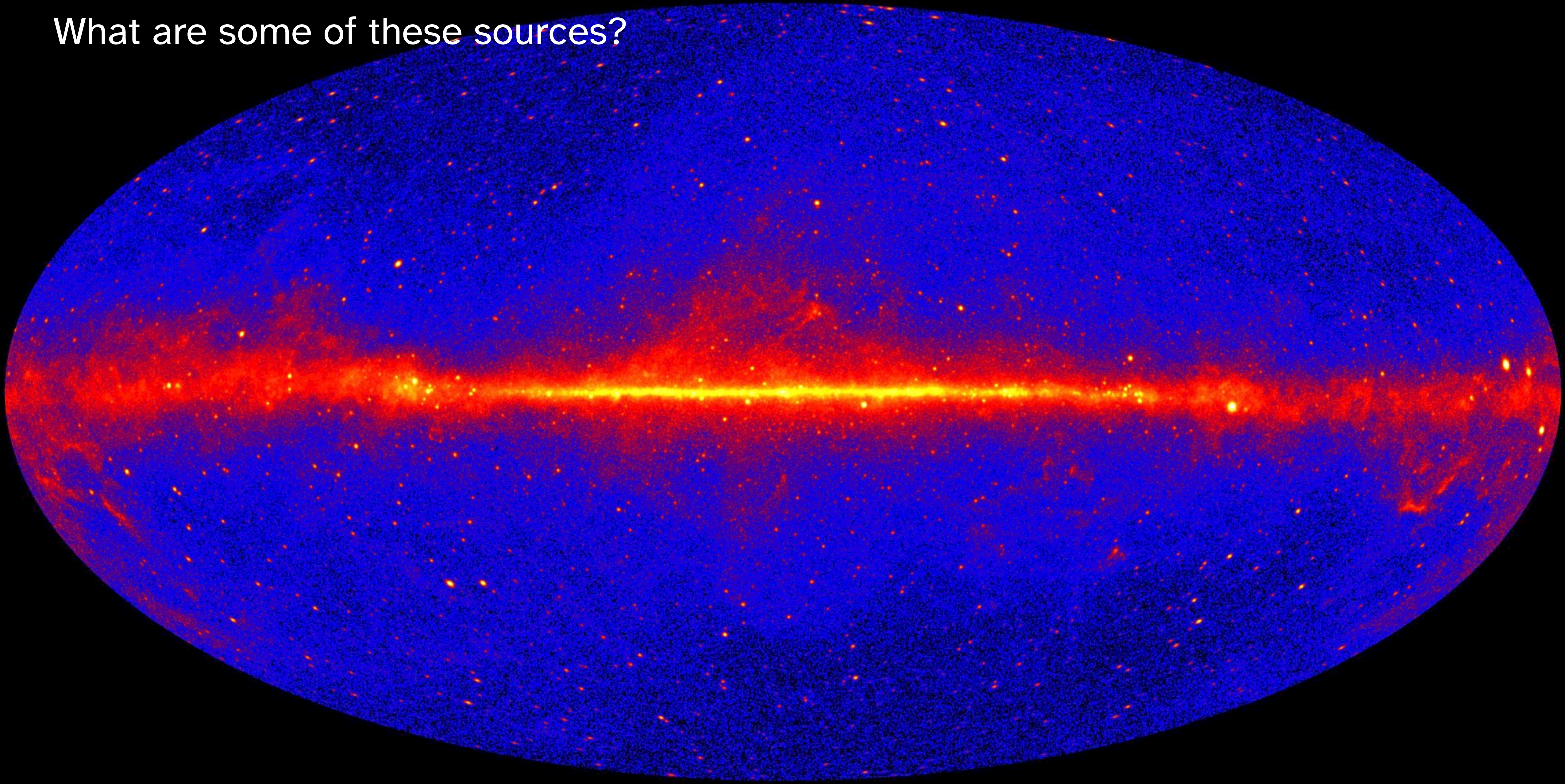
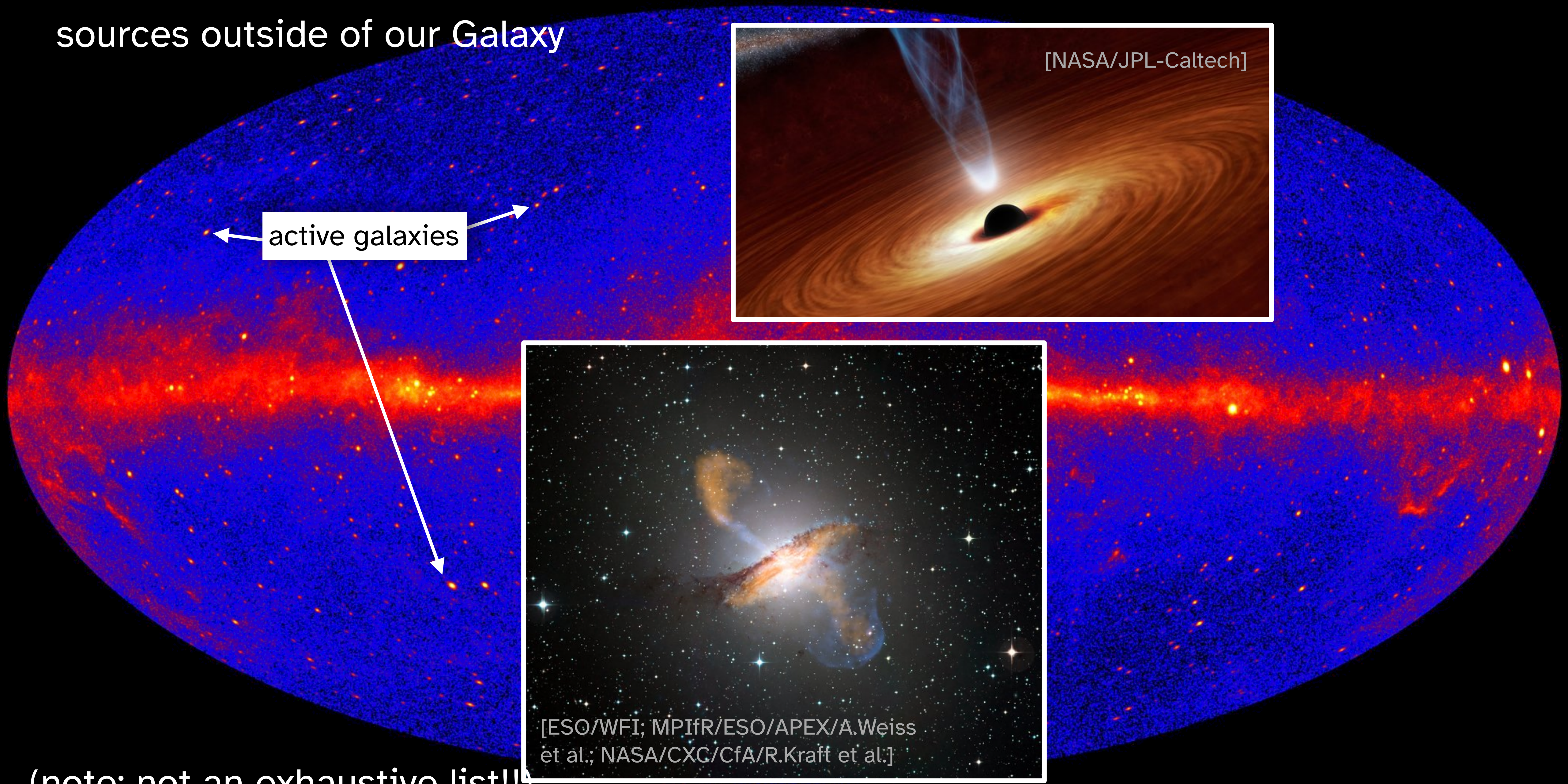
Gamma-ray sources

Note: The rest of these lectures will have a bias toward what I find interesting :)

What are some of these sources?



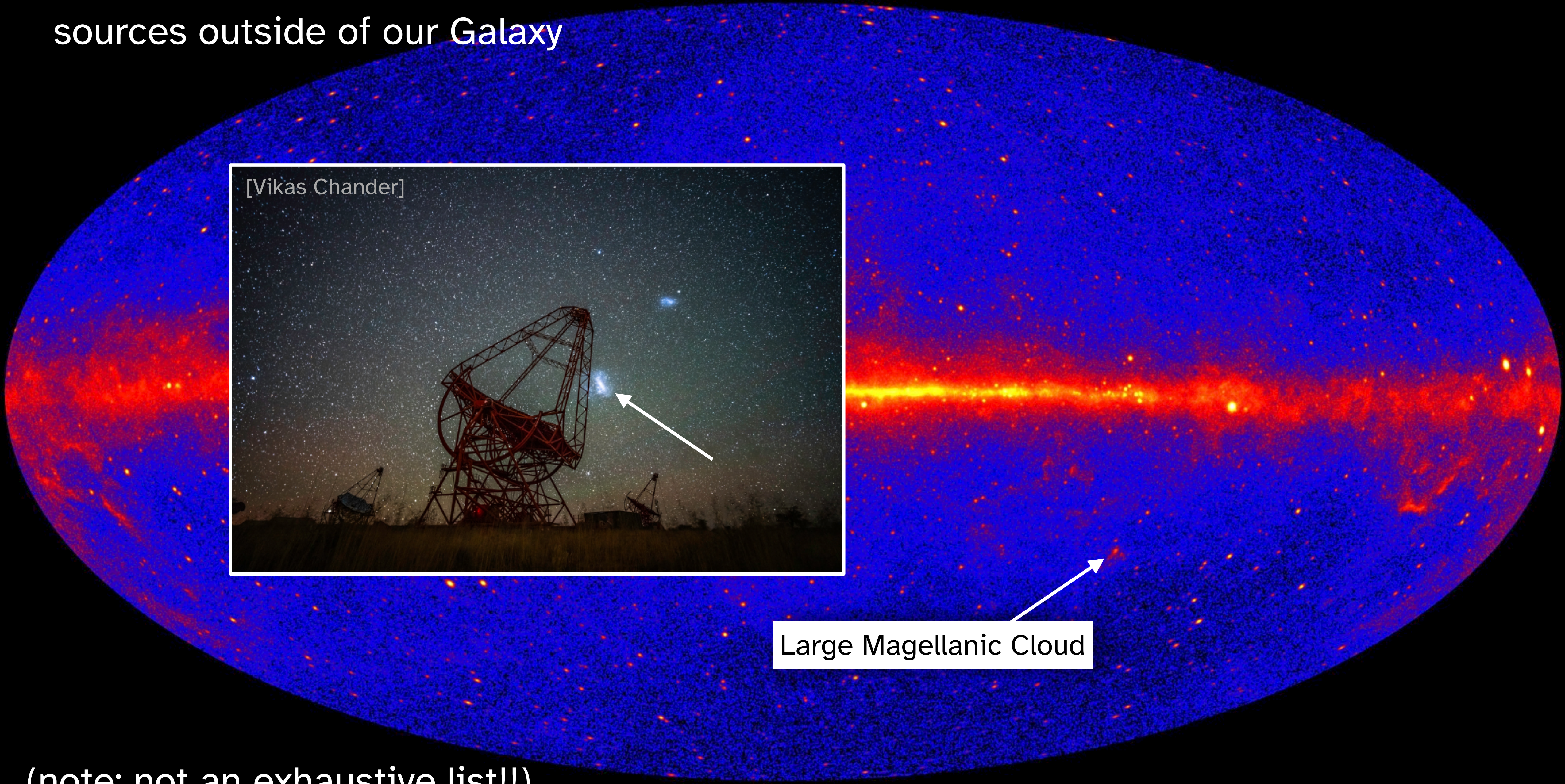
sources outside of our Galaxy



(note: not an exhaustive list!!)

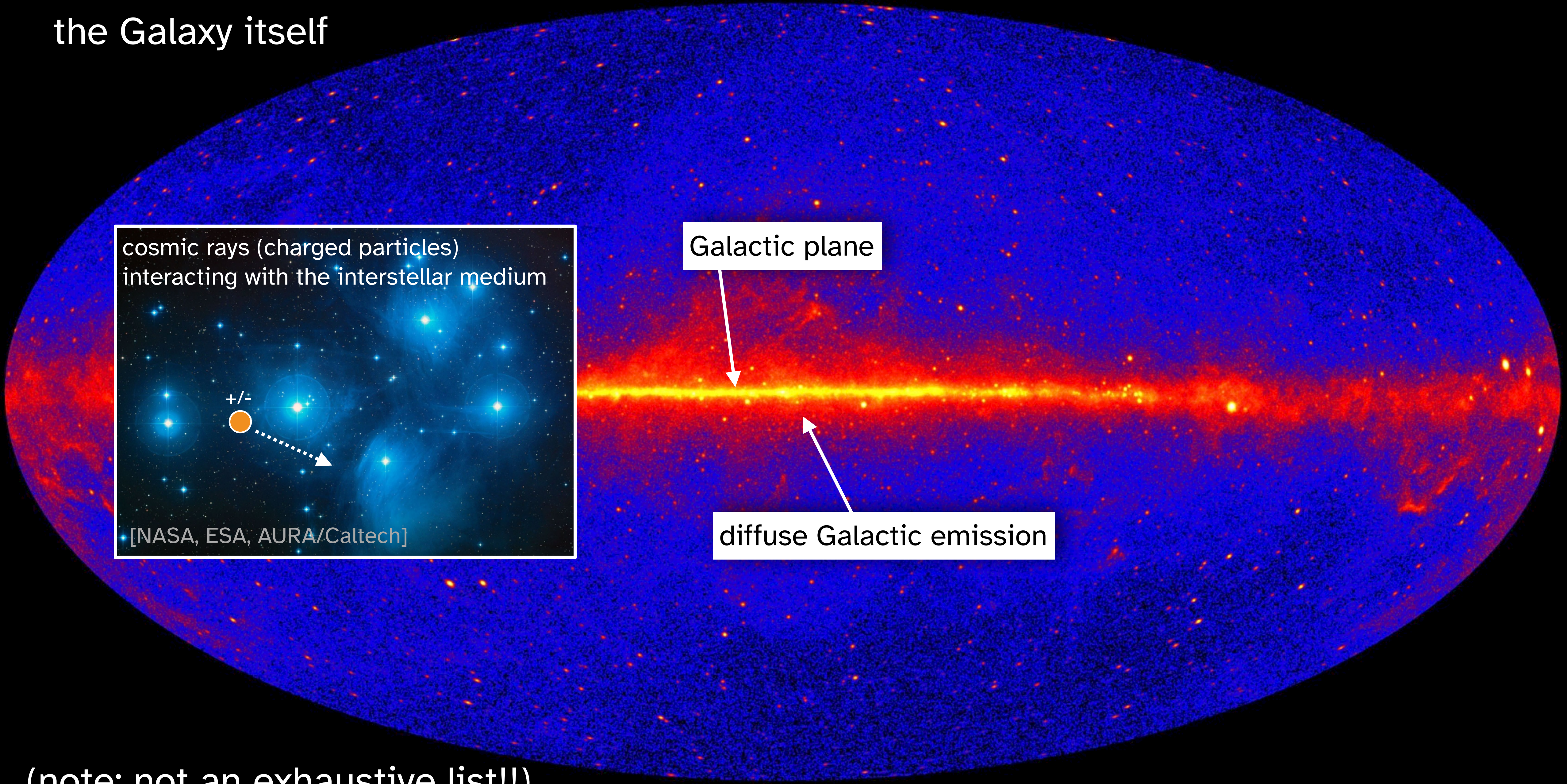
[NASA/DOE/Fermi-LAT Collaboration]

sources outside of our Galaxy



(note: not an exhaustive list!!)

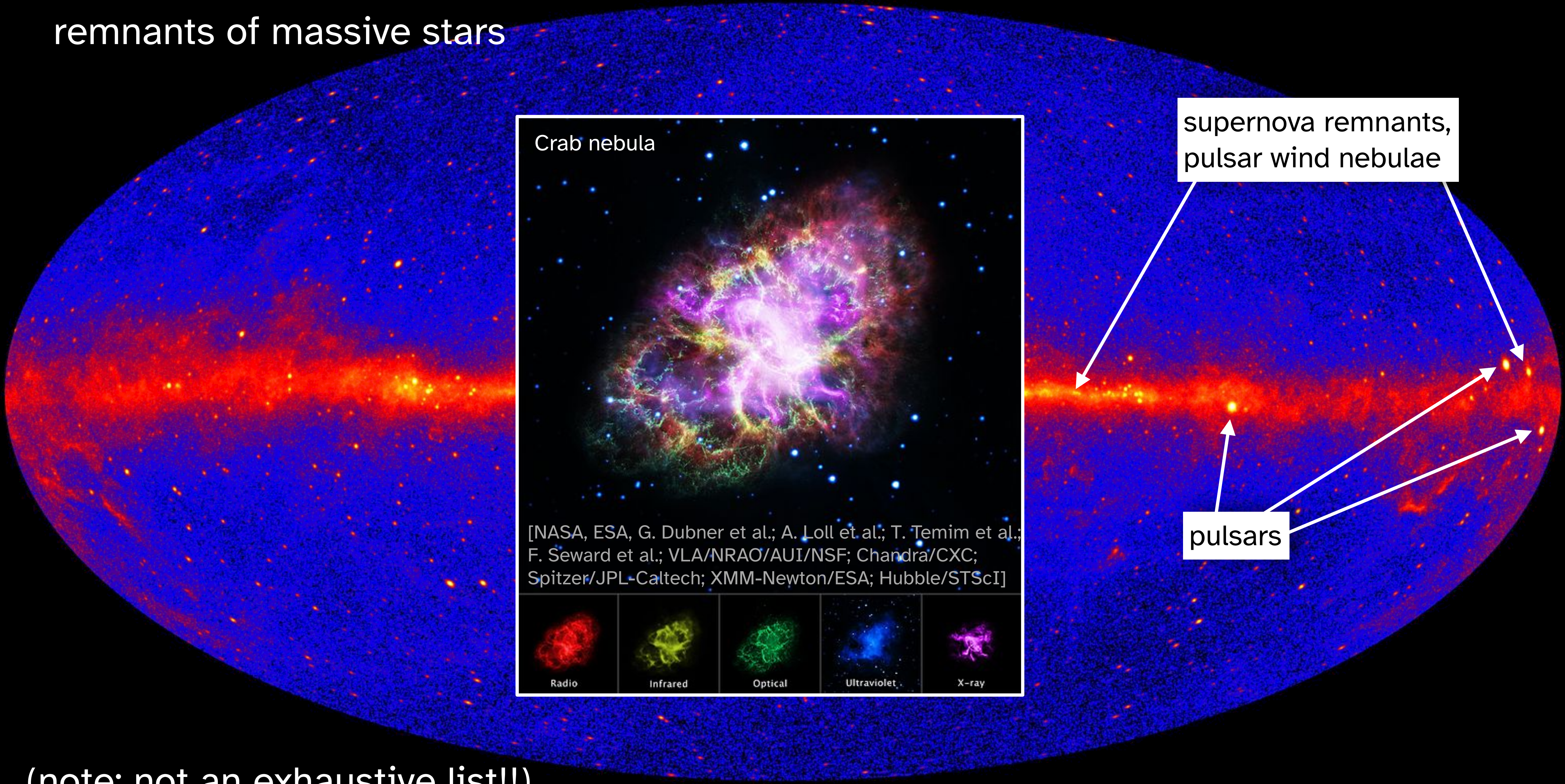
the Galaxy itself



(note: not an exhaustive list!!)

[NASA/DOE/Fermi-LAT Collaboration]

remnants of massive stars



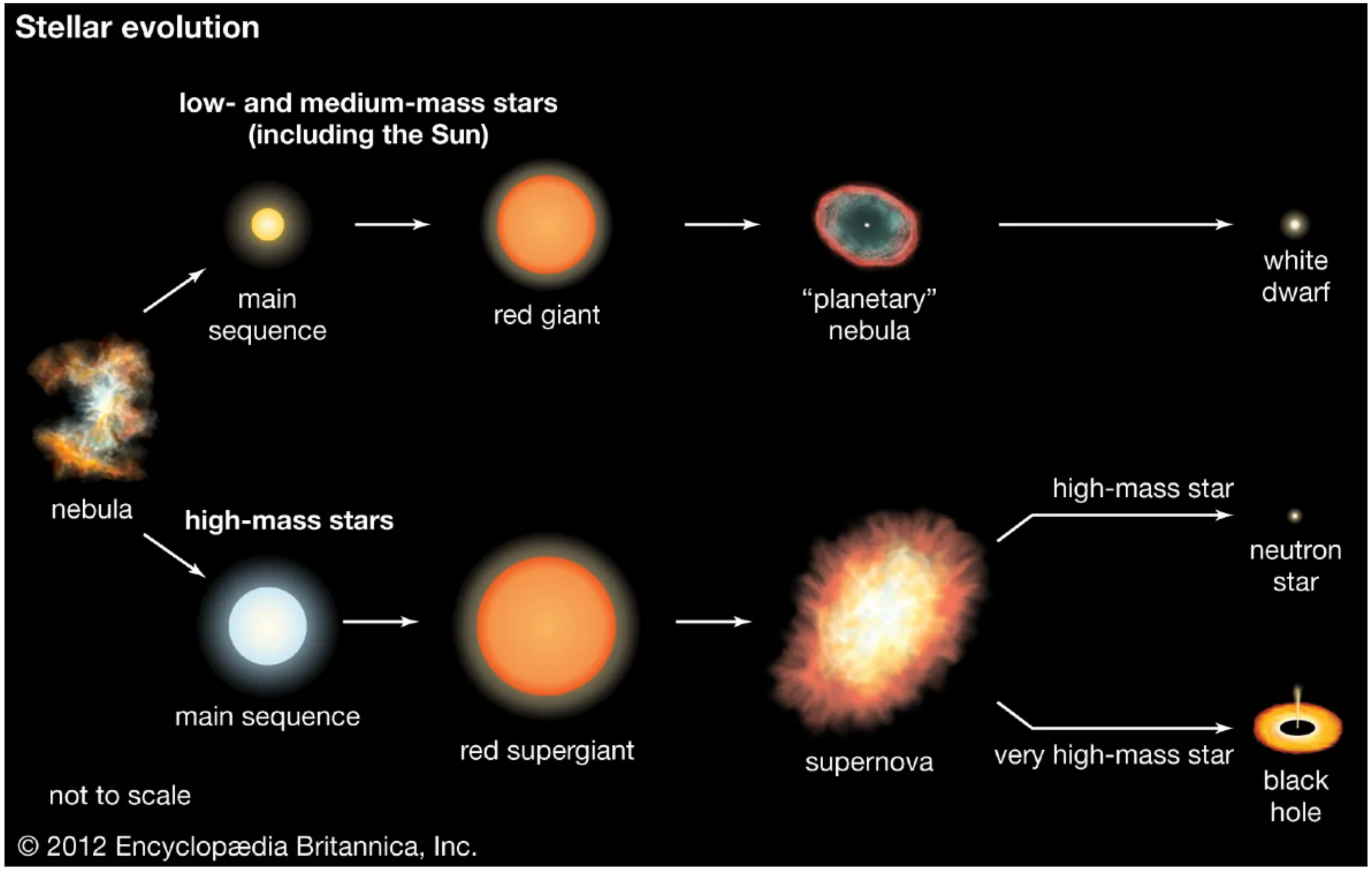
[NASA, ESA, G. Dubner et al.; A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; Hubble/STScI]

(note: not an exhaustive list!!)

What happens at the end of a massive star's life?

core-collapse supernovae

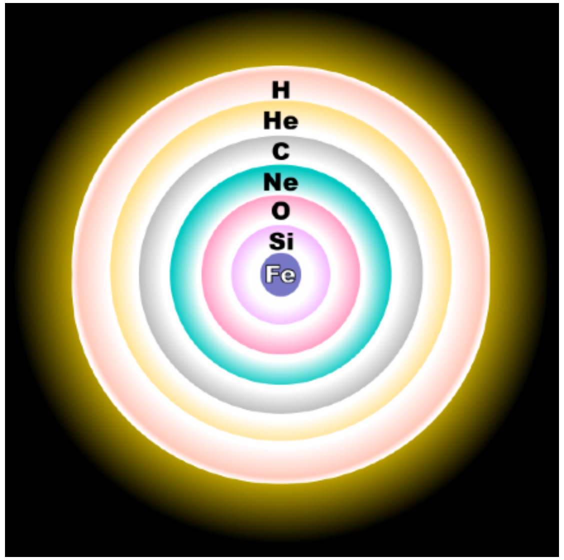
A star's evolution depends mostly on its initial mass



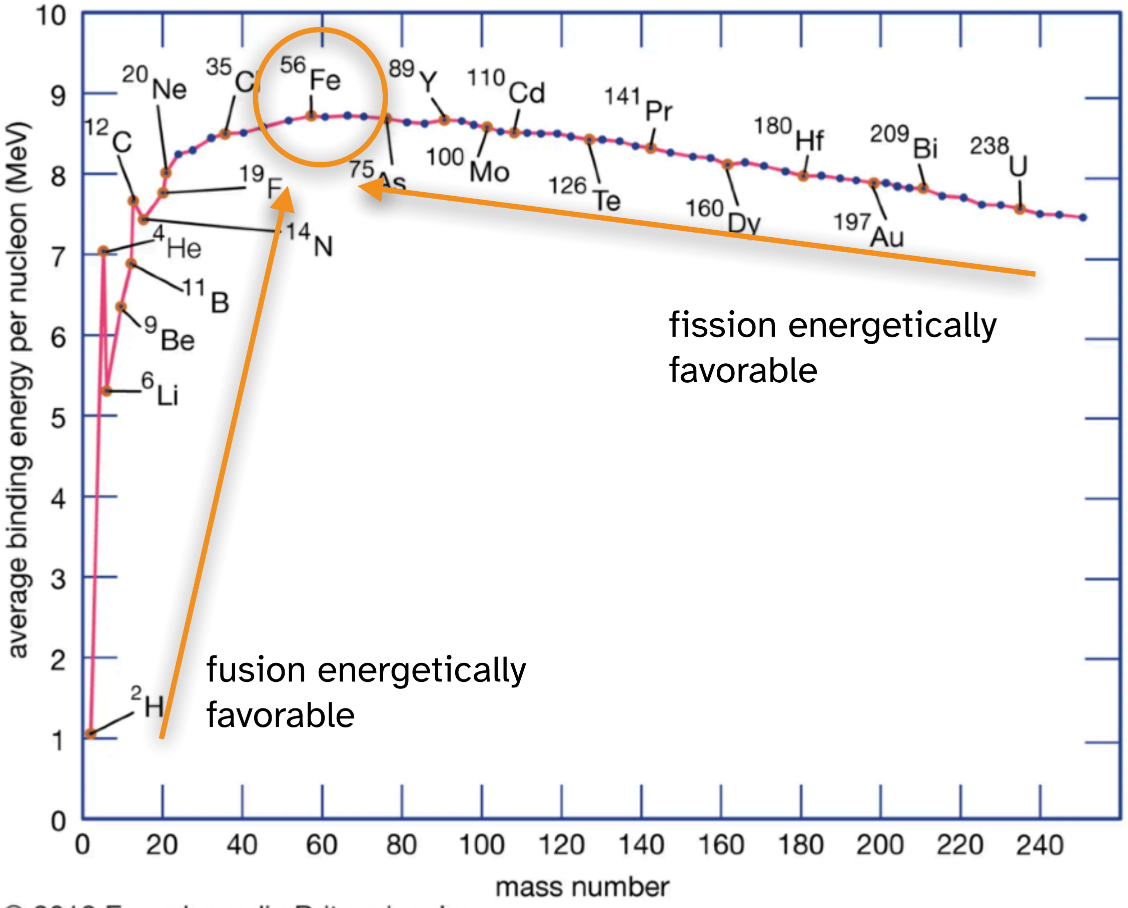
What happens at the end of a massive star's life?

core-collapse supernovae

Massive stars fuses successively heavier elements until iron



R. J. Hall



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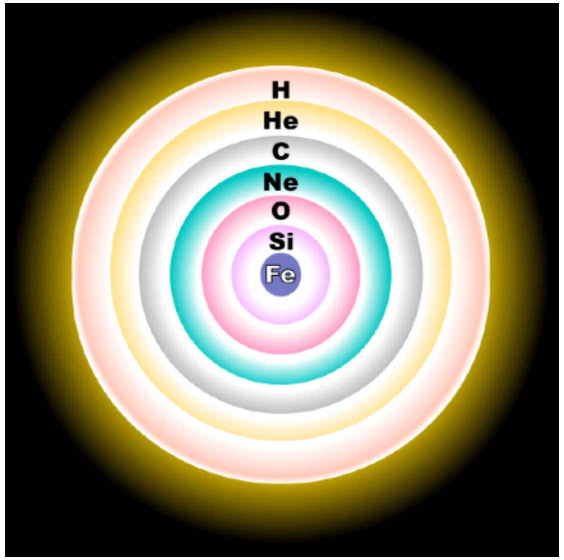
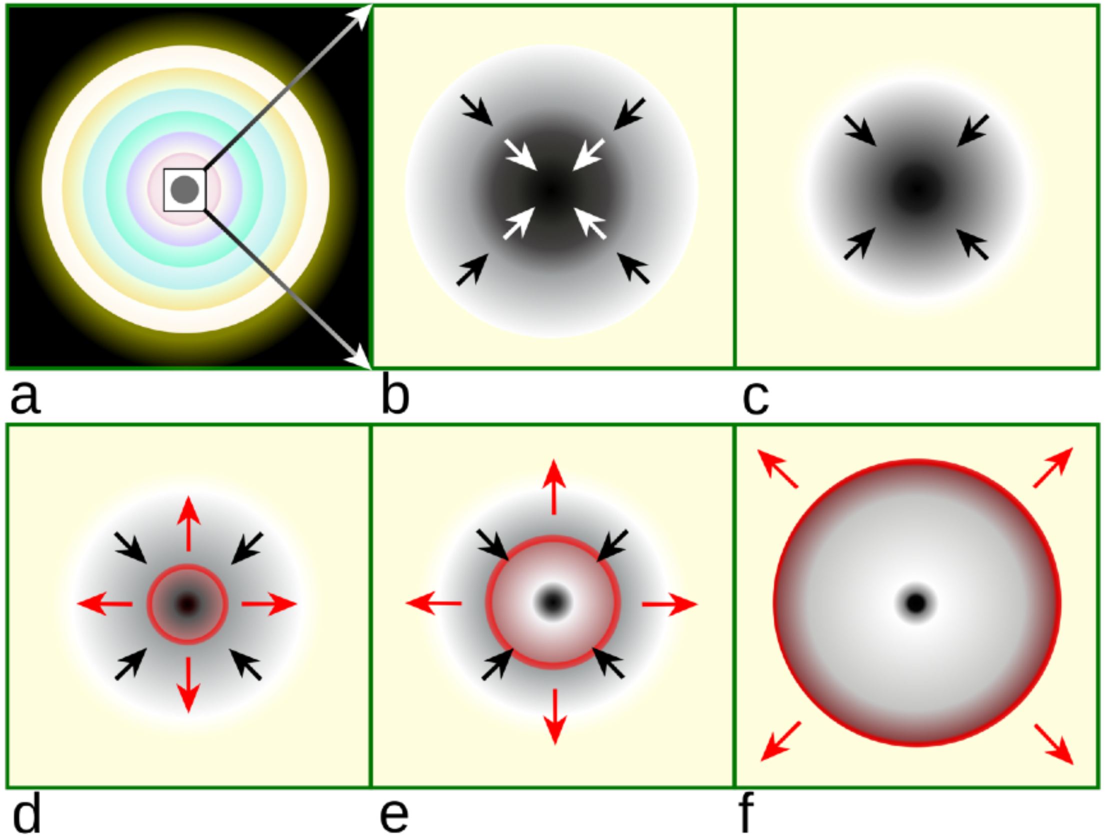


R. J. Hall



R. J. Hall

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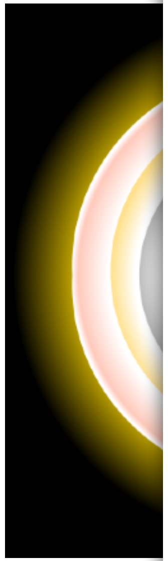
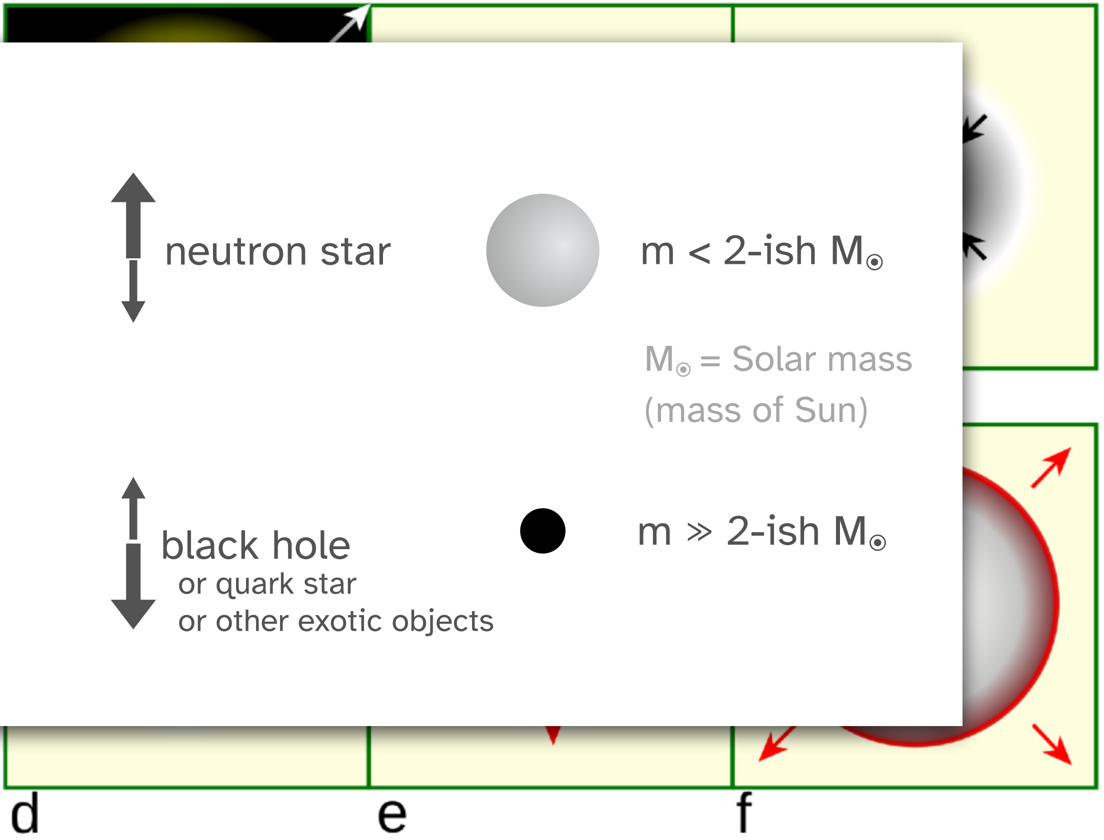
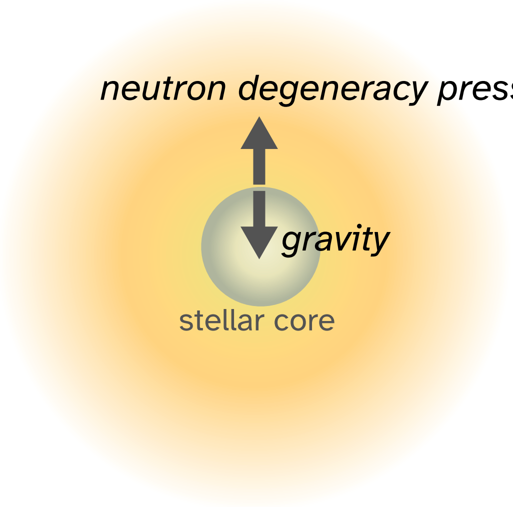


R. J. Hall



R. J. Hall

What’s left behind:



neutron star — $m < 2\text{-ish}\ M_\odot$

$M_\odot$ = Solar mass (mass of Sun)

black hole
or quark star
or other exotic objects — $m \gg 2\text{-ish}\ M_\odot$

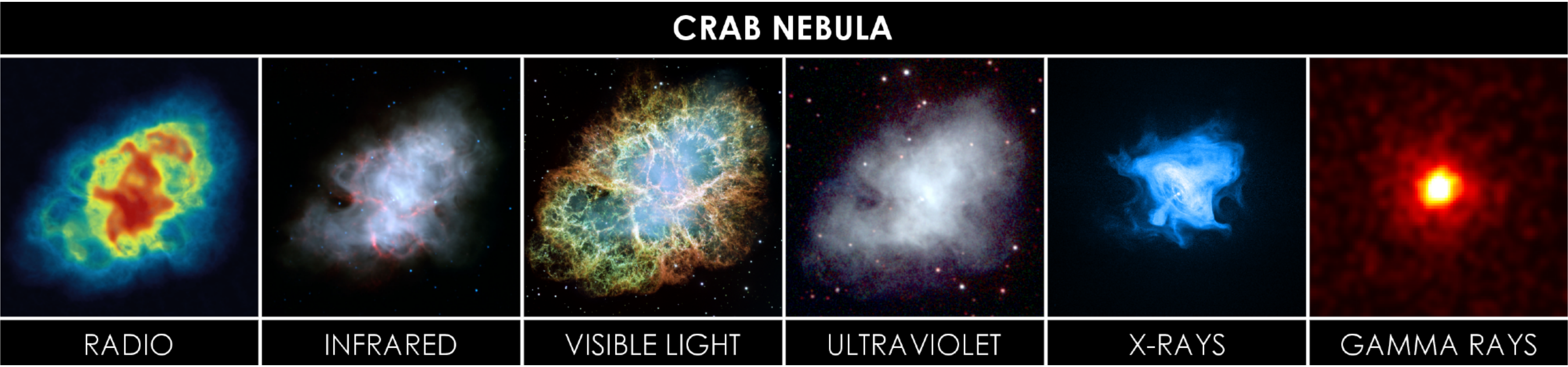
Crab supernova

[ESA/Hubble (M. Kornmesser & L. L. Christensen)]

Crab nebula

a composite system: supernova remnant + pulsar wind nebula + pulsar

Emission at different wavelengths suggests multiple physical processes / components



[NRAO/AUI, M. Bietenholz, J.M. Uson, T.J. Cornwell; NASA/JPL-Caltech/R. Gehrz (University of Minnesota); NASA, ESA, J. Hester and A. Loll (Arizona State University); NASA/Swift/E. Hoversten, PSU; NASA/CXC/SAO/F.Seward et al.; NASA/DOE/Fermi LAT/R. Buehler]

Crab nebula

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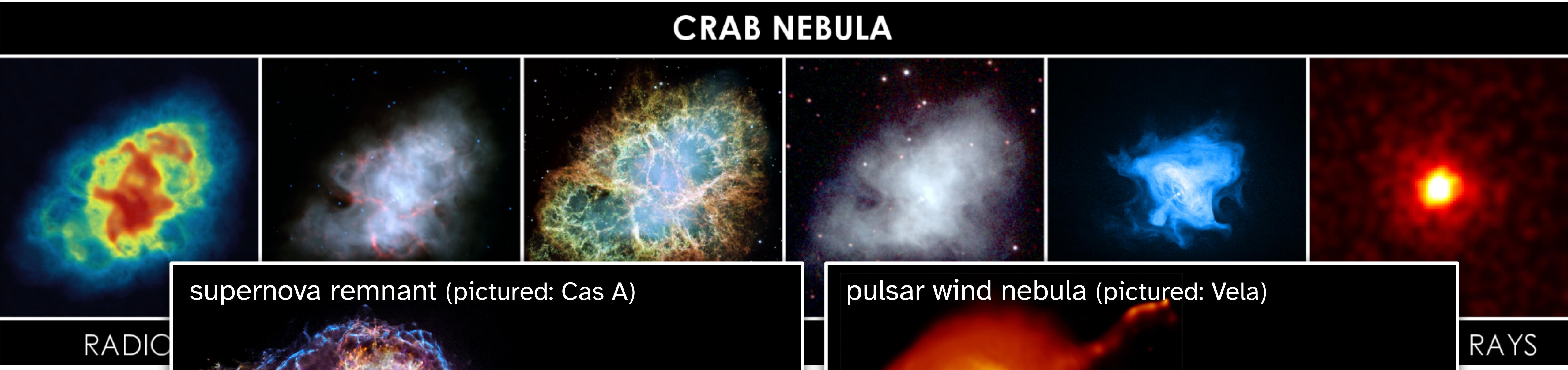
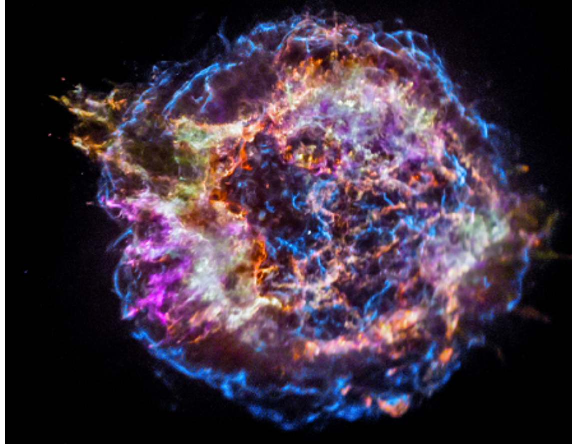


[NRAO/AUI, M
NASA/CXC/S

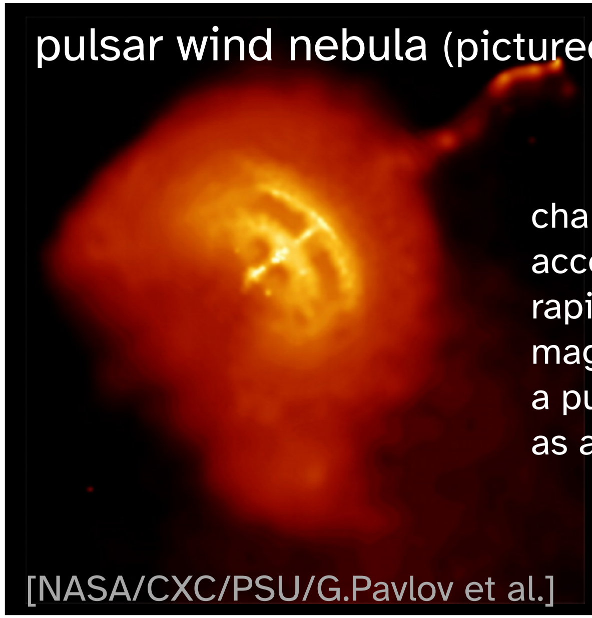
supernova remnant (pictured: Cas A)



material from original supernova explosion encounters and interacts with the surrounding environment

[NASA/CXC/SAO]

pulsar wind nebula (pictured: Vela)



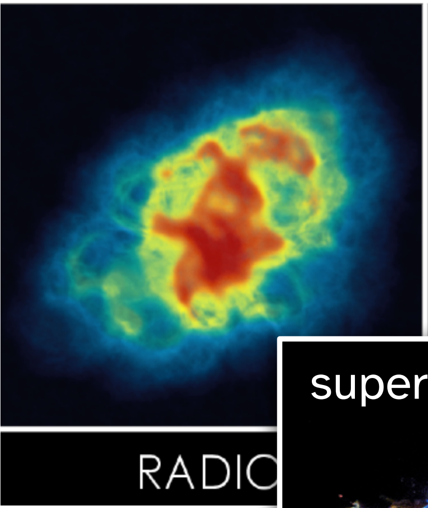
charged particles are accelerated by the rapidly rotating magnetic fields around a pulsar and stream out as a wind

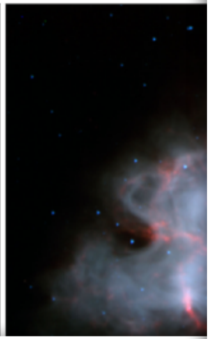
[NASA/CXC/PSU/G.Pavlov et al.]

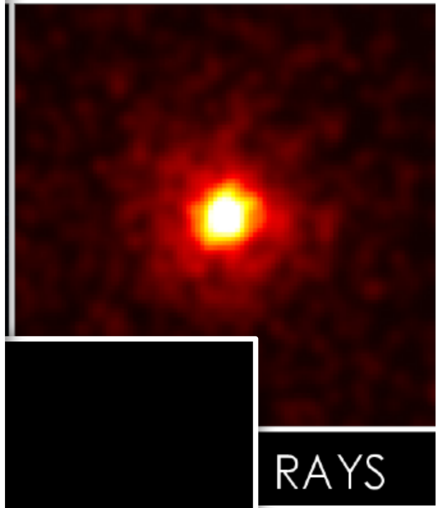
Crab nebula

a composite system: su

Emission at different wave







[NRAO/AUI, M
NASA/CXC/S

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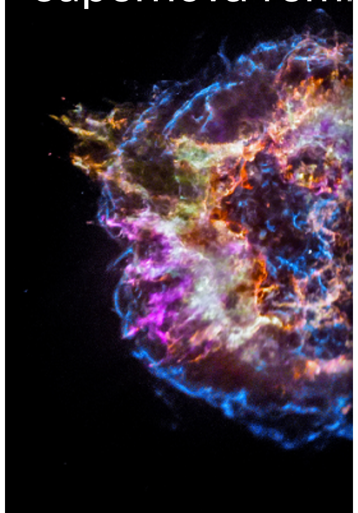
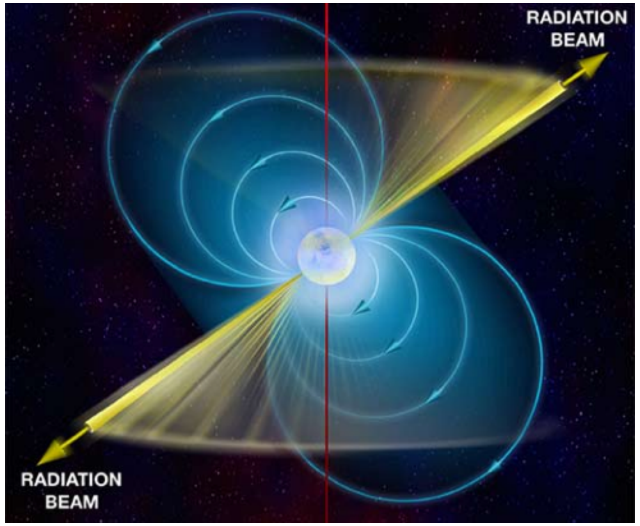
supernova remn



[NASA/CXC/SAO]

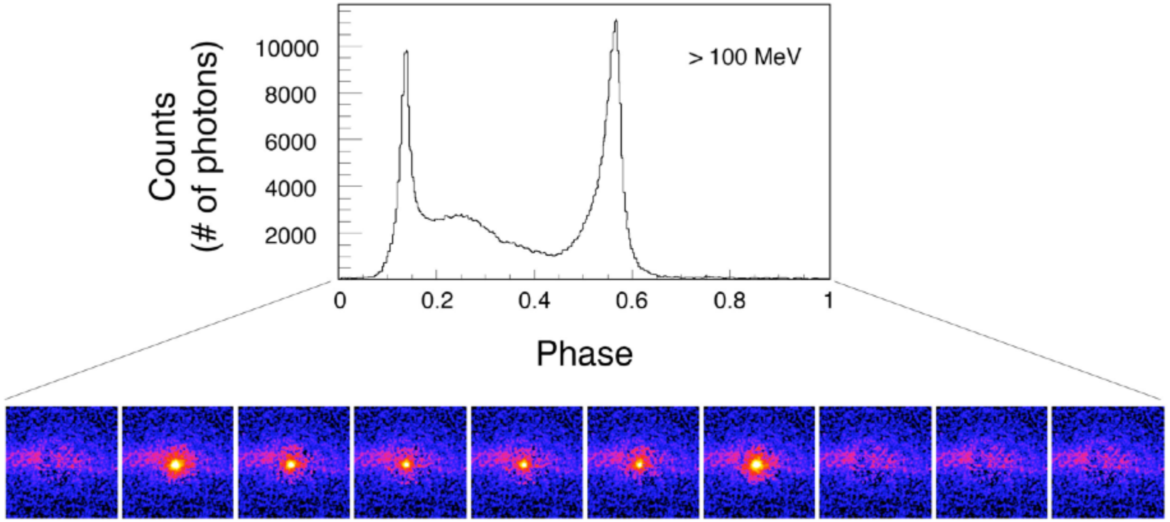
Pause: What is a pulsar?



[NRAO]

The core of a pulsar is a neutron star, usually with a strong magnetic field

Pulsars are often described as lighthouses: beams of radiation that sweep across the sky



[Grodin et al. 2013 ApJ, NASA/DOE/Fermi-LAT]

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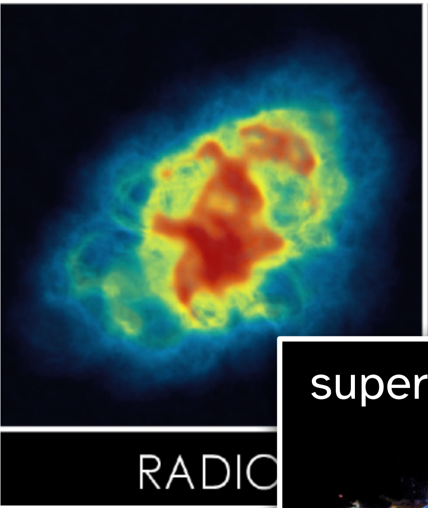
[NASA/CXC/PSU/G.Pavlov et al.]

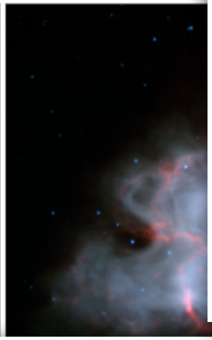
DESY.

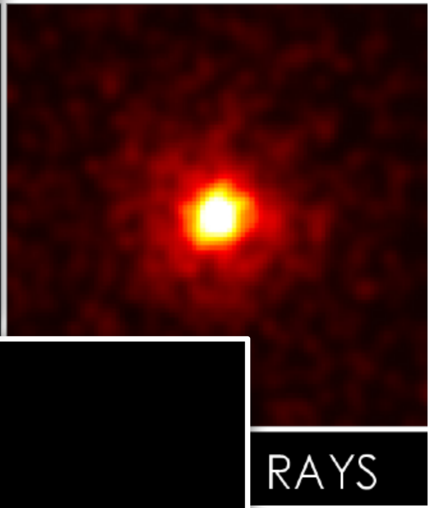
Crab nebula

a composite system: su

Emission at different wave







[NRAO/AUI, M
NASA/CXC/S

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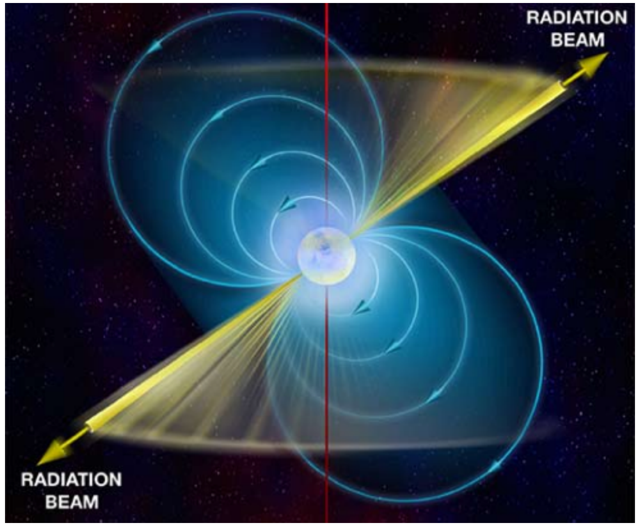

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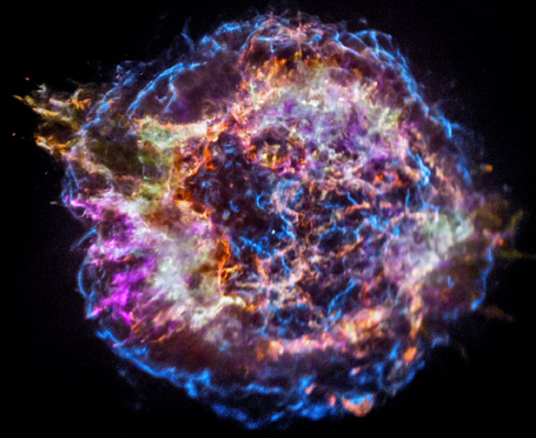
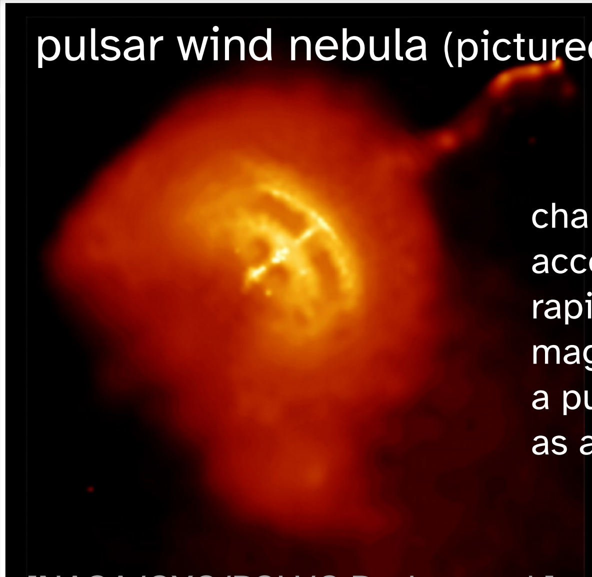


material from original supernova explosion encounters and interacts with the surrounding environment

[NASA/CXC/SAO]

pulsar wind nebula (pictured: Vela)



charged particles are accelerated by the rapidly rotating magnetic fields around a pulsar and stream out as a wind

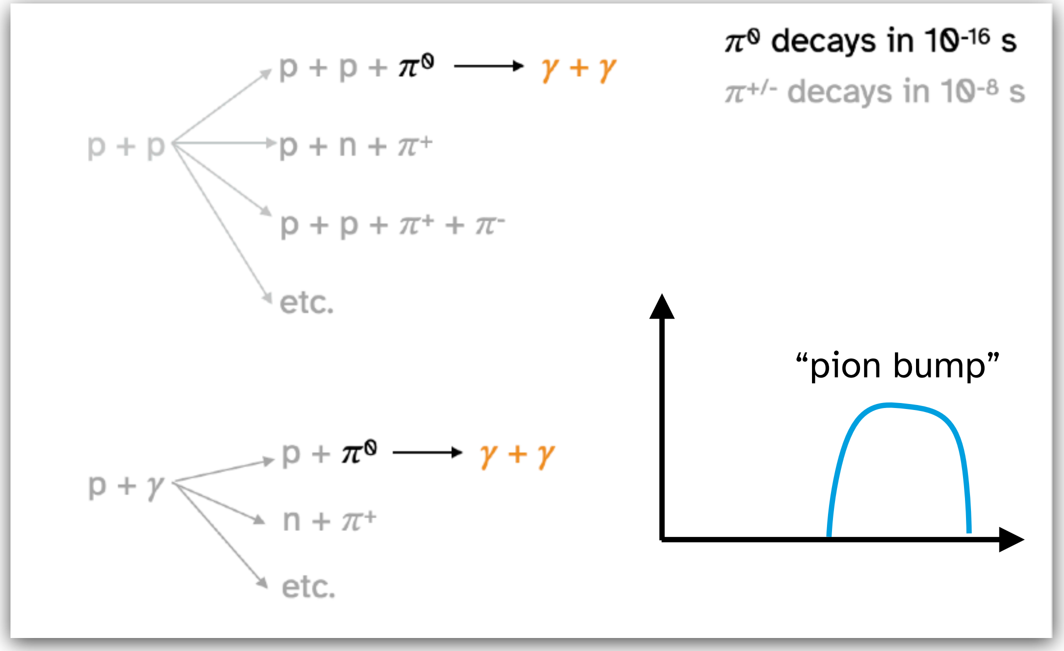
[NASA/CXC/PSU/G.Pavlov et al.]

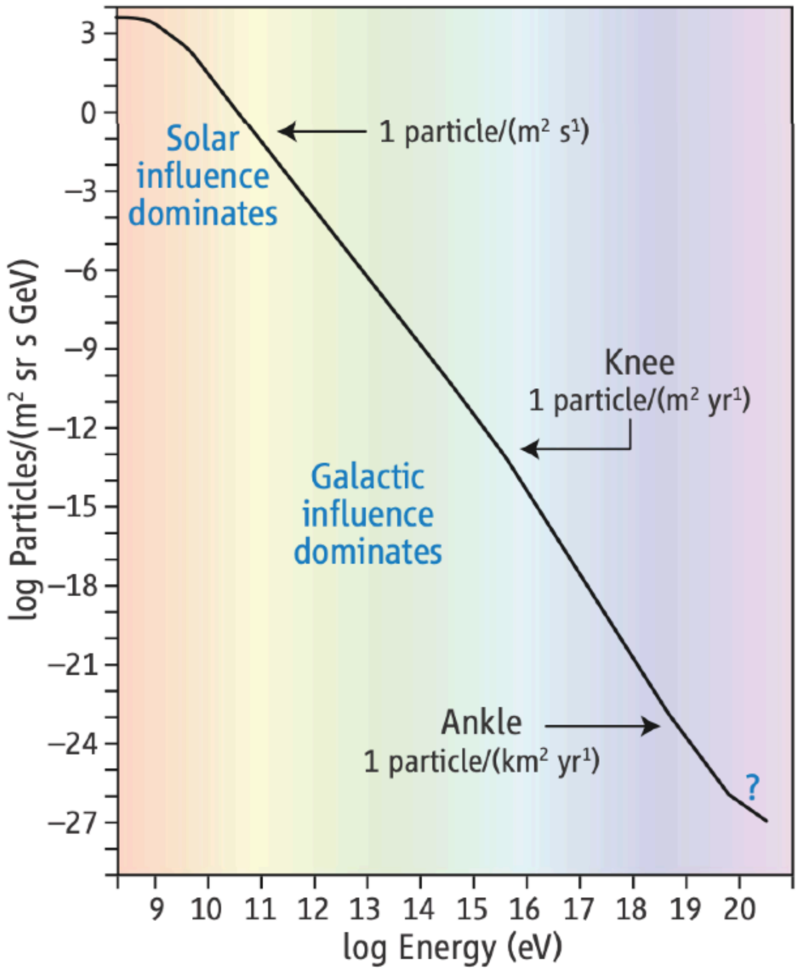
A common goal in Galactic VHE astronomy

Looking for Pevatrons

Reminder: a nice summary: presentation by [H. Fleischhack]

- Cosmic rays up to ~PeV energies should be Galactic
- Their sources are hard to pinpoint directly
- Instead we ask questions like:
  - -> What sources produce ~100 TeV gamma rays?
  - -> Are these gamma rays from *hadronic* processes?





[M. Duldig, Science 314 (2006)]

A common goal in Galactic VHE astronomy

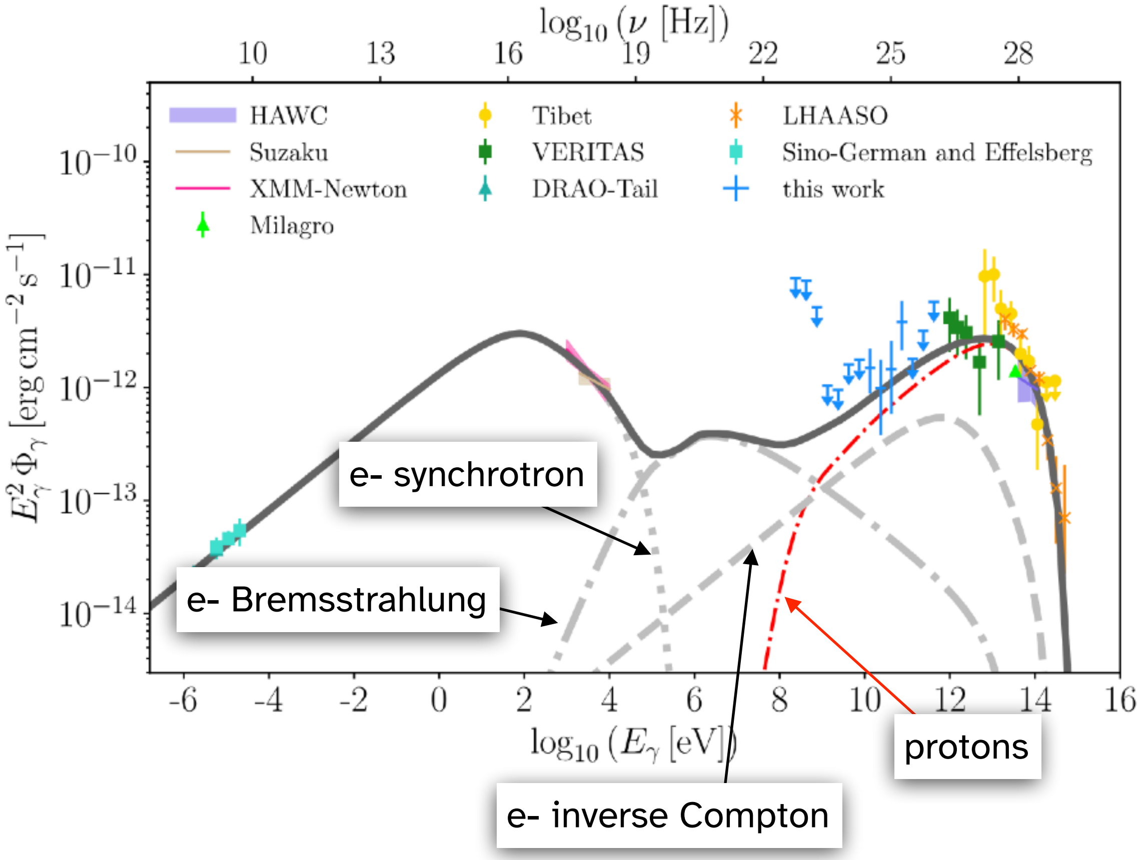
Looking for Pevatrons

Are these gamma rays from *hadronic* processes?

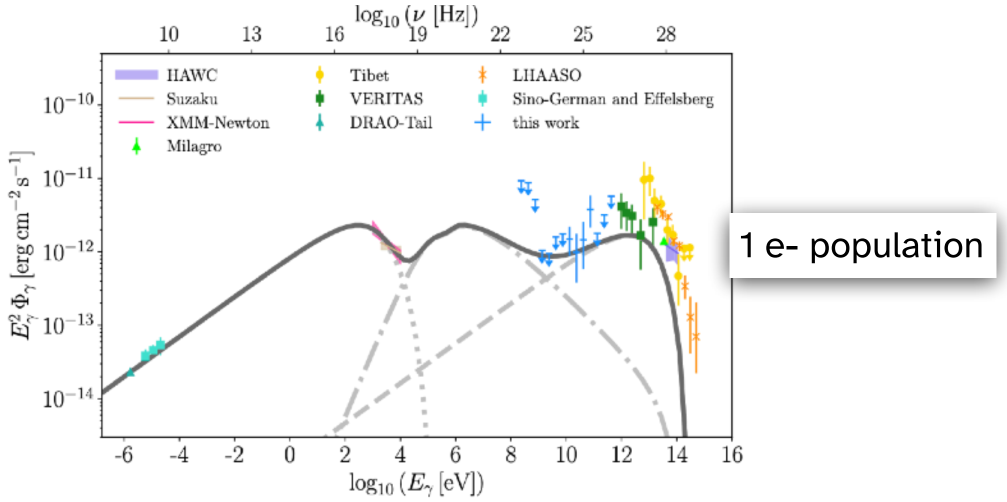
[K. Fang et al., PRL 129 (2022)]

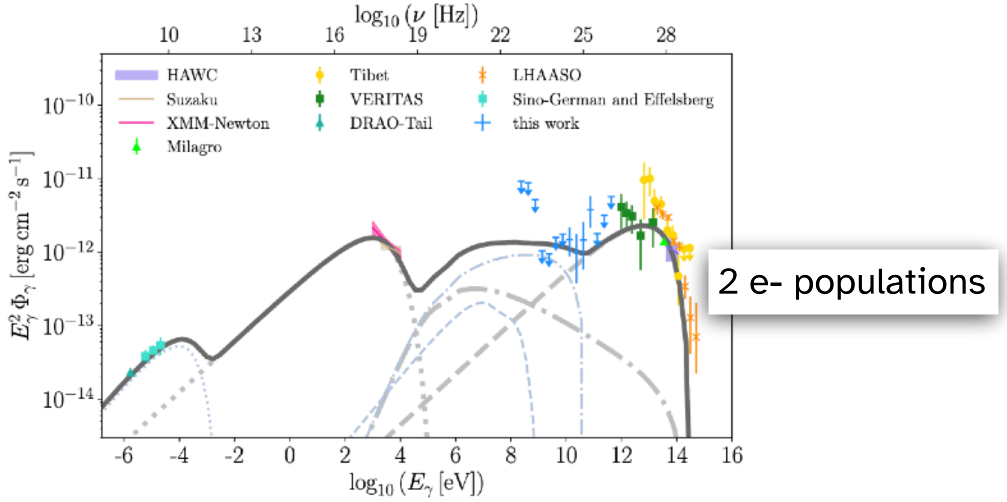
examples for a supernova remnant (G 106.3 +2.7):

hadronic scenario



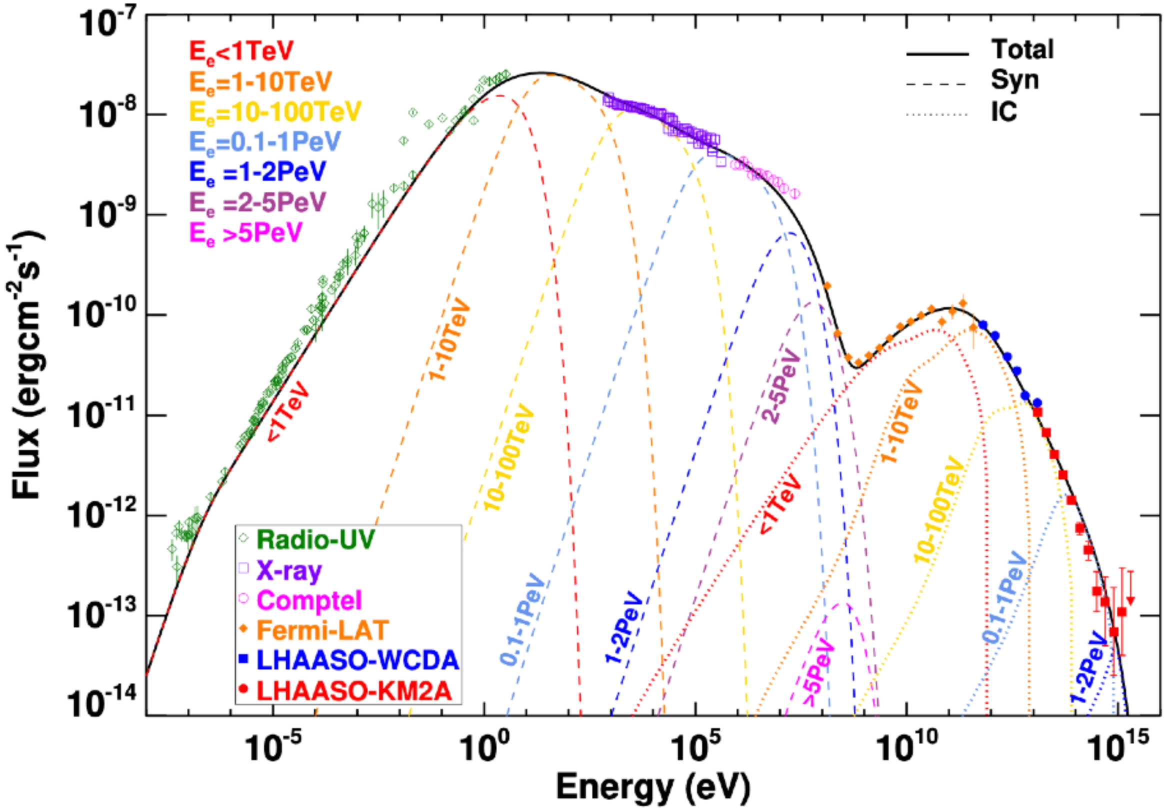
leptonic scenarios





Is the Crab a Pevatron?

Looking for Pevatrons



[LHAASO Collaboration, Science 373 (2021)]

Yes **but** it is a leptonic one

=> The Crab is not a producer of PeV cosmic rays

=> Does this generalize to other composite systems?

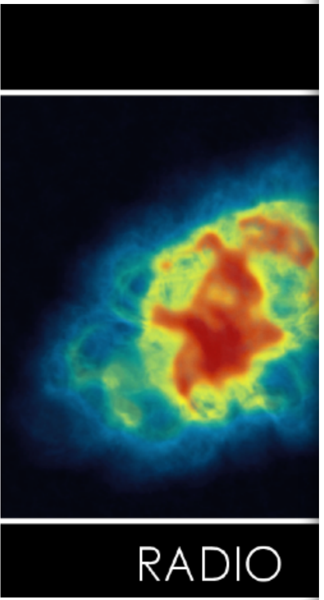
=> What about the individual components?

etc.

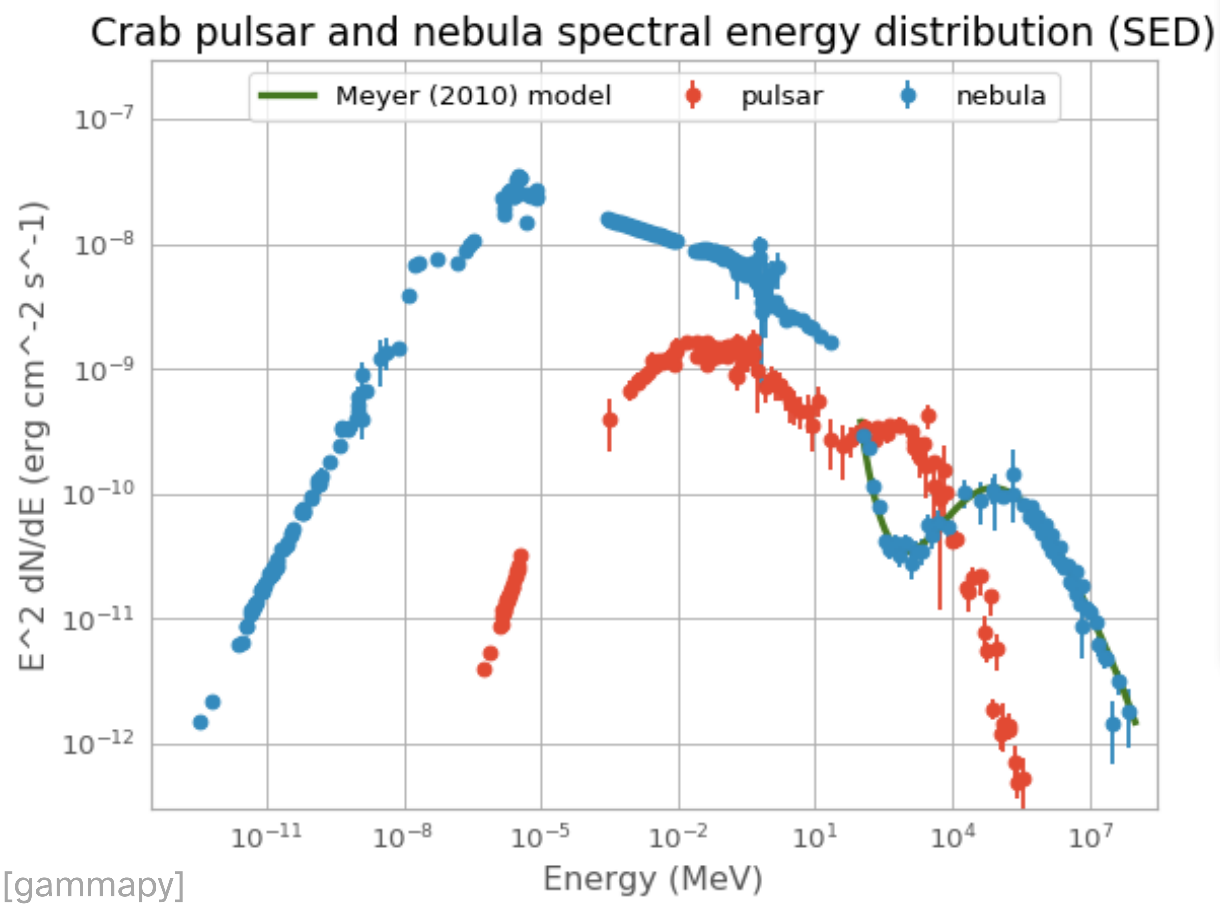
Crab nebula

a composite system: supernova remnant + pulsar wind nebula + pulsar

Emission at different wavelengths suggests multiple physical processes / components

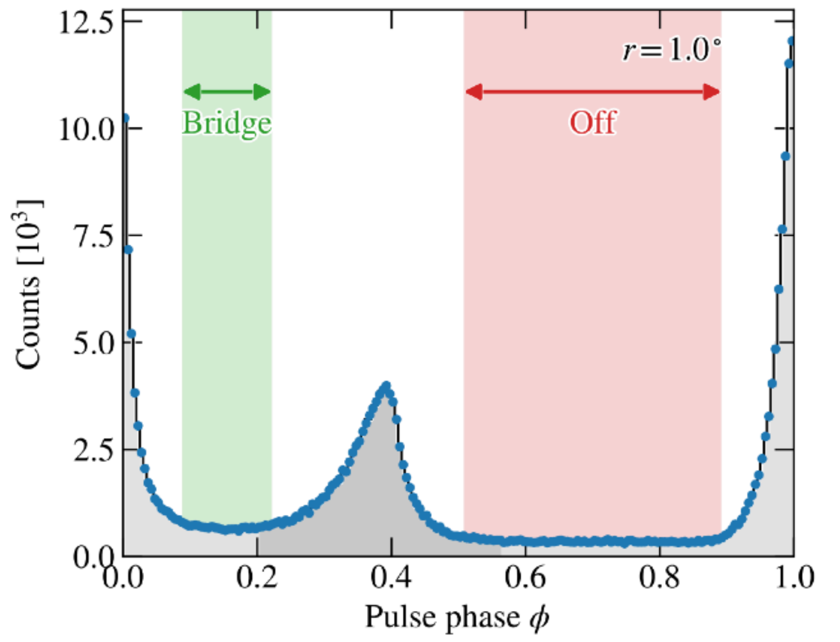


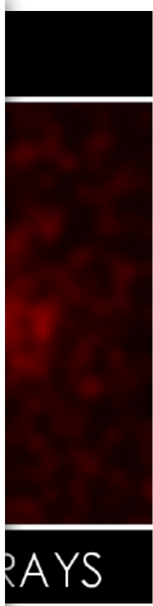
[NRAO/AUI, M. Bi
NASA/CXC/SAO/



[gammapy]

[F. Aharonian et al., A&A 686 (2024)]

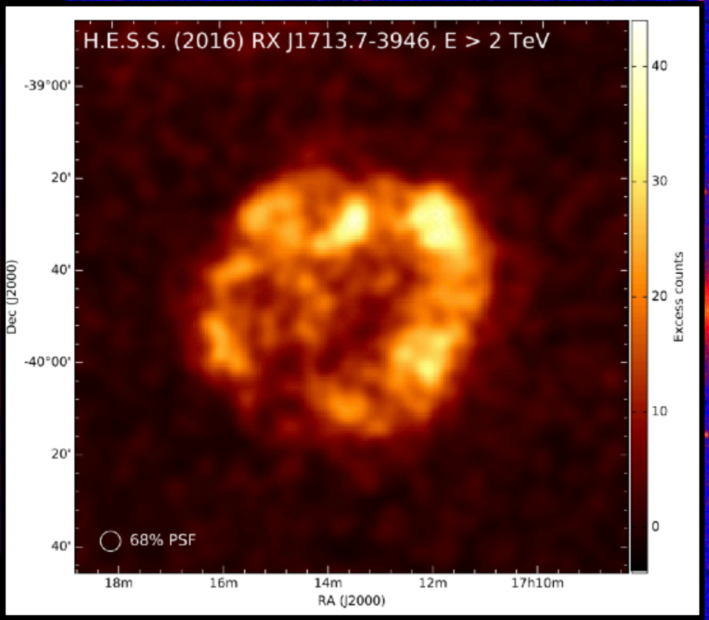




Subtlety: need to separate out the pulsed (pulsar) and unpulsed (nebula) components

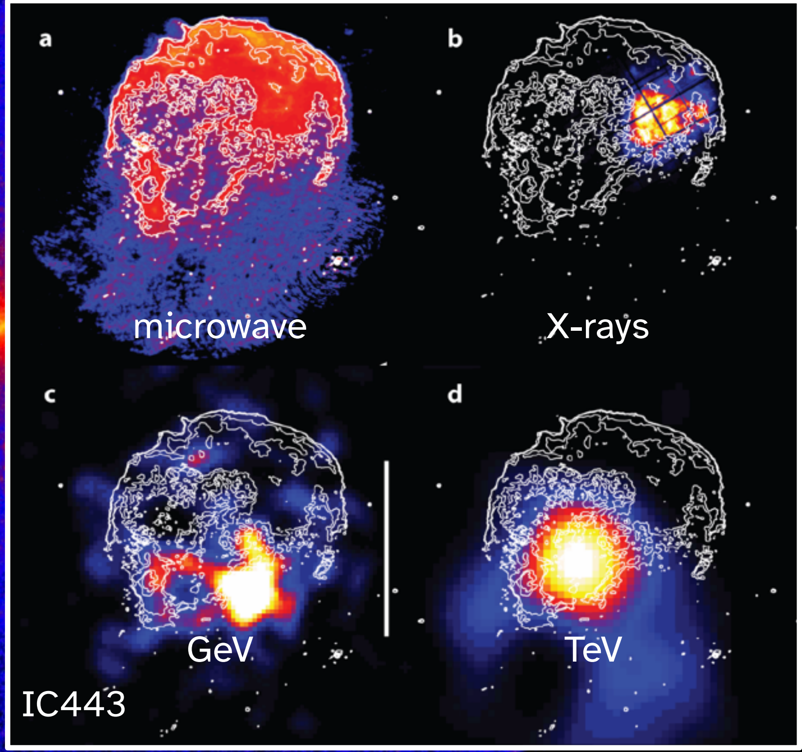
[NASA/DOE/Fermi-LAT Collaboration]

examples of other supernova remnants and pulsar wind nebulae



[H.E.S.S. Collaboration, A&A 612 (2018)]

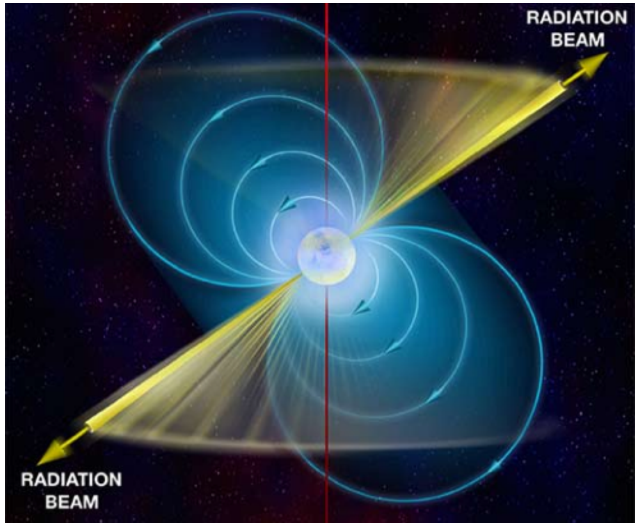
[NASA, ESA, G. Dubner et al.; A. Loll et al.; T. Temim et al.; F. Seward et al.; VLA/NRAO/AUI/NSF; Chandra/CXC; Spitzer/JPL-Caltech; XMM-Newton/ESA; Hubble/STScI]



[S. Funk, ARNPS 65 (2015)]

Pulsars

Nature's lighthouses?



[NRAO]

Pulsars are often described as lighthouses

-> charged particles funnelled along magnetic field lines to the poles, produce relativistically beamed radiation

Pulsars

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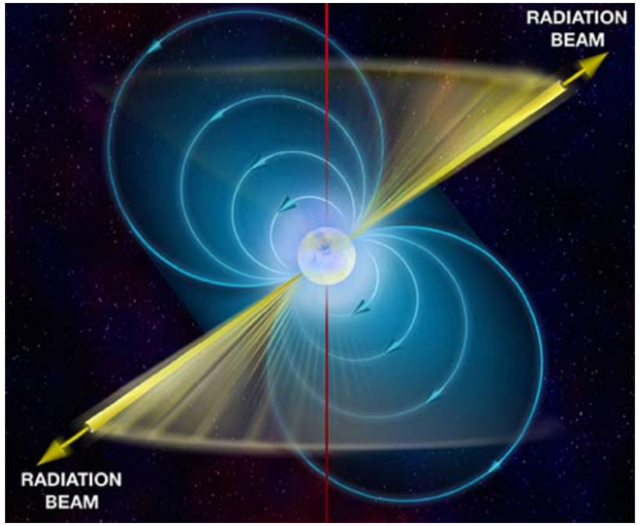

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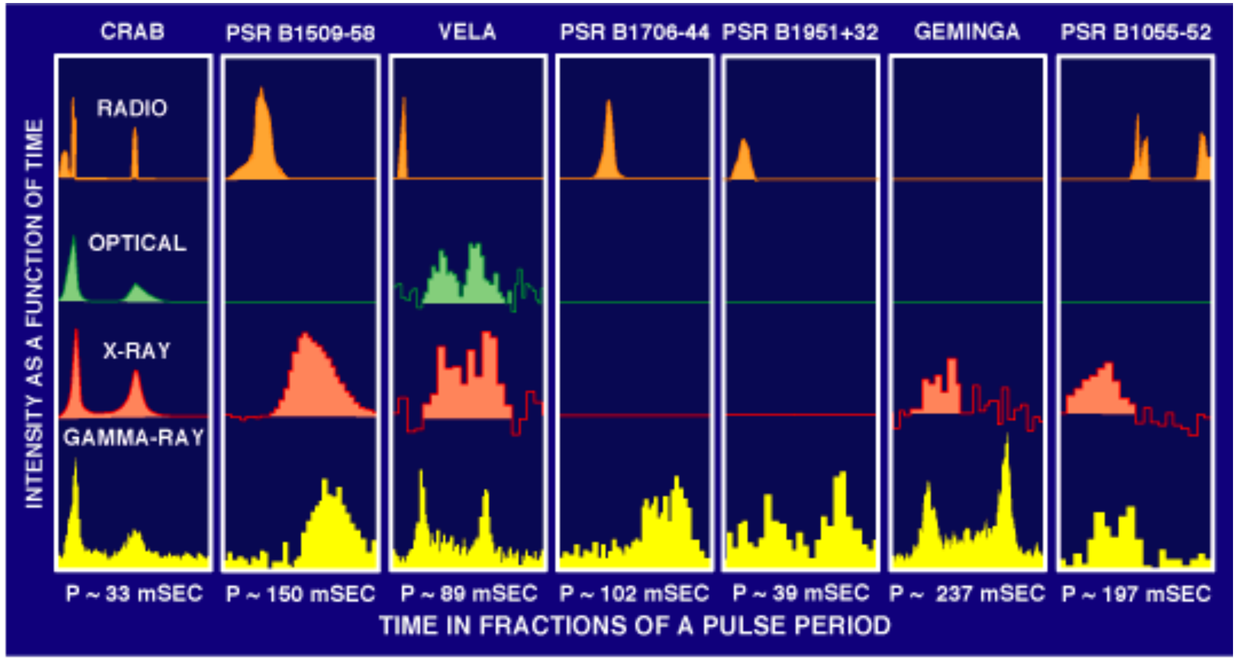
[D.J. Thompson (NASA/GSFC)]

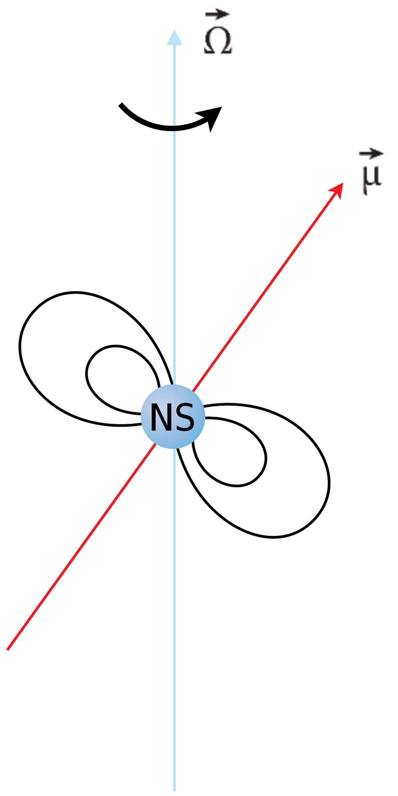


But it's been known for a while that the emission is more complex

compare lightcurves at different wavelengths

Pulsars

So where *are* the photons being produced?



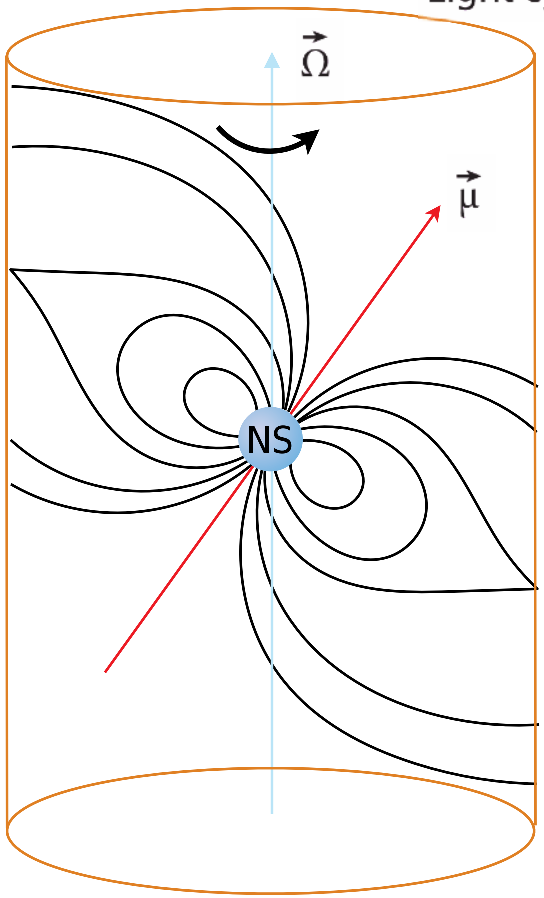
[A. Philippov & M. Kramer, Annu Rev Astron & Astrophys 60 (2022)]

Pulsars

So where *are* the photons being produced?

Light cylinder = where the magnetic field lines would be rotating at the speed of light

$R_{LC} = c/\Omega$



[A. Philippov & M. Kramer, Annu Rev Astron & Astrophys 60 (2022)]

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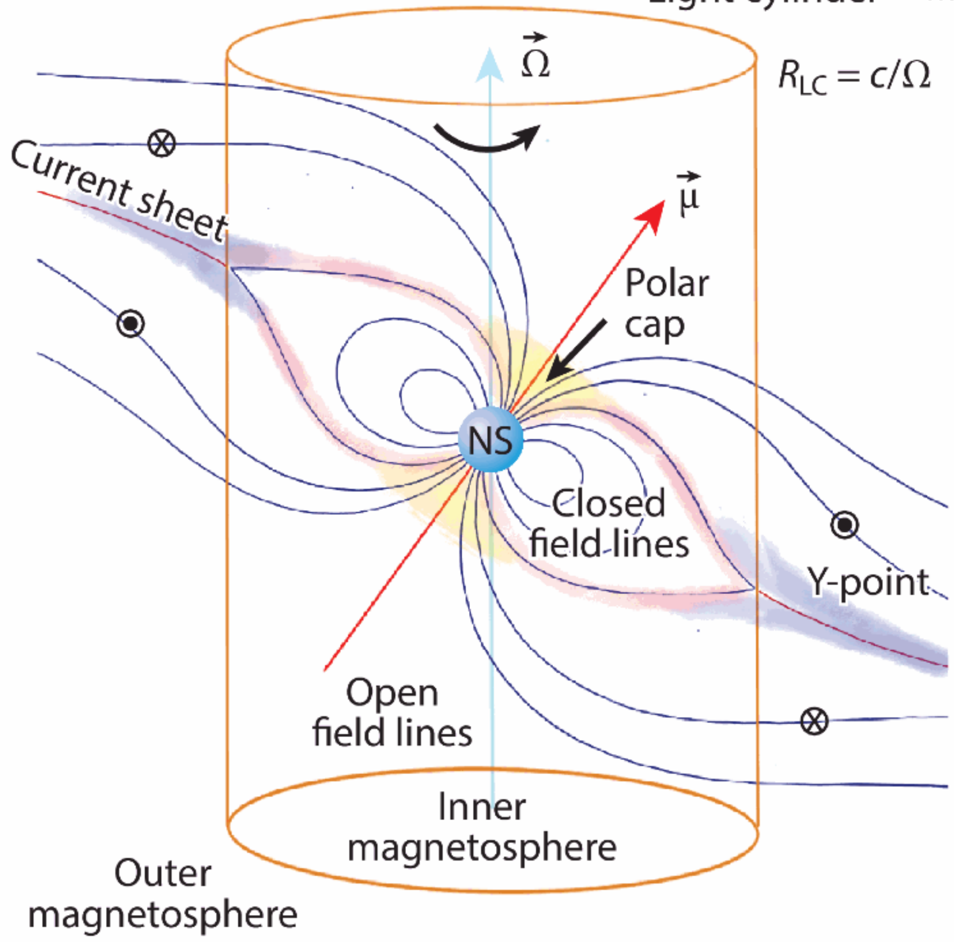
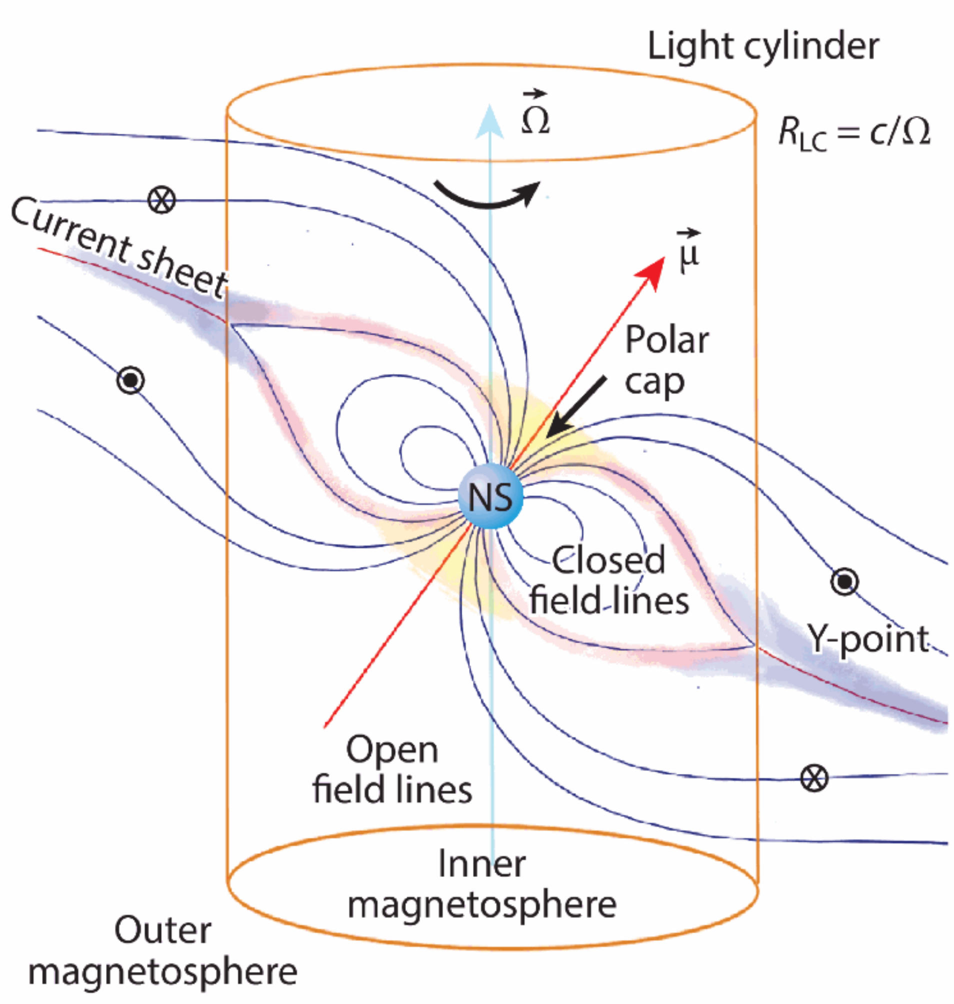


There are multiple regions in the magnetosphere that could be the sources the (gamma-ray) emission

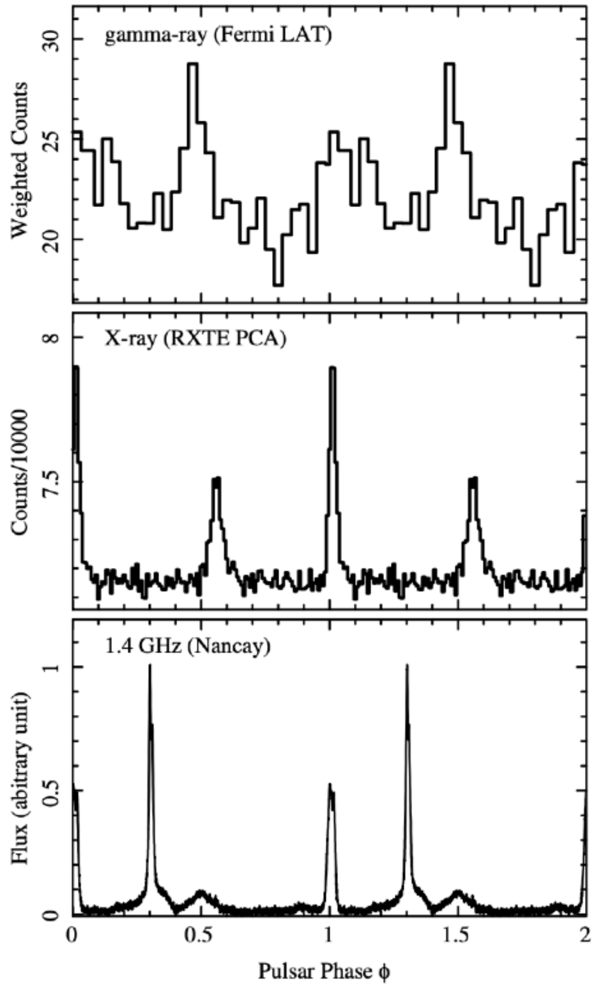
[A. Philippov & M. Kramer, Annu Rev Astron & Astrophys 60 (2022)]

Pulsars

So where *are* the photons being produced?



[A. Philippov & M. Kramer, Annu Rev Astron & Astrophys 60 (2022)]



[Y. Du et al., ApJ 801 (2015)]

if the peaks are not aligned, likely the emission is coming from different regions

=> pulsar modelling is a very active field

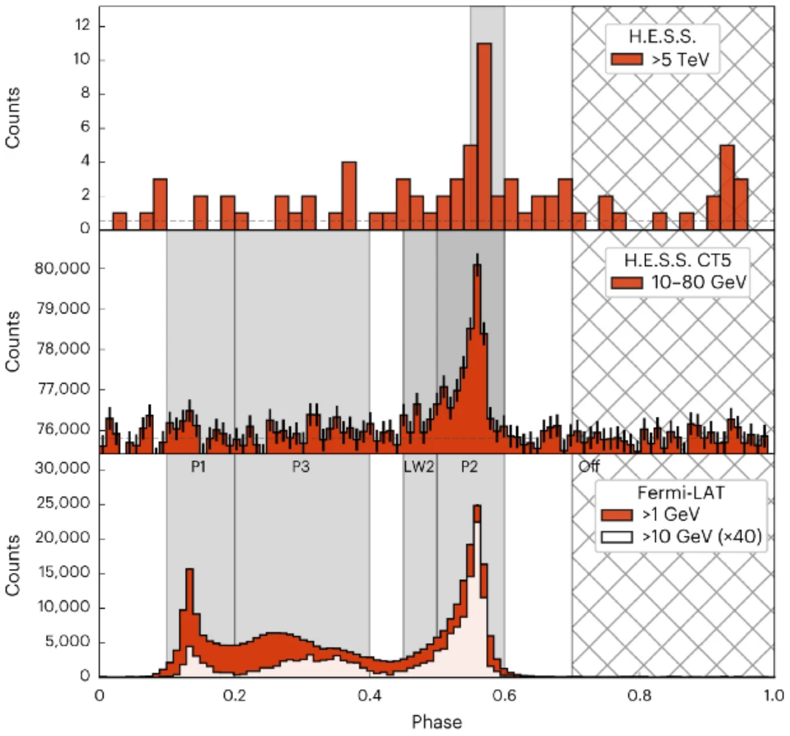
Scientists discover
the highest energy gamma-rays
from a pulsar

[Science Communication Lab for DESY]

Pulsars

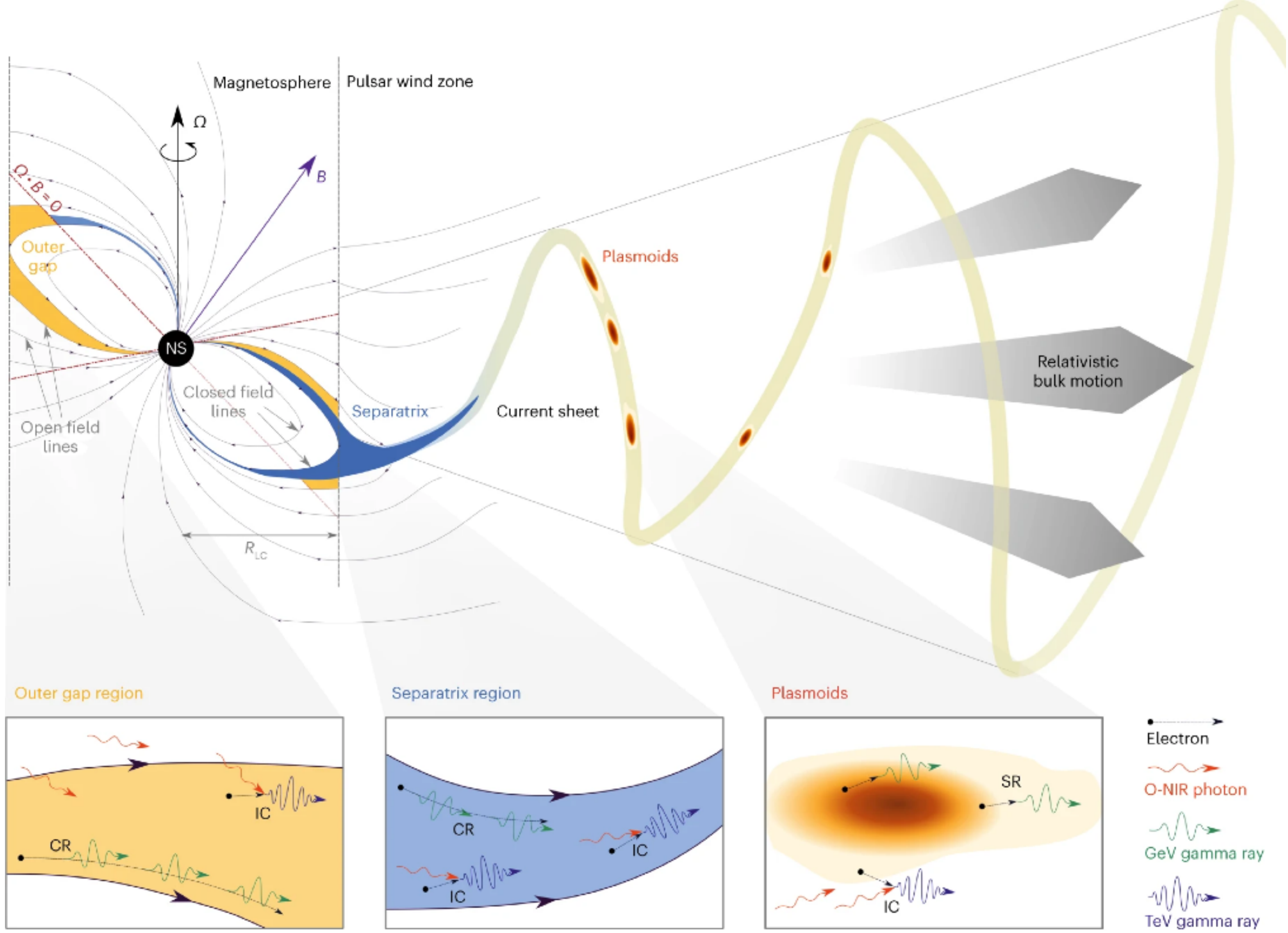
TeV emission

H.E.S.S. detected pulsations >5 TeV from the Vela pulsar



[H.E.S.S. Collaboration, Nature Astro 7 (2023)]

This allows for more detailed investigations of how and where pulsars accelerate charged particles

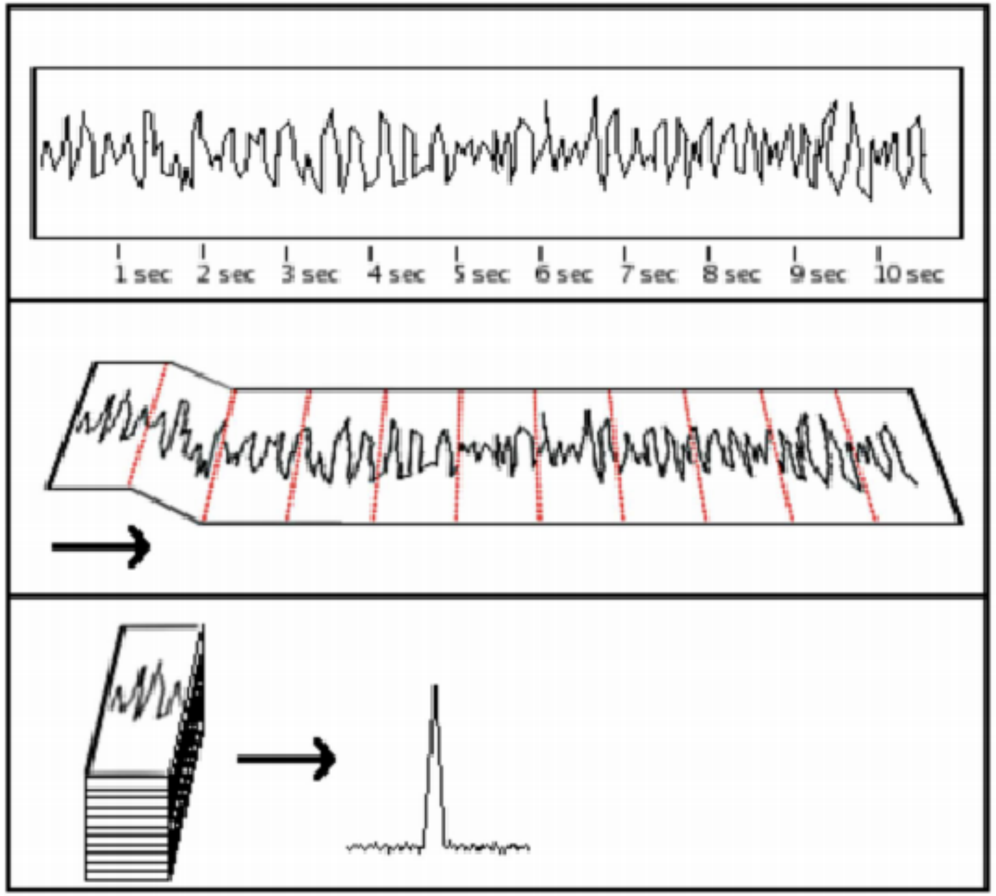


Searching for pulsars

if you don’t have a multiwavelength counterpart

If you have a model for how the pulsar is rotating (ephemeris), you can “fold” the data to look for a signal

(note: this method is common across all wavelengths and isn’t just for gamma rays)



[P. Kumar, J Student Res 10 (2021)]

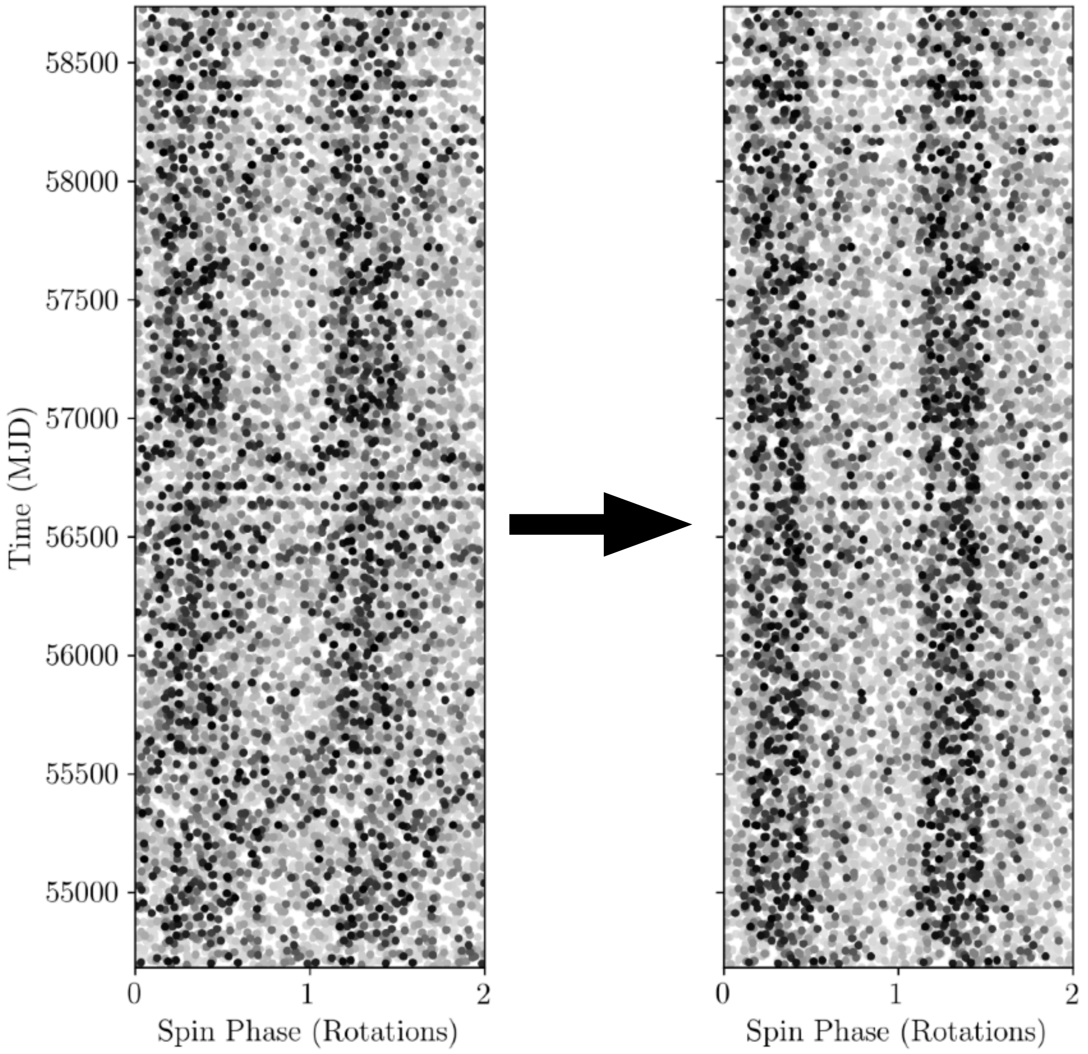
Searching for pulsars

if you don't have a multiwavelength counterpart

If you have a model for how the pulsar is rotating (ephemeris), you can "fold" the data to look for a signal

If you have the right ephemeris, the signal will increase in significance

Fermi-LAT data, PSR J2037-5617 (in a binary)



[C. J. Clark et al., MNRAS 502 (2021)]

Searching for pulsars

if you don't have a multiwavelength counterpart

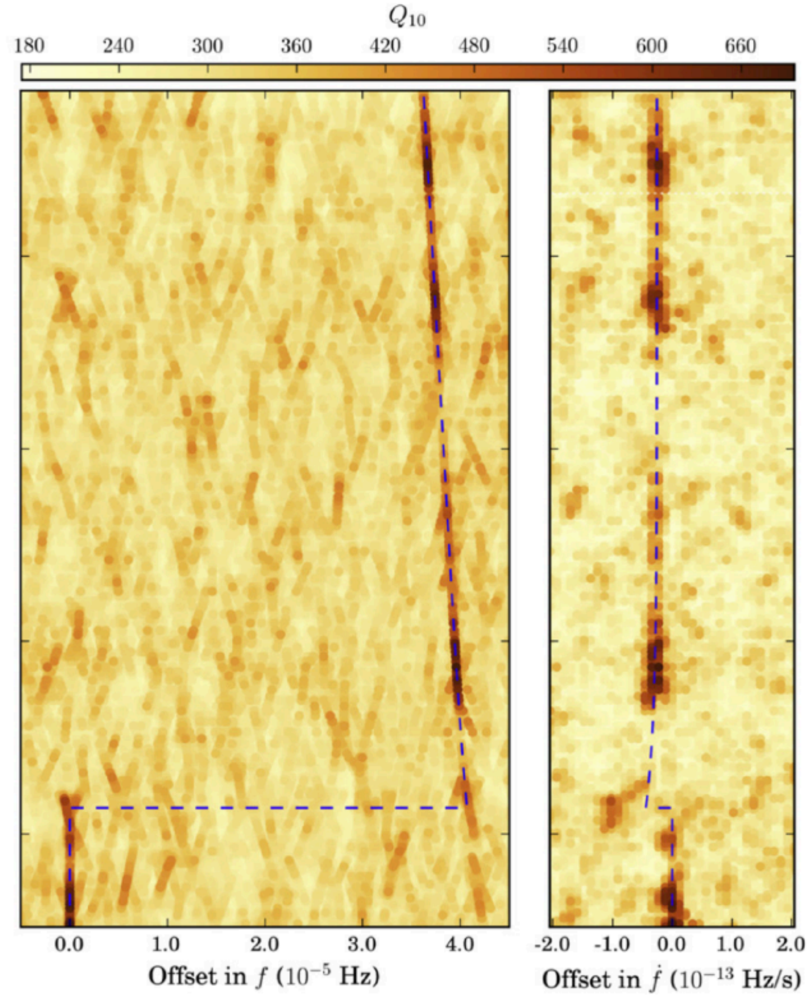
If you have a model for how the pulsar is rotating (ephemeris), you can "fold" the data to look for a signal

If you have the right ephemeris, the signal will increase in significance

Sometimes the pulsar glitches, and the frequency (and frequency derivative) changes suddenly

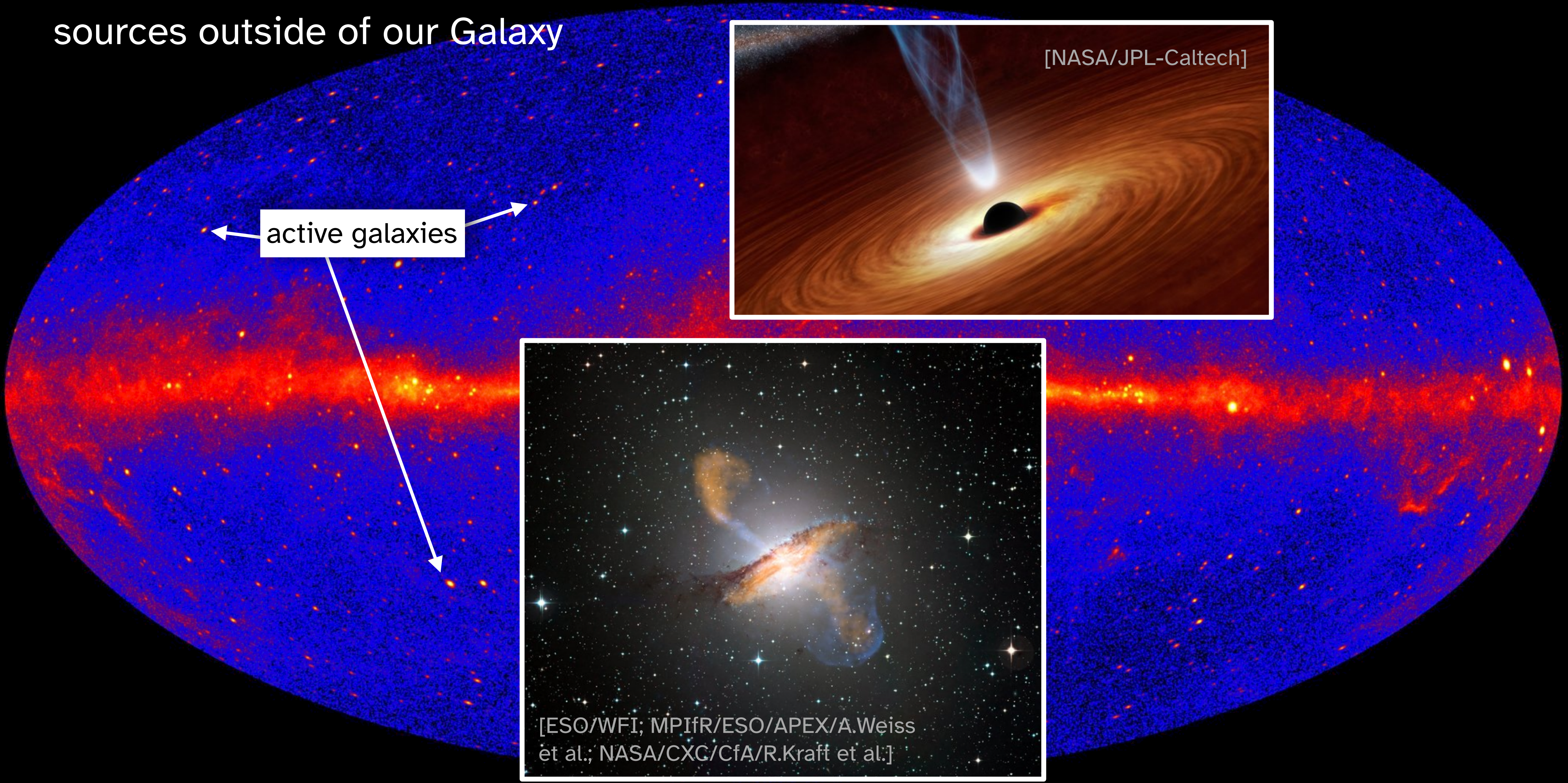
- The reasons for glitches are unknown, might be due to changes in the neutron star's internal structure

Fermi-LAT blind search of PSR J1906+0722



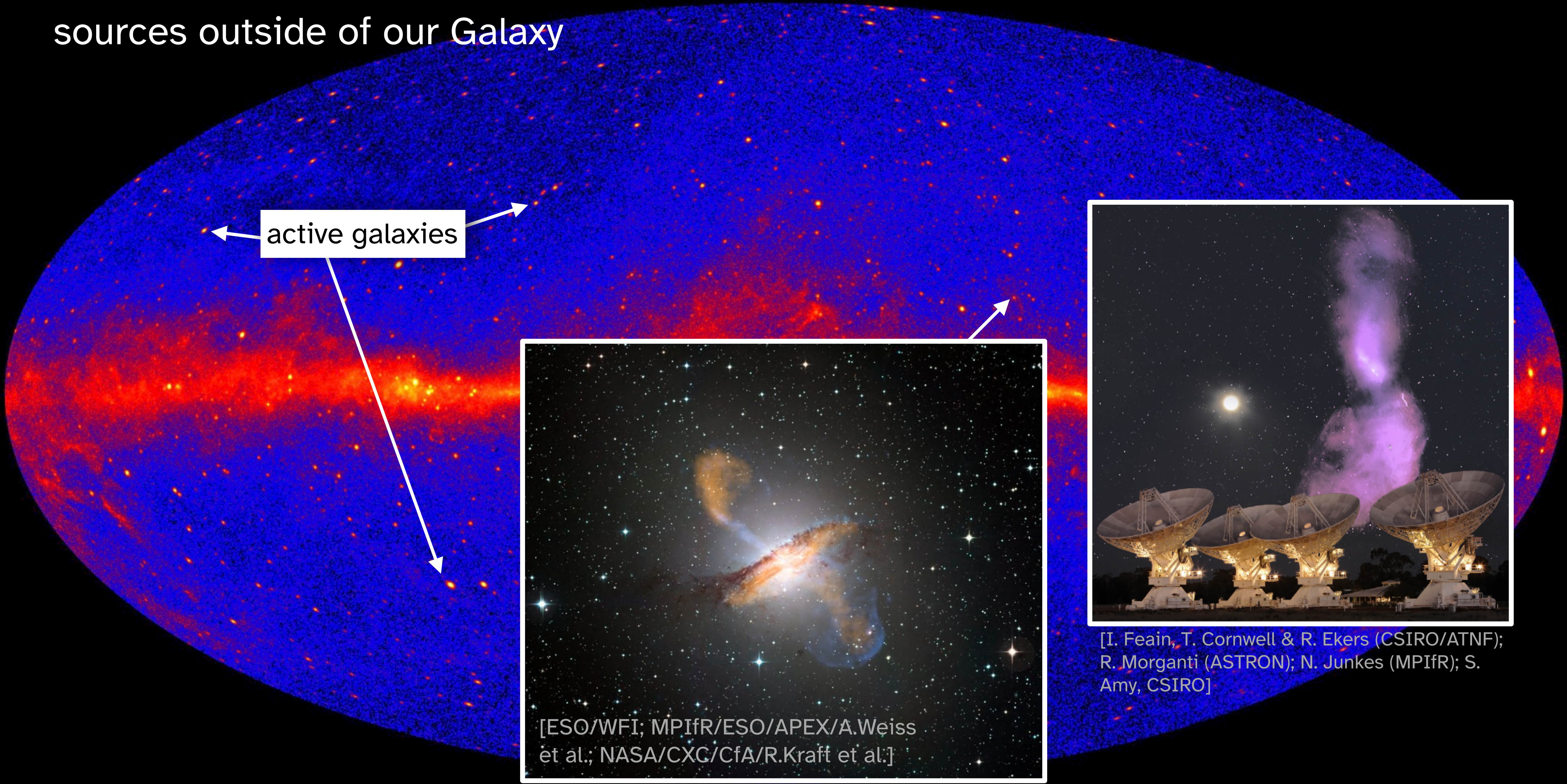
[C. J. Clark et al., ApJ 809 (2015)]

sources outside of our Galaxy



[NASA/DOE/Fermi-LAT Collaboration]

sources outside of our Galaxy

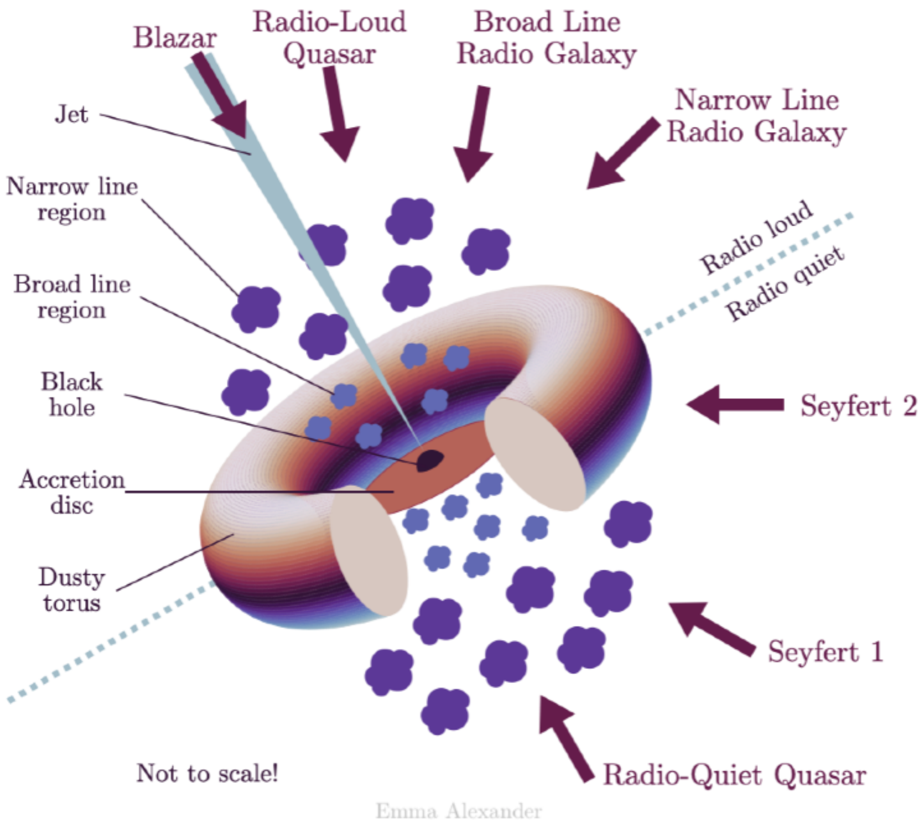


[ESO/WFI; MPIfR/ESO/APEX/A.Weiss et al.; NASA/CXC/CfA/R.Kraft et al.]

[I. Feain, T. Cornwell & R. Ekers (CSIRO/ATNF); R. Morganti (ASTRON); N. Junkes (MPIfR); S. Amy, CSIRO]

Active galaxies in a nutshell

I don't understand them very well though so this is all I'm going to say 😬



[Emma Alexander]

Most galaxies have a supermassive black hole in the center

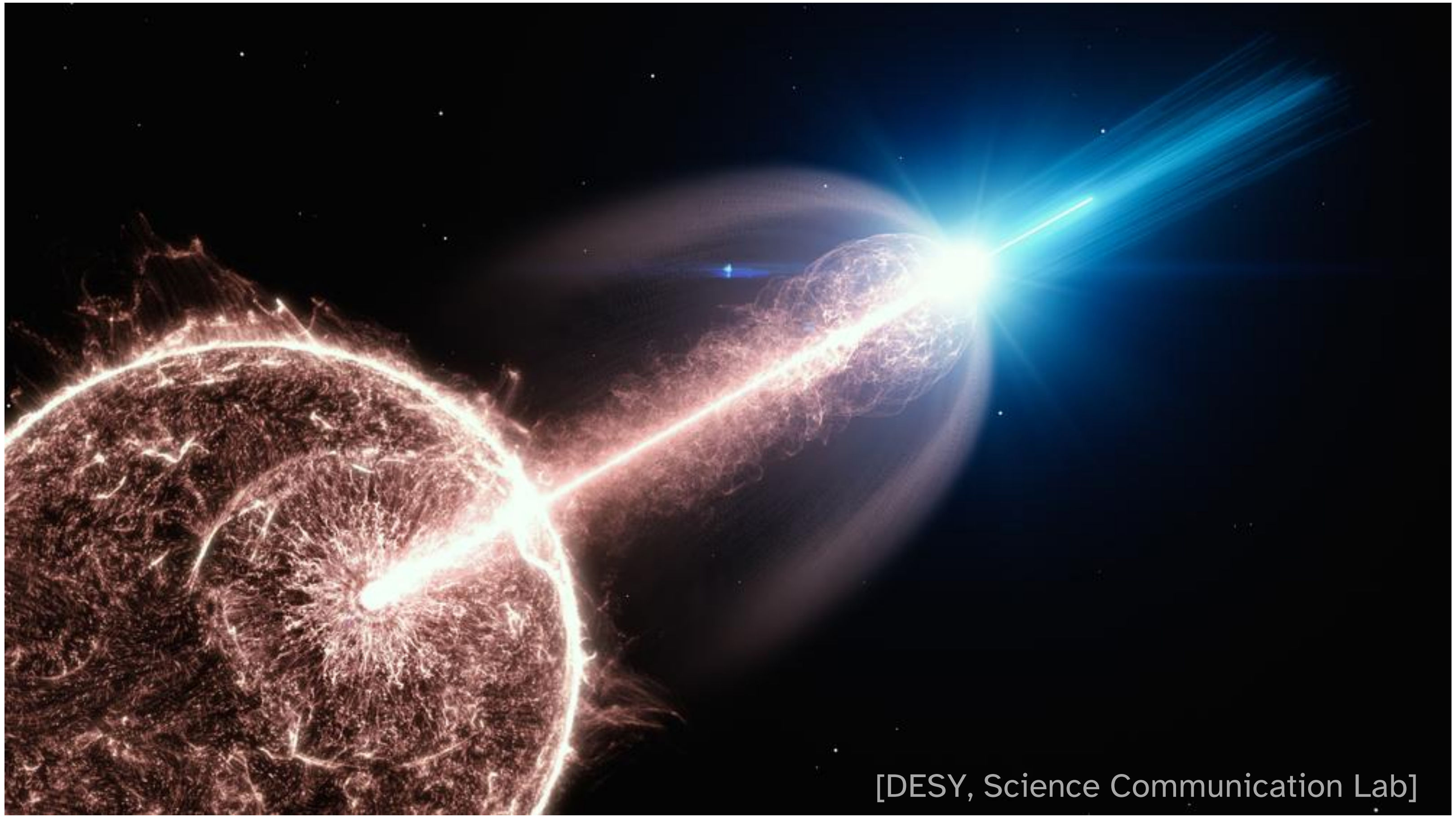
If the black hole is accreting matter, it can emit across the electromagnetic spectrum

How we name it depends on the viewing angle and the properties of the system

e.g., Centaurus A is a radio galaxy

now I'm going to focus on gamma-ray bursts

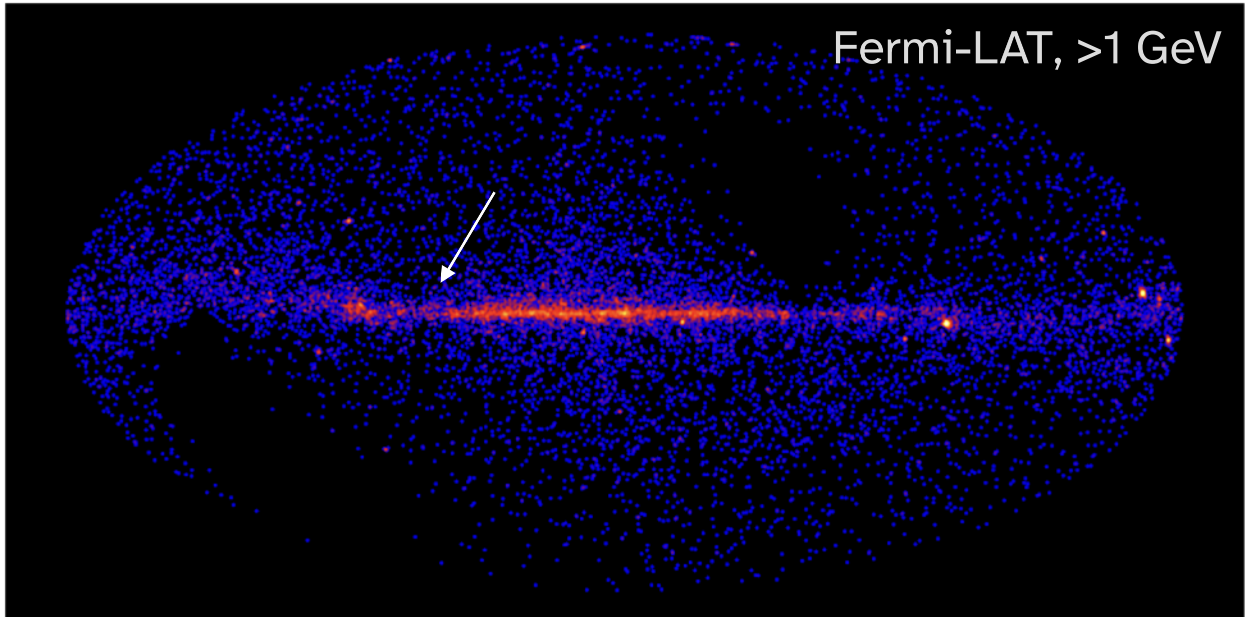
because I'm biased (because this is what I study)



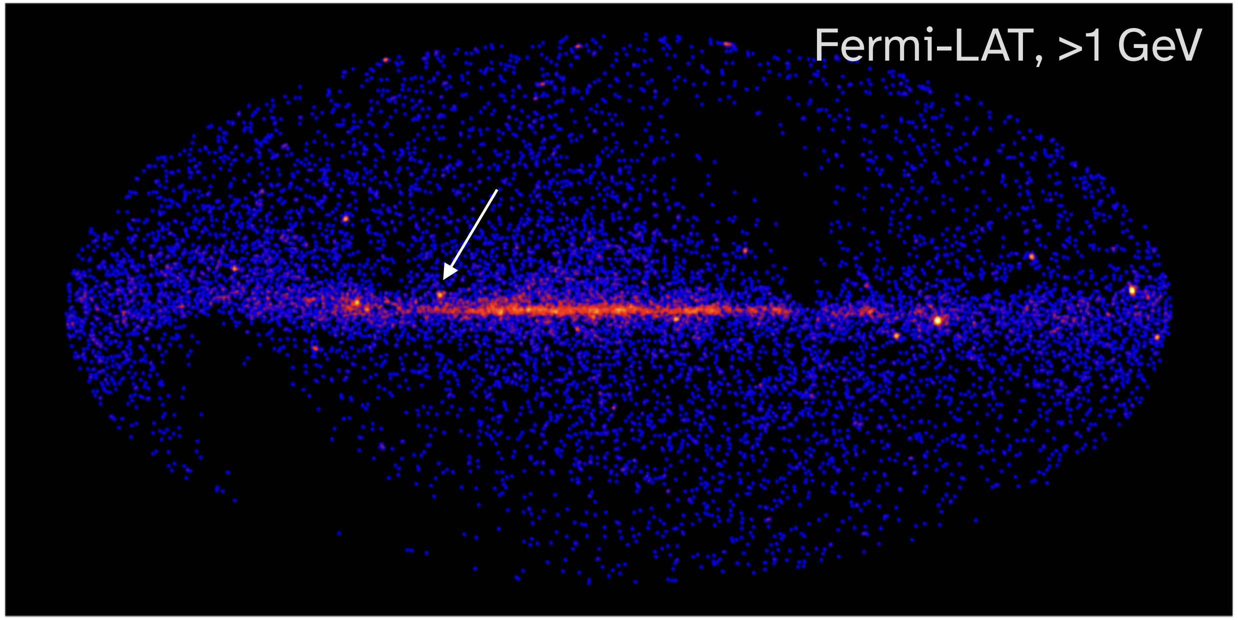
ok but what exactly is a “gamma-ray burst”?

Literally, a burst of gamma rays that easily outshines the rest of the gamma-ray sky for their brief existence

D. Green



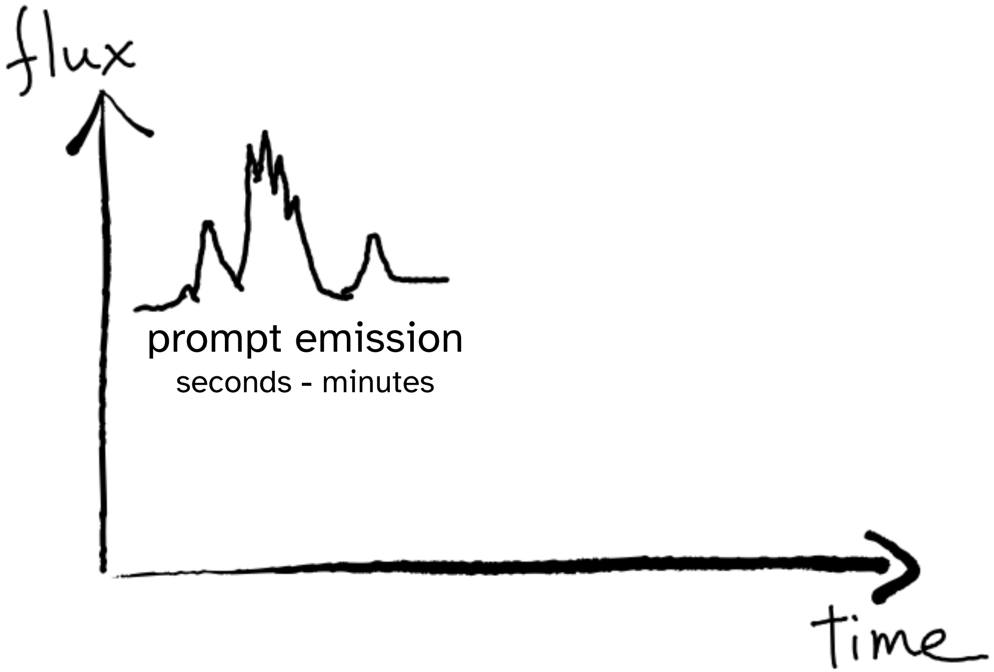
2 days before GRB

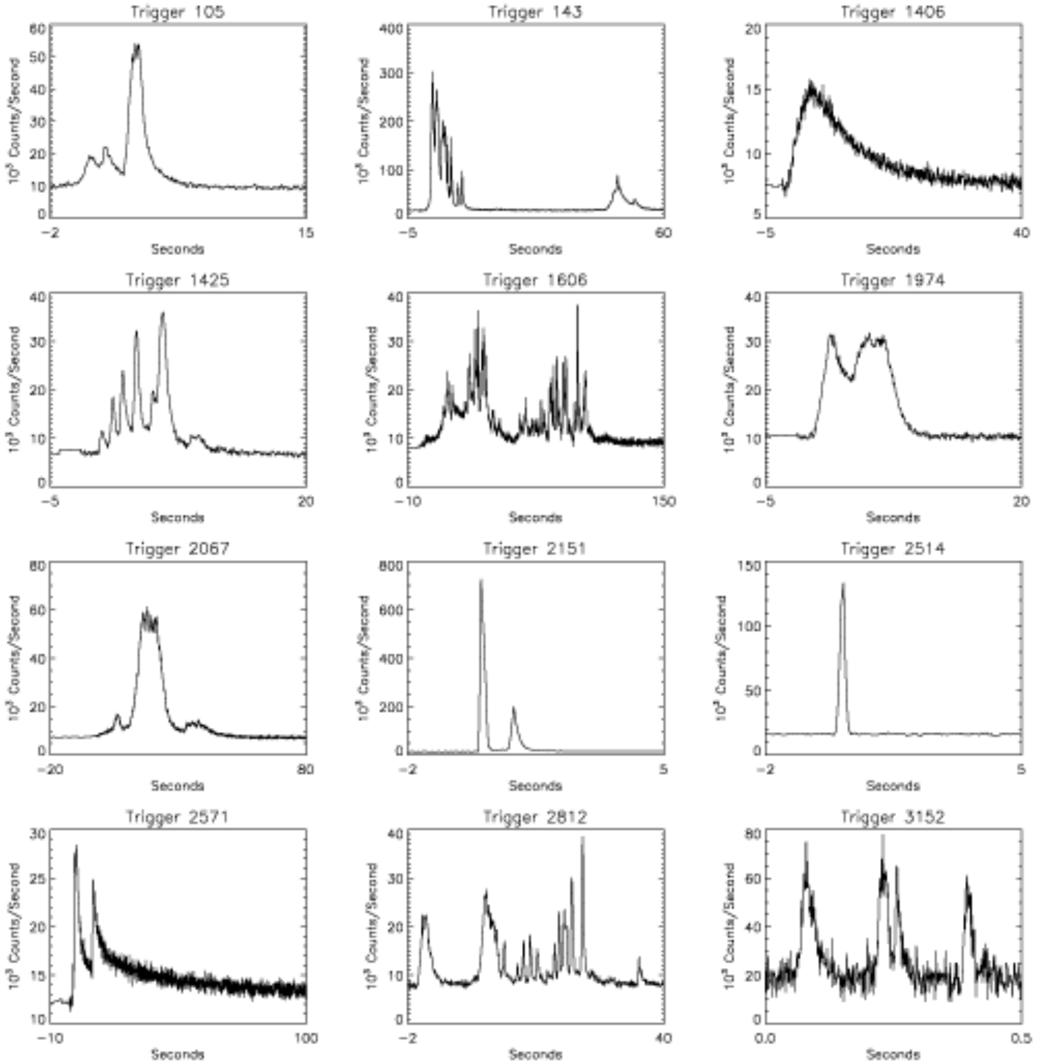


GRB + 2 days after

Gamma-ray bursts

What causes them, and how do we know?



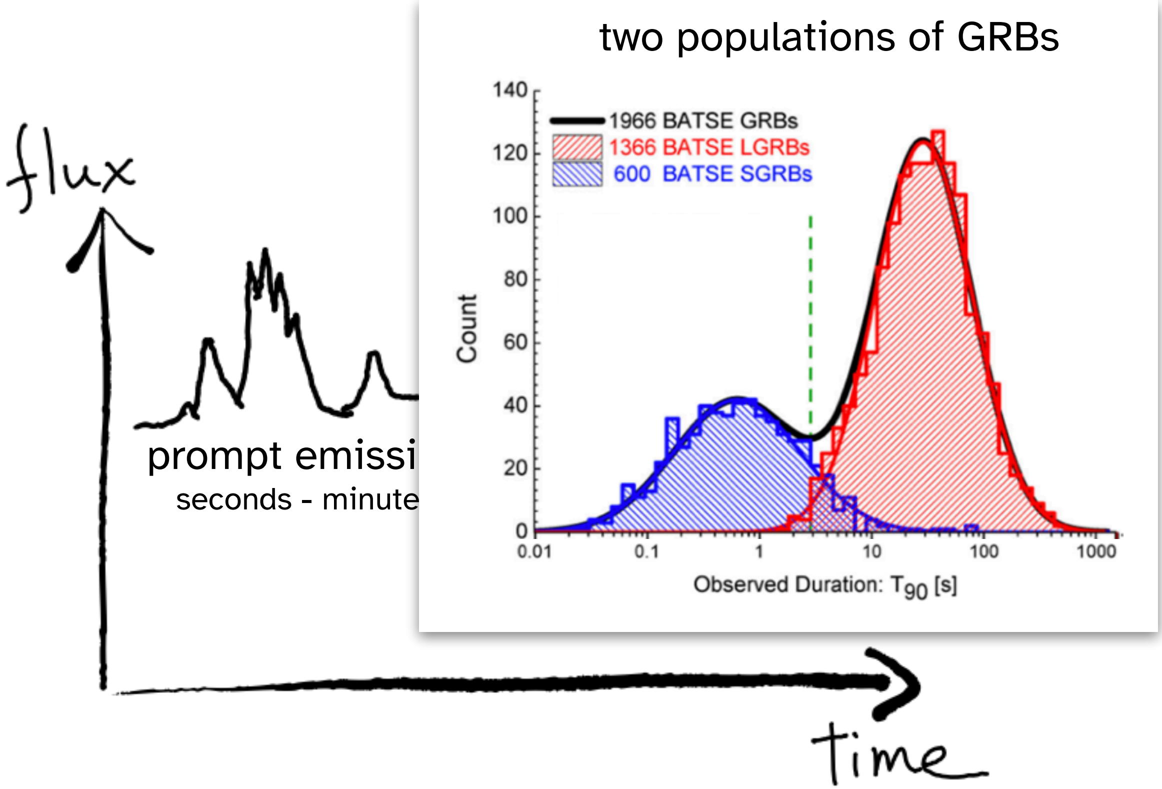


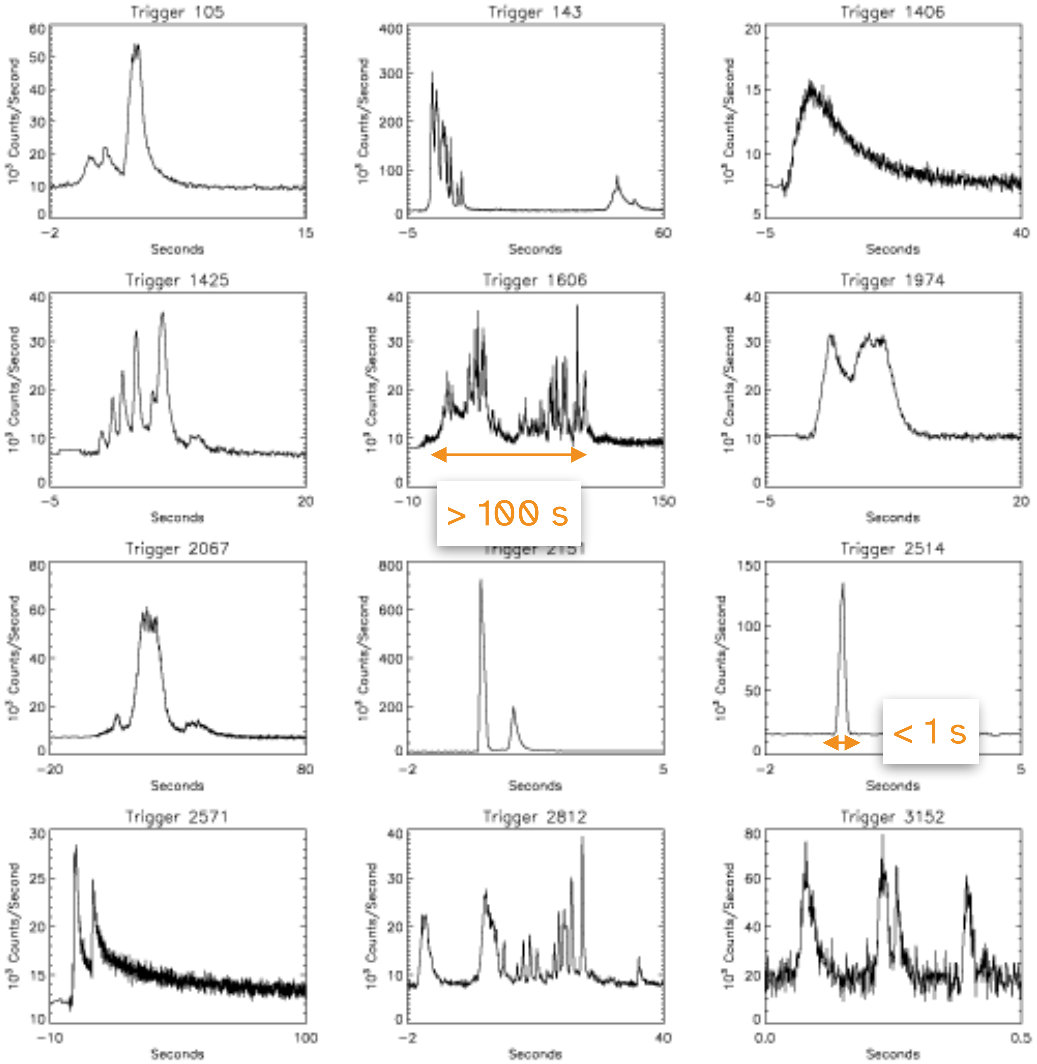
[J. T. Bonnell (NASA/GSFC)]

Gamma-ray bursts

What causes them, and how do we know?

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





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

Gamma-ray bursts

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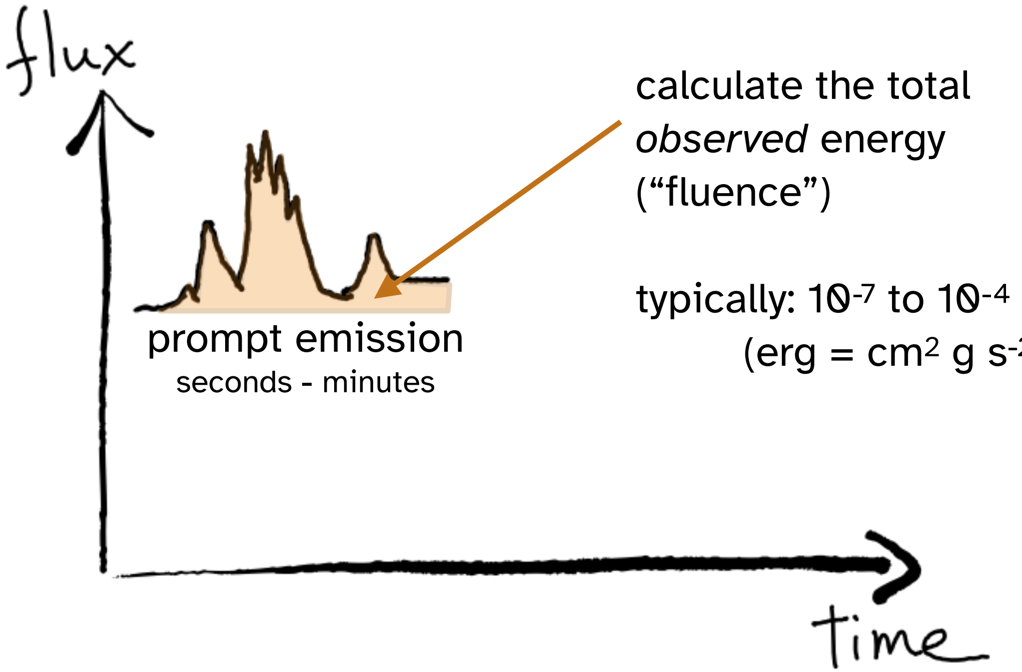
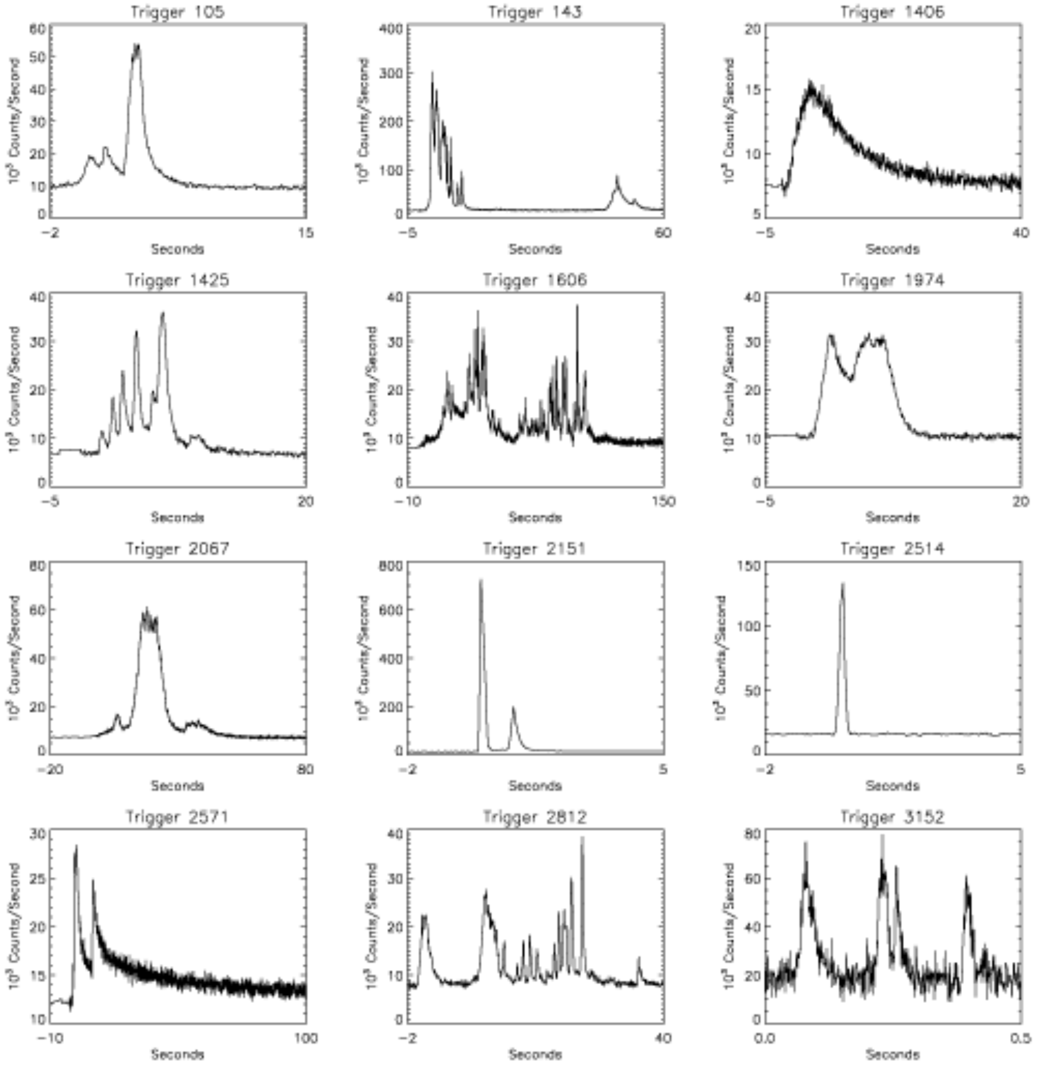


calculate the total *observed* energy ("fluence")

typically: 10^{-7} to 10^{-4} erg
($\text{erg} = \text{cm}^2\ \text{g}\ \text{s}^{-2}$)



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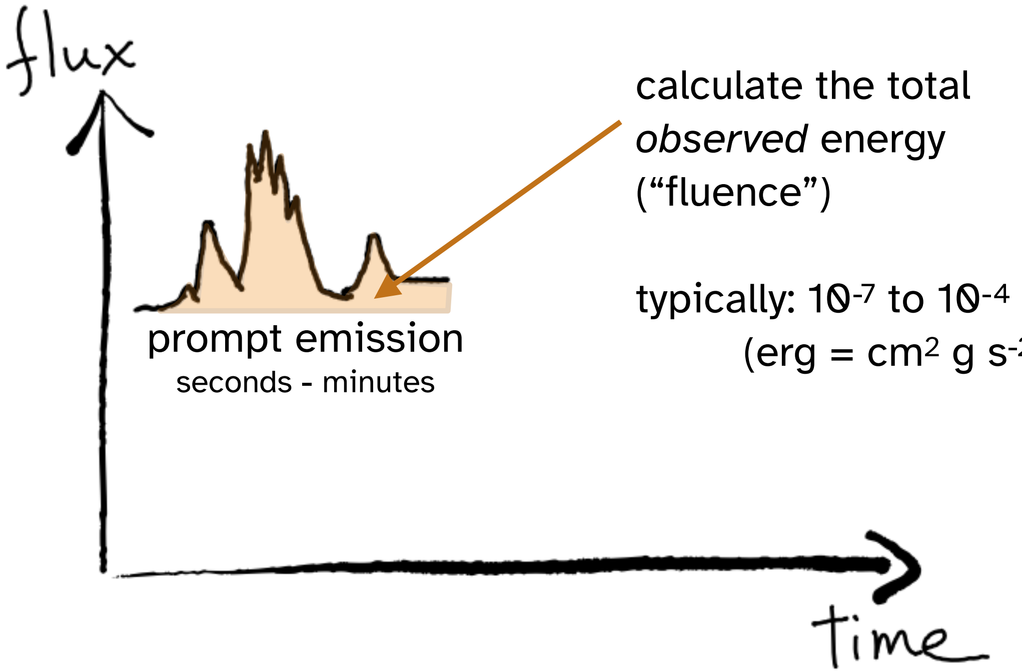

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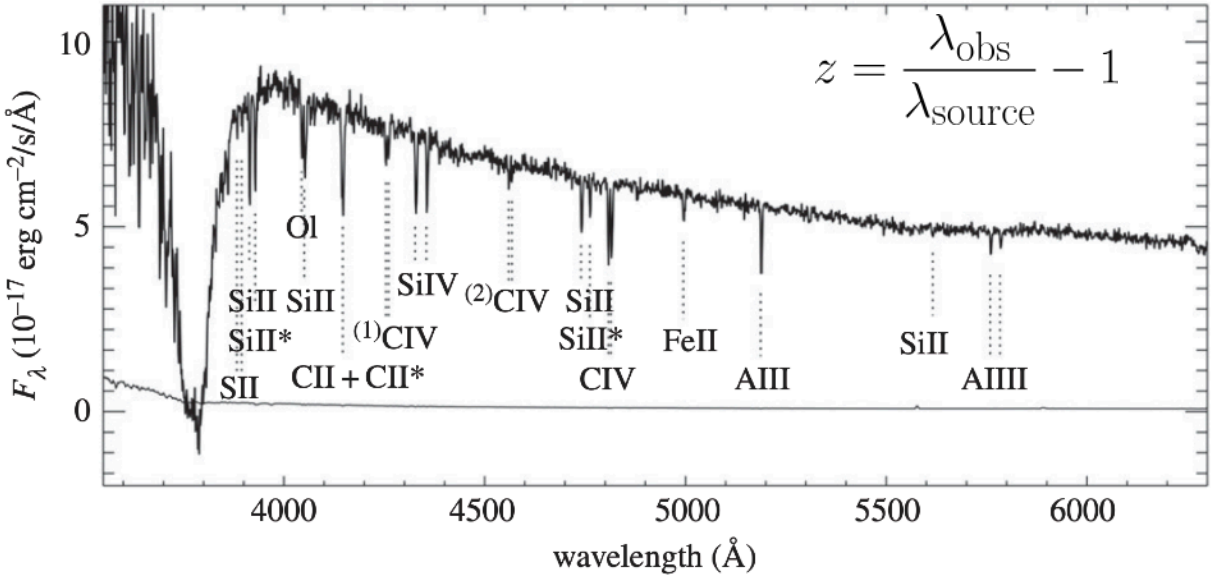
[A. Rau et al., ApJ 720 (2010)]

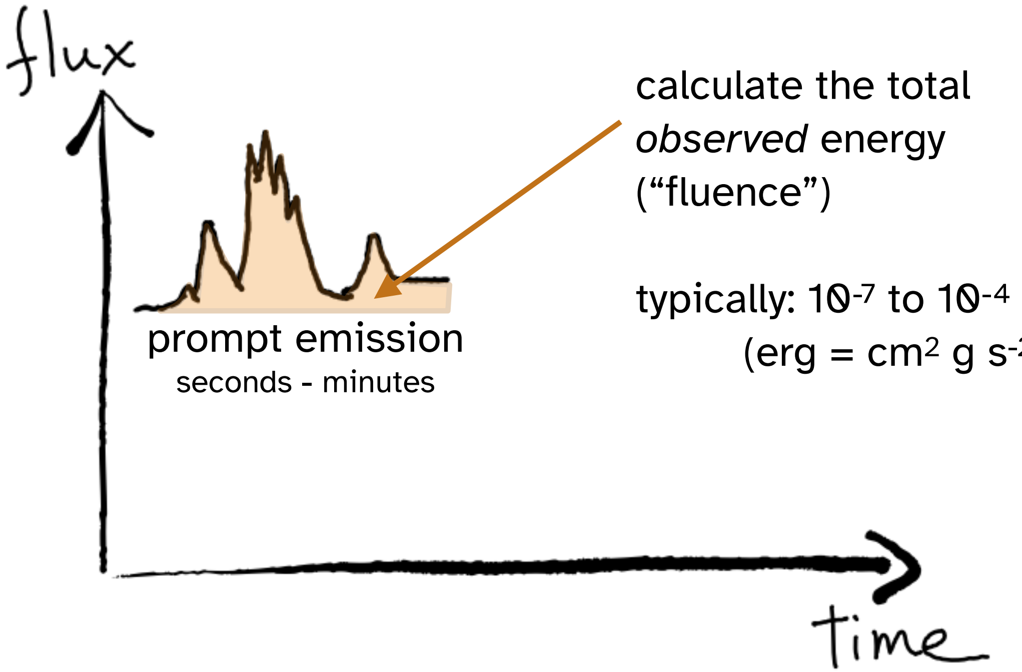


e.g., OI line: 4050 Å here
1356 Å rest frame } z ~ 2 ~ 16 Gpc

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

Gamma-ray bursts

What causes them, and how do we know?



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

typically: 10^{-7} to 10^{-4} erg
(erg = cm^2 g s^{-2})

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

energy emitted by the source (assuming isotropic):

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

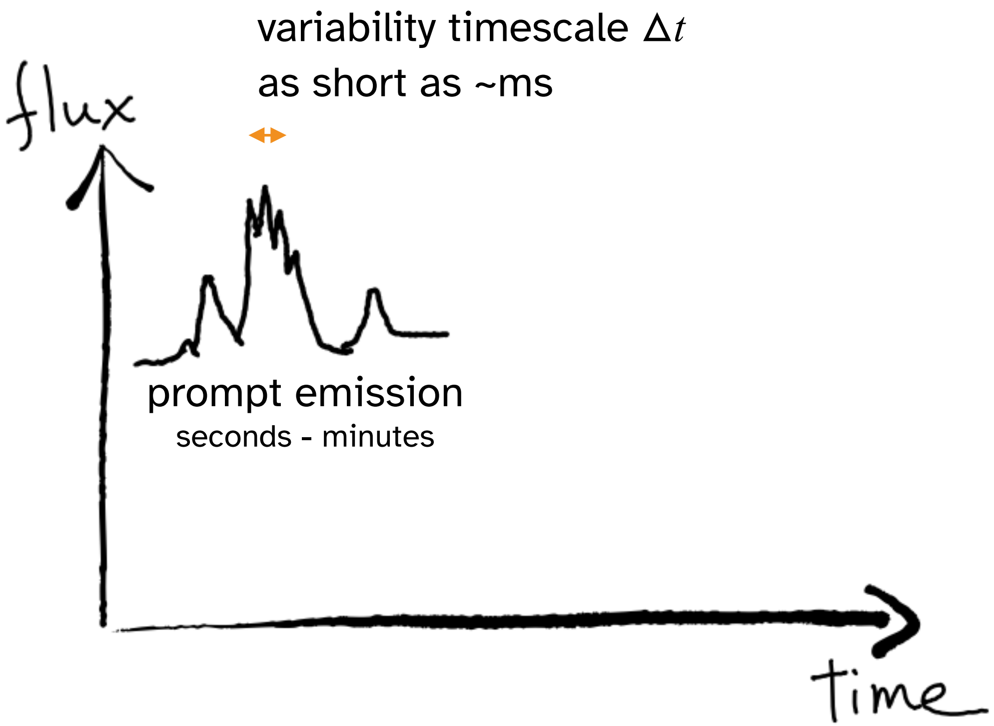
by comparison, the rest energy of the Sun:

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

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, and how do we know?



size of emitting region:

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

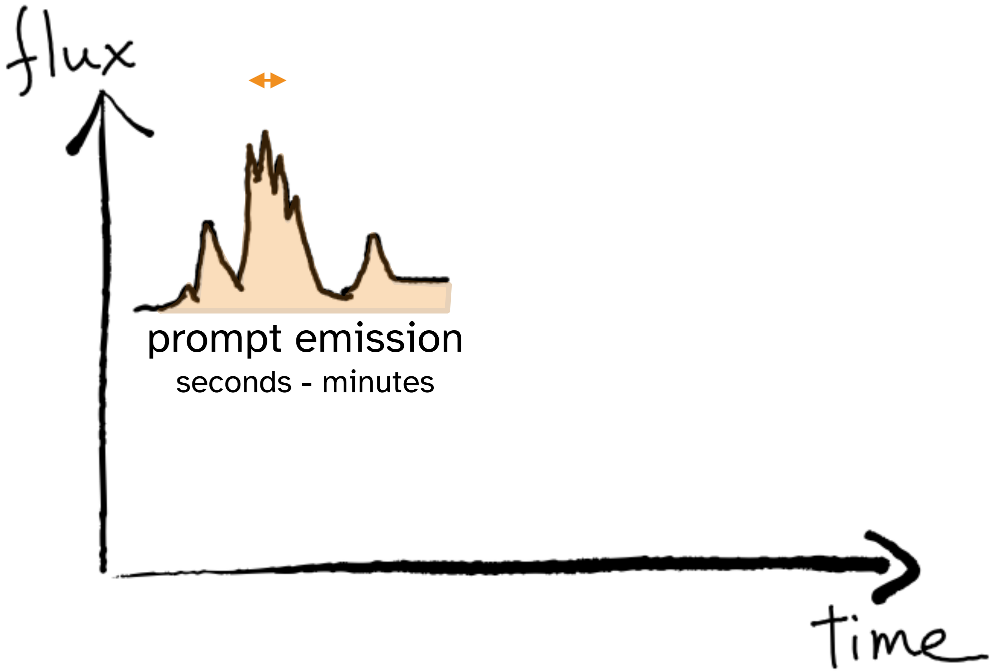
compare to the radius of Earth:

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

so, emission is occurring in regions smaller than the Earth

Gamma-ray bursts

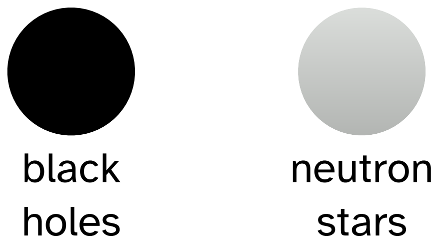
What causes them, and how do we know?



Combining these facts:

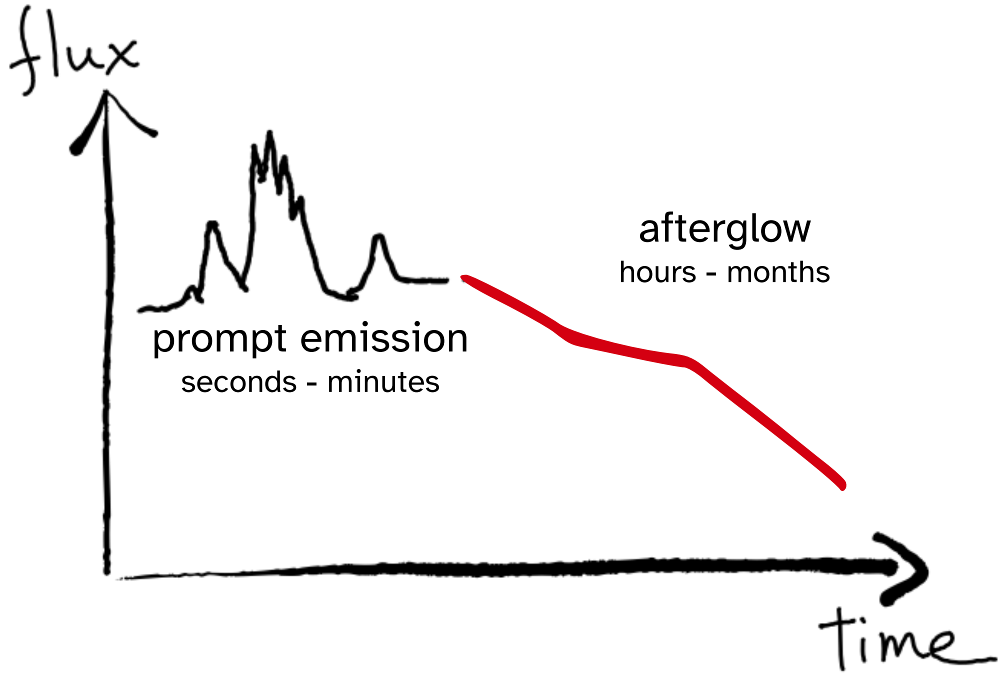
GRBs are stellar-sized phenomena
release $M_\odot c^2$ within minutes
emission occurring in regions smaller than the Earth

=> stellar-mass compact objects must be involved

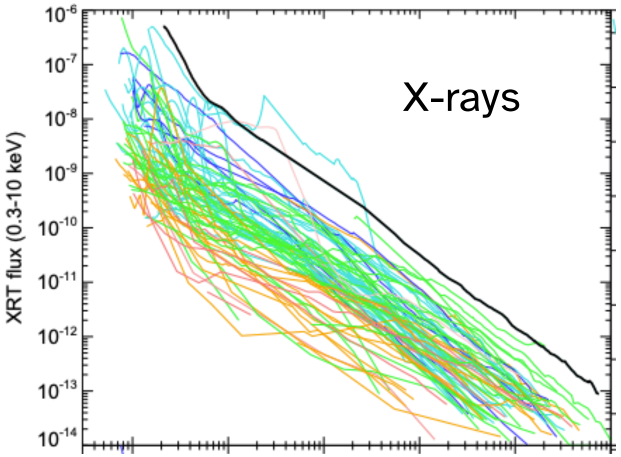


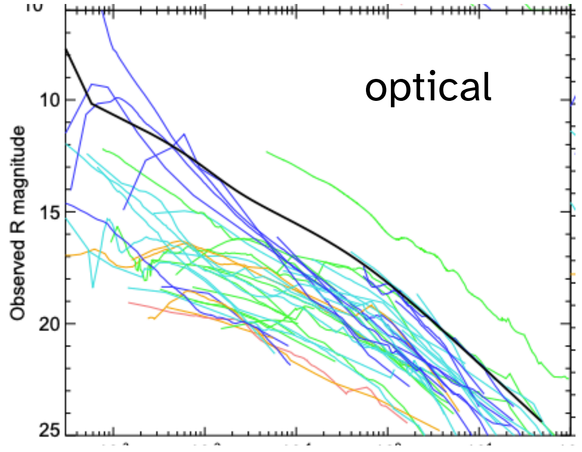
Gamma-ray bursts

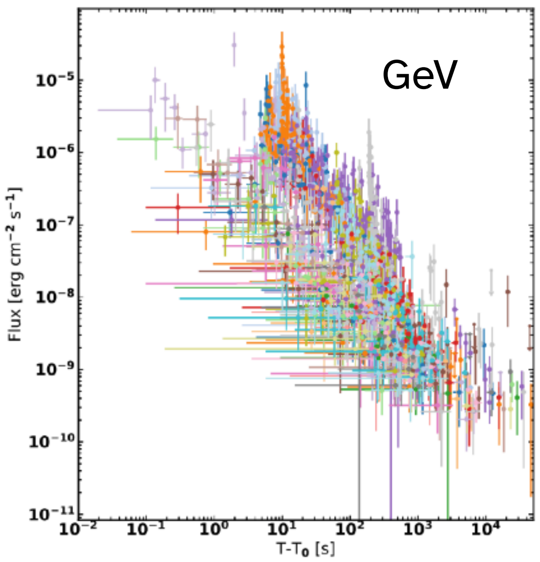
What causes them, and how do we know?



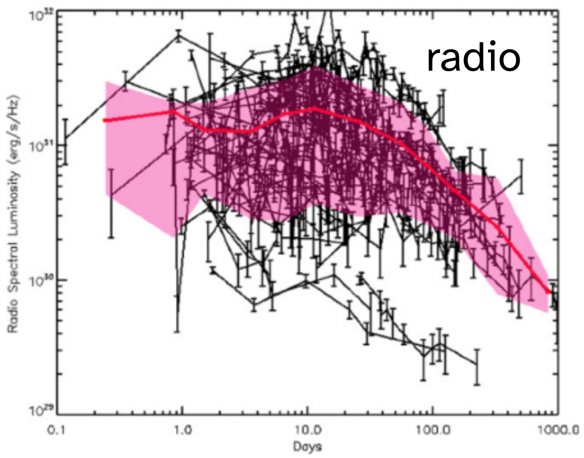
D. A. Perley et al., ApJ 781 (2014)







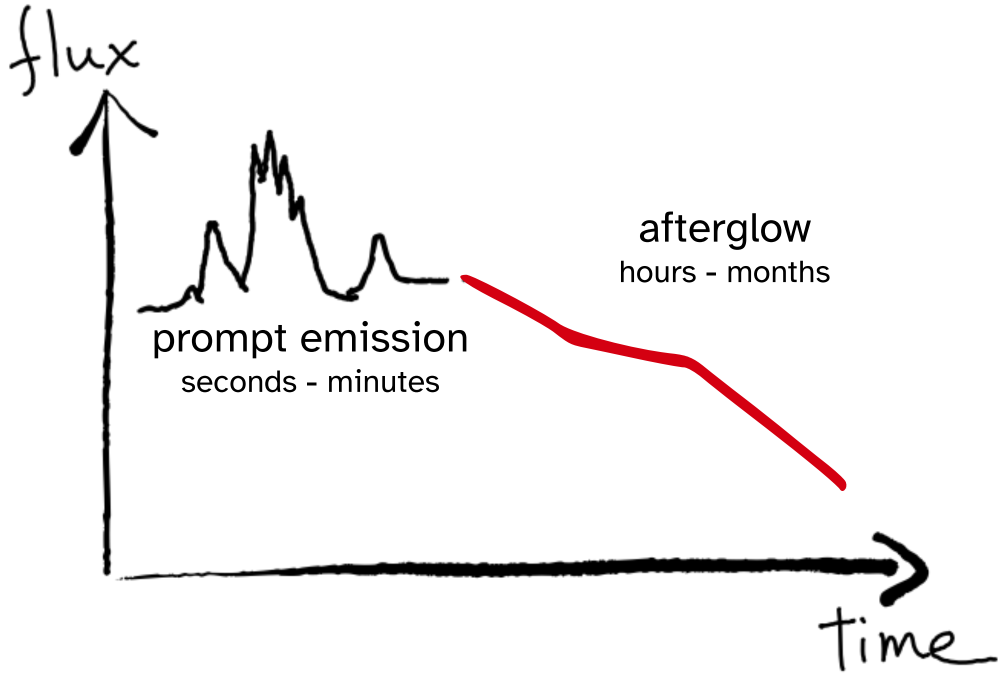
M. Ajello et al., ApJ 878 (2019)



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

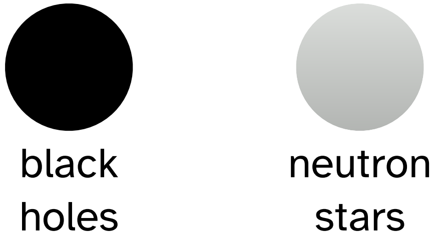
Gamma-ray bursts

What causes them, and how do we know?



Putting all the clues together:

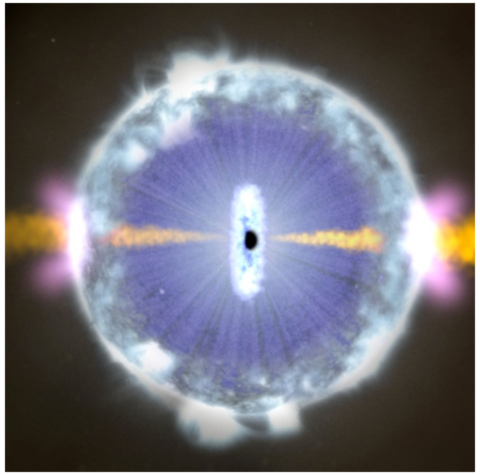
GRBs are stellar-sized phenomena (not, e.g., galaxy-sized)
release $M_{\odot}c^2$ within minutes
emission occurring in regions smaller than the Earth
emission starts out highly variable but then evolves slowly and fades
stellar-mass compact objects are involved



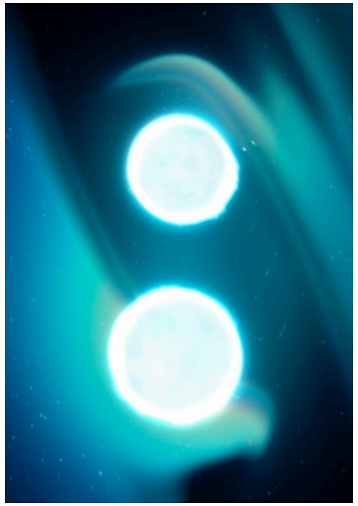
Gamma-ray bursts

What causes them, and how do we know?

[NASA’s Goddard Space Flight Center]



NASA’s Goddard Space Flight Center/CI Lab

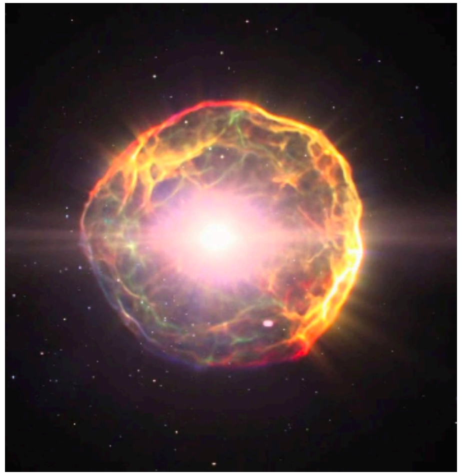


two neutron stars merge

(probably)

or

ESO/L Calçada



a massive star collapses

Gamma-ray bursts

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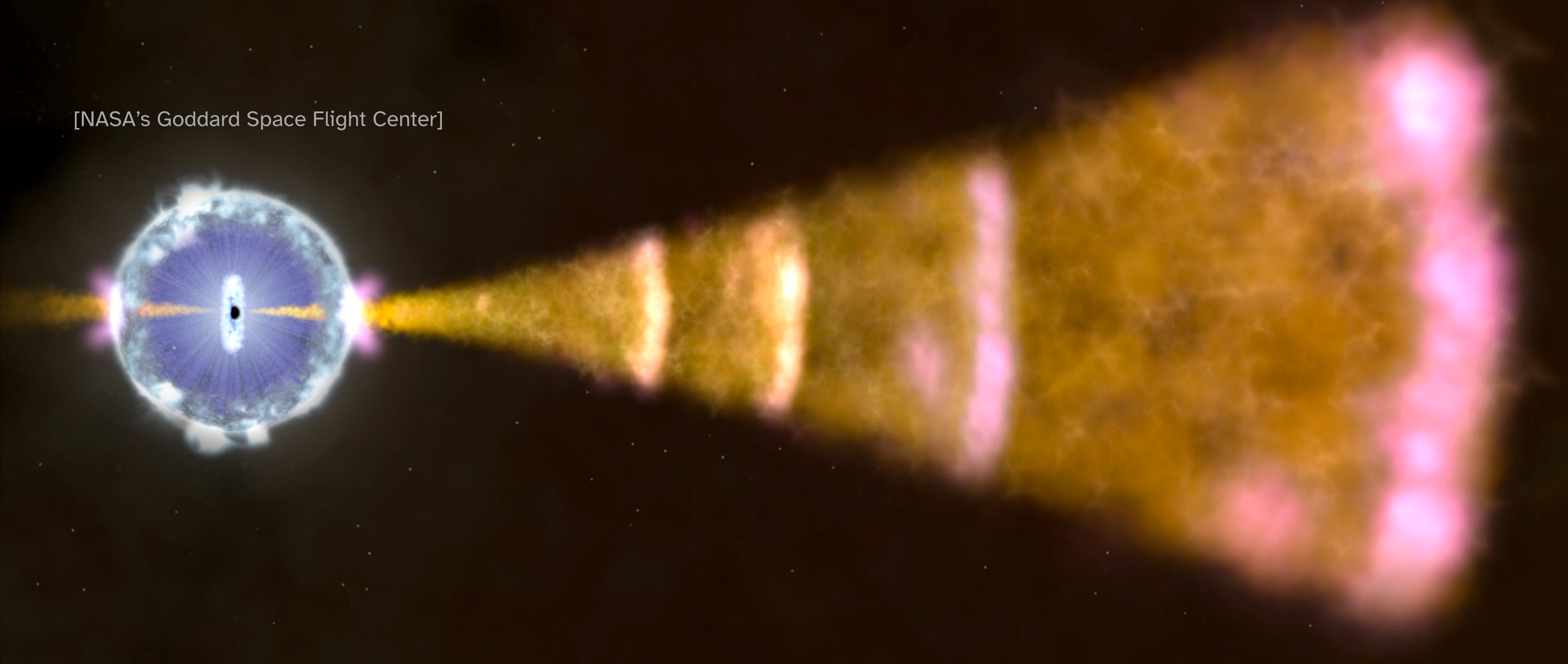

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Gamma-ray bursts

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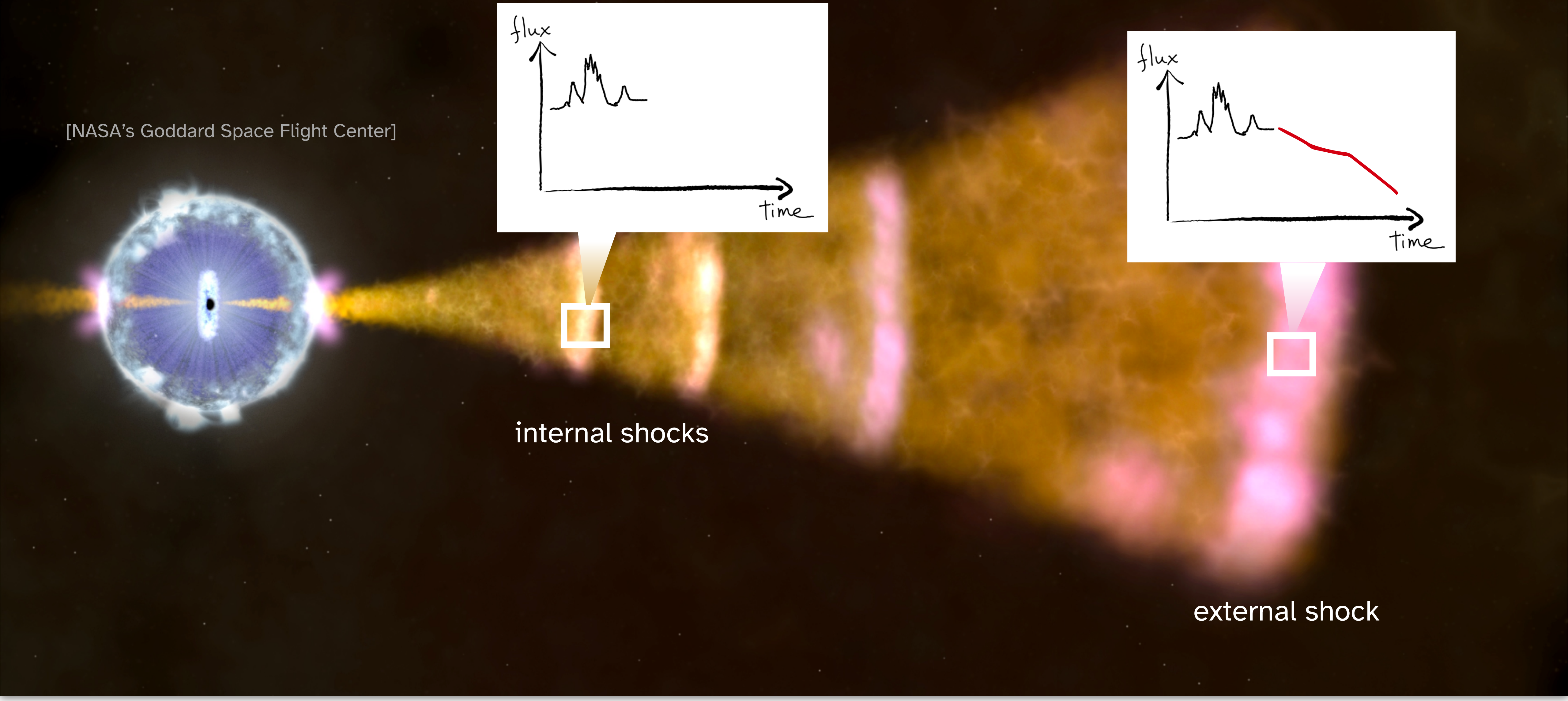


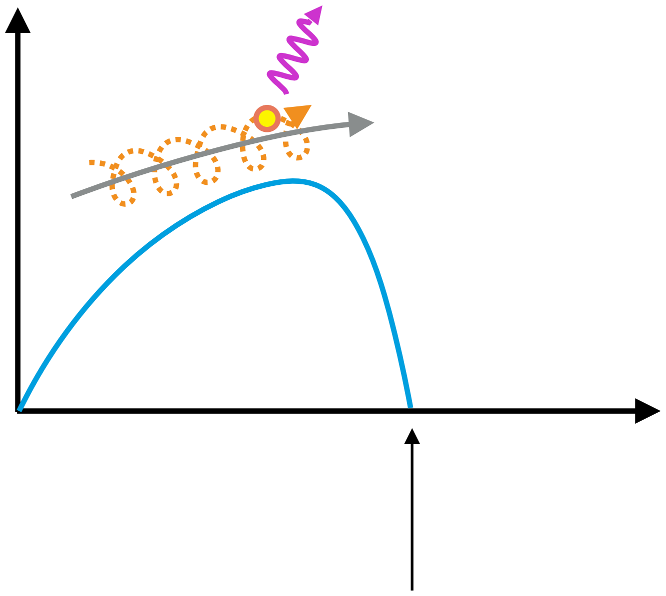
Gamma-ray bursts

How the photons are emitted

[DESY, Science Communication Lab]

Gamma-ray bursts

VHE gamma-ray observations



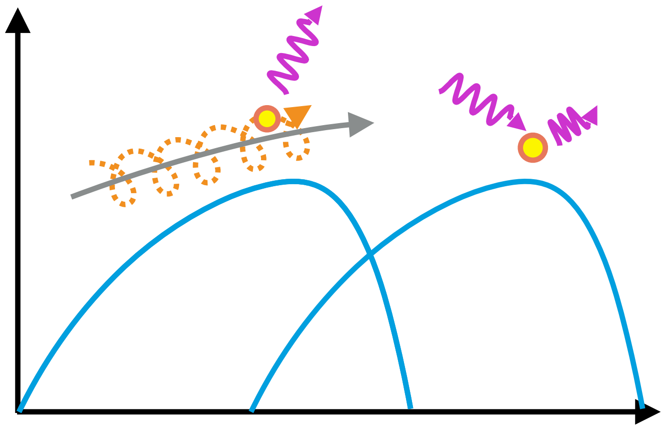
Multiwavelength observations have shown that the afterglow is well described by electron synchrotron

Assuming a **single magnetic field strength** well describes the region (“one-zone”), there is a theoretical maximum synchrotron photon energy, from balancing energy gains and losses

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

Gamma-ray bursts

VHE gamma-ray observations

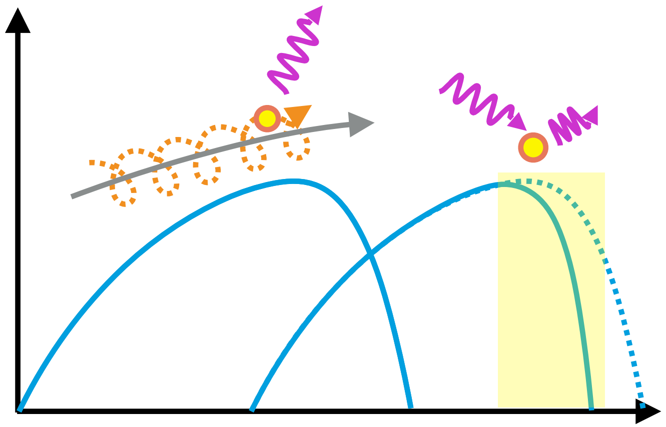


Multiwavelength observations have shown that the afterglow is well described by electron synchrotron

A synchrotron self-Compton component is also expected to exist, would be at >GeV energies

Gamma-ray bursts

VHE gamma-ray observations

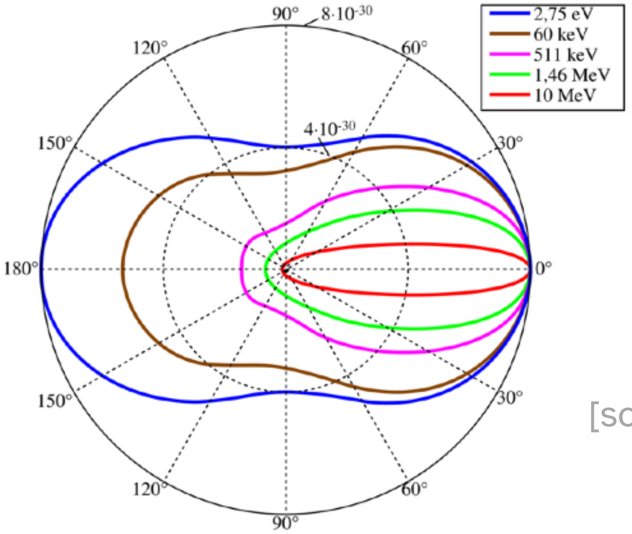


Multiwavelength observations have shown that the afterglow is well described by electron synchrotron

A synchrotron self-Compton component is also expected to exist, would be at >GeV energies

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

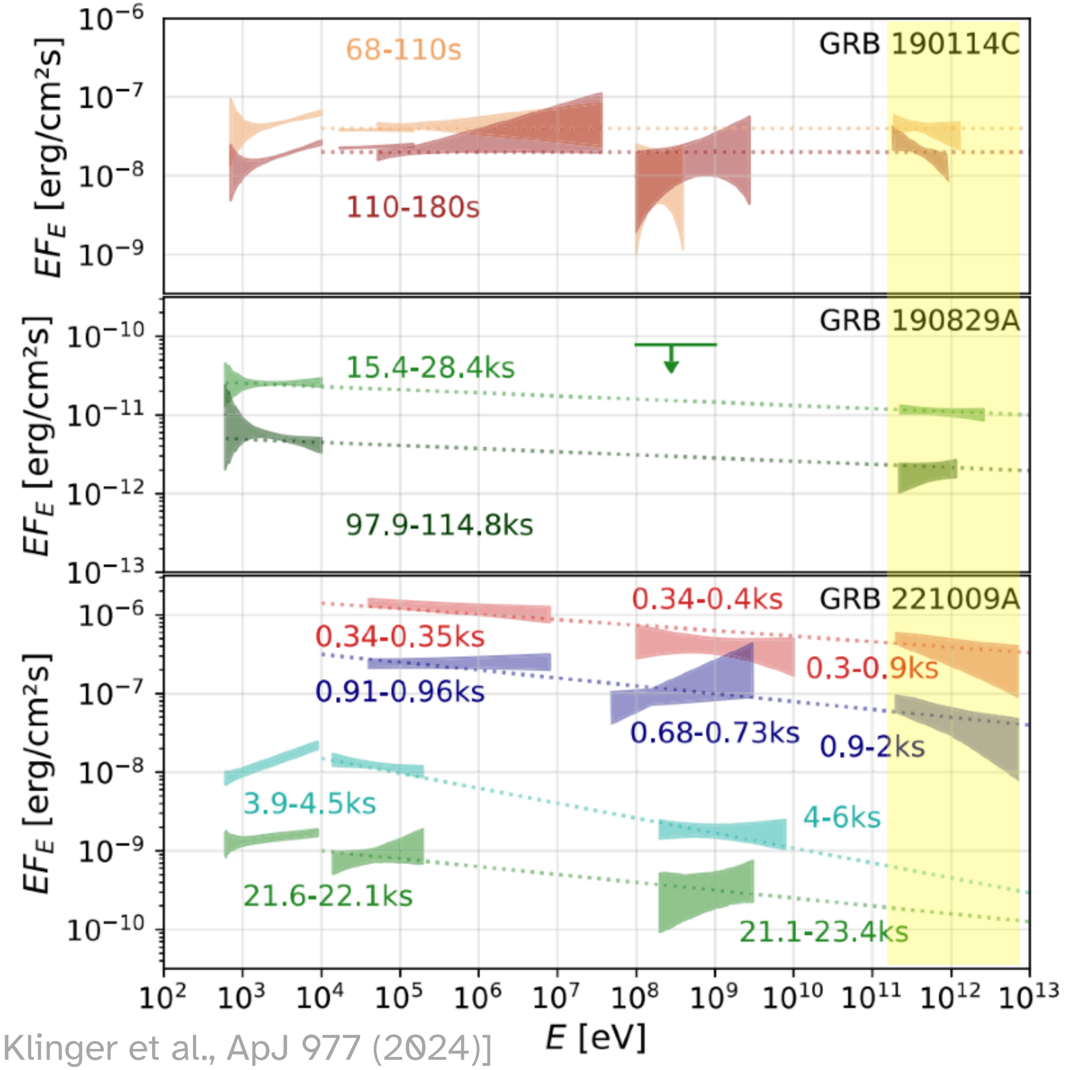
interaction cross section for (inverse) Compton scattering:



[source]

Gamma-ray bursts

Do we see the inverse Compton component?



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

no smoking gun so far

Gamma-ray bursts

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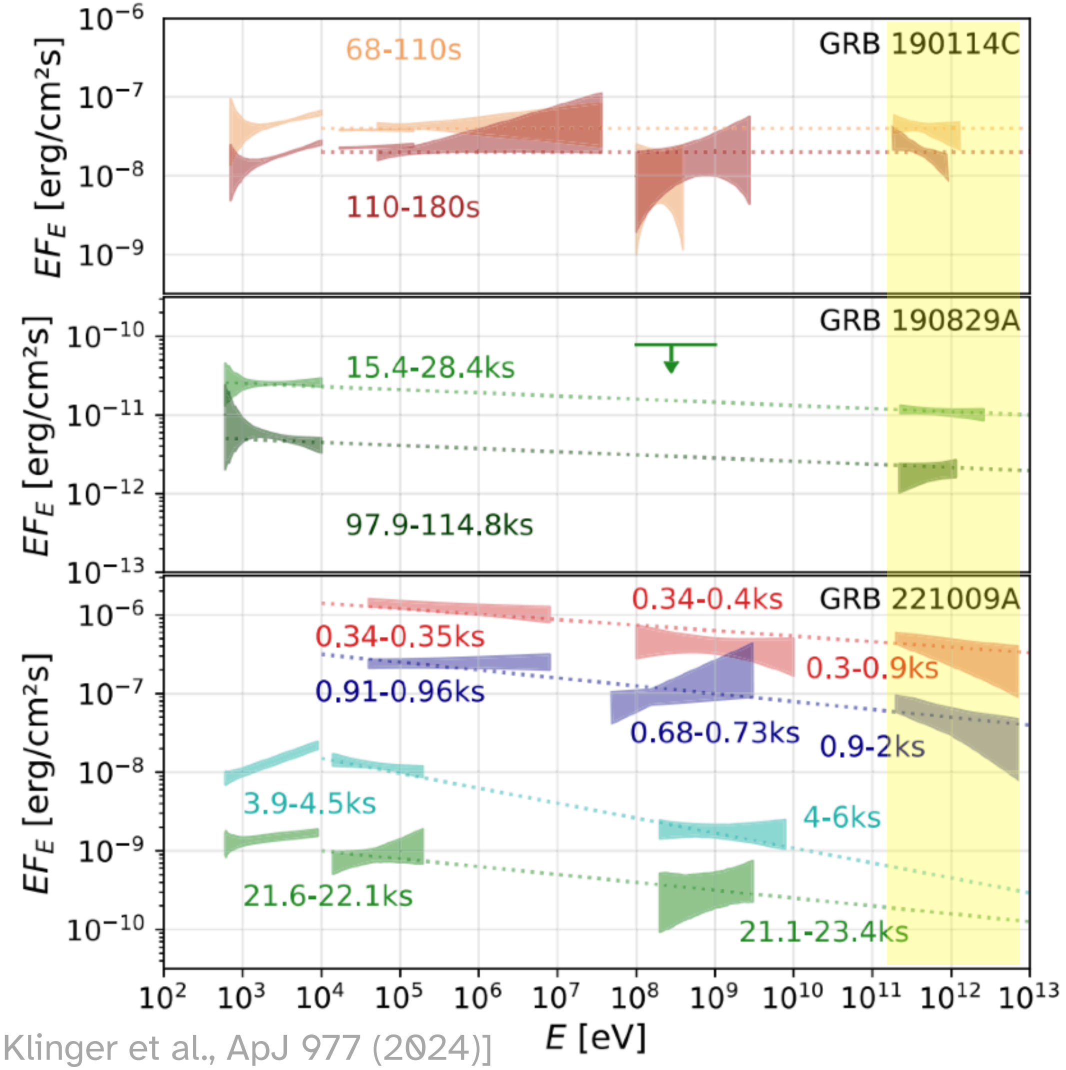
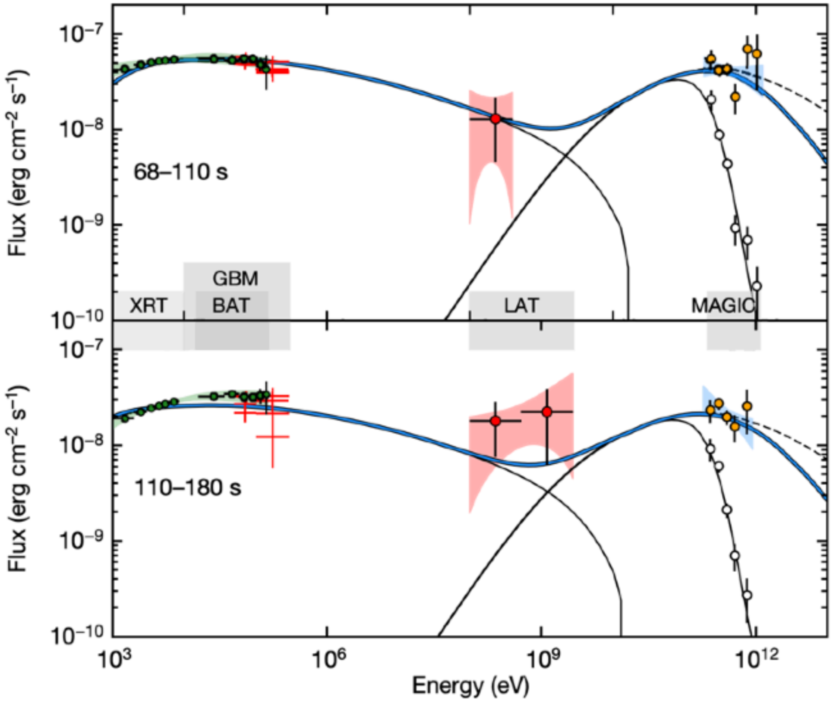


[M. Klinger et al., ApJ 977 (2024)]

no smoking gun so far

(although there is disagreement)



[MAGIC, Nature 575 (2019)]

Gamma-ray bursts

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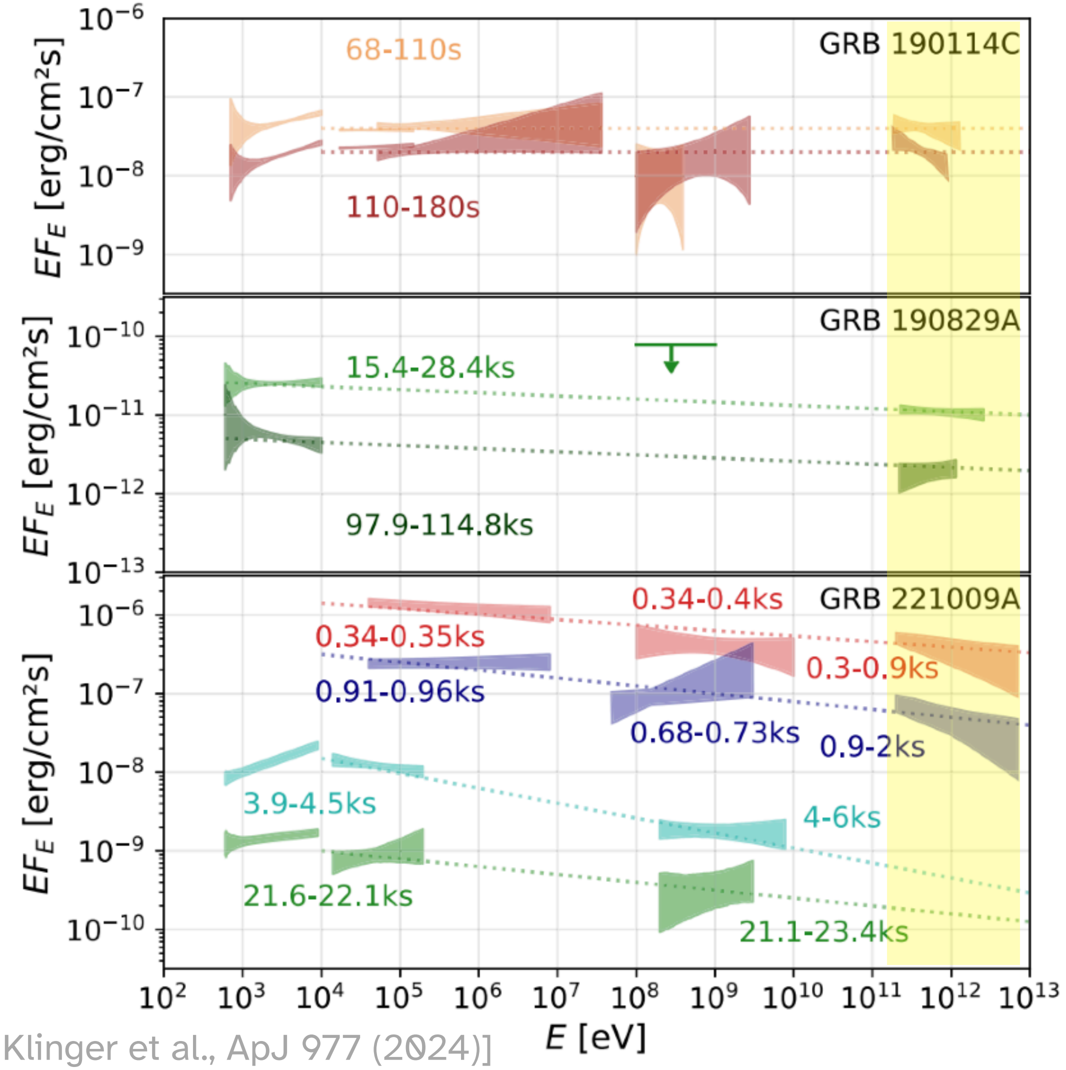
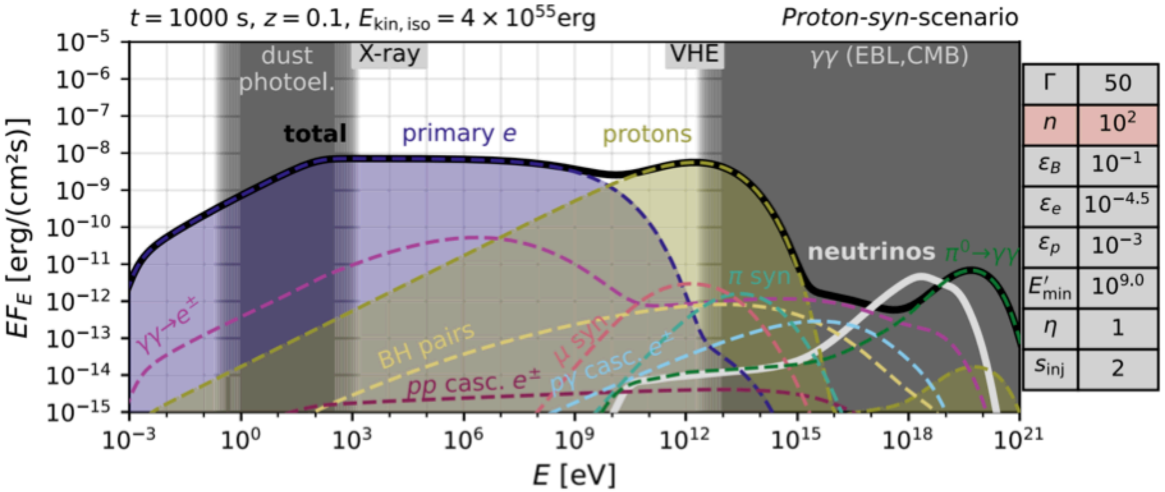


[M. Klinger et al., ApJ 977 (2024)]

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



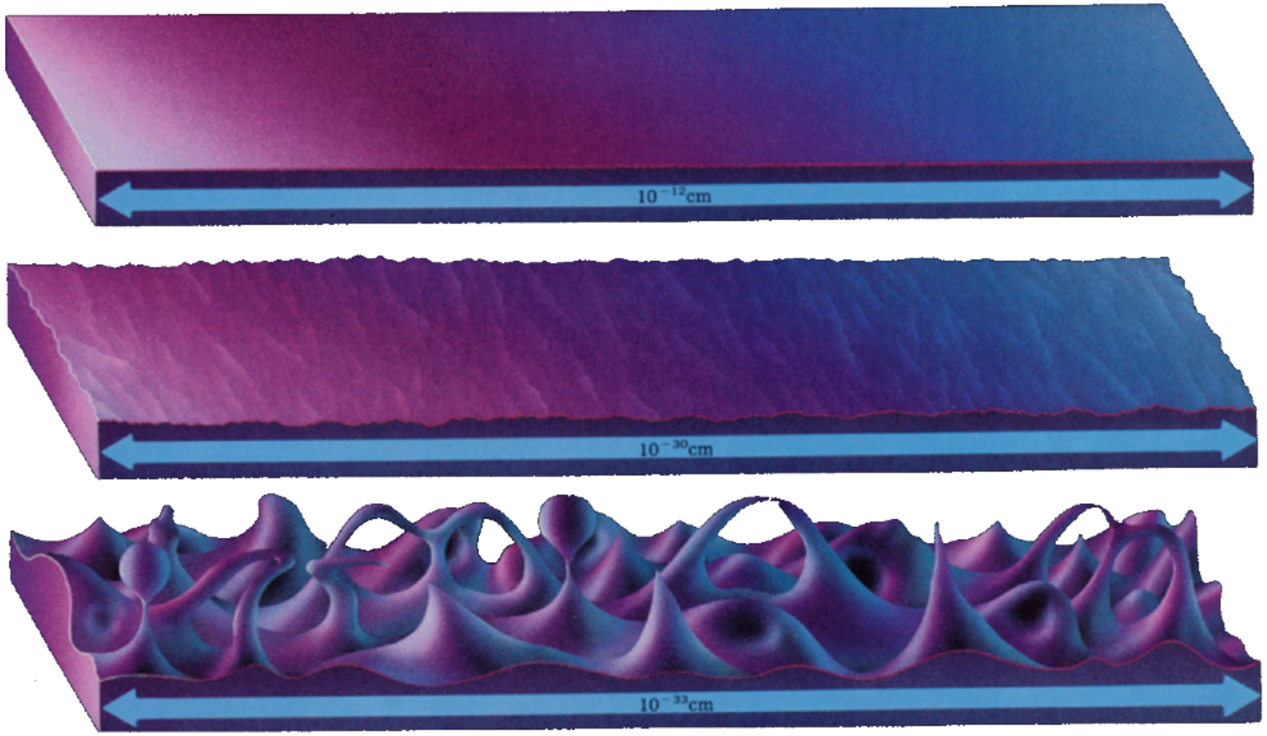
Physics with gamma-ray bursts

Testing Lorentz invariance

Lorentz invariance (special relativity):

The laws of physics are the same for all observers in inertial reference frames

One test is whether the speed of light is the same for photons of different energies



at the Planck scale (E > 10^{19} GeV), quantum gravity effects could make spacetime “foamy”

-> photons at different energies could be affected differently

Physics with gamma-ray bursts

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Lorentz invariance (special relativity):

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One test is whether the speed of light is the same for photons of different energies

e.g.:

$$v = c$$

[T. Piran & D. Ofengeim, PRD 109 (2024)]

Physics with gamma-ray bursts

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e.g.:

photon energy

$$v = c\left[1 + \sigma\frac{n+1}{2}\left(\frac{E}{\mathcal{E}^{(\sigma)}_{\mathrm{QG},n}E_{\mathrm{pl}}}\right)^n\right]$$

±1

energy scale

1.22×10^{19} GeV (Planck energy)

σ = +1: higher-energy photons are faster than c

σ = -1: higher-energy photons are slower than c

[T. Piran & D. Ofengeim, PRD 109 (2024)]

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σ = +1: higher-energy photons are faster than c

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-> different photon arrival times
(assuming emitted at the same time)

-> would have an effect on the overall lightcurve: $\int_{E_1}^{E_2} E\left(\frac{dN}{dE}\right)dE$ $\left(\frac{dN}{dE}\right)_{\text{observed}} \neq \left(\frac{dN}{dE}\right)_{\text{intrinsic}}$

[T. Piran & D. Ofengeim, PRD 109 (2024)]

Physics with gamma-ray bursts

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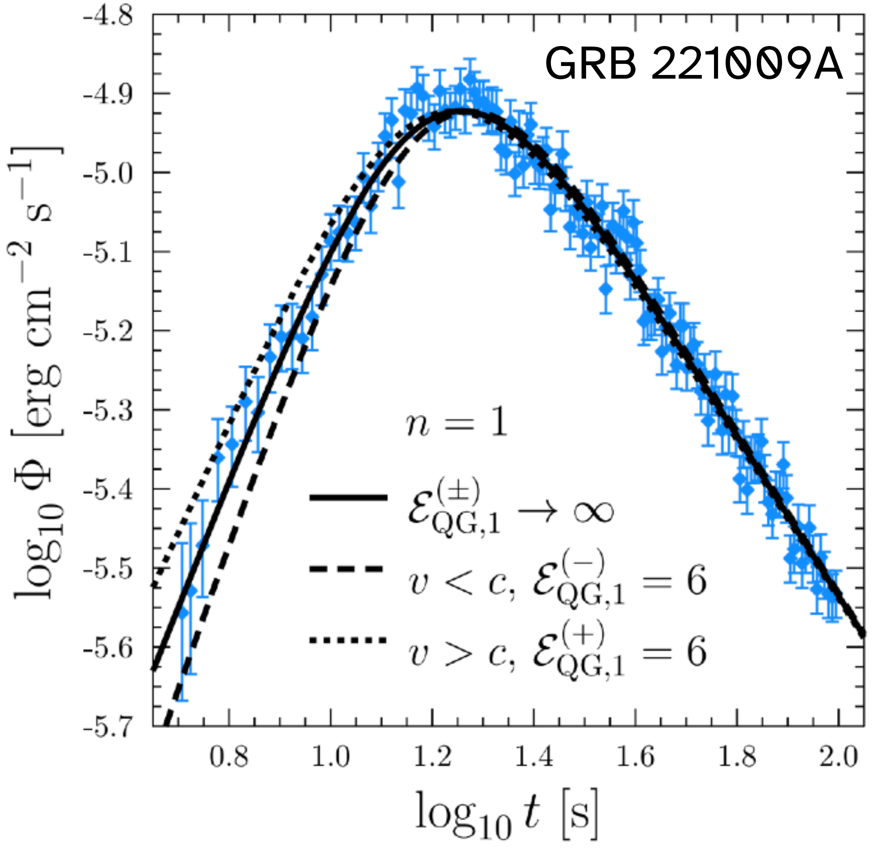
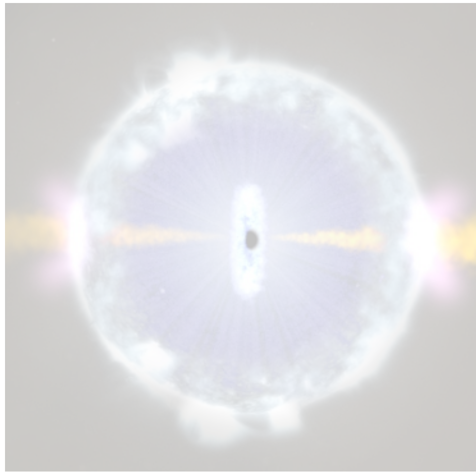


[T. Piran & D. Ofengeim, PRD 109 (2024)]

Gamma-ray bursts

What causes them, and how do we know?

[NASA's Goddard Space Flight Center]



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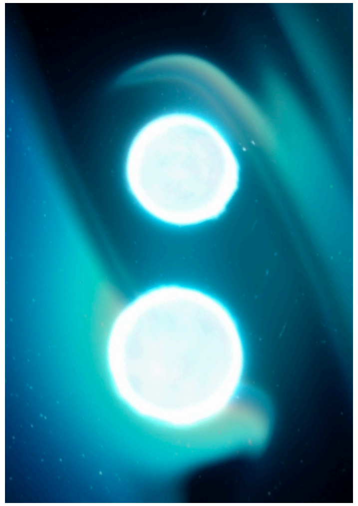
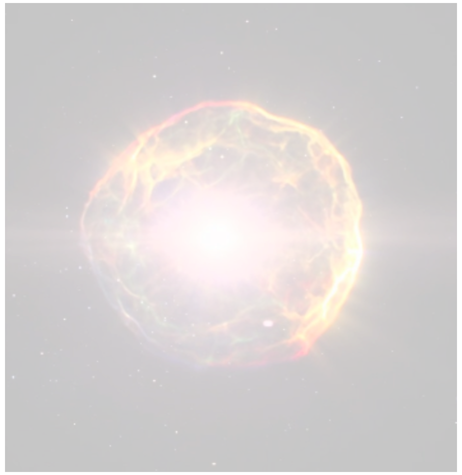


two neutron stars merge
(probably)

or

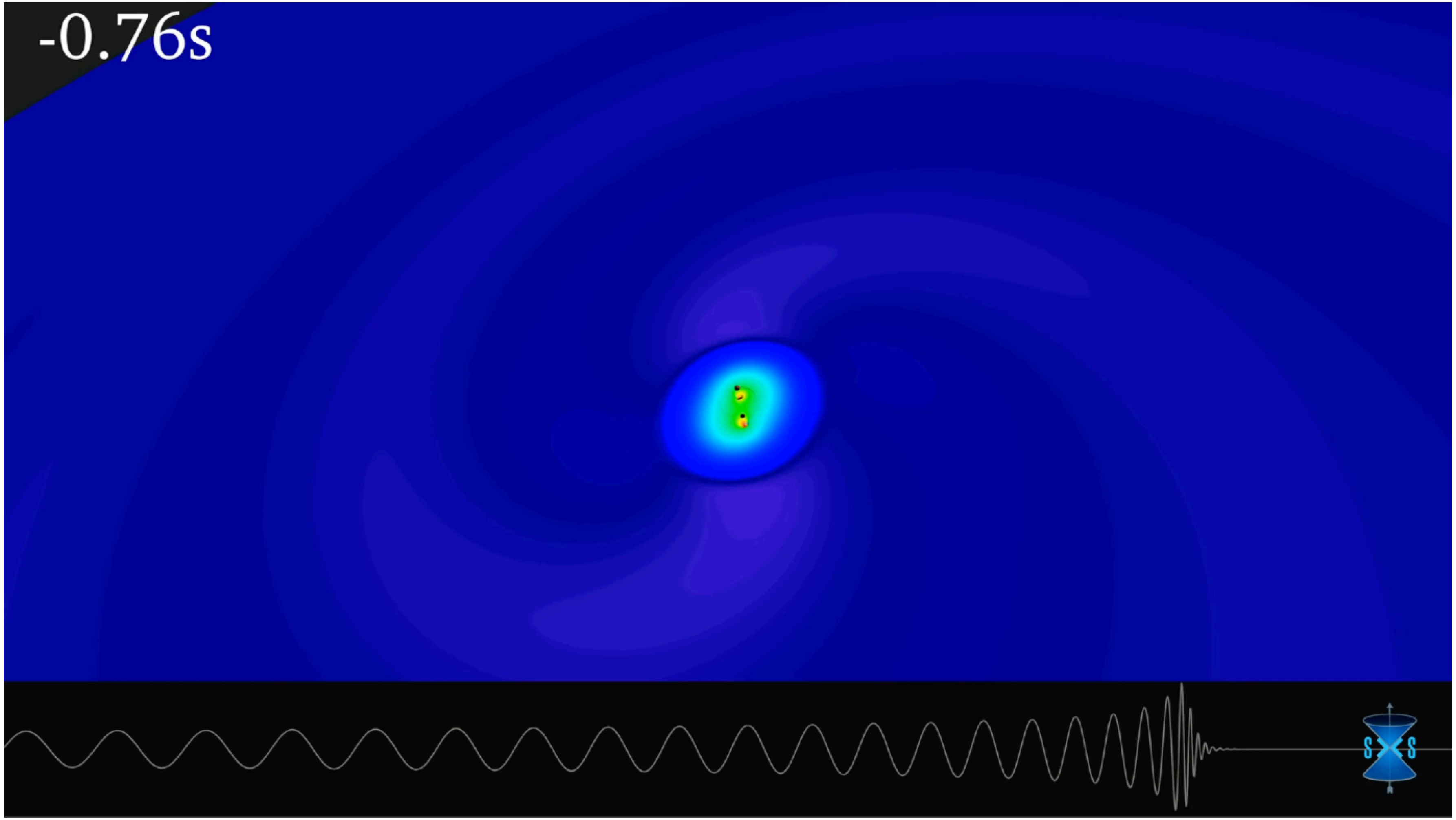
ESO/L Calçada



a massive star collapses

Neutron star mergers

What do the signals look like?



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

Neutron star mergers

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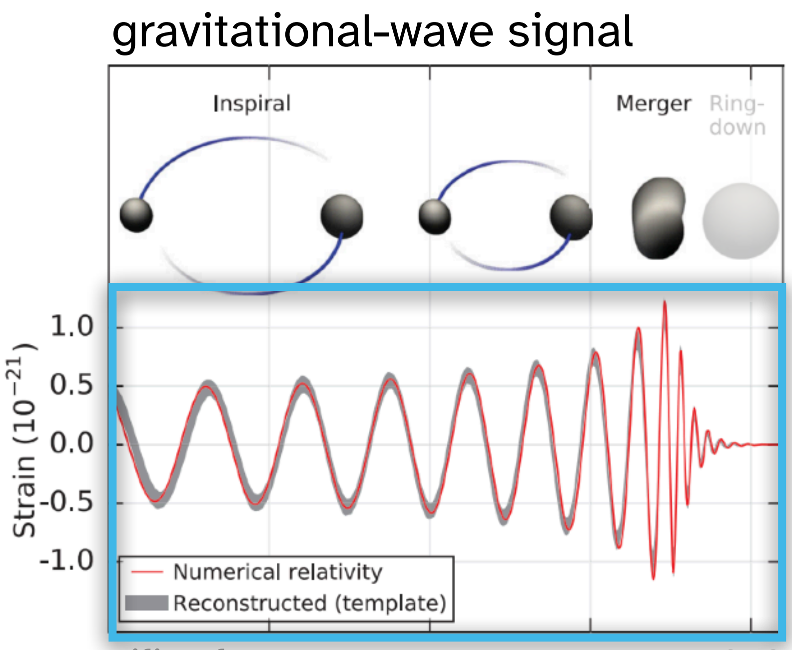
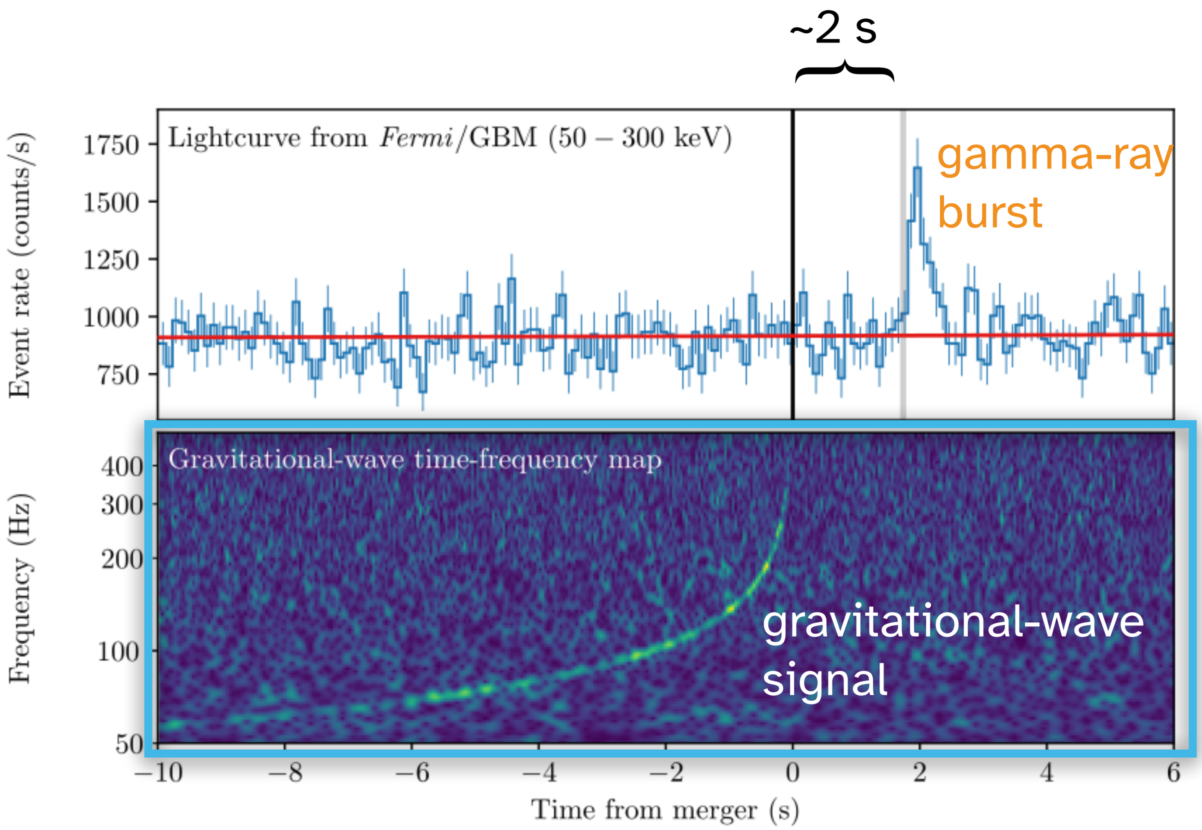


modified from [B. P. Abbott et al., PRL 116 (2016)]



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

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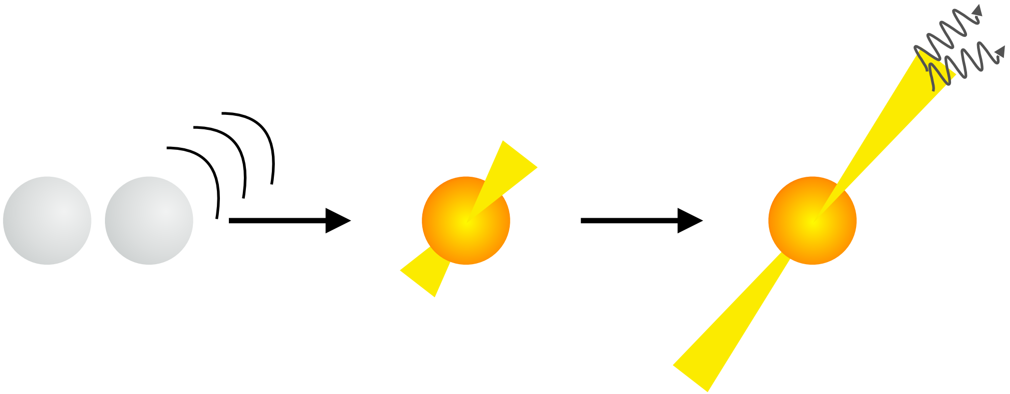
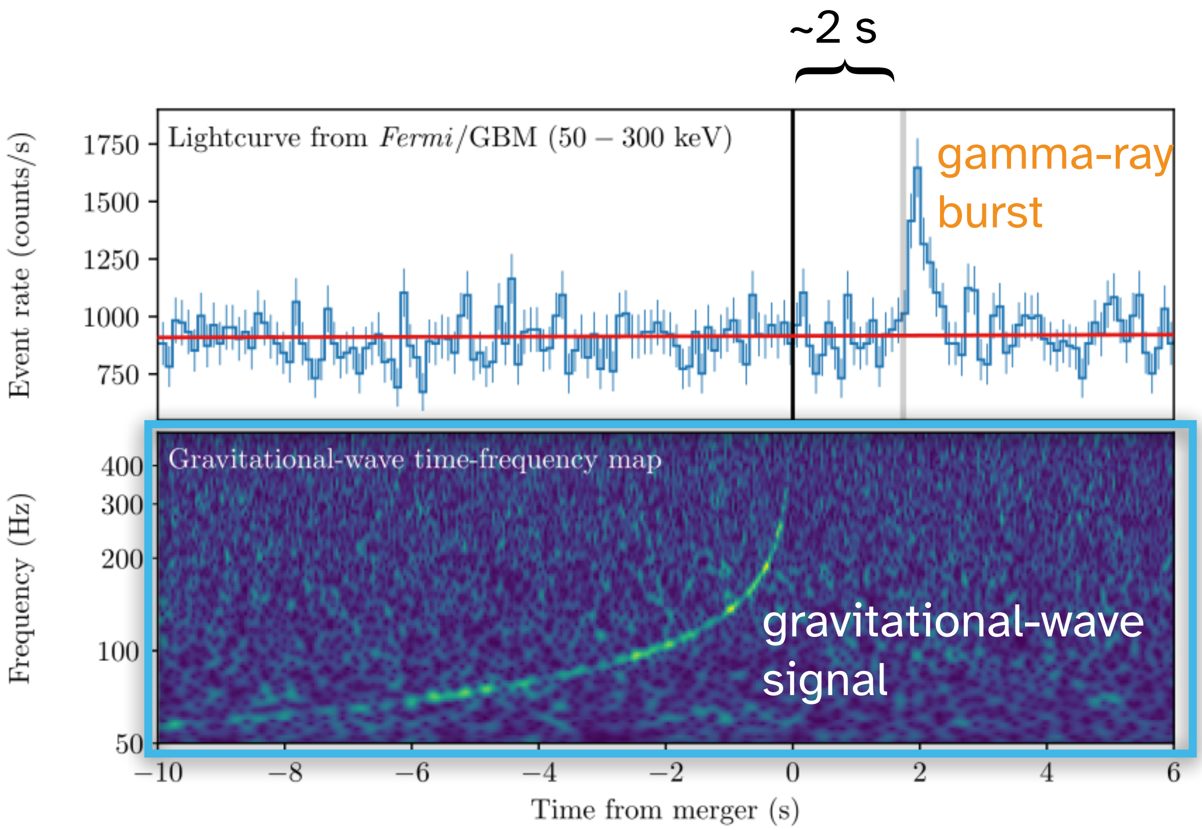




modified from [B. P. Abbott et al., ApJL 848 (2017)]

2-second delay is probably all due to the time necessary to merge -> launch jet -> produce photons … but what if it's not?

Physics of gamma-ray bursts

Speed of light vs speed of gravity

gamma-ray signal came 1.75 seconds after gravitational-wave signal

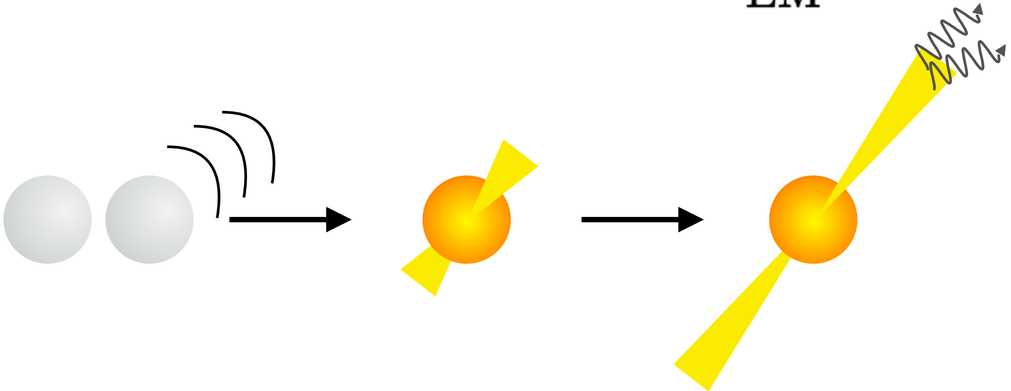
take the distance to source to be 26 Mpc (conservative estimate) = 8e23 m

If the photons and gravitational waves were released at the same time, then gravity travels faster than light

$$\frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \leq +7 \times 10^{-16}$$

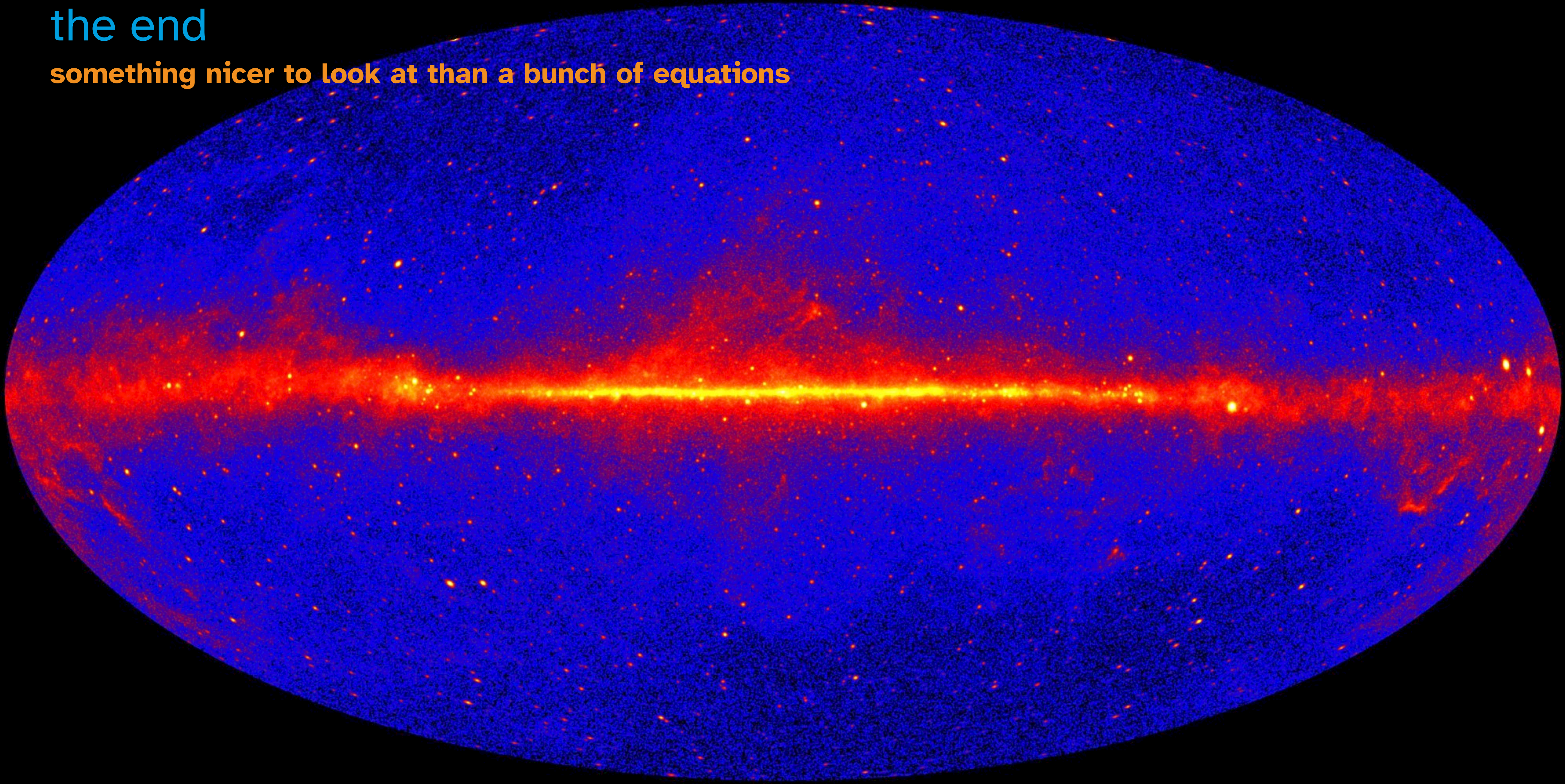
If it actually took *longer* than 2 seconds for the source to produce the photons (e.g., 10 seconds), then gravity travels slower than light

$$\frac{v_{\mathrm{GW}} - v_{\mathrm{EM}}}{v_{\mathrm{EM}}} \geq -3 \times 10^{-15}$$



the end

something nicer to look at than a bunch of equations



[NASA/DOE/Fermi-LAT Collaboration]