高エネルギー天体

樫山和己 （東北大学）

CRCの横(?)串

- 宇宙線
- ガンマ線
- ニュートリノ・地下非加速器物理学
- 重力波

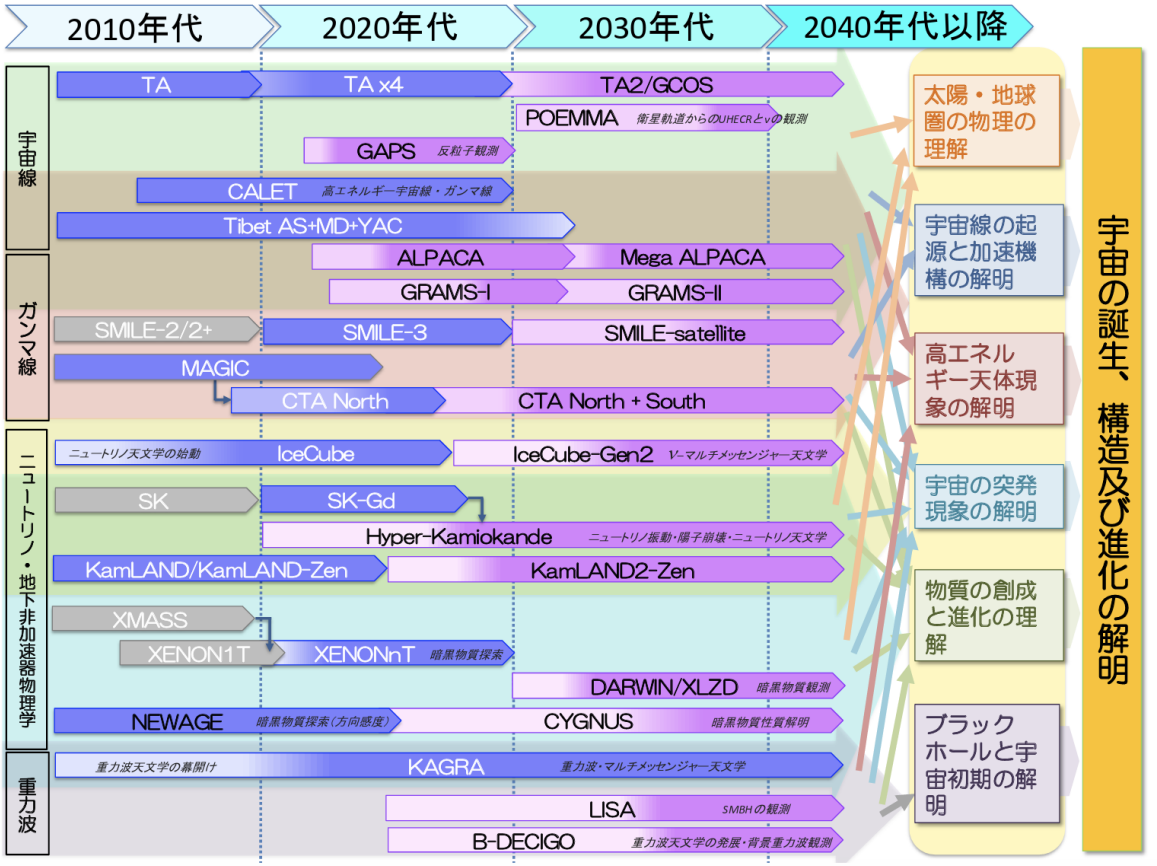


図1　CRC ロードマップ 2023

縦(?)串

- 高エネルギー天体現象（樫山）

- 宇宙線の起源と加速機構の解明（霜田さん）
- 銀河・大規模構造の進化（宮武さん）
- 宇宙線のモジュレーション（宗像さん）
- 宇宙初期・物質の創成（郡さん）
- 超新星のマルチメッセンジャー試み（堀内さん）

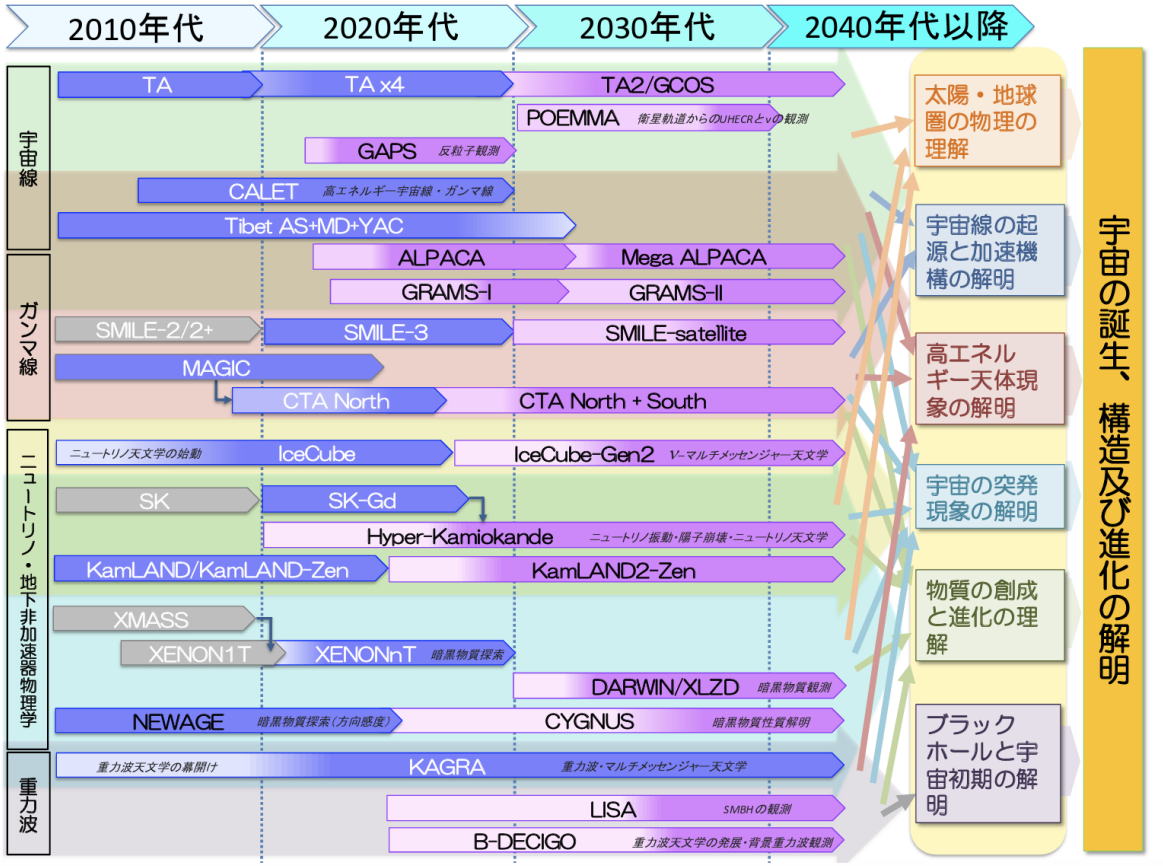


図1　CRC ロードマップ 2023

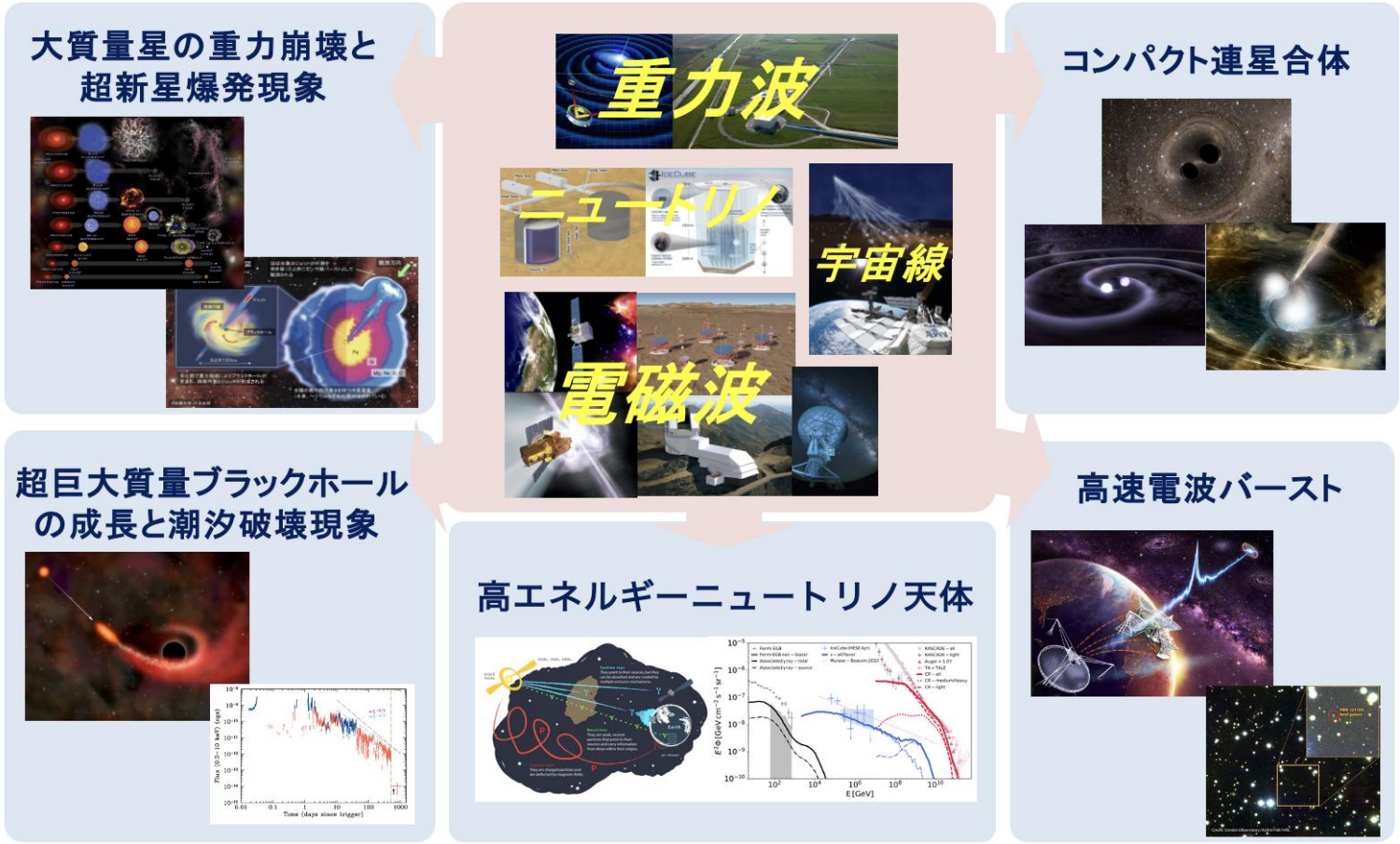
（なんやったら他も全部高エネルギー天体現象と言えなくもない。トップバッターの役得で…。）

自己紹介

（今年度の院試説明会用のスライド）

樫山和己：宇宙物理学（主に理論）

特にマルチメッセンジャー・時間領域天文学



個人的な横(?)串

1. マルチメッセンジャー観測
2. 時間領域観測

What non-EM messengers tell us

- GWs → Compact objects are vibrating (l > 1) or orbiting each other.

  Where, how, and how much compact objects vibrate and orbit each other?

- Neutrinos
  - MeV → Nuclei are burning in cosmic fireballs.

  Where, how, and how much the comic fireballs and what and how much nuclei are formed?
  - > GeV → Charged pions are produced from CRs.

  Where, how, and how much CRs are accelerated in the universe?

- CRs → Charged particles are accelerated in the universe.

  Where, when, and how the CRs arriving at the Earth are accelerated?

Non-EM signals so far : GWs

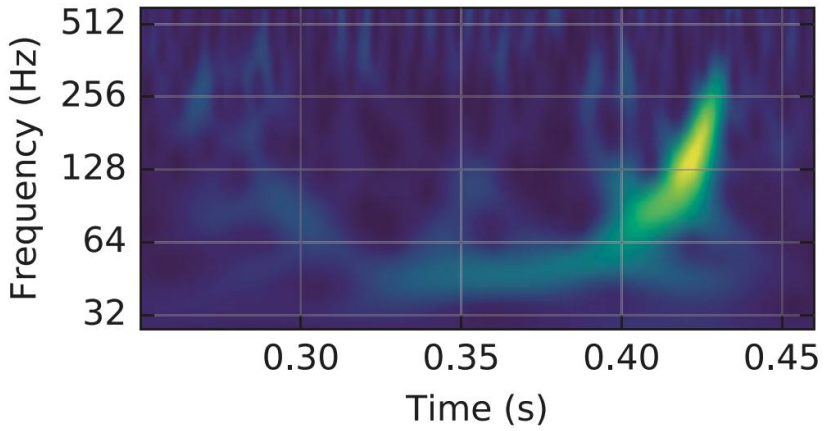
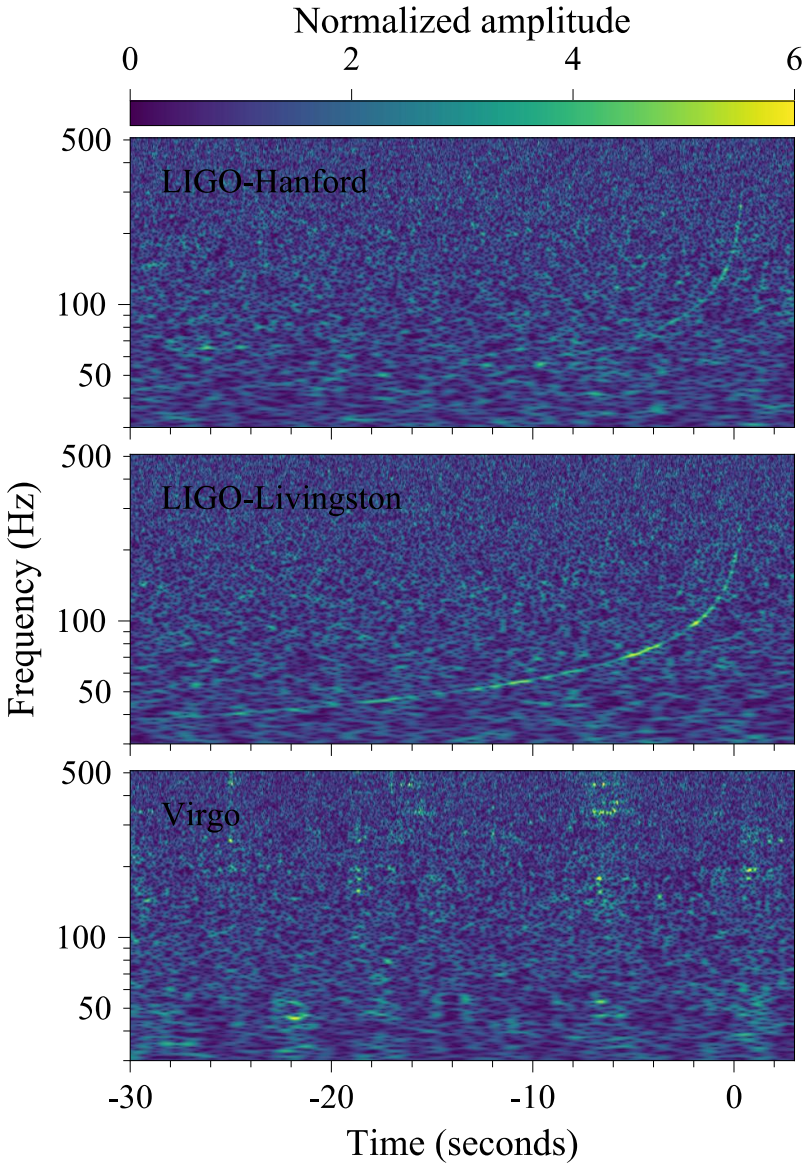
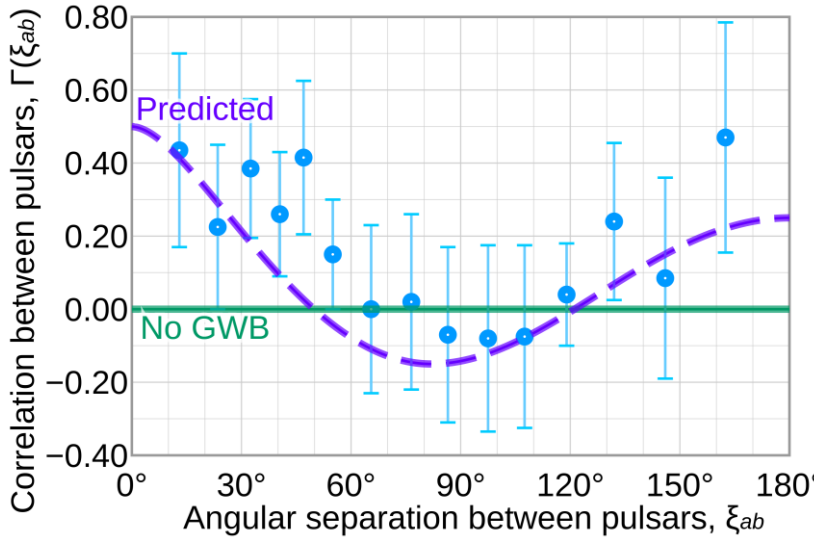


Image credit: Caltech/MIT/LIGO Lab





NANOGrav 2023

Non-EM signals so far : GWs

→ Coalescences of compact binaries consisting of BHs and NSs, supermassive ones too(?)

✓ *How much?*

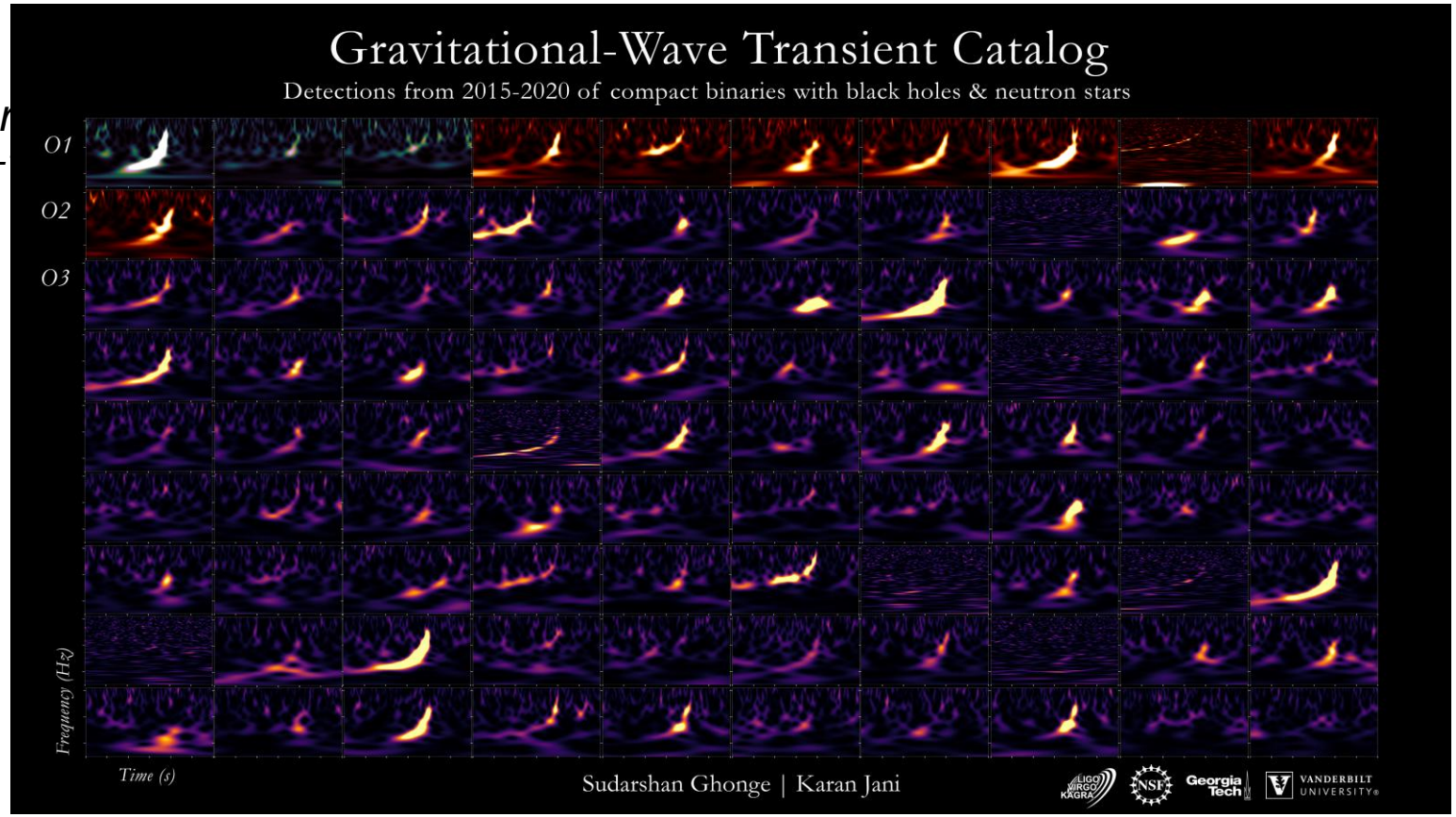
Binaries consisting of BHs and NSs mer
with an event rate of 100-1000 Gpc^{-3} yr

✓ *How?*

With emitting GWs, in a way consistent with the prediction of general relativity, and EM waves when two NSs merge.

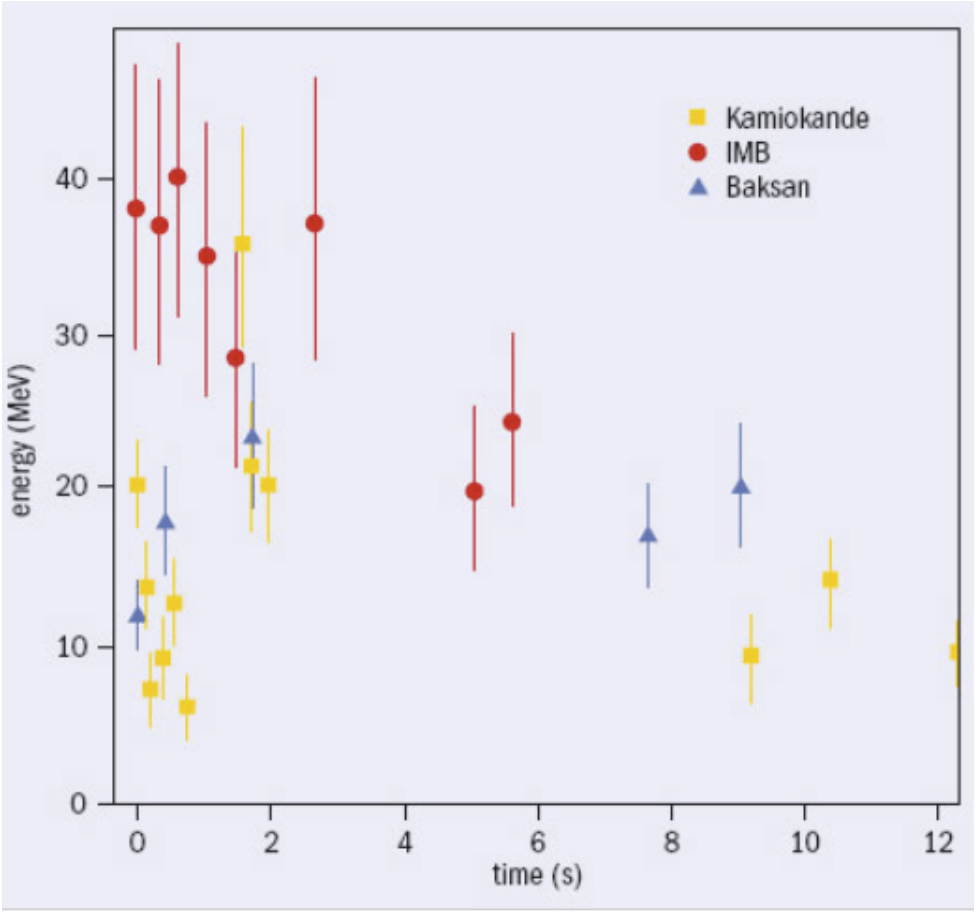
✓ *Where?*

Uncertain mainly due to the low angular resolution.

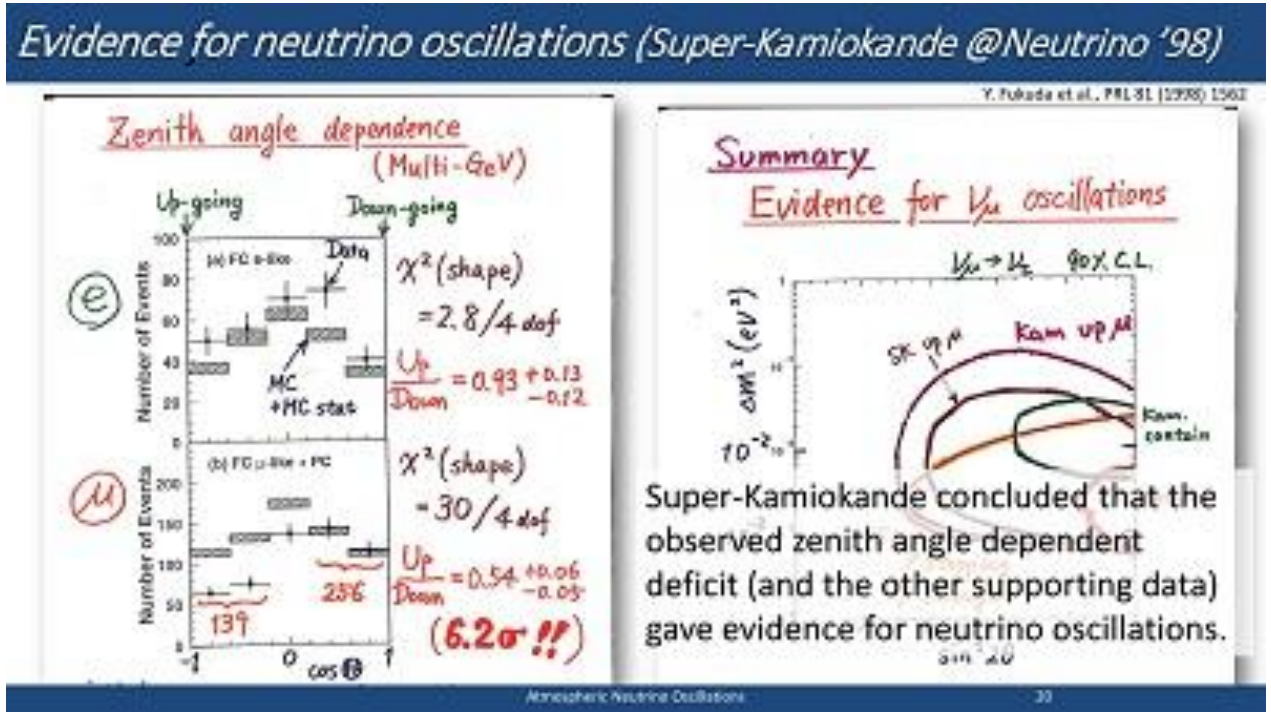


Non-EM signals so far : MeV neutrinos

SN1987A



The sun

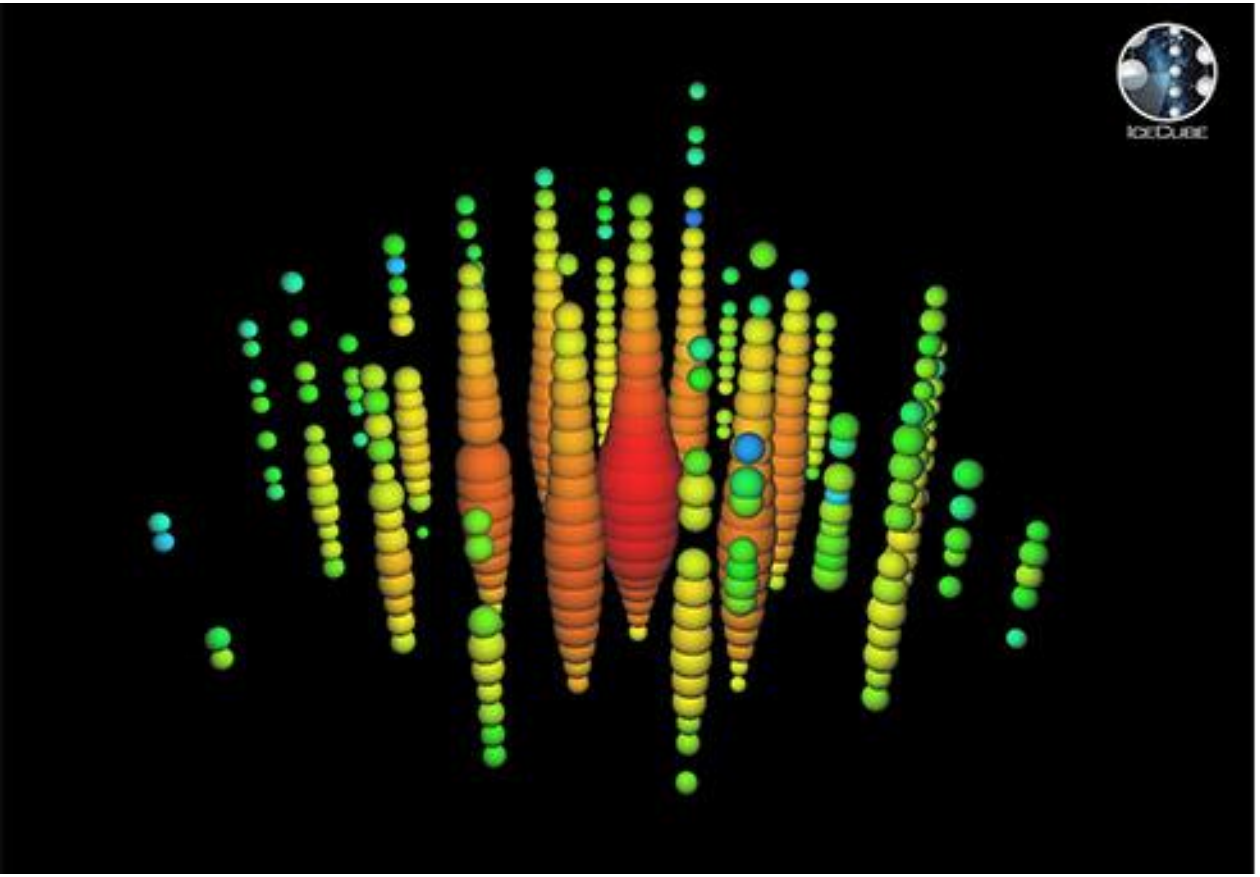


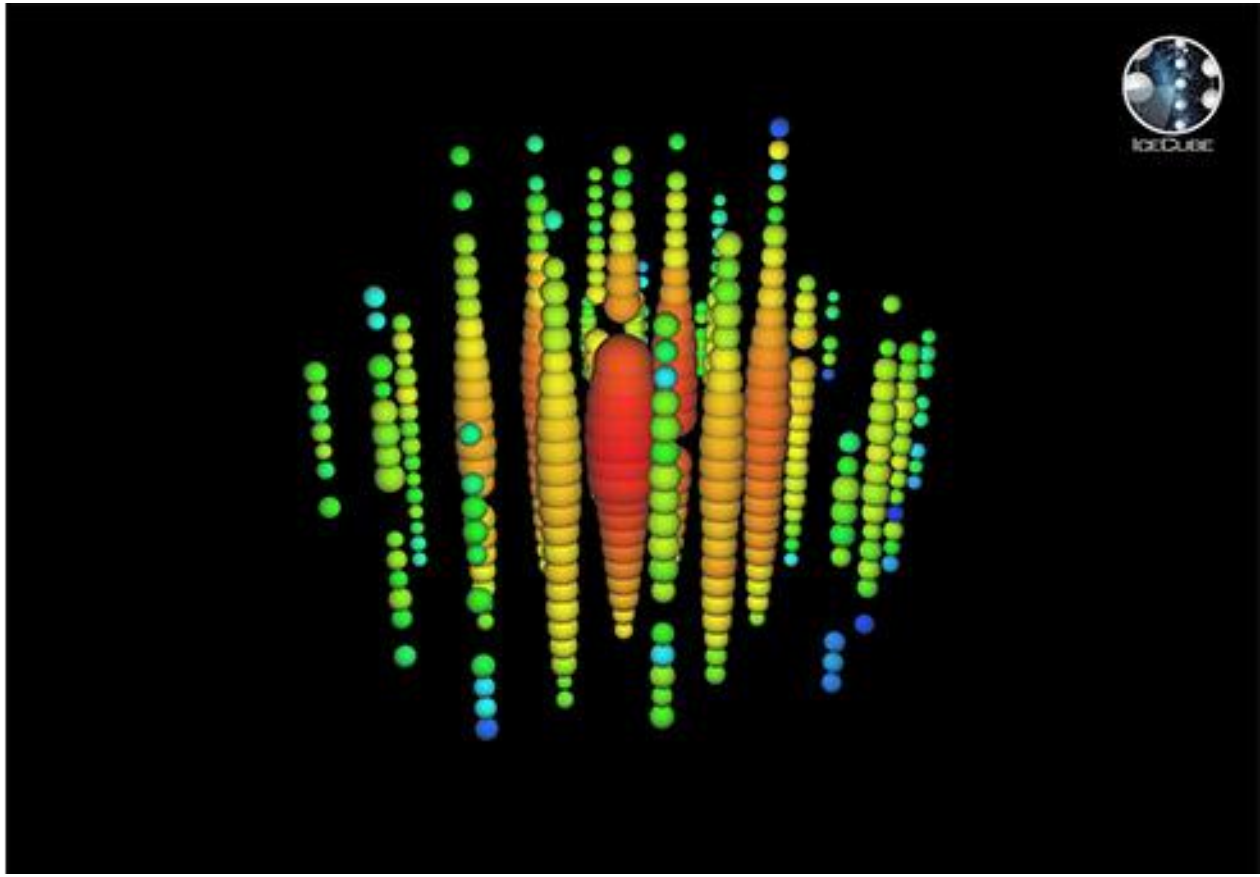
Non-EM signals so far : MeV neutrinos

SN1987A

The sun

Non-EM signals so far : >GeV neutrinos

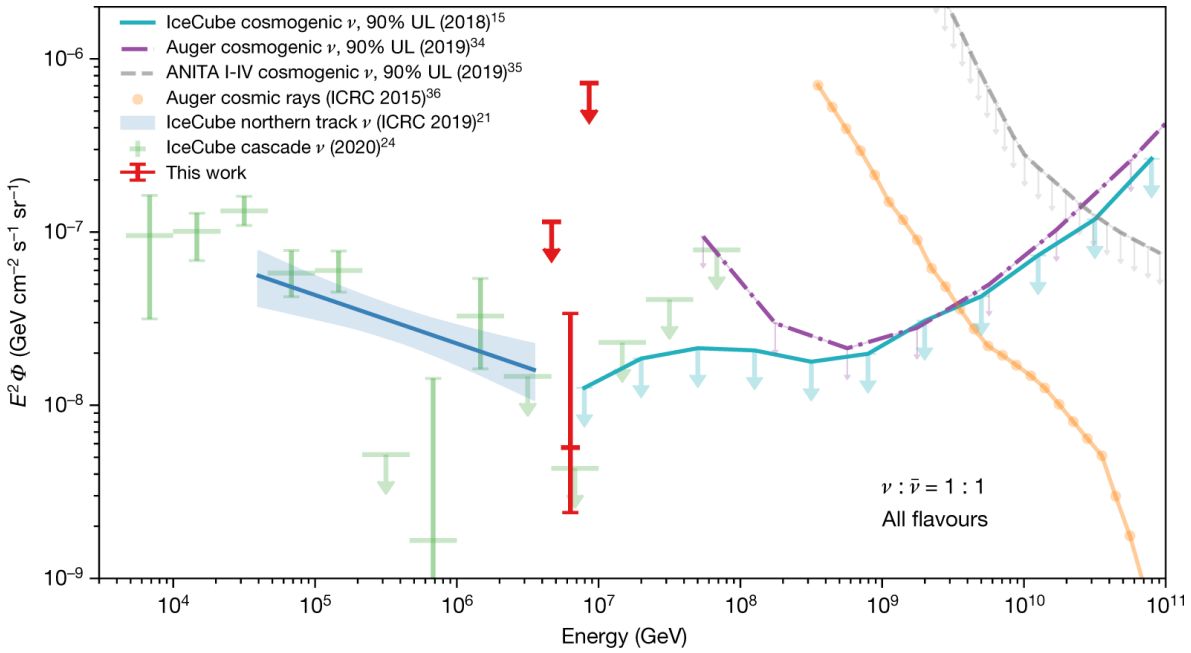


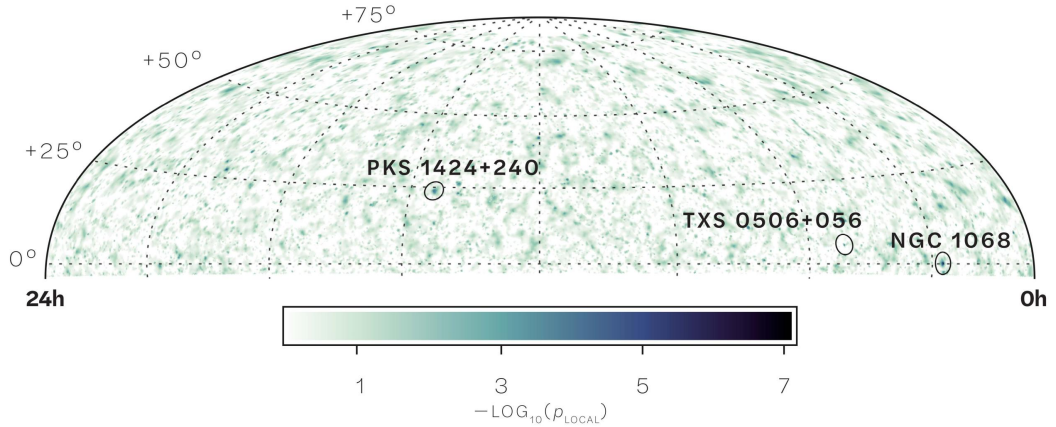


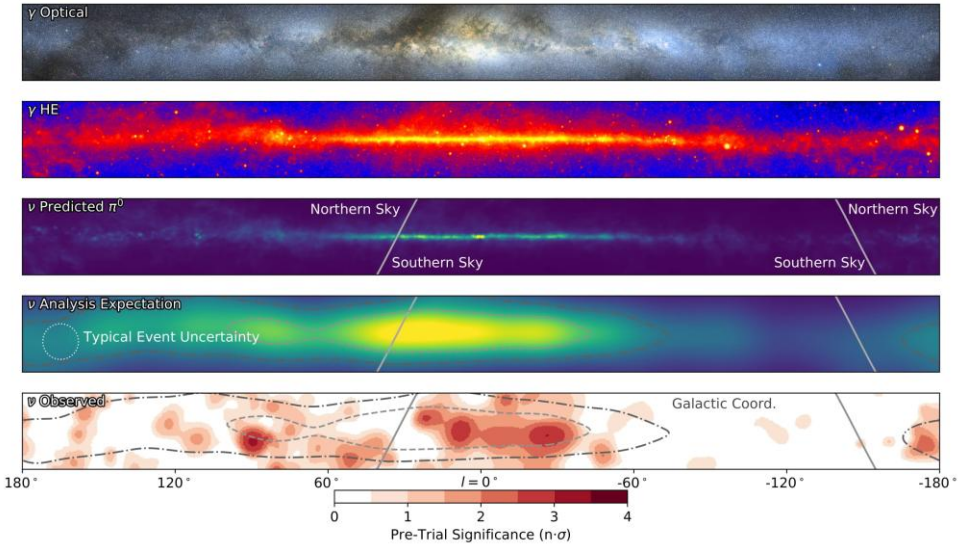
Non-EM signals so far : >GeV neutrinos

→ An extra-galactic diffuse emission, and probably a point source emission from NGC1068 and a galactic diffuse emission

Credit : IceCube Collaboration

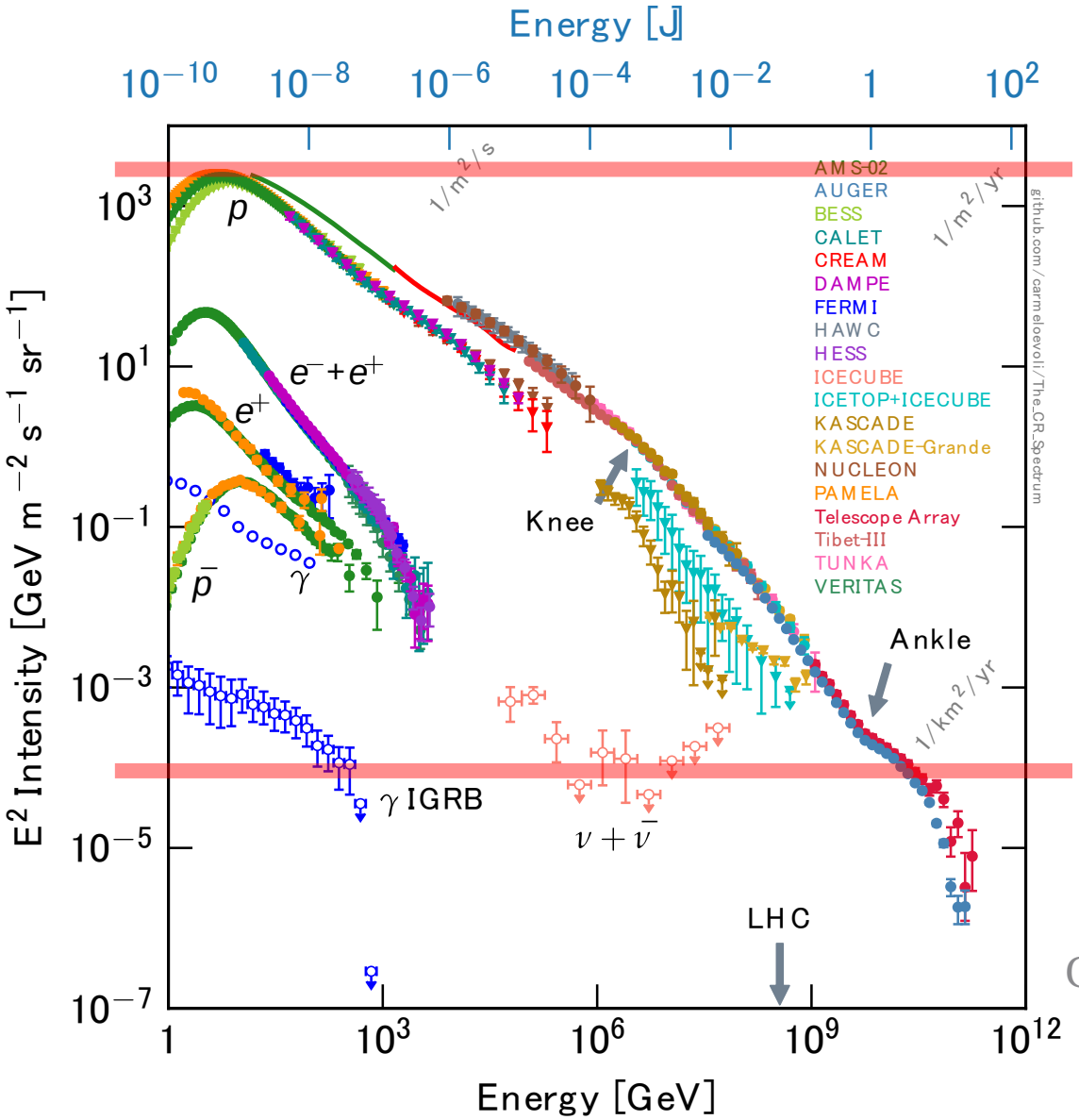






Non-EM signals so far : CRs

Non-EM signals so far : CRs



required energy injection rate

$\sim$ 1 Bethe / galaxy / century

$\gtrsim 10^{45}$ erg Mpc^{-3} yr^{-1}

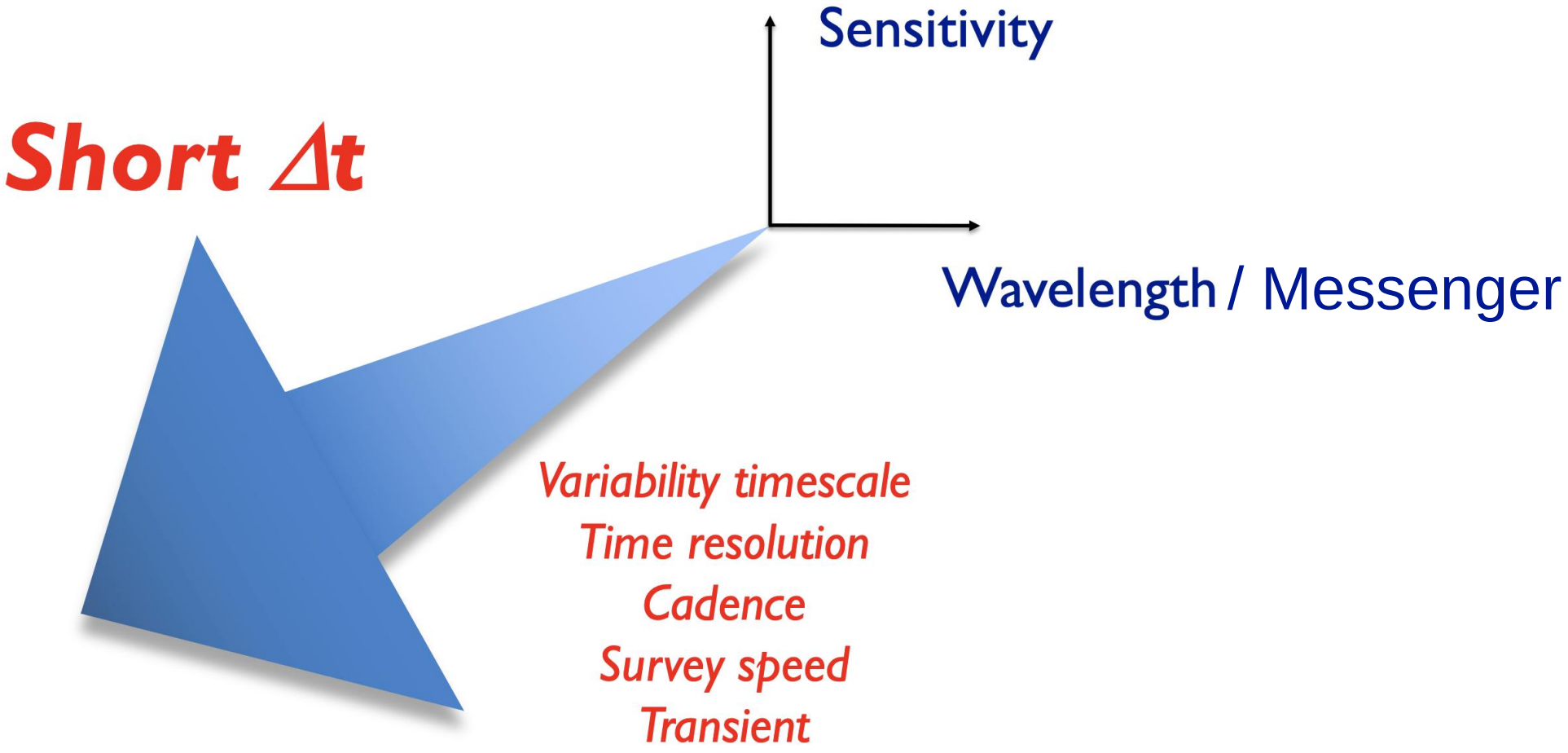
Multi-messenger signals so far

- The sun [photons + CRs + neutrinos] *How the sun shines*
- Milky way [photons + CRs + neutrinos(?)] *Supernovae are most likely the source of cosmic ra*
- Supernova SN1987A [photons + neutrinos] *Massive star explodes with forming NSs/BHs*
- Binary NS merger GW170817 [photons + GWs] *BNSs merge → short GRBs & r-process eleme*

- Seyfert galaxy NGC1068/M77 [photons + neutrinos(?)] *High energy CR acceleration near SMBH ho*

- Blazer TXS0506+056 [photons + neutrinos(??)]
- Tidal disruption events AT2019dsg, AT2019fdr, …[photons + neutrinos(??)]

Time-domain astronomy

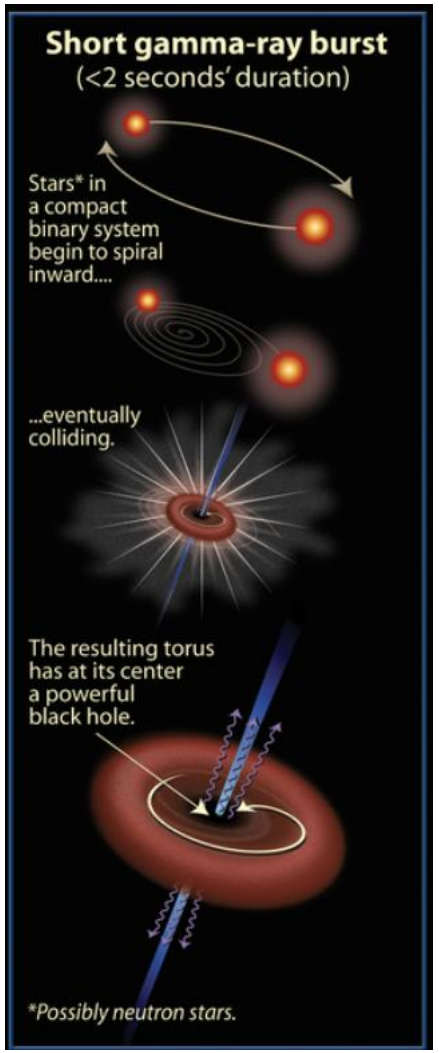


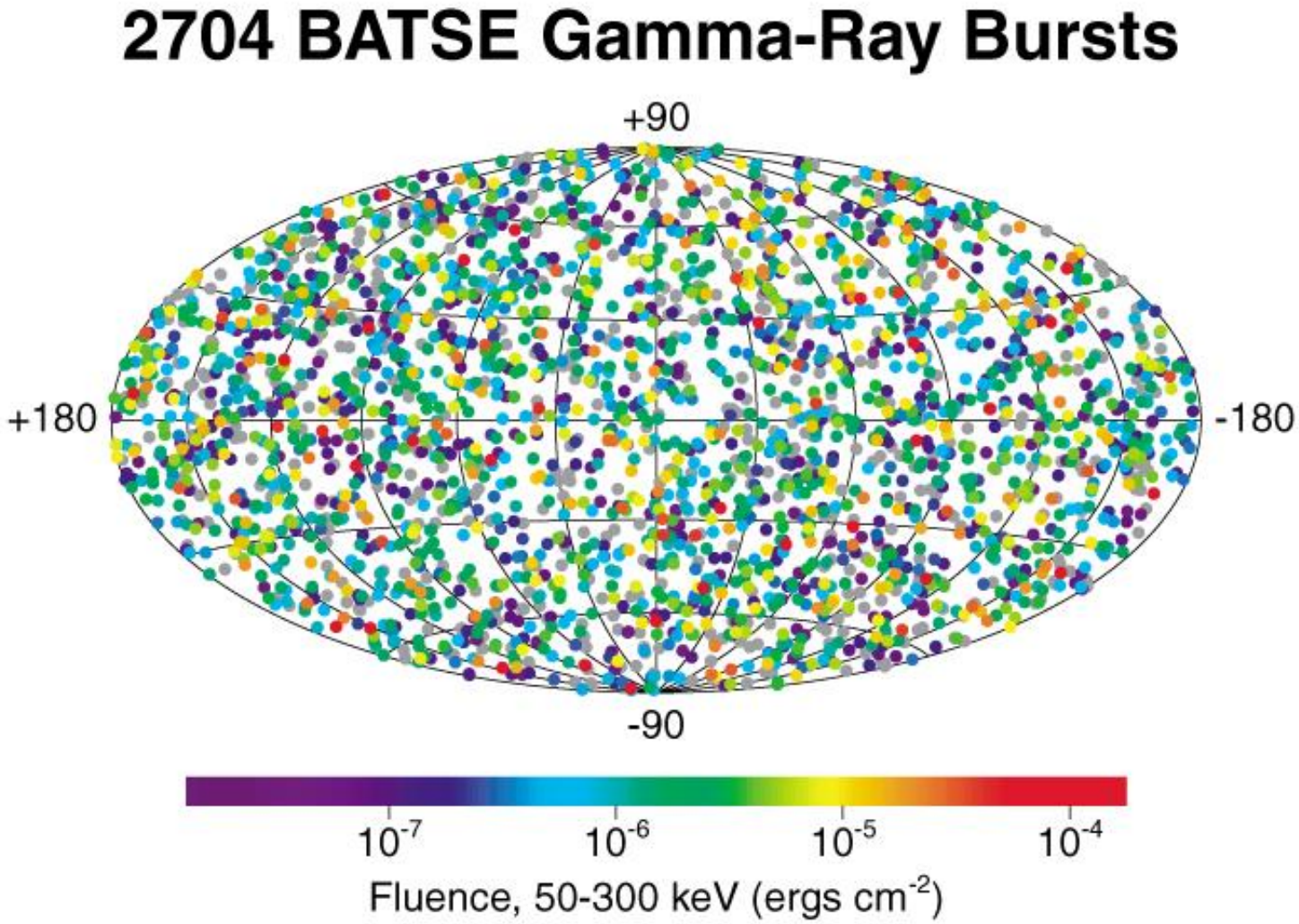
2021年度 国立天文台の将来シンポジウム 井岡さんのスライドより

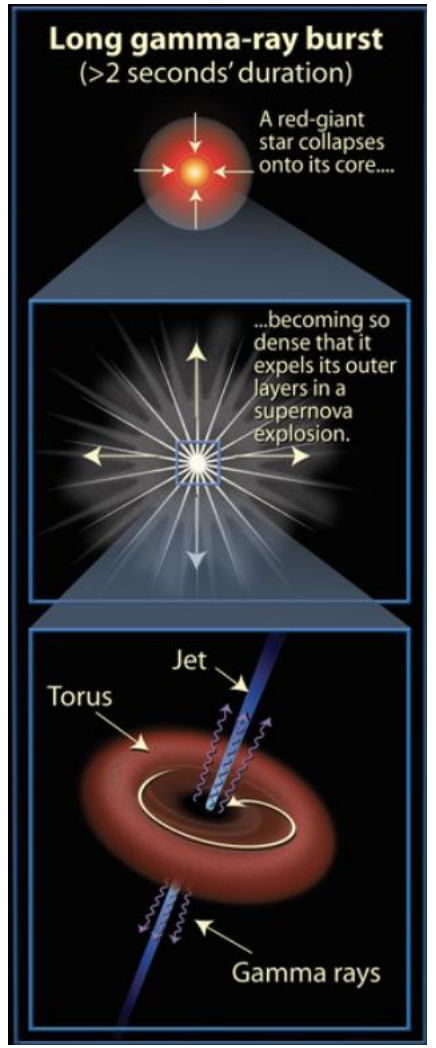
Gamma ray

MeVより熱い火の玉
相対論的なジェット・アウトフロー

since ~ 1967



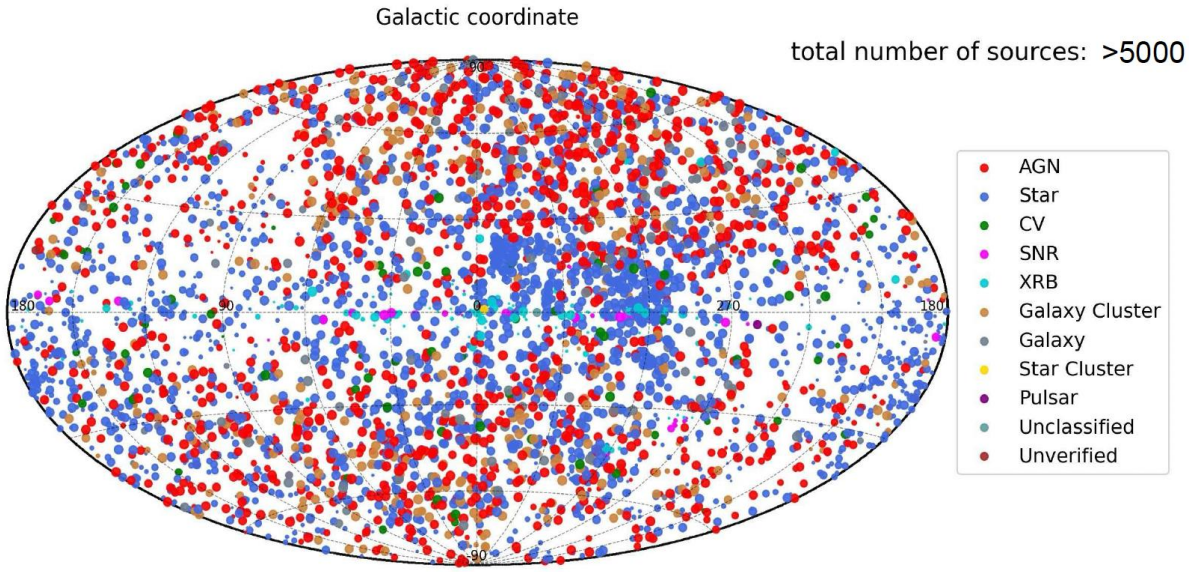


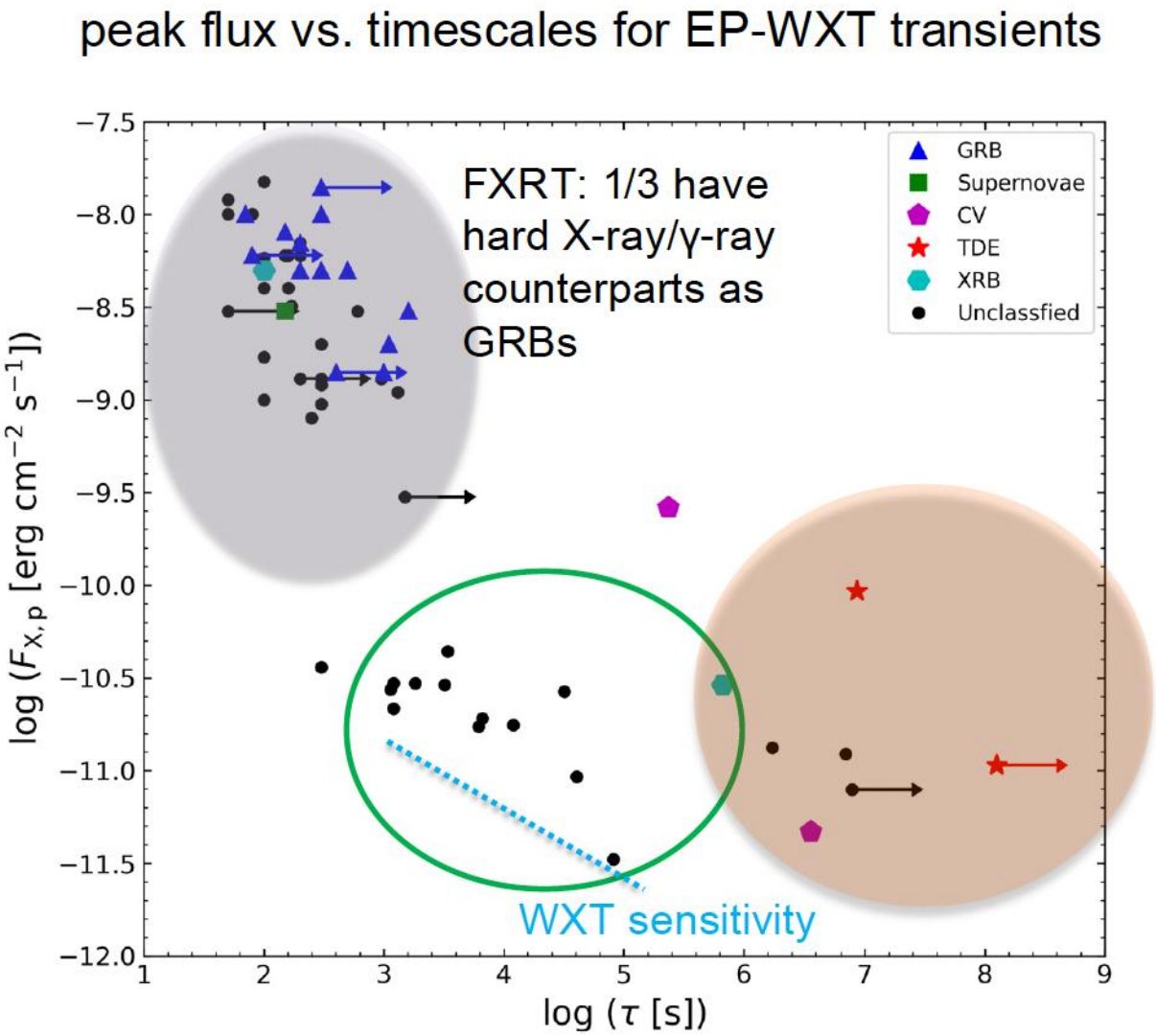


e.g., Einstein Probe

X ray

コンパクト天体付近の高温プラズマ
相対論的なジェット・アウトフロー

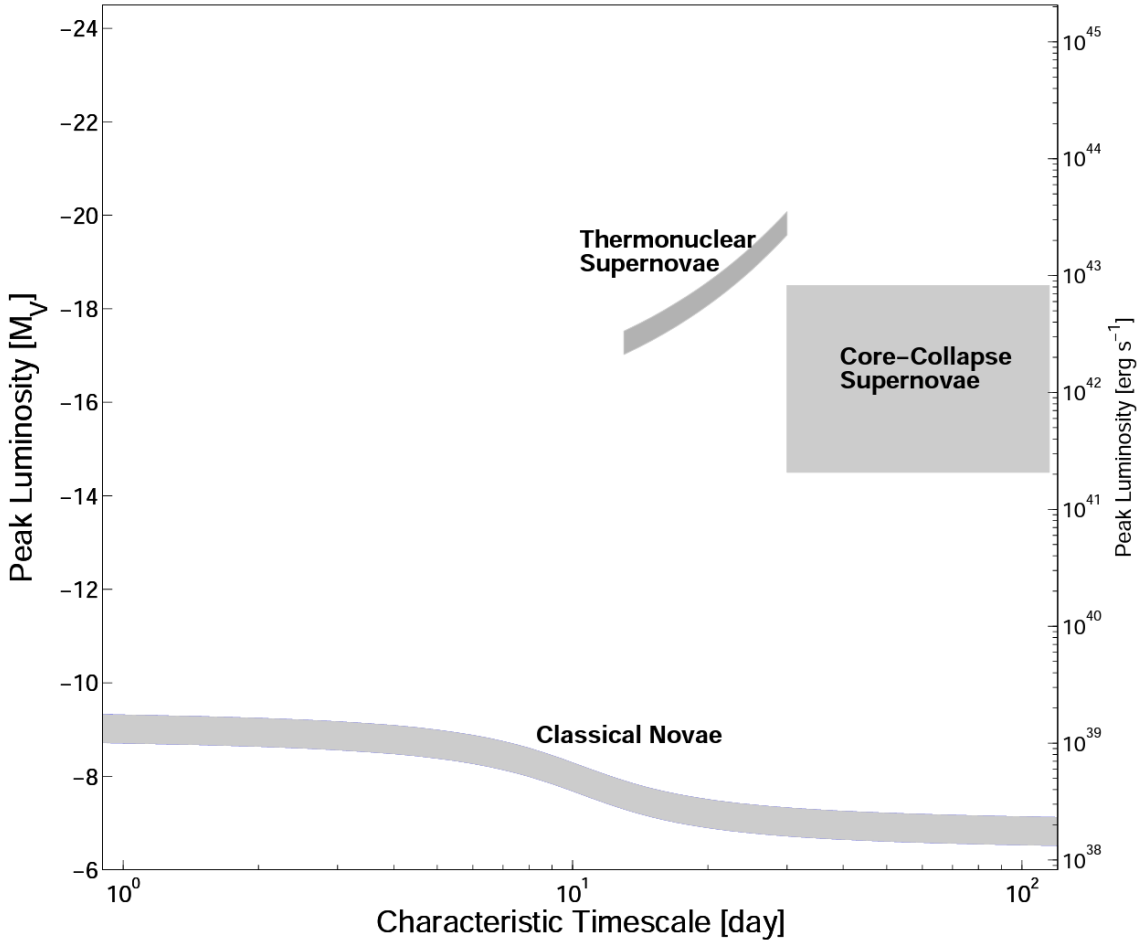




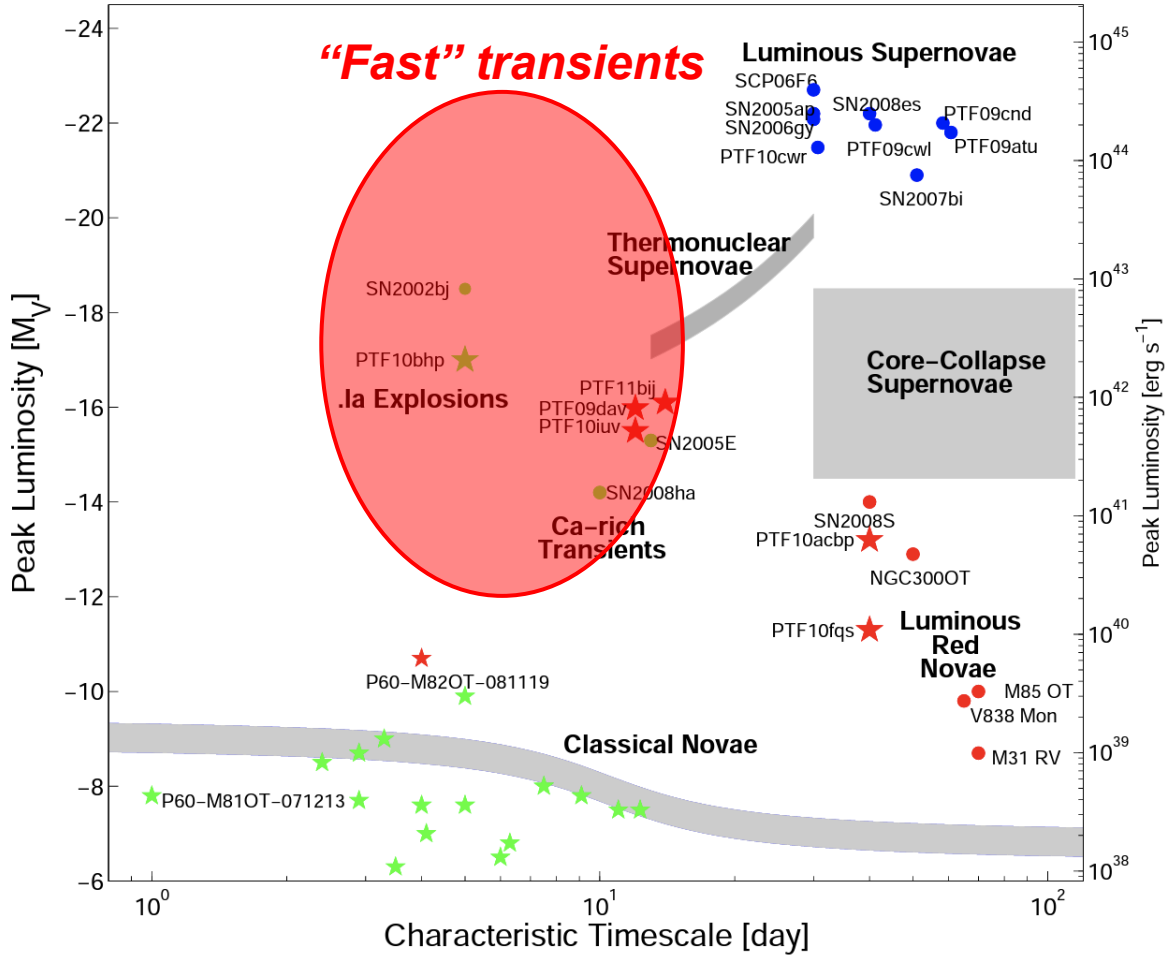
Optical

非相対論的な爆発からの準熱的放射線

before ~ 2005

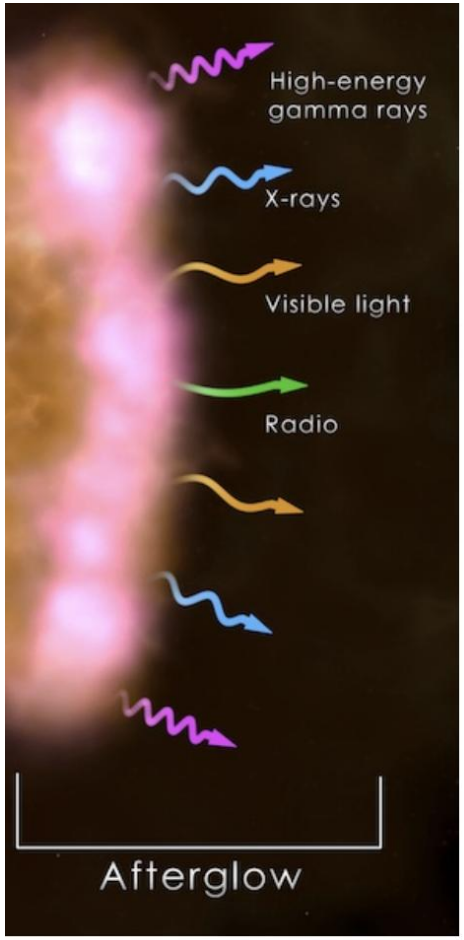


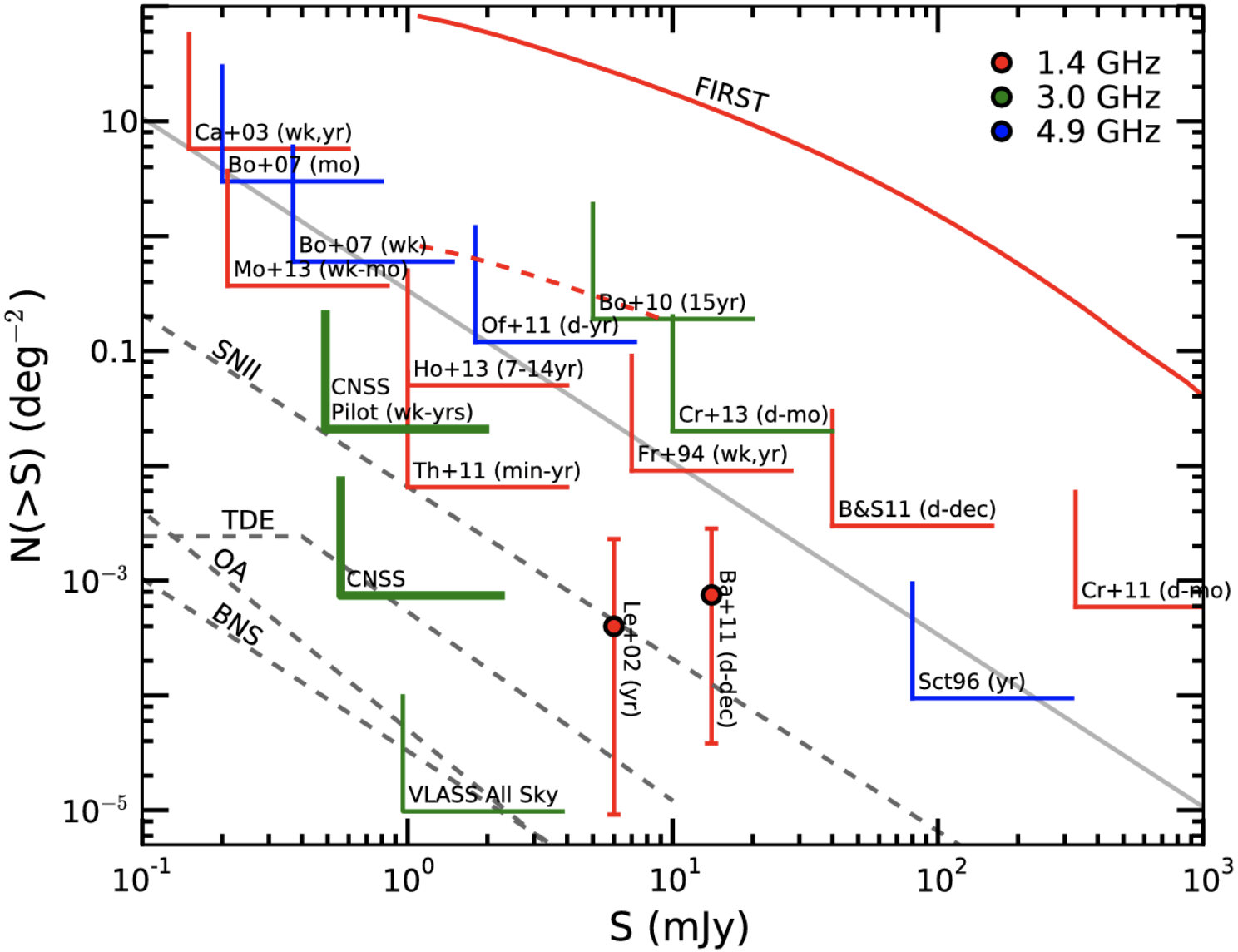
after ~2010



Radio

相対論的/非相対論的なアウトフローの減速過程



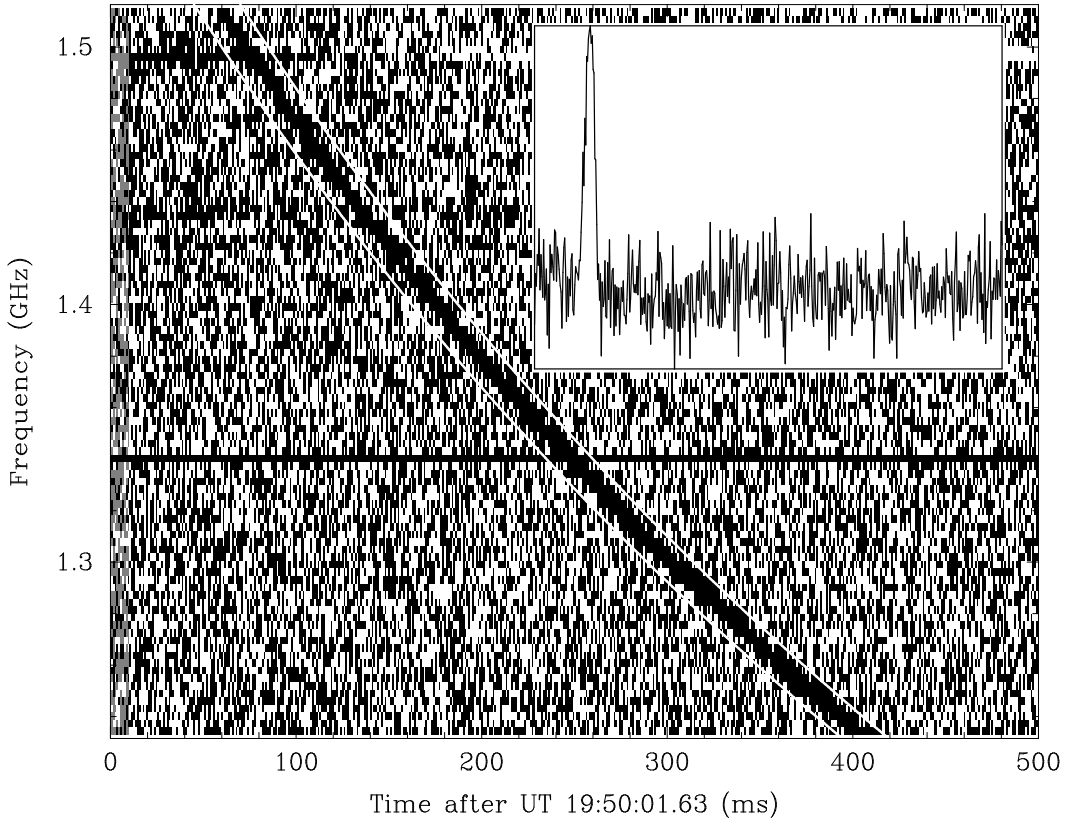


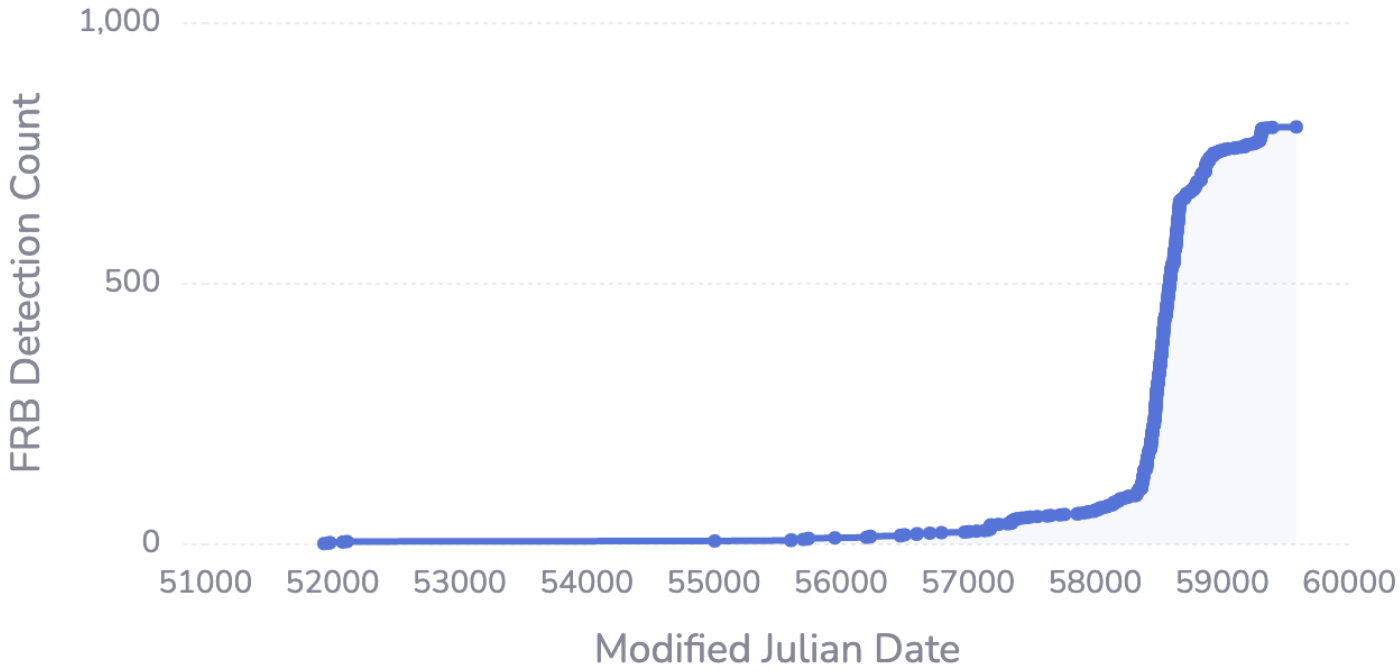
Mooley et al. 16

Coherent radio bursts

宇宙最強の“レーザー”放射

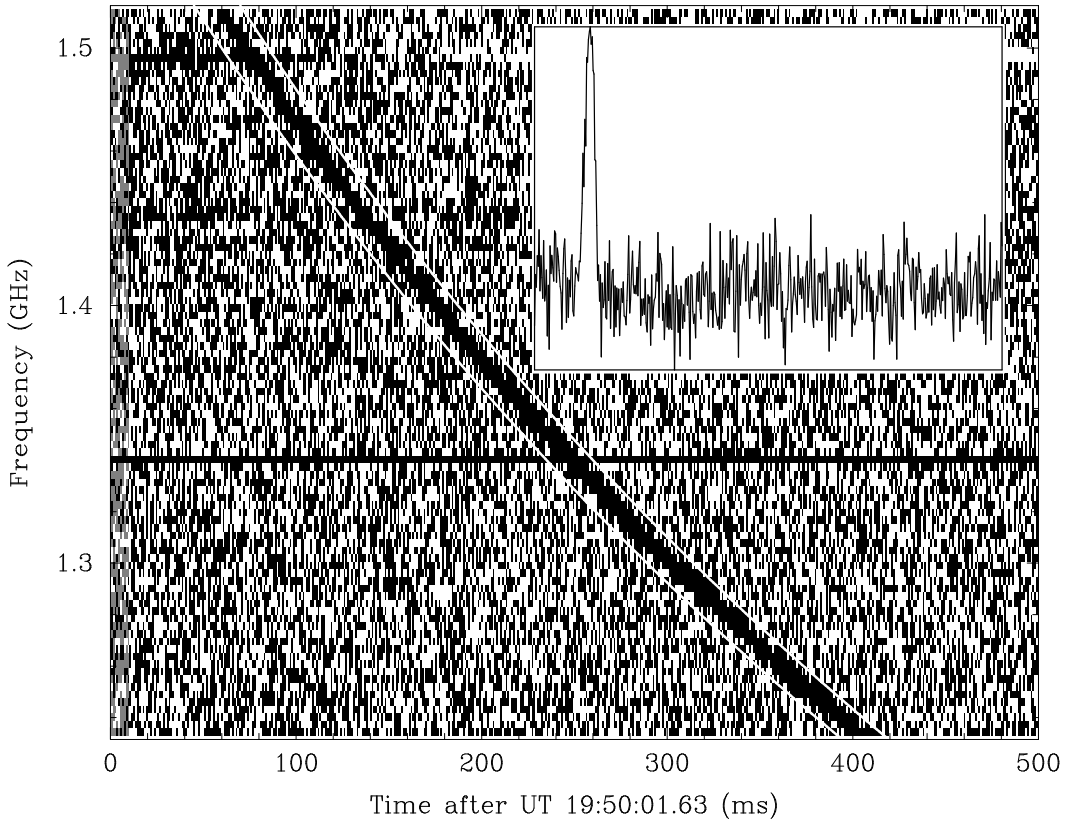
Discovery of an “unknown unknown” in 2007

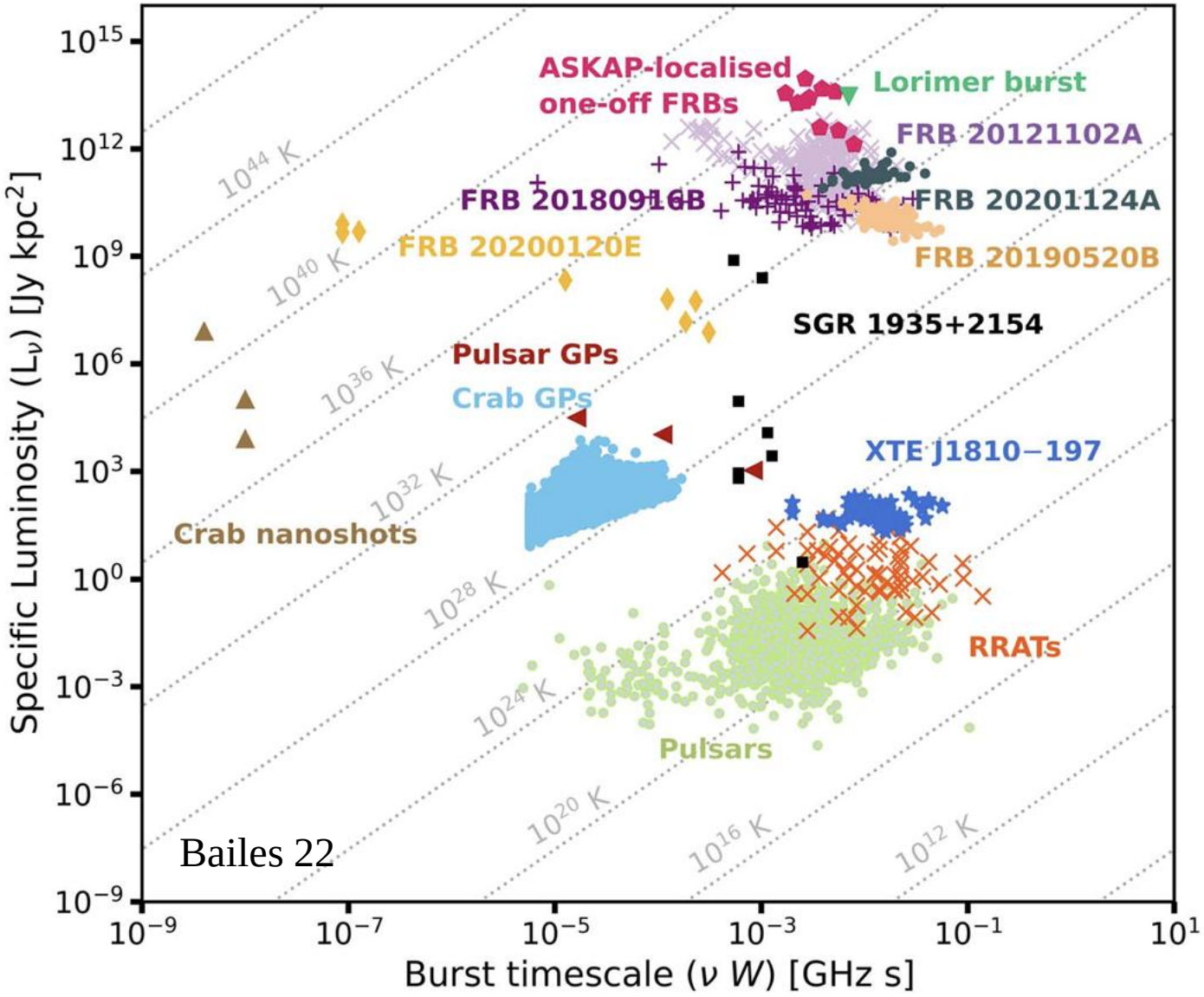




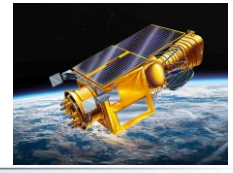
Coherent radio bursts

宇宙最強の“レーザー”放射





UV

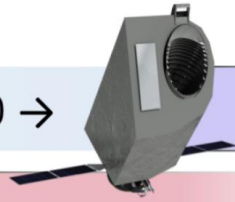


GALEX 2003 – 2013

ULTRASAT 2026 →

HST 1990 →

Swift 2004 →



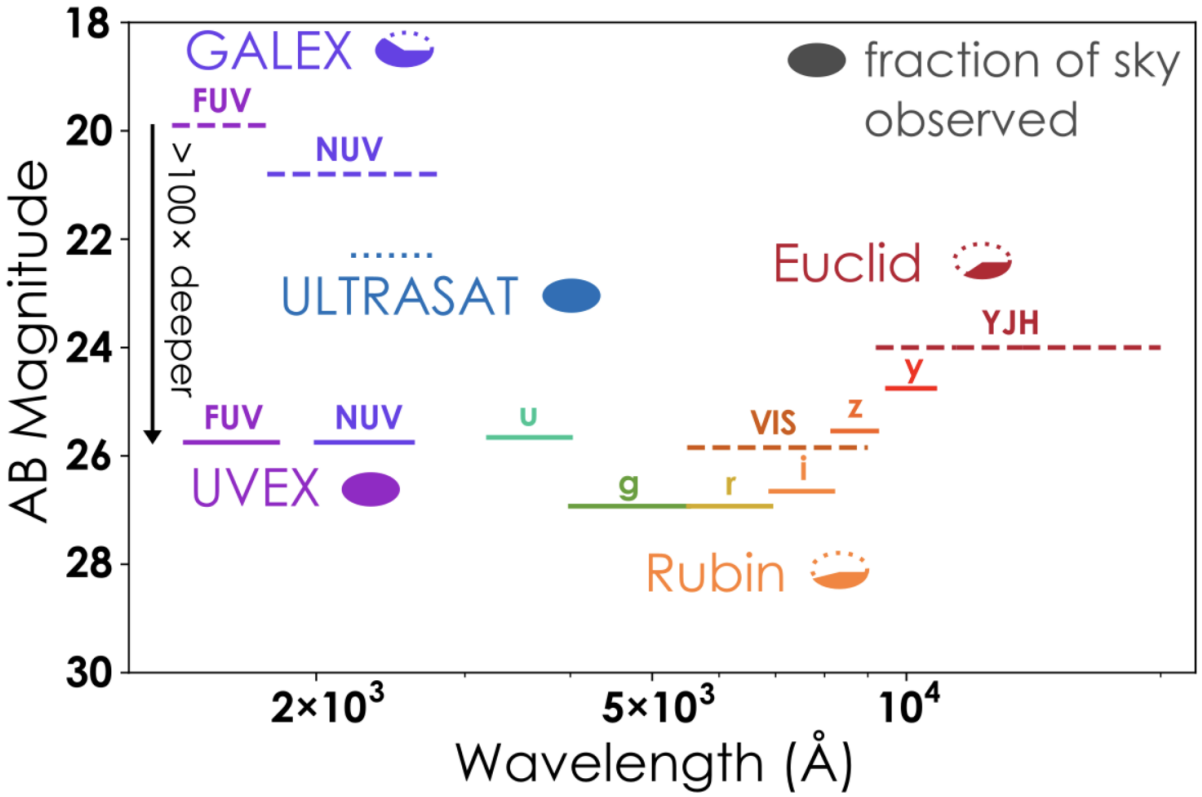
UVEX 2030 →

Euclid 2023 →

Rubin 2025 →

Roman 2027 →

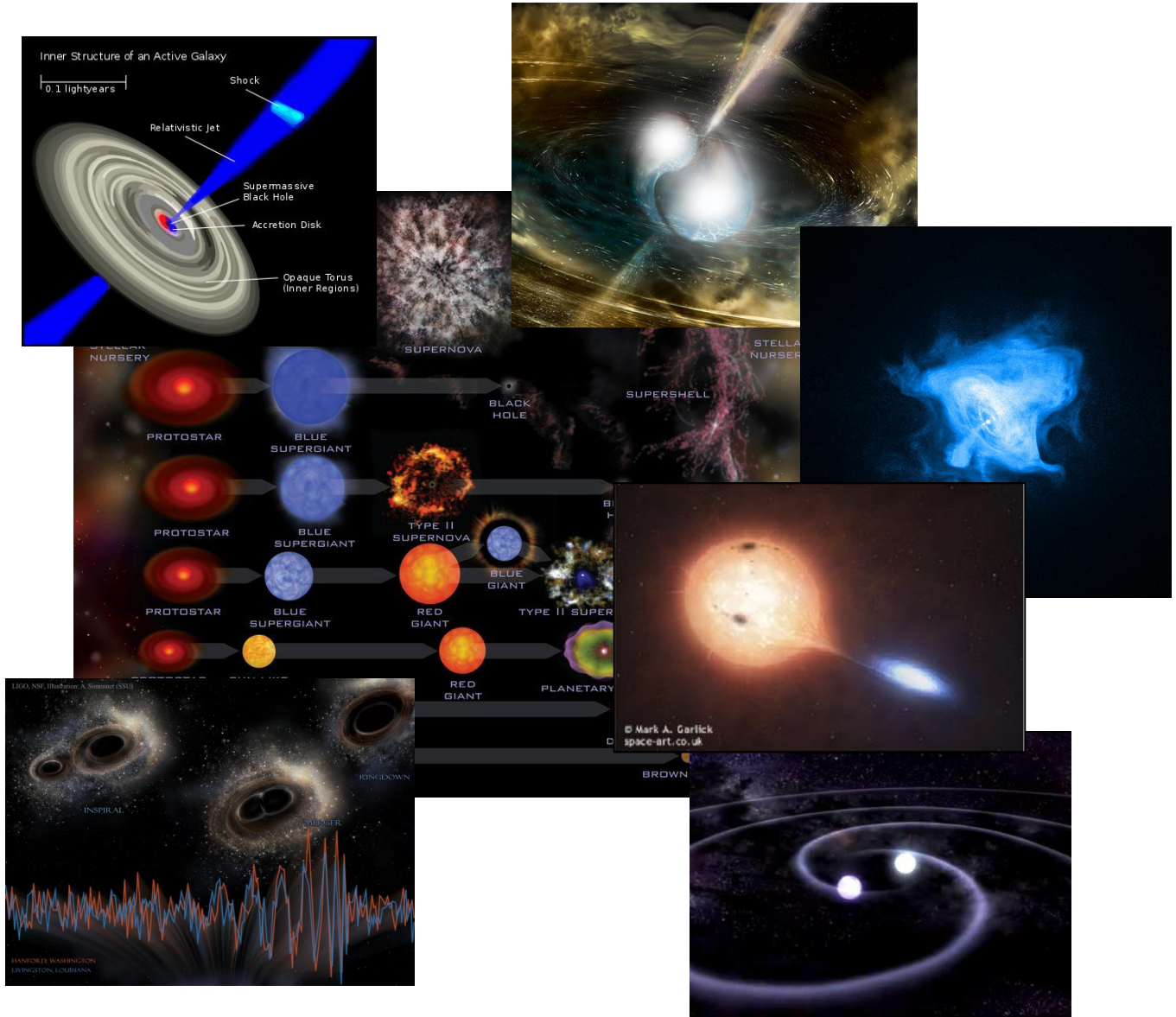
LIGO/Virgo/KAGRA O5 O6



個人的な縦(?)串

1. 降着, ジェット/アウトフロー, 粒子加速
2. コンパクト天体の宇宙物理学
    1. 白色矮星
    2. 中性子星
    3. ブラックホール

Diversity and universality of high energy astrophysics



Gravitational energy liberated around a compact object

↓

- Rotation
- Magnetic field

…

↓

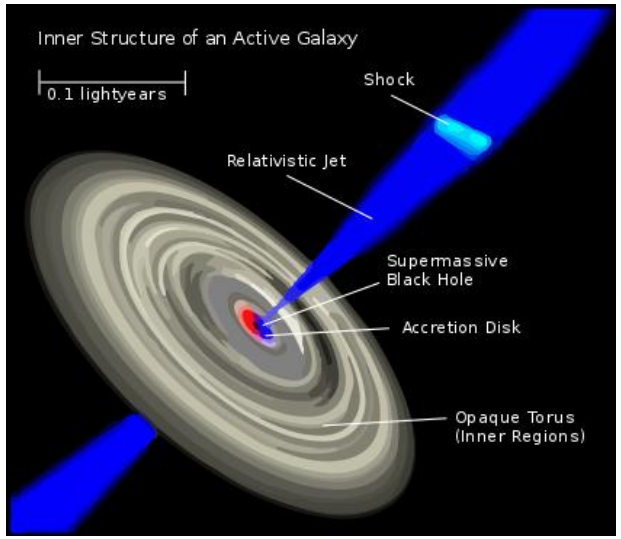
- Outflow/jet
- Shock
- Reconnection

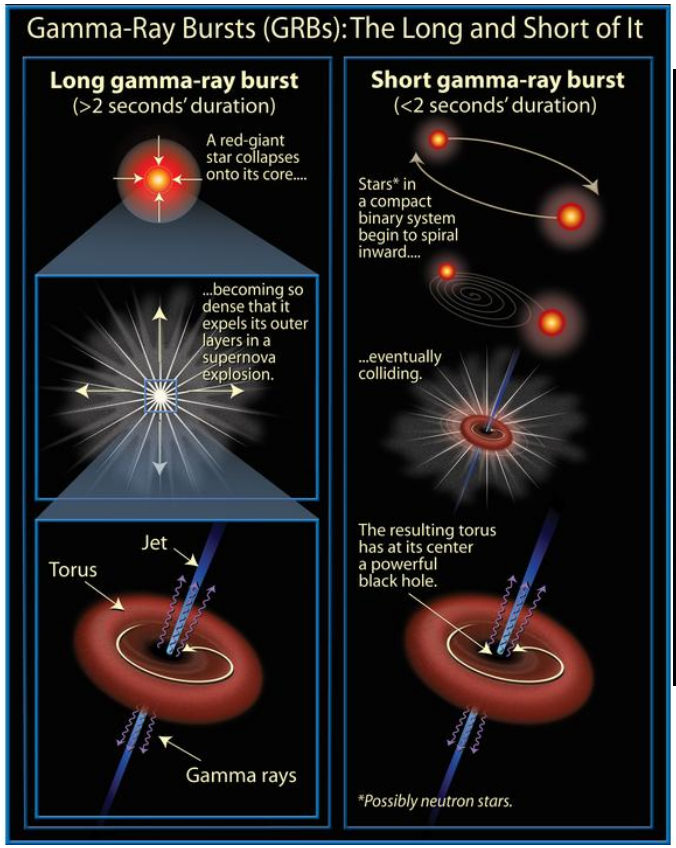
…

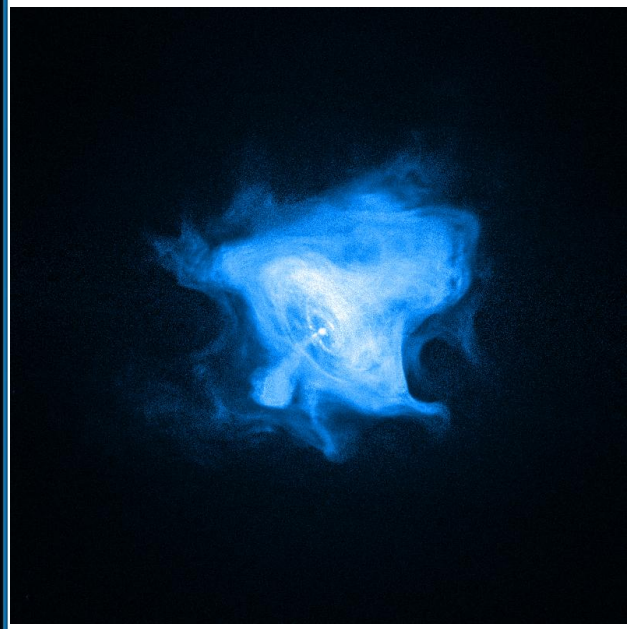
Multi-messenger transient signa

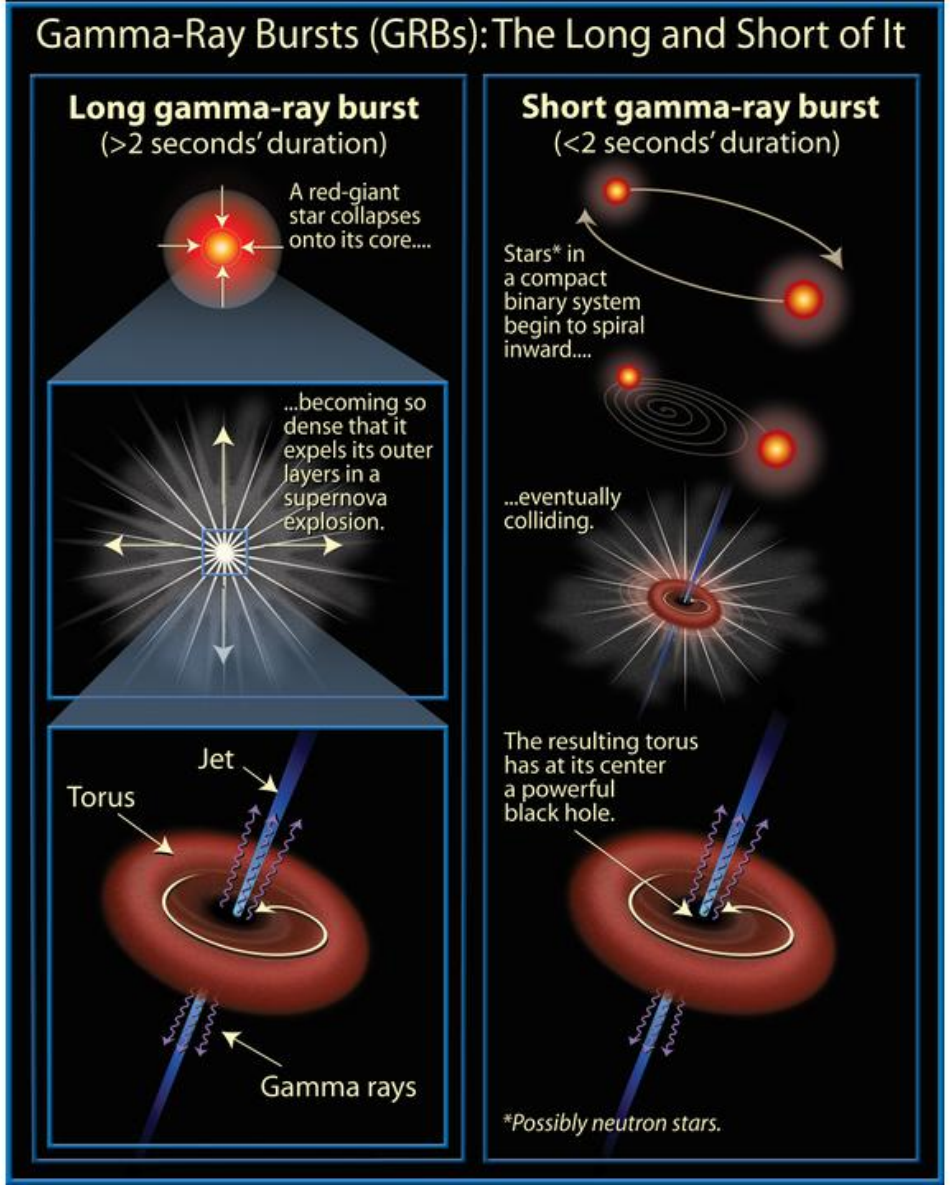
key questions of high energy astrophysics

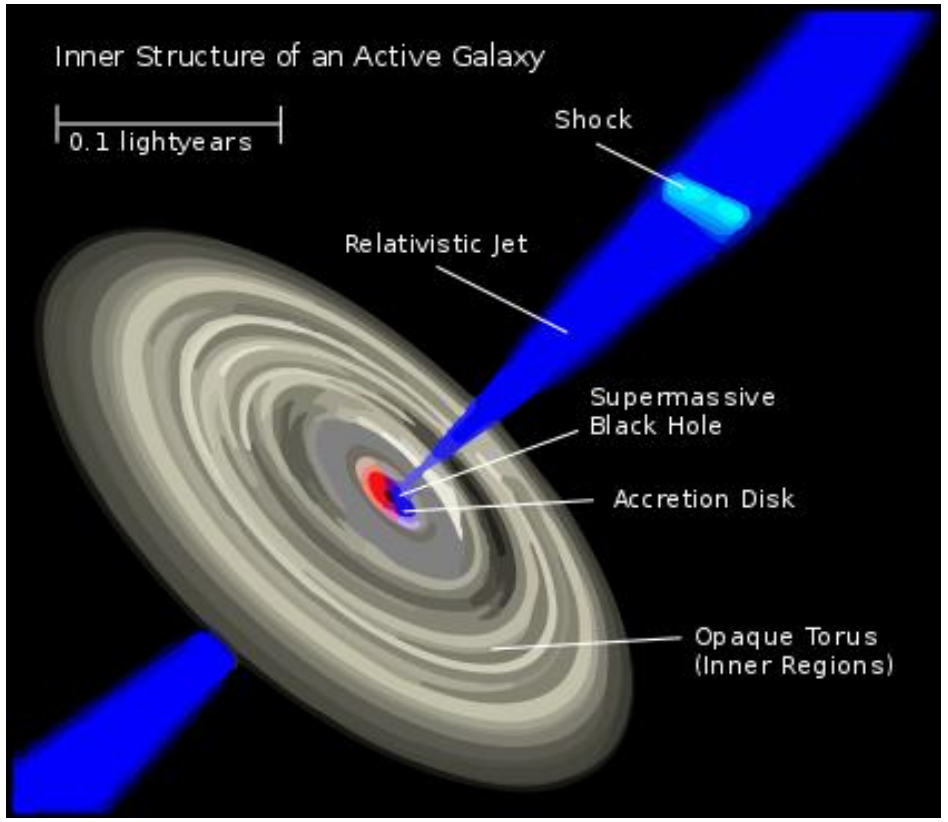
How (relativistic or non-relativistic) outflows/jets are accelerated and how is the energy converted to thermal and non-thermal radiation (EM, CR, neutrinos)? What is the central engine? → mostly compact objects (BH, NS, WD)







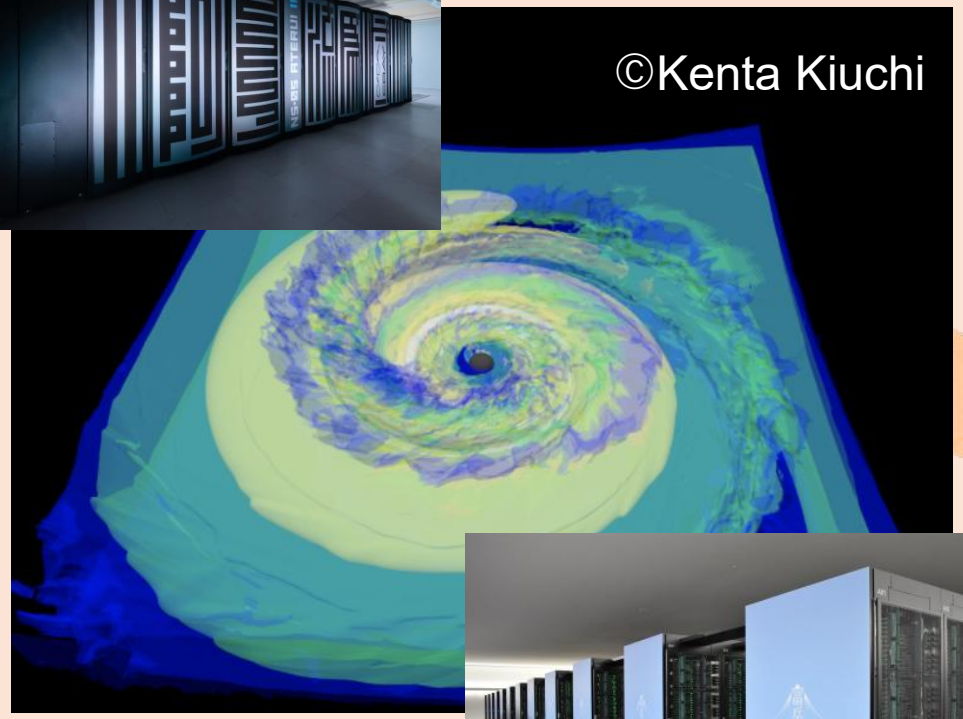


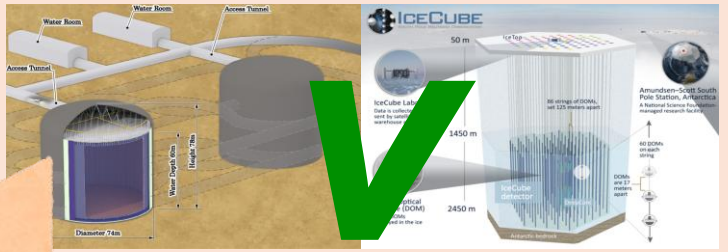


How can be the jet launched and accelerated up to 99.99% of the speed of light?

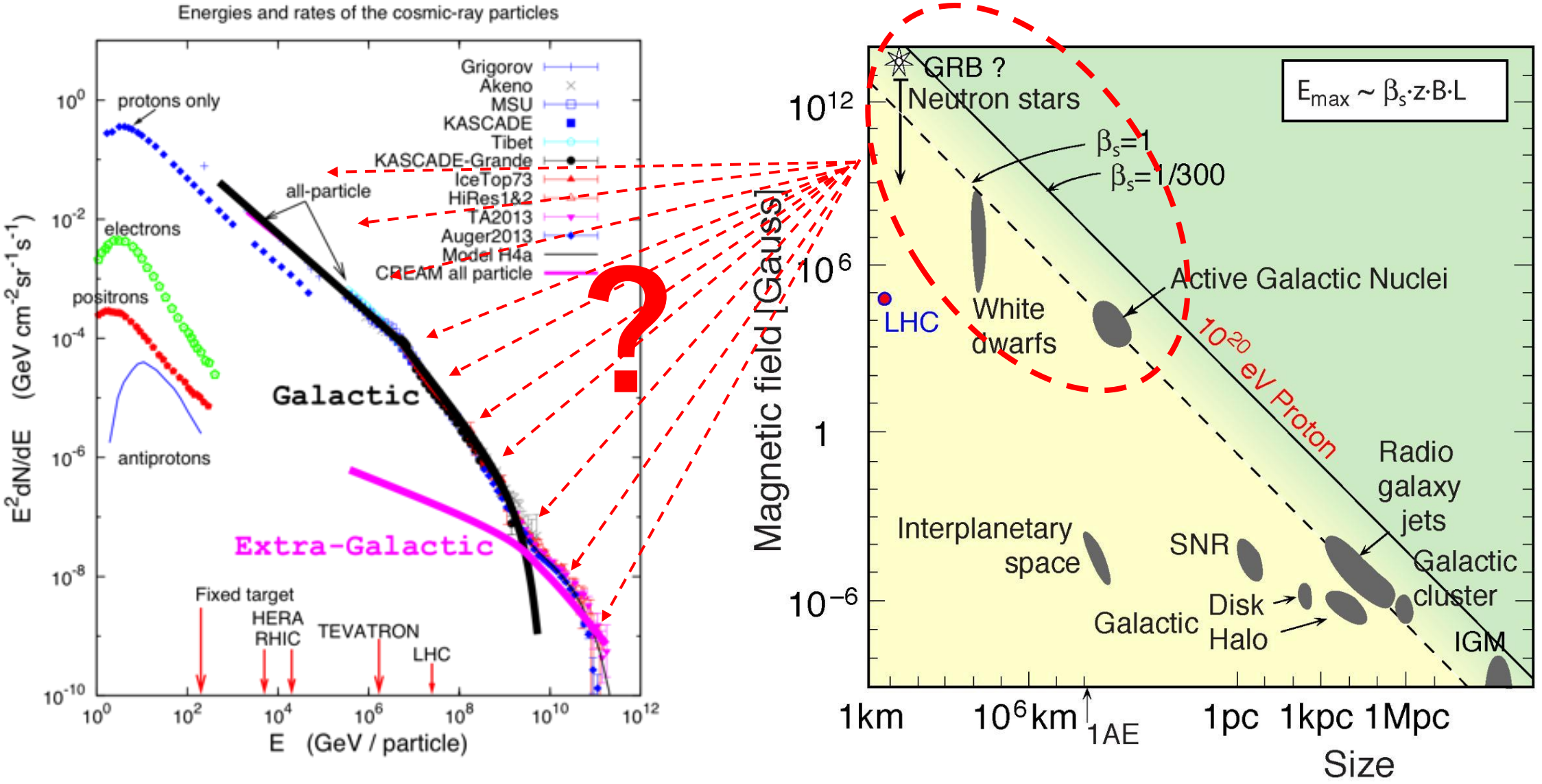
How can be the energy dissipated to produce the most luminous emission in the Universe?

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

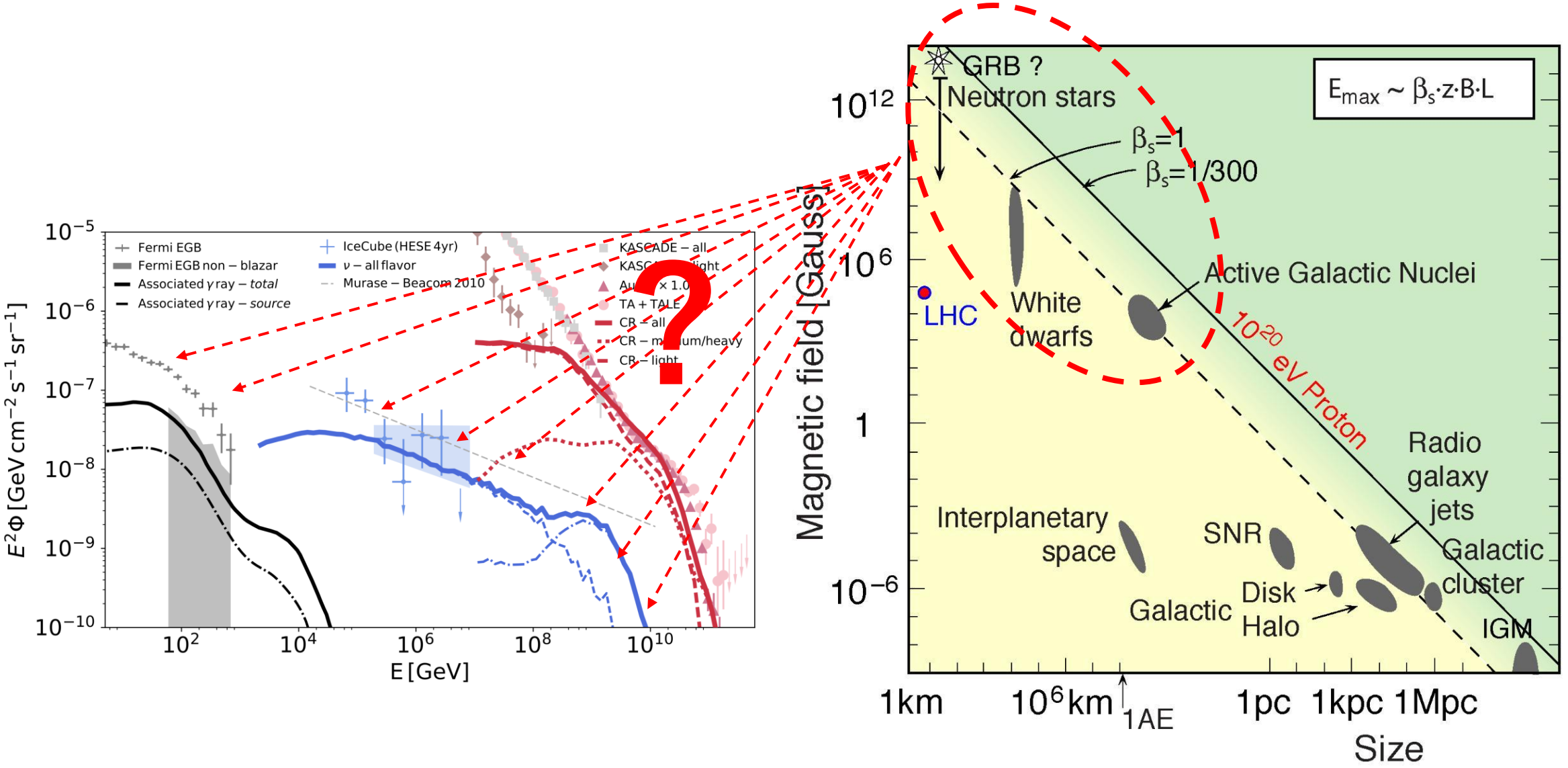




Compact objects as cosmic-ray accelerators

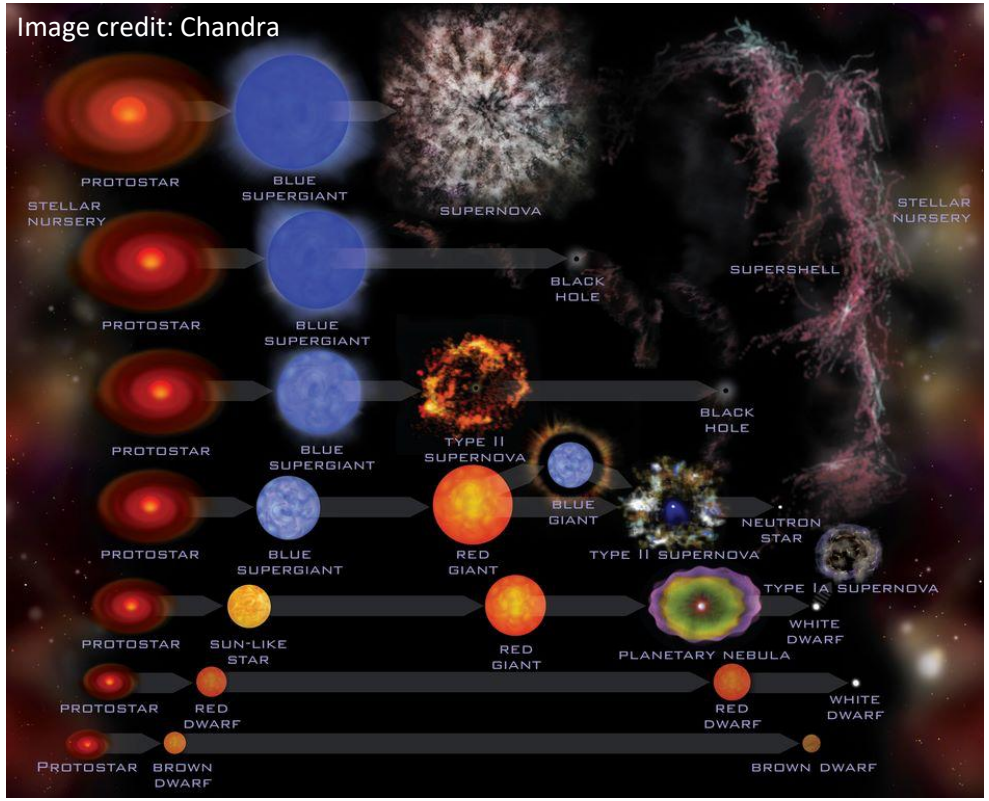


Compact objects as cosmic-ray accelerators

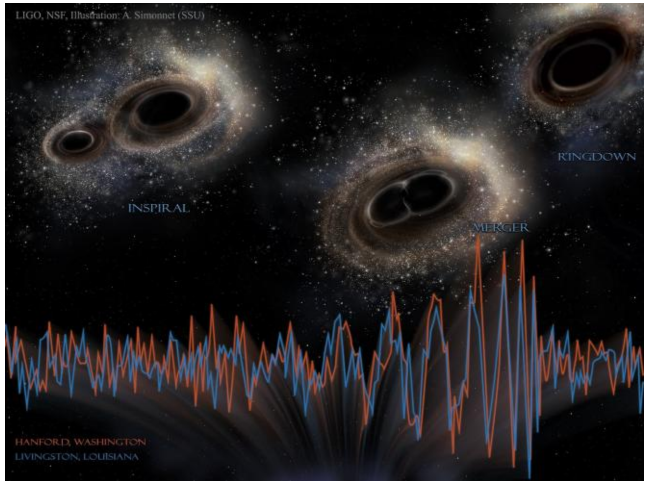


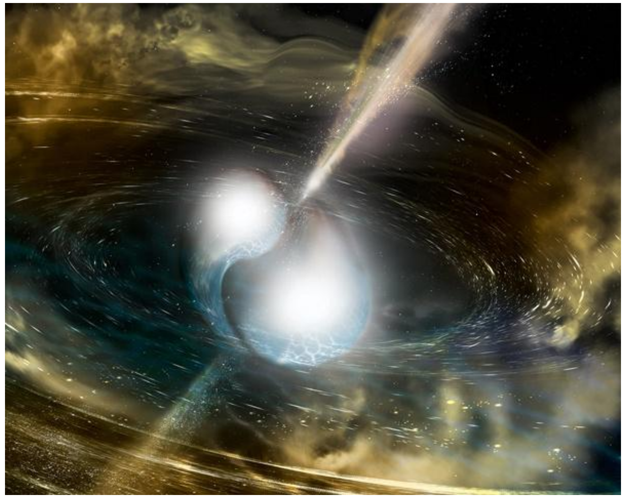
key questions of compact object astrophysics I

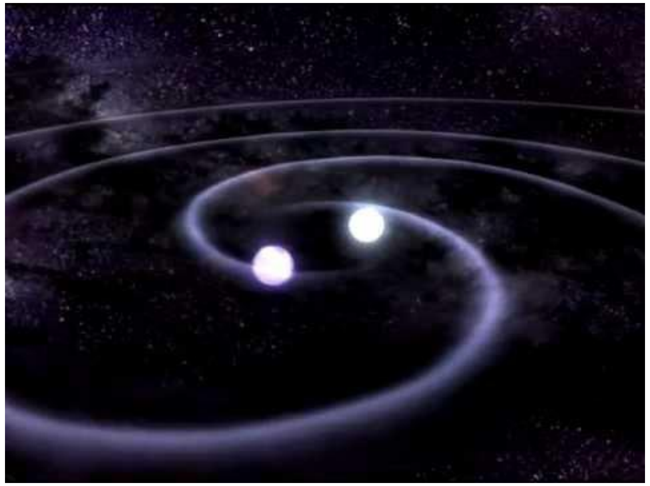
What kind of massive star (RSG, BSG, WR) produces
what kind of compact object (NS or BH? B field, rotation, disk?)
and what kind of explosive transient (SN, GRB or else) ?



key questions of compact astrophysics 2

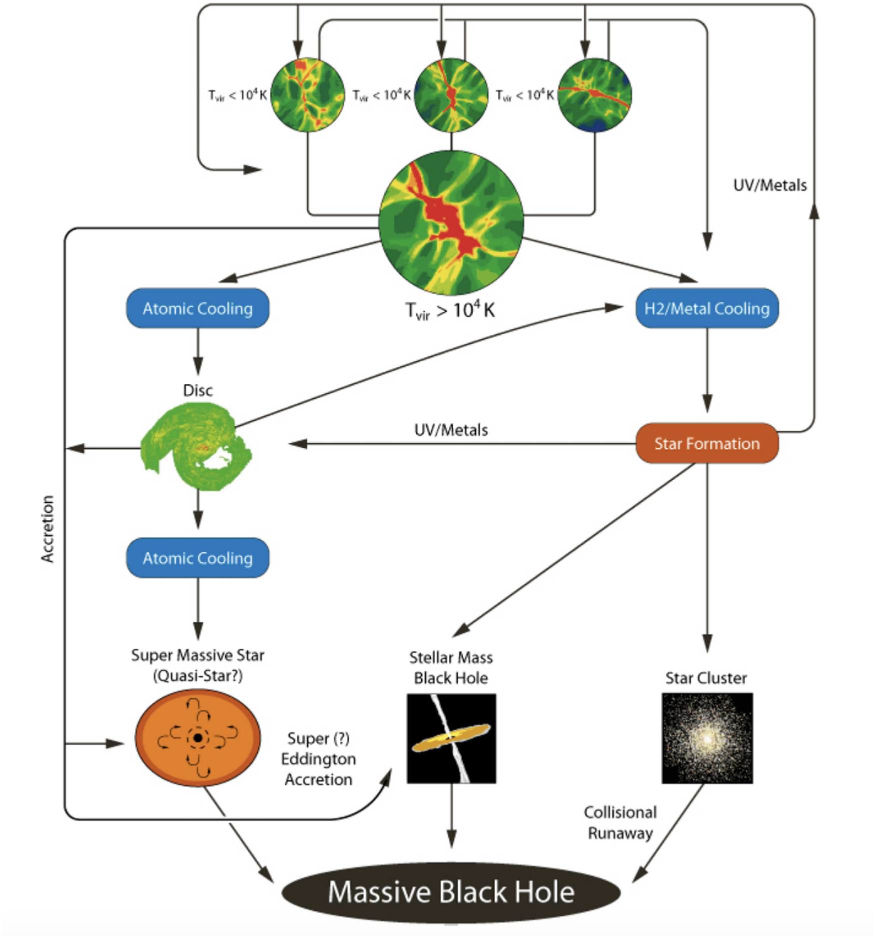


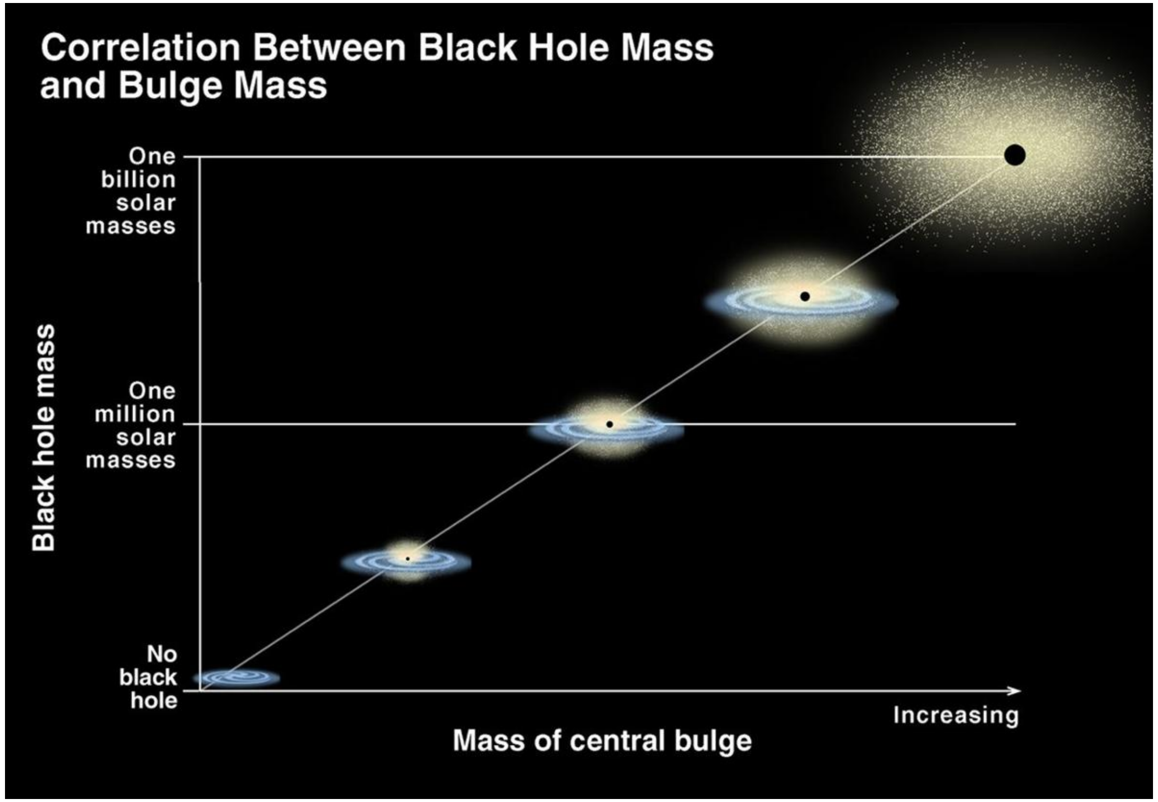


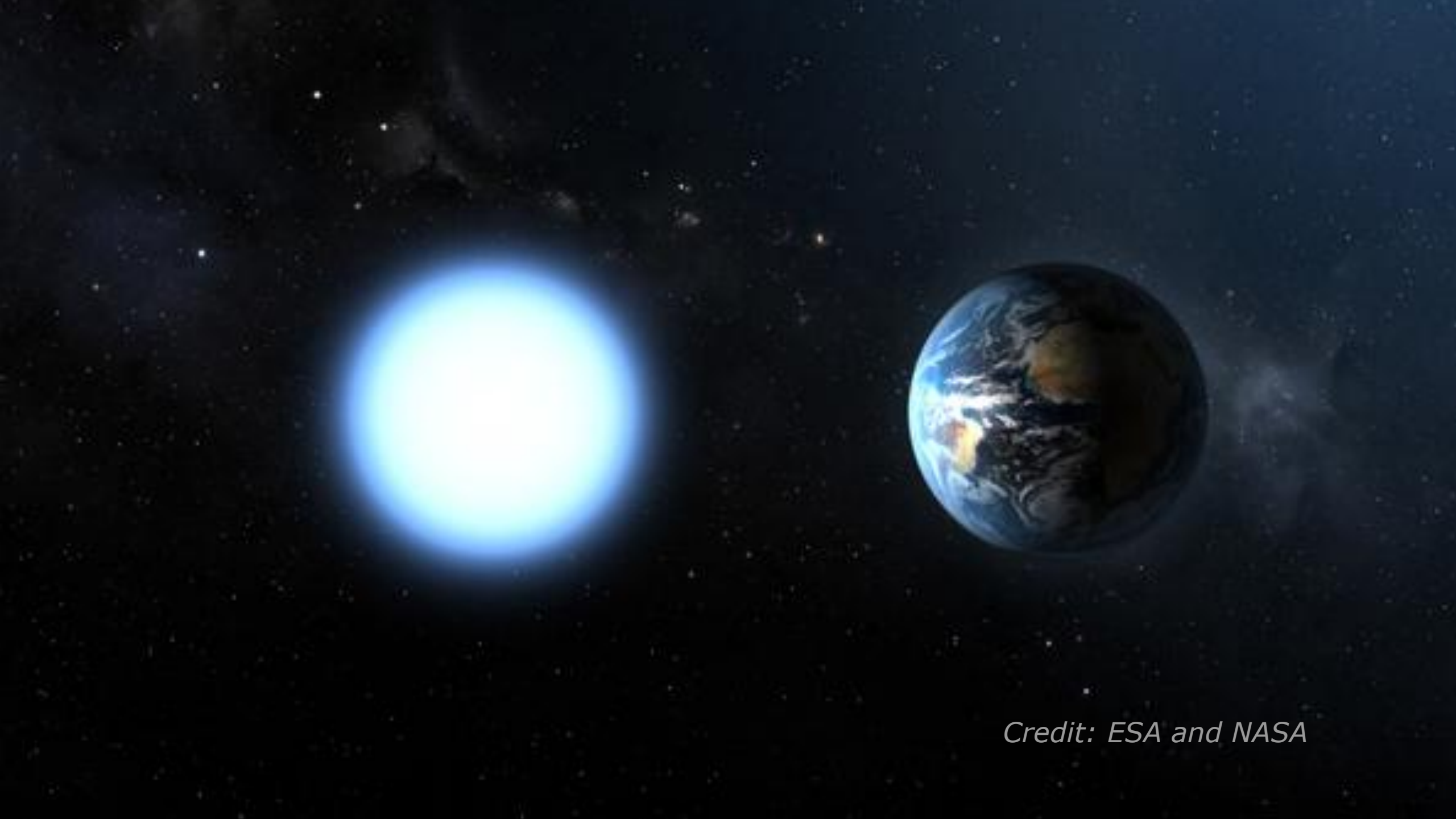


key questions of compact object astrophysics 3

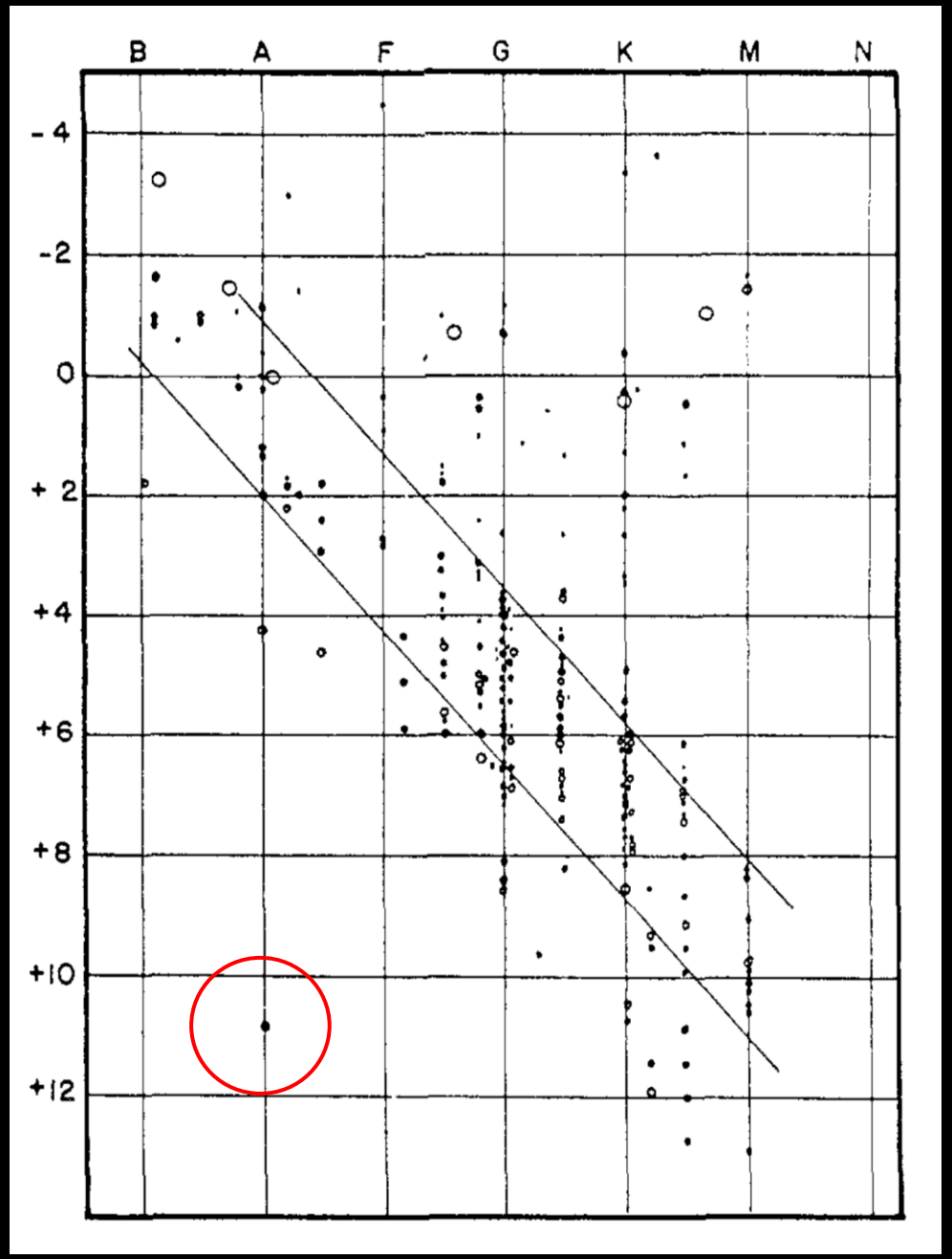
ĢŎR MǾÑŒÞŐÑǾÖMŒŒÒŅÑ NÕMŃÔ OŎÕÑŒNŎǾŌĒ
ĢŎR ŇŎŒÞŐÑǾÖMŒŒÒŅÑ NÕMŃÔ OŎÕÑŒŊÕŎR Ē



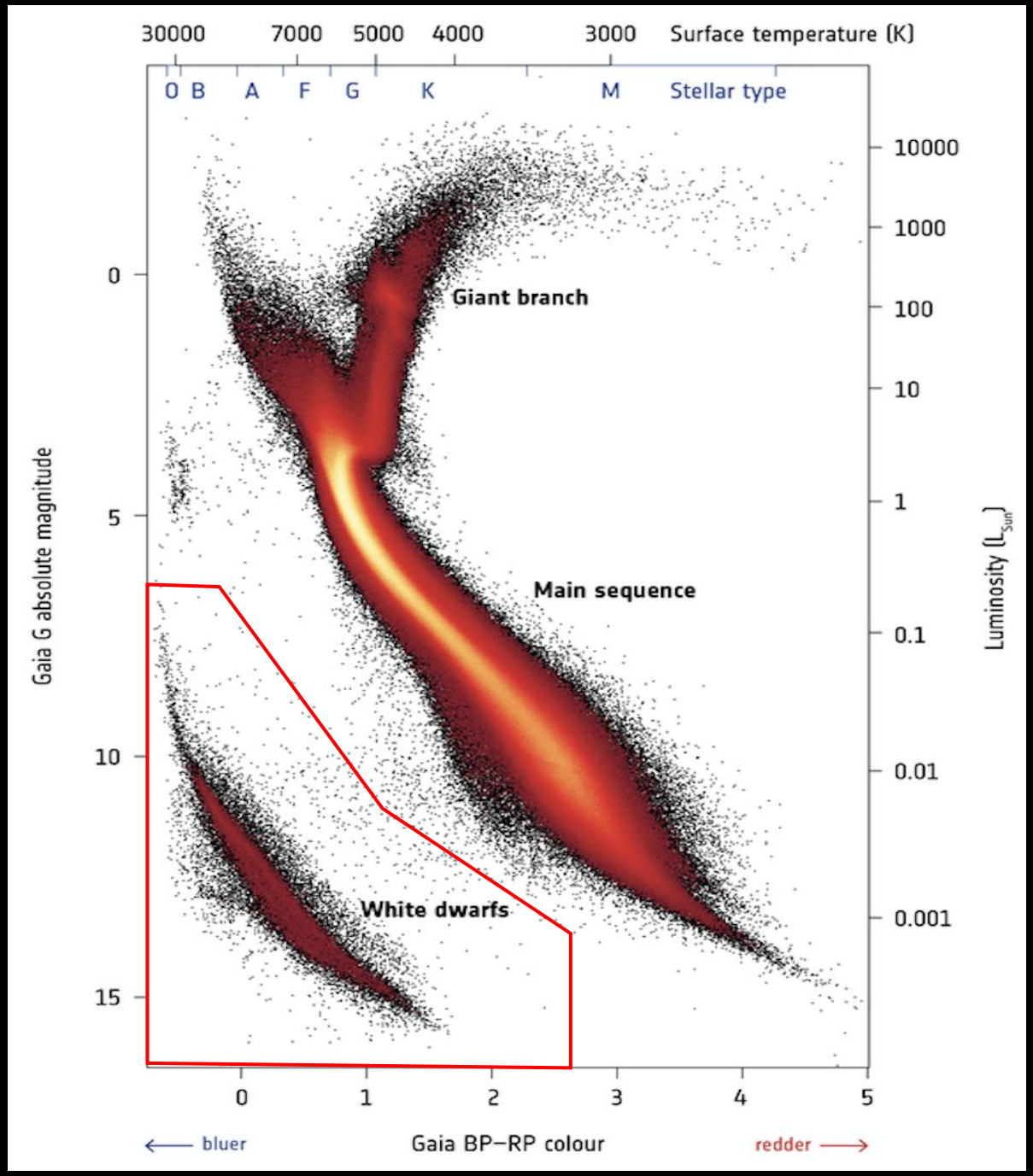




Credit: ESA and NASA

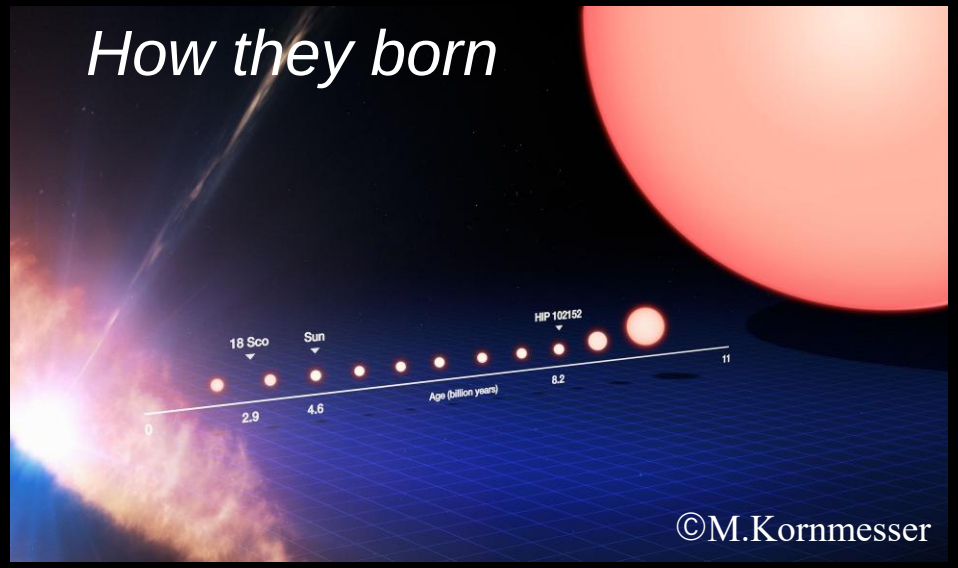


Russel 1914


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

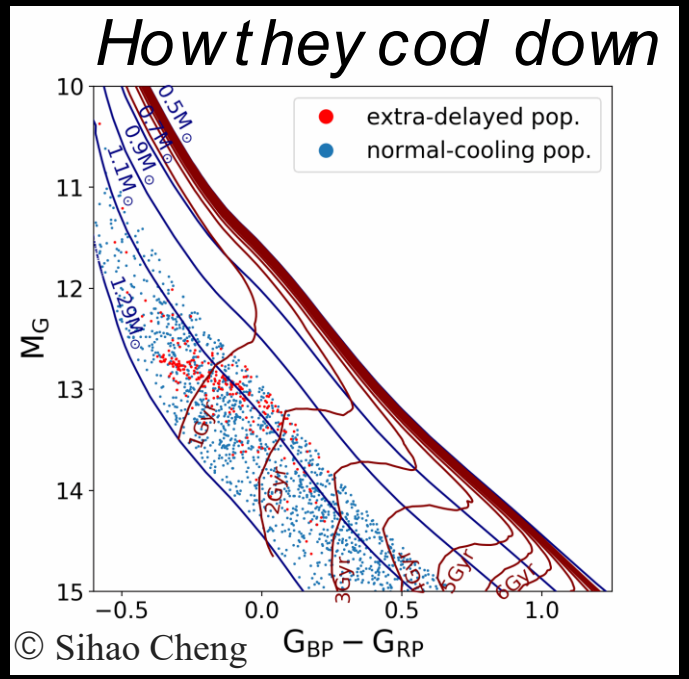
Known knowns about WDs

How they born



When they accrete gas,

How they cod down

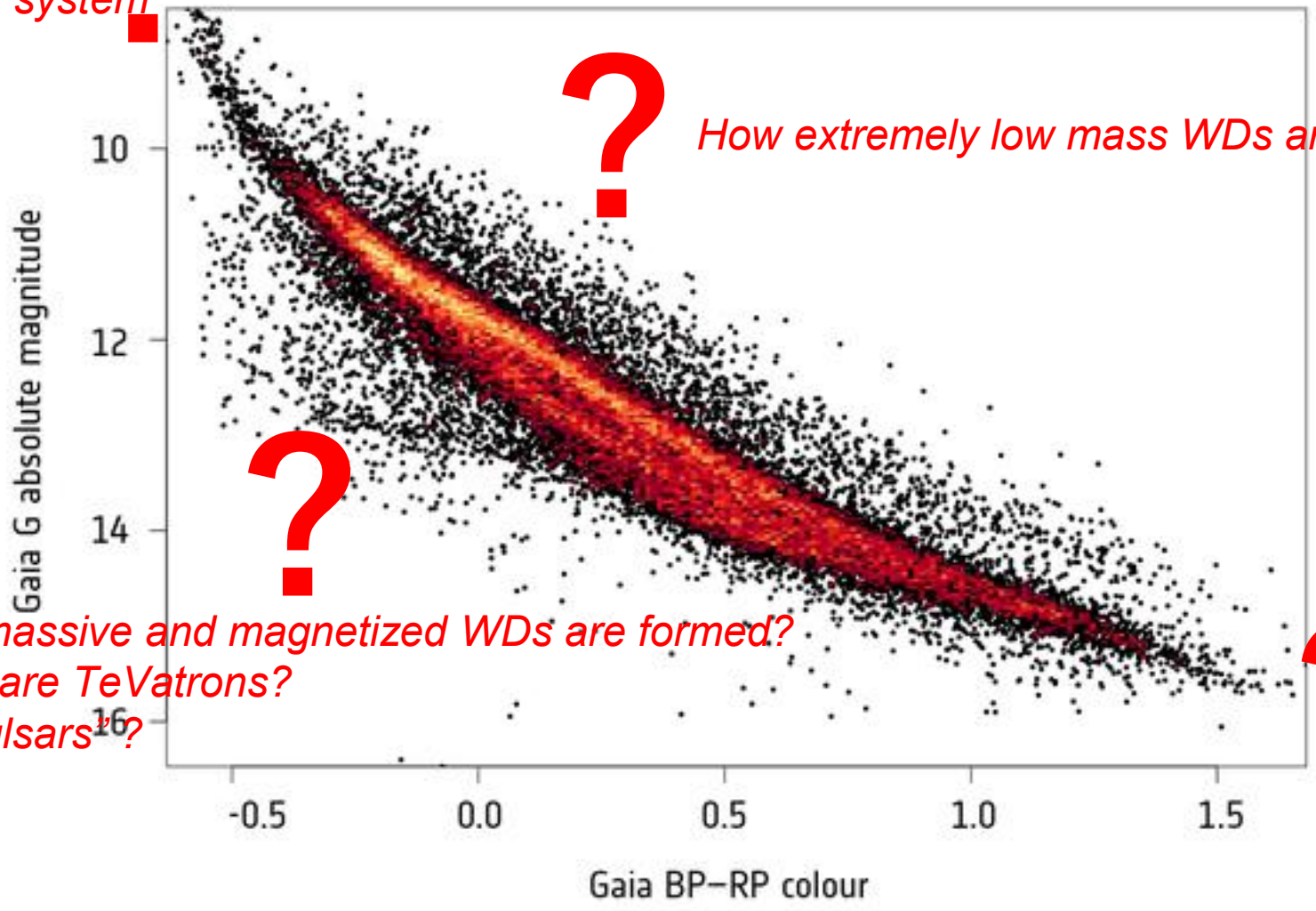


When they explode,

thermonuclear supernova!

- **Known unknowns about WDs**

WD formation in general
Future of the solar system



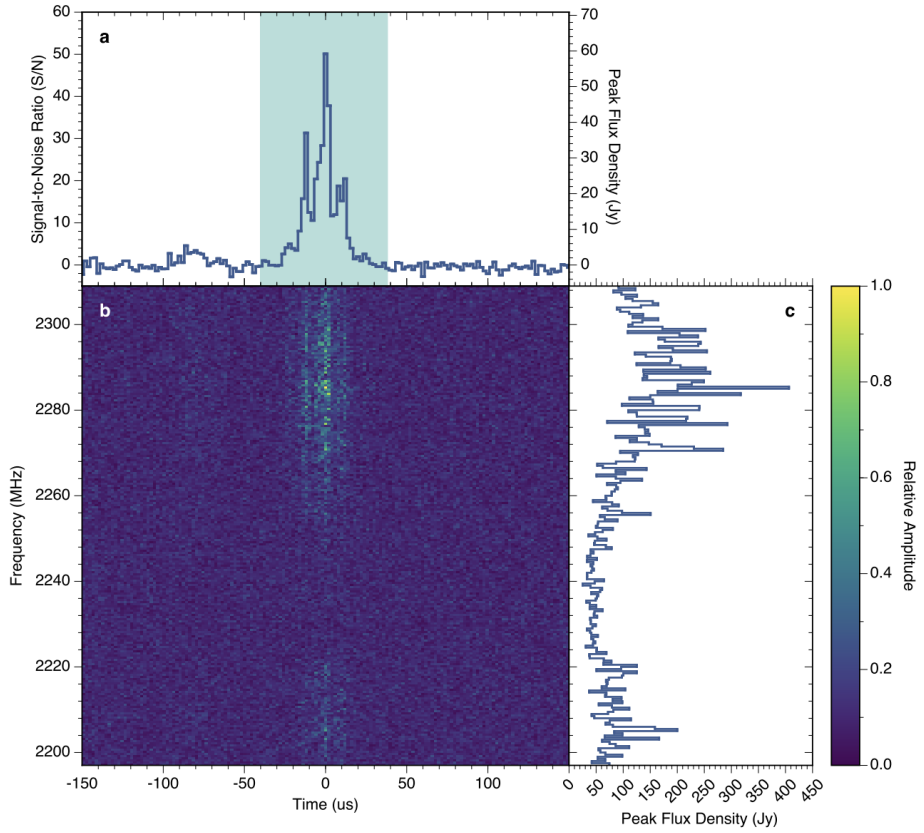
How extremely low mass WDs are formed?

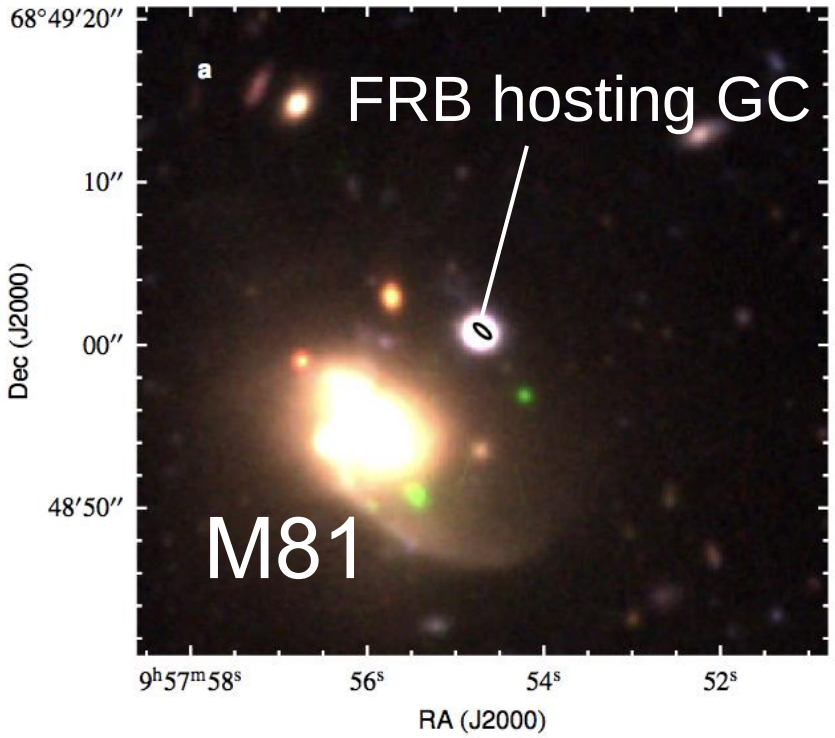
How the most massive and magnetized WDs are formed?
Accreting WDs are TeVatrons?
White dwarf "pulsars"?

Oldest white dwarfs
How they are?
Where they are?

Super Chandrasekhar WDs collapse into NSs?

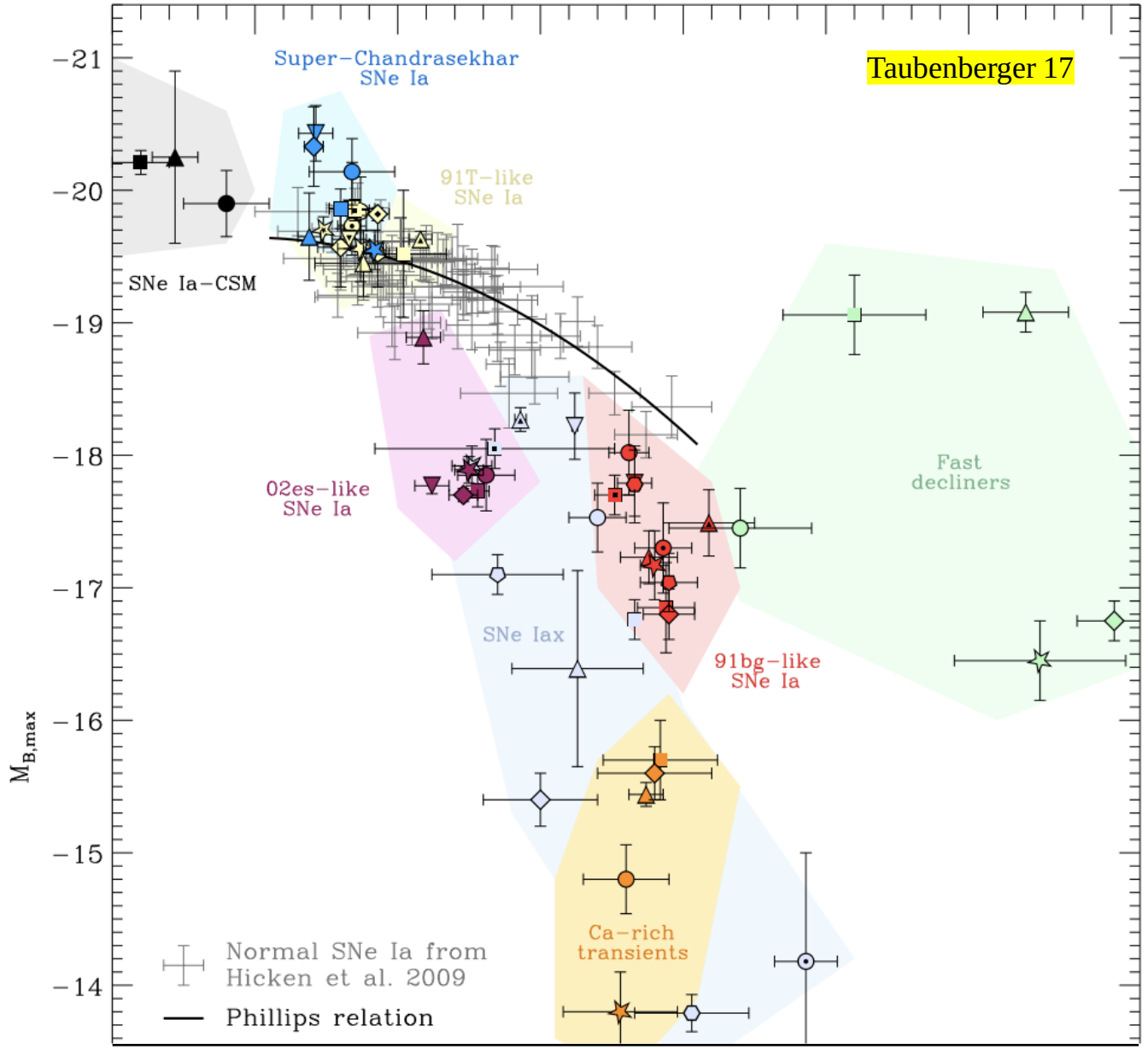
c.f., a repeating FRB source in a globular cluster (GC)



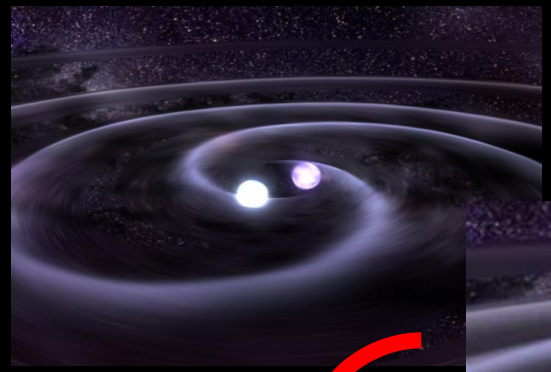


Kirsten et al. 21; Nimmo et al. 21;…

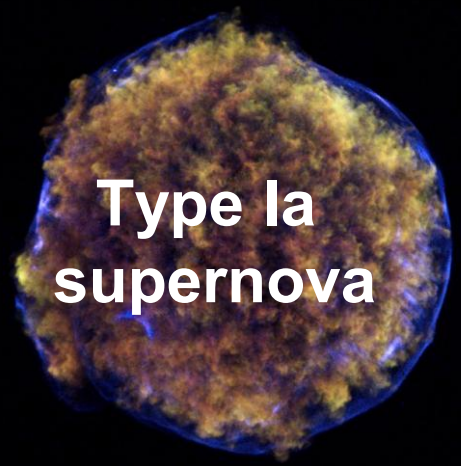
When and how are transients powered by radioactivity?

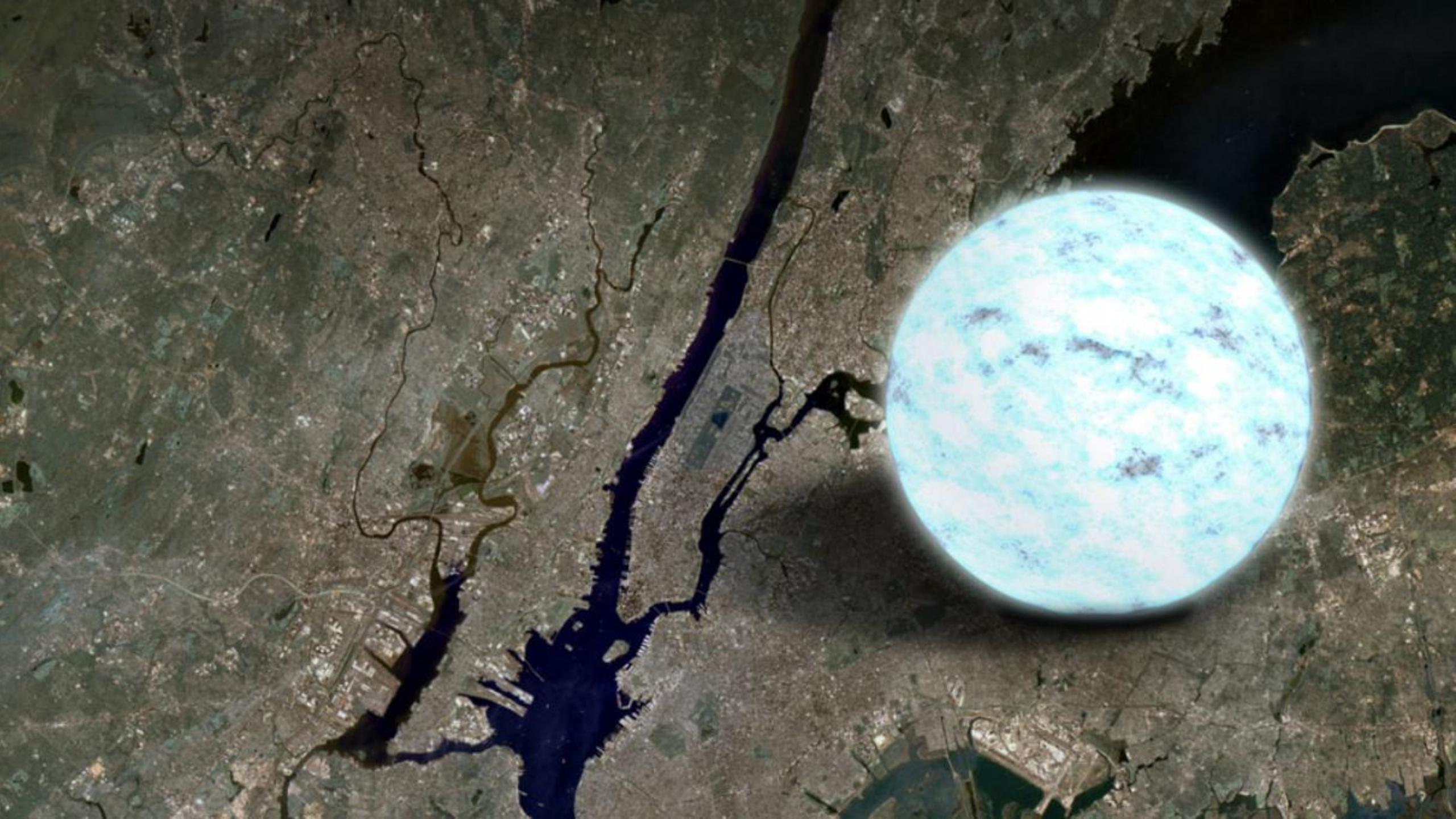


Binary WD mergers and their remnants



mHz GWs





NATURE, VOL. 217, FEBRUARY 24, 1968

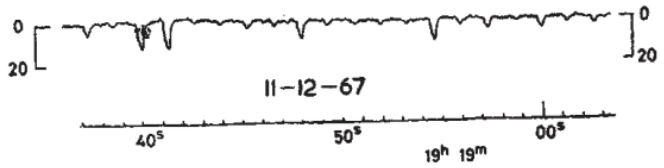
Observation of a Rapidly Pulsating Radio Source

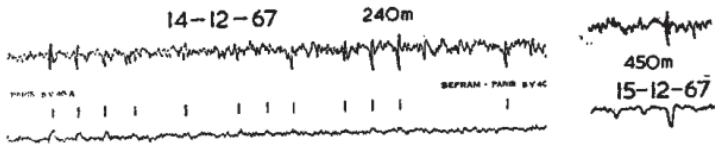
by

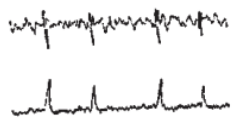
A. HEWISH
S. J. BELL
J. D. H. PILKINGTON
P. F. SCOTT
R. A. COLLINS

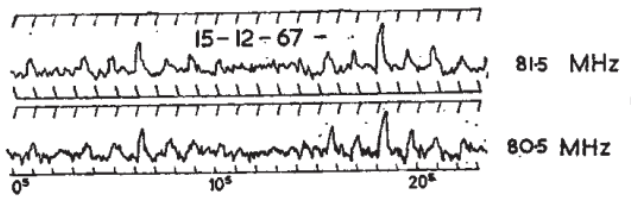
Mullard Radio Astronomy Observatory,
Cavendish Laboratory,
University of Cambridge

Unusual signals from pulsating radio sources have been recorded at the Mullard Radio Astronomy Observatory. The radiation seems to come from local objects within the galaxy, and may be associated with oscillations of white dwarf or neutron stars.

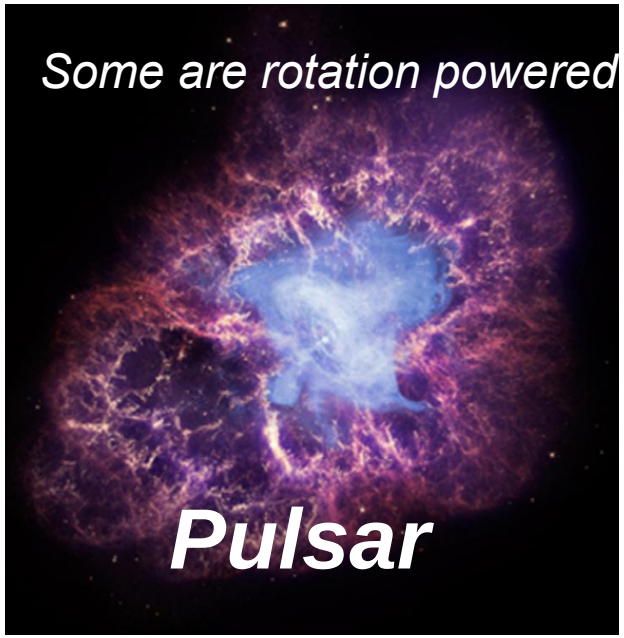


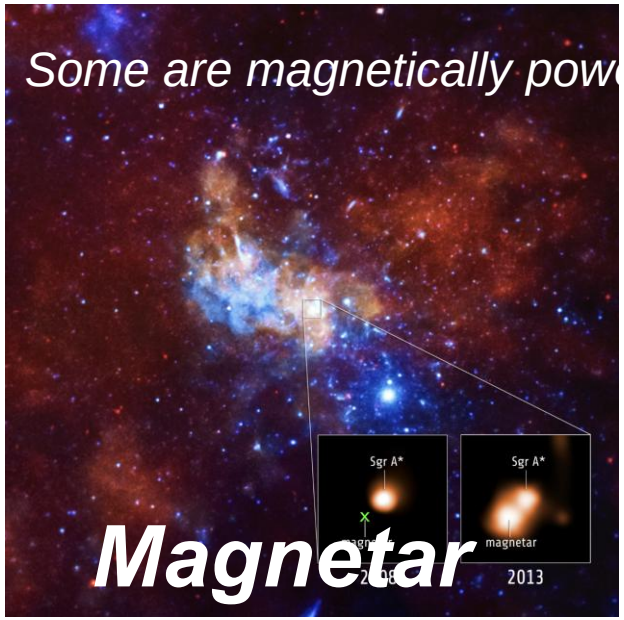


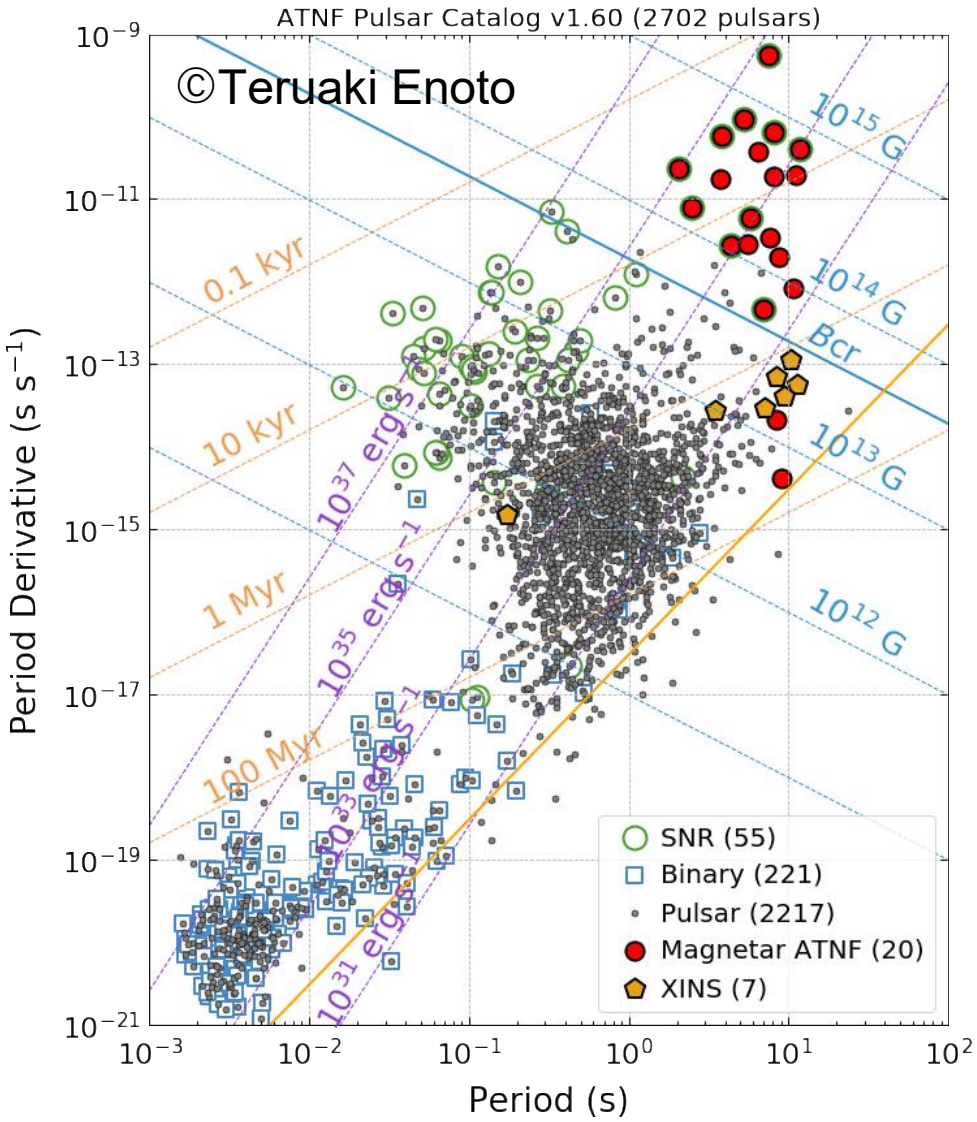


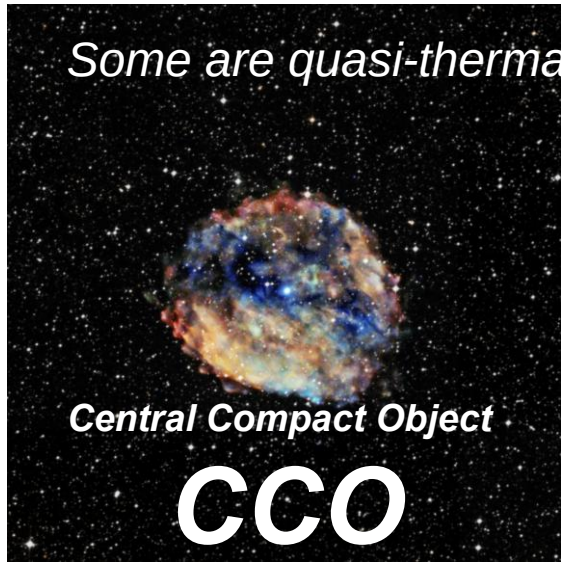


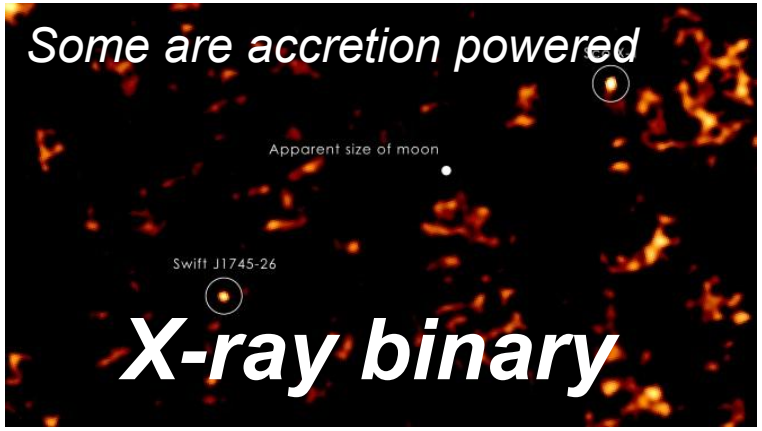
Known knowns about NSs





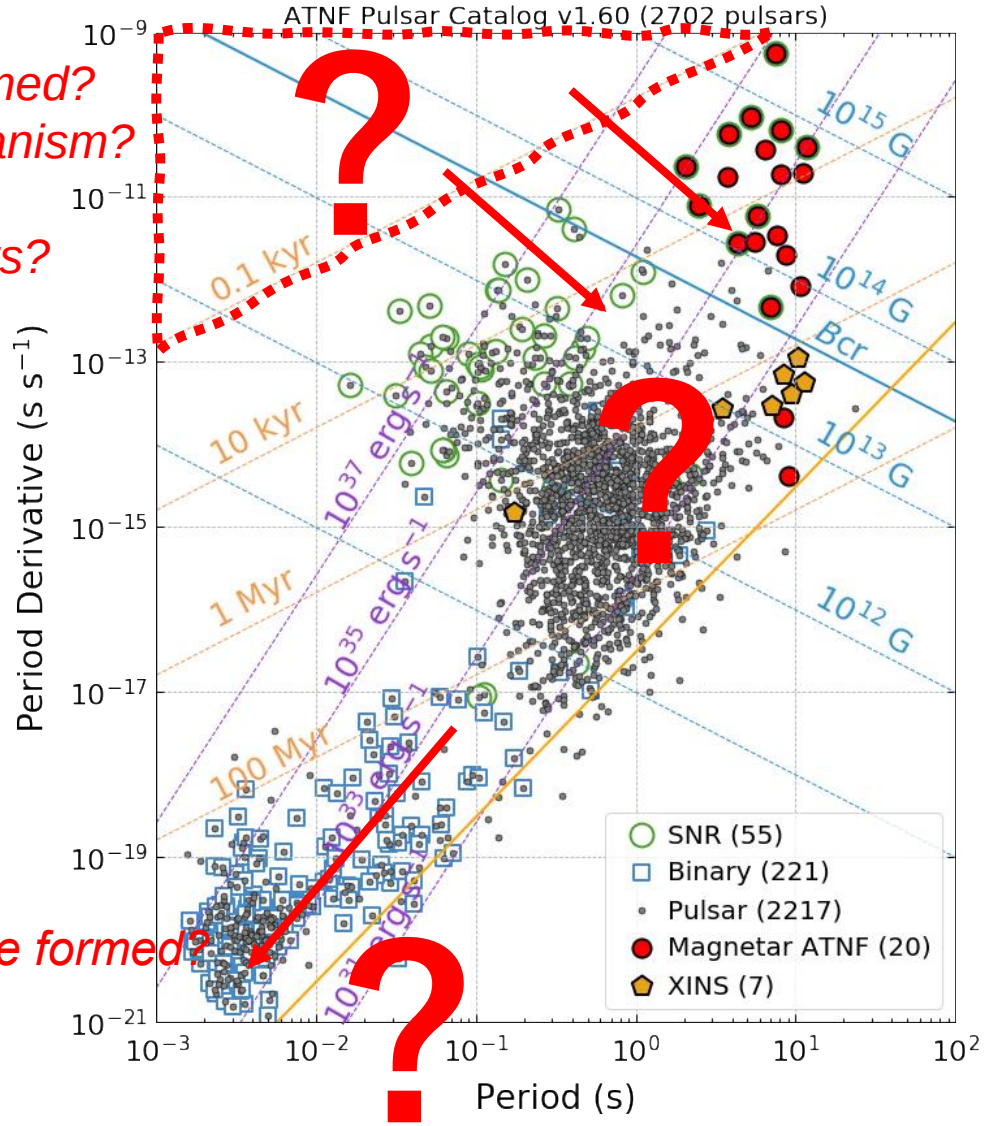






• Known unknowns about NSs

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



How to form ultra-long-period ones?

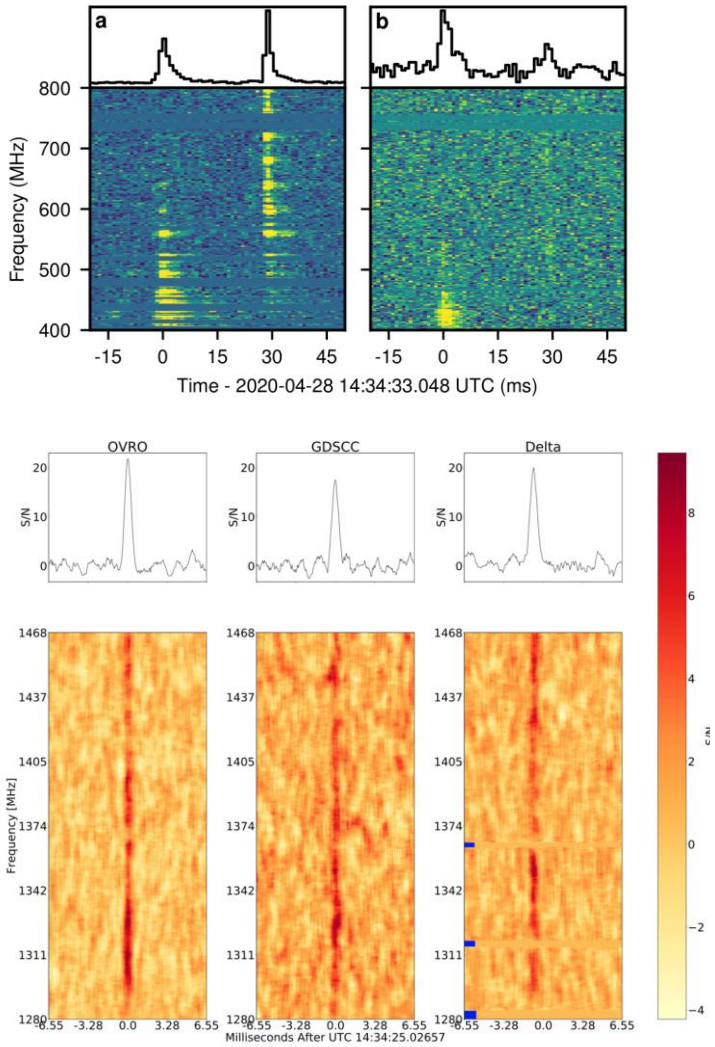
How and when binary NSs are formed?
Ultraluminous X-ray pulsars?
Short gamma-ray bursts?

Particle acceleration & emission mech

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

FRBs from a Galactic magnetar

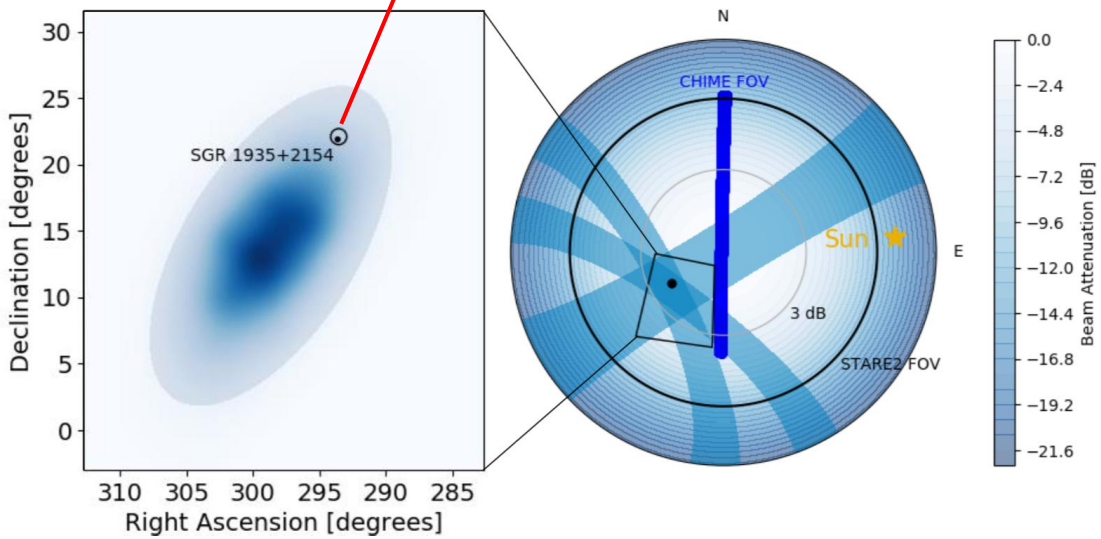
FRB200428 from SGR 1935+2154 detected by CHIME (~kJy @ 400-800 MHz) and STARE2 (~Mega Jy @



$$P = 3.25\,\mathrm{s}$$

$$\dot{P} = 1.4 \times 10^{-11}\,\mathrm{s}\cdot\mathrm{s}^{-1}$$

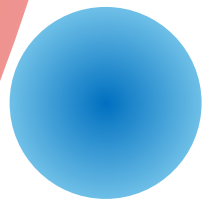
$$B_\mathrm{d} = 2.2 \times 10^{14}\,\mathrm{G}$$

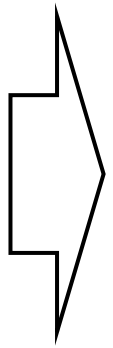


The CHIME/FRB Collaboration et al. 20;
Bochenek et al.20

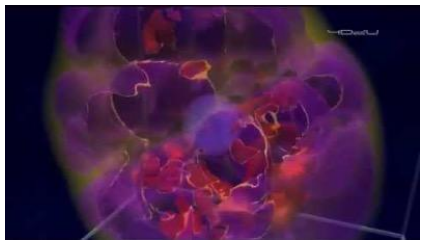
Diversity in NS formation and associated transients

Red supergiant (RSG)

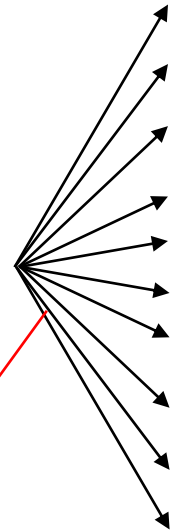




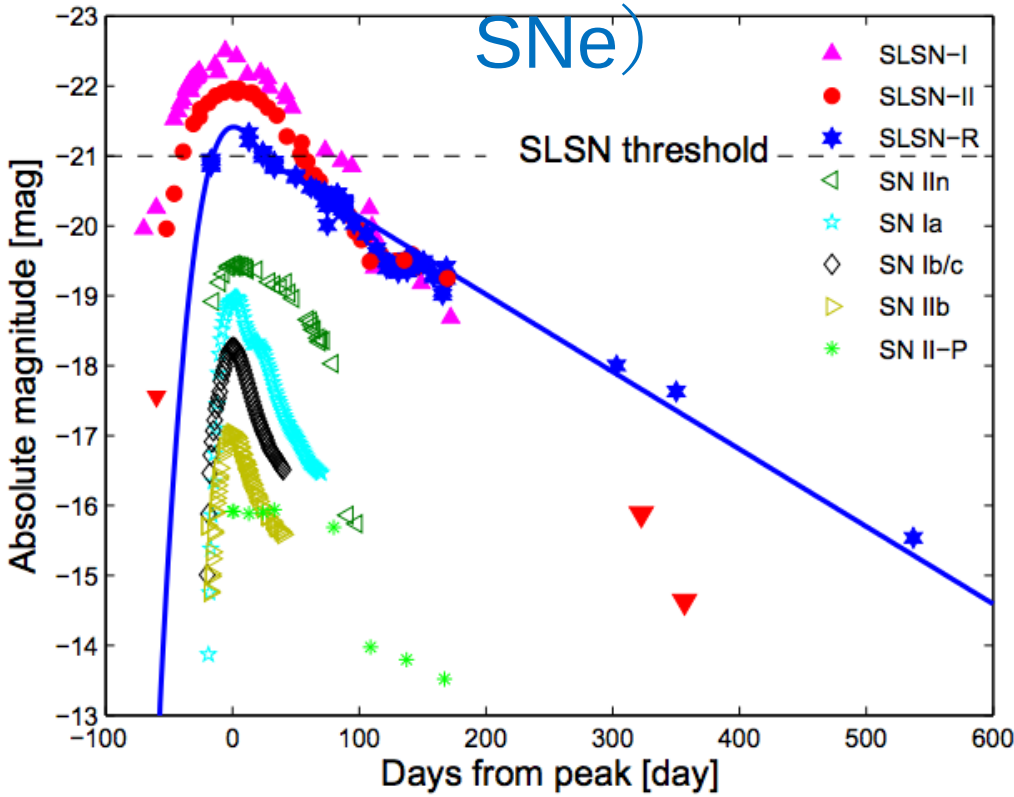
v,GW



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

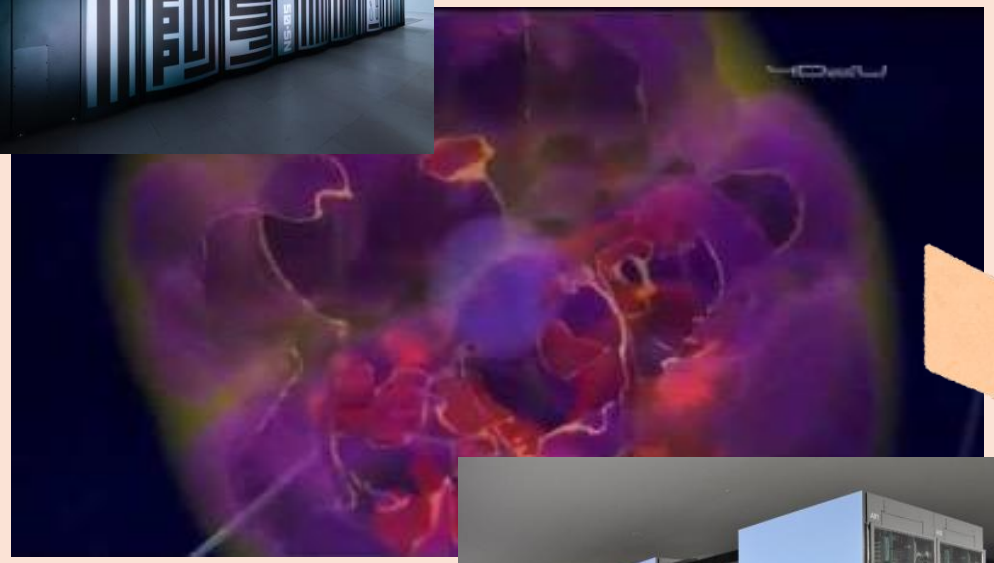


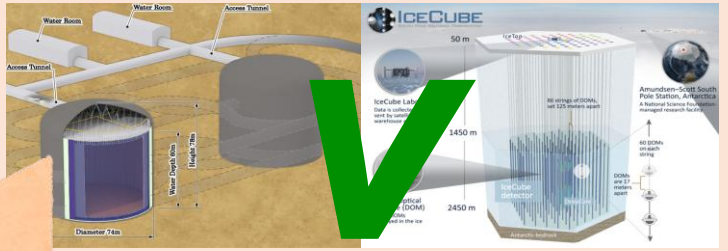
Thermal（UV/opt/IR SNe）

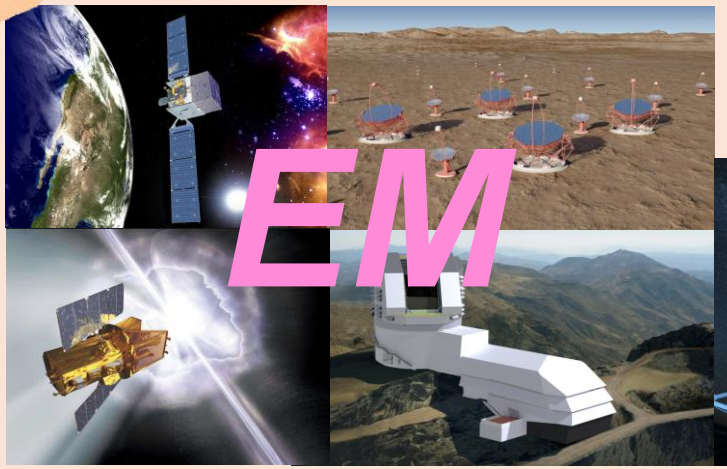


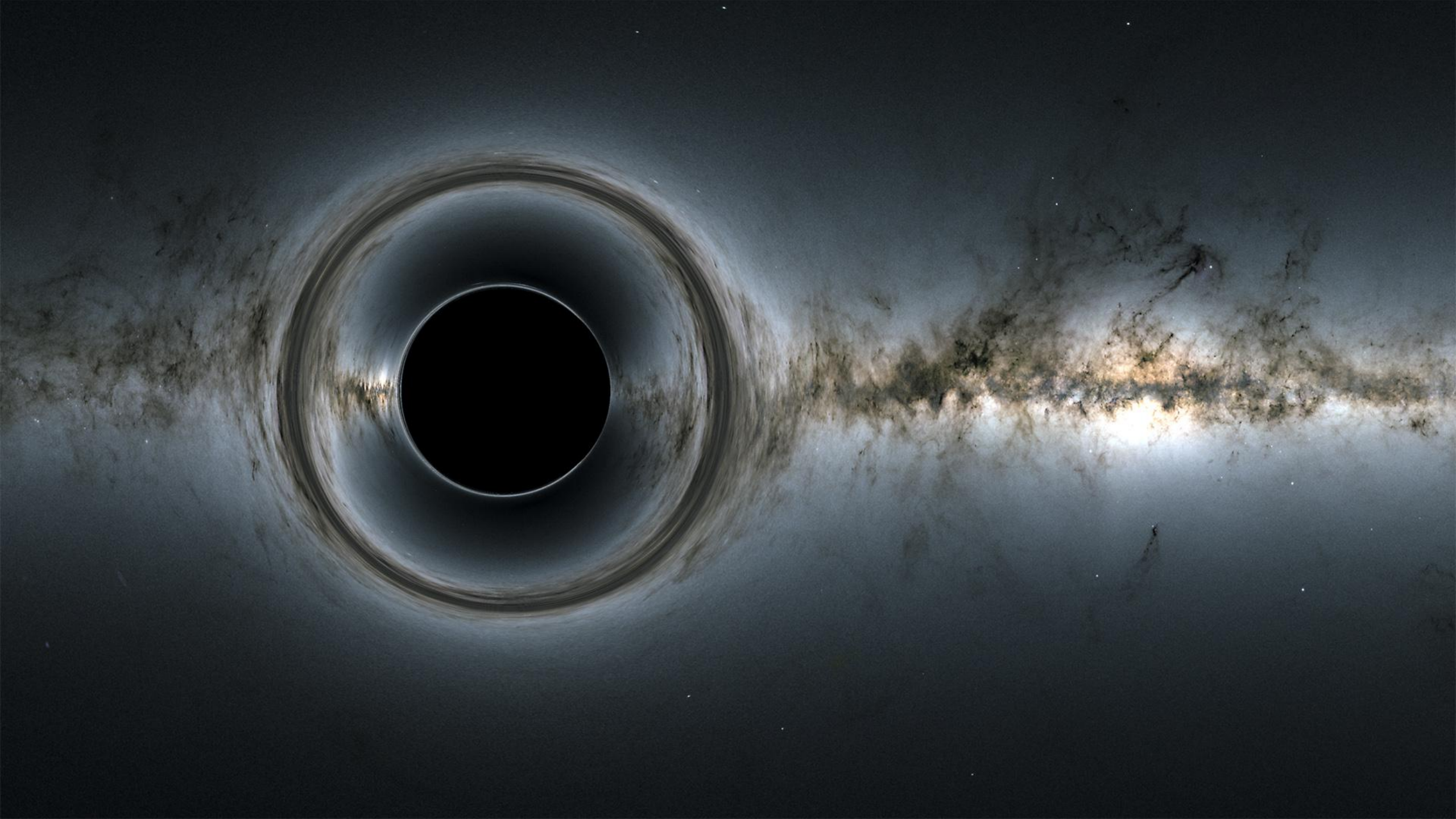
+ Non-thermal radiation (X, γ, ν, CR)

Won’t miss the next Galactic event!







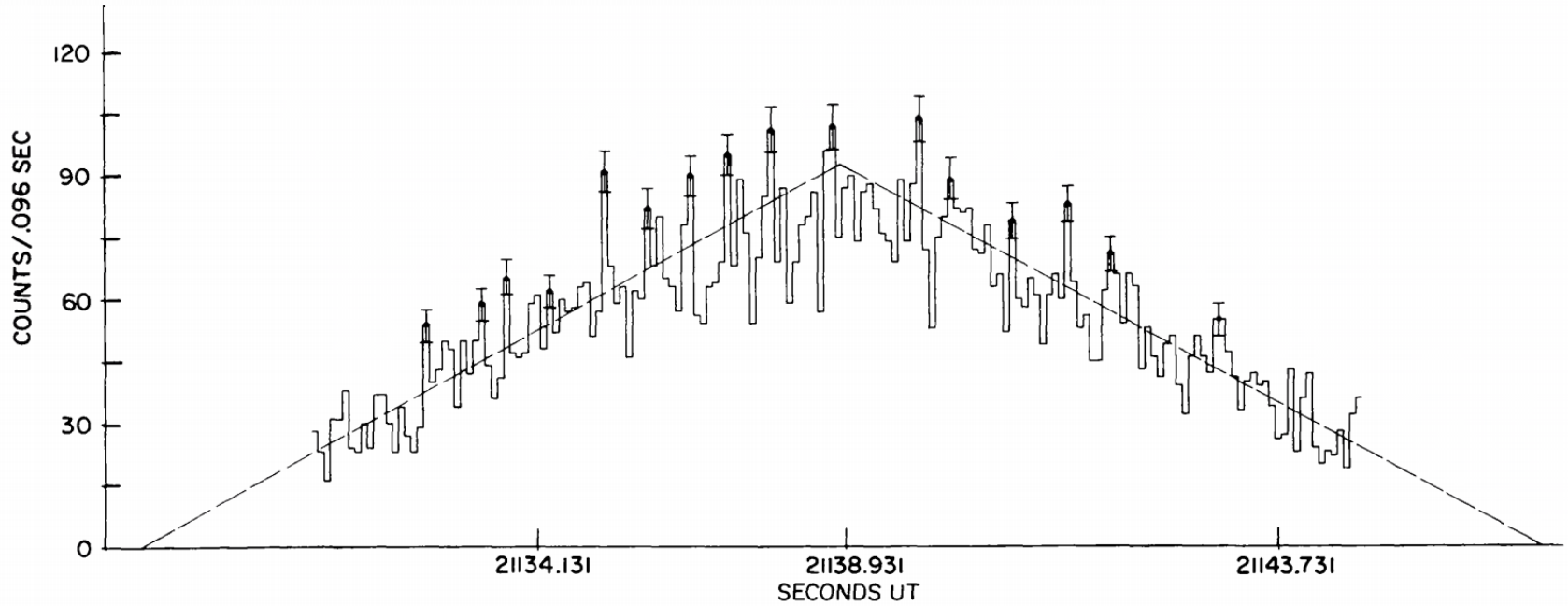


X-RAY PULSATIONS FROM CYGNUS X-1 OBSERVED FROM *UHURU*

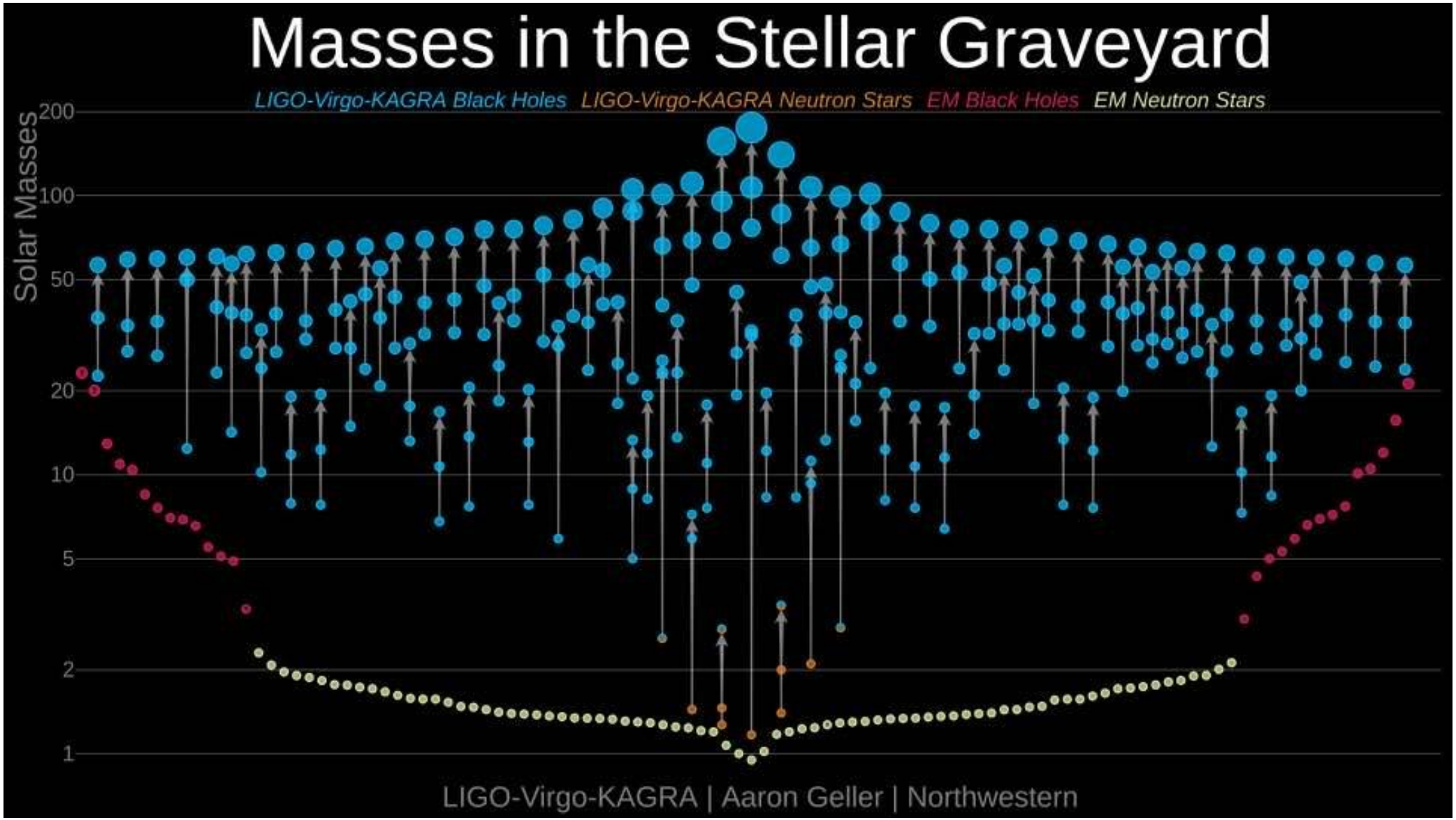
M. ODA,* P. GORENSTEIN, H. GURSKY, E. KELLOGG,
E. SCHREIER, H. TANANBAUM, AND R. GIACCONI
American Science and Engineering, Inc., Cambridge, Mass. 02142
Received 1971 March 22

ABSTRACT

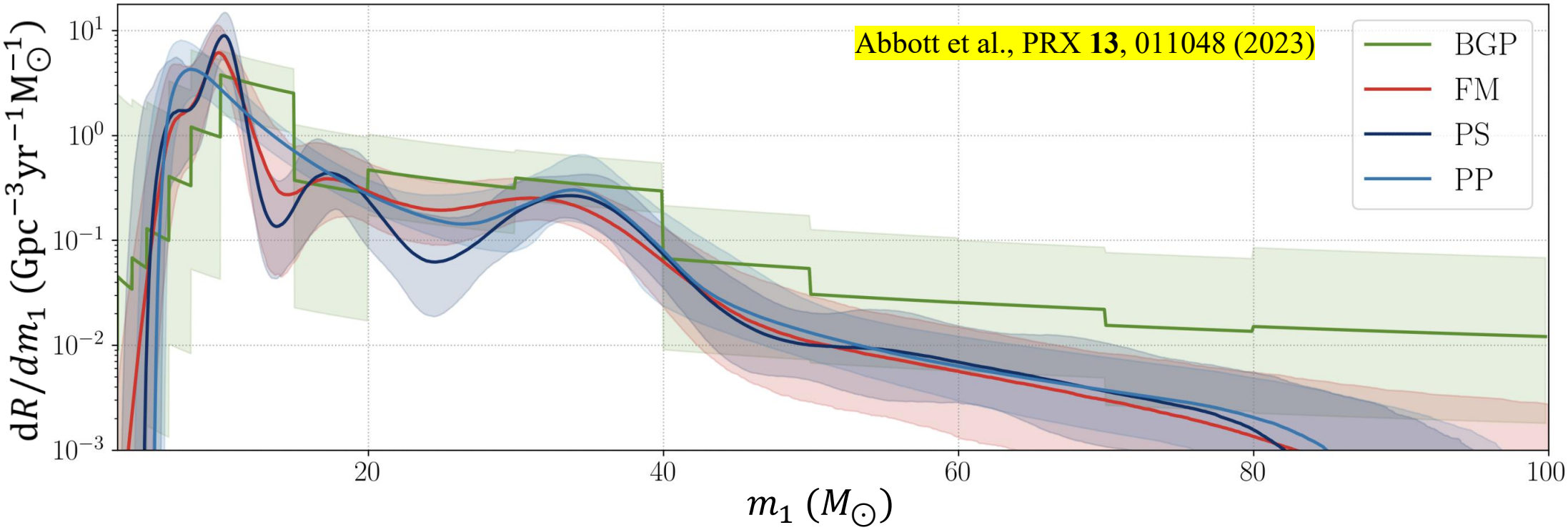
We have observed from *Uhuru* large-amplitude X-ray pulsations from Cyg X-1, which occur several times a second with a duration of less than a fraction of a second. The amplitude of the pulsations at times exceeds 25 percent of the average source intensity. The pulsations do not occur at random. Although 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



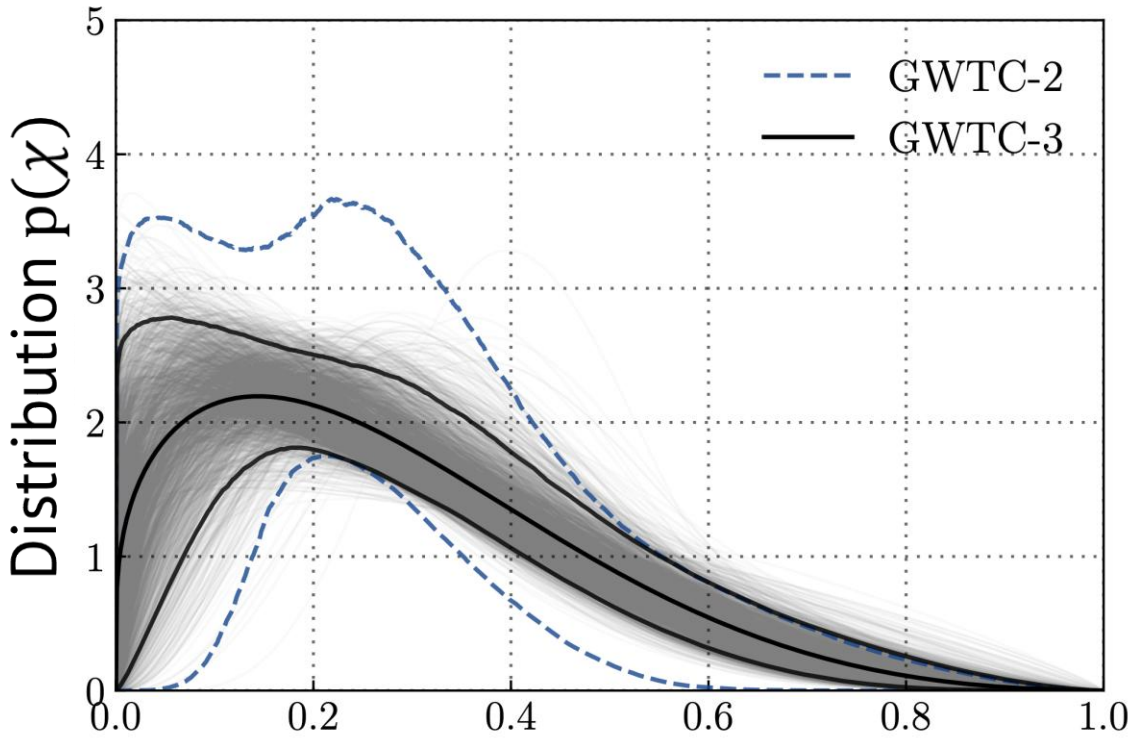
BBH distribution: Mass

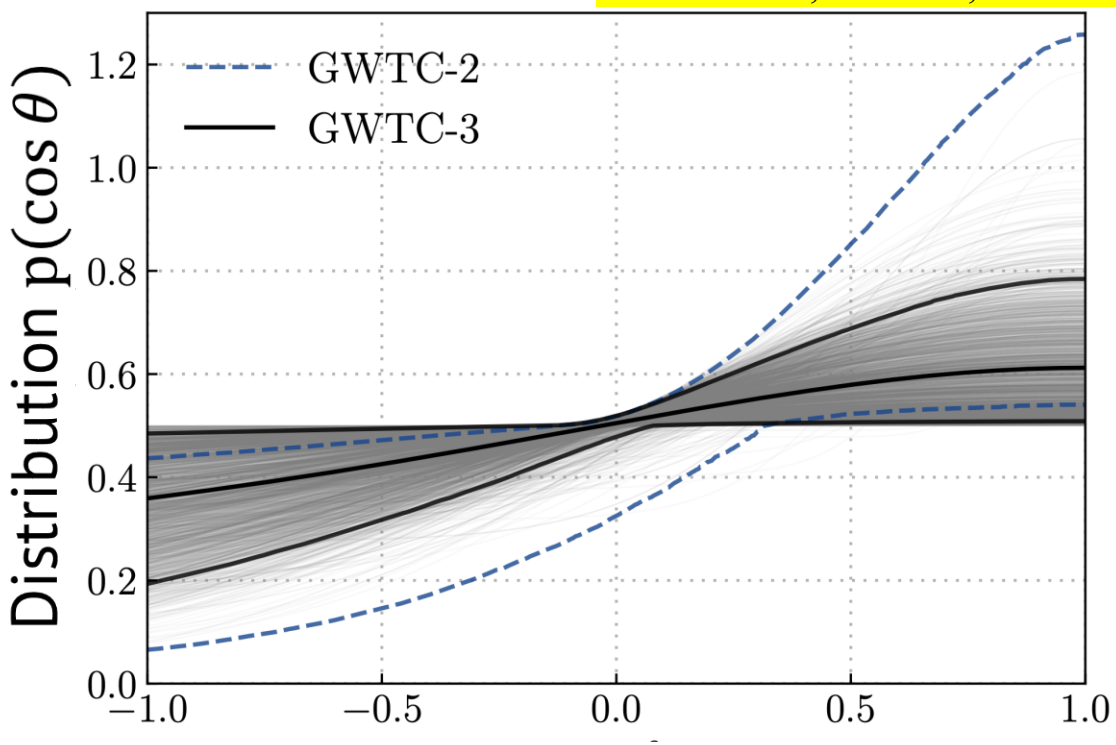


- Local maxima at $m_1 \sim 10M_\odot$ and $m_1 \sim 35M_\odot$ ($> 99\%$ credibility)
- A few massive BBHs e.g. GW190521 ($m_1 = 85^{+21}_{-14}M_\odot$, $m_2 = 66^{+17}_{-18}M_\odot$)
  → Inconclusive evidence for pair-instability mass gap ($65 - 120M_\odot$).

BBH distribution: Spin

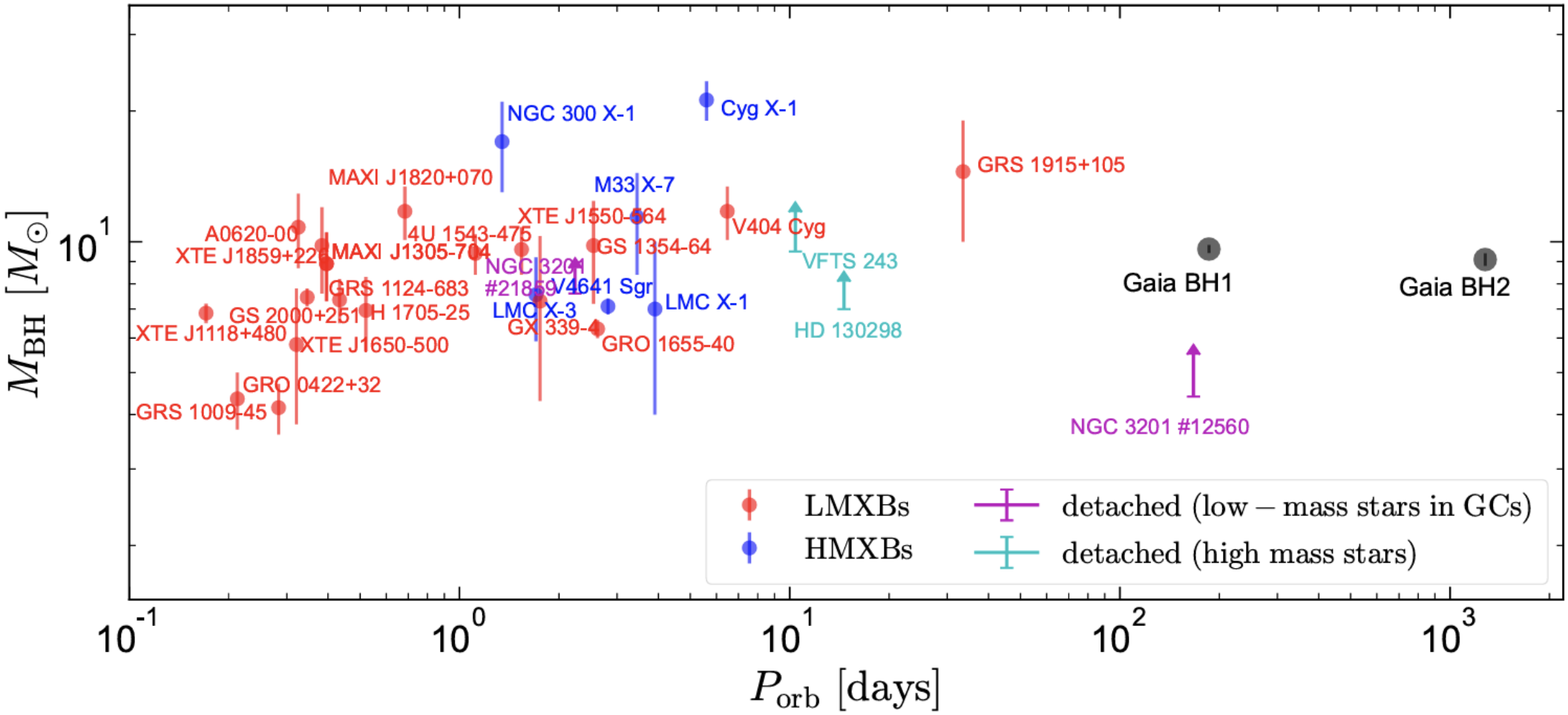
Abbott et al., PRX **13**, 011048 (2023)





- Spin magnitude generally small ($\chi \lesssim 0.4$), but not-vanishing.
- Tilt angle has broad distribution, but $\cos\theta = 1$ preferred (but see Roulet et al 2021 about model dependence).

Galactic black holes



OGLE-2011-BLG-0462
(isolated)

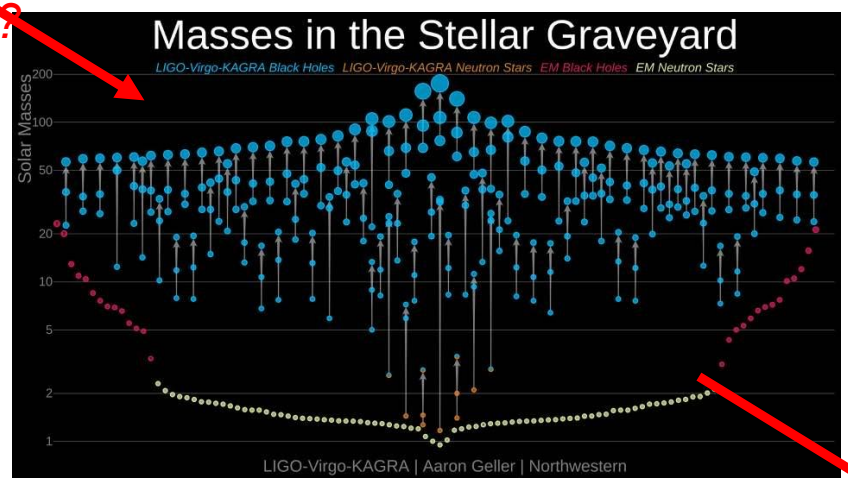
- **Known unknowns about BH**

?

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

?

Mass and spin distribution?
Ultraluminous X-ray sources = intermediate BH
Accreting BHs are Pevatrons?

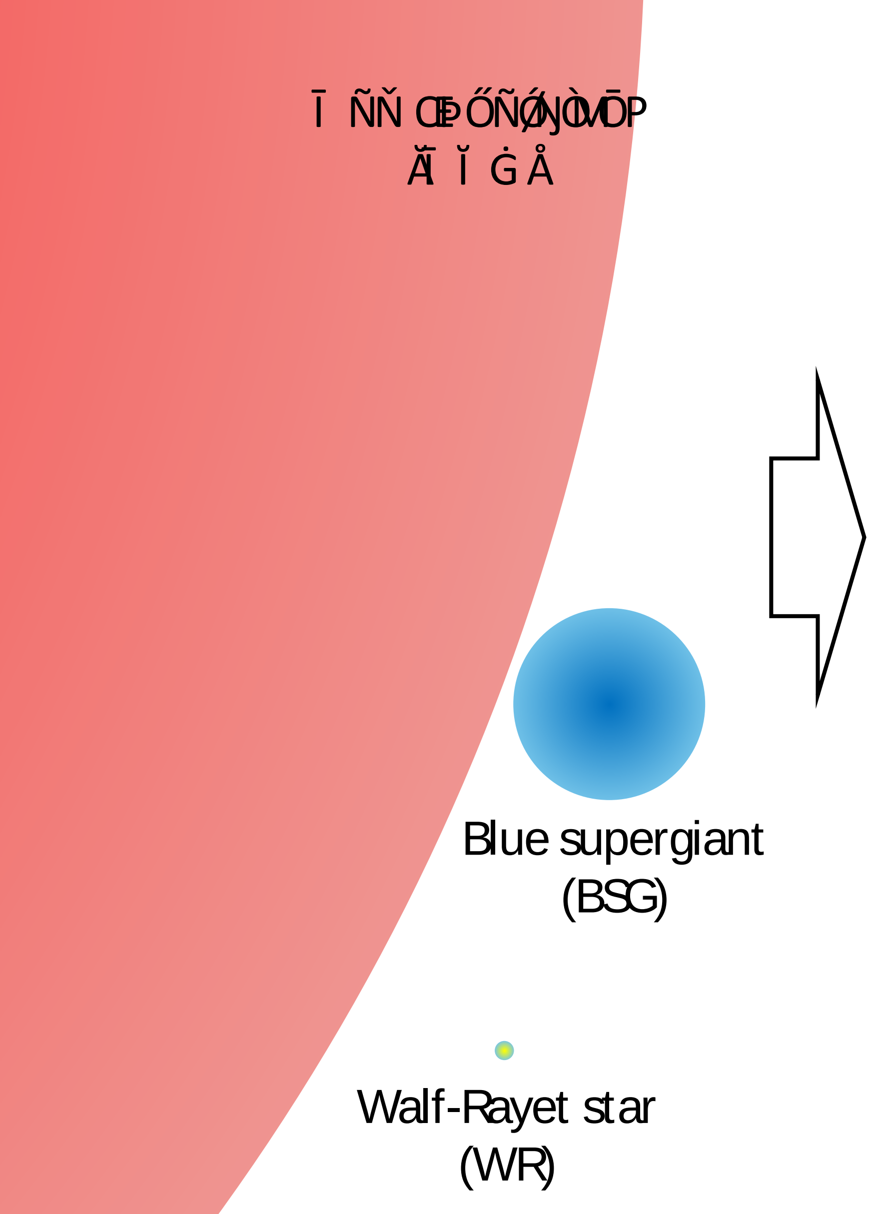


?

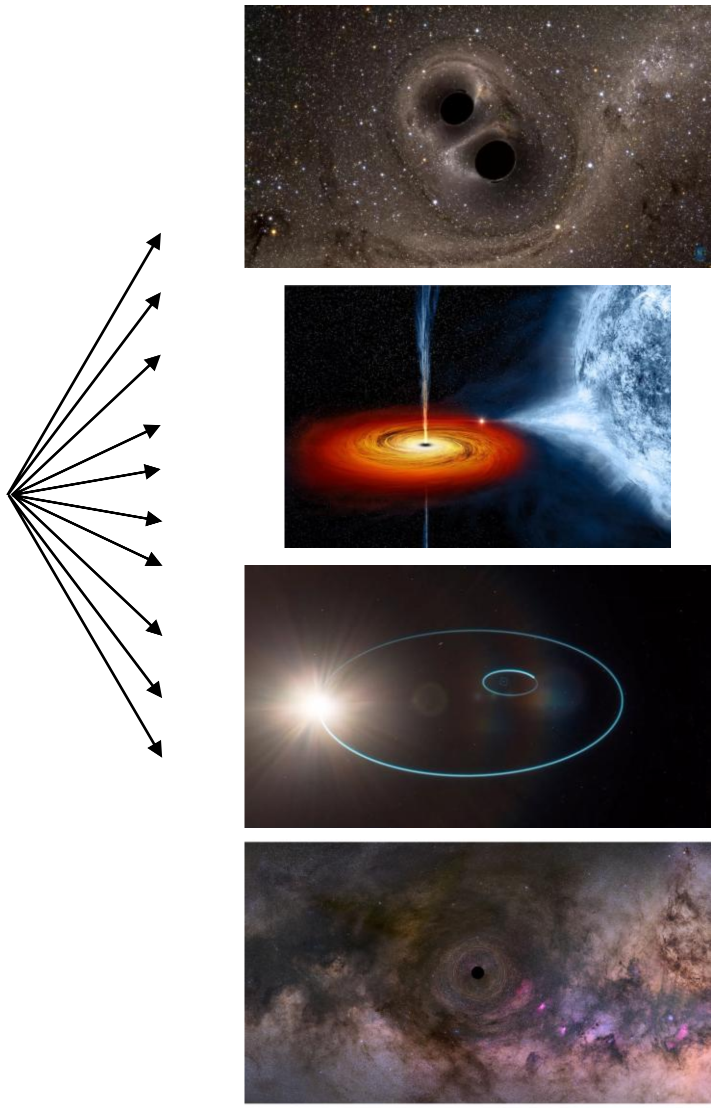
"Floating" BHs in the Galaxy
How are they?
Where they are?

time

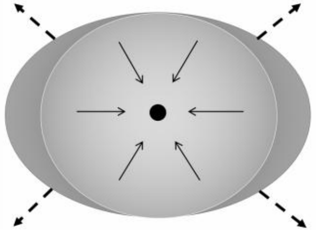
Black hole formation and transients

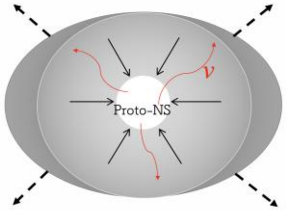


?

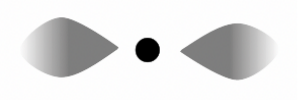


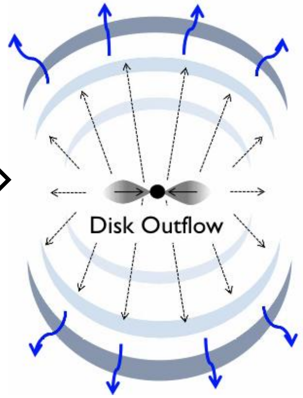
slow rotation

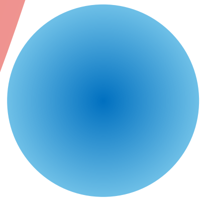


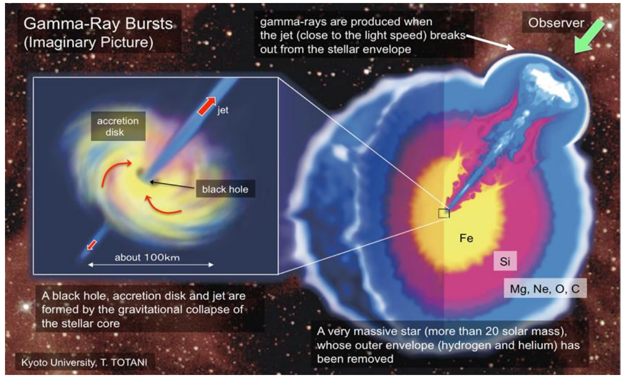


Intermediate rotation

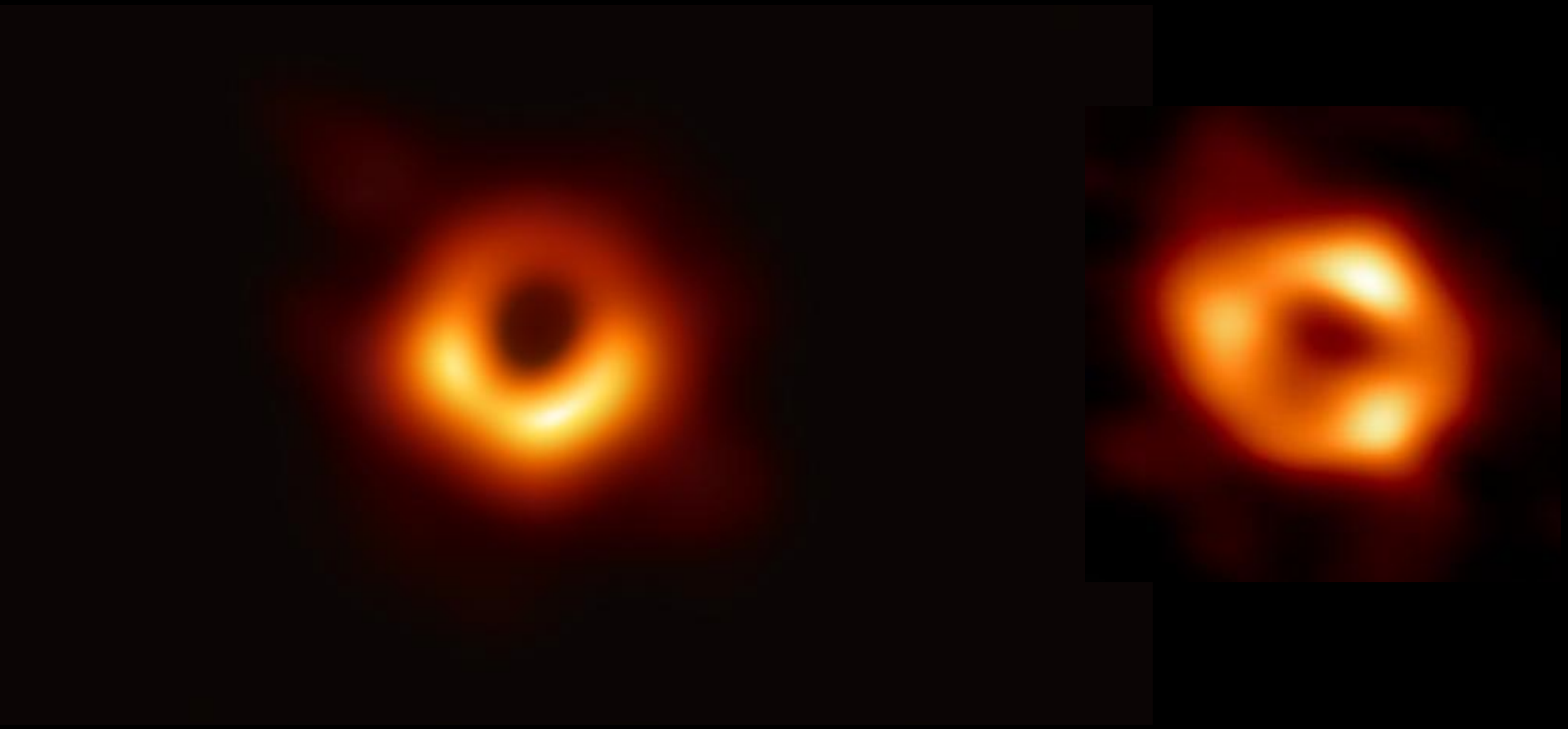








Walf-Rayet star
(WR)

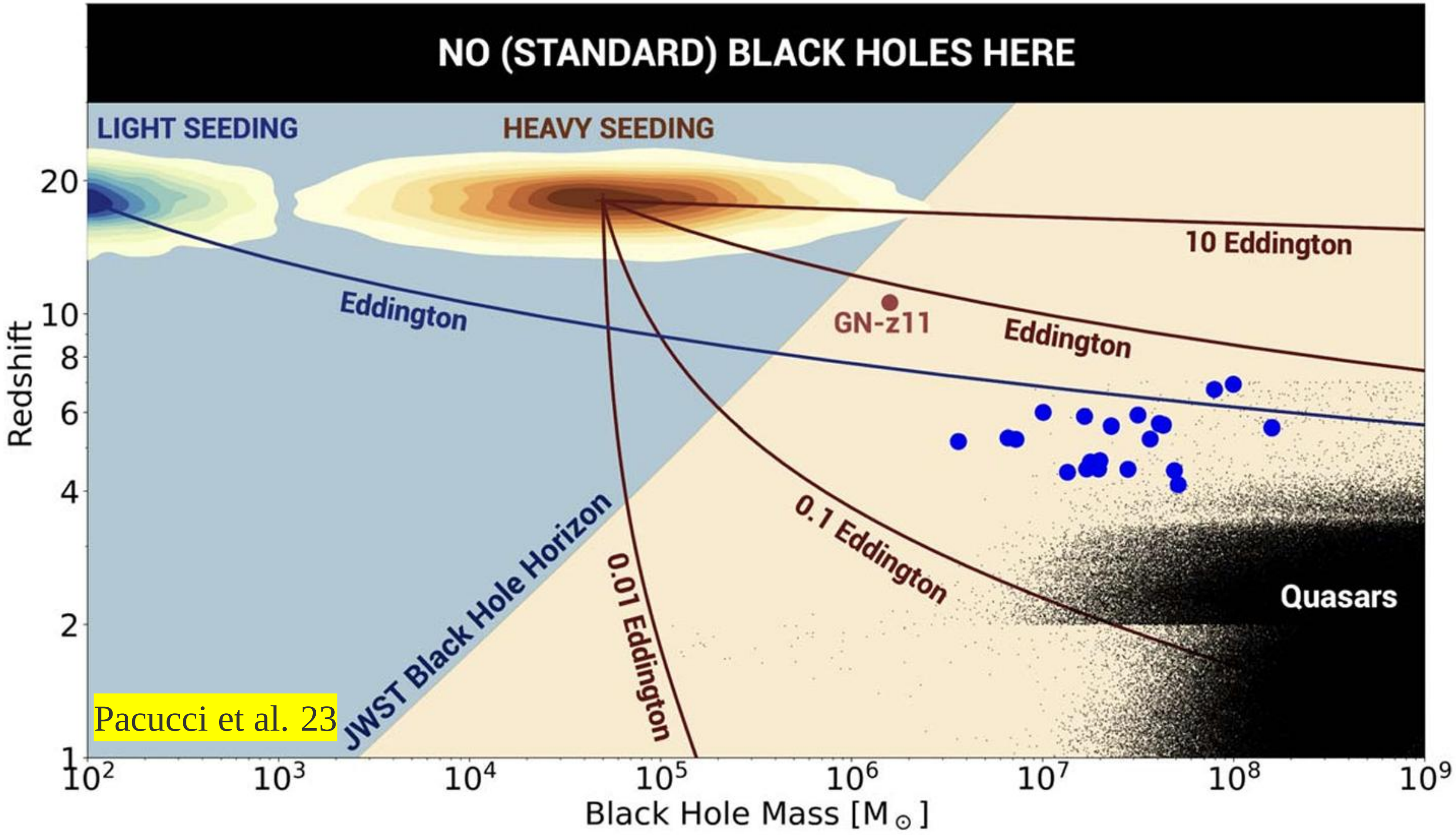


Credit: Event Horizon Telescope Collaboration

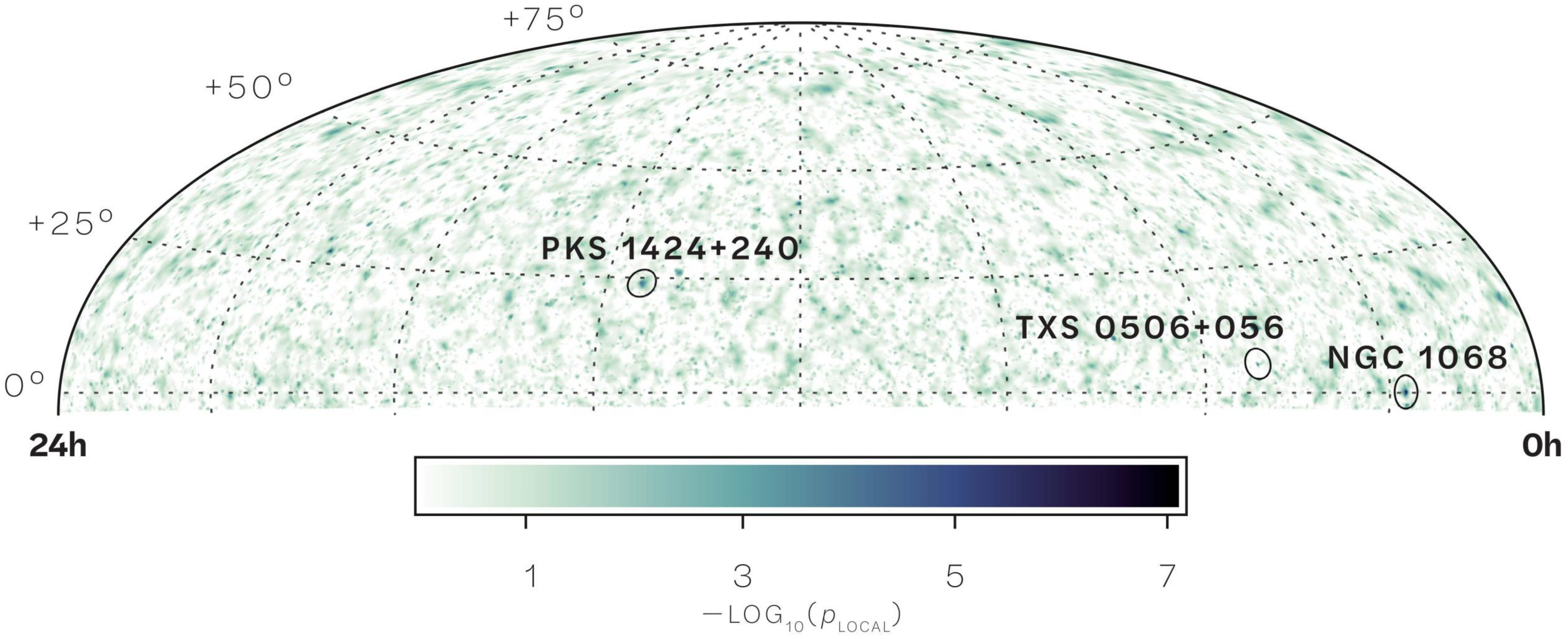
ĢŎR MǾÑ PONŘ NŎǾŌÆMŌŇ OŎR ŇŎ PONŘ ŊǾŎR Ē

Ĭ ÞŐŐÑǾĜŇŇÒŌŊPŎŌ MŃŃǾŃPÒŎŌĒ
F ŎŎMŐŒÒŌŊ ŒÞŐÑǾŎ MŒŒÒŊÑ ŒMǾŒĒ
F ŎŎMŐŒÒŌŊ ŐŎŐ HHŃŎÞ ŒÑǾŒĒ

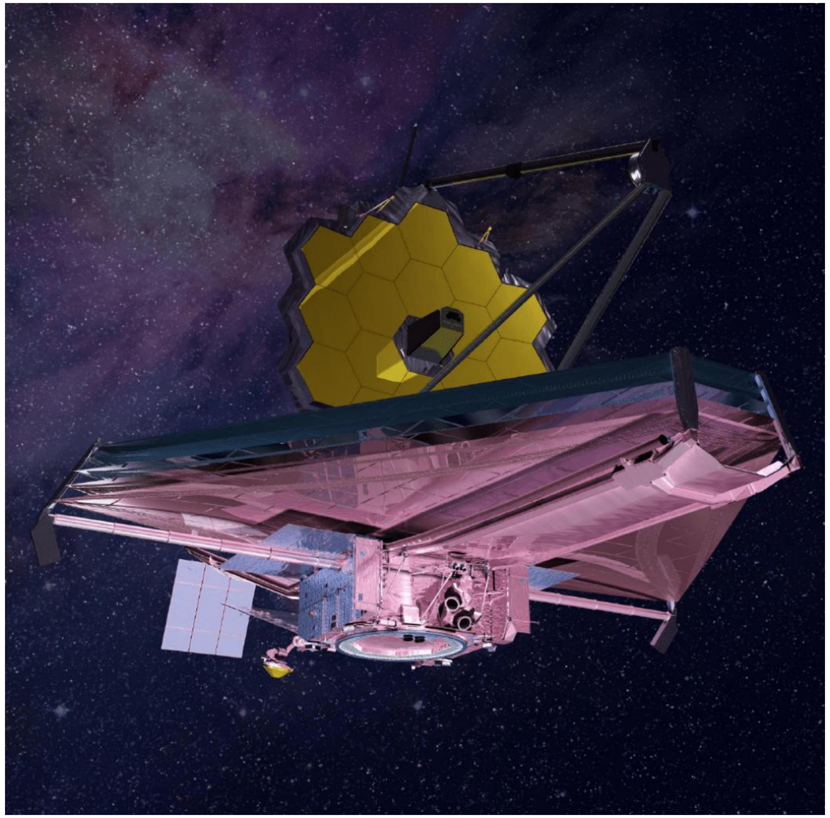
by eating gases/stars/BHs

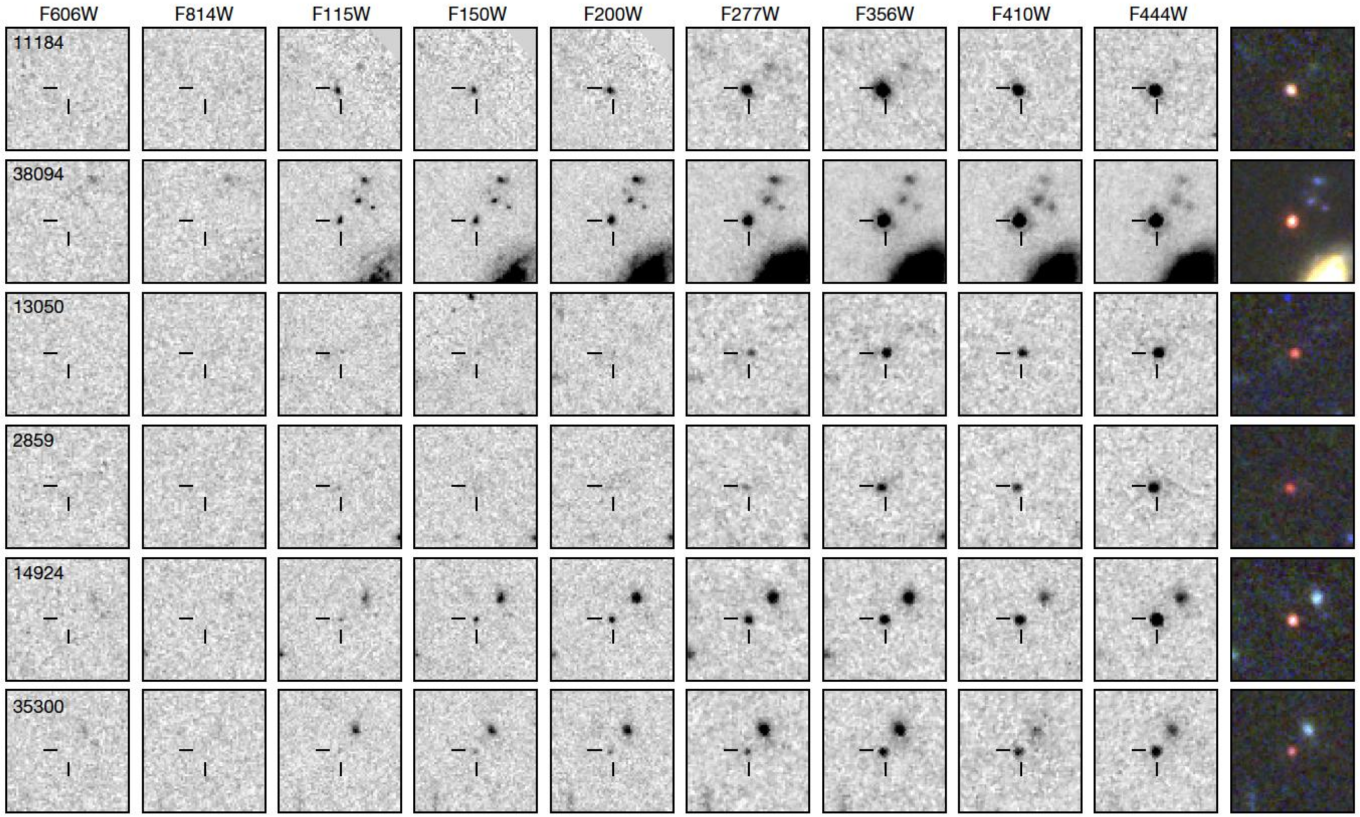


F ÑǾPMÒŌ PŘŐÑŒŎŅPOÑÖ ŐǾŎŇÞŃÑ ĢĜ ̉ R OÒŌÑ ŊǾŎR ÒŌŊ



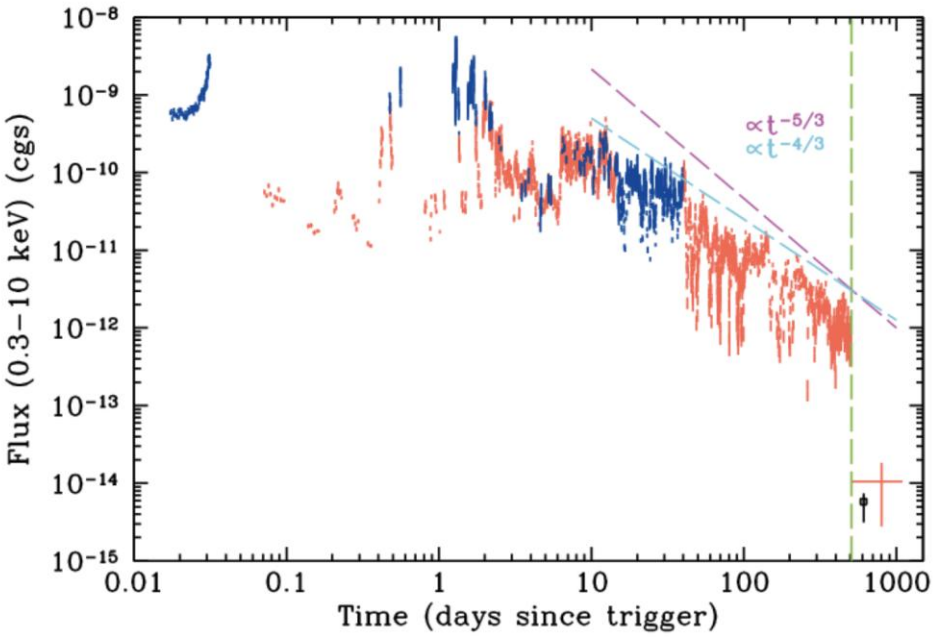
ĤJ Ĭ İ ÒŒÞŌŃŎQÑǾÒŌŊ ÑMǾŘ ŊǾŘ POÆ
R OÒŃO ŒŎÔŒǾÞÒPÑ ŇÒŅŅÑǾÑŌP ŅǾŎÖ PONÑ ŒŃMŌÞŌÒQÑǾŒÑA

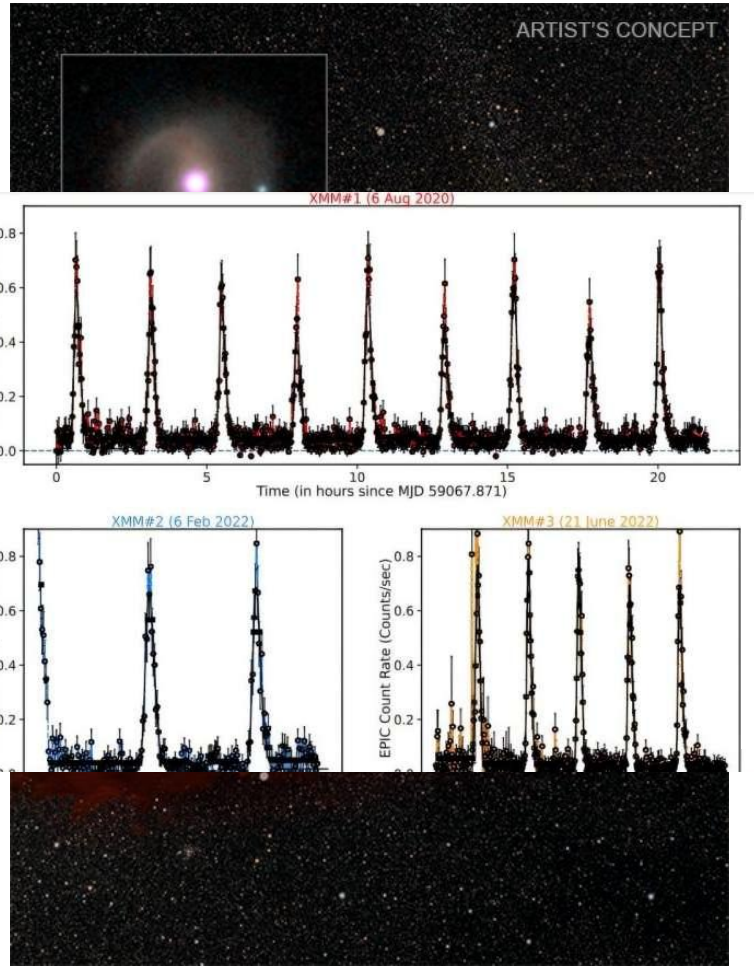




Labbe et al. 23

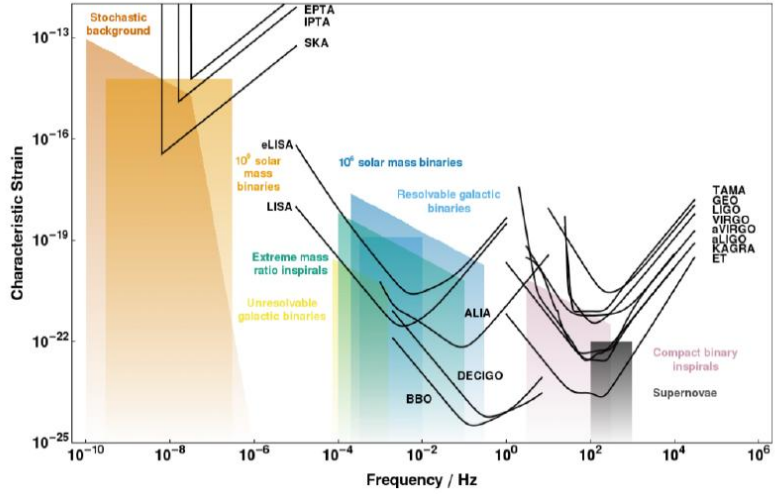
Multi-messenger transients from stars around SMBHs



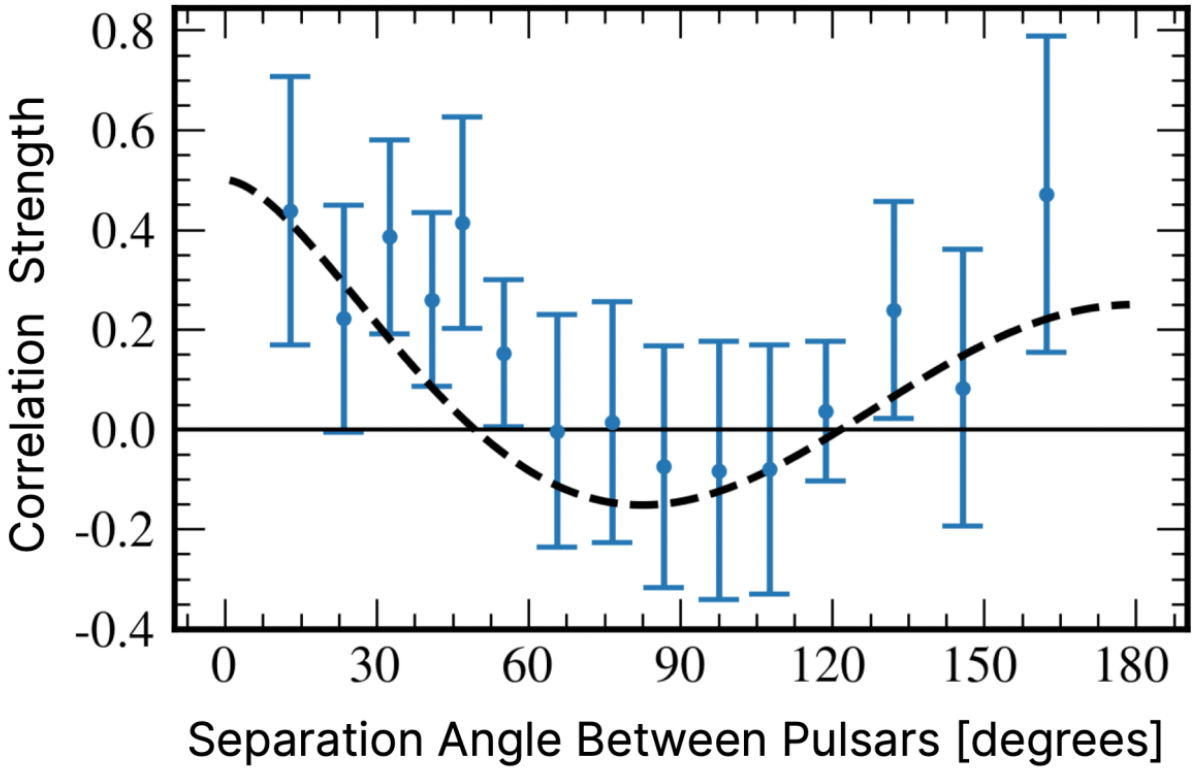


Quasi-periodic mass eruptions

Extreme mass ratio inspirals



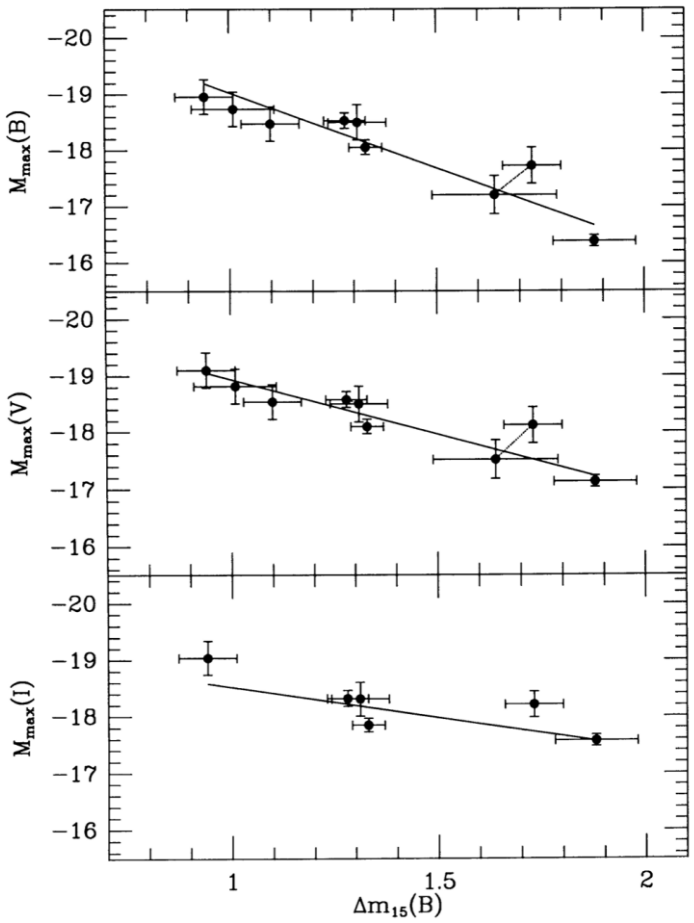
Evidence for a GW background by SMBH mergers

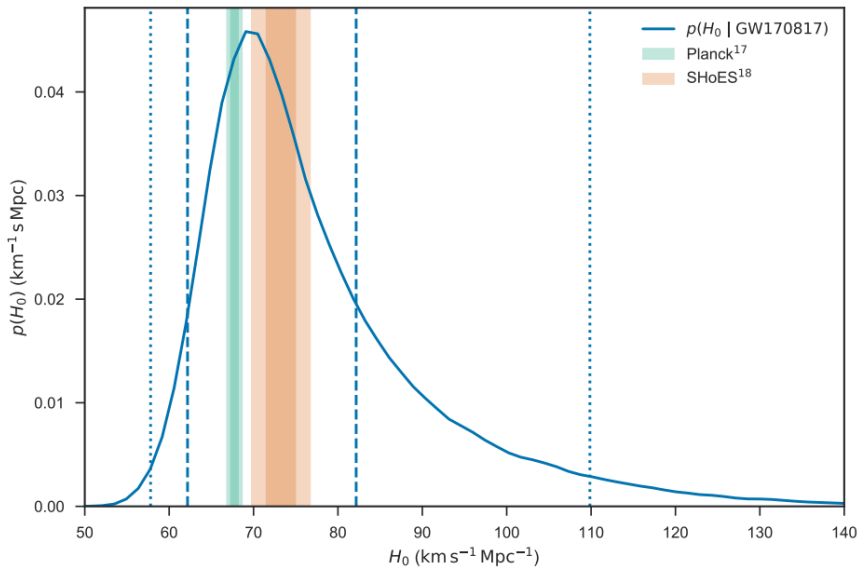


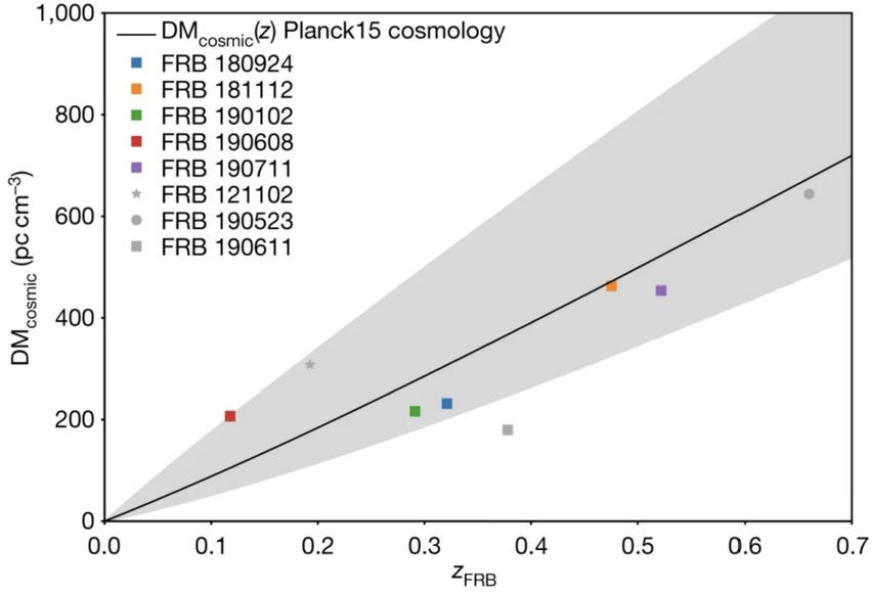
The amplitude is significantly larger than that predicted from the present-day abundance of SMBHs derived from local scaling relations?

e.g., Sato-Polito, Zaldarriaga, Quataert 23

Cosmology with the brightest transients







個人的な縦串 x 横串

- 高エネルギー天体現象を用いて大事な量をちゃんと測りたい
  例：solar neutrino, Hulse-Taylor pulsar, type Ia supernovae, …

- 高エネルギー天体現象をちゃんと測るためにやるべきこと
  - ちゃんとした物差しになるように高エネルギー天体現象をちゃんと理解する
  ⇄ マルチメッセンジャー（というか必要なものをちゃんと組み合わせた）観測
  - 物差しとなる高エネルギー天体現象を新たに見つける（ような観測を応援する）
  ⇄ 未開拓の時間/エネルギー領域観測