Things that go bump in the night: NS Mergers, SNe, ++

Daryl Haggard
McGill University
Canada Research Chair

Chandra 25 Years (Boston, MA)

MEGA

McGill Extreme Gravity & Accretion Group

Daryl Haggard

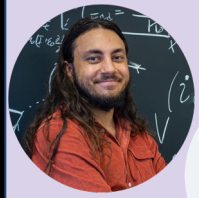
(Dr.) Hannah Dykaar

Dr. Lauren Rhodes*

Dr. Sophia Waddell

Dr. Bailey Tetarenko

Dr. Mervyn Chan*



Nicholas Vieira*

Nicole Ford

Nayyer Raza

Gabriel Sasseville*

Rebecca Hamel*

Zach Sumners*

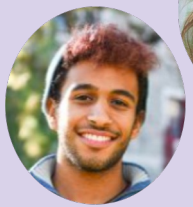
Josh Goodeve*

MEGA Alumni

Prof. John Ruan

Prof. Kristen Dage

Astrophys. Mel Nynka



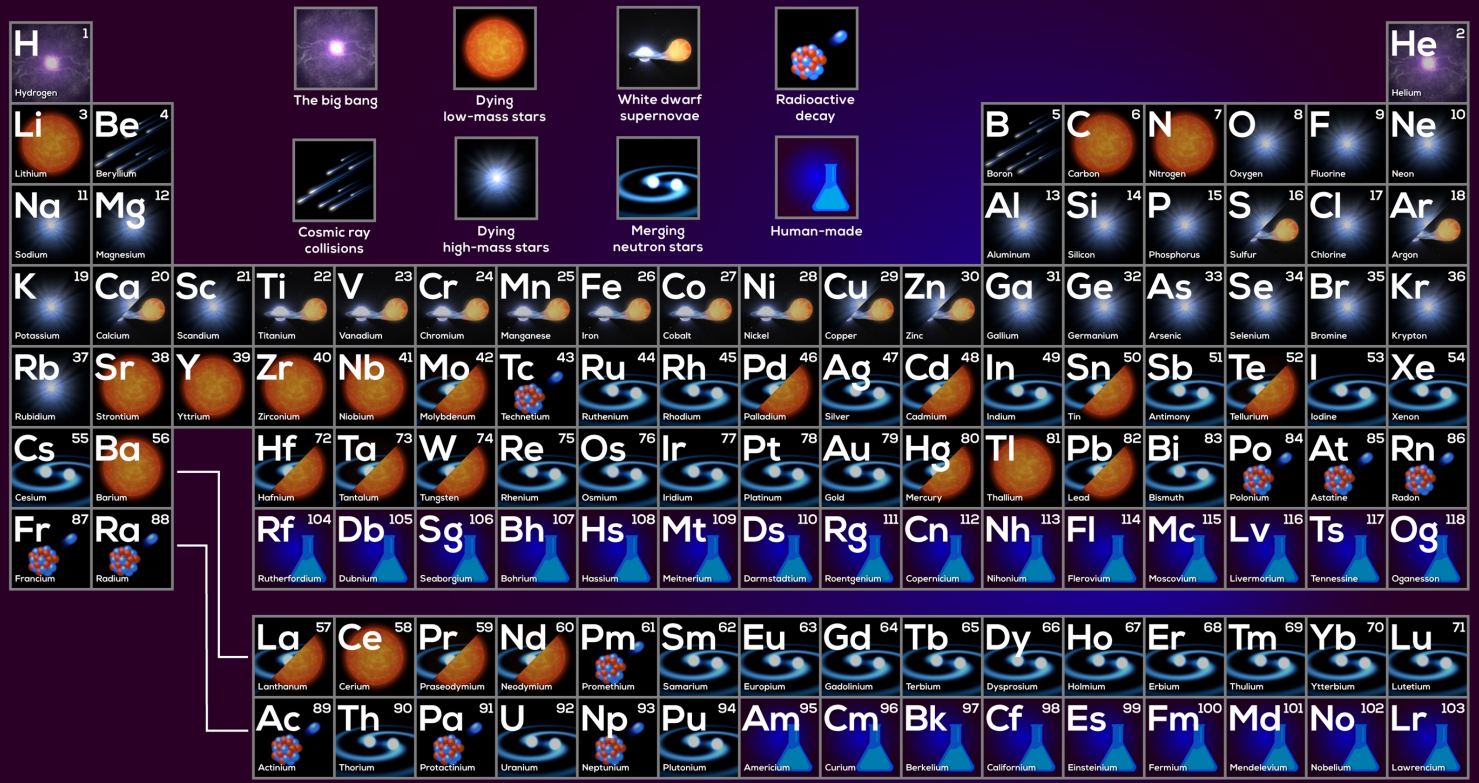
Dr. Soud Al Kharusi*

Dr. Hope Boyce

Dr. Anan Lu

Plus many collaborators, post-bacs, and undergrad researchers at McGill!

Origins of the Elements



This periodic table depicts the primary source on Earth for each element. In cases where two sources contribute fairly equally, both appear.

Philosophy of this talk…

- Highlight high-impact and recent results
- Showcase what Chandra is contributing *right now*
- Not exhaustive – apologies for omitting your favorite(s)!
- Ongoing and future opportunities
  - MWL coordination: JWST, Rubin, Roman, VLT, radio explosion +++
  - Time domain: Fermi, Swift, Einstein Probe, SVOM, *ULTRASAT*, *UVEX, PRIMA/AXIS*
  - Multi-messenger: LIGO-Virgo-KAGRA, IceCube, *P-ONE*, *LISA*, *CE/ET*

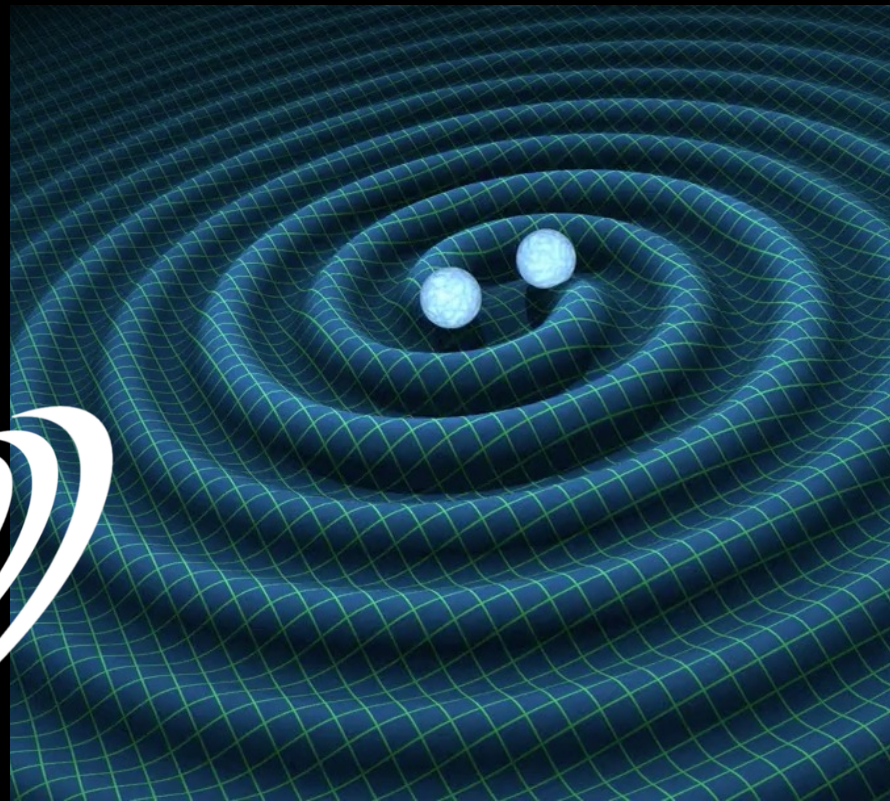
Chandra's expert, experienced team makes all of this happen!

Binary NS Mergers/GRBs

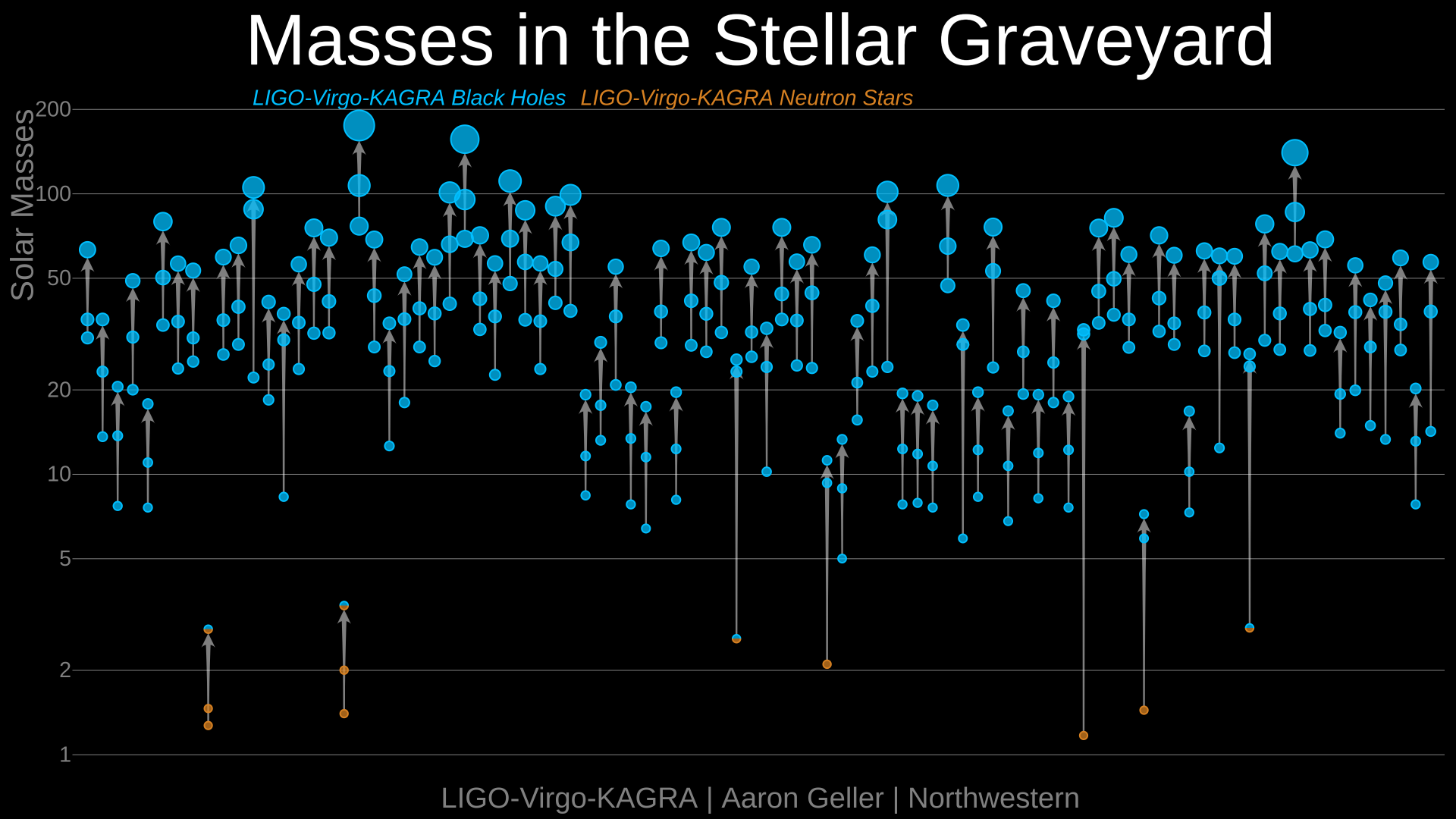
A New Era of Black Hole Discover

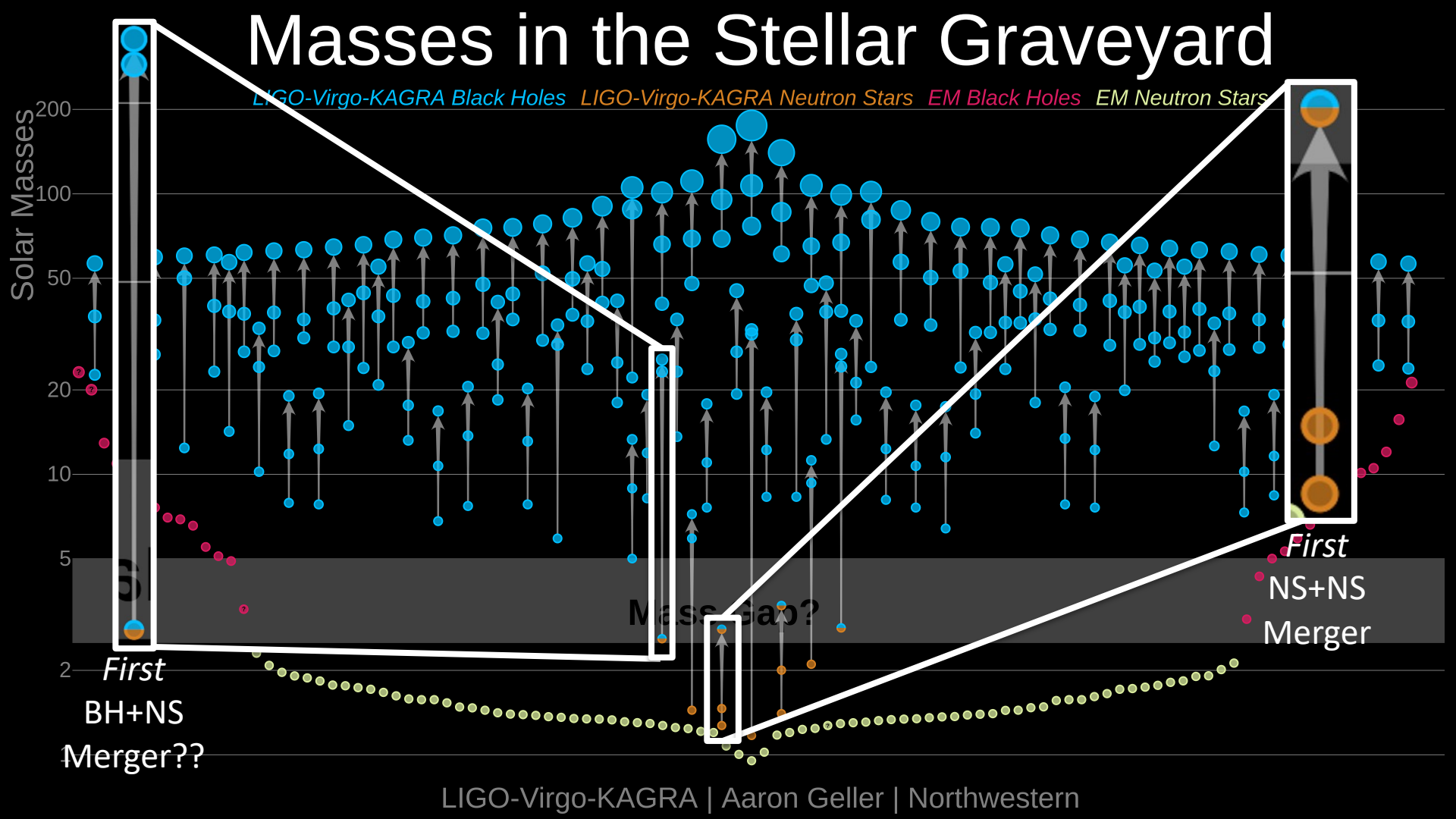
- Detecting gravitational waves is a triumph of ingenuity
- Discoveries offer new tests of GR
- Have also uncovered a spectacular unseen population of BHs and BH-BH mergers
- GW experiments have also seen NS-NS and BH-NS collisions

LIGO
VIRGO
KAGRA

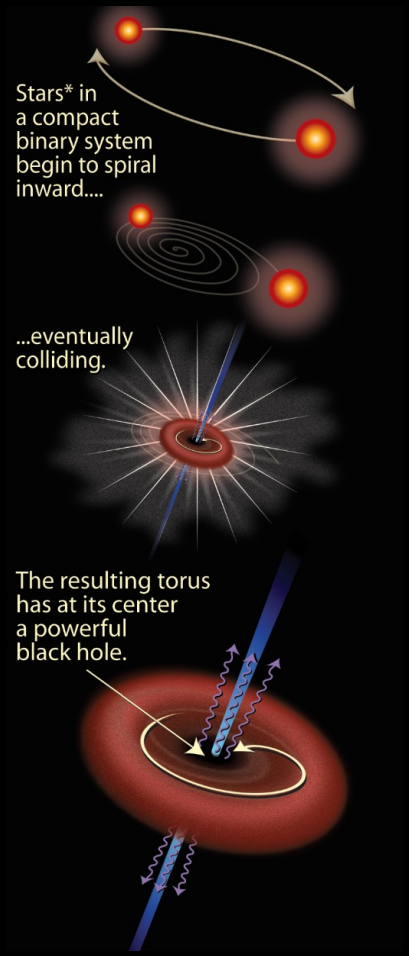


Masses in the Stellar Graveyard



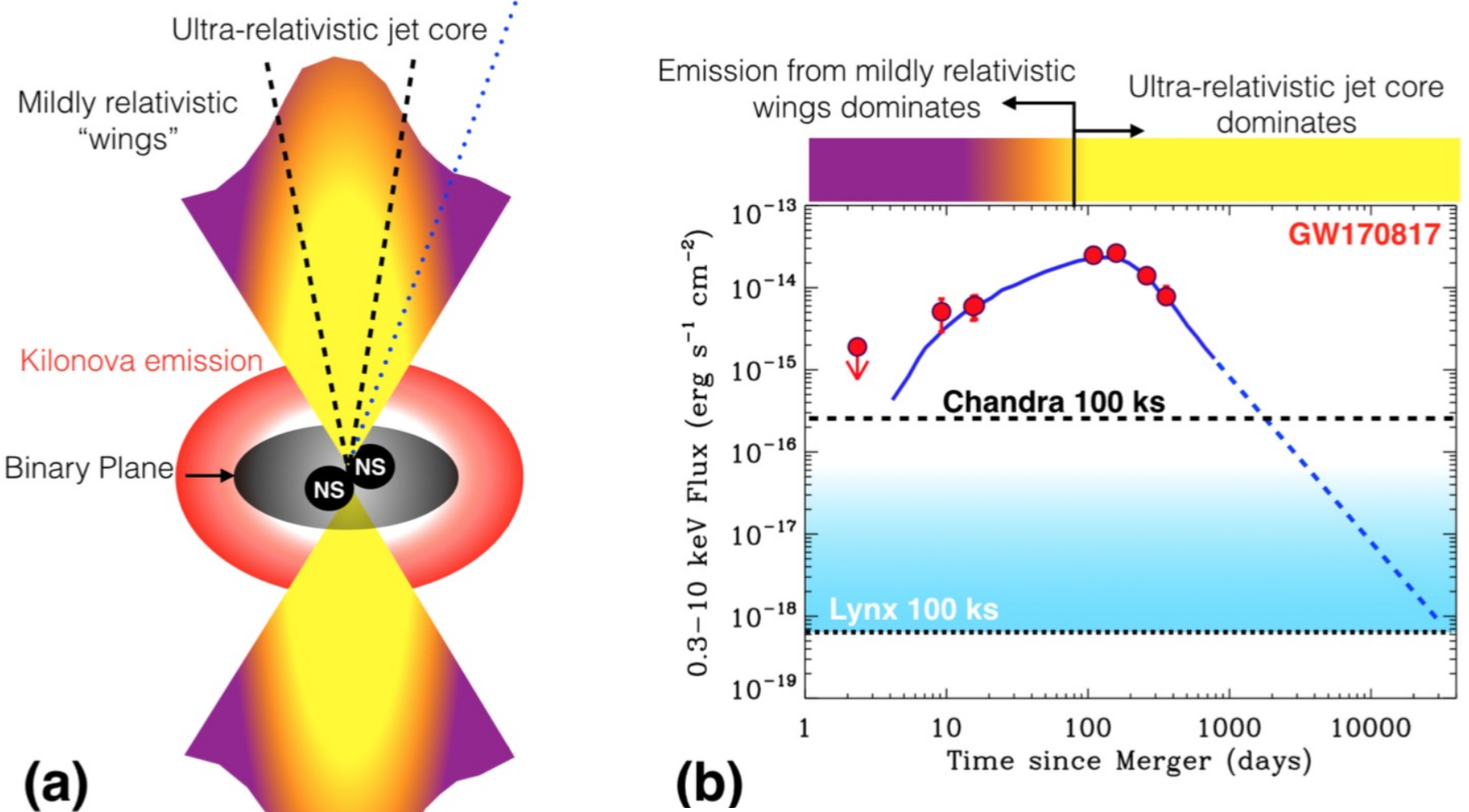

Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
Mass Gap?
First
BH+NS
Merger??
First
NS+NS
Merger
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW170817 confirmed NS merger origin for short GRBs

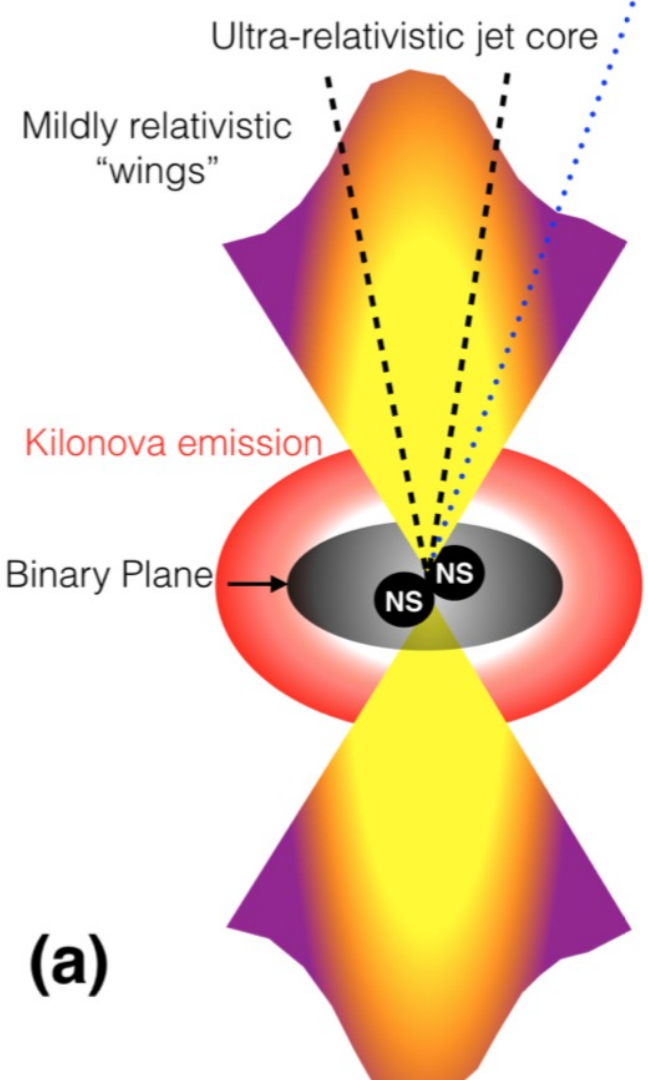


- Accretion onto central compact remnant launches relativistic jet
- Shocks within the jet emit short pulse of Gamma-rays (**GRB**)
- Relativistic jet shocks the ISM, producing synchrotron afterglow emission from X-ray through radio
- NS-NS merger also causes an explosion called a “kilonova” (**KNe**)

Slide Credit: J. Ruan



Margutti, Fong, & **DH** 2019

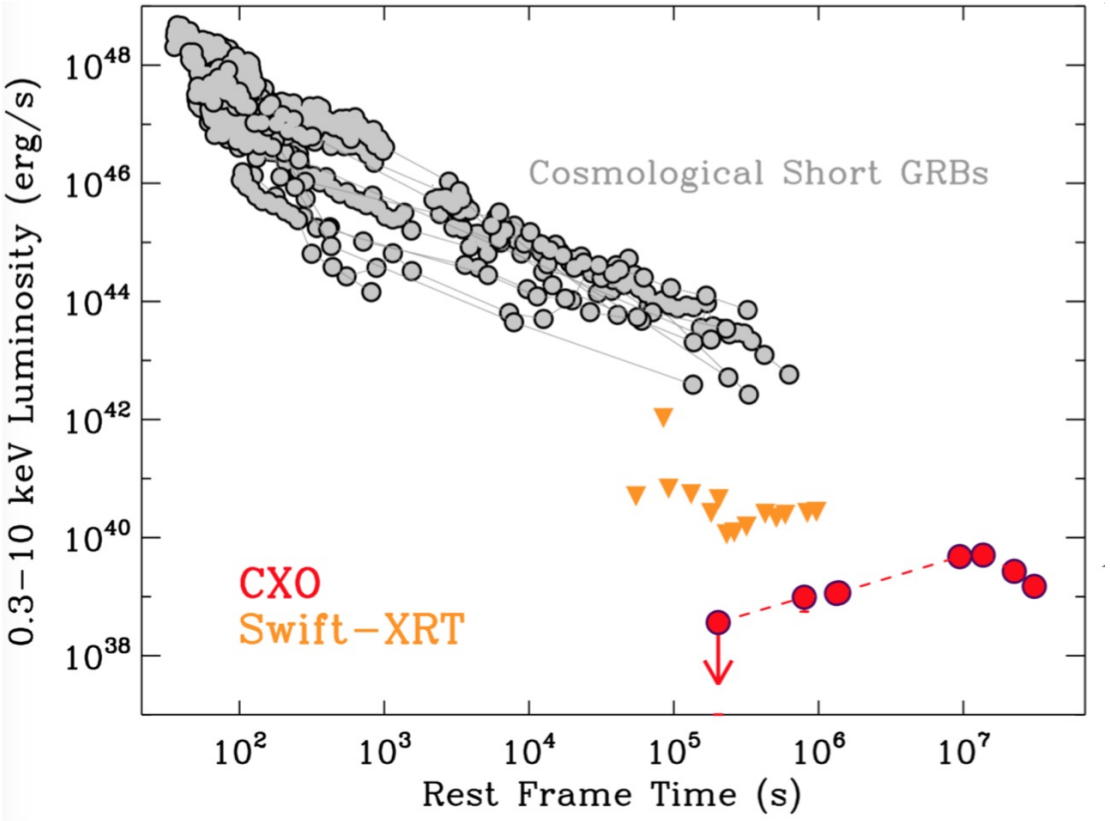


- Observations from *Chandra* (X-ray), *Hubble* (optical), and *VLA/MeerKAT (*radio) beyond ≈100 days probes a jetted, relativistic outflow.
- Light curves exhibited a constant spectral index for the first ≈900 days with a peak at 160 days followed by a rapid decline.
- Modeling of these data supports a structured jet with a relatively narrow, collimated core (3°–5°) and a wider-angle outflow moving at slower velocity.
- Radio and X-ray, in particular, are dominated by emission from this "structured" relativistic off-axis jet propagating into a low-density medium w/ $n < 0.01$ cm^{-3}.

Margutti, Fong, & **DH** 2019

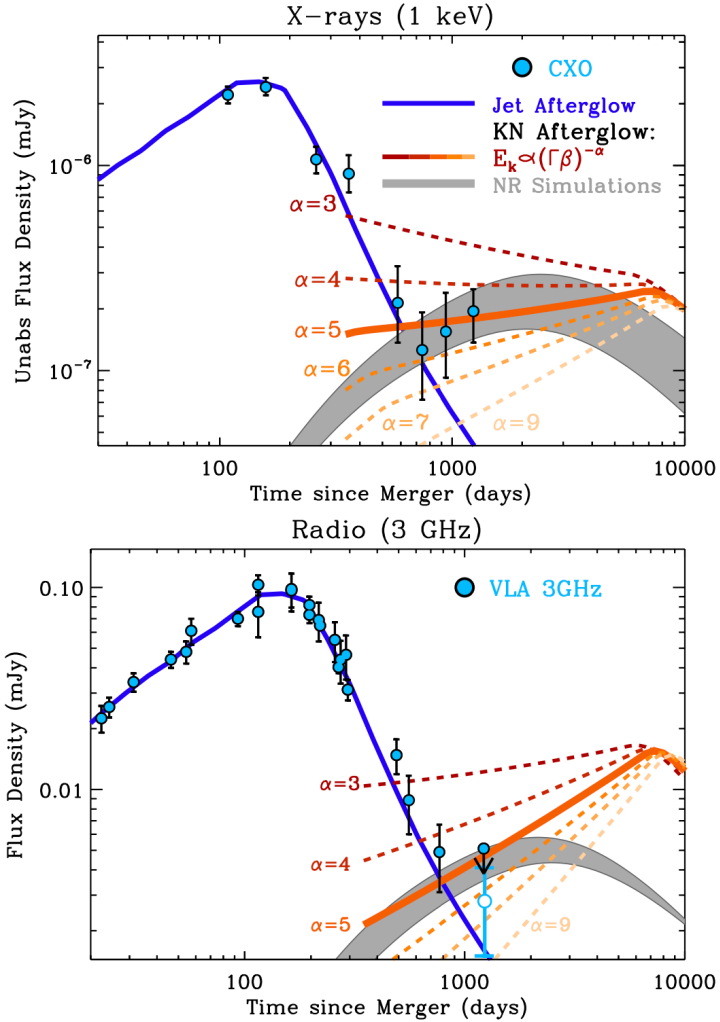
GW170817 vs. sGRBs

Margutti, Fong, & **DH** 2019



- GW170817's rising X-ray emission & low luminosity (despite being close!) set it apart from most sGRBs
- After peak, the decline is consistent with SGRB afterglows
- Expected from a jet pointed away from our line of sight

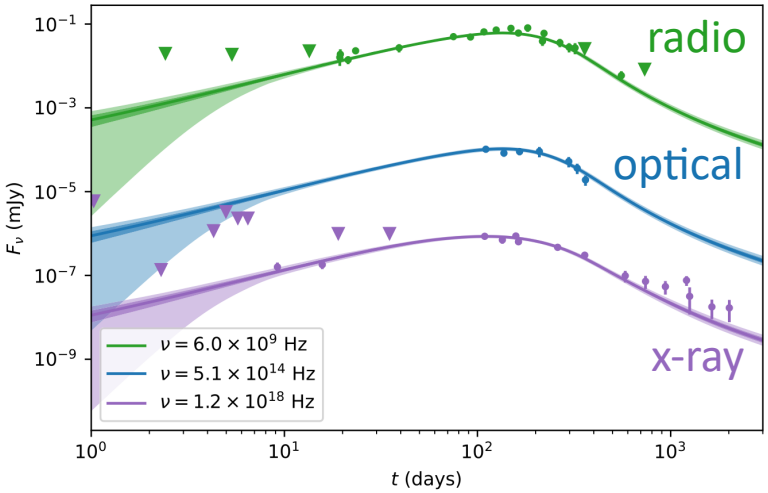
Hajela et al. 2022

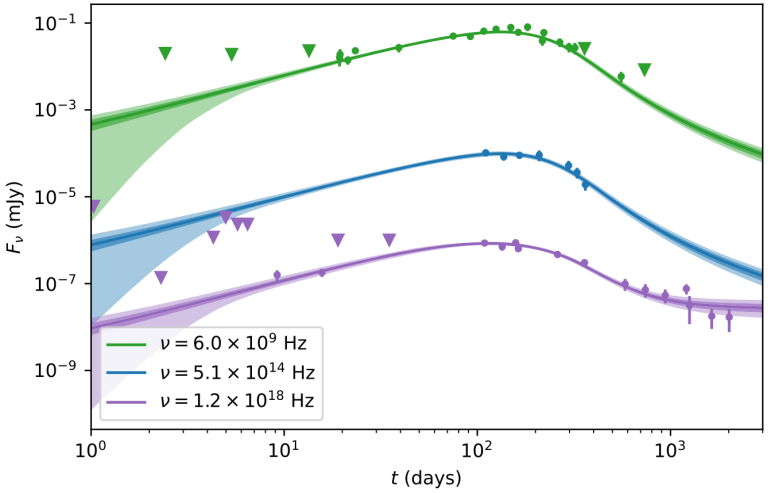


GW170817 Afterglows

- X-ray and radio observations of GW170817 over the first ~3.3 years (1234 days) since the merger
- Emission modeled by off-axis (~30°) structured relativistic jet w/ $E_{tot} \sim 10^{50}$ erg and low density medium ($n \sim 10^{-2}$ cm^{-3}; **blue lines**)
- *New component*: synchrotron radiation from a mildly relativistic shock due to the dynamical ejecta, "kilonova afterglow" (**red lines**)

Ryan et al. 2024

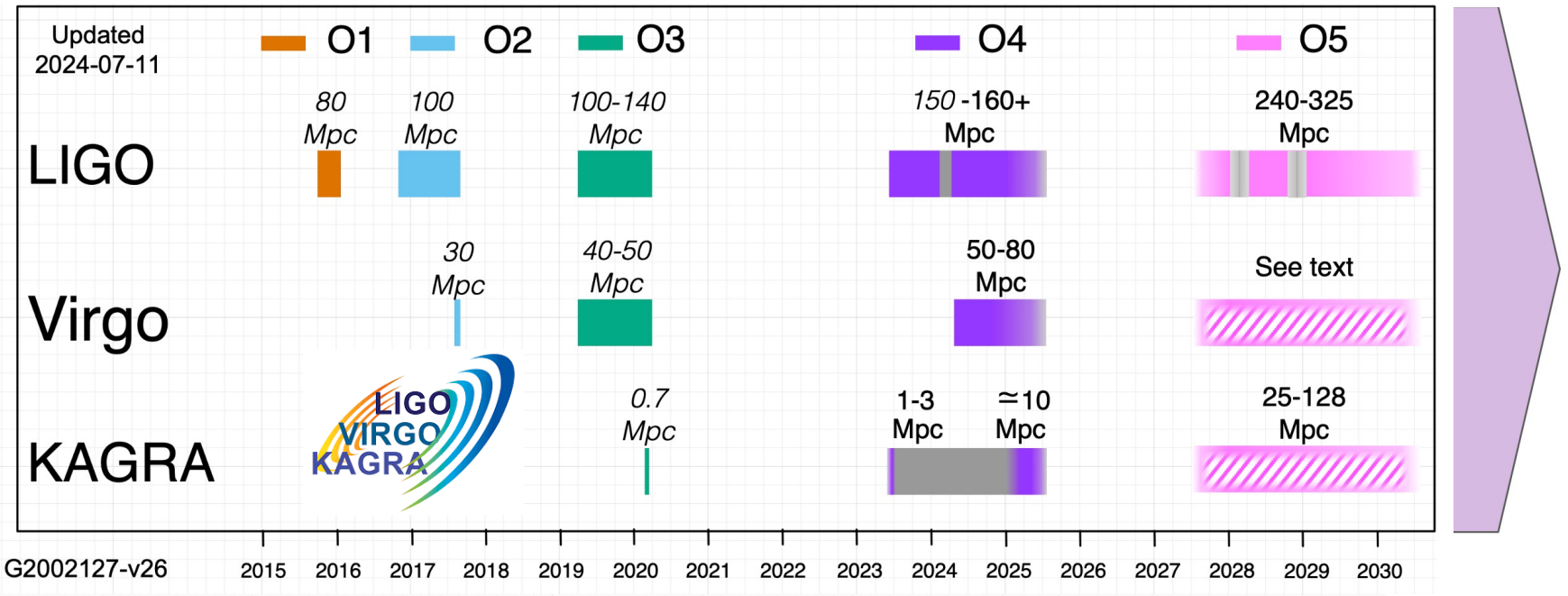




GW170817 Afterglows

- Chandra X-ray observations of GW170817 now extend to 1634 d (~4.5 yr) and 2012 d (~5.5 yr)!!
- Triangles 3σ upper limits; only data points within 20% of the target frequency are shown. Bands modeled afterglow emission after MCMC fitting (afterglowpy).
- *Left*: fit with a Gaussian jet only. *Right*: fit with a Gaussian jet plus additional late-time constant luminous X-ray component L_X.

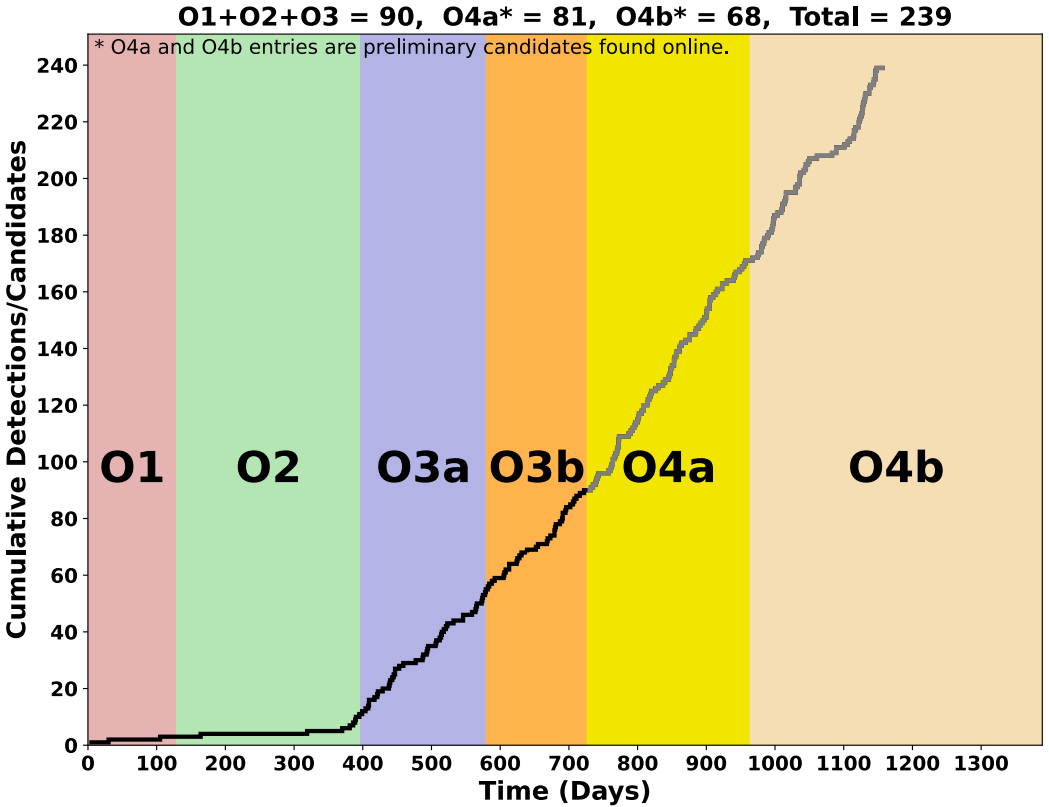
LIGO-Virgo-KAGRA are (mostly) back…



Observing Run 4 (O4):

- O4a ran 24 May 2023 – 16 Jan 2024; O4b started 3 April 2024; planned end date is 09 June 2025.
- Additional observing time will increase the scientific output of O4; coating development for O5 will be finalized; O5 test masses will subsequently be coated for expected start of run in early 2027

BNS compact merger rates = *Very Uncertain*



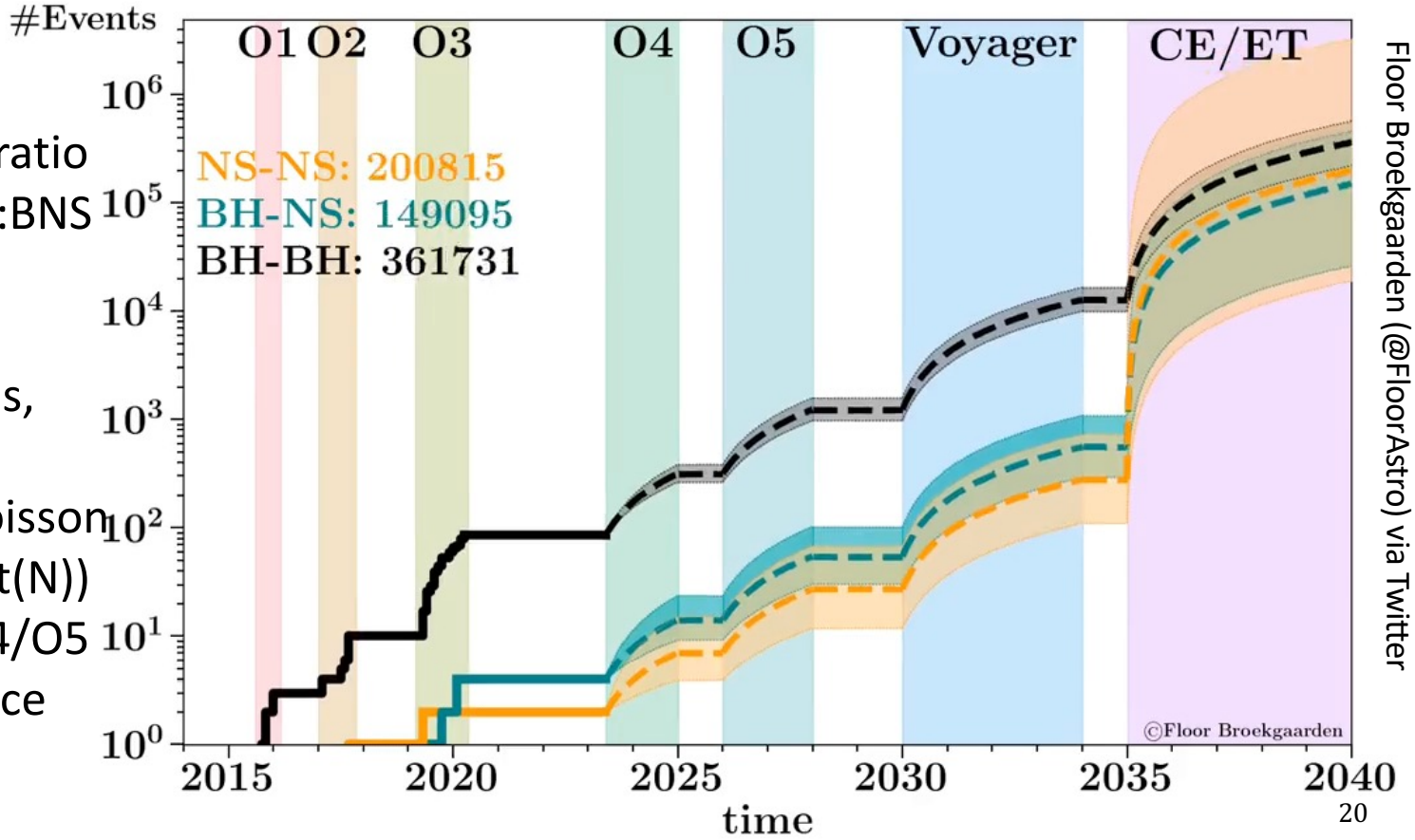
LIGO-G2302098, 23 October, 2024

Credit: LVK Collaboration

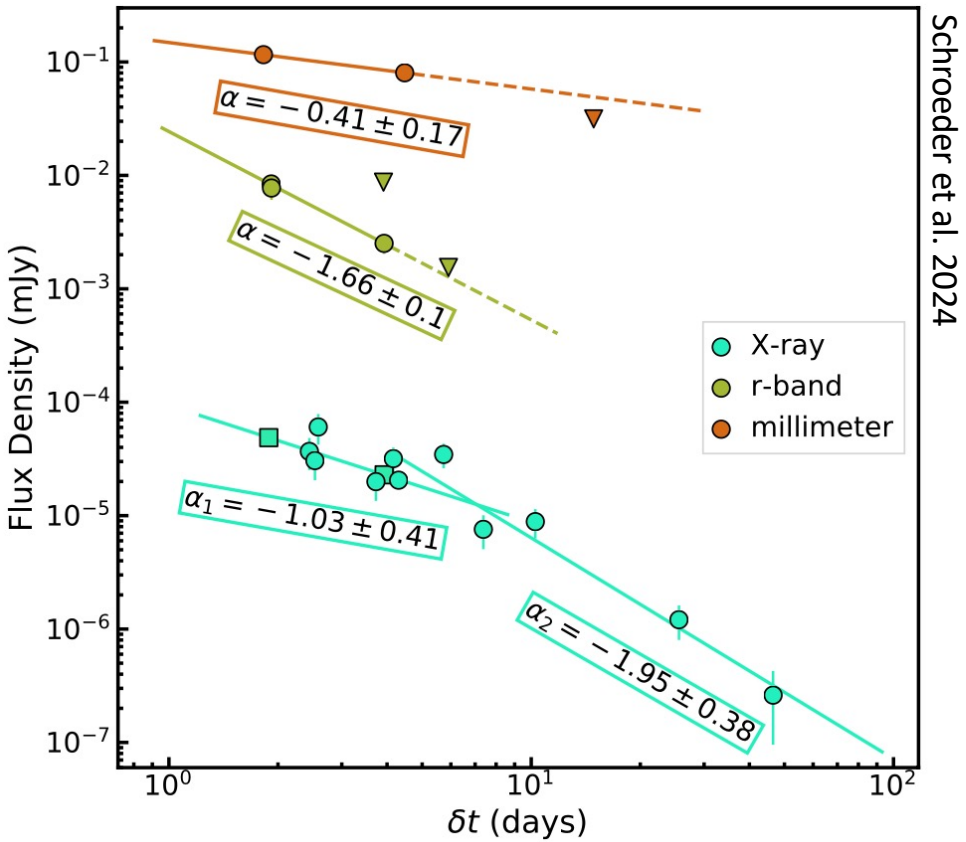
- LVK GWTC-3:
  $10–140\ \mathrm{Gpc^{-3}\ yr^{-1}}$
  (90% conf, PBD pair model; Abbott et al 2023)
- Chandra/XMM sGRB:
  $360–1800\ \mathrm{events\ Gpc^{-3}\ yr^{-1}}$
  (Rouco Escorial et al. 2023)
- Pop synth: $244+325\ \mathrm{Gpc^{-3}\ yr^{-1}}$ (Kim et al. 2015); conversion of 1.16×10^{2} MW-like galaxies $\mathrm{Mpc^{-3}}$ (Abadie et al. 2010; Rosswog et al. 2017; Brethauer et al. 2024).

Are we still in for an avalanche??

- Detection ratio BBH:BHNS:BNS = 86:4:2 (GWTC-3 Populations, LVK+2022)
- Assume Poisson errors (sqrt(N))
- Scale to O4/O5 BNS distance

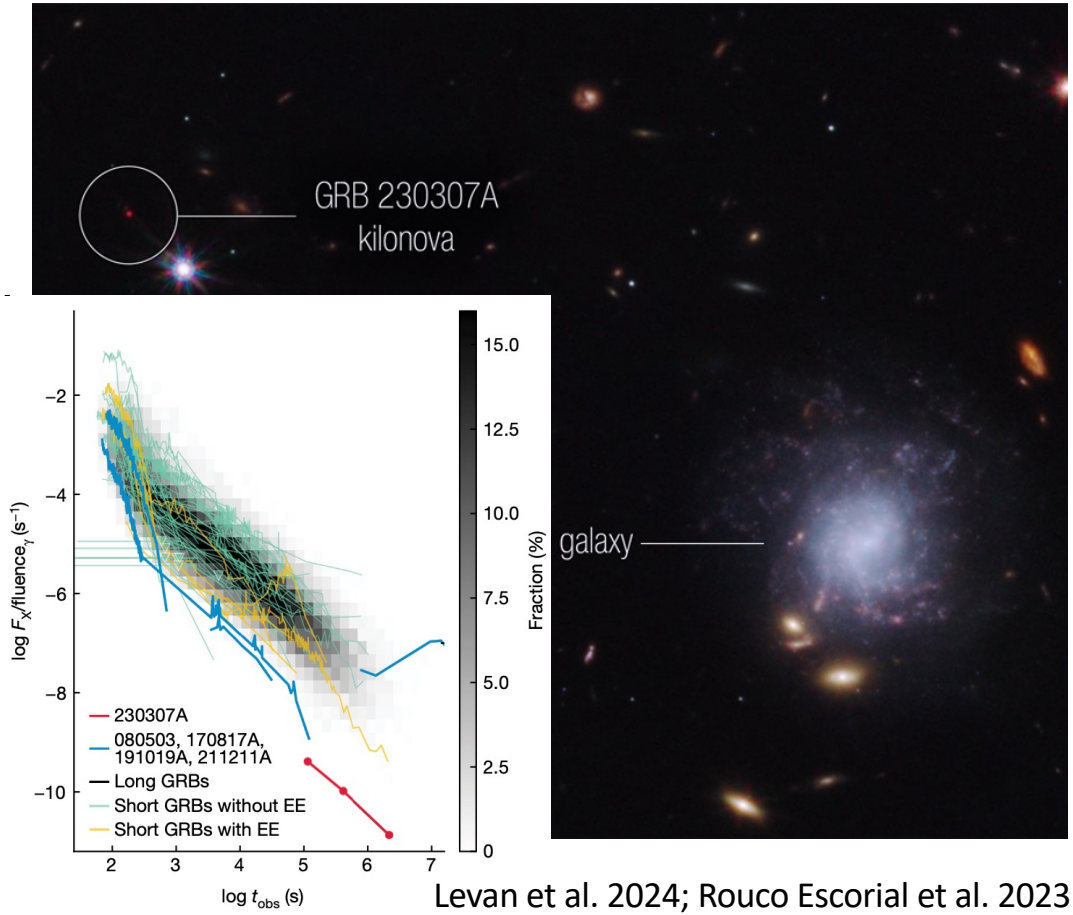


Other cool GRBs: short GRB 231117A



- *Swift* short GRB231117A at z = 0.257 w/ small projected offset (~ 2 kpc).
- Long-lived X-ray (CXO) and radio/millimeter (VLA, MeerKAT, and ALMA) afterglow emission out to ~ 37 d (X), ~ 20 d (R)
- Solid lines are PL fits to the detected afterglow, dashed lines provide an extrapolation past the last detection.

Other cool GRBs: long GRB 230307A

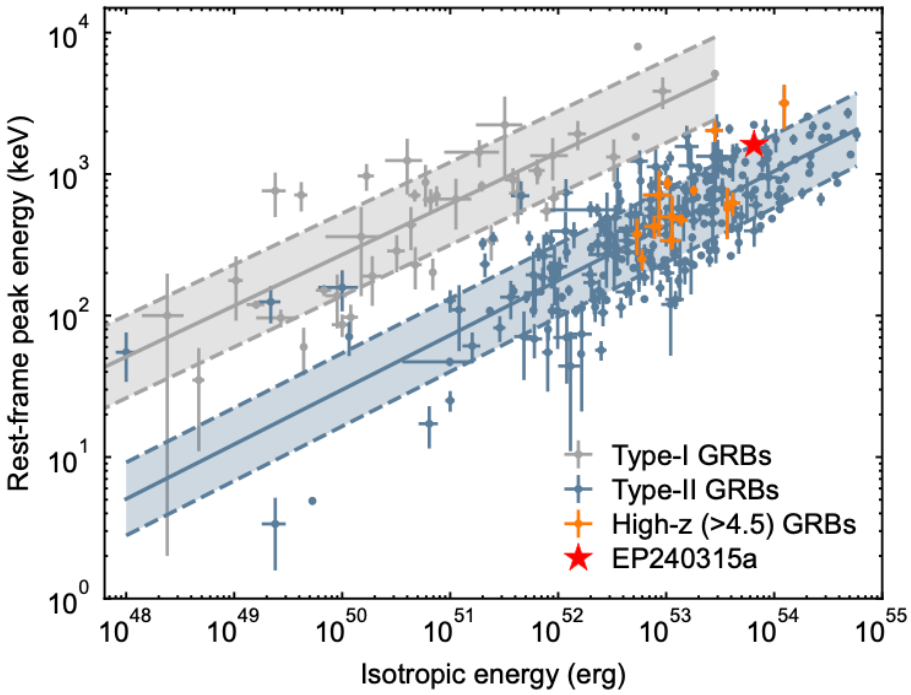


- Exceptionally bright long GRB from compact object merger w/ kilonova detected by JWST
- Emission lines associated with *r-process* elements
- *Chandra* obs ~25 days post-trigger
- Joint fit w/ *Swift* XRT show PL decline (α~-1.3)

Levan et al. 2024; Rouco Escorial et al. 2023

Other cool GRBs: EP240315a

- *Einstein Probe* long GRB at high z = 4.859
- Probe of SF and reionization in early Universe
- Detected by EP WXT & FXT, Swift, Konus-Wind, Chandra + ATLAS, VLT
- Late-time X-ray (and maybe optical) re-brightening attributed to re-activation of the central engine or to structured off-axis jet



Liu et al. 2024

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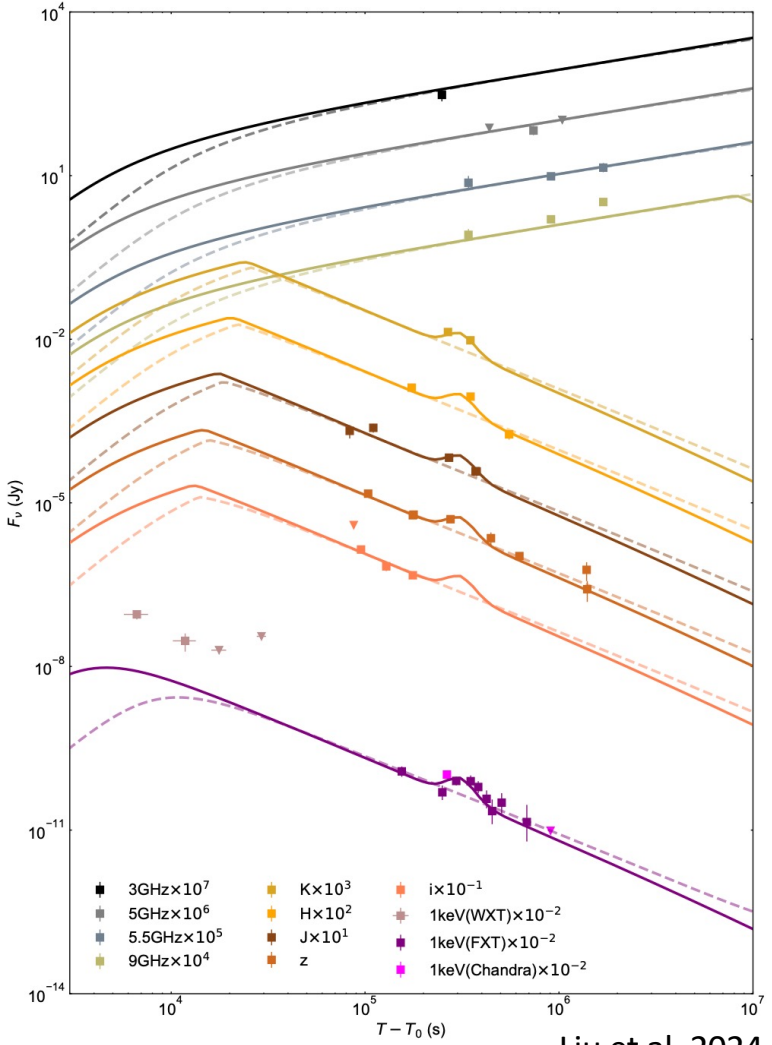
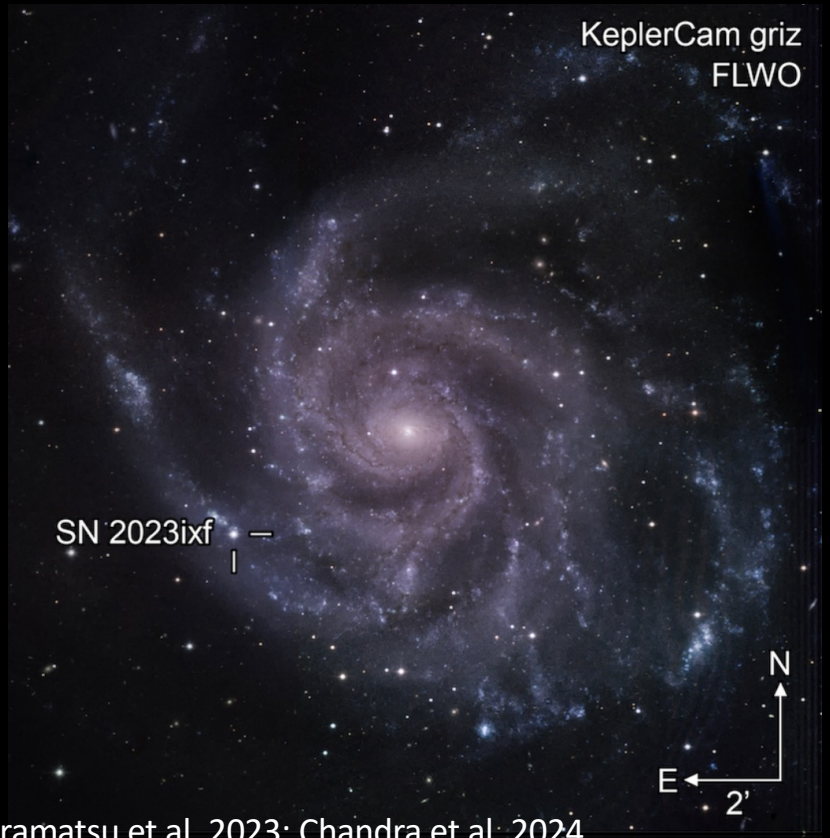


Liu et al. 2024

Supernovae, FBOTs, FXTs

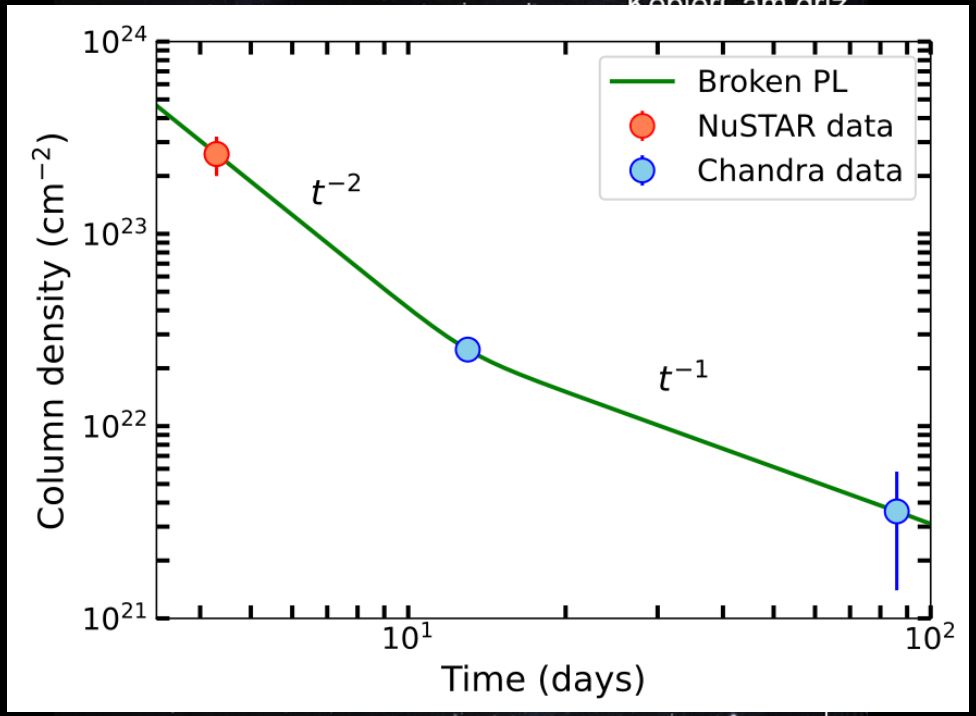
Nearby Supernova SNe 2023ixf



Hiramatsu et al. 2023; Chandra et al. 2024

- Nearest recent core-collapse Type II SN (M101, 6.9 kpc)

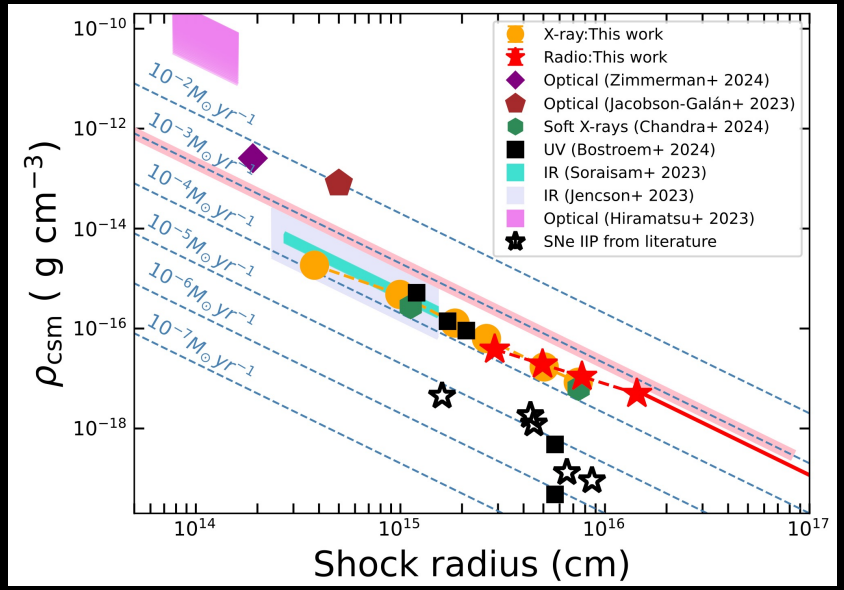
Nearby Supernova SNe 2023ixf



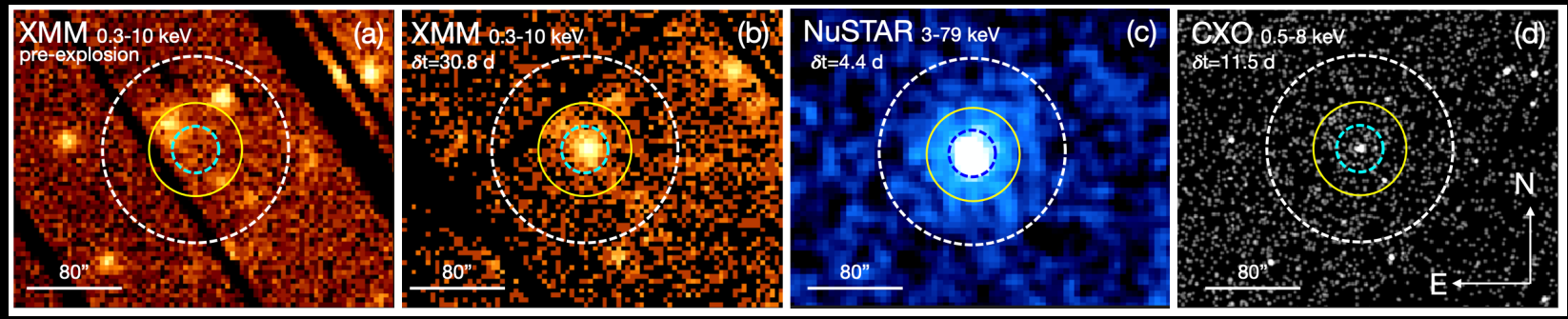
Hiramatsu et al. 2023; Chandra et al. 2024

- Nearest recent core-collapse Type II SN (M101, 6.9 kpc)
- Chandra-ACIS obs 13 and 86 d after the explosion
- Absorption much larger than Galactic, implies local circumstellar matter
- Fe Kα fluorescent line at 6.4 keV (cold material) on day 13, gone on day 86
- Mass loss: $5.6 \times 10^{-4}\ M_{\odot}\ yr^{-1}$

Nearby Supernova SNe 2023ixf



- Extensive X-ray (NuSTAR, Swift-XRT, XMM-Newton, Chandra) and meter-to-mm wave (GMRT, VLA, NOEMA) monitoring spans ~4–165 d
- Points to complex CSM density structure with asymmetries and clumps (~10 x red supergiants)



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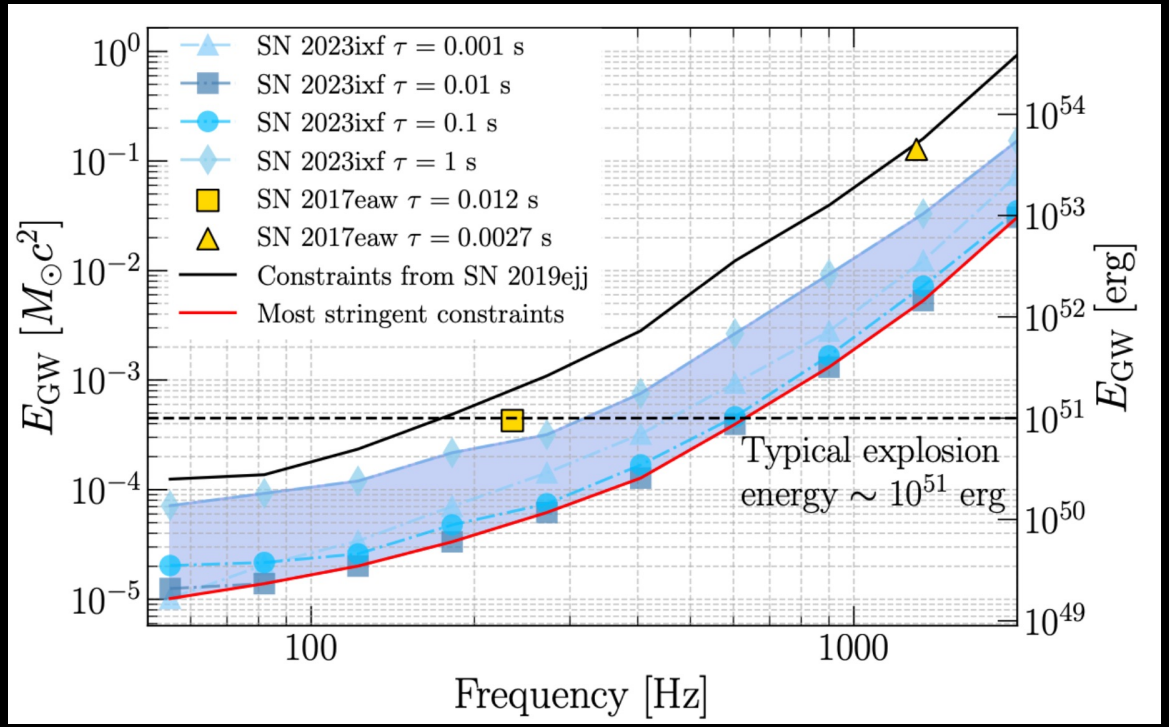
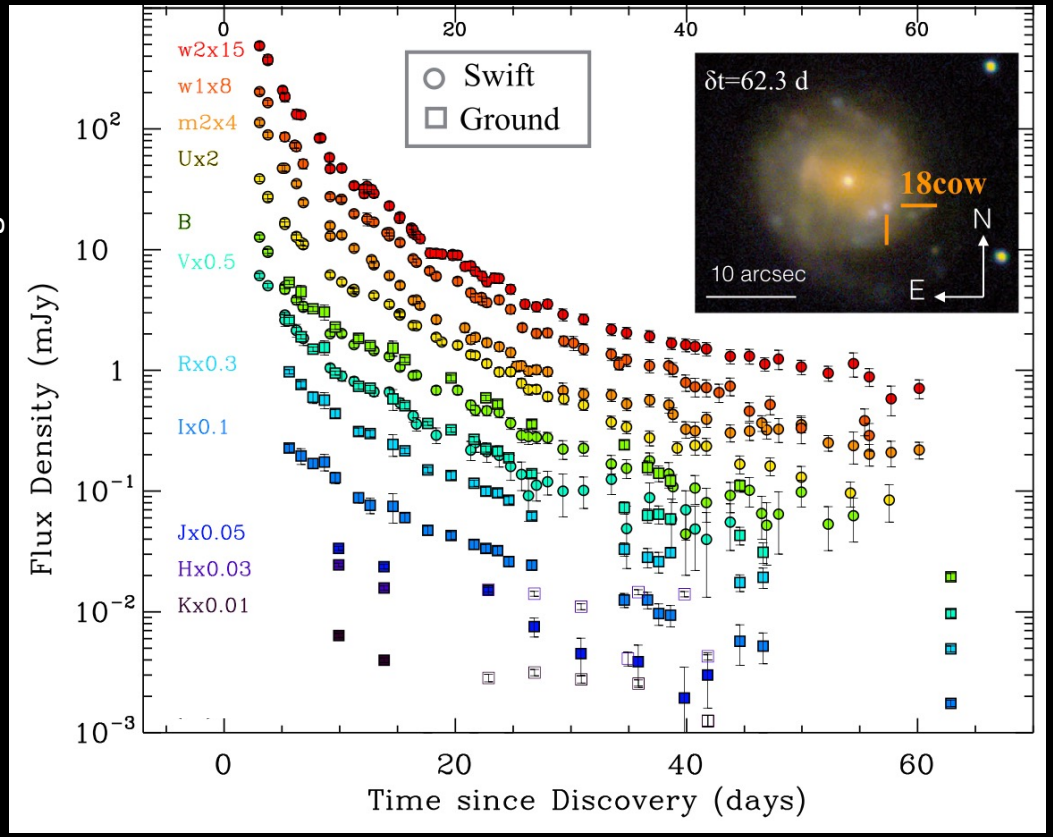


LVK et al. 2024 (arXiv:2410.16565)

- Search ***also*** conducted by LIGO-Virgo-KAGRA
- 5-day window during which GW signal may have occurred (14% coverage w/ 2 detectors)
- Constraints an order of magnitude more stringent than previous GW studies

Fast Blue Optical Transient (FBOT): AT 2018cow

Margutti et al. 2019



- Extensive radio to g-ray obs of FBOT over first ~100 d
- Peak at Lx ~ 4 x 10^{44} erg s^{-1}
- Abrupt change in X-ray decay rate / variability accompanies change in optical spectrum
- AT 2018cow likely harbored a “central engine,” either a compact object (magnetar or black hole) or embedded internal shock

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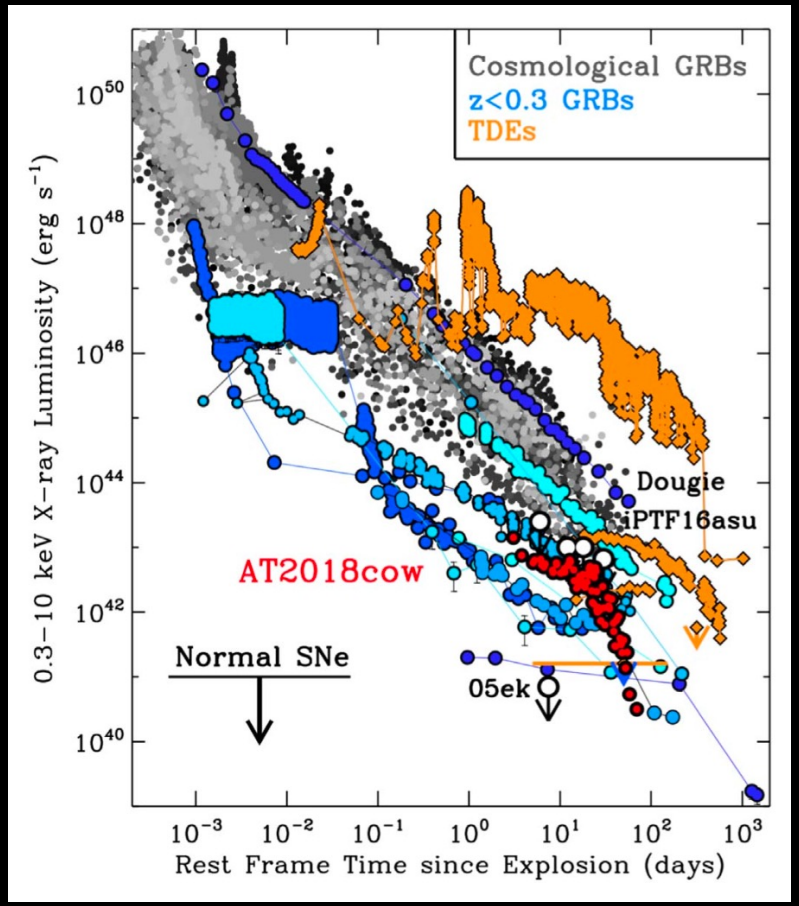

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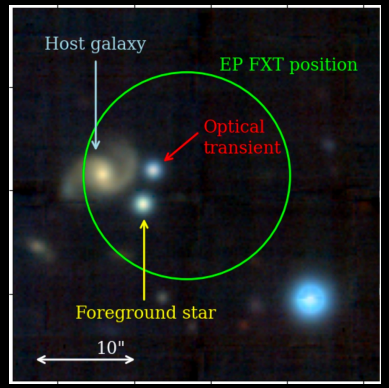
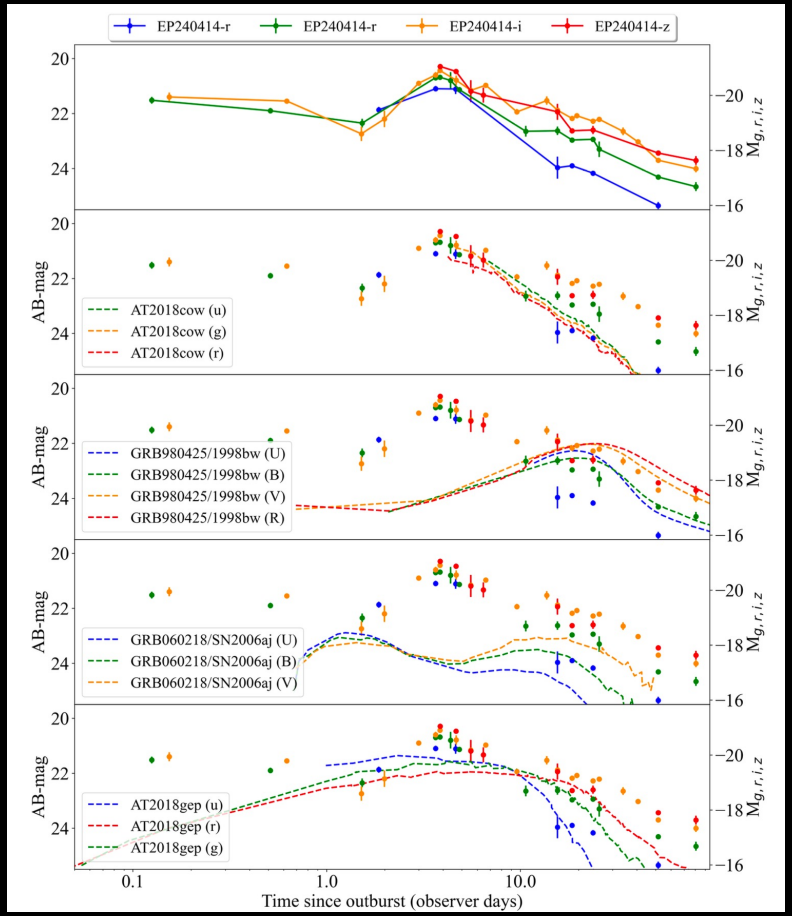
Fast X-ray Transients: FXT EP240414a



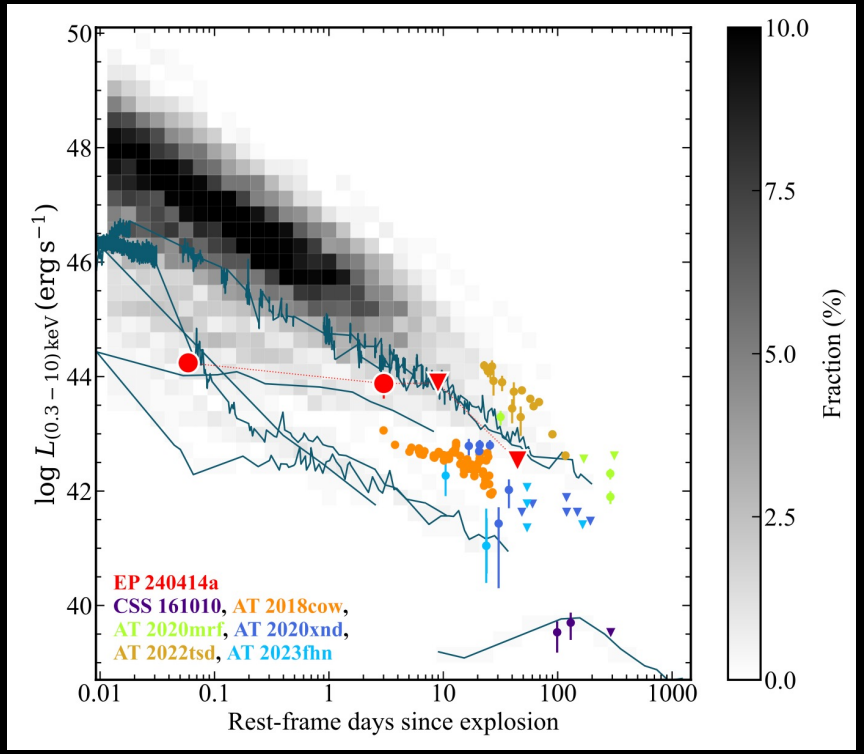
- FXTs may GRBs and/or FBOTs (or other!)
- Einstein Probe detection at 25.7 kpc (projected) from massive galaxy at z = 0.401
- FXT EP240414a has MWL cntrpt, but no γ-rays
- ~3 episodes at ~ 1, 4, and 15 days



Van Dalen et al. 2024

Fast X-ray Transients: FXT EP240414a

- Blue early spectrum from jet / shocks with the stellar envelope + a dense circumstellar medium
- Late-time spectrum evolves toward broad-lined Type Ic SN, like collapsar long-GRBs
- Implies progenitor is a massive star w/ a jet-forming SN inside a dense envelope
- X-ray outburst $L_x \sim 10^{48}$ erg s^{-1}
- Causal link between progenitors of long-GRBs, FXTs and LFBOTs?



Van Dalen et al. 2024; Srivastav et al. 2024

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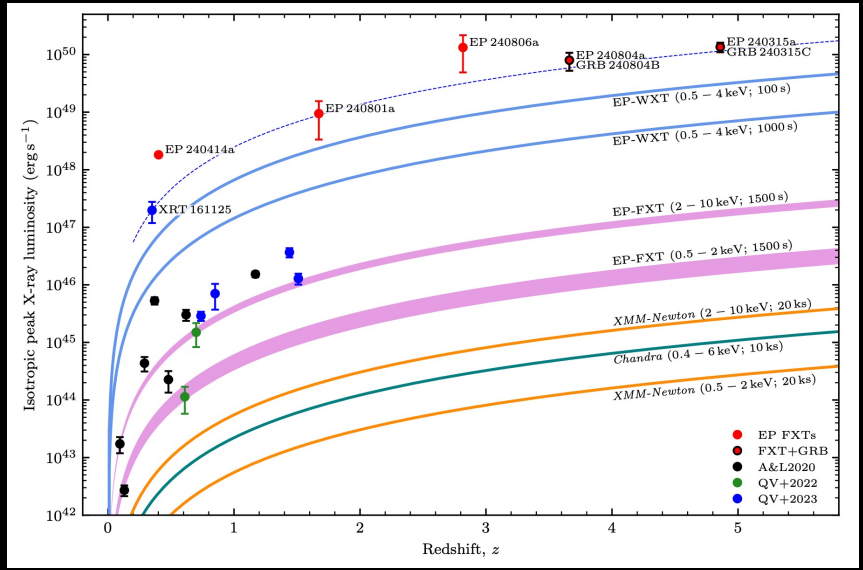
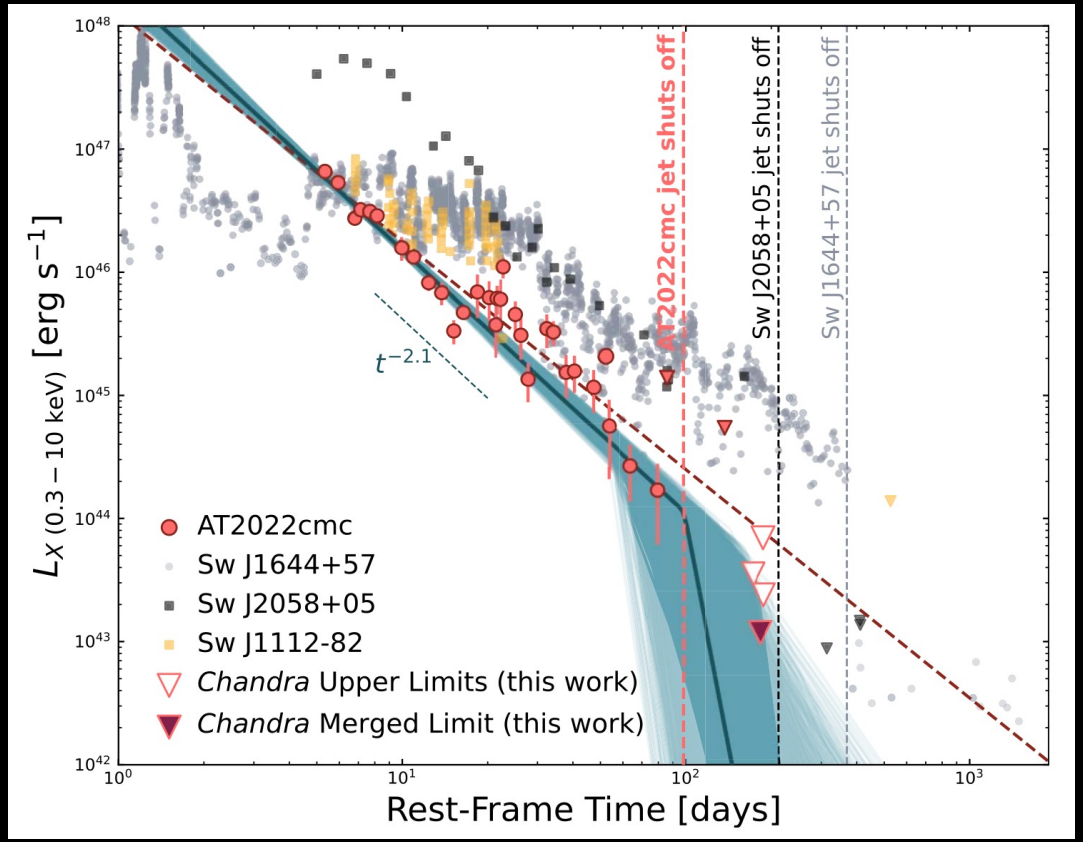


Van Dalen et al. 2024; Srivastav et al. 2024

Tidal Disruption Events

Long term evolution of TDE: AT2022cmc

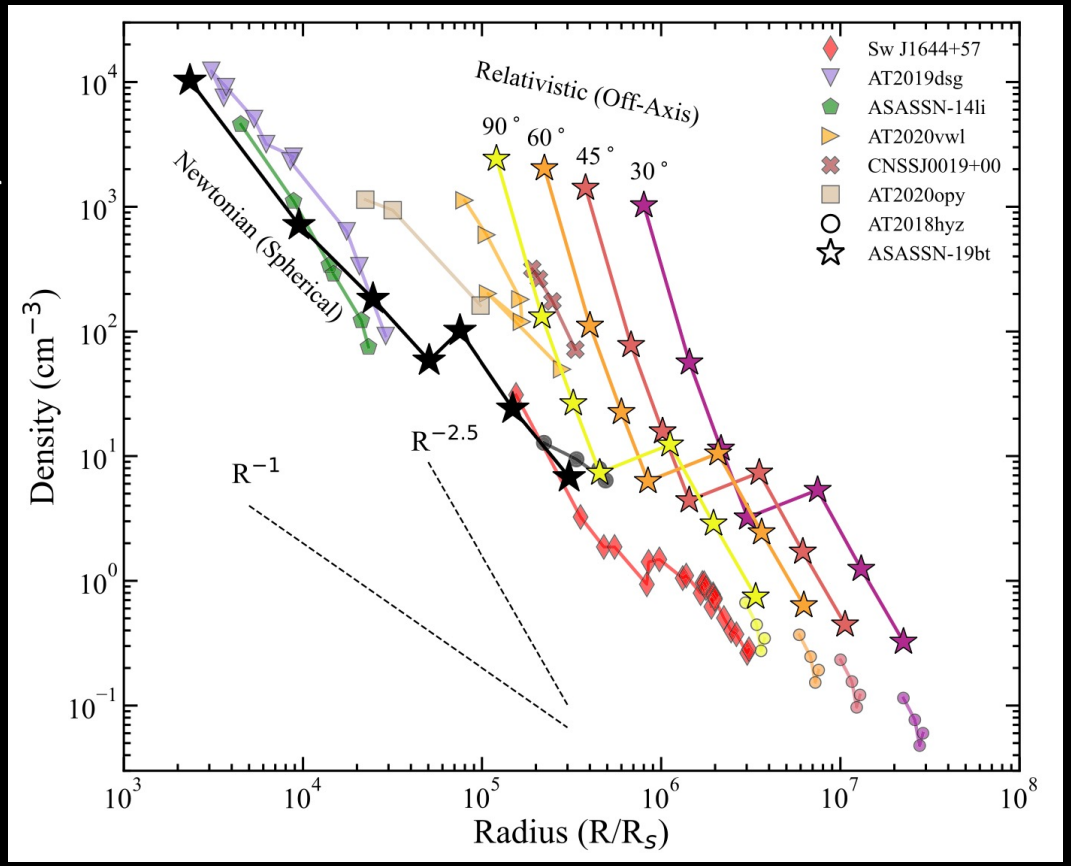
Eftekhari et al. 2024



- AT2022cmc: 4th relativistic jet from the tidal disruption of a stray star
- Chandra obs extend coverage to ~400 d post-disruption
- Sudden decrease in X-ray points to cessation of jet activity at t_{obs} ~ 215 d

Long term evolution of TDEs: ASSASSN-19bt

Christy et al. 2024



- ASASSN-19bt/AT 2019ahk long term radio monitoring + Chandra coverage
- Nonrelativistic spherical blast-wave model (black)
- Off-axis relativistic jet (color-coded from indigo to yellow by viewing angle)
- Neither works well – need better models of radio emission at late times

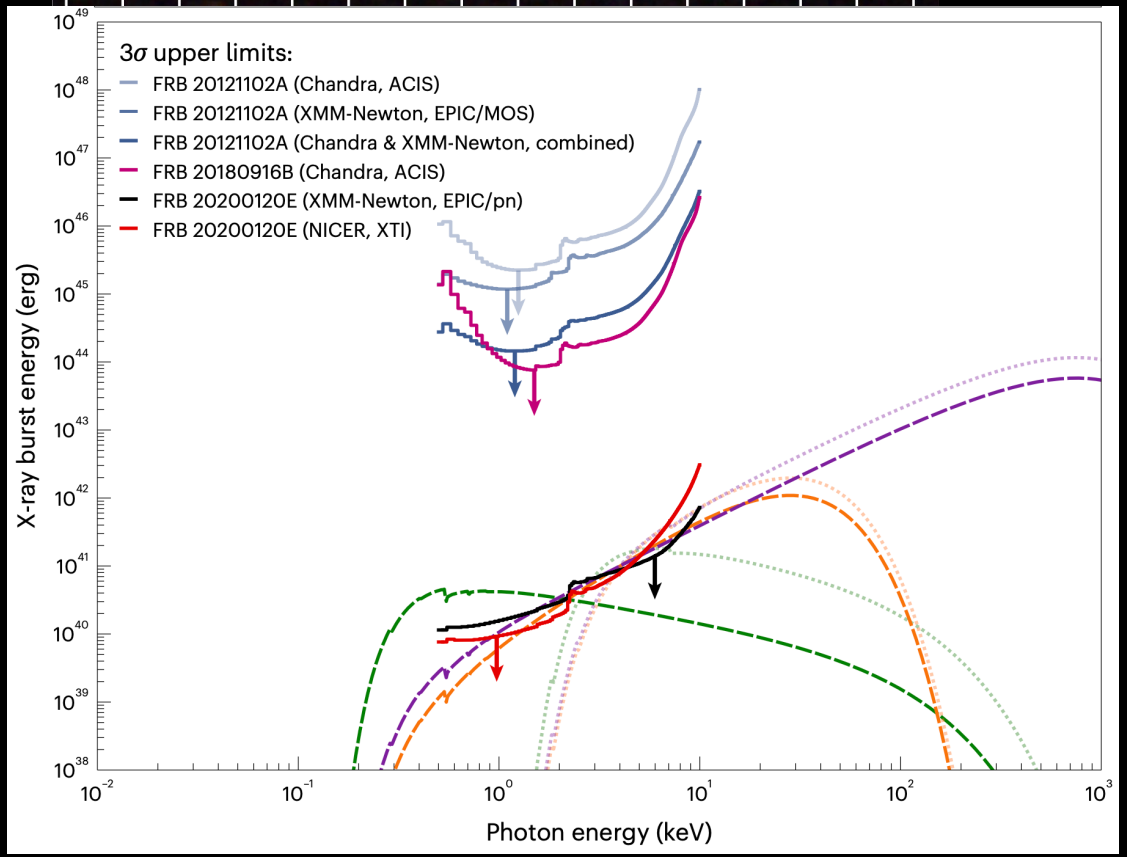
Fast Radio Bursts

Repeating Fast Radio Bursts

- FRB origins remain unclear but many models evoke magnetars
- FRB repeaters offer better prospects for follow up and localization
- So far only X-ray limits, but association with (old) globulars is intriguing/mysterious

Kirsten et al. 2022; Pearlman et al. 2023; see also Cook at al. 2024

Repeating Fast Radio Bursts



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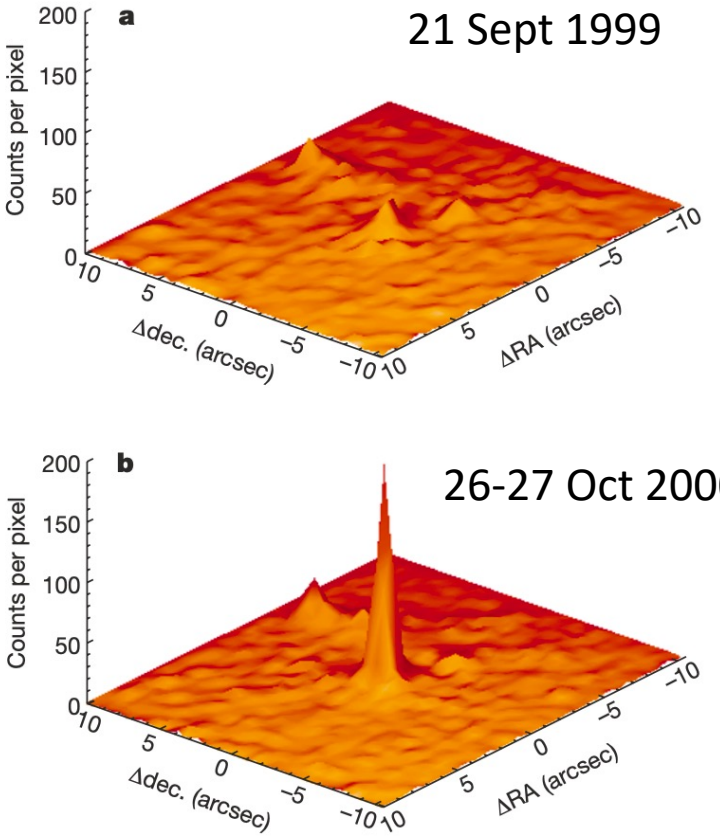
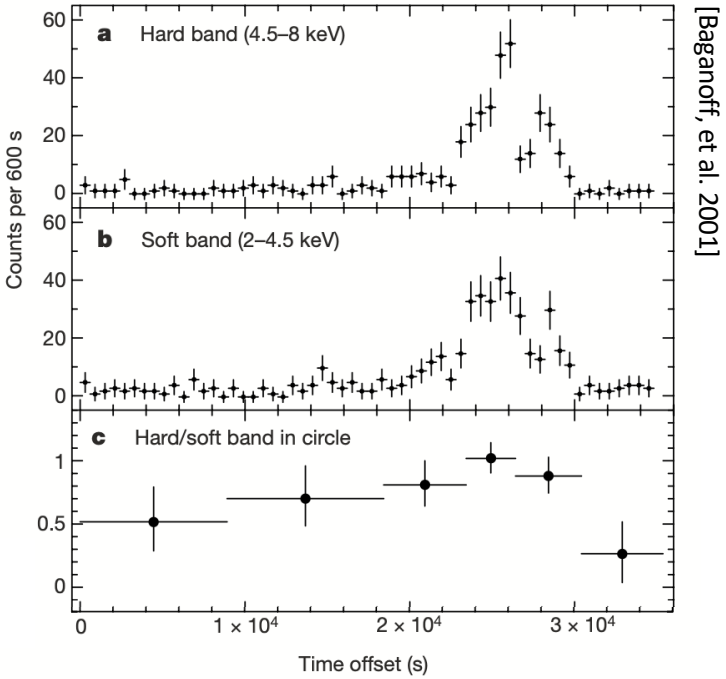
Galactic Center Transients

Chandra Detects Sgr A*'s First X-ray Flares!





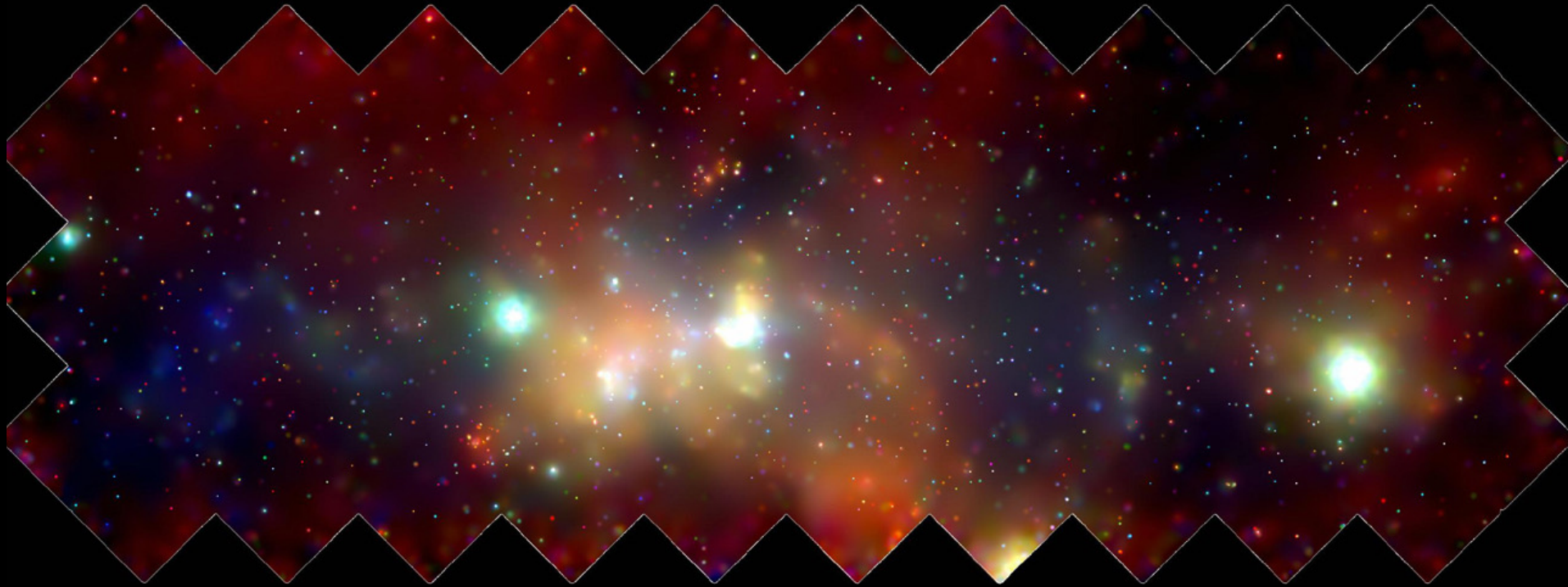
[Baganoff, et al. 2001]

L_x = 2.2 x 10^{33} erg s^{-1} (quies)

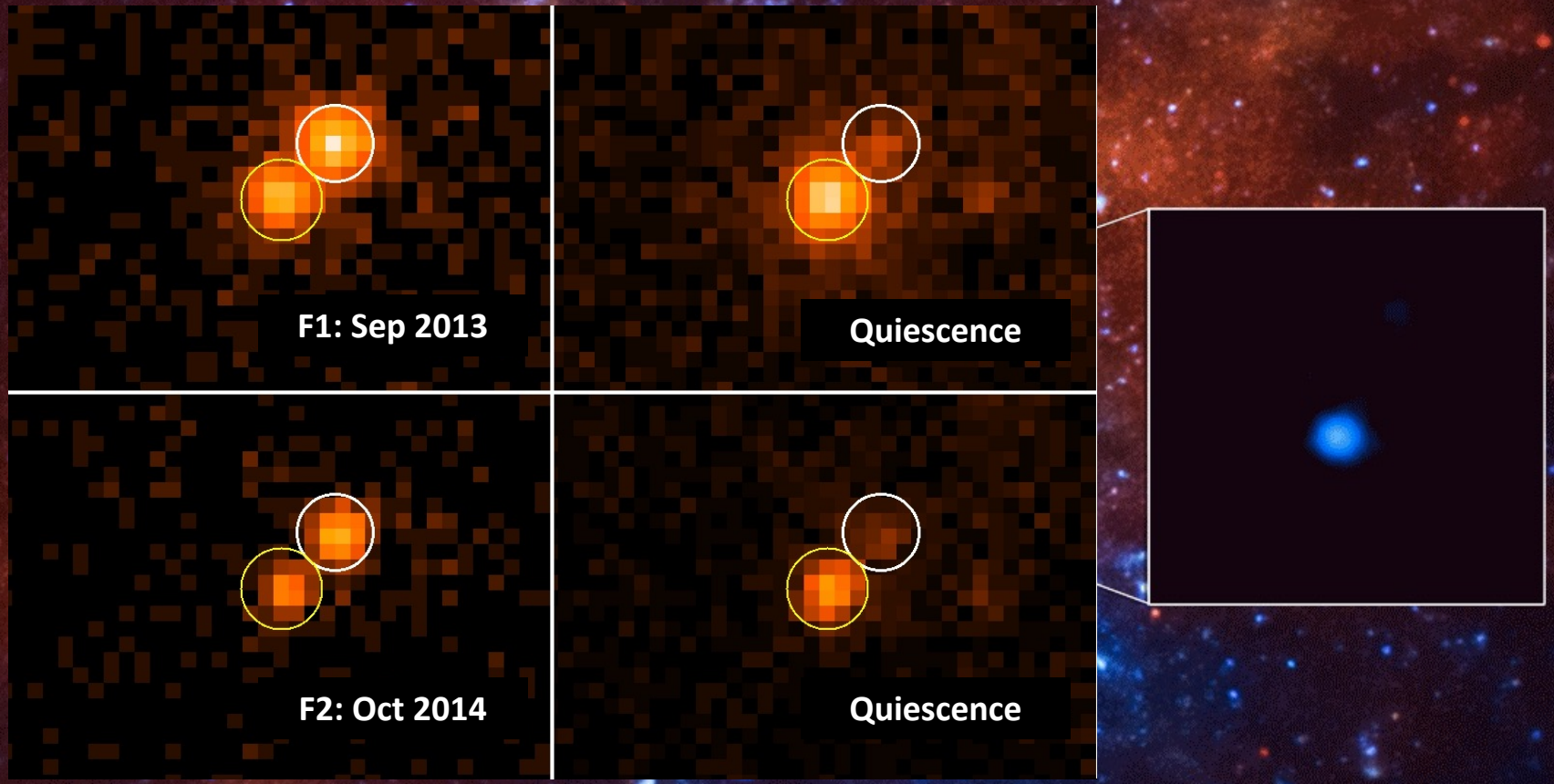
L_x = 1.0 x 10^{35} erg s^{-1} (flare)

→ flare ~45 x quies !!

Sgr A* X-ray Visionary Program w/ HETG



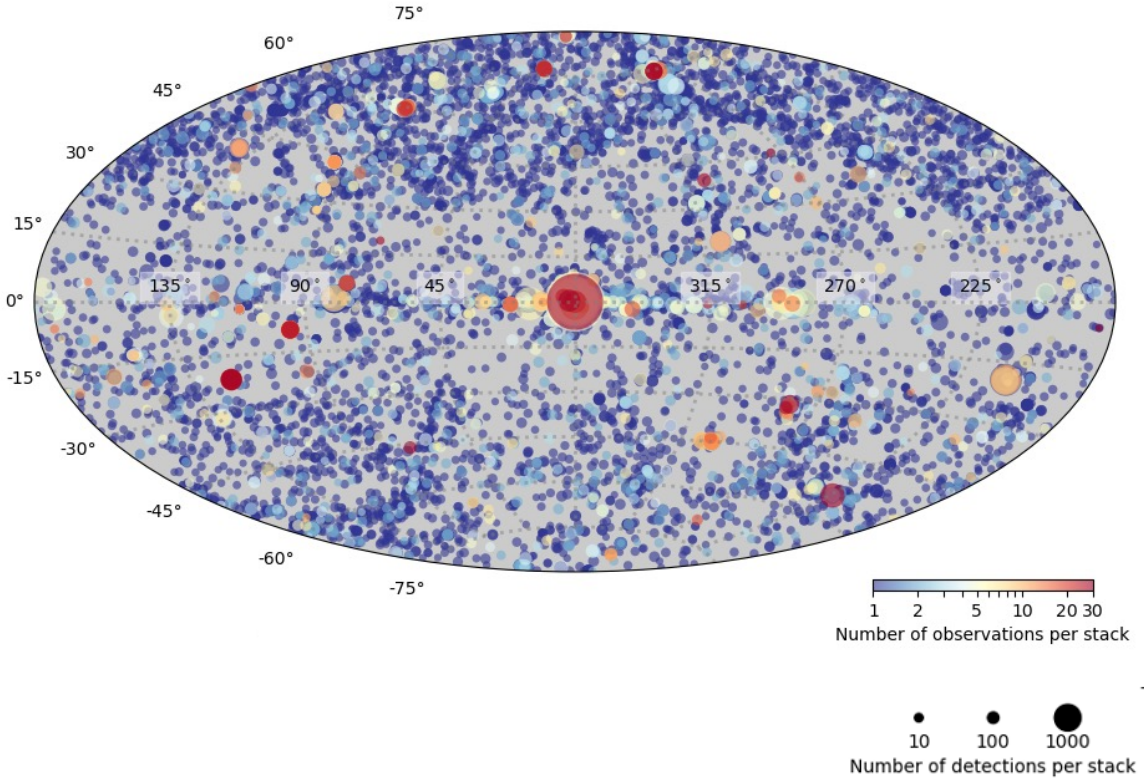
XVP + monitoring reveal even brighter flares!



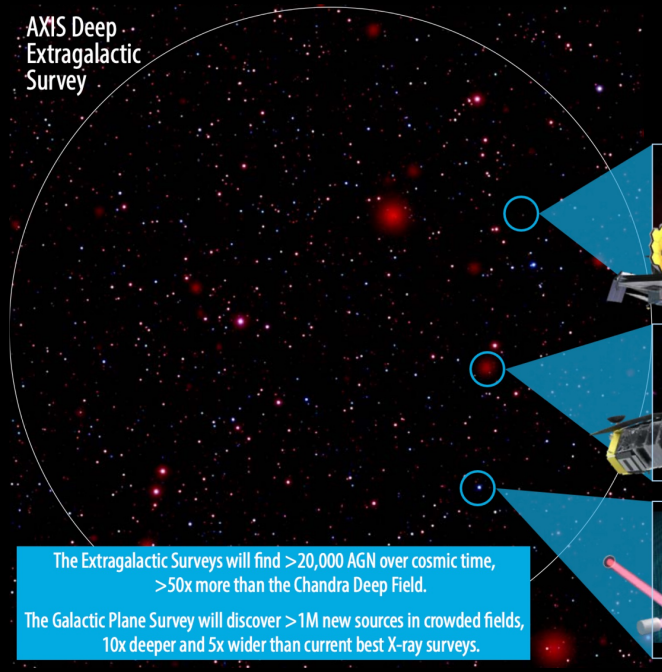
Archives and Catalogs

Chandra Source Catalog

- CSC 2.1 released April 2C
- Measured properties for **407,806 compact & extended X-ray sources**
- **>1.3 million individual detections** observed with ACIS or HRC-I
- Total sky coverage ~730
- DOI: doi:10.25574/csc2

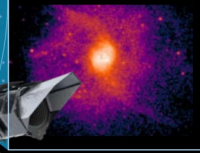


The Advanced X-ray Imaging Satellite

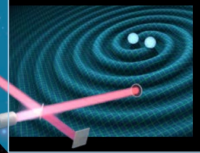


PI-led Science Program targets high-priority Astro2020 science

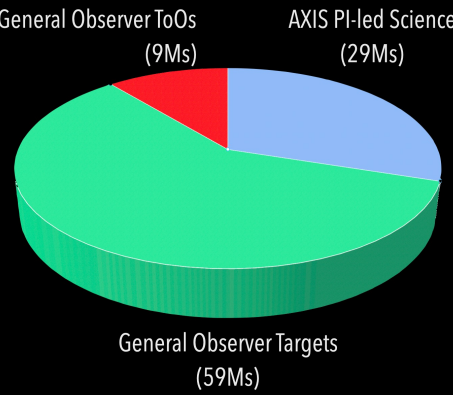
What seeds supermassive black holes and how do they grow?



How do gas, metals, and dust flow into, through and out of galaxies?



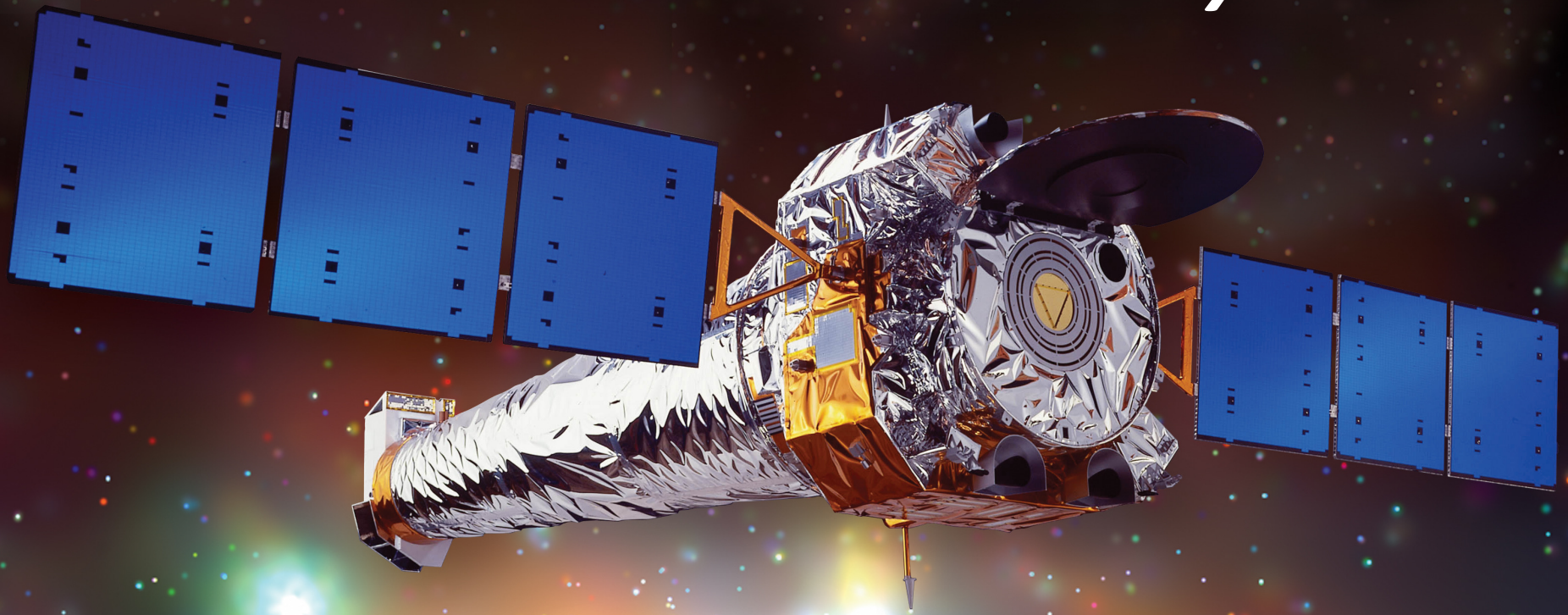
What powers the diversity of explosive phenomena?



AXIS sensitivity & angular resolution enables broad range of General Observer science.

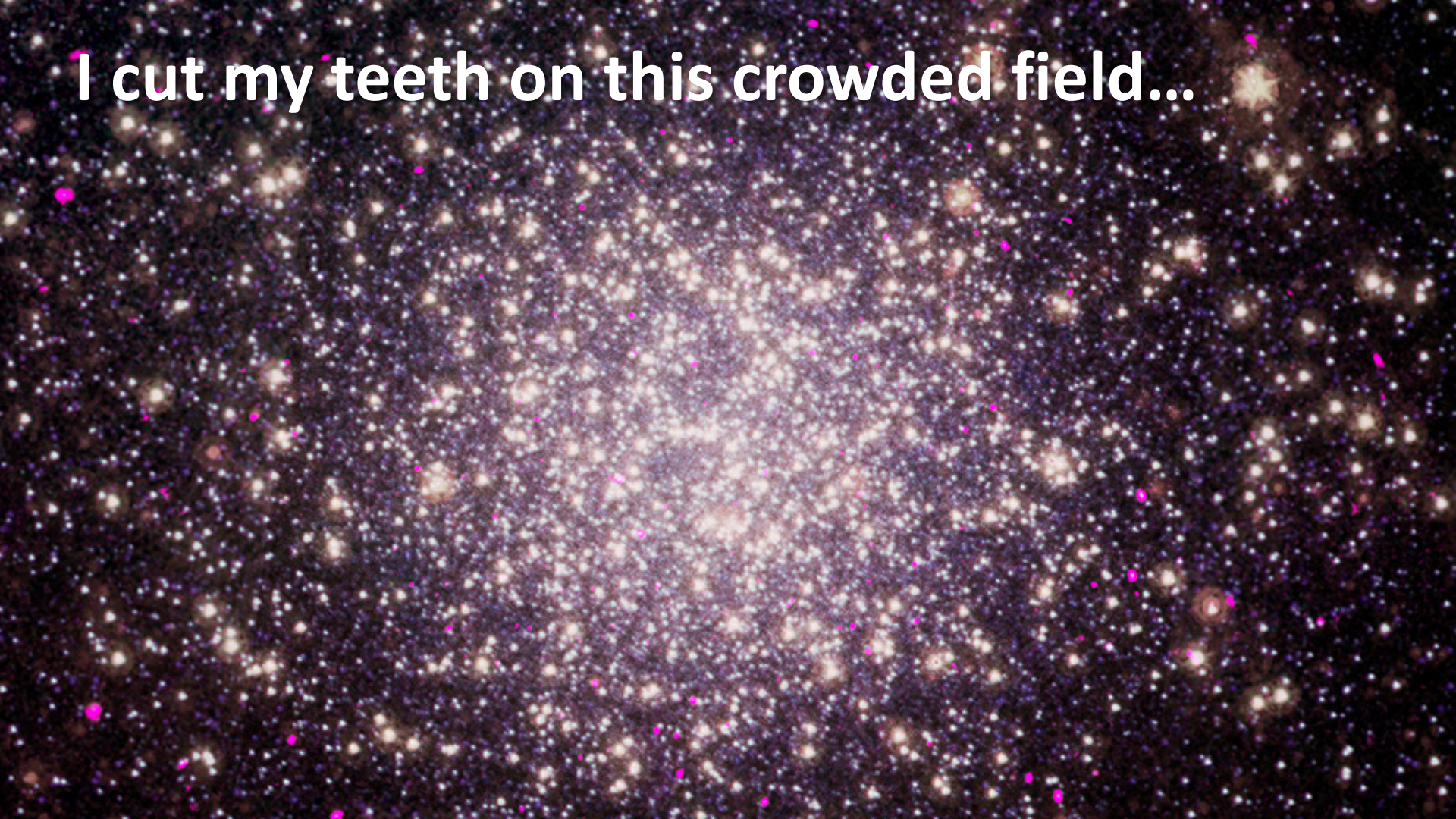
AXIS is a powerful TDAMM facility; rapid response (<2hr) to alerts, and provides triggers from on-board transient detector (<10 mins)

Chandra launch: 23 July 1999

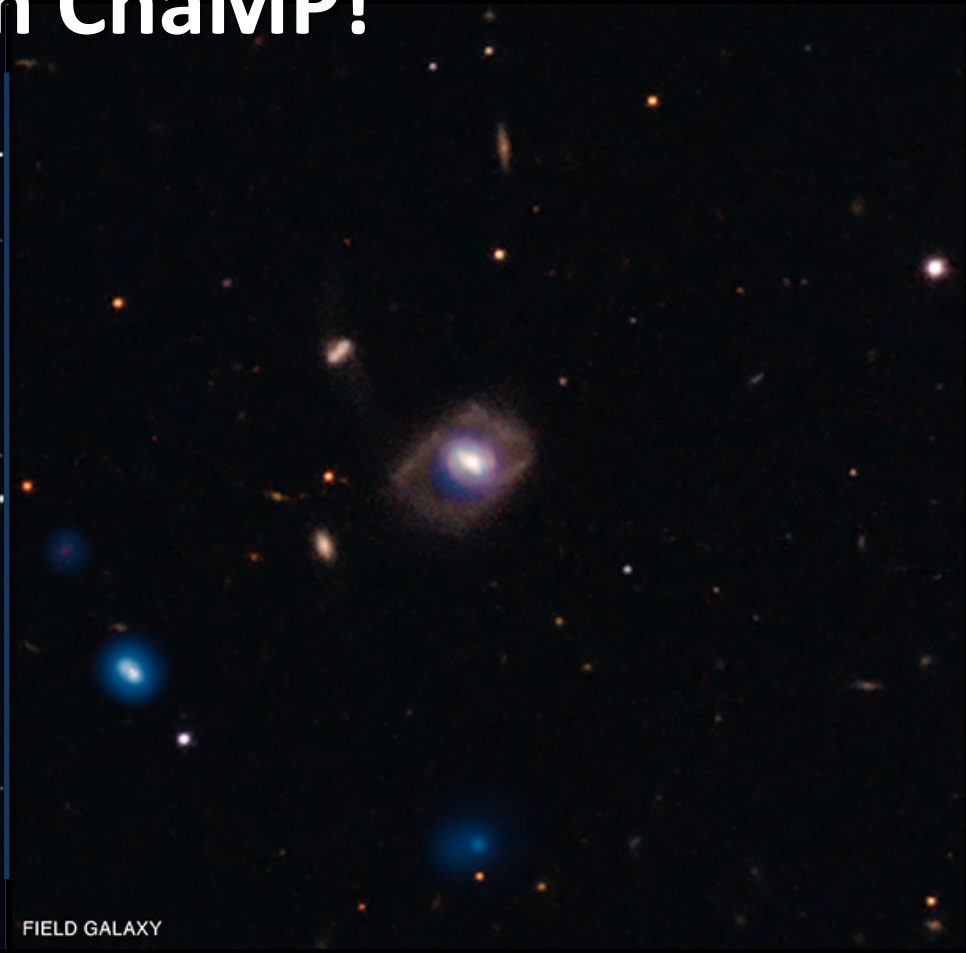


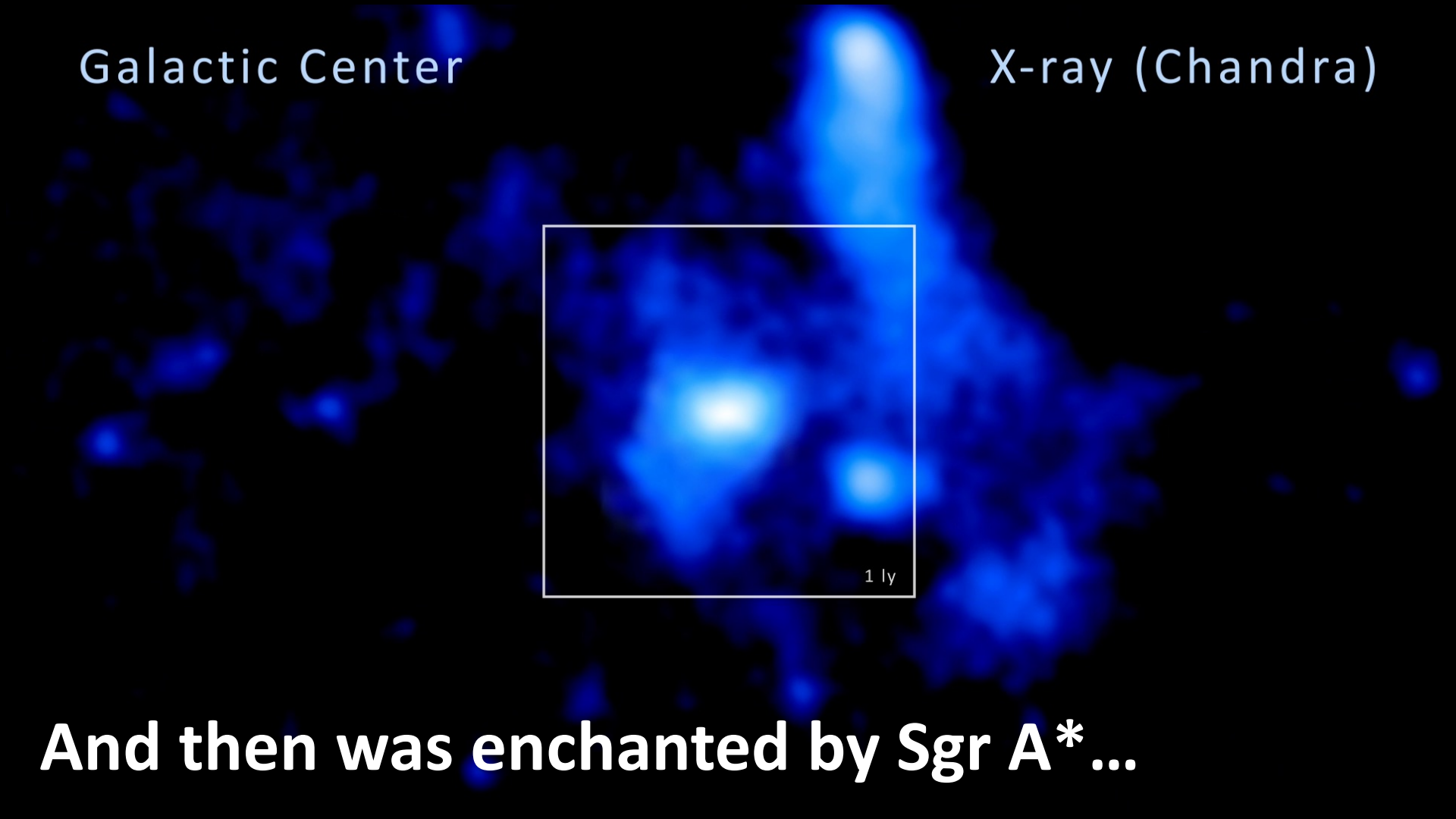
Scientist Daryl launch: ~Aug 1999


Chandra is crucial in this crowded field


I cut my teeth on this crowded field…

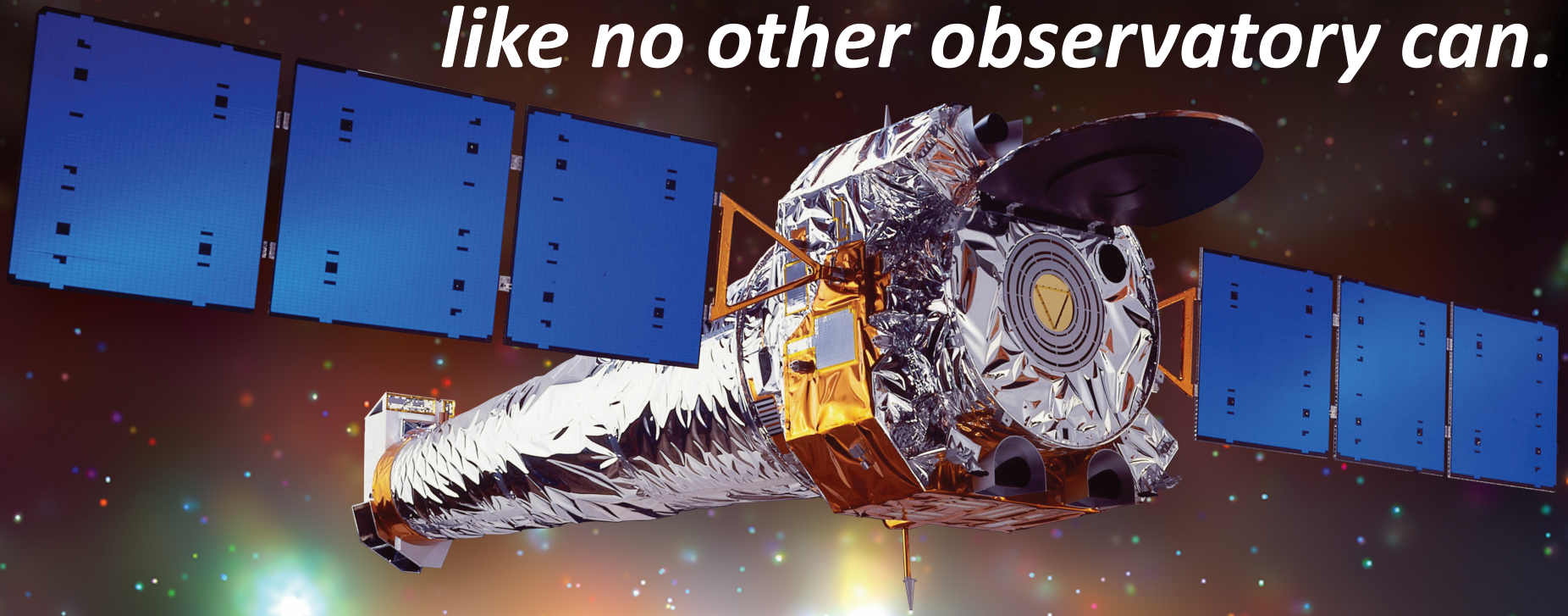
Spent great years with ChaMP!





And then was enchanted by Sgr A*…

Chandra has revealed transient events like no other observatory can.



I'm not done yet – neither is Chandra!


Black hole Folks!

SAVE CHANDRA