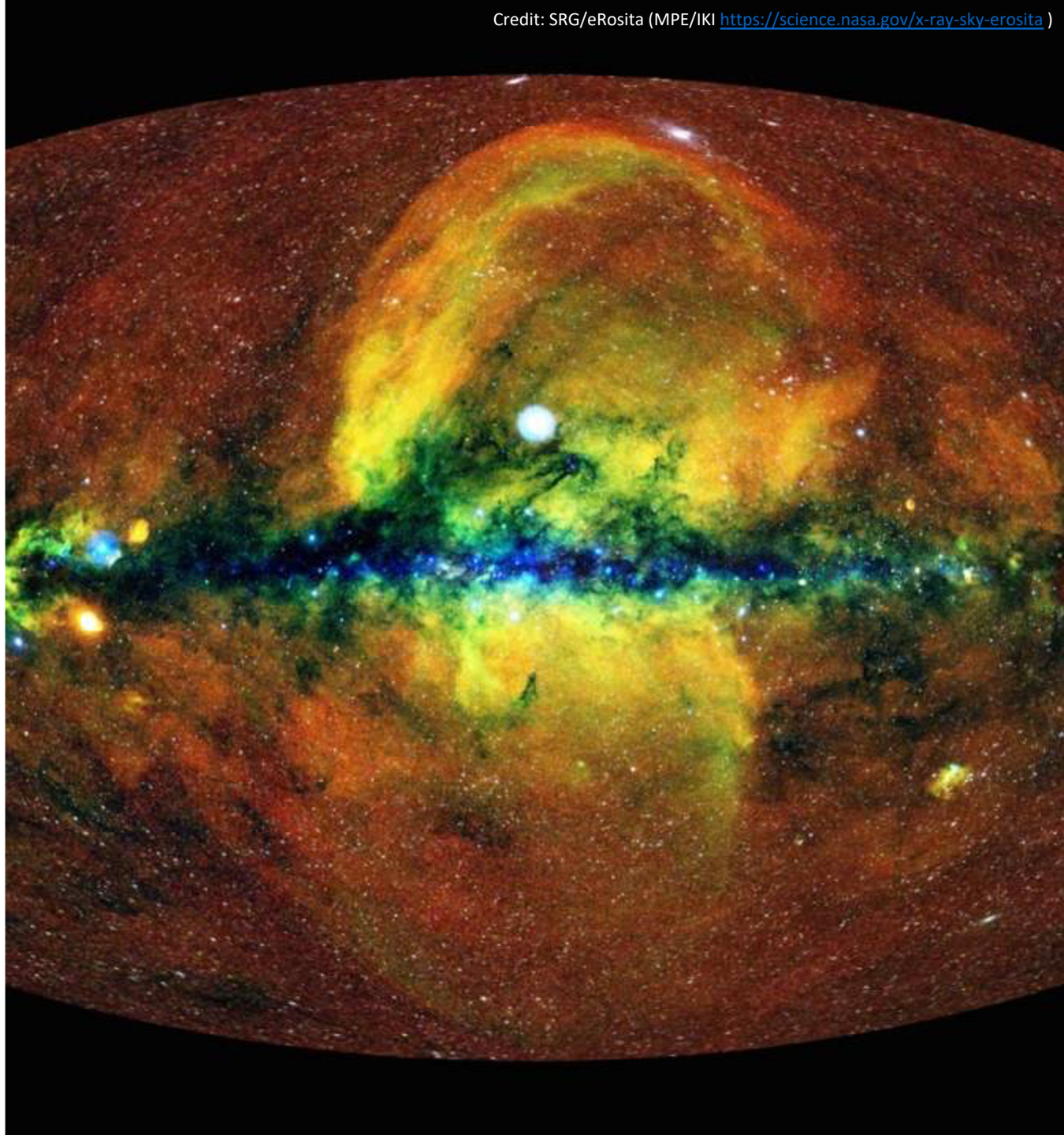
Focusing in on the High Energy Universe

I: The High-energy Astronomical Sky

Dr. Oliver J. Roberts
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Universities Space Research Association



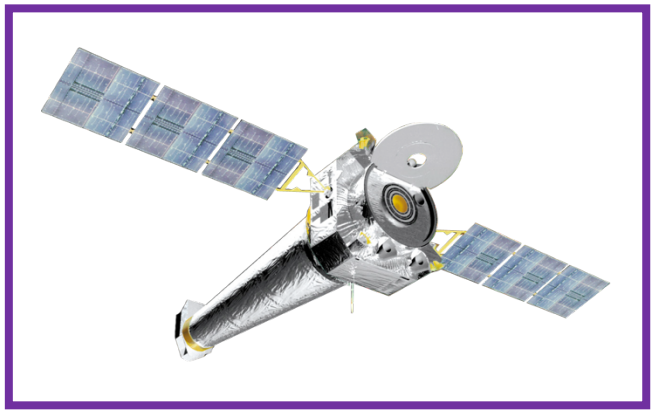


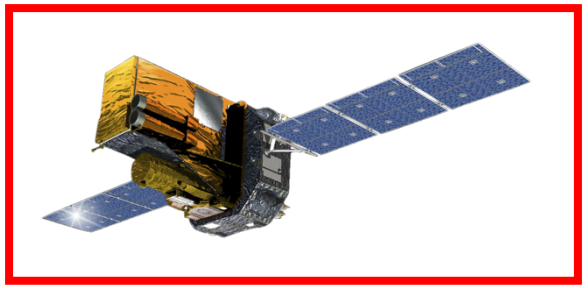
Credit: NASA/ University of Chicago

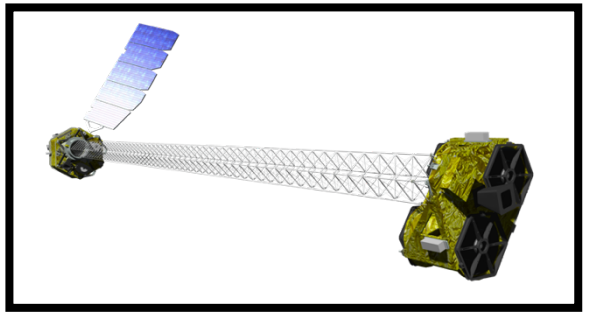
“Golden Age” of X-ray Astronomy

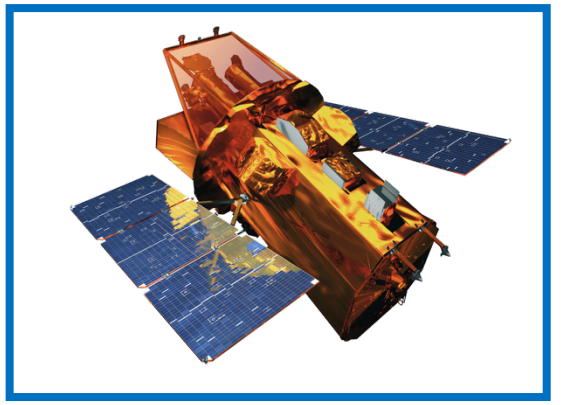
	Launch
• **Chandra**	(1999)
• XMM-Newton	(1999)
• **INTEGRAL**	(2002)
• **Neil Gehrels Swift Observatory**	(2004)
• AGILE	(2007)
• **Fermi Gamma-ray Space Telescope**	(2008)
• MAXI	(2009)
• **NuSTAR**	(2012)
• AstroSat	(2015)
• **NICER**	(2017)
• Insight-HXMT	(2017)
• **eROSITA**	(2019)

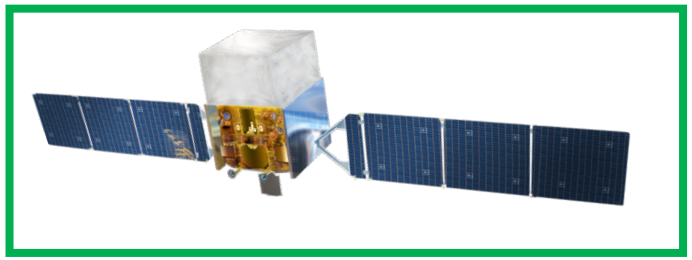
Excludes many smaller Nano- /Cube- / Small-Satellite missions that have been launched over the last decade.



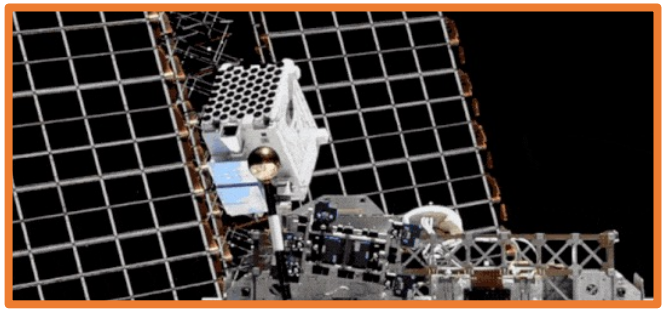










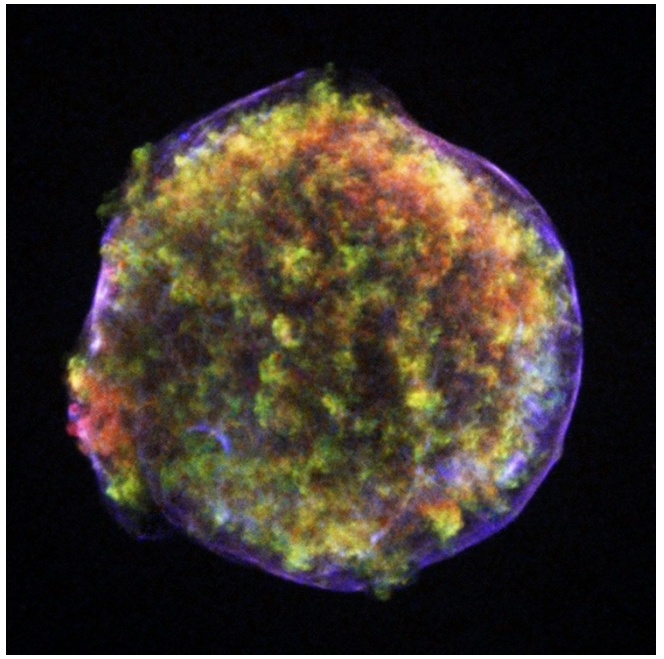


All images from NASA/ESA

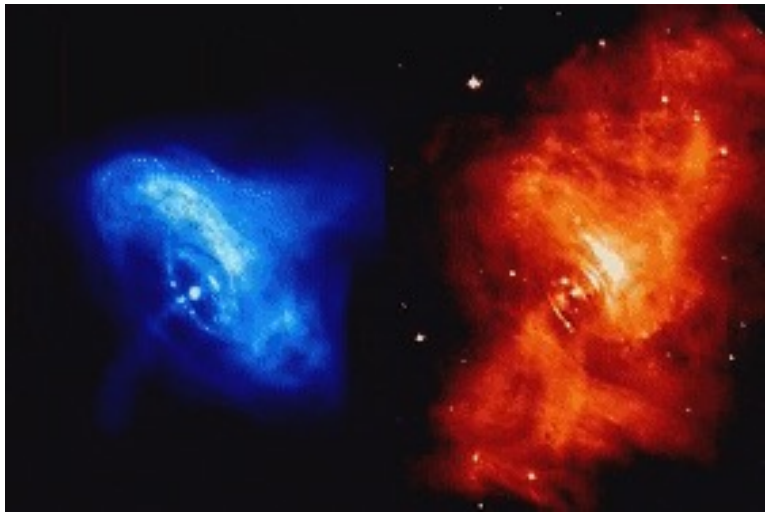
(Some) High-Energy Sources

- Stellar (***Solar***, brown/white dwarfs, etc.)
- *High-/Intermediate-/Low-Mass X-ray Binaries*
- Supernovae remnants
- ***Neutron Stars (i.e. Pulsars, Magnetars)***
- ***Fluorescence (Planets, Comets, etc)***
- *Active Galactic Nuclei (AGN)*
- ***Gamma-ray Bursts***
- Diffuse X-ray Background
- Super-fast X-ray Transients (SFXTs)
- ***And many more...***

Tycho's Supernova Remnant (SN 1572)



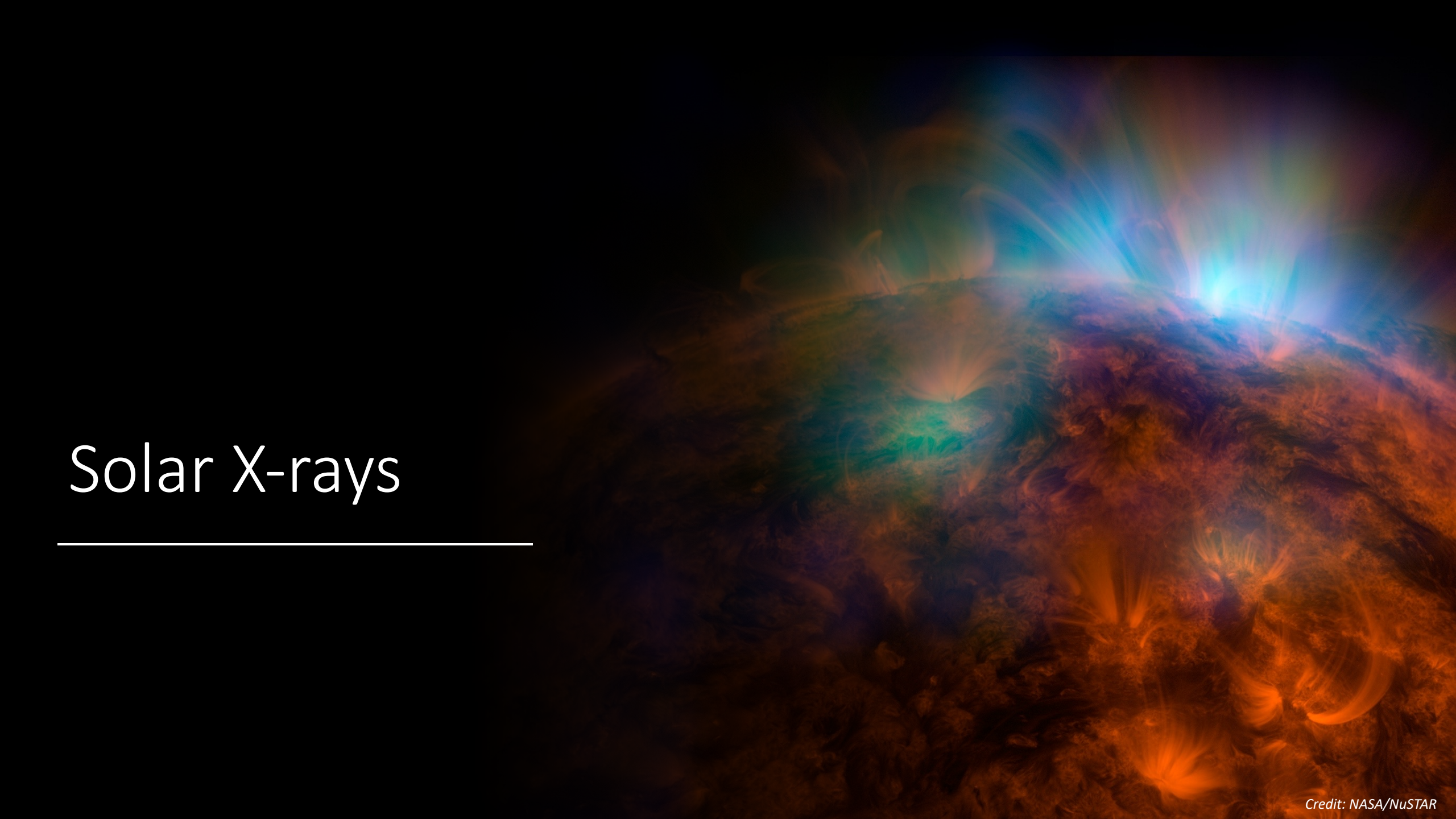
Credit: Chandra/NASA



Credit: Chandra, HST / NASA

Time lapse of the Pulsar Wind in the Crab Nebula

Solar X-rays



Credit: NASA/NuSTAR

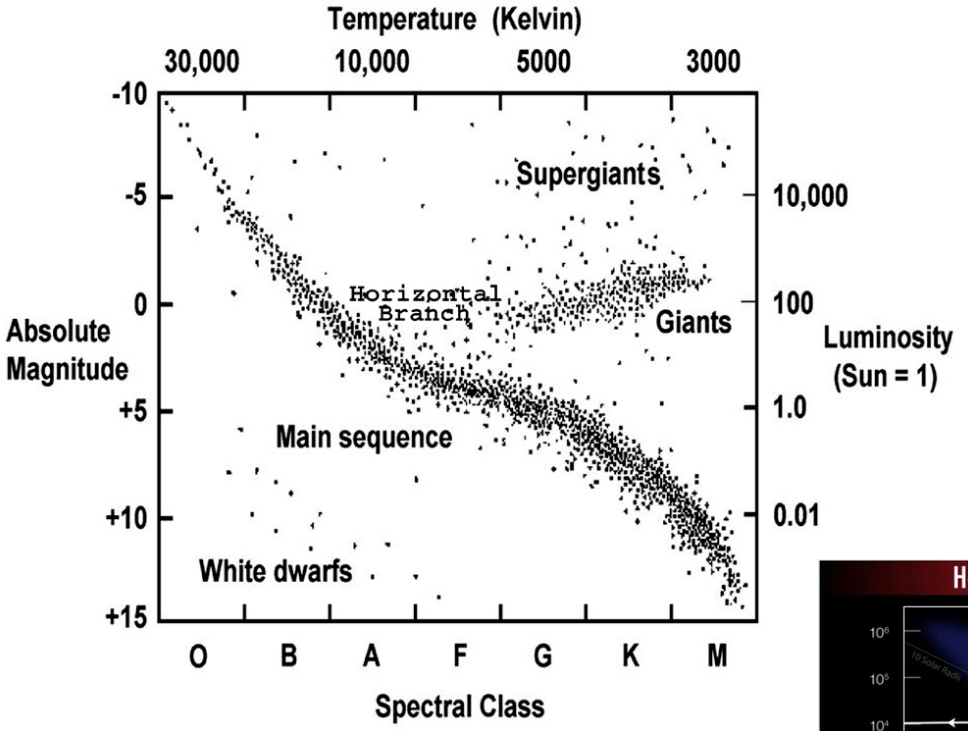
Stellar Road Trip

Stars evolve from their “nurseries” to the “Stellar Highway” that is the Main Sequence (MS).

Stars with similar masses to our Sun “exit” the highway to become red giants, produce a planetary nebula and ultimately a white dwarf.

More massive stars, generally produce explosive Supernovae resulting in a Black Hole or Neutron Star.

Empirical Mass-luminosity relationship of MS stars ($\approx L \alpha M^{3.5\text{-}4}$)



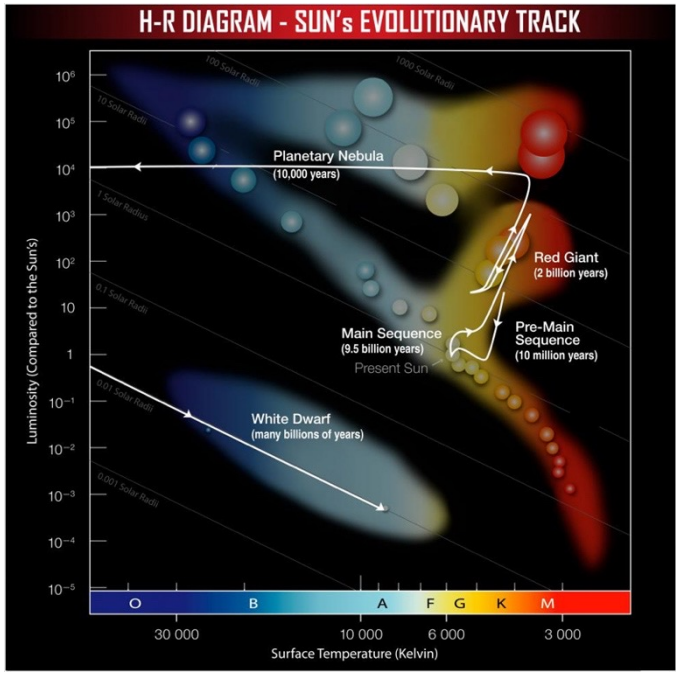
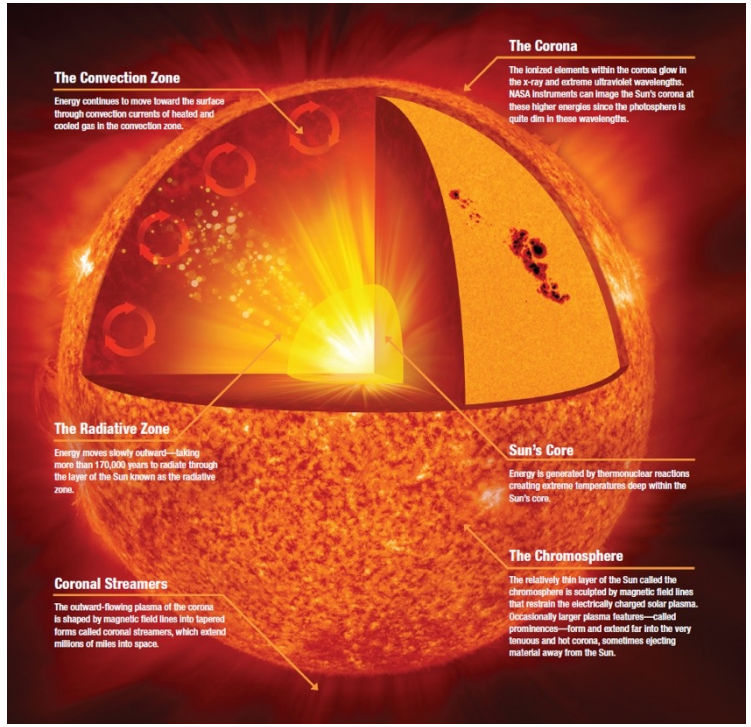


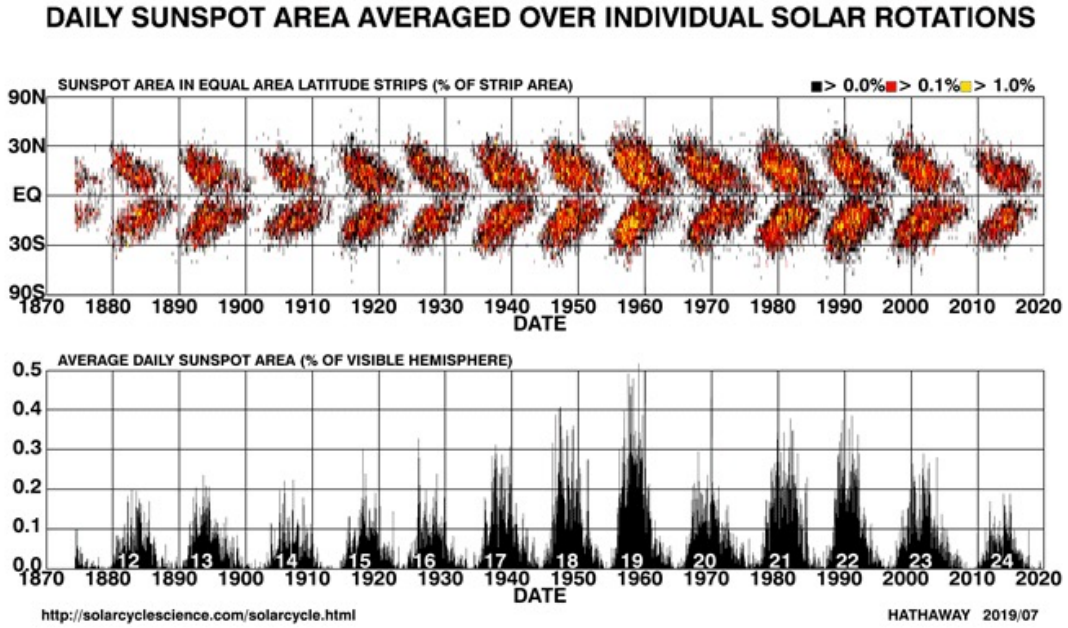
Image credits: NASA/SAO/CXC

Our Star

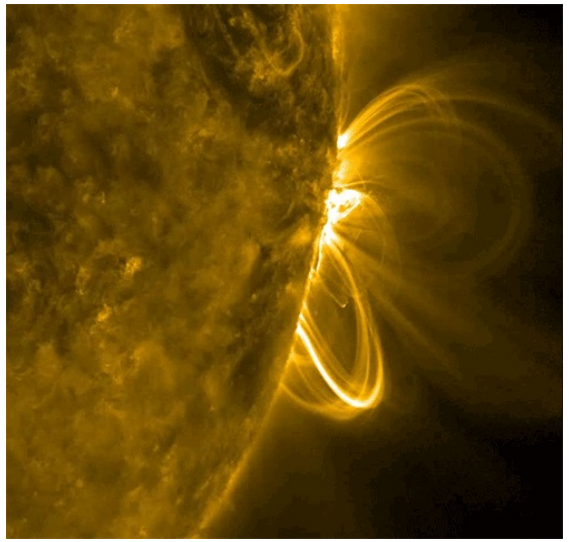
- The Sun is a G-type, main sequence star
- No X-rays from photosphere, only corona
- Concentration of magnetic field fluxes prevent convection on stellar surface -> Sunspots
- Intense magnetic field wound up by Sun's differential rotation.



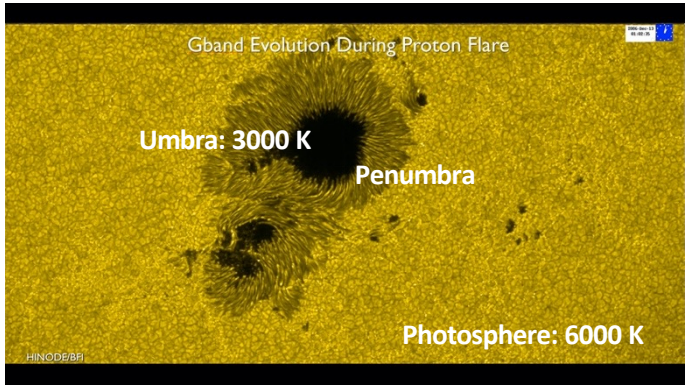
Credit: NASA/Jenny Mottar



Credit: NASA



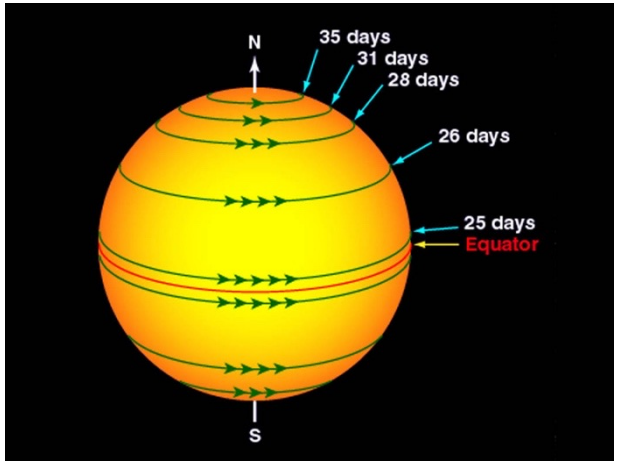
Credit: NASA

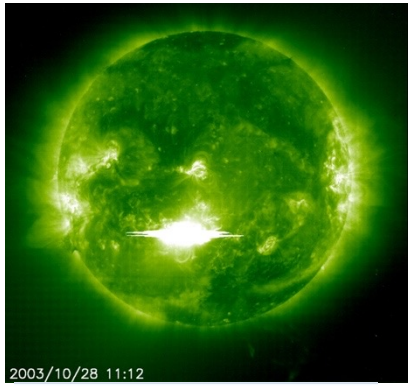


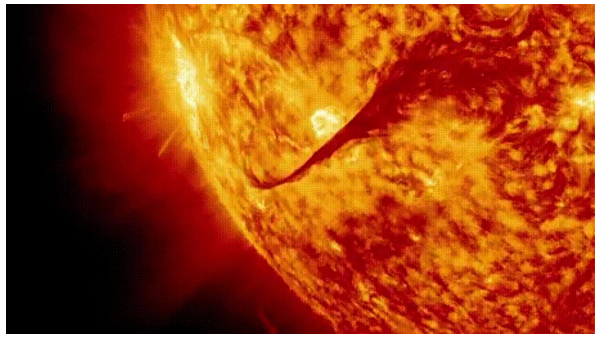
Credit: NASA Hinode

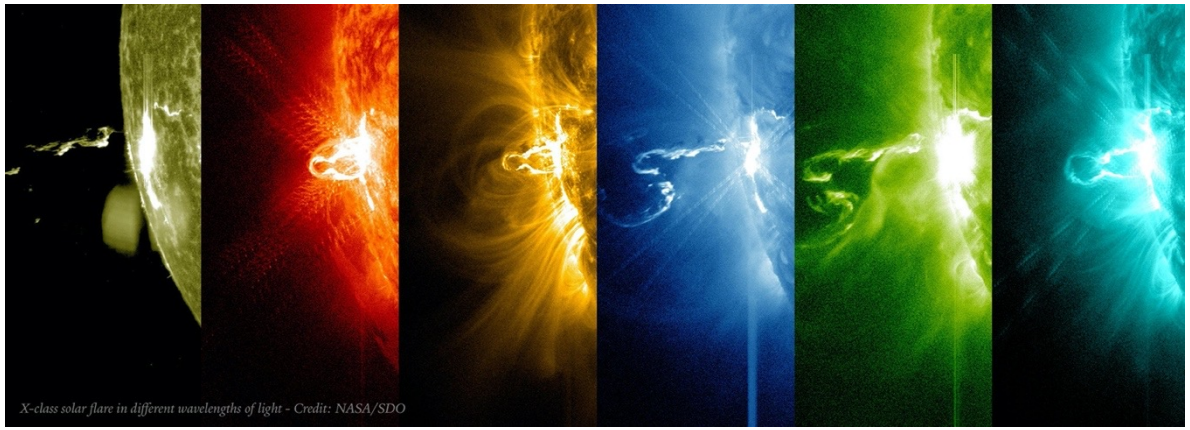
Solar Flares

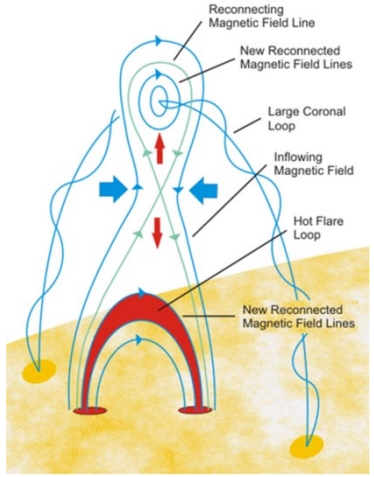
- $10^{20\text{-}25}$ joules of energy*
- Sometimes accompanied by coronal mass ejections (CMEs)
- X-ray flares thought to occur due to magnetic reconnection; where magnetic field lines collide and realign.
- A,B,C, M and X-class flares, latter is most energetic.

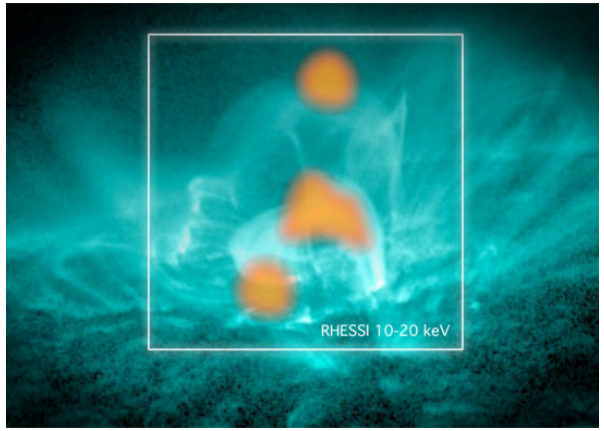








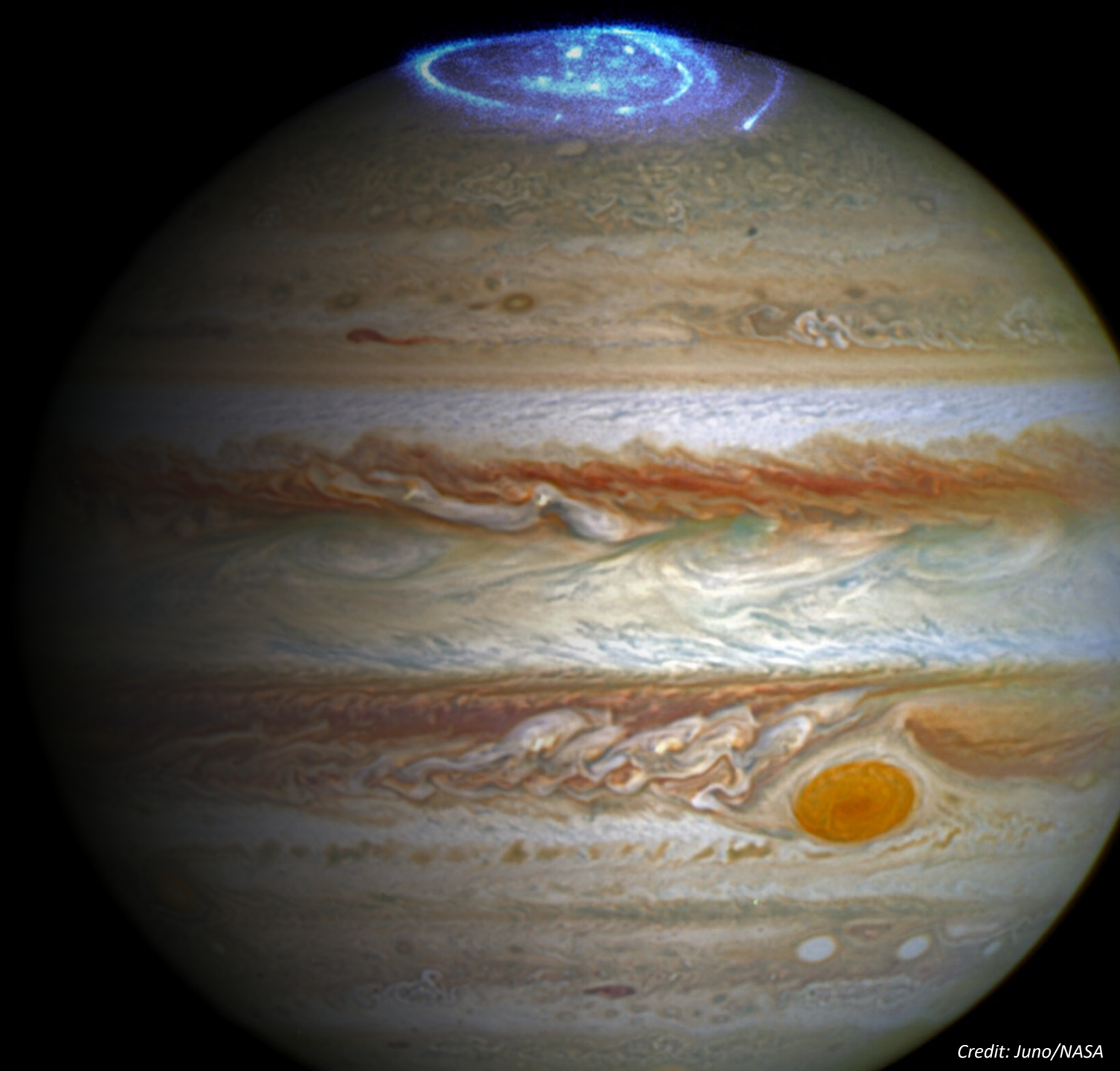




*$5x10^{21}$ joules = Human annual world energy consumption
*10^{24} joules = Energy required to heat all the water on Earth by 1°C

All images Credit: NASA (SDO/RHESSI)

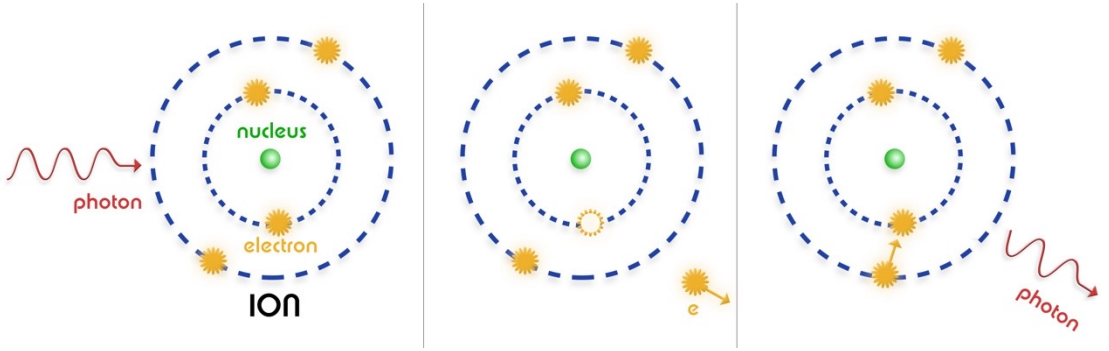
Planets



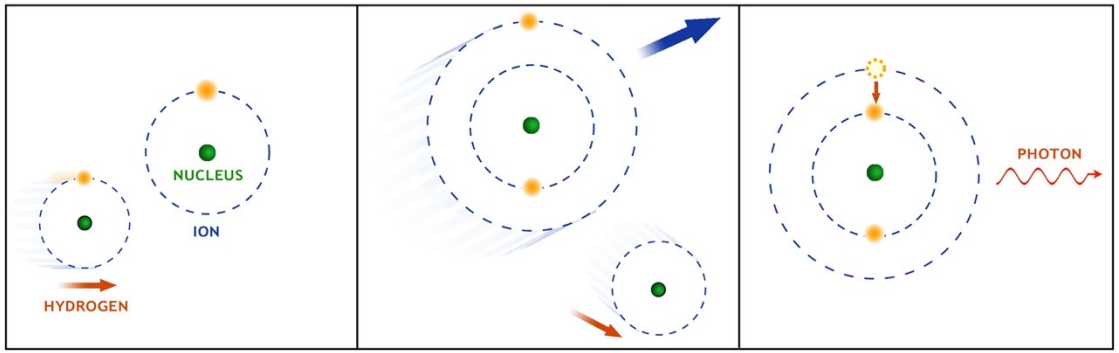
Credit: Juno/NASA

Fluorescence and Charge Exchange

- Fluorescence:
  - X-ray radiation collides with a molecule or neutral atom
  - Electron moves to a higher orbit or kicked out (ionized).
  - Outer electrons “fall” into lower orbitals to fill vacancy, emitting X-ray as it decays at a characteristic energy.



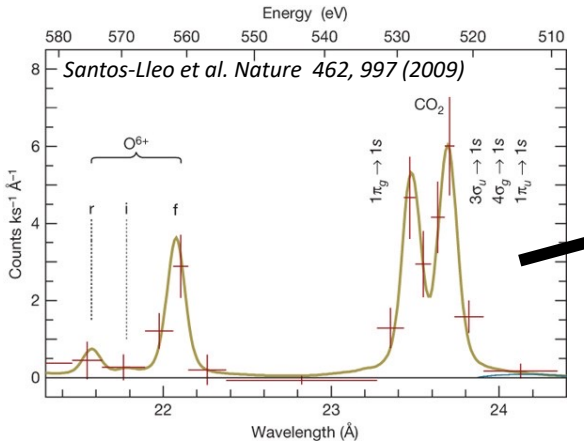
- Charge Exchange:
  - Electron shells of a neutral atoms and a positive or negative ion collide, resulting in transfer of electron from the atom to the ion.
  - Solar wind (i.e. H^+) hits atoms of neutral elements (i.e. O_2) in the atmosphere, which is re-emitted at a characteristic wavelength.



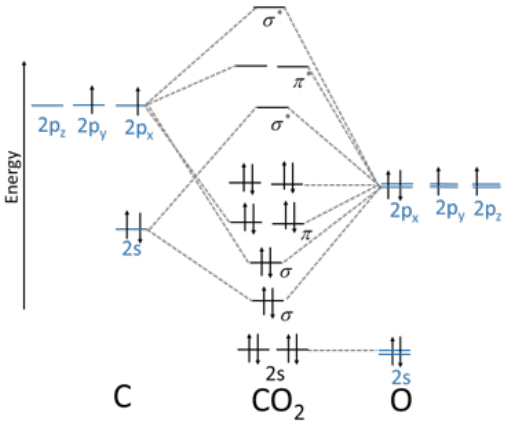
Credit: CXC/NASA/SAO

Inner Solar System

- Venus, Earth, Mars and the Moon give off X-rays, mostly in their coronae (H) and atmospheres.
- Mechanisms are predominately solar wind charge exchange and X-ray fluorescence
- Comets also observed to give off X-rays due to a coma forming from interactions with the solar wind. Plasma in magnetic field heats electrons.

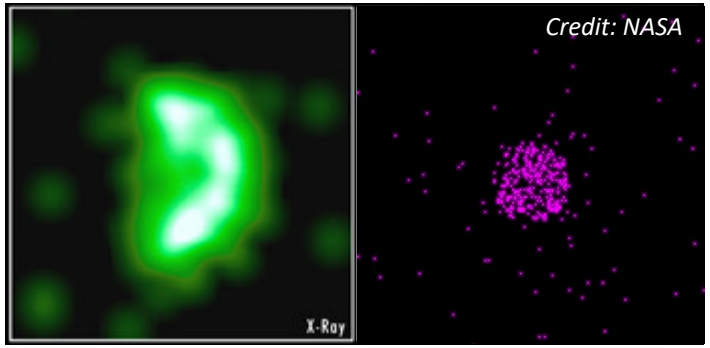


XMM data of Charge Exchange and Fluorescence around Mars

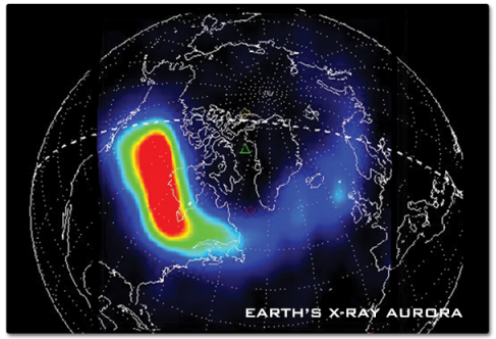


Molecular Orbital diagram of CO_2

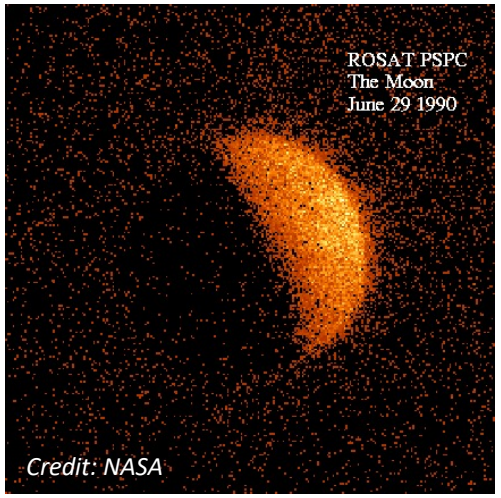
Chandra images of Venus and Mars

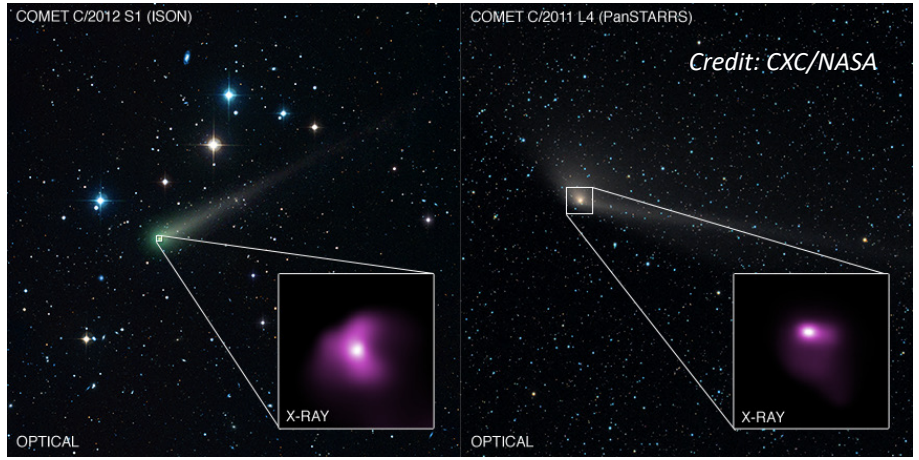


X-rays from Earth's Aurora



Credit: NASA/PIXIE/POLAR





Outer Solar System

- Most outer planets also produce X-rays.
- Jupiter produce aurorae, but Saturn does not!
  - Some of Jupiter's moons (i.e. Europa) also emit X-rays.
  - Possibly due to lower accelerating potential on Saturn.
  - X-rays from Saturn's disk and rings.
- Uranus (recently!)
  - Chandra observed (*flaring*) X-rays from Uranus.
  - Scatters X-ray light from Sun (like Jupiter, etc)
  - One other X-ray mechanism thought to be due to energetic particles colliding with its rings (i.e. Saturn).
- Unexpected, bright X-rays from Pluto
  - No magnetic field (no natural X-ray generator/mechanism)
  - Not from aurorae. Solar wind interaction with Pluto's atmosphere?
    - Not enough gas leaking from Pluto's atmosphere, Solar Wind not strong enough to produce X-ray flux observed.
- No X-rays observed from Neptune.

Credit: Drake, J., SAO, 2019, https://arxiv.org/pdf/1910.05662.pdf

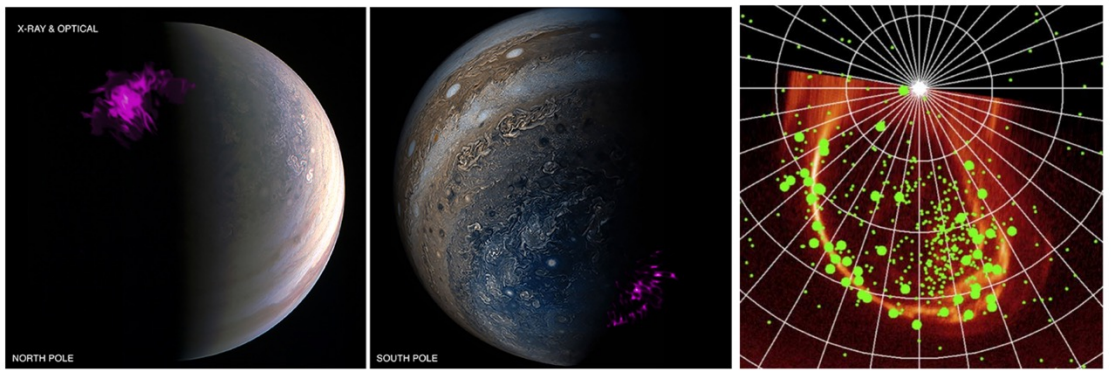
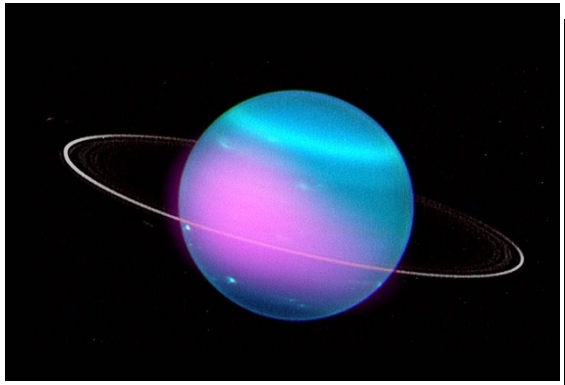
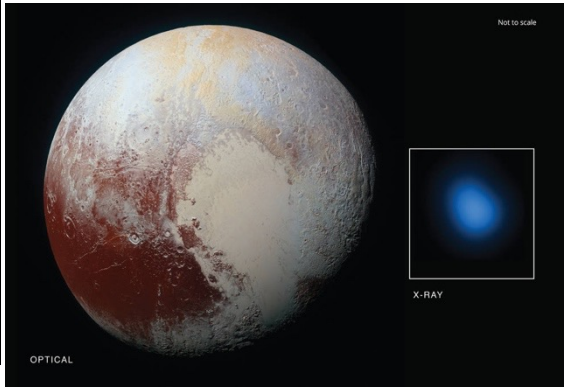


Figure 4: *Left: X-ray emission observed from the north and south aurorae of Jupiter by Chandra (magenta) superimposed on visible light images from the Juno spacecraft. Based on Dunn et al. (2017) from http://chandra.harvard.edu/photo/2017/jupiter/. Right: Polar projection of a Hubble STIS FUV image of Jupiter's northern aurora (orange) overplotted with the positions of X-ray photons detected by Chandra during simultaneous observations on 24 February 2003. Small and large green dots indicate photon energies < 2 keV and > 2 keV, respectively (from Branduardi-Raymont et al. 2008).*

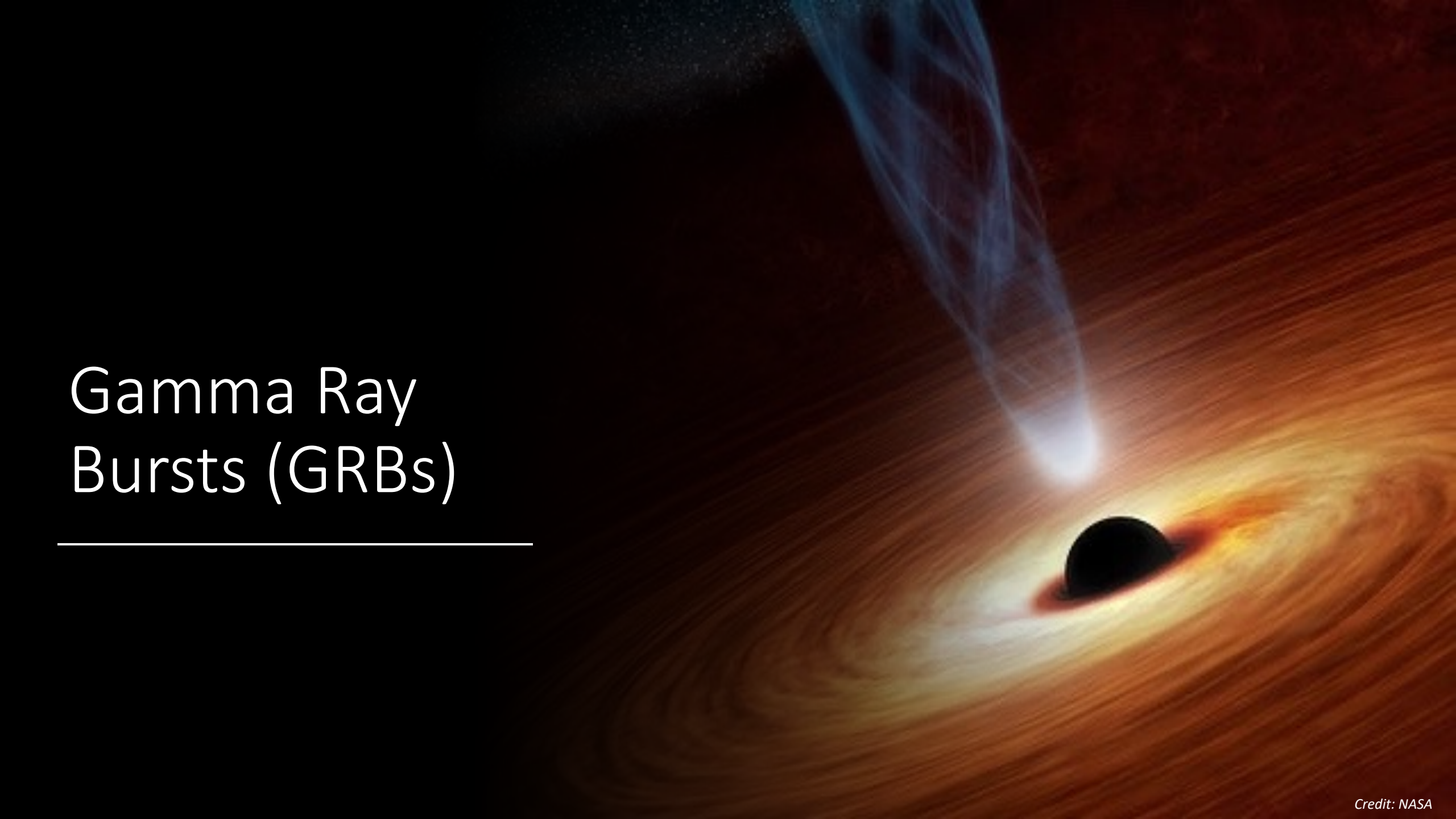


Credit: X-ray: NASA/CXO/UCL/W. Dunn et al; Optical: W.M. Keck Observatory



Credit: NASA/CXC/SAO/New Horizons

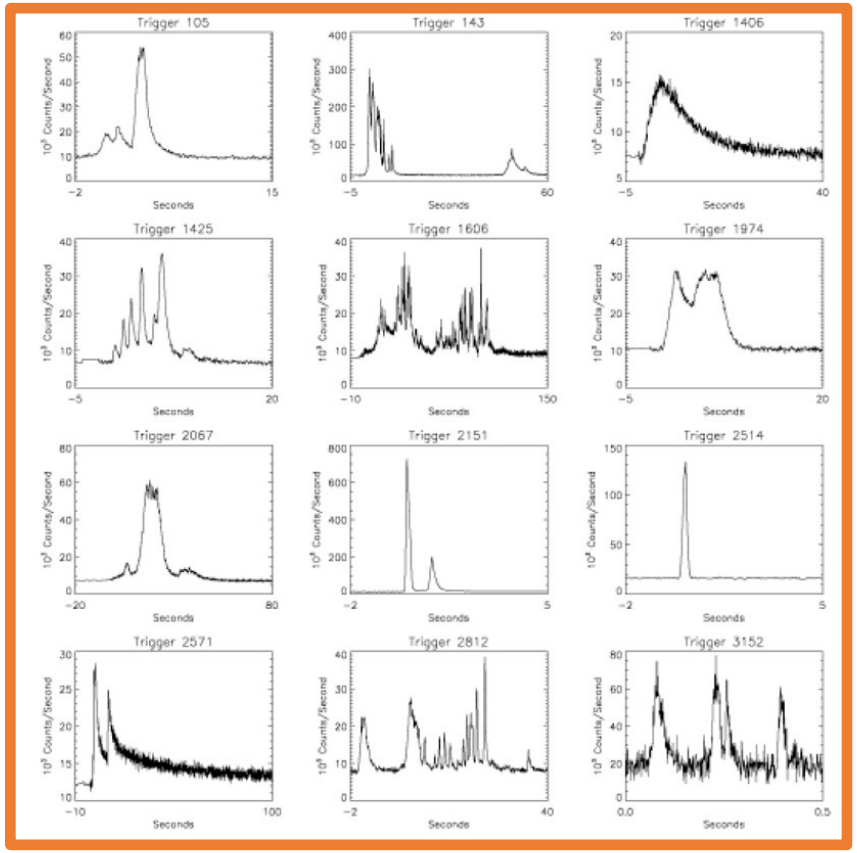
Gamma Ray Bursts (GRBs)



Credit: NASA

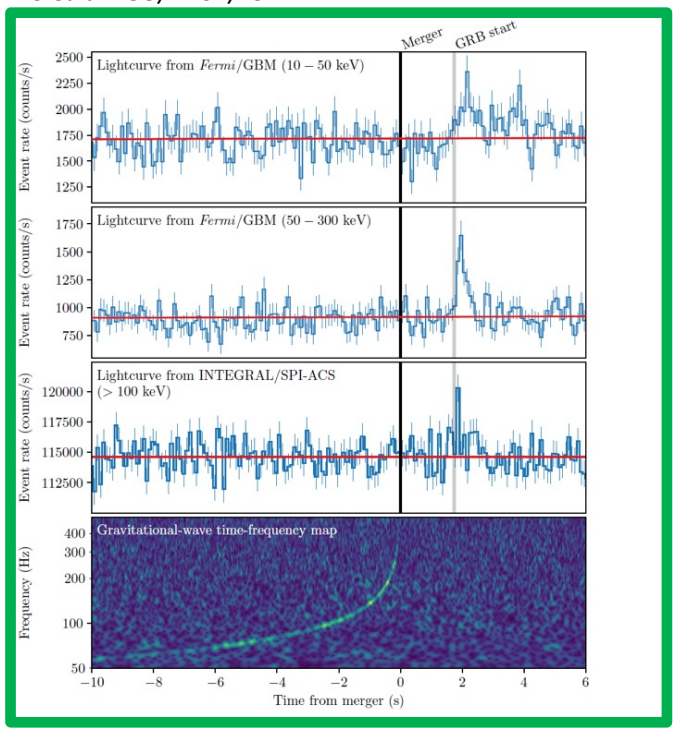
Gamma-ray Bursts (GRBs)

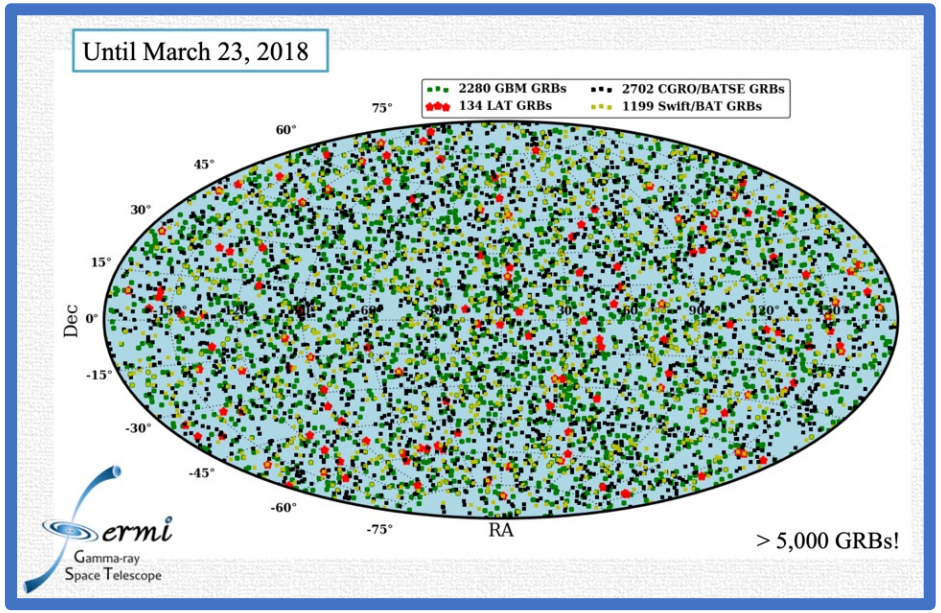
- First discovered in 1967 by Vela 3 and 4 to monitor nuclear weapons testing.
- **BATSE** (1991), **BeppoSAX** (1996), **Swift** (2004), **Fermi** (2008)
- Brightest and most energetic EM transients in the Universe.

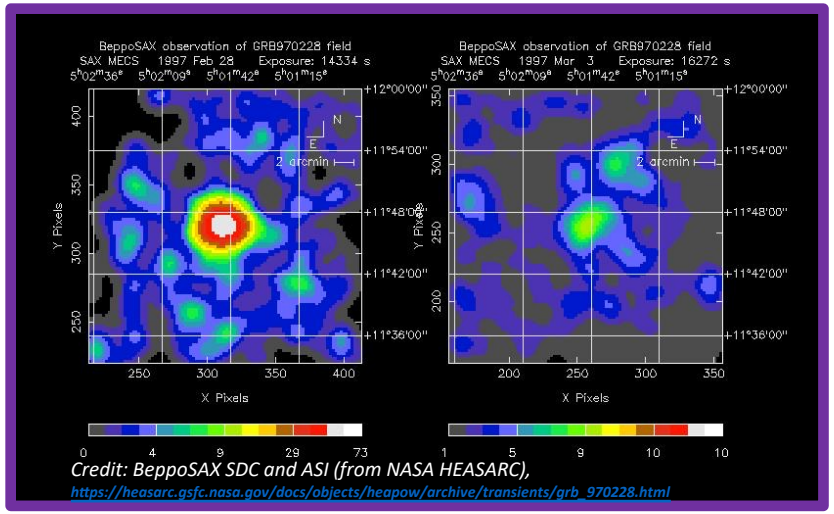


Credit: J.T. Bonnell (NASA/GSFC)

Credit: LIGO/NASA/Fermi





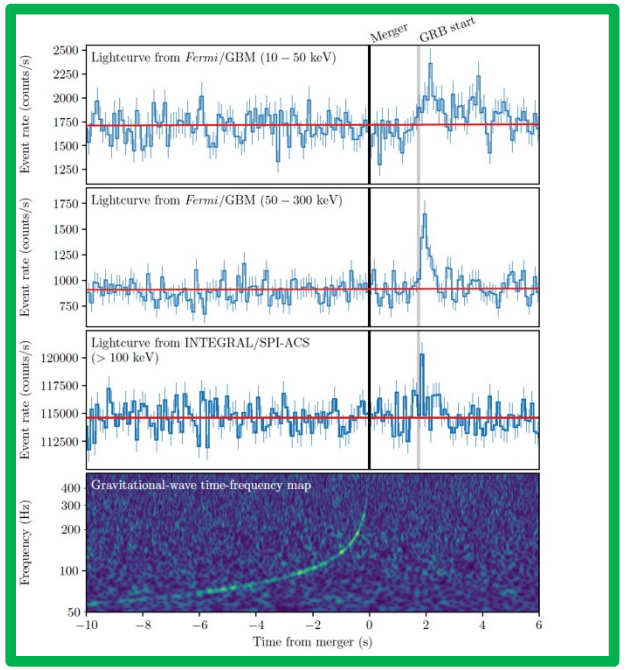


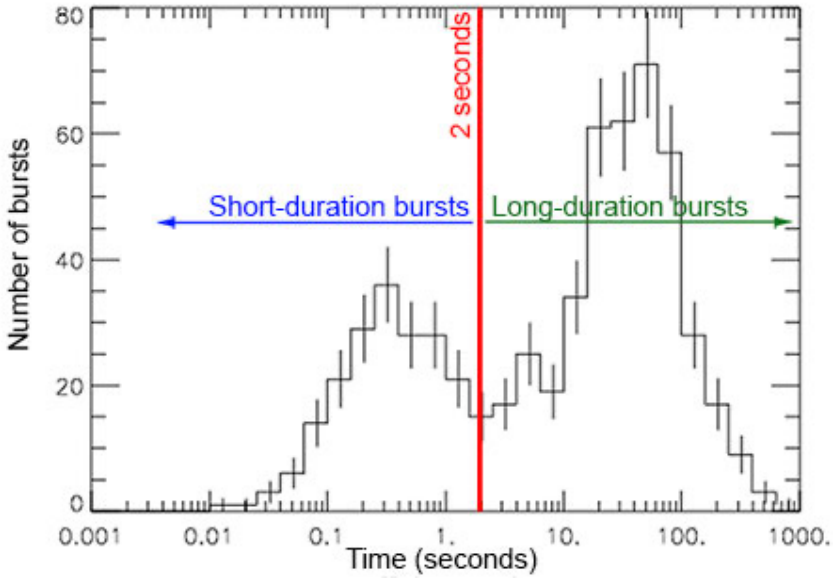
Credit: BeppoSAX SDC and ASI (from NASA HEASARC),
https://heasarc.gsfc.nasa.gov/docs/objects/heapow/archive/transients/grb_970228.html

Gamma-ray Bursts (GRBs)

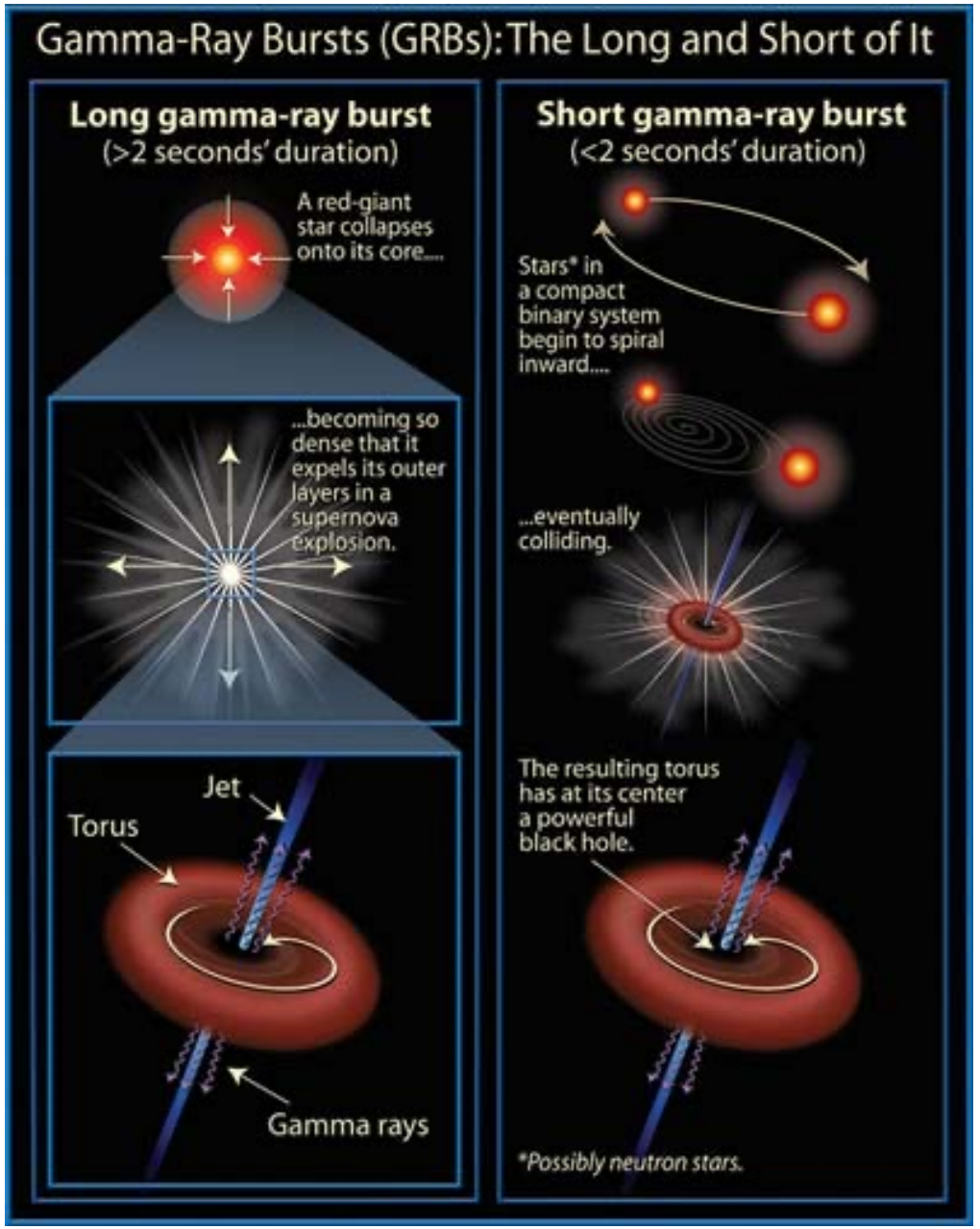
- Two types of GRB:
  - ***Short*** GRBs - <2 s, spectrally hard (energetic)
  – NS-NS merger (**170817A**)
  - **Long** GRBs - >2 s, Diverse morphology and slightly less energetic (Fireball/shock model)

Credit: LIGO/NASA/Fermi





Credit: NASA/BATSE/CGRO

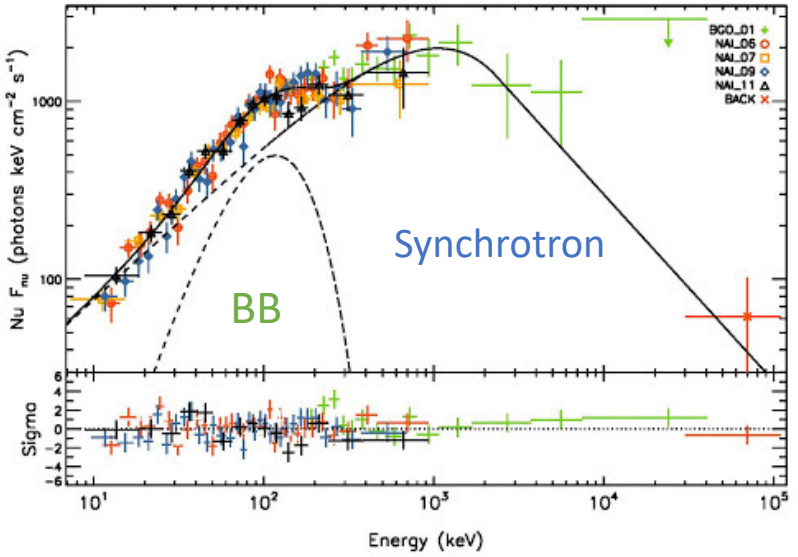


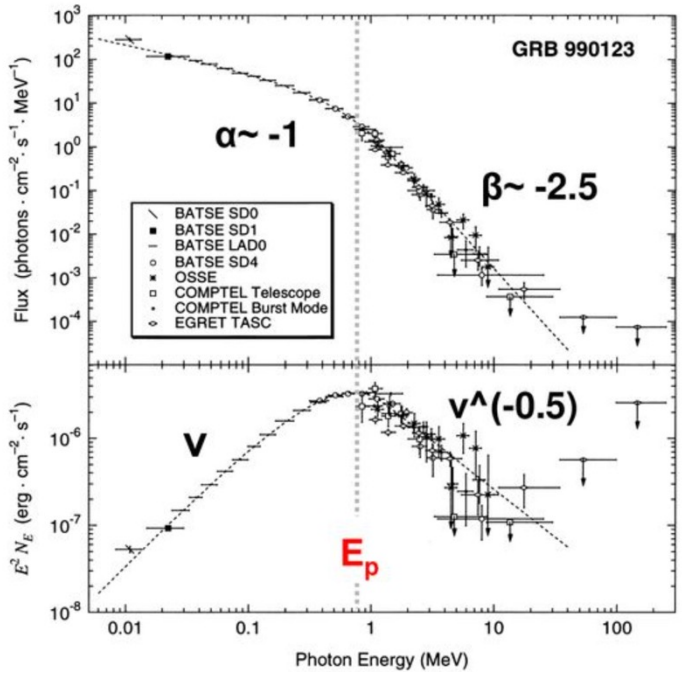
Credit: NASA and A. Feild (STScI)

Typical GRB Prompt Spectra…

- Power Law Synchrotron spectrum:
  - Relativistic electrons driven by jet physics. Power-law decreases with energy. **Generally featureless continuum.**
- "Comptonized" spectrum:
  - Compton Scattering of electrons at a different temperatures produces a power law spectrum with an energy cutoff.
- "Band" function:
  - Joint smoothly broken power-law function, with high energy, β component.
- Blackbody (BB) /thermal spectrum
  - Thermal emission has T of millions of K and is due to Bremsstrahlung from optically thin gas or Black-body radiation from optically thick gas. Thermal spectra have exponential decrease with energy.
- Other spectral models for higher energy bursts and afterglow (IC, etc)

Axelsson et al.
GRB 110721A





Briggs et al. 1999

Prompt Emission Spectrum:

$$F_\nu \propto \nu^{-\alpha} \; (h\nu < E_p)$$
$$F_\nu \propto \nu^{-\beta} \; (h\nu > E_p)$$

Long GRB:

$\langle E_p \rangle \sim 160$ keV

$\langle \alpha \rangle \sim -0.9$

Short GRB:

$\langle E_p \rangle \sim 490$ keV

$\langle \alpha \rangle \sim -0.5$

$\langle \beta \rangle \sim -2.3$

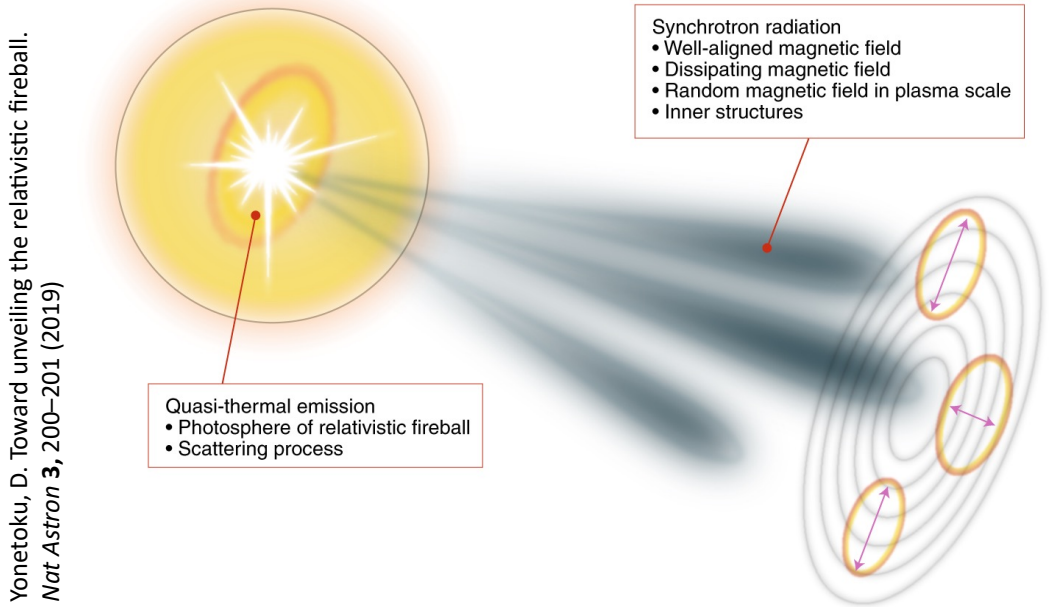
Nava+, 2011
Gruber+, 2014

Typical GRB Prompt Spectra..

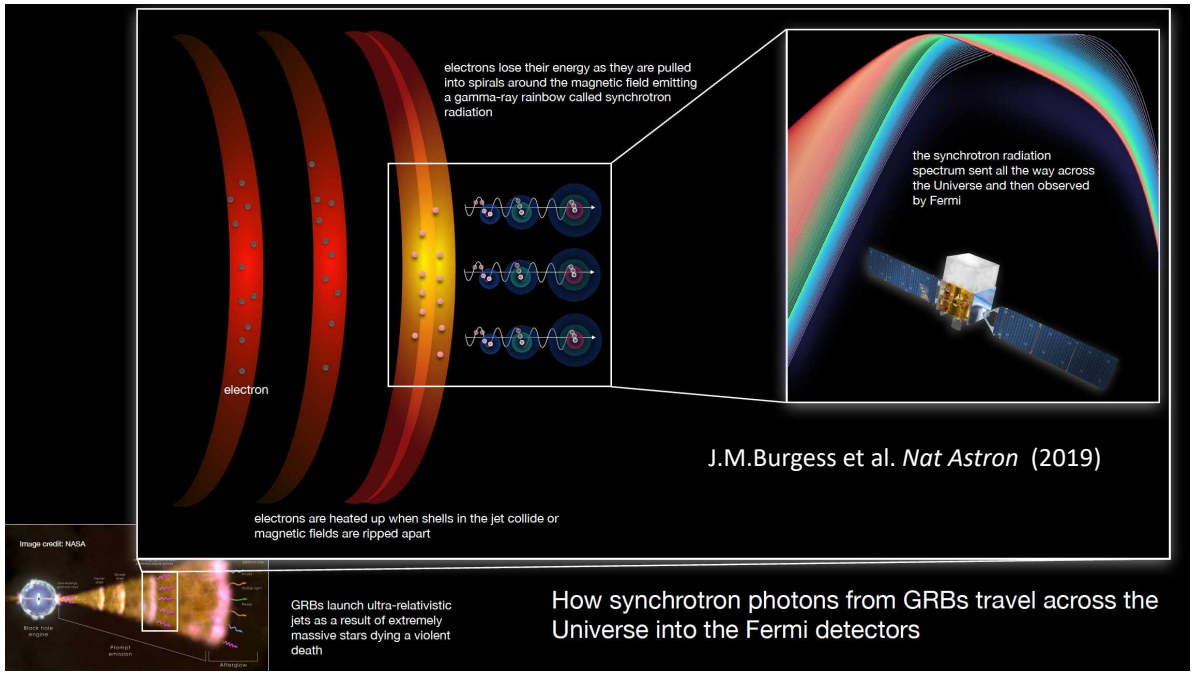
- Leading candidate radiation mechanisms for GRB prompt emission:
  - Comptonization of quasi-thermal photons from the photosphere
  - Synchrotron radiation

- Both successfully reproduce observed values of:
  - E_p (peak energy in the νF_ν spectrum),
  - β (the high-energy power-law spectral index).

- Predictions deviate with observations for low-energy power-law index α .



Yonetoku, D. Toward unveiling the relativistic fireball. *Nat Astron* **3**, 200–201 (2019)



J.M.Burgess et al. *Nat Astron* (2019)

Magnetized Stars (Magnetars)



Credit: NASA GSFC / GESTAR

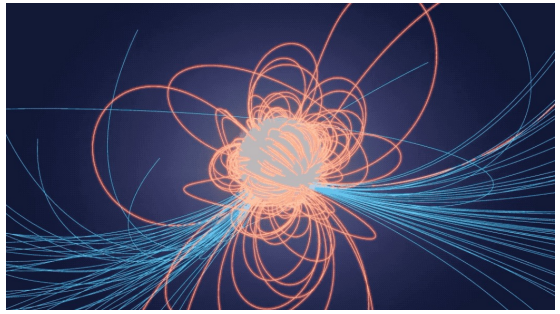
Magnetars

- Magnetized neutron stars (*Magnetars*) are smoldering remnants of >10 $M_\odot$ stellar explosions (core-collapse supernovae).

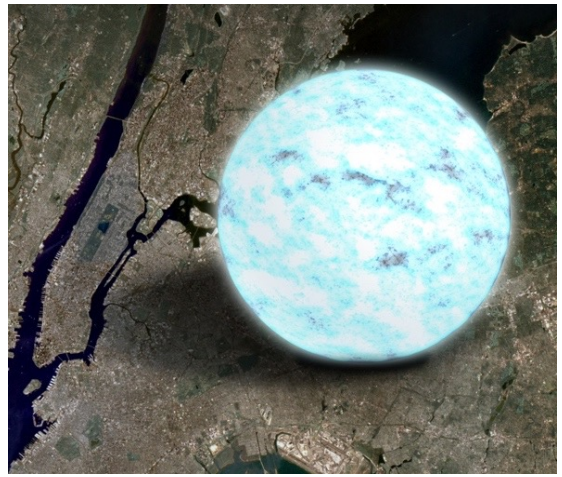
- Magnetar's:
  - Have a magnetic field of $10^{13\text{-}15}$ G
    (fridge magnet = 100 G, 10 trillion times weaker)
  - Spin once on their axis every 1-10 s.
  - Are the size of a large city (*d* = 15-20 km)
  - Weigh 1-3 Solar masses (typically 1.4 $M_\odot$)

- MHD dynamo is the dominant, though still contentious, theory behind presence of large magnetic field.

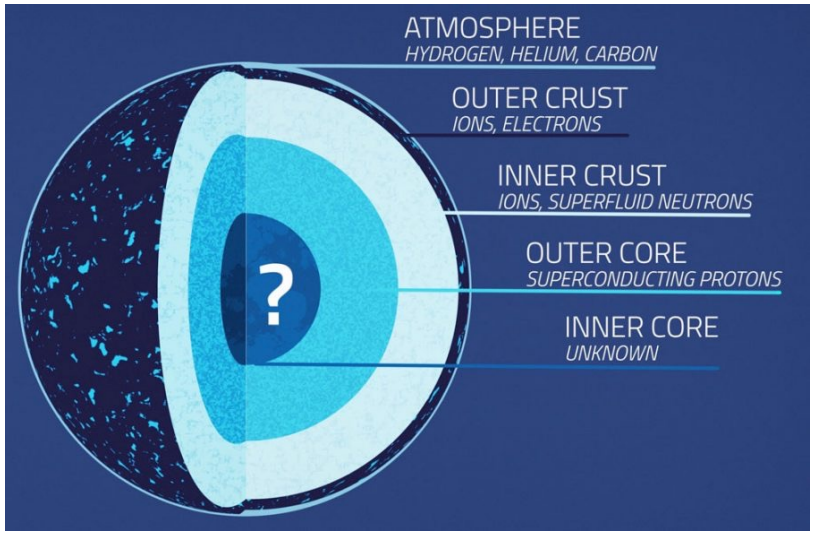
- Recently confirmed to be a source of some (all?) Fast Radio Bursts (FRBs).







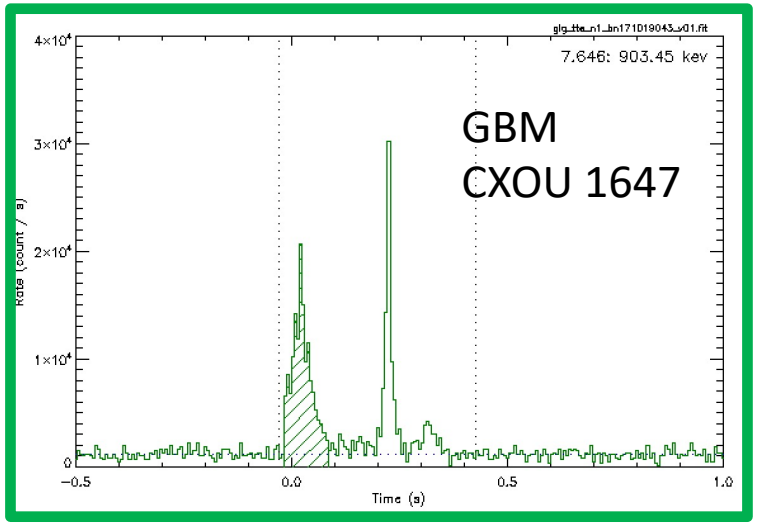
Credit: NICER / NASA

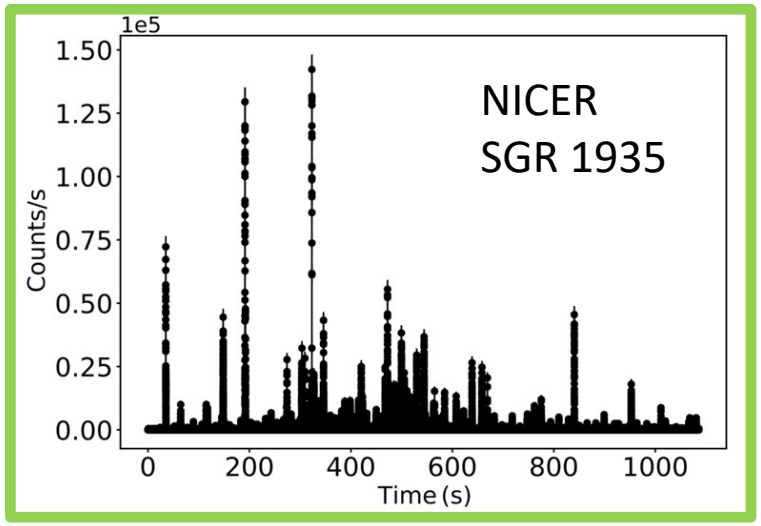


Credit: NASA's Goddard Space Flight Center / Conceptual Image Lab

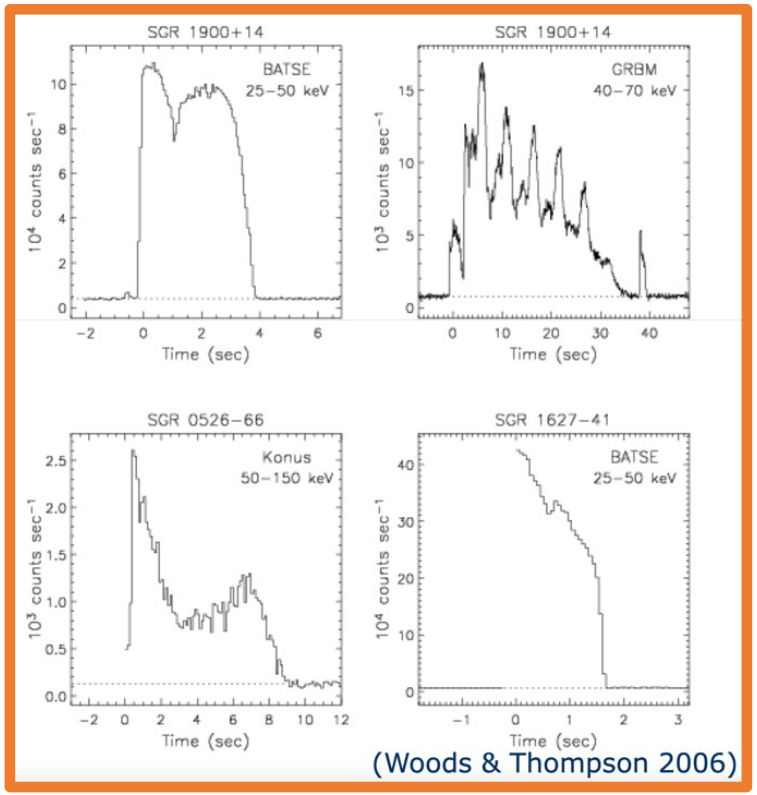
- Transient behaviors:
  - **Episodic bursts**:
    - Most frequent
    - 10^{-2} - 1s
    - $10^{36\text{-}41}$ erg
  - **Intermediate flares**:
    - Uncommon
    - 1-50 s
    - $10^{41\text{-}43}$ erg
  - **Giant Flares**:
    - Rare
    - >100 s
    - $10^{44\text{-}47}$ erg

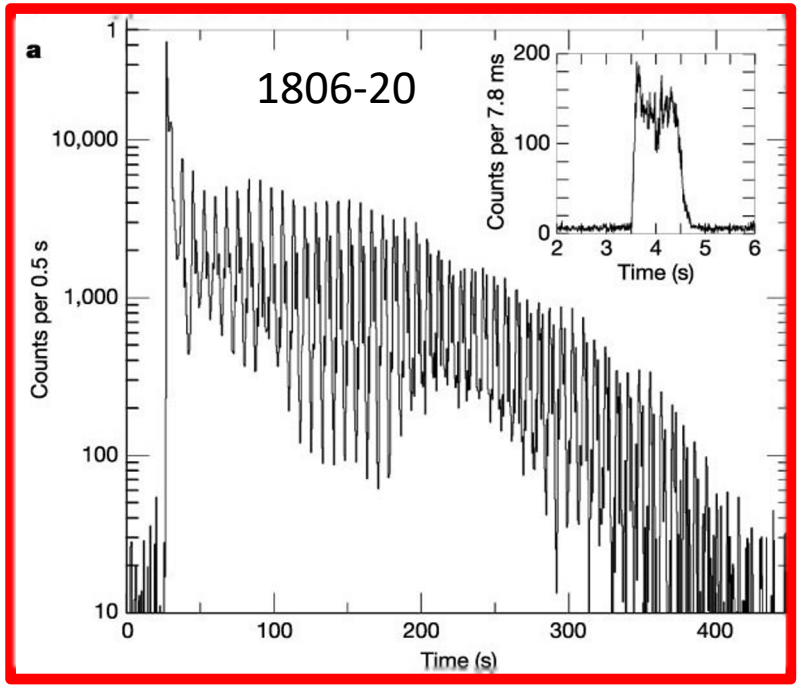
NB: 1 **erg** = 10-7 Joules or one common house fly performing one "push up". OR about **10^{34} erg to boil all the Earth's ocean's**





NICER Nugget 2020,
https://heasarc.gsfc.nasa.gov/docs/nicer/science_nuggets/20200507.html

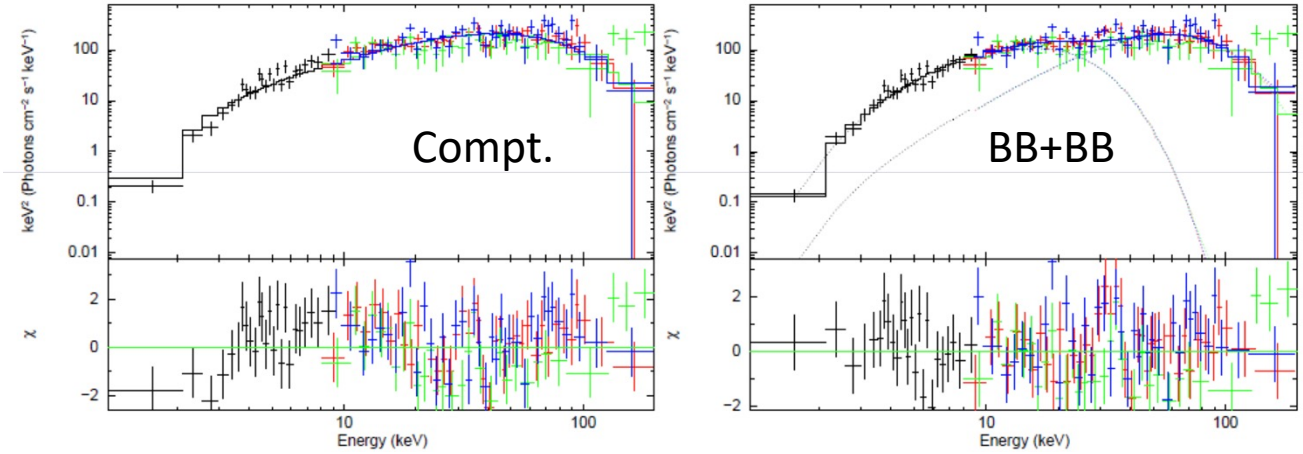


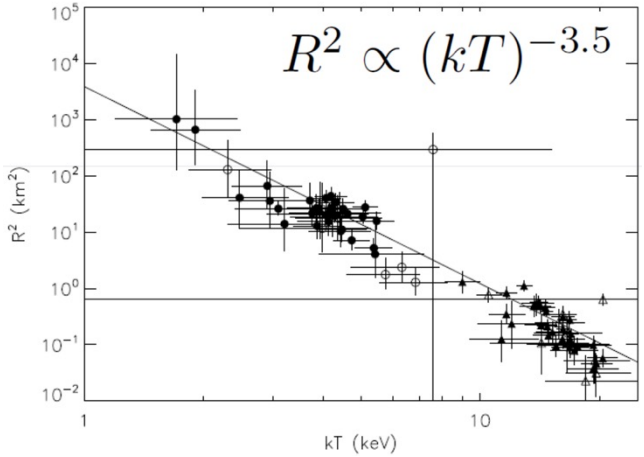


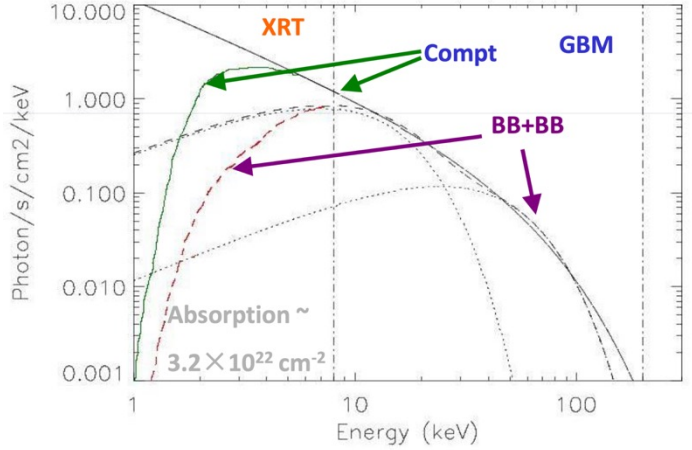
Hurley, K., Boggs, S., Smith, D. *et al. Nature* **434,** 1098–1103 (2005)

Magnetar Spectra

- **A Power-Law (PL) Spectrum**
- **A ”Comptonized” spectrum**
  - Compton Scattering of electrons at a different temperature produces a power law spectrum with an energy cutoff.
- **A Blackbody (BB) /thermal spectrum**
  - T of millions of K due to Bremsstrahlung from optically thin gas or Black-body radiation from optically thick gas. Exponential decrease with energy.
- **BB+BB**
  - Two temperatures usually fit with one hotter than the other.





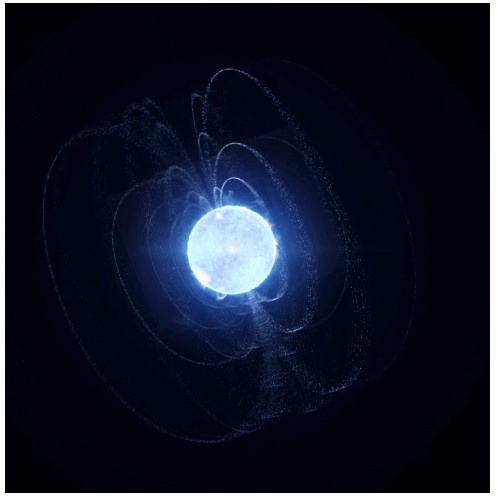


SGR J1550-5418 normal bursts, XRT+GBM, 0.5-200 keV (Lin et al. 2012)

- GRBs:
  - Cosmological
  - Very Energetic (10^{52} erg)
  - **Short** (NS-NS; <2 s) and *Long* (Collapsing Star; >2 s) types
  - Thermal (Photosphere) and Synchrotron /PL (Jets) spectra
  - Typically fit well with a **featureless** PL spectrum (variations/combinations)



- Magnetars:
  - Predominately Galactic, extragalactic too.
  - Three classes based on their energy release:
    - Episodic (**Common**, ms-s, $10^{36\text{-}41}$ erg)
    - Intermediate Flares (**Uncommon**, s-min, $10^{41\text{-}43}$ erg)
    - Giant Flares (**Rare**, mins, $10^{43\text{-}46}$ erg)
  - Typically fit well using a thermal spectrum (blackbody).



All Image Credit: NASA GSFC and Chris Smith (GESTAR/USRA)

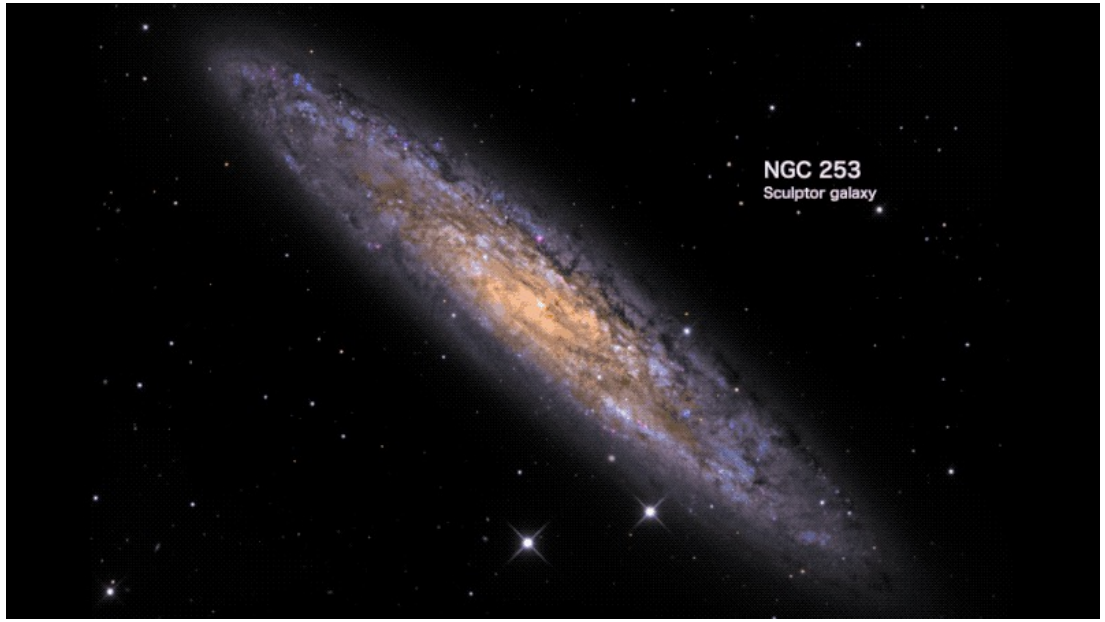
Case Study: GRB 200415A

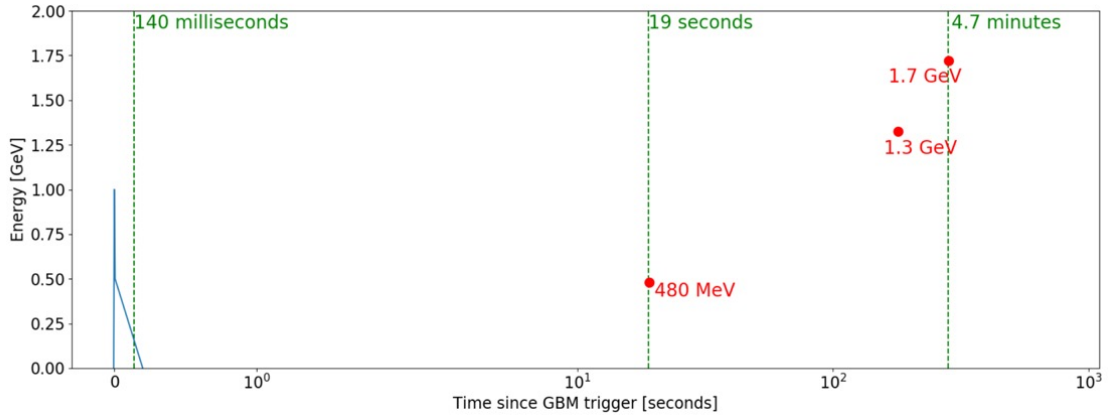
- Triggered the Inter-Planetary Network (**IPN**) on the **15th April 2020,** triangulated to a 17 sq. arcmin. region centered on NGC 253 (Sculptor Galaxy), 11Mly away
  (D. Svinkin, K. Hurley et al. Nature, 2021)

- Chance coincidence with NGC 253: **1 in 230,000**
  (E. Burns et al., ApJL,2021)

- **High Energy Emission (GeV) detection in the LAT**
  (N. Omodei et al., Nature Astronomy, 2021)

- AAS Press briefing of these results:
  https://www.youtube.com/watch?v=LjroNW7D-E4



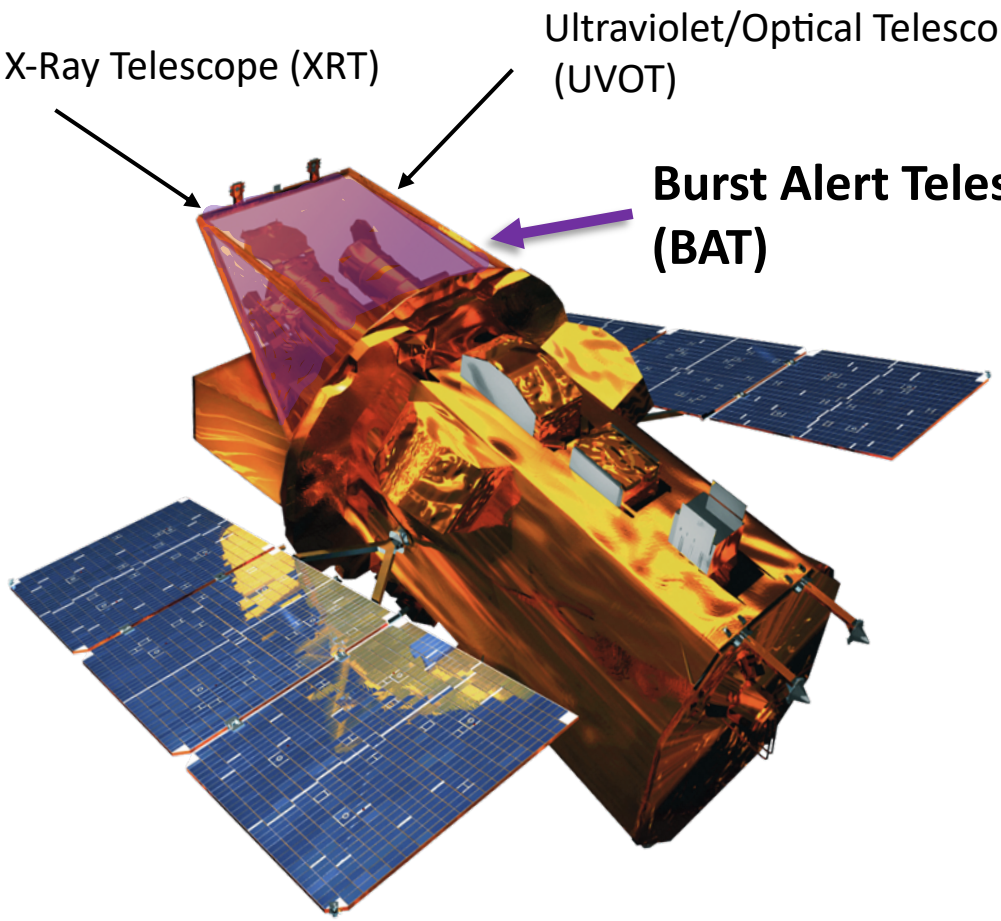


Credit: Nicola Omodei, Stanford University. Obtained with permission.

Fermi Gamma-ray Space Telescope (*Fermi*)

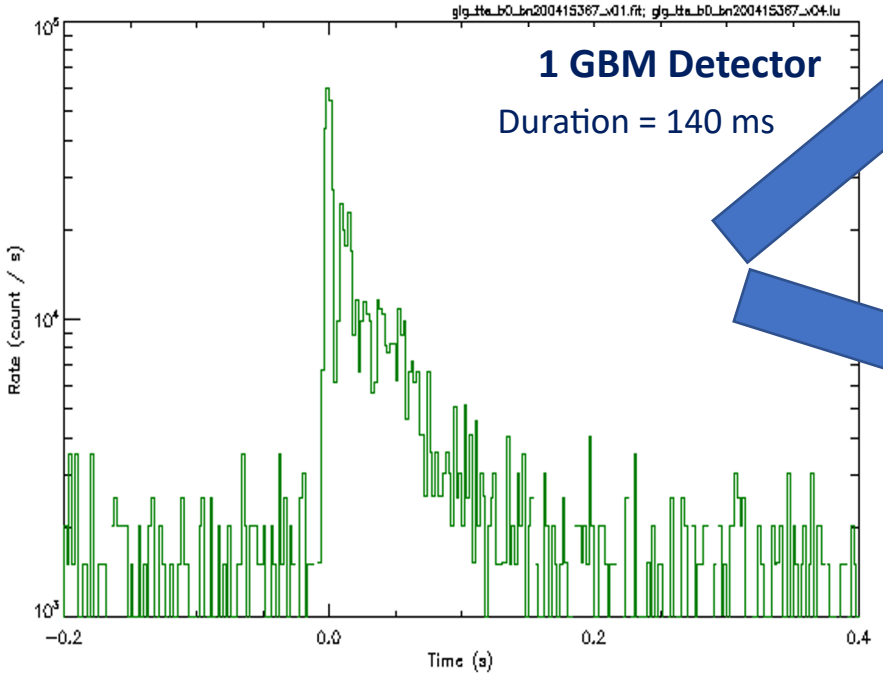


Neil Gehrels Swift Observatory (*Swift*)

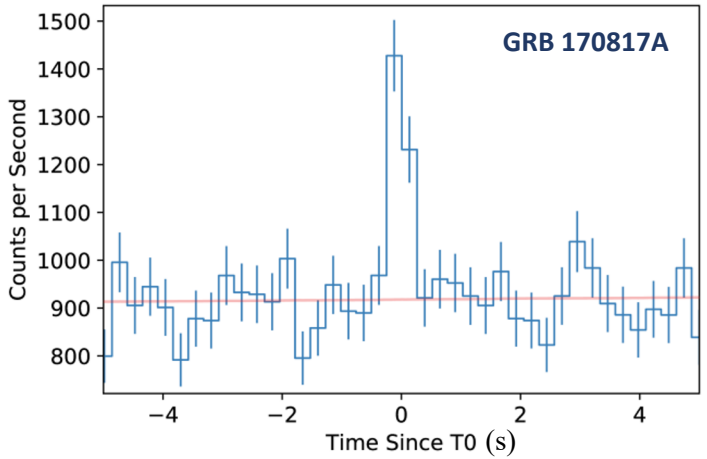


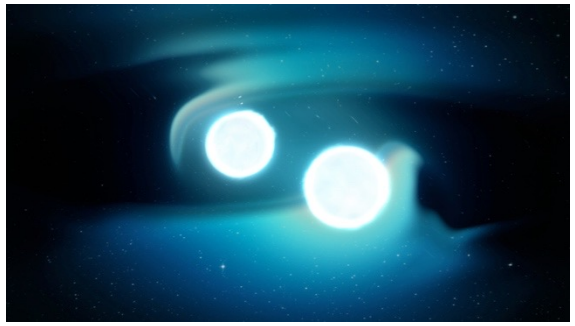
GRB 200415A detected offline using the Gamma-ray Urgent Archiver for Novel Opportunities (**GUANO**), a BAT pipeline to search for transients coincident with Gravitational waves.

All images courtesy of NASA



Short Gamma-ray Burst (sGRB)

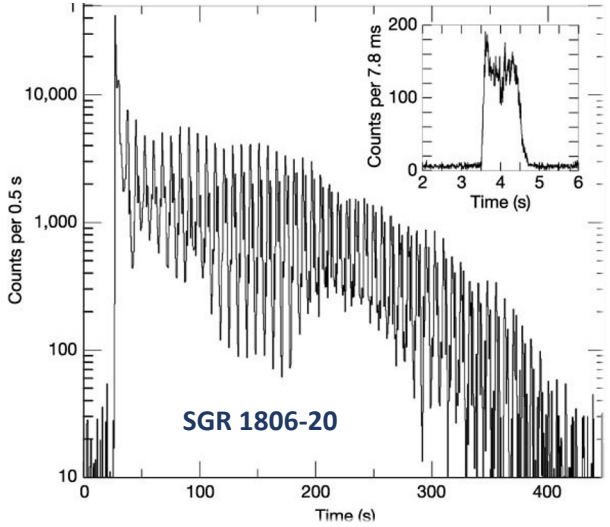


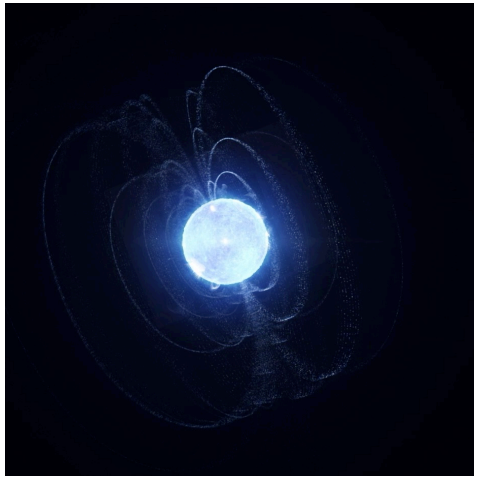


NASA GSFC Visualization Explorer (Brian Moore).

*Goldstein, A., et al., ApJL **848** (2), L14 2017.*

Magnetar Giant Flare





NASA Goddard and Chris Smith (USRA)

Hurley, K., Boggs, S., Smith, D. *et al. Nature* **434,** 1098–1103 (2005)


Credit: NASA GSFC / USRA GESTAR

Total energy emitted: 10^{46} erg

- ***All*** nuclear tests: 10^{25} erg
- **10 quadrillion times** more energy than Chicxulub impact (10^{30} erg)

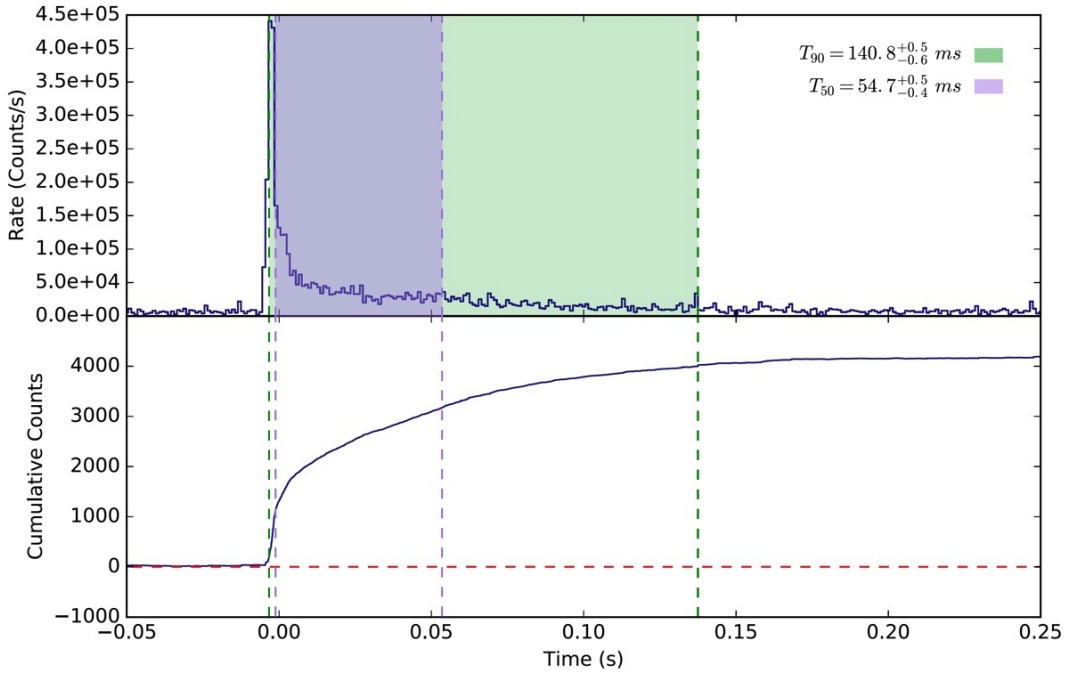
Total luminosity emitted: 10^{47} erg s^{-1} ($L_{iso,max}$= 10^{48} erg s^{-1})

Flare onset is 77 microseconds (>10x quicker than camera flash)

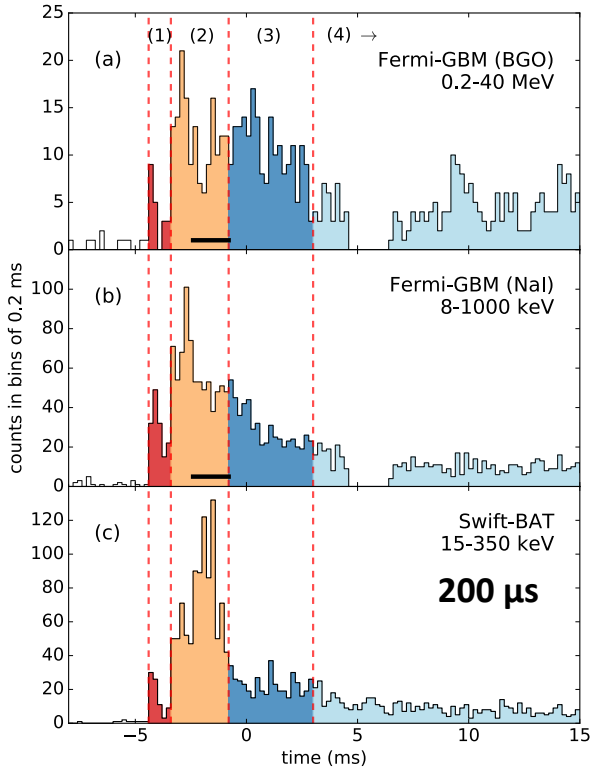
Comptonized spectrum throughout, non-thermal.

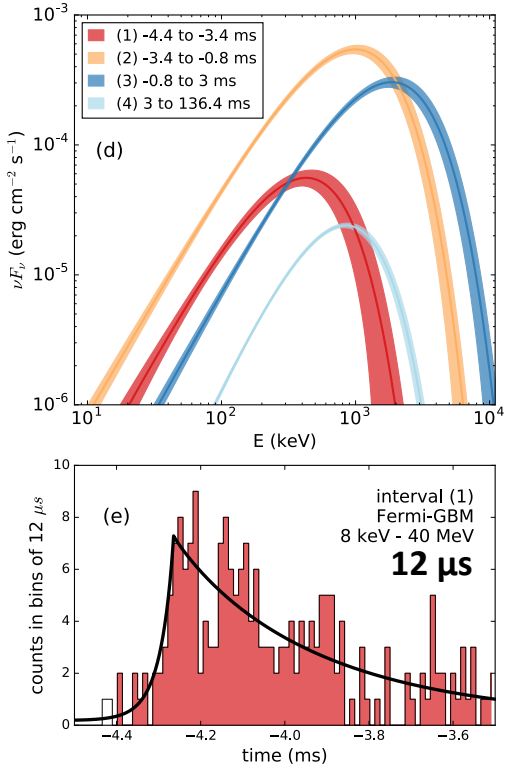
No modulated tail after the initial, 140 ms bright burst





Further Details: O.J. Roberts et al., Nature: http://doi.org/10.1038/s41586-020-03077-8

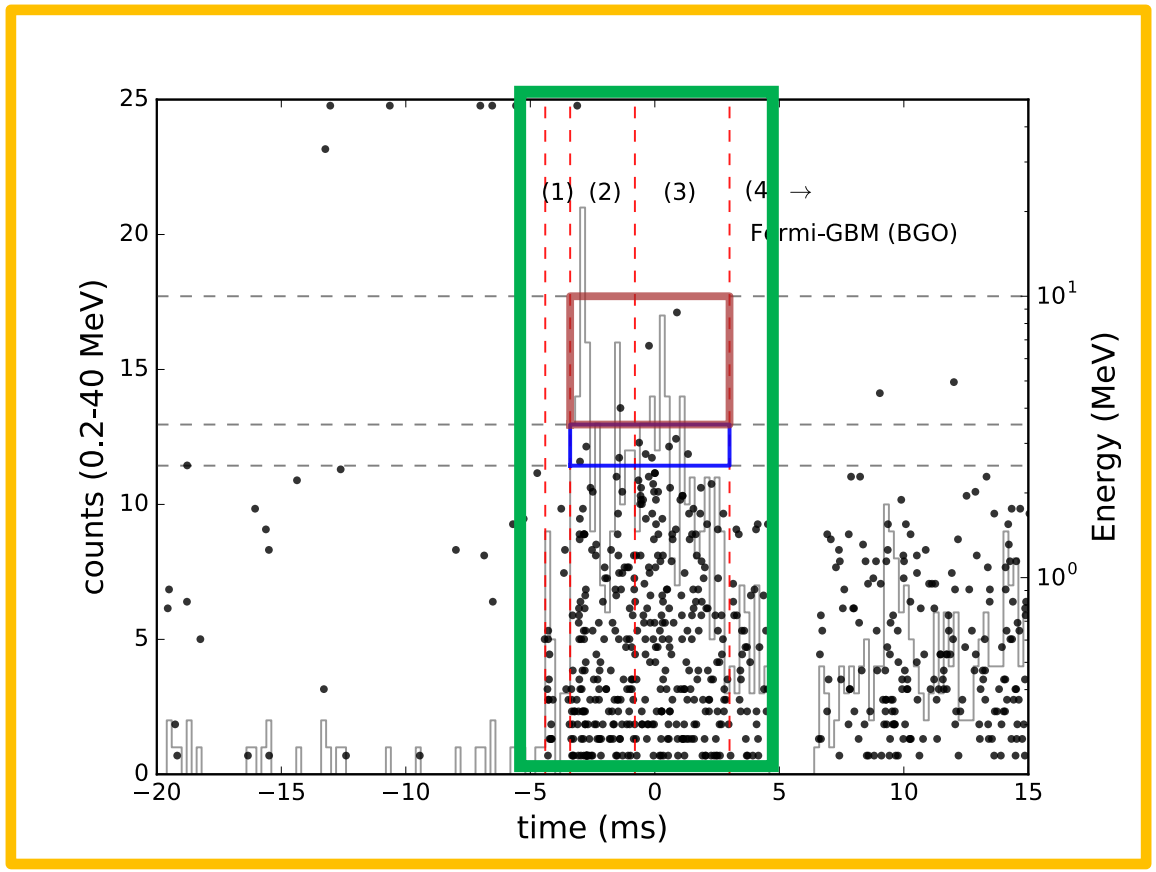


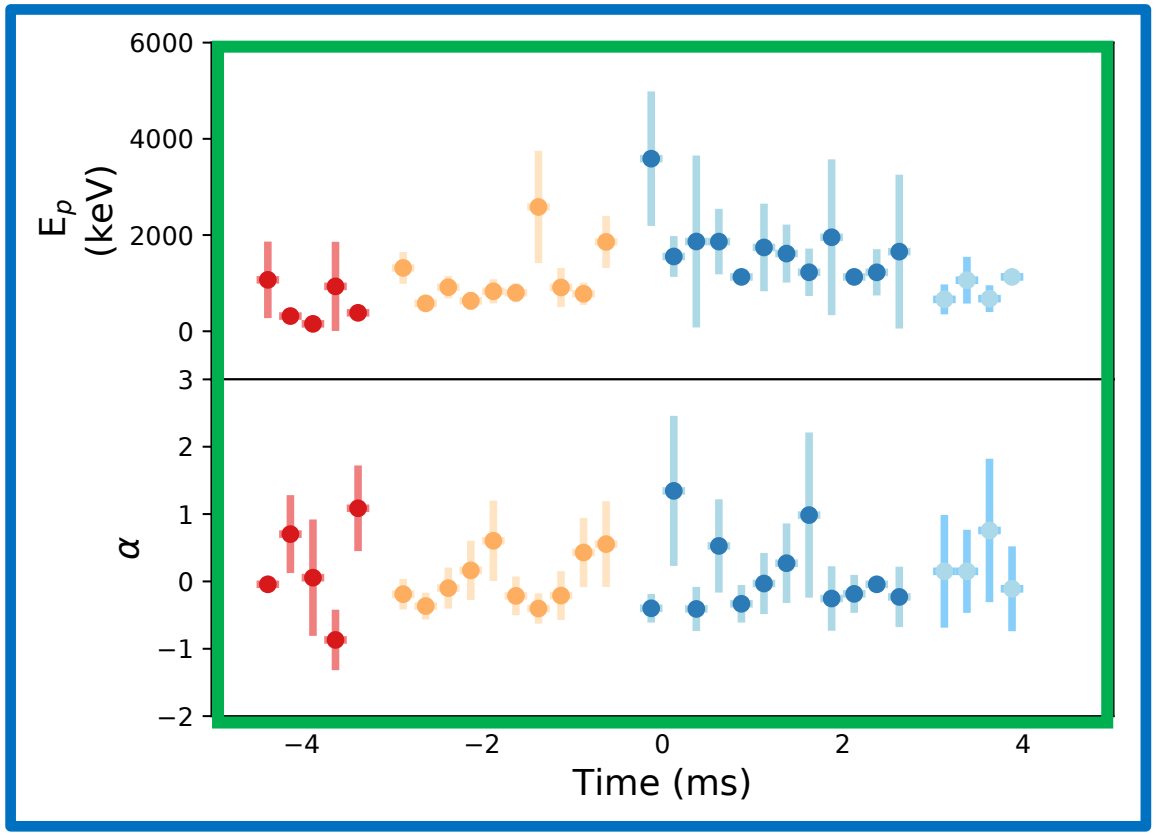


Highest energy photon: 3 MeV in GBM

- A million times more energy than blue light (~3 eV).
- 50x more energy than a typical medical X-ray.

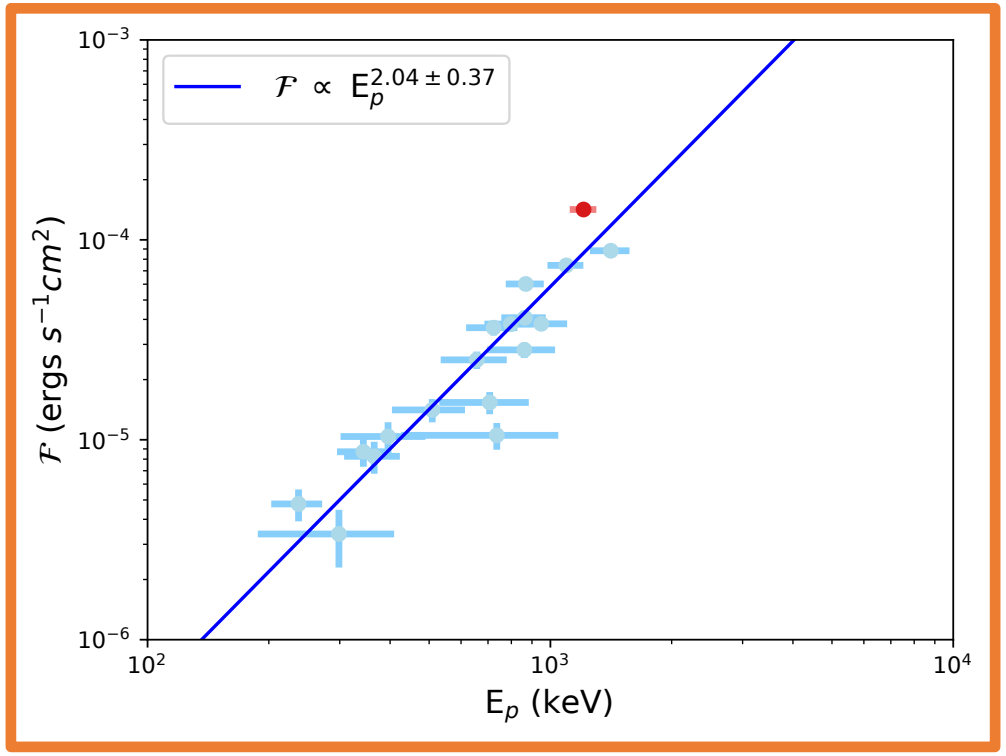
Variable, submillisecond changes in photon energy

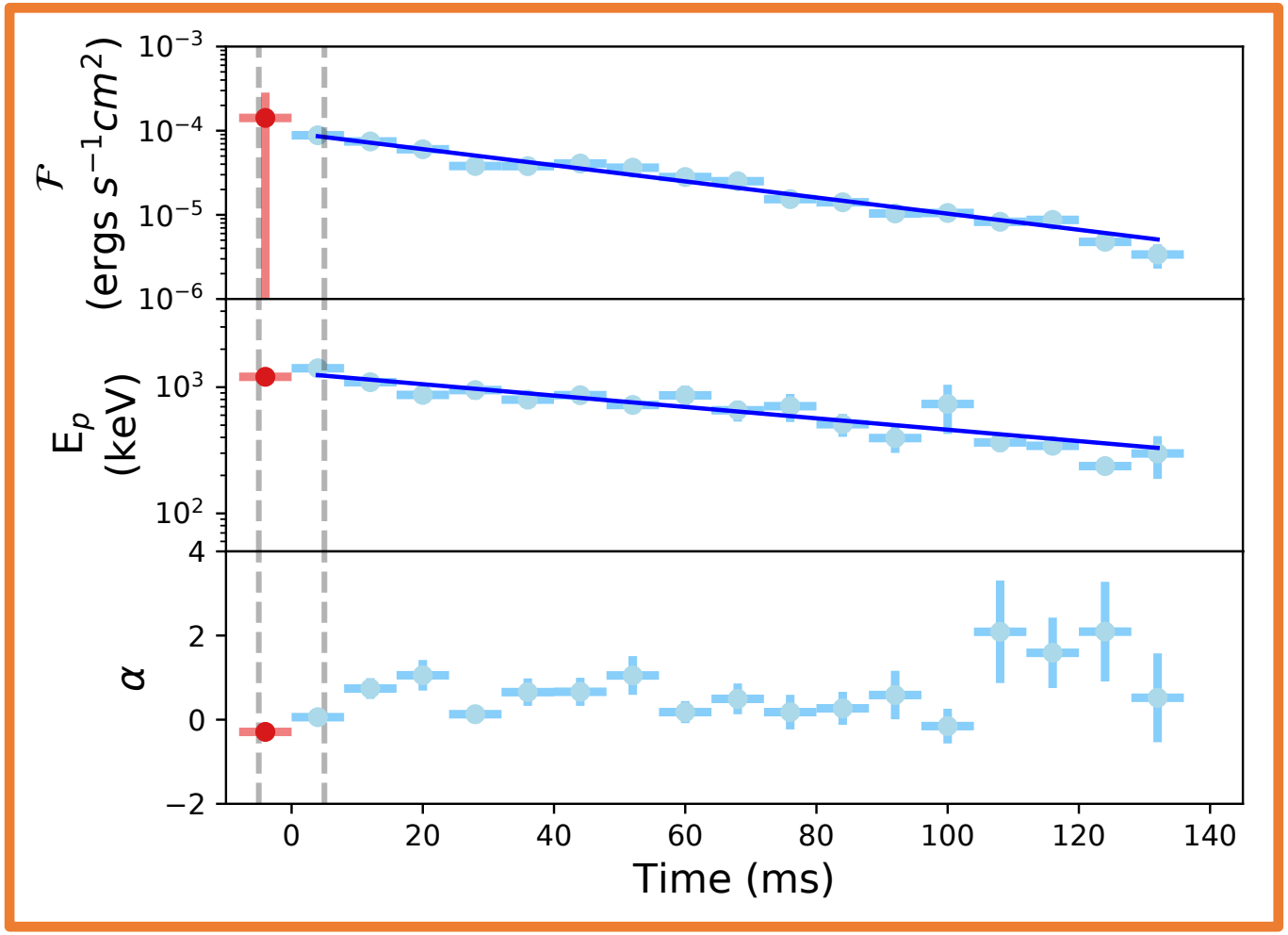




Further Details: O.J. Roberts et al., Nature: http://doi.org/10.1038/s41586-020-03077-8

- **Energy Flux Decay; $\tau_{\mathcal{F}}$ = 45±3 ms.**
- **Peak Energy Decay; τ_{Ep} = 100±1 ms.**
- **Non-variable α over burst duration.**
- **$\mathcal{F} \propto E_p^2$**



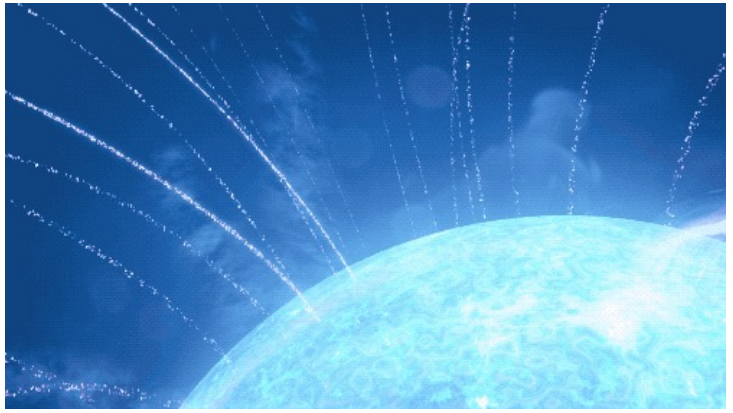


Temporal binning = 8 ms

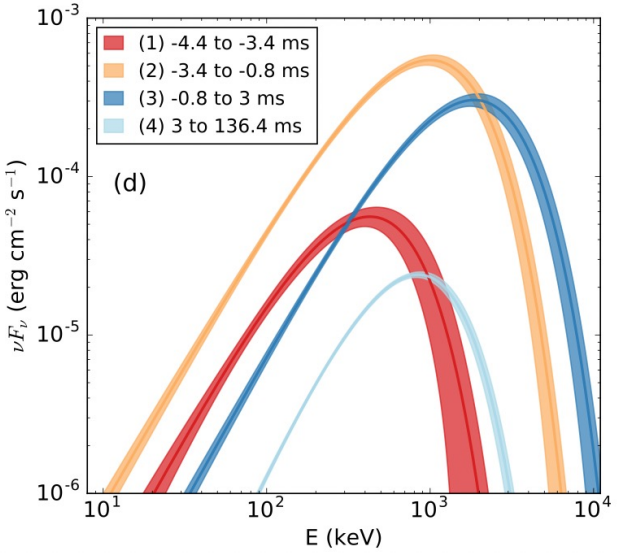
Further Details: O.J. Roberts et al., Nature: http://doi.org/10.1038/s41586-020-03077-8

Interpretations

- **Energy released by crustal fractures ejects hot plasma, like a photon torpedo…**
- **MeV-band emission:** Relativistic outflow that is initially, highly opaque.
  - $L_{iso} >> L_{edd}$ ($10^{47\text{-}48} >> 10^{38}$ erg s^{-1}), relativistic wind ($\Gamma >> 1$)
  - Wind transparency to QED pair-production by 3 MeV photons implies $\Gamma \sim 6$
- $\mathcal{F} \alpha E_p^2$**:** Explained by relativistic Doppler boosting
- **α~0:** Wind that is highly opaque to electron scattering; Compton cloud. *Inconsistent with synchrotron GRB emission scenarios*
- **Sub-ms spectral evolution:** Relativistic lighthouse beaming effect or relativistic-boosted wind acceleration and subsequent coasting/cooling
- **77 μs risetime:** *Extremely unlikely for a GRB.*



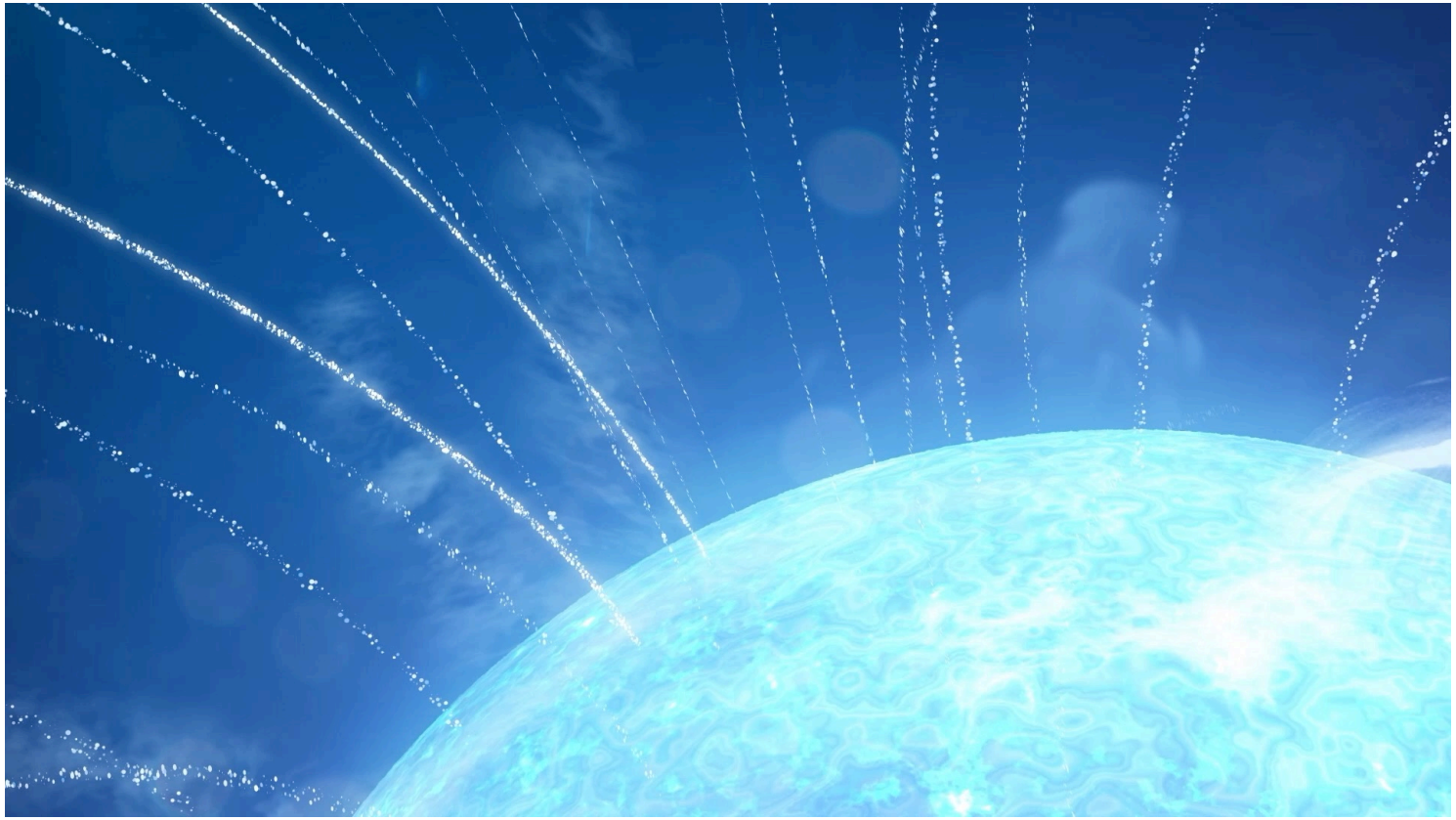
Credit: NASA GSFC / GESTAR



Roberts+2021

The flux, and spectral shape of GRB 200415A are **unusual/unlikely for a short GRB**, when compared to catalogs from previous space missions

Credit: NASA-GSFC/USRA GESTAR

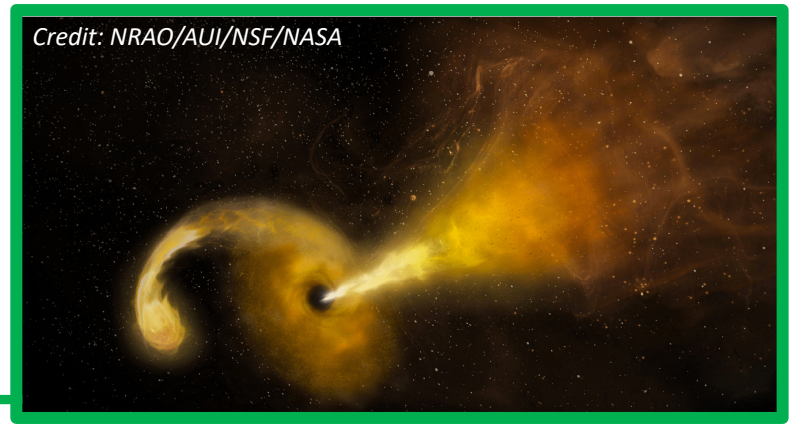


- 200415A is the clearest example yet of a giant flare from an extragalactic magnetar
- Unsaturated instrument spectra allow new discoveries to be made, opening a new front on studying the emission mechanism of these cataclysmic events.
- These “repeating GRBs” may contribute a sizeable fraction of events to be present in GRB catalogs.

Future Discoveries…

- Hottest topics right now:
  - Fast Radio Bursts (FRBs)
  - Fast Blue Optical Transients (FBOTs)
  - Factories for optical transients (Multi-Messenger Astronomy / Time Domain Astronomy)
  - Tidal Disruption Events (TDEs)
  - High-luminosity Supernovae
  - Supernova shock breakout
  - Quasi-periodic Eruption Sources
  - Active Galactic Nuclei
  - *And many more discoveries…*





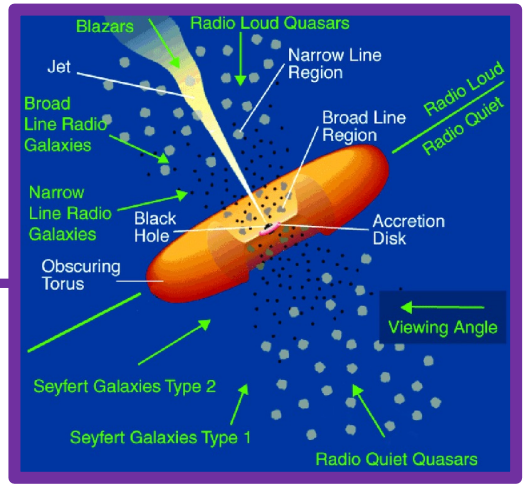
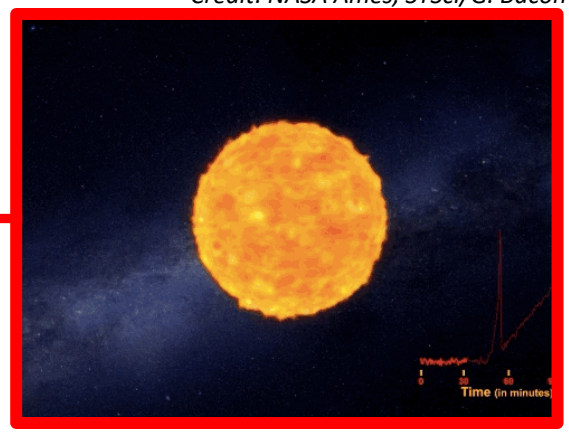


Figure from Urry & Padovani (1995), DOI: 10.1086/133630

Credit: NASA Ames, STScI/G. Bacon



Extras

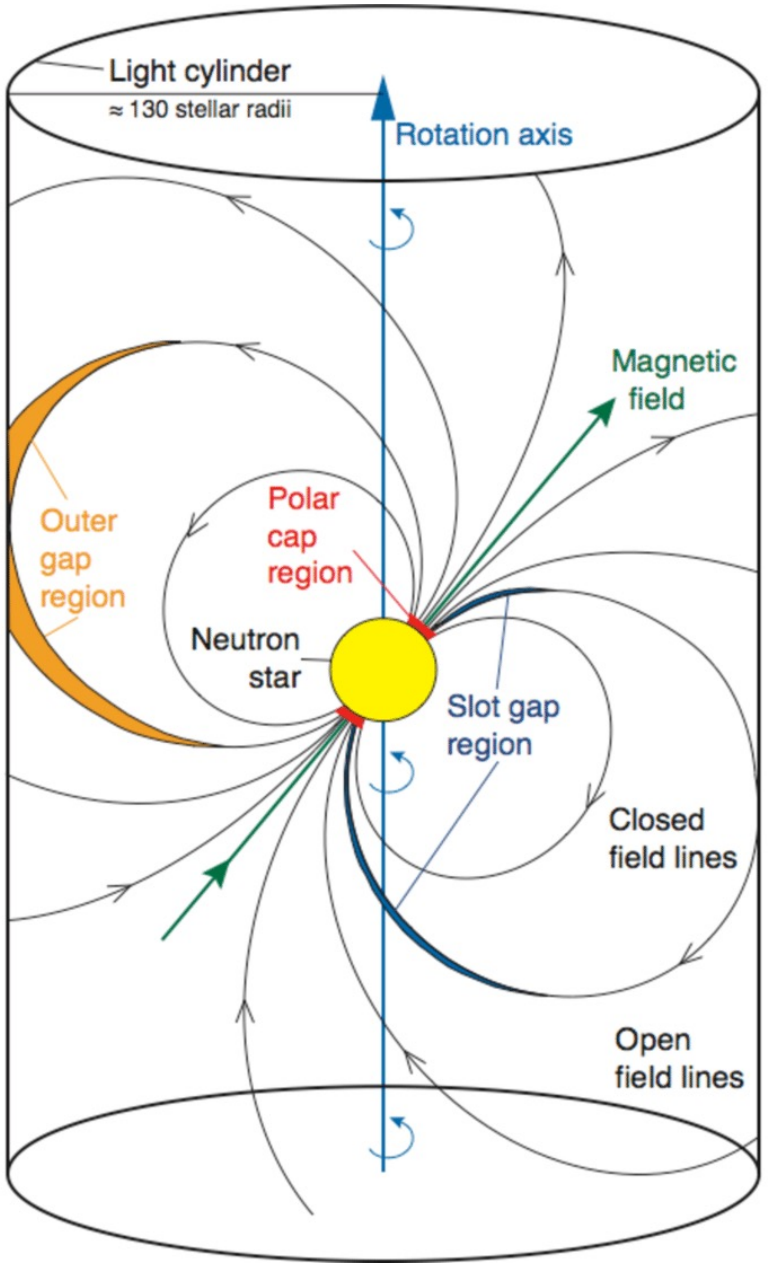
Pulsating Quasars (Pulsars)



Credit: NASA/CXC

Pulsating quasars (Pulsars)

- Neutron Stars with incredibly high magnetic fields ($10^{8\text{-}15}$ G).
- Very fast and stable rotators (up to about 700 times a second).
- Rotation and magnetic field axes misaligned resulting in pulses emitted are similar to lighthouses beams.
- X-ray, Gamma-ray and Radio radiation mostly from the magnetic poles of the star.
- Discovered in 1967 by Jocelyn Bell and Antony Hewish. Initially called LGM-1 (Little Green Men)

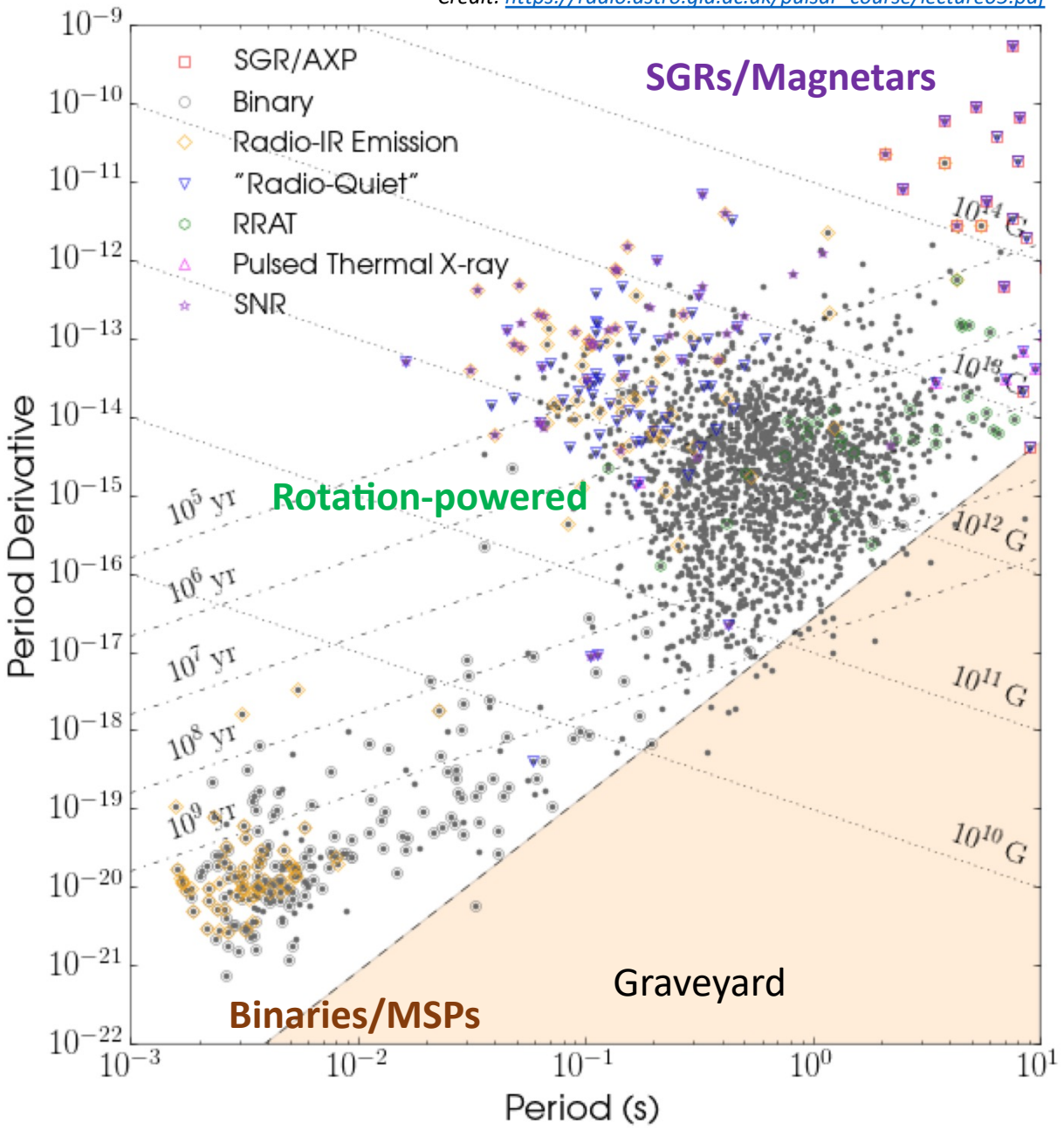


Aliu, E et al. (2008). Science. 322. 1221-1224.

Pulsars

- Age: $\tau \propto P/\dot{P}$
  - Young pulsars spin more rapidly than older ones and have a strong magnetic field
- Magnetic field: $B \propto (\dot{P}P)^{1/2}$
  - Old pulsars weaker magnetic fields than younger ones.
- Rotation so stable, we can measure the rate of change of the period ("spin period derivative" or "Pdot").
- Spin-down luminosity: $L \propto P/\dot{P}^3$
- Graveyard is filled with extinct pulsars too faint to detect from Earth

Credit: https://radio.astro.gla.ac.uk/pulsar_course/lecture05.pdf



Diverse Population

- 10% of known pulsars are millisecond pulsars, but 80% of these are in binary systems.

- CCOs (Compact Central Objects)
  - Located in the center of Supernova remnants
  - i.e. young, oxygen rich CCO in SNR Cassiopeia A.
  - Only a handful fit this category
  - Lack of X-ray pulsations.
  - Very low rotation slow-down rates (small **B** field).

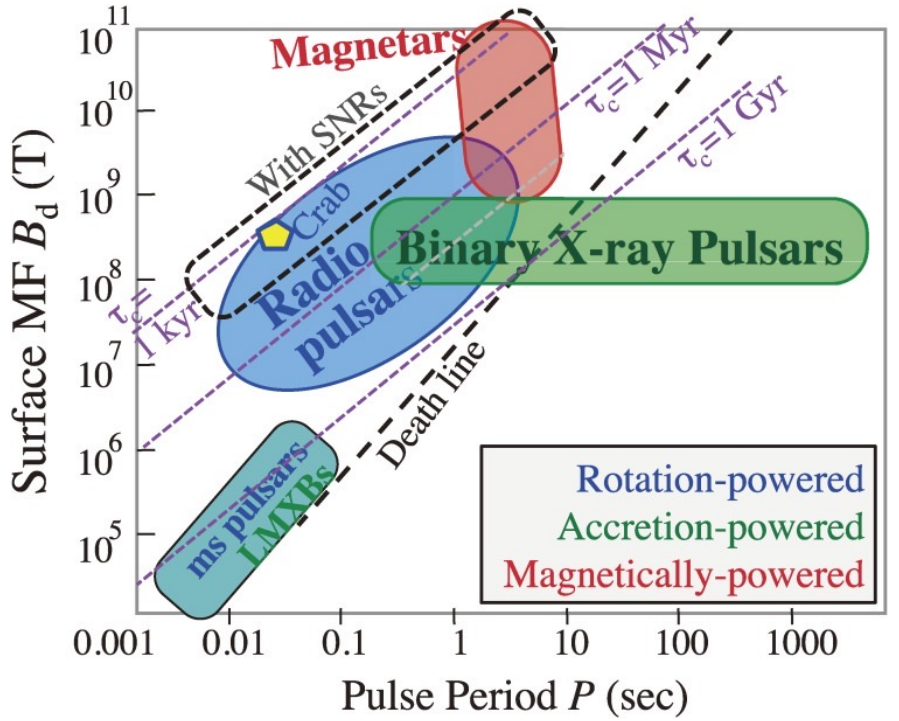
- XDINS (X-ray Dim Isolated Neutron Stars)
  - group of 8 isolated, young, cooling NS.
  - 120-500 parsecs from Earth
  - Thermally powered (Blackbody spectrum).
  - Spin periods of 3-12 seconds.

Three distinct classes:

Rotation-powered
(rotation loss powers the star)

Accretion-powered
(gravitational potential energy of accreted matter provides powers the star)

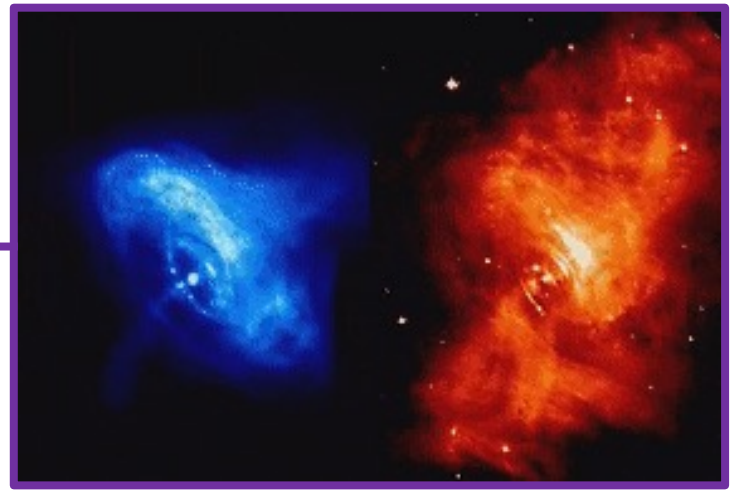
Magnetars
(extremely strong magnetic field decay powers star)



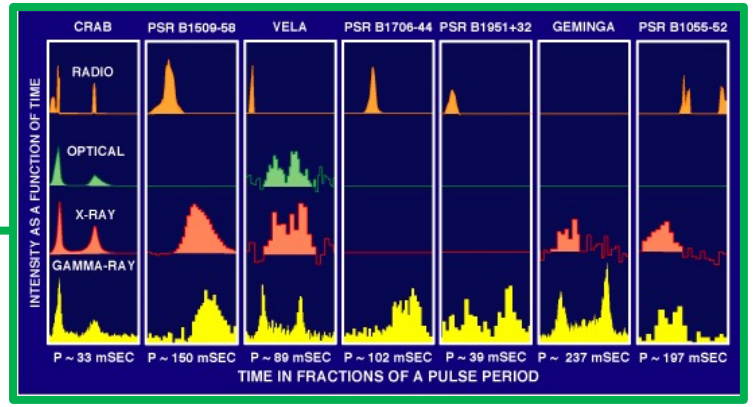
Makishima K. X-ray studies of neutron stars and their magnetic fields. Proceedings of the Japan Academy. Series B, Physical and Biological Sciences. 2016 ;92(5):135-155.

Case Study: The Crab Pulsar

- Discovered in 1939. Remnant of a Supernova (July 1054 AD) 7000 light years away, remained visible for 23 days after explosion.
- Neutron Star (d=20 km) spins once every 33 ms.
- Relativistic wind (PWN) from NS generates synchrotron emission, which produces most of the observed multiwavelength emission.
- Long regarded to be most promising source of gravitational waves due to high spin down rate -> multiple mechanisms for rotational energy loss.
- In 2019, the nebula/pulsar was observed to emit 100 TeV gamma-rays, the first identified source of ultra-high-energy cosmic rays. (CERN LHC CoM collison energy is 14 TeV).
- Often used as a calibration source in X-ray Astronomy as the flux density and spectrum of this very bright X-ray source are known to be nearly constant **(recent papers suggest large fluctuations at harder X-rays*).**
  - 1 mCrab corresponds to a flux density of 2.4x10-11 erg s-1cm-2 in the 2-10 keV band.
  - "Crab-like" X-ray spectrum has power law in photon energy of $E^{-1.1}$.



Credit: Chandra, HST / NASA

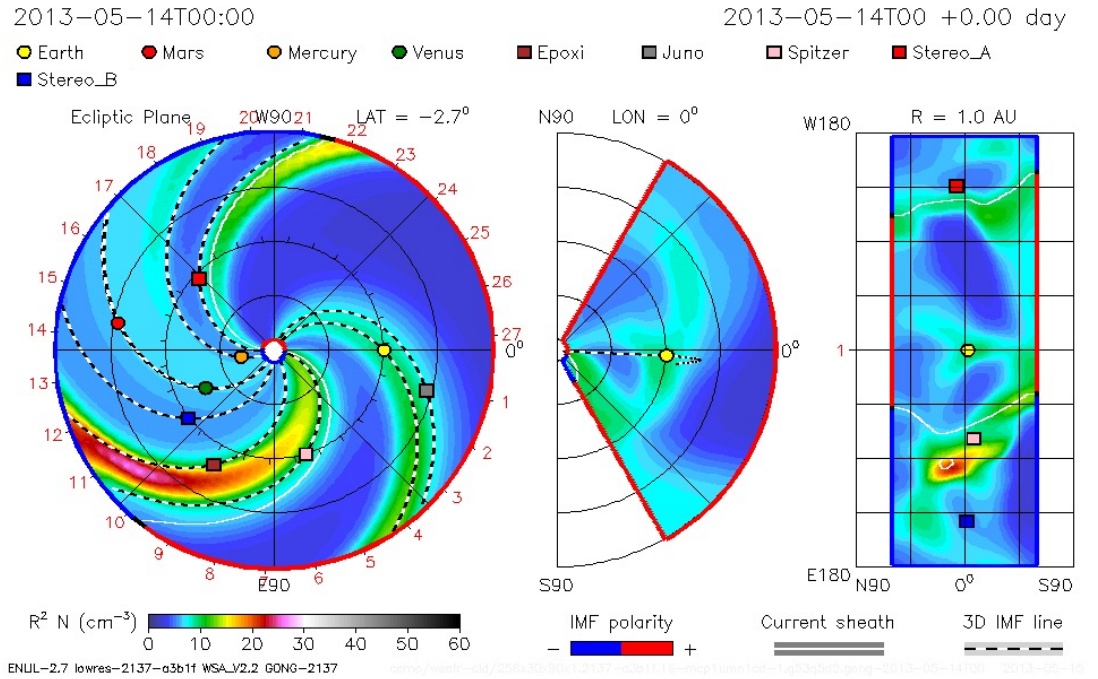


Credit: NASA/HEASARC

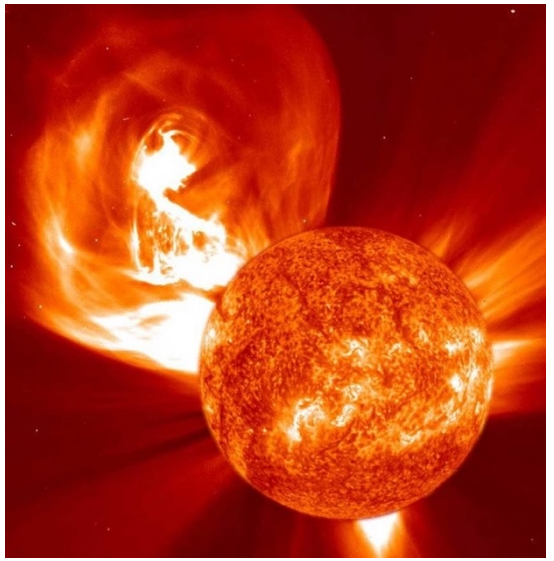
*Wilson-Hodge, C.A. et al. *2011 ApJL **727** L40,* 10.1088/2041-8205/727/2/L40

Space Weather

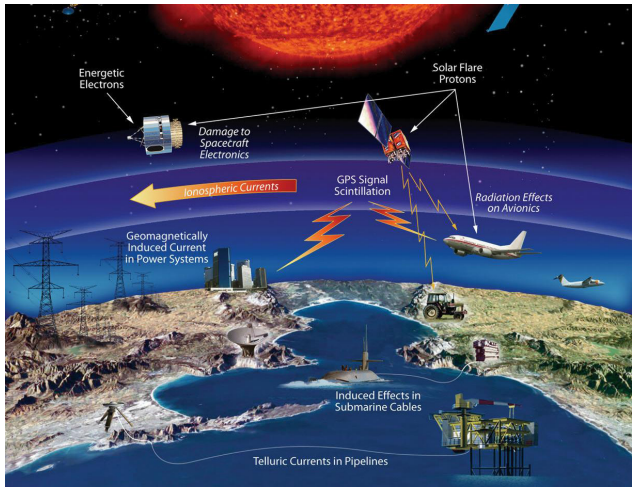
- Space weather is mostly just monitoring the Sun.
- While CMEs and flares produce beautiful Aurora, strong events can be catastrophic.
- Important when looking for exoplanets around active stars.



Credit: NASA GSFC, NOAA Space weather lab



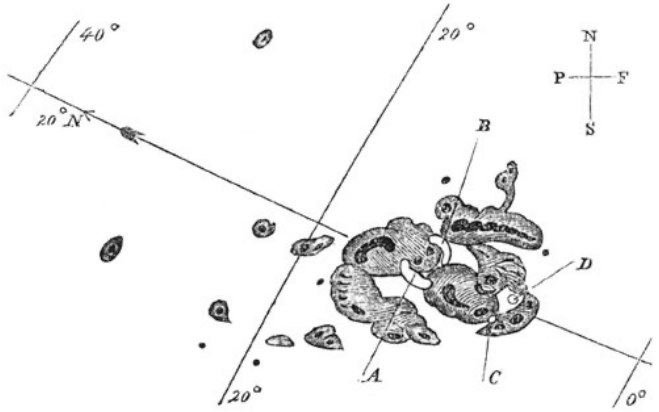
Credit: SOHO ESA/NASA



Credit: NASA

Space Weather

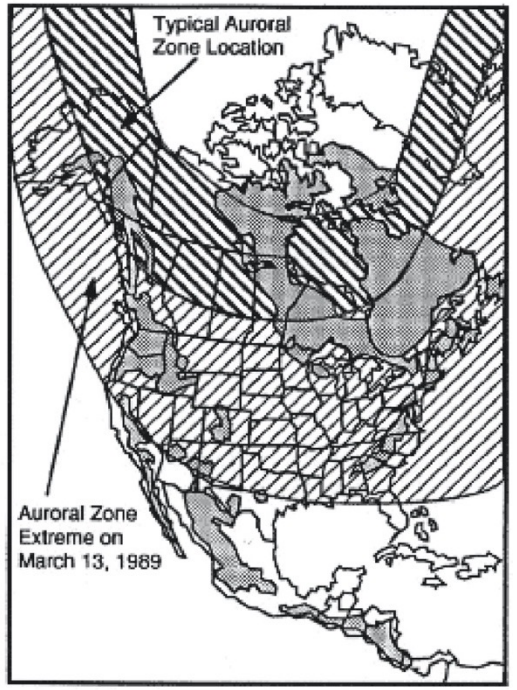
- **Carrington Event in 1859**
  - Worst solar storm in recorded history
  - Mexican Aurora, telegraph disruption
- **Quebec Event on March 13th, 1989**
  - Geomagnetically induced currents destroyed transformers in North American power grid (igneous rock encouraged current to overflow network)
  - Power grid failure > 9 hours in Canadian province of Quebec, left millions without power.
  - 4-10 B$ in damage
- **2012 Solar Storm**
  - Outburst region at Solar equator not pointed at Earth and due to the 25 days it takes for the Sun to revolve once on its axis, missed the Earth by about 9 days.
  - If it had hit Earth, it would have seriously damaged the global power grid, causing 0.6-2.6 $T in damage and causing a recovery time of 4-10 years.



Sketch by Richard Carrington of the sunspot group responsible for the 1859 event.

American Scientist, 95, pp540, Nov. 2007

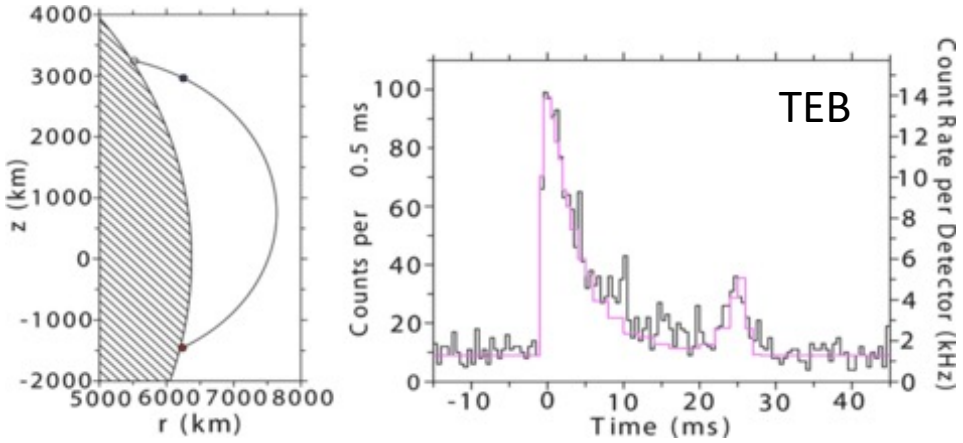
Auroral zone from the 1989 Geomagnetic storm.



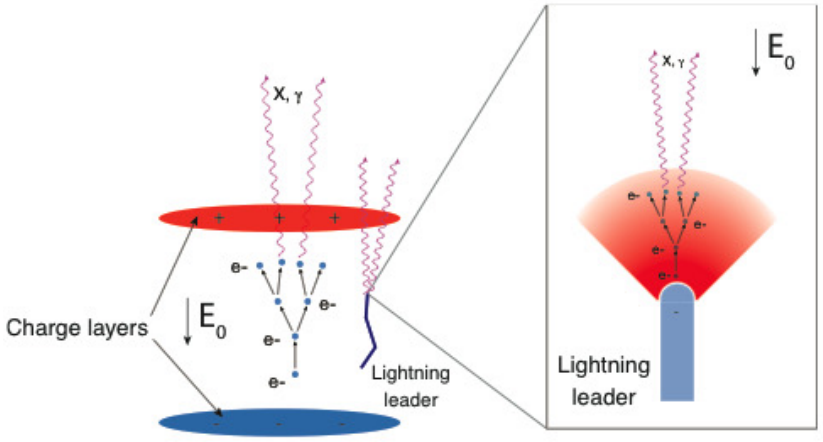
Credit: NASA/AGU

Earth: TGFs and TEBs

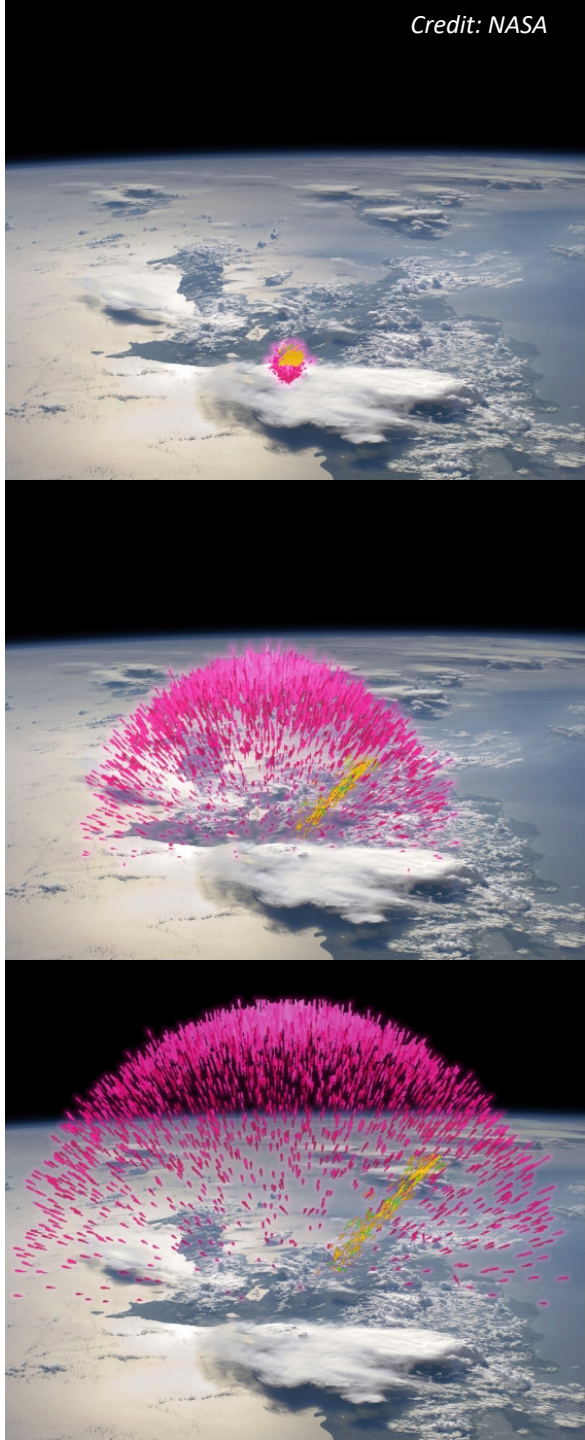
- Discovered in 1993, Terrestrial Gamma-ray Flashes (TGFs) produced by bremsstrahlung emission in the electric fields of thunderstorm charge layers.
- Very short (<1 ms) and have energies from 0.01-10 MeV.
- Expected to exist on Jupiter, Mars and Venus, possibly other gas planets. Not observed, though Elves/Sprites observed in Jupiter's atmosphere.
- Terrestrial Electron Beams (TEBs) also produced from thunderstorms due to electron and positron pairs becoming trapped in magnetic field lines. Usually spectrally energetic (<10 MeV) and ms long.



*Dwyer et al. Space Science Reviews, **173**, 133–196 (2012)*



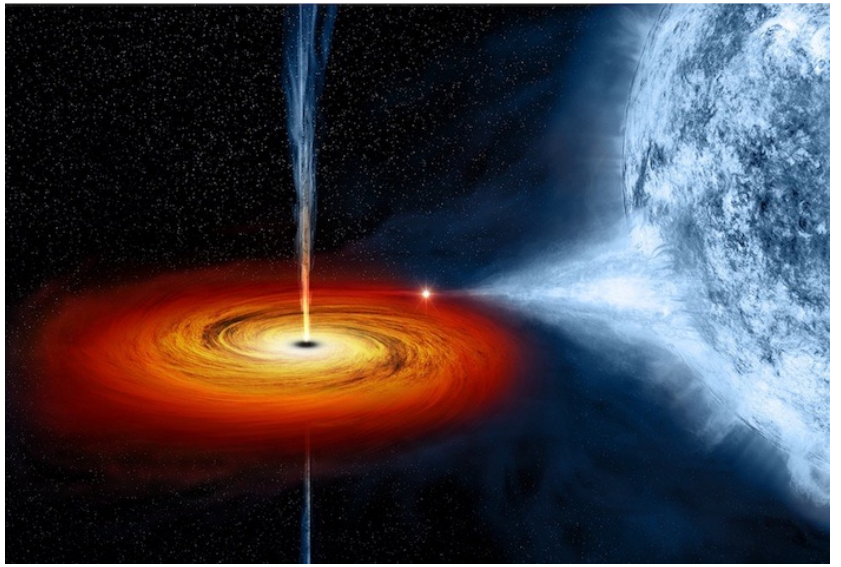
Celestin & Pasko 2011, JGR 116, A03315



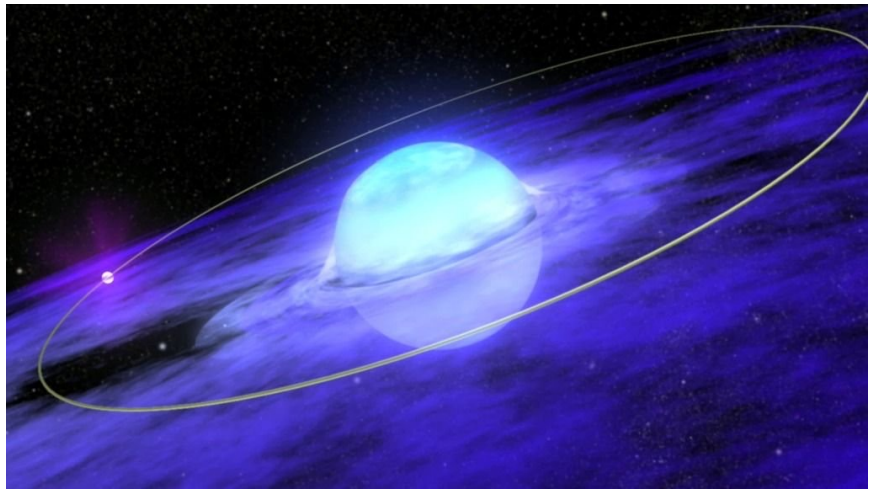
X-ray Binaries

- Comprise of a donor (i.e. star) and accretor (i.e. BH or NS)
- X-rays produced by in-falling matter (gravitational potential energy) from the donor star onto the compact object (accretor)
- Low-mass X-ray Binaries (LMXBs)
  - Progenitors of millisecond pulsars
  - Soft X-ray transients
  - Symbiotic X-ray binaries
  - Super-soft X-ray sources
- Intermediate-mass X-ray Binaries (IMXBs)
  - Ultracompact X-ray binaries
- High-mass X-ray Binaries (HMXBs)
  - Be/X-ray binaries
  - Supergiant X-ray binaries
  - Supergiant Fast X-ray Transients
- Also X-ray bursters, X-ray pulsars and Microquasars.

Persistent source are usually stellar wind-fed systems (i.e. Vela X-1). Supergiant FXTs also wind-fed (clumpy). *Transient* sources due to circumstellar disk accretion.



Credit: NASA/CXC.



Credit: NASA GSFC (W.Feimer).

Accretion basics

- **Eddington Limit** is balance between outward stellar radiation and inward gravitational force; limits accretion rate. For purely ionized hydrogen plasma:

$$\frac{GM_* m_p}{r^2} = \frac{L_{acc}}{4\pi r^2}\frac{\sigma_T}{c}$$

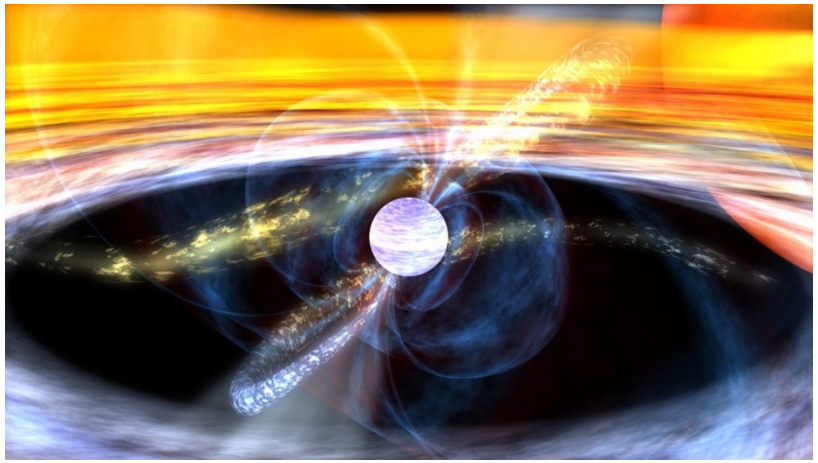
Grav. **Rad.**

σ_T is the Thompson electron scattering cross-section, m_p is the mass of the proton

NB: σ_T and m_p are from the opacity of the stellar material ($\kappa = \sigma_T/m_p$), the fraction of radiation energy flux absorbed by the star/medium.

$$L_{acc} = \frac{4\pi G M_* m_p \sigma_T}{c} = 1.8\times10^{38}\left(\frac{M_*}{1.4M_\odot}\right) erg/s$$

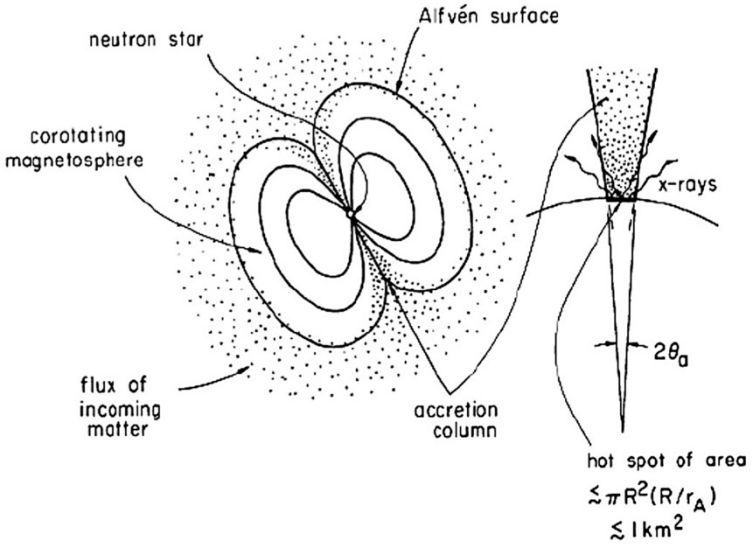
$$\dot{M}_{Edd} = \frac{4\pi R_* m_p \sigma_T}{c} = 1.6\times10^{-8}\left(\frac{R_*}{10km}\right) M_\odot/yr$$



Credit: NASA

Accretion basics

Credit: Longair 13.5.2- Also Ch 14



- Gravitational energy is converted into radiation
- Colder radiation → Blackbody (optically thick)

$$L_{acc} = \sigma T_{bb}^4 \times 4\pi R_*^2 \qquad h\nu_{min} = kT_{bb} = k\left(\frac{L_{acc} 4\pi R^2}{\sigma_T}\right)^{1/4} \approx 1\ keV$$

- Hotter radiation → direct conversion to radiation.

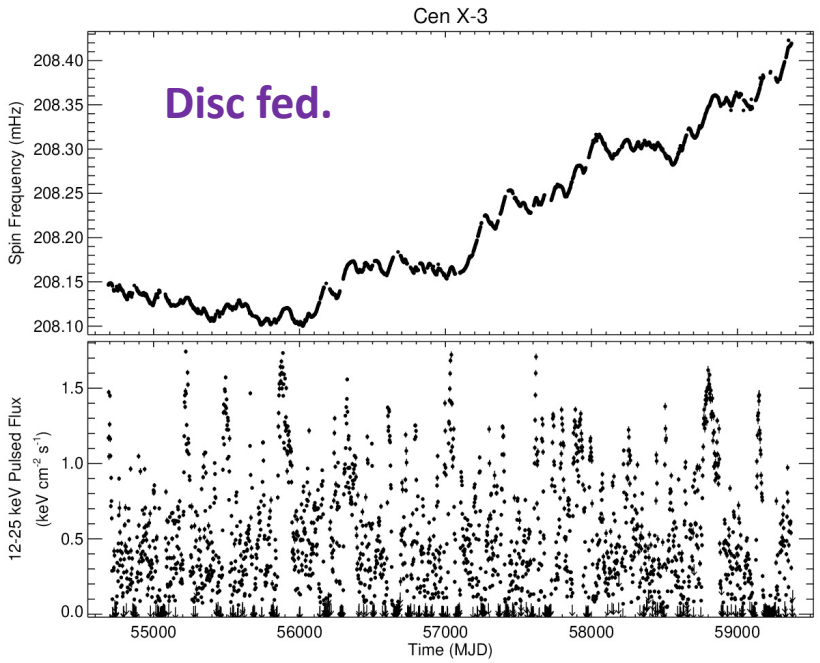
$$\frac{GMm_p}{R_*} = \frac{2\times 3}{2} kT_{th} \qquad h\nu_{max} = kT_{th} = \frac{GMm_p}{3R_*} \approx 50\ MeV$$

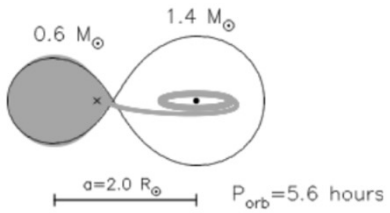
LMXBs:

- Weak stellar wind
- Low-mass star (<1.5 $M_\odot$), white dwarf, red giant, etc.
- Mass loss via L_1, (under)fills Roche Lobe
- Bulging accretion disc, transfers mass onto compact object, changes spin period (low **B** field).
- Not so concentrated towards galactic plane, older >10^9 yr
- Relatively hard X-ray spectra: kt < 15 keV.
- regular X-ray bursts, sometimes regular pulsations.

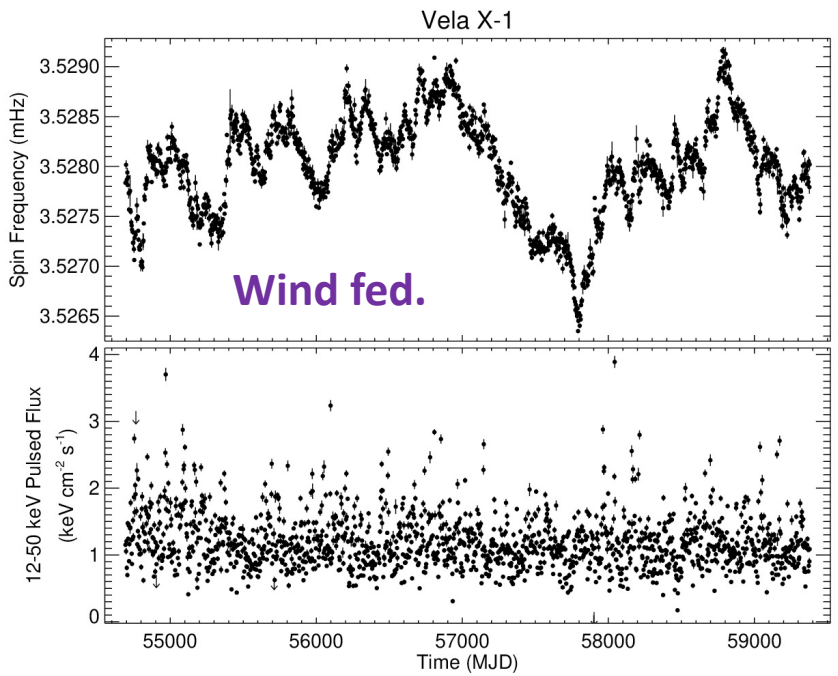
HMXBs:

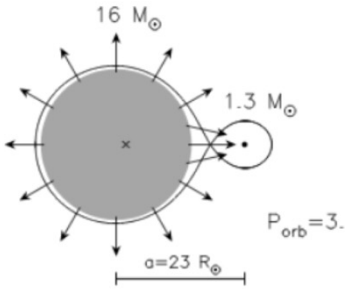
- Very powerful stellar wind
- High-mass star (>10 $M_\odot$), usually type O,B, blue supergiant, or Wolf Rayet.
- Compact object ploughs through wind during orbit as well as accretes onto its poles (high **B** field).
- Concentrated towards galactic plane, age < 10^7 yr.
- Relatively hard X-ray spectra: kt > 15 keV.
- No X-ray burst, regular pulsations.





Source Monitor Parameters	
RA	170.3133 deg
Decl	-60.6233 deg
Orbital Parameters	
Orbital Period	2.0869953 days
Period Deriv.	-1.0150E-08 days/day
$T_{\pi/2}$	2455073.68504 (JED)
axsin(i)	39.653 light-sec
Long. of periastron	0.00 deg
Eccentricity	0.0000
Egress	0.11
Ingress	0.89





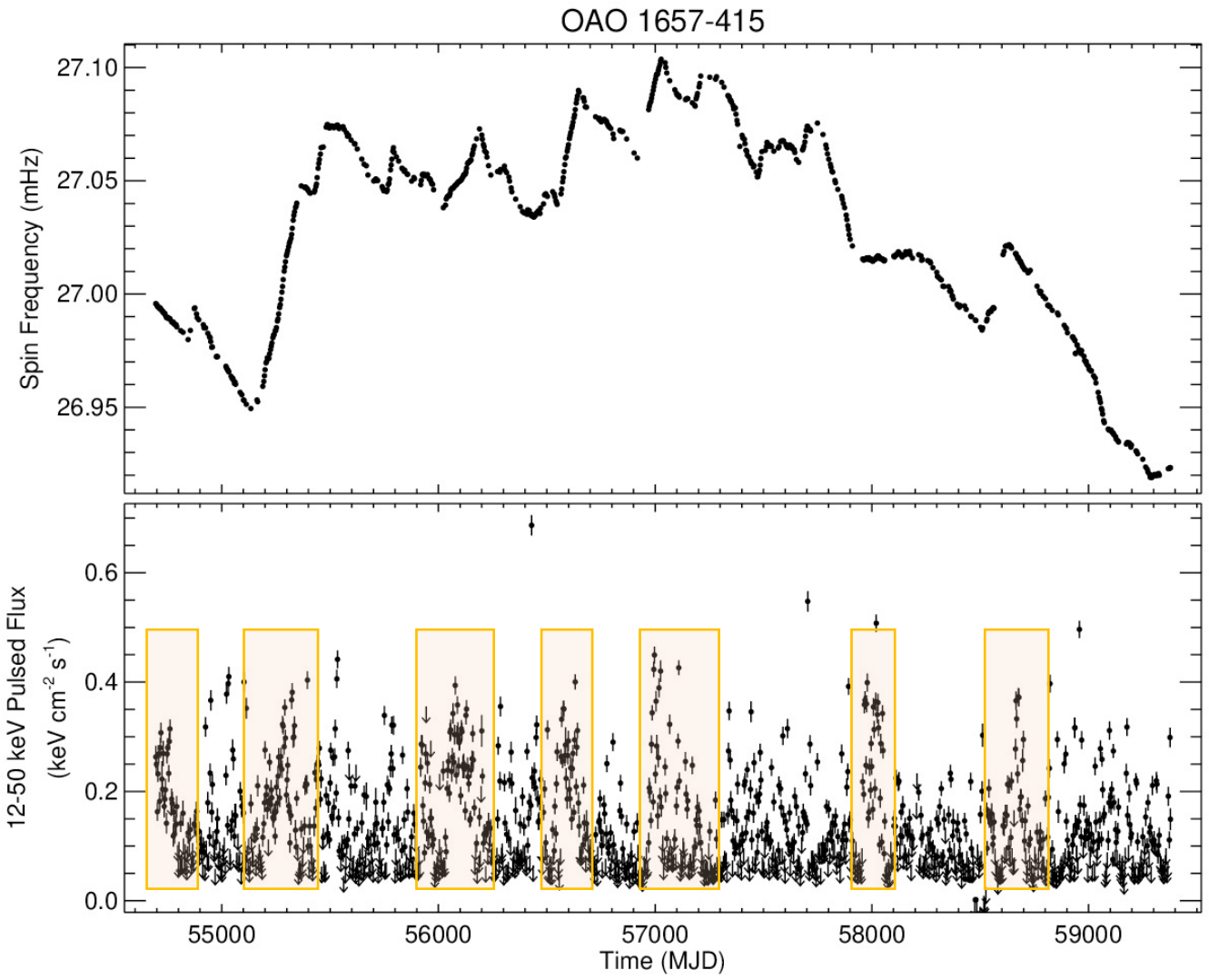
Source Monitor Parameters	
RA	135.5286 deg
Decl	-40.5547 deg
Orbital Parameters	
Orbital Period	8.9642140 days
Period Deriv.	0.0000E+00 days/day
$T_{\pi/2}$	2459115.02085 (JED)
axsin(i)	113.105 light-sec
Long. of periastron	162.33 deg
Eccentricity	0.0872
Egress	0.12
Ingress	0.92

Credit: https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html

Image Credit: Tauris & vdHeuvel, 2006

Credit: https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html

Missing link; OAO 1657-415?



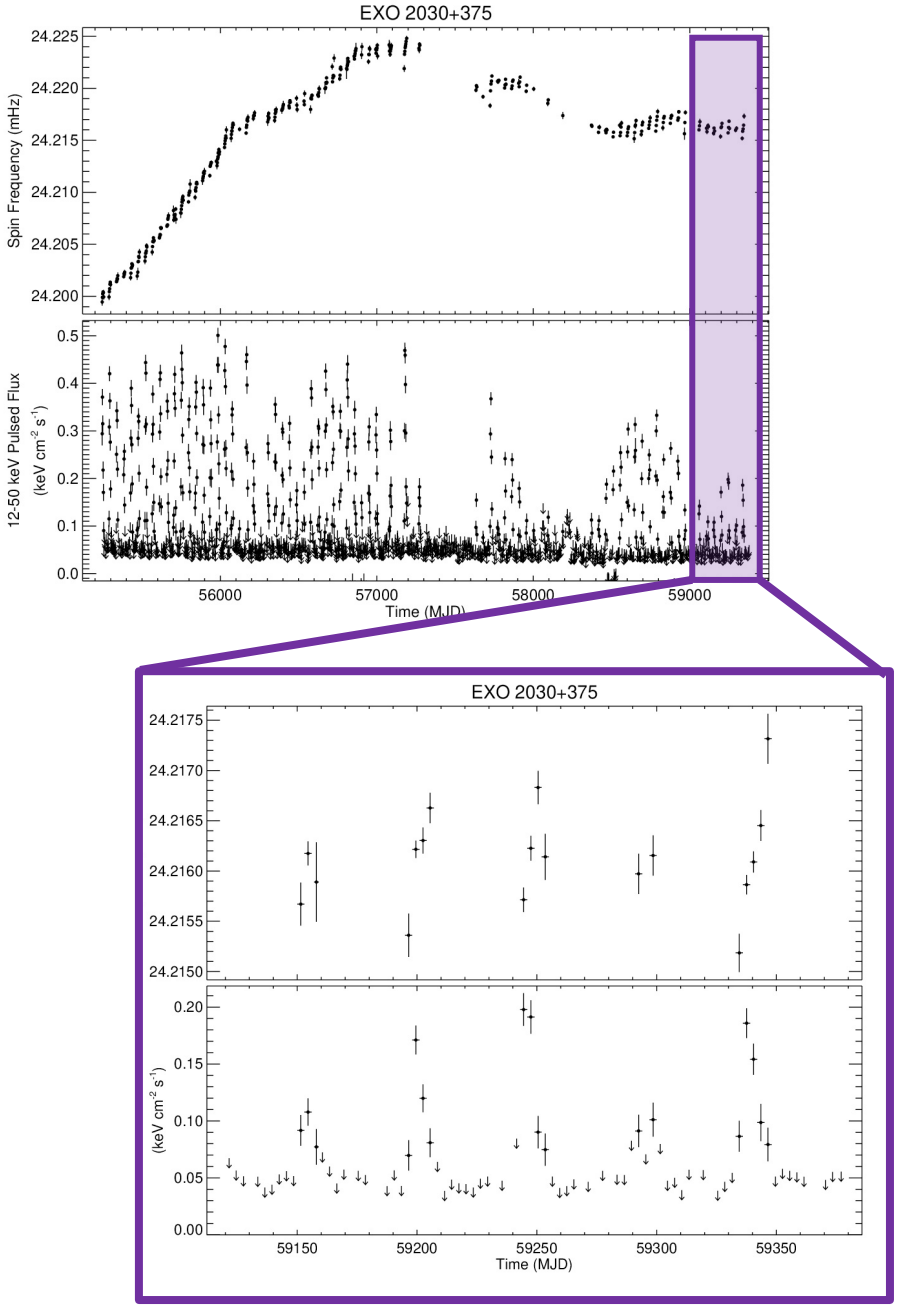
Source Monitor Parameters	
RA	255.2038 deg
Decl	-41.6560 deg
Orbital Parameters	
Orbital Period	10.447292 days
Period Deriv.	-9.7400E-08 days/day
$T_{\pi/2}$	2452298.51790 (JED)
axsin(i)	106.157 light-sec
Long. of periastron	92.69 deg
Eccentricity	0.1075
Egress	0.07
Ingress	0.91

OAO 1657-415 is thought to be wind-fed and disc-fed.

Credit: https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html

BeXRBs

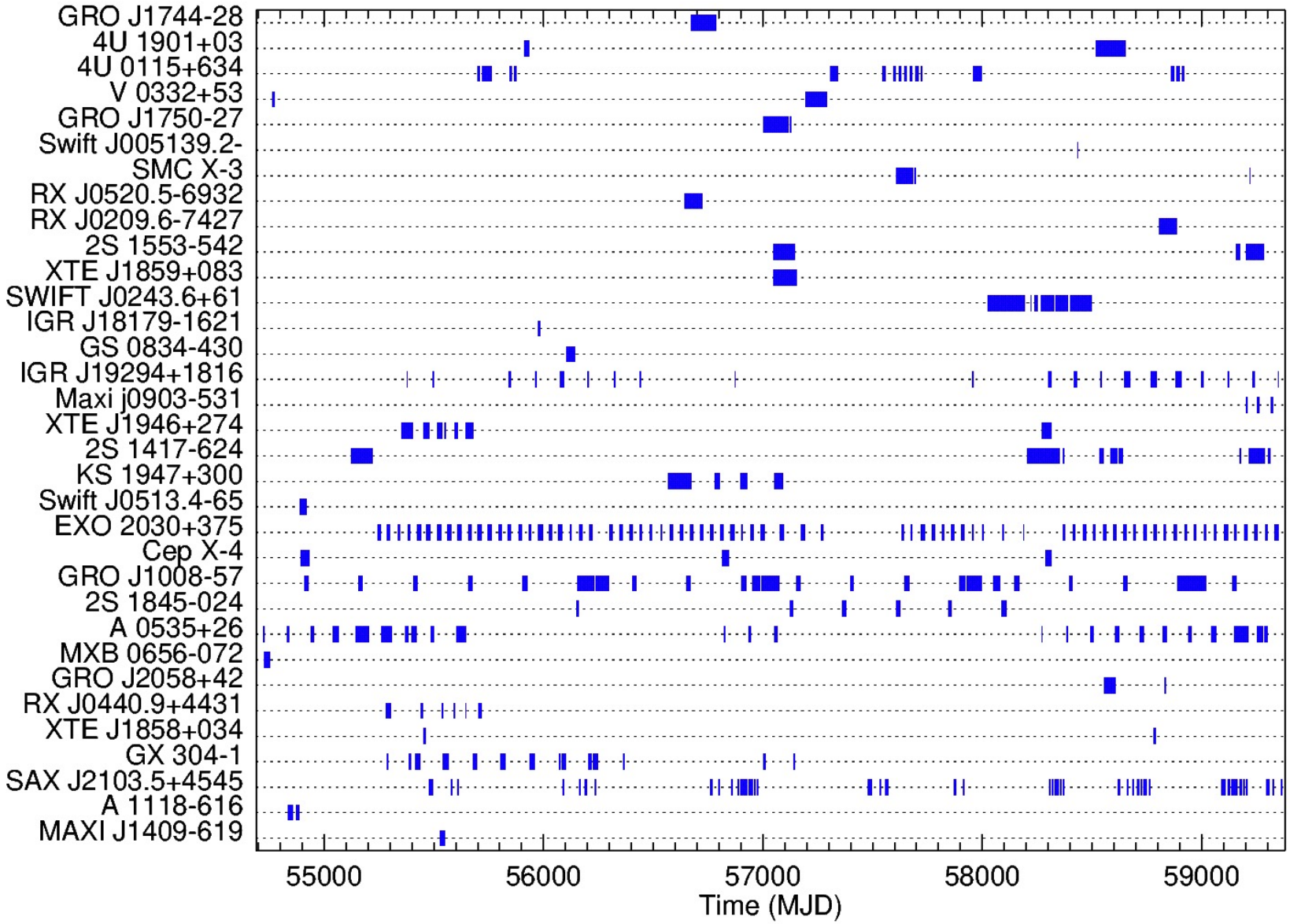
- Two discs in this system, an ***excretion*** disc around the *Be Star* and ***accretion*** disc *around the pulsar*
- i.e. EXO 2030+375, 42-s pulsar in a 46 day orbit as part of a BeXRB.
- A decline in the density of the Be star's disc caused a drop in the pulsed flux and a transition from spin-up to spin-down



Source Monitor Parameters	
RA	308.0633 deg
Decl	37.6375 deg
Orbital Parameters	
Orbital Period	46.021300 days
Period Deriv.	0.0000E+00 days/day
$T_{Periastron}$	2452756.67000 (JED)
axsin(i)	246.000 light-sec
Long. of periastron	211.90 deg
Apsidal Rate	0.18 deg/year
Eccentricity	0.4100

Credit: https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html

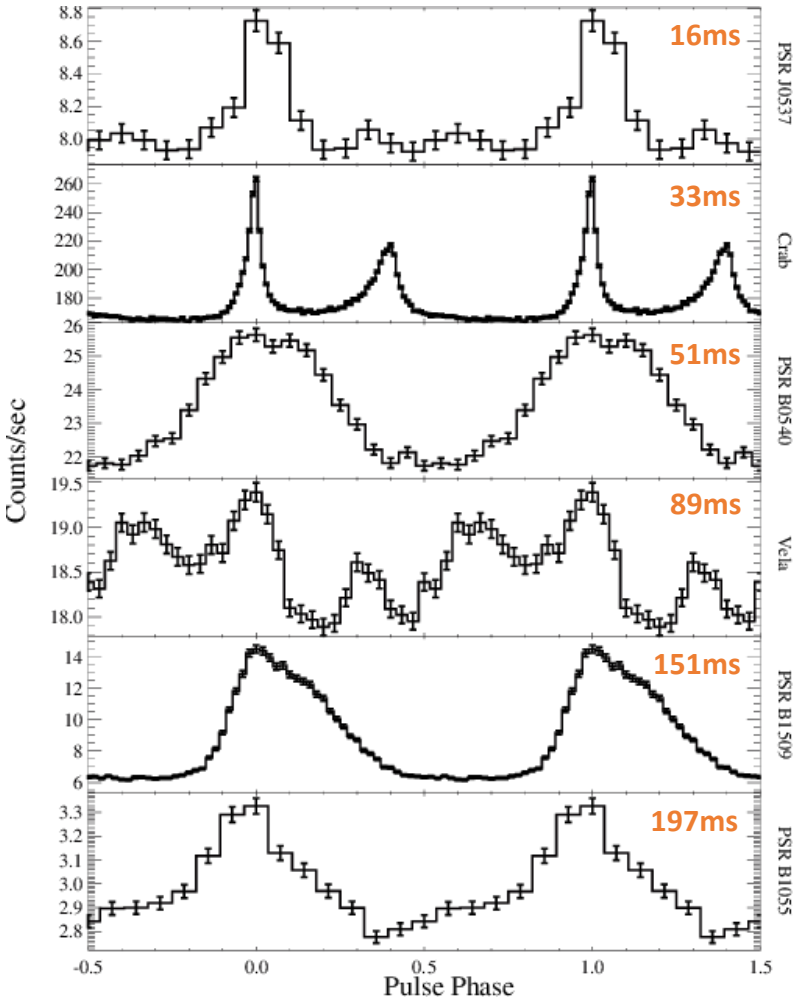
Transient Outburst Detections by Fermi-GBM



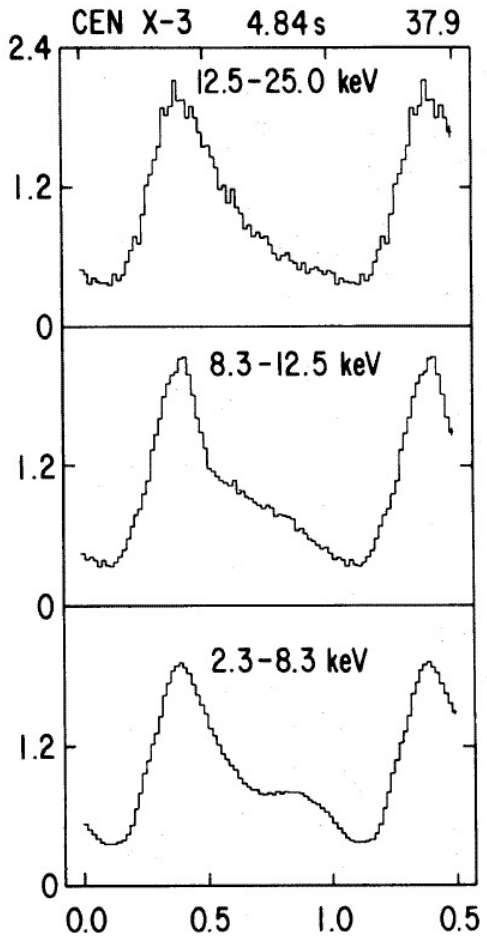
Credit: https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html

Spectral behavior

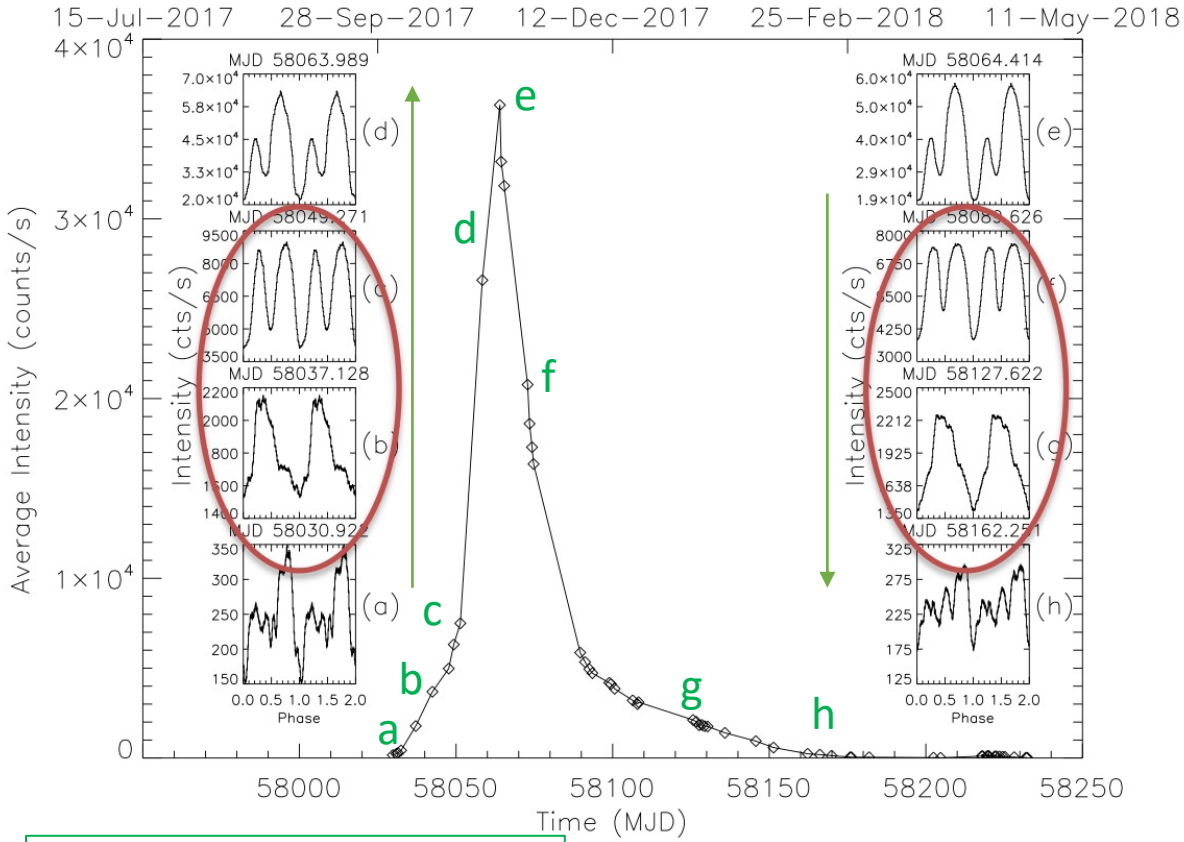
XMM; 0.2-12 keV



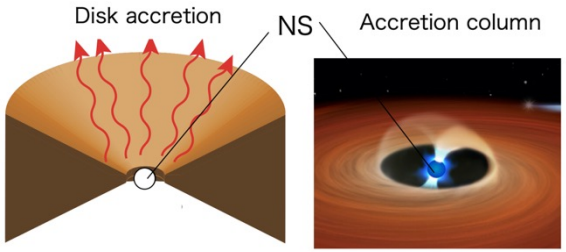
(Martin-Carrillo, 2012)



(White, 1982)



NICER observations (4-10 keV) of Ultraluminous X-ray (ULX) Pulsar Swift J0243+6124 (BeXRB). Brightest X-ray pulsar in our Galaxy and first ULX ($L>10^{39}$ erg/s). Red shows transition between two accretion regimes. Enormous disc.



Credit: NICER/NASA; https://heasarc.gsfc.nasa.gov/docs/nicer/science_nuggets/20180621.html

Spectral behavior

- X-ray burst from a compact object (i.e. NS) in a LMXB.
- Soft spectrum (~several keV, cooling blackbody)
- Burst oscillations can tell us about Equation of state of ultra dense matter, NS crust, NS spin frequency, explosion propagation on NS surface, etc.

- Type I X-ray Burst:
  - Caused by thermonuclear runaway (nucleosynthesis - rp process)
  - Rapid rise time (0.3-10 s) → Explosive He ignition (sudden T↑)
  - Slow decay (5-100 s) → Cooling of stellar surface.
  - Regular, separated by hours or days.
  - Common

- Type II X-ray Burst:
  - Gravitational energy release due to sudden accretion increase, though still not fully understood.
  - Start and stop abruptly (rapid succession over minutes)
  - Rare (only two ever observed).

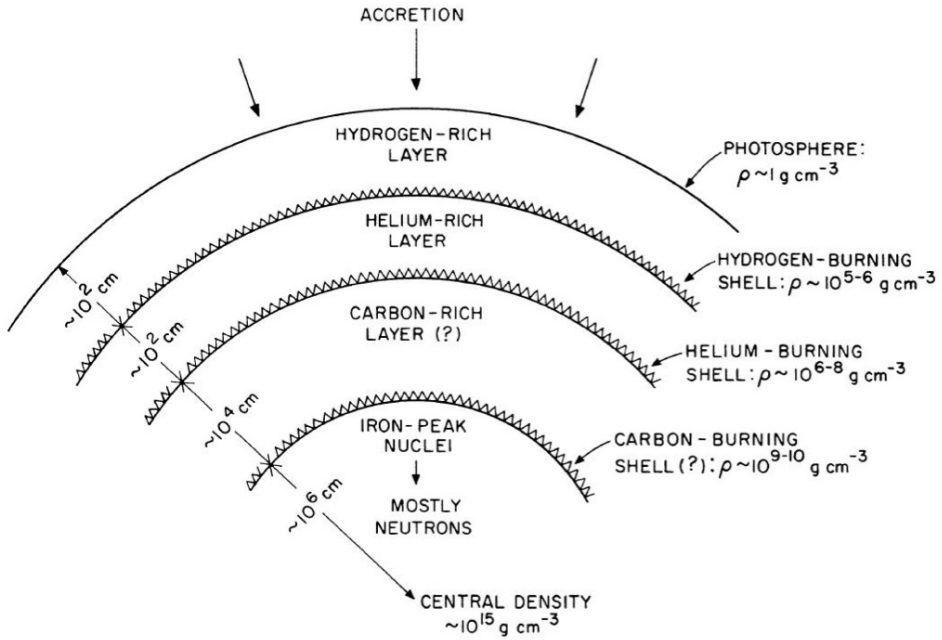


Fig. 37. Schematic sketch of the surface layers of an accreting neutron star. This figure is from Joss [143].

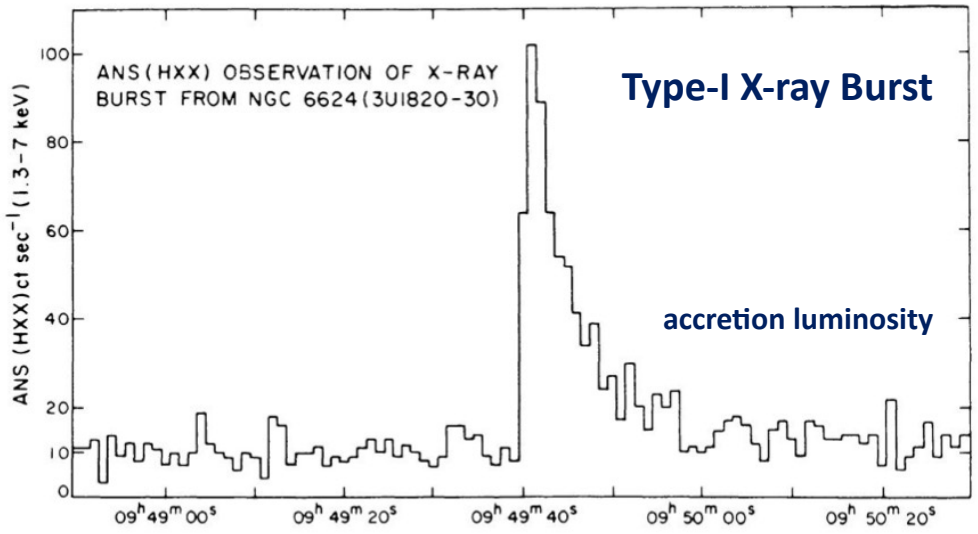


Fig. 3. The discovery of X-ray bursts. Detection of an X-ray burst from a source located in the globular