Magnetic fields of compact objects
コンパクト天体磁場

Kazumi Kashiyama (U. of Tokyo)

○ レビューアー：[コンパクト天体磁場]

コミュニティ	プロジェクト	（萌芽的テーマ）
	KamLAND-2	
宇電懇	SKA1	
	ngVLA	
高宇連	XRISM　（中型）	
	ATHENA　（ESA L2）	
	FORCE　（小型）	
	HIZ-GUNDAM	
	PhoENiX	
	SuperDIOS　（中型（予定））	

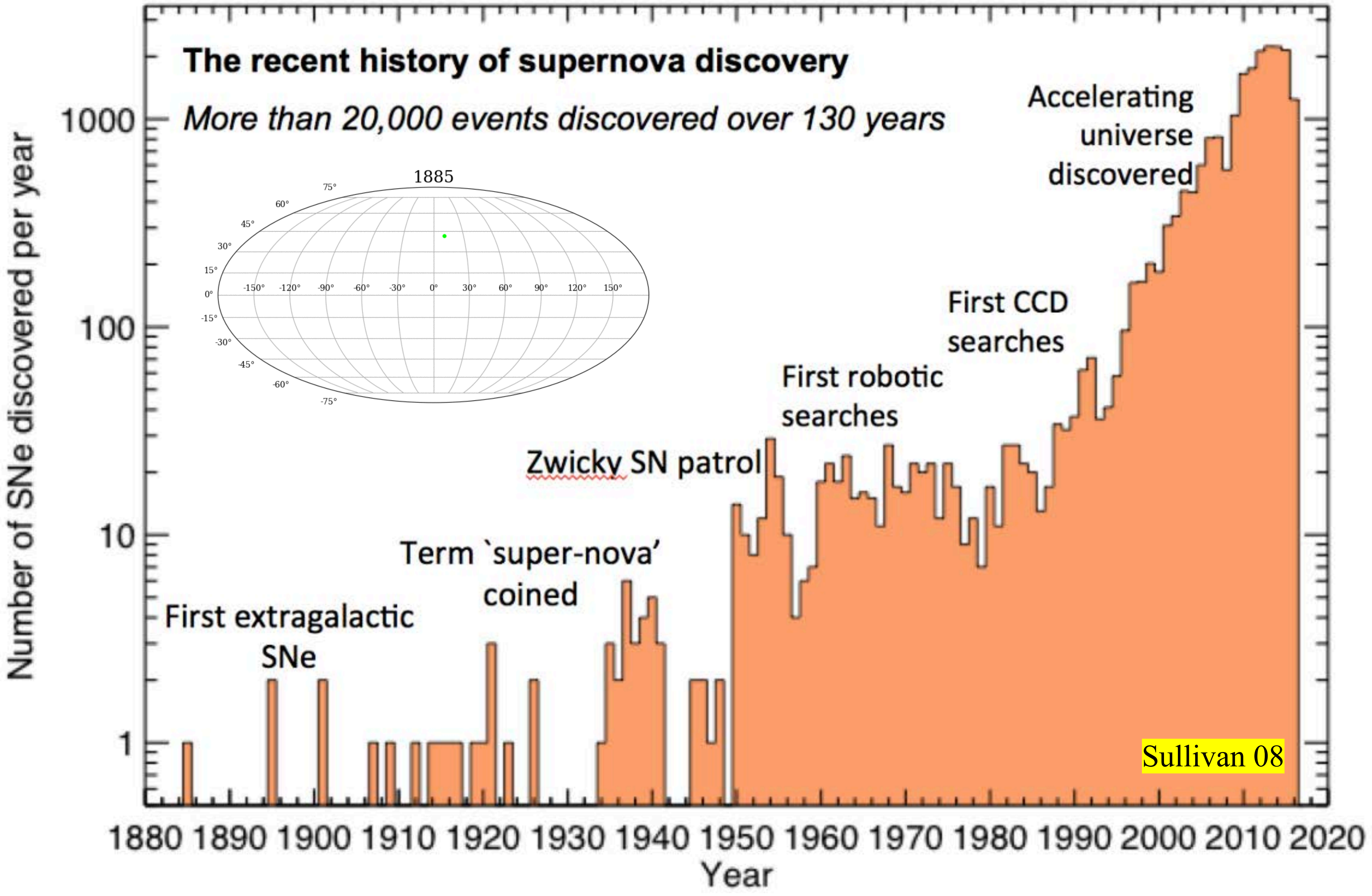
Compact objects and magnetic fields
コンパクト天体と磁場

Kazumi Kashiyama (U. of Tokyo)

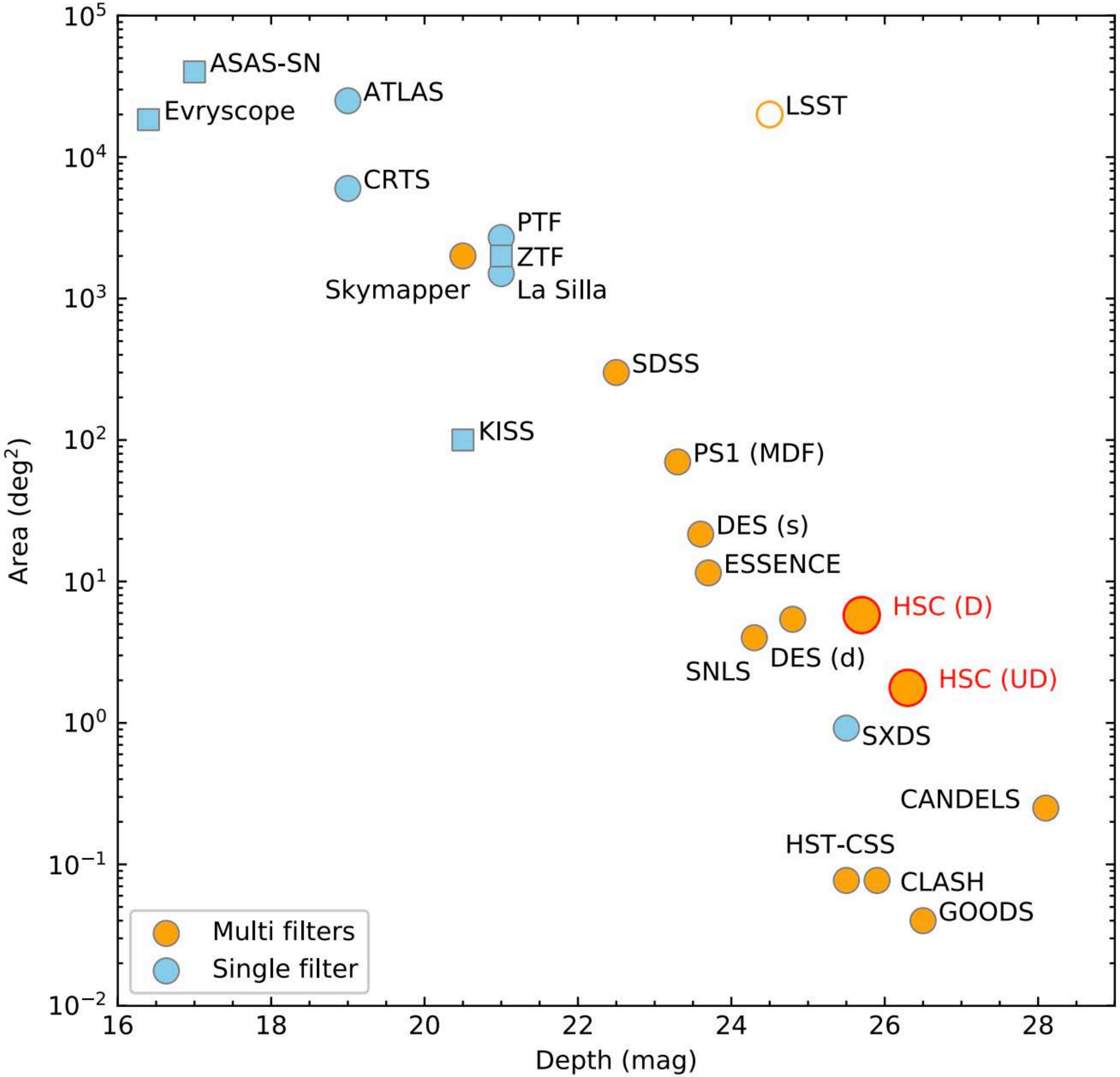
Why compact objects?

= white dwarfs (WDs), neutron stars (NSs), and black holes (BHs)

- As a laboratory of extreme physics
- As a high-energy astrophysical object
  - What kind of compact objects produce what kind of emission?
  - How and when?
- As a beacon from the universe far far away
- As an end product of stellar evolution
  - What kind of stars produce what kind of compact objects?
  - How and when?

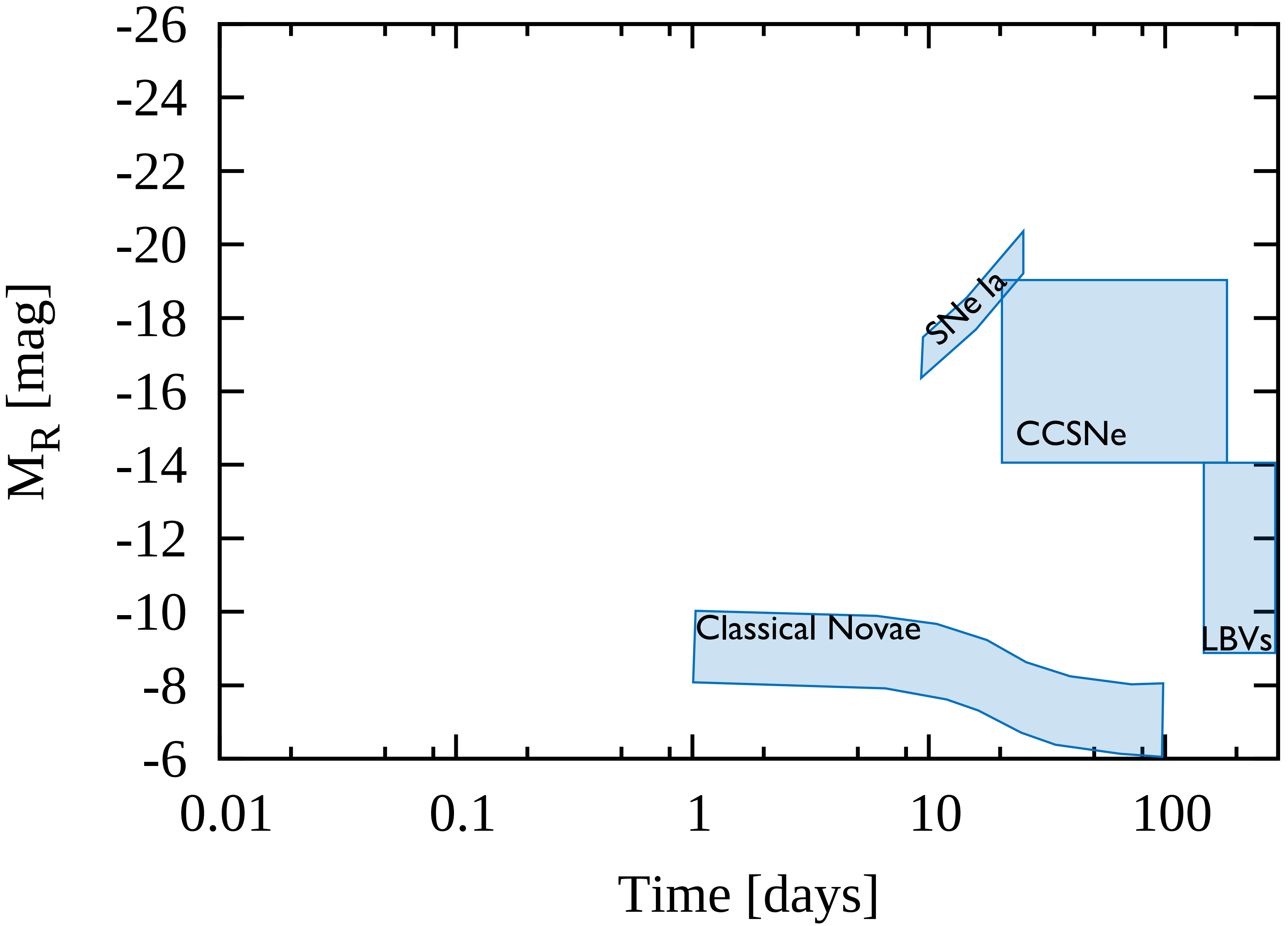


The recent history of supernova discovery
More than 20,000 events discovered over 130 years
1885
Accelerating universe discovered
First CCD searches
First robotic searches
Zwicky SN patrol
Term `super-nova' coined
First extragalactic SNe
Number of SNe discovered per year
1000
100
10
1
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010 2020
Year
Sullivan 08

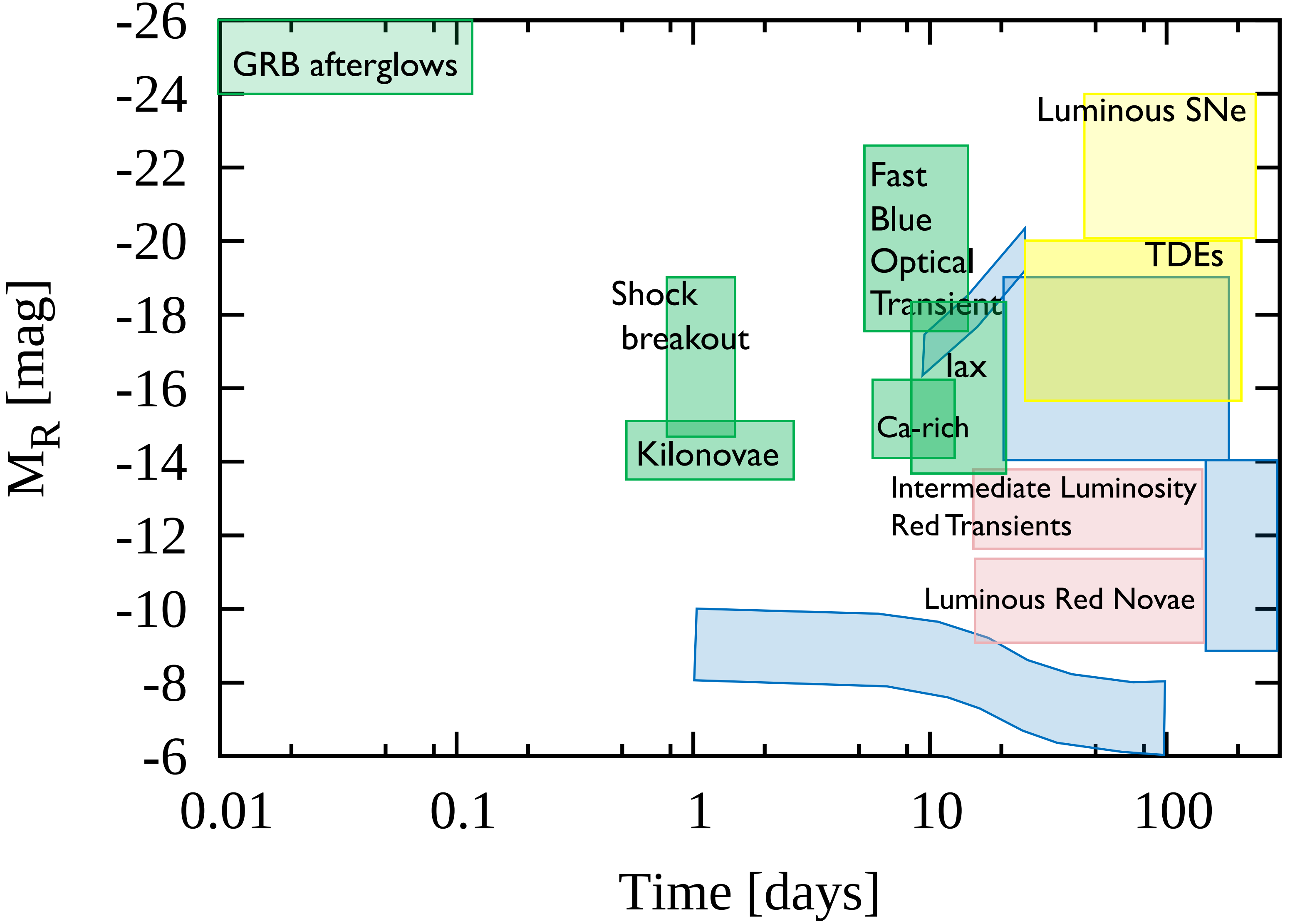


Yasuda et al. 19

Optical-transient zoo (~2000)

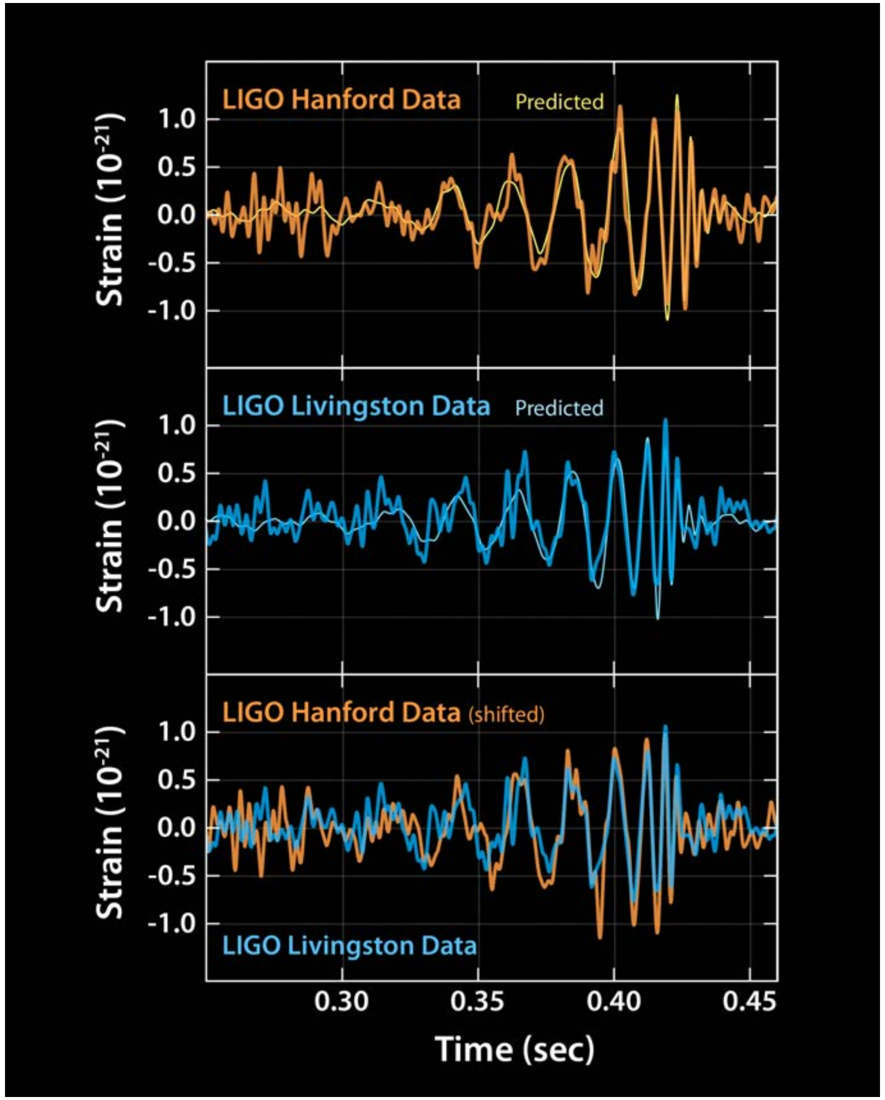


Optical-transient zoo (~2020)

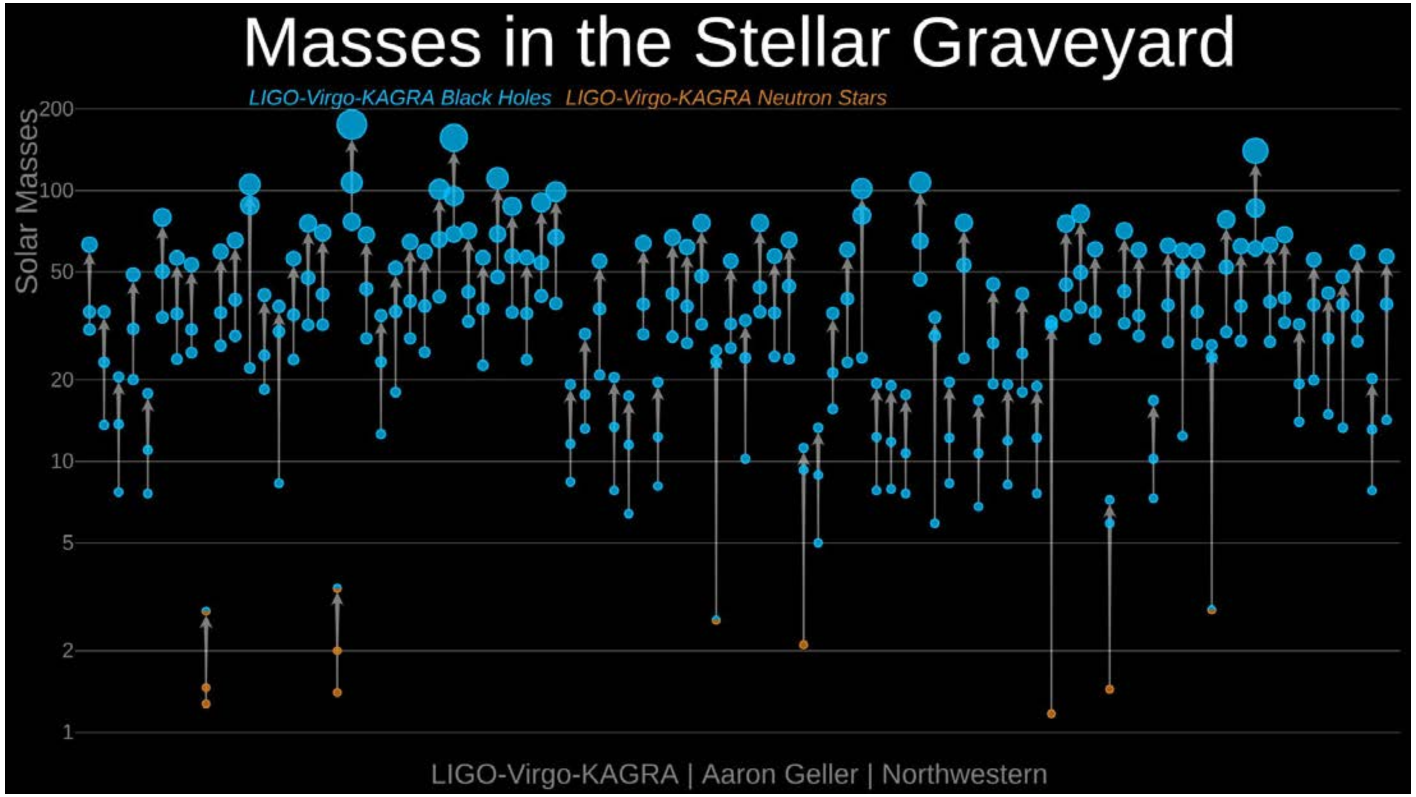


c.f., binary BH merger

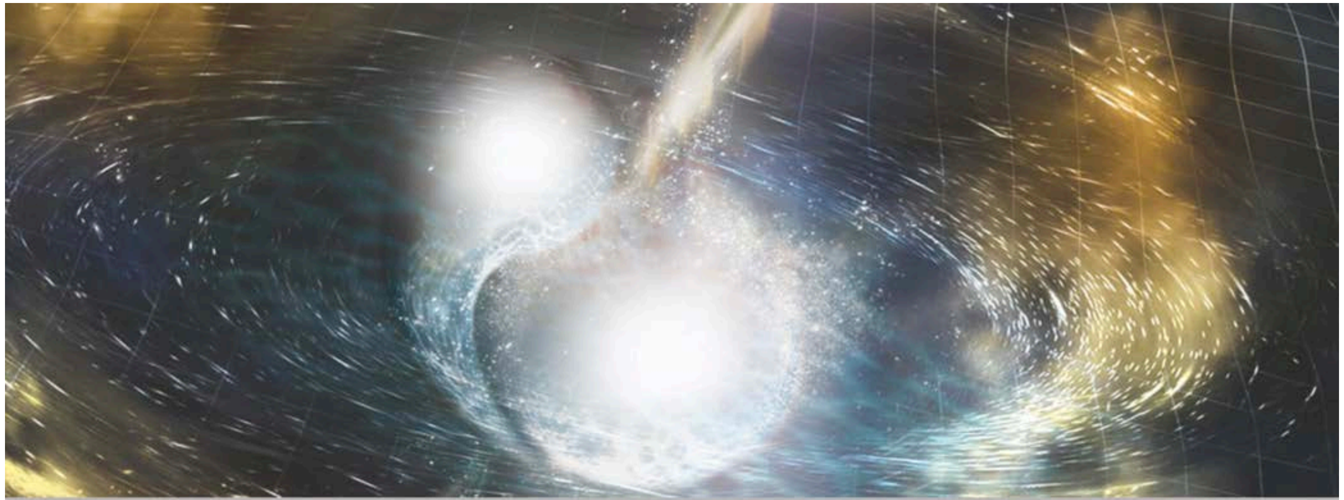
The first detection in 2015



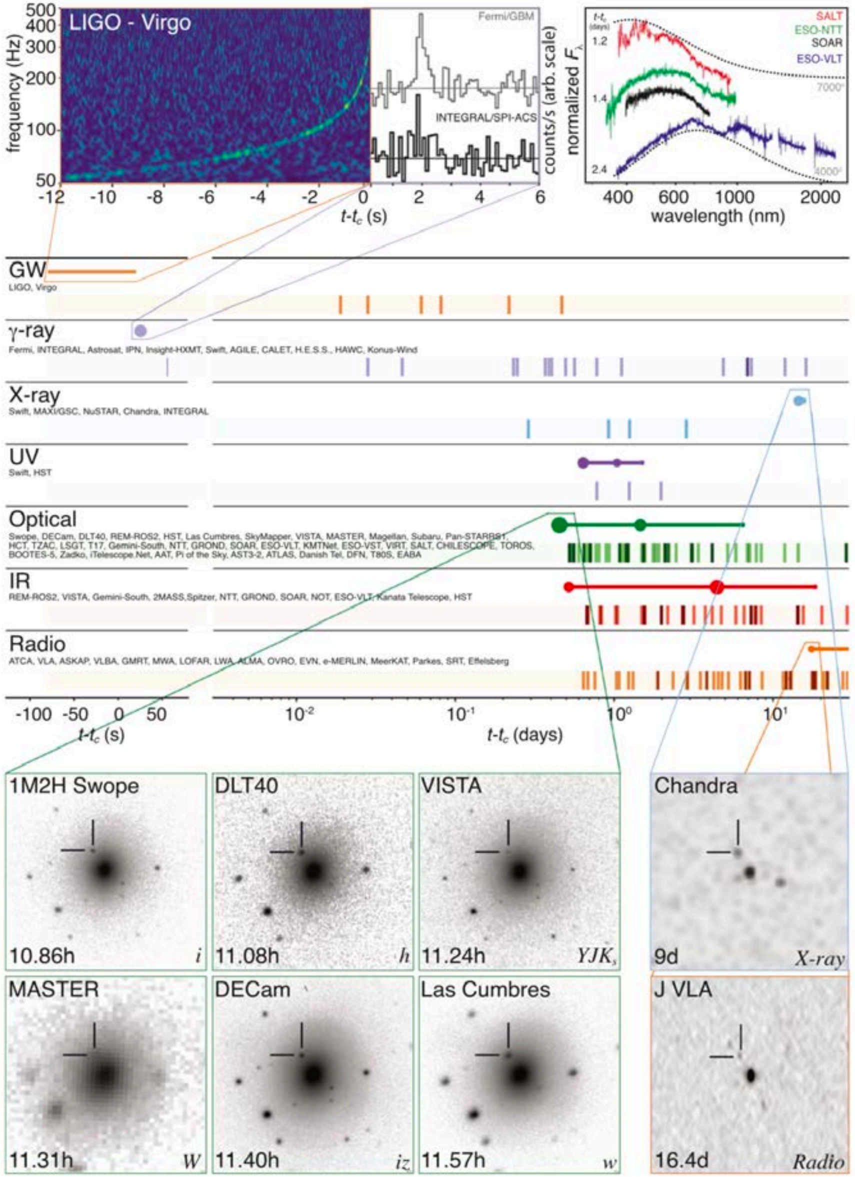
Now



c.f., detection of a binary NS merger (2017)

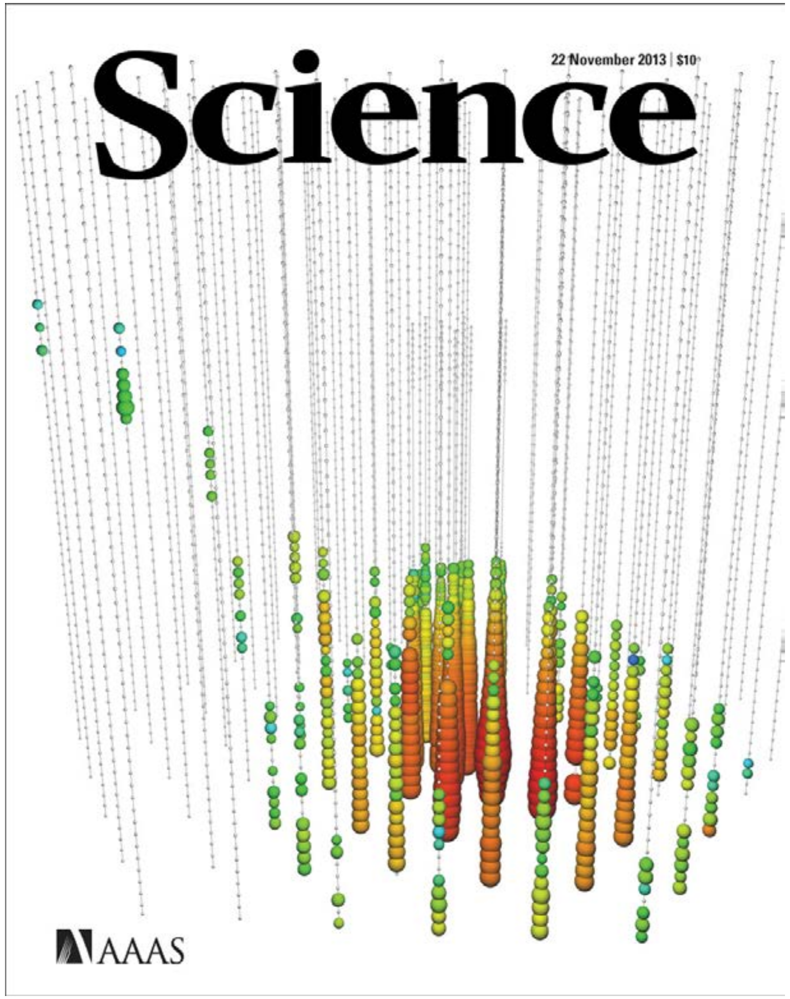


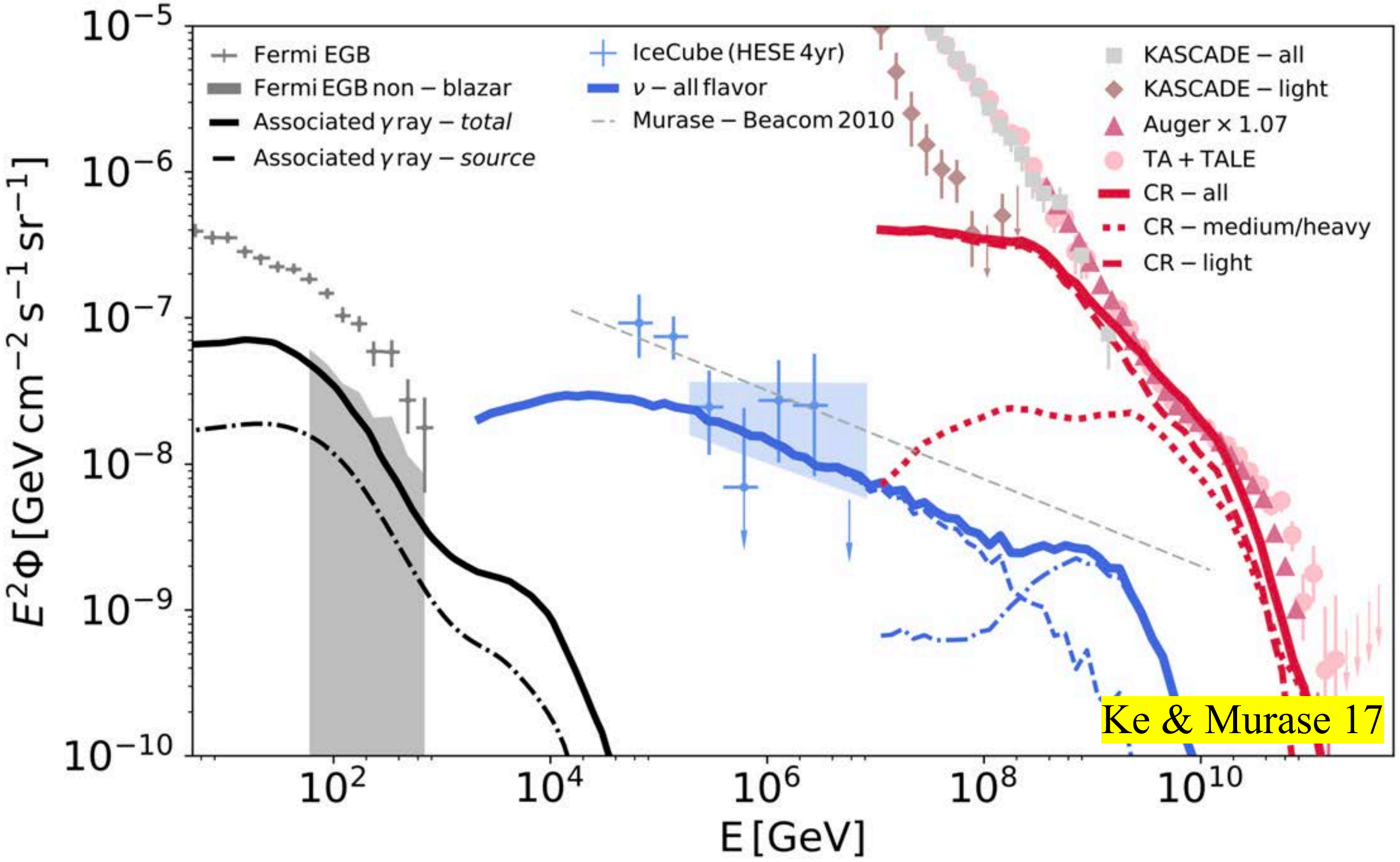
Cataclysmic Collision Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves. Swirling clouds of material ejected from the merging stars are also depicted. The clouds glow with visible and other wavelengths of light. Image credit: NSF/LIGO/Sonoma State University/A. Simonnet



c.f., high-energy neutrinos

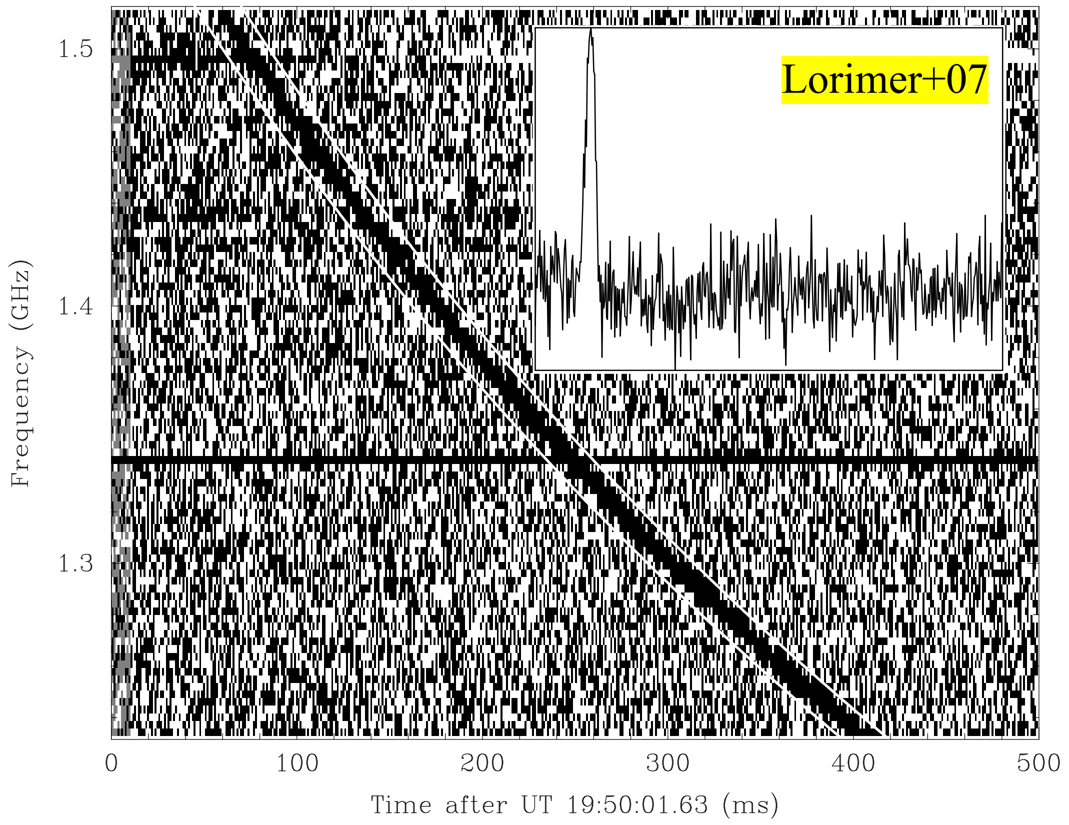
Discovered 2013



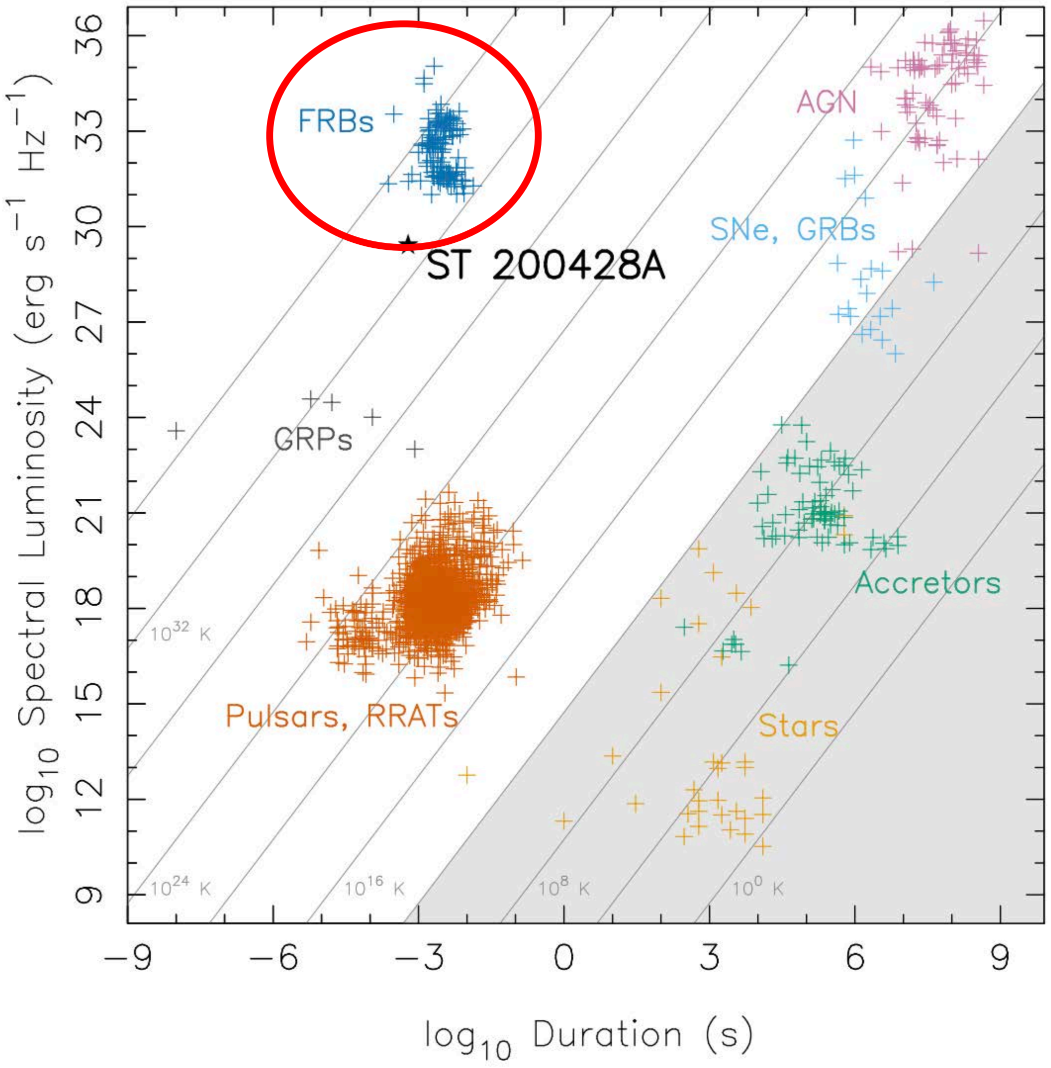


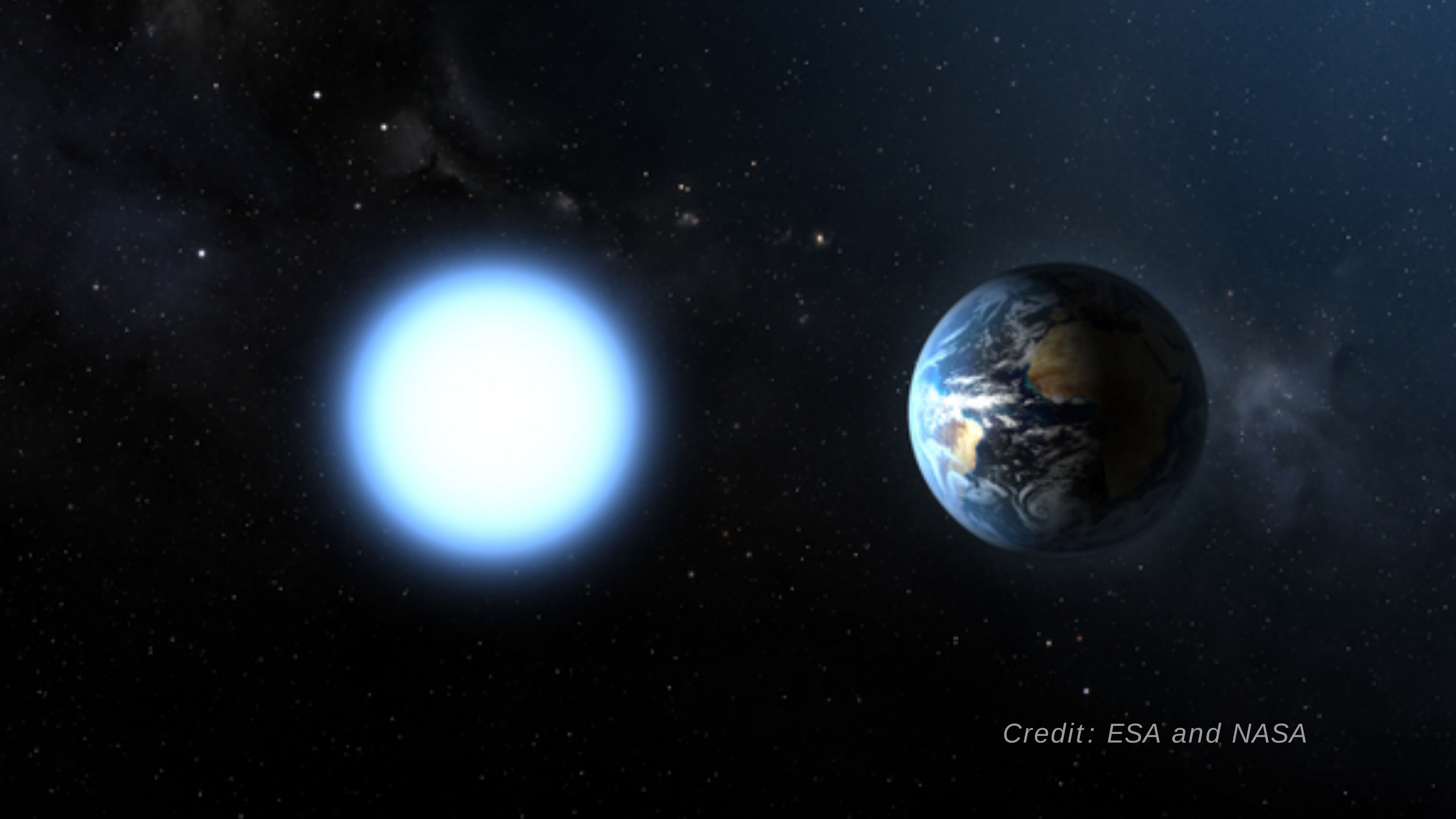
c.f., fast radio burst (FRB)

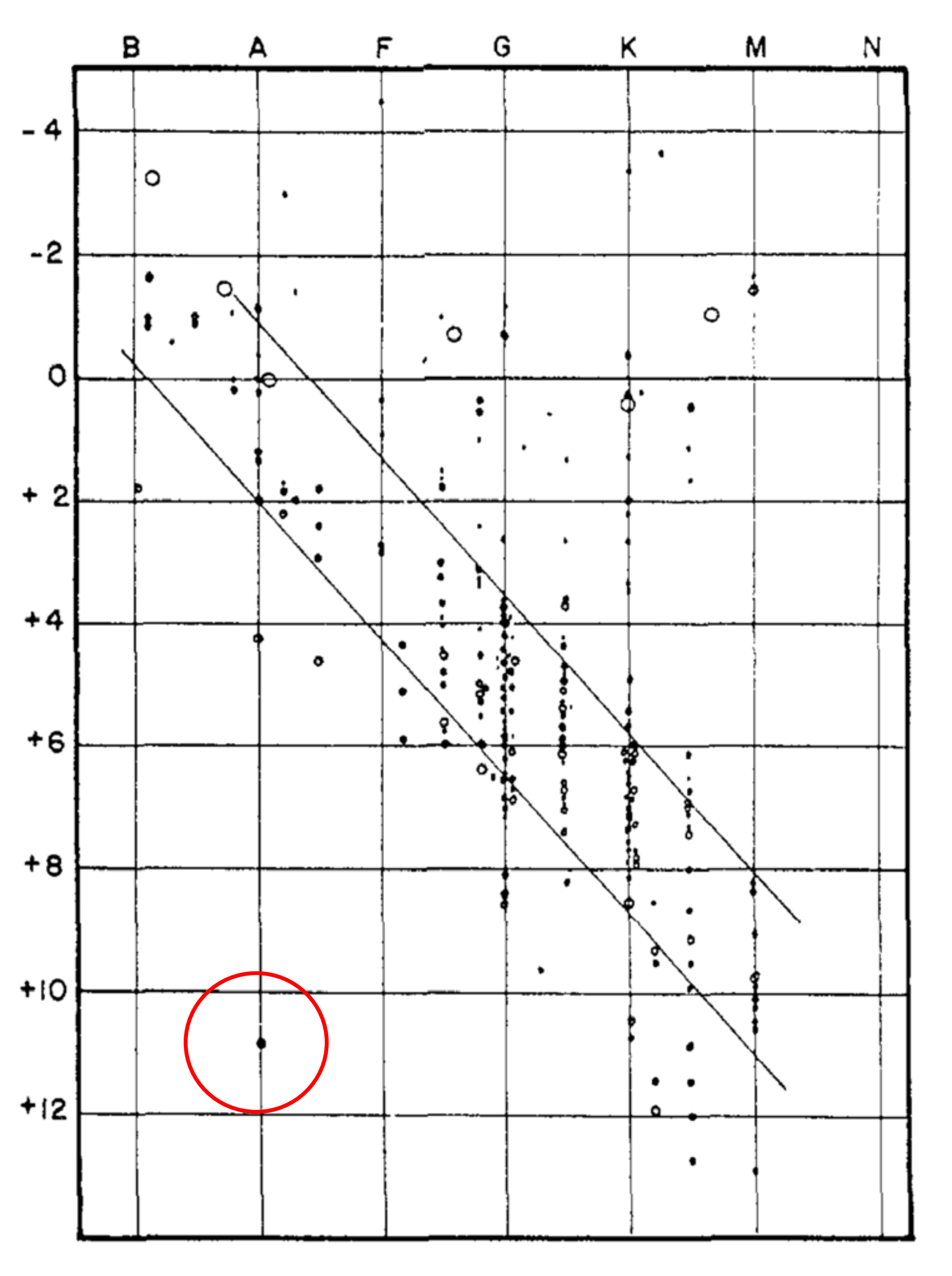
Discovered 2007, established ~2013



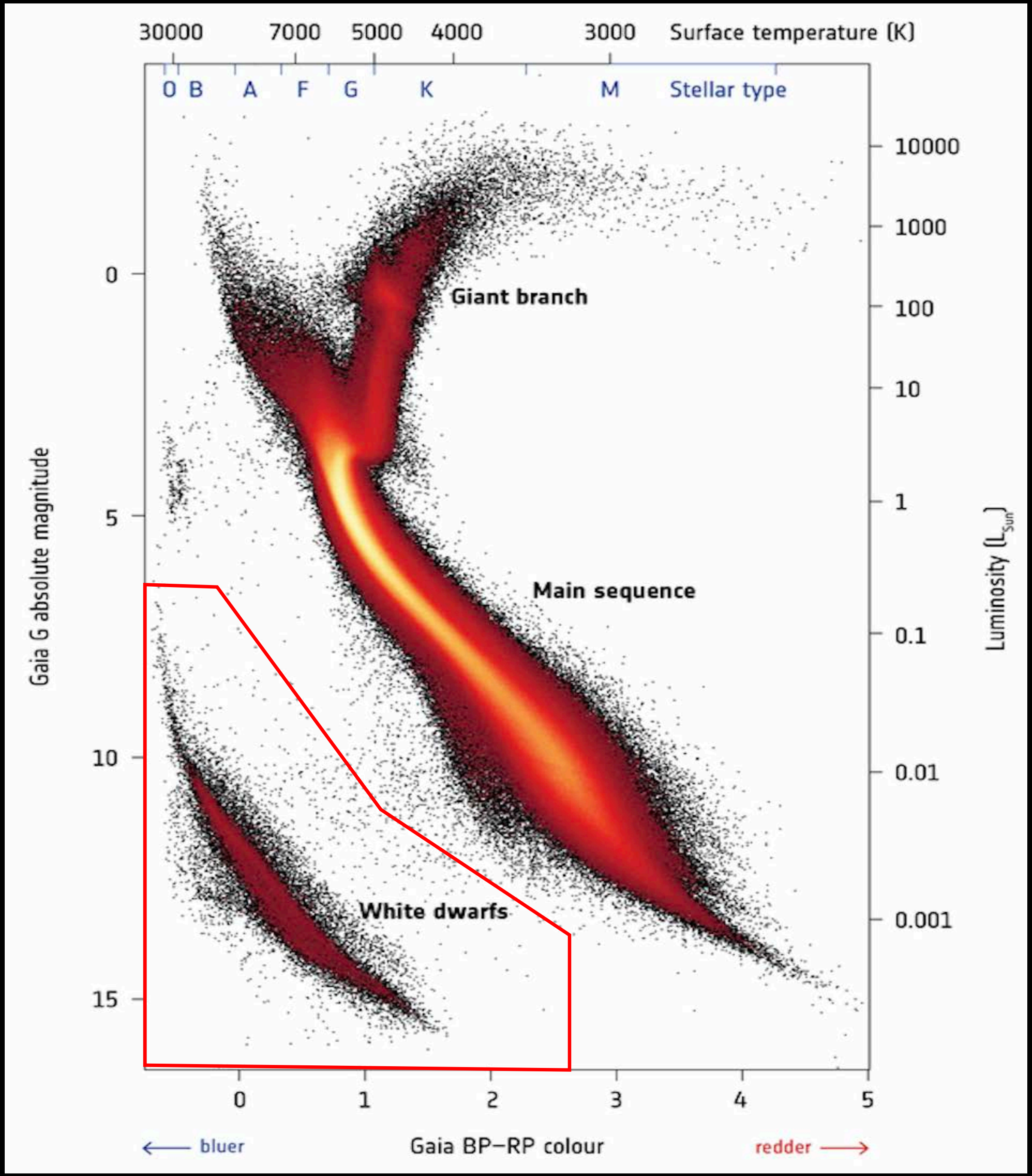
Now ~1000 events (a few 10 with known redshift)



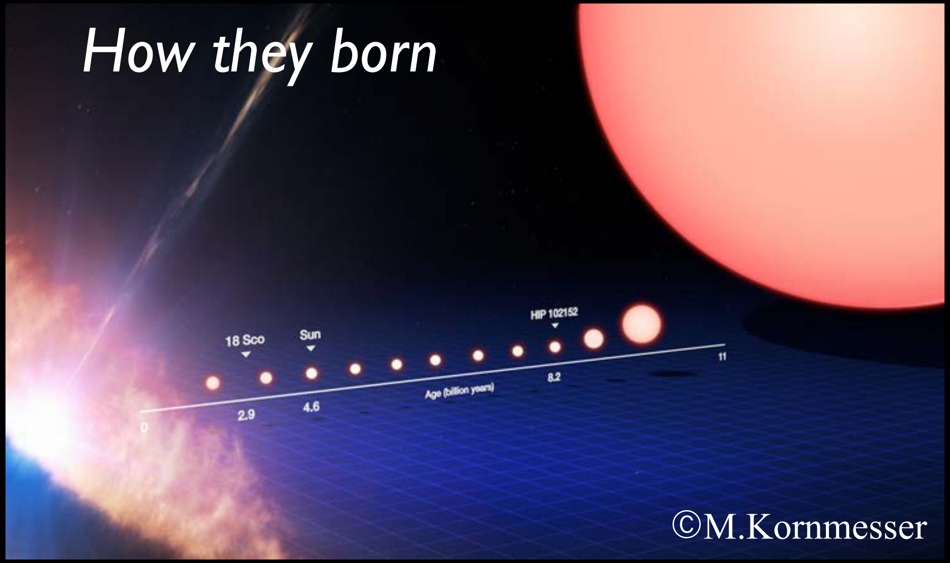

Credit: ESA and NASA

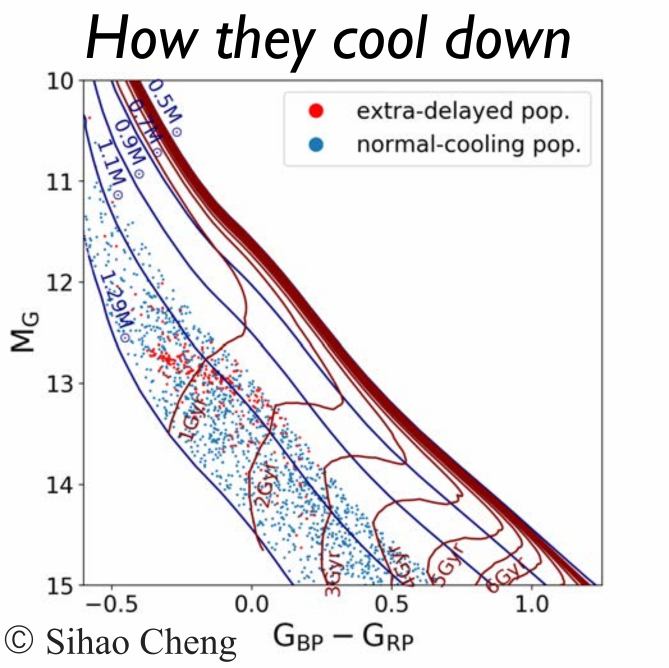


Russel 1914


30000
7000
5000
4000
3000
Surface temperature (K)
O B A F G K M Stellar type
10000
1000
100
10
1
0.1
0.01
0.001
Luminosity (L_{Sun})
0
5
10
15
Gaia G absolute magnitude
Giant branch
Main sequence
White dwarfs
0
1
2
3
4
5
← bluer
Gaia BP–RP colour
redder →

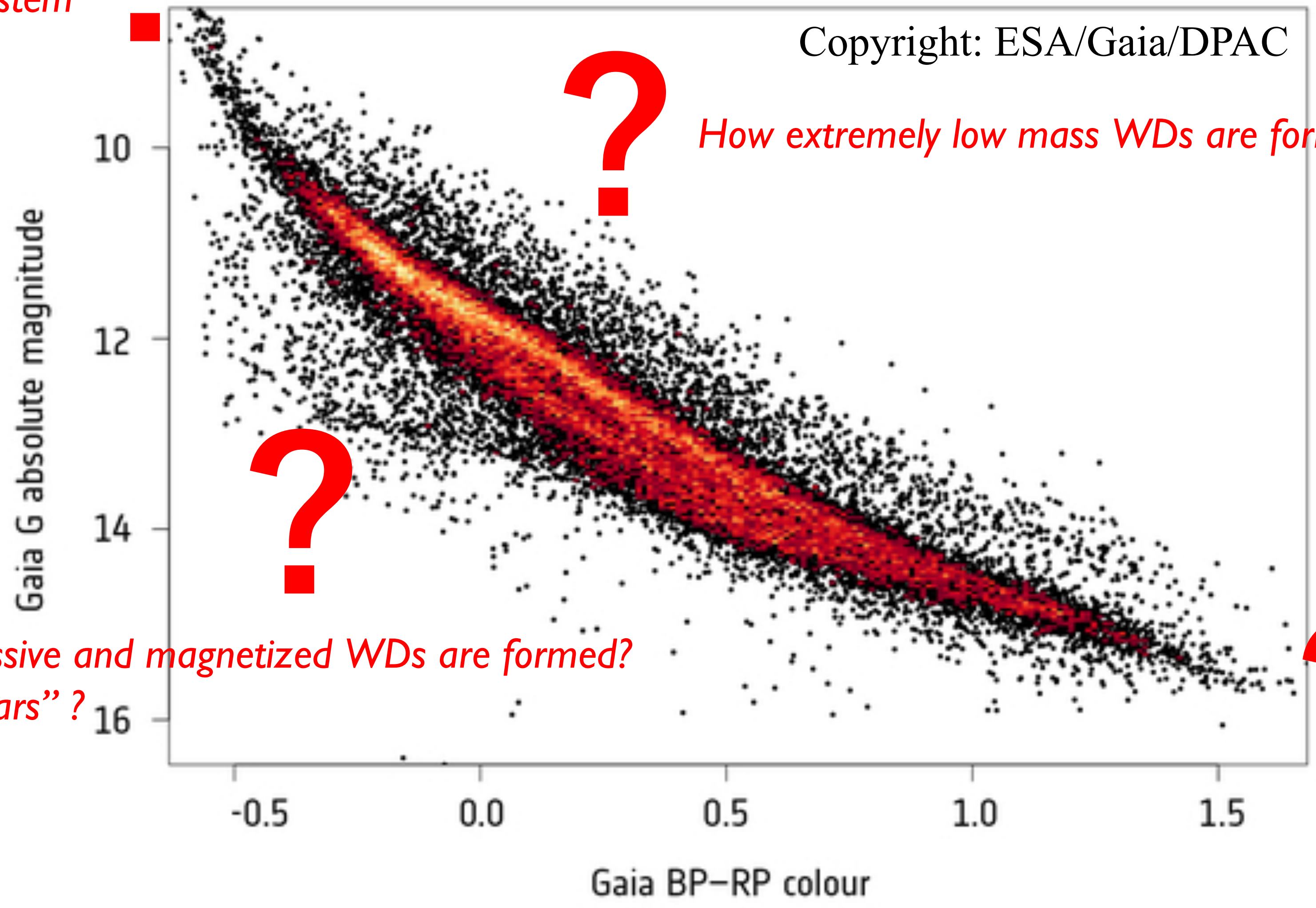
Known knowns about WDs





- **Known unknowns about WDs**

WD formation in general
Future of the solar system



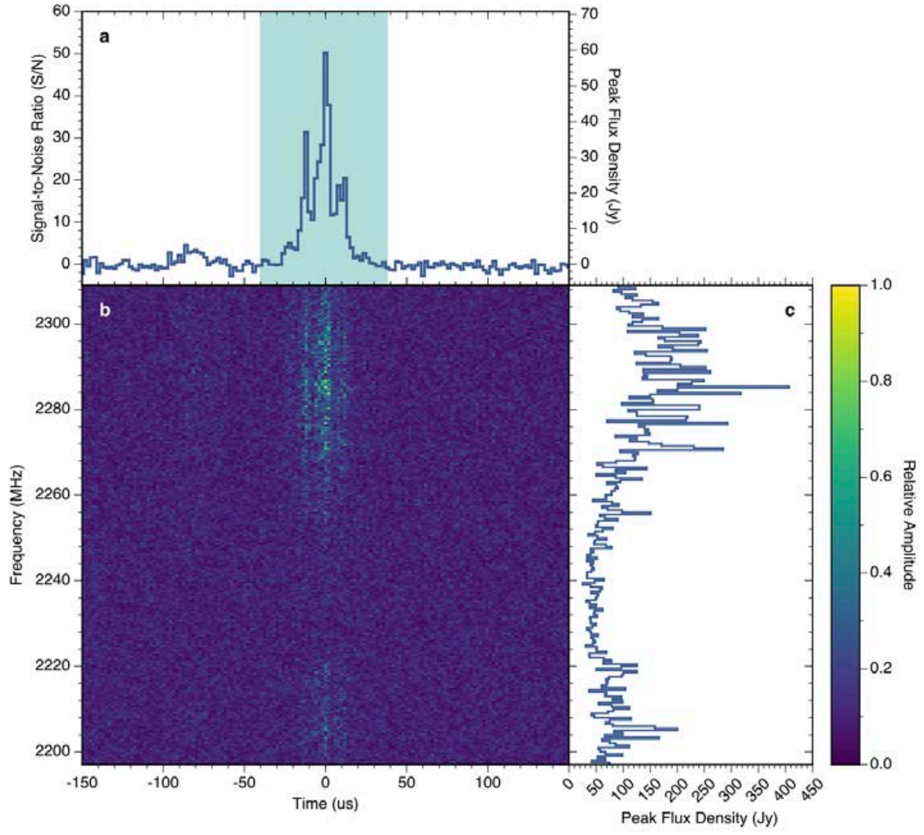
How extremely low mass WDs are formed?

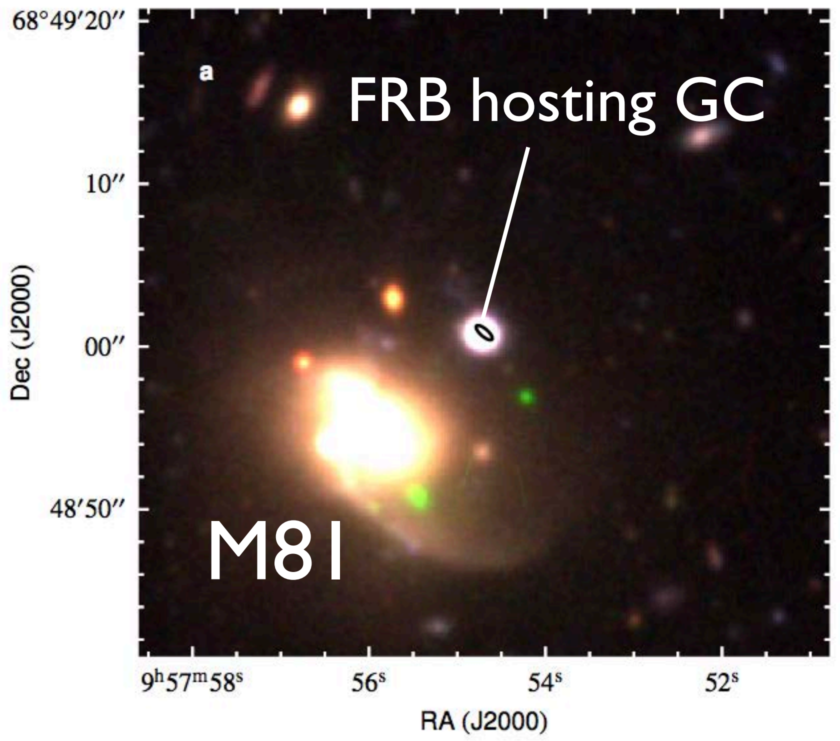
How the most massive and magnetized WDs are formed?
White dwarf "pulsars" ?

Oldest white dwarfs
How they are?
Where they are?

Super Chandrasekhar WDs collapse into NSs?

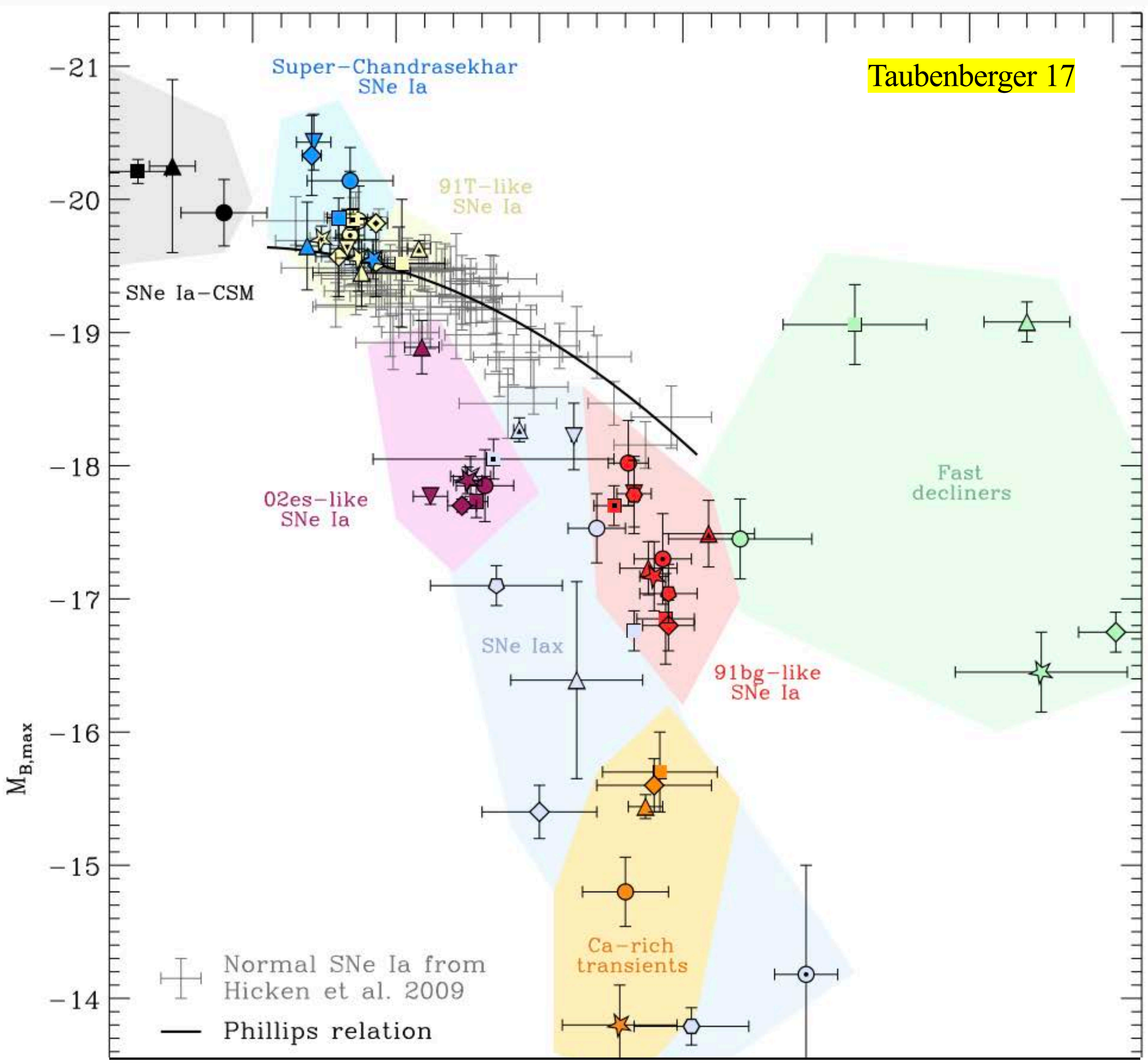
c.f., a repeating FRB source in a globular cluster (GC)



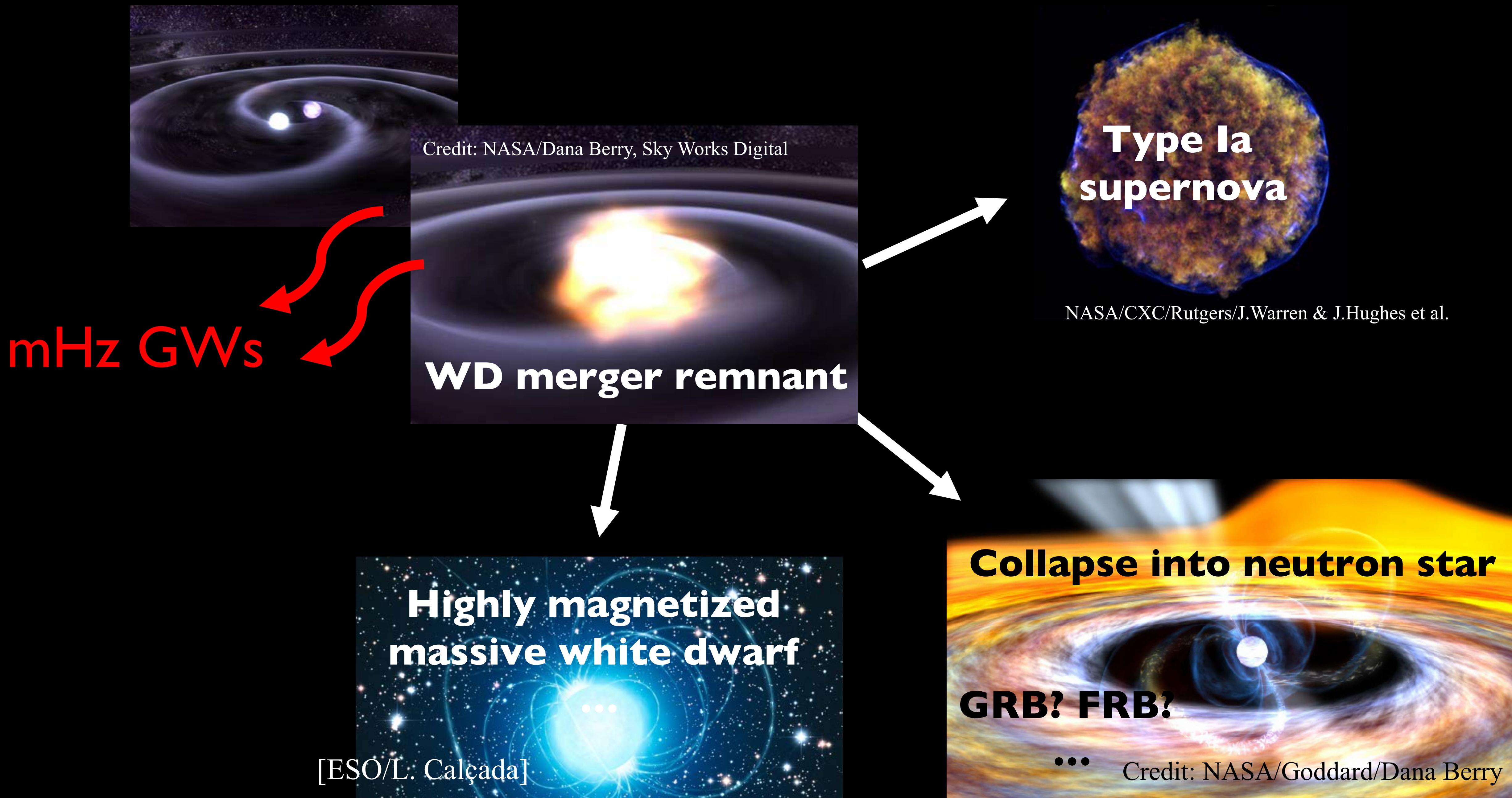


Kirsten et al. 21; Nimmo et al. 21;…

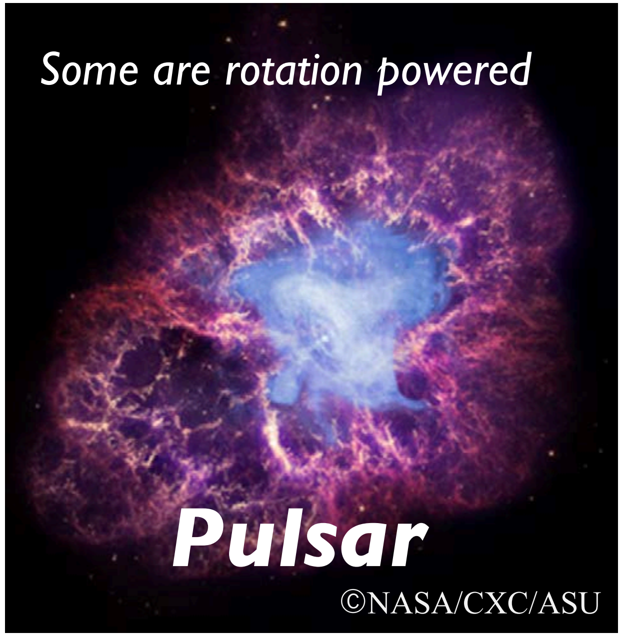
When and how are transients powered by radioactivity?

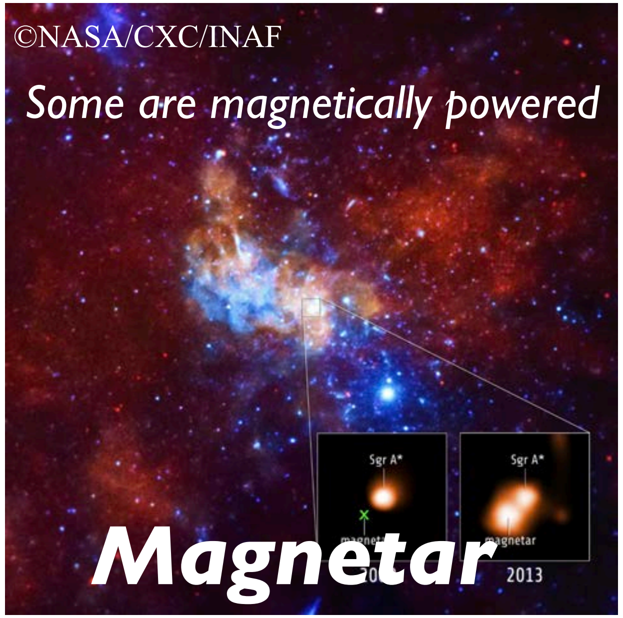


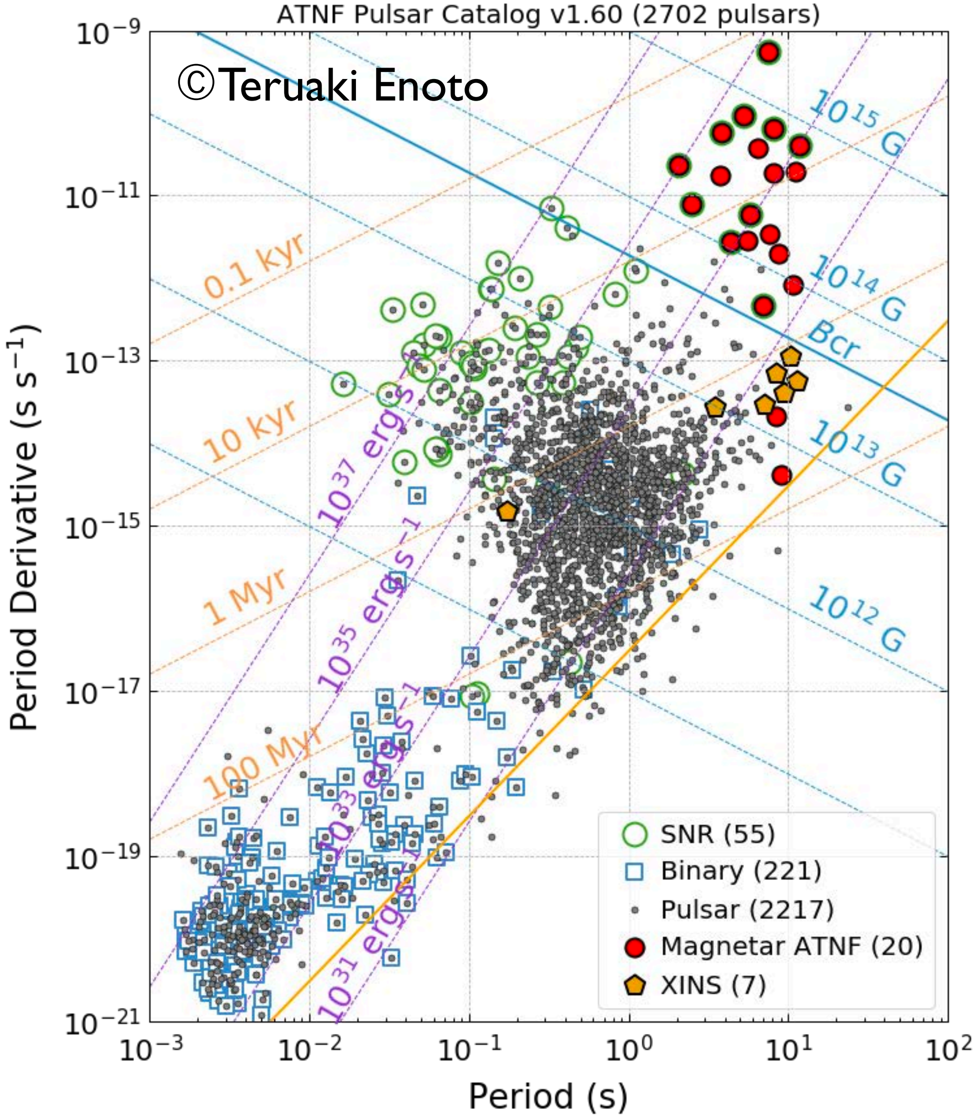
Binary WD mergers and their remnants



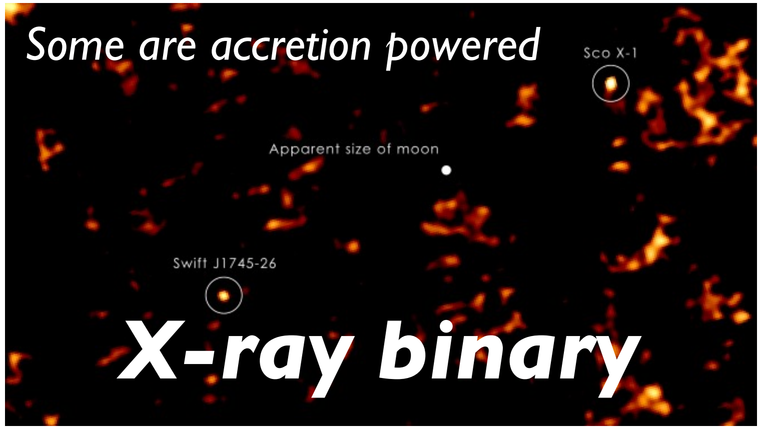
Known knowns about NSs







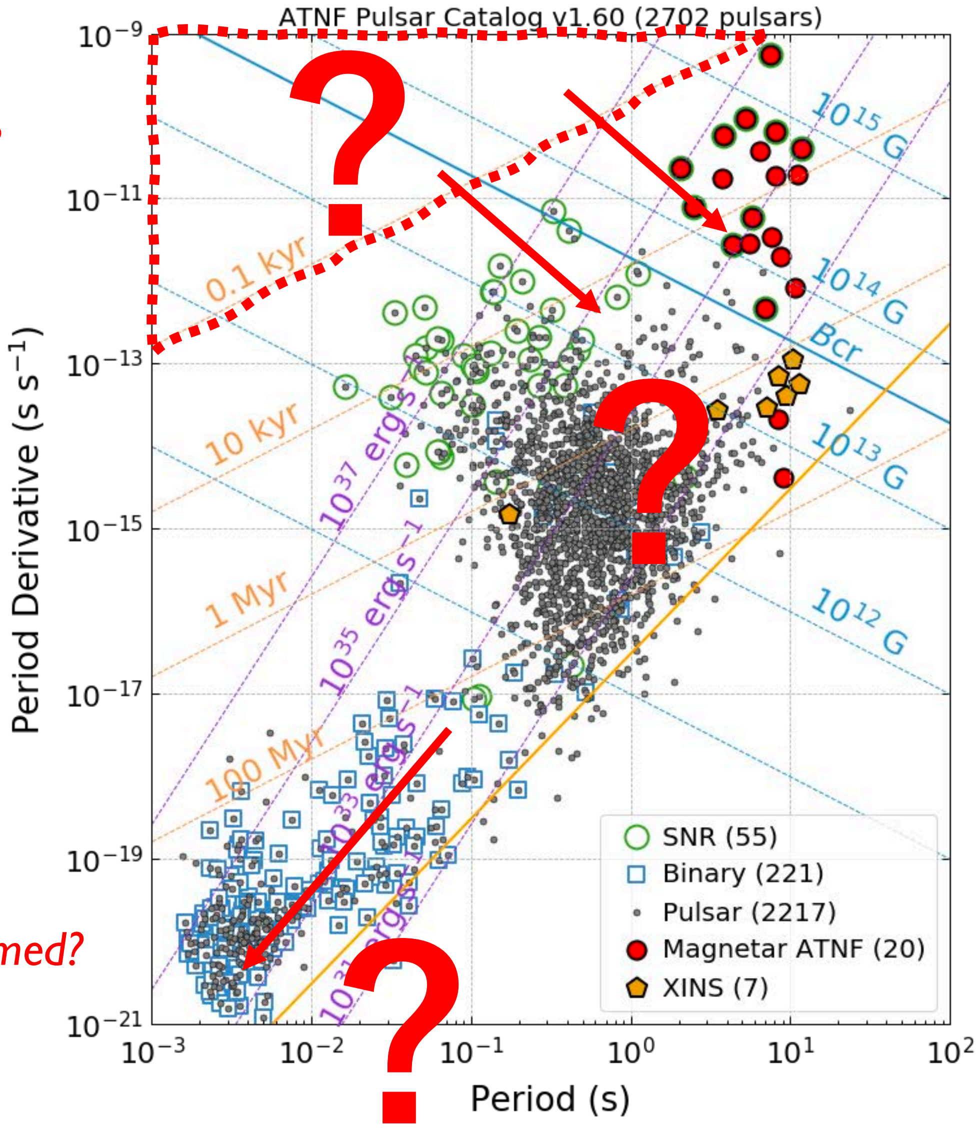
©NASA/CXC/DSS



©NASA/Goddard Space Flight Center

• **Known unknowns about NSs**

How and when NSs are formed?
Supernova explosion mechanism?
How the trifurcation of pulsar/magentar/CCO occurs?



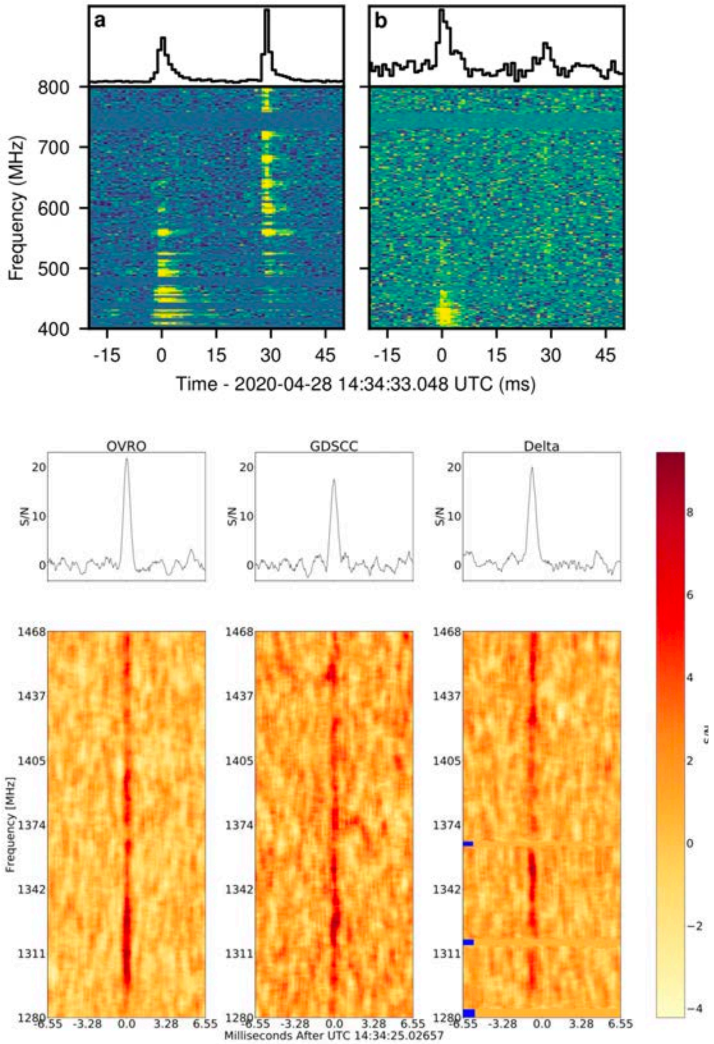
Particle acceleration & emission mechanism

- *Coherent radio emission?*
- *Magnetar flare?*
- *When an NS can be an FRB source?*
- *NSs are pevatrons?*

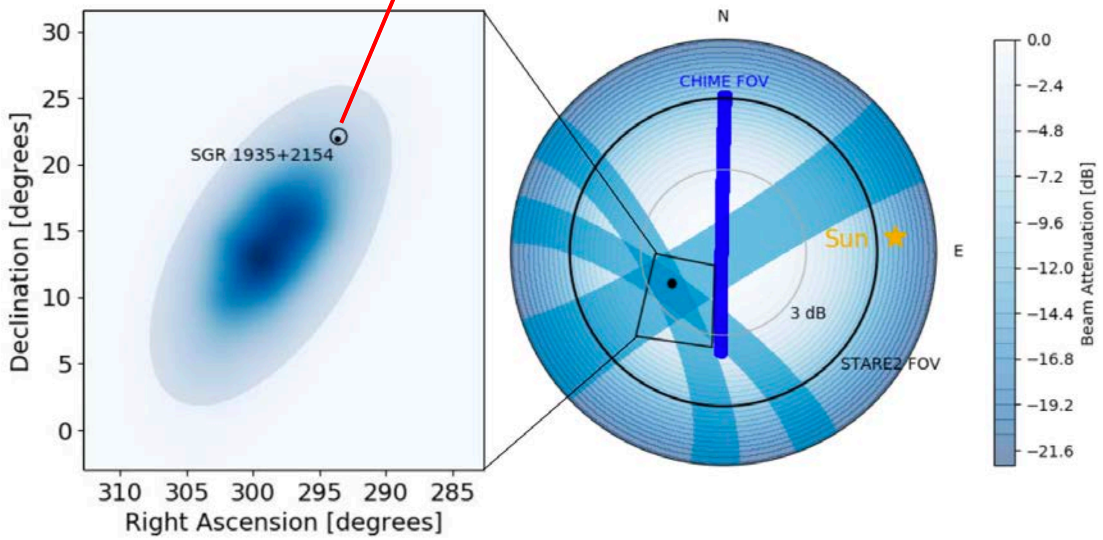
How and when binary NSs are formed?
Ultraluminous X-ray pulsars?
Short gamma-ray bursts?

FRBs from a Galactic magnetar

FRB200428 from SGR 1935+2154 detected by CHIME (~kJy @ 400-800 MHz) and STARE2 (~Mega Jy @ 1.3GHz)



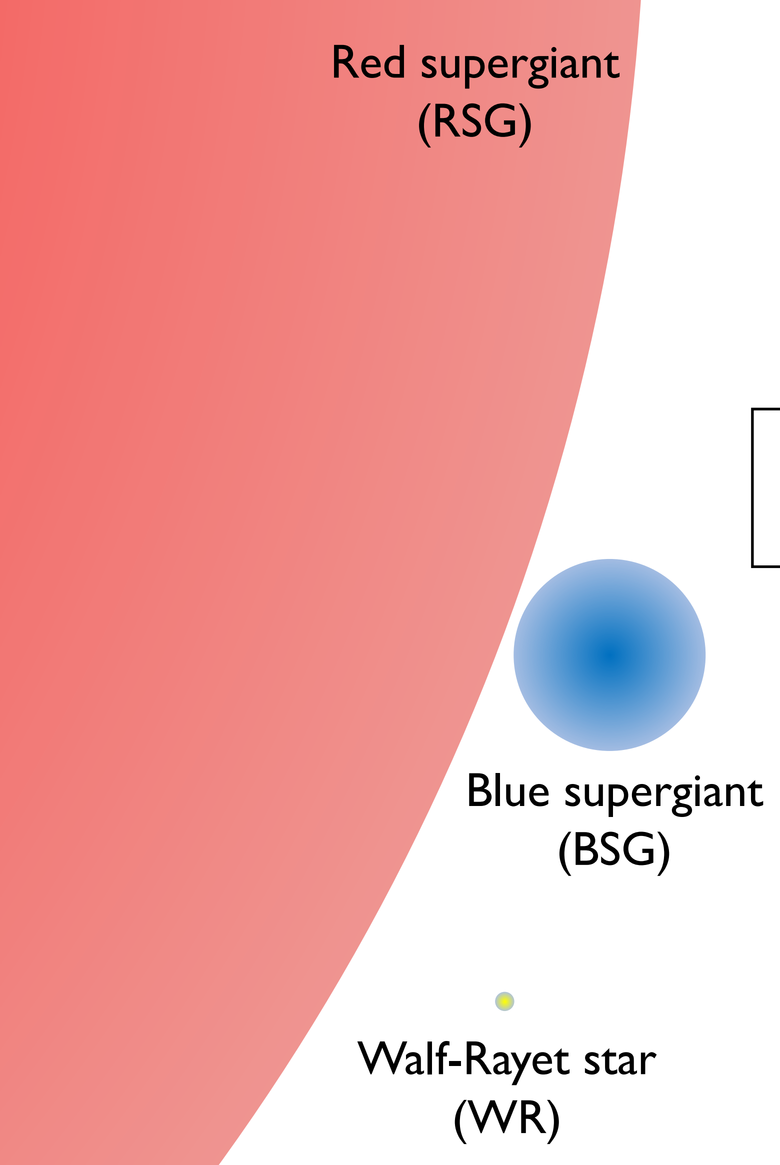
$$P = 3.25\,\mathrm{s}$$
$$\dot{P} = 1.4 \times 10^{-11}\,\mathrm{s \cdot s^{-1}}$$
$$B_{\mathrm{d}} = 2.2 \times 10^{14}\,\mathrm{G}$$



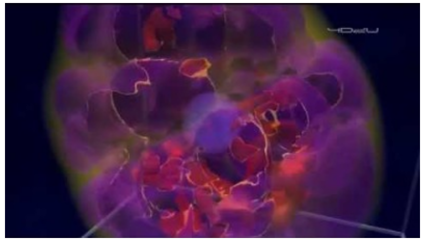
The CHIME/FRB Collaboration et al. 20; Bochenek et al.20

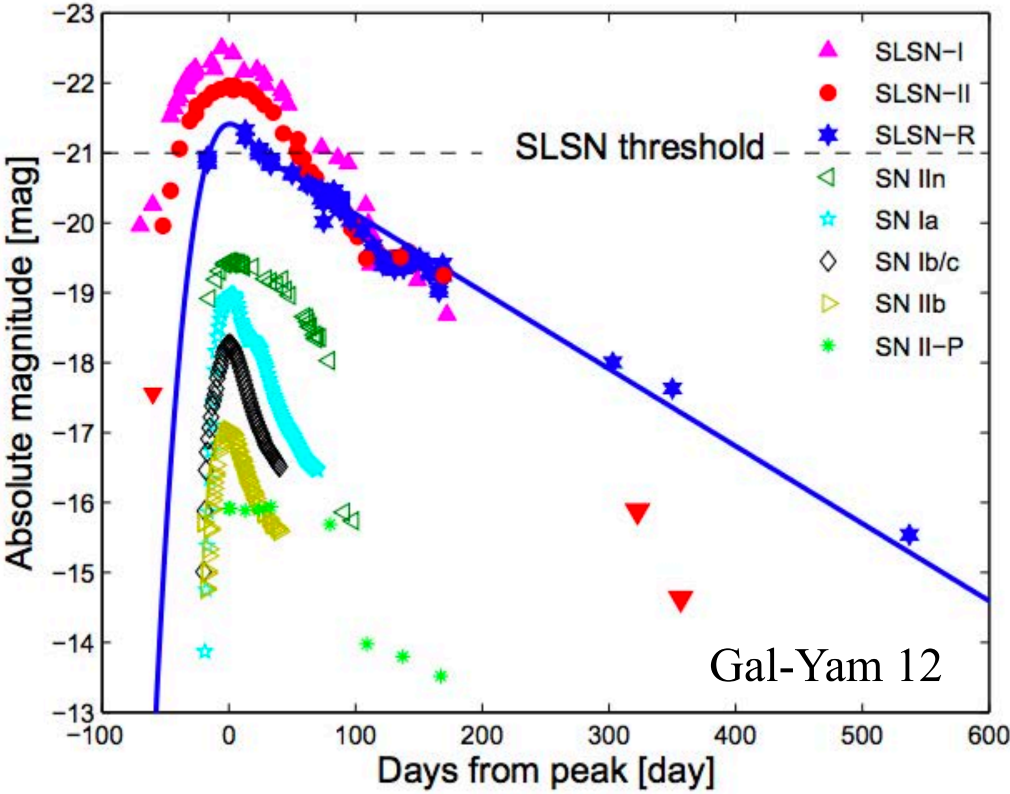
Won’t miss the next Galactic event!

Diversity in NS formation and associated transients



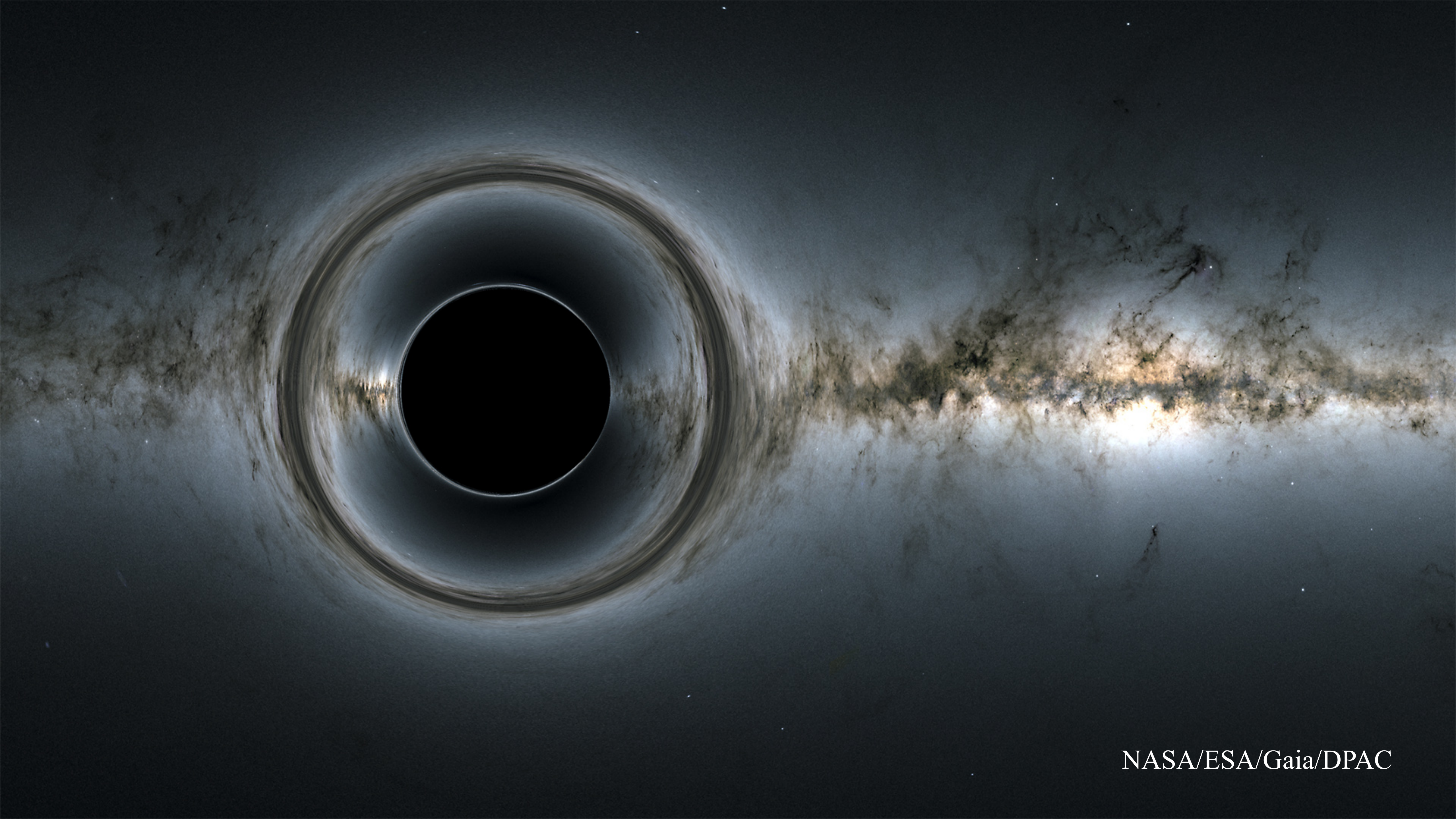
©4D2U





rotation, magnetic field,
pre-collapse mass eruption,
single or binary, …

Won't miss especially the "on-axis" event!

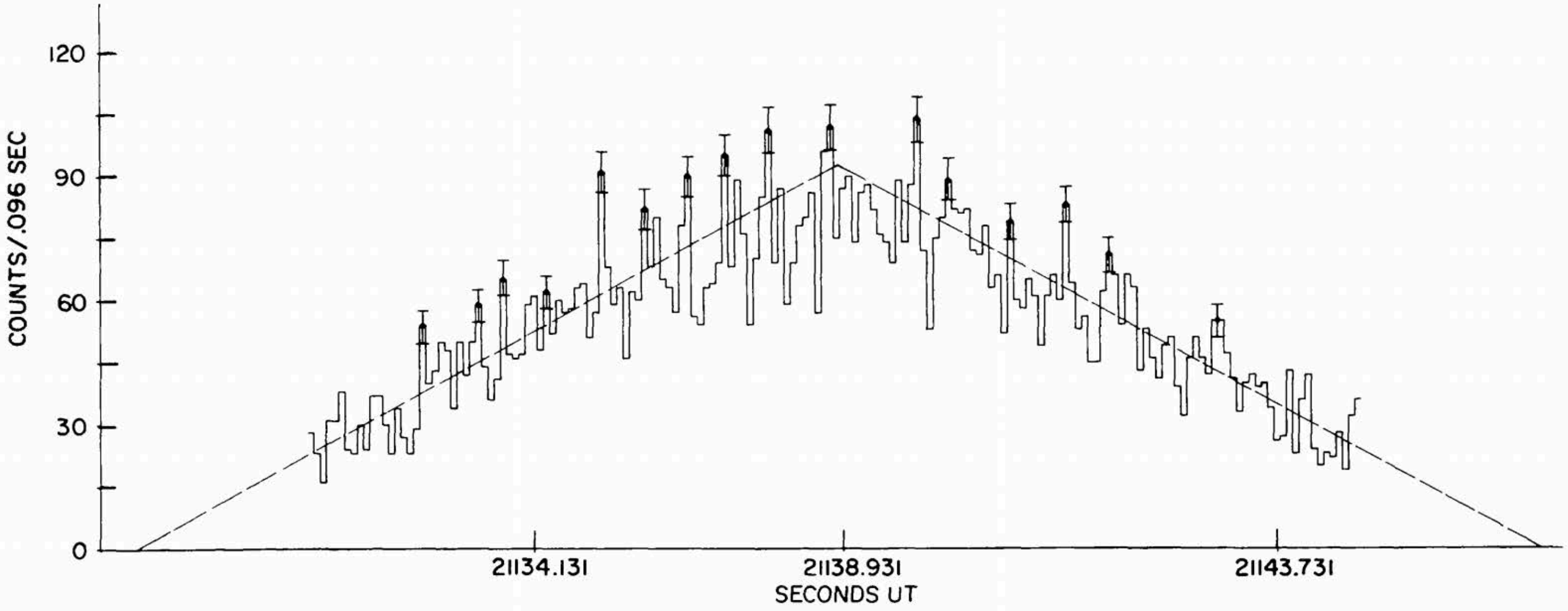

NASA/ESA/Gaia/DPAC

X-RAY PULSATIONS FROM CYGNUS X-1 OBSERVED FROM *UHURU*

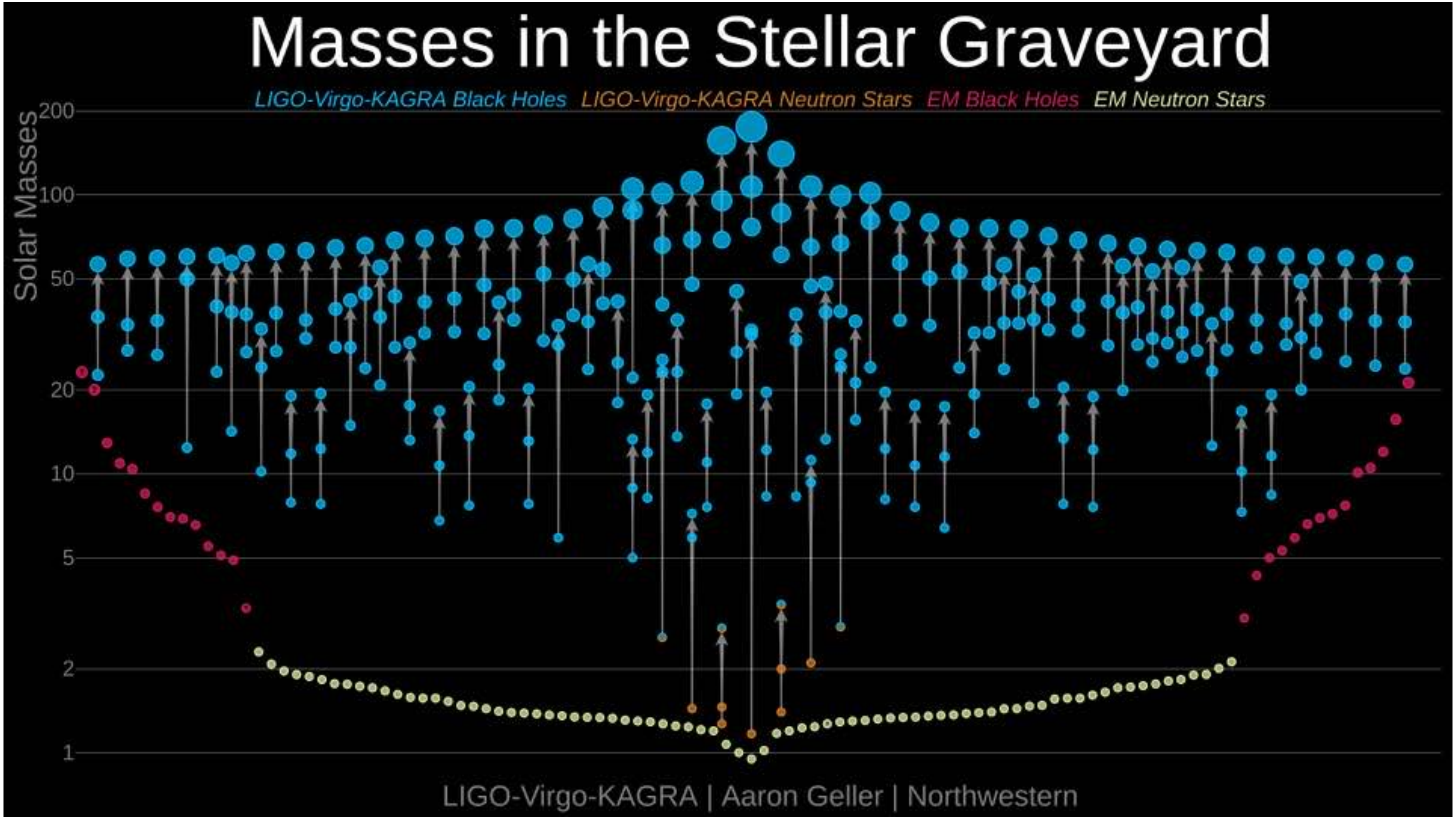
M. Oda,* P. Gorenstein, H. Gursky, E. Kellogg,
E. Schreier, H. Tananbaum, and R. Giacconi
American Science and Engineering, Inc., Cambridge, Mass. 02142
Received 1971 March 22

ABSTRACT

We have observed from *Uhuru* large-amplitude X-ray pulsations from Cyg X-1, which occur several times a second with a duration of less than a fraction of a second. The amplitude of the pulsations at times exceeds 25 percent of the average source intensity. The pulsations do not occur at random. Although we cannot within our data uniquely determine their period, we find that the data are consistent with a period of 73 milliseconds. In addition to fine-scale time variations, the average X-ray intensity from the source changes by factors of 2 over times of the order of 10^3 seconds. We conclude that we have discovered a pulsating X-ray star, whose characteristics are quite different from those of NP 0532.



Known knowns about BHs



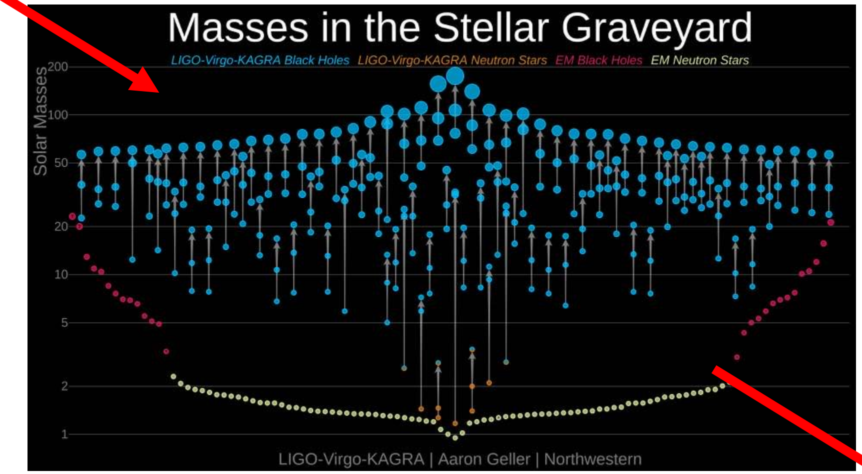
- **Known unknowns about BH**

?

How and when (binary) BHs are formed?
Associated with energetic transients?

?

Mass and spin distribution?
Ultraluminous X-ray sources = intermediate BH?



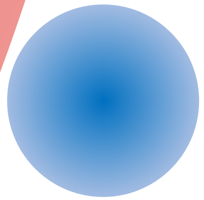
?

"Floating" BHs in the Galaxy
How are they?
Where they are?

time

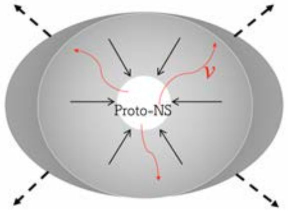
Diversity in BH formation and associated transients

Red supergiant
(RSG)

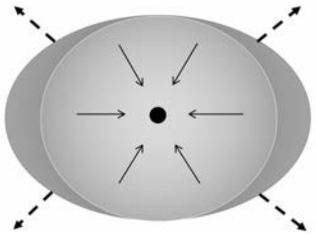


Blue supergiant
(BSG)

Walf-Rayet star
(WR)

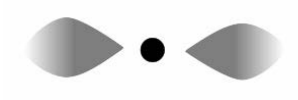


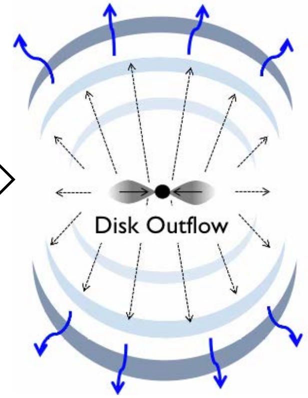
slow rotation



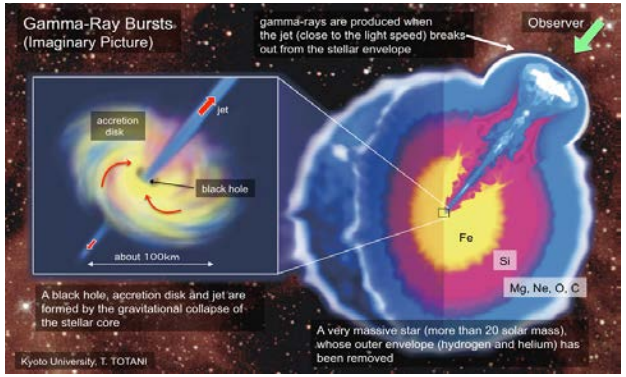
Weak explosion

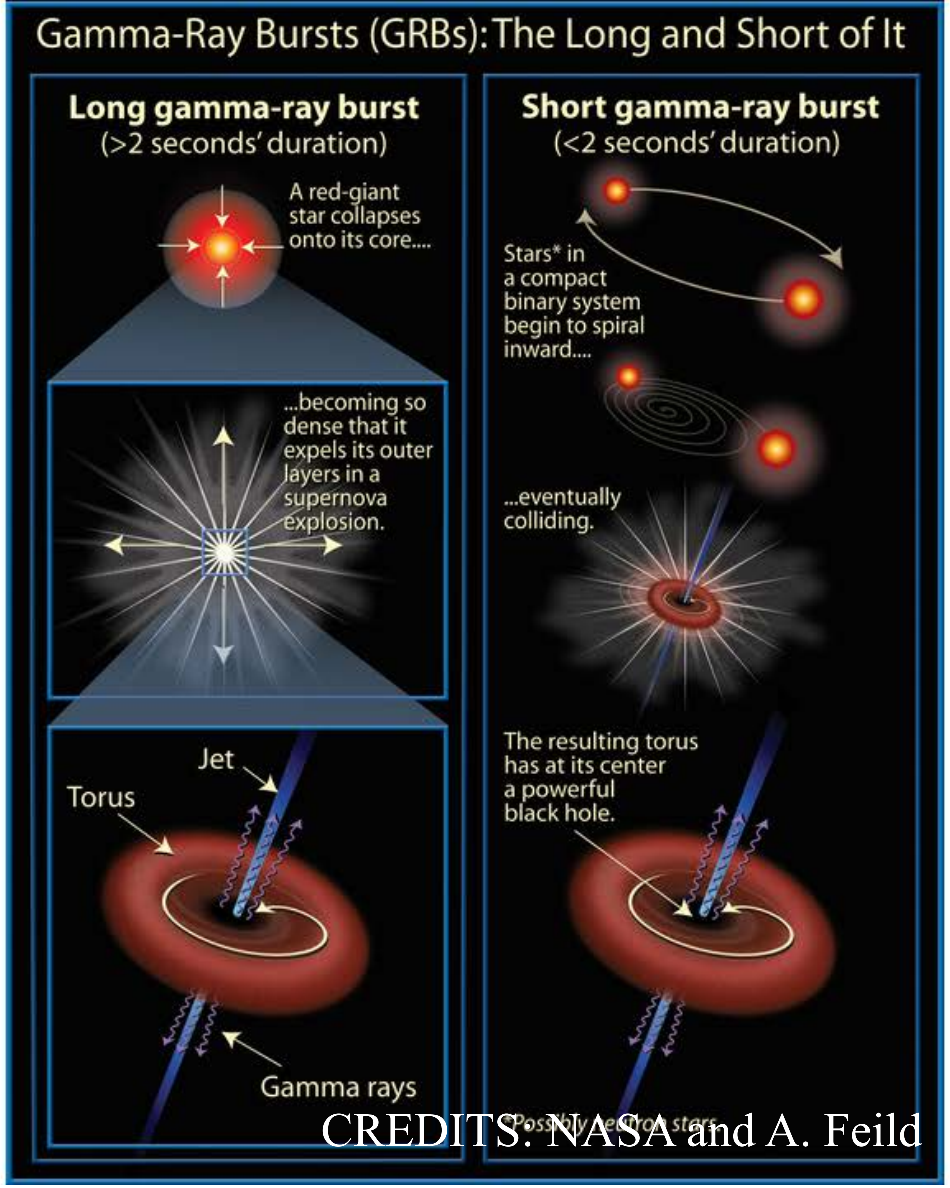
Intermediate rotation



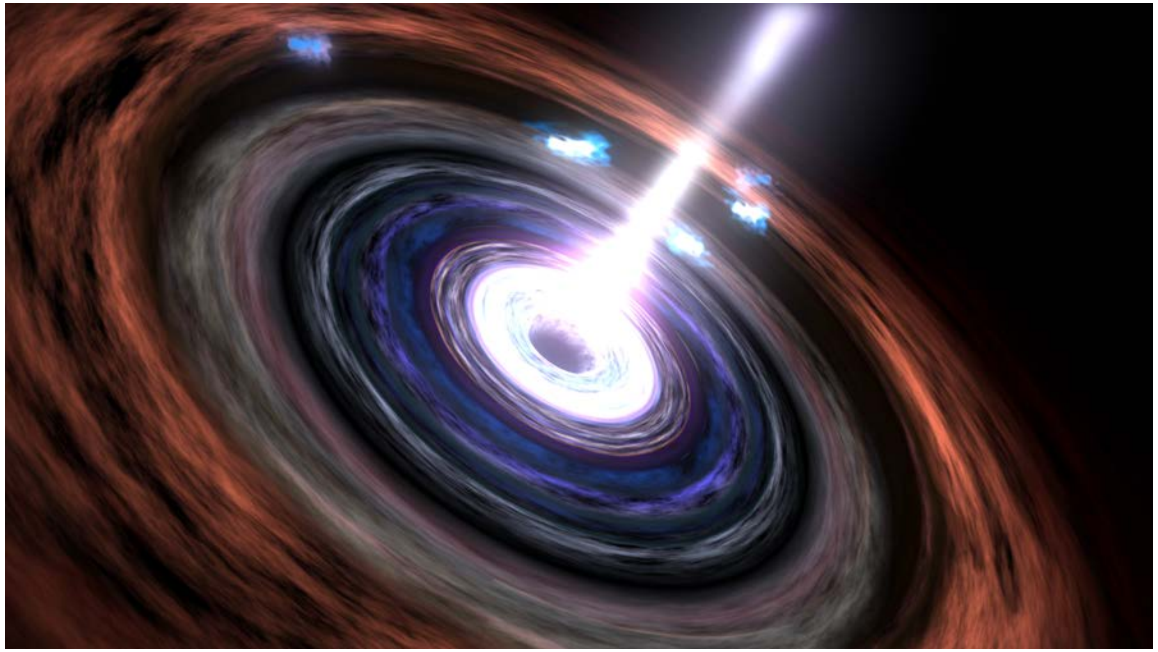


Fast rotation





CREDITS: NASA and A. Feild


NASA/Goddard Space Flight Center Conceptual Image Lab

How can be the jet launched and accelerated up to 99.99% of the speed of light?
How can be the energy dissipated to produce the most luminous emission in the Universe?

Diversity and universality of compact objects

Gravitational energy

↓

- Rotation
- Magnetic field

…

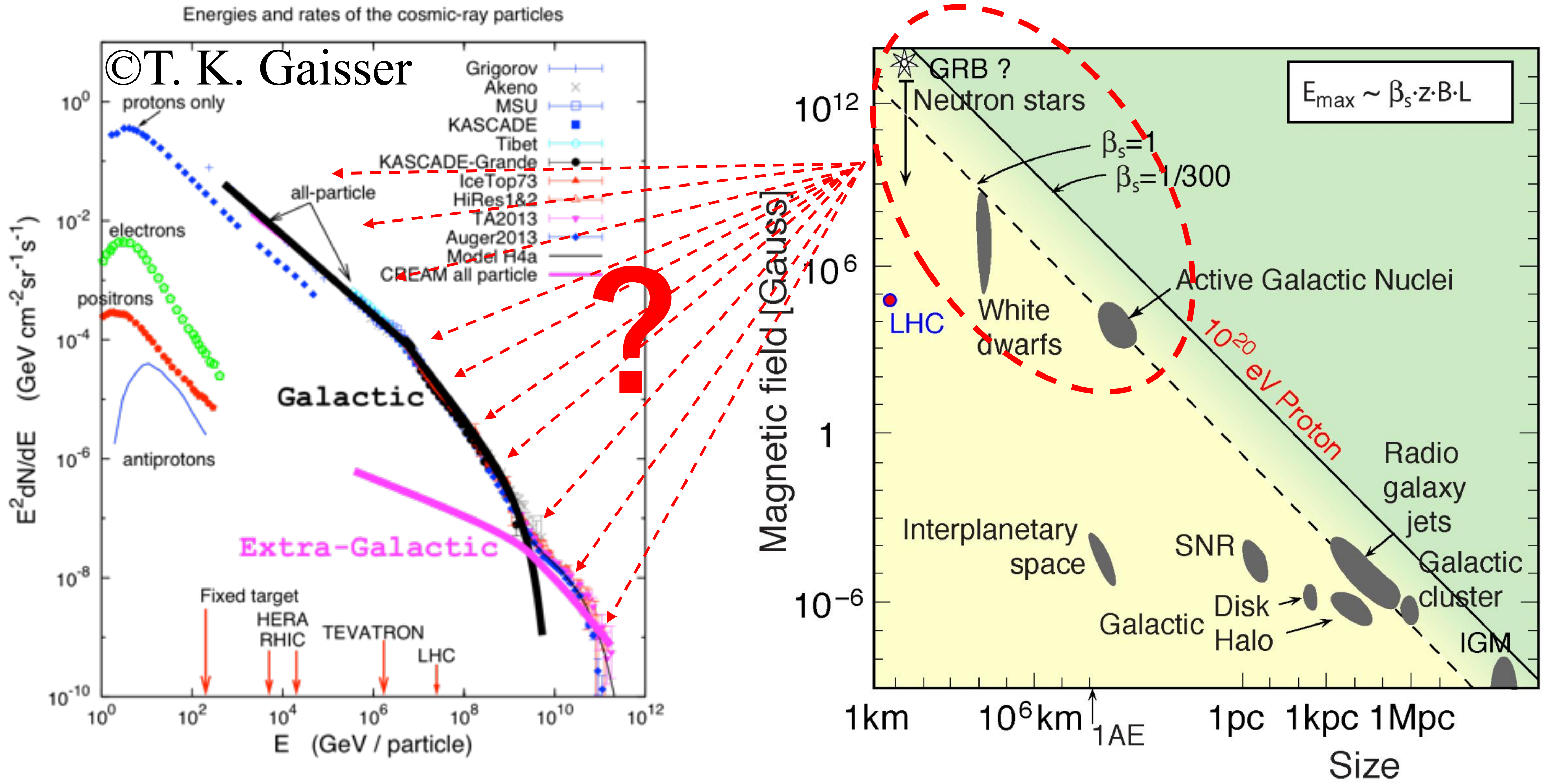
↓

- Outflow/jet
- Shock
- Reconnection

…

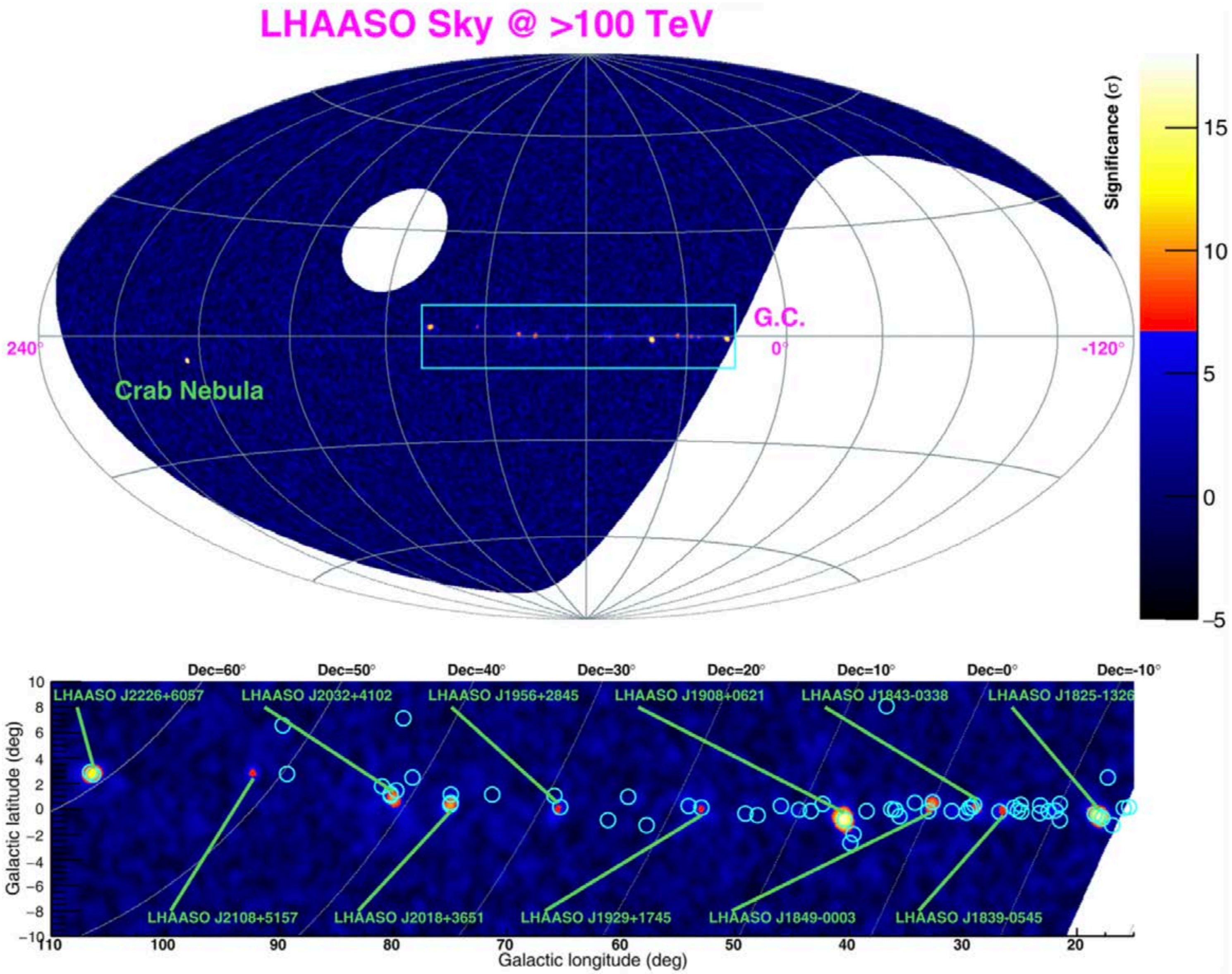
Multi-messenger signal

Compact objects as cosmic-ray accelerators

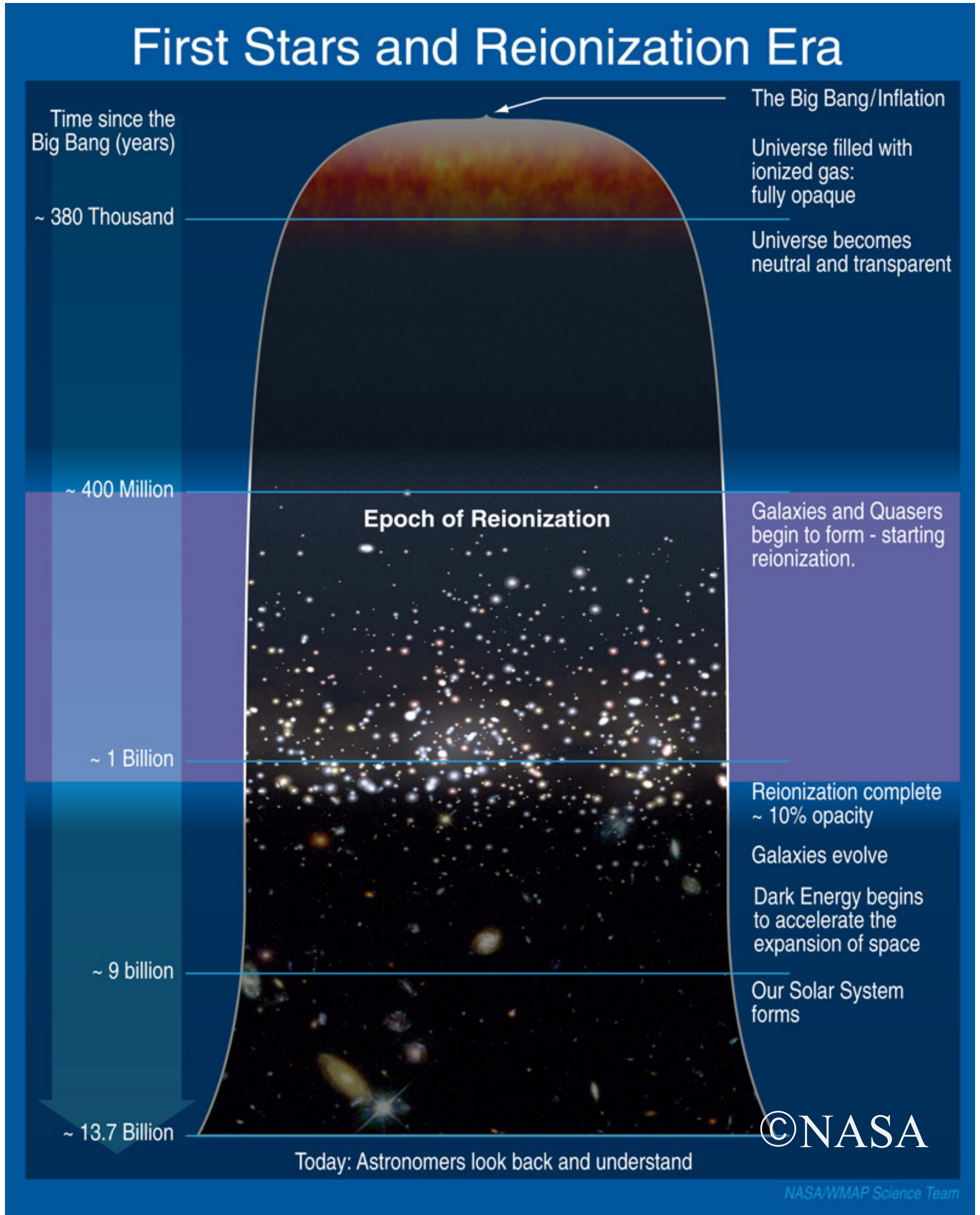


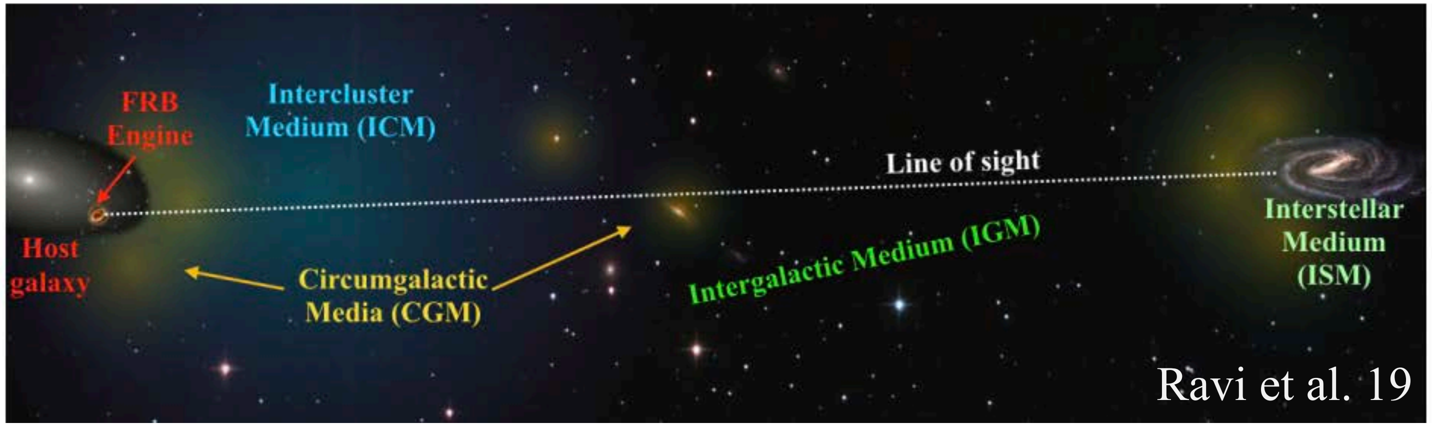
Young Pulsars are Pevatrons?

Cao et al.21



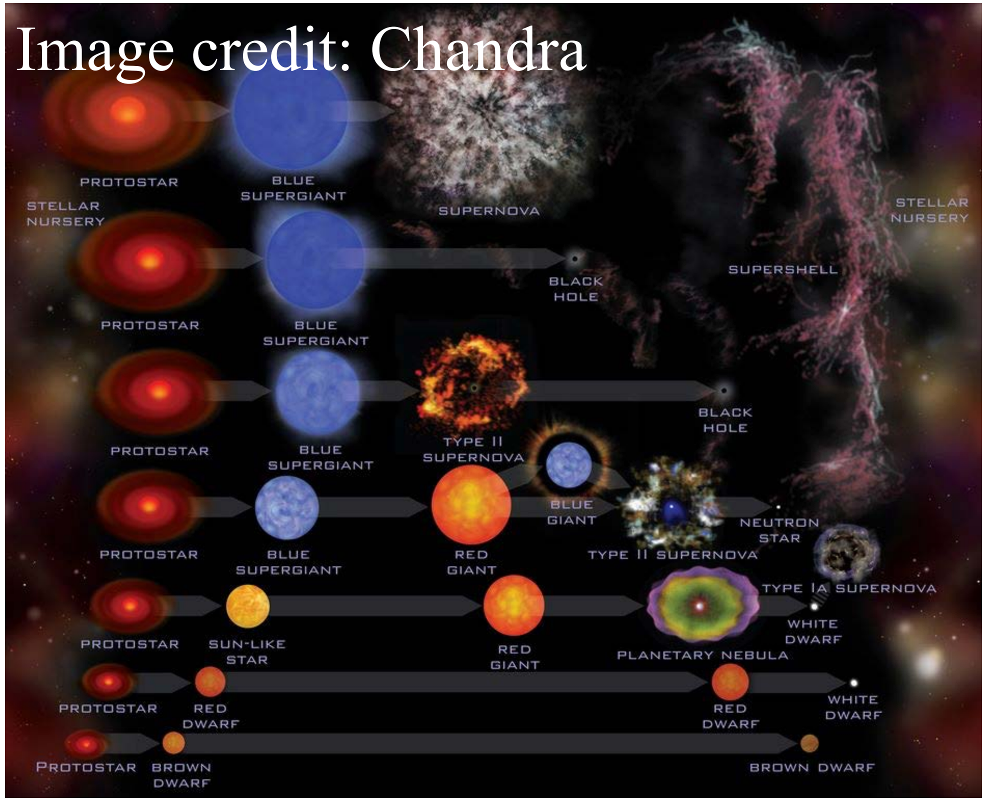
SN/GRB/FRB cosmology





key questions of compact objects I

What kind of massive star (RSG, BSG, WR) produces
what kind of compact object (NS or BH? B field, rotation, disk?)
and what kind of explosive transient (SN, GRB or else) ?



key questions of compact objects II

What kind of compact binaries (BBH, BNS, BHNS, …) produces what kind of compact object (NS or BH? B field, rotation, disk?) and what kind of explosive transient (GRB, FRB, or else) ?

How compact binaries are formed?

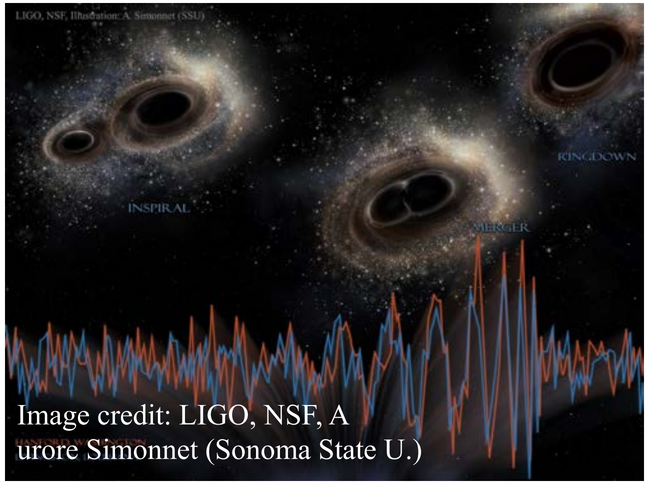
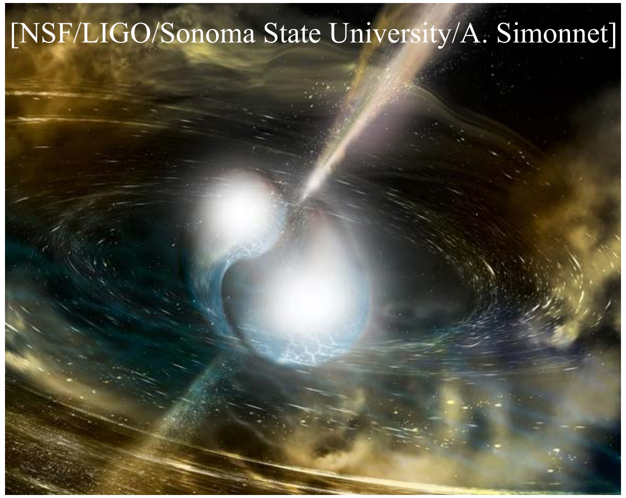


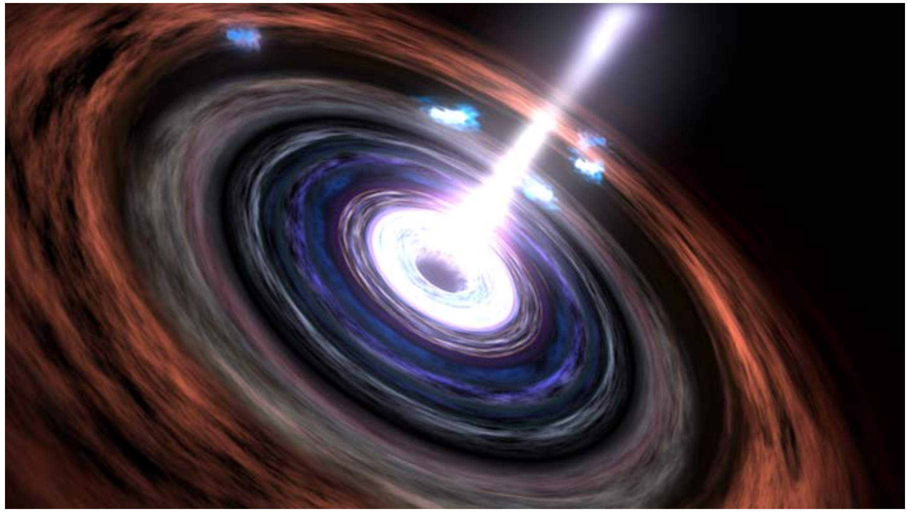
Image credit: LIGO, NSF, Aurore Simonnet (Sonoma State U.)


[NSF/LIGO/Sonoma State University/A. Simonnet]

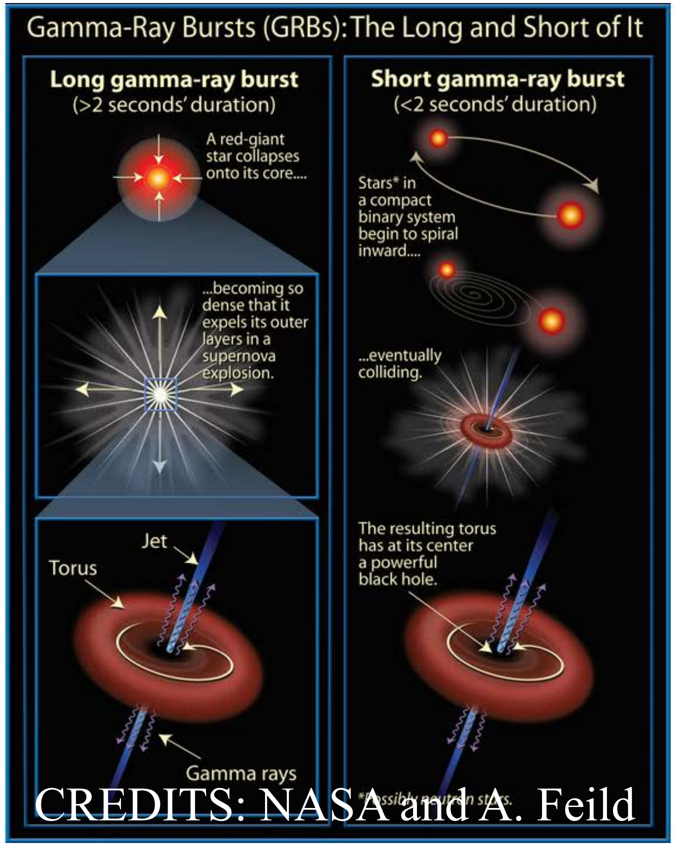

Credit: NASA/Dana Berry, Sky Works Digital

key questions of compact objects III

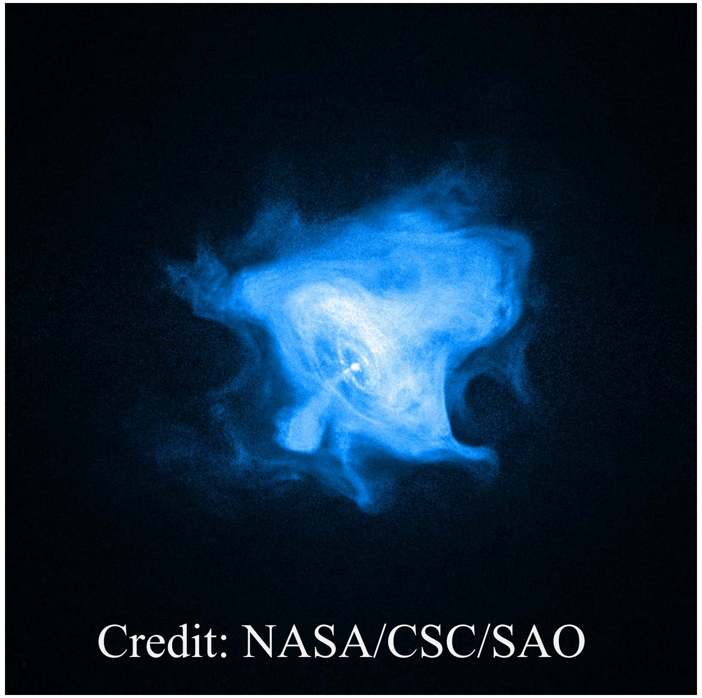
How (relativistic or non-relativistic) outflows are accelerated and how is the energy converted to thermal and non-thermal emission?
What is the central engine? → *mostly compact objects (BH, NS, WD)*



NASA/Goddard Space Flight Center Conceptual Image Lab



CREDITS: NASA and A. Feild



Credit: NASA/CSC/SAO

So, what we do?

- Multi-messenger and time domain astronomy
  → find transients as many as possible and characterize them with follow up observations

- Deeper surveys/observations in multi-wavelength
  → find and characterize Galactic compact objects as many as possible

- New windows?
  - e.g., sub-hr cadence optical surveys
  - space based GW detectors
  - MeV gamma rays
  - X-ray polarization
  - …

c.f.,

Astro2020: Panel on Compact Objects and Energetic Phenomena

- … . Its scope will include white dwarfs; neutron stars; pulsars; magnetars; stellar mass black holes; compact binary systems; novae; supernovae; gamma-ray bursts; fast radio bursts; physical processes and accretion onto supermassive black holes; and gravitational radiation and high-energy particles and radiation from astrophysical sources.

Q1: What are the mass and spin distributions of neutron stars and stellar-mass black holes?

- Q1a: What do the mass and spin distributions tell us about neutron star and black hole formation and evolution?
- Q1b: What is the population of noninteracting or isolated neutron stars and stellar-mass black holes?
- Q1c: What is the equation of state of ultradense matter?

Q2: What powers the diversity of explosive phenomena across the electromagnetic spectrum?

- Q2a: When and how are transients powered by neutron stars or black holes?
- Q2b: When and how are transients powered by shocks?
- Q2c: When and how are transients powered by radioactivity?
- Q2d: What are the unexplored frontiers in transient phenomena?

Q3: Why do some compact objects eject material in nearly light-speed jets, and what is that material made of?

- Q3a: How do jets launch and accelerate?
- Q3b: What are jets composed of and how are particles accelerated within them?
- Q3c: Are TeV-PeV neutrinos and ultra-high- energy cosmic rays produced in relativistic jets?

Q4: What seeds supermassive black holes and how do they grow?

- Q4a: How are the seeds of supermassive black holes formed?
- Q4b: How do central black holes grow?

TABLE B.2 Required Capabilities

Capability	Science Enabled	Current/ Expected Facilities	Future Needs
Radio time-domain surveys	B-Q1: ms-PSR searches and timing B-Q2/DA: FRB searches; transient detection	GBT, Arecibo, CHIME, FAST, JVLA, SKA, and Pathfinders	Multipixel cameras for single-dish pulsar observations. Pulsar search/timing backends for arrays. Arcsec localization for transients. Commensal FRB searches for all cm-band observations.
High-angular-resolution radio/mm imaging and polarimetry	B-Q2/DA: Transient follow-up B-Q3: Jet formation, acceleration and composition; particle acceleration B-Q4: Accreting IMBHs; binary AGN	JVLA, MeerKAT, GMRT, ATCA, ALMA, VLBI, EHT, SKA	Extremely high angular resolution (sub-mas to μas). Polarimetry and Faraday rotation.
O/IR time-domain surveys	B-Q1: Noninteracting binary or free-floating NSs and BHs B-Q2/DA: Transient detection; pre-explosion imaging of SNe B-Q4: TDEs in IMBHs; binary AGN	ASAS-SN, ZTF, Rubin/LSST, APOGEE, DESI, SDSS-V, ATLAS, Gaia, TESS, WFIRST, Euclid	Broad range of cadences (hours to weeks) and sensitivities (magnitude 10–24 in single images); prompt public release.
Massively multiplexed O/IR spectroscopy	B-Q1: Noninteracting binary NSs and BHs B-Q2/DA: Transient follow-up	APOGEE, DESI, SDSS-V	Rapid response (<1 hr). Cadences of hours to weeks. ELT-class sensitivity. $R \sim 1000$.
Deep O/IR line spectroscopy	B-Q1: Radial velocity curves of binaries of interest B-Q2/DA: Transient follow-up B-Q4: redshift of high-z AGN	8–10 m-class ground, HST, JWST	ELT-class sensitivity. Rapid response to transients. $R \sim 100$ for classification, $R \sim 1000$–5000 for follow-up and RVs.
High-angular-resolution O/IR imaging and spectroscopy	B-Q3: Jet acceleration; particle acceleration B-Q4: Dynamical confirmation of local IMBHs; binary SMBHs	8–10 m-class ground AO, HST, JWST, WFIRST	<10 mas angular resolution and ELT-class sensitivity. Rapid response to transients. $R > 5000$ for IMBH masses.
UV imaging and spectroscopy	B-Q2/DA: Transient follow-up	Swift/UVOT, HST	Comparable post-Swift and post-HST coverage. Rapid response to transients.
Wide-field X-ray (0.5–100 keV) monitors	B-Q1: New NS/BH transients B-Q2/DA: Transient detection	Swift/BAT, MAXI, Fermi/GBM, eROSITA	Post-Swift and post-Fermi coverage. Range of capabilities optimizing trades between high sensitivity, wide-field coverage, and <arcmin localization.
X-ray imaging and spectroscopy	B-Q1: NS/BH disk reflection lines B-Q2/DA: Transient follow-up B-Q3: Jet spectroscopy	Chandra, XMM, NICER, NuSTAR, XRISM, Athena	10^{-19} erg/cm^2/s sensitivity and moderate ($R \sim 100$) spectral resolution. Hard X-ray coverage (10–100 keV) with 10^{-14} erg/cm^2/s sensitivity. Rapid response to transients.
X-ray spectral timing	B-Q1: NS/EOS pulse profile modeling; pulsar timing B-Q2/DA: Transient follow-up	XMM, NICER	Post-NICER/XMM coverage. <0.1 ms time resolution. Larger effective area (>1 m^2 @ 1 keV; >4 m^2 @ 10 keV). High throughput.

Capability	Science Enabled	Current/ Expected Facilities	Future Needs
High-angular resolution X-ray imaging	B-Q1: ULXs and other point sources in nearby galaxies B-Q2/DA: Transient follow-up B-Q3: Jet acceleration, particle acceleration B-Q4: SMBH seeds	Chandra, XMM, NuSTAR, Athena	High angular resolution (<1 arcsec @1 keV; <15 arcsec @20 keV). Hard X-ray (>10 keV) coverage. 10× Chandra/NuSTAR sensitivity.
X-ray/gamma-ray polarimetry	B-Q3: Jet and disk orientation and geometry	INTEGRAL, IXPE	10× IXPE sensitivity. Soft X-ray and MeV gamma-ray coverage.
MeV gamma-ray line spectroscopy	B-Q2/DA: Nuclear lines from SNe	INTEGRAL/SPI	Wide (>1 sr) FOV. Sensitivity $<8 \times 10^{-6}$ ph/cm^2/s in 10^6 s for ~1 SN-Ia/yr detected.
MeV/GeV gamma-ray imaging	B-Q1: Faint ms pulsars B-Q2/Q3/DA: Transients; counterparts for neutrino/UHECR sources; GRB jet launch	Fermi	MeV coverage. Post-Fermi GeV coverage.
TeV gamma-rays	B-Q3/DA: Counterparts for neutrino/UHECR jet sources, EM sources; particle acceleration	HAWC, MAGIC, HESS, VERITAS, LHAASO	Post-HAWC/VERITAS coverage.
Low-frequency (nHz/mHz) gravitational waves	B-Q1: NS and BH binaries B-Q4: SMBH binaries B-DA: GW counterparts of EM sources	NANOGrav and other PTAs, LISA	Continued PTA coverage with larger pulsar sample. Detect all merging SMBHs, localize loudest to <10 arcmin^2. Full U.S. access to LISA data.
High-frequency (Hz/kHz) gravitational waves	B-Q1/Q3: NS and BH mergers/jets B-Q2: Transient detection B-Q4: IMBH mass function B-DA: GW counterparts of EM sources	LIGO/Virgo, KAGRA, LIGO-India, LIGO/A+	BNS mergers to $z \sim 10$; 30/30 $M_\odot$ BBH and IMBH mergers to $z \sim 20$. Localization to <10 deg^2.
MeV neutrinos	B-Q2/DA: SNe (including diffuse thermal background)	Super-K, Hyper-K	10× Hyper-K volume for ~1 SN/yr.
TeV/PeV/EeV neutrinos	B-Q3: Jet counterparts/composition B-DA: ν counterparts of EM sources; diffuse TeV/PeV background	IceCube, ANTARES, KM3NeT	10× IceCube volume for ~1 ν /yr from TXS 0506-like transients. EeV coverage.
Ultra-high-energy (EeV) cosmic rays	B-Q3: Jet counterparts/composition B-DA: UHECR counterparts of neutrino and EM sources	Auger, TA, LHAASO	Continued coverage. 10× larger exposure. >4× larger detector area.
Theory, computation, and simulations	B-Q1/Q2/Q3/Q4/DA	Broad support for theory and computation across all areas. Next-generation computing for multidimensional radiation hydrodynamics and PIC simulations, numerical relativity. Training for GPU-based computation. Advanced nuclear reaction network, cosmic ray transport, and hadronic cascade simulations.	