Time-domain astronomy

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Rough outline

Day 1: Intro

How are gamma rays produced? What do we learn from them?

Day 2: Observations

How do we detect gamma rays? How do we decide what/when to observe?

Day 3 + 4: Sources

What astronomical objects do we observe in the time domain?

Part 3a. Sources: Gamma-ray bursts and related phenomena

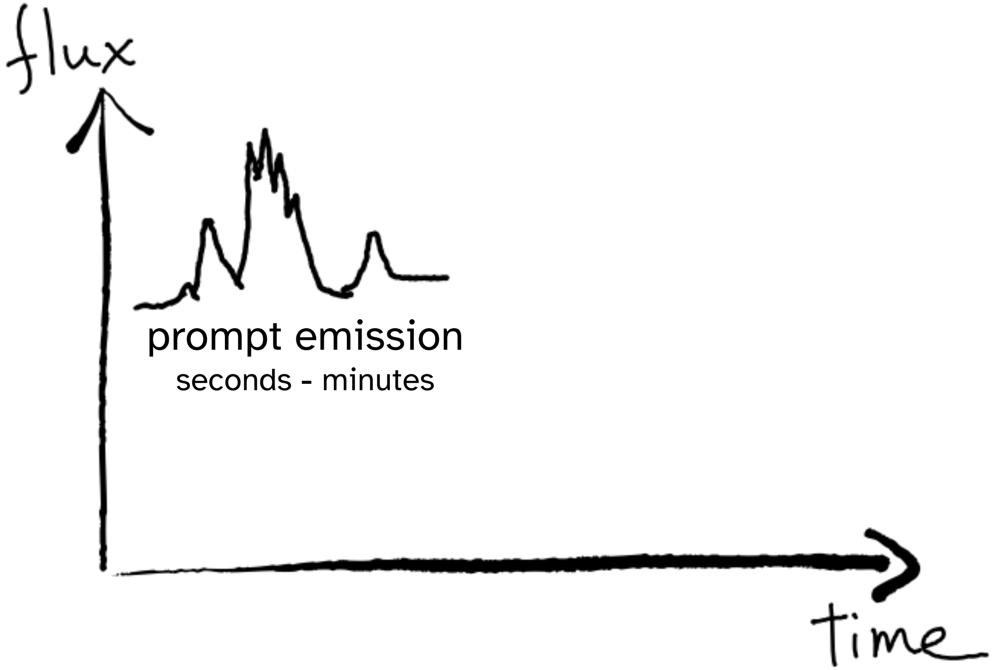
MORE ABOUT GAMMA-RAY BURSTS

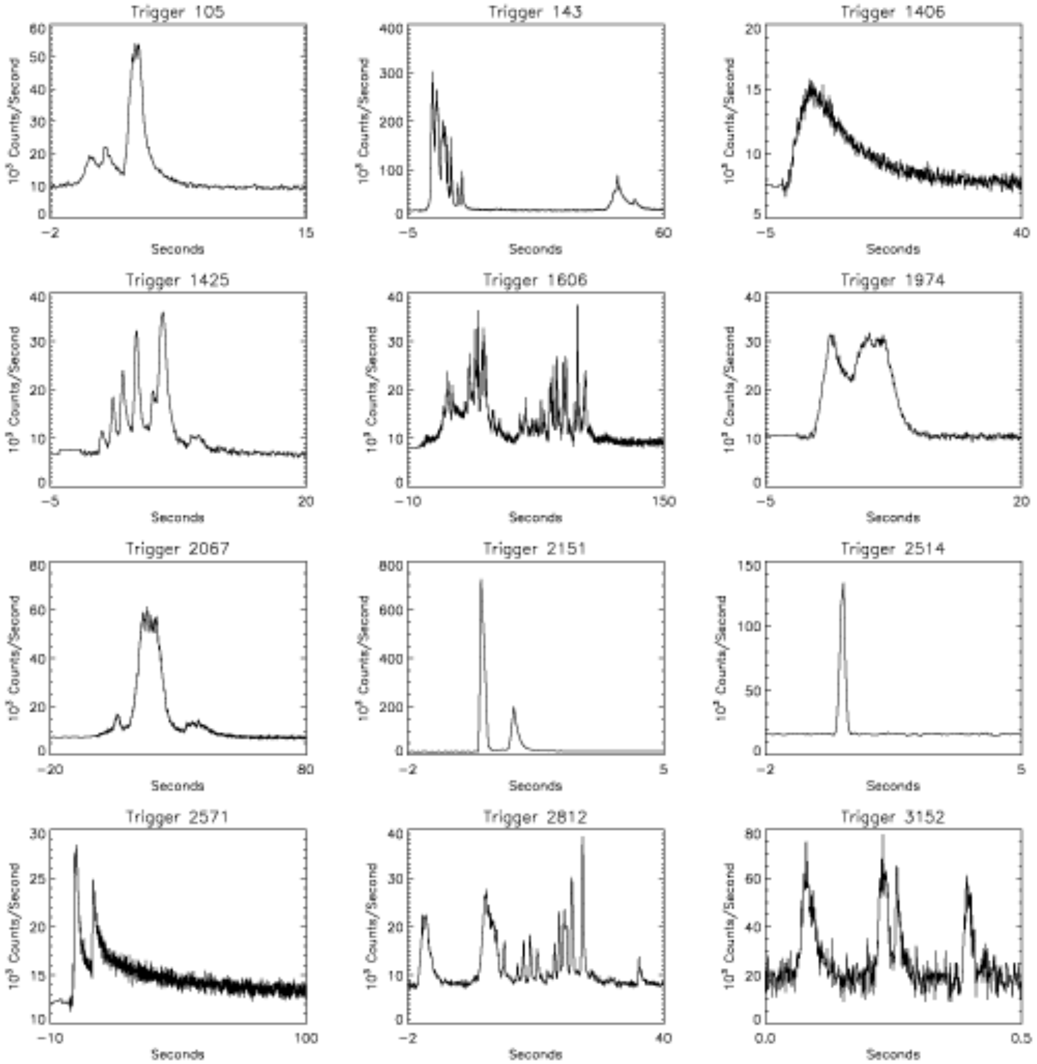
disclaimer: This is from a data analyst POV!
All the theory will be vastly simplified!!!

👋 👋

Gamma-ray bursts

What causes them?



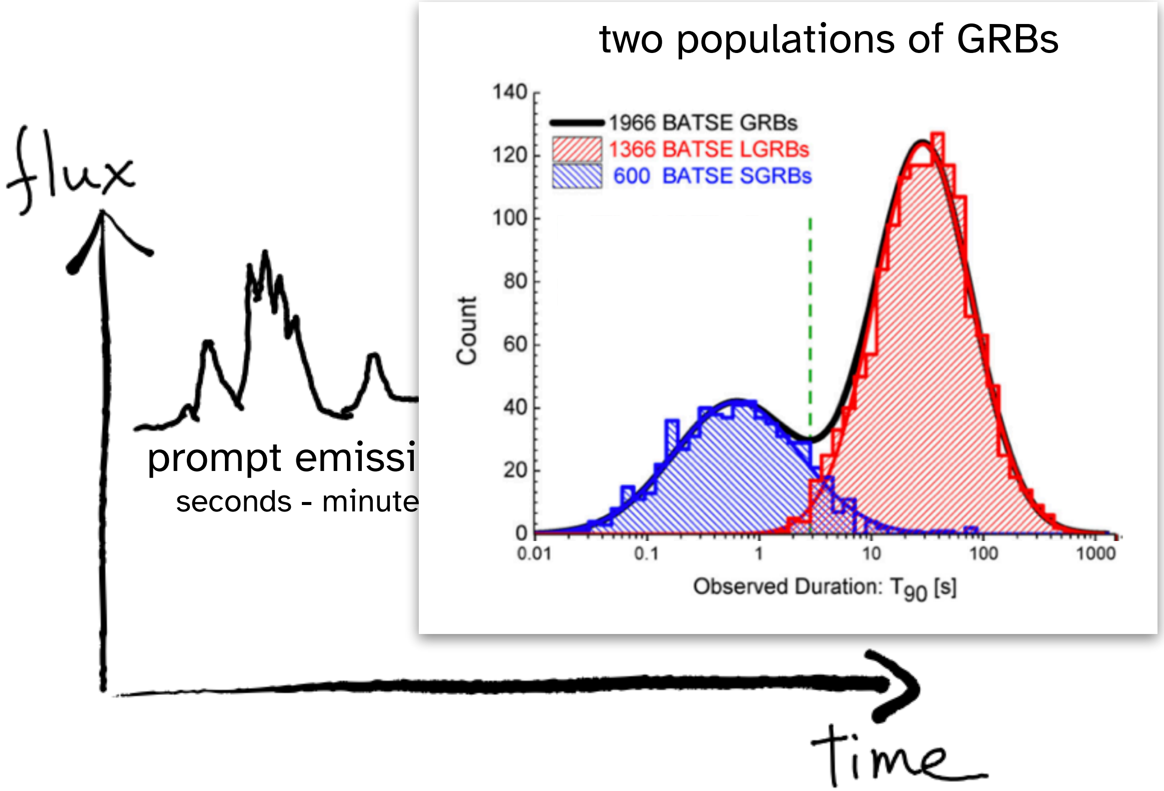


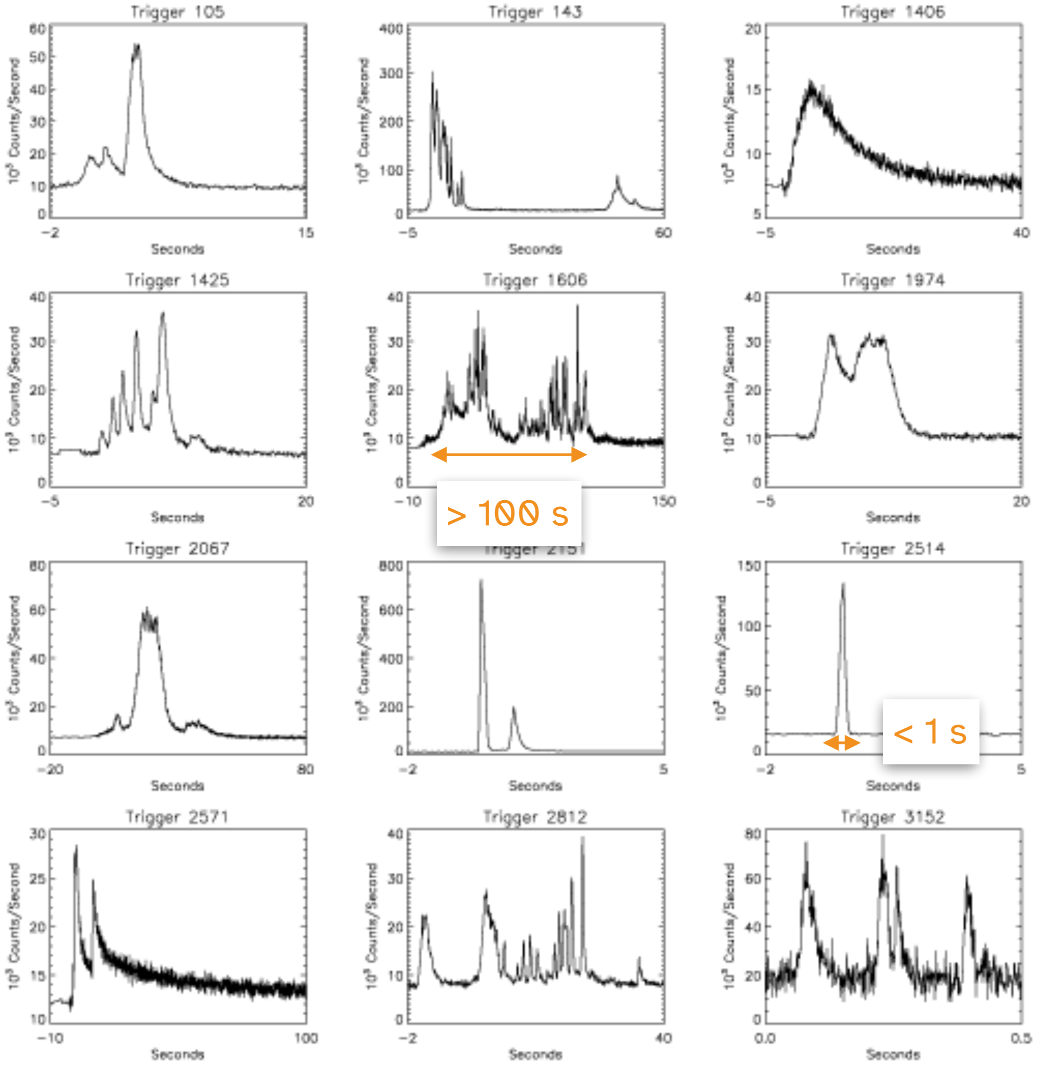
[J. T. Bonnell (NASA/GSFC)]

Gamma-ray bursts

What causes them?

[A. Shahmoradi & R. J. Nemiroff, MNRAS 451 (2015)]





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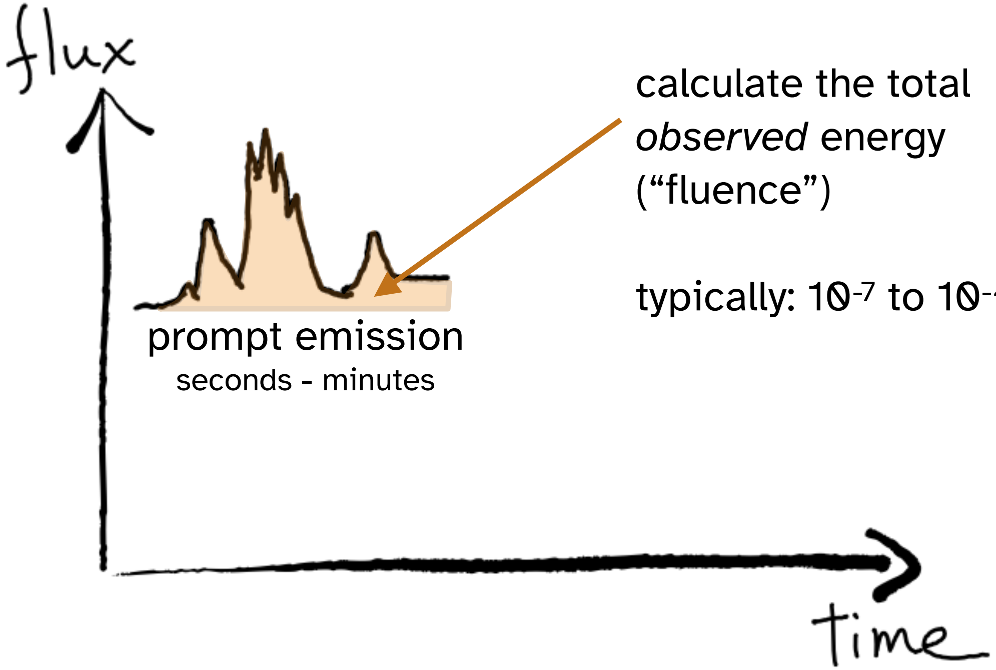
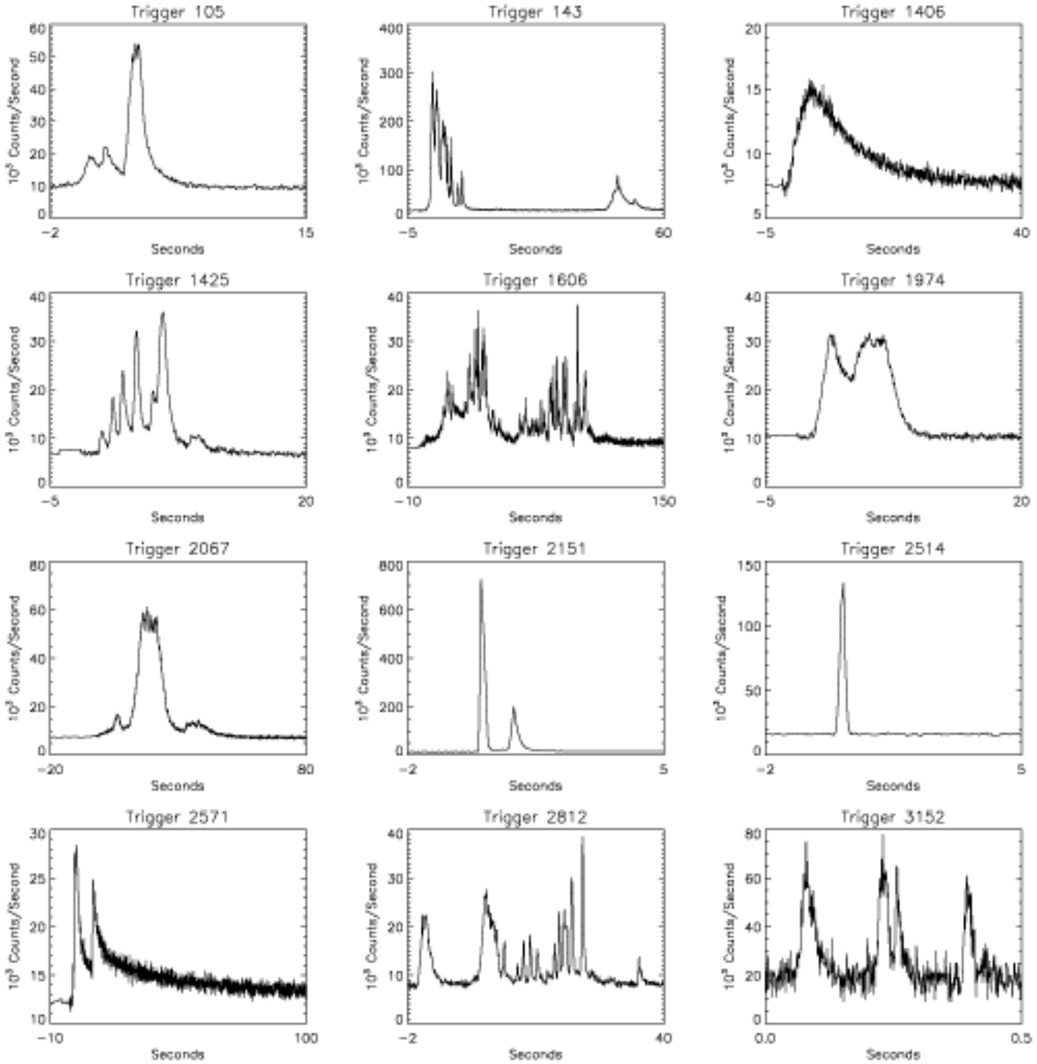


calculate the total
observed energy
(“fluence”)

typically: 10^{-7} to 10^{-4} erg



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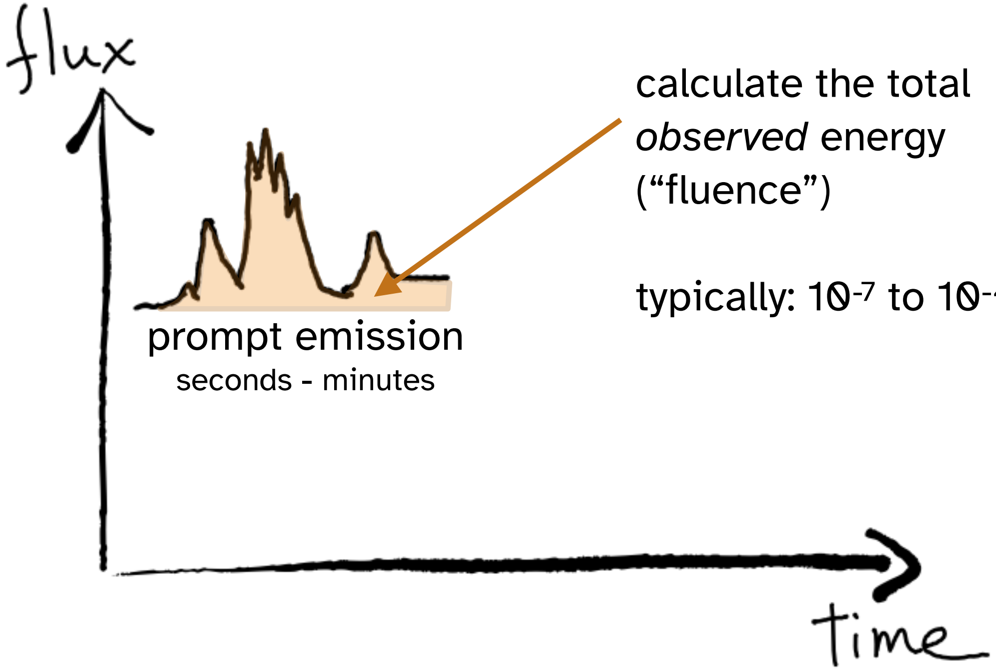
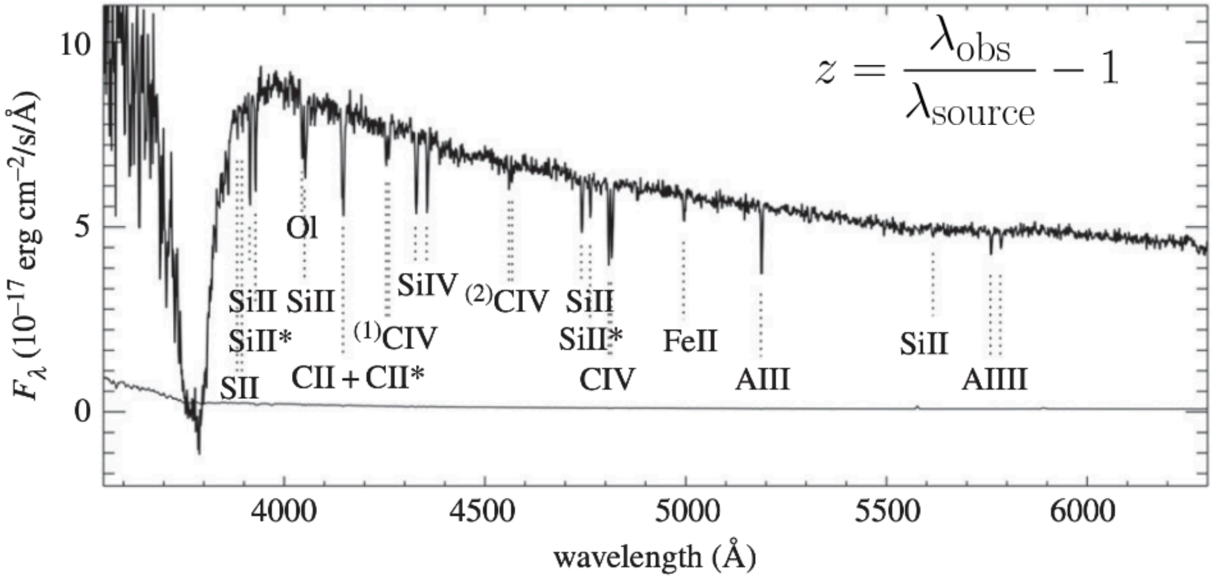


prompt emission
seconds - minutes

calculate the total *observed* energy ("fluence")

typically: 10^{-7} to 10^{-4} erg

[A. Rau et al., ApJ 720 (2010)]

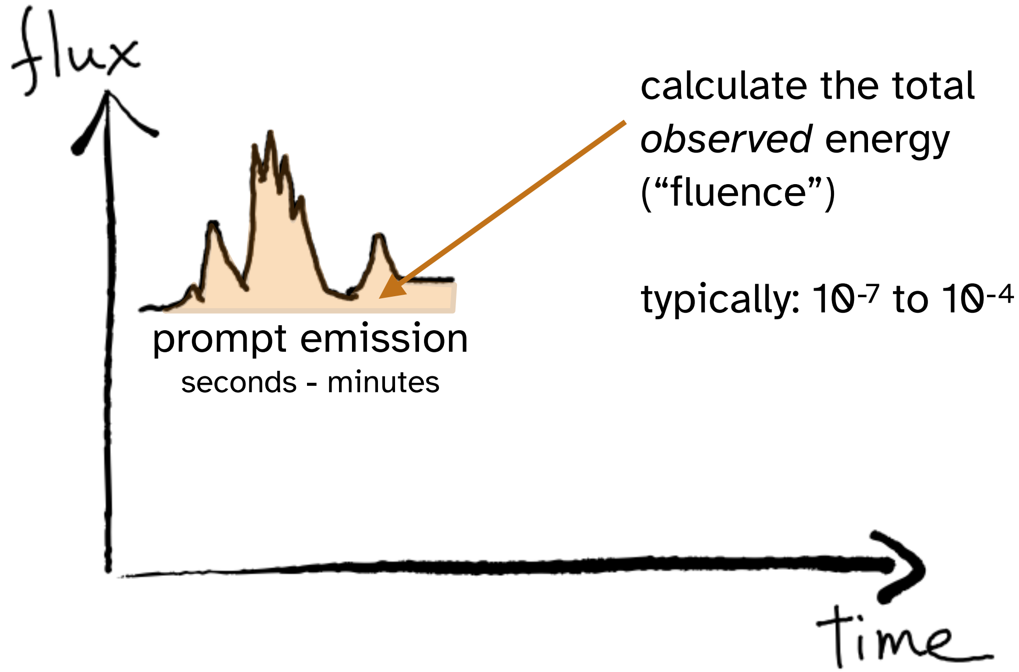


e.g., OI line: 4050 Å here
1356 Å rest frame } z ~ 2 ~ 16 Gpc

Very useful: [Cosmology Calculator]
BUT be careful about default cosmology values

Gamma-ray bursts

What causes them?



calculate the total *observed* energy ("fluence")

typically: 10^{-7} to 10^{-4} erg

fluence S: 10^{-4} erg/cm^2
distance r: 16 Gpc

energy emitted by the source (assuming isotropic):

$$E_{\text{iso}} = 4\pi r^2 S \sim 10^{54}\,\text{erg}$$

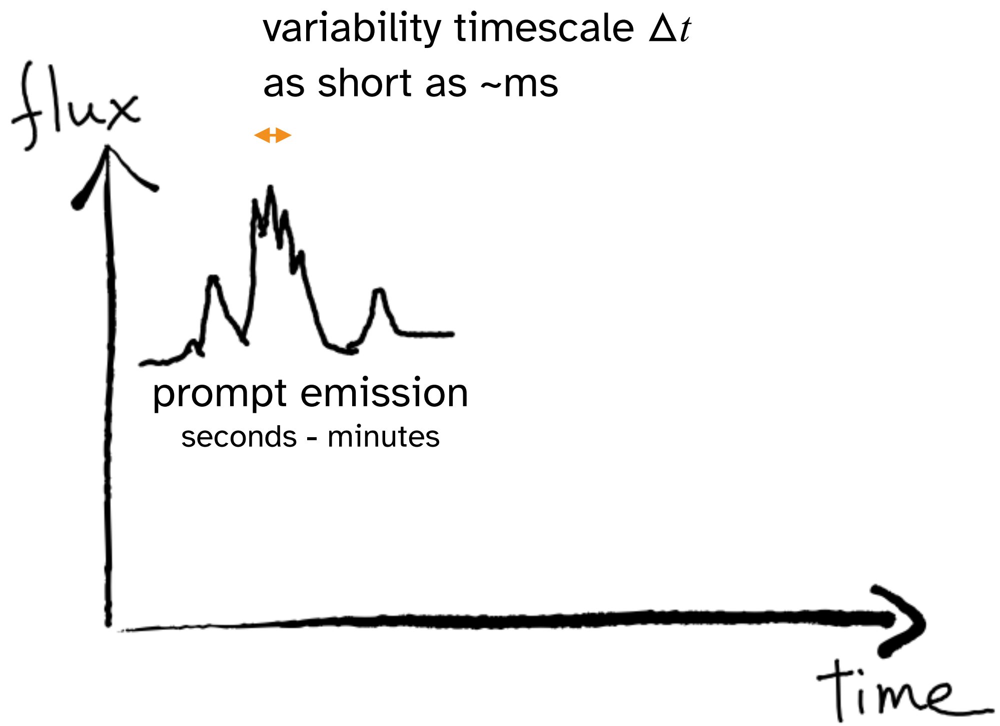
by comparison, the rest energy of the Sun:

$$E_{\odot} = 10^{54}\,\text{erg}$$

So: GRBs are stellar-sized phenomena (not, e.g., galaxy-sized)
release as much energy in minutes as the Sun will in its entire lifetime

Gamma-ray bursts

What causes them?



size of emitting region:

$$d = c\Delta t \sim 10^5\,\mathrm{m}$$

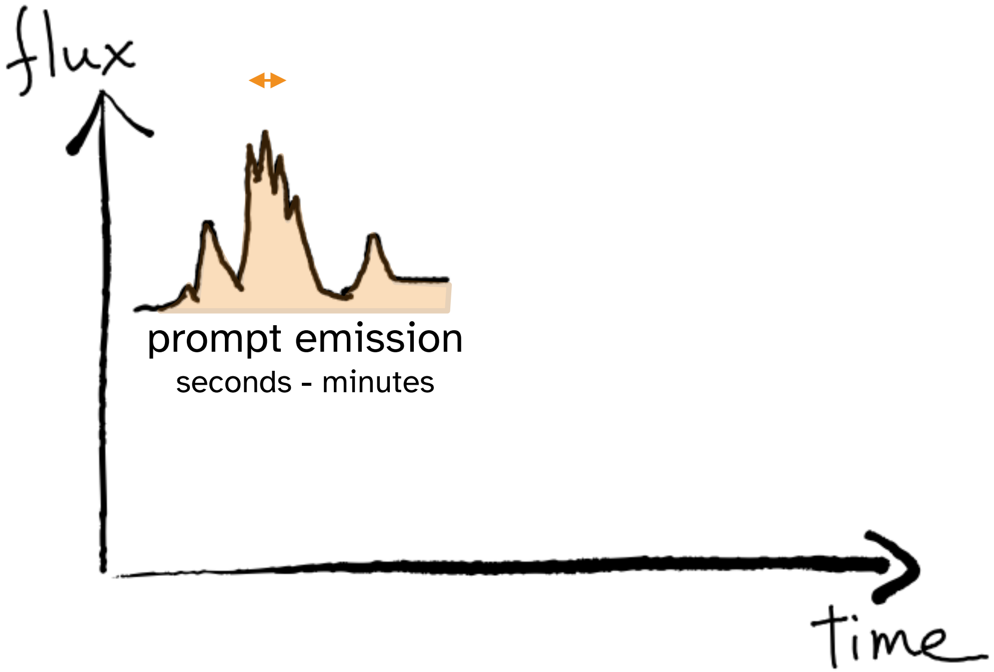
compare to the radius of Earth:

$$R_\oplus = 6 \times 10^6\,\mathrm{m}$$

so, emission is occurring in regions smaller than the Earth

Gamma-ray bursts

What causes them?



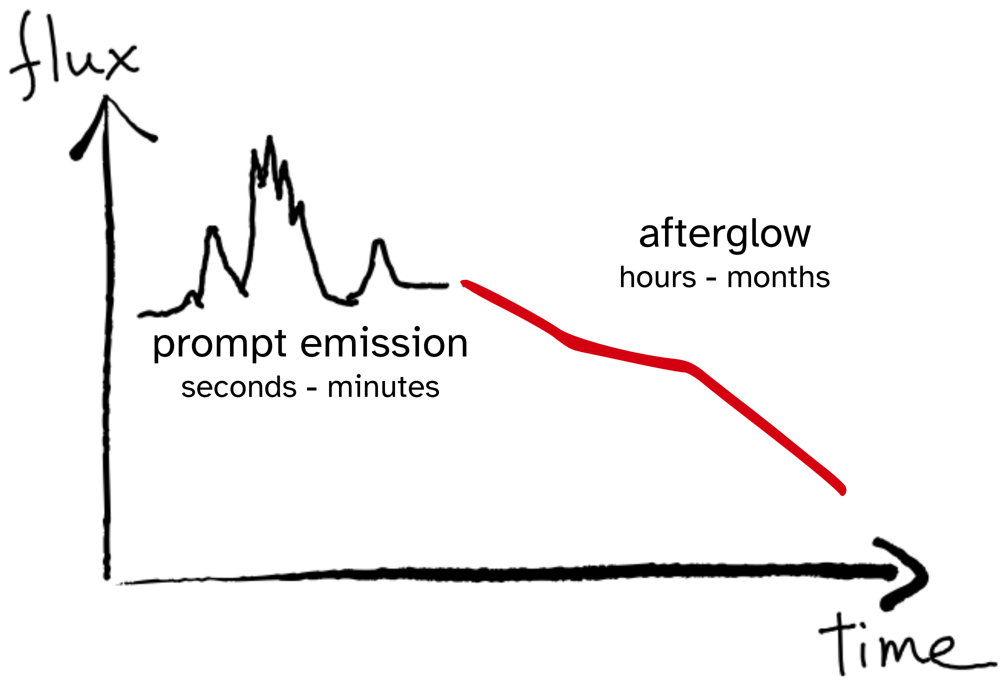
Combining these facts:

GRBs are stellar-sized phenomena
release $M_{\odot}c^2$ within minutes
emission occurring in regions smaller than the Earth

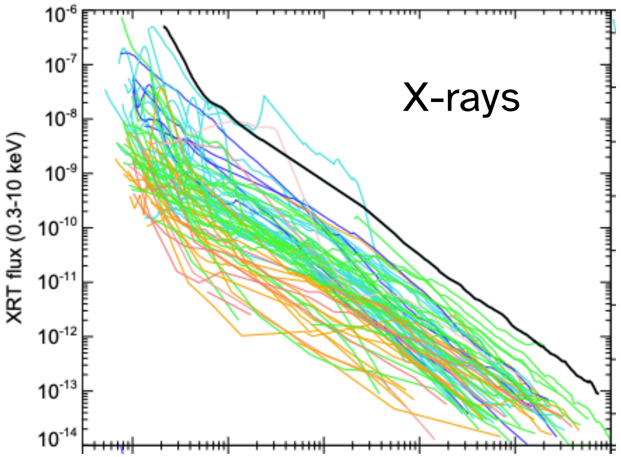
=> stellar-mass compact objects must be involved

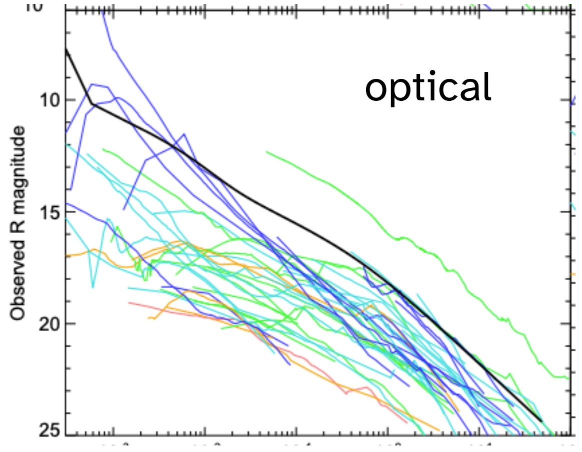
Gamma-ray bursts

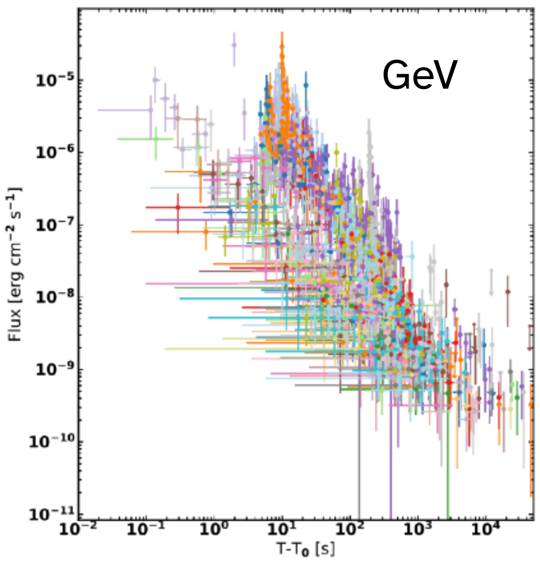
What causes them?



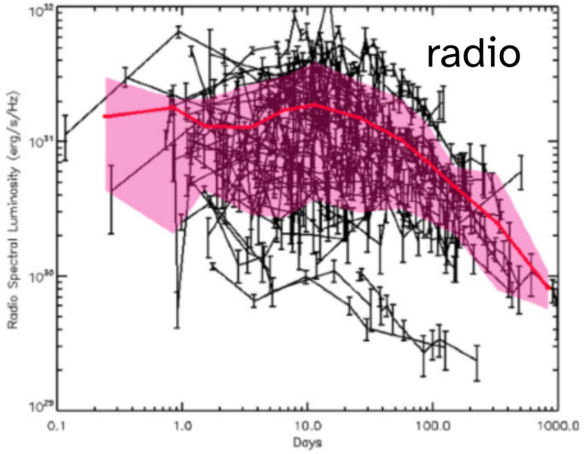
D. A. Perley et al., ApJ 781 (2014)







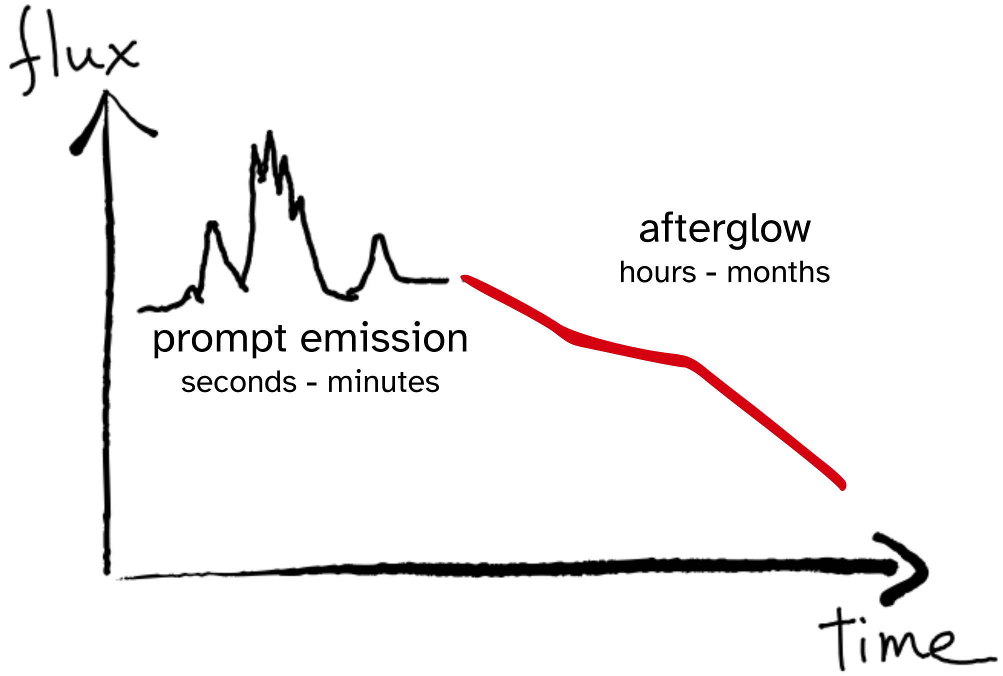
M. Ajello et al., ApJ 878 (2019)



P. Chandra & D. A. Frail, ApJ 746 (2012)

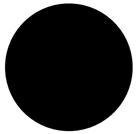
Gamma-ray bursts

What causes them?

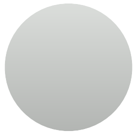


Putting all the clues together:

GRBs are stellar-sized phenomena (not, e.g., galaxy-sized)
release $M_\odot c^2$ within minutes
emission occurring in regions smaller than the Earth
emission starts out highly variable but then evolves slowly and fades
stellar-mass compact objects are involved



black holes

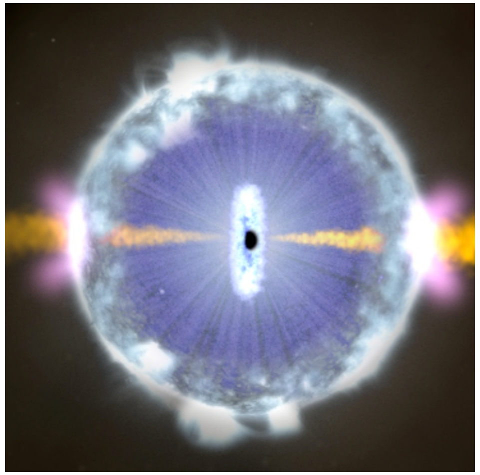


neutron stars

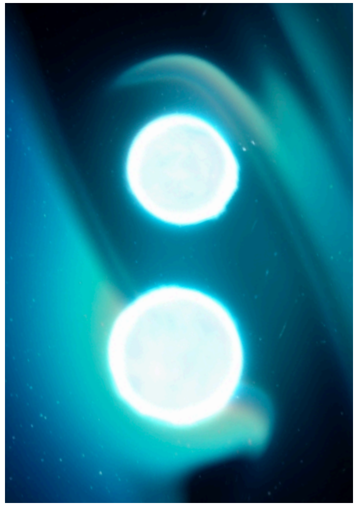
Gamma-ray bursts

What causes them?

[NASA's Goddard Space Flight Center]



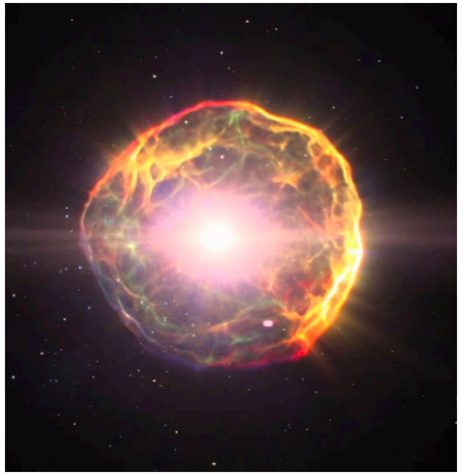
NASA's Goddard Space Flight Center/CI Lab



two neutron stars merge
(probably)

or

ESO/L Calçada



a massive star collapses

Gamma-ray bursts

What causes them?

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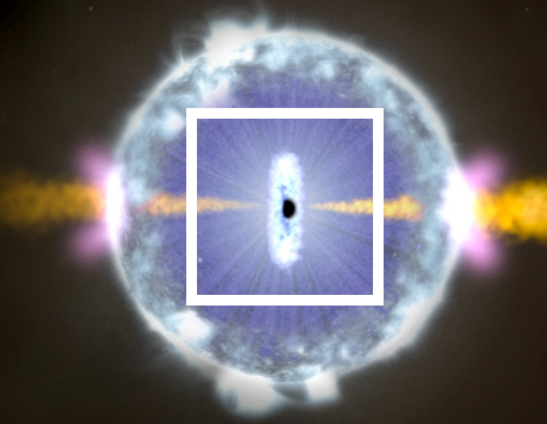
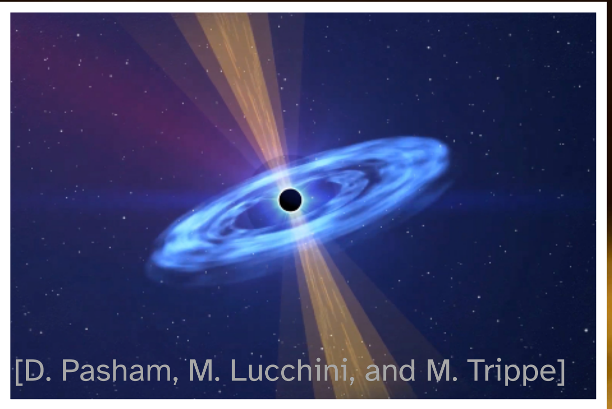
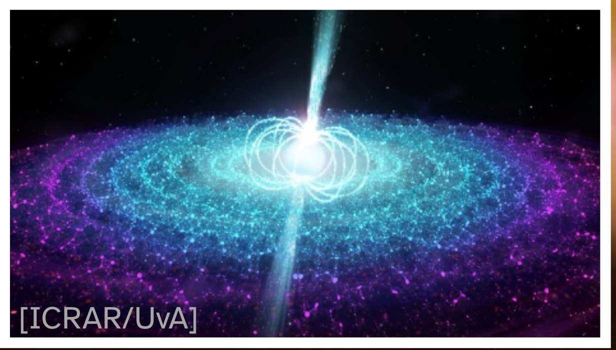


What is the central engine?



[D. Pasham, M. Lucchini, and M. Trippe]



[ICRAR/UvA]

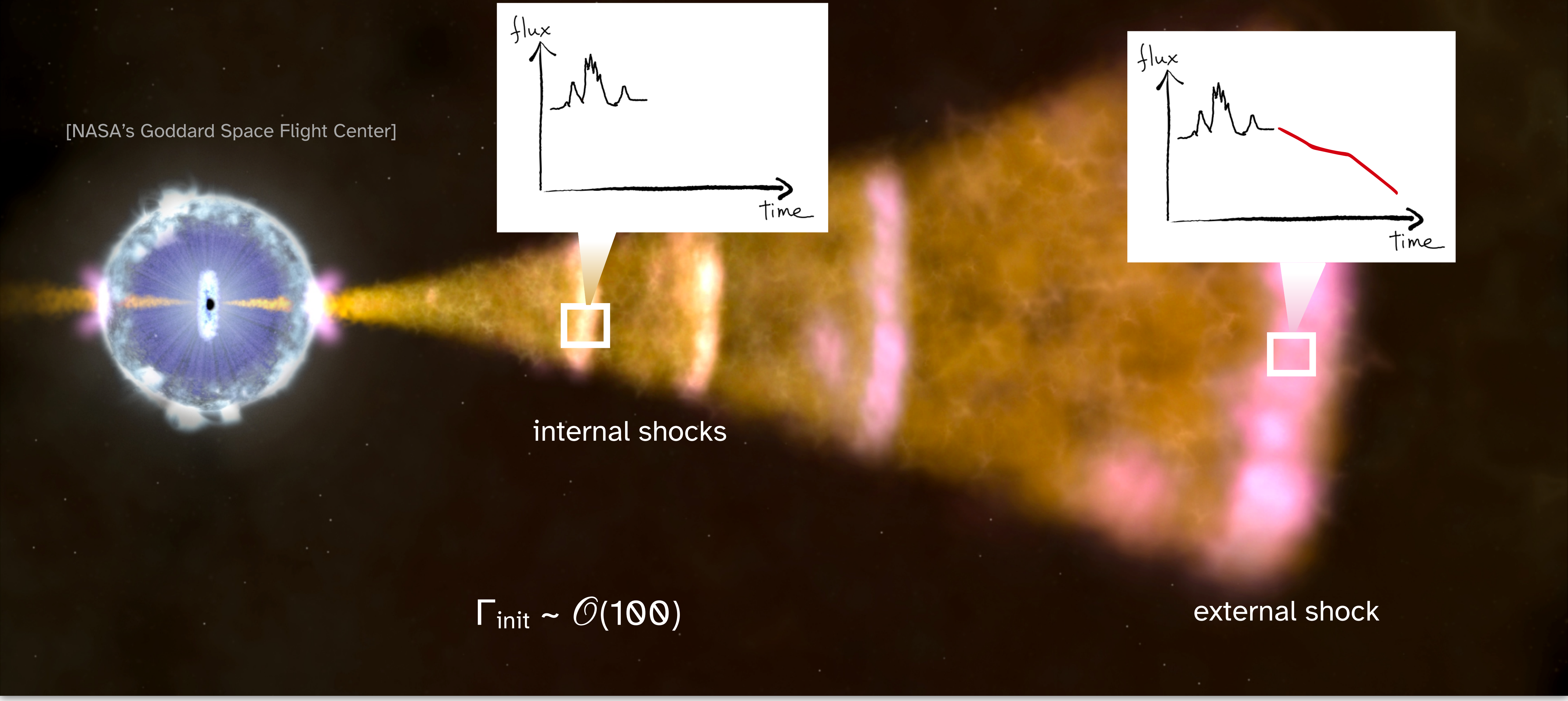
We know both black holes and neutron stars can produce jets from accreting material

For GRBs in particular:

- Simulations can more easily launch jets with black holes (cannot fully produce for neutron stars yet); but:
- Neutron star central engine more naturally explains certain lightcurve features

Gamma-ray bursts

What causes them?



Brief pause while a data analyst tries to explain shock physics

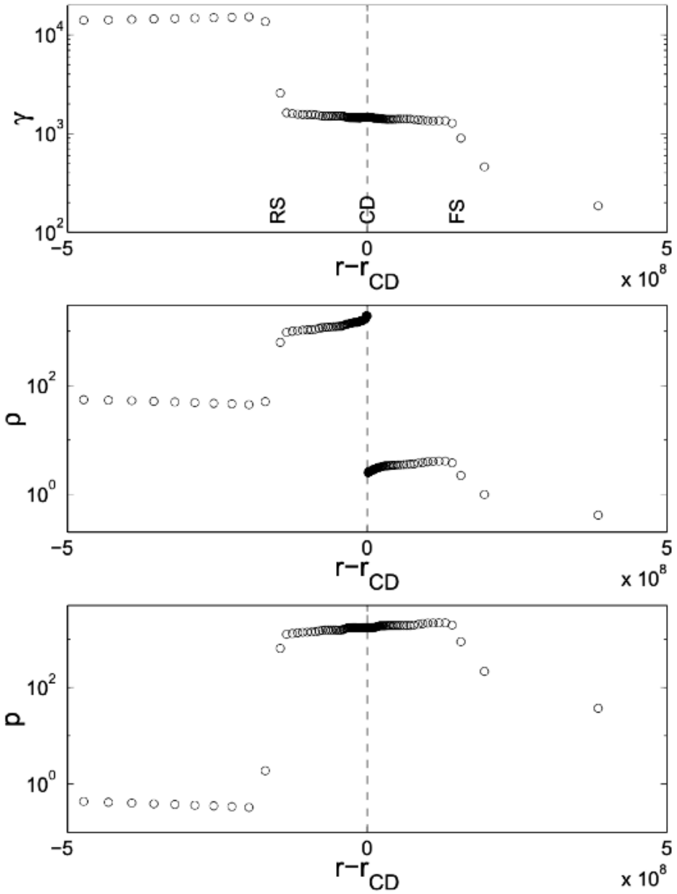
most relevant for high-energy astrophysical phenomena: relativistic **collisionless shocks**

[S. Kobayashi et al., ApJ 513 (1999)]

Lorentz factor

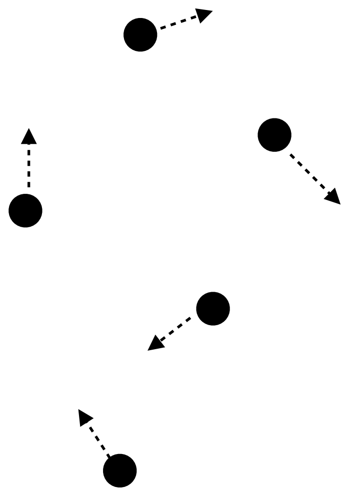
density

pressure



shock size is much smaller than particle's mean free path
=> electromagnetic interactions determine the behavior

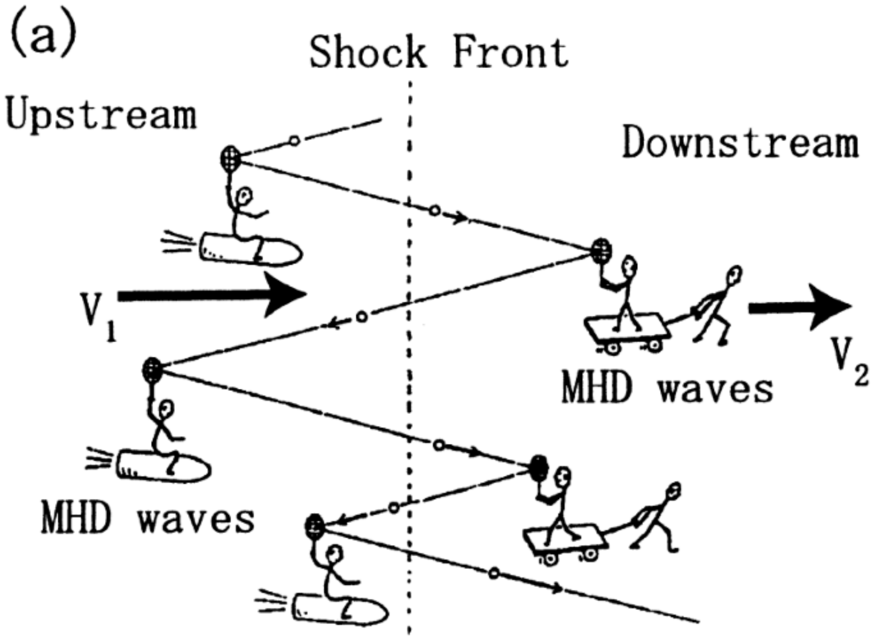
shock ~ discontinuity in some physical parameters, transition in others



Brief pause while a data analyst tries to explain shock physics

most relevant for high-energy astrophysical phenomena: relativistic **collisionless shocks**
charged particles are accelerated at these shocks

shocked material



unshocked material

e.g., first order Fermi acceleration: particles gain energy with each shock crossing

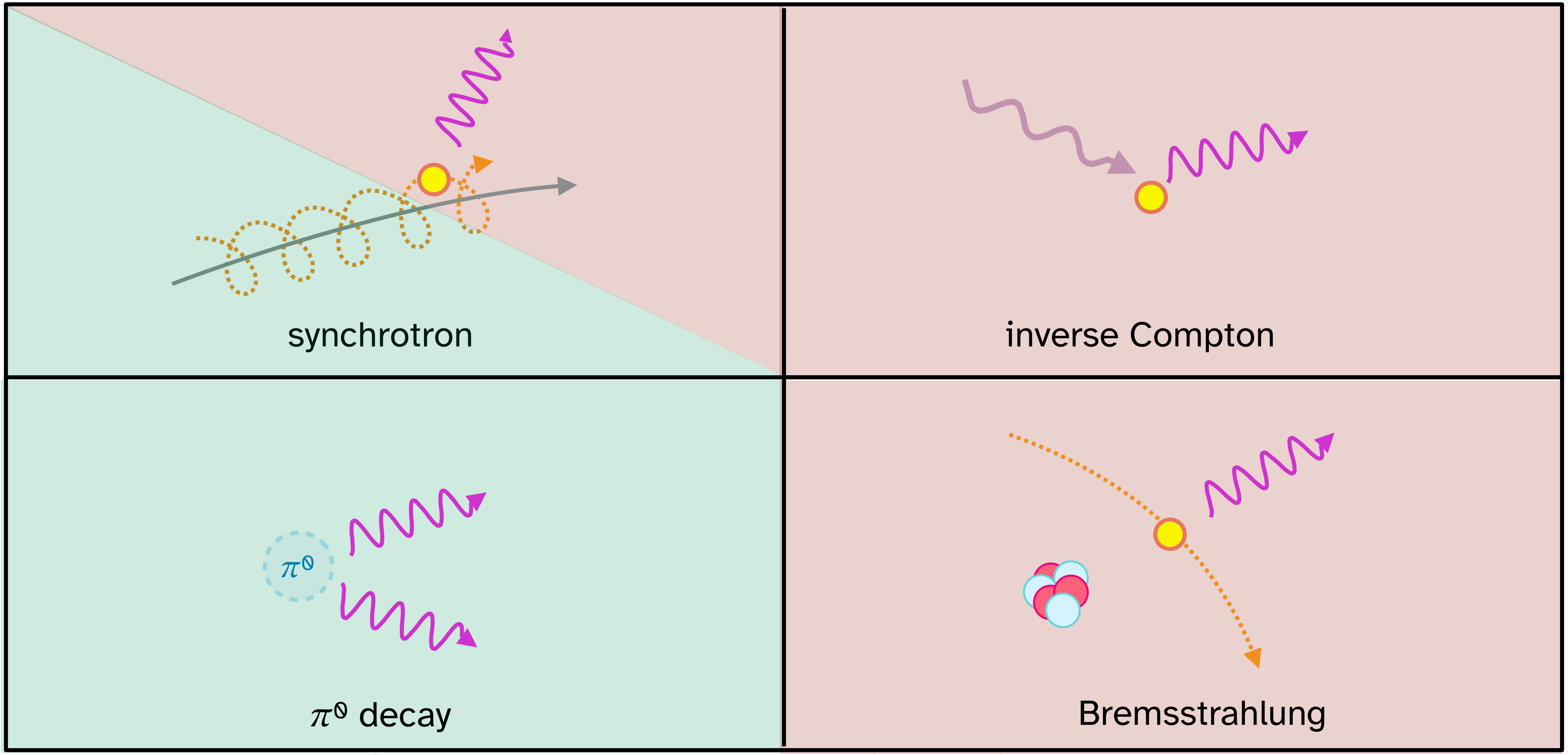
to actually learn about collisionless shocks:
[A. Marcowith et al., Rep Prog Phys 79 (2016)]

How do we get gamma rays?

Nonthermal emission

(coloring indicates what is relevant to these lectures)

Charged particles are **accelerated** to high energies before radiating photons
The charged particles can be **leptons** (e.g., electrons) or **hadrons** (e.g., protons)



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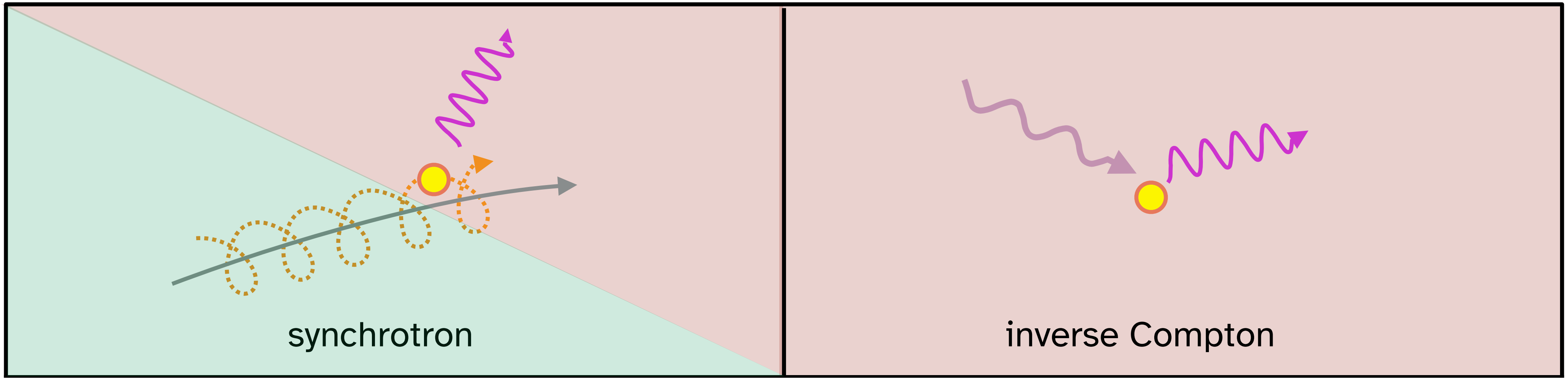
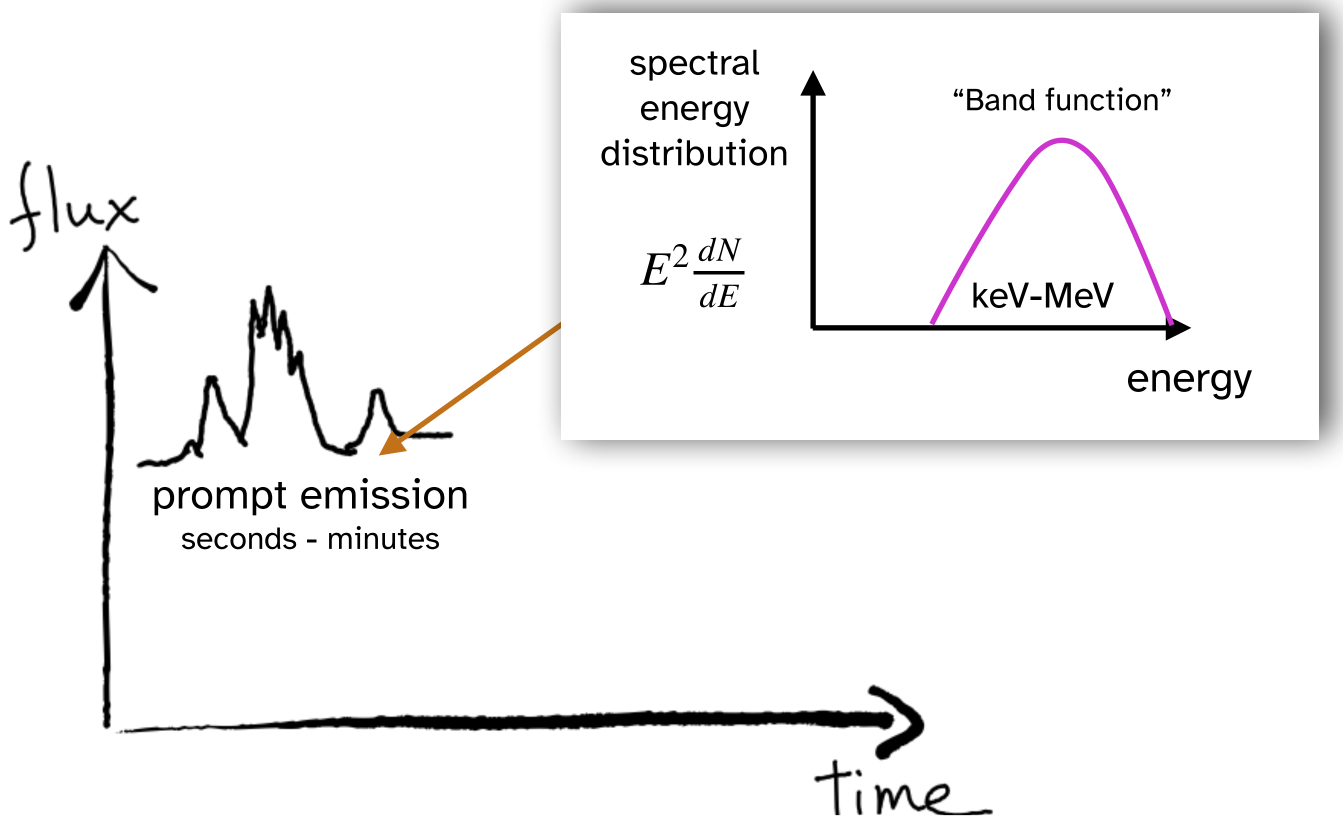


GRB jets have $\Gamma > 100$ => Must have low **baryon loading**
=> conditions are most favorable for (leptonic) synchrotron and IC

GRB photon emission

Prompt emission



depending on who you ask

Prompt emission is probably lepton synchrotron, from particles accelerated …

at internal shocks (matter dominated)

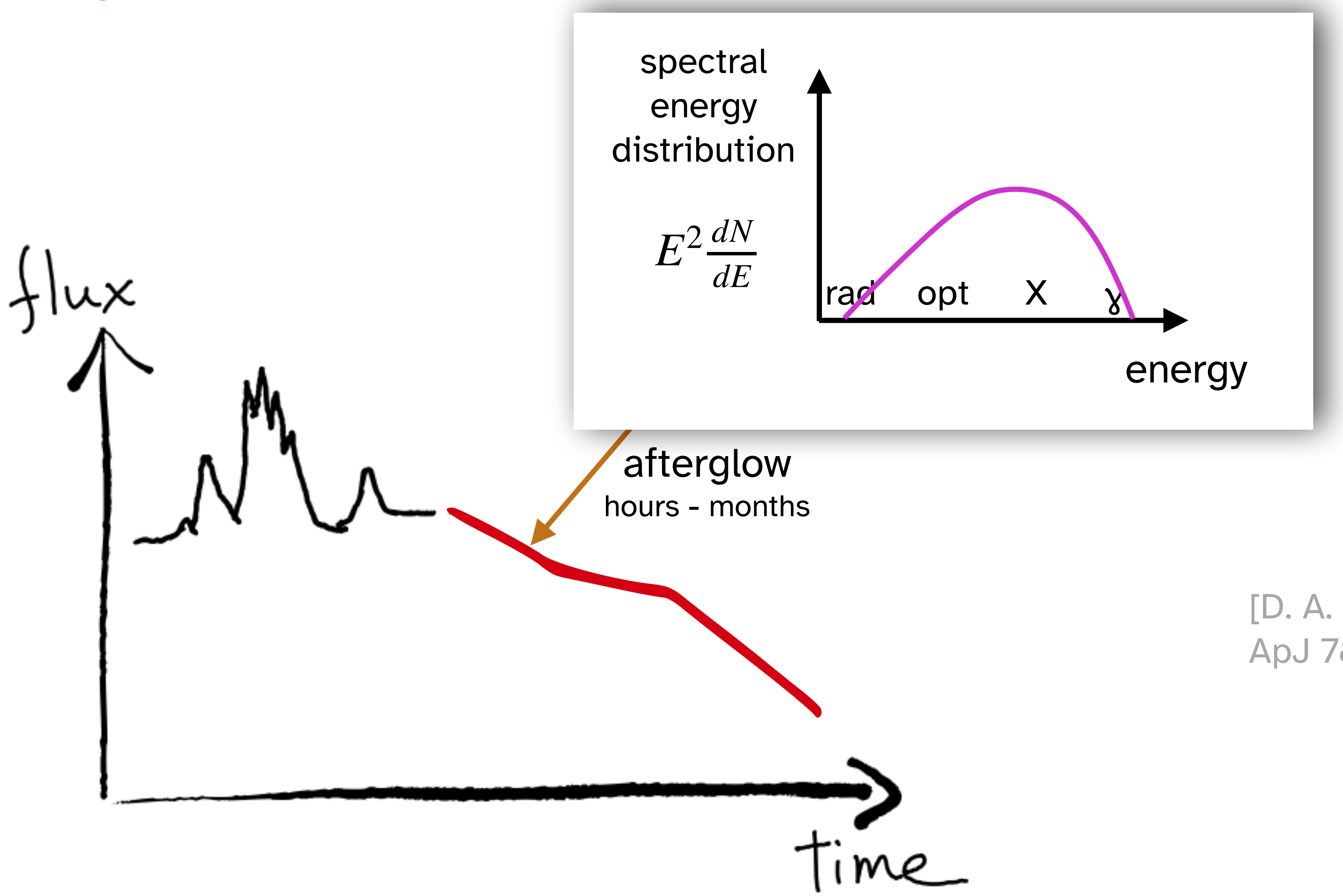
or

by magnetic fields (electromagnetic dominated)

Most likely a combination of the two

GRB photon emission

Afterglow emission



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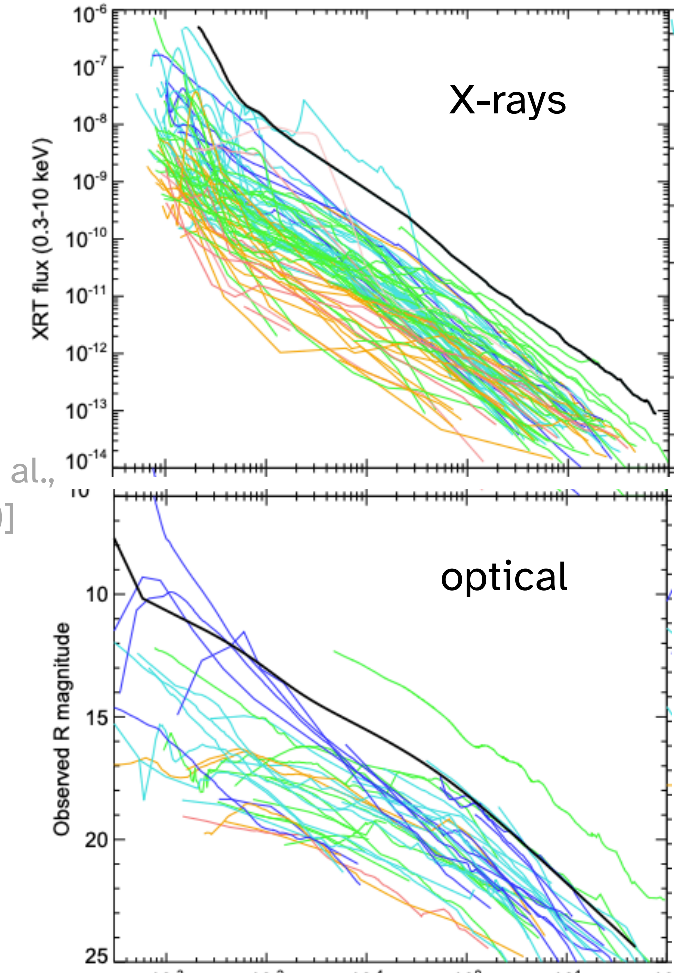
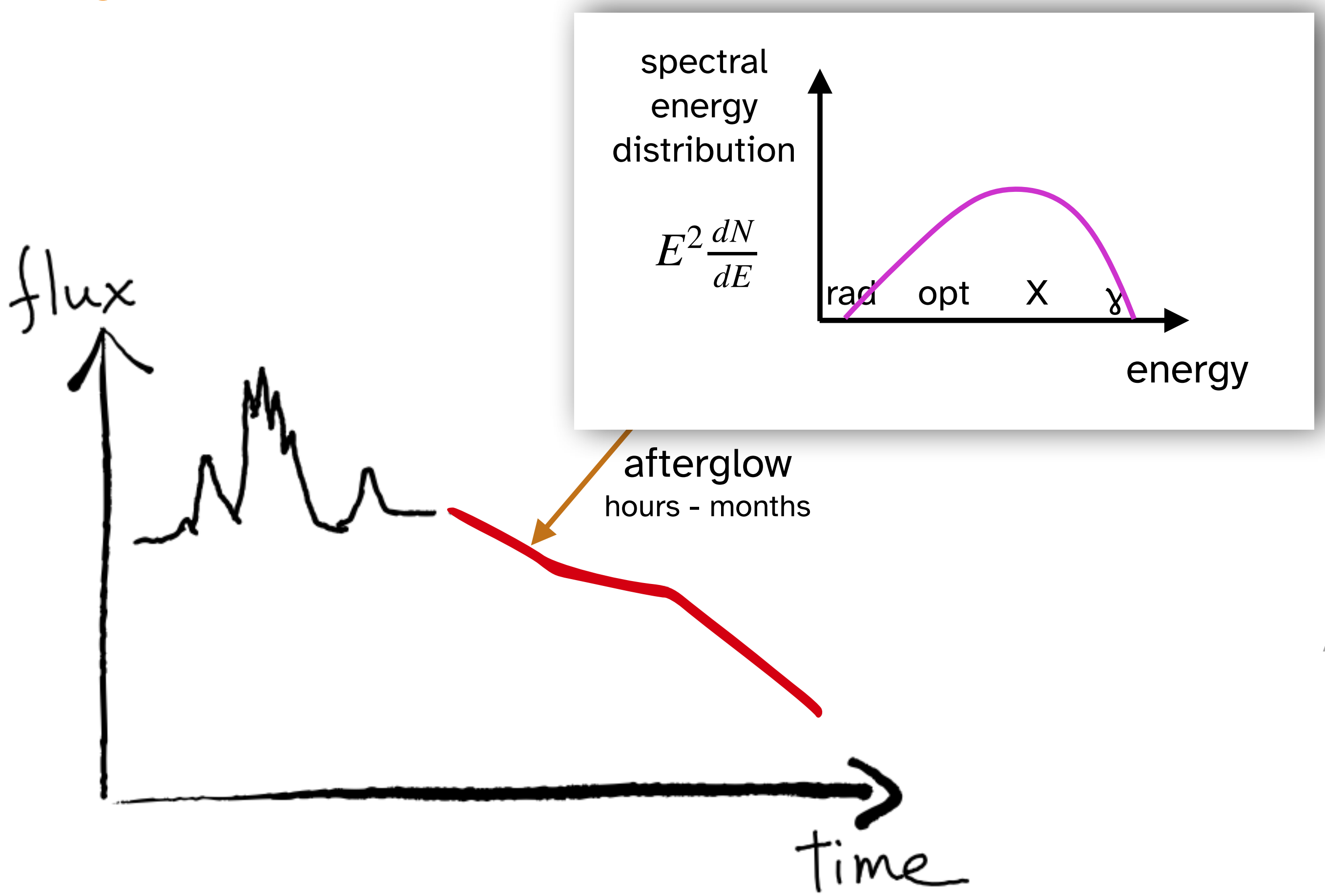
Afterglow emission is well established as leptonic synchrotron from external shocks



[D. A. Perley et al., ApJ 781 (2014)]

GRB photon emission

Afterglow emission



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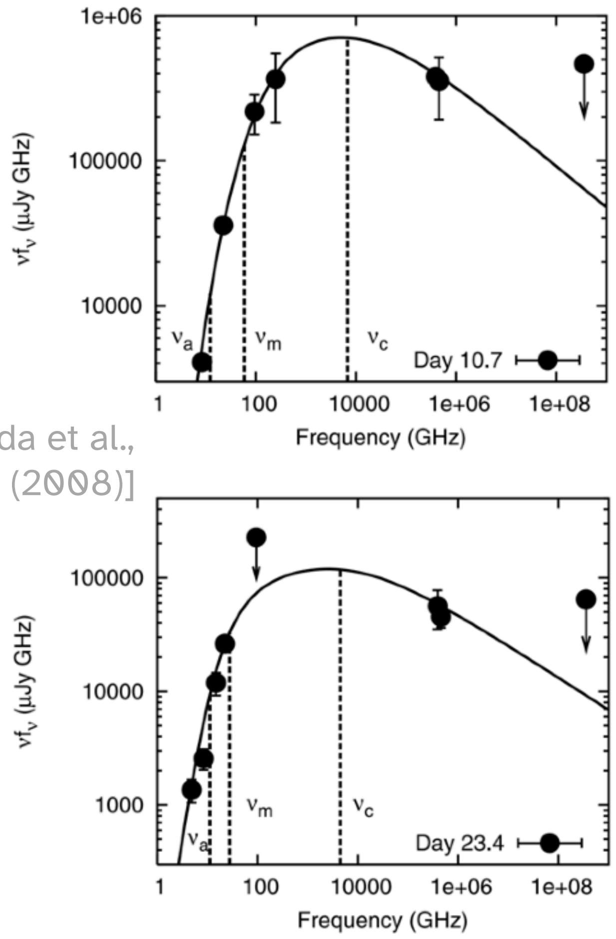
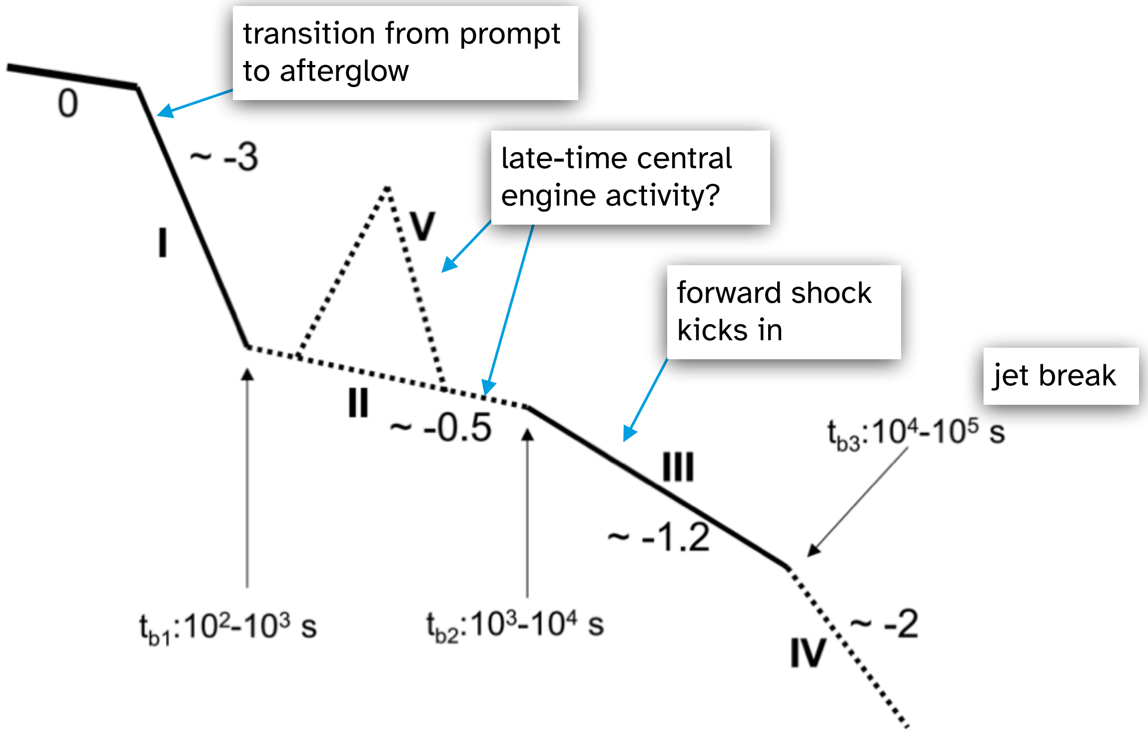


[P. Chanda et al., ApJ 683 (2008)]

GRB photon emission

Afterglow emission

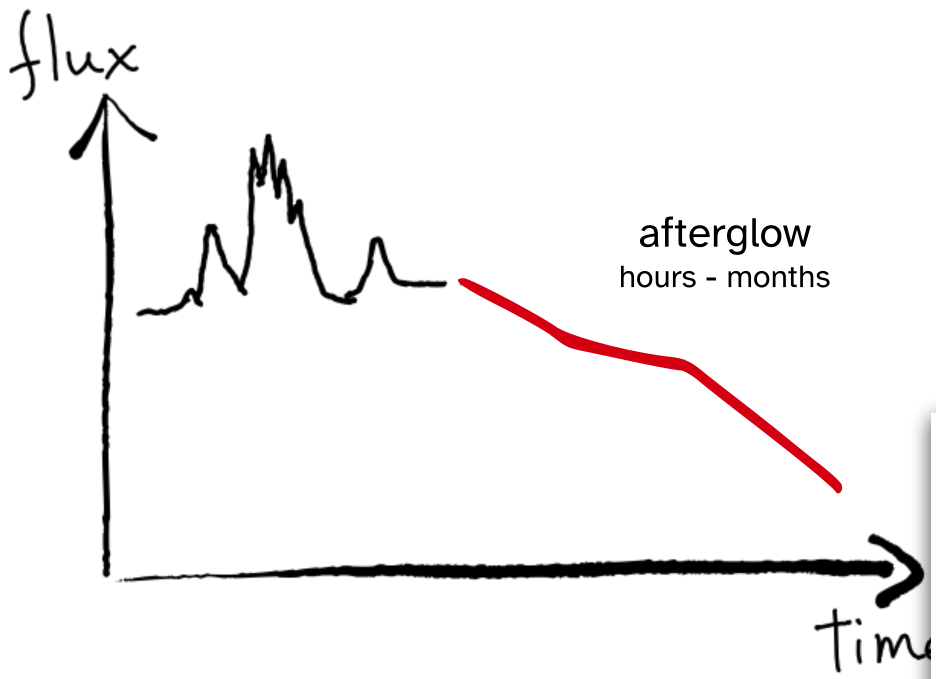
“canonical” X-ray afterglow lightcurve



[B. Zhang et al., ApJ 642 (2006)]

GRB photon emission

Afterglow emission



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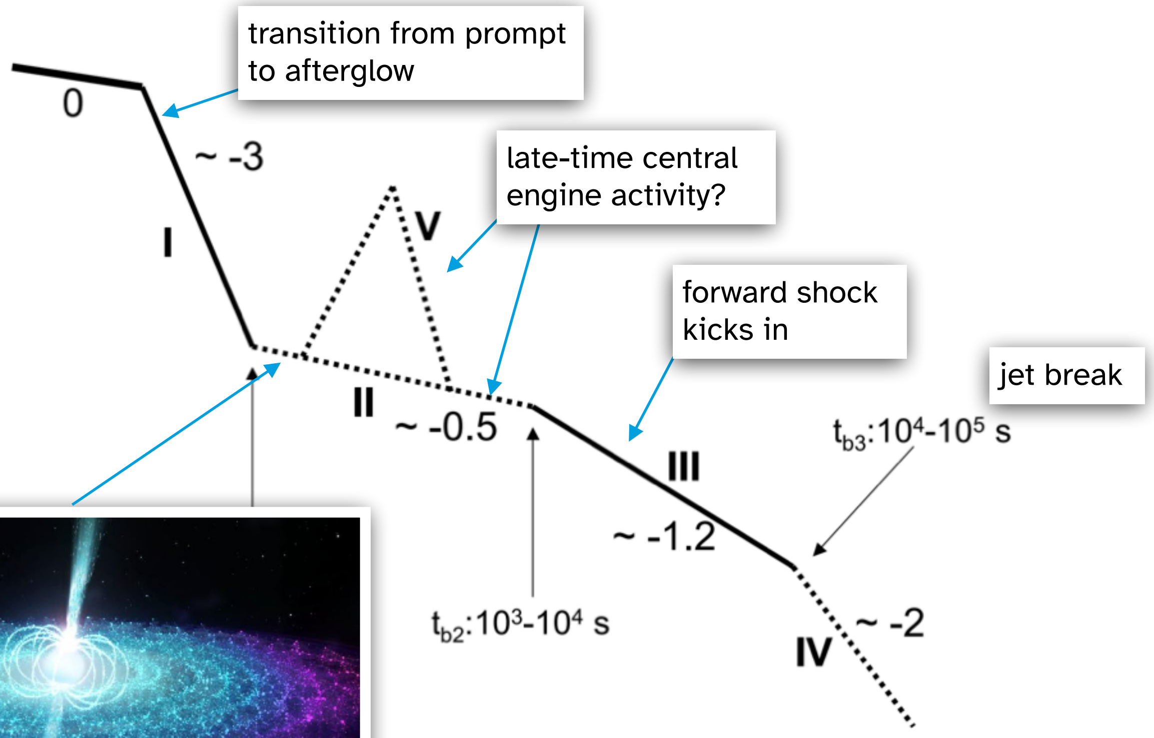

[ICRAR/UvA]

ApJ 642 (2006)]

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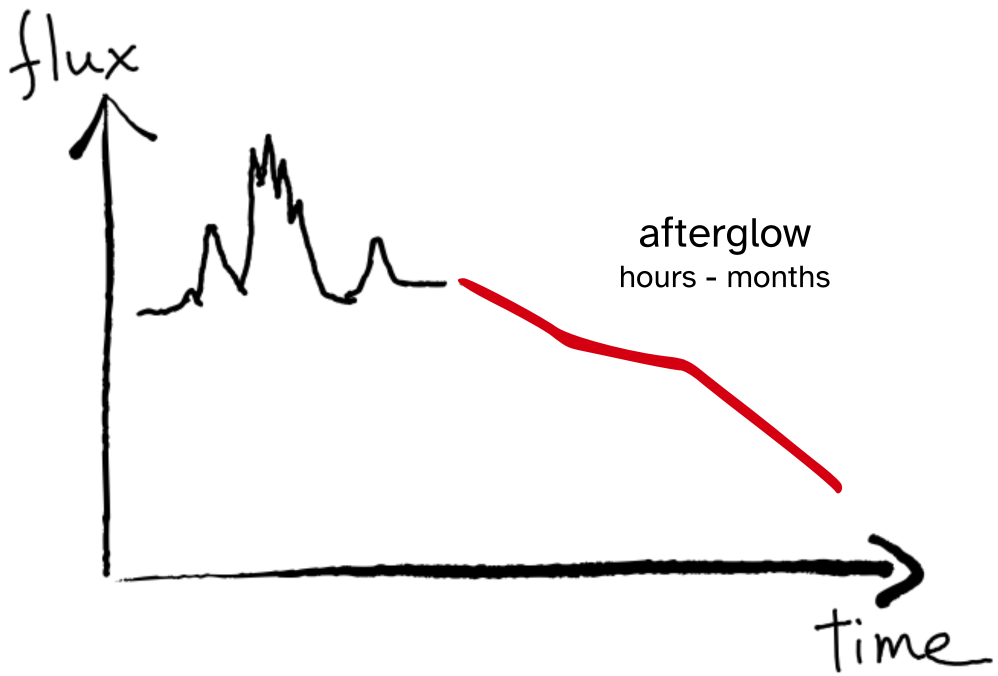

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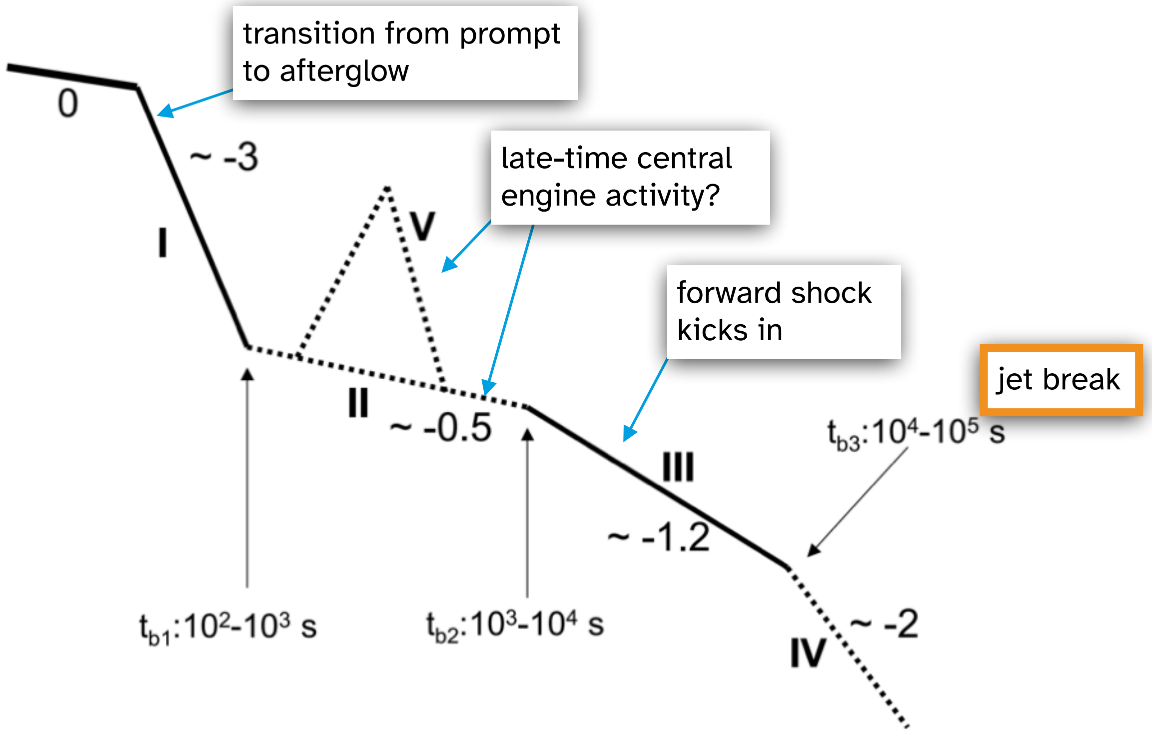
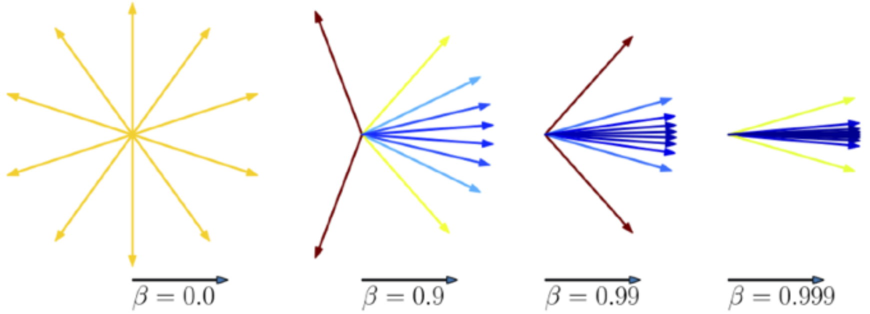


[B. Zhang et al., ApJ 642 (2006)]

GRB jet break

GRB emission is relativistically beamed

[D. C. Bailey]



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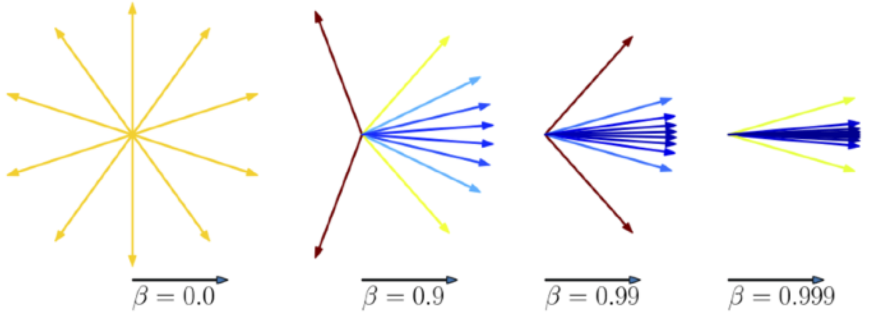
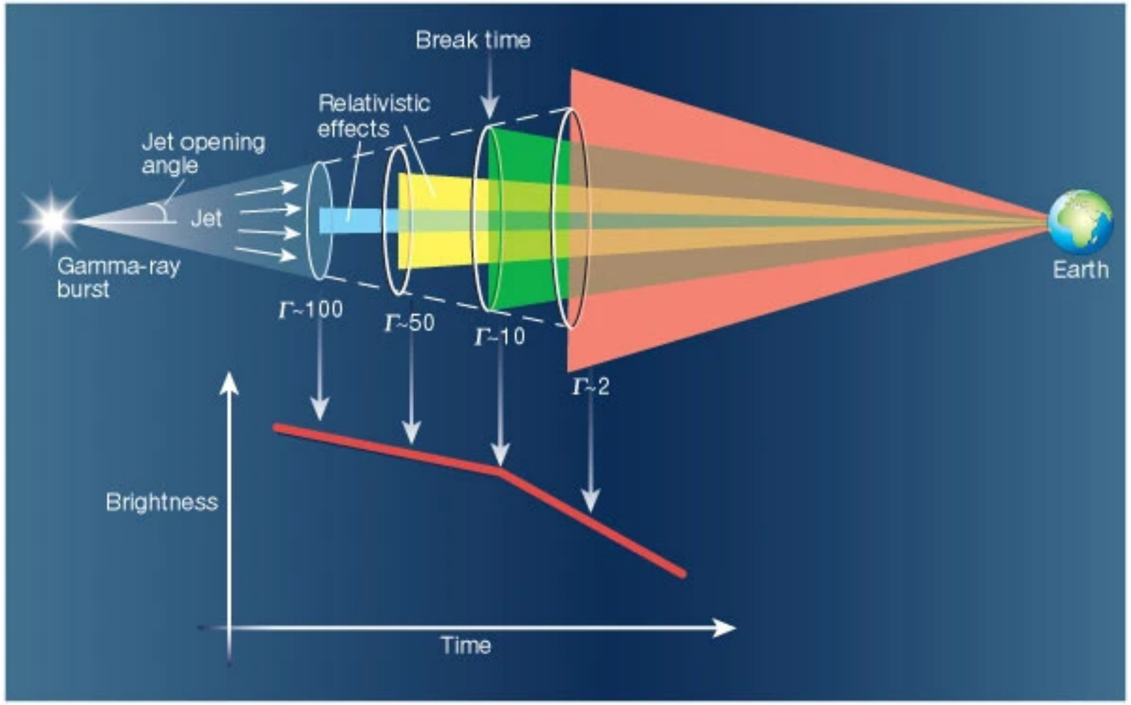
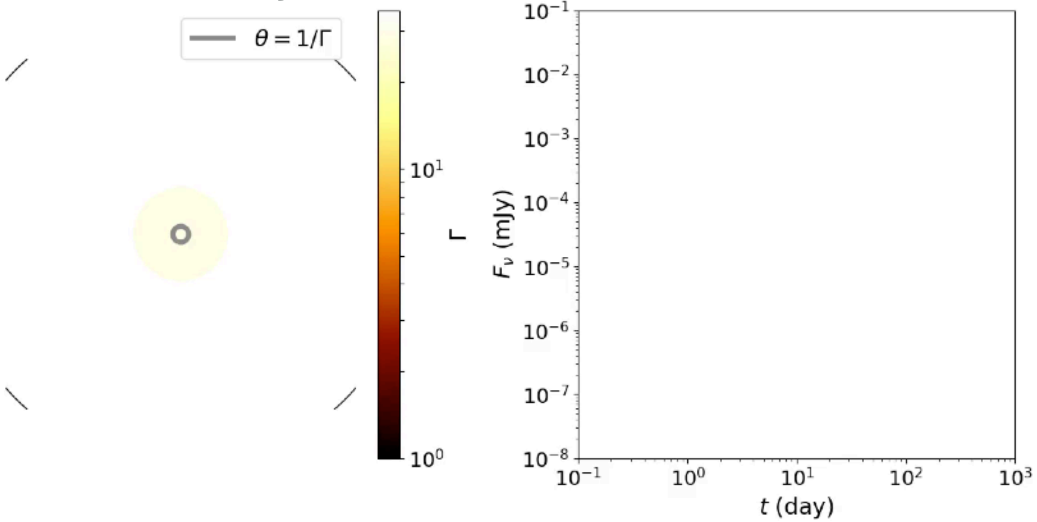


[S. Woosley, Nature 414 (2001)]



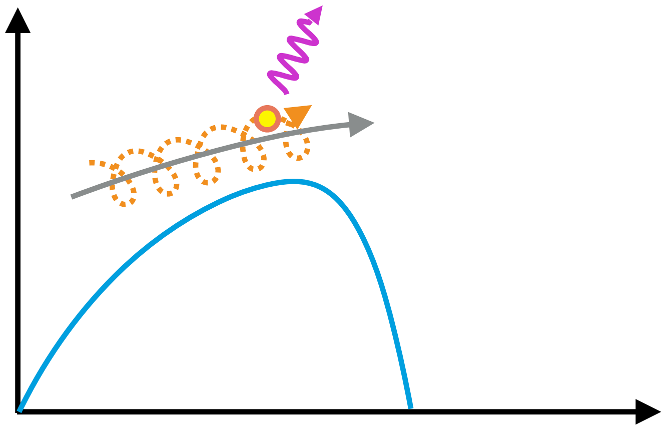
More of the emitting surface becomes visible at later times as the jet slows

G. Ryan, Perimeter Institute



GRB photon emission

Afterglow emission

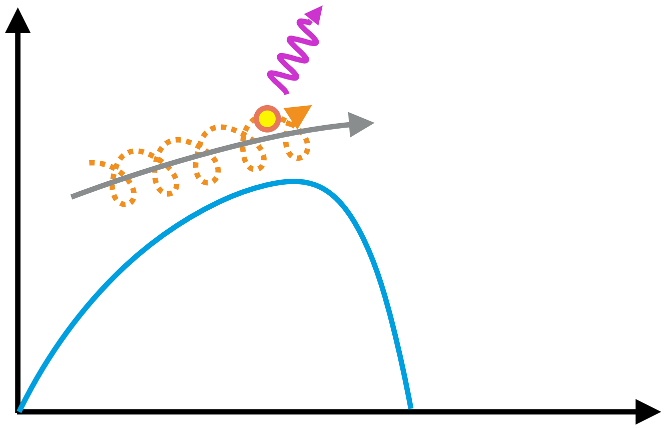


In general, gamma-ray bursts produce most of the afterglow via (electron) *synchrotron emission*

although there are exceptions, and it's usually not very clear what it is, and how the synchrotron spectrum should look depends on a lot of other factors, and there are other possibilities that could explain the emission, and sometimes electron synchrotron doesn't work very well at all …

GRB photon emission

Afterglow emission



In general, gamma-ray bursts produce most of the afterglow via (electron) *synchrotron emission*

GRB afterglow modeling almost always assumes a **one zone** scenario: The same magnetic field strength is responsible for both the **acceleration** and the **cooling**

If we balance the acceleration and cooling timescales, we can calculate a theoretical maximum synchrotron photon energy:

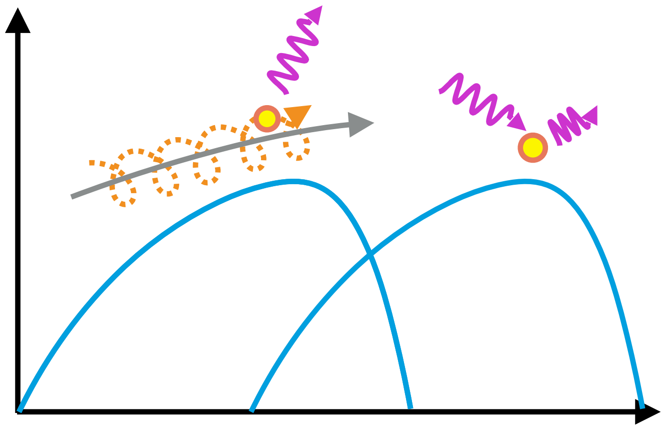
$$E_{\mathrm{max}} \sim \mathcal{O}(100)\,\mathrm{MeV}$$

(actual value depends on Γ)

learn more: [P. Kumar et al., MNRAS 427 (2012)]

GRB photon emission

Afterglow emission



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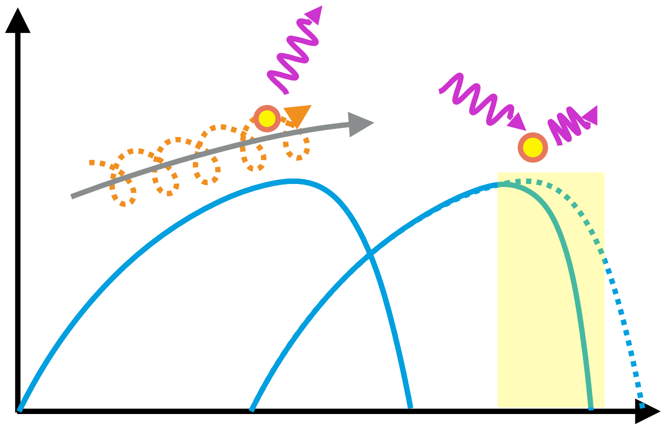
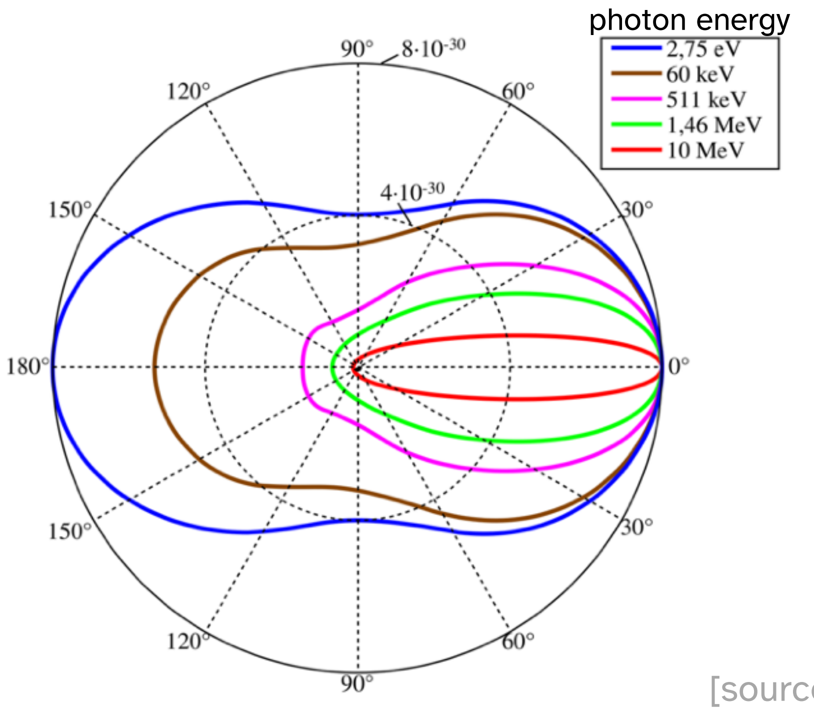


In general, gamma-ray bursts produce most of the afterglow via (electron) *synchrotron emission*

Inverse Compton is usually invoked for photons ≳GeV

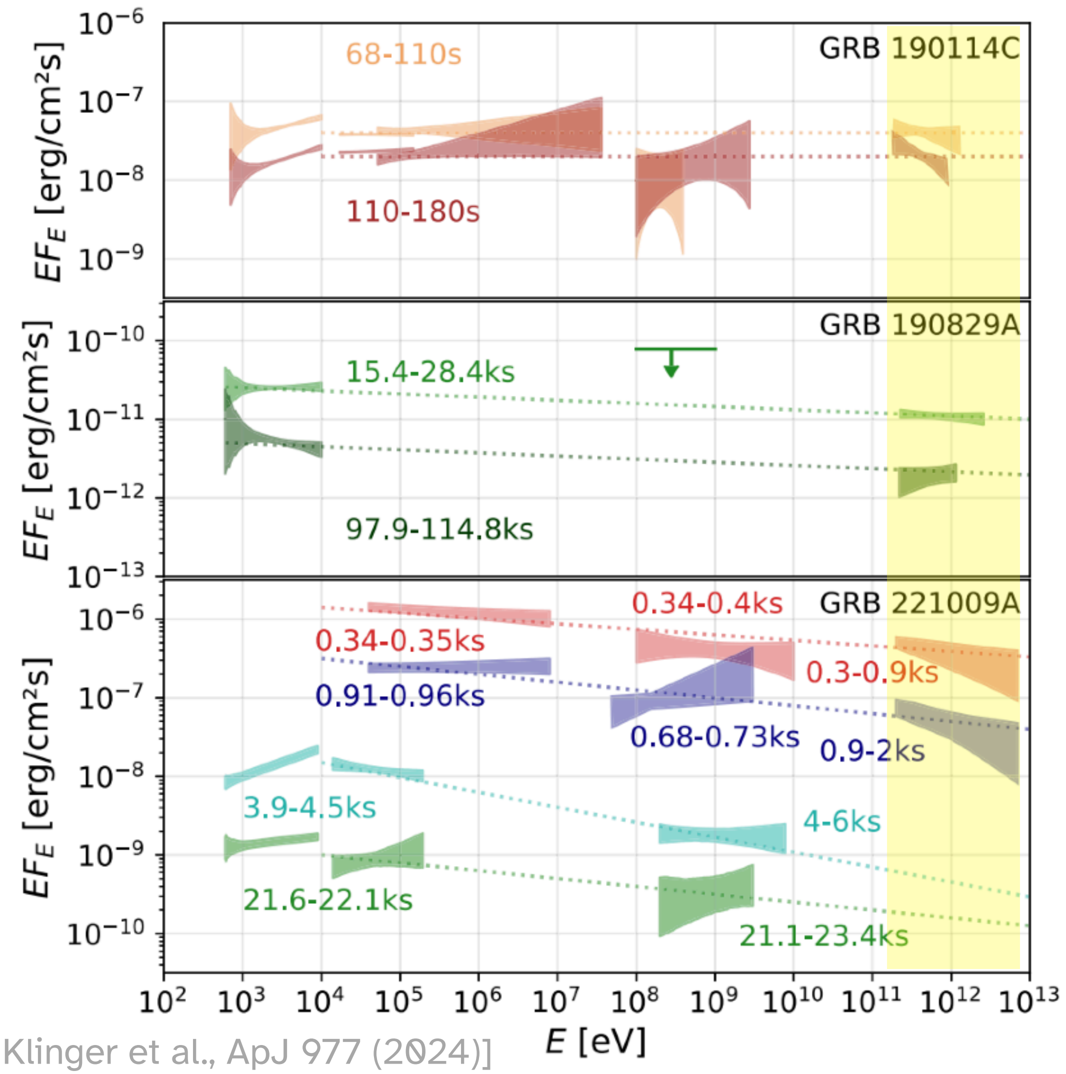
At TeV energies, we expect a very **steep** spectrum as the interaction cross section greatly decreases

interaction cross section for (inverse) Compton scattering



[source]

Do we see the inverse Compton component in VHE GRBs?



[M. Klinger et al., ApJ 977 (2024)]

no smoking gun so far

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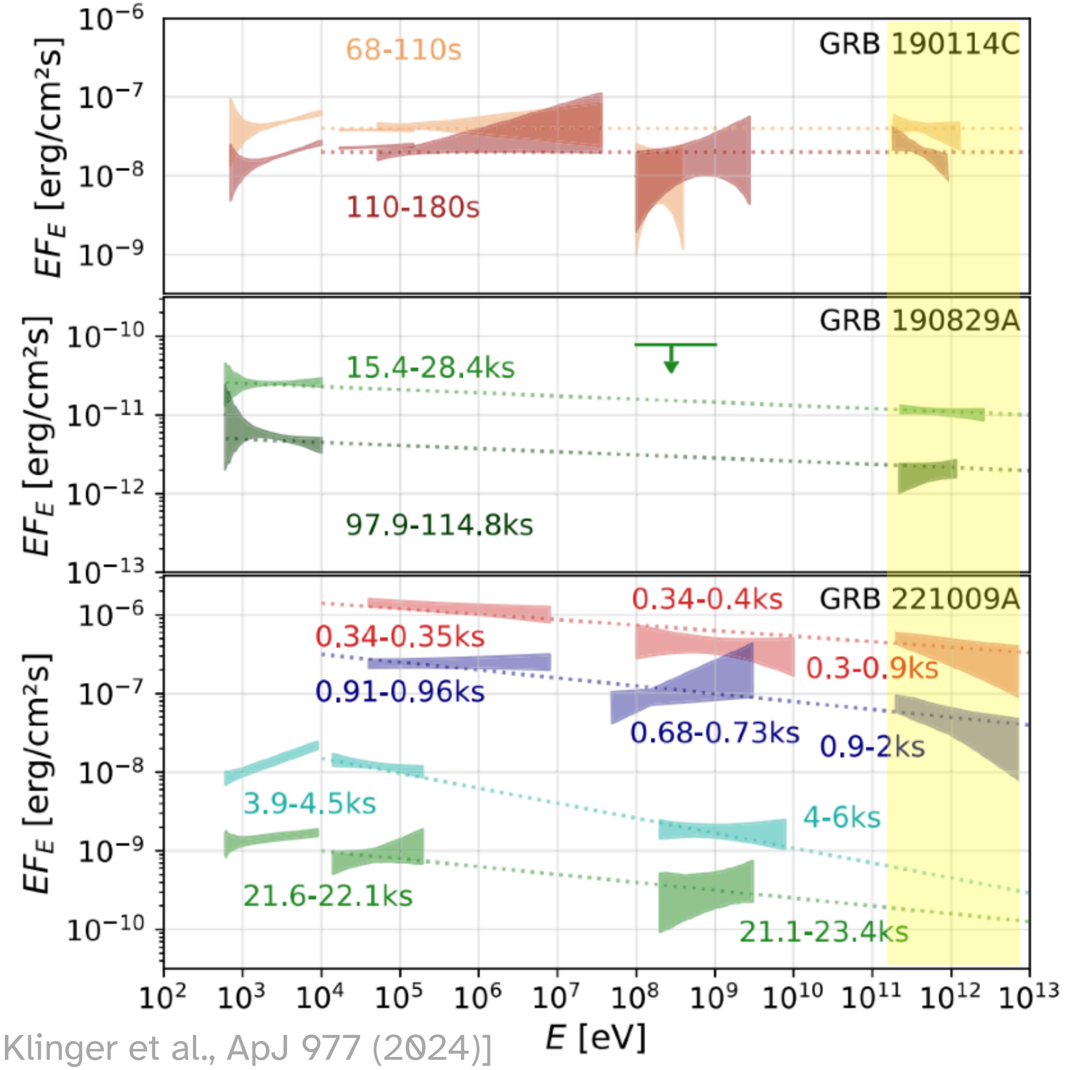

[M. Klinger et al., ApJ 977 (2024)]

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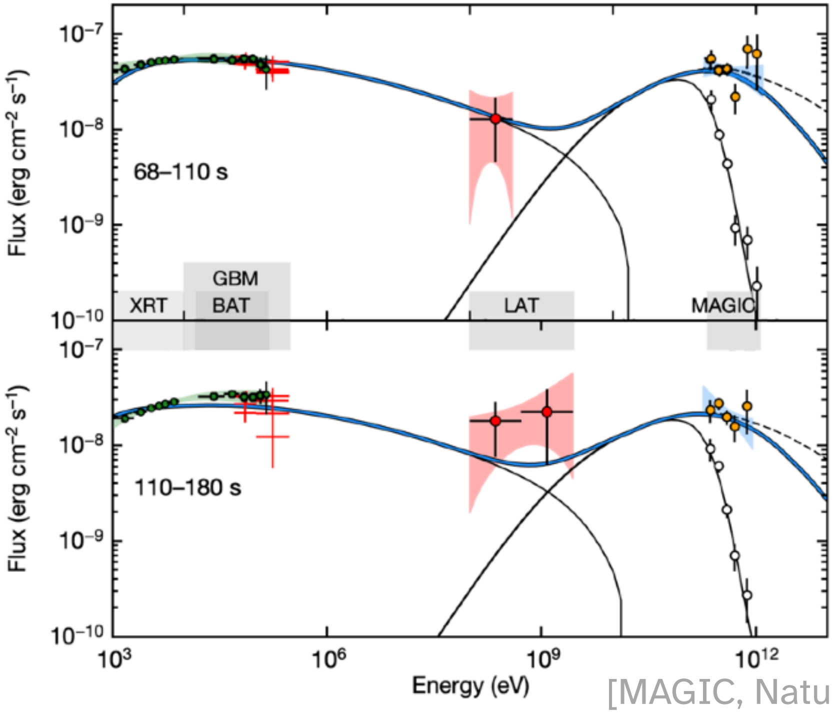
although there is disagreement:



[MAGIC, Nature 575 (2019)]

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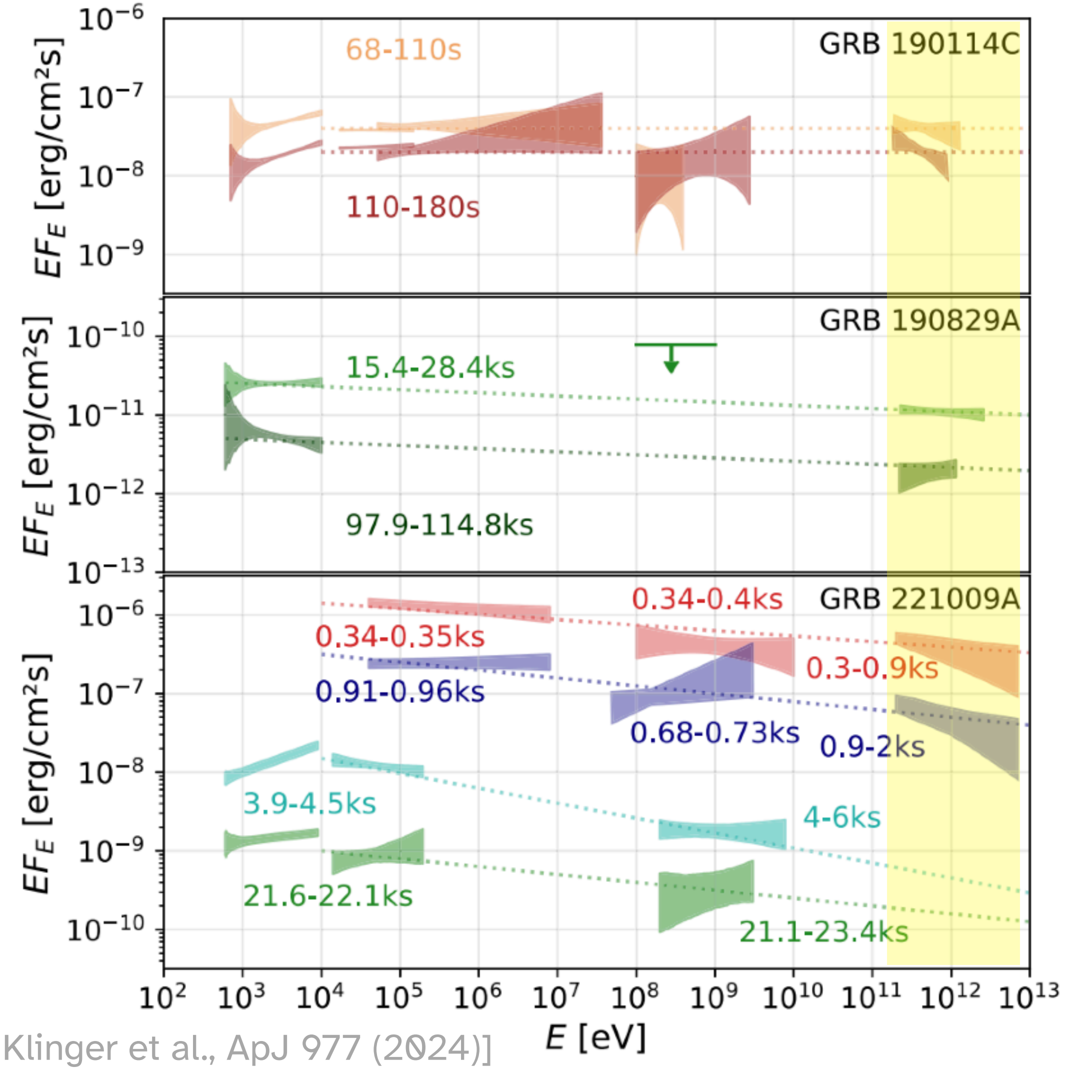
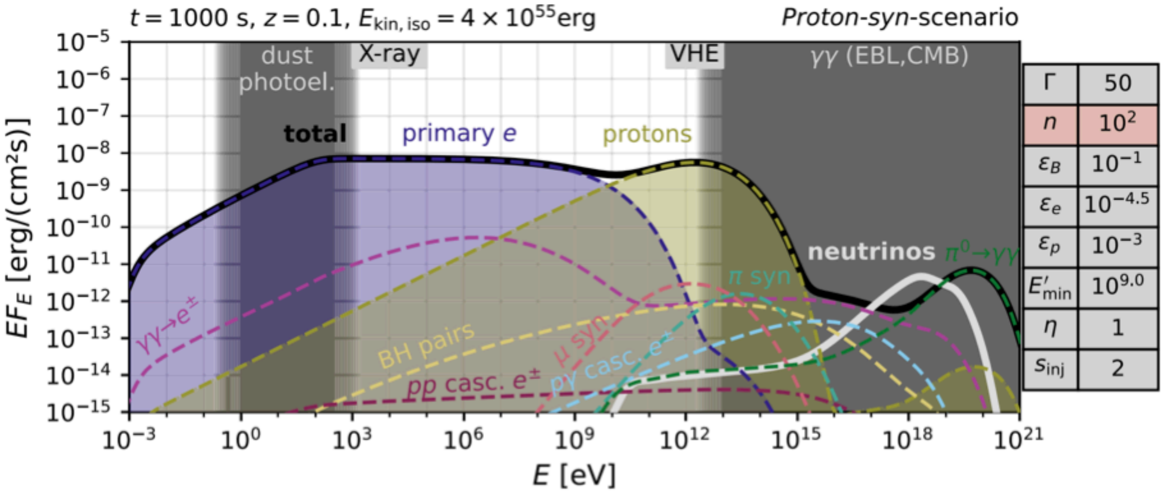


[M. Klinger et al., ApJ 977 (2024)]

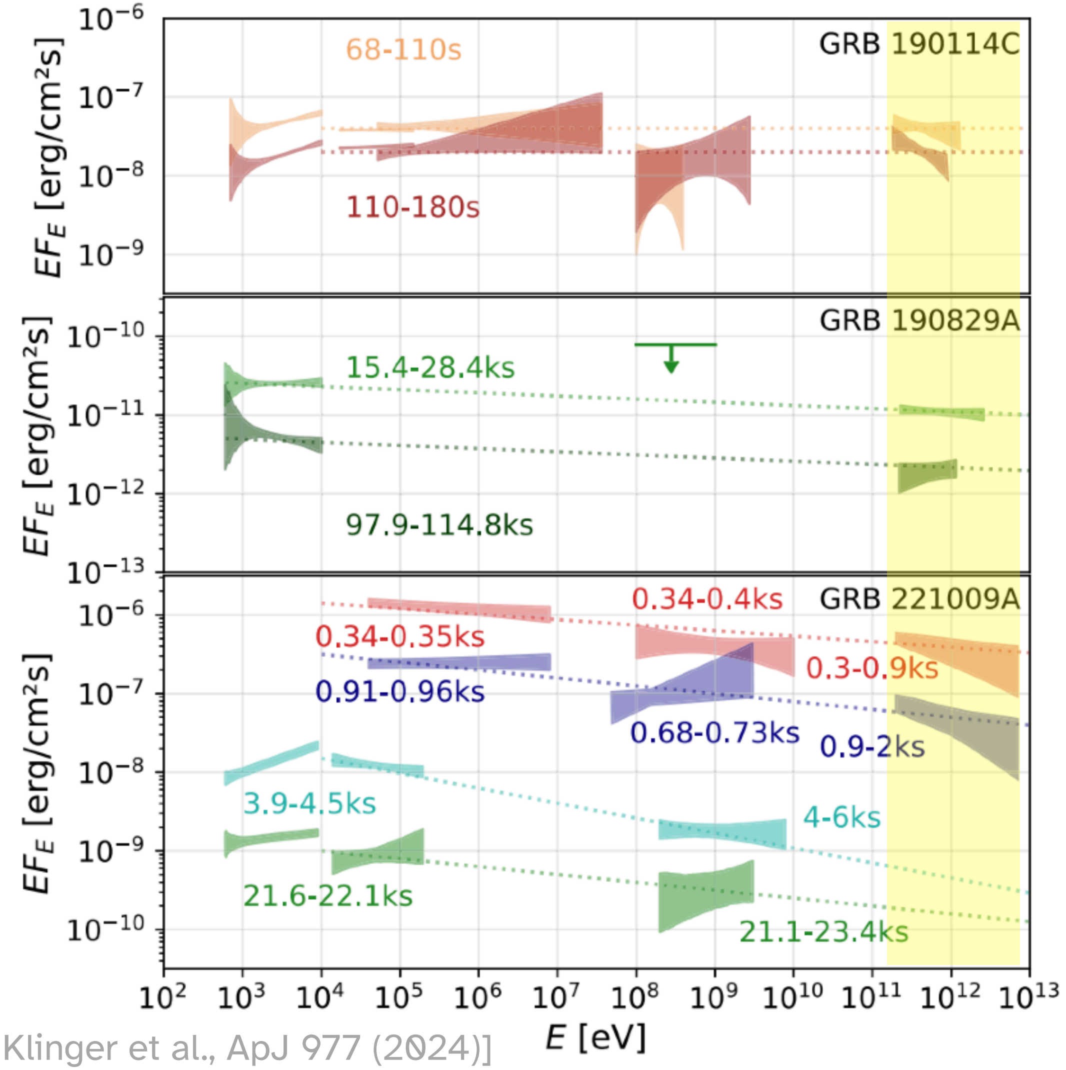
How do we get flat spectra across such a wide energy range?

Possibilities:

- structure in the magnetic field (multi-zone)
- exploring more complex single-zone scenarios



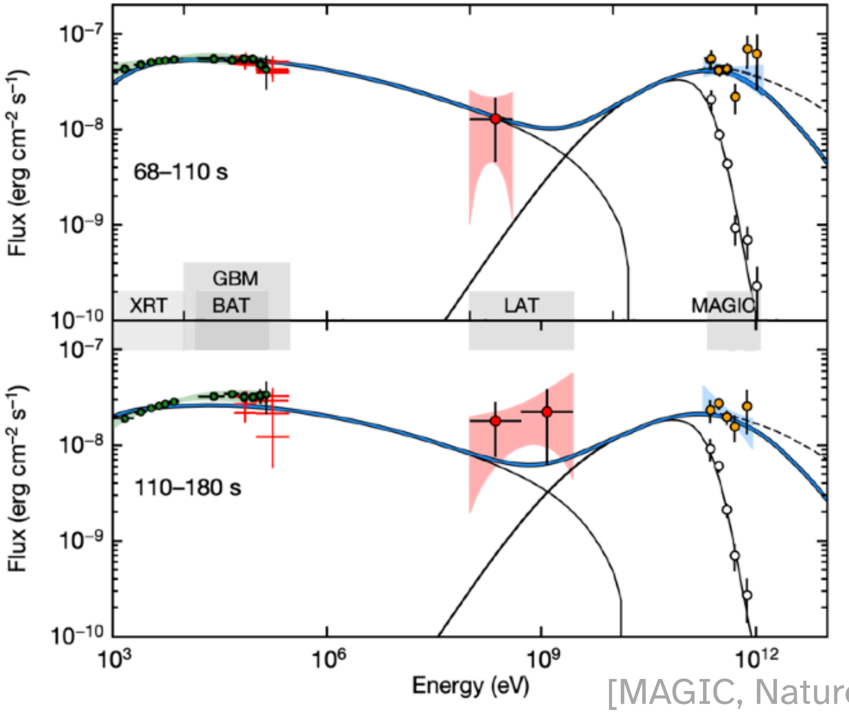
Do we see the inverse Compton component in VHE GRBs?



[M. Klinger et al., ApJ 977 (2024)]

no smoking gun so far

although there is disagreement:

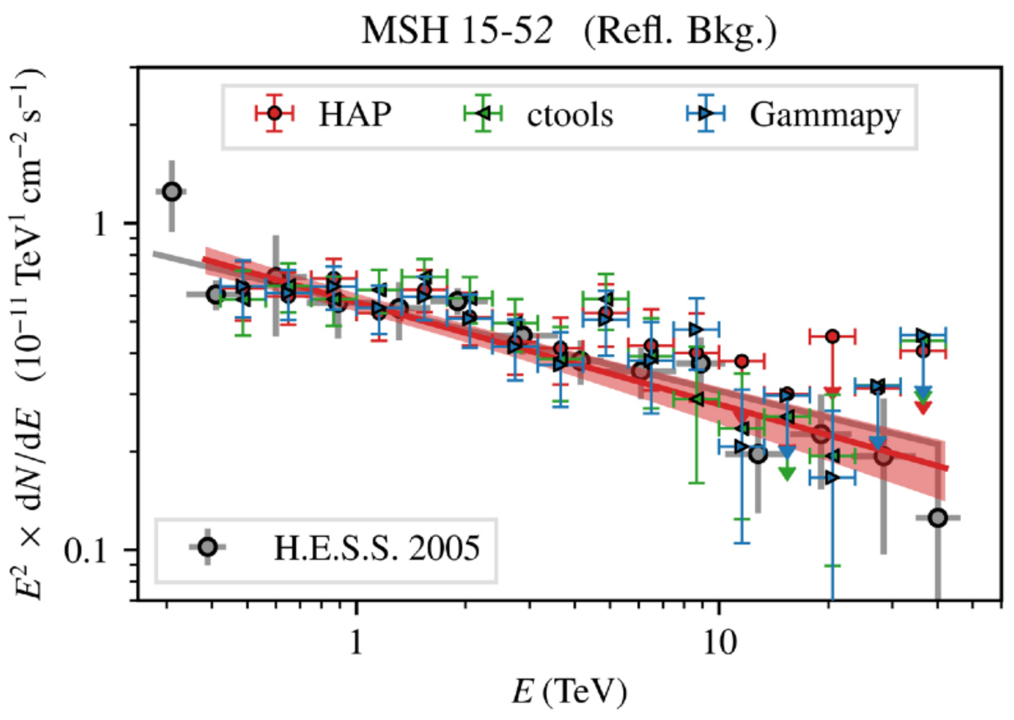


[MAGIC, Nature 575 (2019)]

Pause to talk about systematic uncertainties

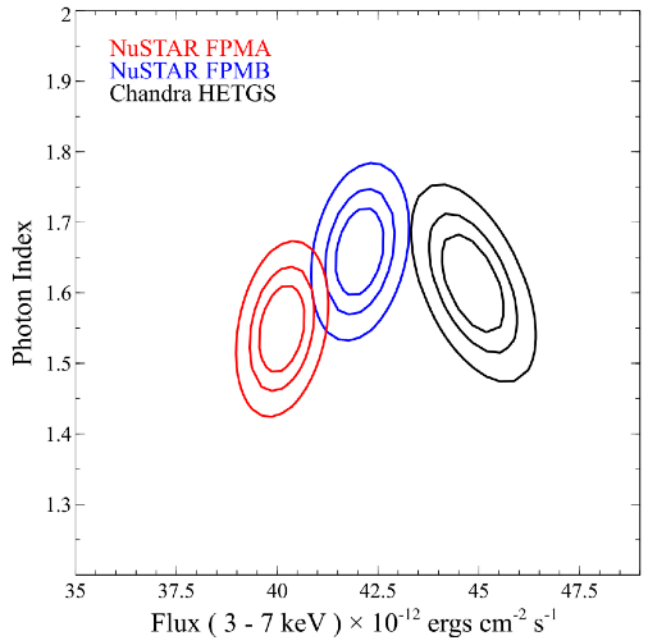
How well are we reconstructing the data? How much do we believe our reconstruction?

different reconstruction pipelines, analysis choices, or software can give different results



[L. Mohrmann et al., A&A 632 (2019)]

different telescopes have their own systematic uncertainties



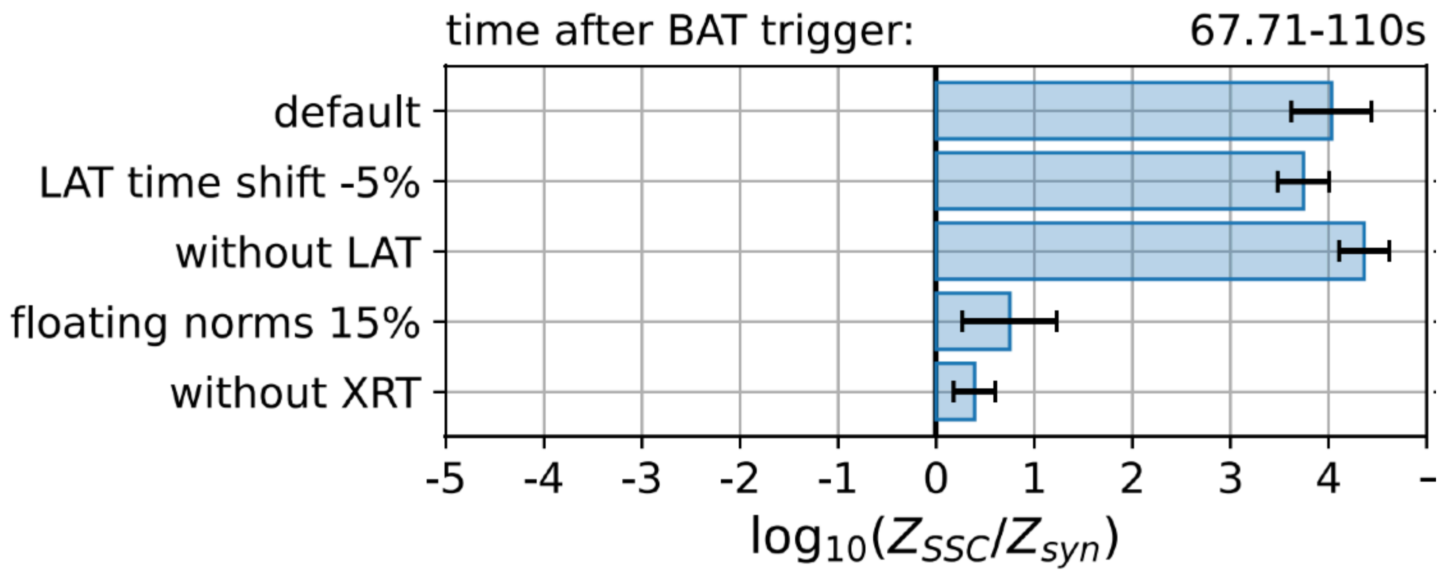
[K. K. Madsen et al., Astro J 153 (2017)]

Do we see the inverse Compton component in VHE GRBs?

Systematic uncertainties

Allowing for systematic uncertainties (esp. between instruments) can make a big difference in your result

[M. Klinger et al., MNRAS 520 (2023)]



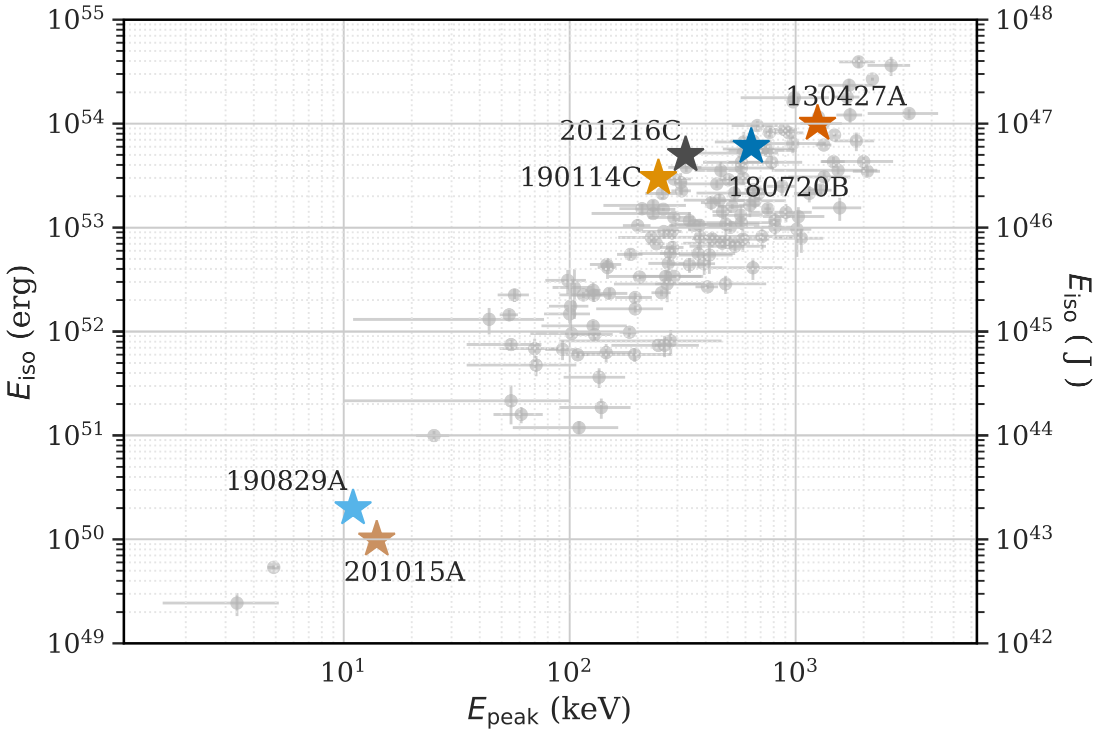
without allowing for systematic uncertainties, SSC is preferred

preference disappears when taking this into account

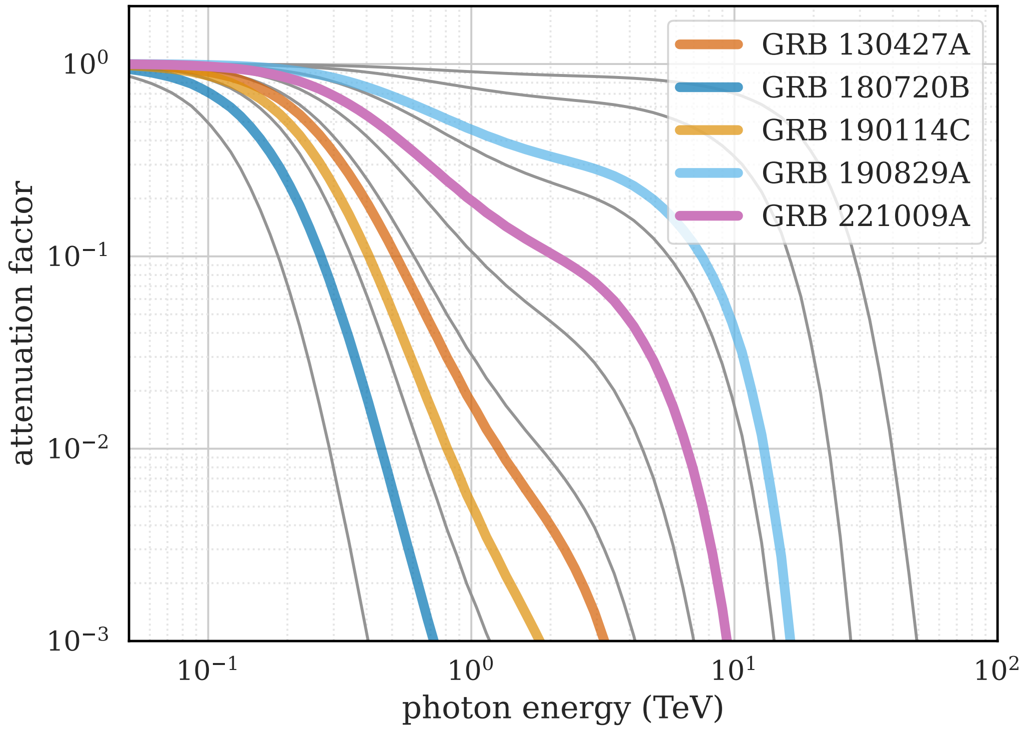
Comparing the VHE GRBs as a population

n < 10

data from Liu and Wei 2015



model from Franceschini et al. 2008



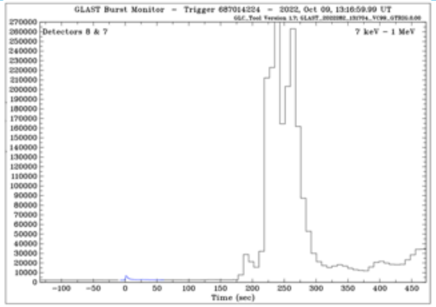
GRB 221009A

the BOAT ("Brightest of All Time")

what follows next is a series of slides for a presentation at a conference right after the GRB went off

ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!!! pls forgive me :(



13:16:59 UTC, GBM triggers (GCN 32636)
"the brightest among the GBM detected GRBs"
go find **Eric Burns** if you want more gossip about the GBM detection

At this time, the source is not visible to BAT

2022-10-09 — 2022-10-10 — 2022-10-11 — 2022-10-12

DESY.

Sylvia J. Zhu, 10th Fermi Symposium, October 2022

ok fine let's briefly talk about GRB 221009A now

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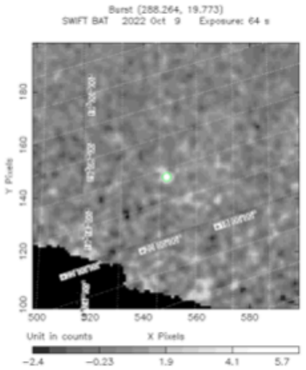

14:10:17 UTC, BAT triggers (GCN 32636), nearly an hour after the GBM trigger
-> Still bright enough for an image trigger

go find **Judy Racusin** if you want more gossip about the Swift observations

2022-10-09

2022-10-10

2022-10-11

2022-10-12

DESY.

Sylvia J. Zhu, 10th Fermi Symposium, October 2022

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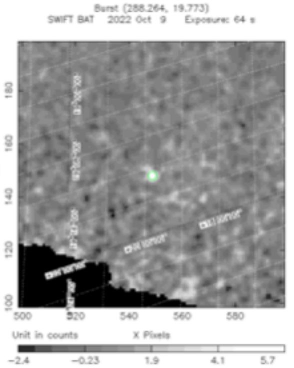

14:10:17 UTC, BAT triggers (GCN 32636), nearly an hour after the GBM trigger
-> Still bright enough for an image trigger

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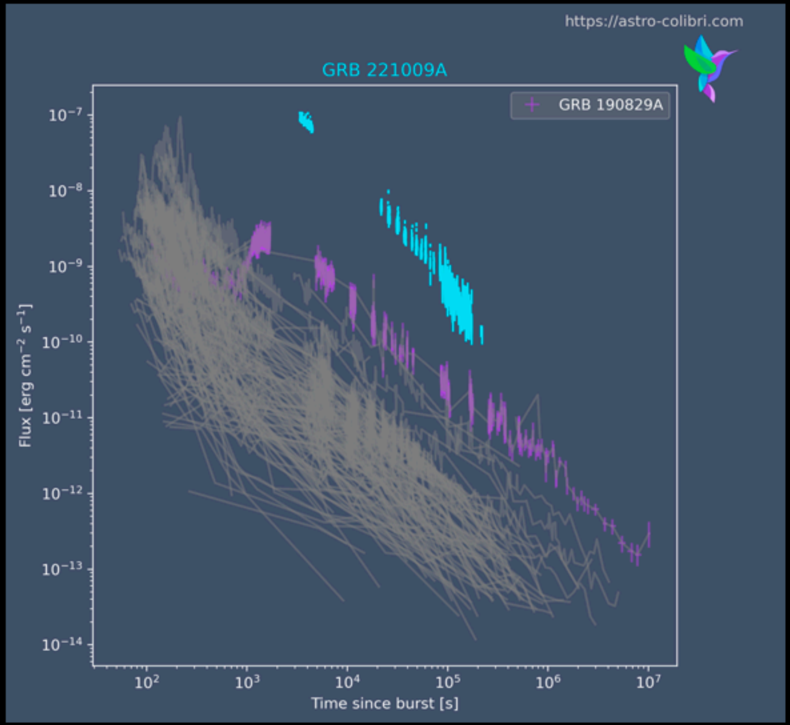
brightest XRT afterglow by far



2022-10-09

2022-10-10

2022-10-11

2022-10-12

DESY.

Sylvia J. Zhu, 10th Fermi Symposium, October 2022

ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!!! pls forgive me :(

LAT detected the prompt emission
(GCNs 32637, 32658)

"bright structured emission episode … temporally coincident with the GBM main emission episode"
"extending for about 25ks post GBM trigger"
"The highest-energy photon is 99.3 GeV … 240 seconds after the GBM trigger."

go find **Nicola Omodei** if you want more gossip about the LAT detection

DESY.

Sylvia J. Zhu, 10th Fermi Symposium, October 2022

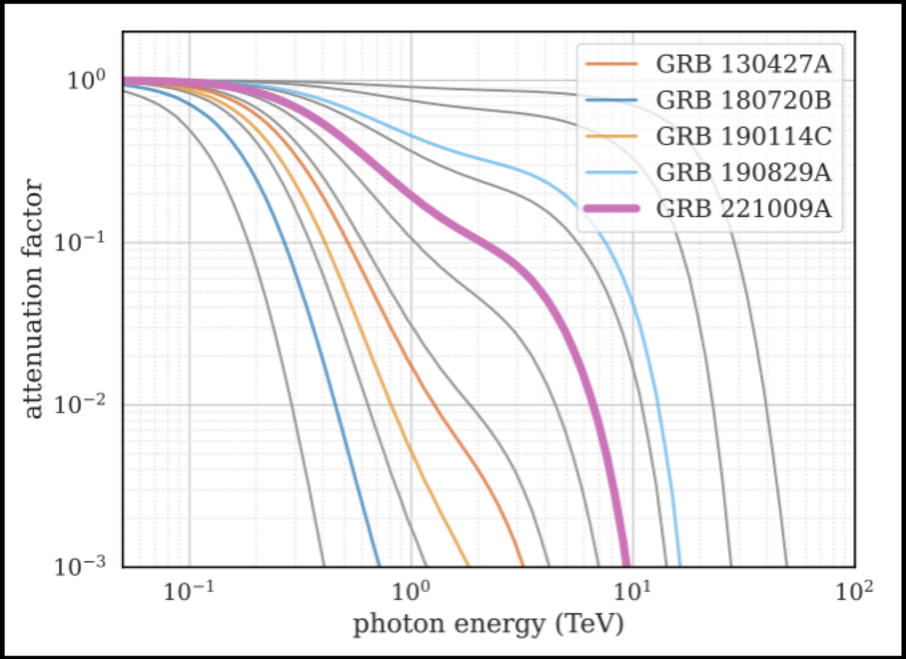
ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!!! pls forgive me :(

X-shooter/VLT: *z* = 0.151
(GCN 32648)

Eiso ~ 2e54 erg based on GBM fluence
but: GBM has strong systematic issues because the burst was TOO BRIGHT

go find **Eric Burns** if you want more gossip about the GBM systematic issues



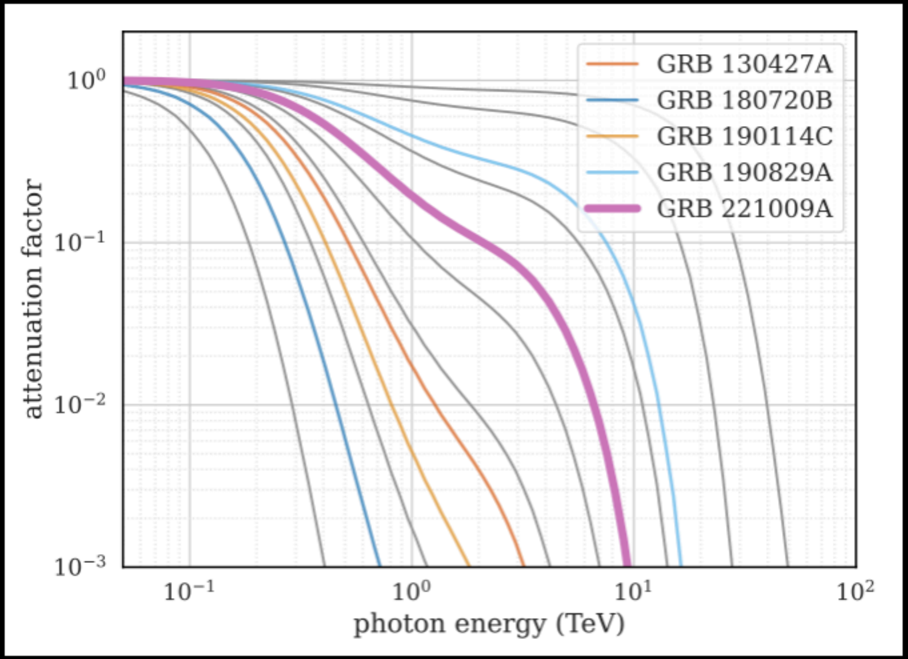
DESY.
Sylvia J. Zhu, 10th Fermi Symposium, October 2022

ok fine let's briefly talk about GRB 221009A now

So what happened? — NOTE: Not an exhaustive list!!! Sorry if I missed your telescope!!!!! pls forgive me :(

LHAASO (GCN 32677)

"more than 5000 VHE photons up to around 18 TeV" !!!!
(previous record: 4 TeV)
"within 2000 seconds after T0"

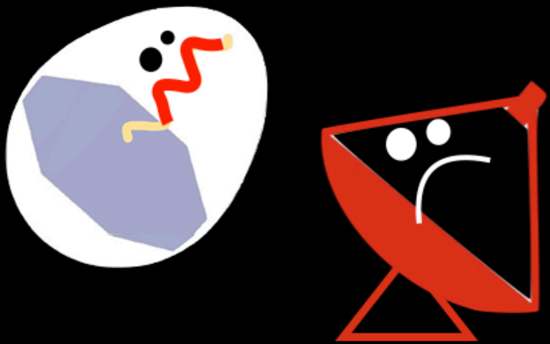


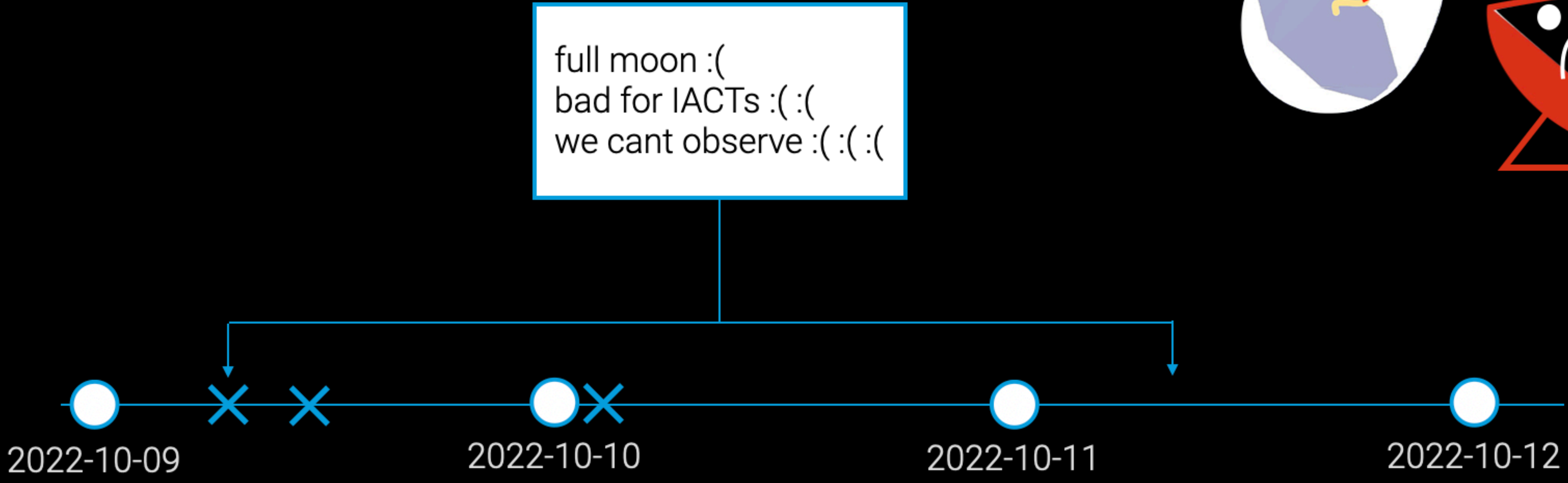
DESY.

Sylvia J. Zhu, 10th Fermi Symposium, October 2022

ok fine let's briefly talk about GRB 221009A now

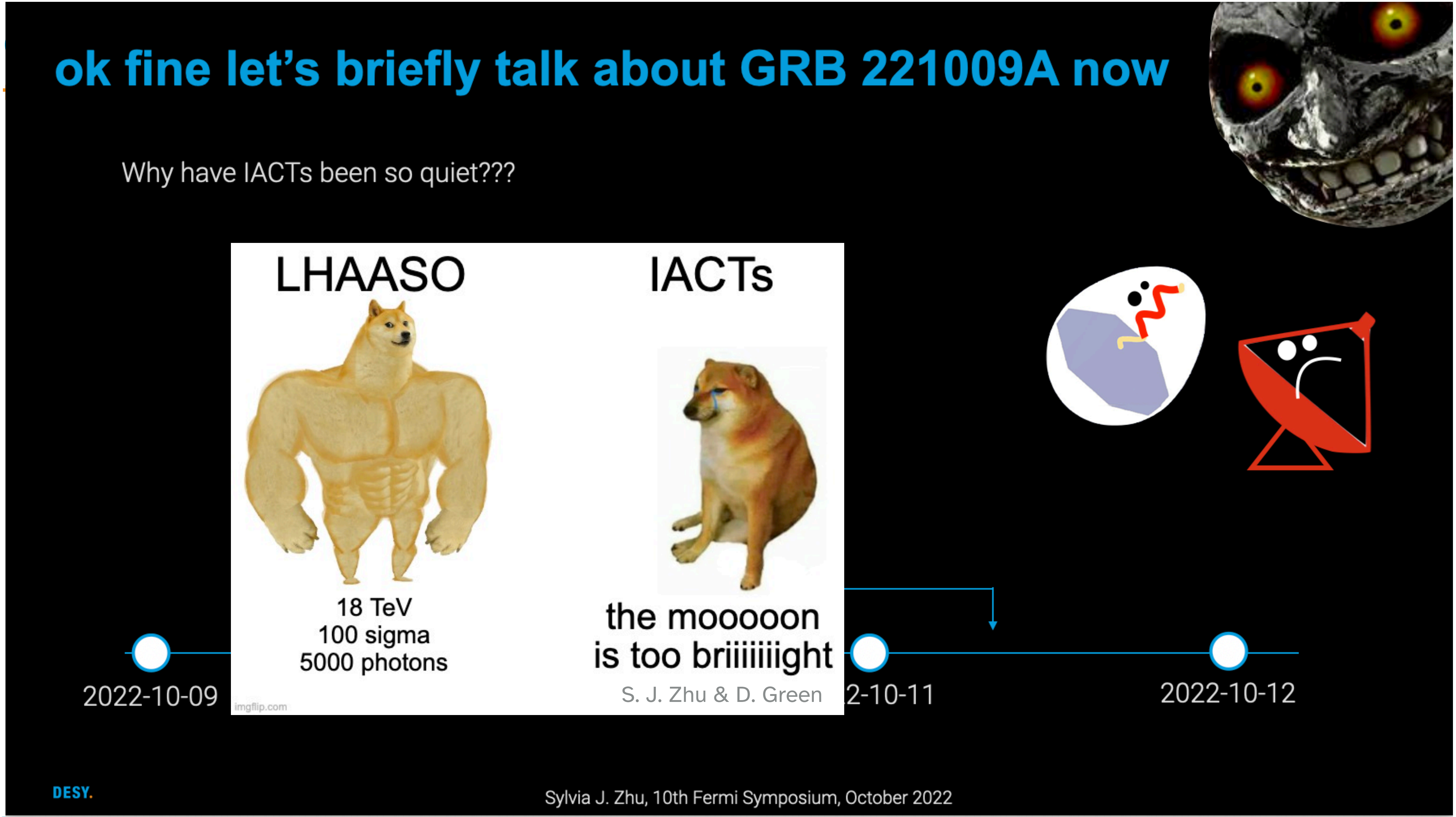
Why have IACTs been so quiet???





DESY.

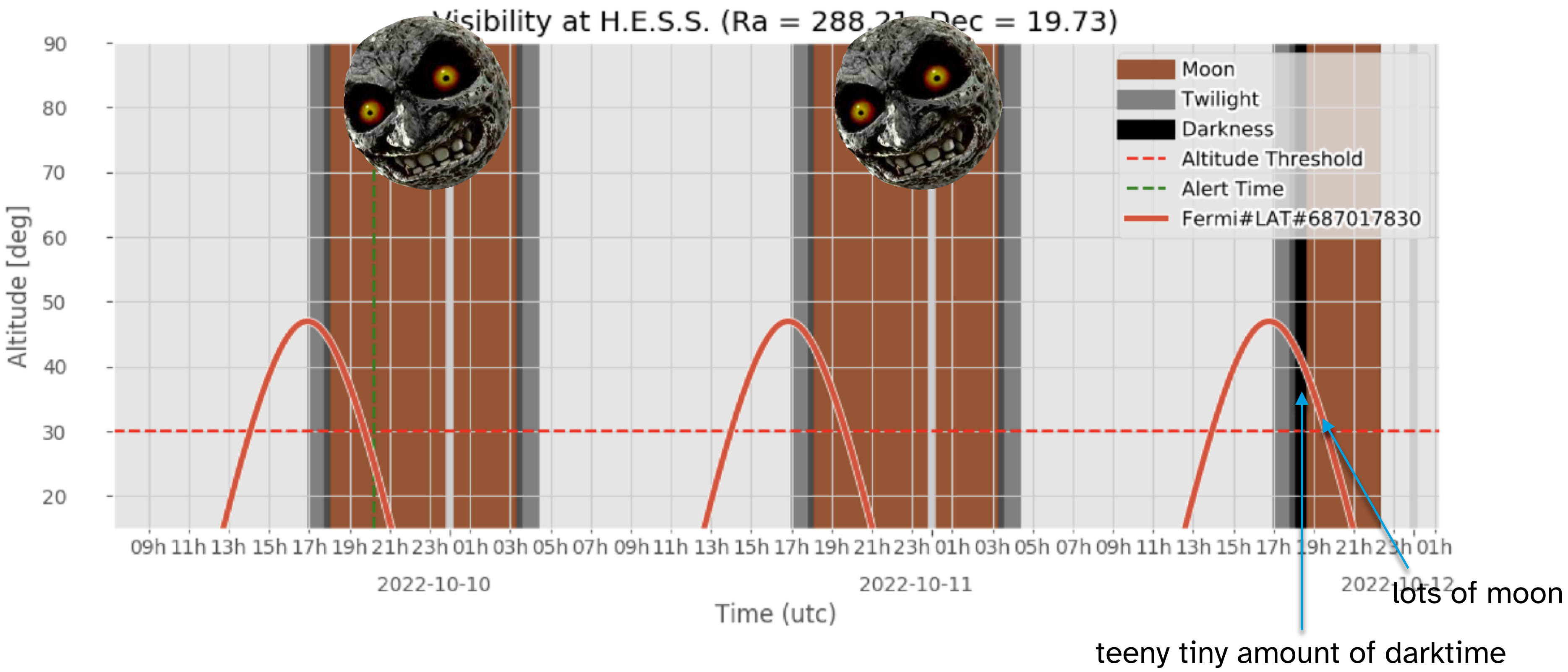
Sylvia J. Zhu, 10th Fermi Symposium, October 2022


ok fine let's briefly talk about GRB 221009A now
Why have IACTs been so quiet???
LHAASO
IACTs
18 TeV
100 sigma
5000 photons
the moooooon
is too briiiiiiight
S. J. Zhu & D. Green
imgflip.com
2022-10-09
2-10-11
2022-10-12
DESY.
Sylvia J. Zhu, 10th Fermi Symposium, October 2022

GRB 221009A

IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight …)



GRB 221009A

IACTs tried

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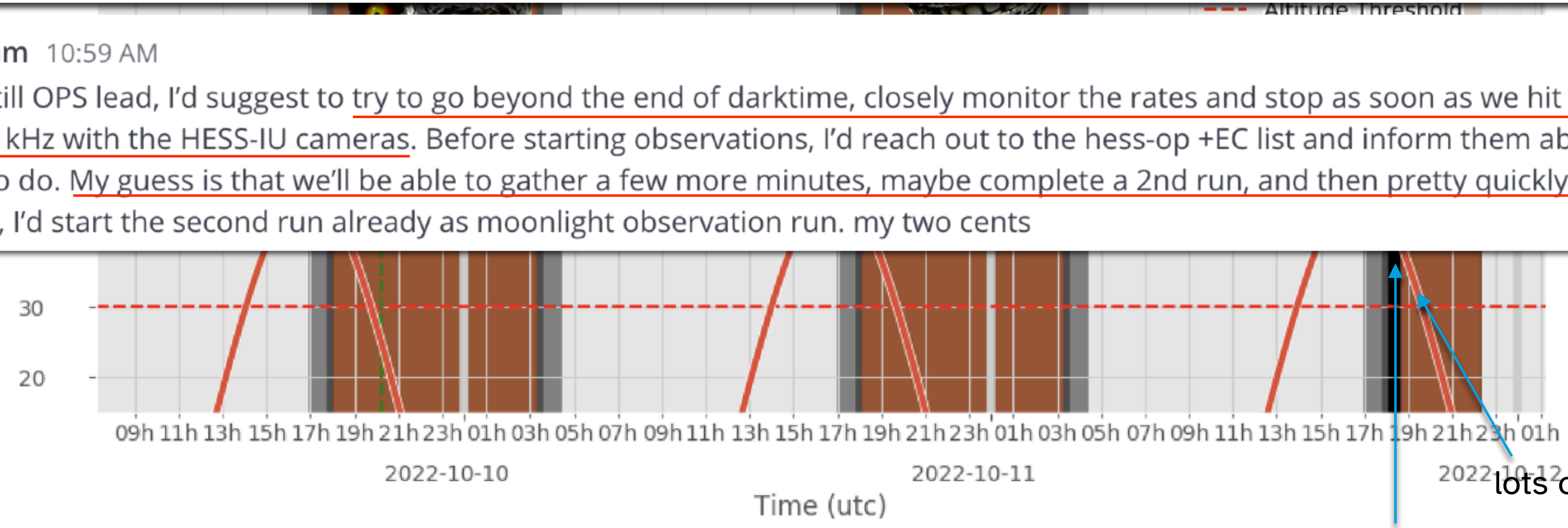
conversations on 10 October

Fabian Schuessler 10:47 AM
Feedback from the operations channel: observations will start tomorrow. I think we should try to get as much observations as possible. At least one run with standard settings and then pushing into moonlight until the trigger rates become impossible...

Stefan Ohm 10:59 AM
If I were still OPS lead, I'd suggest to try to go beyond the end of darktime, closely monitor the rates and stop as soon as we hit the predetermined limit of 10 kHz with the HESS-IU cameras. Before starting observations, I'd reach out to the hess-op +EC list and inform them about what you propose to do. My guess is that we'll be able to gather a few more minutes, maybe complete a 2nd run, and then pretty quickly hit the wall. If we do it this way, I'd start the second run already as moonlight observation run. my two cents



GRB 221009A

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so we tried it

00:08:08

Observation date: 2022-10-11

Darkness Start: 18:04:17 UTC / Duration: 00:31:27

No Moonlight tonight

preparing for observations

GRB 221009A

IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight …)

```
----------------------------------
| H.E.S.S. Shift Log 2022-10-11 |
----------------------------------

 Night: 18:04:21 - 18:38:29
On Shift: Heiko, Kai & Ben

----> Summary

3 x GammaRayBurst_221009

----> Run List

| 1 178577 SoftTrigger CT1,2,3,4,5, Crab Nebula ra0.5393d 16:05-16:07 2min, alt 0d, rate 0Hz
| 2 178578 Tracking CT1,2,3,4,5, GammaRayBurst_221009 17:41-17:41 0min, alt 0d, rate 0Hz
| 3 178579 Observation CT1,2,3,4,5, GammaRayBurst_221009 ra-0.74d 18:05-18:37 32min, alt 40d, rate 824Hz
| 4 178580 MoonlightObservation CT1,2,3,4,5, GammaRayBurst_221009 dec0.7d, 18:40-18:52 12min, alt 0d, rate 0Hz
 SubArray01/Manager: Required process (CT4/CameraTrigger) disappeared!
Node15/Receiver: CT4 has 99.3421% of missing data
| 5 178581 MoonlightObservation CT5, GammaRayBurst_221009 dec0.70d, 18:54-19:20 26min, alt 0d, rate 0Hz
 CT5/CameraLogger: Can't contact subsystem CameraLogger via thrift! Check camera pc of CT5!
| 6 178582 PointToHorizon CT5, 19:25-19:25 0min, alt 0d, rate 0Hz
```

getting ready

1 full normal run

cameras on small telescopes gave up

camera on big telescope kept going for another 26 min!!

… because it was really cloudy

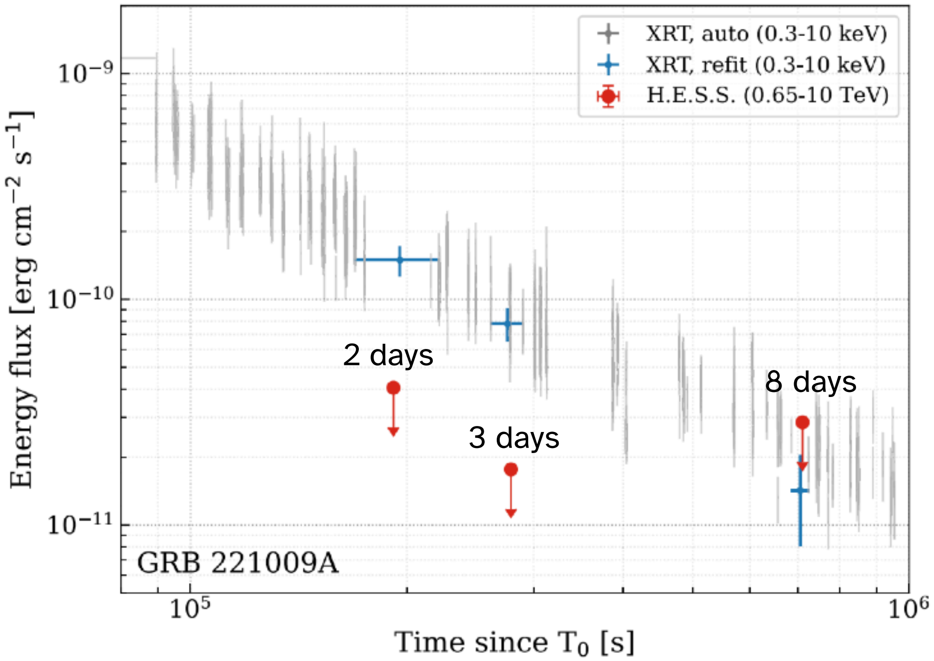
GRB 221009A

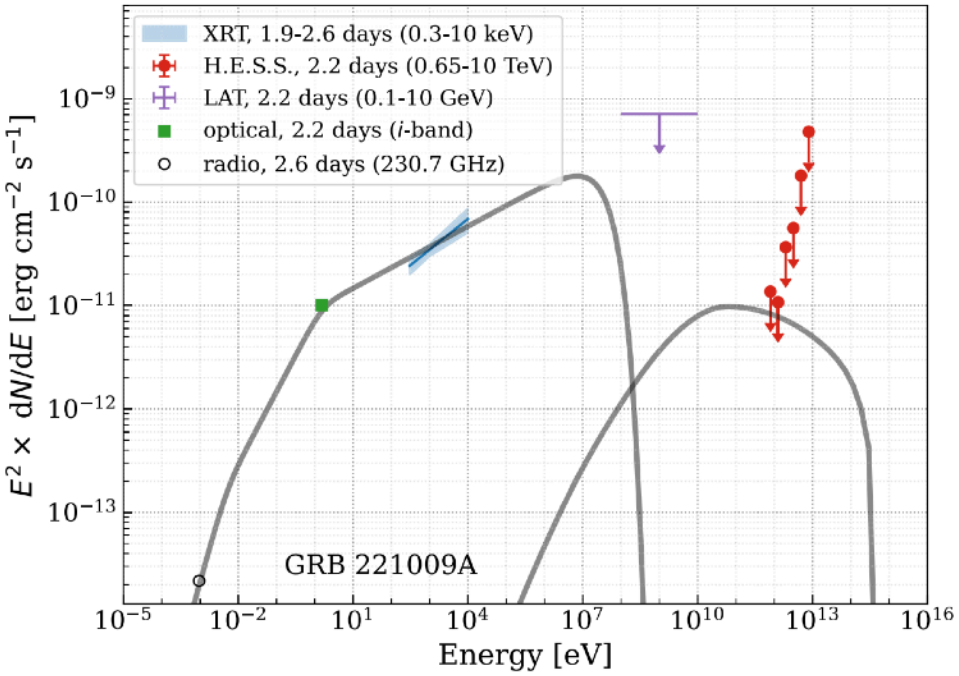
IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight ...)

H.E.S.S. observations

[F. Aharonian et al., ApJL 946 (2023)]



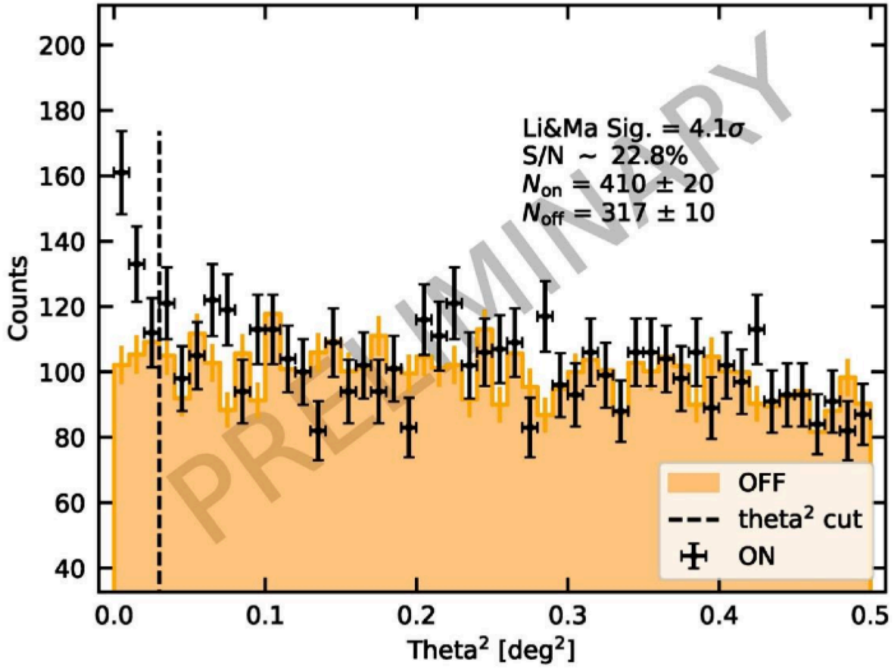


one zone SSC model

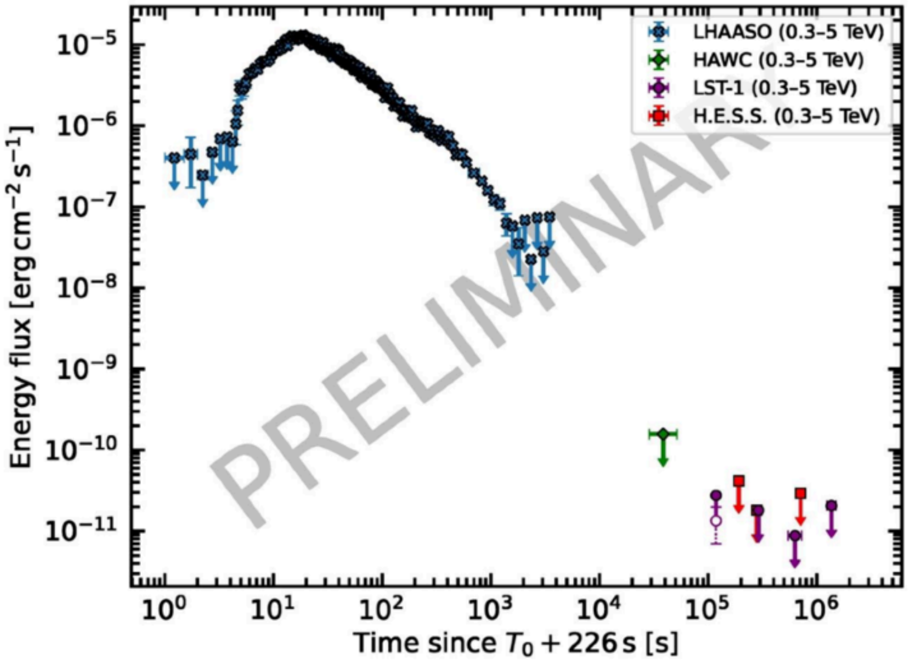
GRB 221009A
IACTs tried

the IACTs observed as soon as we all could (even during extremely bright moonlight …)

LST-1 observations [A. Aguasca-Cabot, Gamma 2024]



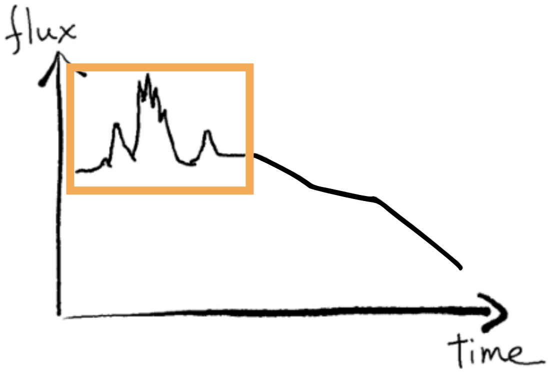
θ^2-plot for the moon data (Oct. 10)



LST-1 light curve using moon and dark data

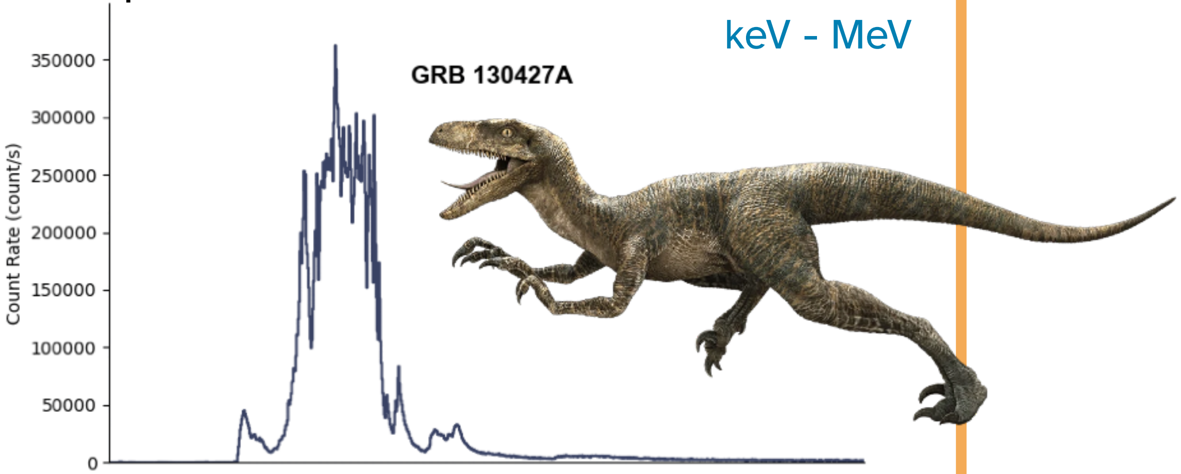
GRB 221009A

the BOAT (“Brightest of All Time”)



the previous record holder

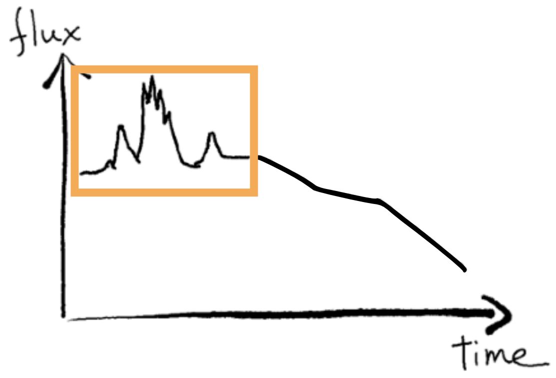
Fermi-GBM
keV - MeV

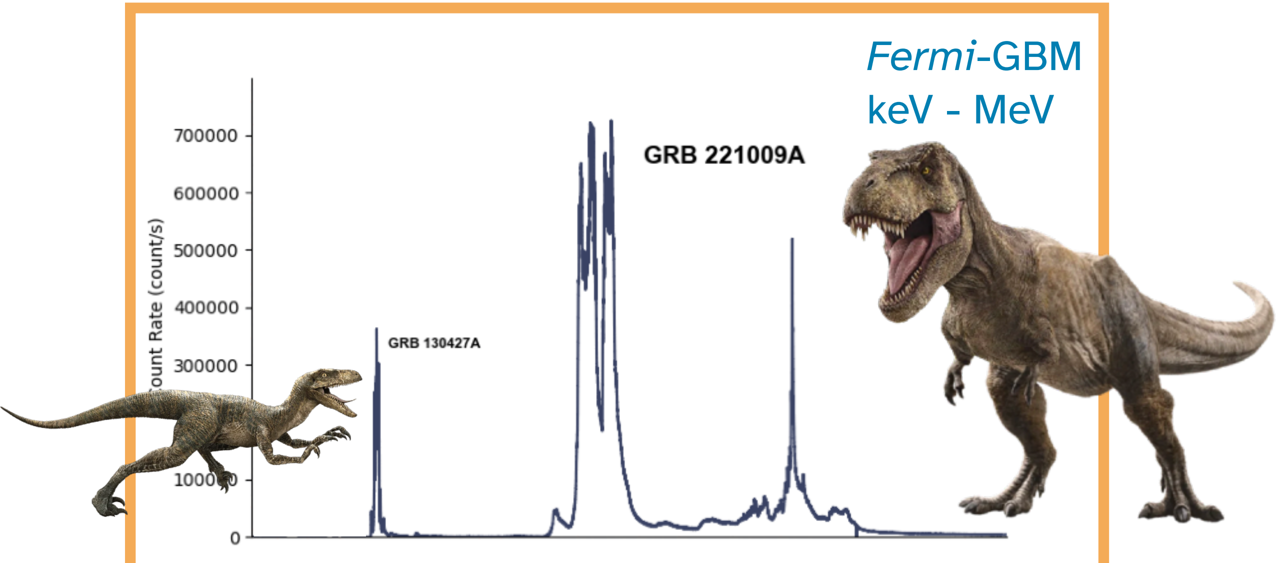


A. Goldstein, *Fermi*-GBM

GRB 221009A

the BOAT ("Brightest of All Time")





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GRB 221009A

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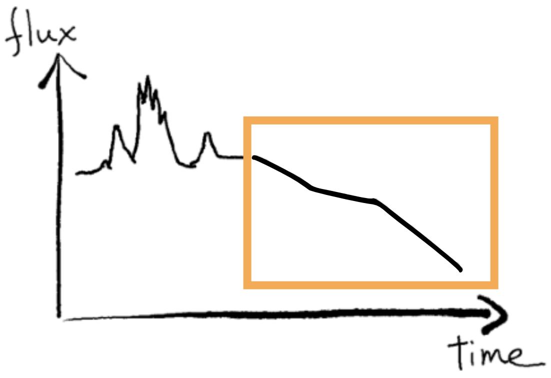
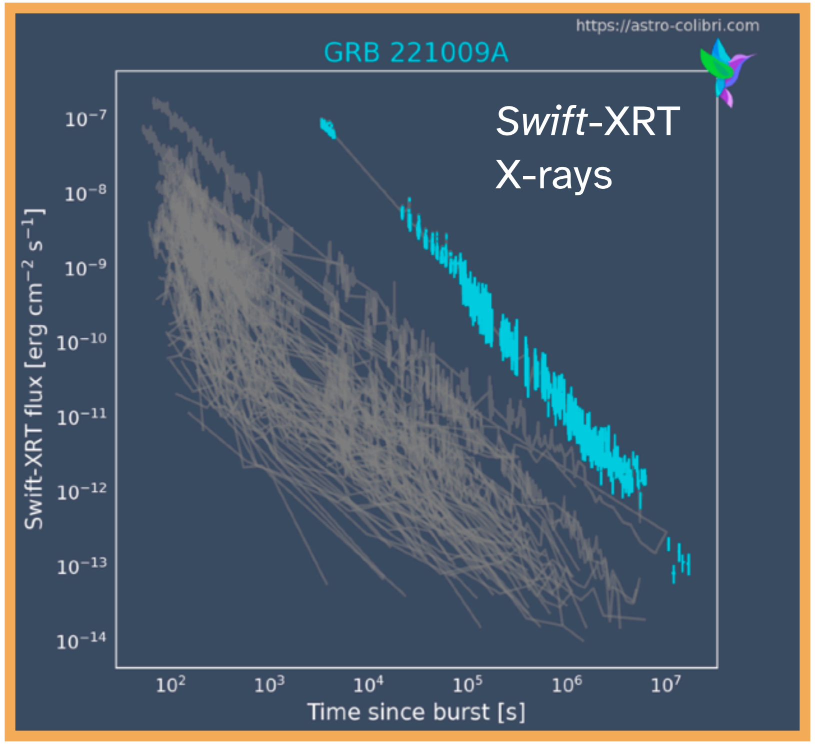
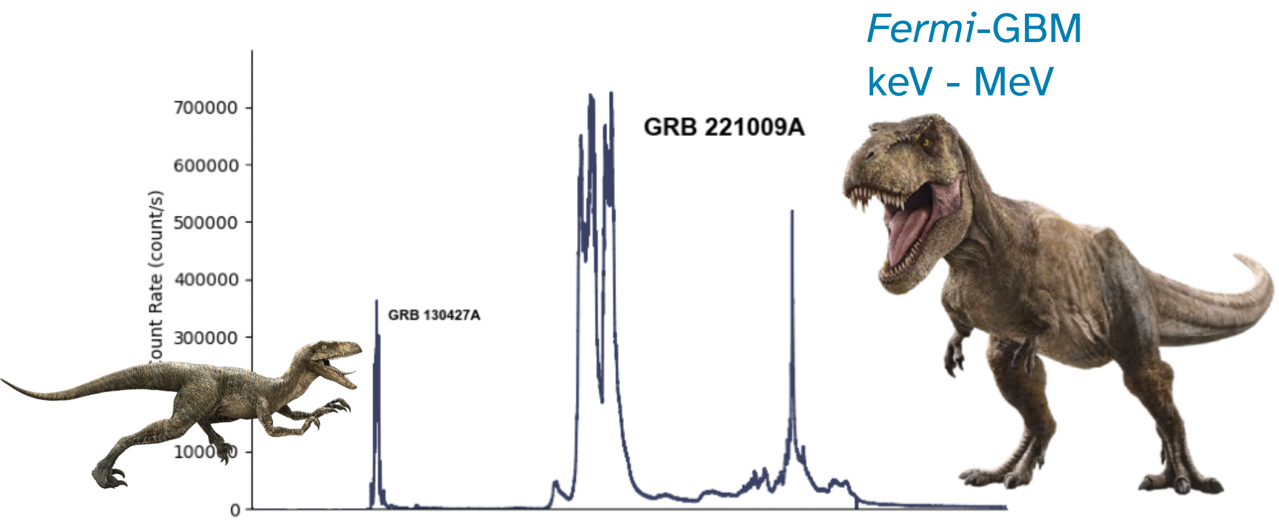




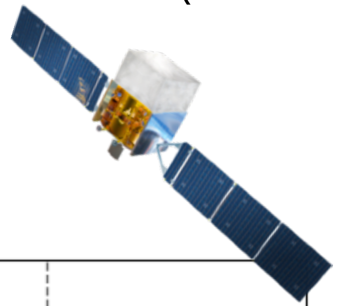


A. Goldstein, *Fermi*-GBM

GRB 221009A

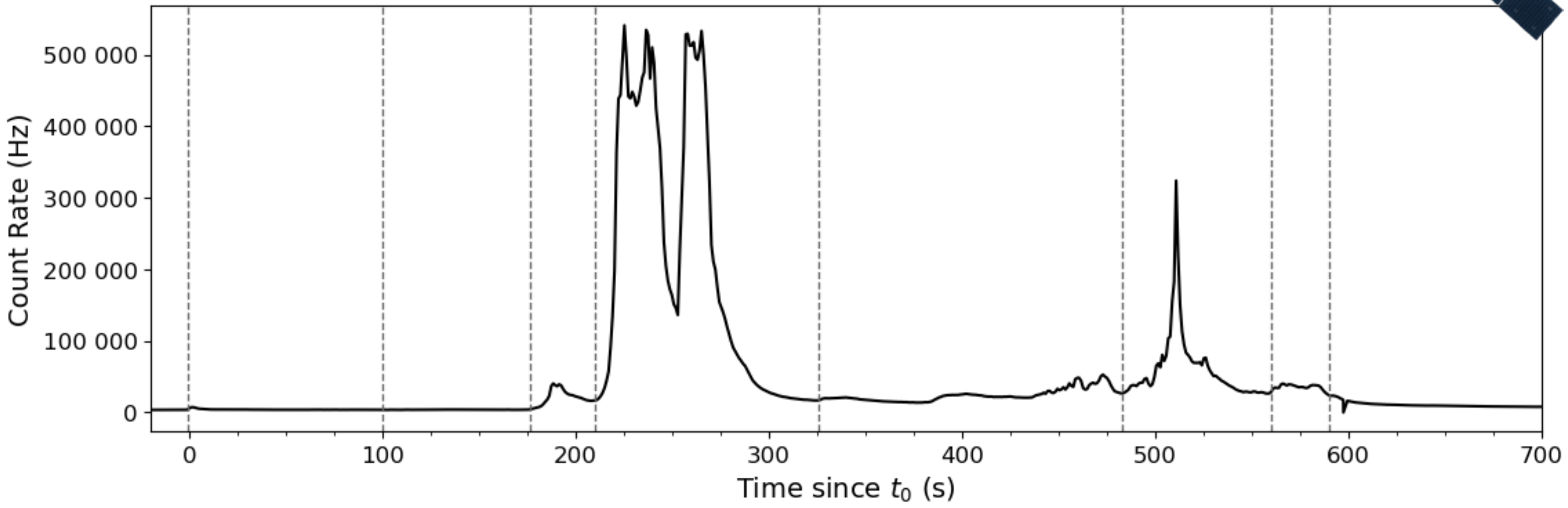
Too much of a good thing

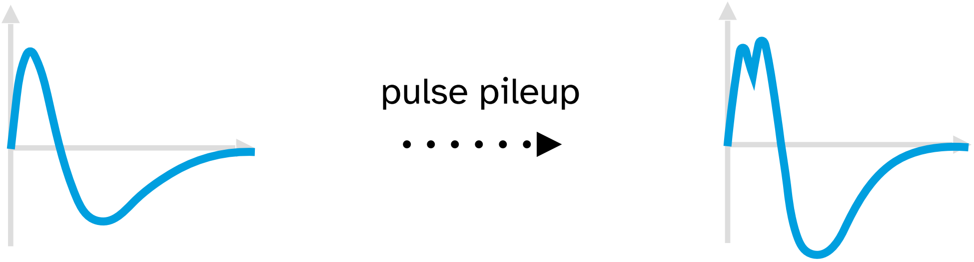
Fermi-GBM (keV - MeV)



The prompt emission was so bright that it caused problems for the detectors

e.g.: photons were hitting the detectors faster than the signals could be read out





[V. Chaplin, NIMPA 717 (2013)]

GRB 221009A

Too much of a good thing

Fermi-GBM (keV - MeV)

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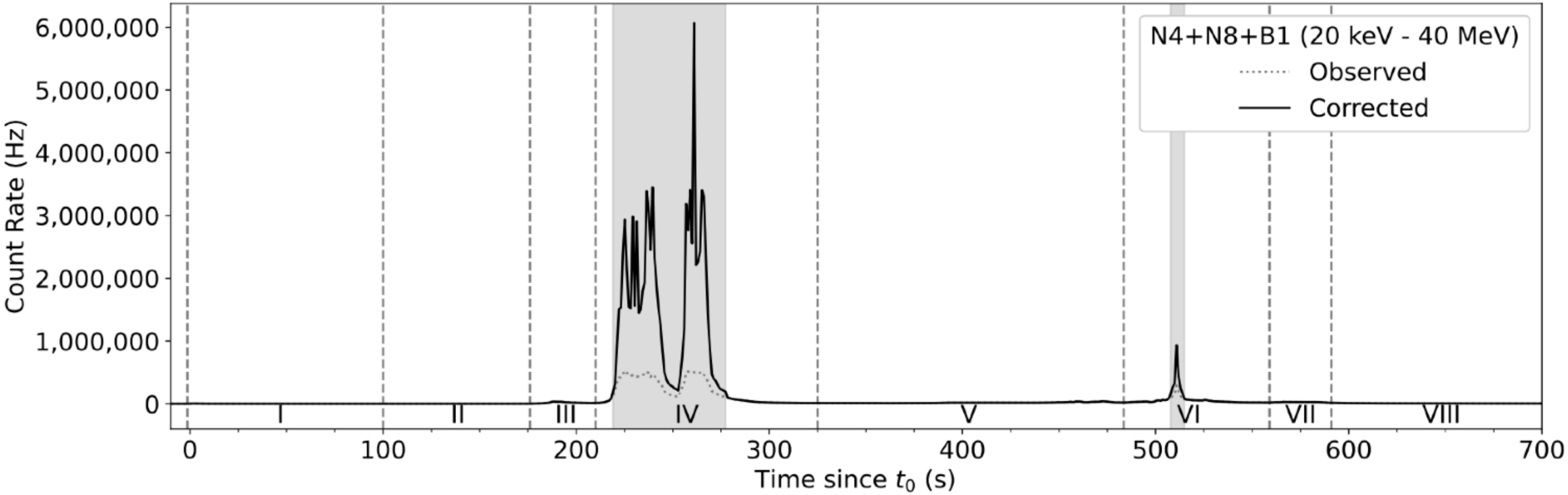
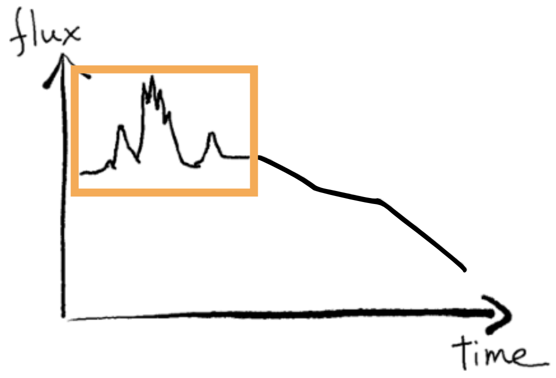


[S. Lesage et al., ApJL 592 (2023)]

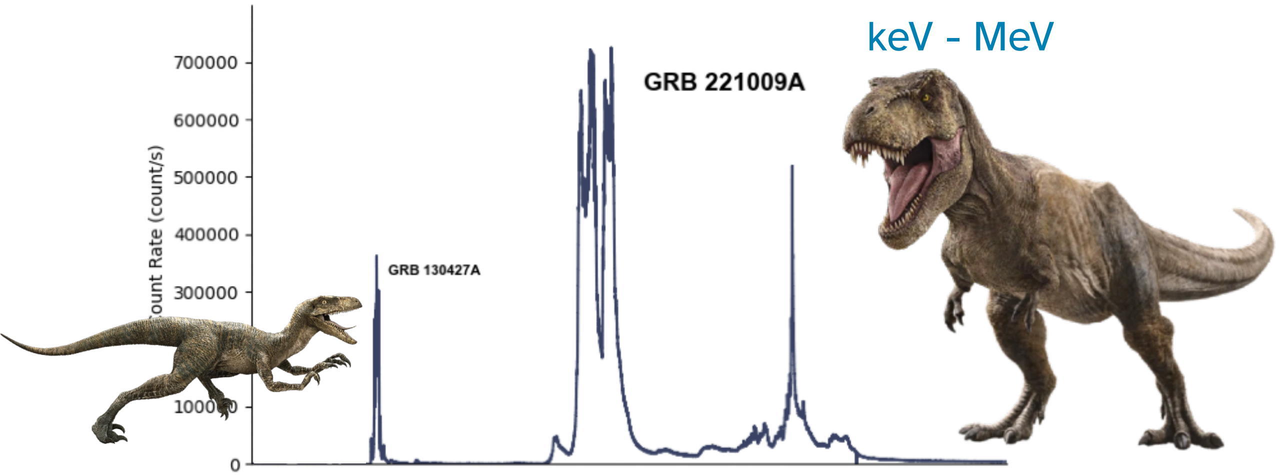
The corrected light curve was even more extraordinary

GRB 221009A

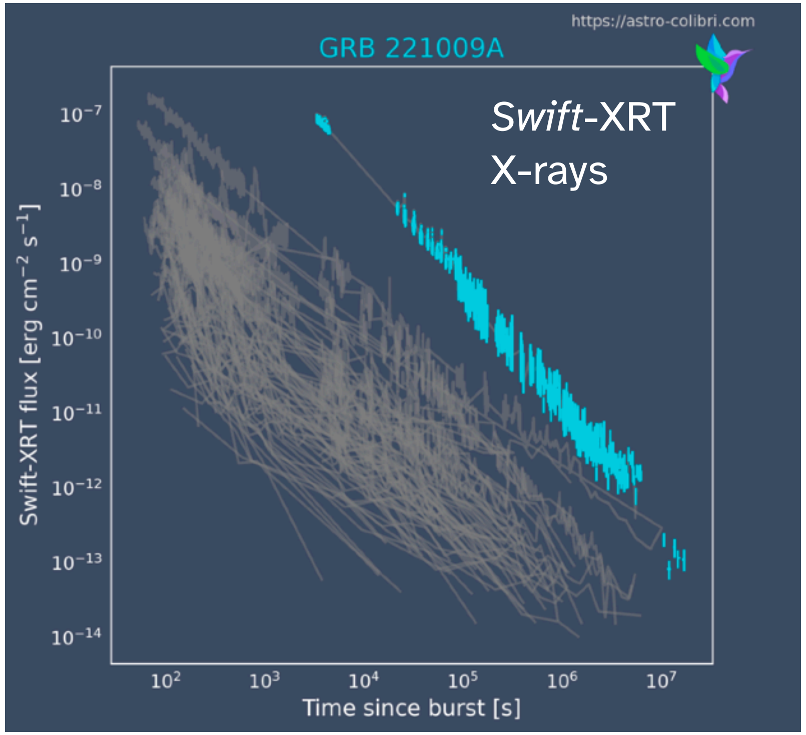
the BOAT ("Brightest of All Time")



Fermi-GBM
keV - MeV



A. Goldstein, *Fermi*-GBM



GRB 221009A

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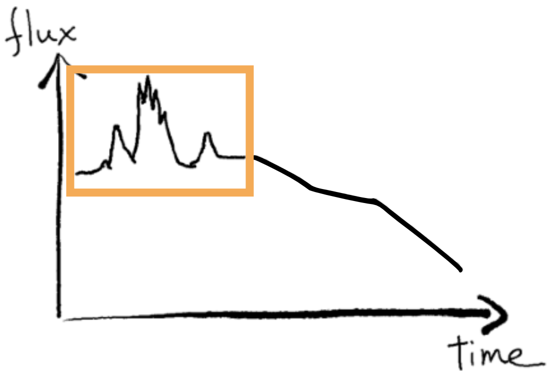
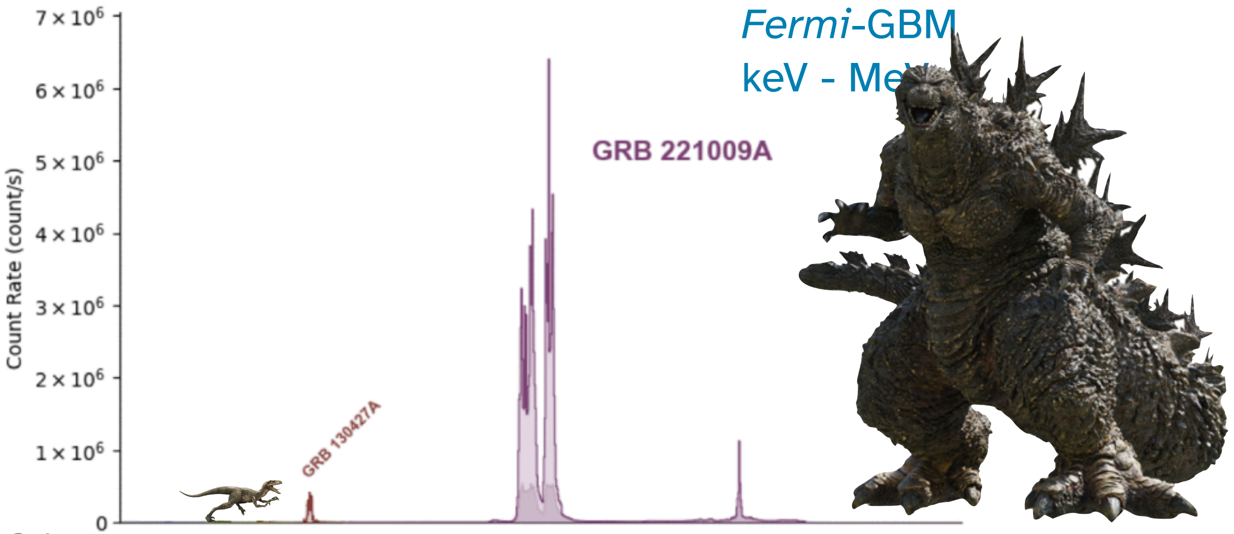
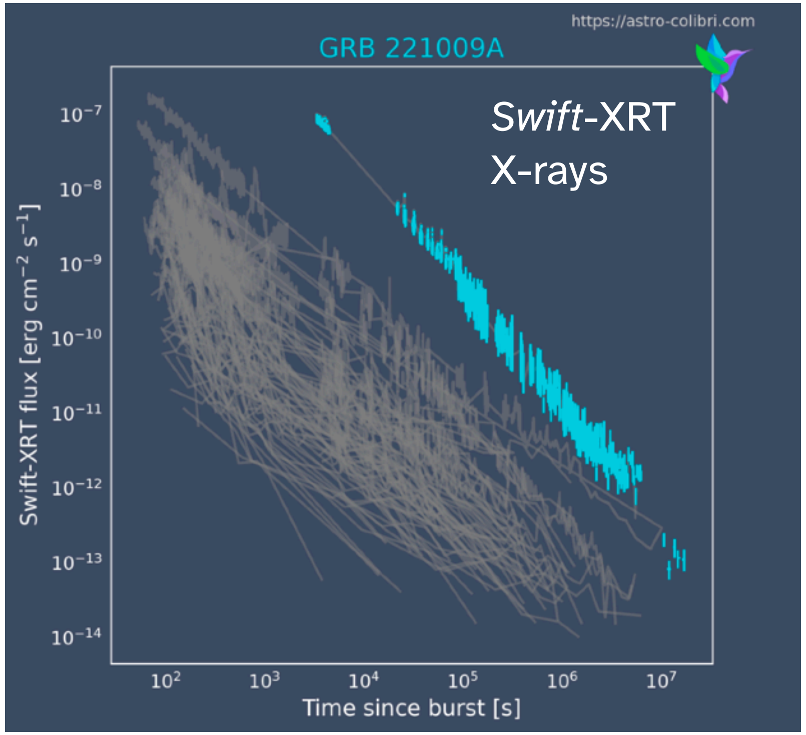




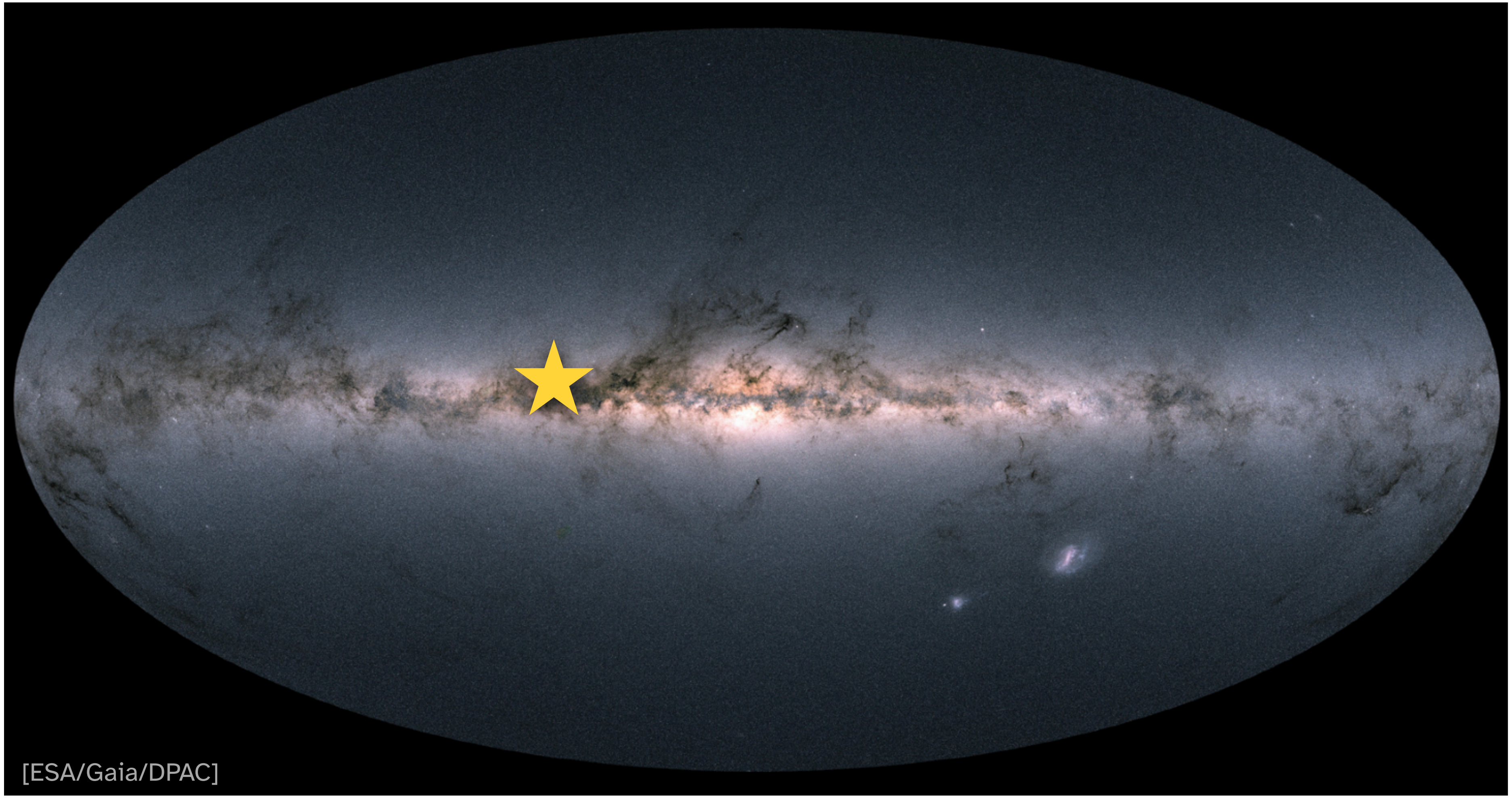
S. Lesage



GRB 221009A

the BOAT ("Brightest of All Time")

GRB 221009A was at very low Galactic latitudes

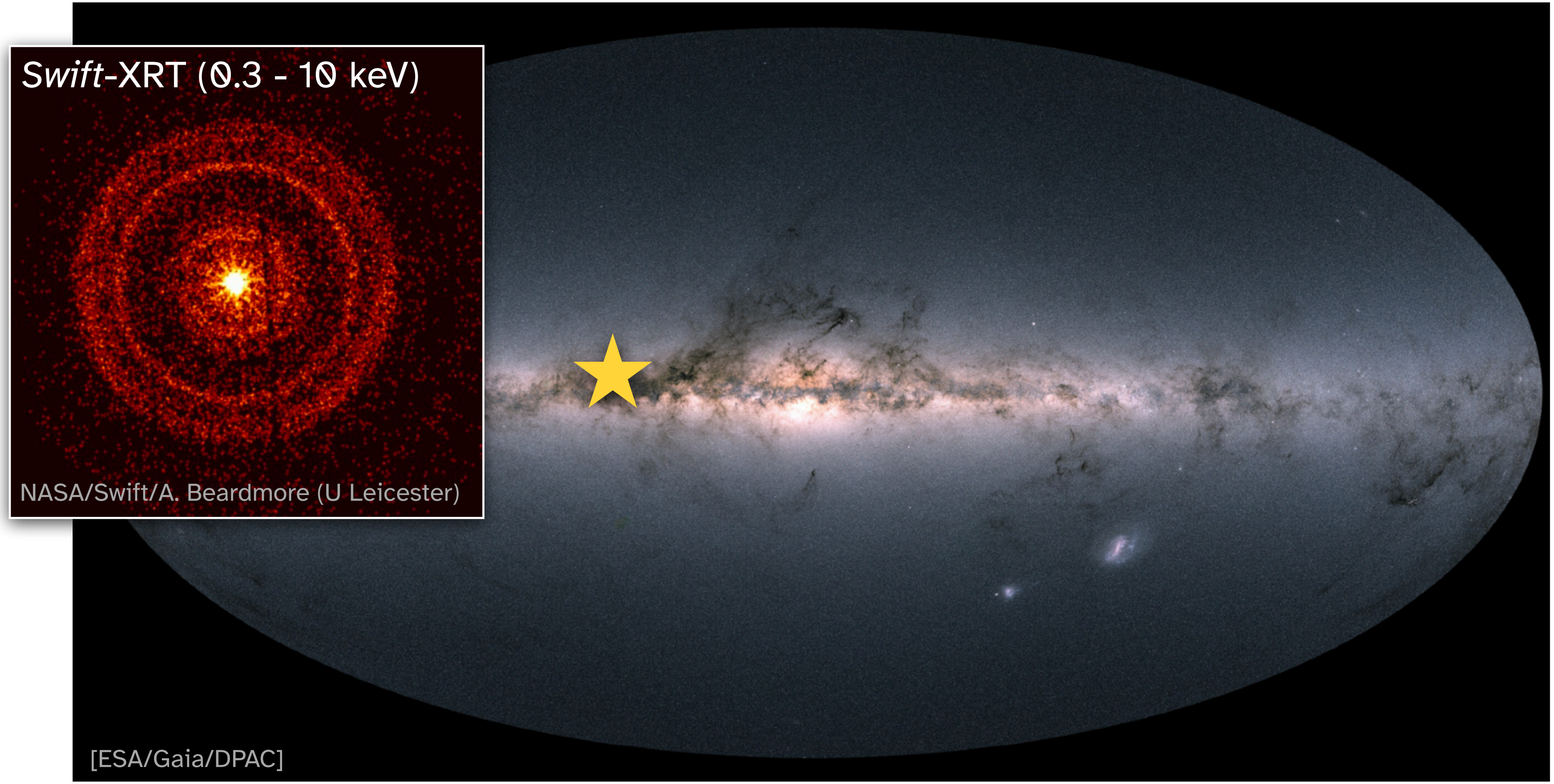


GRB 221009A

the BOAT ("Brightest of All Time")

GRB 221009A was at very low Galactic latitudes -> X-ray telescopes saw *dust rings*

[G. Vasilopolous et al., MNRAS 521 (2023)]
[A. Tiengo et al., ApJL 946 (2023)]

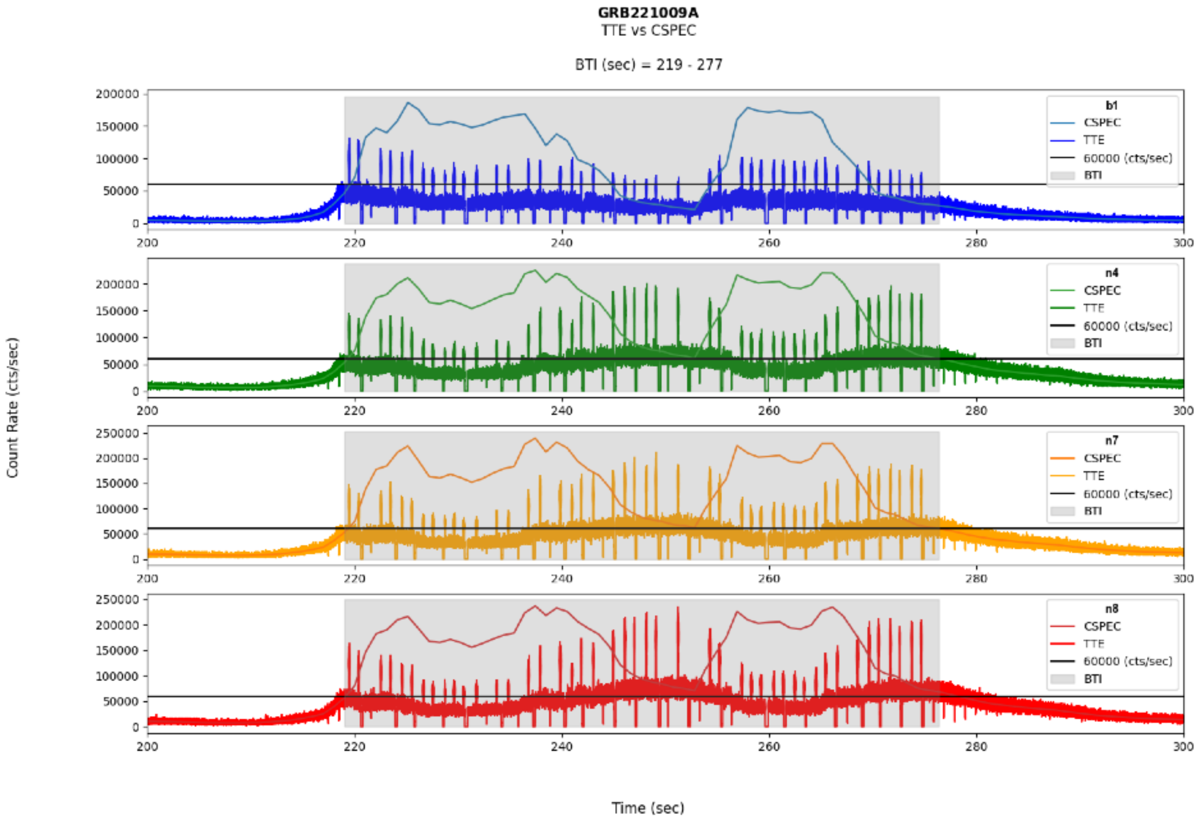


GRB 221009A

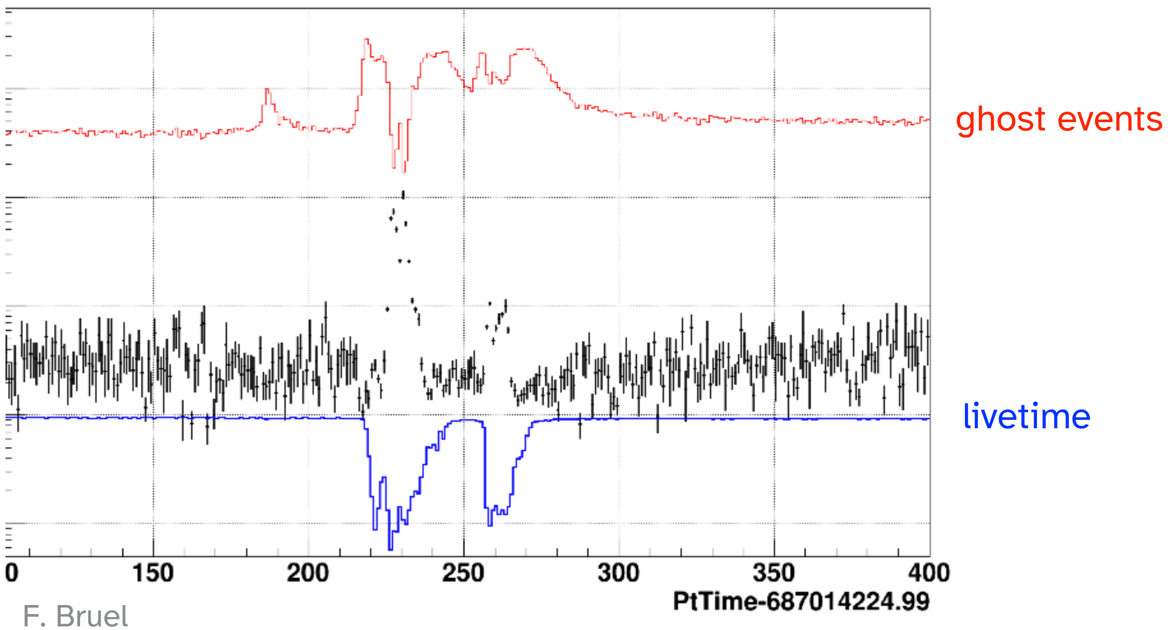
Too much of a good thing

[link]

some GBM data is entirely missing (time-tagged events)
+ the issue of pulse pileup discussed before



some LAT time intervals can't be safely analyzed

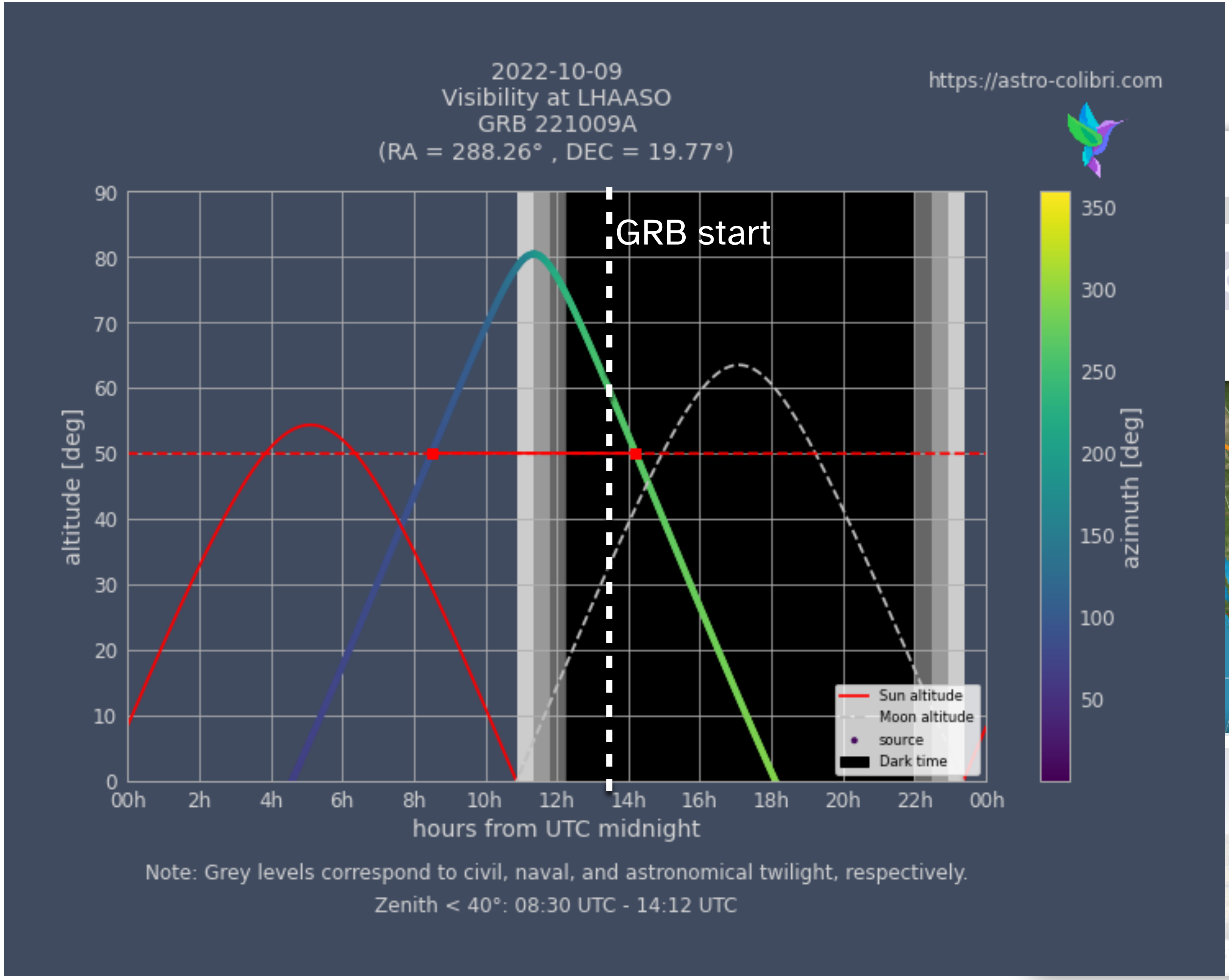


F. Bruel

VHE gamma-ray detectors

[Daniel R. Strebe]

V



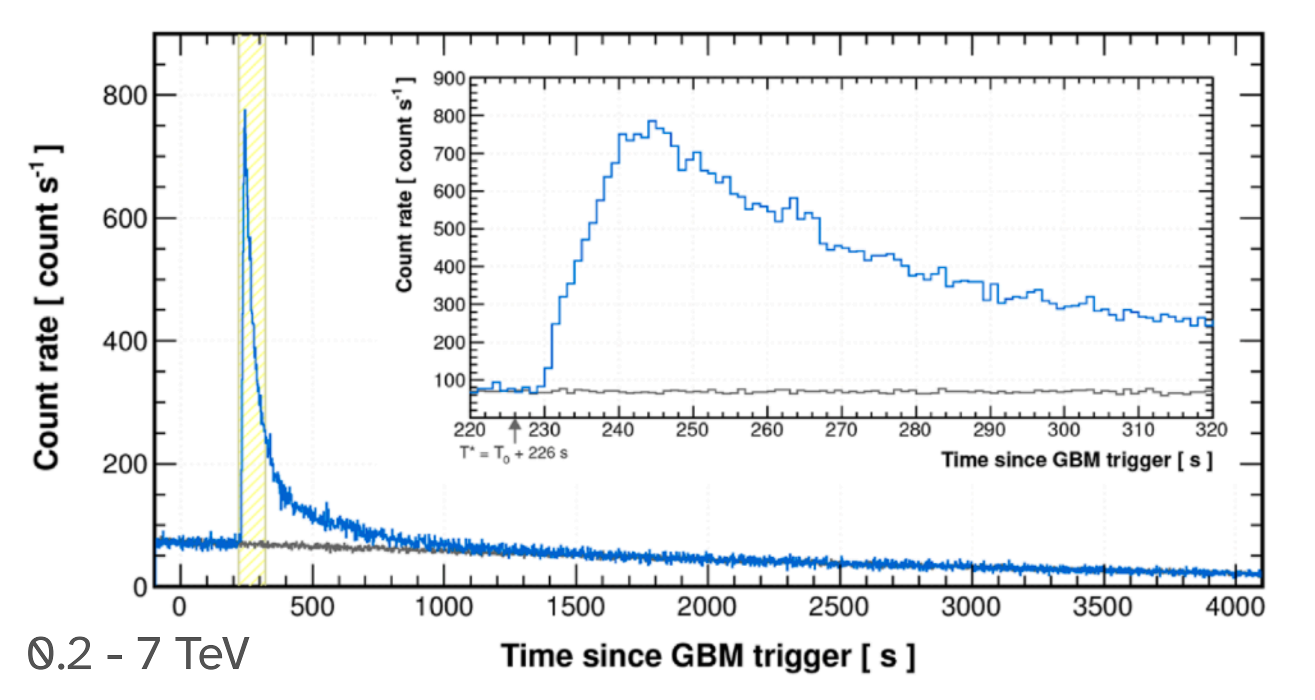
[Daniel R. Strebe]

GRB 221009A

the BOAT ("Brightest of All Time")

the record-breaking LHAASO detection

[LHAASO Collaboration, Science 380 (2023)]



[NASA's Goddard Space Flight Center]

GRB 221009A

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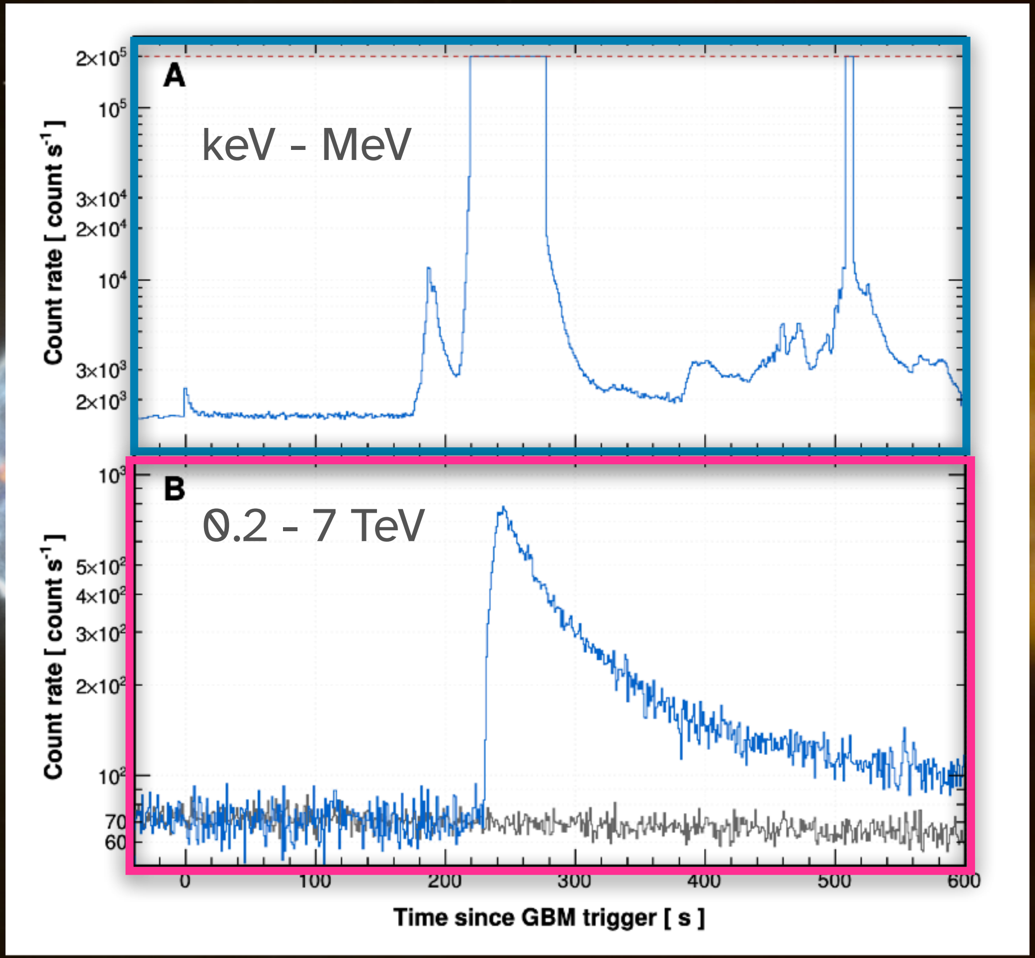
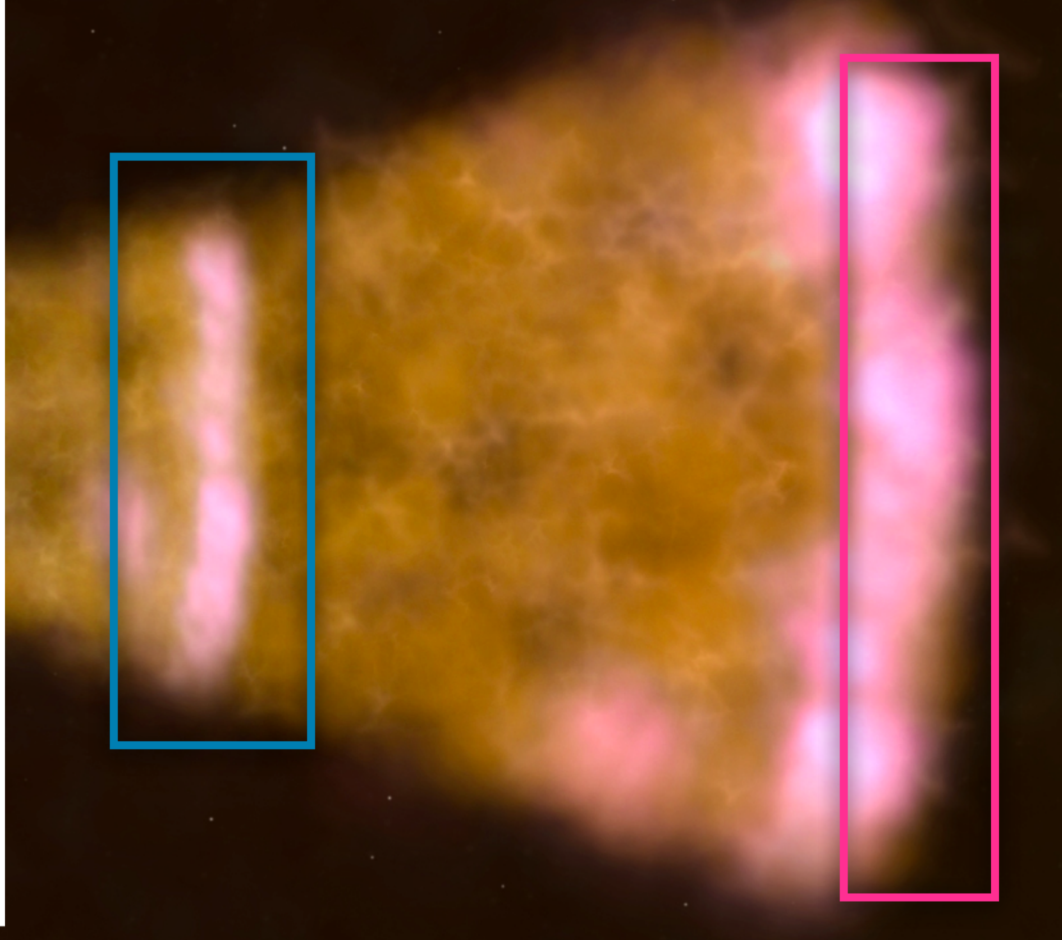


the record-breaking LHAASO detection

[LHAASO Collaboration, Science 380 (2023)]



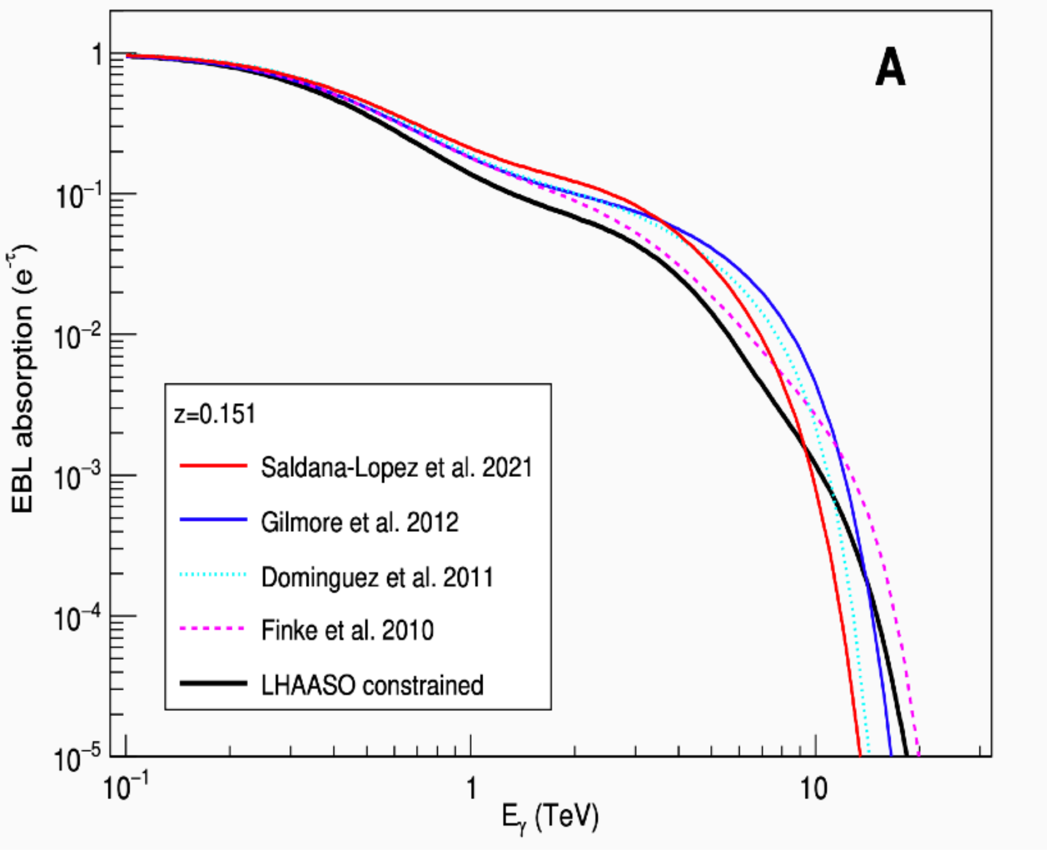
[NASA's Goddard Space Flight Center]

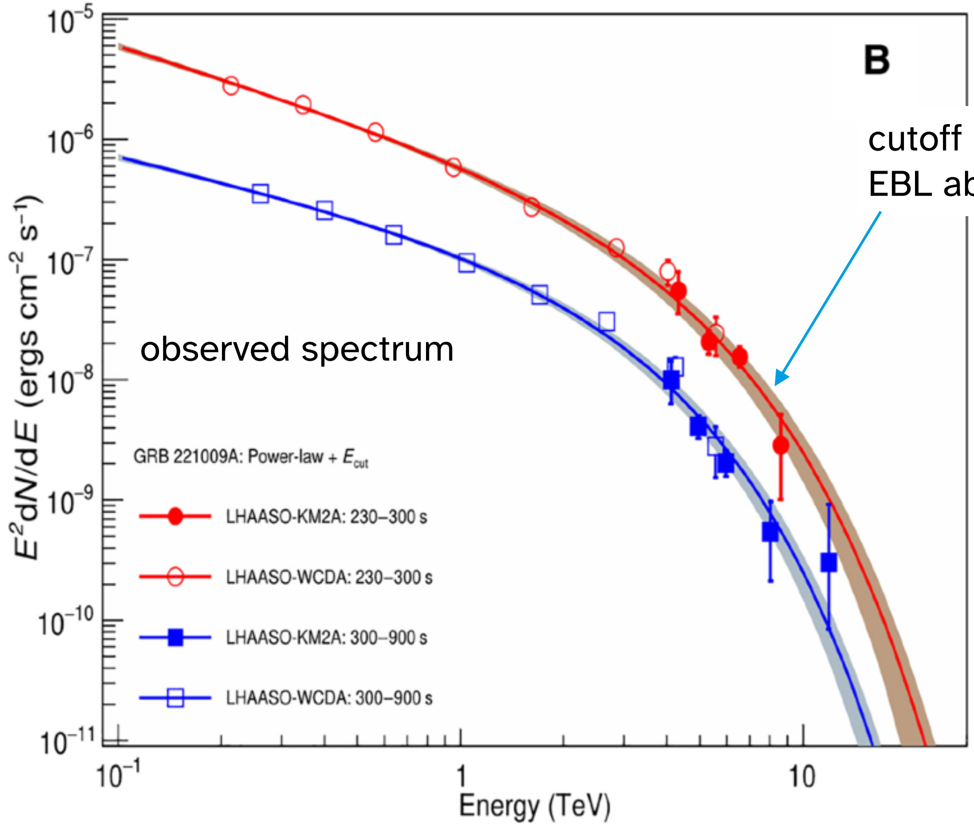
GRB 221009A

the BOAT ("Brightest of All Time")

For a redshift of 0.151, the EBL absorption has a large effect at E > 10 TeV
and the **uncertainty** in the EBL is also very important!

[Z. Cao et al., Science Advances 9 (2023)]





observed spectrum

cutoff attributed to EBL absorption

GRB 221009A

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For a redshift of 0.151, the EBL absorption has a large effect at E > 10 TeV
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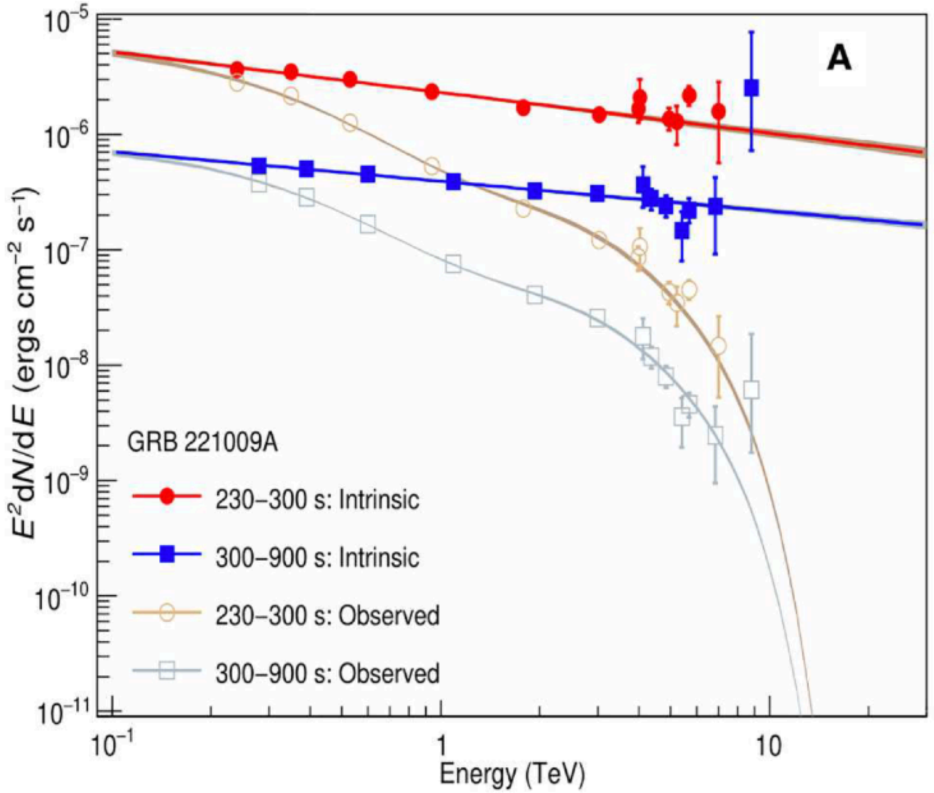
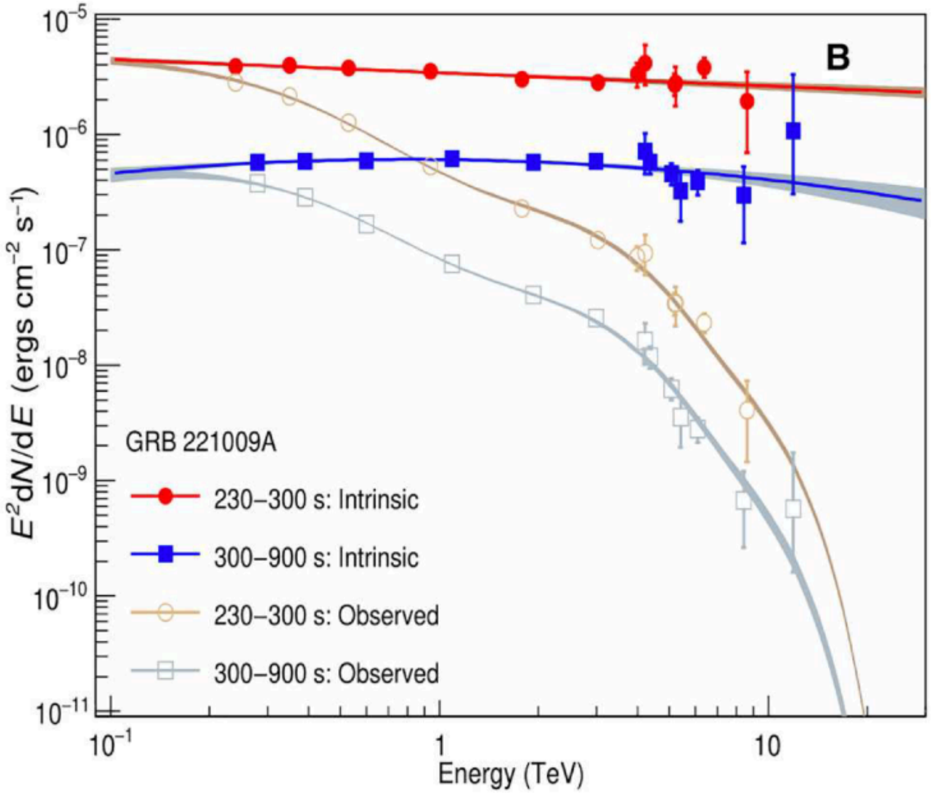
[Z. Cao et al., Science Advances 9 (2023)]

assuming an EBL model (Saldana-Lopez et al. 2021)



rescaling the EBL model at different wavelengths



GRB 221009A

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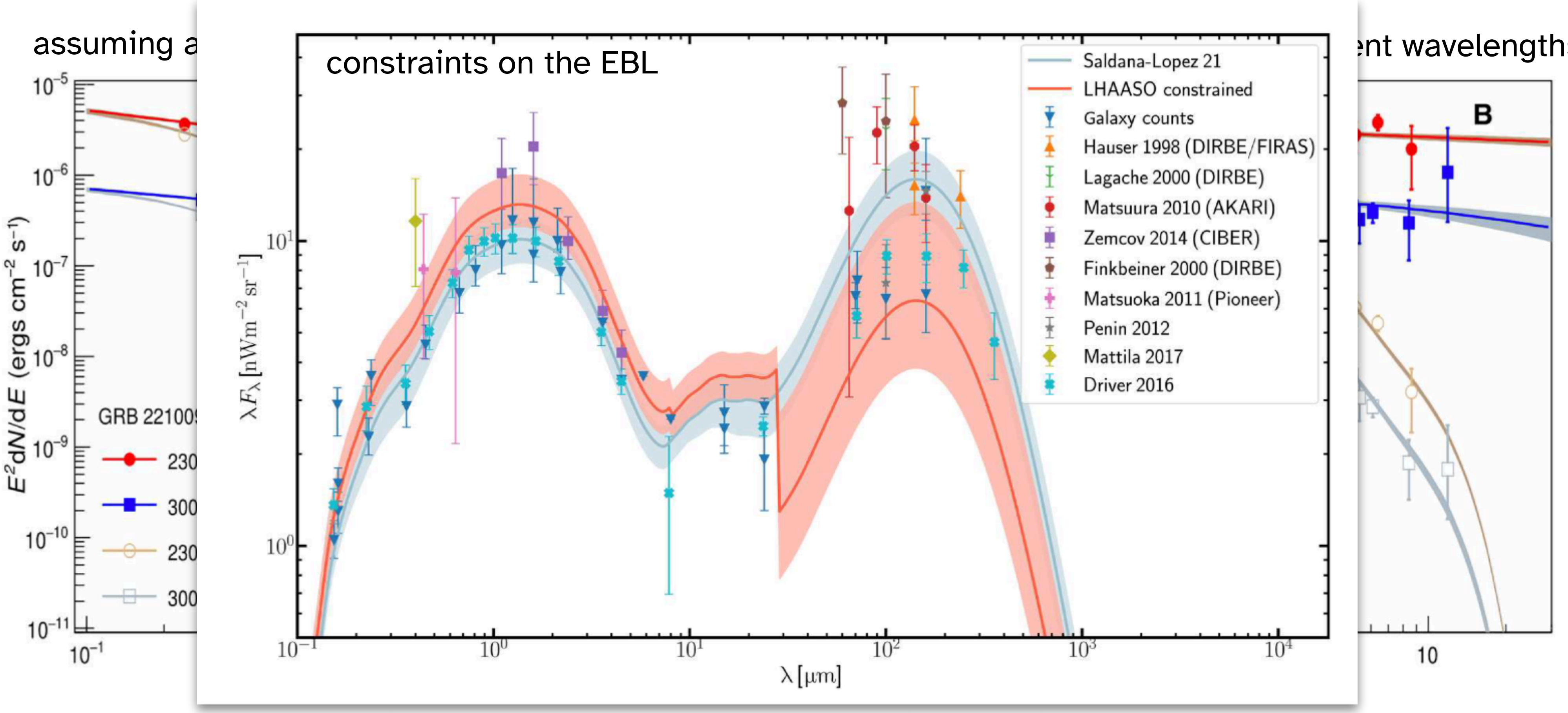
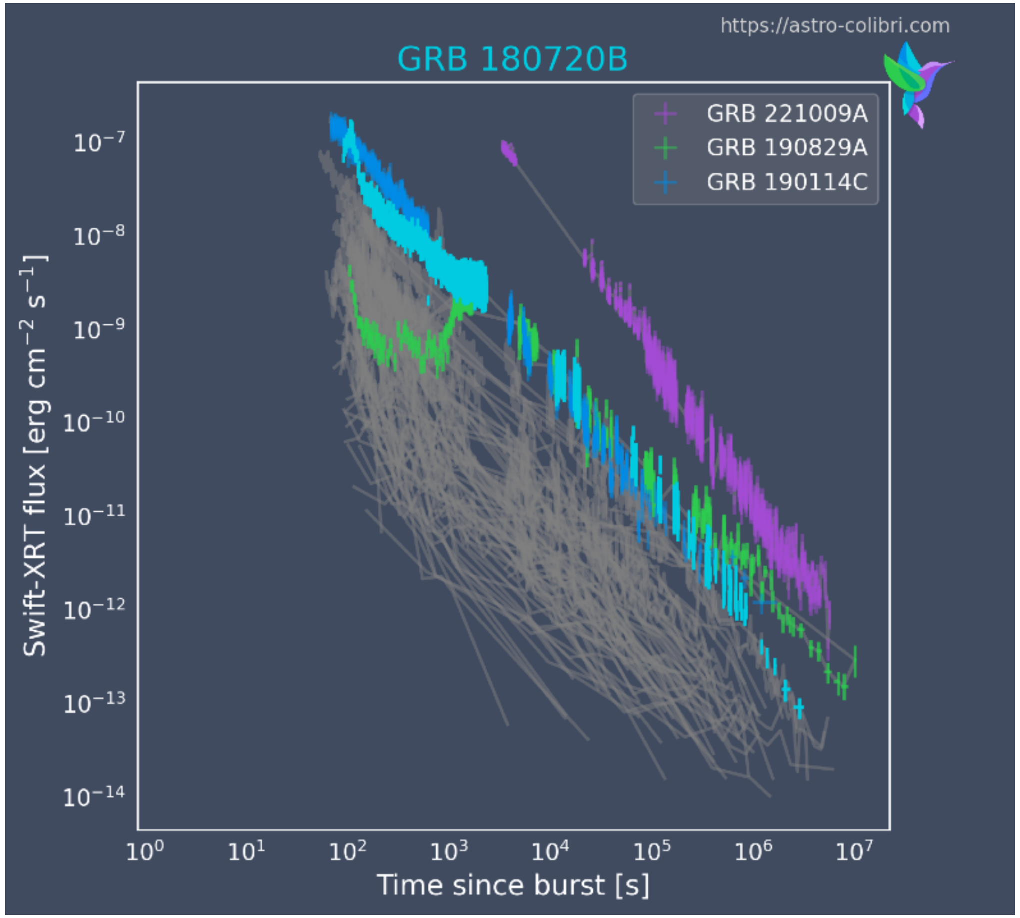


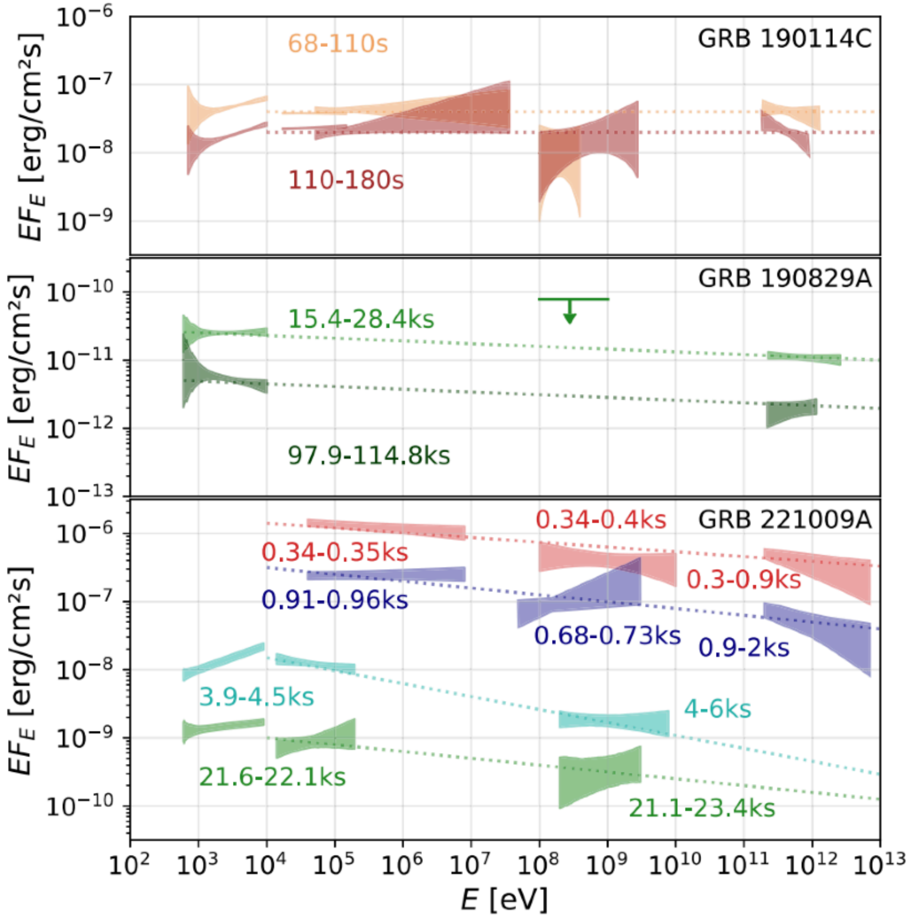
Gamma-ray bursts

Prospects for CTAO?

VHE GRBs seem to be X-ray bright



[M. Klinger et al., ApJ 977 (2024)]

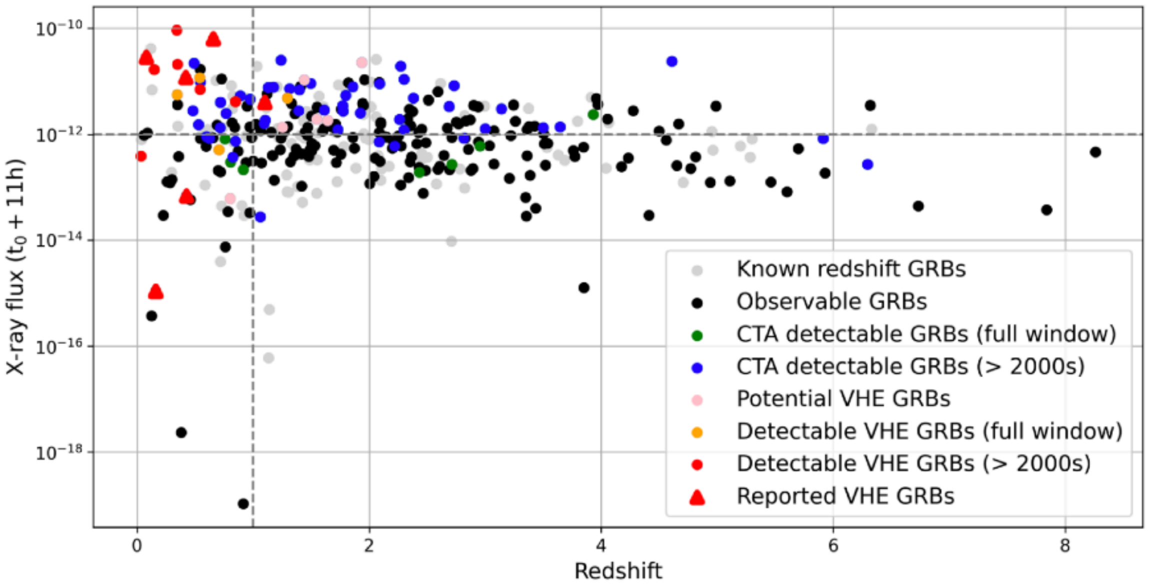


Gamma-ray bursts

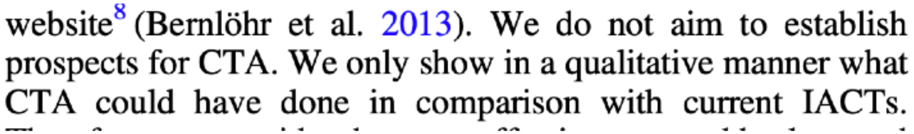
Prospects for CTAO?

Assuming a relation between X-ray and VHE emission, we can predict what would be detectable by CTAO

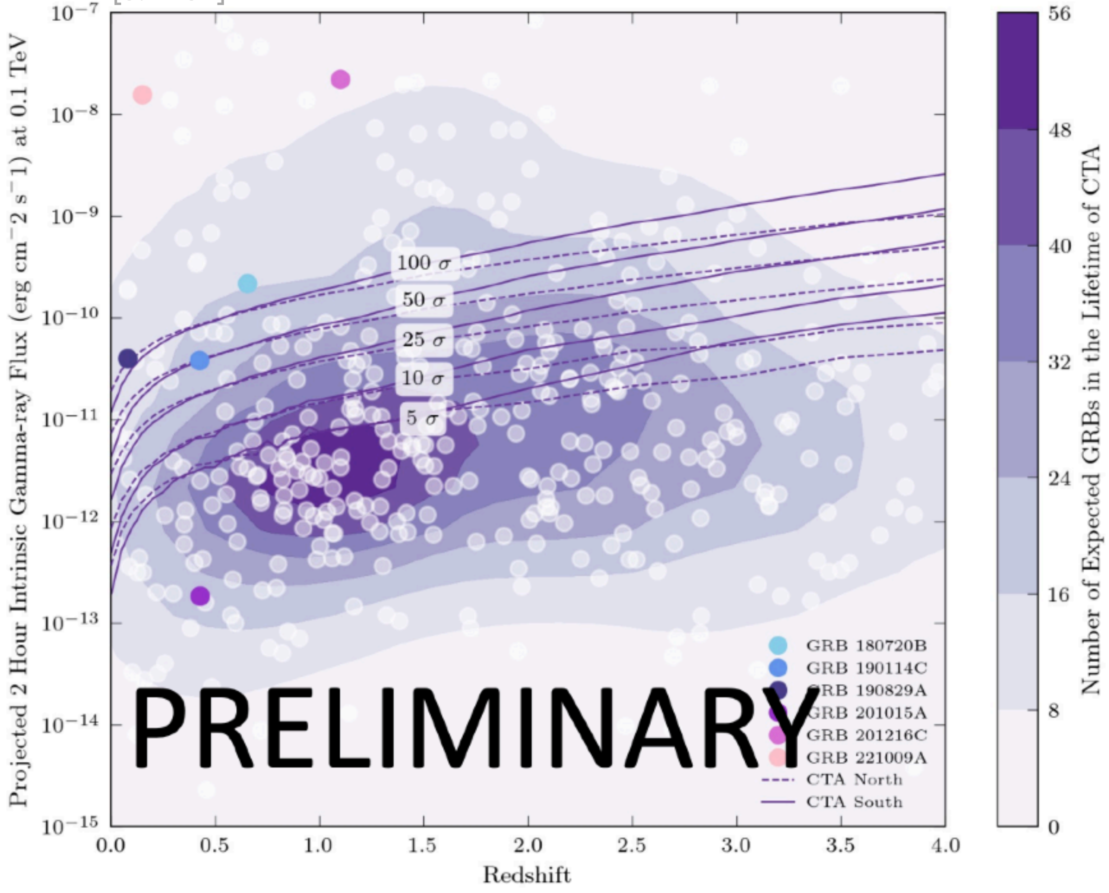
[H. Ashkar et al., ApJ 964 (2024)]



although:


website[8] (Bernlöhr et al. 2013). We do not aim to establish prospects for CTA. We only show in a qualitative manner what CTA could have done in comparison with current IACTs.

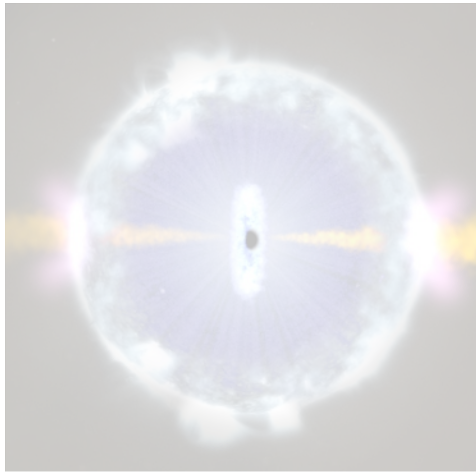
[J. Pfeil]



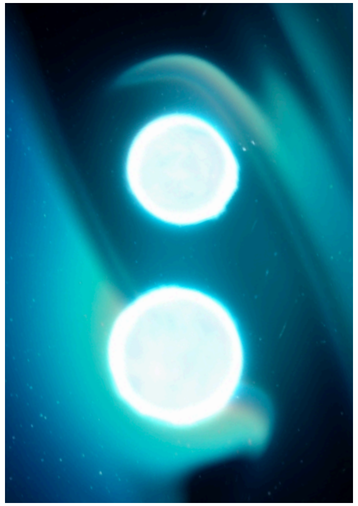
Gamma-ray bursts

What causes them?

[NASA's Goddard Space Flight Center]



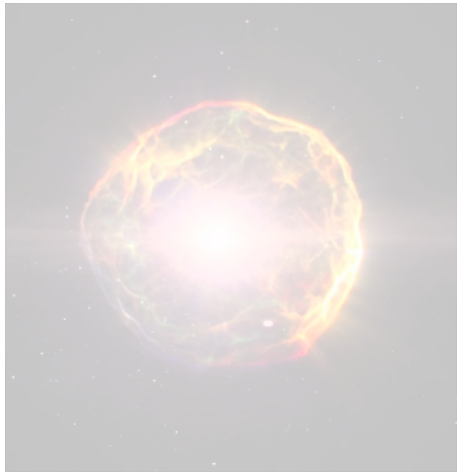
NASA's Goddard Space Flight Center/CI Lab



two neutron stars merge
(probably)

or

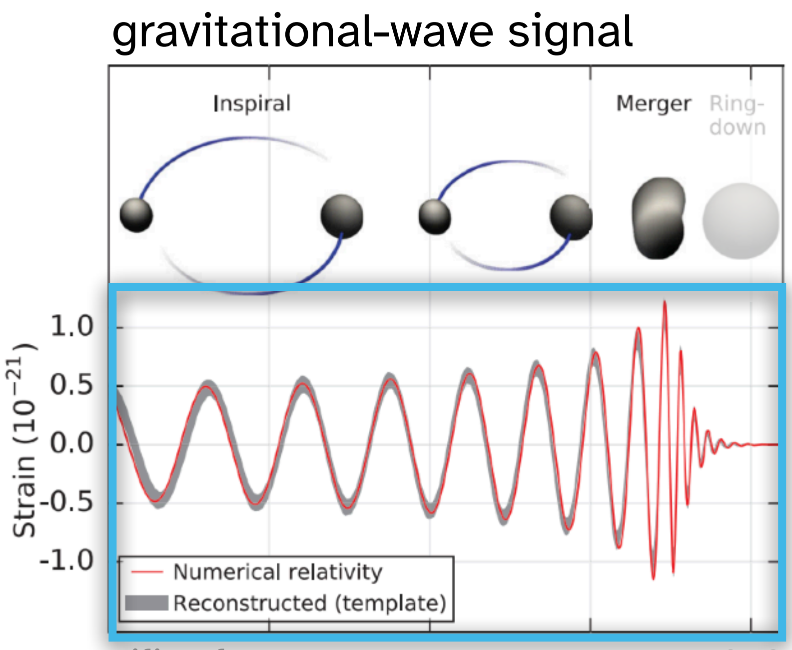
ESO/L. Calçada



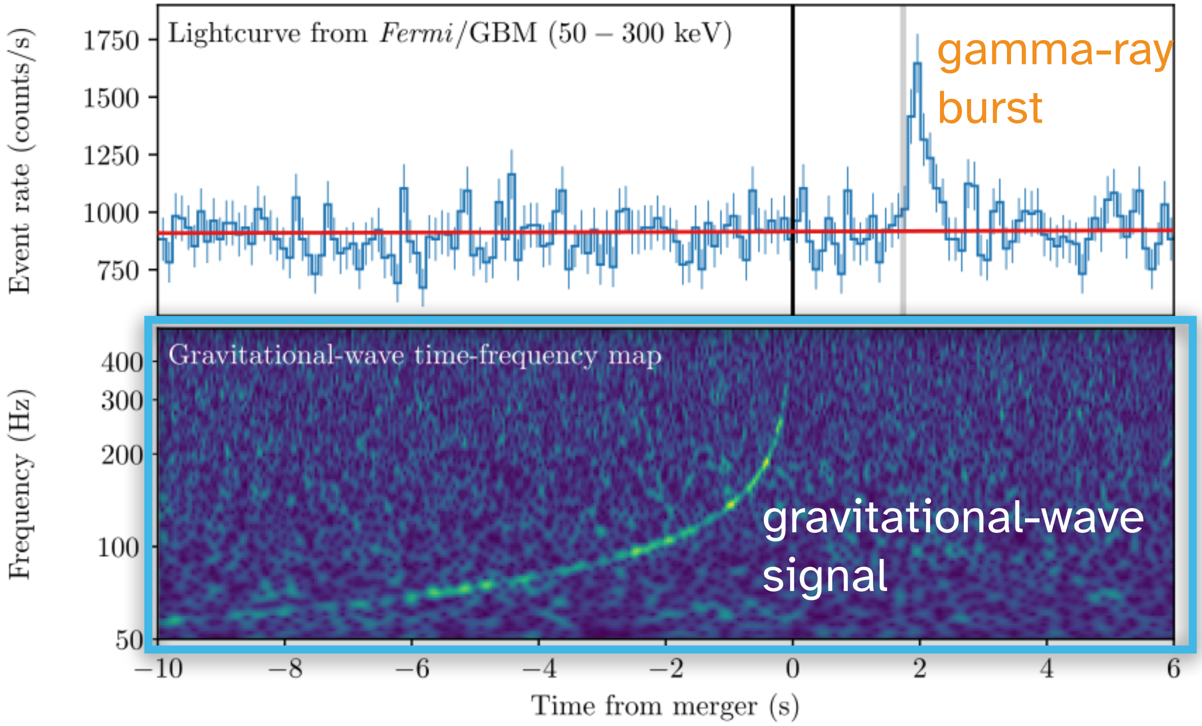
a massive star collapses

GW170817 + GRB 170817A

The only clear case (so far) of multimessenger detections of a neutron star merger



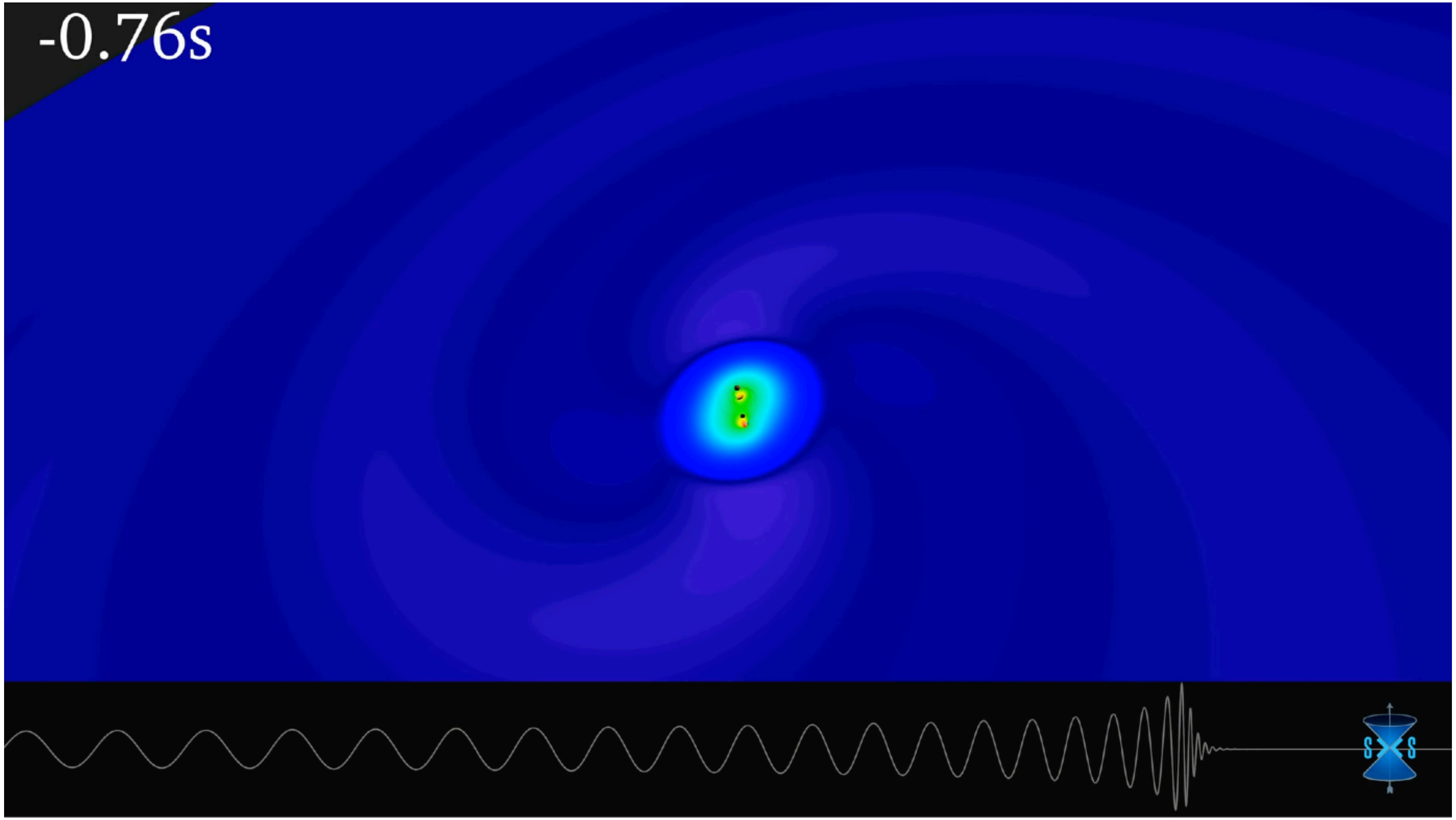
modified from [B. P. Abbott et al., PRL 116 (2016)]



modified from [B. P. Abbott et al., ApJL 848 (2017)]

Pause for gravitational waves

How do gravitational-waves interferometers work?

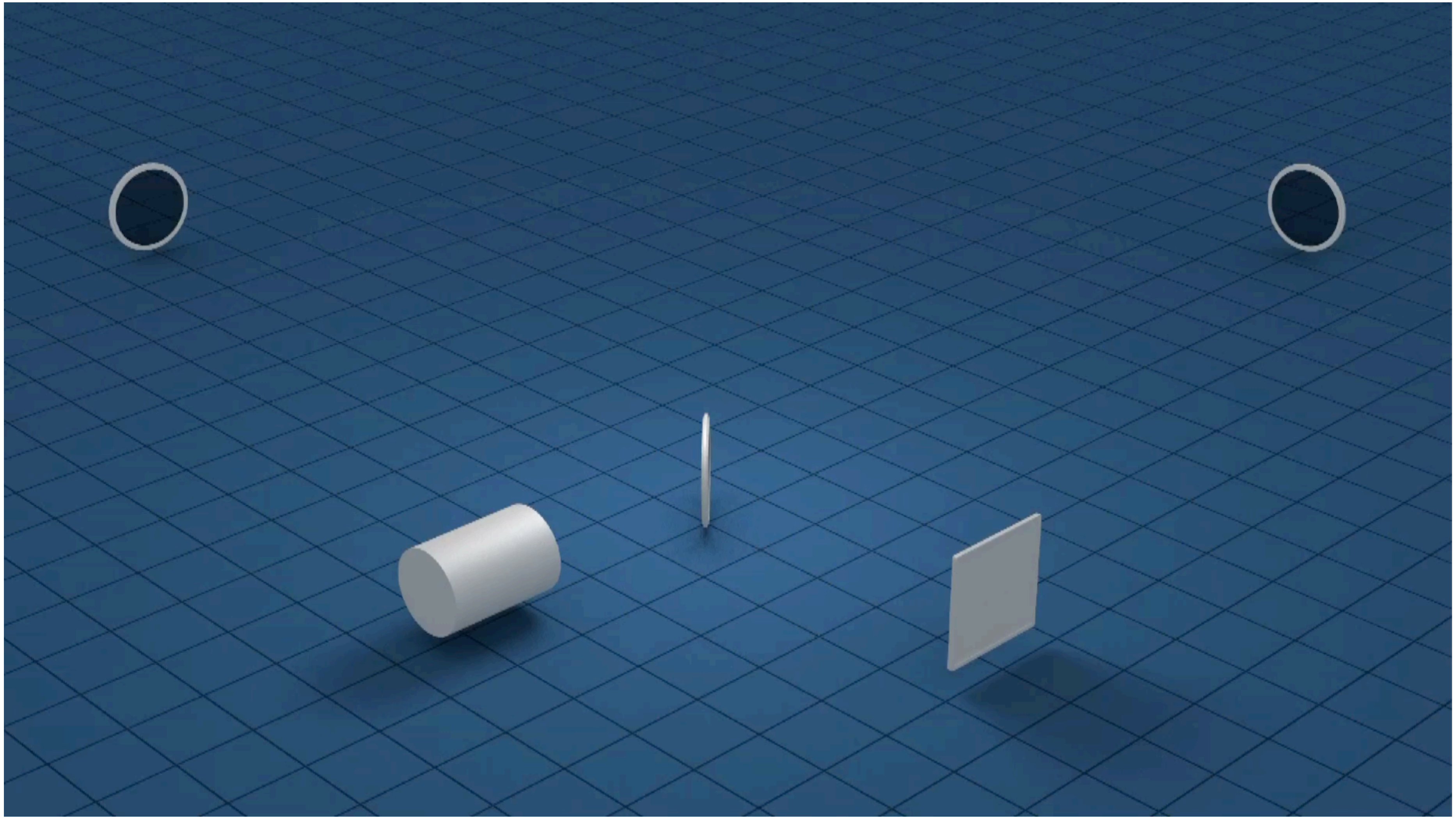


Animation created by SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes.org)
Video and explanation: https://www.ligo.caltech.edu/video/ligo20160211v10

Pause for gravitational waves

How do gravitational-waves interferometers work?

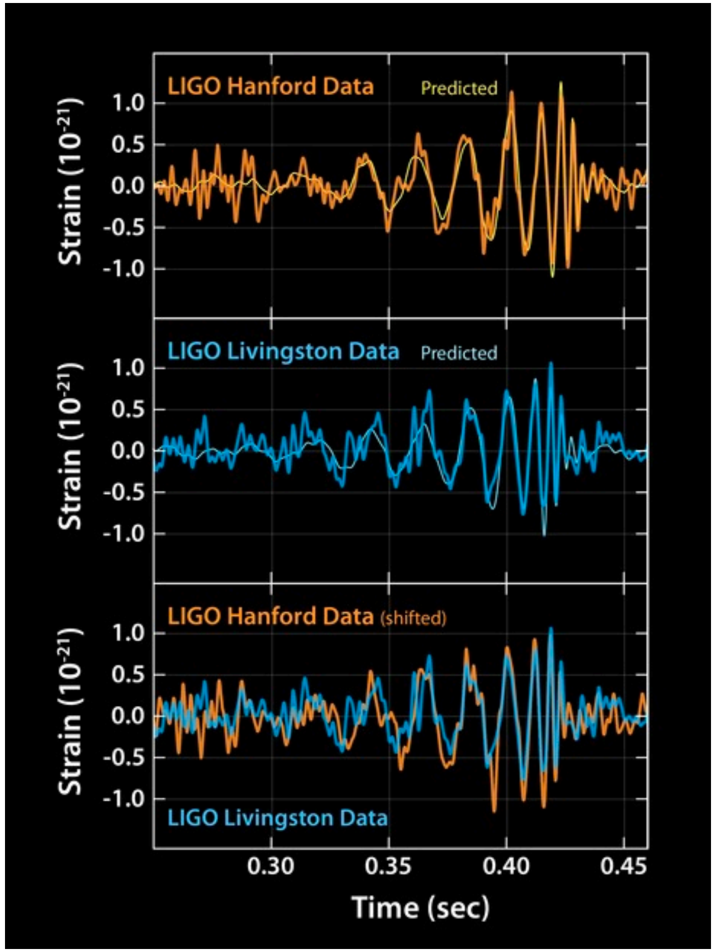
LIGO/T. Pyle



Pause for gravitational waves

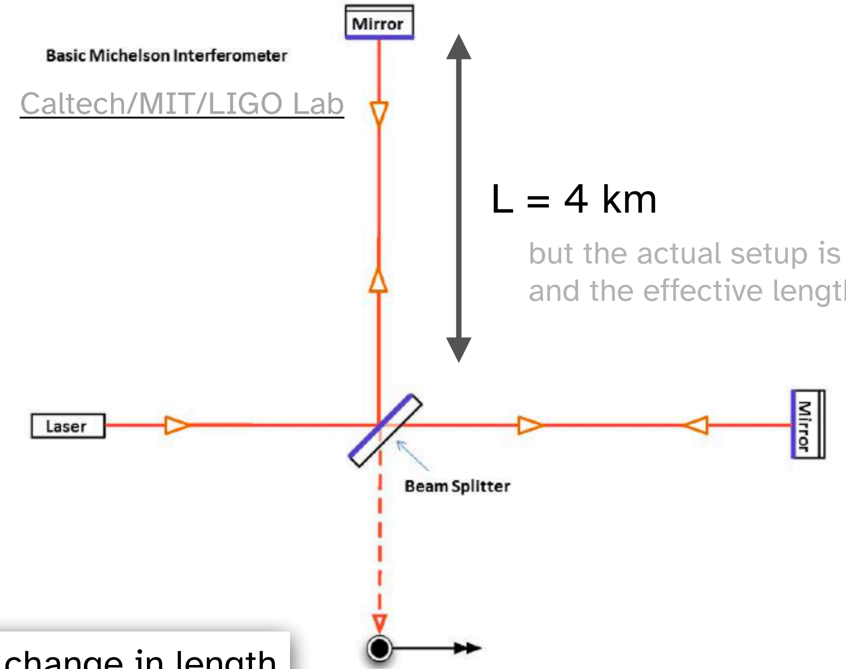
How do gravitational-waves interferometers work?

Caltech/MIT/LIGO Lab



Basic Michelson Interferometer

Caltech/MIT/LIGO Lab



L = 4 km

but the actual setup is more complicated than this, and the effective length is more like 1000 km

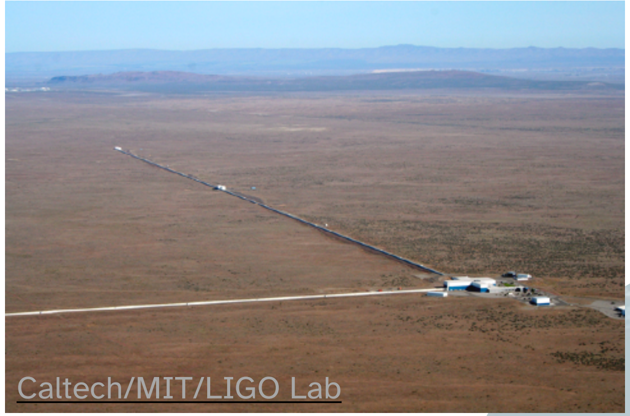
fractional change in length

$$h = \frac{\Delta L}{L} = 10^{-21} \quad \text{so} \quad \Delta L \sim 10^{-18}\ \text{m}$$

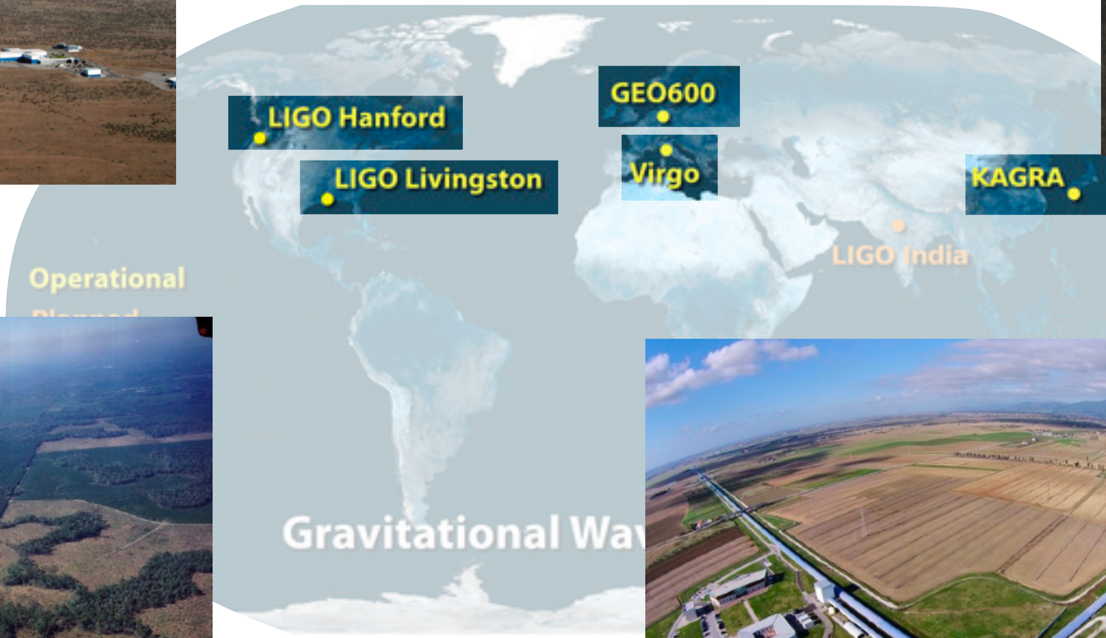
(in comparison, a proton radius is 10^{-15} m)

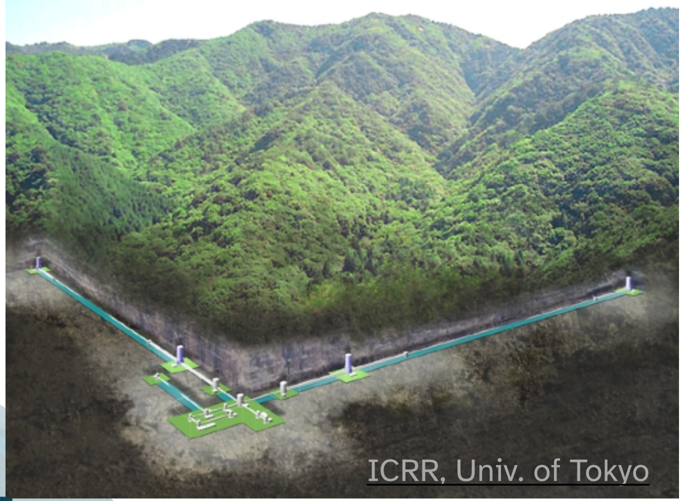
Pause for gravitational waves

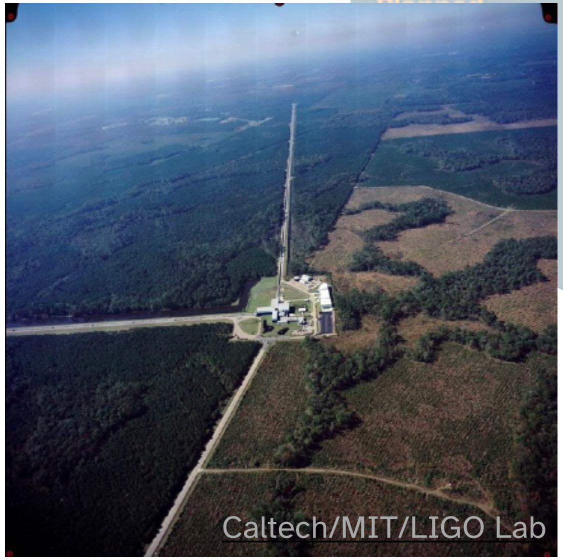
The network of GW interferometers



Caltech/MIT/LIGO Lab



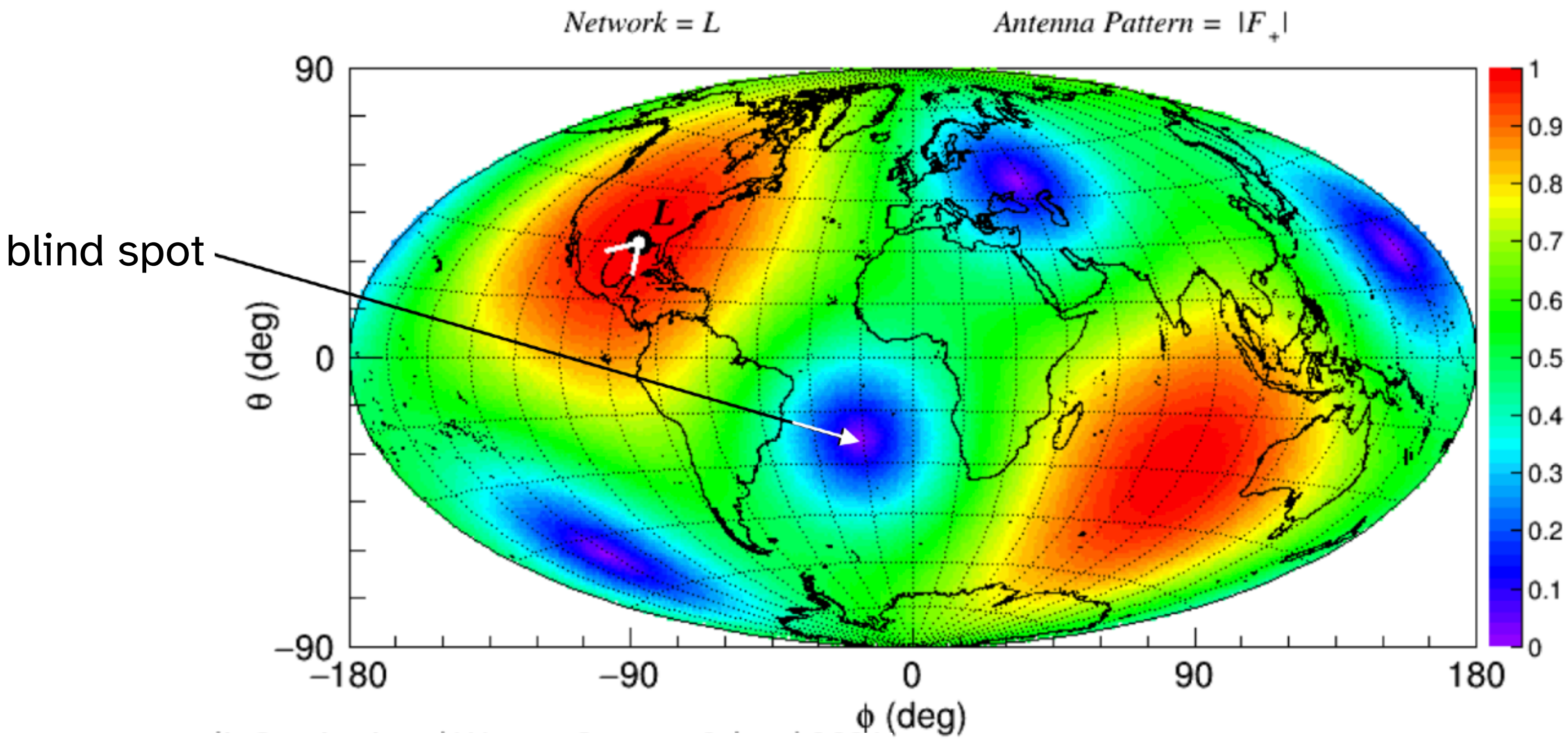




Pause for gravitational waves

Why are GW localizations so uncertain?

GW interferometers individually have very poor localization capabilities



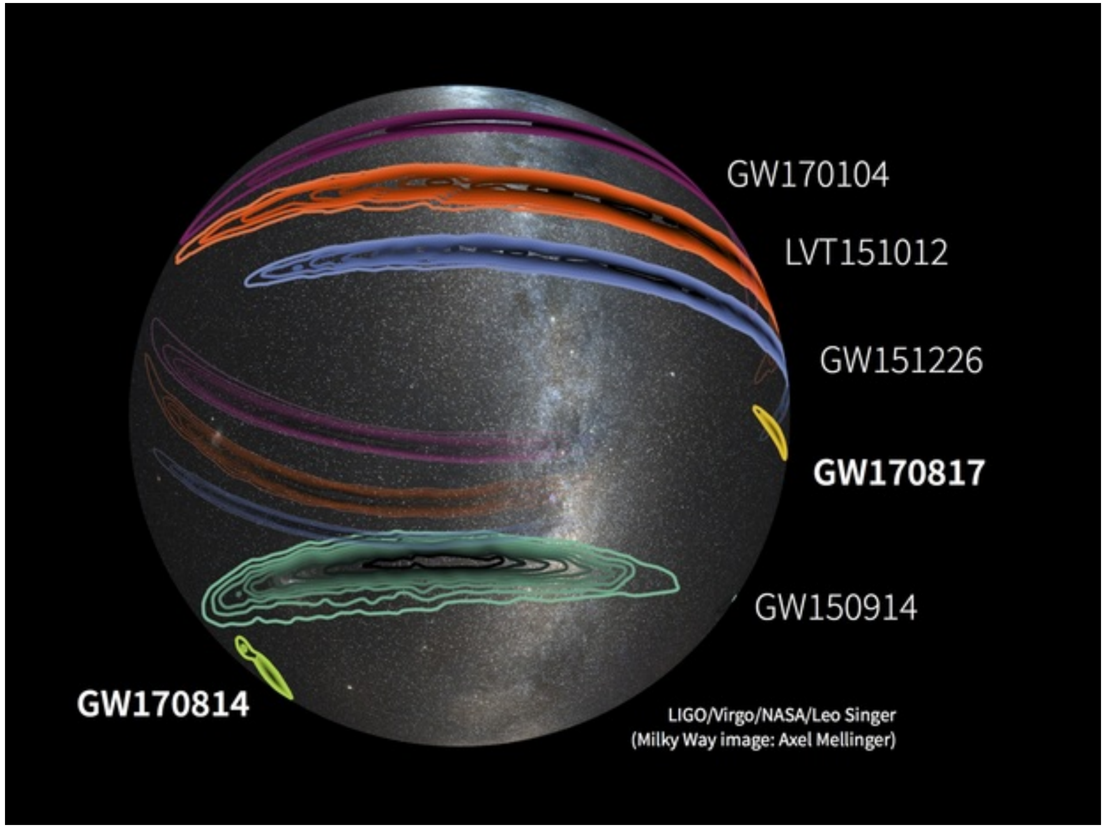
[G. A. Pronti, Otranto School 2021]

Pause for gravitational waves

Why are GW localizations so uncertain?

GW interferometers individually have very poor localization capabilities

Detection by …	localization is …
single detector	~all sky
two detectors	bananas
three+ detectors	manageable

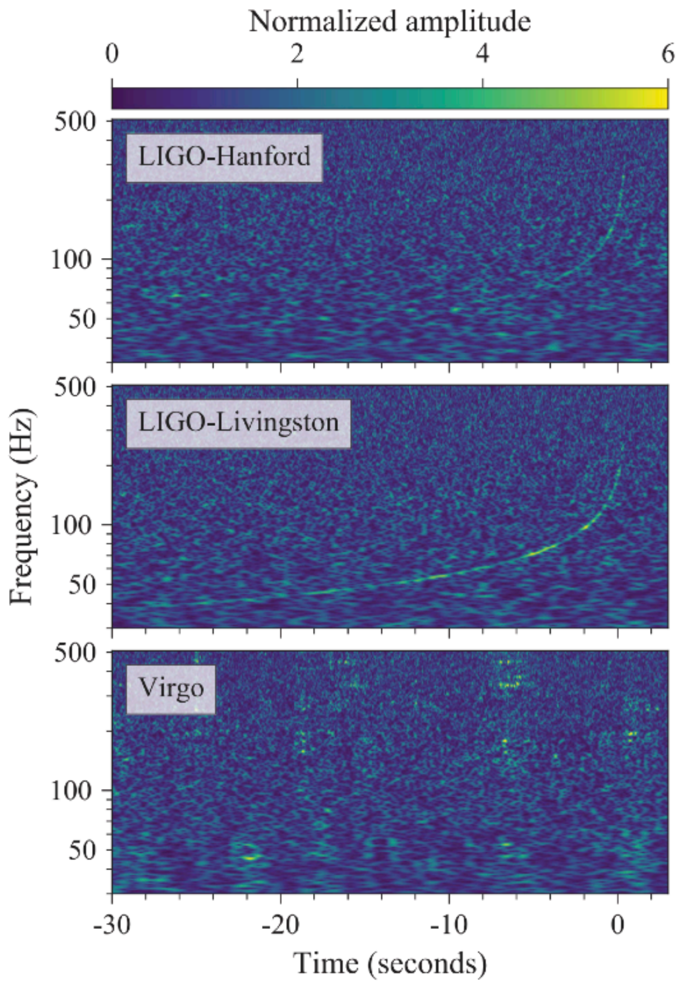


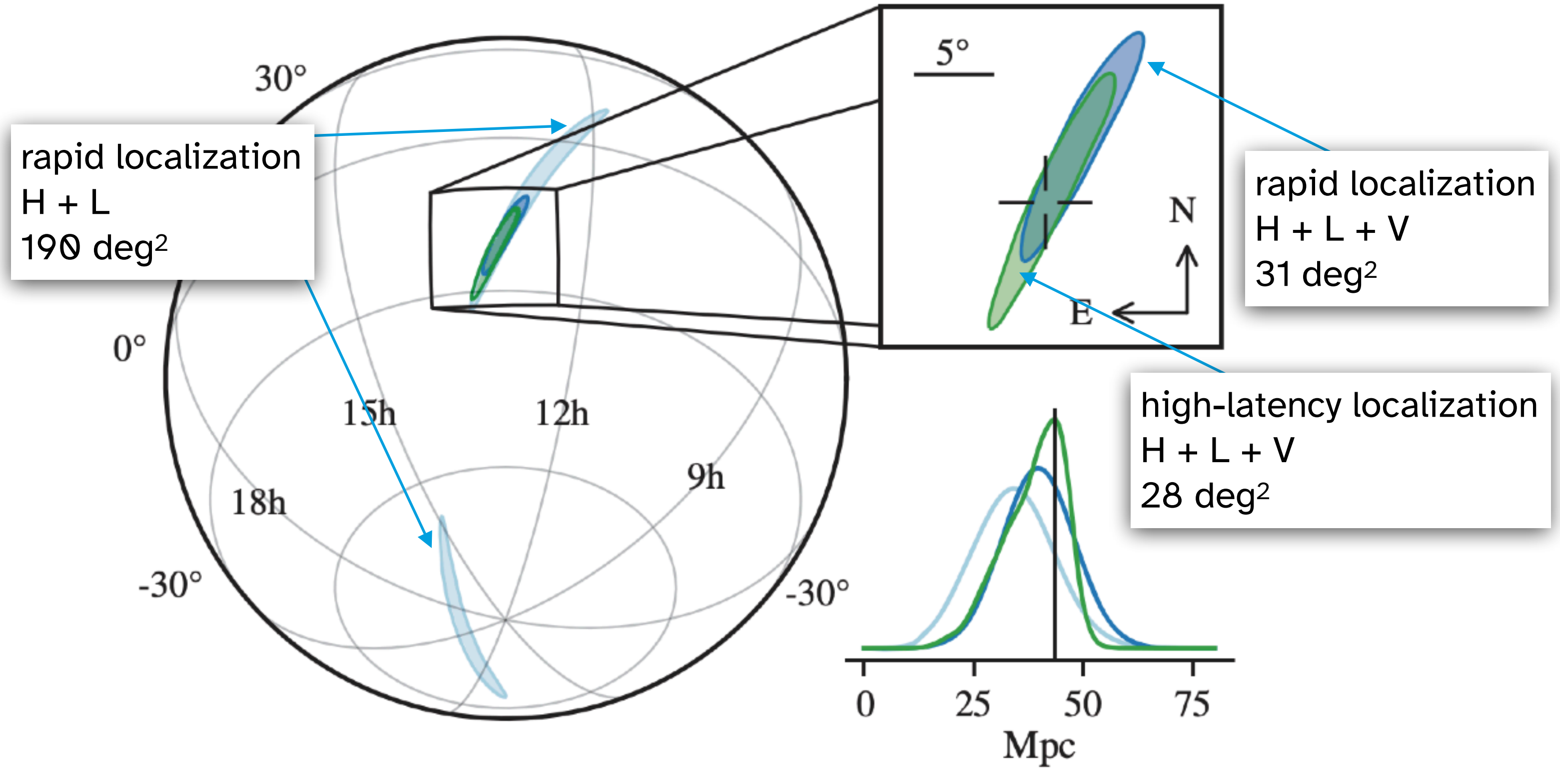
[LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)]

GW170817

GW 170817 was ~detected by three GW interferometers

[B. P. Abbott et al., PRL 119 (2017)]





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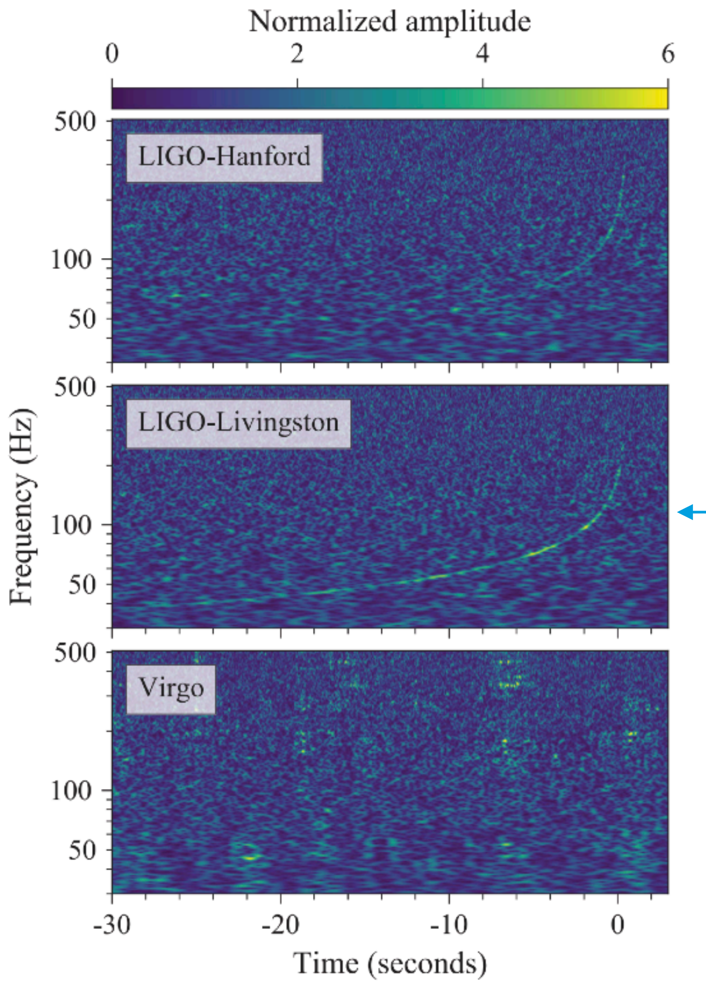
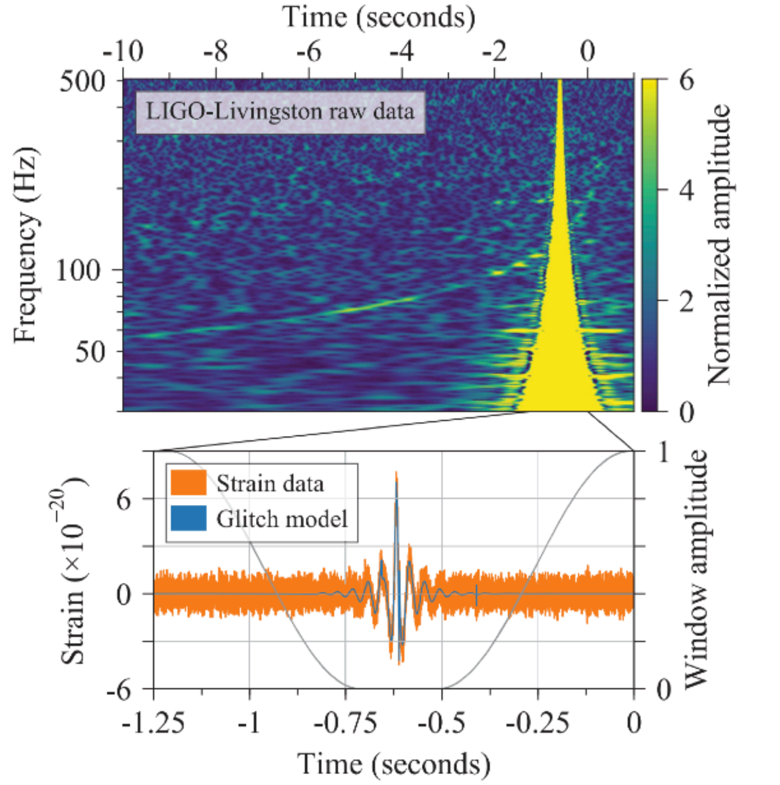
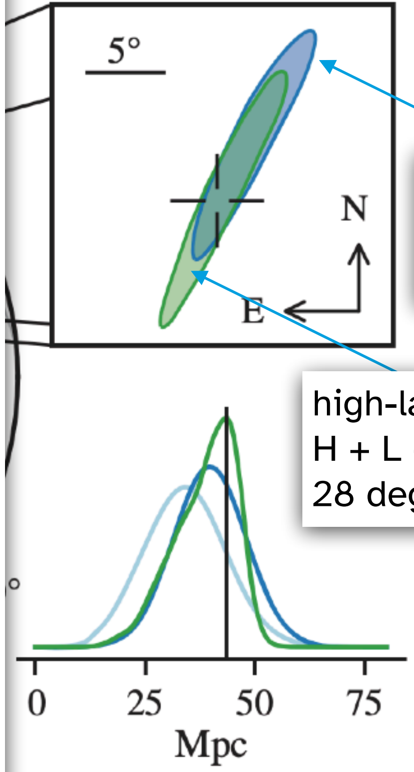




glitch had to be subtracted from Livingston data



rapid localization
H + L + V
31 deg^2

high-latency localization
H + L + V
28 deg^2

GW170817 + GRB 170817A

The only clear case (so far) of multimessenger detections of a neutron star merger

[GCNs]

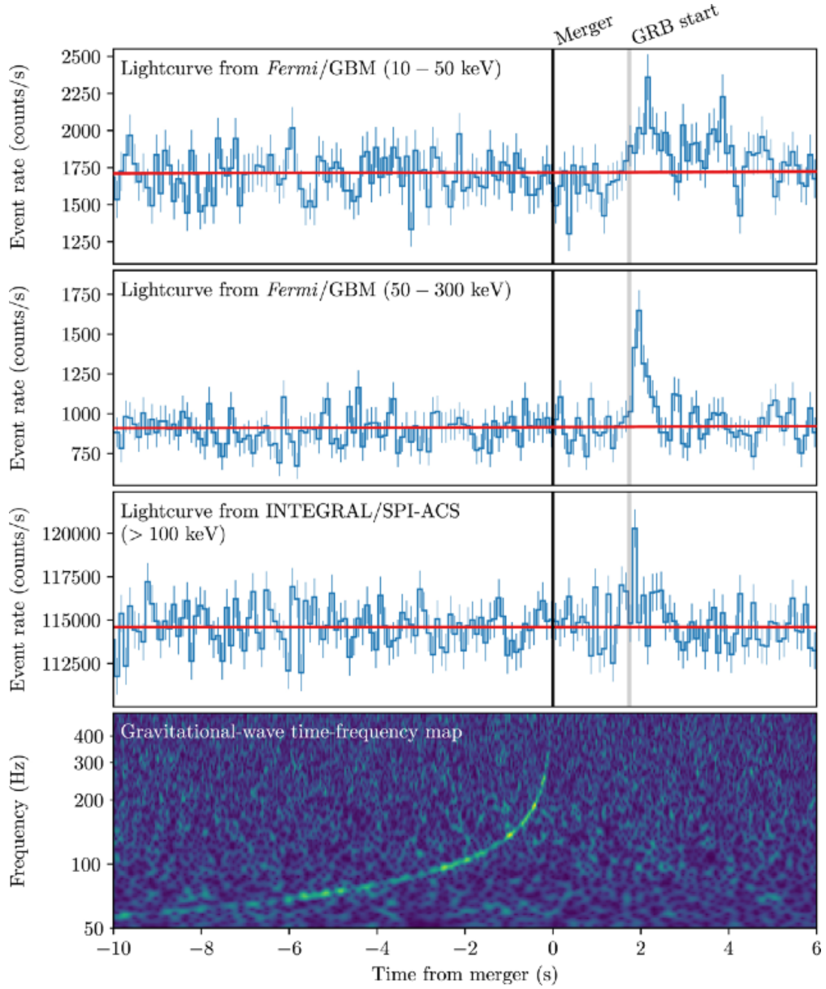
```
//////////////////////////////////////////////////////////////////////
TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: LIGO/Virgo G298048: Fermi GBM trigger 524666471/170817529: LIGO/Virgo
Identification of a possible  gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT  <ressick@mit.edu>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary
identification of a GW candidate associated with the time
 of Fermi GBM trigger 524666471/170817529 at gps time 1187008884.47
 (Thu Aug 17 12:41:06 GMT 2017) with RA=186.62deg Dec=-48.84deg and an error radius of
17.45deg.

The candidate is consistent with a neutron star binary coalescence with
False Alarm Rate of ~1/10,000 years.

An offline analysis is ongoing. Any significant updates will be provided
by a new Circular.
```

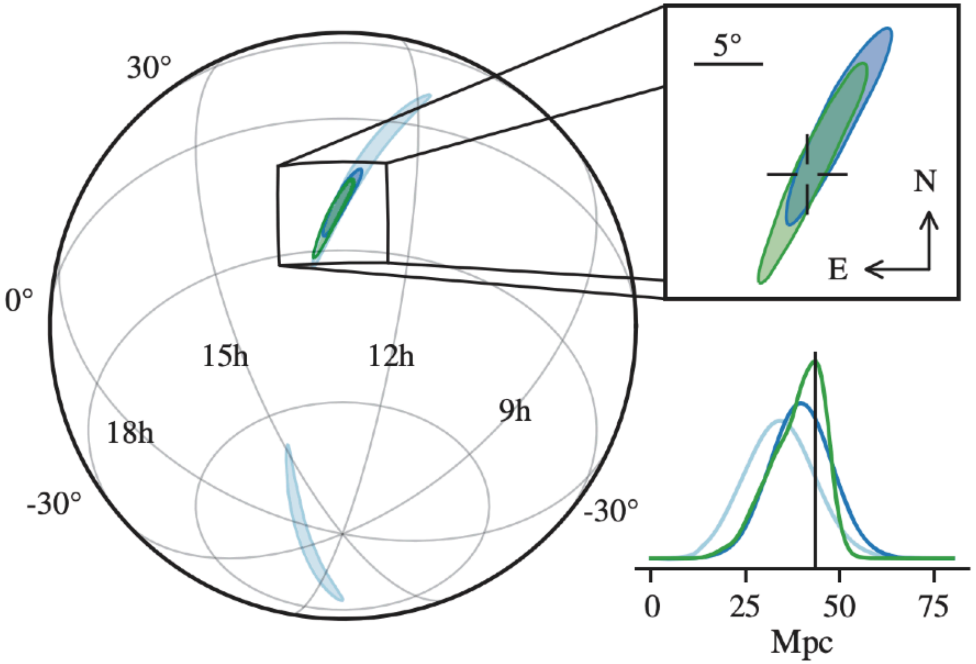


[B. P. Abbott et al., ApJL 848 (2017)]

GW170817 localization

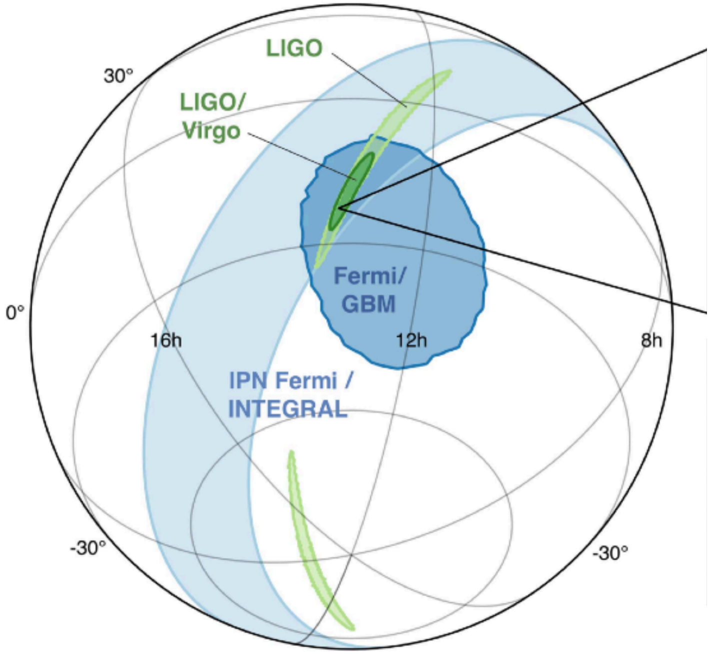
Adding the electromagnetic detections

GW-only localization



[B. P. Abbott et al., PRL 119 (2017)]

GW+GRB localization

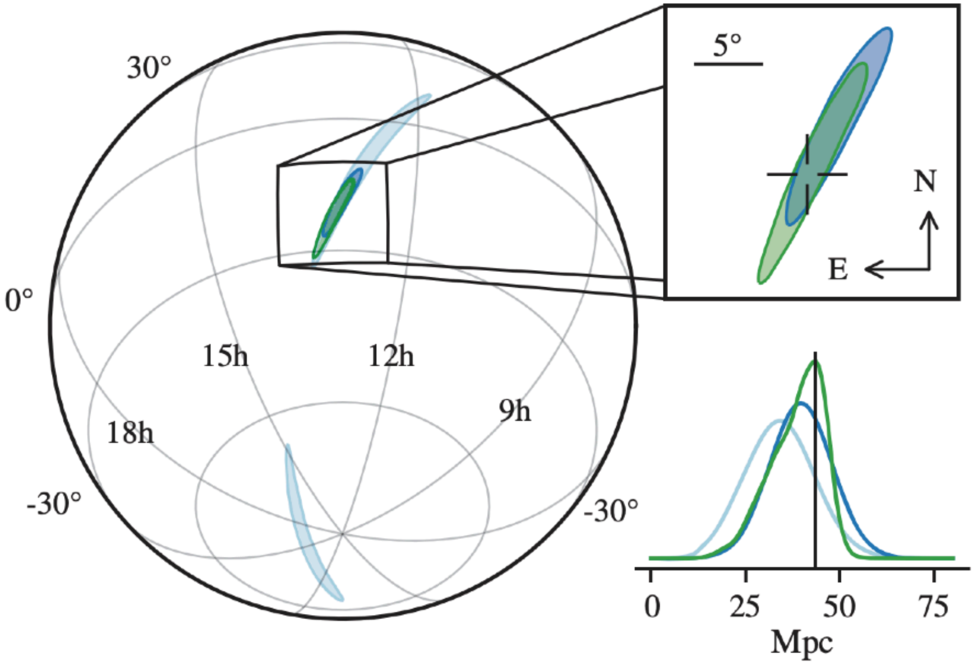


[B. P. Abbott et al., ApJL 848 (2017)]

GW170817 localization

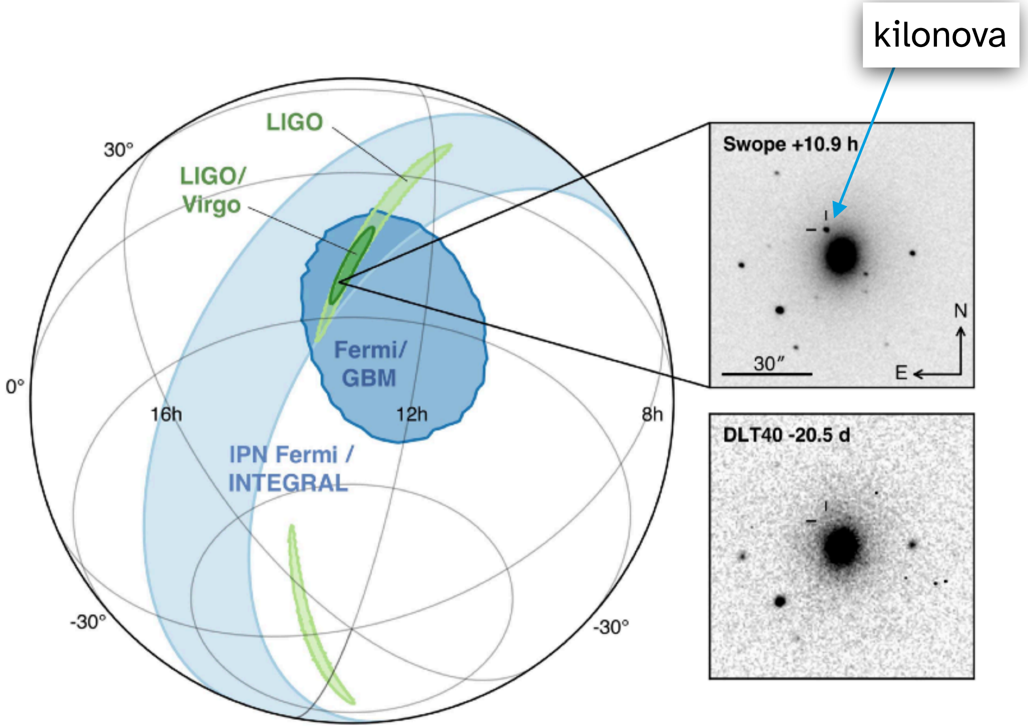
Adding the electromagnetic detections

GW-only localization



[B. P. Abbott et al., PRL 119 (2017)]

GW+GRB localization

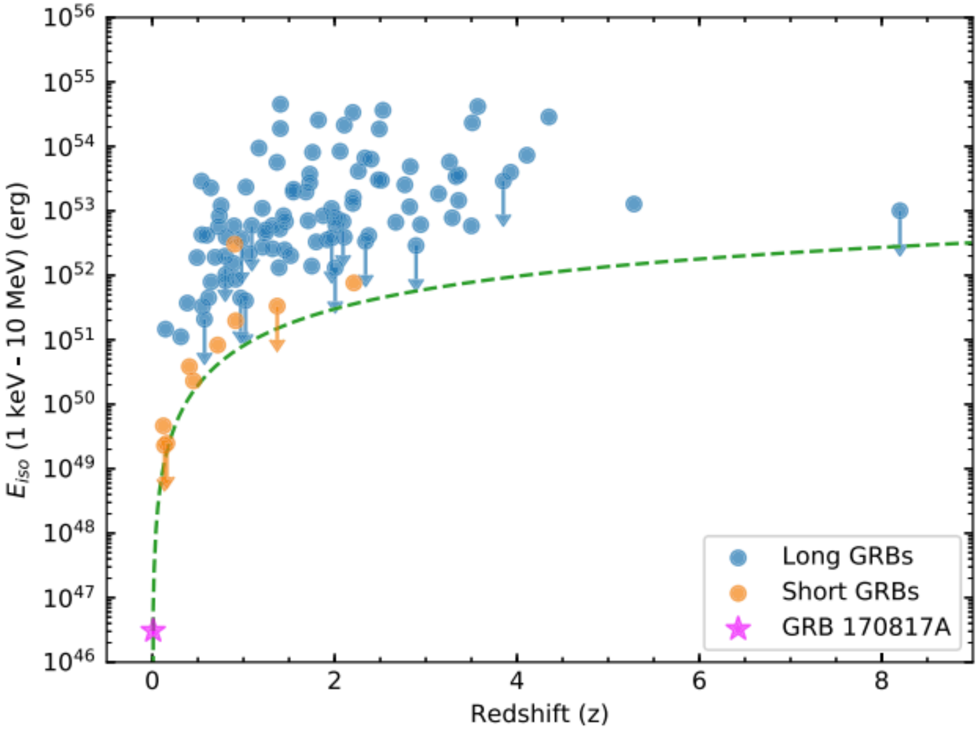


[B. P. Abbott et al., ApJL 848 (2017)]

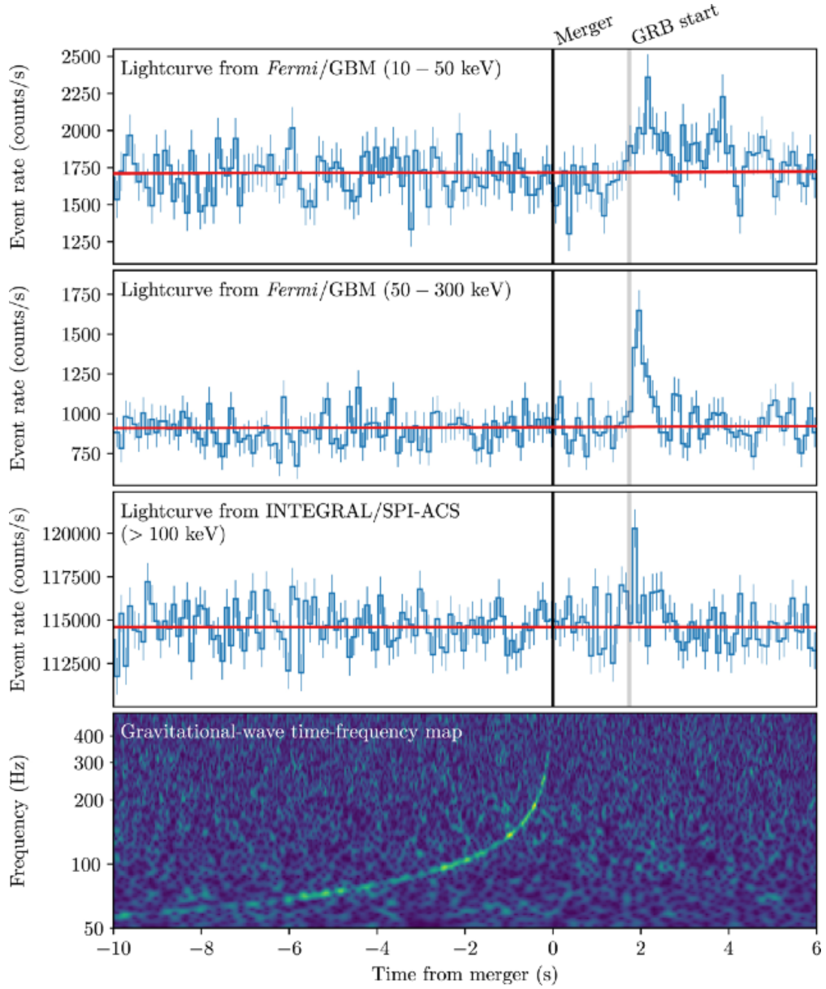
GW170817 + GRB 170817A

The only clear case (so far) of multimessenger detections of a neutron star merger

Very close, but very small energy output?



[B. P. Abbott et al., ApJL 848 (2017)]

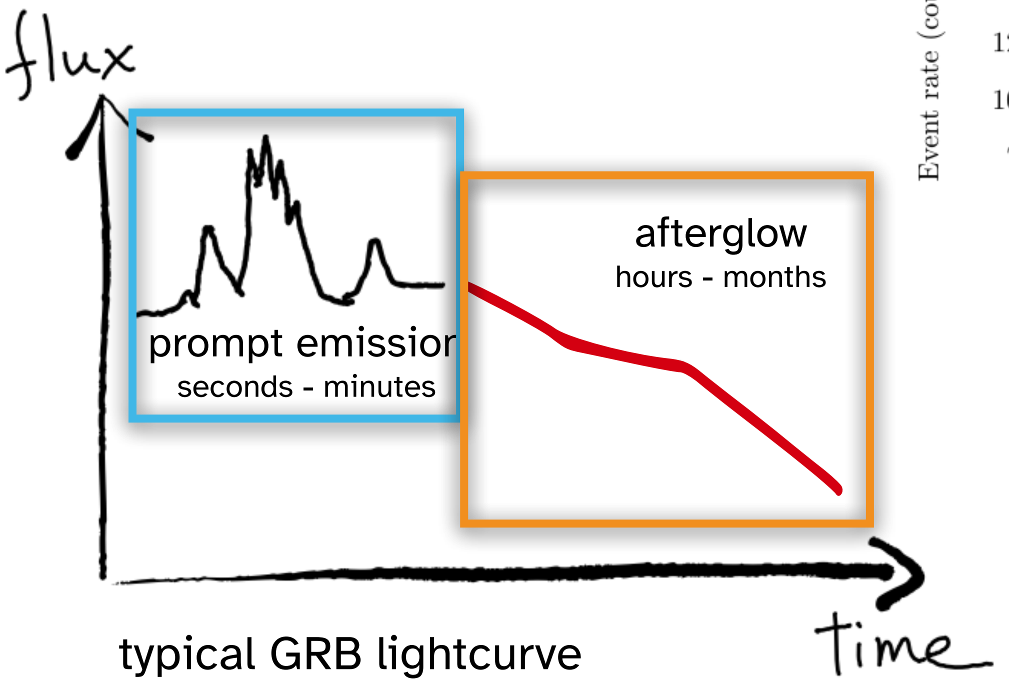


[B. P. Abbott et al., ApJL 848 (2017)]

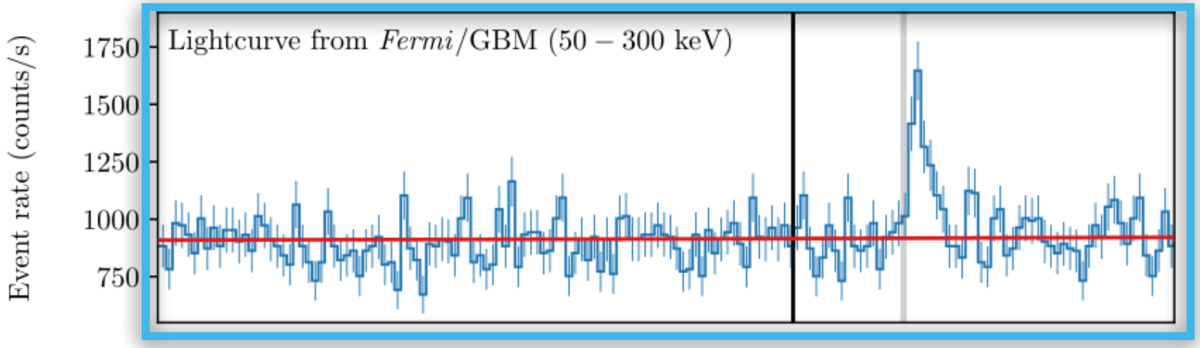
GW170817 + GRB 170817A

The only clear case (so far) of multimessenger detections of a neutron star merger

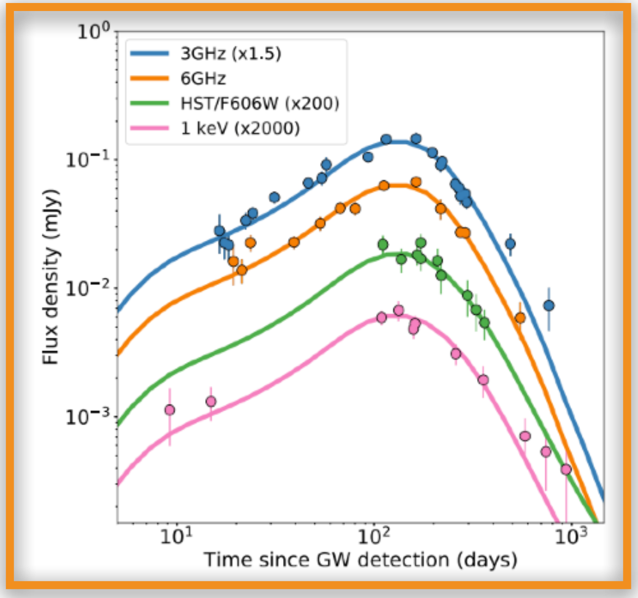
The lightcurves were odd when compared to the rest of the GRB population



typical GRB lightcurve



[B. P. Abbott et al., ApJL 848 (2017)]



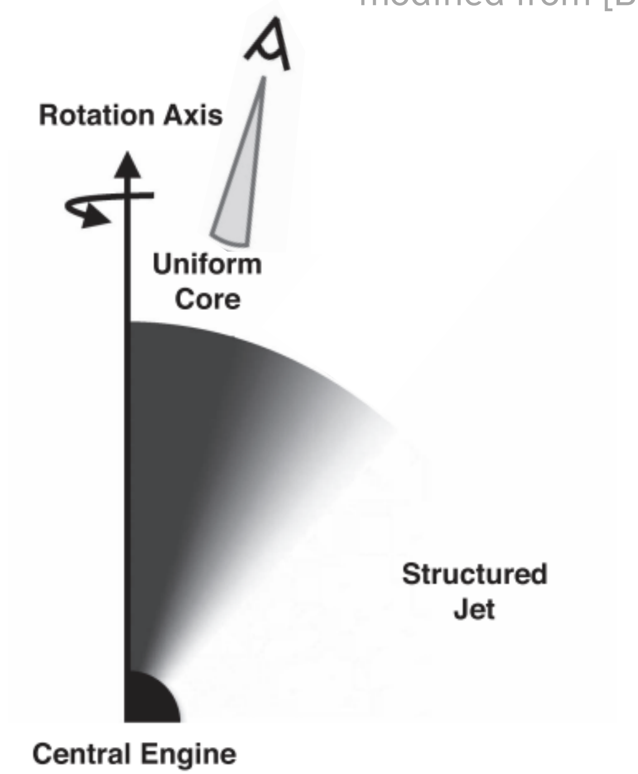
[S. Makhathini et al., ApJ 922 (2021)]

GW170817 + GRB 170817A

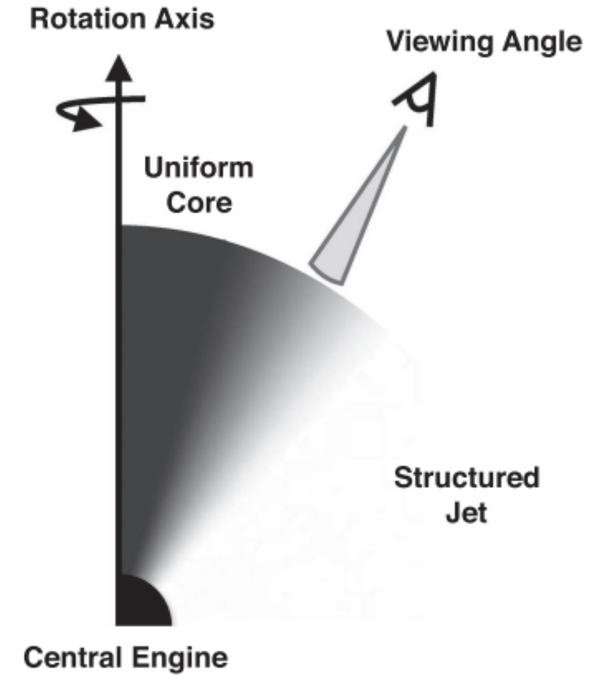
an off-axis GRB

Explanation: We were observing a GRB from outside of the (core of the) jet

modified from [B. P. Abbott et al., ApJL 848 (2017)]



most GRBs are observed on-axis

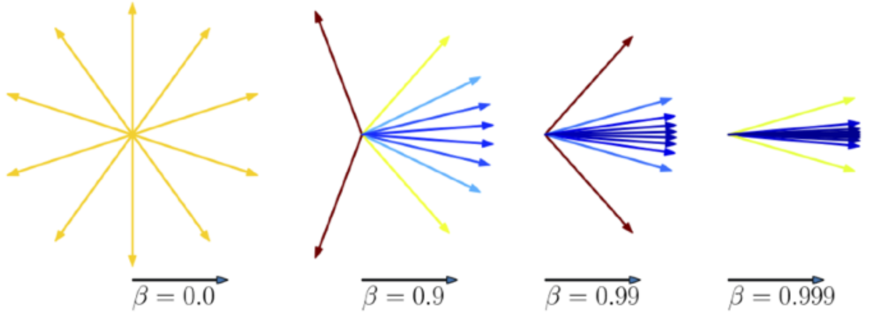


GRB 170817A was observed off-axis

“standard” GRBs

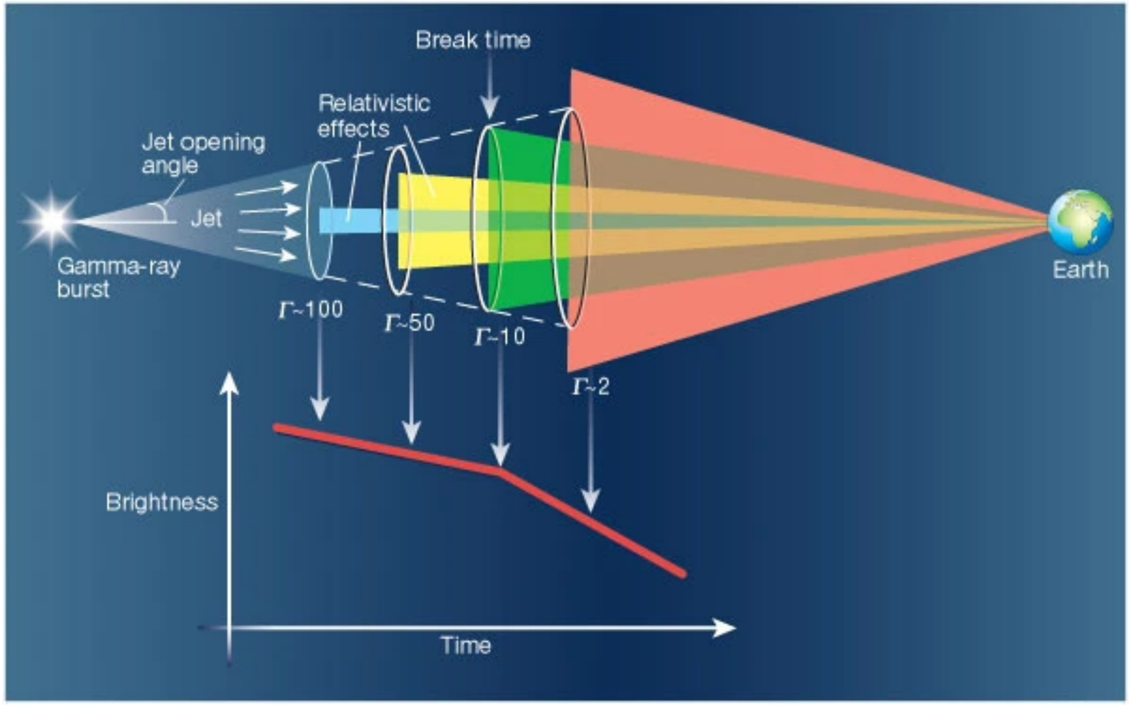
on-axis

[D. C. Bailey]



GRB emission is relativistically beamed

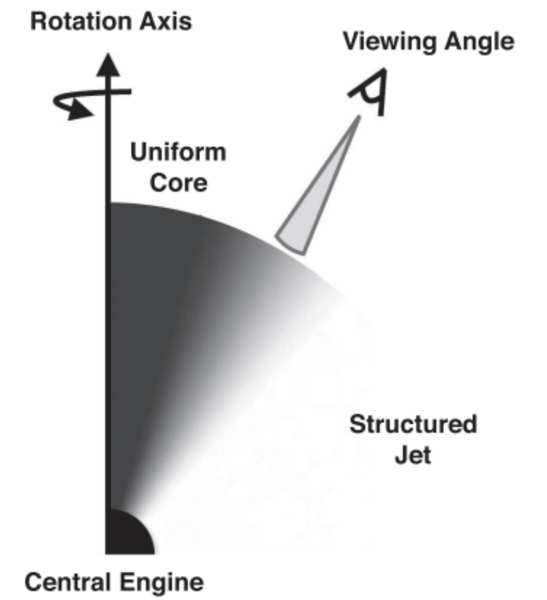
[S. Woosley, Nature 414 (2001)]



For a standard on-axis GRB:
More of the emitting surface becomes visible at later times as the jet slows

GW170817 + GRB 170817A

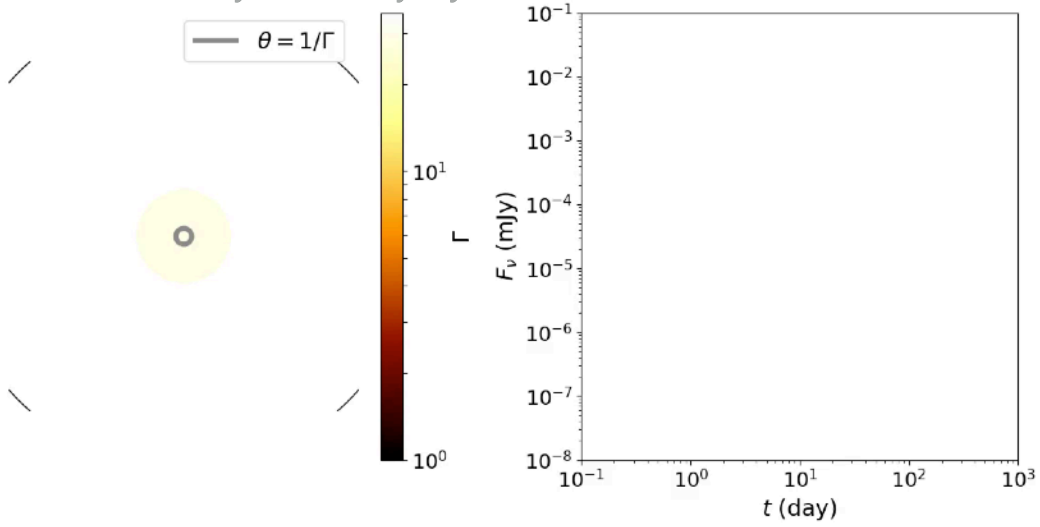
an off-axis GRB



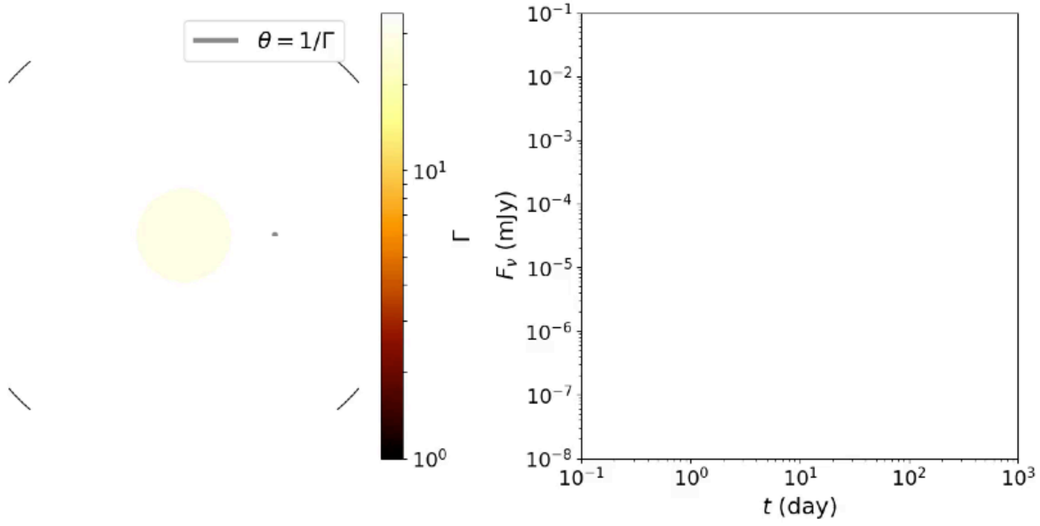
The afterglow of an off-axis GRB looks very different

simulations by Geoffrey Ryan, Perimeter Institute

on-axis:



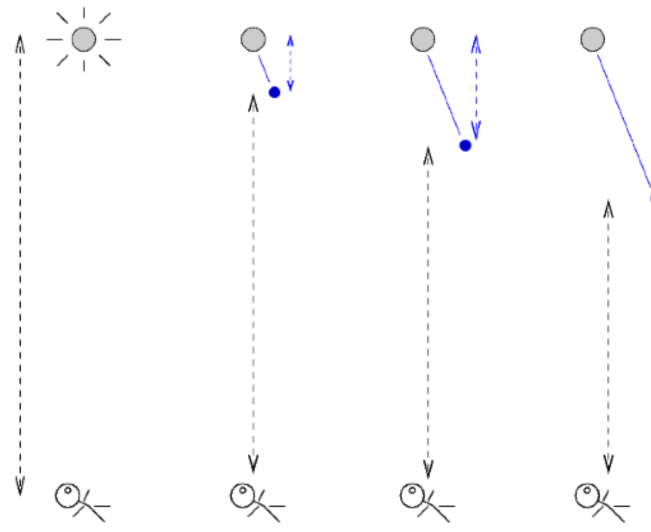
off-axis:



GW170817 + GRB 170817A

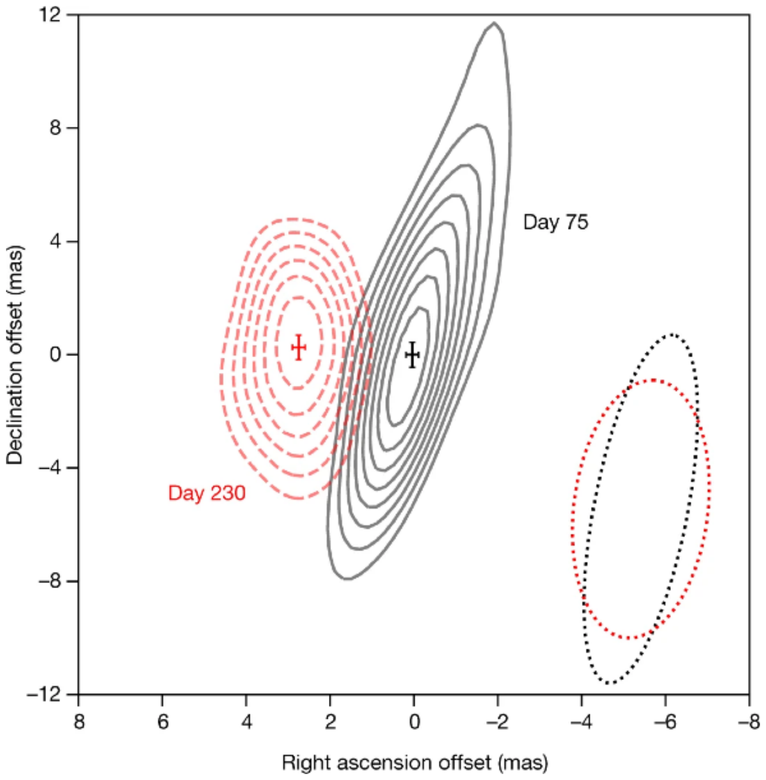
an off-axis GRB

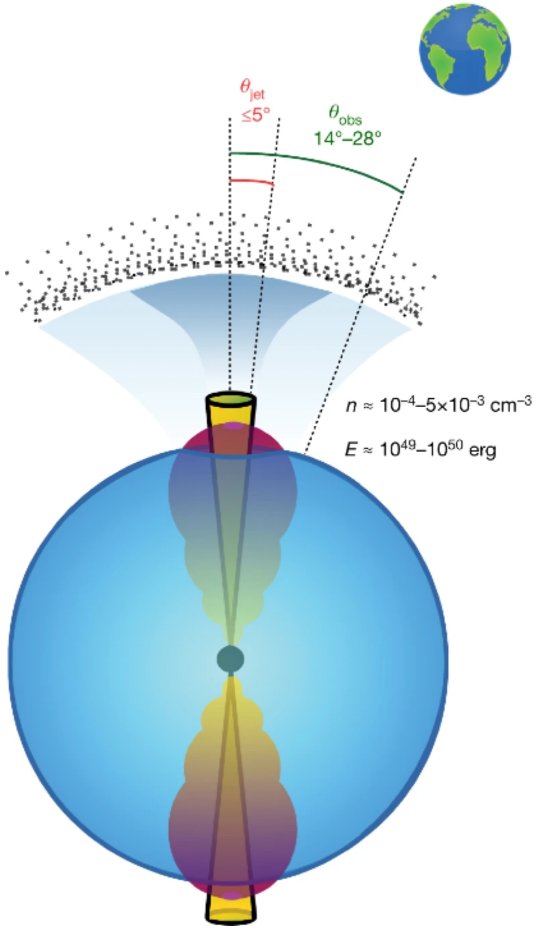
Late-time radio images showed superluminal motion



[M. Richmond]

[K. P. Mooley et al., Nature 561 (2018)]

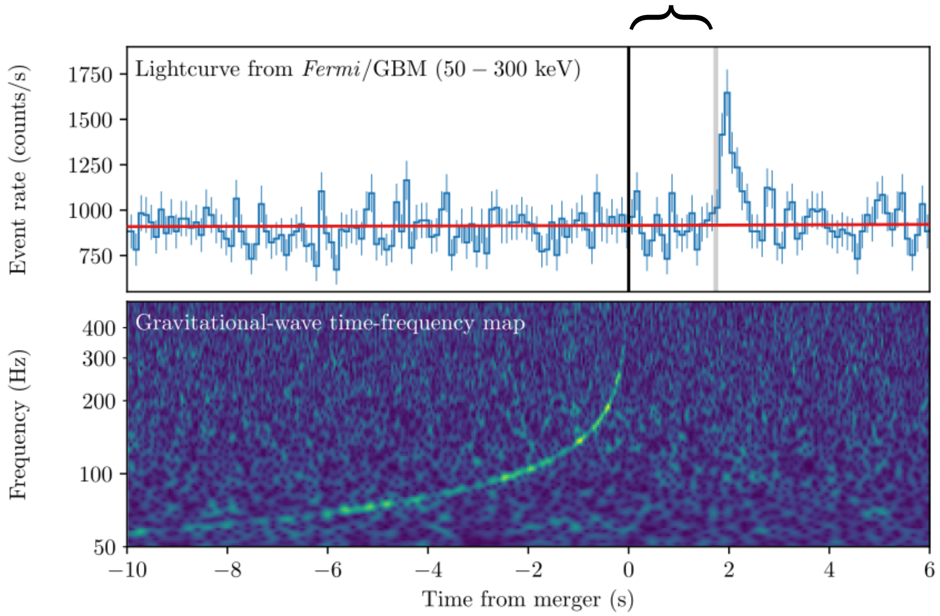




GW170817 + GRB 170817A

speed of light vs. speed of gravity

the two signals were detected 1.75s apart



modified from [B. P. Abbott et al., ApJL 848 (2017)]

This delay is (likely) because of the delay in producing gamma rays, but if we make some assumptions, we can calculate the relative difference between the speed of light and speed of gravity

$$\Delta v = v_{GW} - v_{EM}$$

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{EM}} \leqslant +7 \times 10^{-16}$$

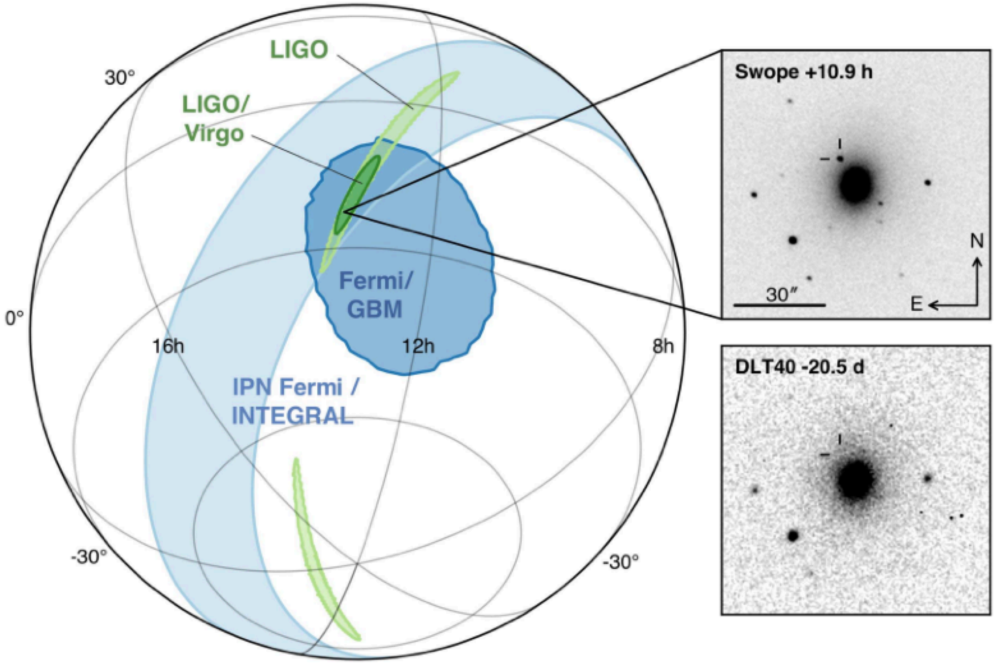
assume photons were emitted some (unreasonably) long time after the gravitational waves (here, 10s)

assume photons and gravitational waves were emitted simultaneously

IACT observations of GRB170817A

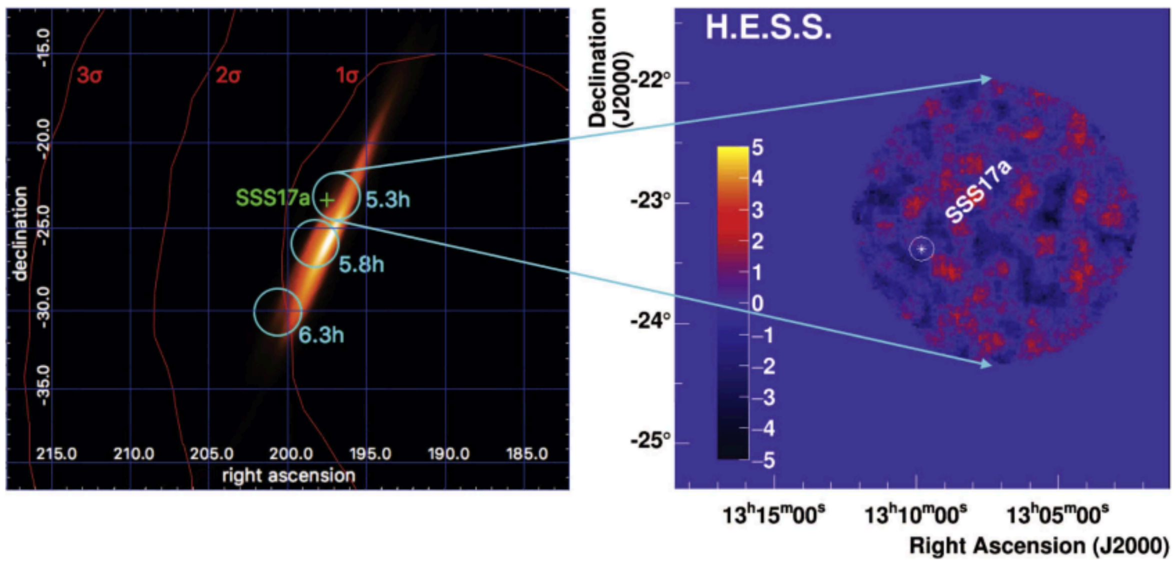
immediately after the merger

[B. P. Abbott et al., ApJL 848 (2017)]



gravitational-wave localization
gamma-ray burst localization

[H. Abdalla et al., ApJL 850 (2017)]

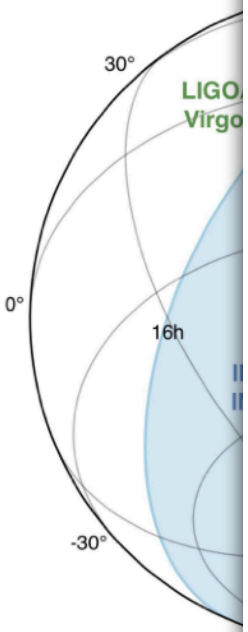


H.E.S.S. serendipitously observed the correct sky position in its first tile

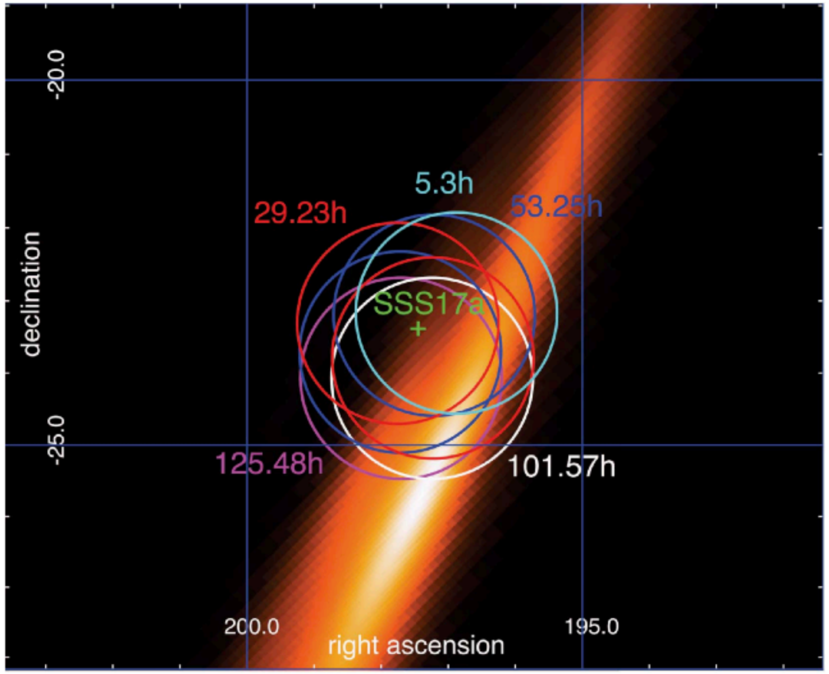
IACT observations of GRB170817A

immediately after the merger

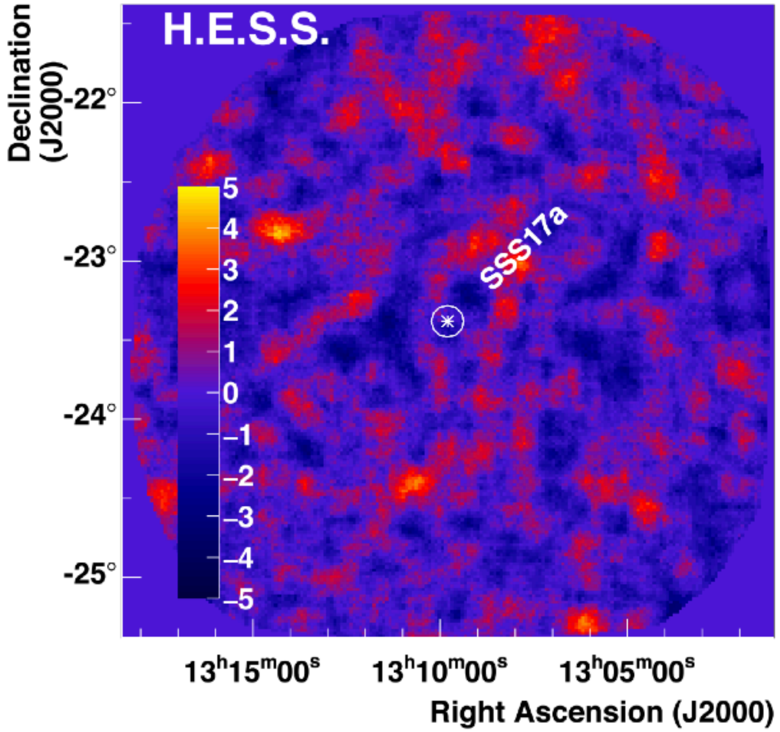
[B. P. Abbott e



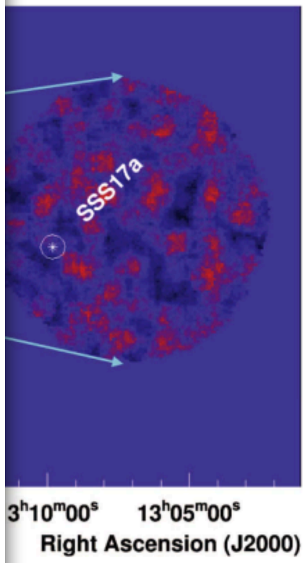
[H. Abdalla et al., ApJL 850 (2017)]



(a) SSS17a: H.E.S.S. pointings



(b) SSS17a: H.E.S.S. significance map



rrect

gravita

gamma

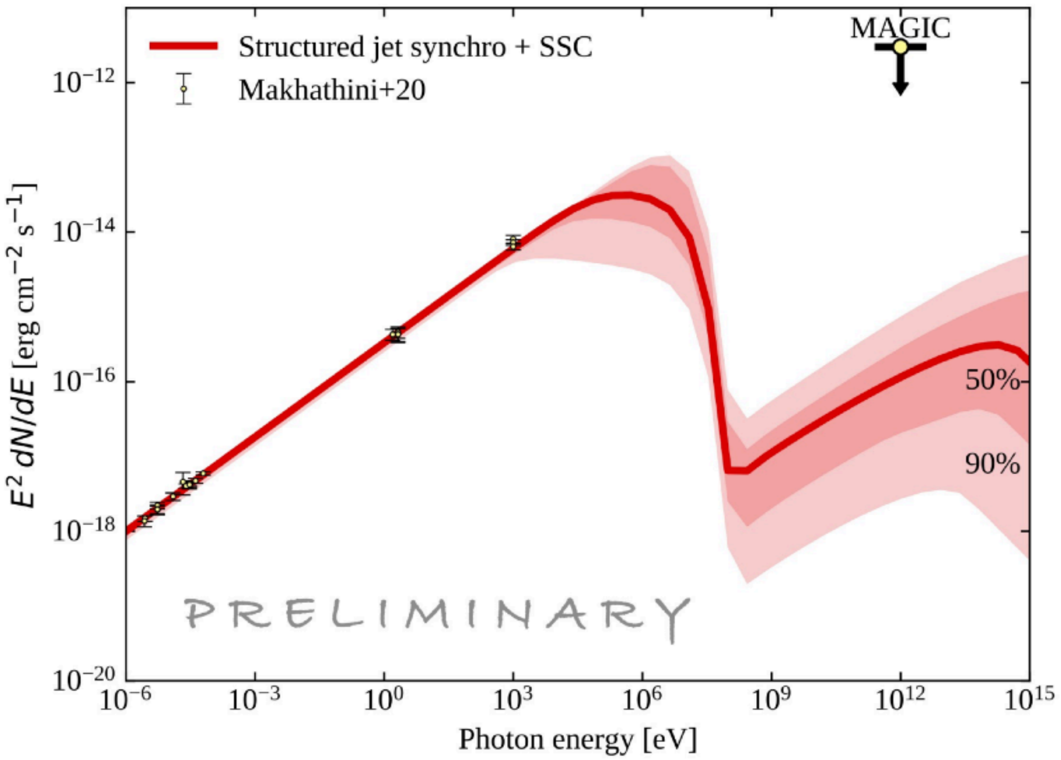
H.E.S.S. revisited the region over the next few days

(too far south for the other IACTs)

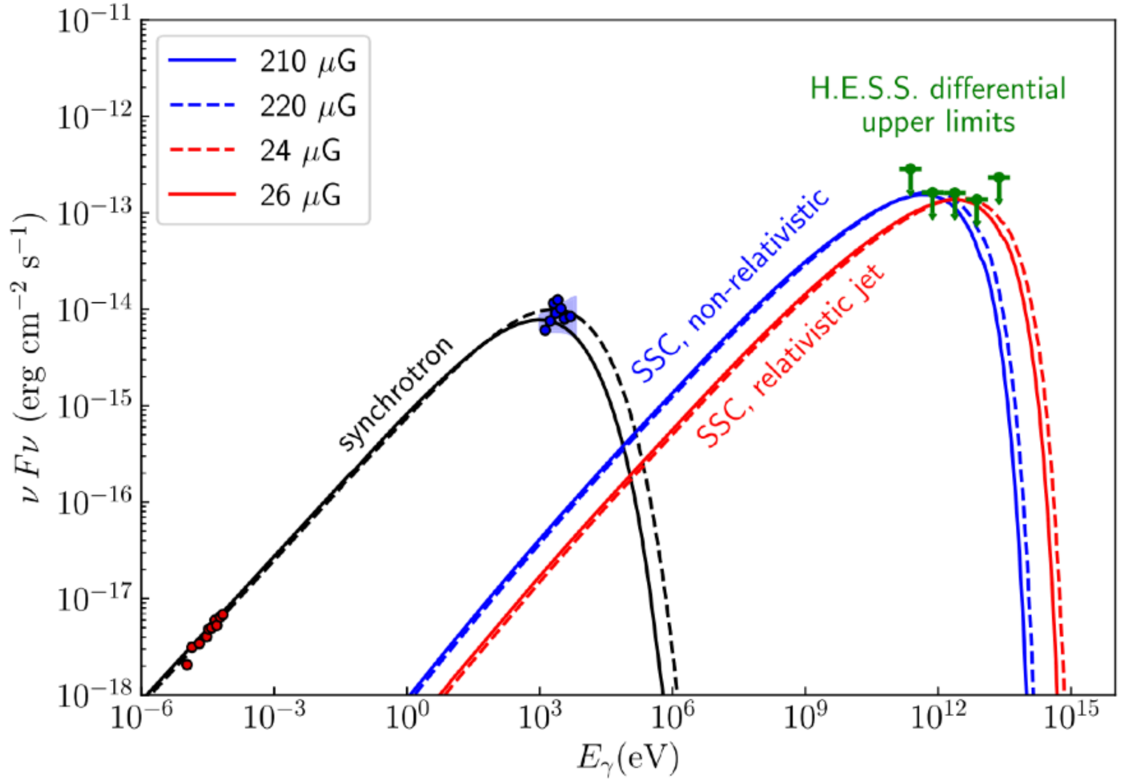
IACT observations of GRB170817A

deep in the afterglow phase

[A. Stamerra et al., ICRC (2021)]



[H. Abdalla et al., ApJL 894 (2020)]



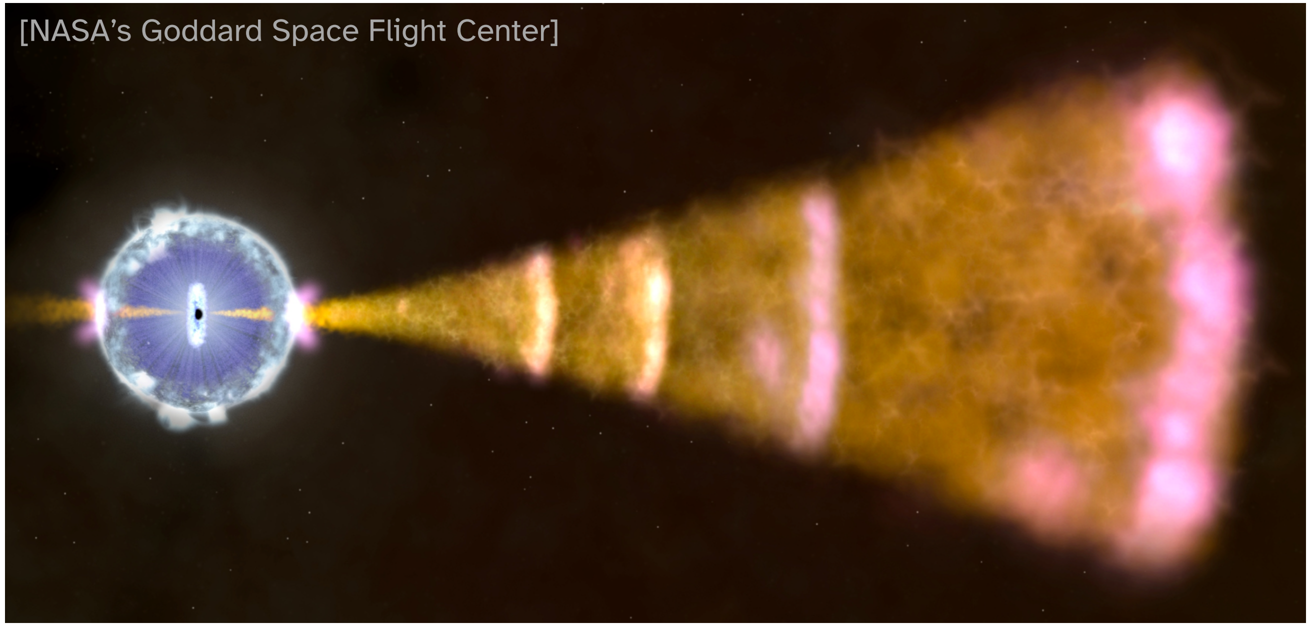
MAGIC and H.E.S.S. also observed at late times

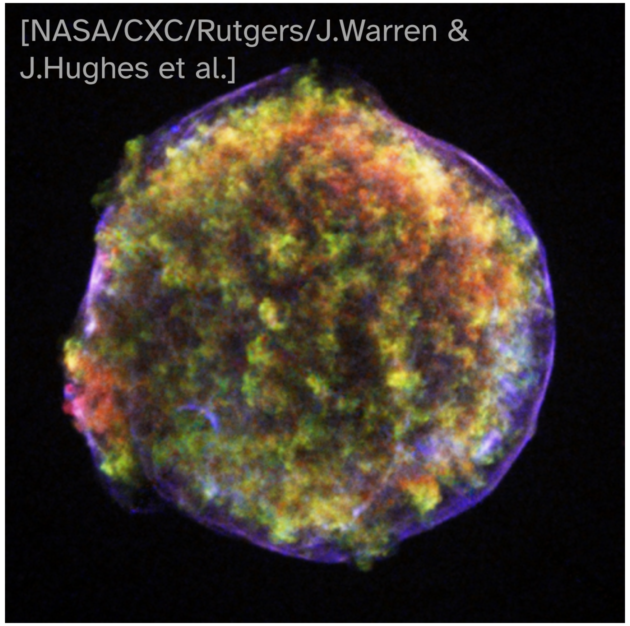
AGN flares

this section is empty because Matteo covered these 🥳

Non-jetted phenomena

So far my focus has been on jetted phenomena, but gamma rays don't have to come from jets
-> *Shocks* are what produce the gamma rays (jets just provide relativistic shocks)





To get shocks, we just need matter running into some medium

(also: we don't always need shocks but we won't talk about that)