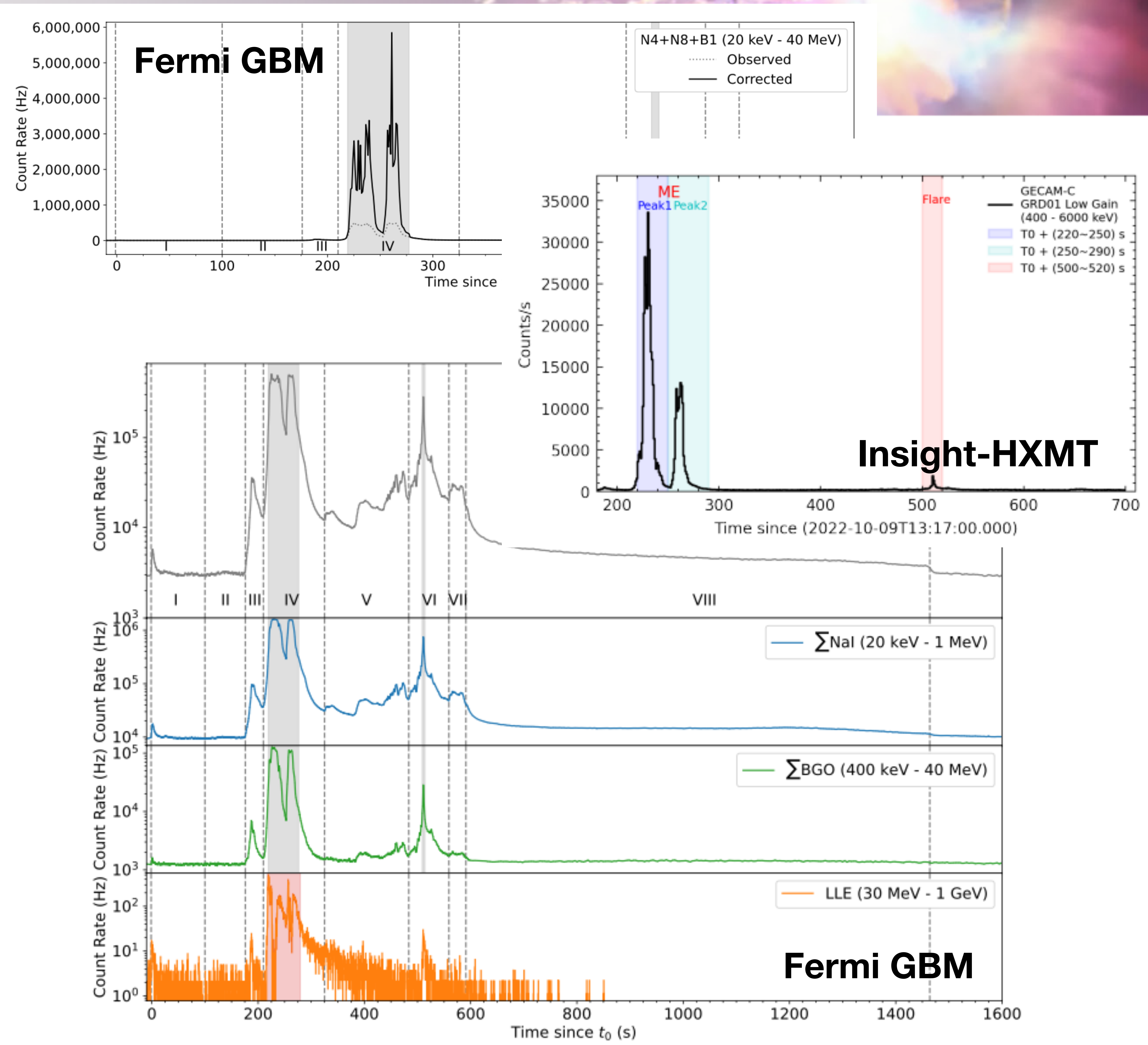
Summary

- Acceleration (and deceleration) of relativistic jets produces memory-type GW signals.
- For typical sources (GRBs, some SNe) the GW frequency is at the deciHz range.
- Some SNe harbor relativistic jets whose GW signals might be stronger than the classical GW signal from the collapse
- Galactic giant SGR flares may produce signals detected by LVC.

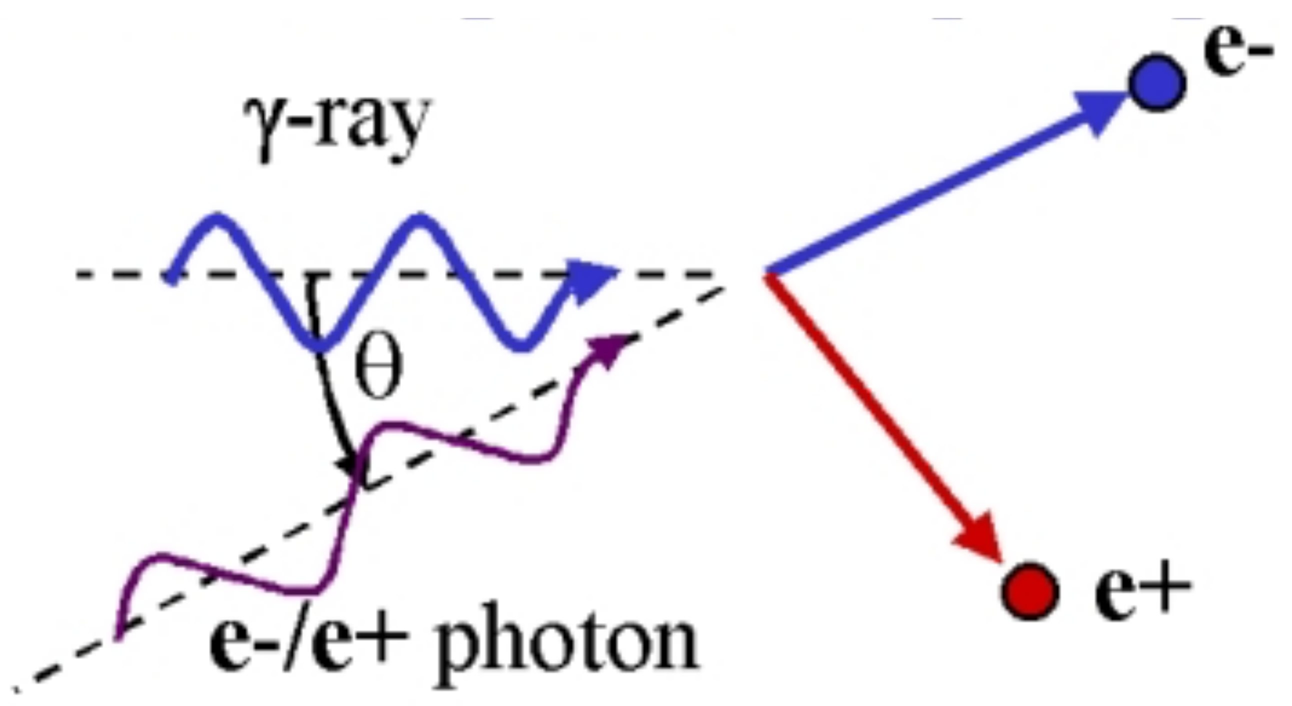

221009A

221009A

- $Z=0.151$ (745 Mpc)
- $E_{iso}=1.5 \times 10^{55}$ erg
- If $\vartheta_j=0.7^o$ then $E=1.15 \times 10^{51}$ erg
- $T_{90}=330$ sec
- LHAASO 5000 photons > 500 GeV up to 18 TeV
- The afterglow emission is much less energetic, and it is comparable to other TeV GRBs e.g. 990114c.



Pair production threshold



$$\epsilon_{thr} = m_e^2/E_\gamma$$

Optical Depth and the 18 TeV photon

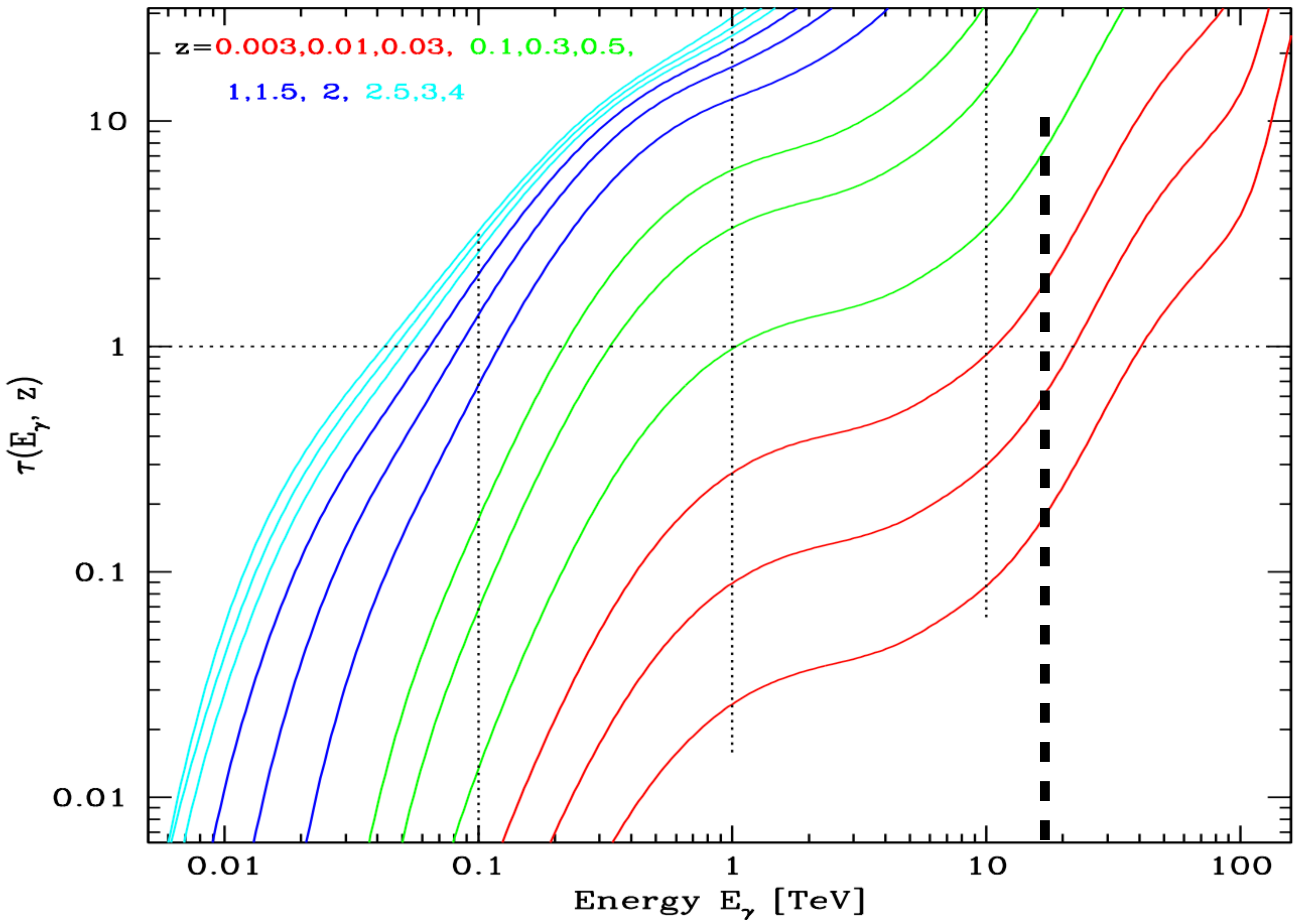


Figure 4. The optical depth by photon–photon collision as a function of the photon energy for sources located at $z = 0.003, 0.01, 0.03, 0.1, 0.3, 0.5, 1, 1.5, 2, 2.5, 3, 4$, from bottom to top. The fast rise at the high τ and E_γ values is due to the large volume density of CMB photons. The graph is based on the model by [82].

From: Francesini 2021

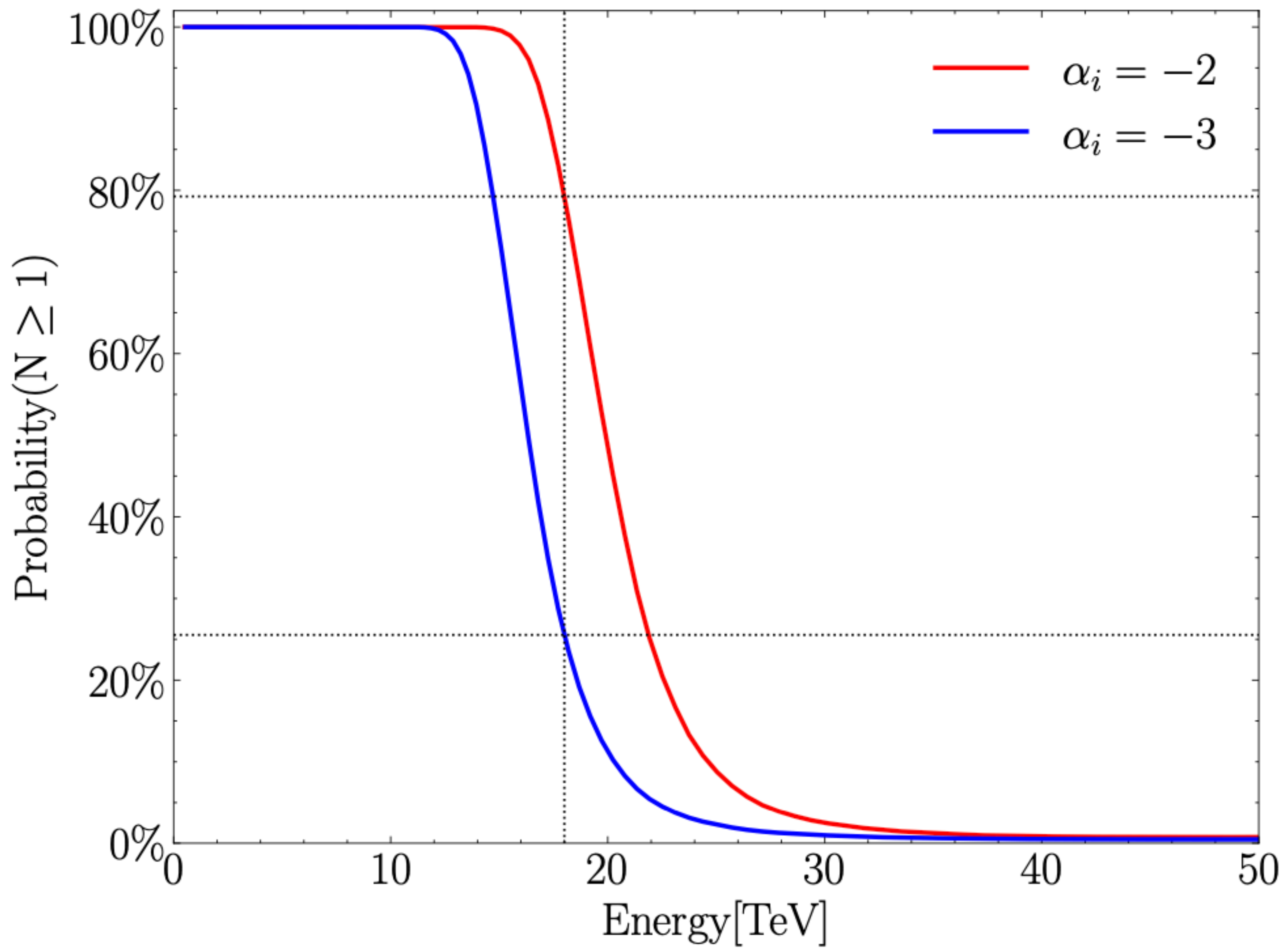


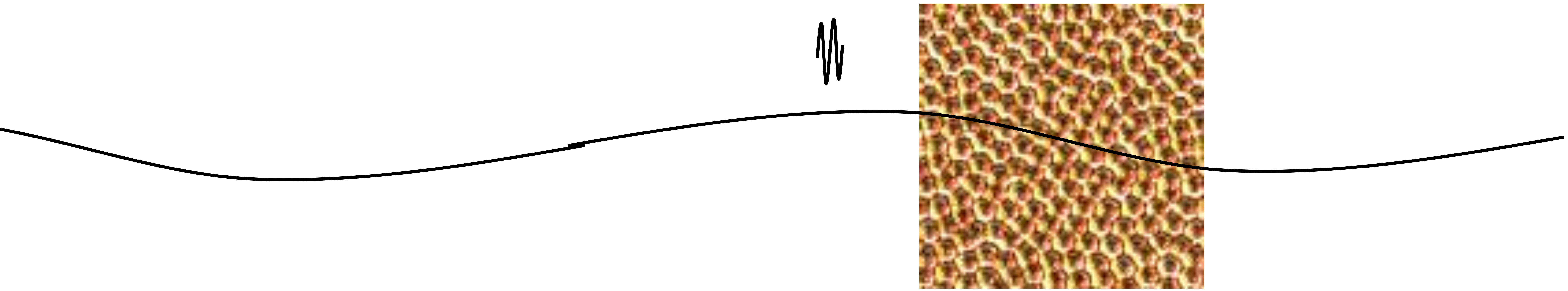
Fig. 2 Probability of predicting that LHAASO observes at least one photon from GRB 221009A within 2000 seconds. The vertical dotted line denotes 18 TeV. The coloring of curves is consistent with that of Fig. 1.

From: Zhao et al., 2022

Quantum Gravity Effects at low energies

Lorentz Violation (or deformation) appears in various Quantum Gravity Theories.

Energy dependent dispersion and speed of light.



A phenomenological Approach

The simplest leading order low-energy approximation of any theory that breaks Lorentz Invariance at a very high energy scale: ξm_{pl}, for the deformed dispersion relation:

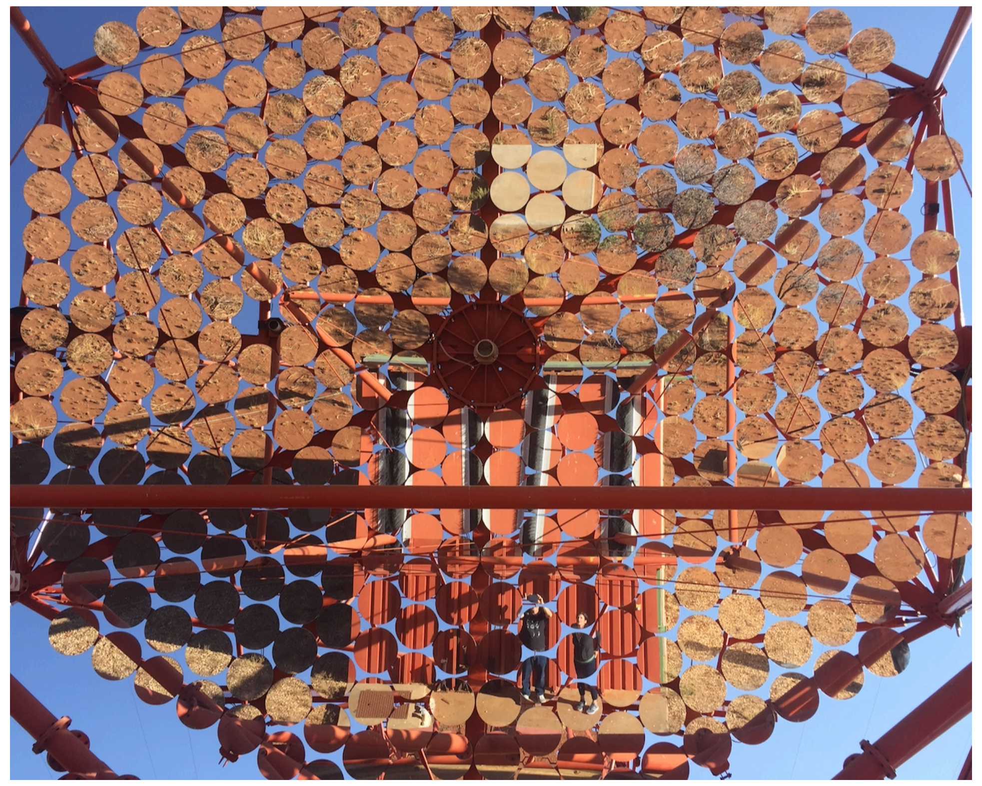
$$E^2 - p^2 - m^2 \approx \pm \left(\frac{E}{\xi_n m_{pl}} \right)^n$$

$$v \approx c \left[1 \pm \frac{(1+n)}{2} \left(\frac{E}{\xi_n m_{pl}} \right)^n \right]$$

Higher energy photons will arrive later (or earlier) than low energy ones emitted **simultaneously**.

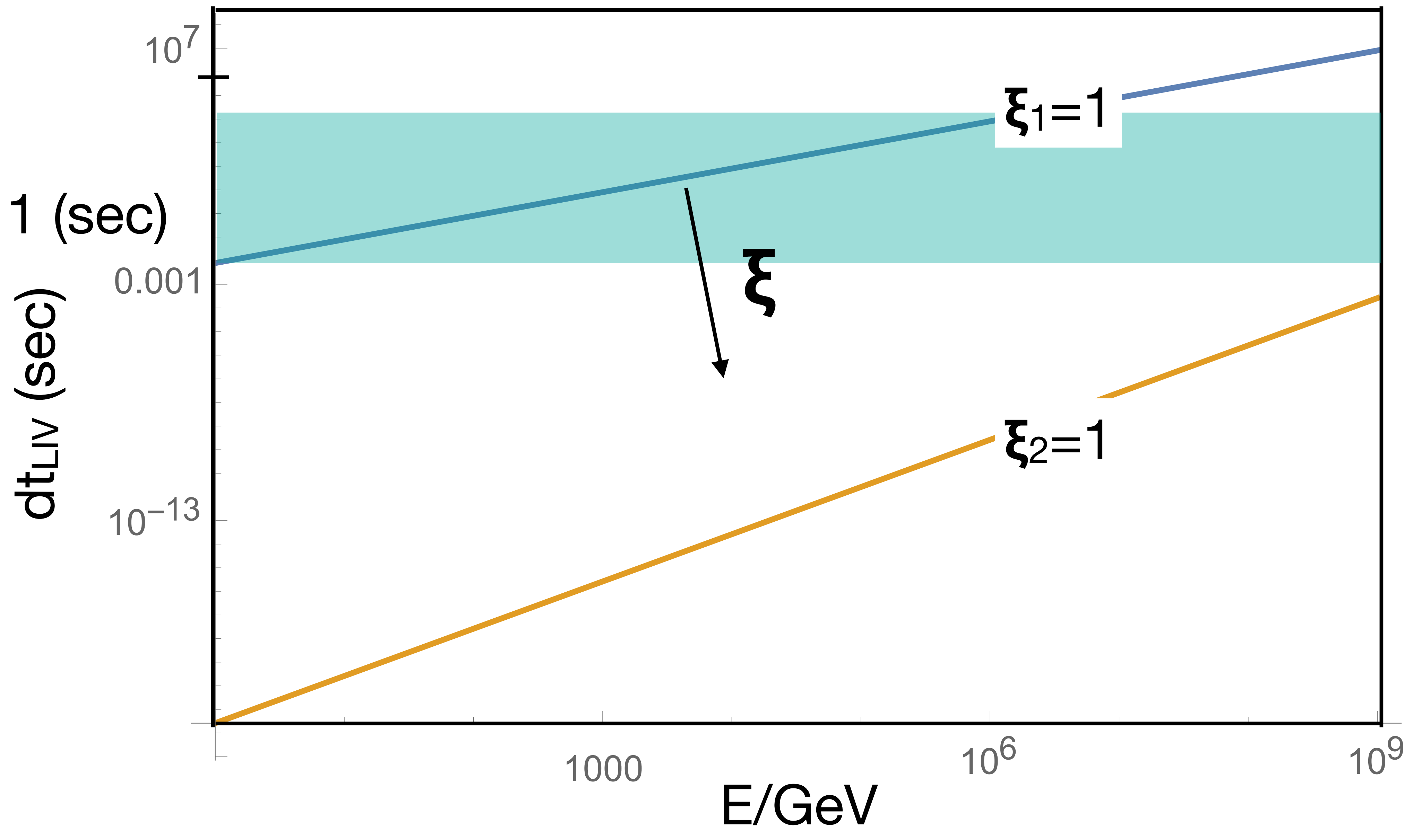
$$dt_{LIV} \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n m_{pl}}\right)^n \approx 0.01\mathrm{sec}\ 10^{-19(n-1)}\left(\frac{E}{\xi_n GeV}\right)^n$$

Fermi

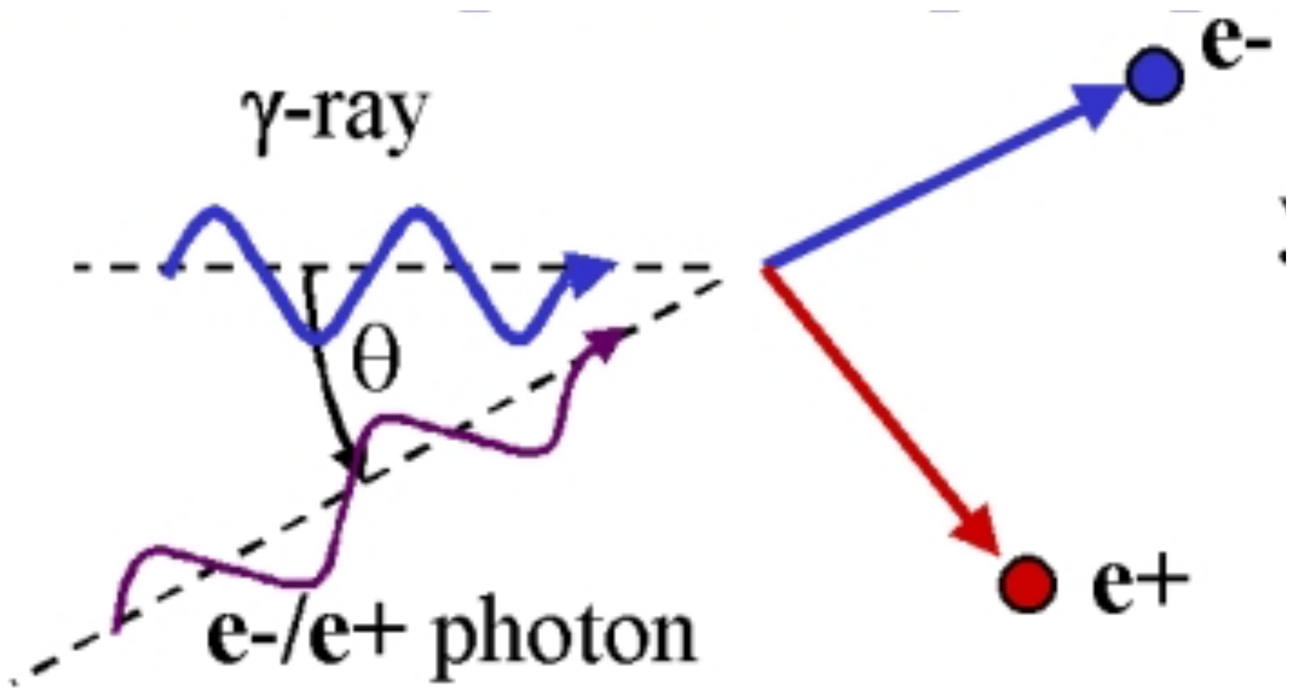


H.E.S.S. ; Magic

dt for a cosmological source at z=1 for n=1,2 (ξ=1)



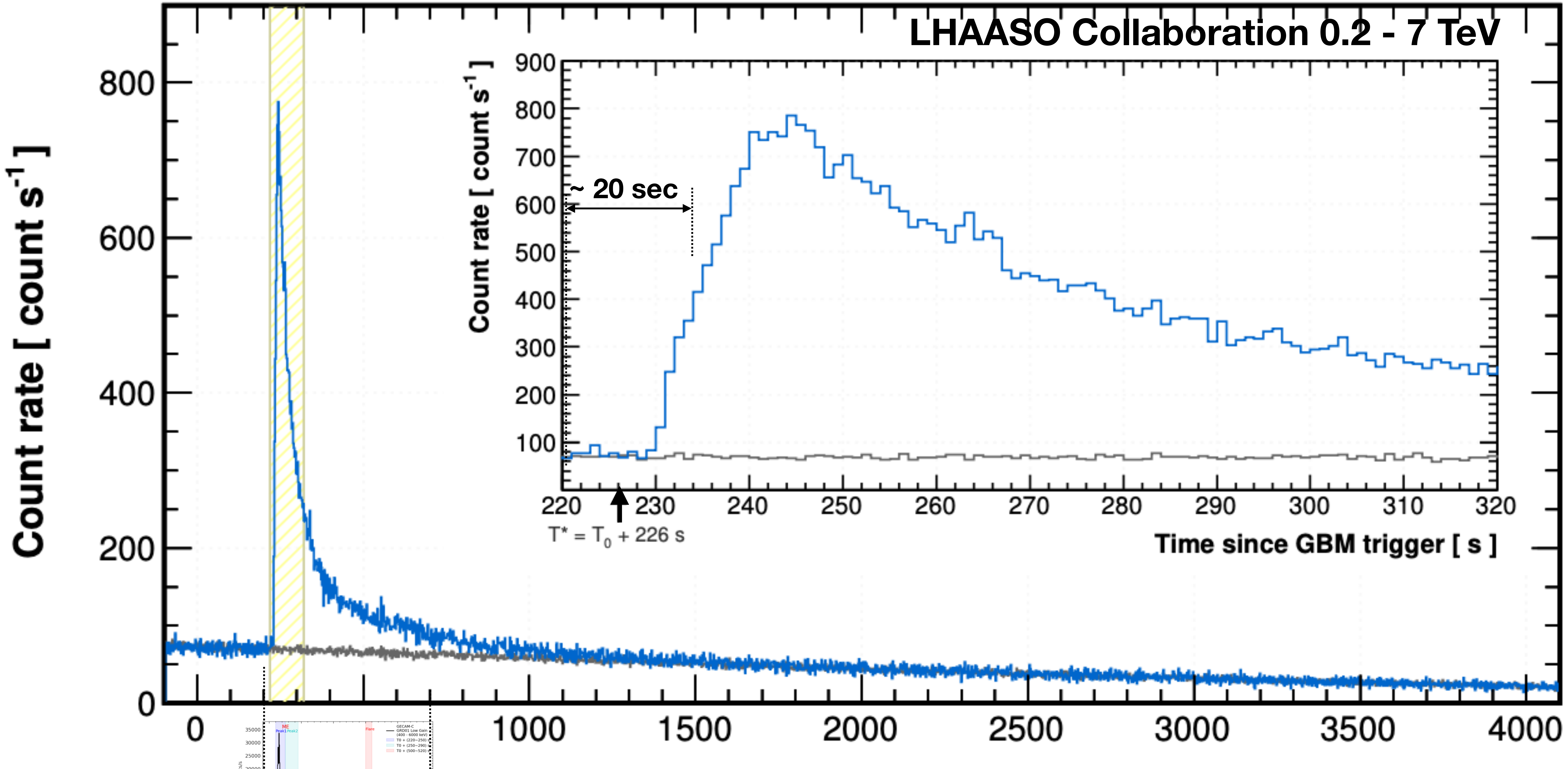
LIV induced change in thresholds

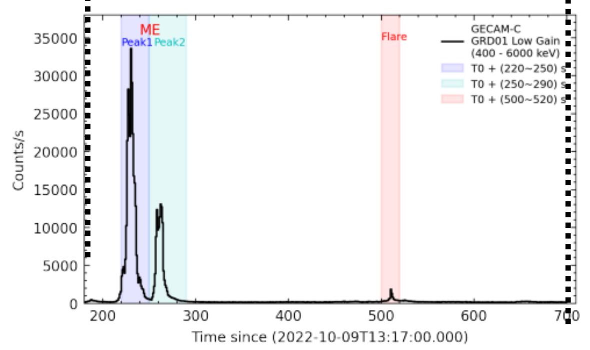


$$\epsilon_{thr} = m_e^2/E_\gamma + \frac{1}{4}(1 - 2^{-n}) \left(\frac{E_\gamma}{\xi_n E_{pl}} \right)^n E_\gamma,$$

=> Several suggestions that the 18 TeV photon is evidence for LIV

221009A TeV Afterglow





Prompt

A phenomenological Approach

The simplest leading order low-energy approximation of any theory that breaks Lorentz Invariance at a very high energy scale: ξm_{pl}, for the deformed dispersion relation:

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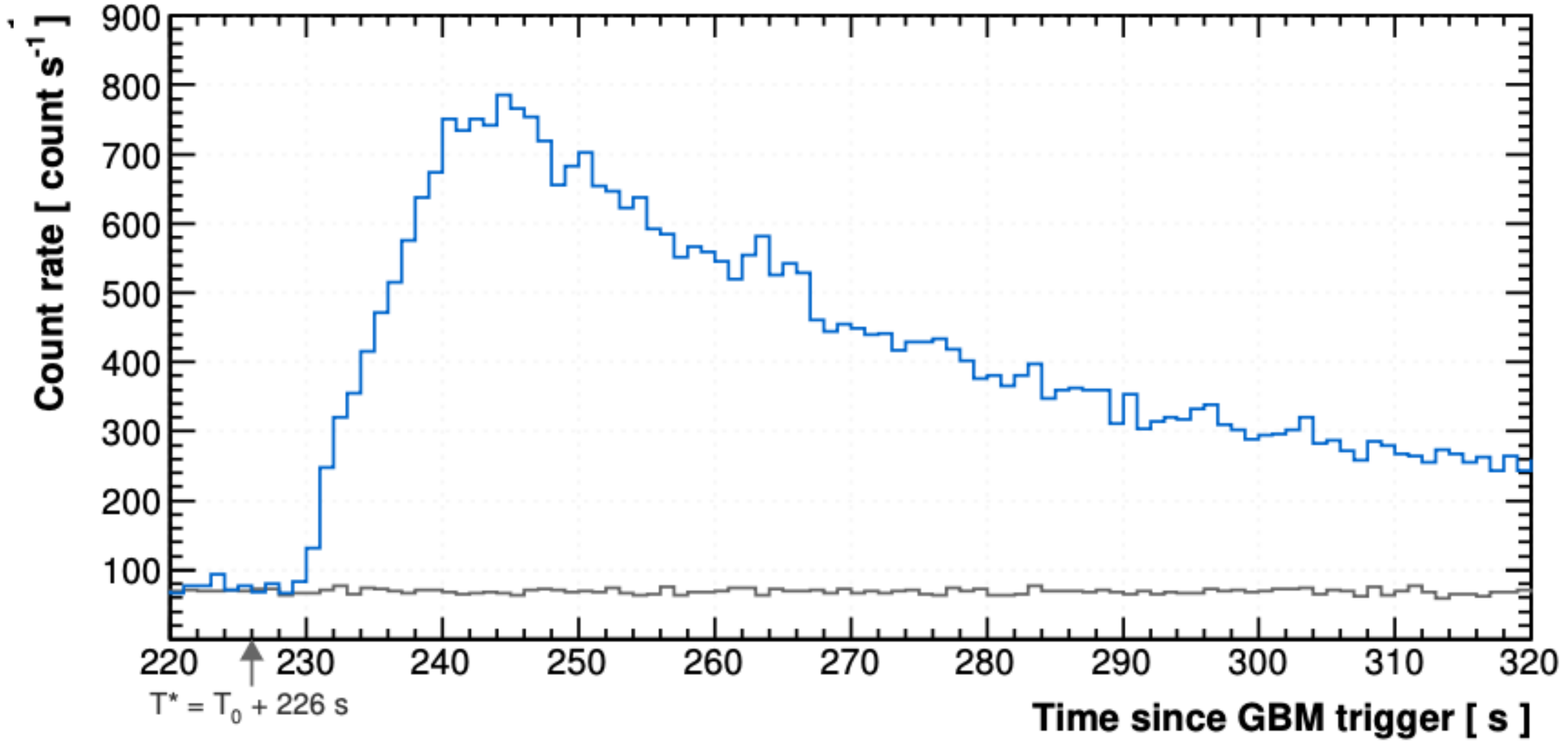
$$v \approx c \left[1 \pm \frac{(1+n)}{2} \left(\frac{E}{\xi_n m_{pl}} \right)^n \right]$$

Higher energy photons will arrive later (or earlier) than low energy ones emitted **simultaneously**.

LIV limits from 221009A TeV Afterglow

Offenghiem & Piran 2023



The typical time from onset to the peak of the afterglow

$$t_{dec} \approx 6 \text{ sec } (1+z)\left(\frac{E_k/10^{53} \text{ erg}}{n}\right)^{1/3}(\Gamma/300)^{-8/3}$$

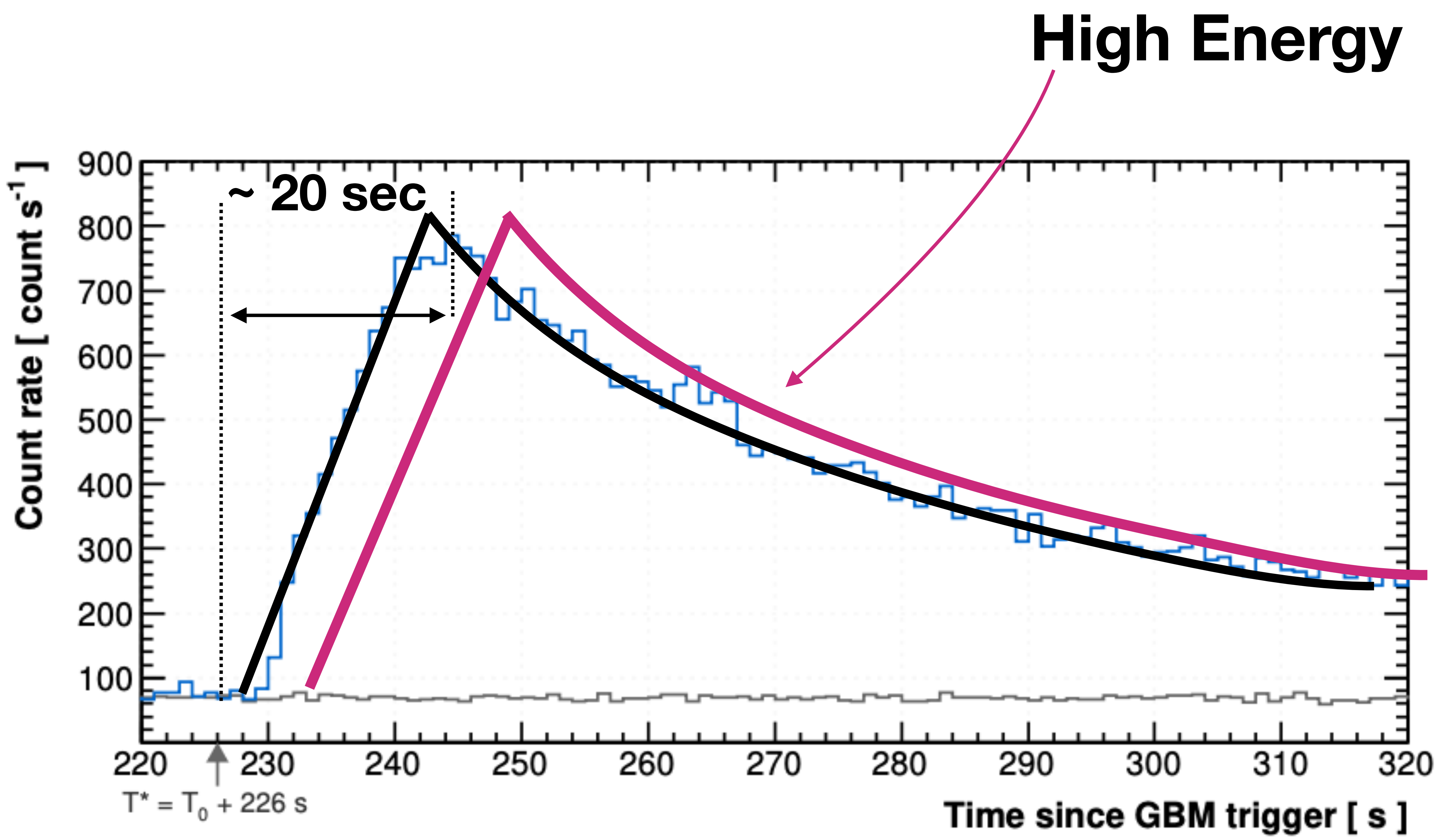
Kinetic Energy (E_k)

Lorentz factor (Γ)

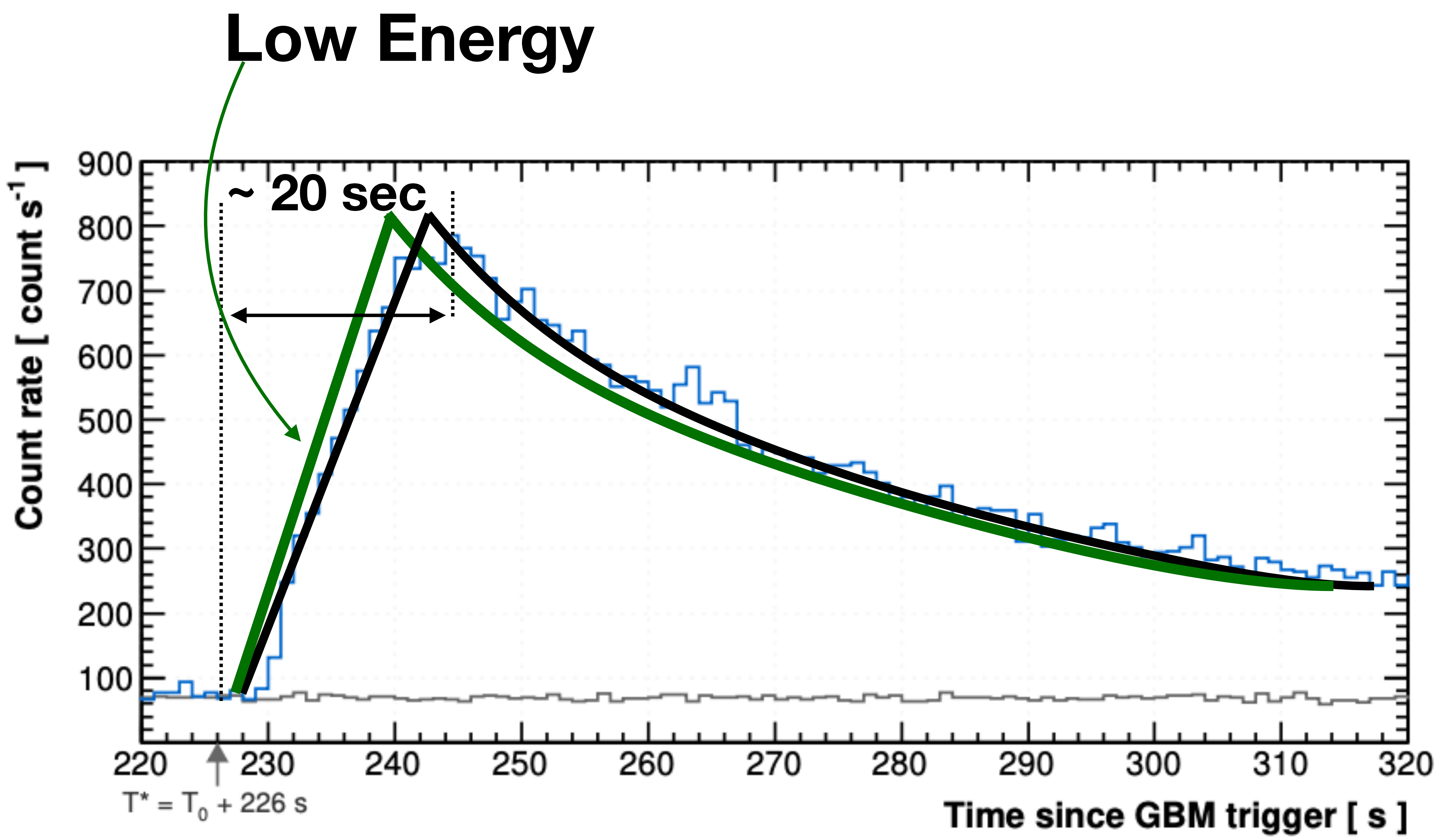
Red shift (z)

Surrounding density (n)

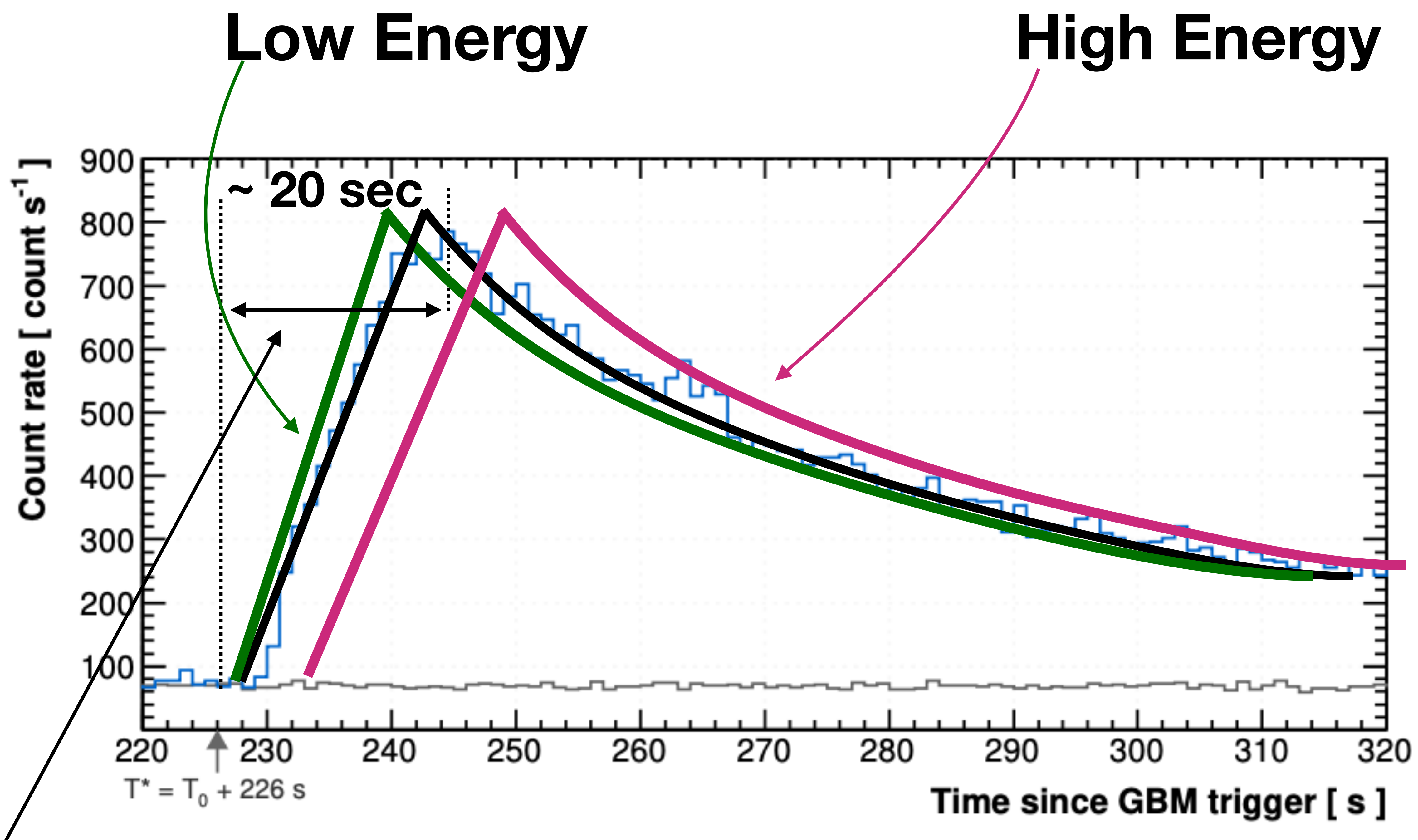
LIV limits from 221009A TeV Afterglow



LIV limits from 221009A TeV Afterglow



LIV limits from 221009A TeV Afterglow



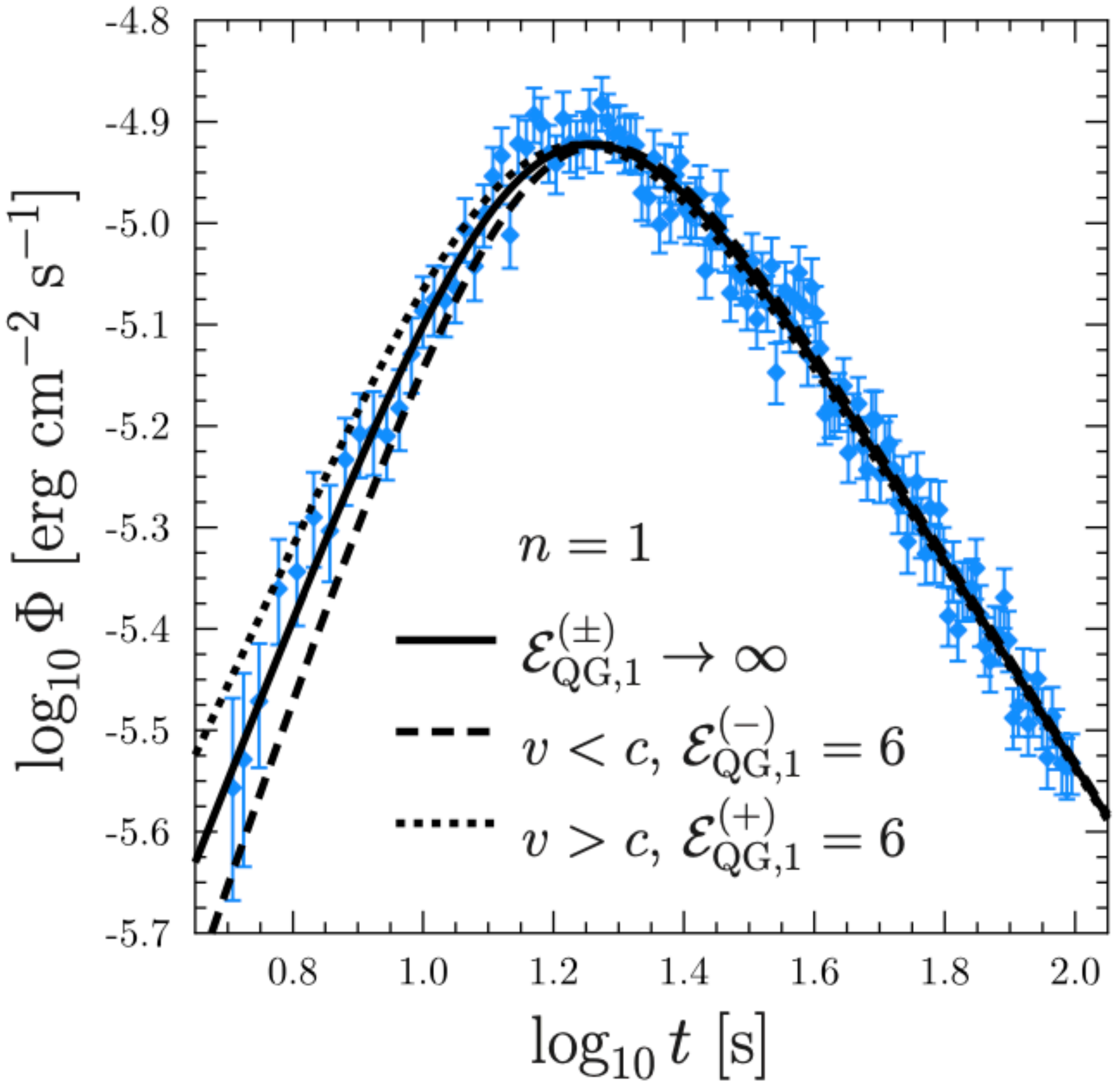
A constant spectral shape during the first 20-40 seconds
=> Strong LIV limits

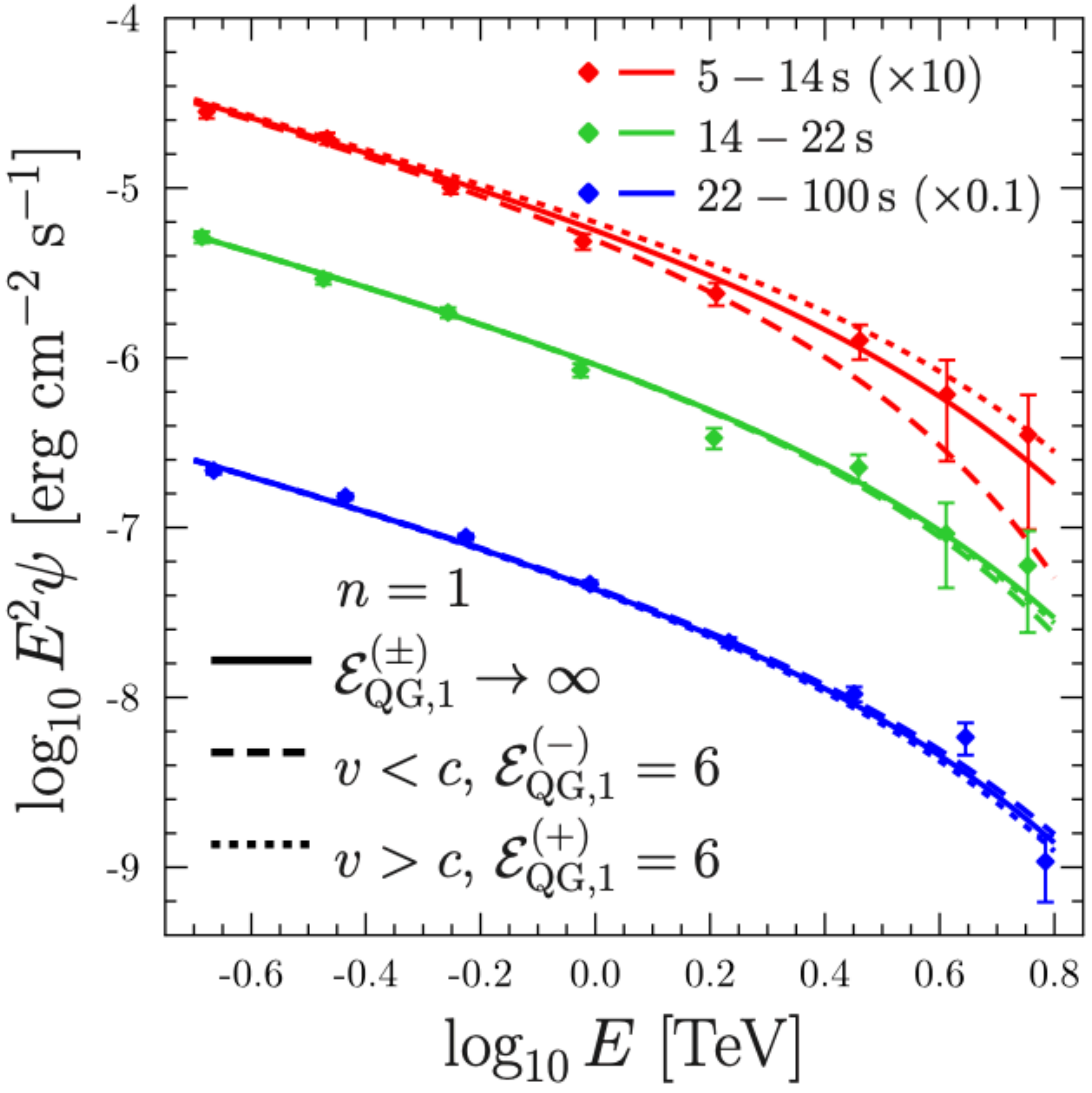
$$20\ \text{sec} \approx \pm \frac{d}{c}\left(\frac{E}{\xi_n m_{pl}}\right)^n \approx 2\ \text{sec}\ 10^{-16(n-1)}\left(\frac{7\ \text{TeV}}{\xi_n TeV}\right)^n \qquad \begin{cases} \xi_1 > 0.5 \\ \xi_2 > 10^{-8} \end{cases}$$

For a source at z=0.15

Inconsistent with LIV "solution" for an 18 TeV photon from z=0.151 (EBL)

LIV limits from 221009A TeV Afterglow





LIV limits from 221009A TeV Afterglow

TABLE I. Best-fit parameters for the model given by Eq. 8 and a combined χ^2 fit for both the lightcurve and the spectra of the afterglow of GRB 221009A in the time region $5-100$ s. The observational data is taken from [1]. If not specified differently, a fit parameter is dimensionless.

	Best fit	95% confidence interval
A^{a}	8.1	6.5 — 9.8
$C_{a.c.}$	0.25	0.24 — 0.26
$t_b{}^{b}$	16.0	14.3 — 17.6
α_1	1.6	1.1 — 2.0
α_2	−1.02	−1.08 — −0.95
ω	1.5	0.8 — 2.1
γ	2.93	2.84 — 3.02
$E_{cut}{}^{c}$	3.1	2.1 — 4.1
$\mathcal{E}^{(\sigma)}_{QG,1}$	—[d]	$\mathcal{E}^{(-)}_{QG,1} \geqslant 5.9$; $\mathcal{E}^{(+)}_{QG,1} \geqslant 6.2$
$\mathcal{E}^{(\sigma)}_{QG,2}$	—[e]	$\mathcal{E}^{(-)}_{QG,2} \geqslant 5.8 \times 10^{-8}$; $\mathcal{E}^{(+)}_{QG,2} \geqslant 4.6 \times 10^{-8}$

[a] $[10^{-6}\ \mathrm{erg}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]$
[b] [s]
[c] [TeV]
[d] The formal fit result is $\sigma/\mathcal{E}^{(\sigma)}_{QG,1} = 0.005 \pm 0.083$.
[e] The formal fit result is $\sigma(10^{-8}/\mathcal{E}^{(\sigma)}_{QG,2})^2 = -0.009 \pm 0.019$.

From Piran and Offengheim 2013
***LHASSO published last week similar reulsts**

LIV limits

TABLE II. A comparison of with LIV TOF limits from GRBs 090510, 190114C, and 221009A.

GRB	090510[a]	190114C	221009A
Red Shift	0.903	0.425	0.151
ΔE [TeV]	10^{-4} — 0.03	0.3 — 1	0.2 — 7
$\Delta T_{\rm obs}$ [s]	0.15 — 0.217	30 — 60	9 — 14
$\mathcal{E}^{(\sigma)}_{\rm QG,1}$	11^{-} 5.2^{+}	0.23^{-} 0.45^{+}	5.9^{-} 6.2^{+}
$\mathcal{E}^{(\sigma)}_{\rm QG,2}/10^{-8}$	0.7^{-} 0.77^{+}	0.46^{-} 0.52^{+}	5.8^{-} 4.6^{+}

[a] From [31] with ML method.

Summary

- Phenomenological models of LIV induces time of flight differences between photons of different energy and threshold shifts for different reactions (e.g. pair production)
- Time of flight LIV limits of GRB 221009: LIV - $\xi_1 \approx 5$, $\xi_2 \approx 10^{-8}$ (Best for n=2, comparable to GRB 090510 for n=1)
- A comparable limit for stochastic LIV for GRB 090510 (but some concern?)
- There is no need for “new physics” by the TeV emission observed in GRB 221009A