High Energy Astrophysics

Kunihito Ioka

(Center for Gravitational Physics, YITP, Kyoto U.)

Main Conclusion

Multi-messenger

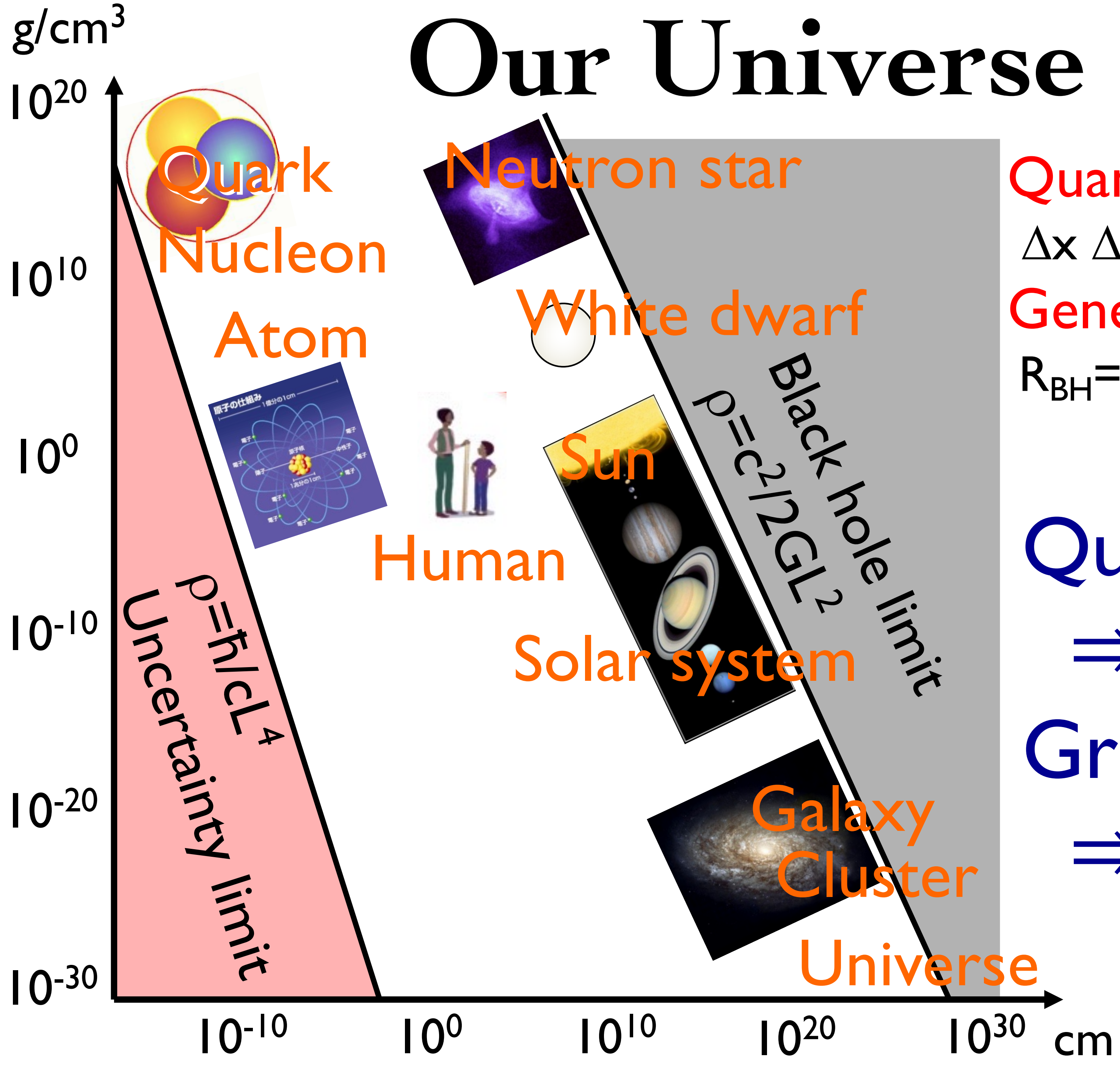
+

Time-domain

+

Numerical simulation

Our Universe



Quantum mechanics

$\Delta x \, \Delta p \geq \hbar$

General relativity

$R_{BH}=2GM/c^2$

Quantum "ħ"

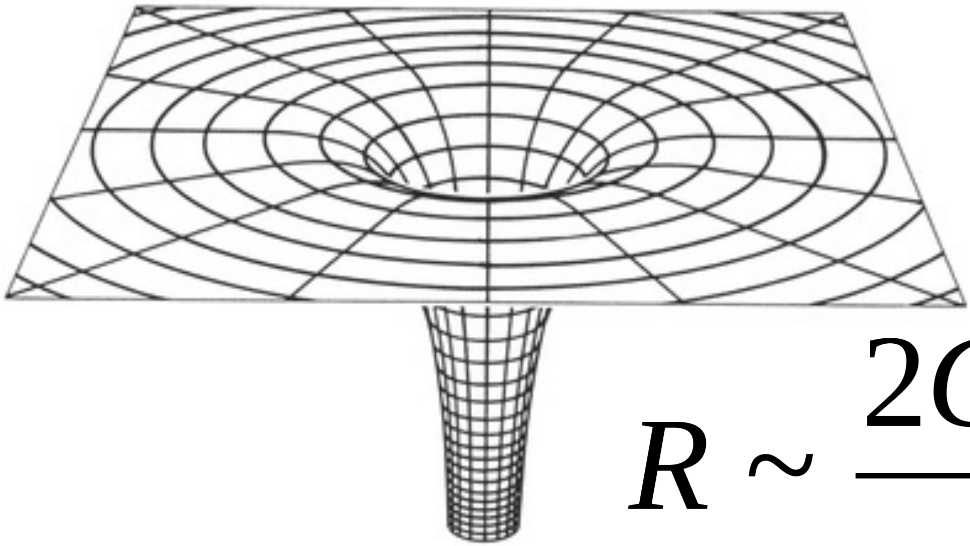
⇒ Particle

Gravity "G"

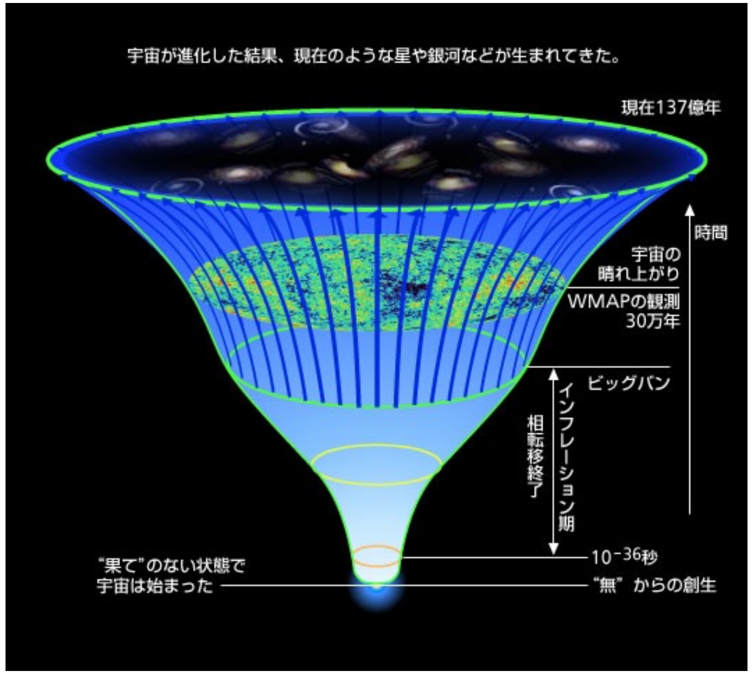
⇒ Universe

Gravity

Black Hole **Expanding Universe**



$$R \sim \frac{2GM}{c^2}$$

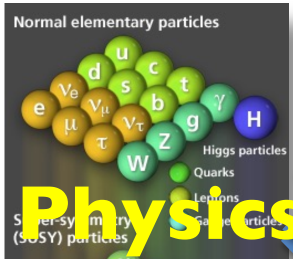


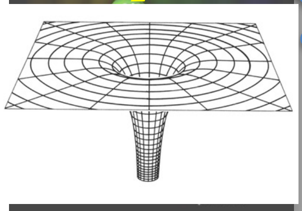
Final fate of stellar evolution Big Bang

Astrophysics ***Cosmology***

Evolution to Black Holes

Gravity
Quantum

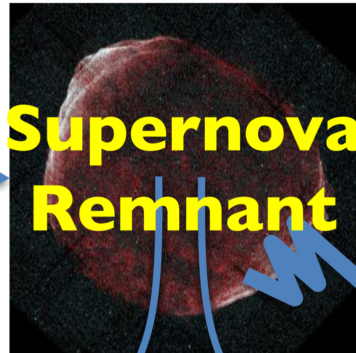




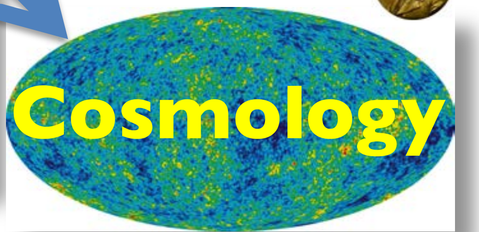
Chandrasekhar
Bethe

Davis
Koshiba

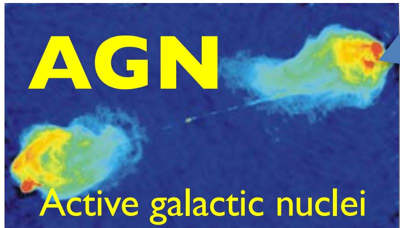
Weiss, Barish & Thorne



W. A. Fowler



Penzias, Wilson
Mather, Smoot
Perlmutter, Riess, Schmidt
Peebles



Massive black hole
at the center of galaxy

Penrose, Genzel, Ghez

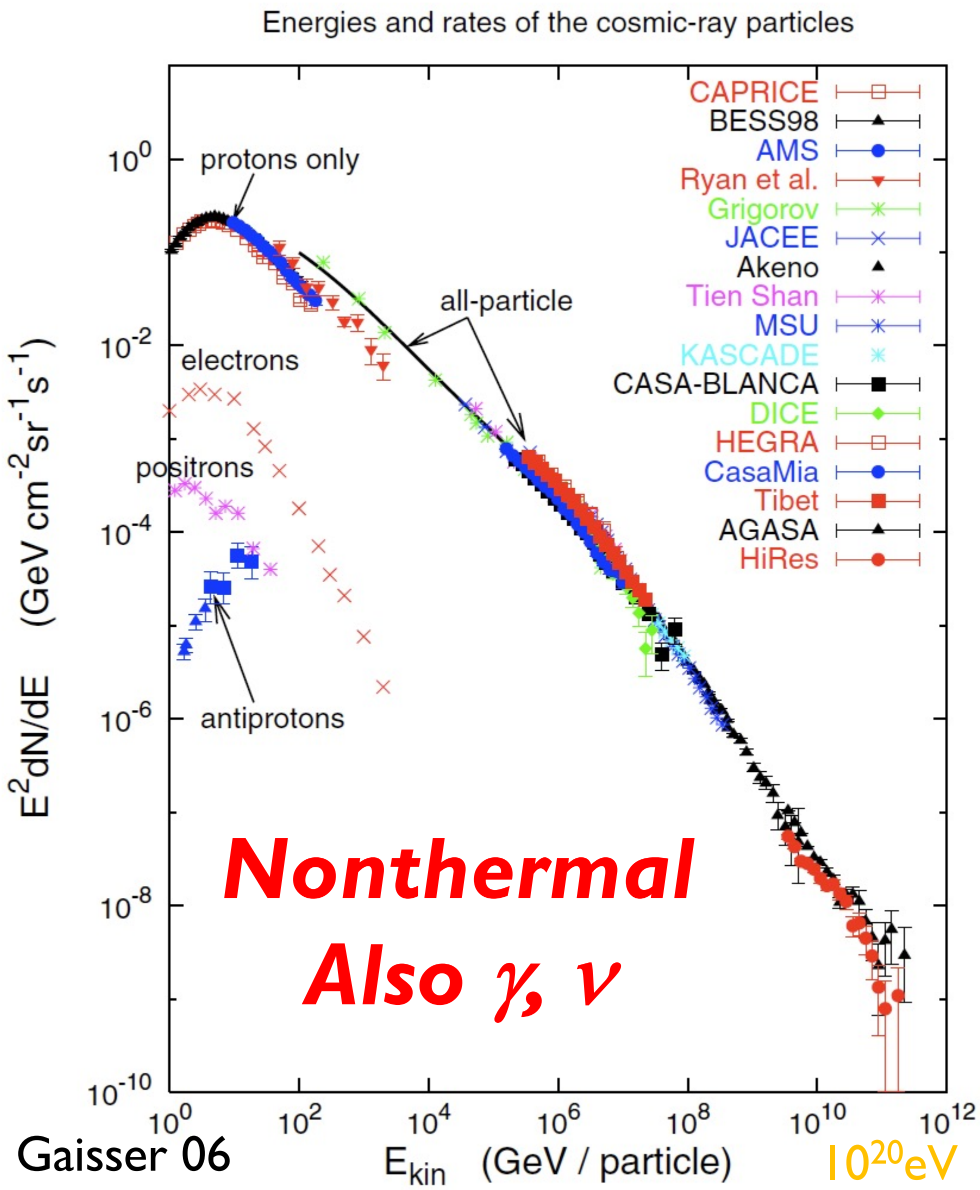
Black Hole
Neutron Star
White Dwarf

Giacconi
Hewish
Hulse, Taylor

Hess
Anderson
Yukawa
Powell
Kajita

High Energy Universe

Particle Acceleration



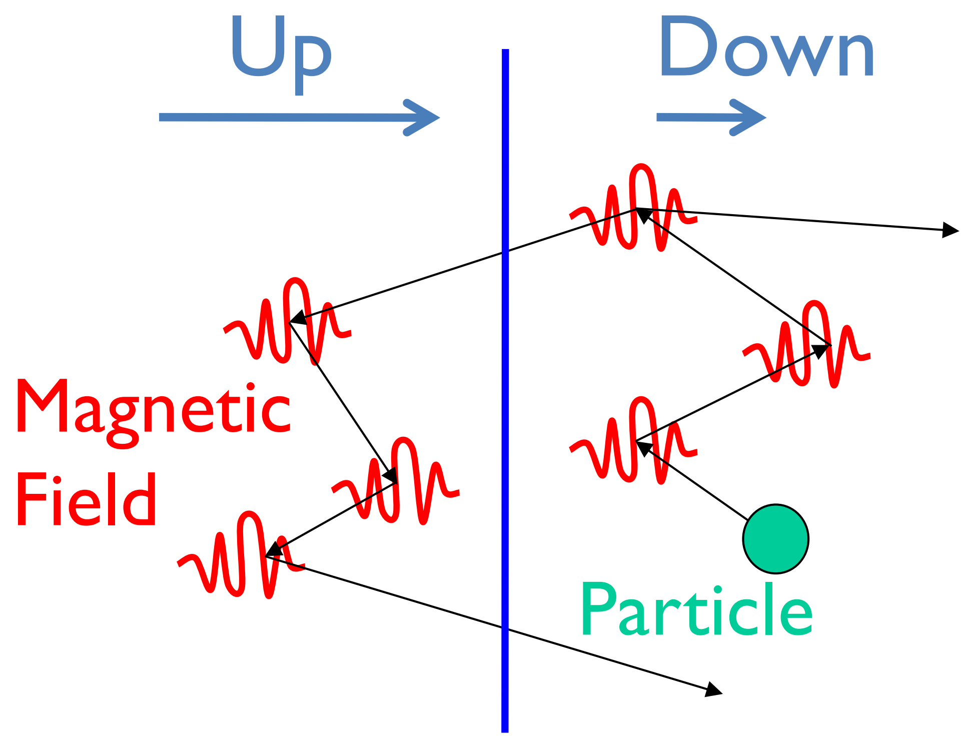
Nonthermal

Also γ, ν

10^{20}eV

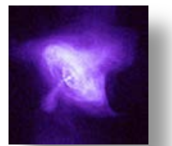
Gaisser 06

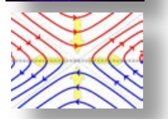
Fermi acceleration



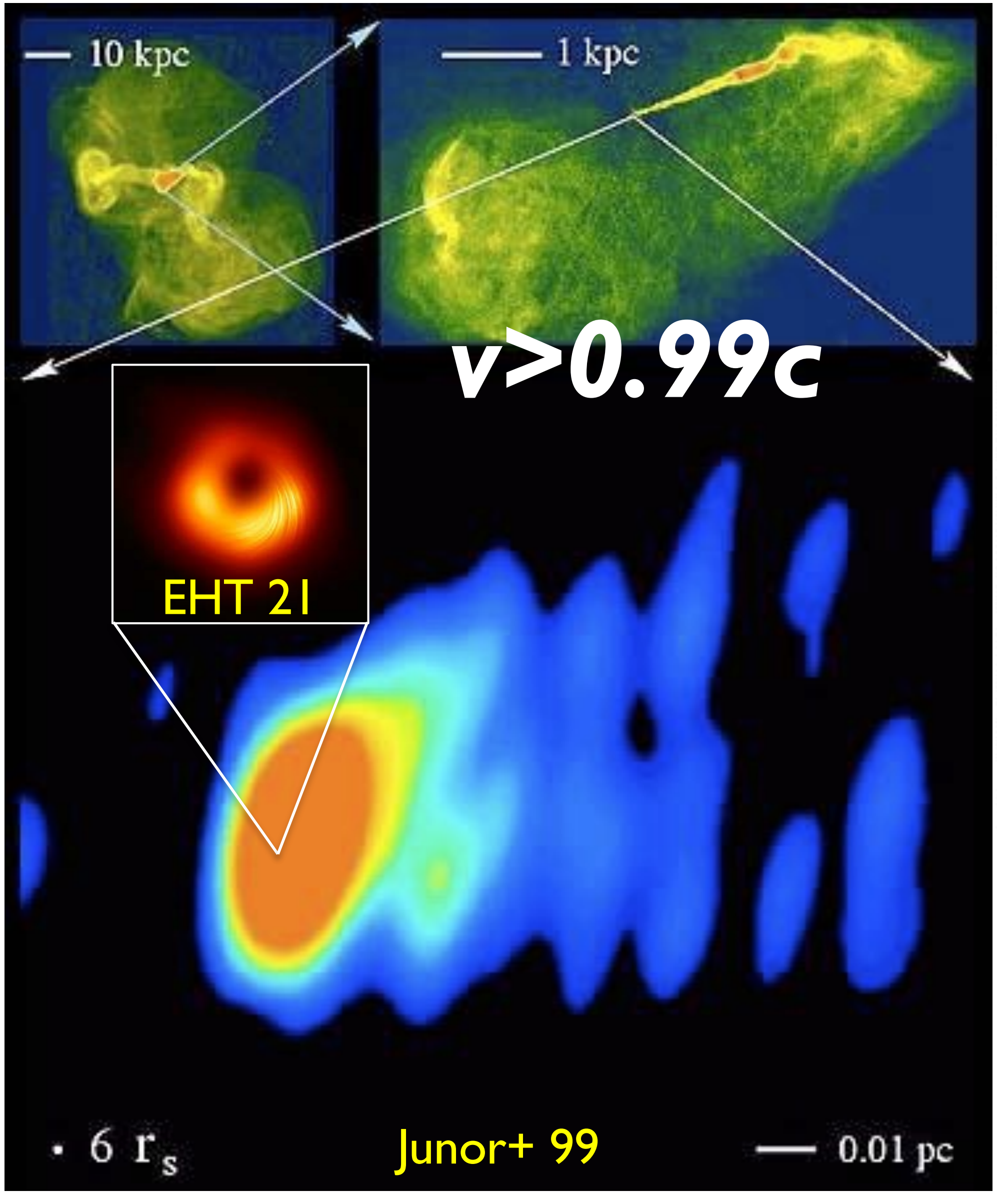
Unipolar induction

Reconnection, …

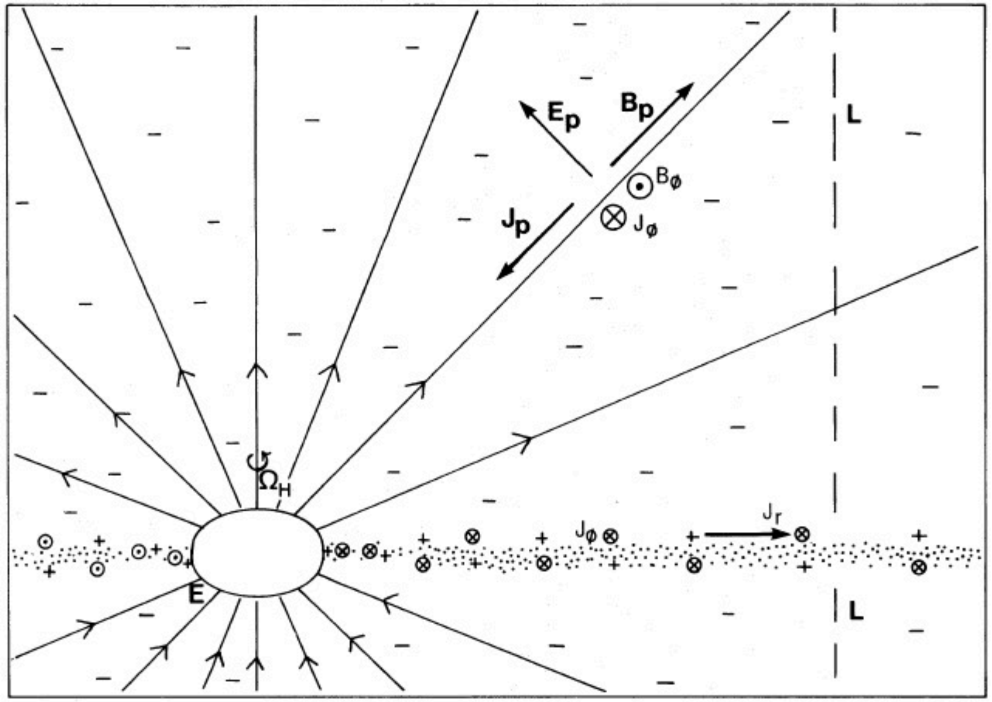




Jet



Blandford-Znajek 77

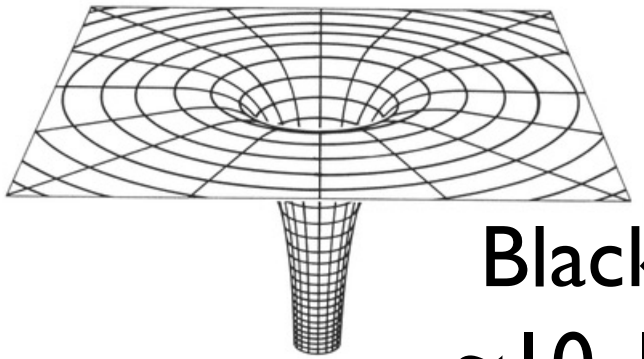


Outflow (ordered/turbulent B)
σ-problem, Feedback, …

multi-scale problems

Extreme Universe

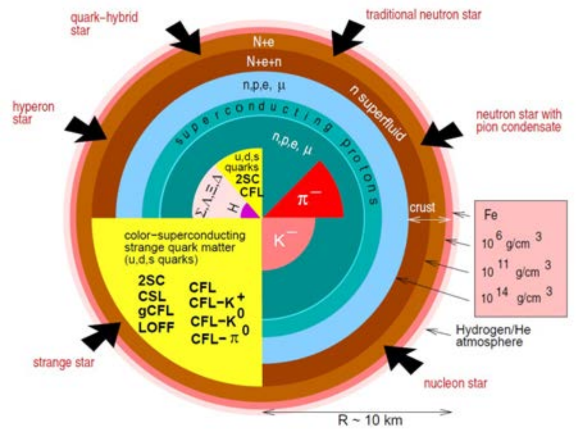
Strong Gravity



Black Hole

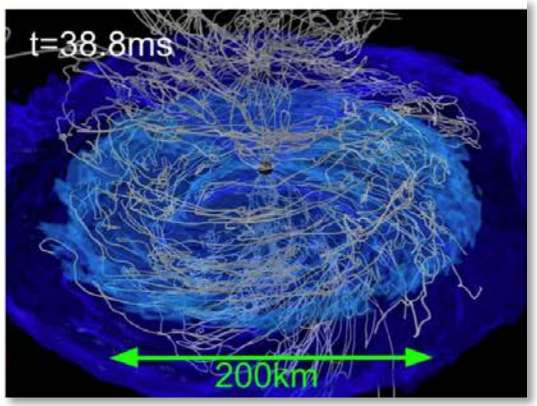
$\sim 10\text{-}10^{10} M_\odot$

High Density



$\rho_{NS} \sim$
10^{15} g/cc
$> \rho_{nuclear}$

Strong B Field



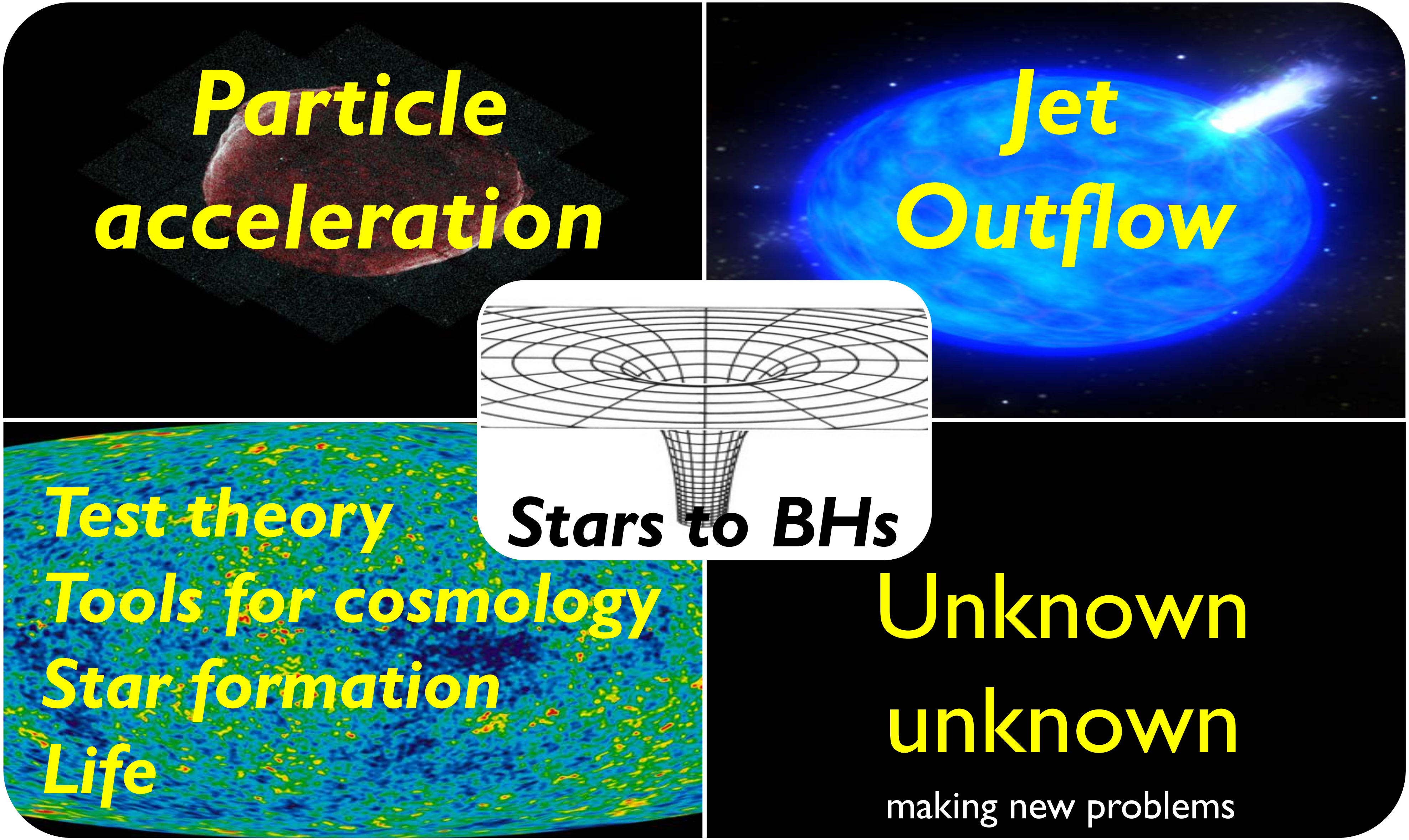
Kiuchi+ 14

Magnetar
Neutron
star merger
$B \sim 10^{14\text{-}17}$G

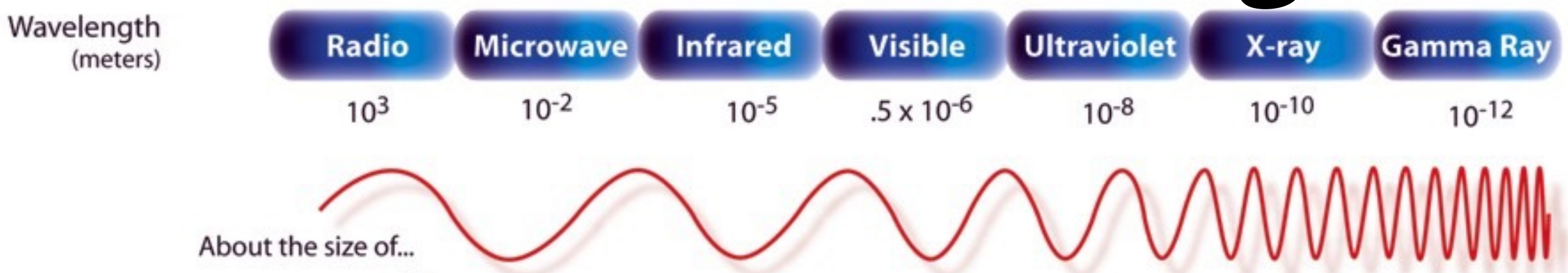
High Luminosity

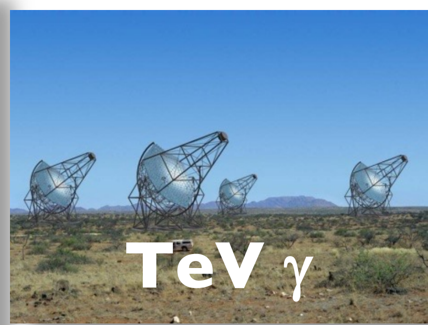
$L \sim 10^{51}$erg/s
$\sim$ J-PARC
$\times 10^{38}$

Science Goal



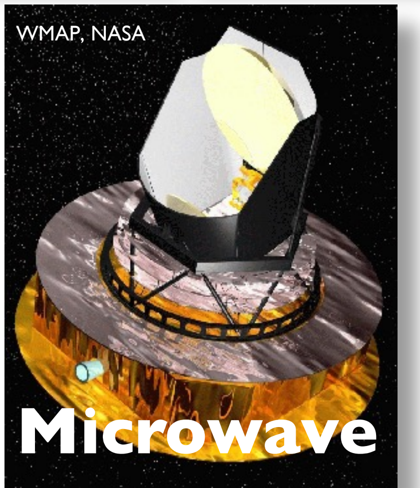
Multi-Wavelength

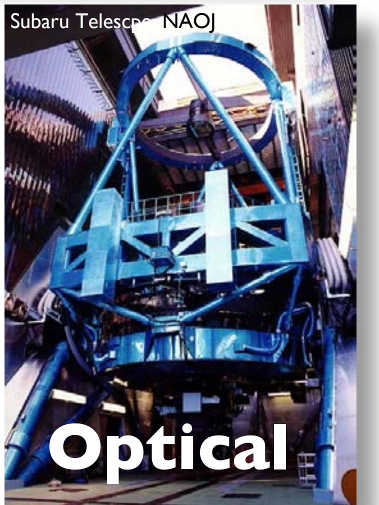




TeV= 10^{12}eV
GeV= 10^{9}eV

20th century observations:
In particular,
X-γ-VHE γ

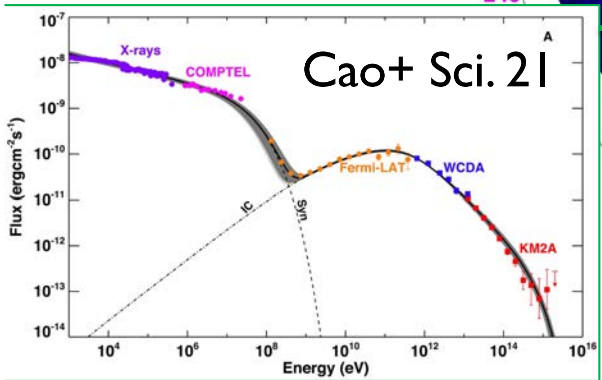




PeVatron

PeV=10^{15}eV

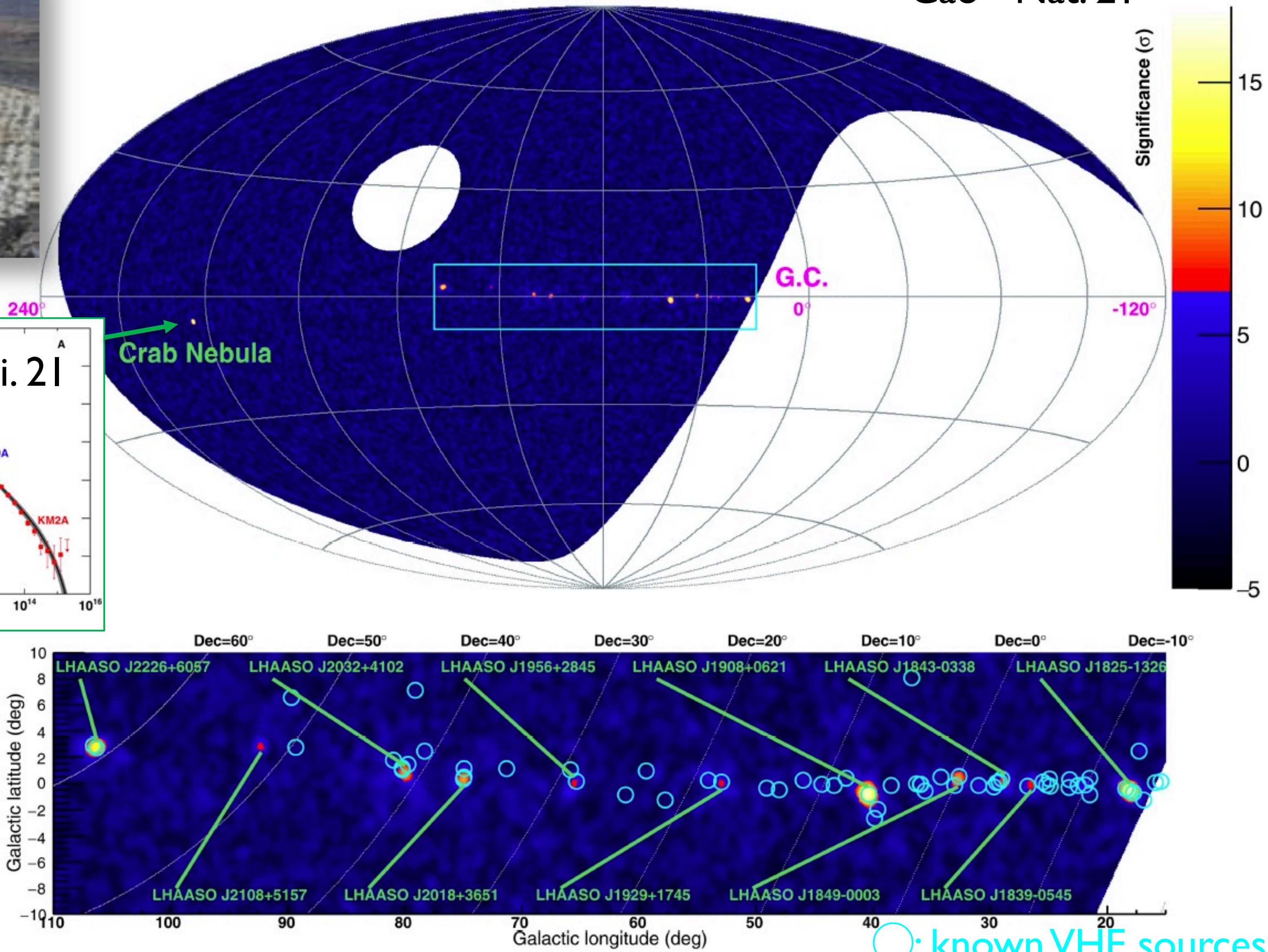
©LHAASO



Cao+ Sci. 21

LHAASO Sky @ >100 TeV

Cao+ Nat. 21



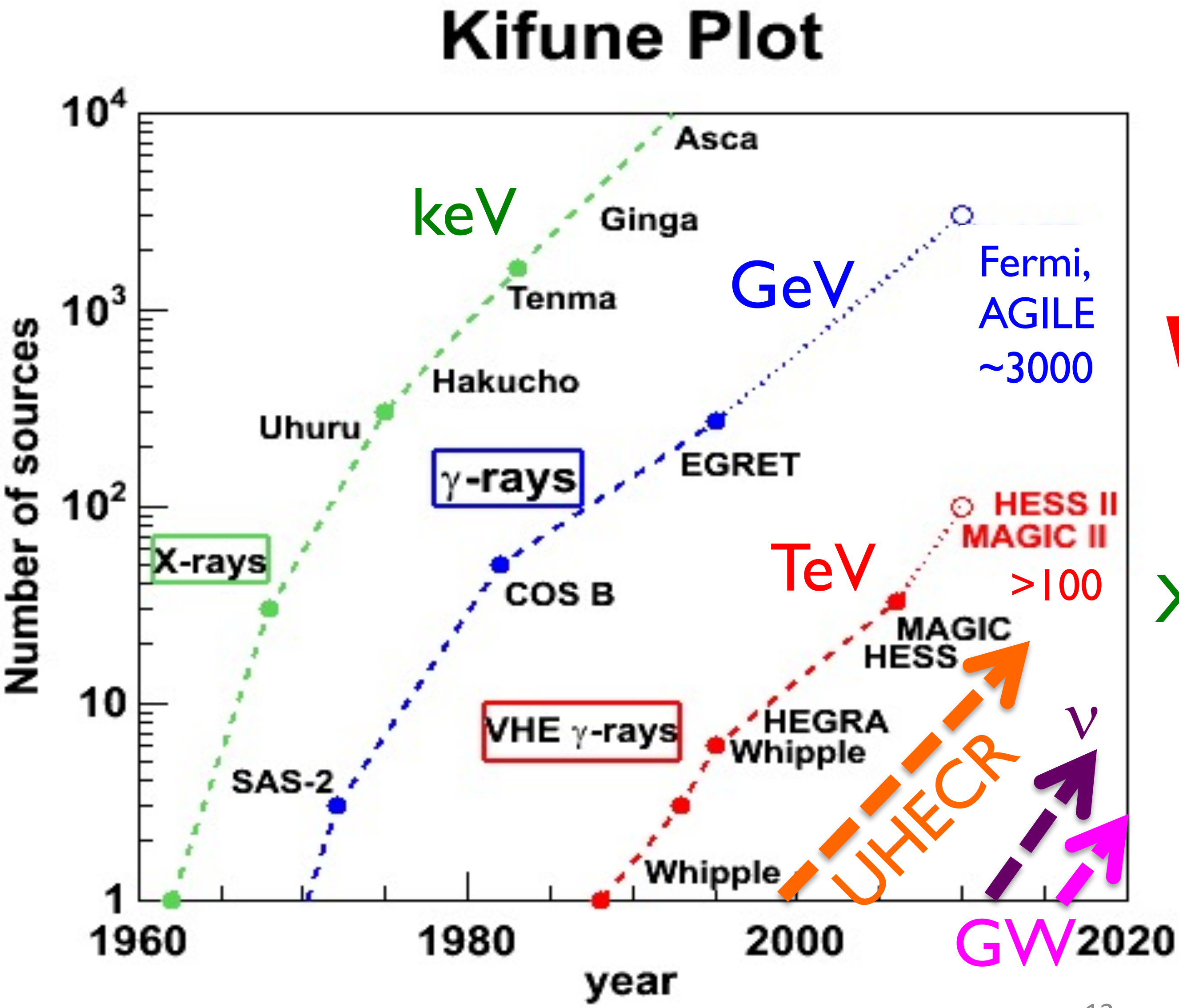
◯: known VHE sources

J2032+4102:
E_{max}=1.42 PeV
Cygnus OB2?

Multi-Messenger Era

21th Century: Multi-Messenger Era

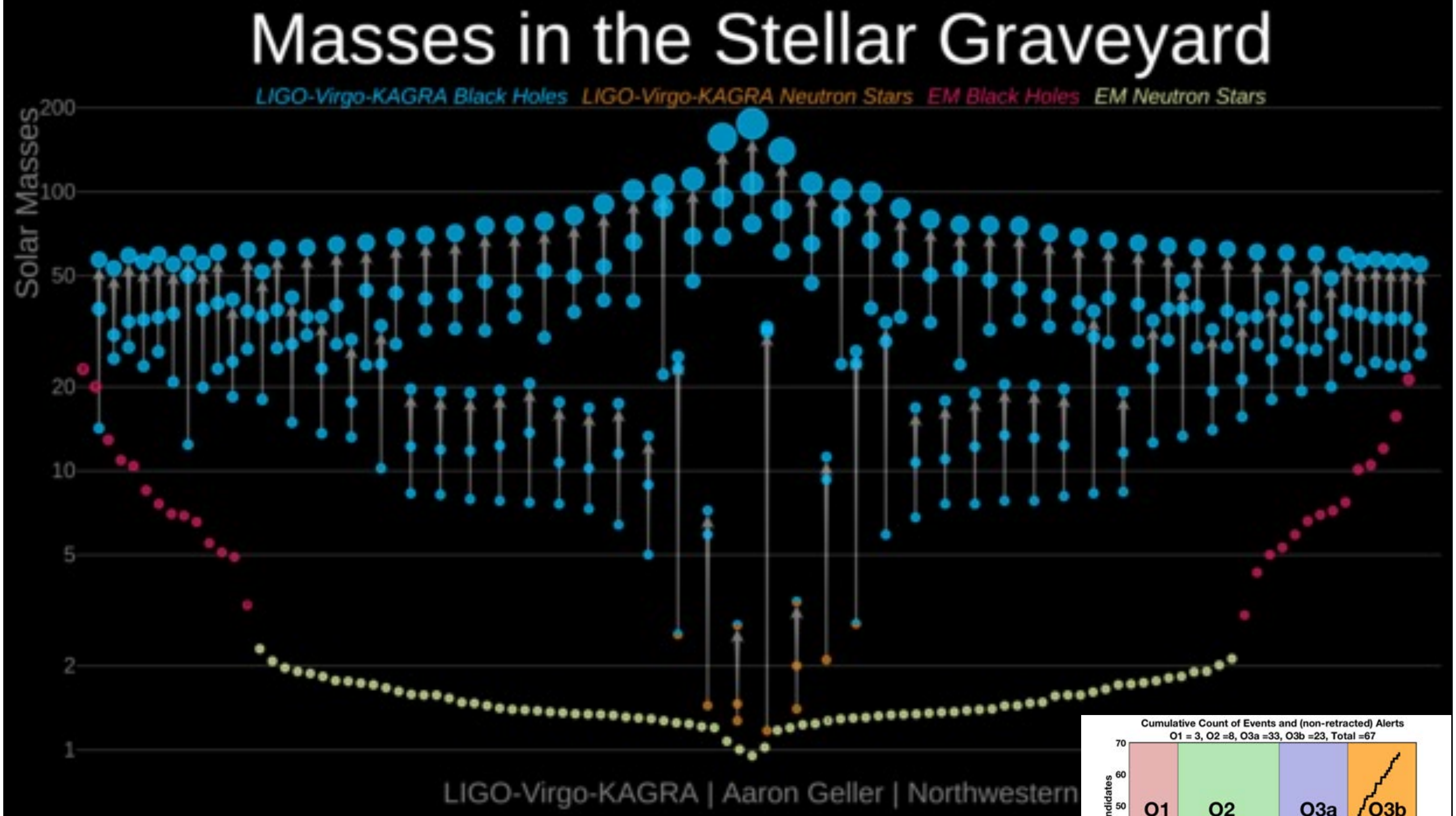
Multi-Messengers

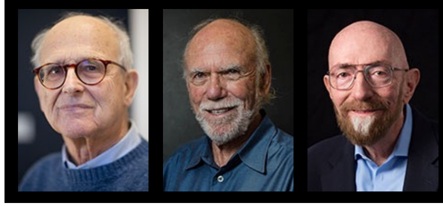


+
Multi-wavelength

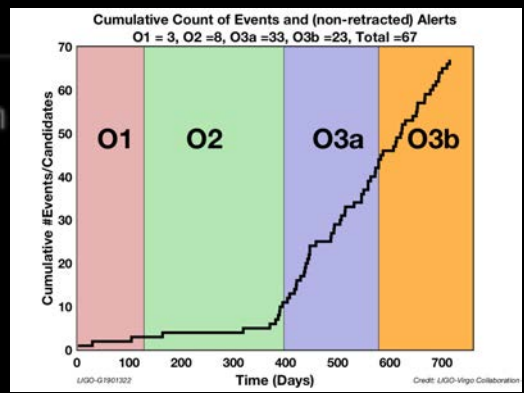
μeV radio-μwave-Infrared-Optical-X-GeV γ-TeV γ-rays

# of sources are increasing exponentially



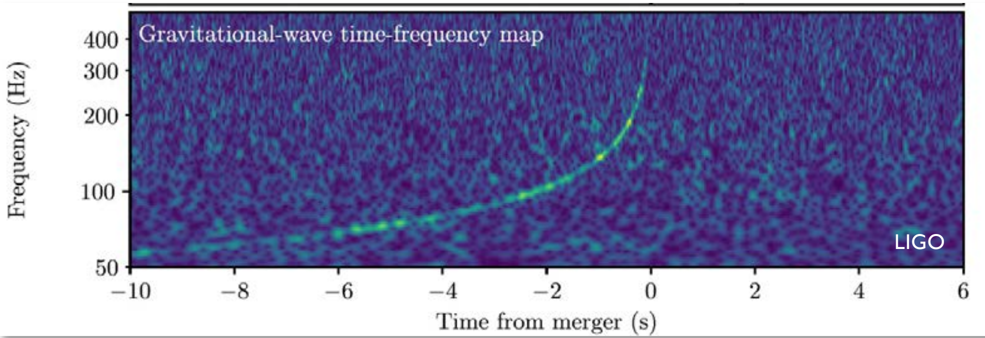


Weiss, Barish, Thorne
2017 Nobel prize



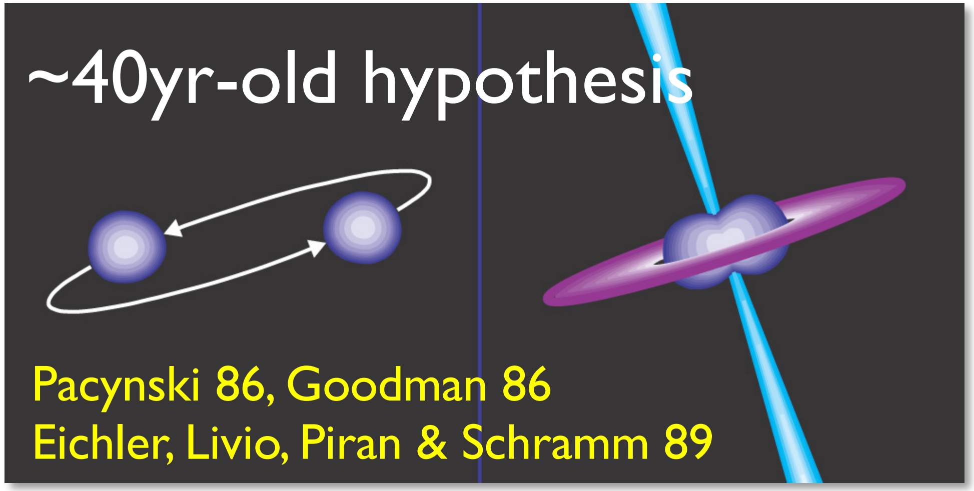
GW170817

1^{st} GW from NS^2



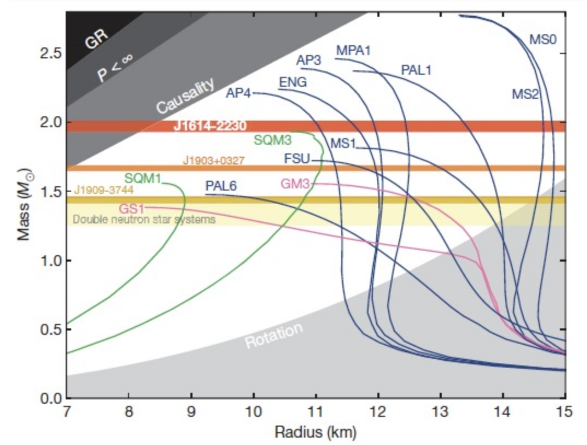
~100 sec chirp ⇒ NS-NS

NS^2 = Short GRB?

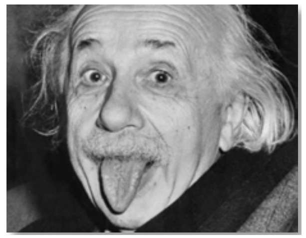


R-process elements

Equation of state

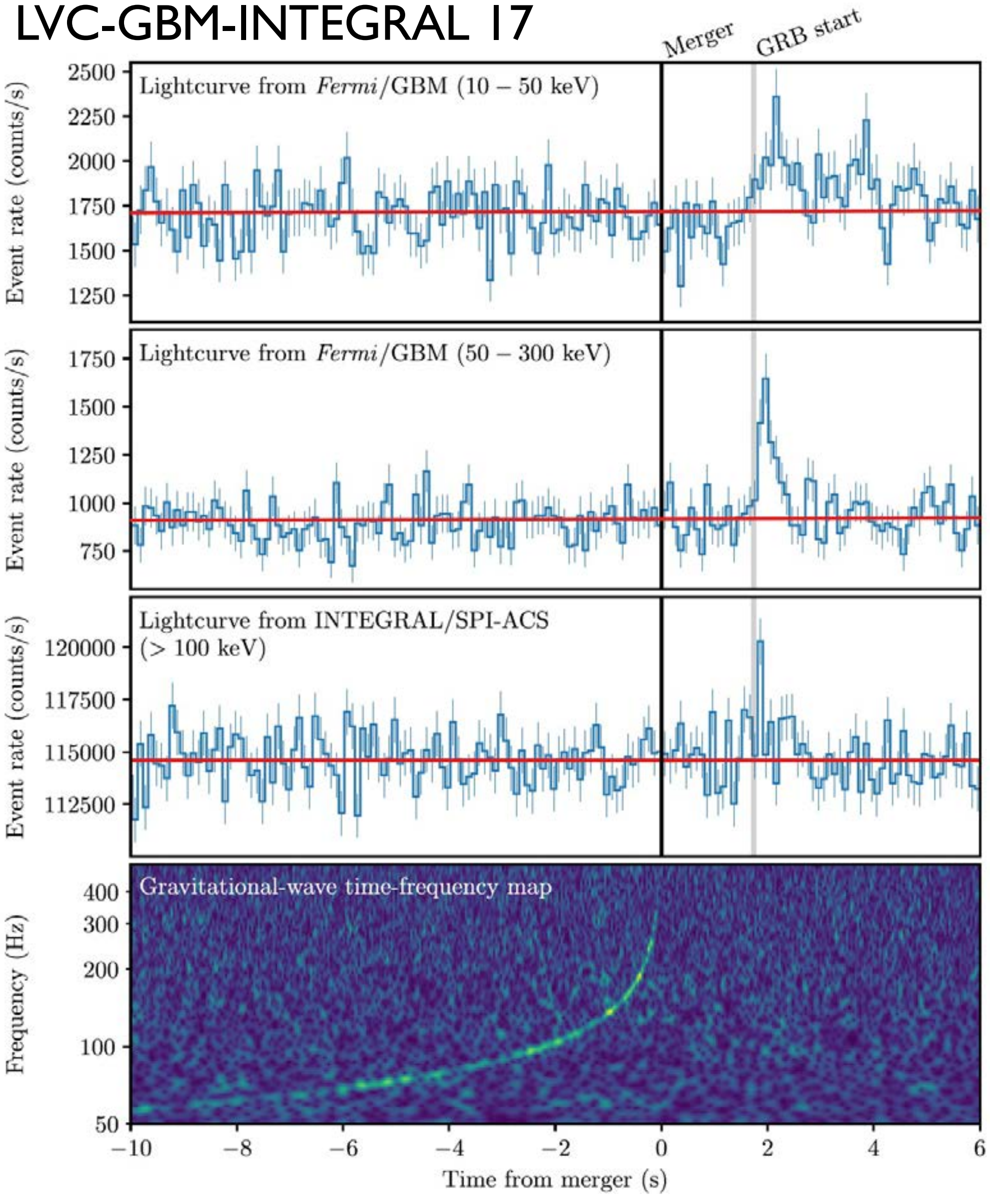


Relativity,
Cosmology,
…



GW170817 & GRB 170817A

LVC-GBM-INTEGRAL 17

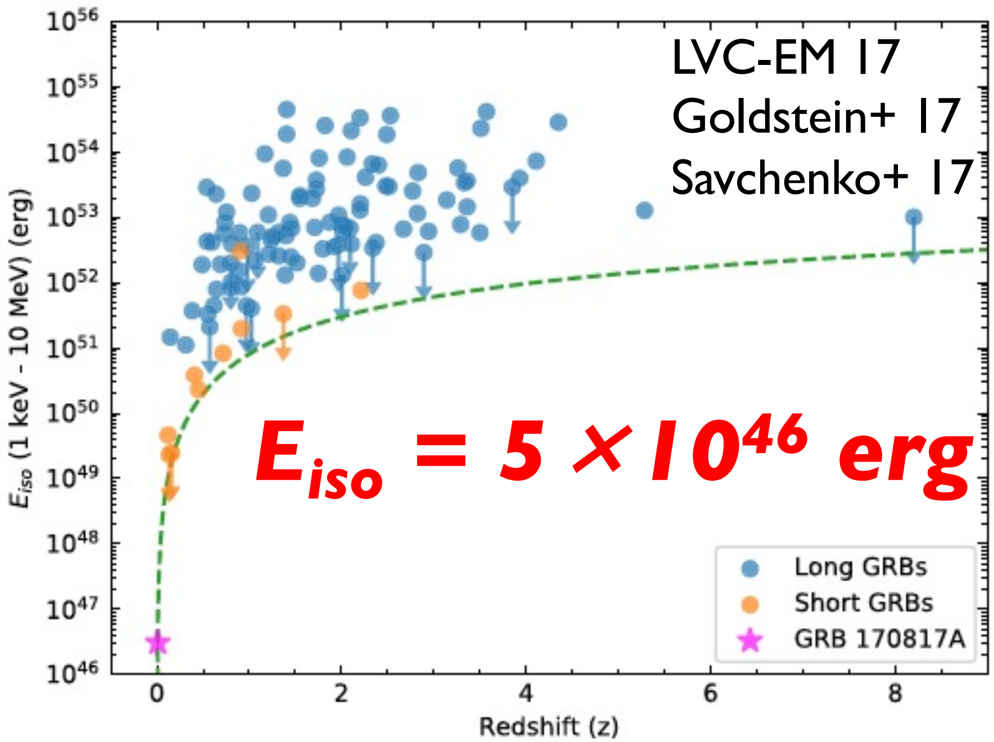


3 (of 12) GBM NaI detectors

T_0=1.74±0.05 sec (68%)

T_{90}=2.0±0.5 sec

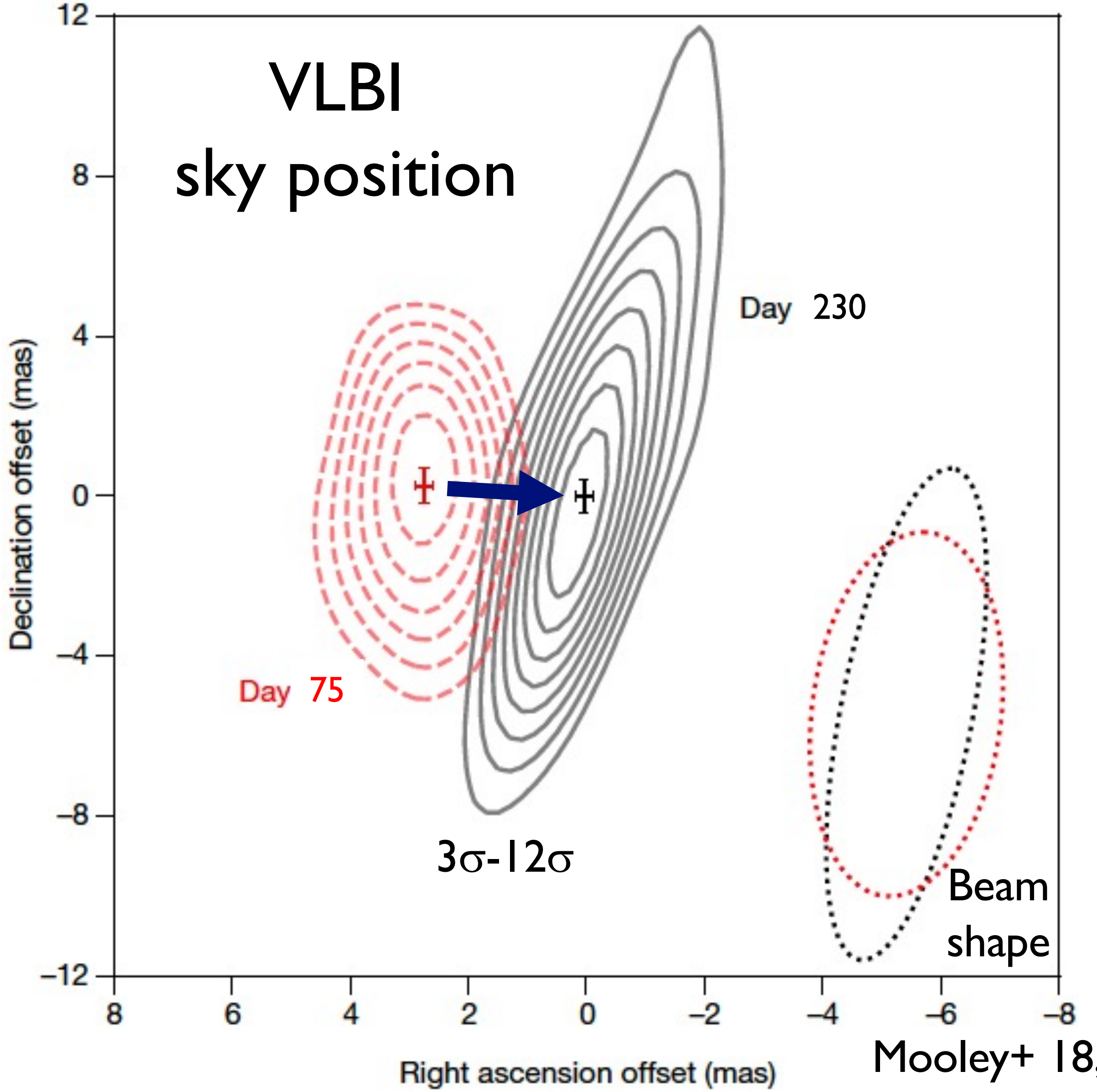
Detected but Weak



LVC-EM 17
Goldstein+ 17
Savchenko+ 17

$E_{iso} = 5 \times 10^{46}$ erg

Superluminal Motion



Mooley+ 18, Ghirlanda+ 19

v_{app}~4.1 ±0.5 c!

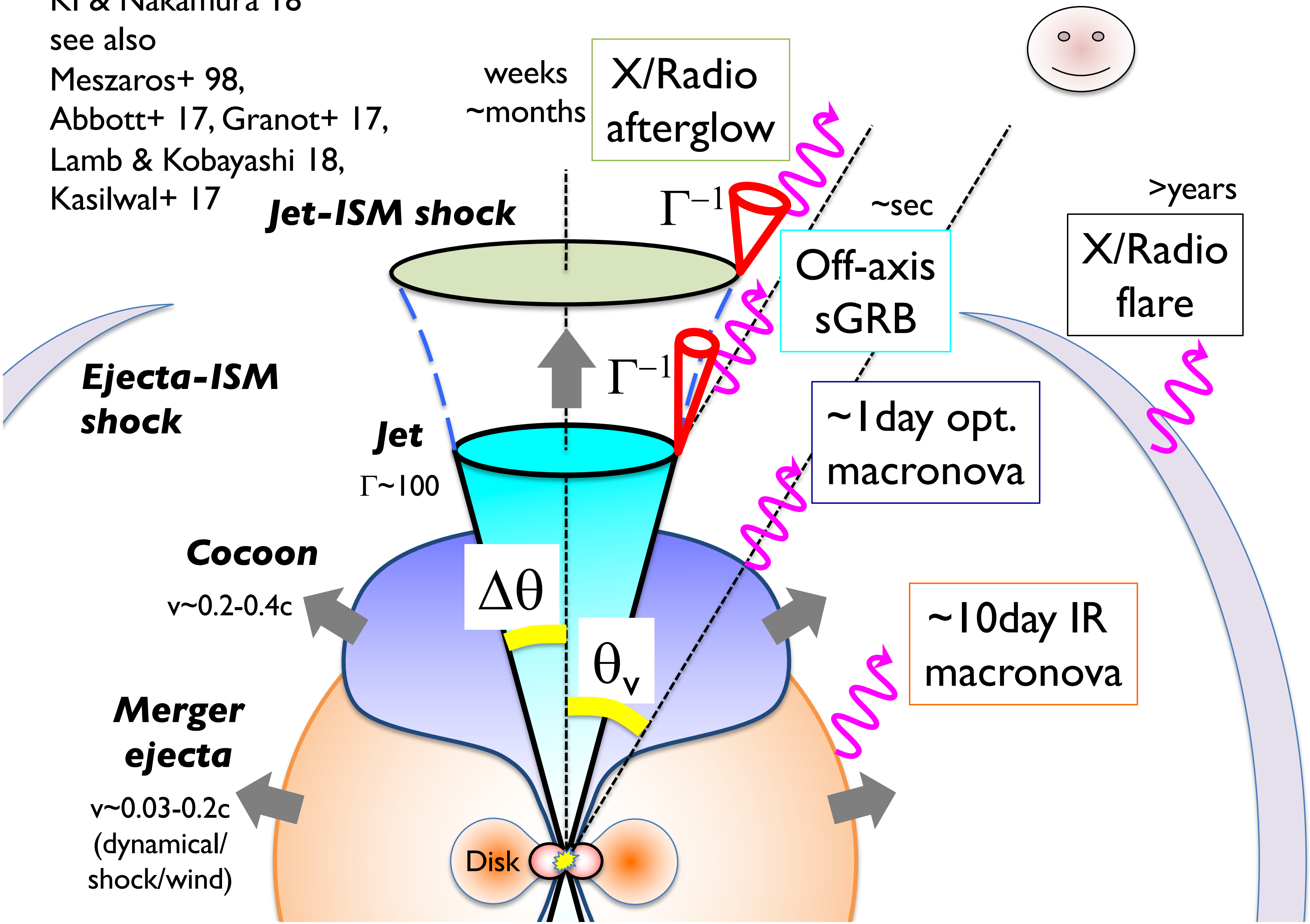
Unresolved

$R_{//}$<0.2pc(1mas),
$R_{\perp}$<2pc(10mas)

Not consistent with a spherical source

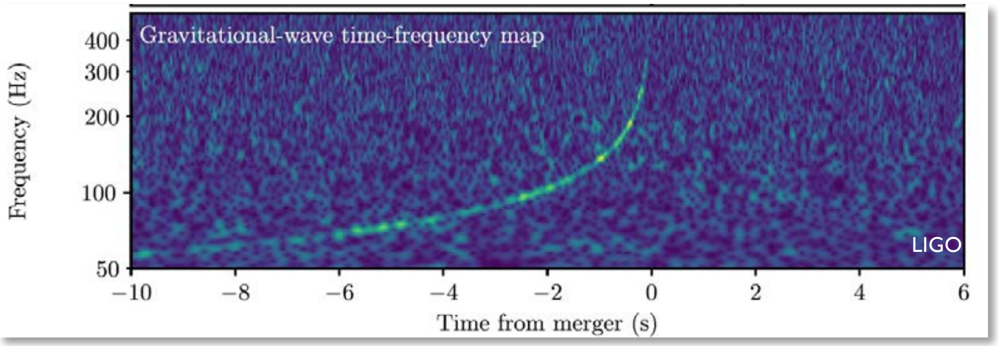
Γ~4 at t~t_{peak}

KI & Nakamura 18
see also
Meszaros+ 98,
Abbott+ 17, Granot+ 17,
Lamb & Kobayashi 18,
Kasilwal+ 17



GW170817

1^{st} GW from NS^2



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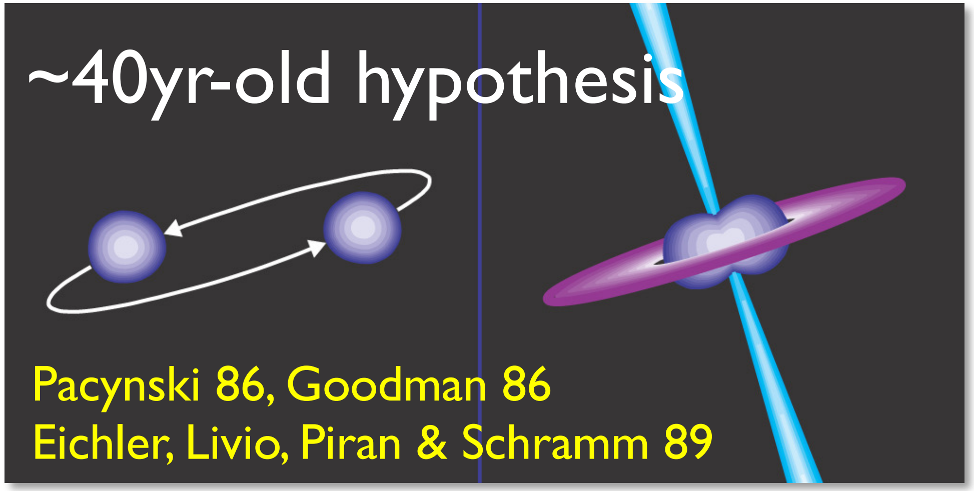
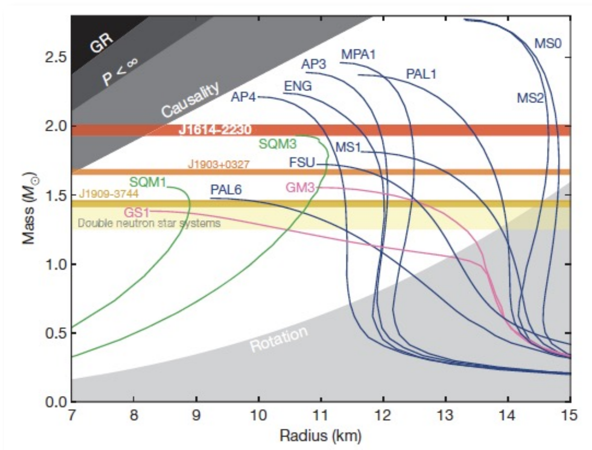
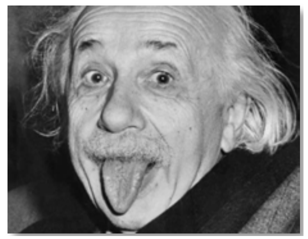


R-process elements

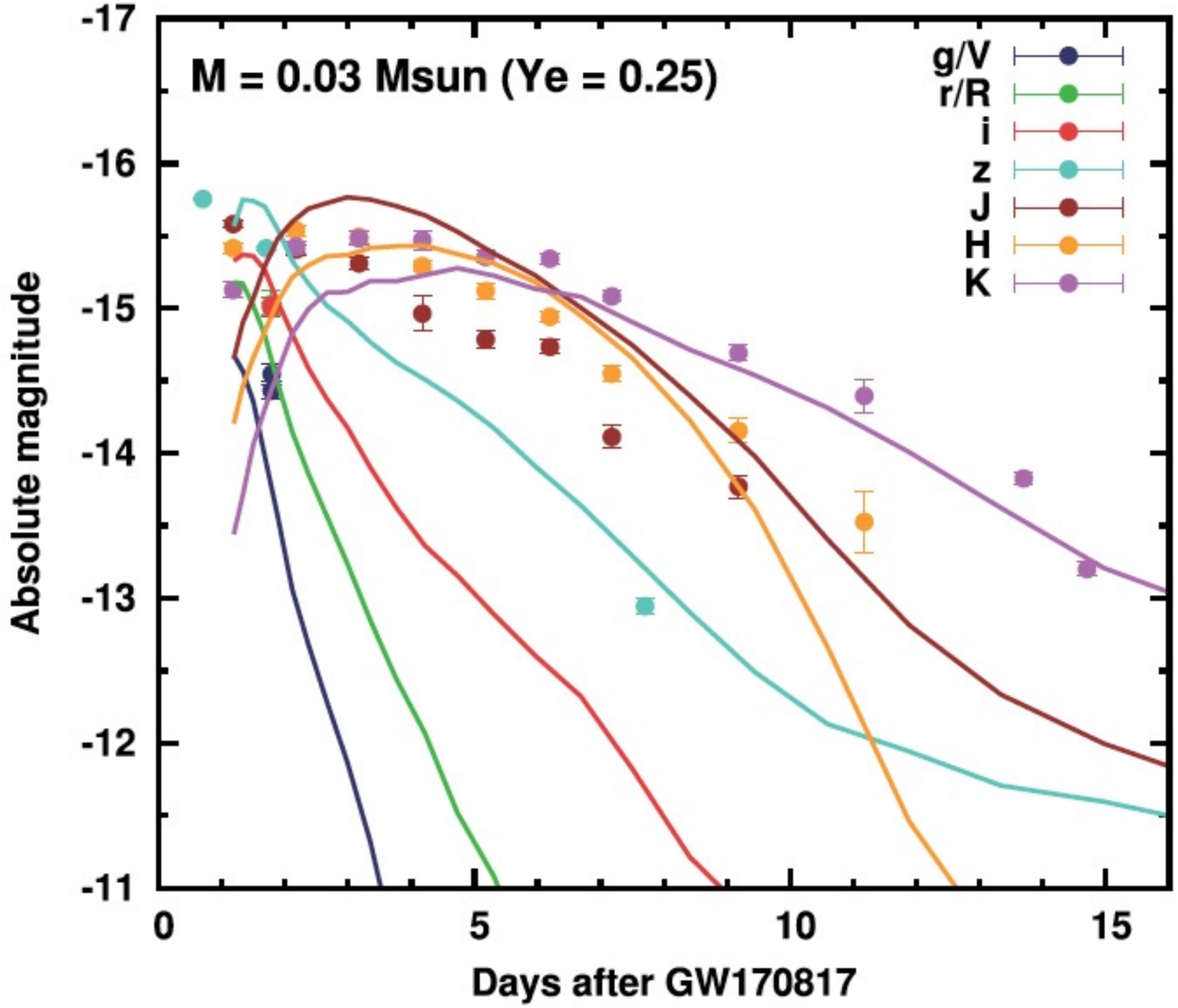
Equation of state



Relativity,
Cosmology,
…



Macronova/Kilonova



J-GEM 17, Tanaka+ 17, Utsumi+ 17, Tominaga+ 17, Arcavi+ 17, Drout+ 17, Cowperthwaite+ 17, Villar+ 17, Kasliwal+ 17, Kasen+ 17, Smartt+ 17, Kilpatrick+ 17, Pian+ 17, Chornock+ 17, Coulter+ 17, Evans+ 17, …

Blue macronova

$v \sim 0.3c$

$M \sim 0.02 M_\odot$

$\kappa \sim 0.3\ \mathrm{cm^2/g}$

$(X_{\mathrm{Lan}} \sim 10^{-4})$

Red macronova

$v \sim 0.1\text{-}0.2c$

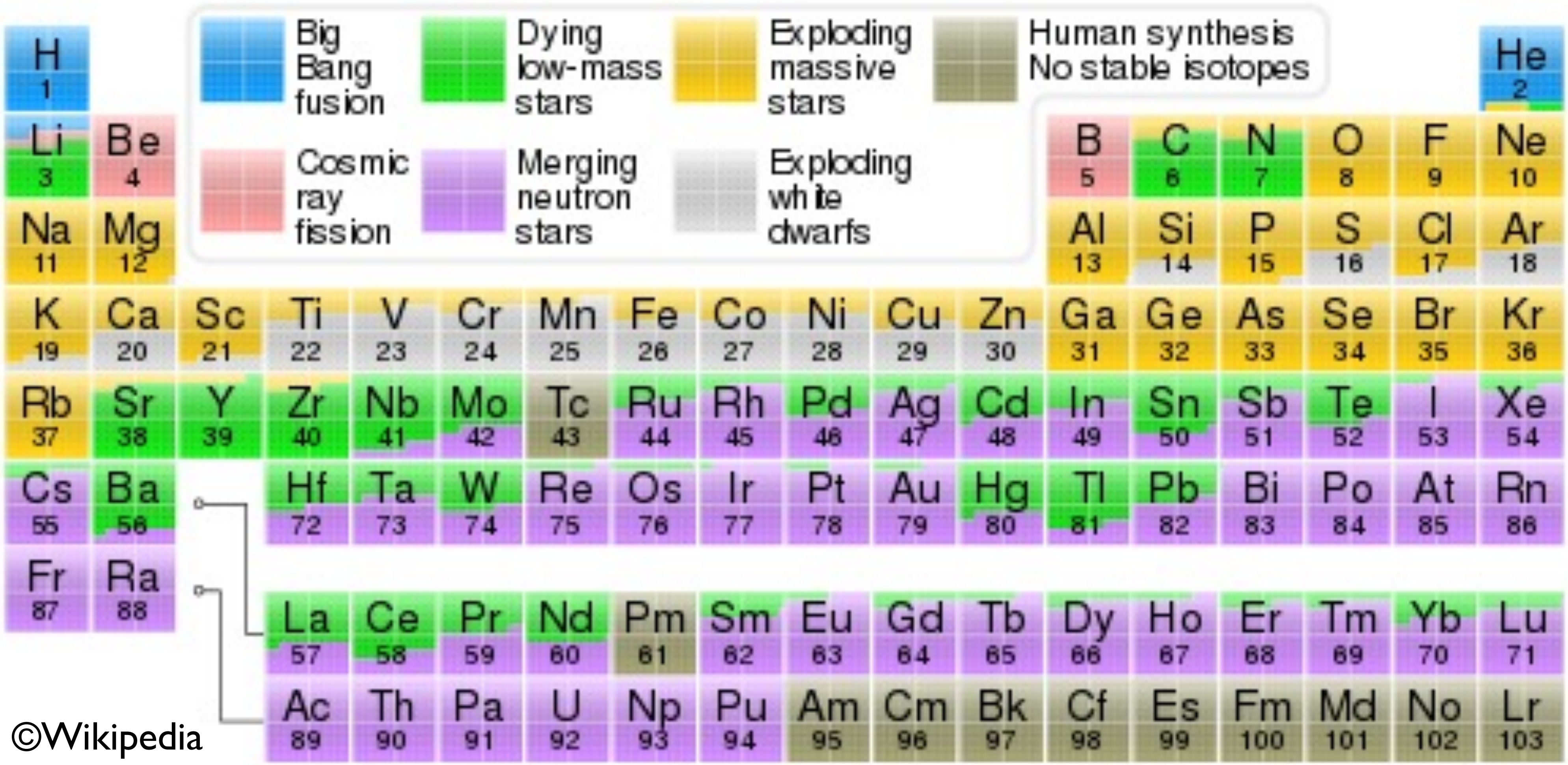
$M \sim 0.03 M_\odot$

$\kappa \sim 3\ \mathrm{cm^2/g}$

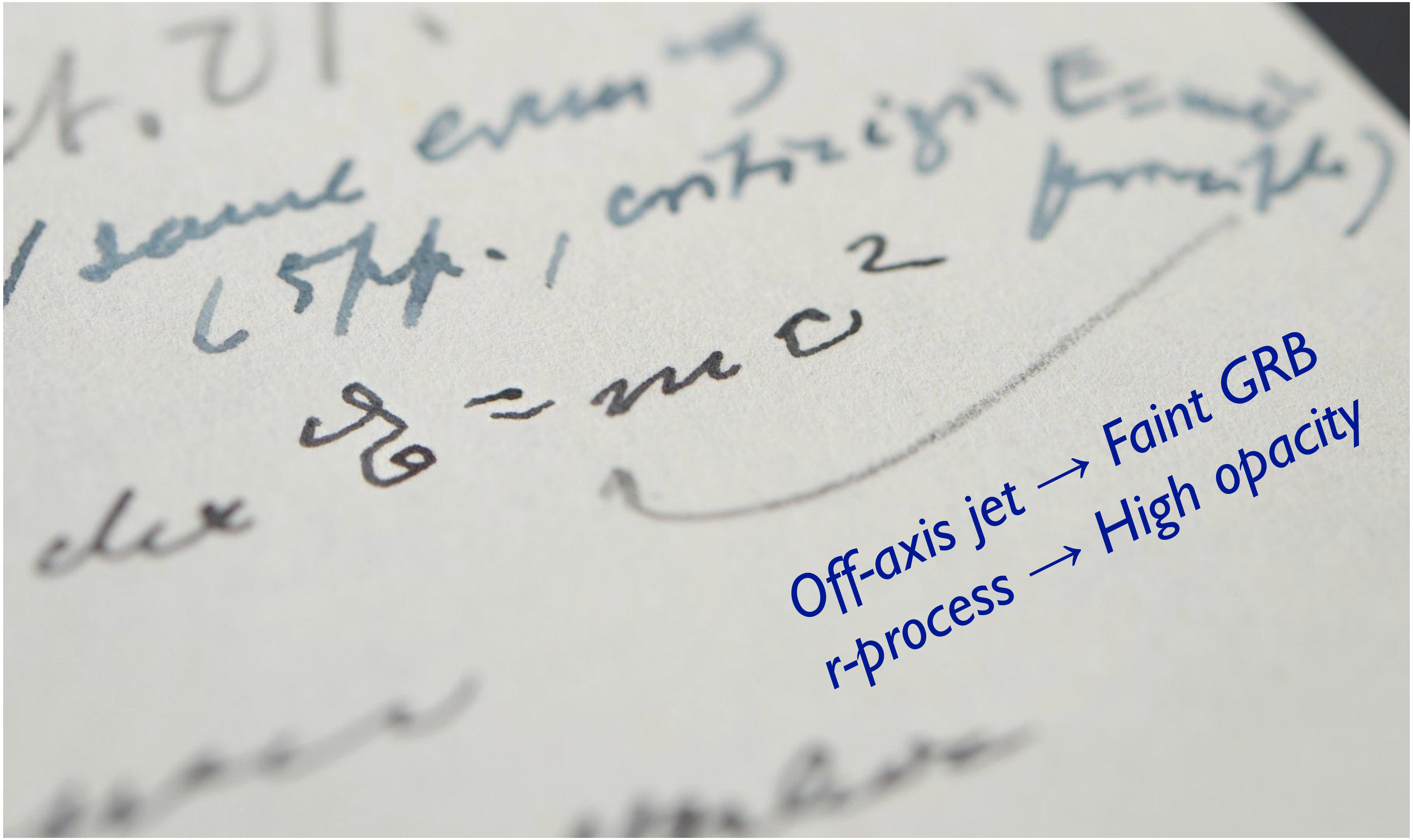
$(X_{\mathrm{Lan}} \sim 10^{-2})$

Origin of Elements

R-process: Neutron-capture >> β-decay



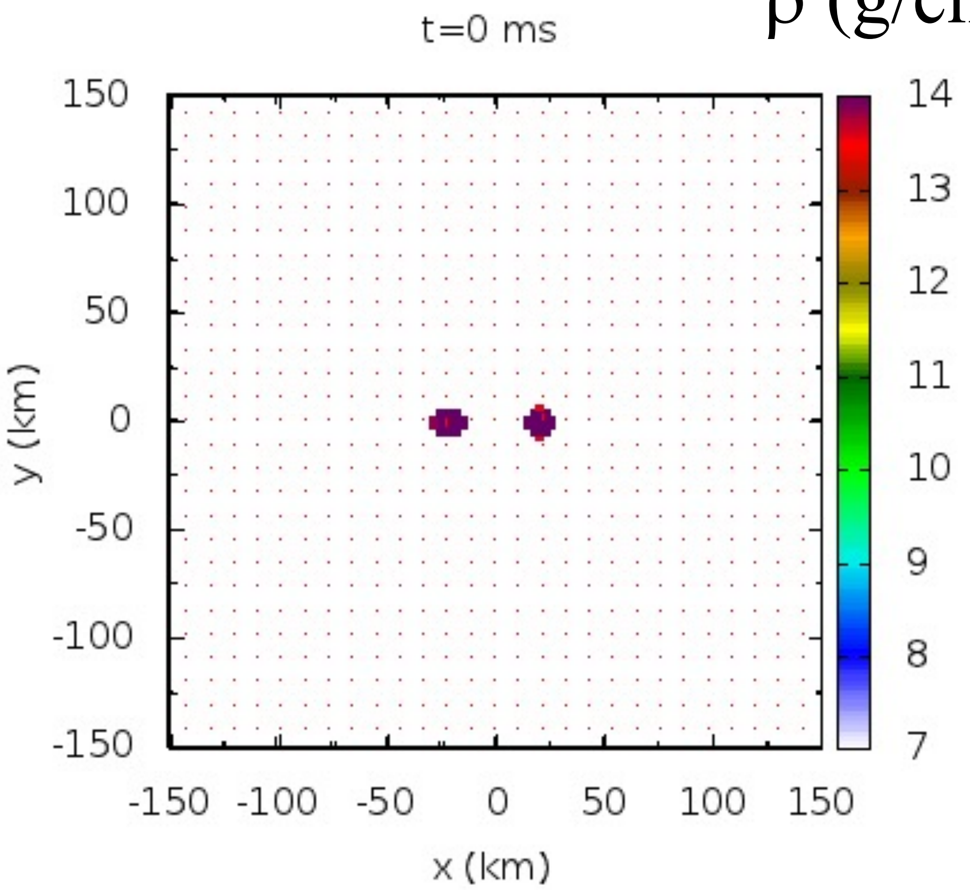
Theory

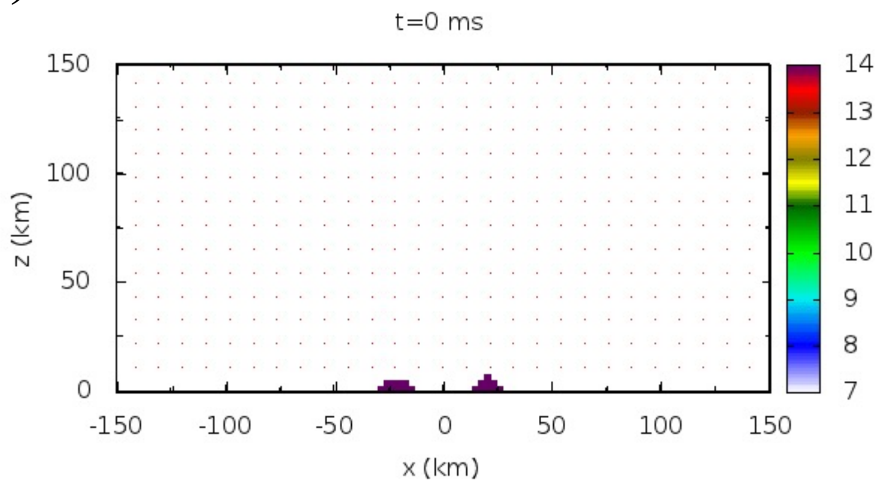


Merger of 1.3-1.4 M_{sun} NS:

EOS=APR4; stiff but relatively soft

ρ (g/cm^3)





Relatively wider view

Orbital plane

***X-Z* plane**

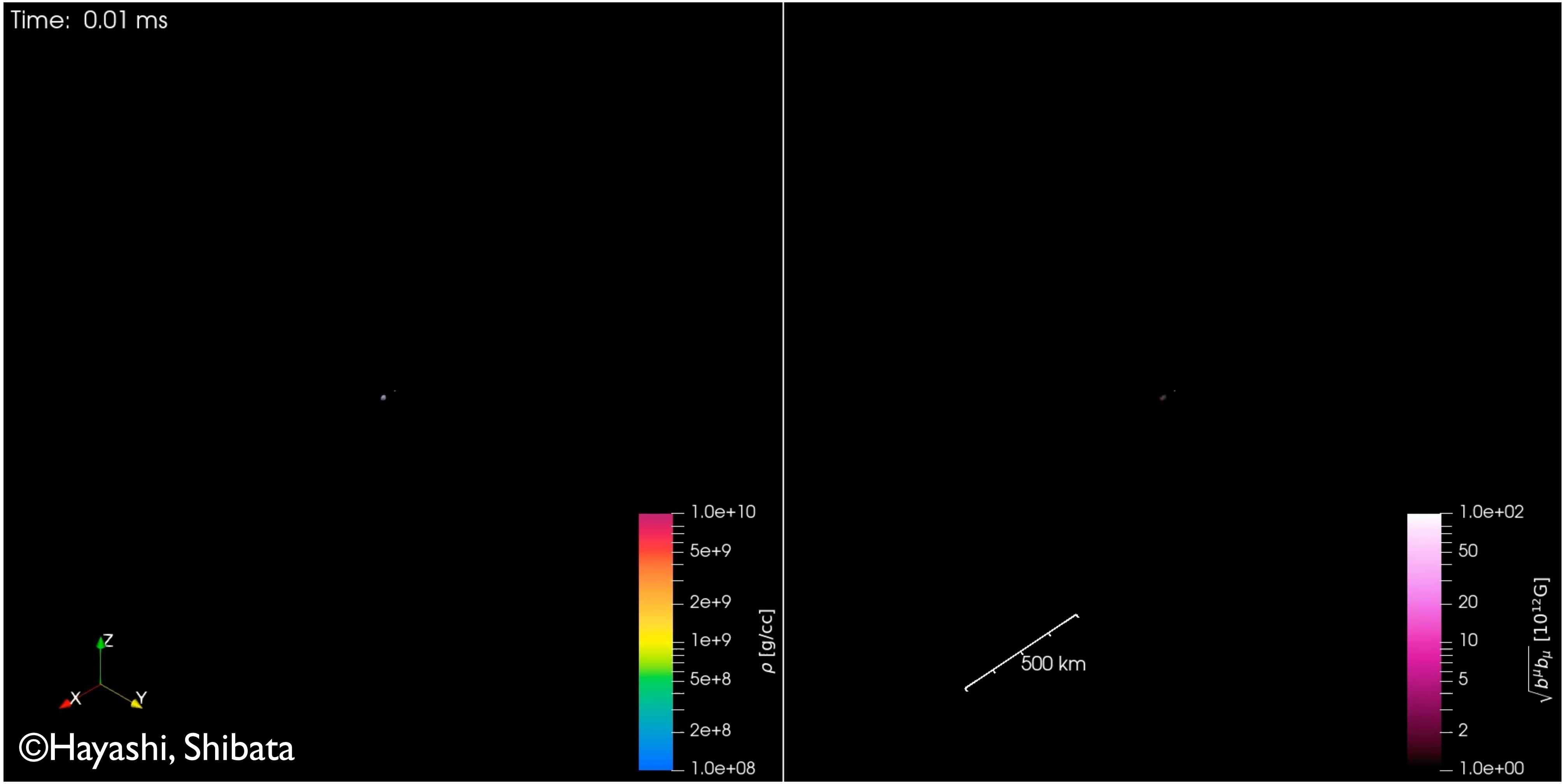
Approach

- ***Observation***
  - Multi-wavelength: radio to PeV γ-ray
  - Multi-messenger: γ, CR, ν, GW
- ***Theory***
  - Analytic
  - Numerical

* NAOJ / JAXA / ICRR
vertically segmented?

Best example: GW170817

Numerical Development



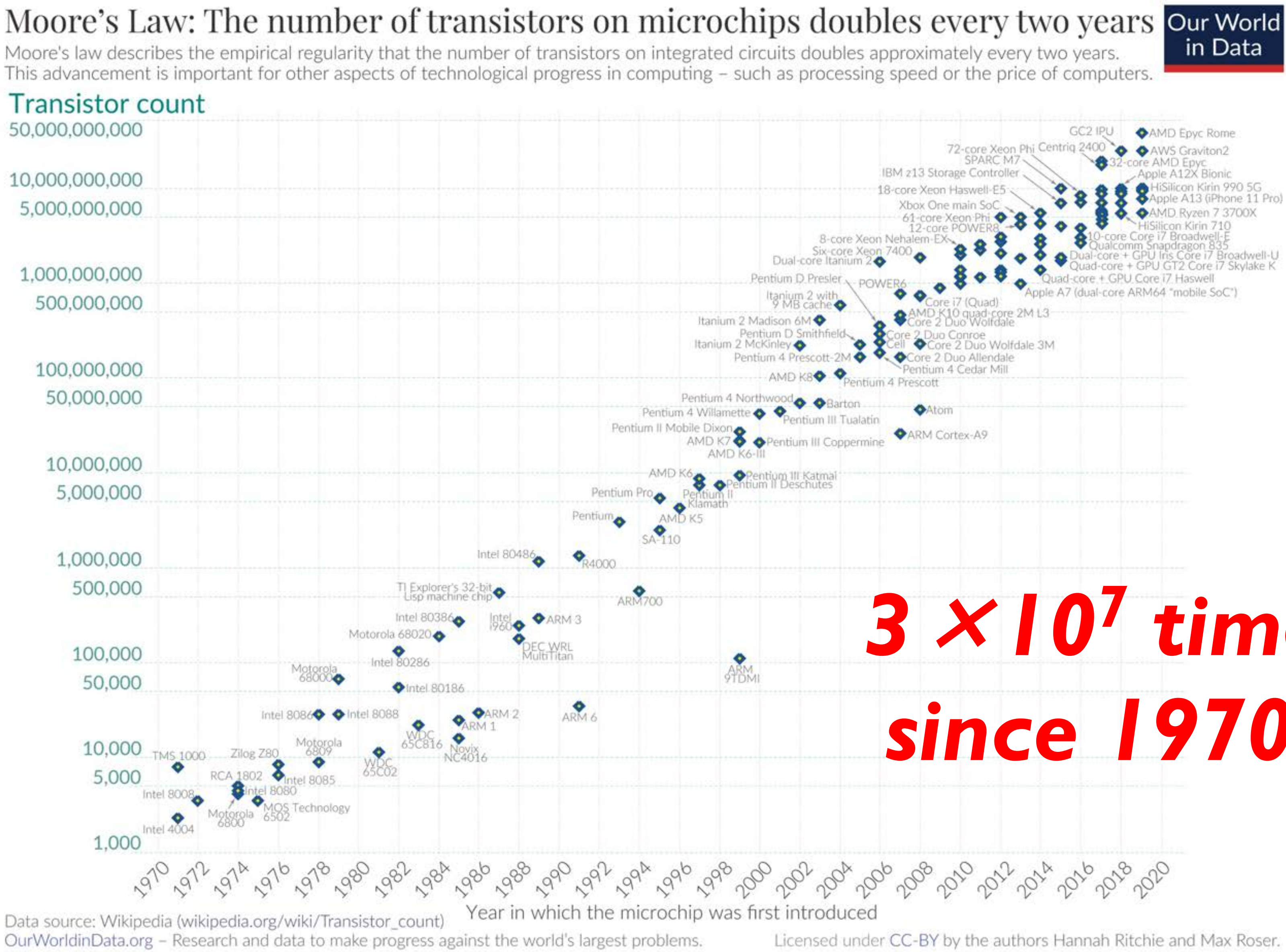
B connected to horizon

Hayashi+ 21

GR+B+ν & Long-term

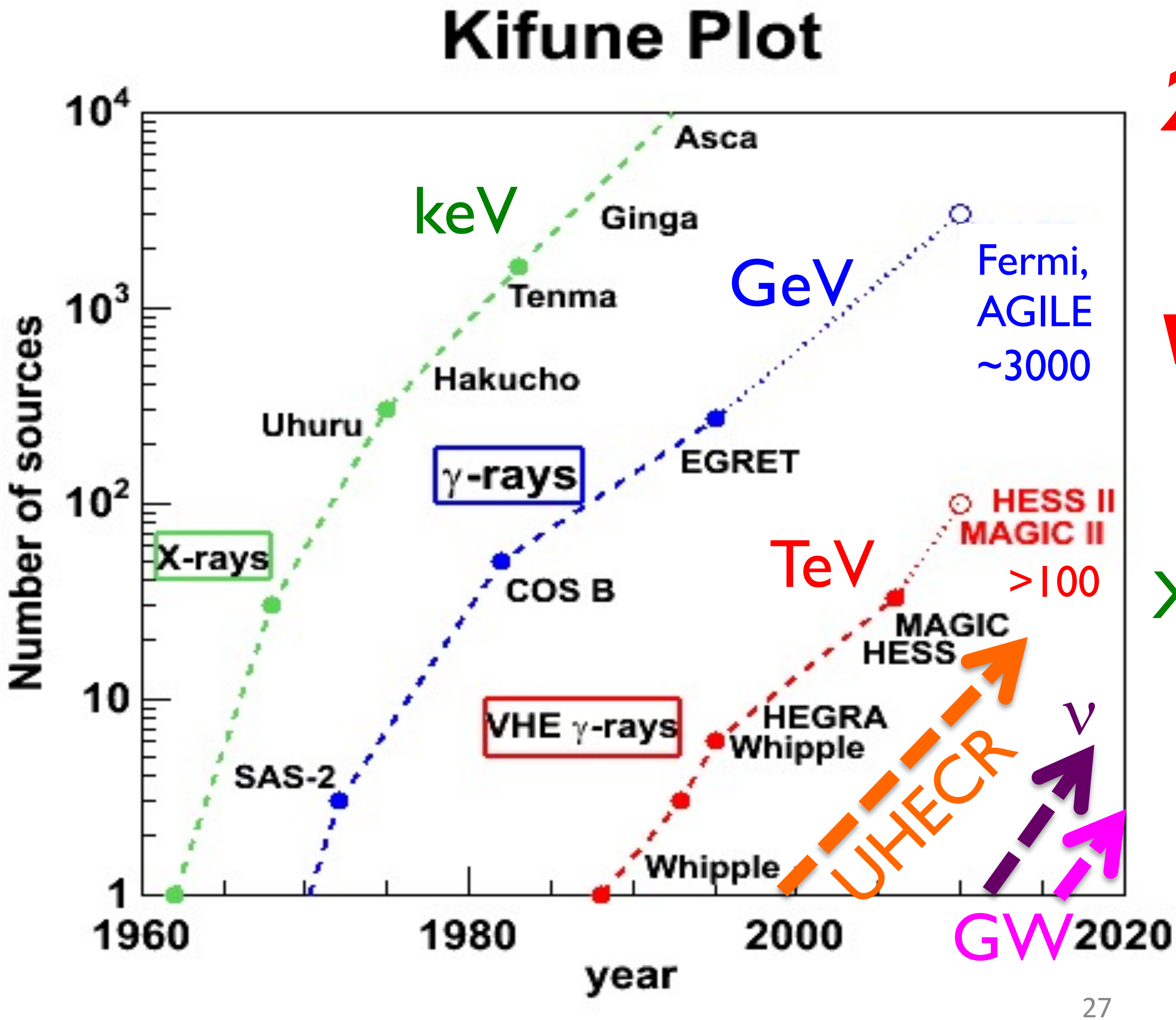
(ATERUI II is not enough)

Moore's Law



3×10^{7} times since 1970 !!

Multi-Messenger Era

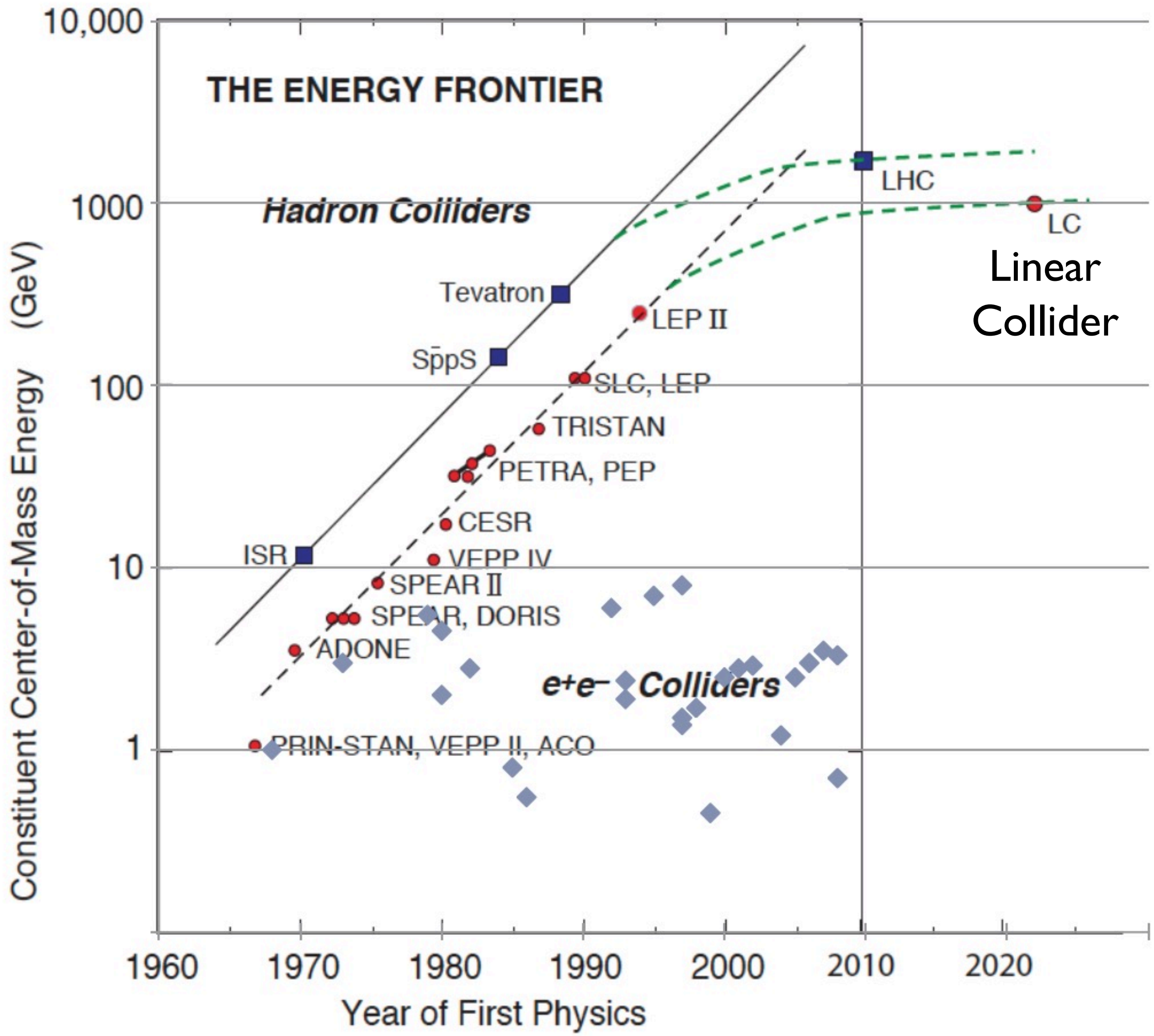


20th century: *Multi-wavelength*

μeV radio-μwave-Infrared-Optical-X-GeV γ-TeV γ-rays

# of sources are increasing exponentially

Livingston Plot



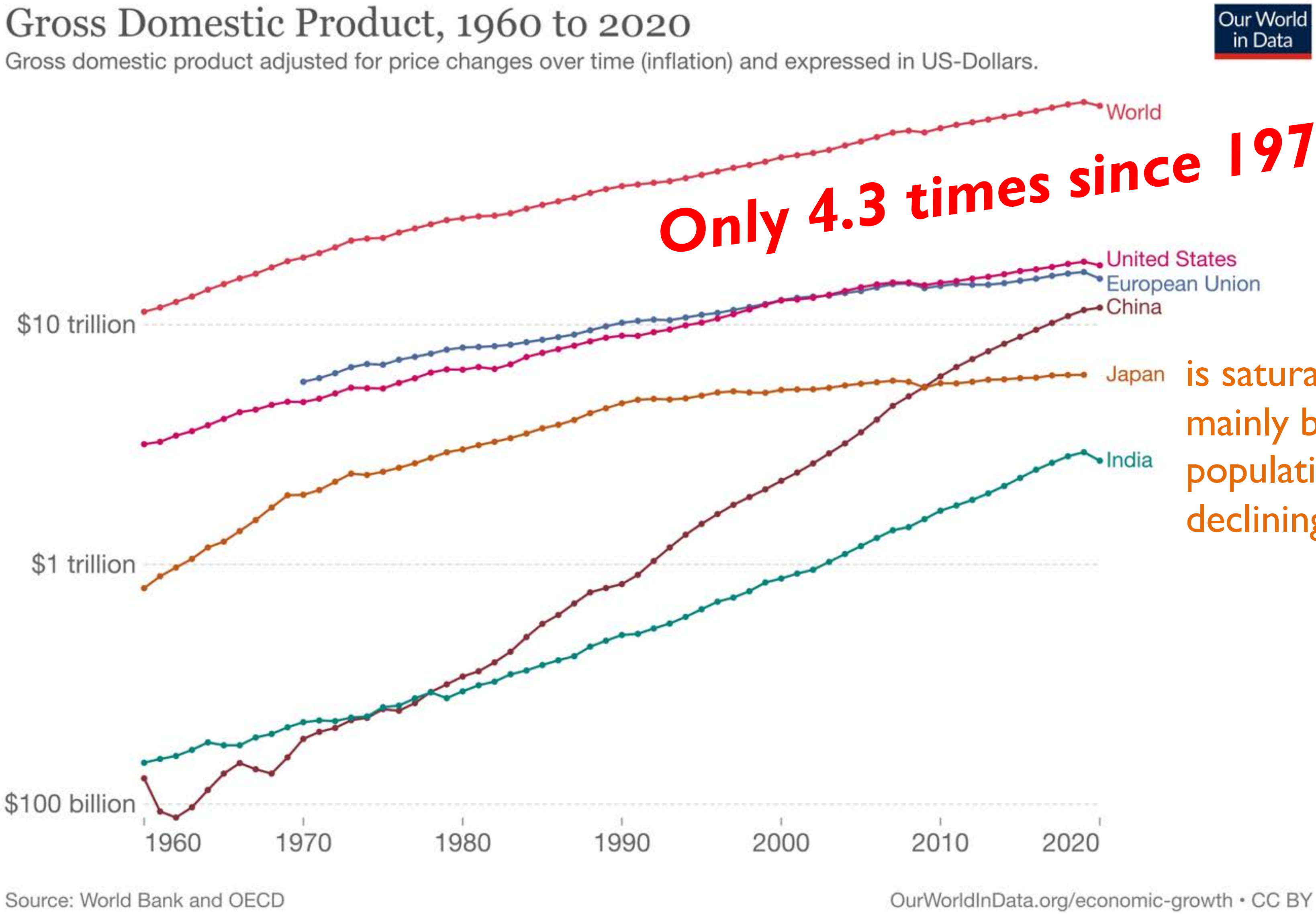
Accelerators are saturating probably due to budget

~\$7 billion ~1兆円 for LC

cf. ~\$9.7 billion for JWST

© Jordan Nash,
Imperial College London

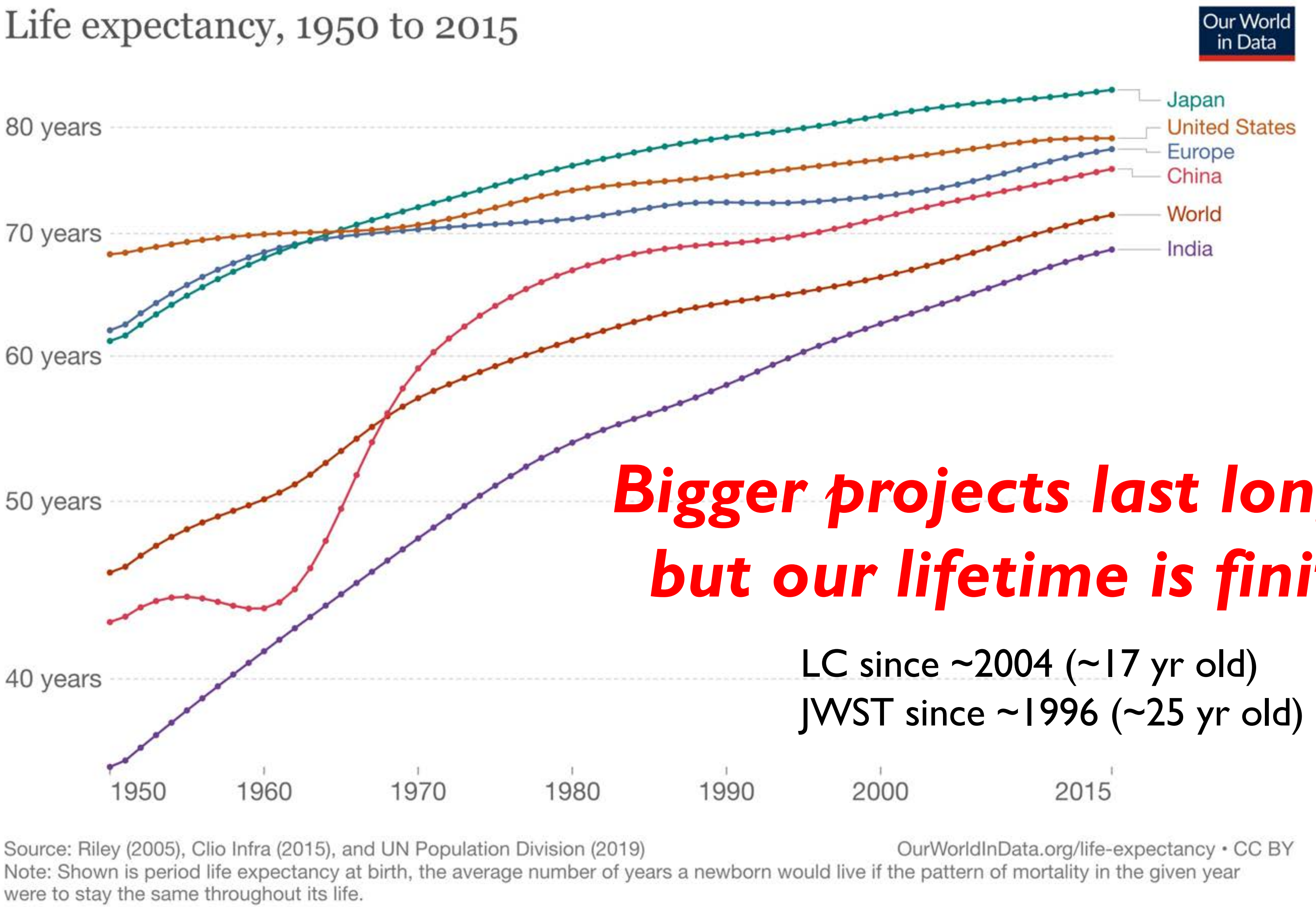
Budget Limit



Only 4.3 times since 1970

is saturated mainly because population is declining

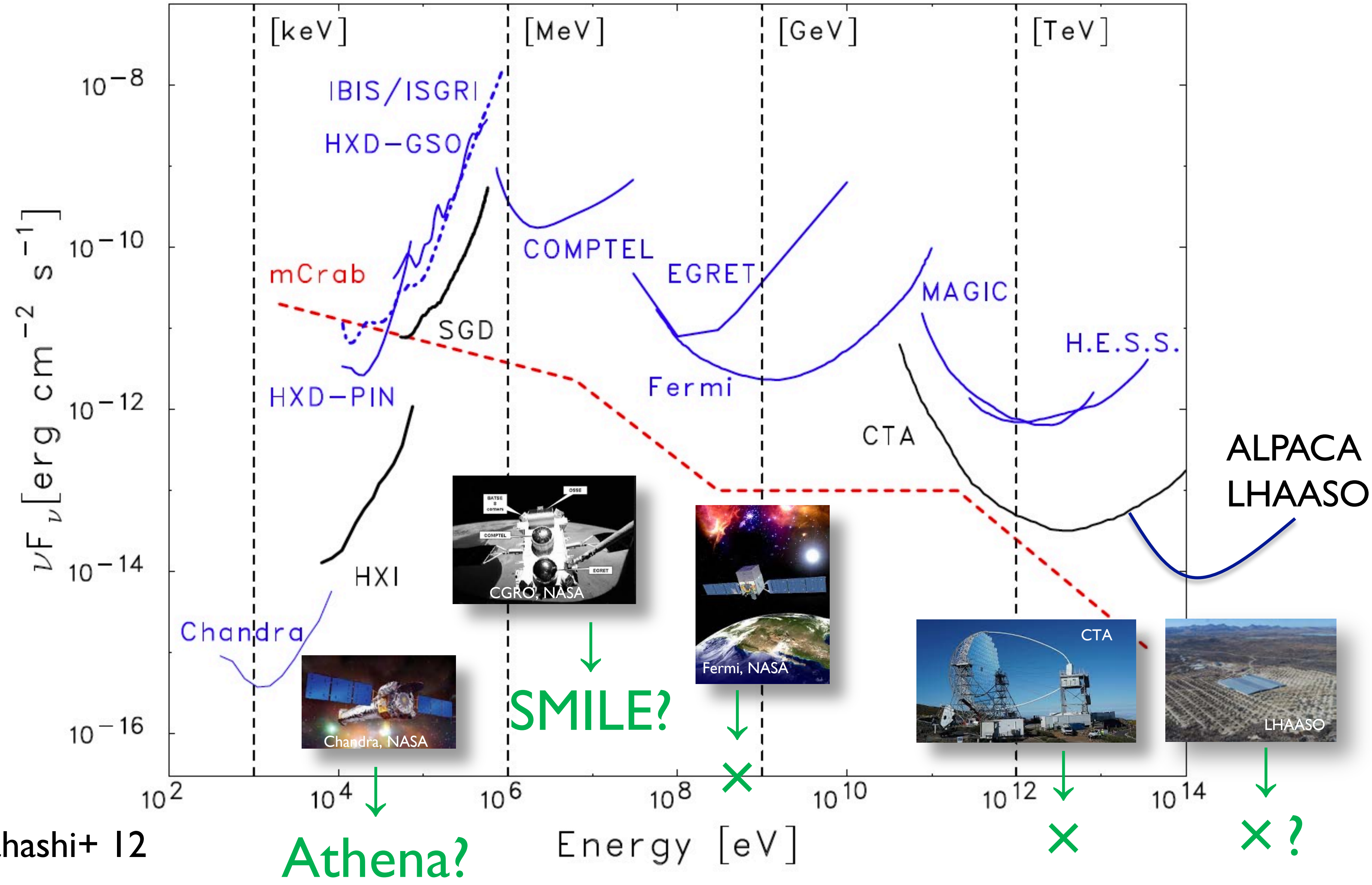
Age Limit



Bigger projects last longer but our lifetime is finite

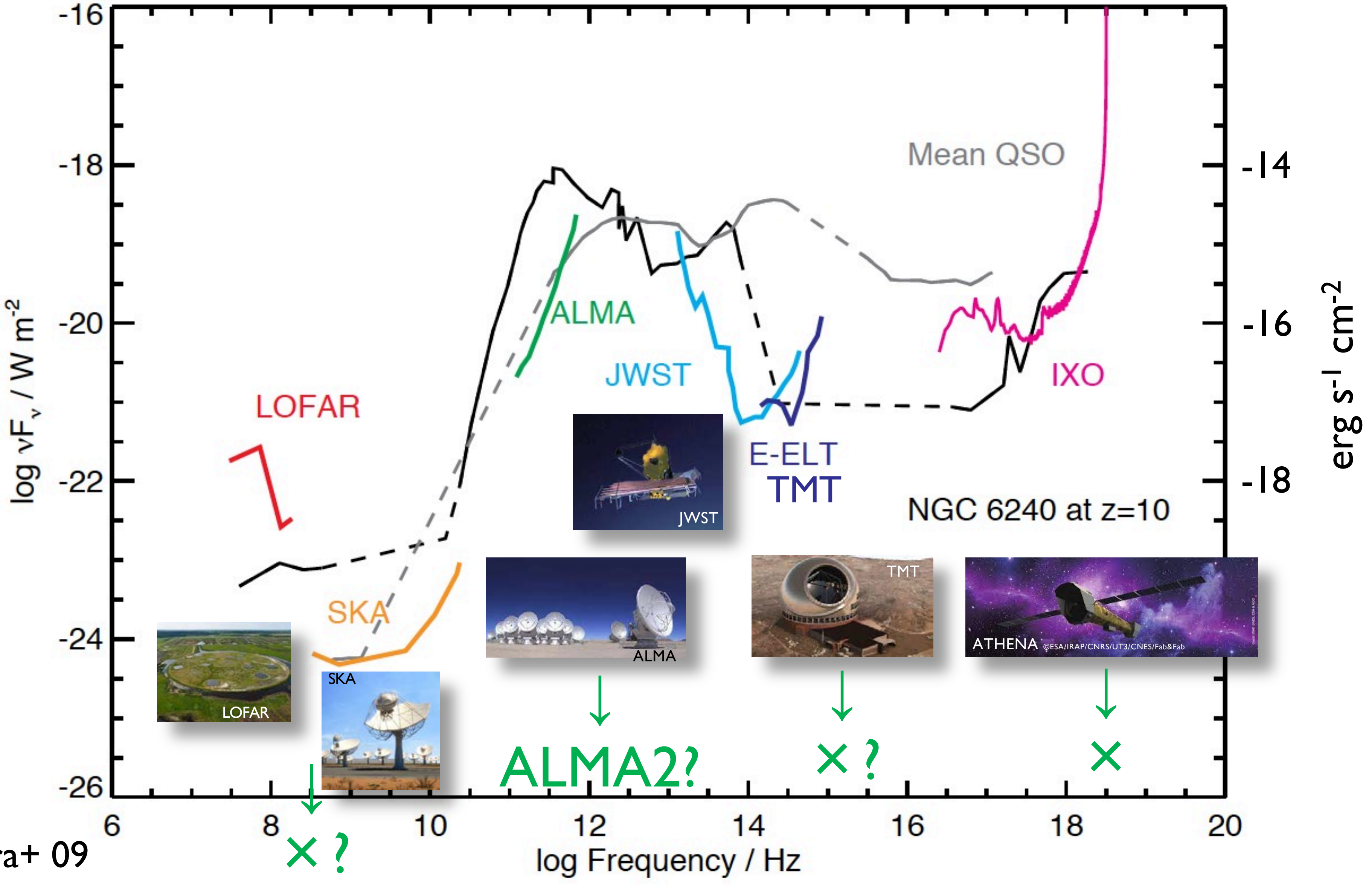
LC since ~2004 (~17 yr old)
JWST since ~1996 (~25 yr old)

Saturation? keV-PeV



Takahashi+ 12

Saturation? GHz-keV



Nandra+ 09

Saturation? CR, ν, GW

- ***Cosmic ray***
  - EeV-ZeV: Auger, TA, TALE, EUSO?
  - GeV-TeV: AMS-02, CALET, DAMPE
- ***Neutrino***
  - MeV: Super-Kamiokande, Hyper-Kamiokande
  - PeV: IceCube, KM3NeT, Baikal, IceCube-Gen2
- ***Gravitational wave***
  - LIGO, Virgo, KAGRA, Einstein telescope?, Cosmic explorer?
  - LISA, Taiji + TianQin, DECIGO?

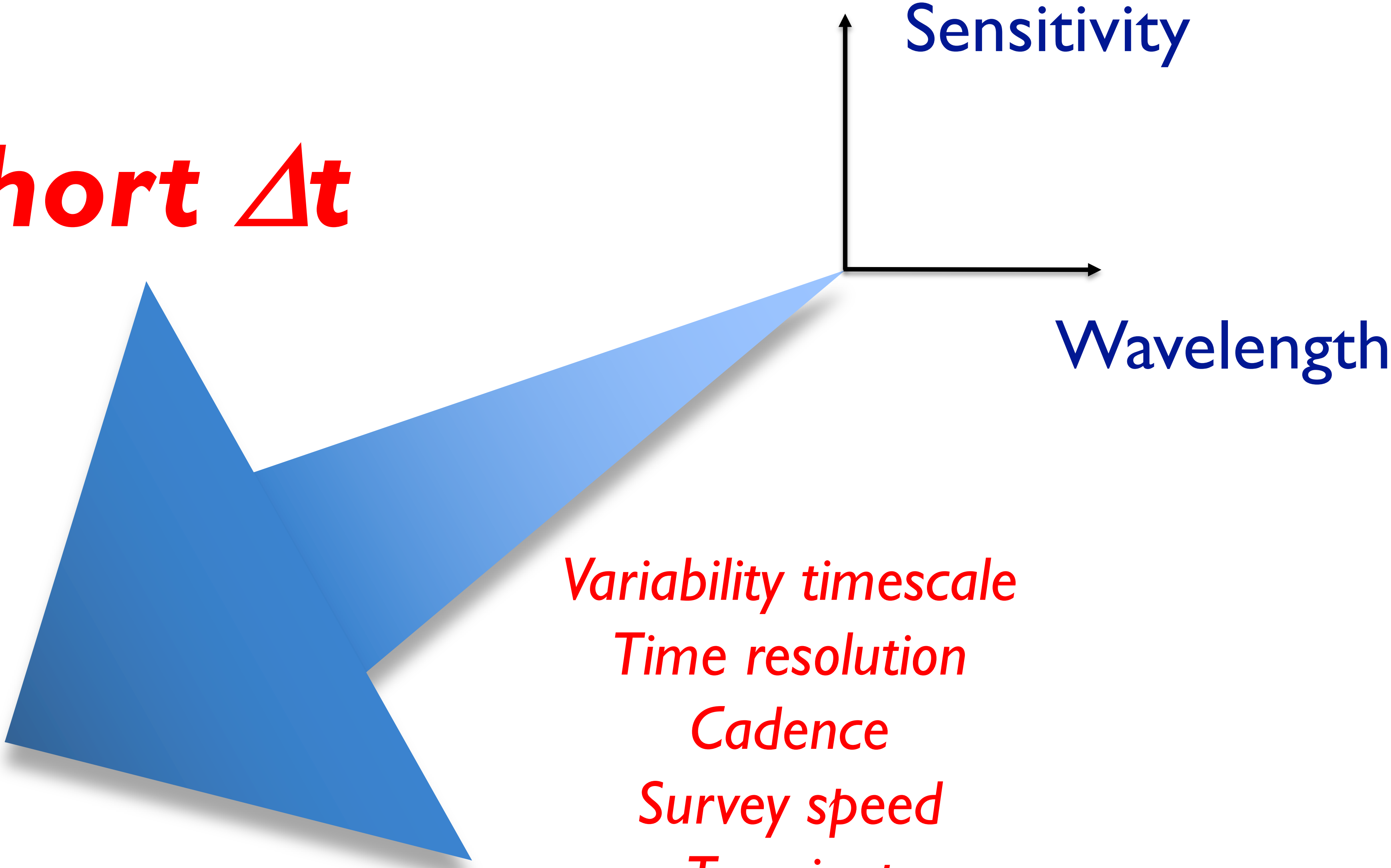
Sensitivity is saturating

ν & GW still have space to grow

* A similar project will not be approved (Sustaining problem)

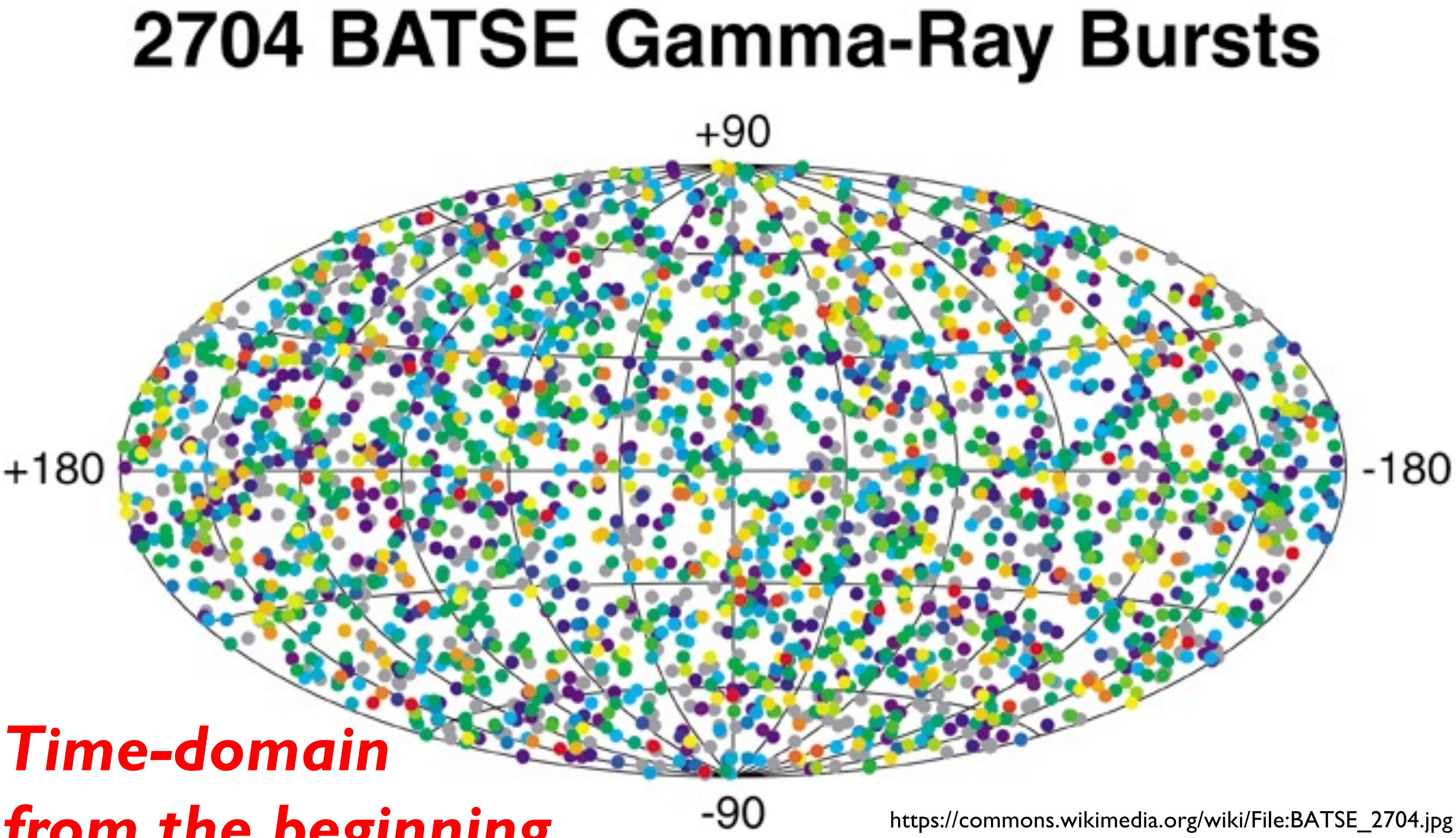
Time-Domain

Short Δt



Variability timescale
Time resolution
Cadence
Survey speed
Transient

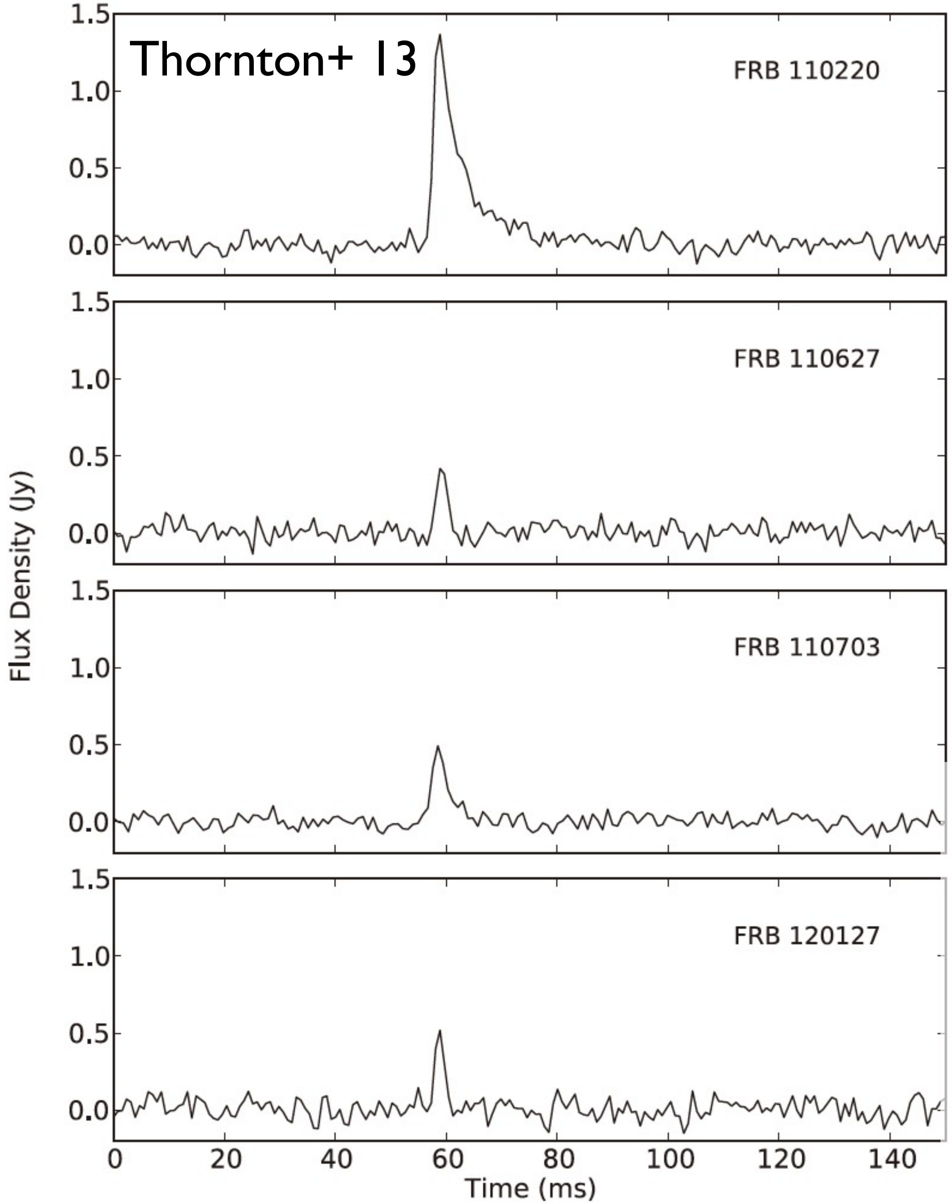
γ-Ray Transients

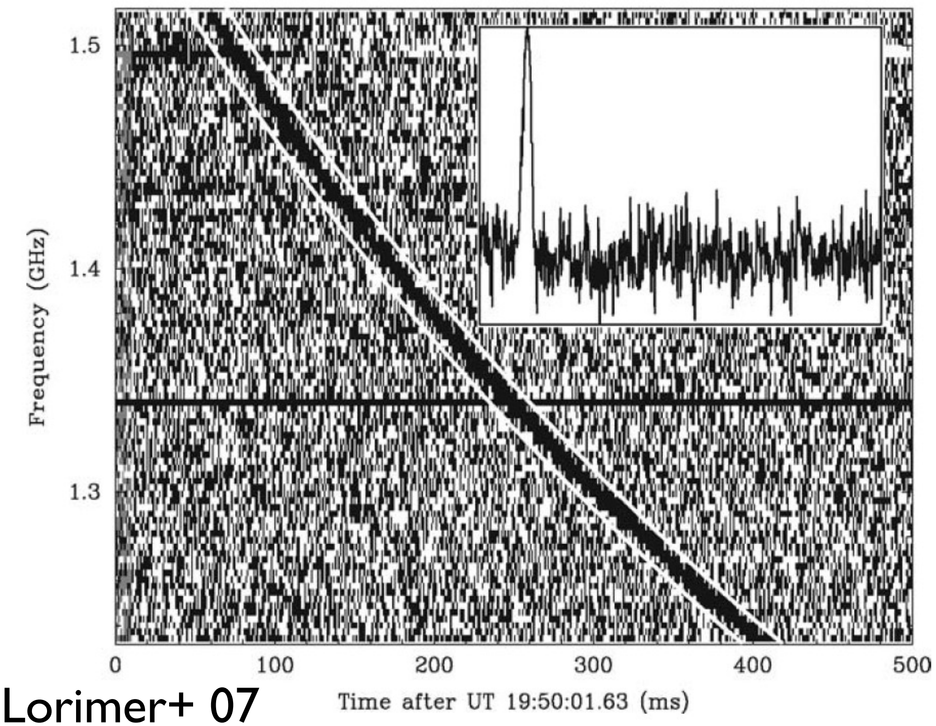


Time-domain from the beginning

https://commons.wikimedia.org/wiki/File:BATSE_2704.jpg

Fast Radio Bursts (FRB)

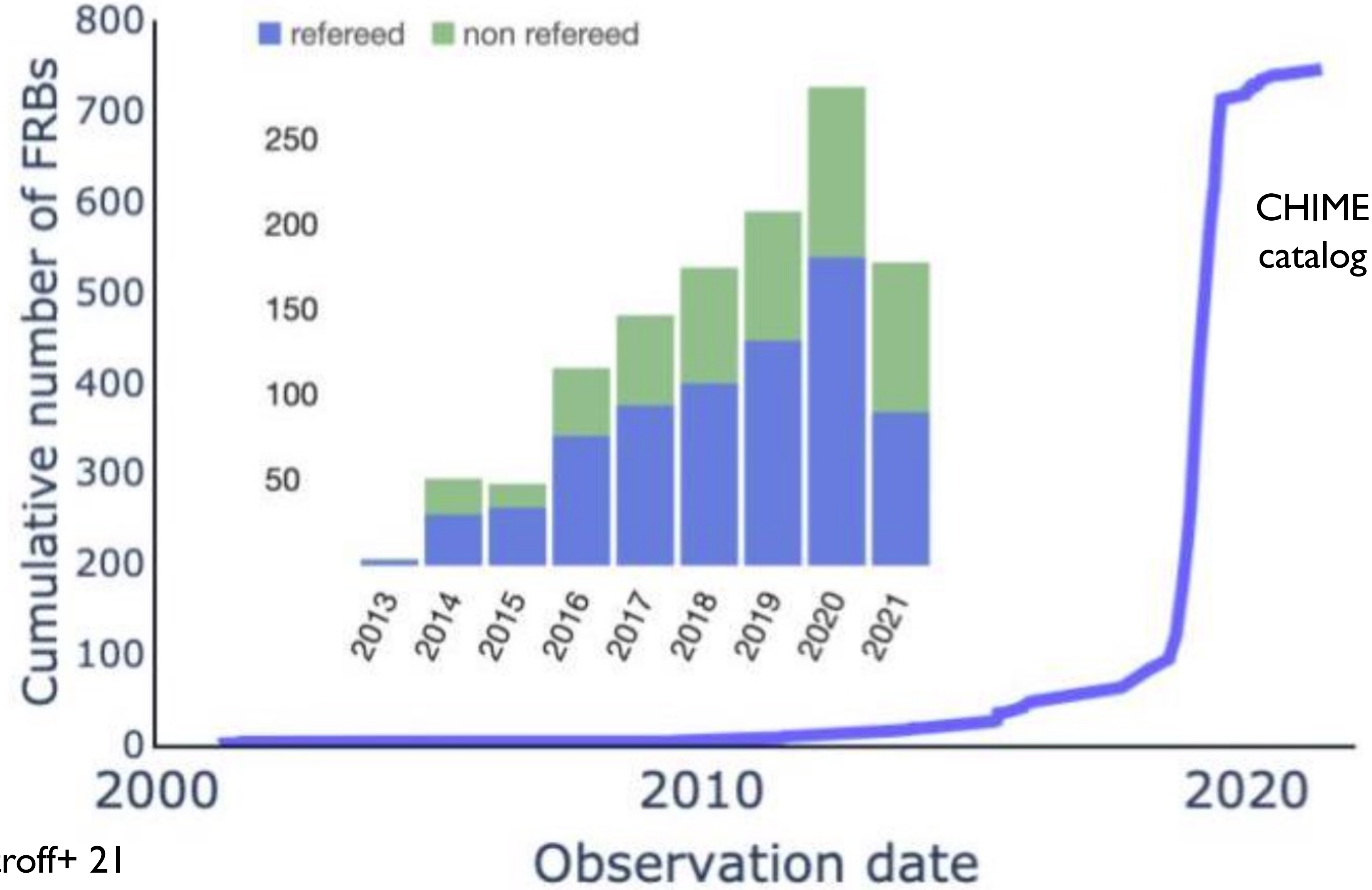




Lorimer+ 07

Most luminous radio transients discovered in 2007

FRB Events are Growing



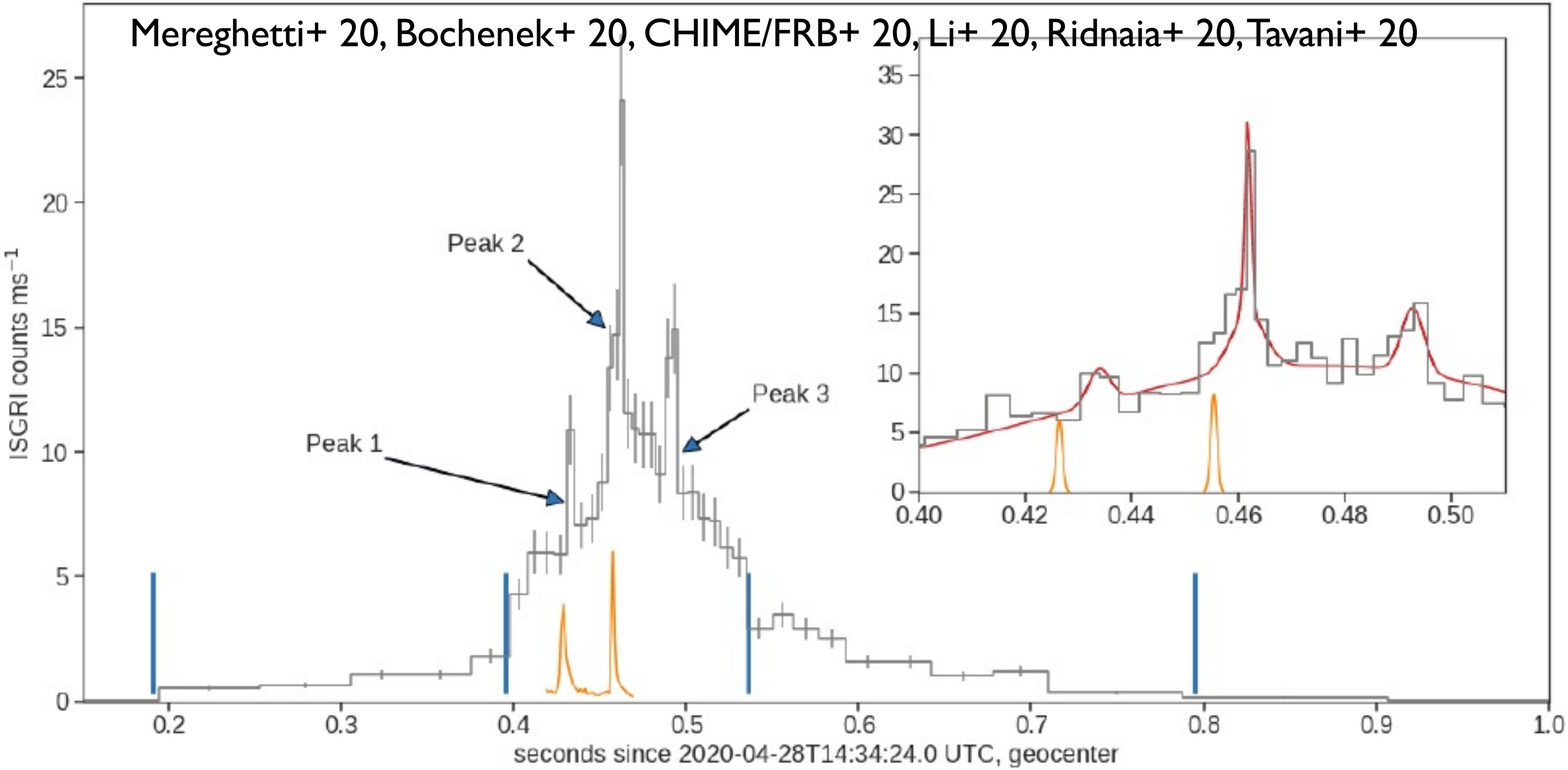
CHIME
catalog

Petroff+ 21

Galactic FRB from Magnetar Bursts

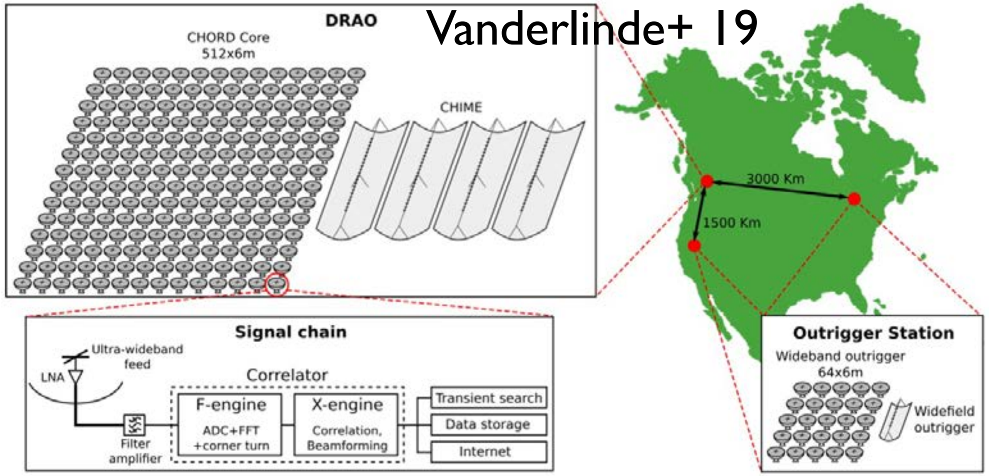
A smoking gun! Magnetar: One of the origins

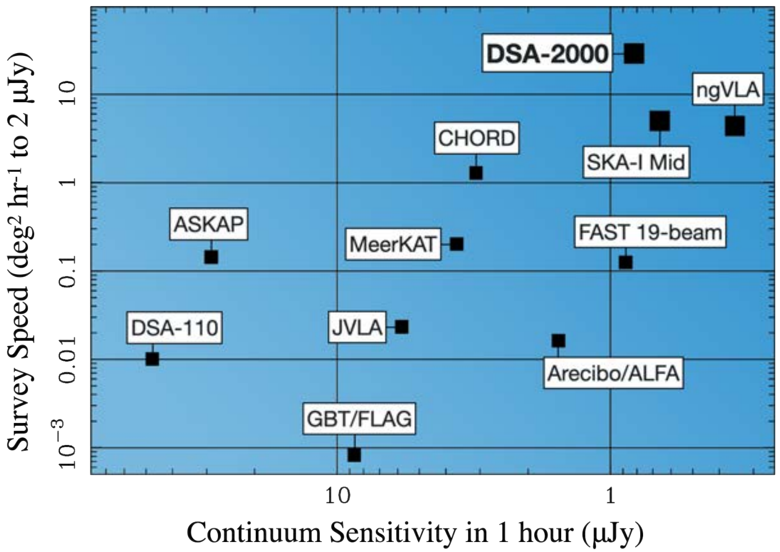
Mereghetti+ 20, Bochenek+ 20, CHIME/FRB+ 20, Li+ 20, Ridnaia+ 20, Tavani+ 20



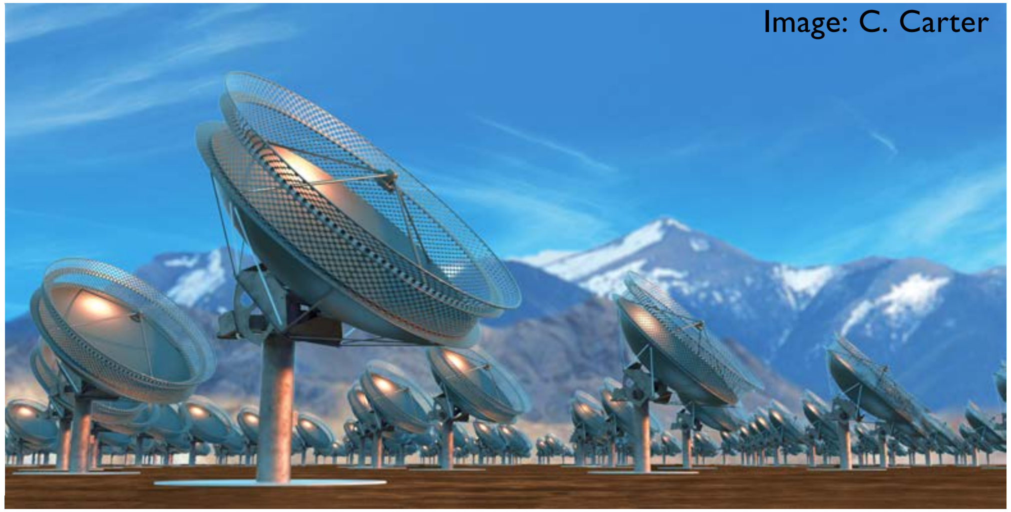
FRB Science will Grow

CHORD (CHIME upgrade)





DSA-2000



1000s FRBs/yr

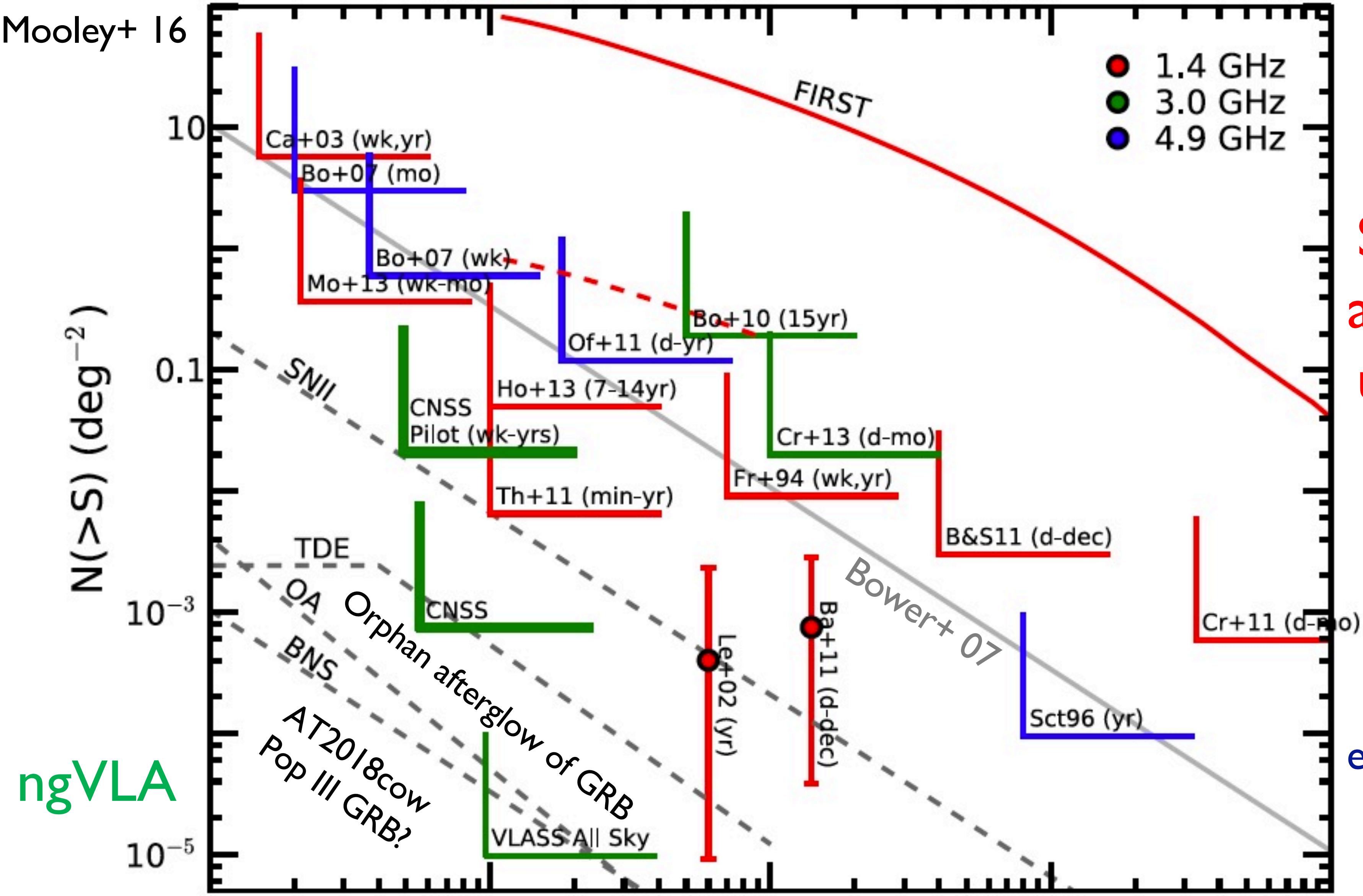
$\Delta\theta$~3.5 arcsec

→ FRB cosmology

* NAOJ: concentration & diversity

Radio Transients (>days)

Mooley+ 16



ngVLA

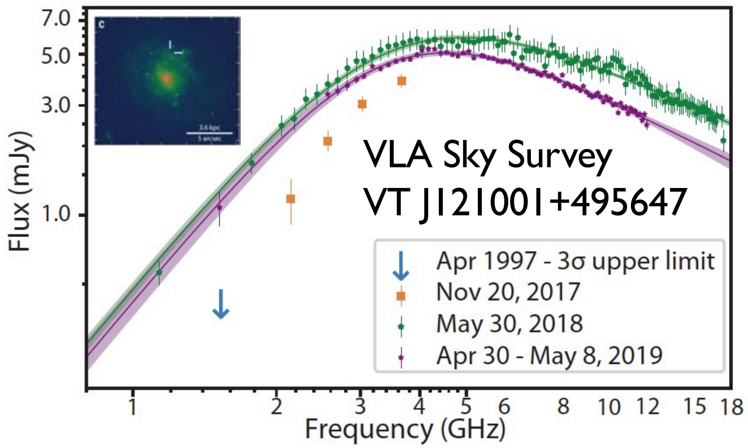
So far almost upper limits

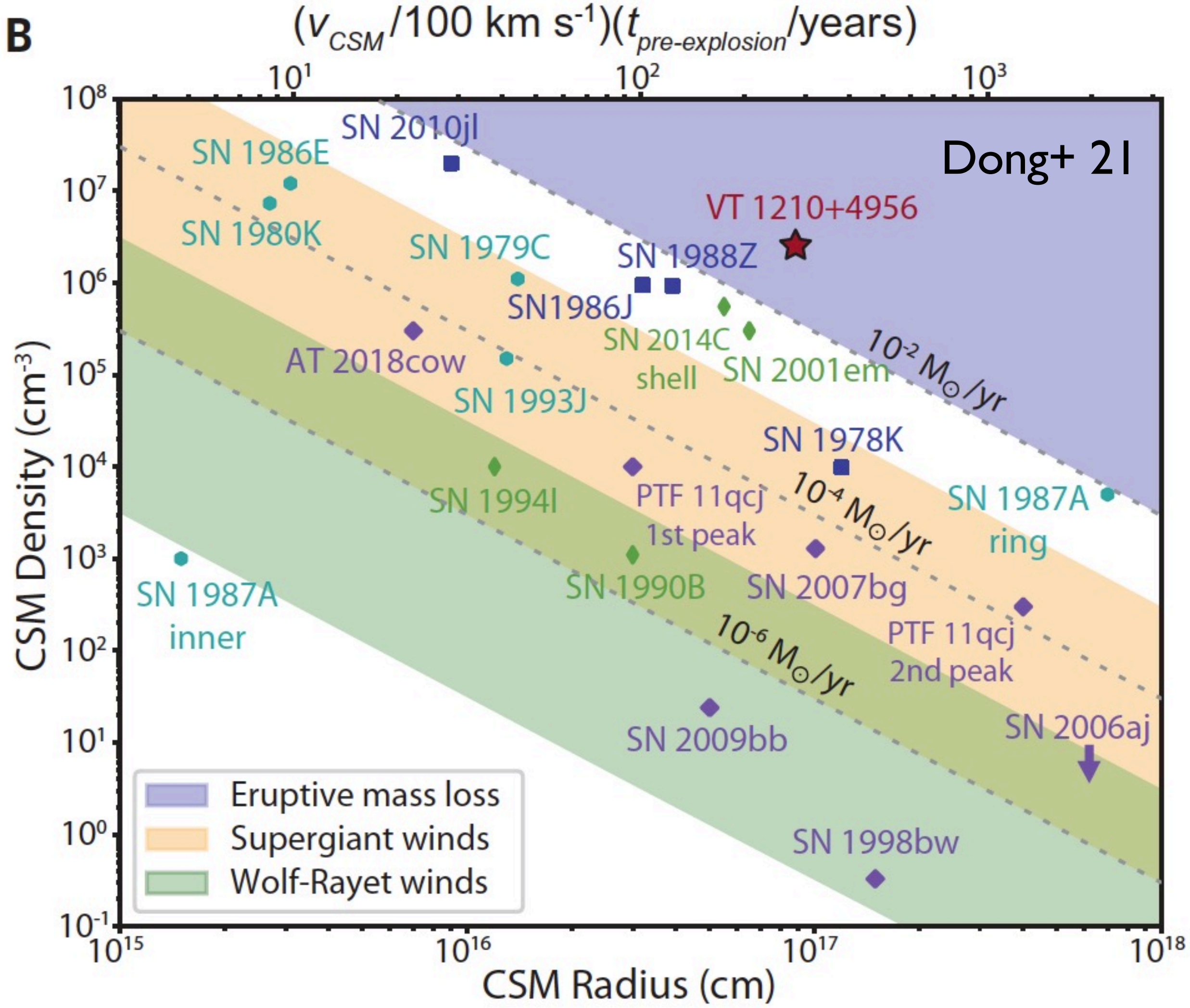
excluding AGNs

Tip of Radio Transients

Merger-triggered CC supernova?

Dawn of radio transient science



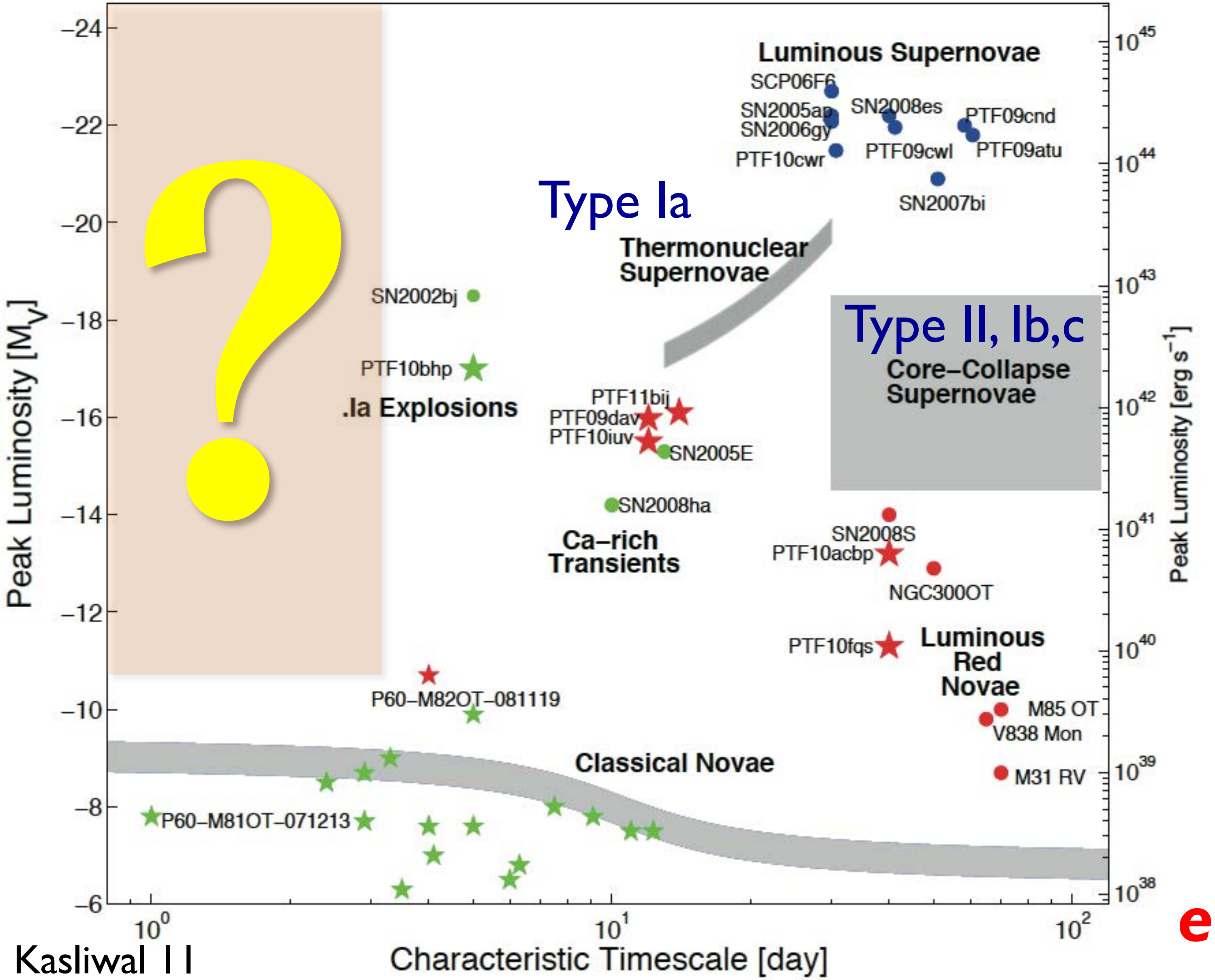


E_{radio}~7e49 erg,
v~6e-3 c ($\varepsilon_e=\varepsilon_B=0.1$)

L_X~4e46 erg/s, ~20 s

~10-80 Gpc^{-3} yr^{-1}
~ 10^{-4} $R_{Supernova}$

IR-Optical Transients

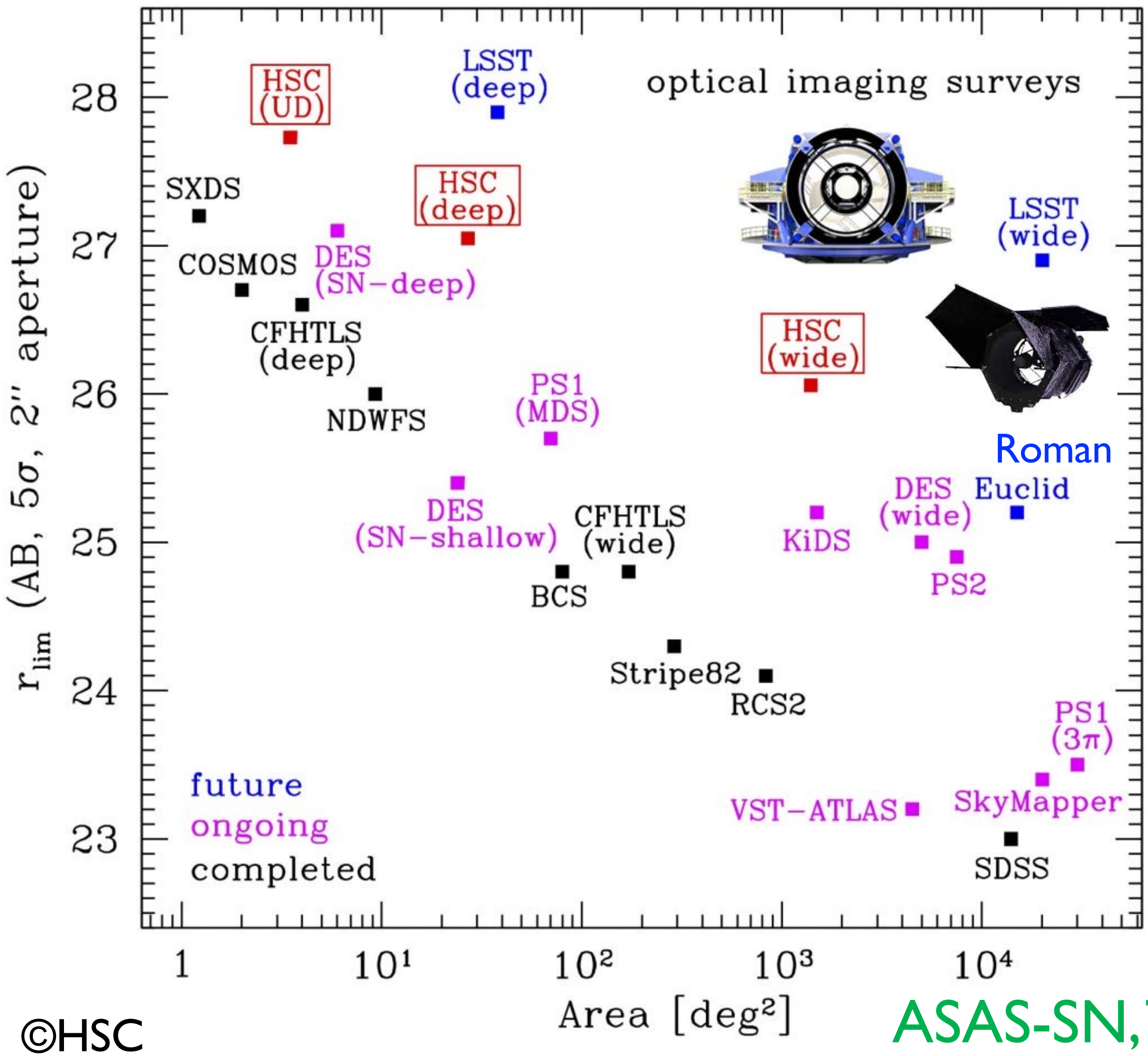


Kasliwal 11

Supernova
Hypernova
SLSN
Stripped-env.
TDE
kilonova
Ca-rich
LRN
AT2018cow
…

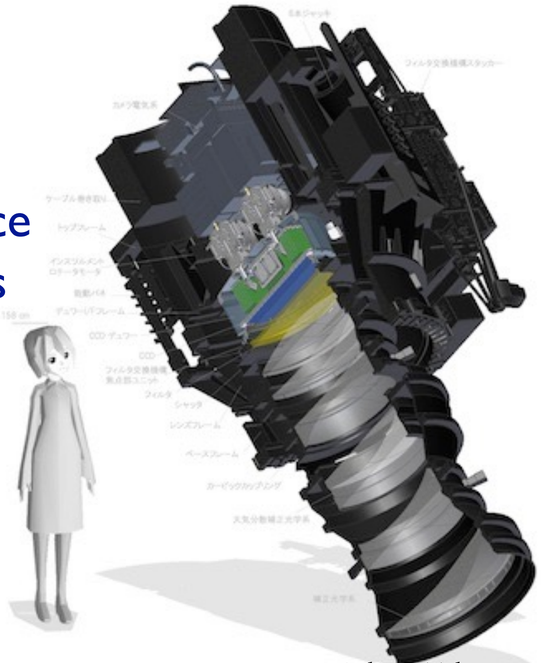
Some are engine-driven

Deep-Wide-Fast Survey



©HSC

cadence
~days



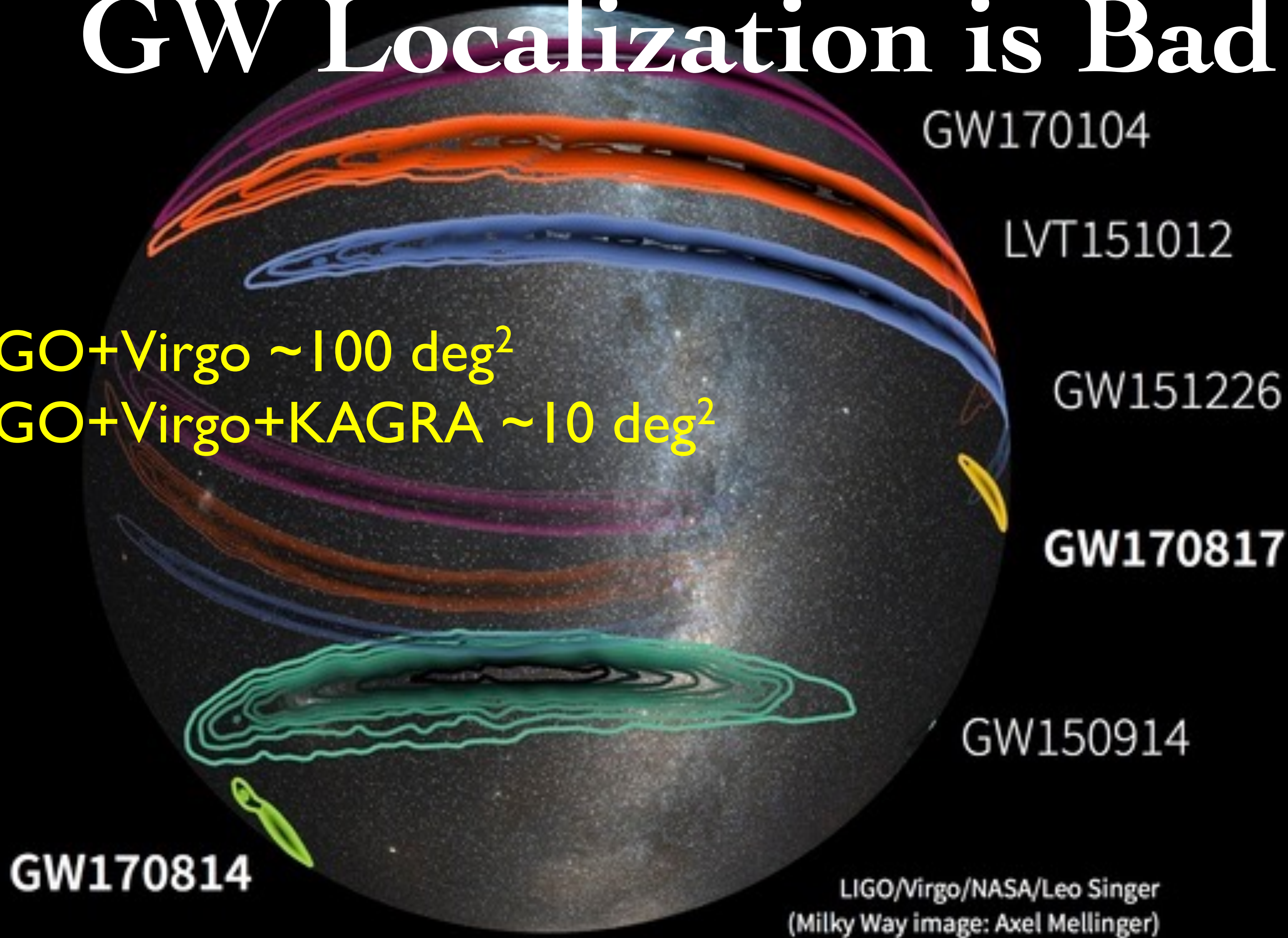
©Subaru Telescope, NAOJ

Dark-energy-driven
supernova survey:
Transient factory

ASAS-SN, Tomo-e, Seimei, ZTF (r~21)

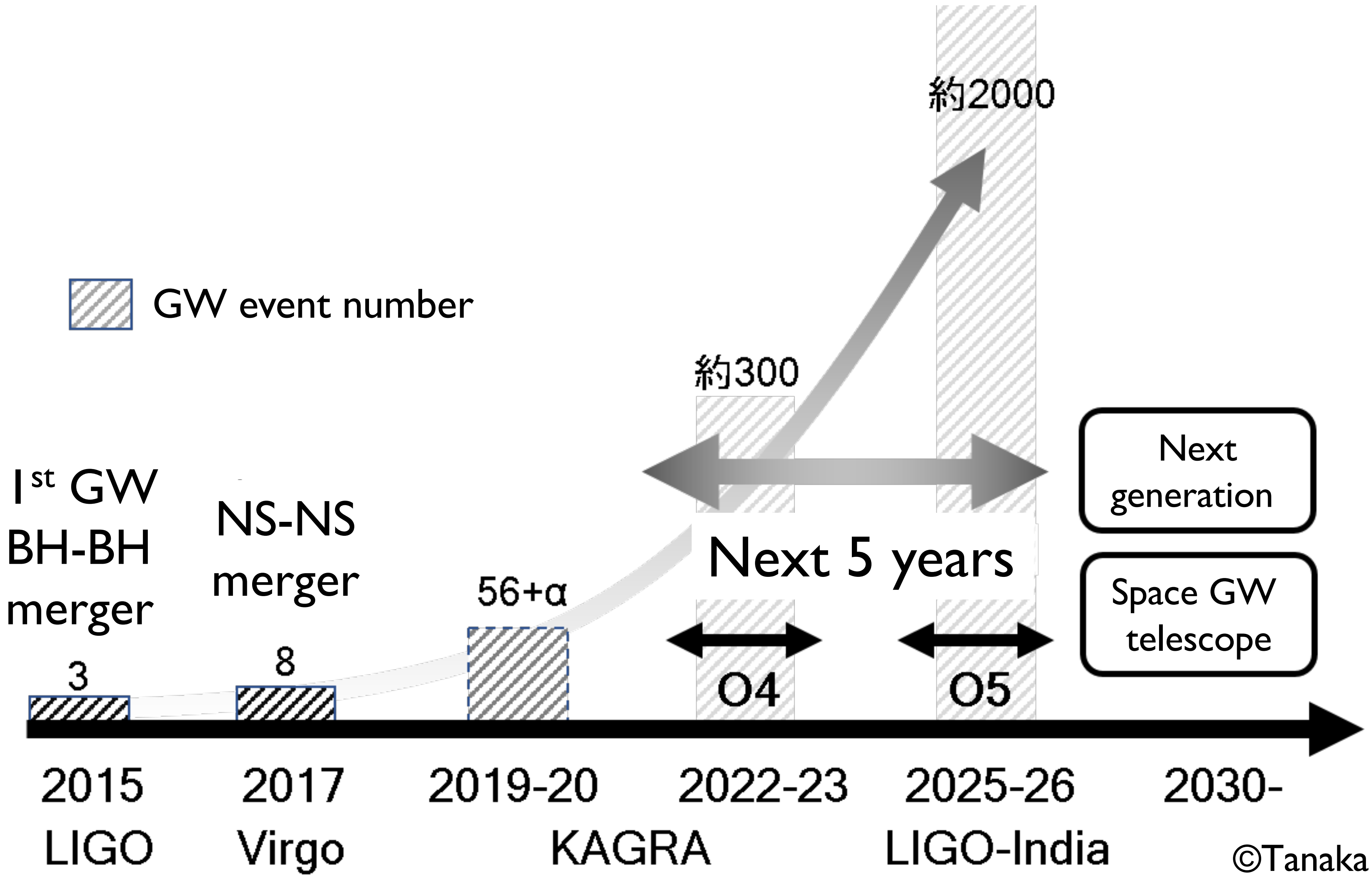
GW Localization is Bad

LIGO+Virgo ~100 deg^2
LIGO+Virgo+KAGRA ~10 deg^2

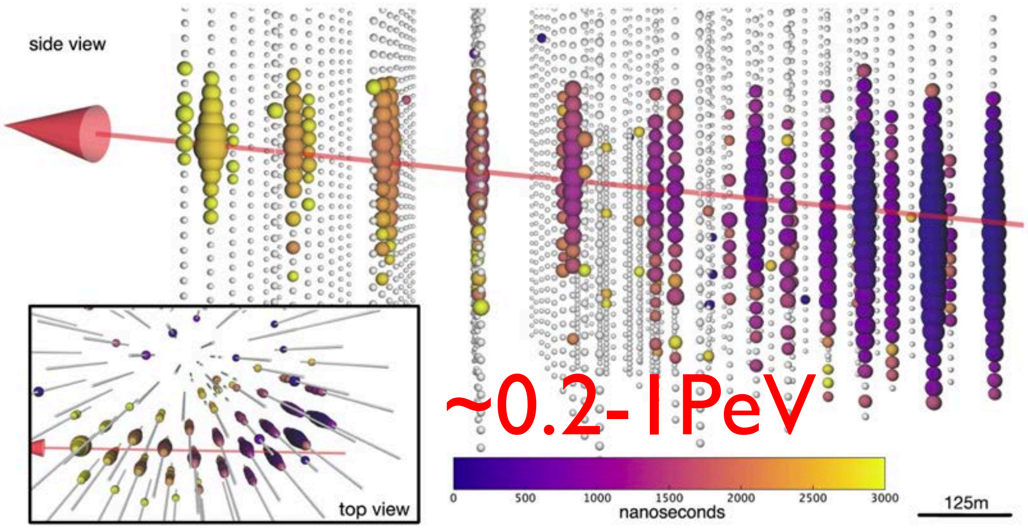


Multi-messenger + Time-Domain

GW Event Inflation



IceCube-170922A



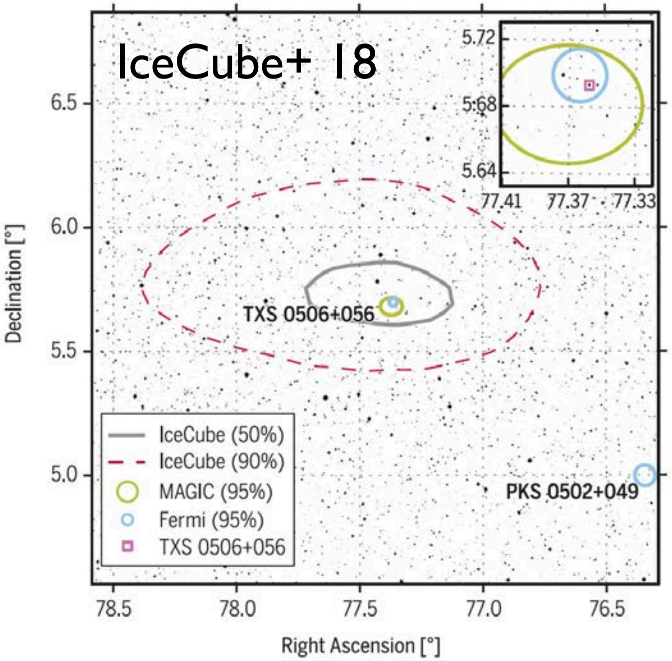
~0.2-1PeV

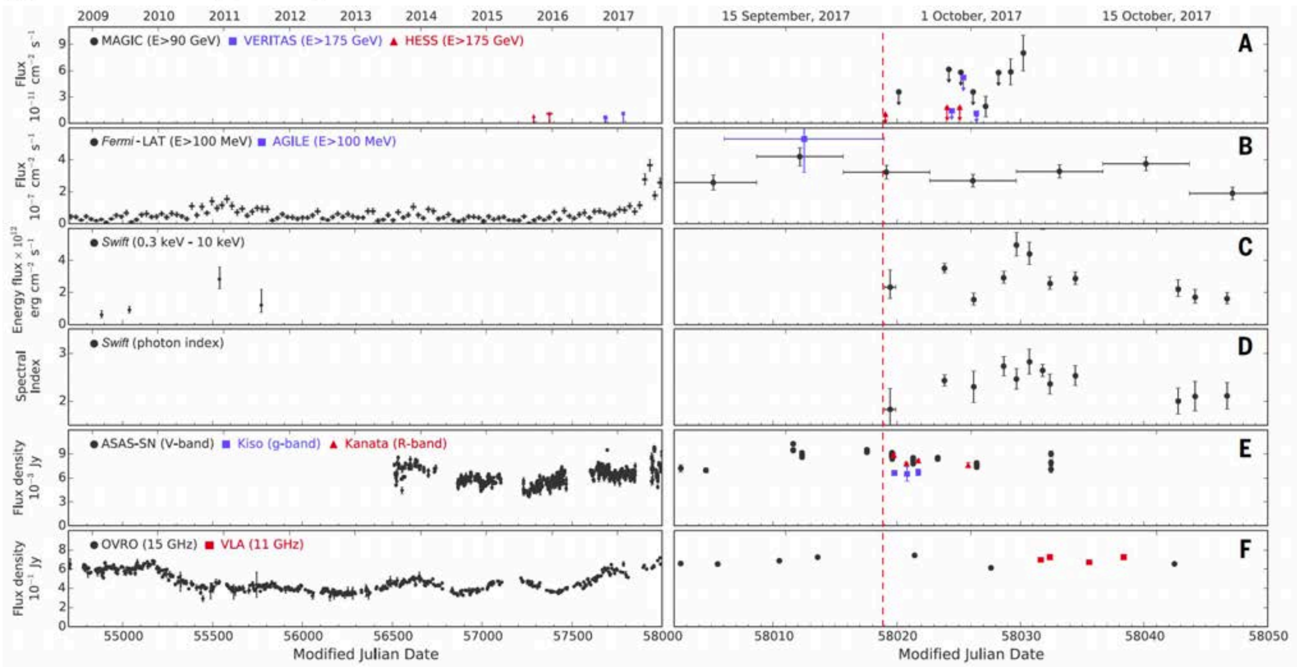
Multi-messenger source

Blazar TXS 0506+056

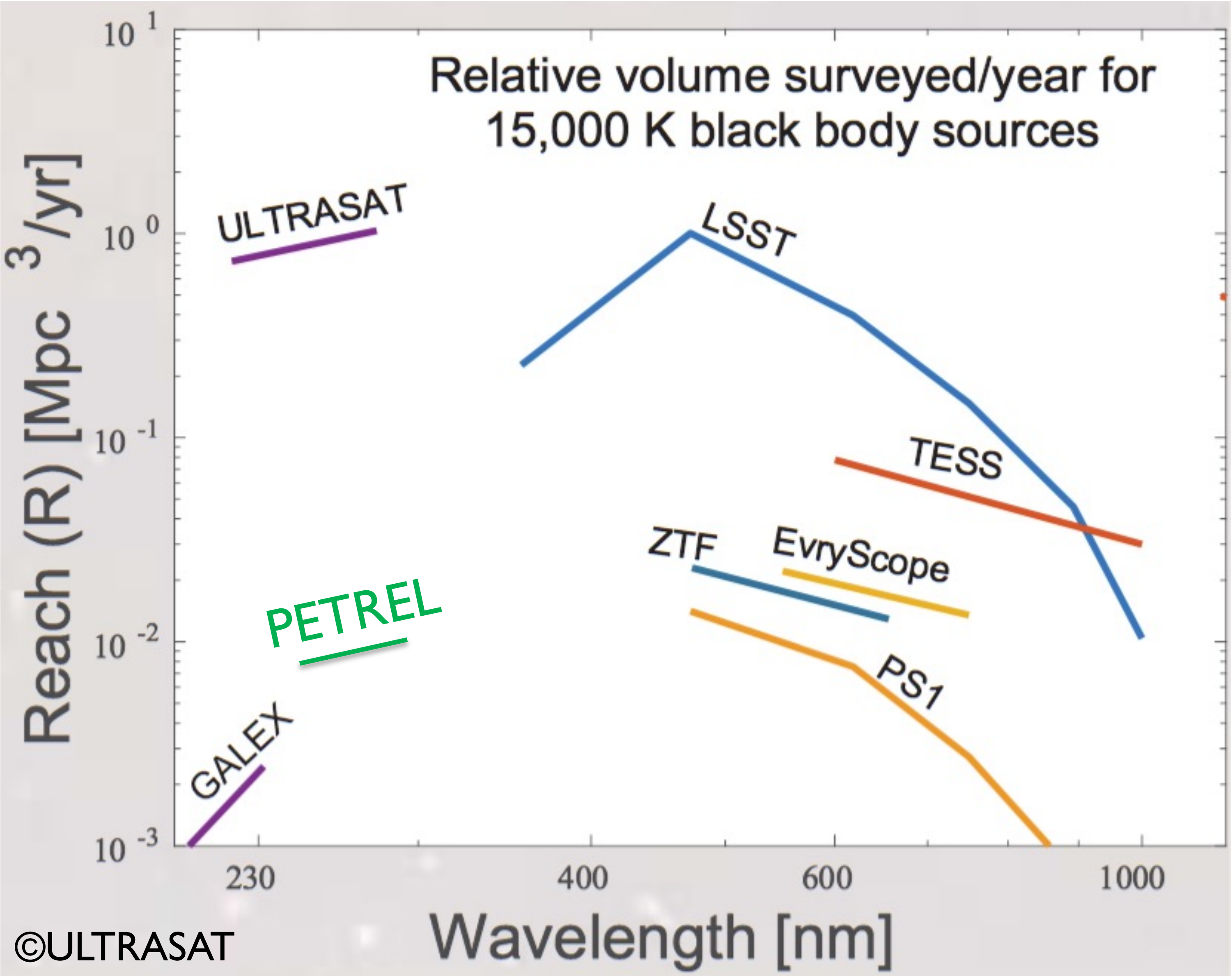
~3σ coincidence

More data are needed



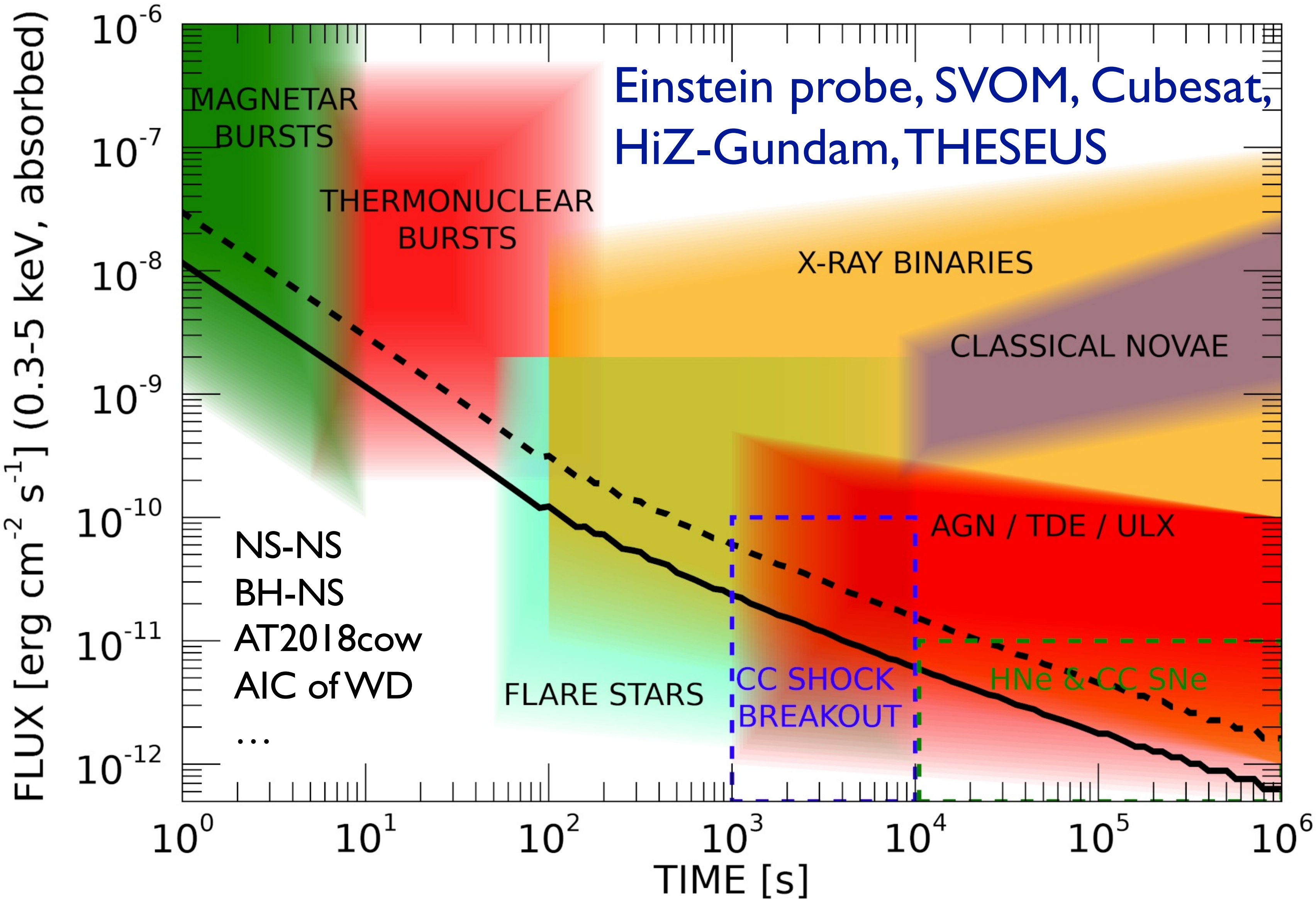


UV Transients



NS-NS
BH-NS
Supernova
(shock breakout)
TDE
Stellar flare
AT2018cow?
AIC of WD?
(accretion induced collapse)
…

X-ray Transients



Millimeter Transients

Expected event #

	Experiment	LGRB On-axis	LGRB $\theta_{obs}=0.4$	LGRB $\theta_{obs}=0.8$	LGRB RS, $\Gamma=200$	LGRB RS, $\Gamma=50$	LGRB high-energy, On-axis	LGRB high-energy, $\theta_{obs}=0.4$	LGRB high-energy, $\theta_{obs}=0.8$	LGRB high energy RS, $\Gamma=200$	LGRB high energy RS, $\Gamma=50$	SGRB On-axis	SGRB $\theta_{obs}=0.4$	TDE On-axis	TDE Off-axis	NSM: stable remnant	FBOT
	ACT (7 yr)	0.6	0.0	0.0	0.8	1.9	6.5	0.5	0.0	2.1	10.4	0.0	0.0	0.0	0.0	0.0	0.1
	SPT-3G (5.5 yr)	0.5	0.0	0.0	3.8	10.0	5.4	0.3	0.0	8.5	39.1	0.0	0.0	0.0	0.0	0.0	0.1
	Simons Observatory (5 yr)	1.3	0.0	0.0	7.6	12.8	12.6	0.8	0.0	13.6	63.3	0.0	0.0	0.0	0.0	0.0	0.1
	CMB-S4 (7 yr)	4.5	0.1	0.0	16.9	40.9	43.7	2.4	0.1	35.2	162.5	0.1	0.0	0.1	0.0	0.0	0.5
	CMB-HD (7.5 yr)	23.5	0.7	0.0	53.1	197.8	182.4	15.0	0.5	71.2	412.6	0.7	0.1	0.4	0.1	0.1	2.0
7 day Stacks	SPT-3G (5.5 yr)	1.9	0.1	0.0			18.9	1.3	0.1			0.1	0.0	0.0	0.0	0.0	0.3
	Simons Observatory (5 yr)	1.8	0.1	0.0			34.3	3.0	0.1			0.1	0.0	0.1	0.0	0.0	0.6
	CMB-S4 (7 yr)	12.4	0.5	0.0			114.3	10.4	0.4			0.5	0.0	0.3	0.1	0.1	2.1
	CMB-HD (7.5 yr)	63.1	2.6	0.1			515.5	55.7	2.2			2.7	0.2	1.9	0.3	0.3	11.5
30 day Stacks	ACT (7 yr)	0.2	0.0	0.0			1.3	0.7	0.1			0.0	0.0	0.1	0.0	0.0	0.1
	SPT-3G (5.5 yr)	2.0	0.1	0.0			28.9	3.2	0.1			0.1	0.0	0.1	0.0	0.0	0.7
	Simons Observatory (5 yr)	1.9	0.3	0.0			16.6	5.9	0.3			0.3	0.0	0.3	0.1	0.1	0.9
	CMB-S4 (7 yr)	6.3	0.9	0.0			57.7	20.5	1.2			0.9	0.1	1.0	0.2	0.2	3.4
	CMB-HD (7.5 yr)	33.3	4.8	0.2			282.6	117.2	6.5			5.1	0.6	5.6	0.8	0.9	18.2

LiteBIRD

Eftekhari+ 21

CMB* + *Transient

Big project

HE astro

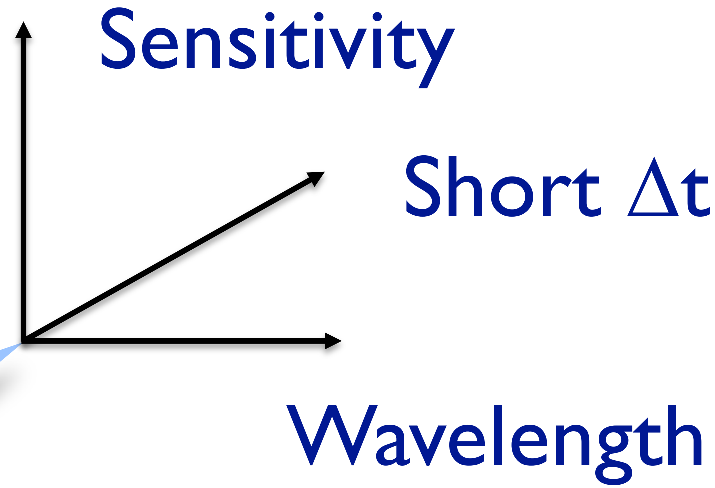
Cosmology

NAOJ/ JAXA/ ICRR

vertically segmented?

The Other Domains

Spectral resolution
Angular resolution
Polarization
Coronagraph
…

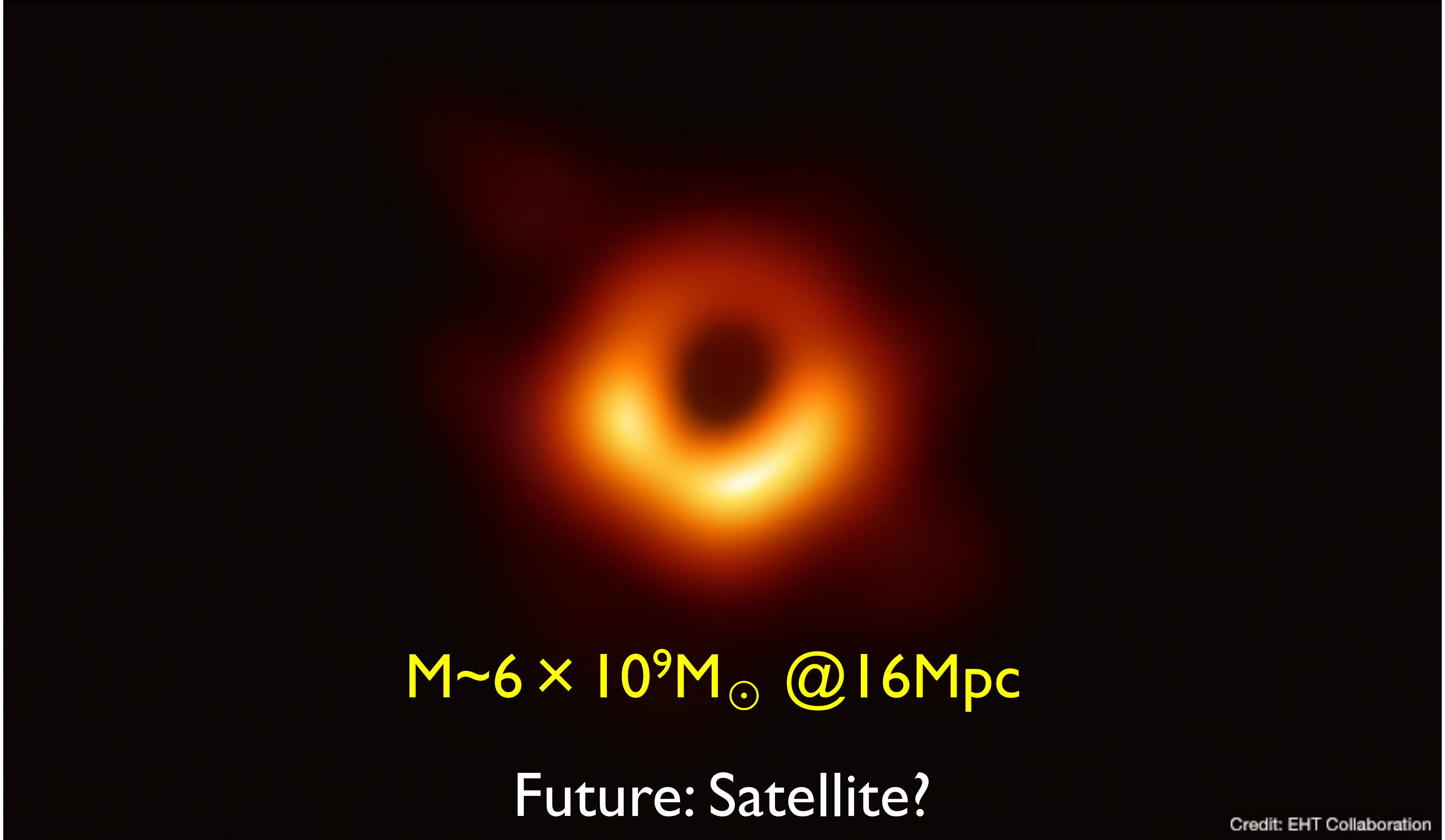


X-ray: XRISM, FORCE, IXPE, XL-Calibur
IR-Opt: JASMINE, HabEx, LUVOIR
Radio:VERA, LST

Astro2020

Details: Maniac? ↔

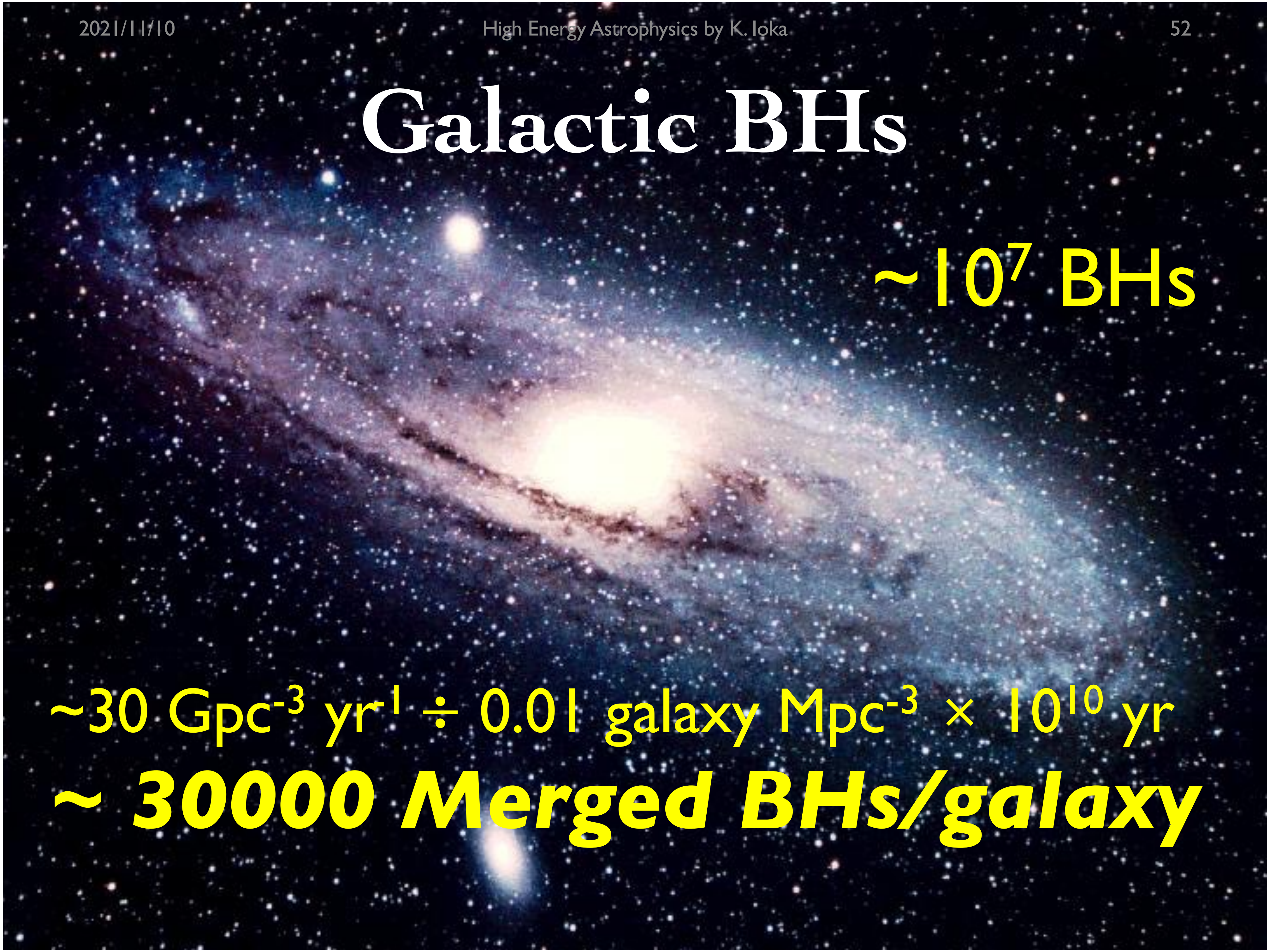
M87 Black Hole



$M \sim 6 \times 10^9 M_\odot$ @16Mpc

Future: Satellite?

Galactic BHs

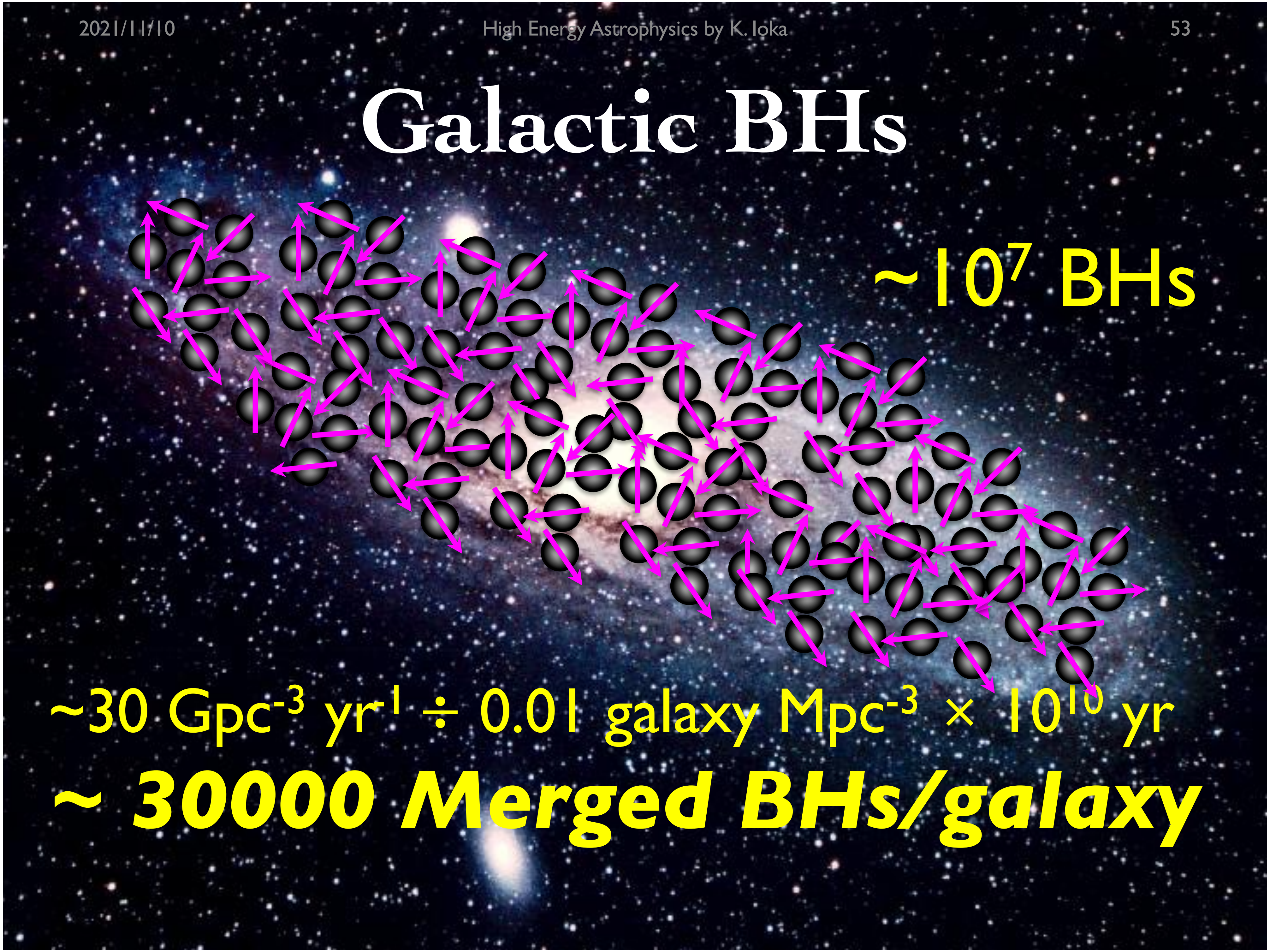


~10^7 BHs

~30 $\mathrm{Gpc^{-3}\,yr^{-1}} \div 0.01$ galaxy $\mathrm{Mpc^{-3}} \times 10^{10}$ yr

~ 30000 Merged BHs/galaxy

Galactic BHs



~10^7 BHs

~30 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1} \div 0.01$ galaxy $\mathrm{Mpc}^{-3} \times 10^{10}$ yr

~ 30000 Merged BHs/galaxy

High-Energy Astrophysics

- ***Gravity: Stars to black holes***
  - particle acceleration, jet, unknown^2, …
- ***Multi-Wavelength & Multi-Messenger***
  - EM sensitivity is saturating

NAOJ / JAXA / ICRR
vertically segmented?

- ***Numerical simulations & Theory***
  - Upgrade super-computers & human resource
- ***Time-domain*** (radio, IR-opt, UV?, X?, CMB?)
  - Gravitational wave, Fast radio burst, ν, …

Vast frontiers

Concentration & Diversity
Maniac & General

Table 1 | UHE γ-ray sources

Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26 - 0.10^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71 - 0.07^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Celestial coordinates (RA, dec.); statistical significance of detection above 100 TeV (calculated using a point-like template for the Crab Nebula and LHAASO J2108+5157 and 0.3° extension templates for the other sources); the corresponding differential photon fluxes at 100 TeV; and detected highest photon energies. Errors are estimated as the boundary values of the area that contains ±34.14% of events with respect to the most probable value of the event distribution. In most cases, the distribution is a Gaussian and the error is 1σ.

Extended Data Table 2 | List of energetic astrophysical objects possibly associated with each LHAASO source

LHAASO Source	Possible Origin	Type	Distance (kpc)	Age (kyr)^a	L_s (erg/s)^b	Potential TeV Counterpart^c
LHAASO J0534+2202	PSR J0534+2200	PSR	2.0	1.26	4.5×10^{38}	Crab, Crab Nebula
LHAASO J1825-1326	PSR J1826-1334	PSR	3.1 ± 0.2^d	21.4	2.8×10^{36}	HESS J1825-137, HESS J1826-130,
	PSR J1826-1256	PSR	1.6	14.4	3.6×10^{36}	2HWC J1825-134
LHAASO J1839-0545	PSR J1837-0604	PSR	4.8	33.8	2.0×10^{36}	2HWC J1837-065, HESS J1837-069,
	PSR J1838-0537	PSR	1.3^e	4.9	6.0×10^{36}	HESS J1841-055
LHAASO J1843-0338	SNR G28.6-0.1	SNR	9.6 ± 0.3^f	$< 2^f$	—	HESS J1843-033, HESS J1844-030,
						2HWC J1844-032
LHAASO J1849-0003	PSR J1849-0001	PSR	7^g	43.1	9.8×10^{36}	HESS J1849-000, 2HWC J1849+001
	W43	YMC	5.5^h	—	—	
LHAASO J1908+0621	SNR G40.5-0.5	SNR	3.4^i	$\sim 10 - 20^j$	—	MGRO J1908+06, HESS J1908+063,
	PSR 1907+0602	PSR	2.4	19.5	2.8×10^{36}	ARGO J1907+0627, VER J1907+062,
	PSR 1907+0631	PSR	3.4	11.3	5.3×10^{35}	2HWC 1908+063
LHAASO J1929+1745	PSR J1928+1746	PSR	4.6	82.6	1.6×10^{36}	2HWC J1928+177, 2HWC J1930+188,
	PSR J1930+1852	PSR	6.2	2.9	1.2×10^{37}	HESS J1930+188, VER J1930+188
	SNR G54.1+0.3	SNR	$6.3^{+0.8\ d}_{-0.7}$	$1.8 - 3.3^k$	—	
LHAASO J1956+2845	PSR J1958+2846	PSR	2.0	21.7	3.4×10^{35}	2HWC J1955+285
	SNR G66.0-0.0	SNR	2.3 ± 0.2^d	—	—	
LHAASO J2018+3651	PSR J2021+3651	PSR	$1.8^{+1.7\ l}_{-1.4}$	17.2	3.4×10^{36}	MGRO J2019+37, VER J2019+368,
	Sh 2-104	H II/YMC	$3.3 \pm 0.3^m/4.0 \pm 0.5^n$	—	—	VER J2016+371
LHAASO J2032+4102	Cygnus OB2	YMC	1.40 ± 0.08^o	—	—	TeV J2032+4130, ARGO J2031+4157,
	PSR 2032+4127	PSR	1.40 ± 0.08^o	201	1.5×10^{35}	MGRO J2031+41, 2HWC J2031+415,
	SNR G79.8+1.2	SNR candidate	—	—	—	VER J2032+414
LHAASO J2108+5157	—	—	—	—	—	—
LHAASO J2226+6057	SNR G106.3+2.7	SNR	0.8^p	$\sim 10^p$	—	VER J2227+608, Boomerang Nebula
	PSR J2229+6114	PSR	0.8^p	$\sim 10^p$	2.2×10^{37}	

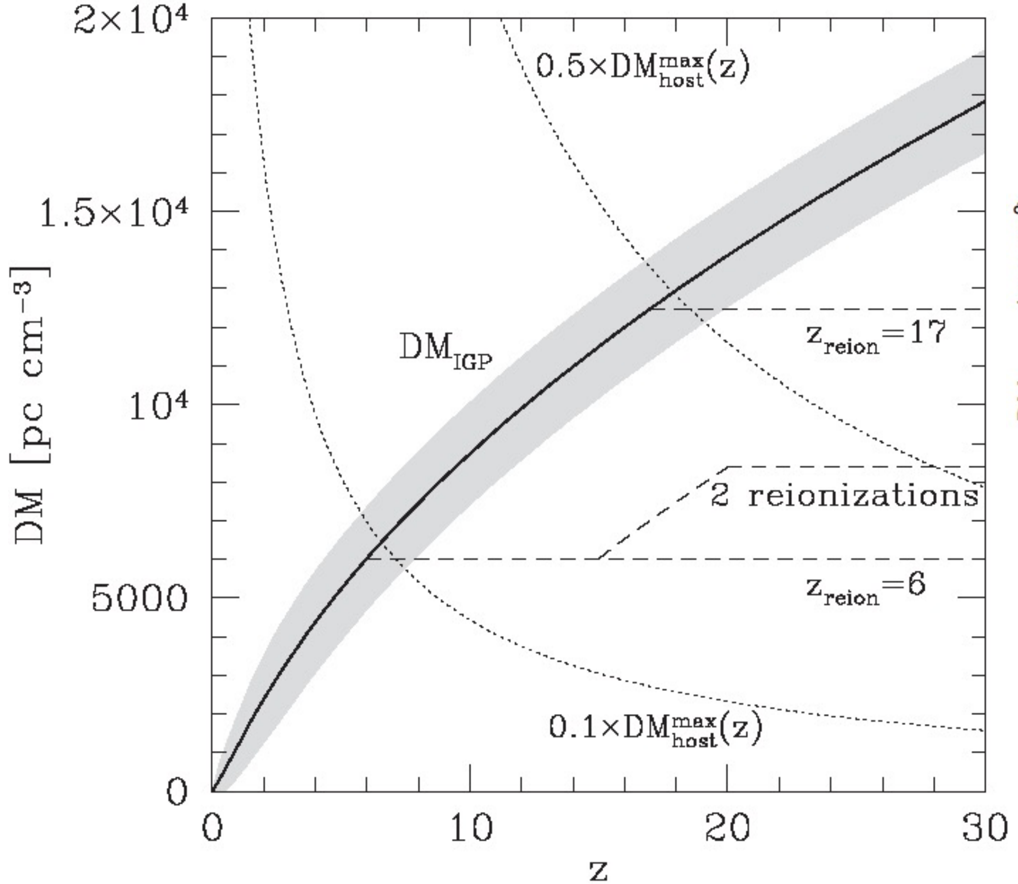
The properties of pulsars are retrieved from the ATNF pulsar catalogue[36] or as specified.

[a]Characteristic age of pulsars.

[b]Present spindown luminosity of pulsars.

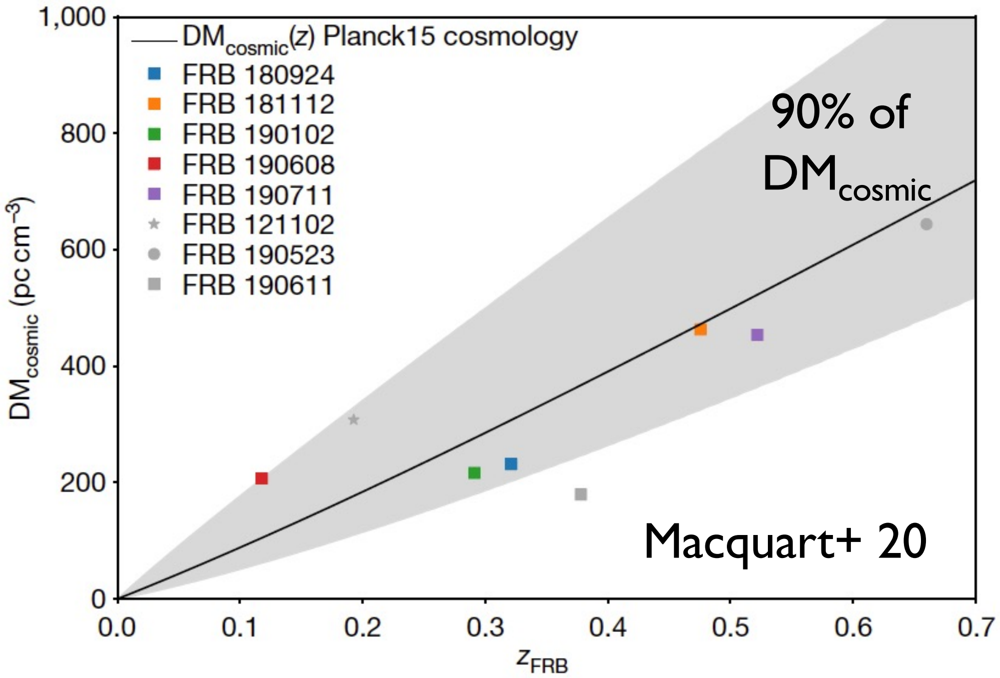
[c]Nearby teraelectronvolt sources within 1° of the centre of the LHAASO source, according to http://tevcat.uchicago.edu/ (ref. [36]).

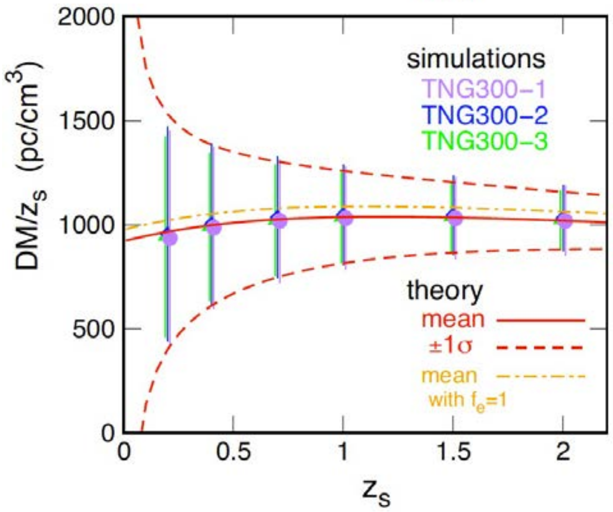
FRB Cosmology



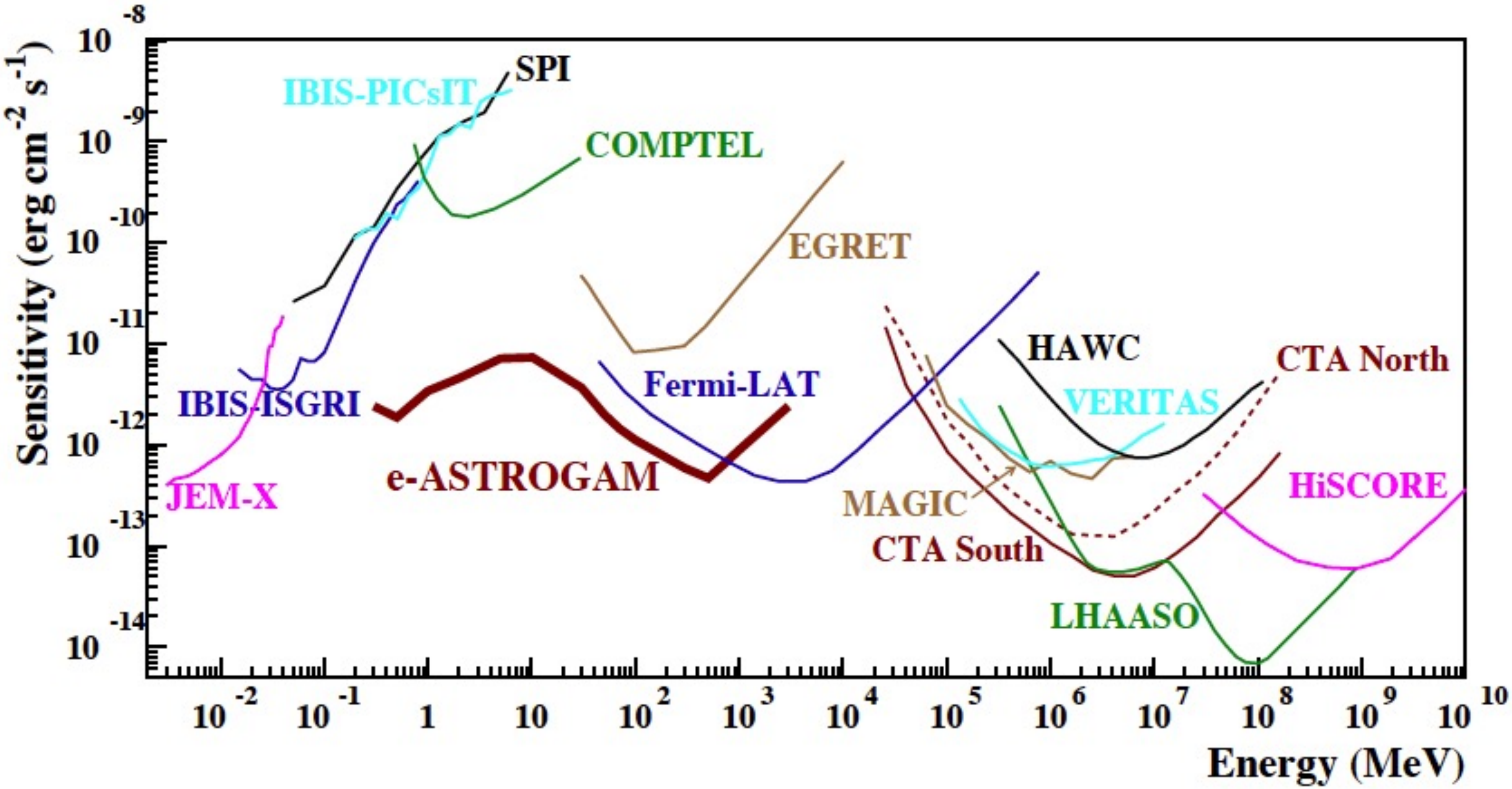
$$\mathrm{DM_{IGP}} = \frac{3cH_0\Omega_b}{8\pi G m_p}\int_0^z \frac{(1+z)dz}{[\Omega_m(1+z)^3+\Omega_\Lambda]^{1/2}}$$

KI 03, Inoue 04



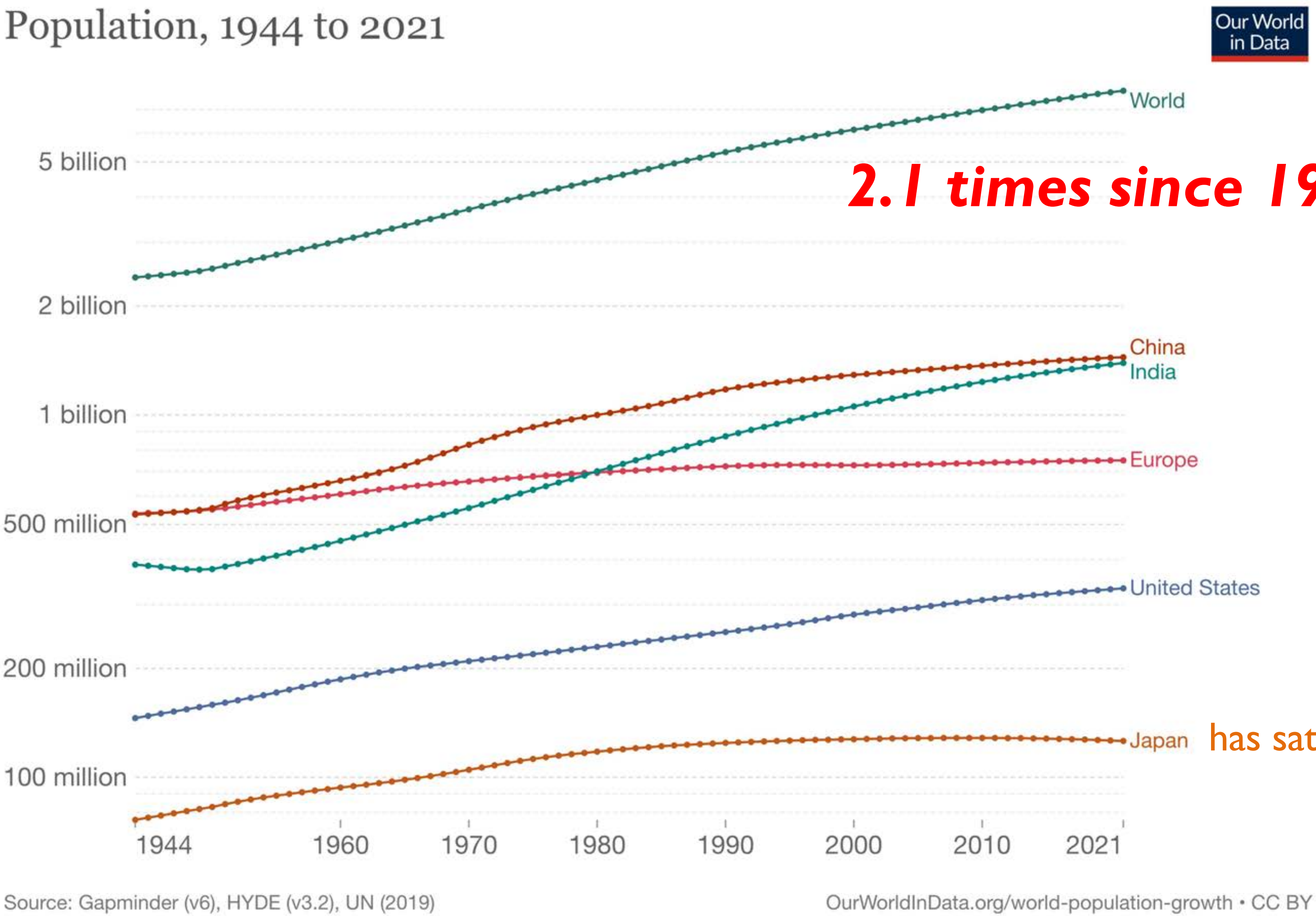


Takahashi, KI+ 20



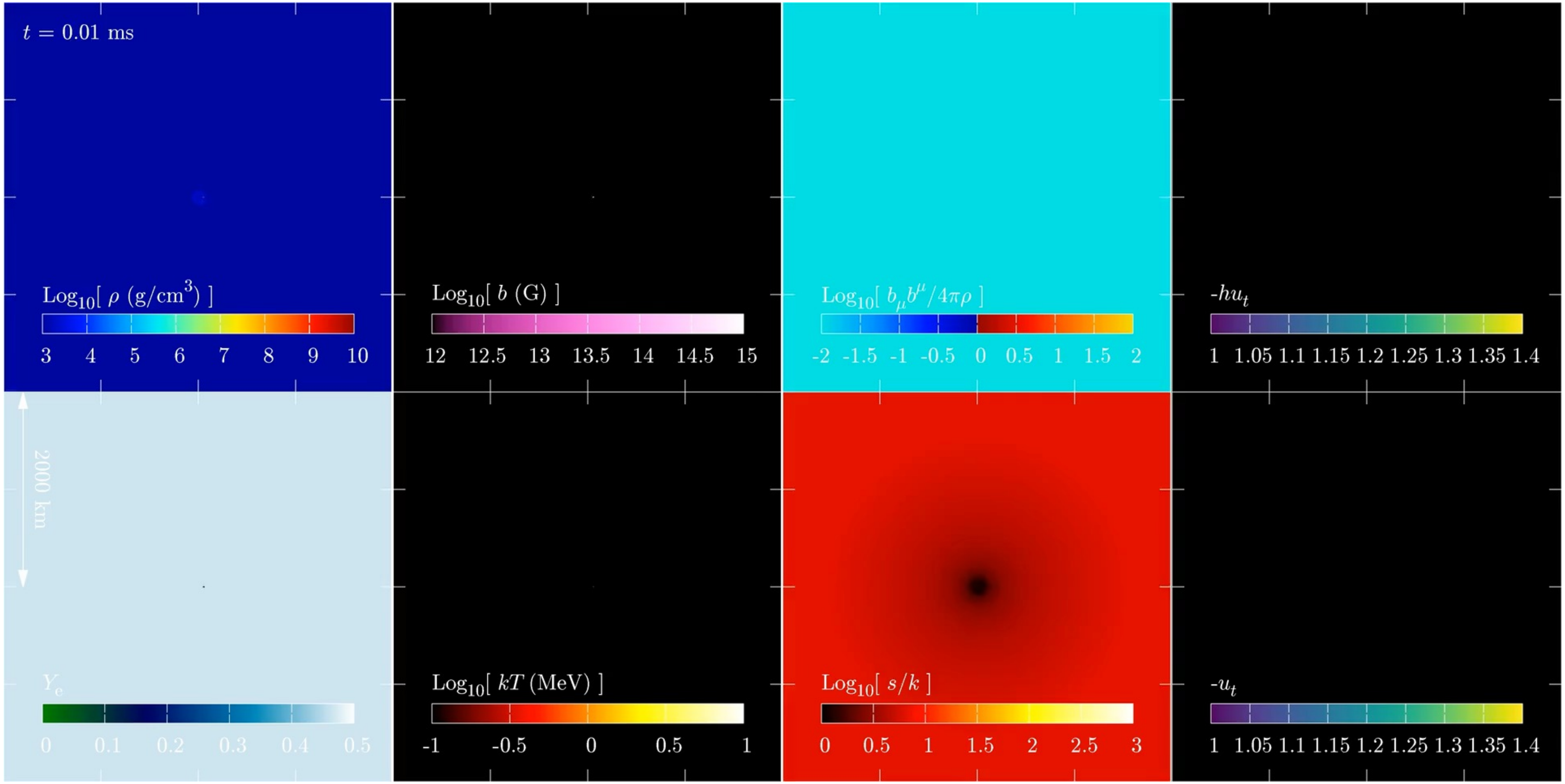
De Angelis+ 16

Population

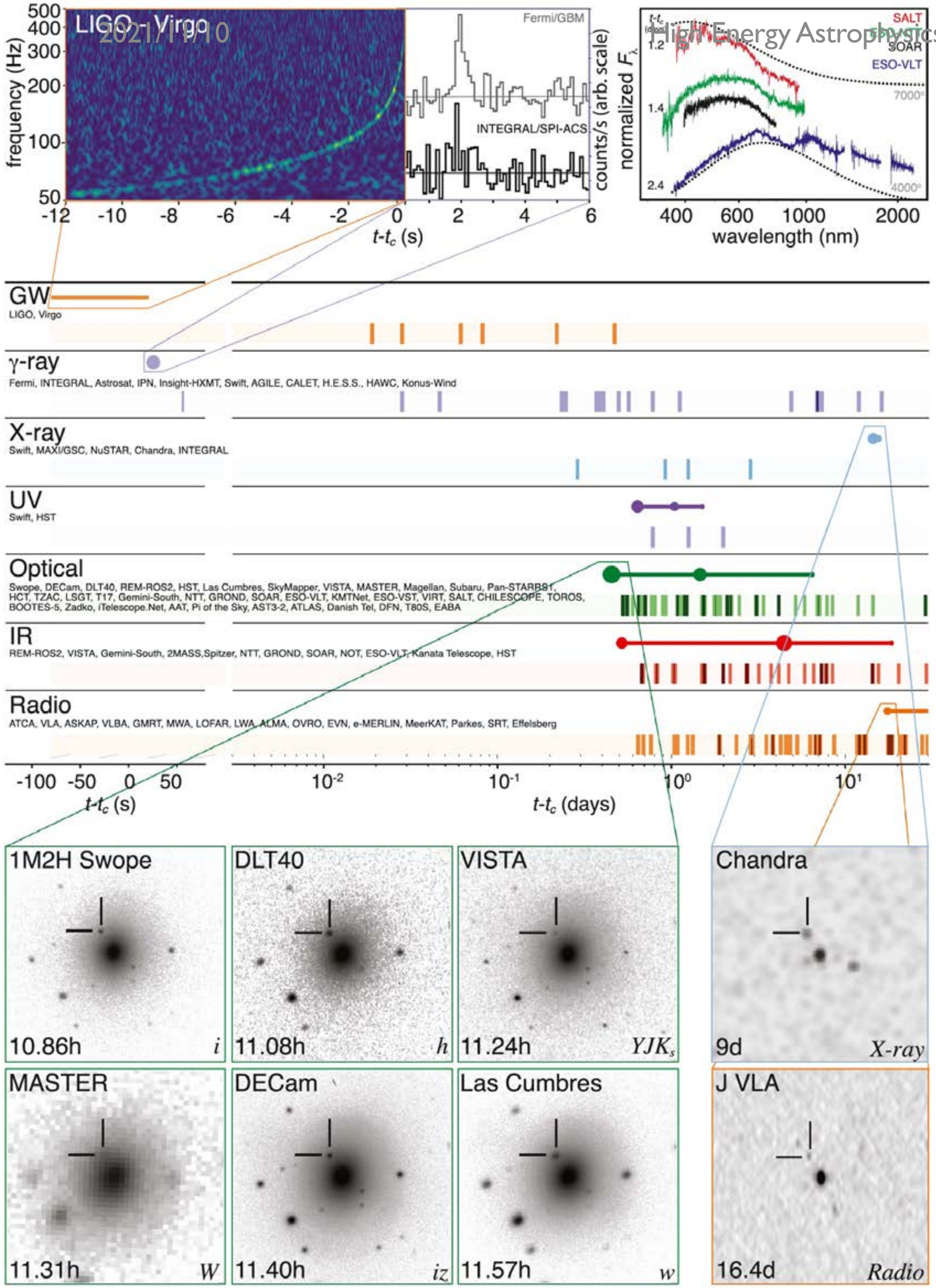


2.1 times since 1970

has saturated


t = 0.01 ms
Log10[ρ (g/cm3)]
3 4 5 6 7 8 9 10
Log10[b (G)]
12 12.5 13 13.5 14 14.5 15
Log10[bμbμ/4πρ]
-2 -1.5 -1 -0.5 0 0.5 1 1.5 2
-hut
1 1.05 1.1 1.15 1.2 1.25 1.3 1.35 1.4
2000 km
Ye
0 0.1 0.2 0.3 0.4 0.5
Log10[kT (MeV)]
-1 -0.5 0 0.5 1
Log10[s/k]
0 0.5 1 1.5 2 2.5 3
-ut
1 1.05 1.1 1.15 1.2 1.25 1.3 1.35 1.4

New Era of Multi-Messenger



Follow-up observations

>3000 people

γ-ray: ~1.734±0.054 sec

⇒ Short GRB 170817A

UV-Opt-IR: 10.86 hr

⇒ Macronova/Kilonova

X, radio: ~10 day

⇒ Afterglow

LVC-EM 17

Band: GCN circ., Circles ∝ brightness