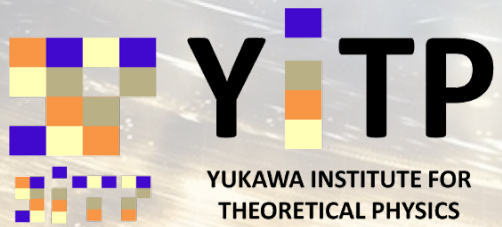
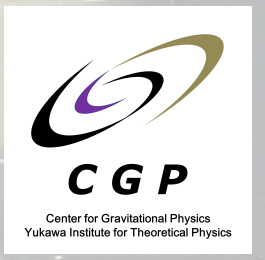
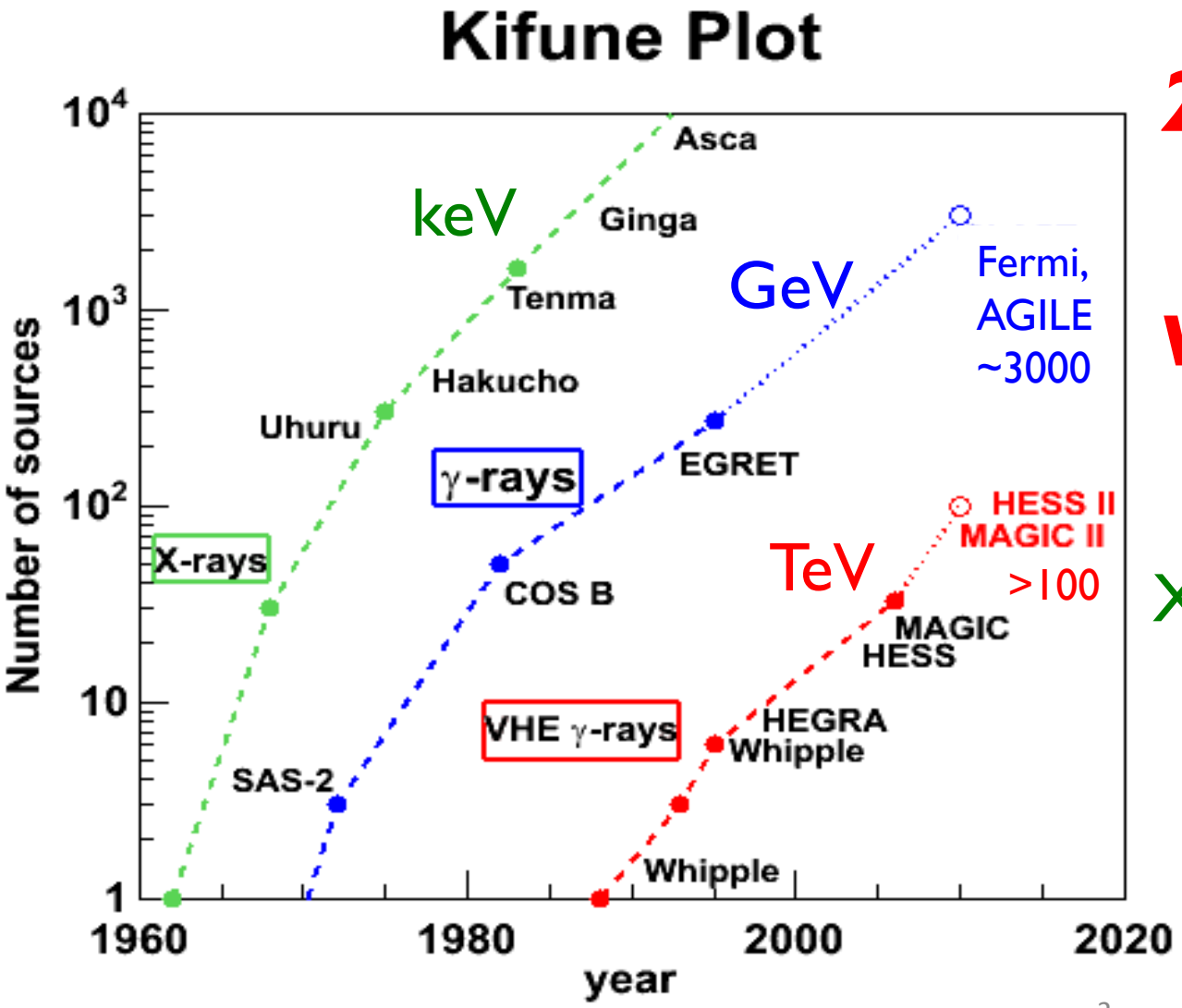
重力波と
マルチメッセンジャー
天文学

井岡 邦仁
(Center for Gravitational Physics,
YITP, Kyoto U)





Multi-Wavelength Era

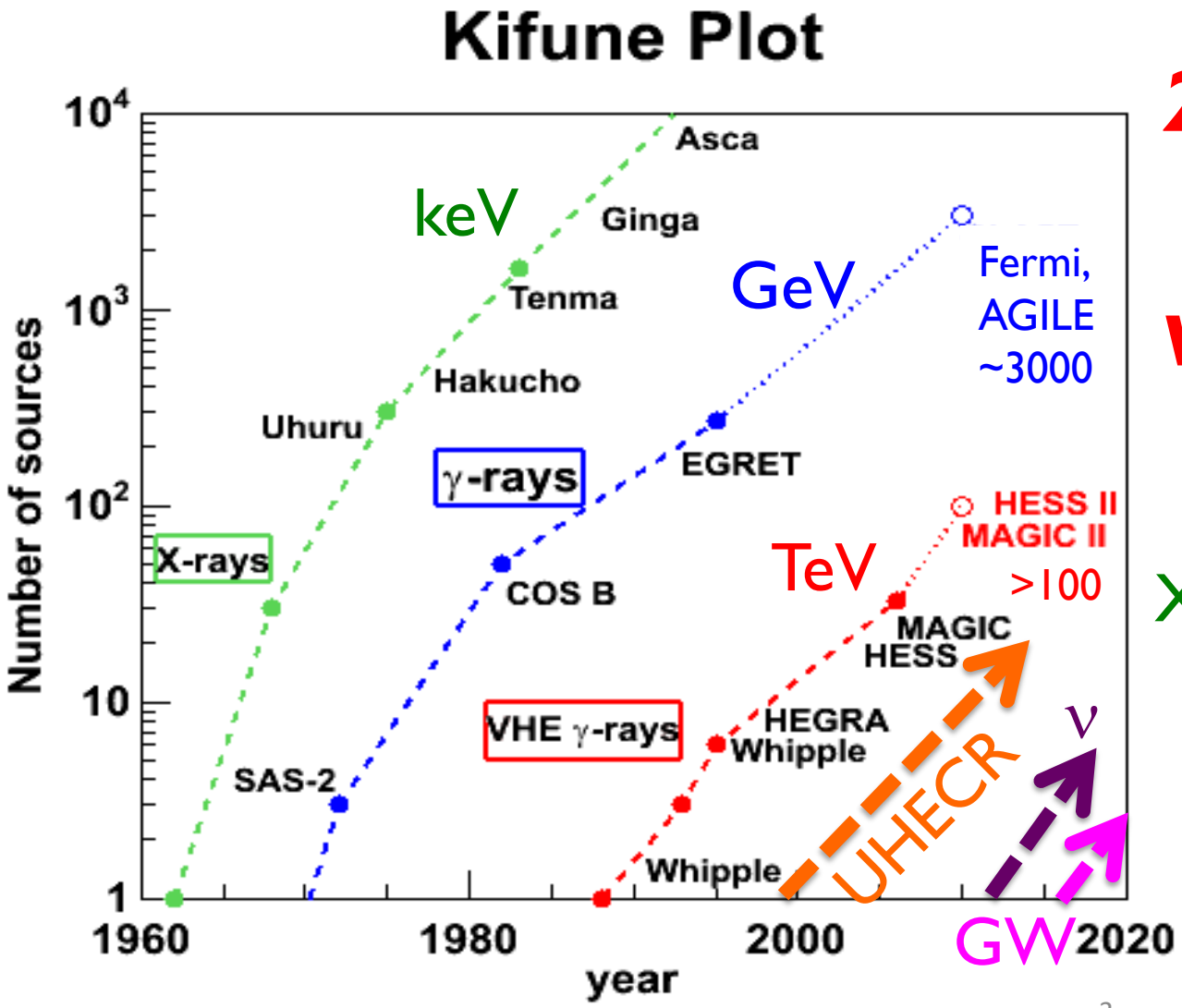


20th century: Multi-wavelength

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

# of sources are increasing exponentially

Multi-Messenger Era



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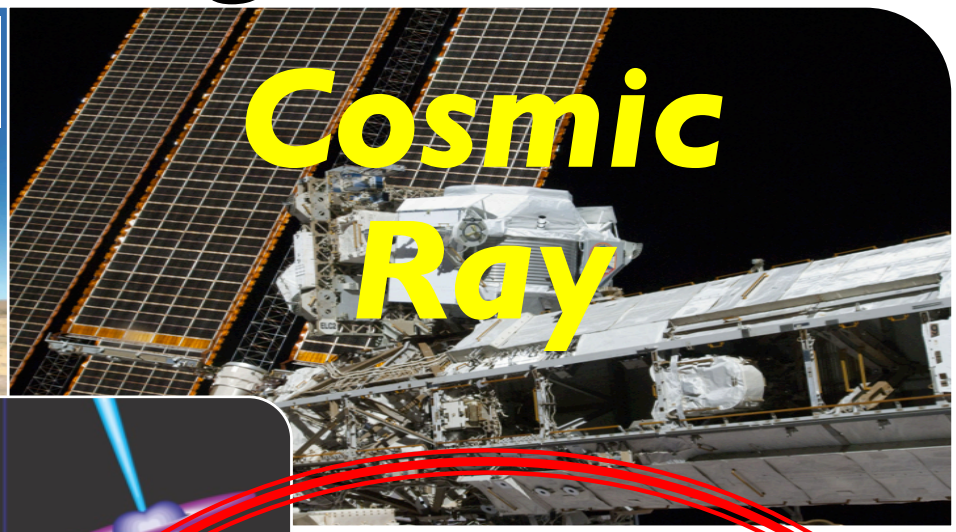
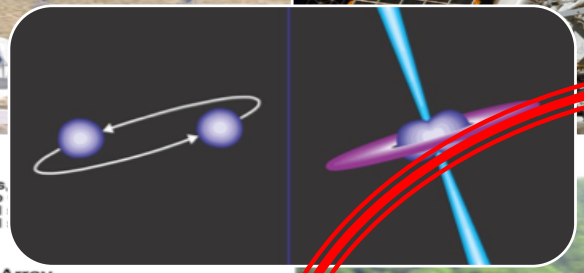
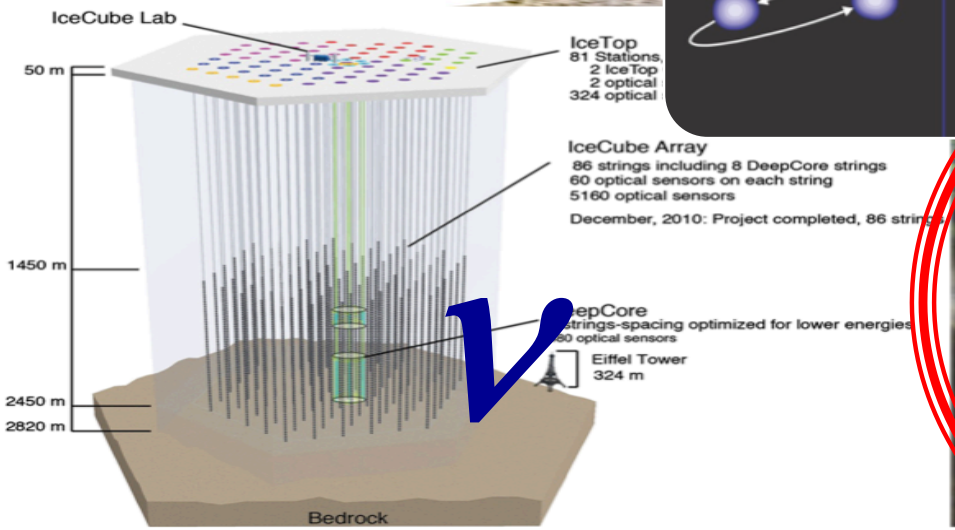
Multi-Messenger Era

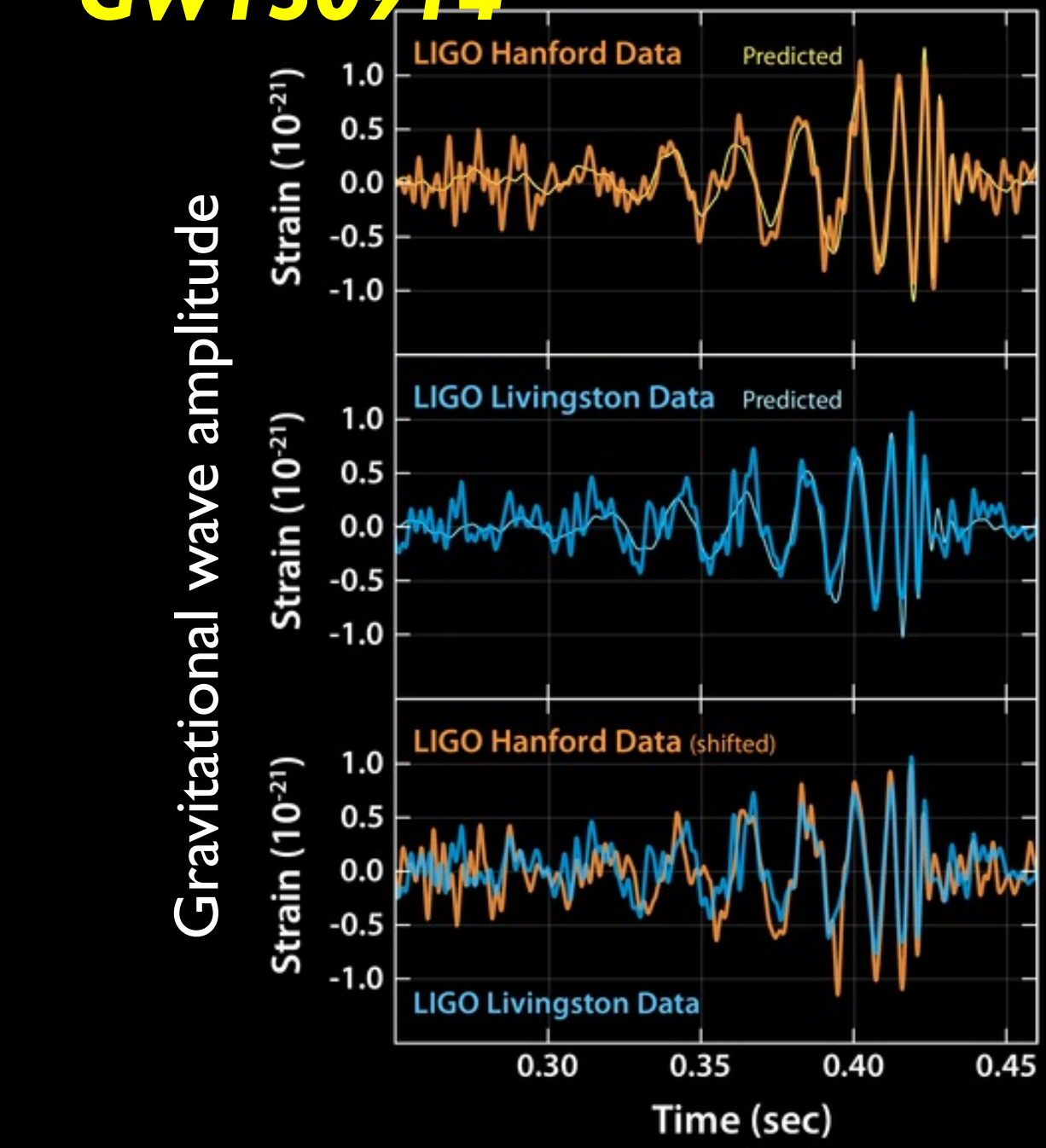


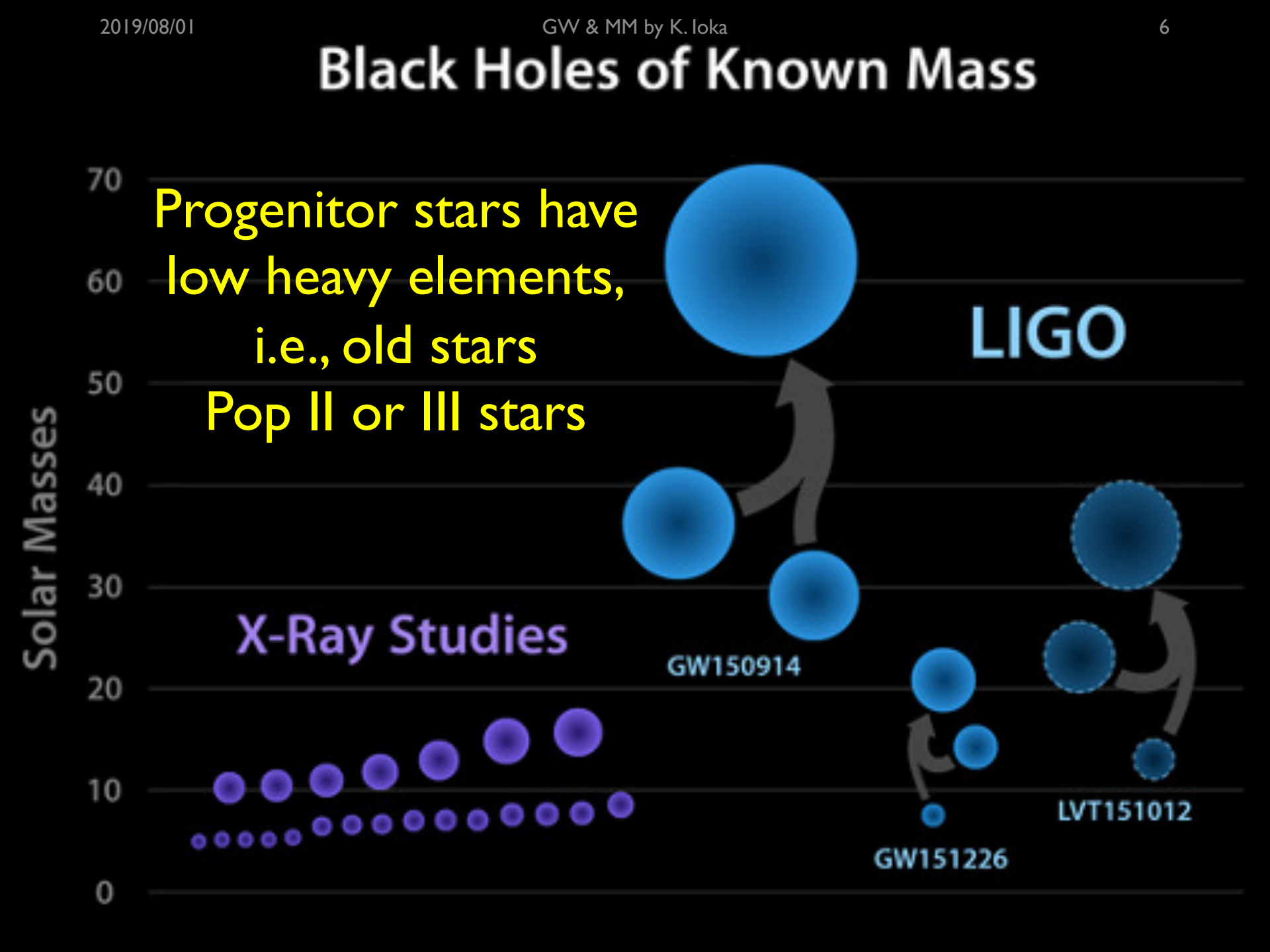




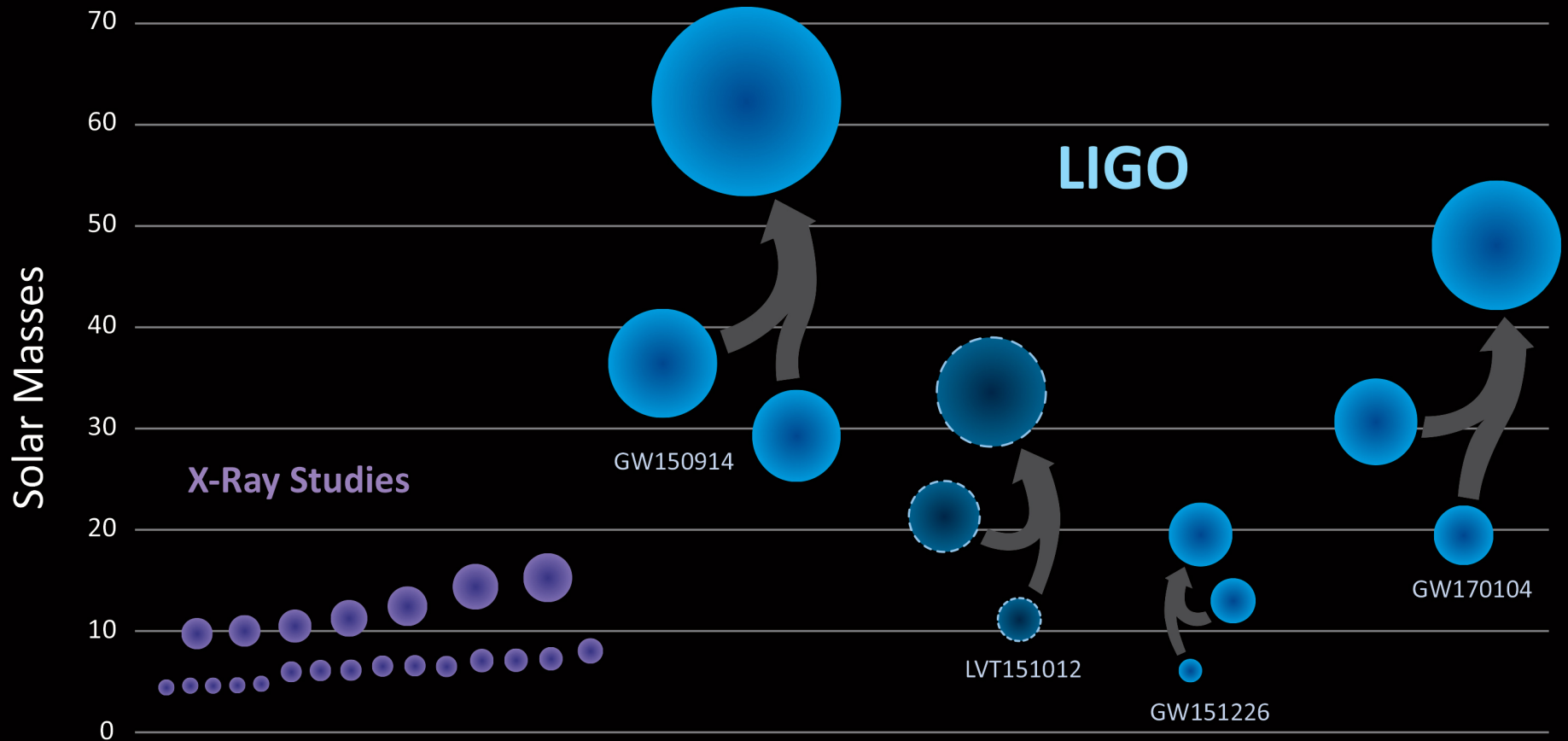
21th Century: Multi-Messenger Era

GW150914

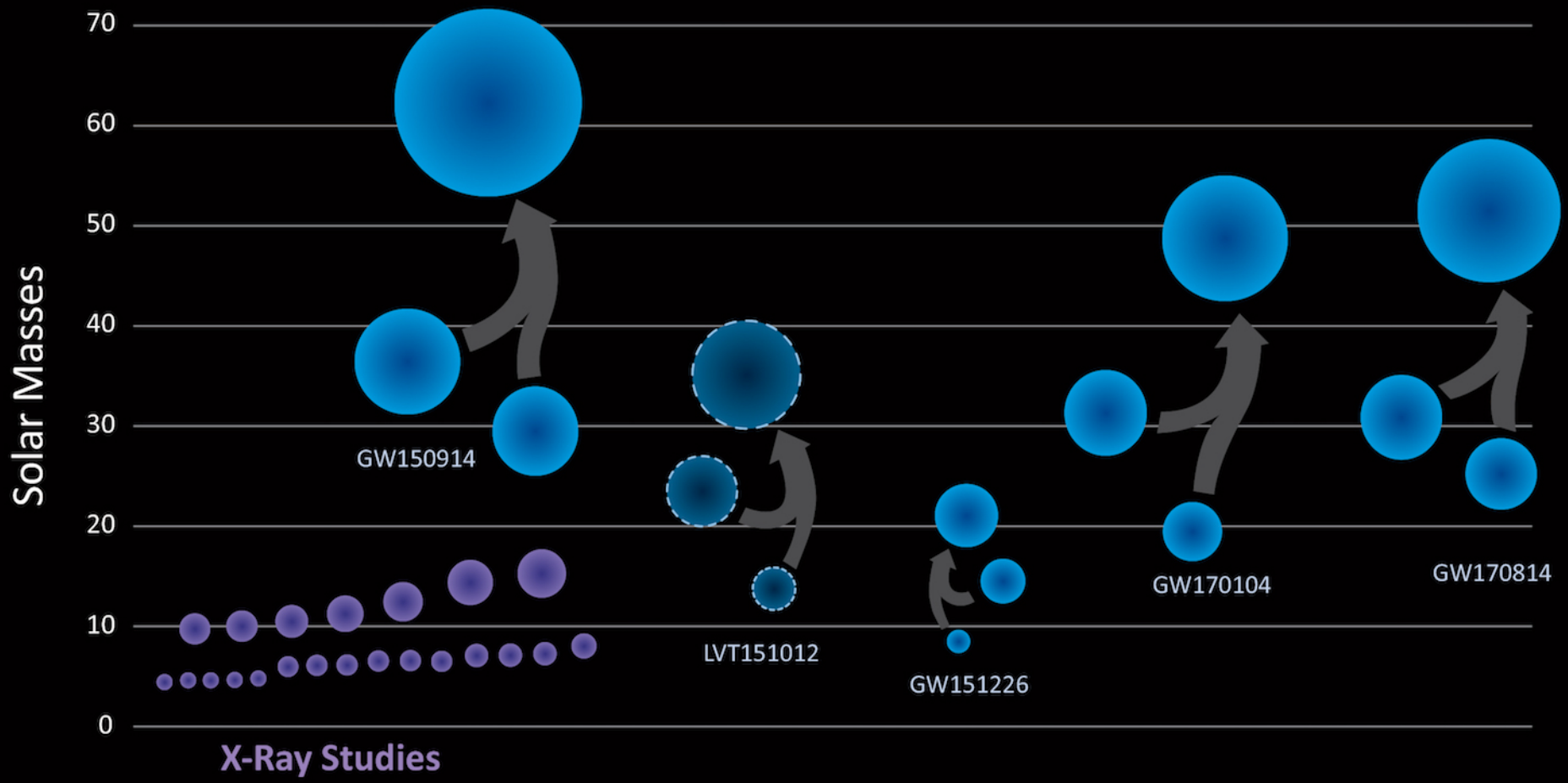

Gravitational wave amplitude
LIGO Hanford Data
Predicted
LIGO Livingston Data
Predicted
LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)


Black Holes of Known Mass
Progenitor stars have
low heavy elements,
i.e., old stars
Pop II or III stars
LIGO
X-Ray Studies
GW150914
GW151226
LVT151012
Solar Masses
70
60
50
40
30
20
10
0

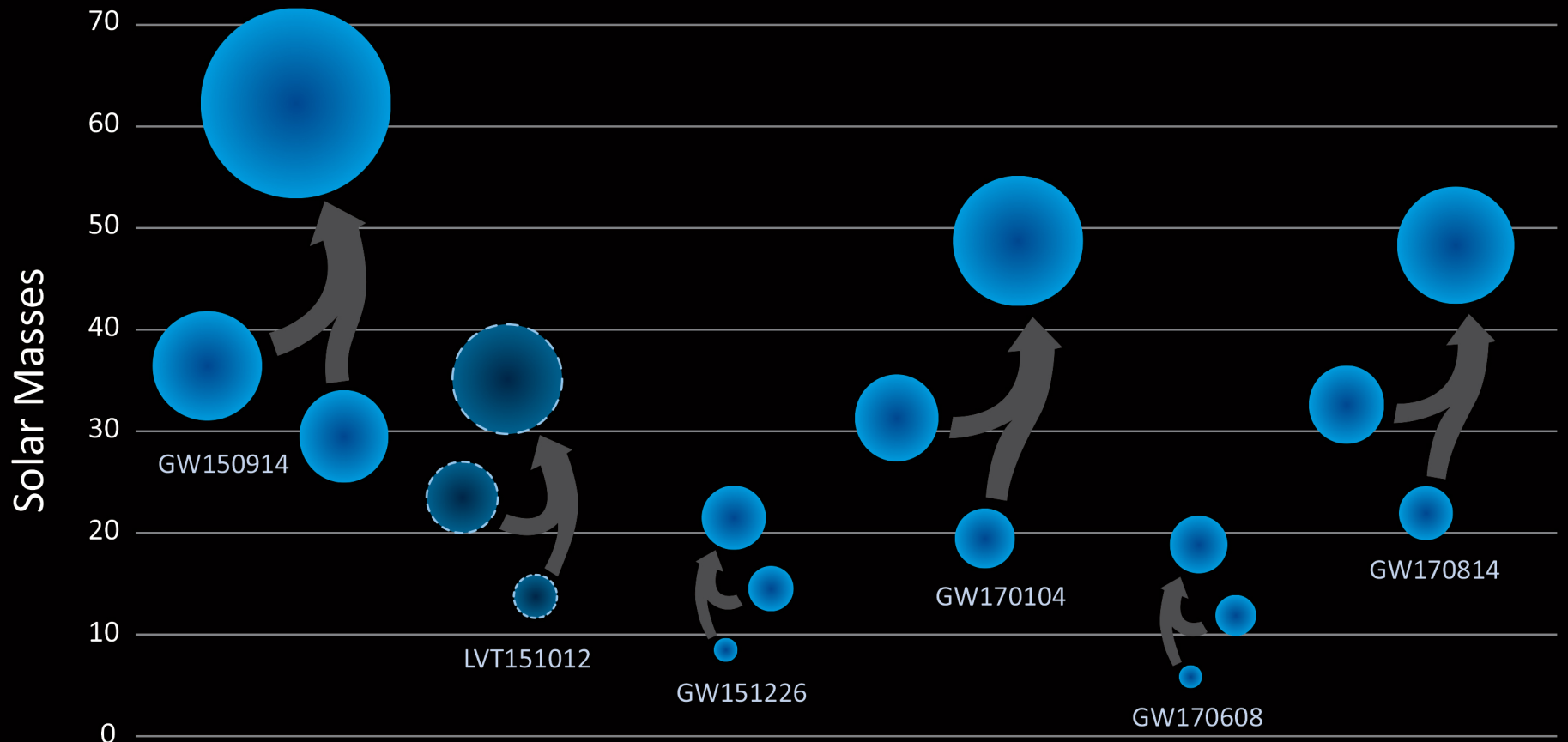
Black Holes of Known Mass



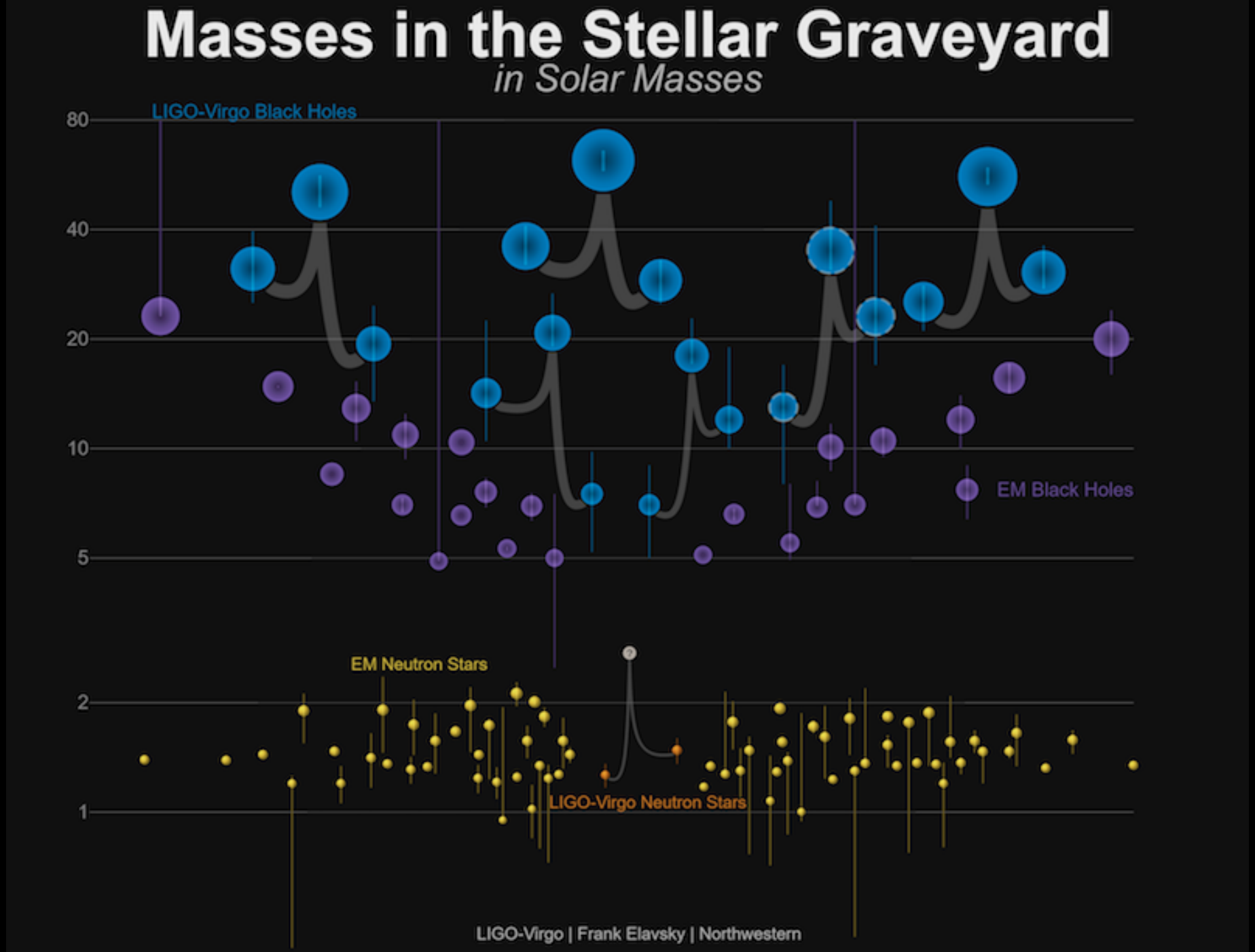
Black Holes of Known Mass



Black Holes of Known Mass

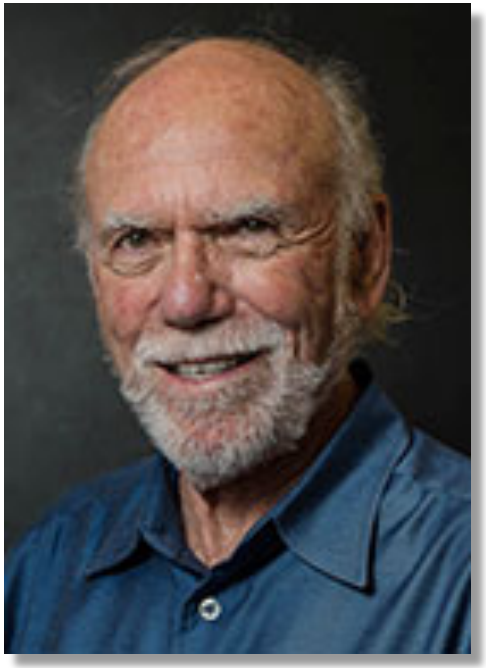


LIGO/VIRGO


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

The Nobel Prize in Physics 2017

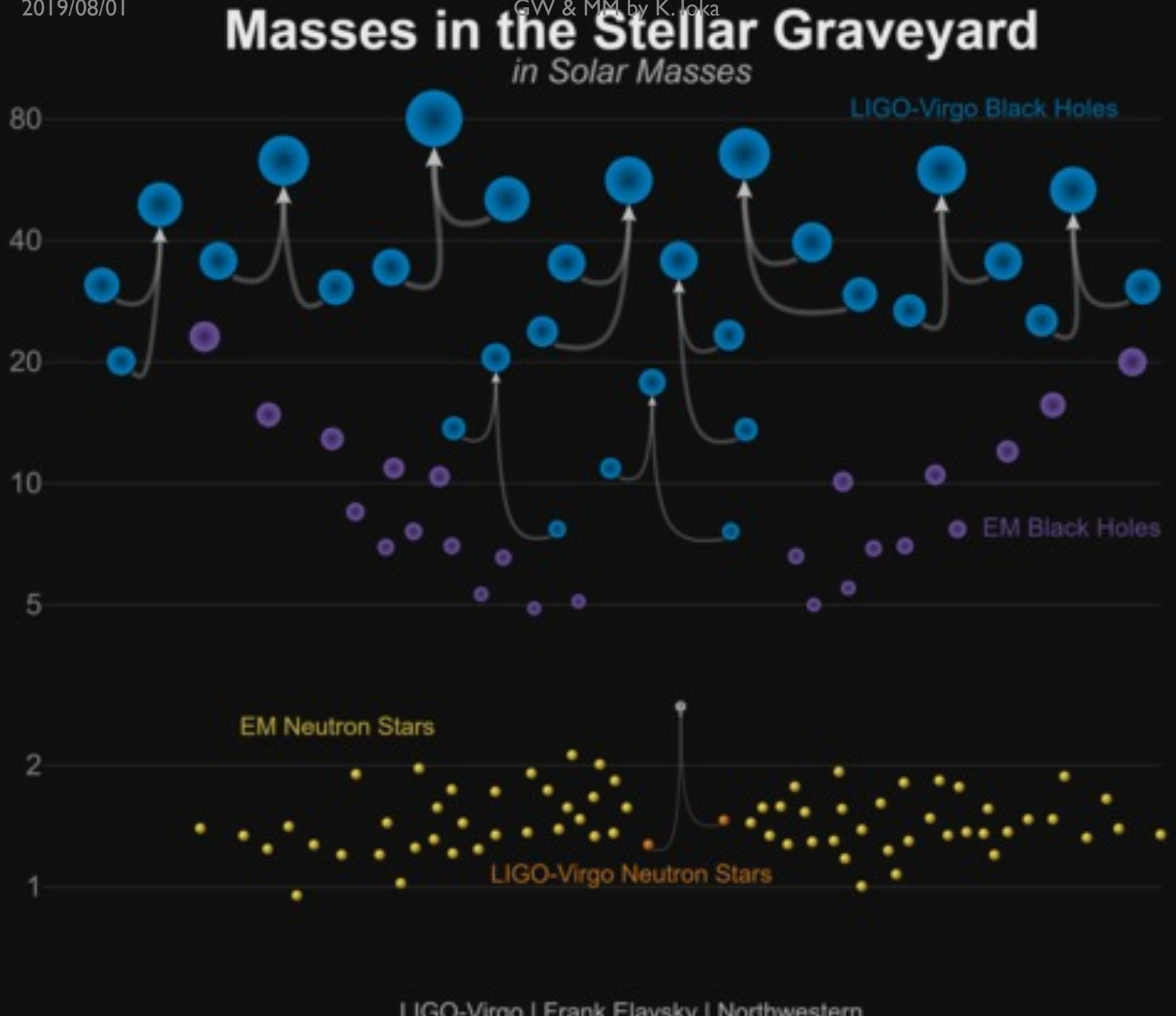
Rainer Weiss



Barry C. Barish

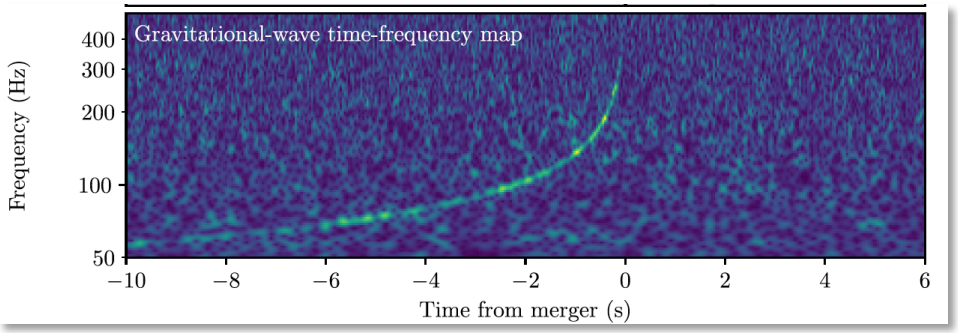
Kip S. Thorne

for decisive contributions to the LIGO detector and the observation of gravitational waves


Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

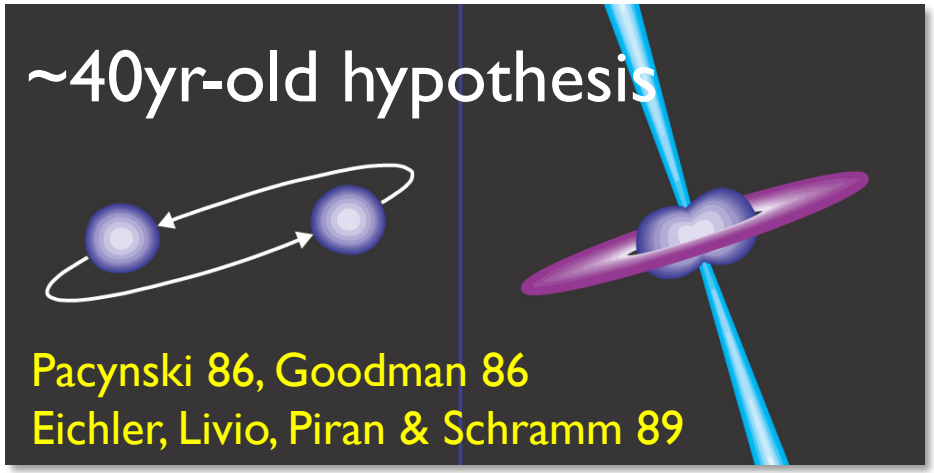
GW170817

1st GW from NS²



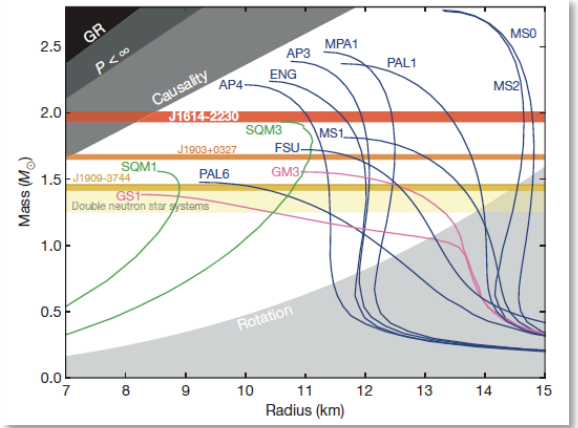
~100 sec chirp ⇒ NS-NS

NS² = Short GRB?

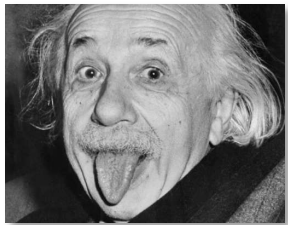


R-process elements

Equation of state



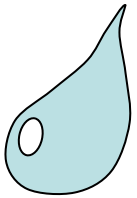
Relativity,
Cosmology,
…

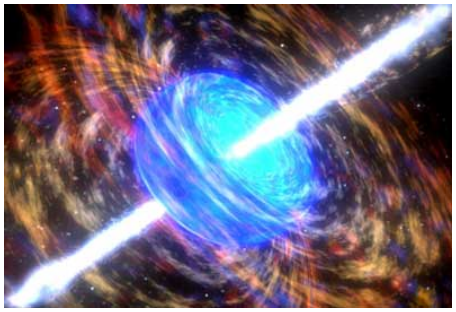


Gamma-Ray Bursts

$E=mc^2$ (Einstein)

=





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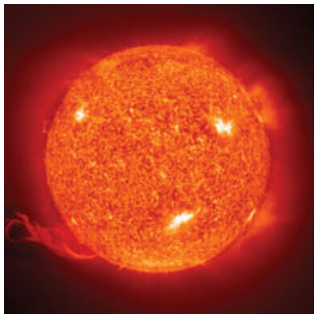


Atomic bomb ~1kg

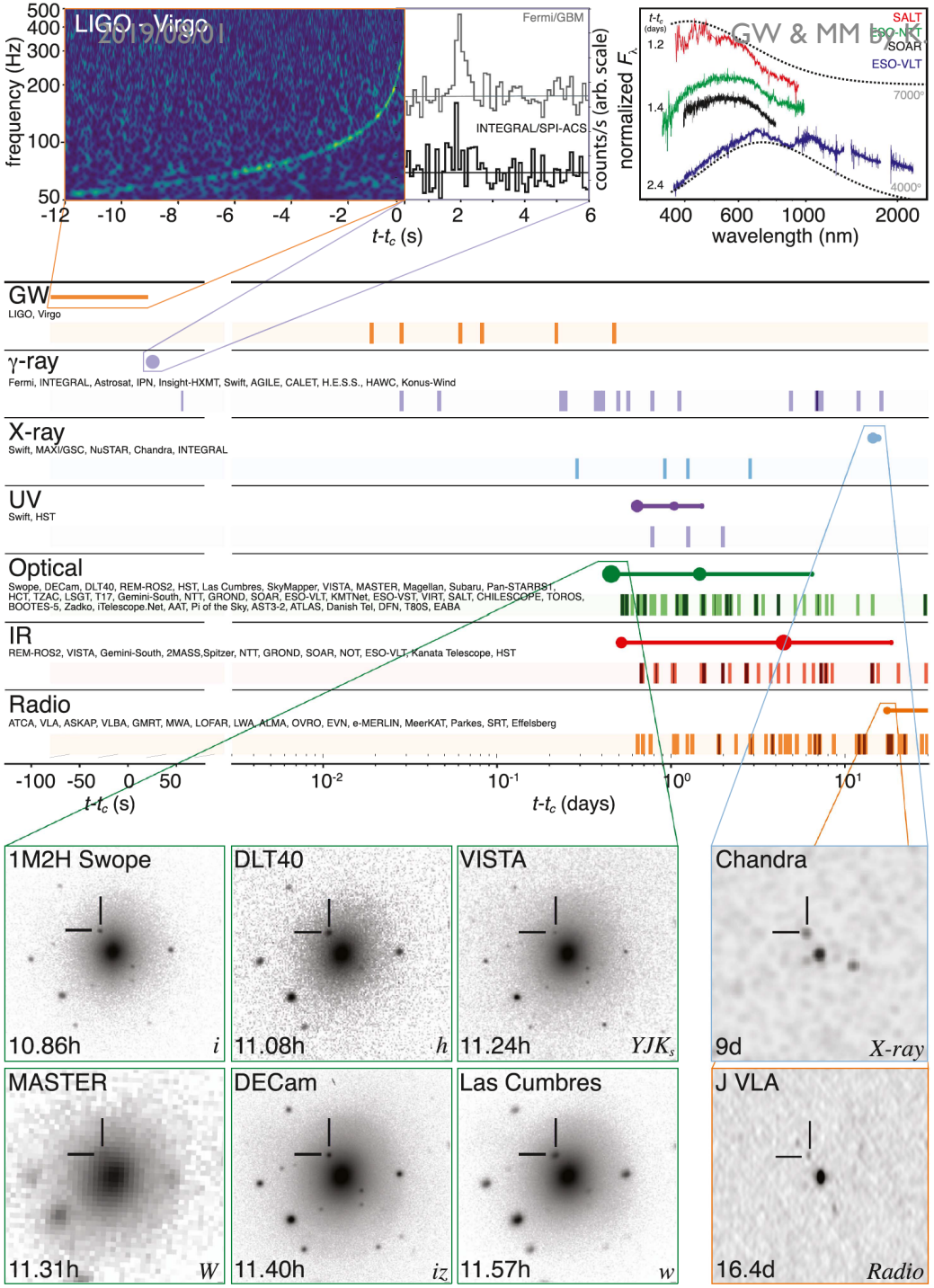
GRB $\sim 10^{52}$erg

Sun $\sim 10^{33}$g

In ~sec, GRB release energy Sun emit over lifetime

The most luminous EM object

New Era of Multi-Messenger



Follow-up observations

>3000 people

γ-ray: ~1.734±0.054 sec

⇒ sGRB 170817A

UV-Opt-IR: 10.86 hr

⇒ Macronova/Kilonova

X, radio: ~10 day

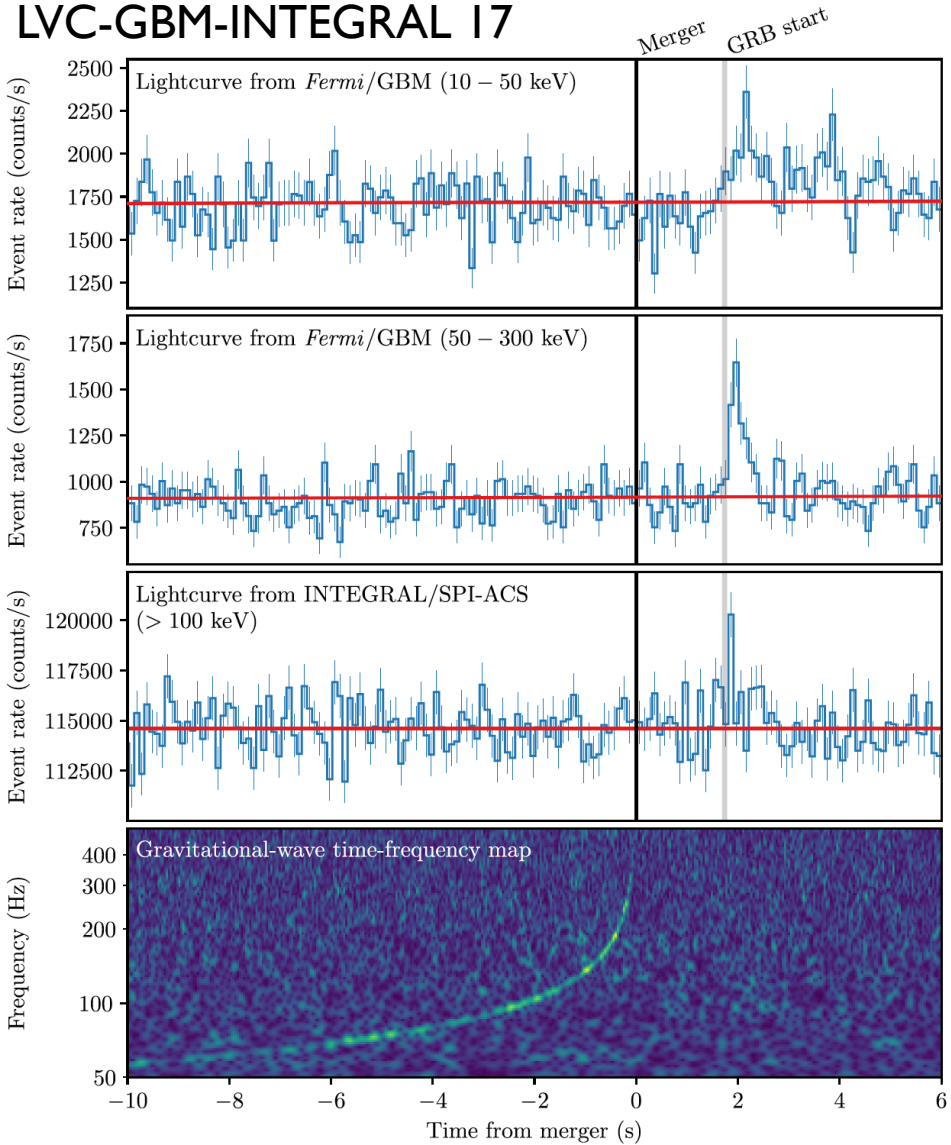
⇒ Afterglow

LVC-EM 17

Band: GCN circ., Circles ∝ brightness

GW170817 & GRB 170817A

LVC-GBM-INTEGRAL 17

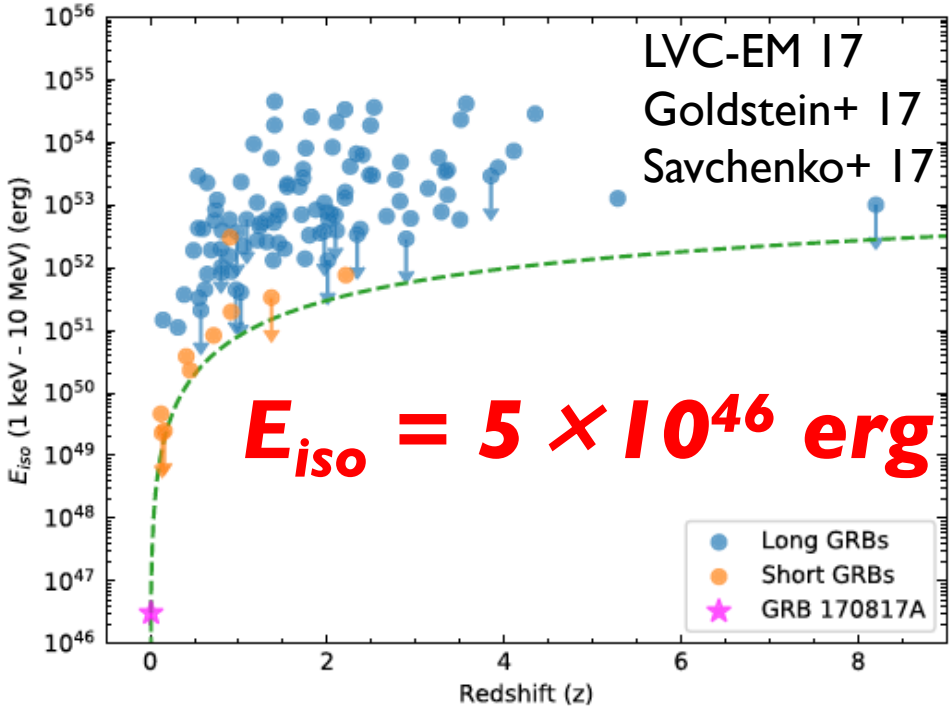


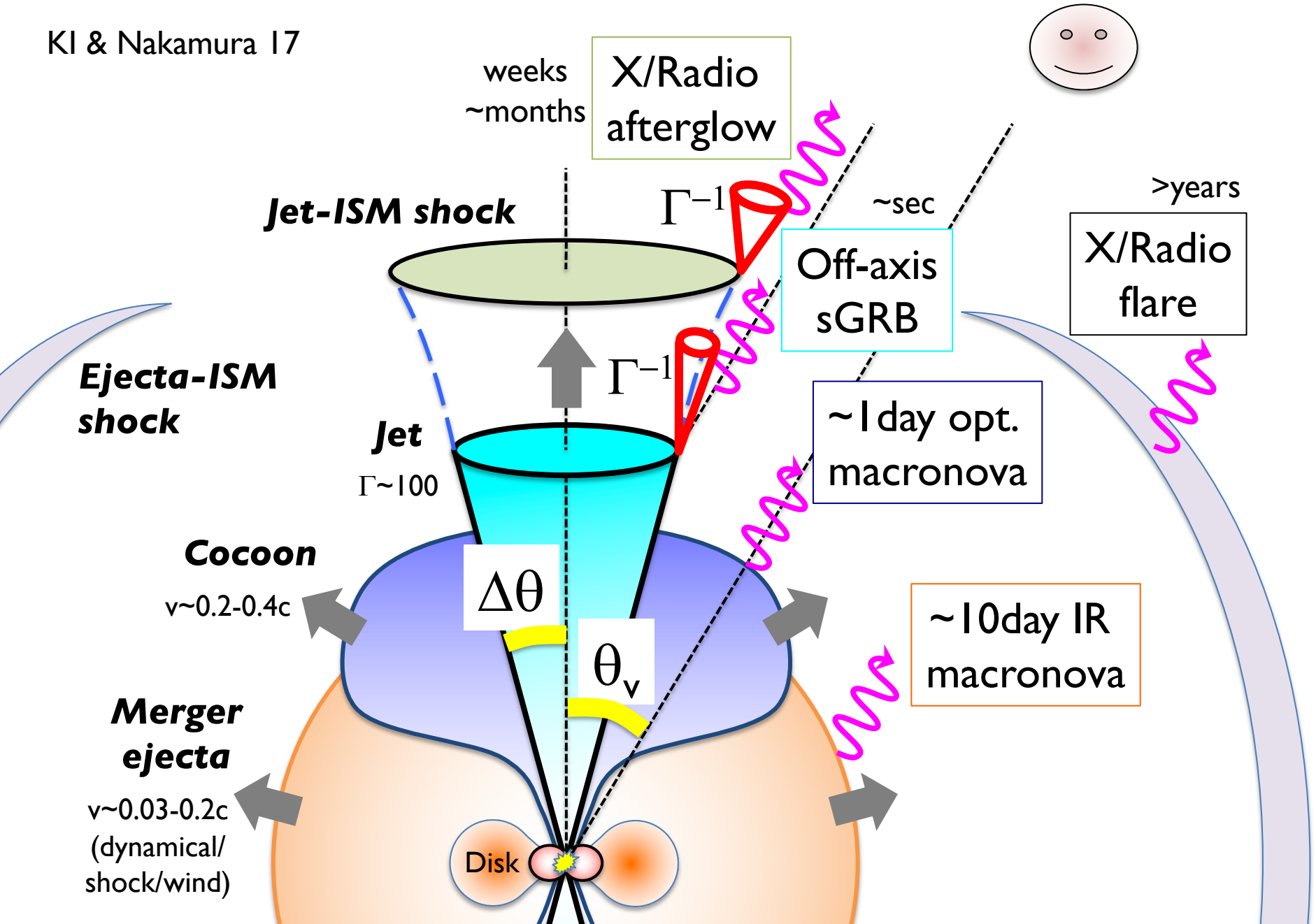
3 (of 12) GBM NaI detectors

T_0=1.74±0.05 sec (68%)

T_{90}=2.0±0.5 sec

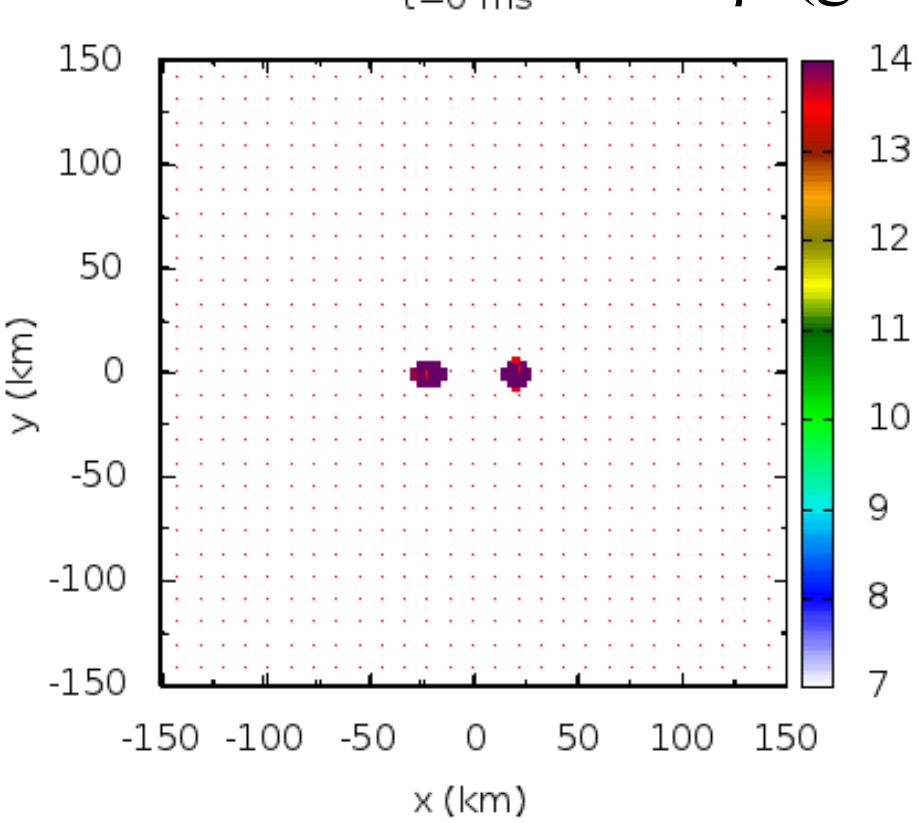
Weak but Detected

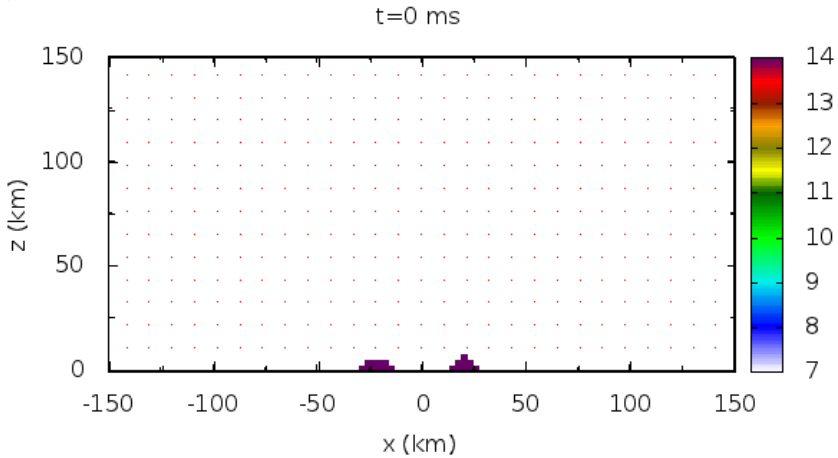



KI & Nakamura 17
weeks
~months
X/Radio
afterglow
Jet-ISM shock
Γ^{-1}
~sec
Off-axis
sGRB
>years
X/Radio
flare
Ejecta-ISM
shock
Γ^{-1}
Jet
Γ~100
~1day opt.
macronova
Cocoon
v~0.2-0.4c
Δθ
θ_v
~10day IR
macronova
Merger
ejecta
v~0.03-0.2c
(dynamical/
shock/wind)
Disk

Merger of 1.3-1.4 M_{sun} NS:
EOS=APR4; stiff but relatively soft

ρ (g/cm^3)





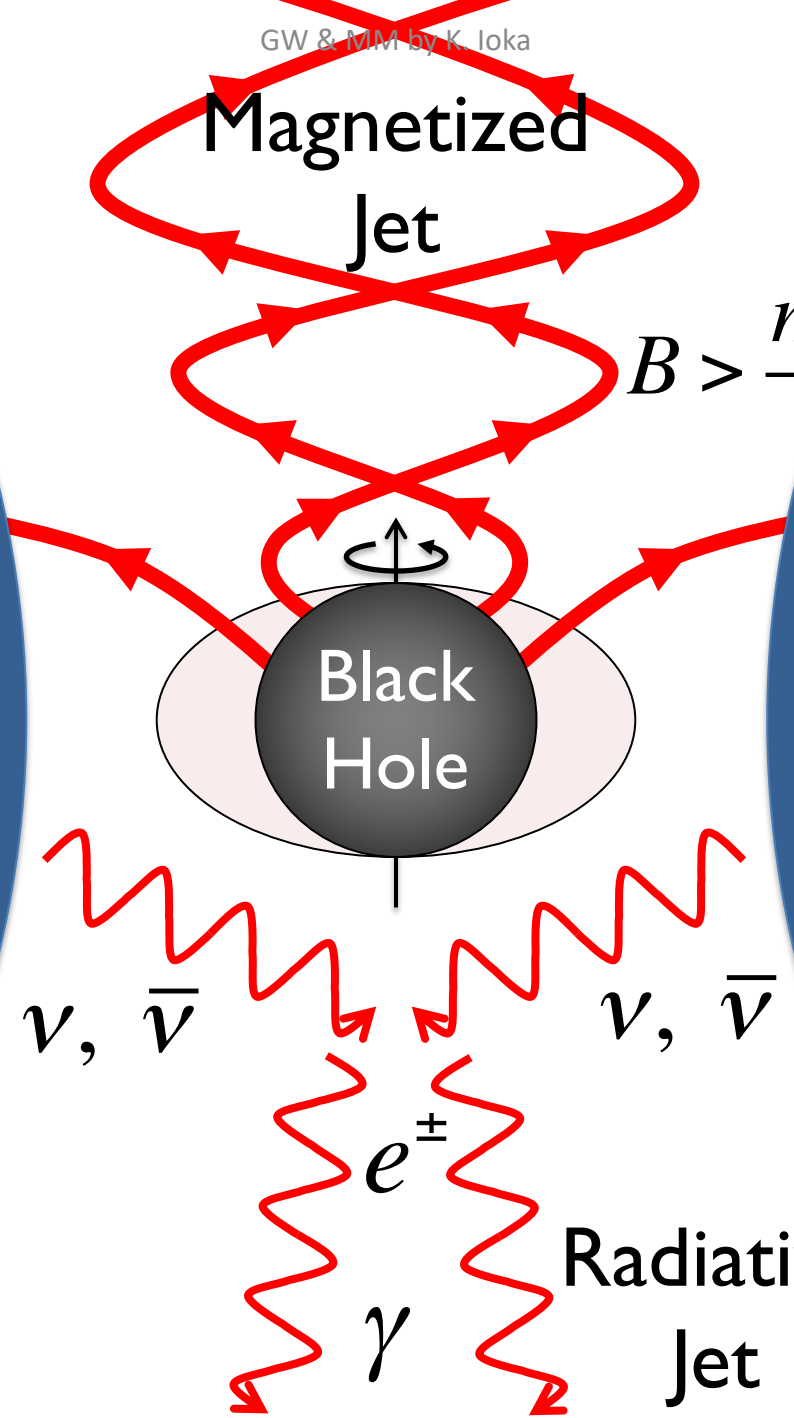
Relatively wider view

Orbital plane

***X-Z* plane**

©Shibata, Hotokezaka

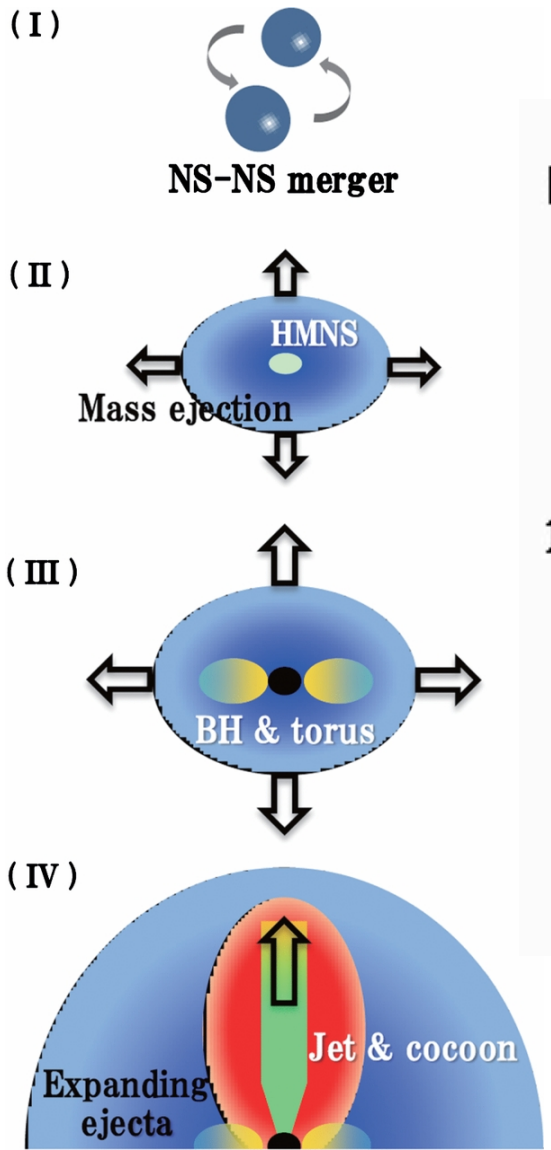
?



$$B > \frac{m_e^2 e^3}{e\hbar} \approx 4\times 10^{13}\,\mathrm{G}$$

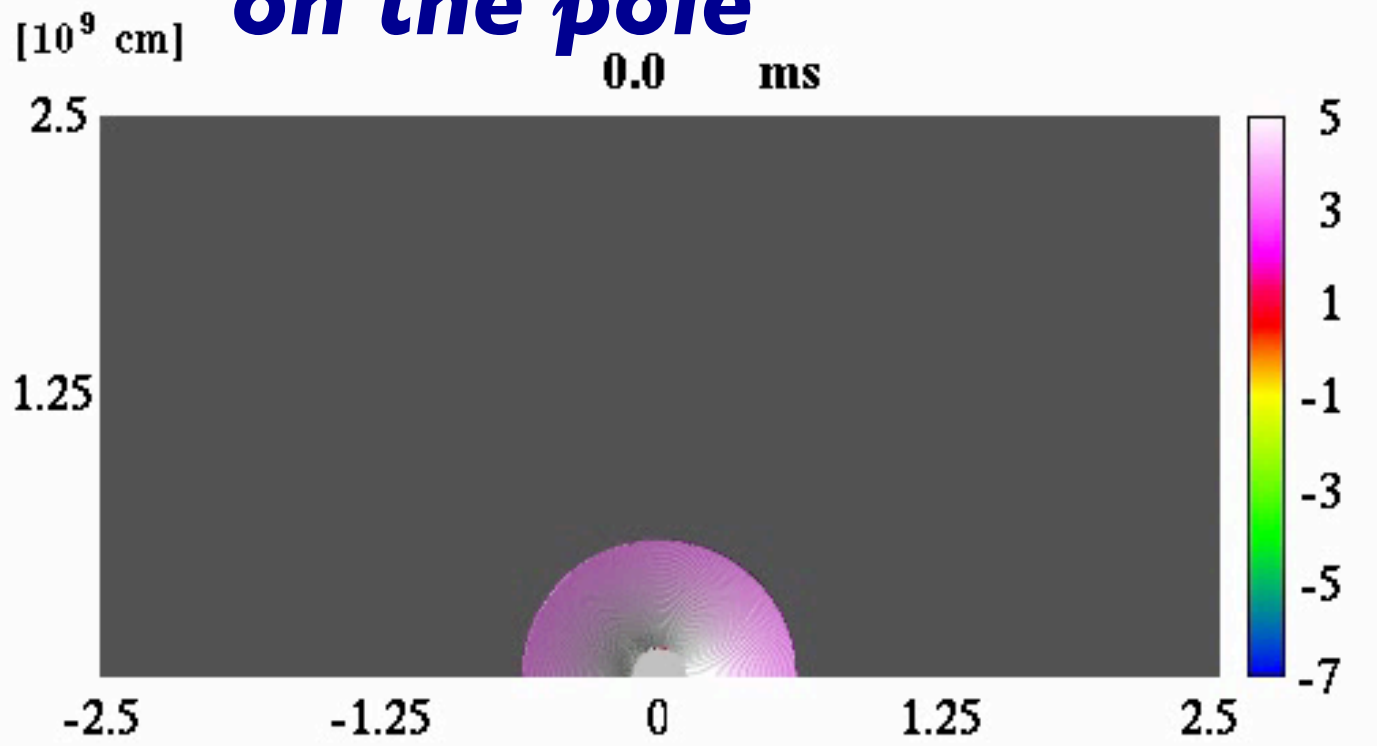
Accretion Disk
(Baryon)

Jet Breakout from Ejecta



Ejecta is also on the pole

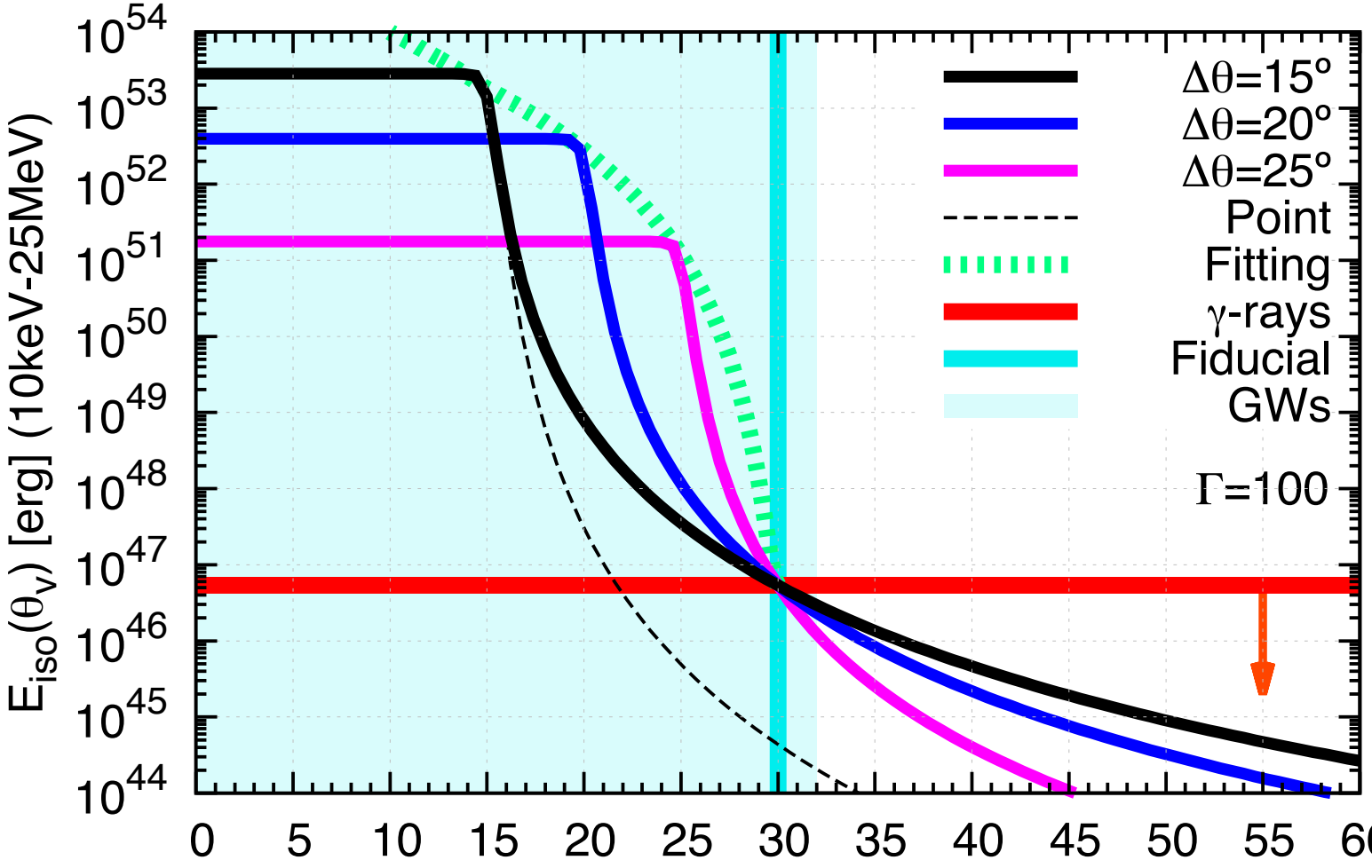
Nagakura+ 14
Murguia-Berthier + 14



Similar to collapsars (long GRBs)

Weak jet ~10^{46} erg/s cannot break out

Off-Axis Jet



$\theta_v \sim \Delta\theta$
⇒ **Point approx. is bad**

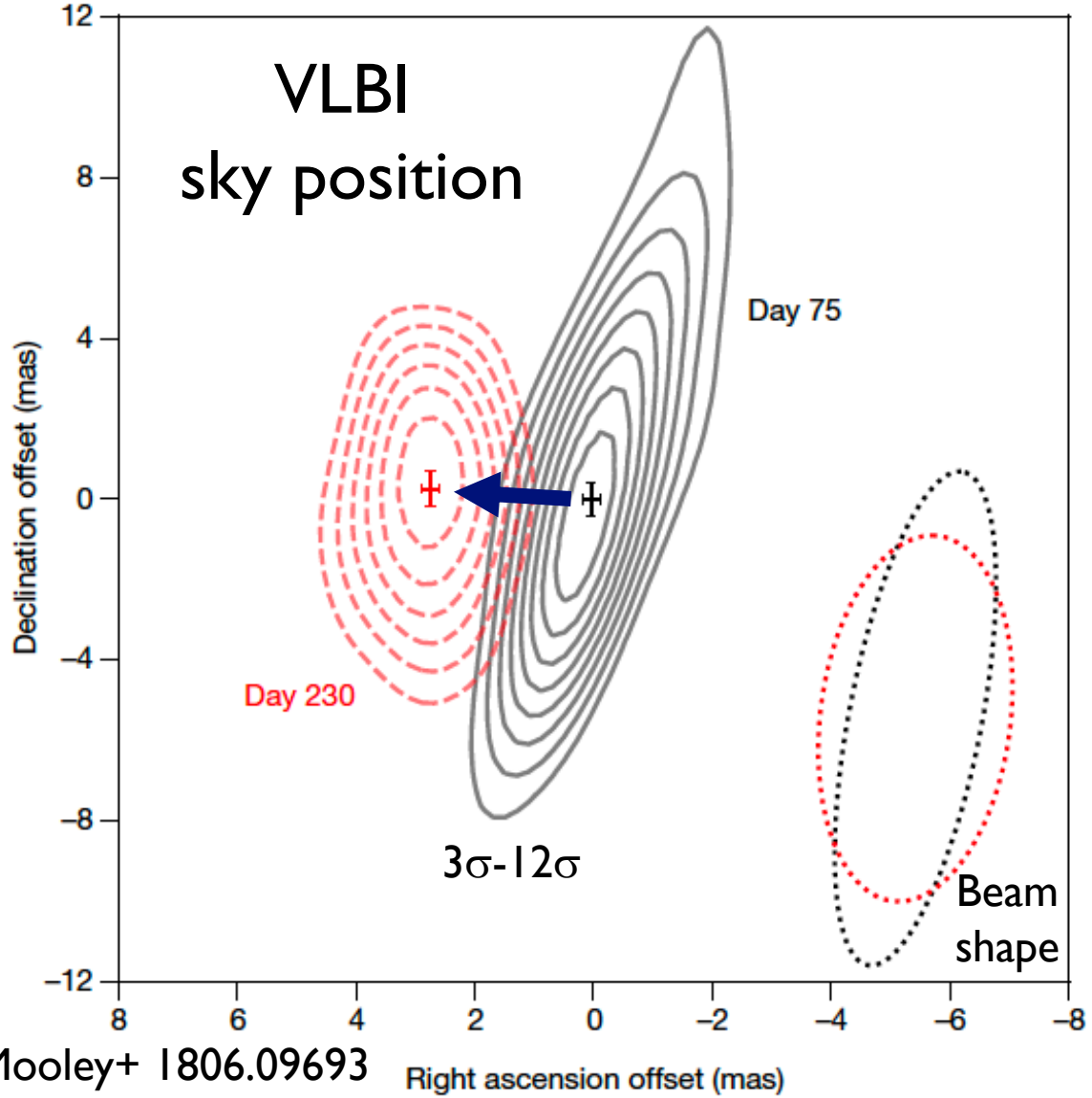
$E_{iso} \propto \theta_v^{-6}$
↓
$E_{iso} \propto \theta_v^{-4}$

KI & Nakamura 17, 01
Yamazaki, KI & Nakamura 02, 03, 04

LVC-GBM-INTEGRAL 17
Granot+ 17, Kasliwal+ 17

Kasliwal+ 17
Gottlieb+ 17
Bromberg+ 17

Superluminal Motion



Mooley+ 1806.09693

v_{app}~4.1±0.5 c!

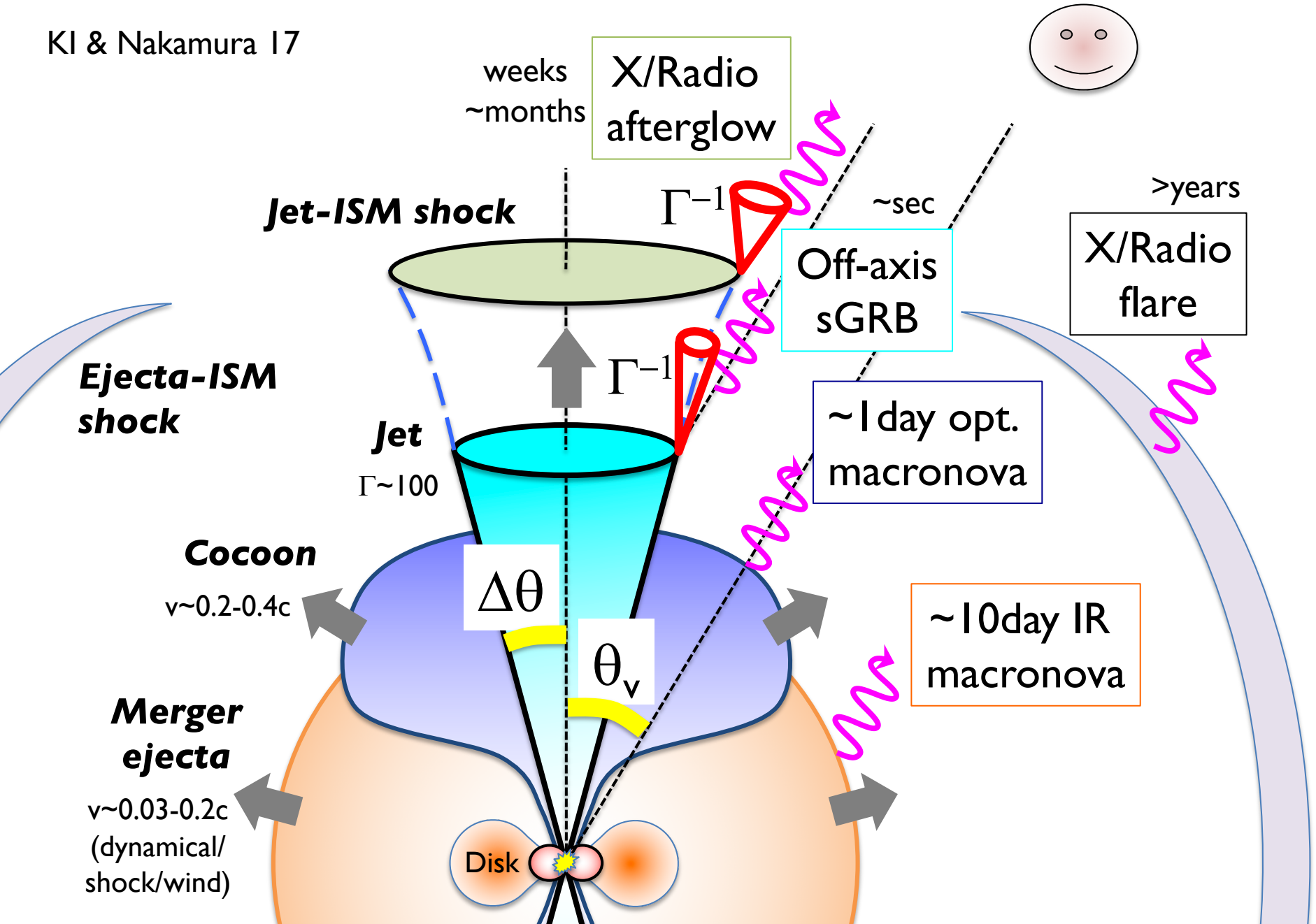
Unresolved

R<0.2pc(1mas),
<2pc(10mas)

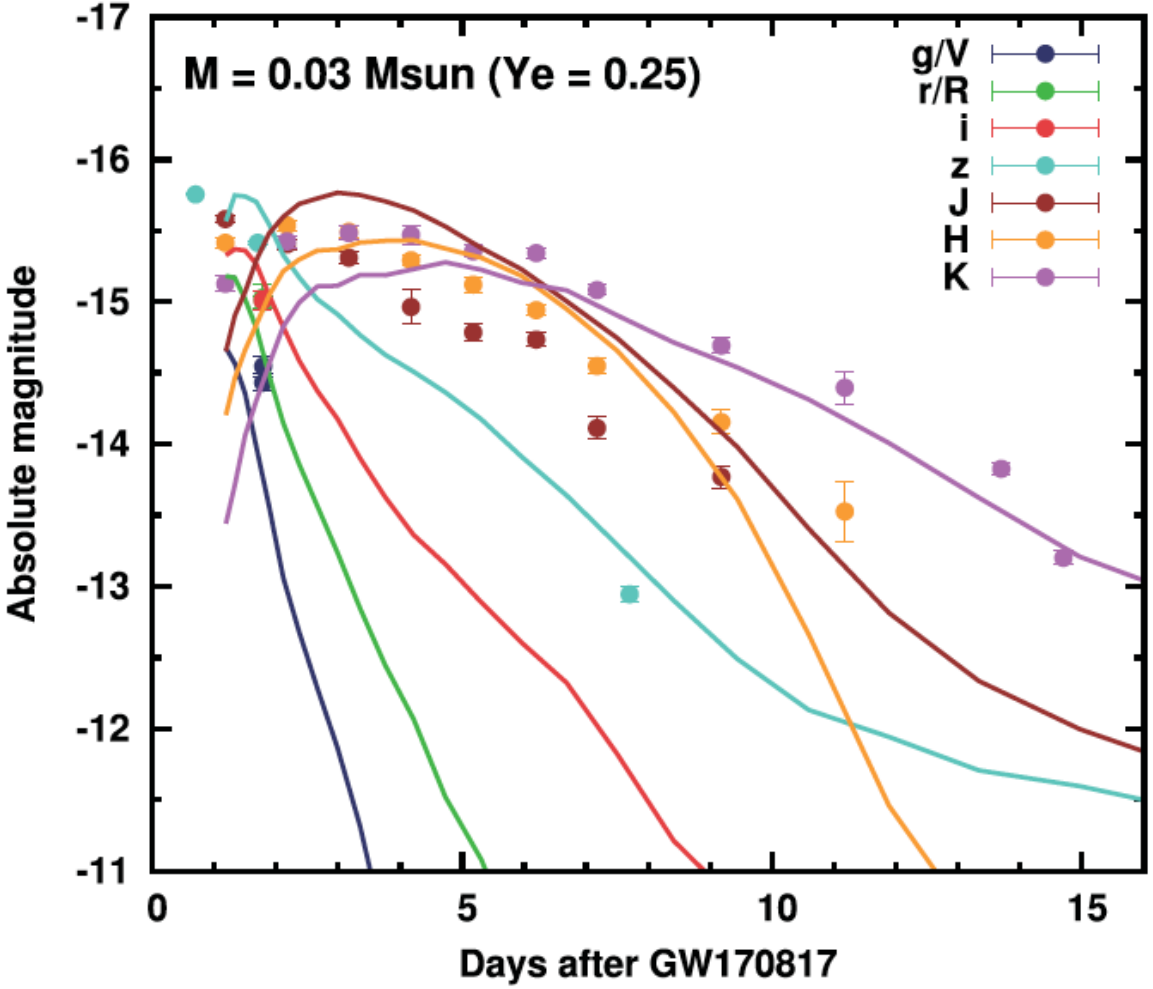
Not consistent with a spherical source

Γ~4 at t~t_{peak}

KI & Nakamura 17



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

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

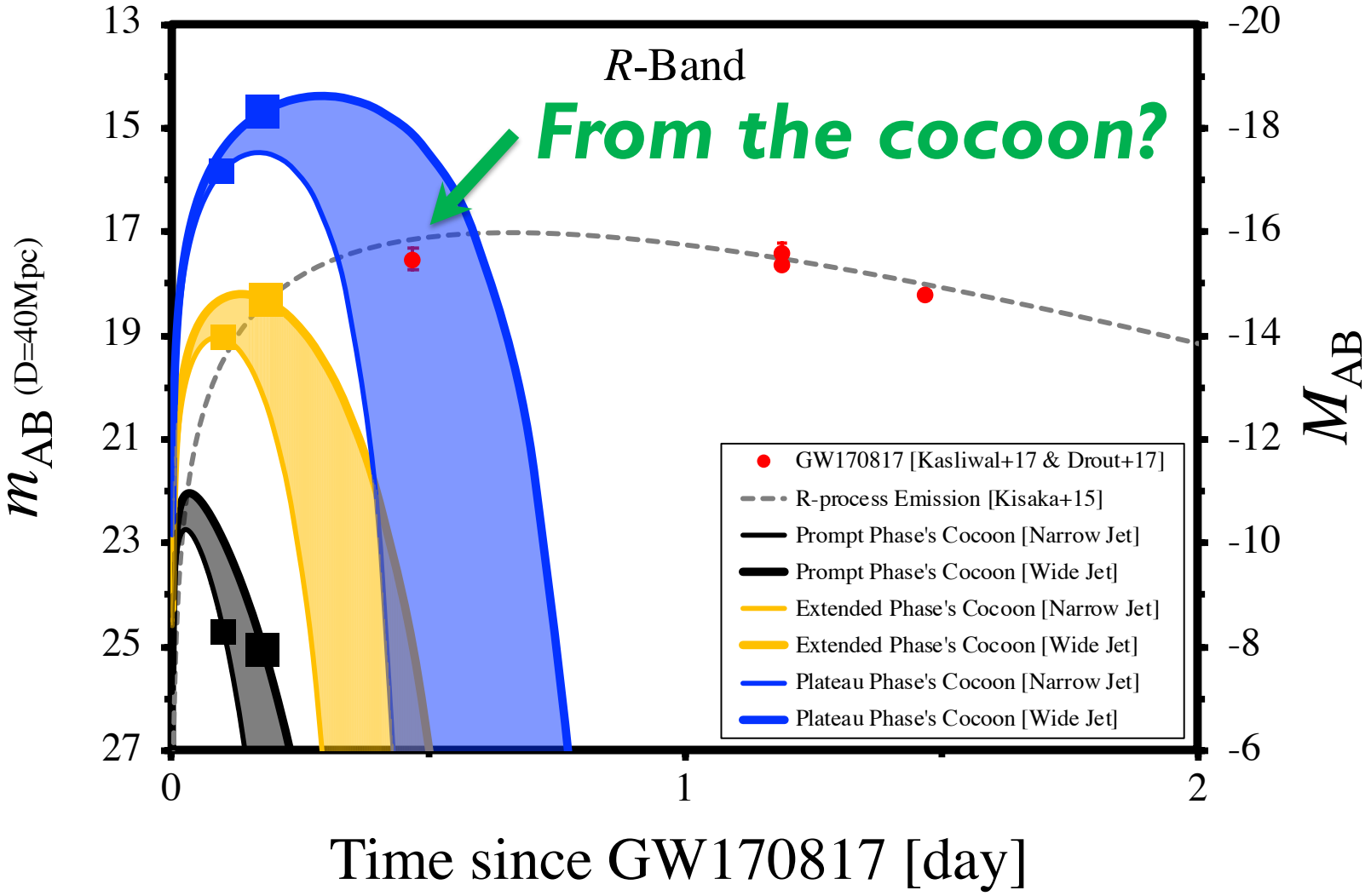
$M \sim 0.03 M_\odot$

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

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

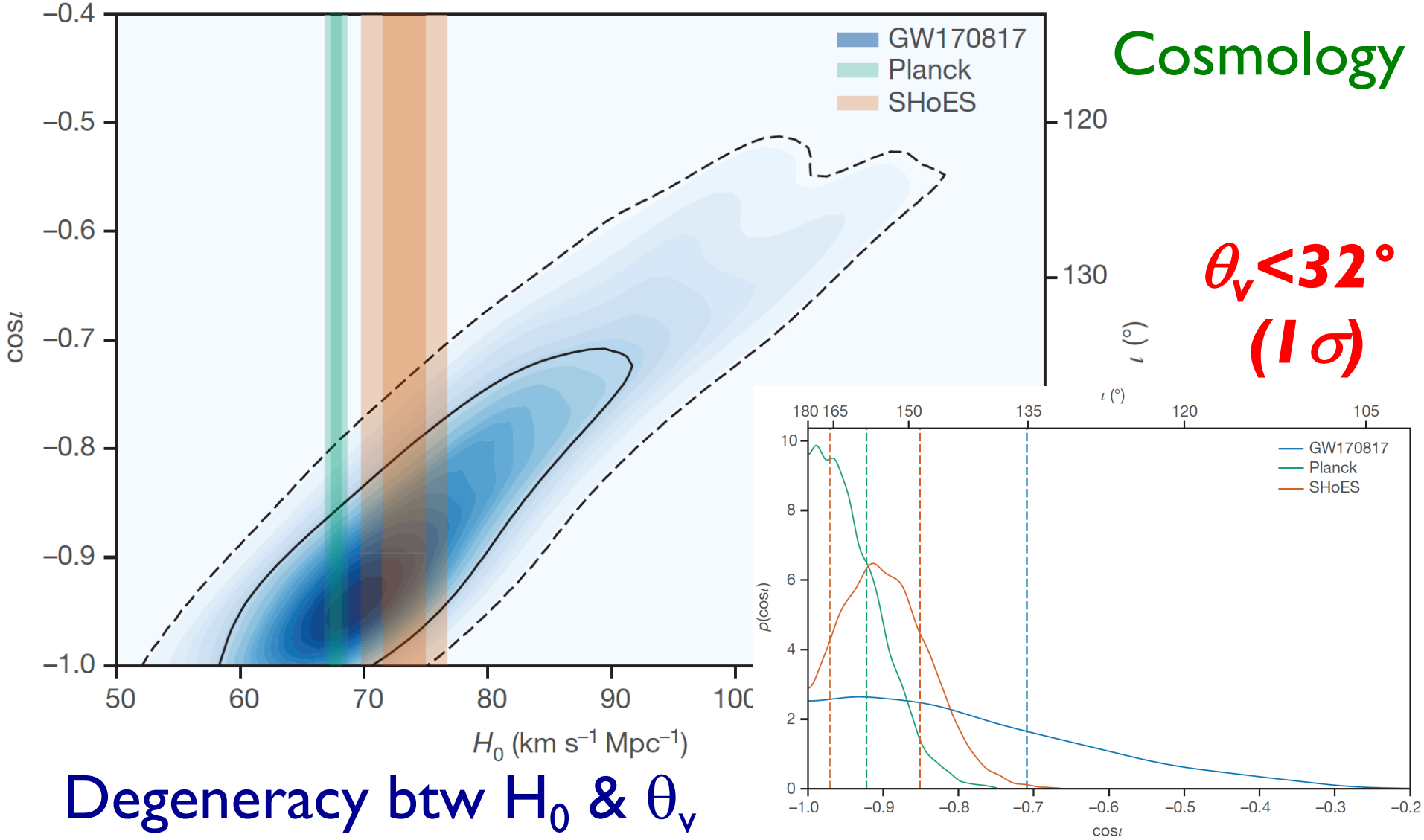
Polar or Radial

Cocoon Emission



rep.

Viewing Angle & H_0

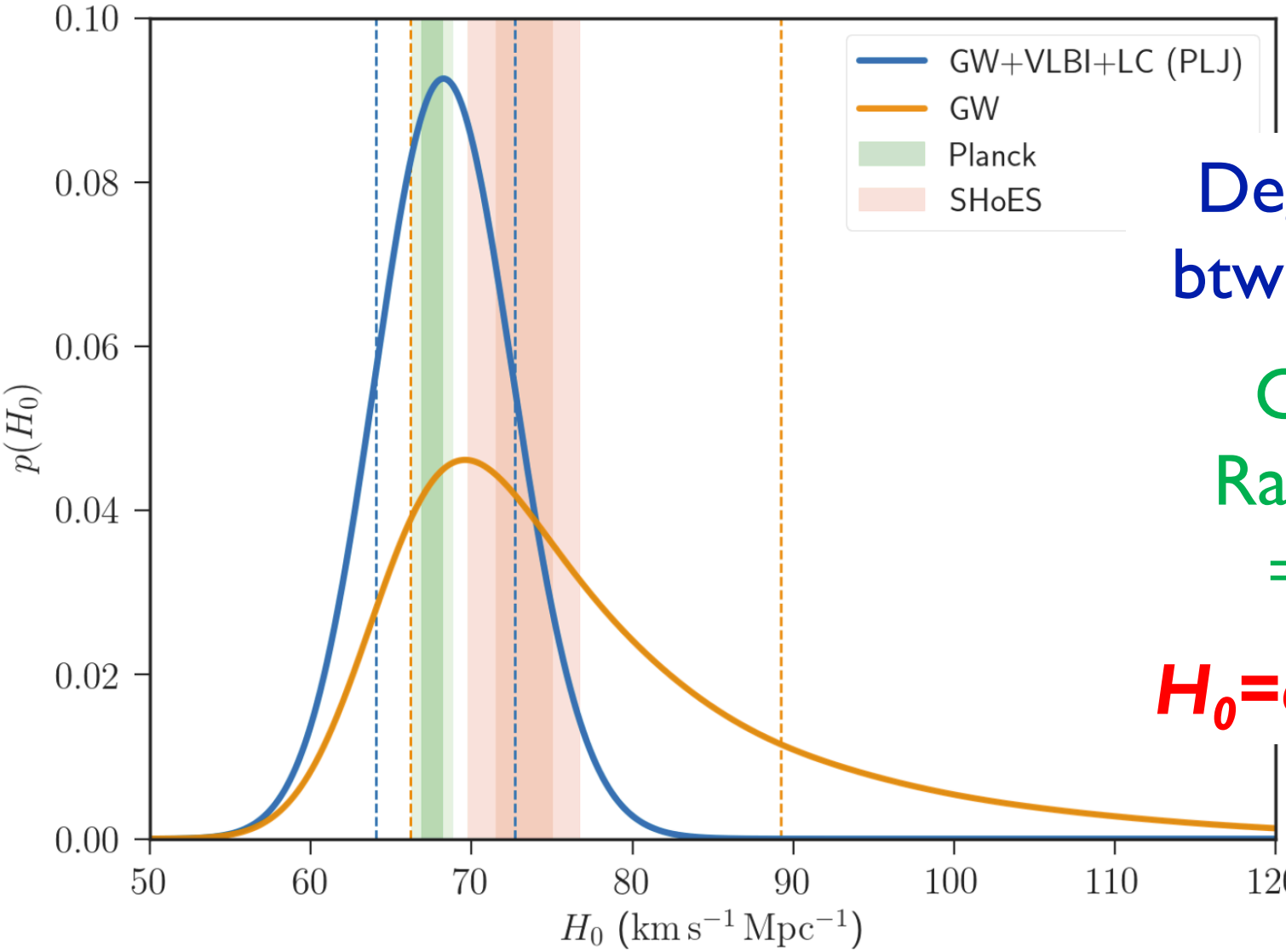


Cosmology

θ_v<32° (1σ)

Degeneracy btw H_0 & θ_v

H_0 & GRB Jet



Degeneracy btw d_L & θ_{view}

GRB Jet Radio VLBI $\Rightarrow \theta_{view}$

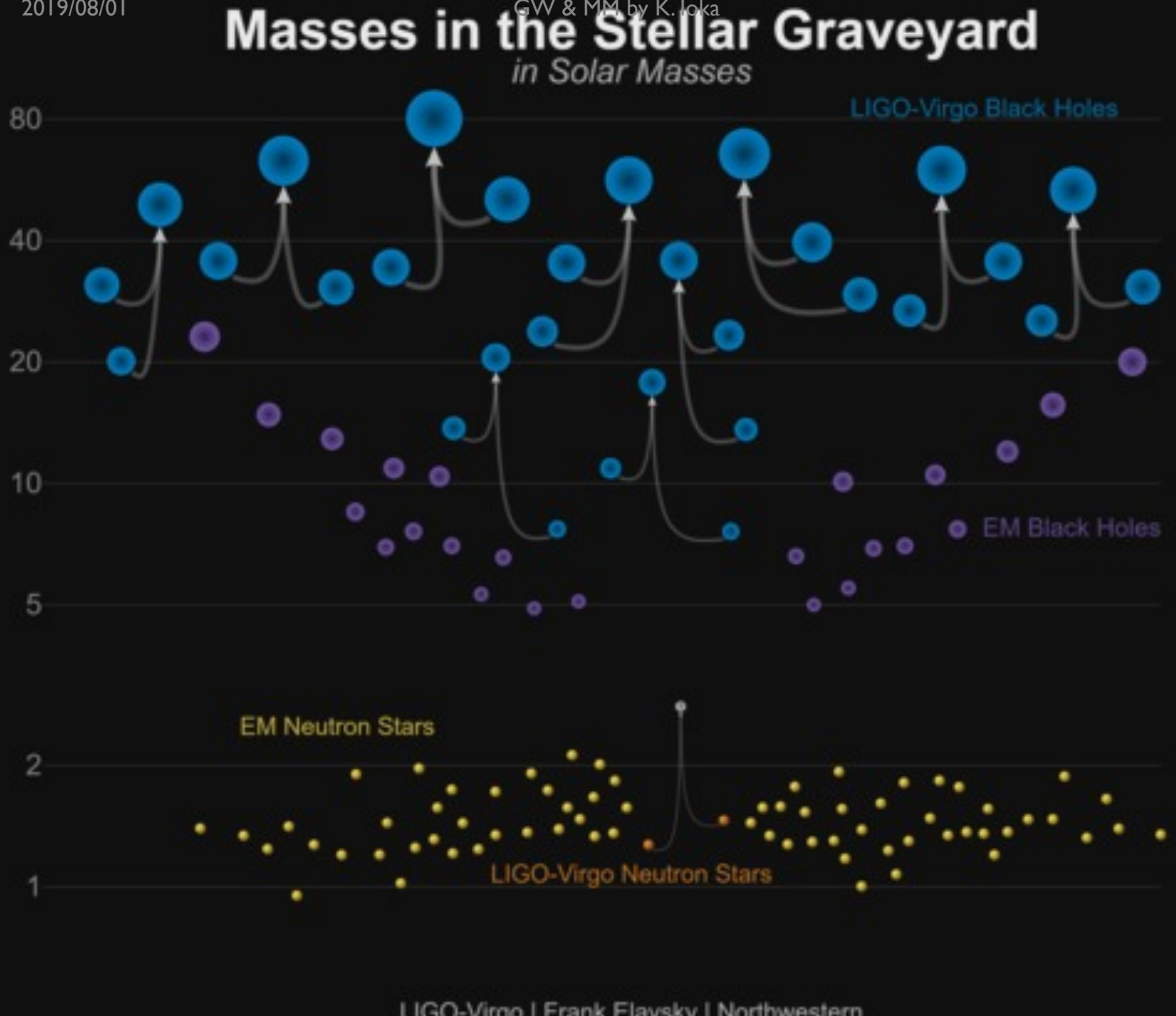
$H_0=68.9^{+4.7}_{-4.6}$

Hotokezaka+ 19

New Problems

- ***sGRB 170817A (gamma)***
  - Jet, Cocoon breakout, or Scattering?
- ***Afterglow (X, opt, radio)***
  - ***Jet is verified***, Jet structure?
- ***Macronova/Kilonova (UV, opt, IR)***
  - Radioactive energy or Central engine?
  - r-process abundance & pattern?

Great Progress!!


Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
EM Black Holes
EM Neutron Stars
2
1
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

Too(?) Many O3 Events

S190425z NS-NS (>99%) @~156±41Mpc

S190426c NS-BH (~60%) @375±108Mpc

$\Delta\Omega \sim 10^3\ \mathrm{deg}^2$

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | LATEST | DOCUMENTATION | LOGIN

Latest — as of 27 May 2019 06:34:25 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	Created (UTC)
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

App Store Preview

This app is only available on the App Store for iOS devices.

Gravitational Wave Events 4+

LIGO/Virgo alerts from GCN

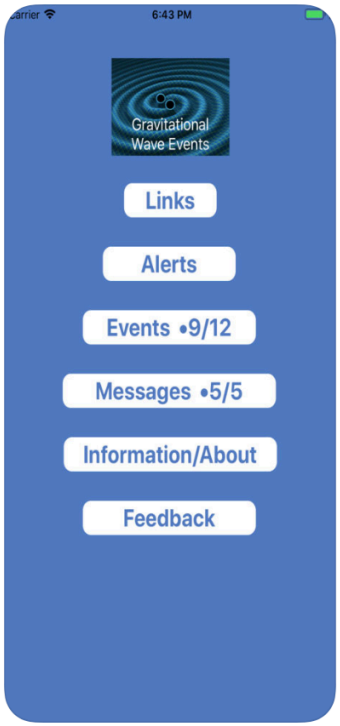
Peter Kramer

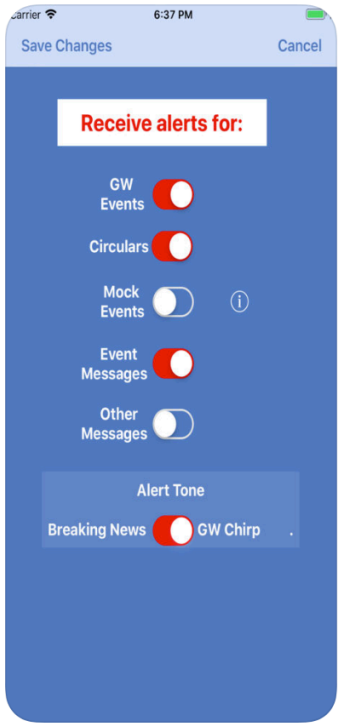
★★★★½ 4.6, 7 Ratings

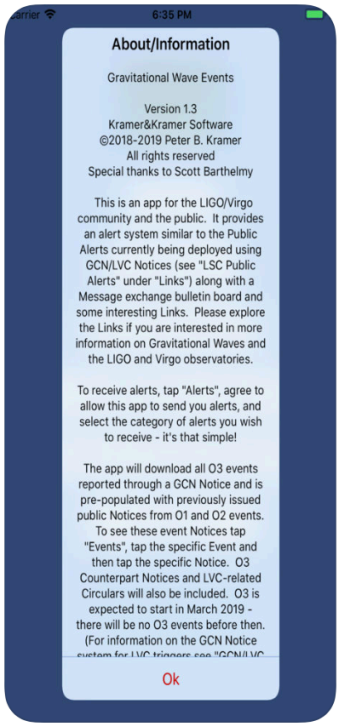
Free

Download NOW!!

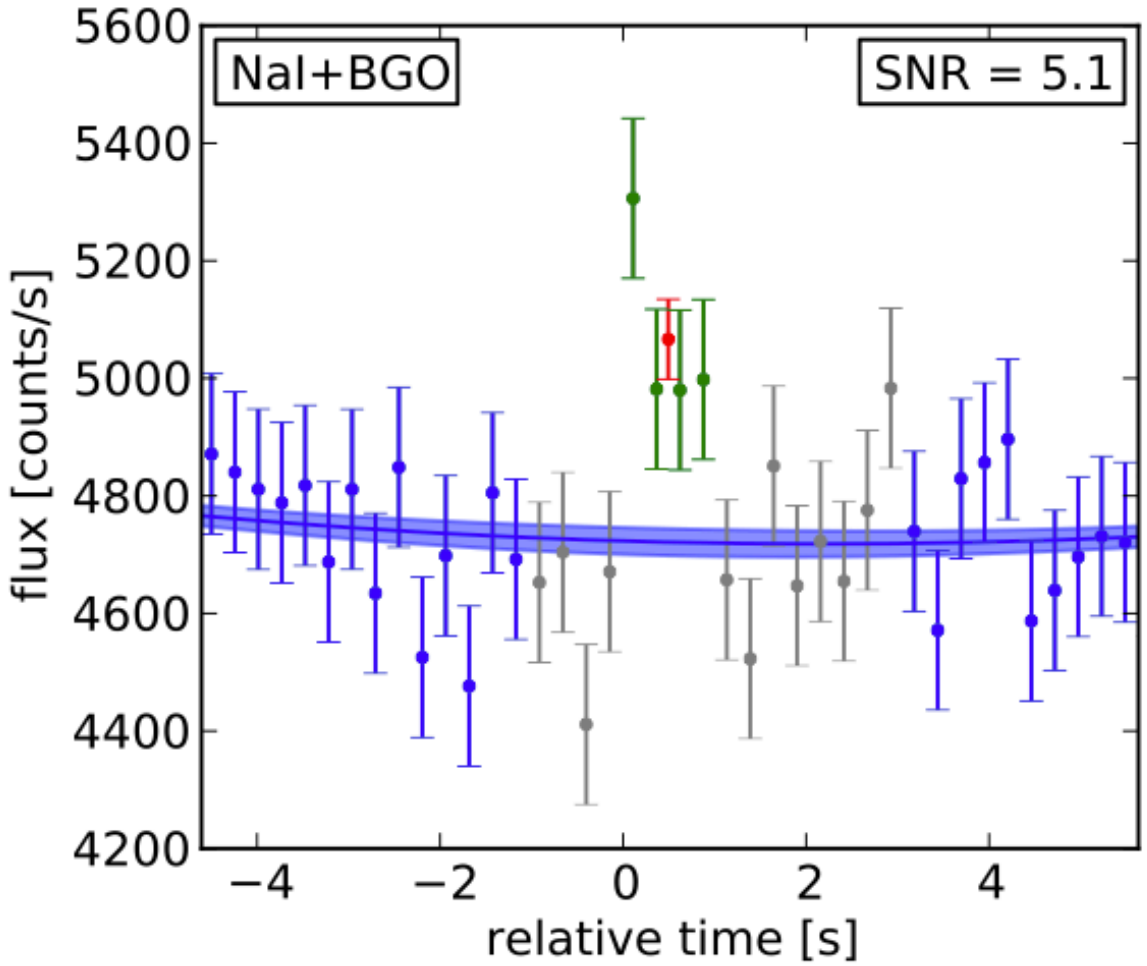
iPhone Screenshots







GRB from GW150914?



Fermi GBM >50keV

0.4s after GW

T~1sec

False alarm~0.0022

$L \sim 1.8^{+1.5}_{-1.0} e49 erg/s$

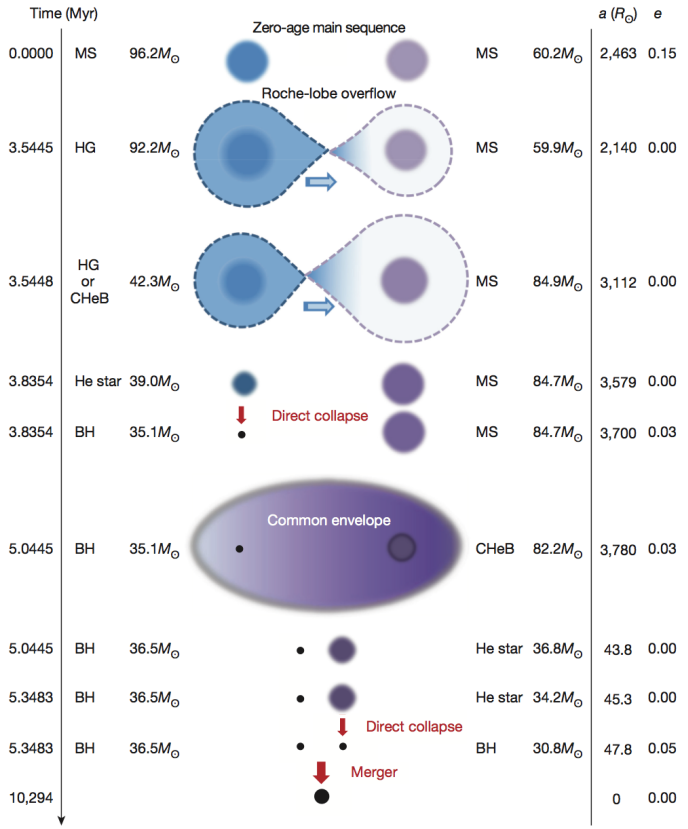
Short GRB!?

INTEGRAL: no signal

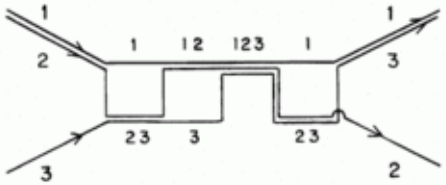
Fermi+ 16

What is the Origin?

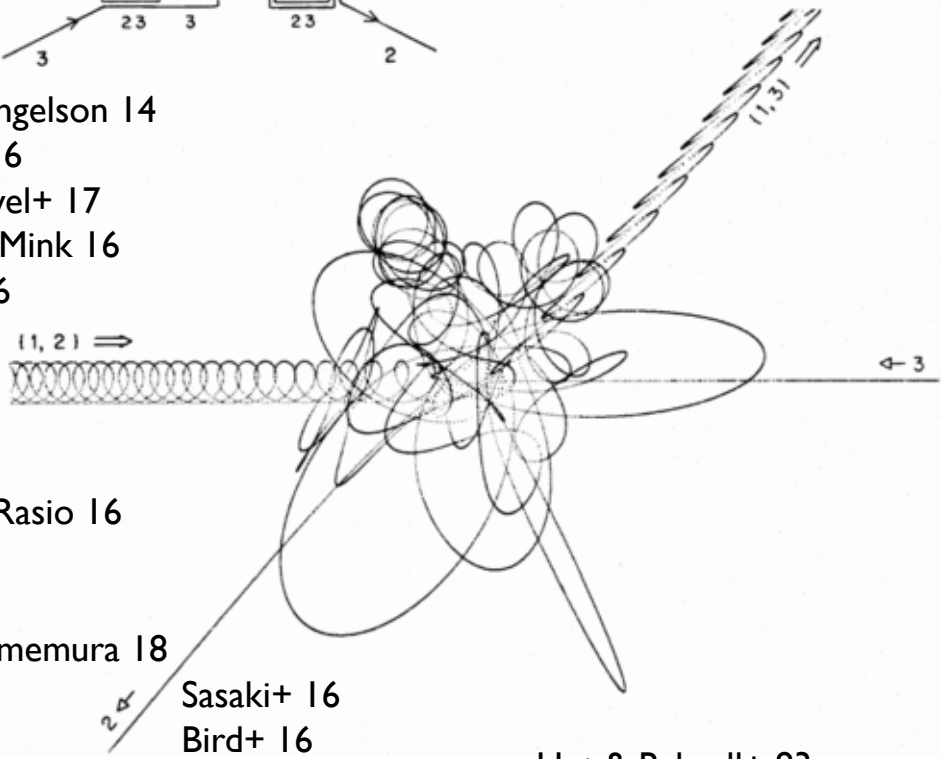
Isorated binary?



Stellar cluster?



Postnov & Yungelson 14
Belczynski+ 16
van den Heuvel+ 17
Mandel & de Mink 16
Kinugawa+ 16



Antonini & Rasio 16
Bartos+ 16
Stone+ 16
Tagawa & Umemura 18

Sasaki+ 16
Bird+ 16
Binnilov+ 16
Carr+ 16
Kawasaki+ 16

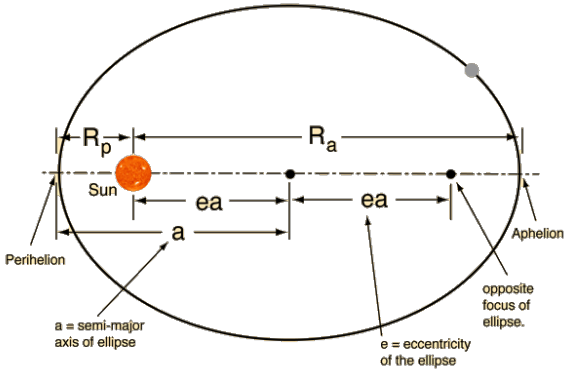
Hut & Bahcall+ 83
Rodriguez+ 16
O'Leary+ 16

Near galactic nuclei?
Primordial black hole?

Very Close Binary

GW coalescence time

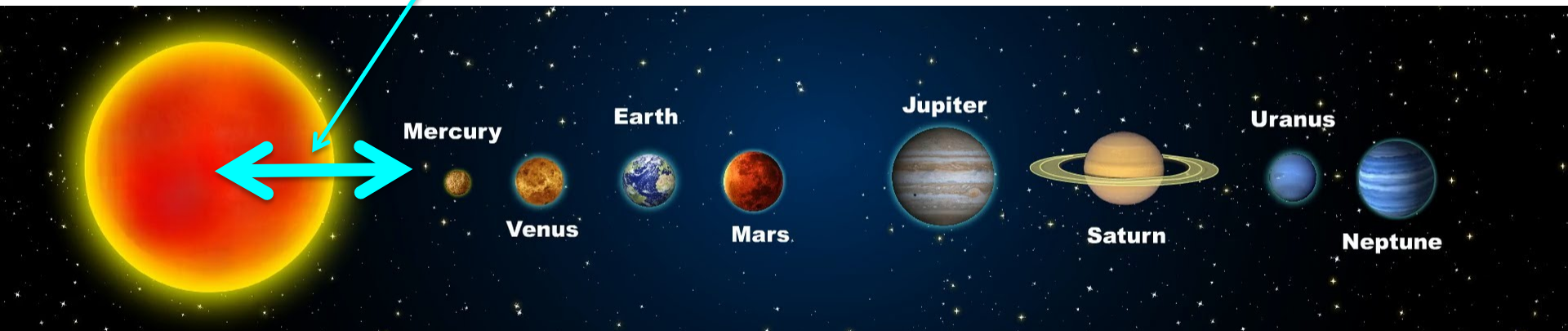
$$t_{GW} \cong \frac{5}{256}\frac{a}{c}\frac{c^2 a}{Gm_1}\frac{c^2 a}{Gm_2}\frac{c^2 a}{GM}\left(1-e^2\right)^{7/2}$$



$R_a = a(1+e)$ $R_p = a(1-e)$

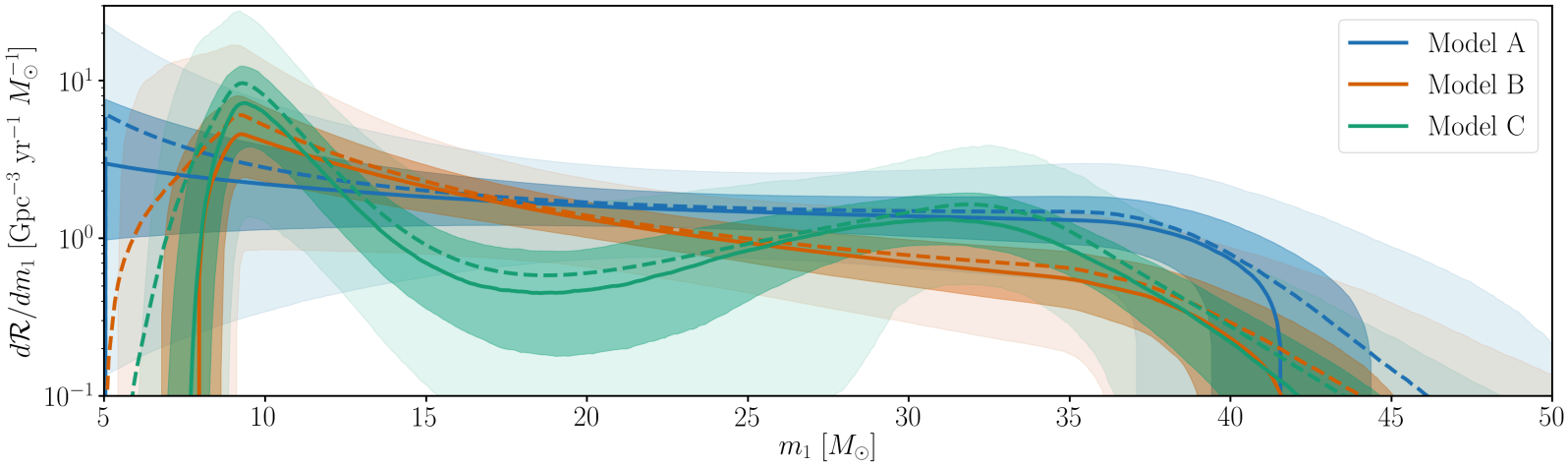
$$\approx 10^{10}\,\mathrm{yr}\left(\frac{a}{3\times10^{12}\,\mathrm{cm}}\right)^4\left(\frac{m_1}{30M_\odot}\right)^{-3}\left(\frac{2/q}{1+q}\right)\left(1-e^2\right)^{7/2}$$

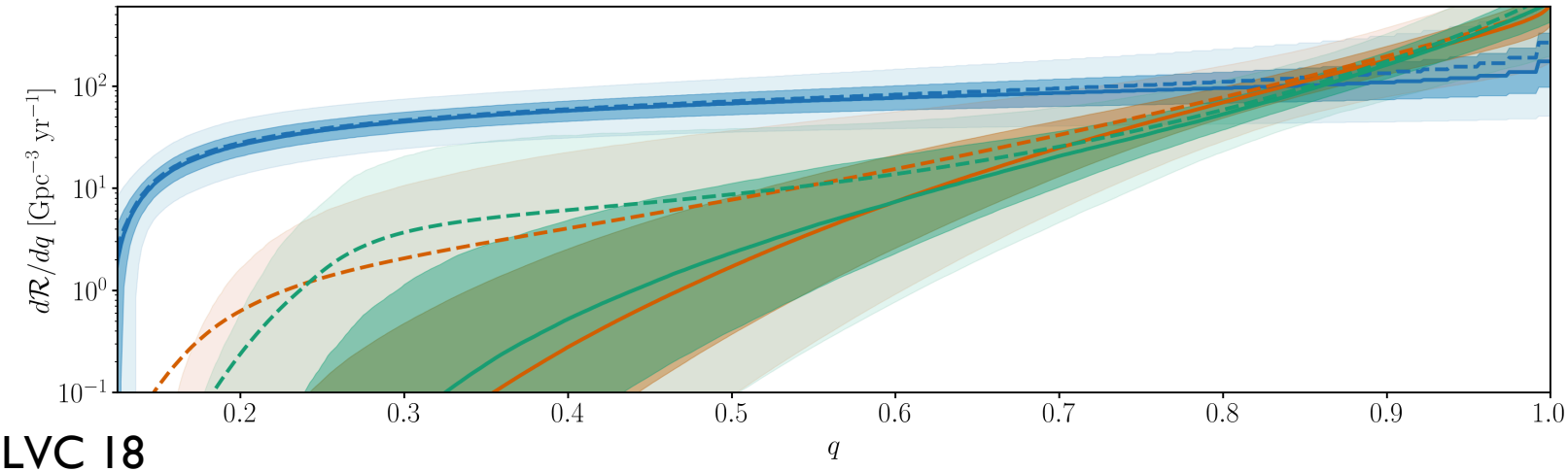
closer than Mercury for $t_{GW}<t_H$!



Mass Function

$$p(m_1) \propto m_1^{-\alpha}, \alpha \sim 1.6^{+1.5}_{-1.7}(90\%), M < 45M_\odot$$



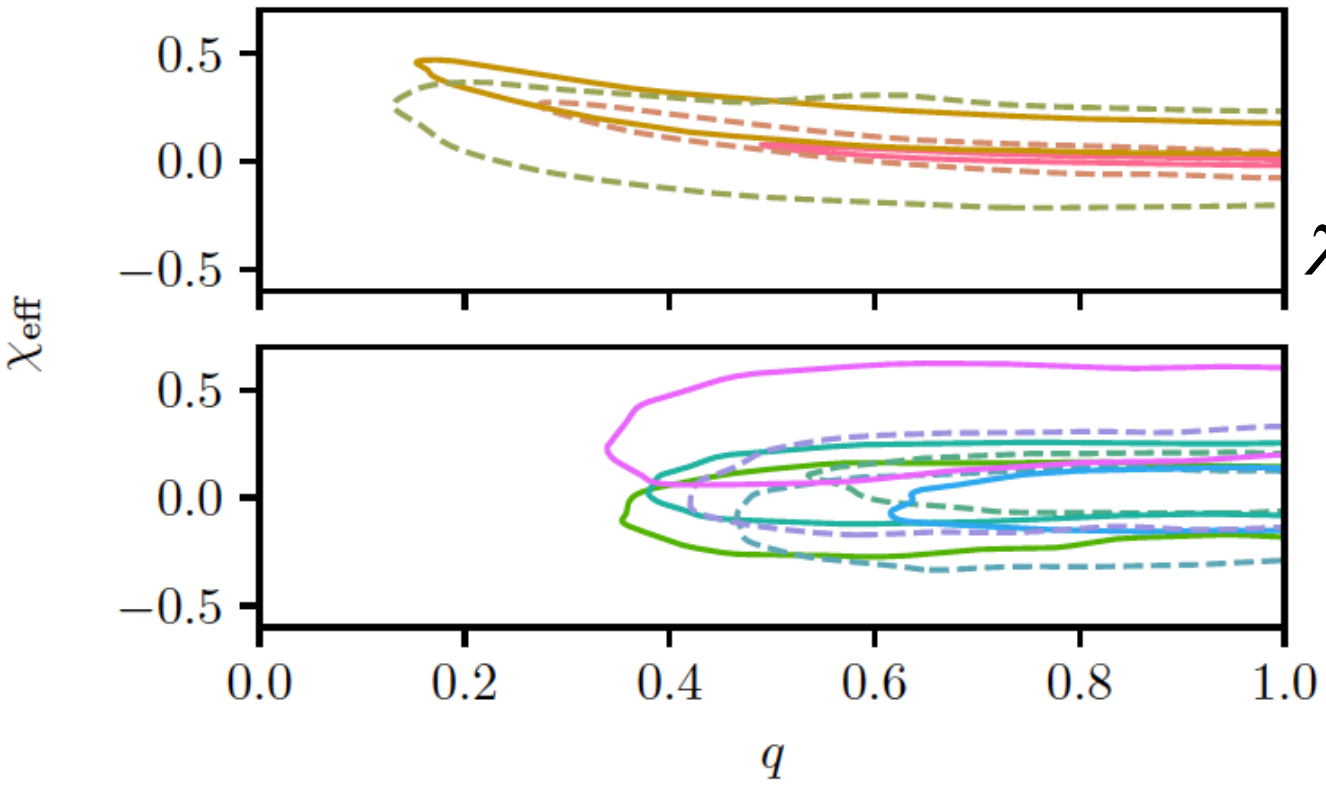


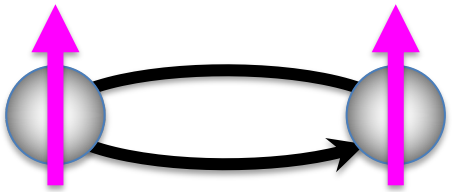
Pair-instability?

MBH→ SMBH?

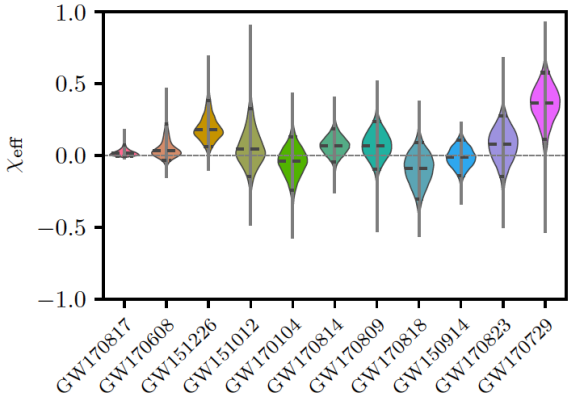
LVC 18

Low Spin?





$$\chi_{\rm eff} \equiv \frac{m_1}{M}\chi_1 + \frac{m_2}{M}\chi_2$$



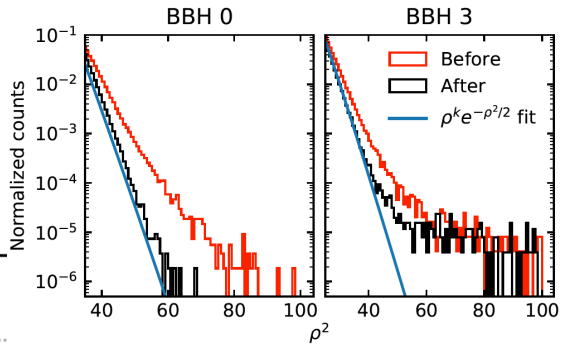
The Sun (P~26 days) ⇒ χ~0.2

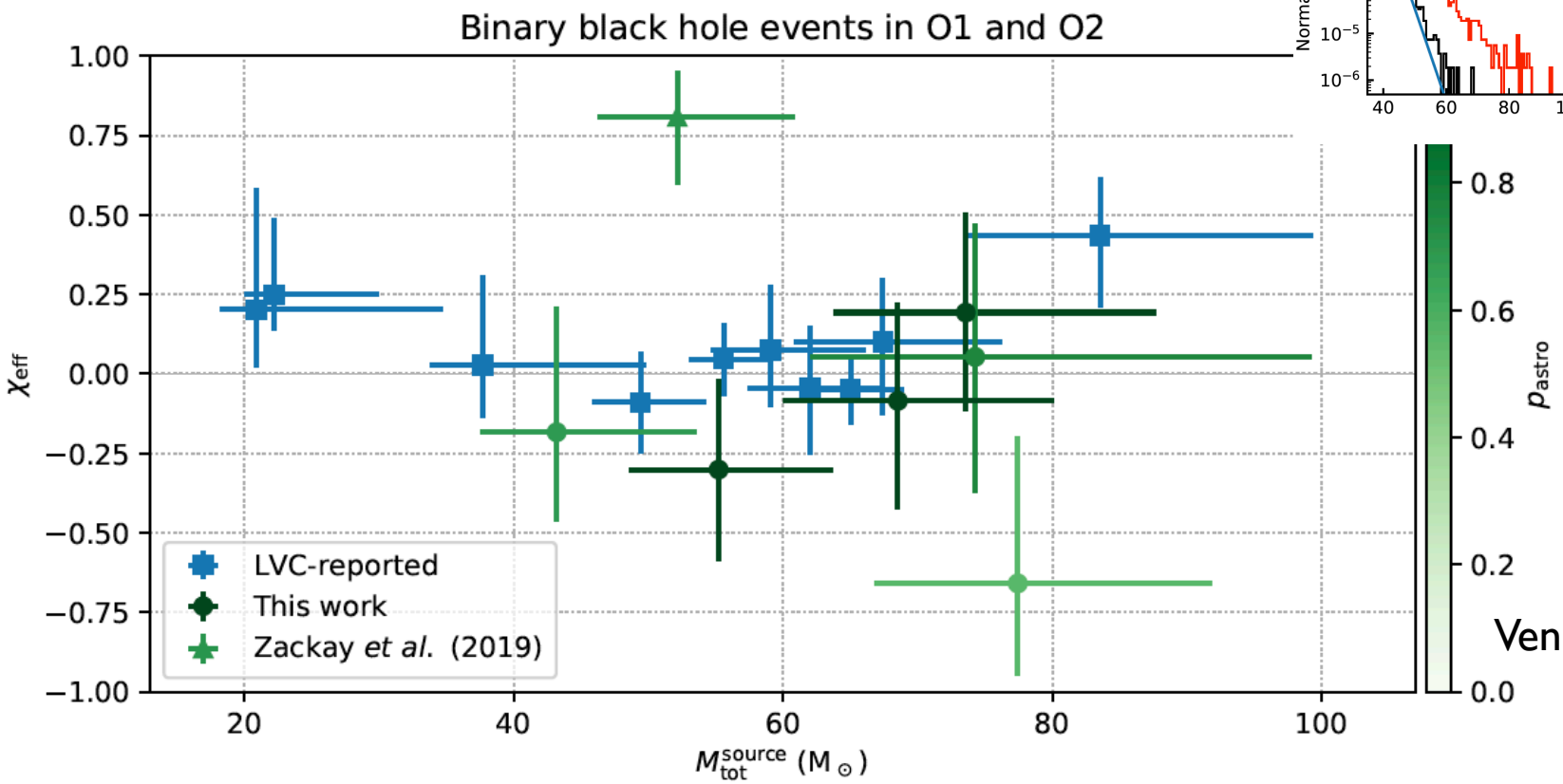
Typical O star (R~10^{12}cm, v~100km/s) ⇒ χ~30

High Spin Events?

Princeton group develops a new GW analysis

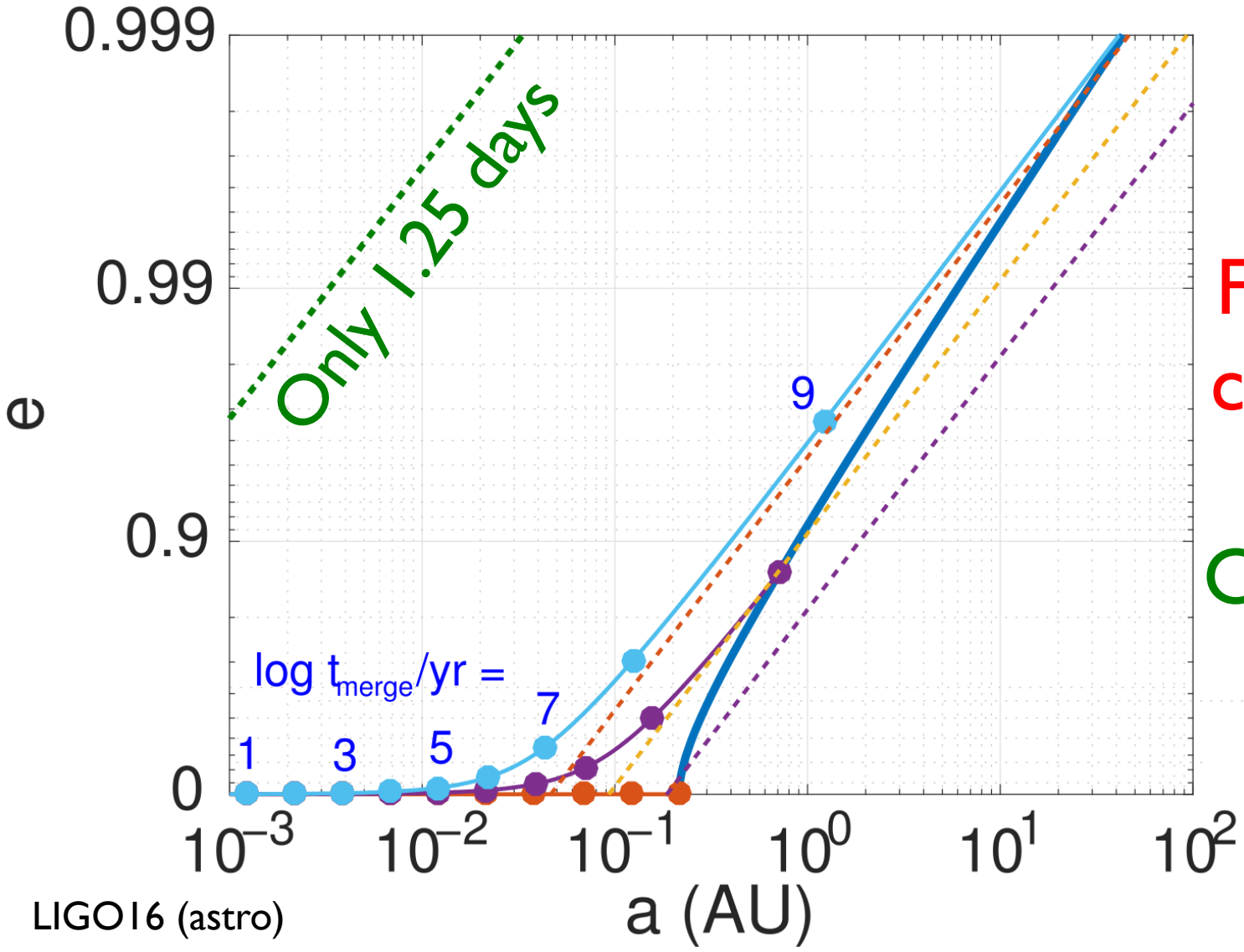
Track the noise on ~10 sec (PSD drift),
New detections of glitches, New vetoes, …





Venumadhav+ 19
Zackay+ 19

Eccentricity



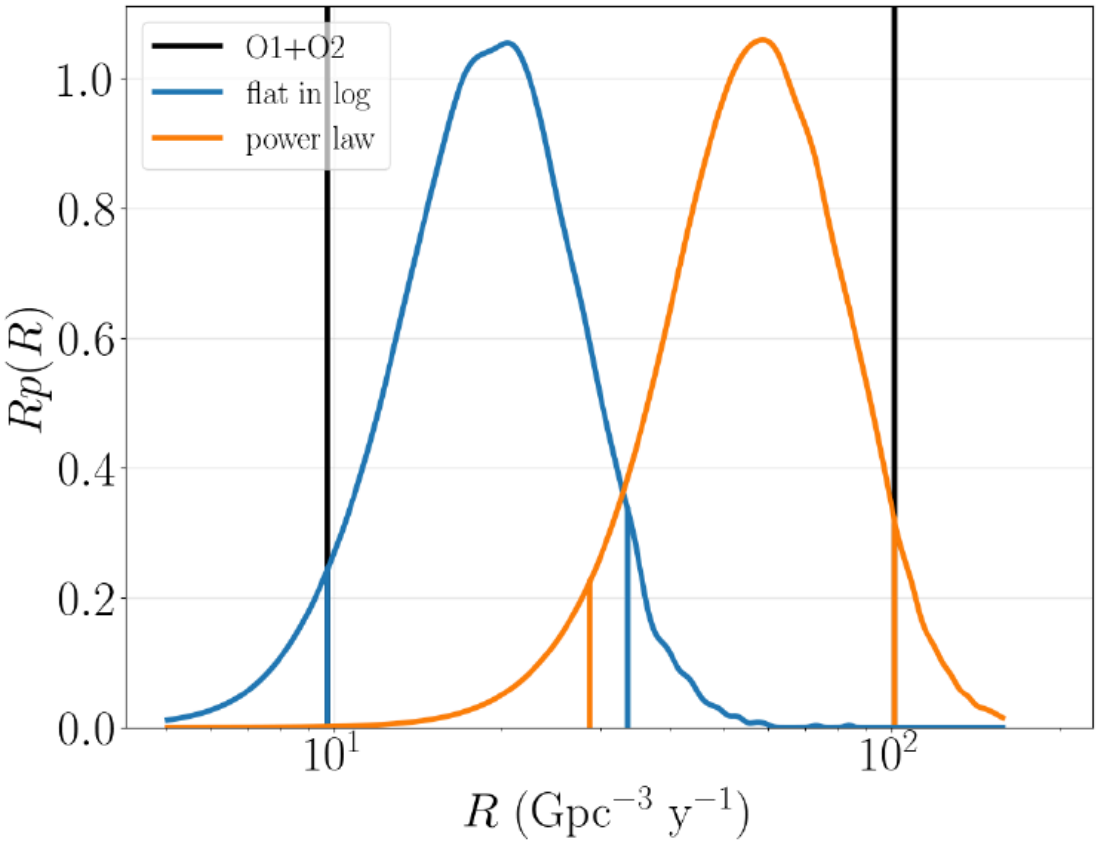
Quickly
$e \to 0$

Field binary
cannot have
$e \neq 0$

Only cluster
and PBH

LIGO16 (astro)

Event Rate



9.7-101 Gpc^{-3} yr^{-1}

~0.1% $R_{supernova}$

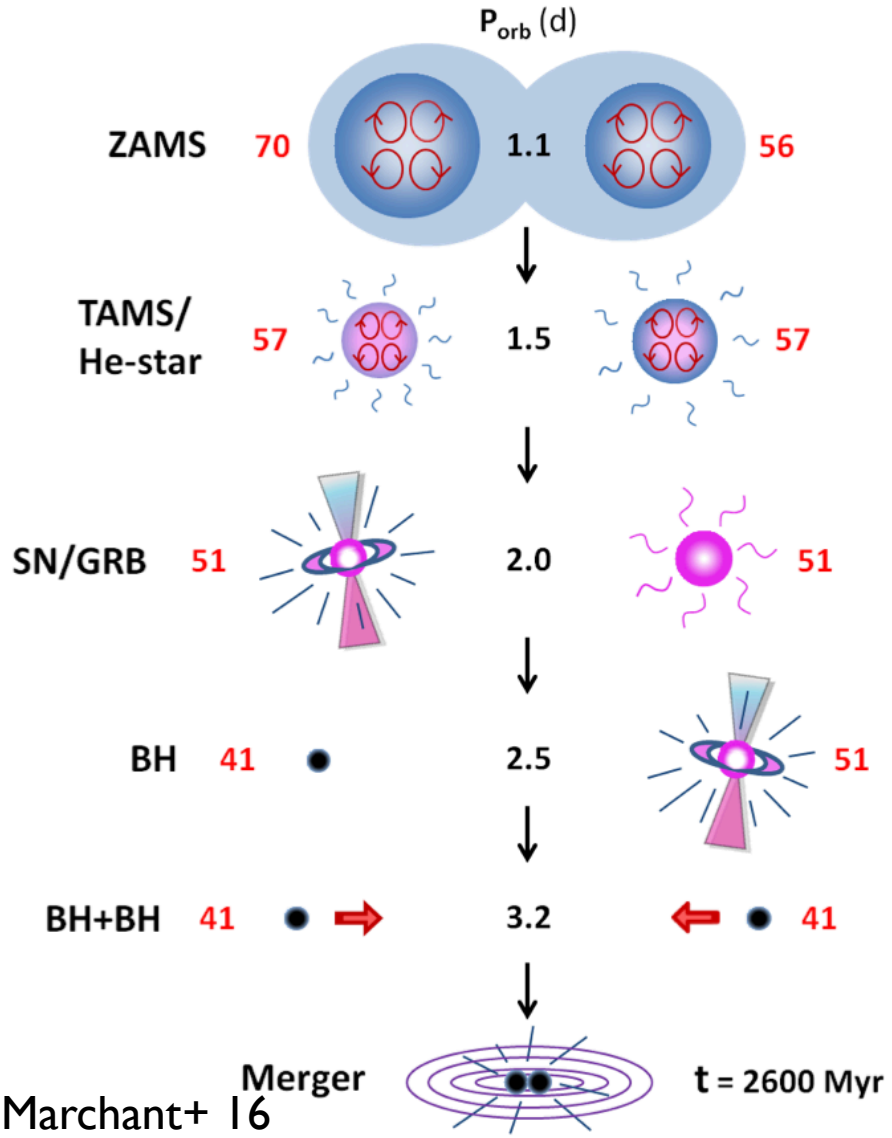
~$R_{superluminous\ SN}$

~$R_{GRB\ (beaming\ corr.)}$

~0.1 $R_{NS\text{-}NS}$

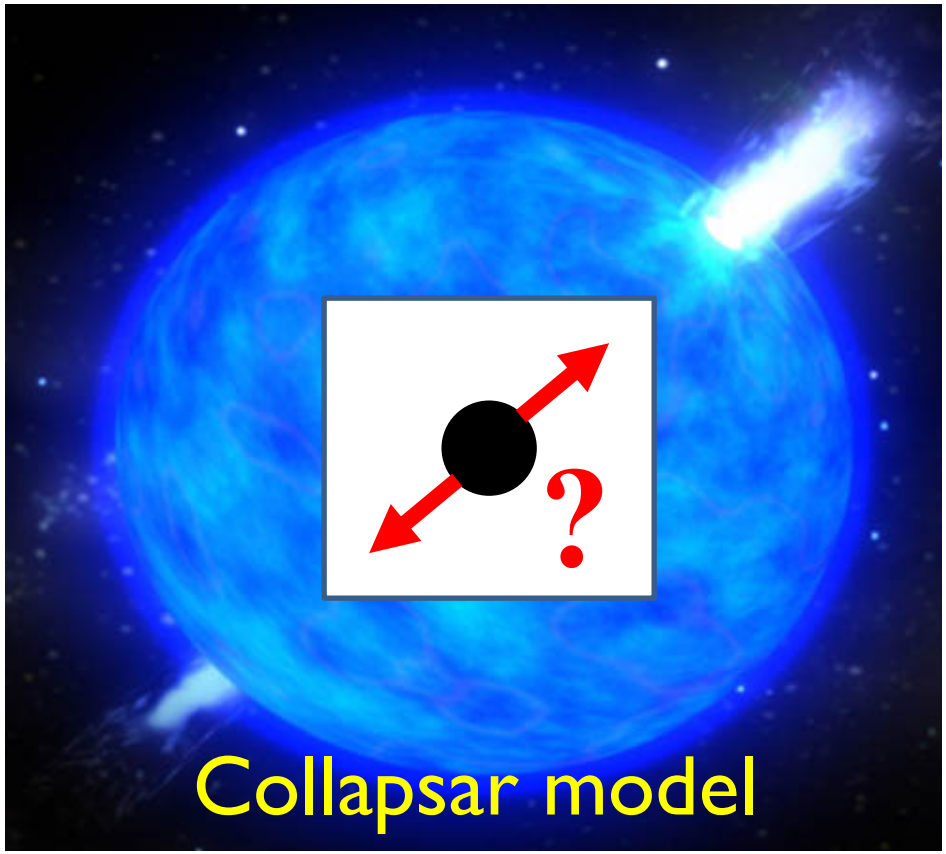
~3/hr/Universe

Gamma-Ray Bursts?



Marchant+ 16

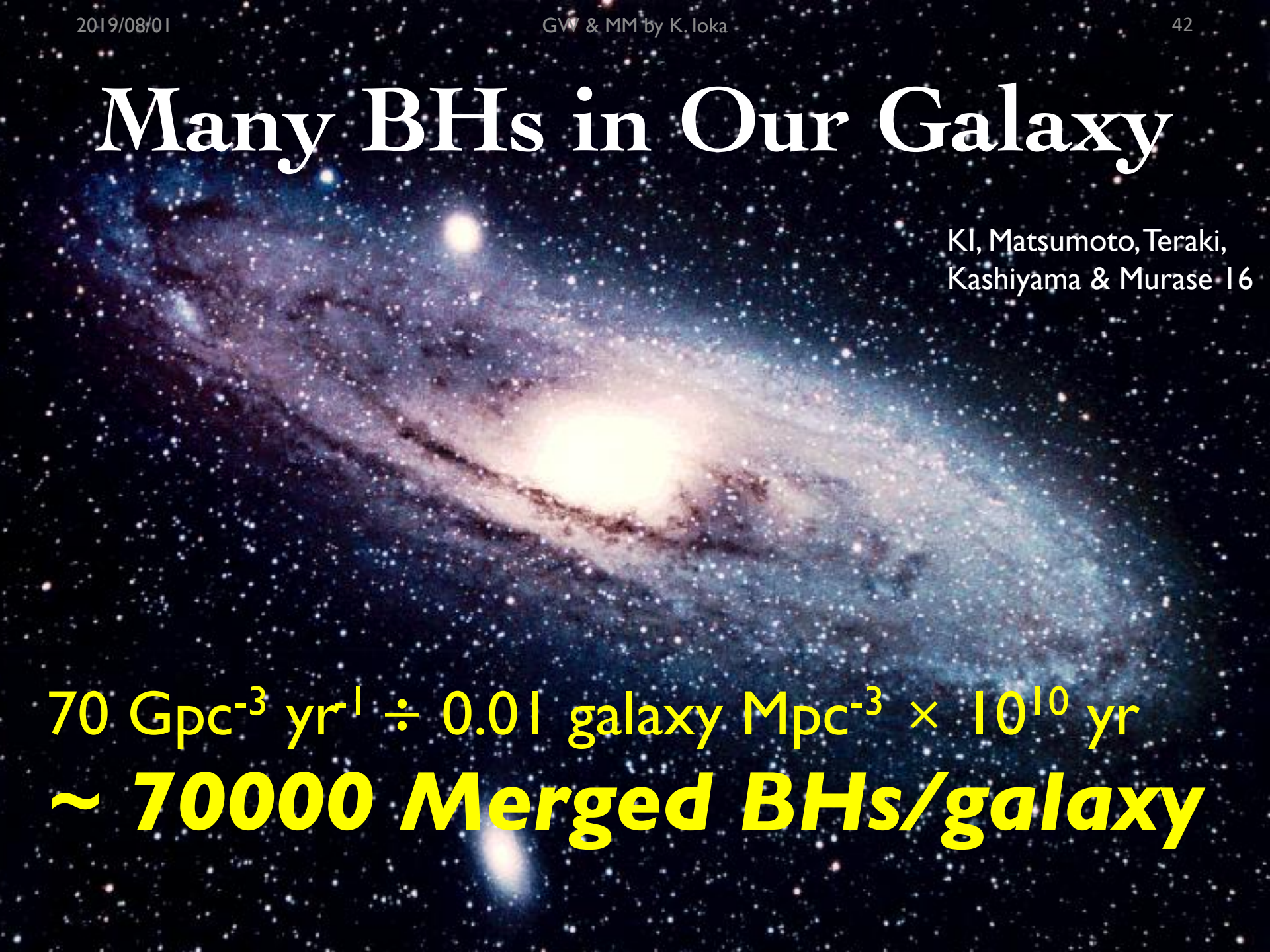
~ BH formation



GW rate ~ GRB rate

Many BHs in Our Galaxy

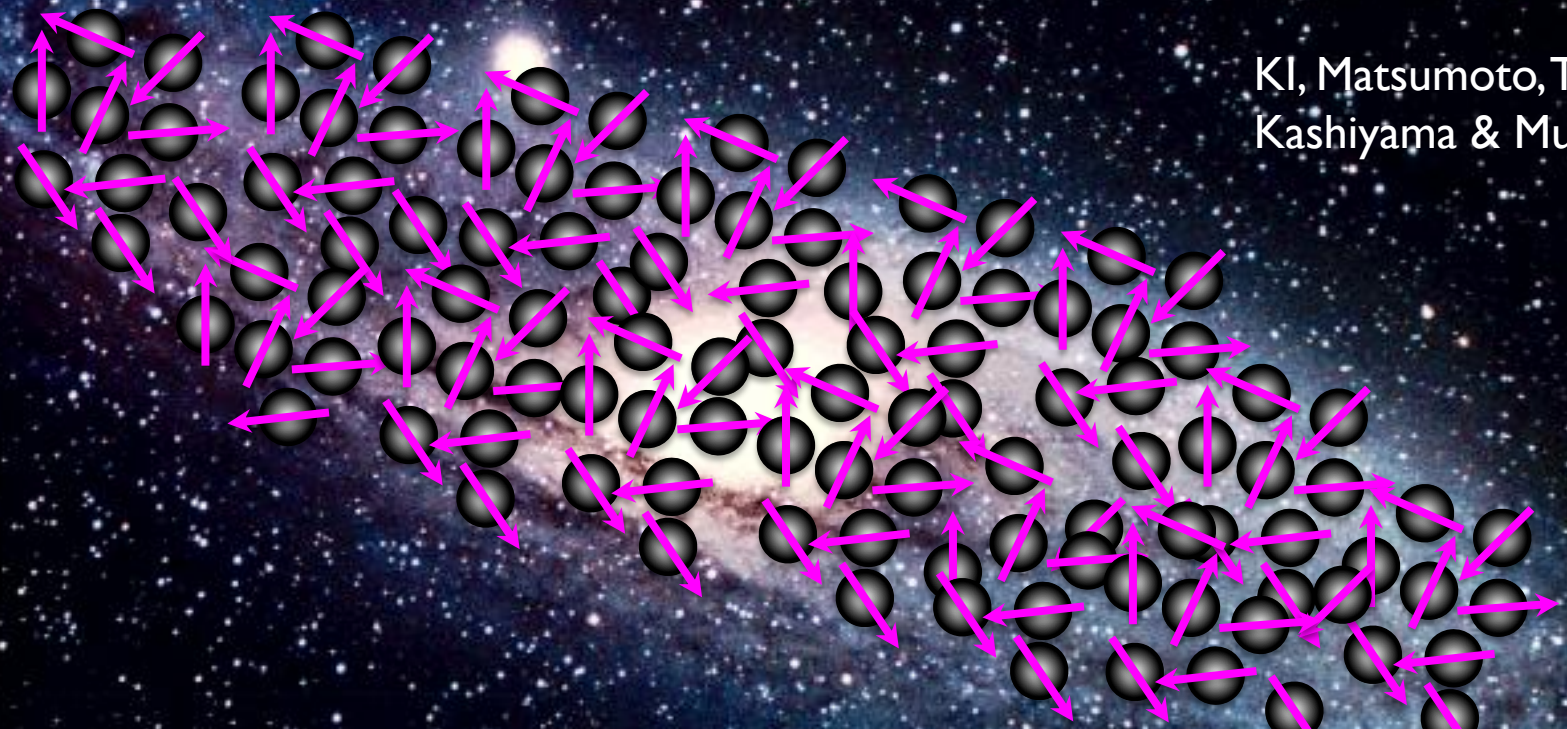
KI, Matsumoto, Teraki, Kashiyama & Murase 16



$70\ \mathrm{Gpc^{-3}\ yr^{1}} \div 0.01\ \mathrm{galaxy\ Mpc^{-3}} \times 10^{10}\ \mathrm{yr}$

$\sim$ 70000 Merged BHs/galaxy

Many BHs in Our Galaxy



KI, Matsumoto, Teraki, Kashiyama & Murase 16

$70\ \mathrm{Gpc^{-3}\ yr^{1}} \div 0.01\ \mathrm{galaxy\ Mpc^{-3}} \times 10^{10}\ \mathrm{yr}$

~ 70000 Merged BHs/galaxy

E_{spin}~10^{8} Supernovae

Spin Energy

$$E_{\rm spin} = \left(1 - \sqrt{\frac{1+\sqrt{1-a_*^2}}{2}}\right) Mc^2$$

$$\cong 7\% \times Mc^2 \sim 1\times 10^{54}\,{\rm erg}\left(\frac{M}{10M_\odot}\right)$$

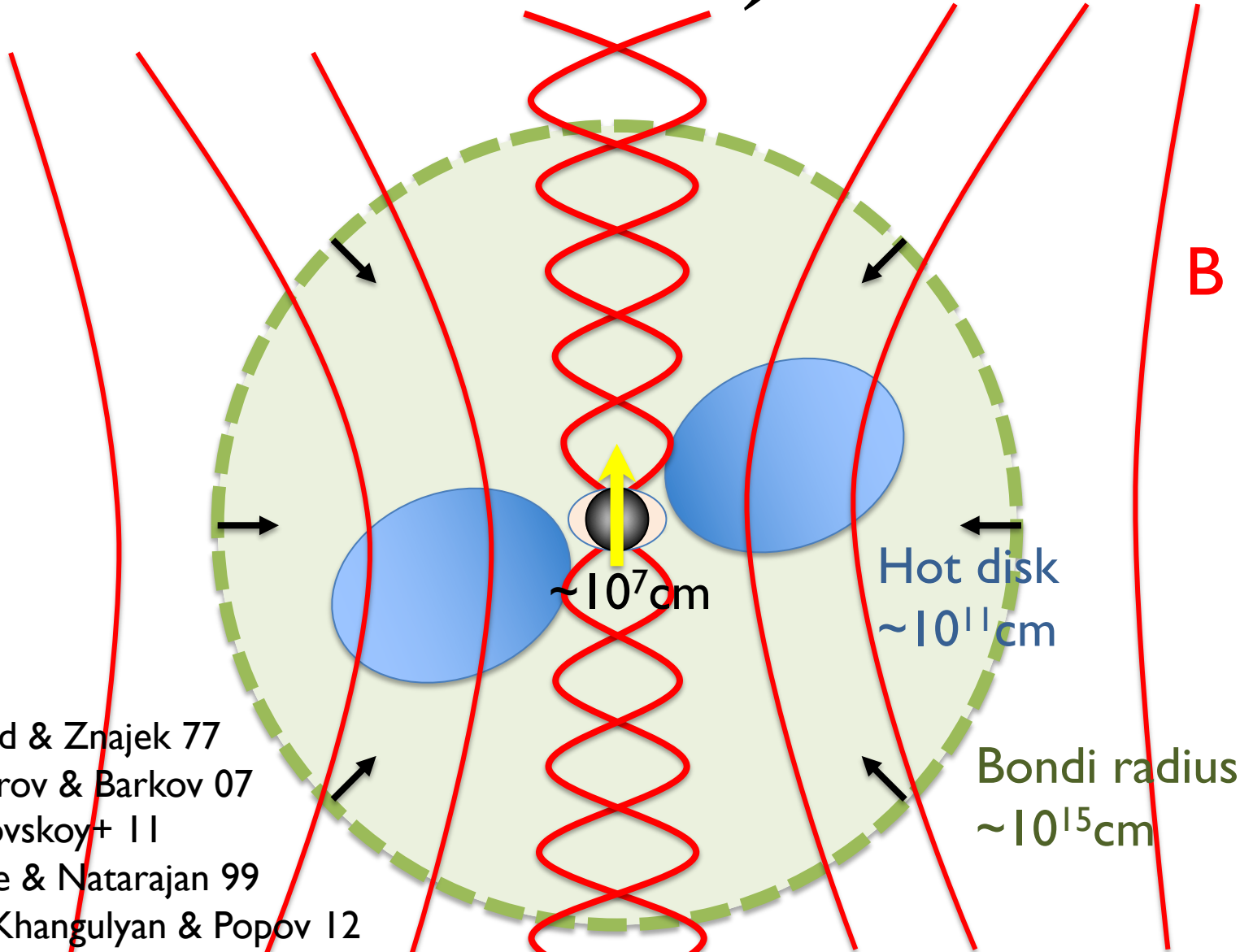
$$E_{\rm tot} \sim N_{BH} E_{\rm spin} \sim 7\times 10^4\ {\rm BHs} \times 1\times 10^{54}\,{\rm erg}$$

$$\sim 9\times 10^{58}\,{\rm erg}$$

$$\sim \frac{10^{10}\,{\rm yr}}{100\,{\rm yr}}\ {\rm supernovae}$$

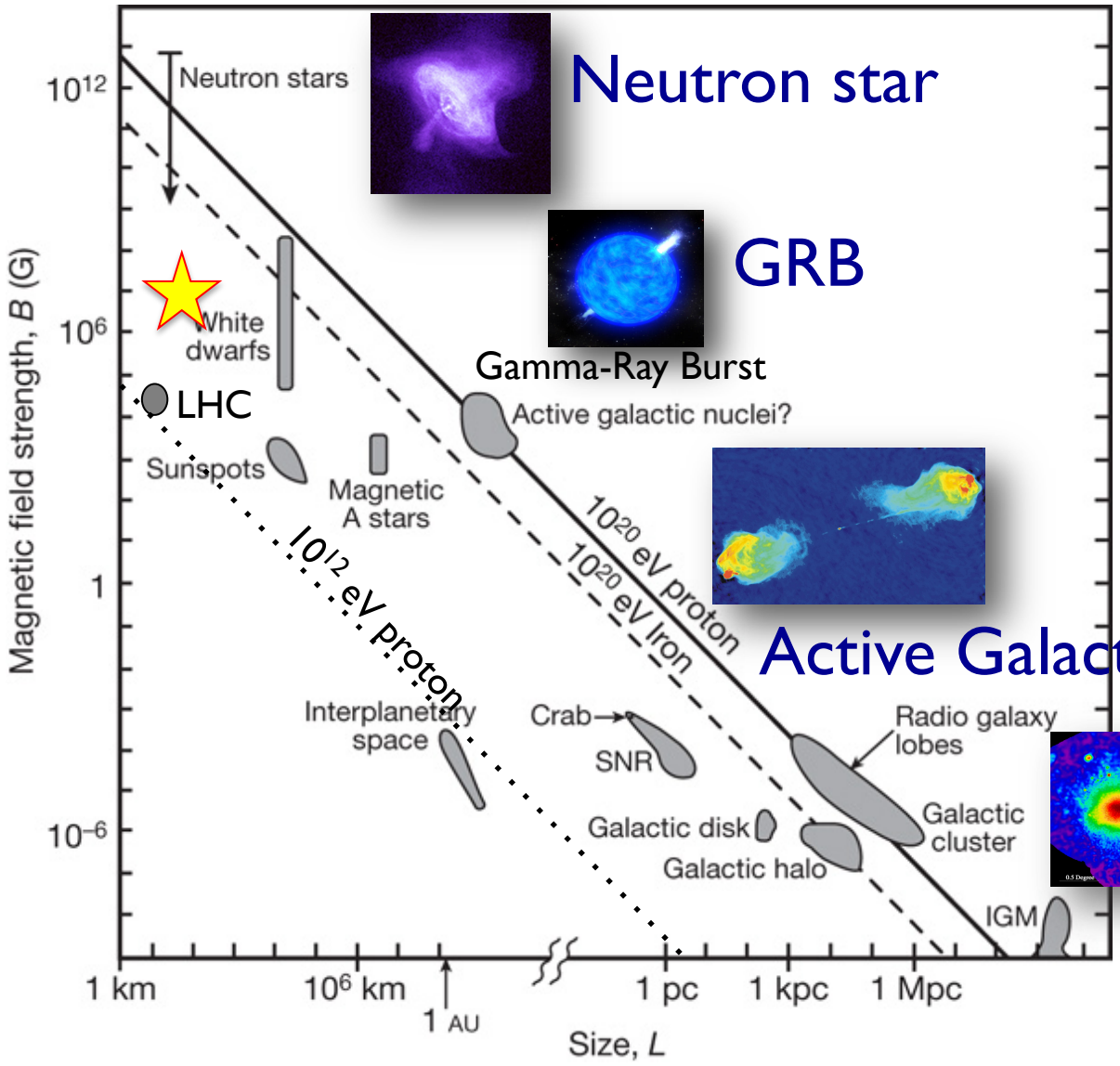
Comparable to supernovae ever happened!

Blandford-Znajek Effect



Blandford & Znajek 77
Komissarov & Barkov 07
Tchekhovskoy+ 11
Armitage & Natarajan 99
Barkov, Khangulyan & Popov 12

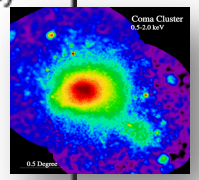
Particle Acceleration



Neutron star

GRB

Active Galactic Nuclei



Galaxy Cluster

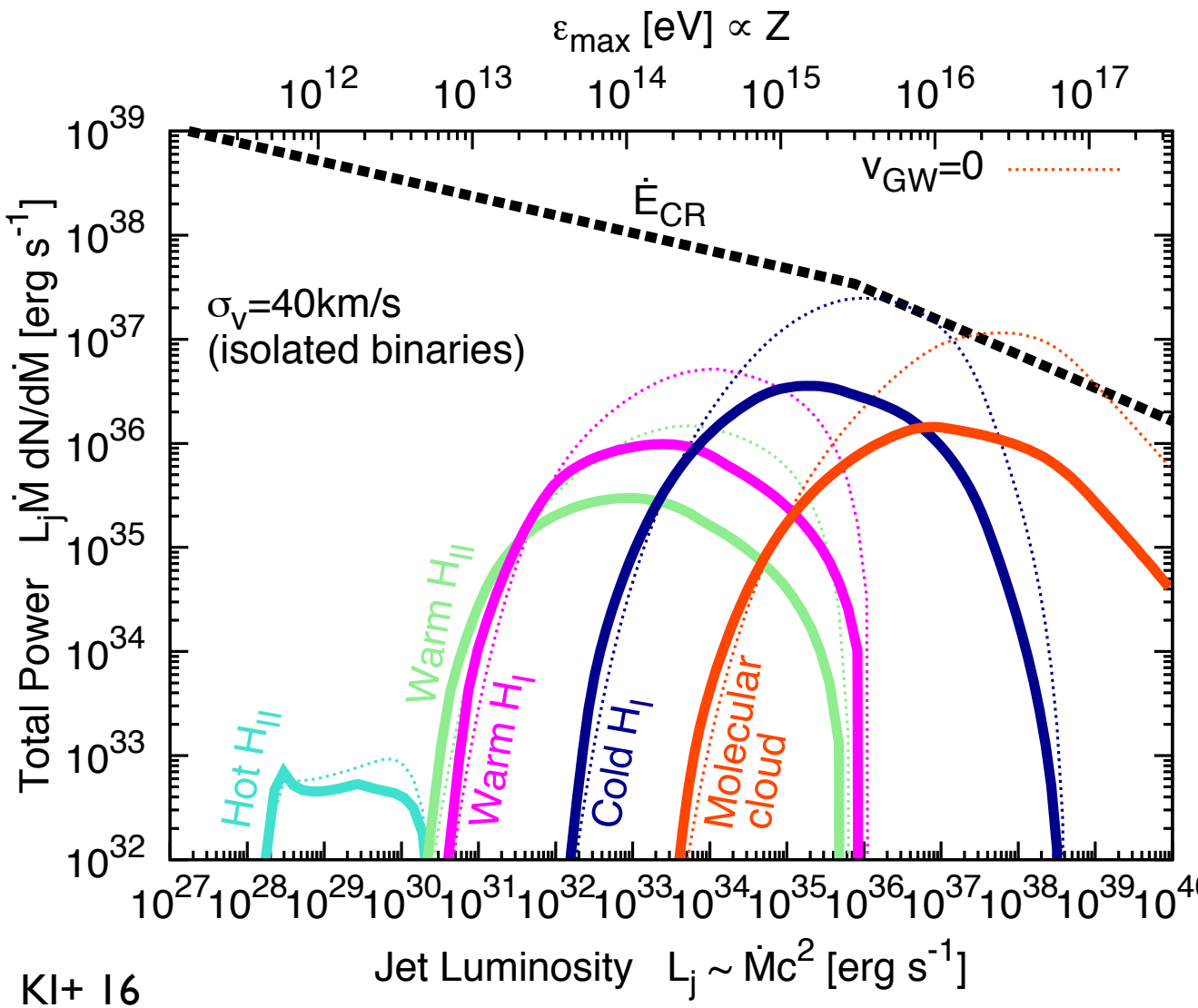
- Hillas condition
  E<ZqBR
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
  $\propto (BR)^2$ Blandford 00
  Waxman 04
- E_{max}>PeV

PeVatron!!!

Barkov+ 12
KI+ 16

Dark Matter?

Total Power



KI+ 16

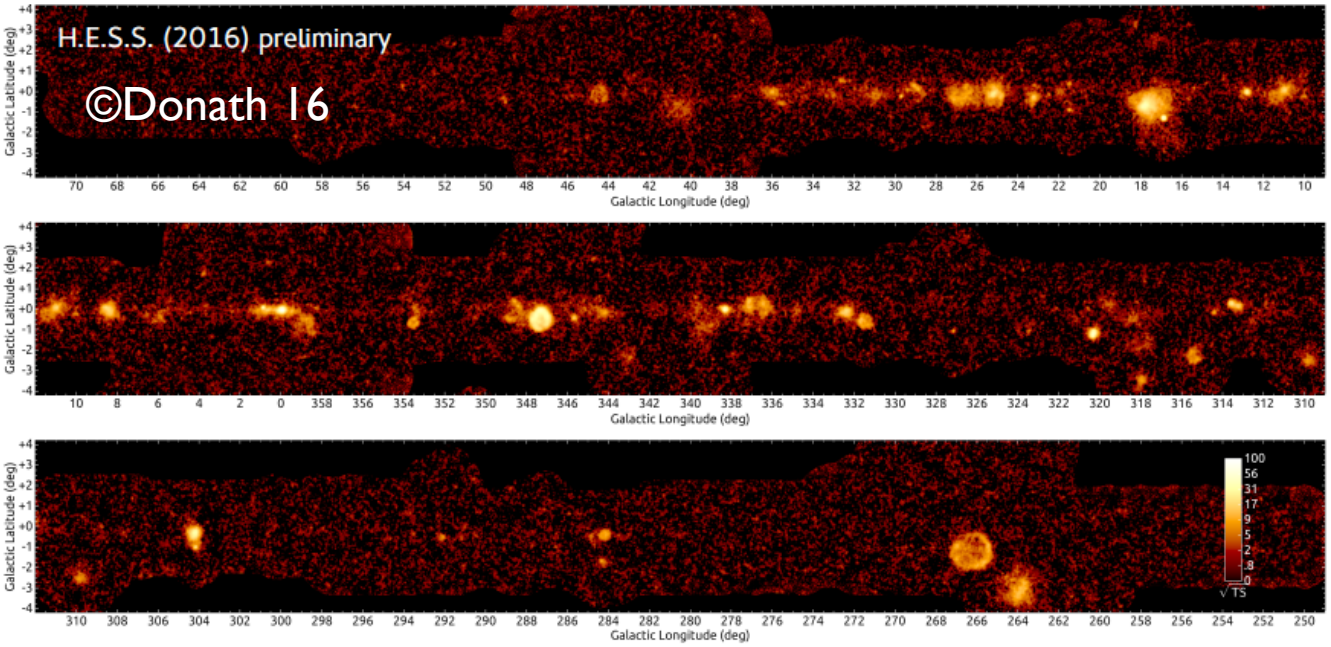
BHs ⇔ Cosmic rays beyond PeV?

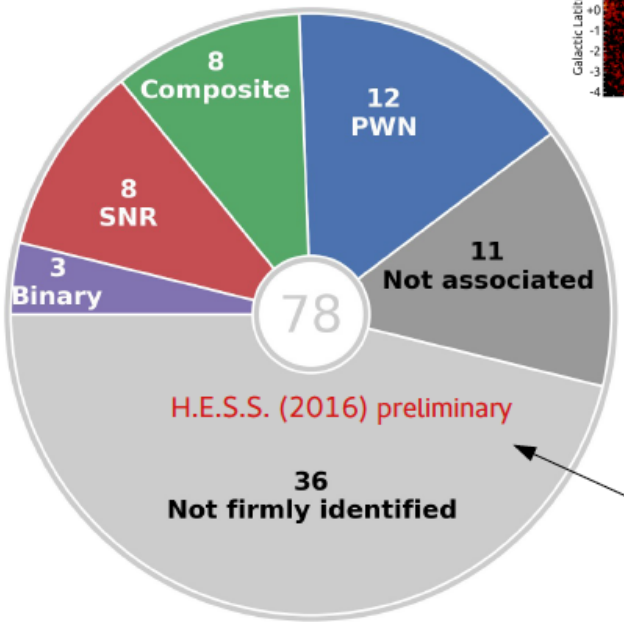
$$\frac{\varepsilon_{\rm CR} E_{\rm SN}}{100\,{\rm yr}} \sim 3\times10^{40}\ {\rm erg\ s^{-1}}$$

If leptonic ⇔ $e^{\pm}$ excess?

High Energy Sources?

TeV-PeV γ-ray & cosmic-ray sources in our Galaxy





Sources with multiple associations

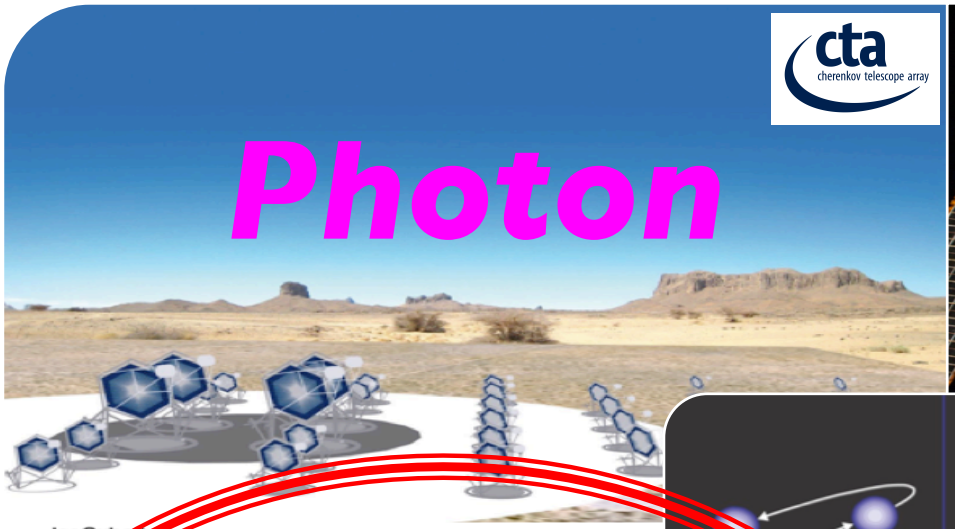
Most are unidentified

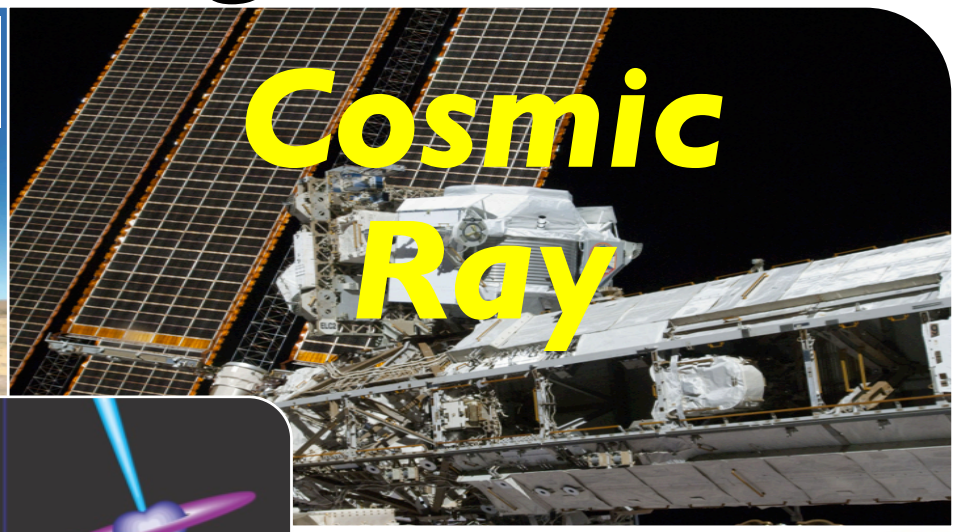
Some are dark accelerators

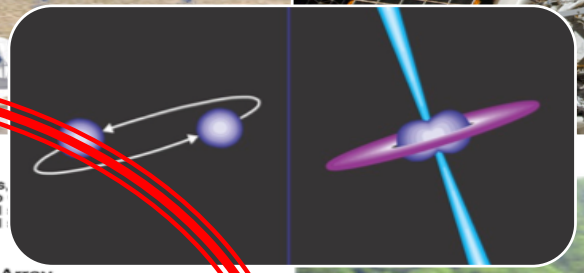
⇔ Accreting BHs?

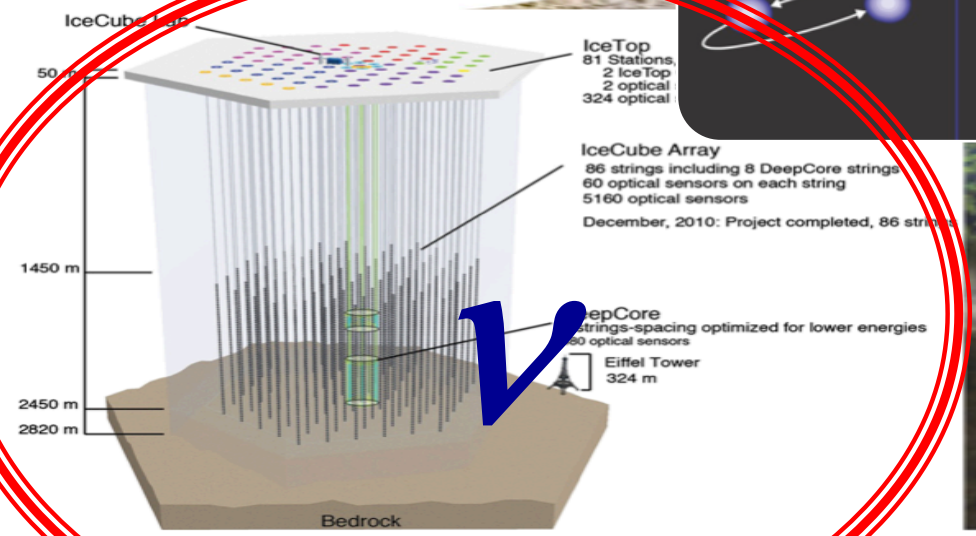
KI, Matsumoto, Teraki, Kashiyama & Murase 16

Multi-Messenger Era



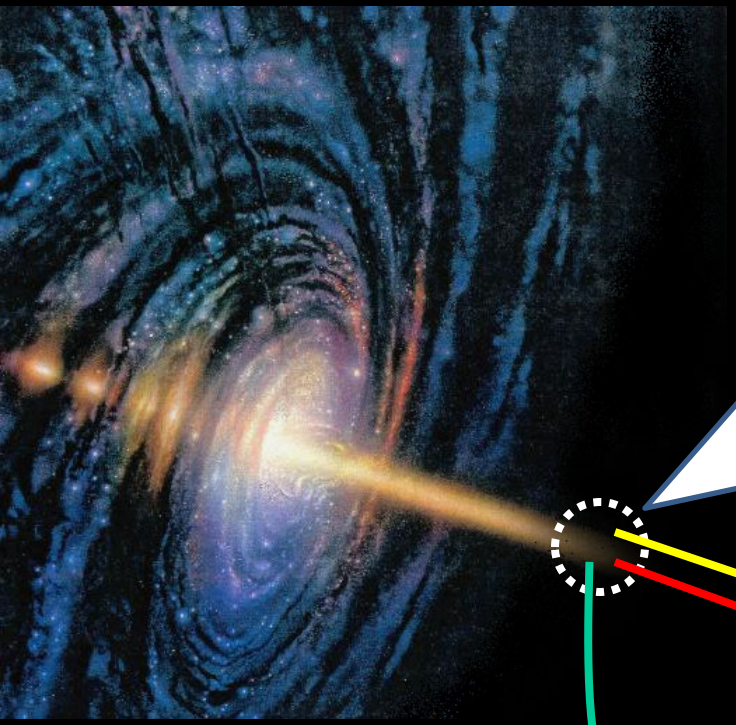


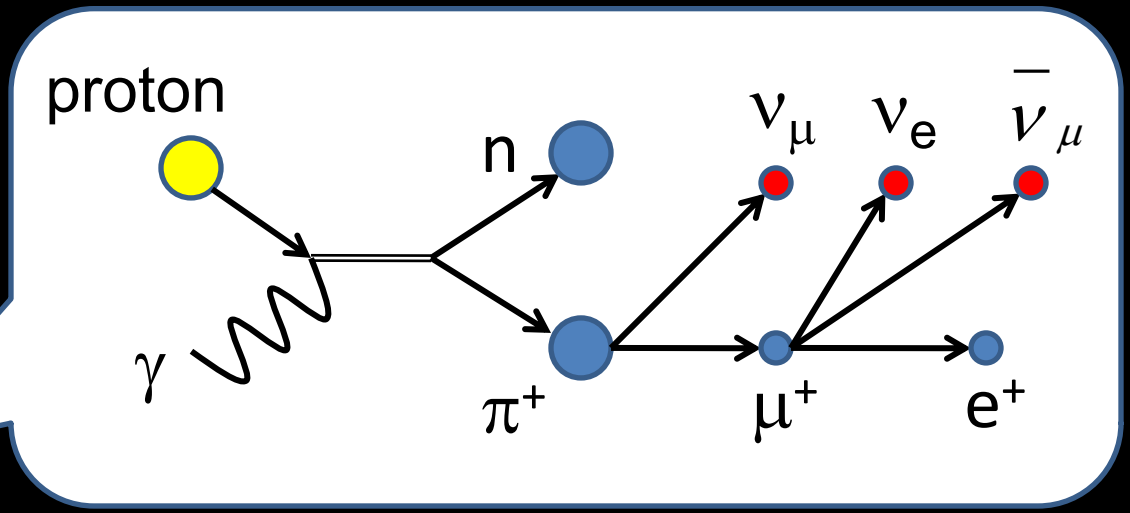




21th Century: Multi-Messenger Era

Cosmic ν





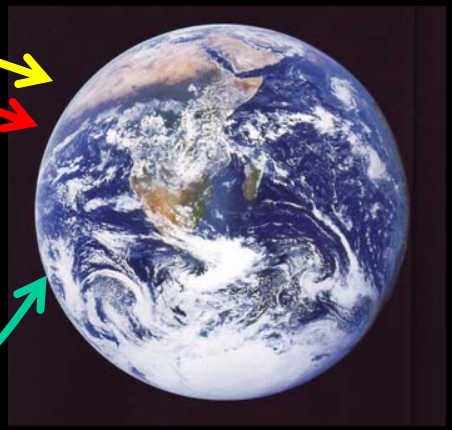
ν

γ

Strong penetration
Not delayed

CR origin
ν interaction@>TeV
τ appearance
Limiting ν speed
Equivalence principle

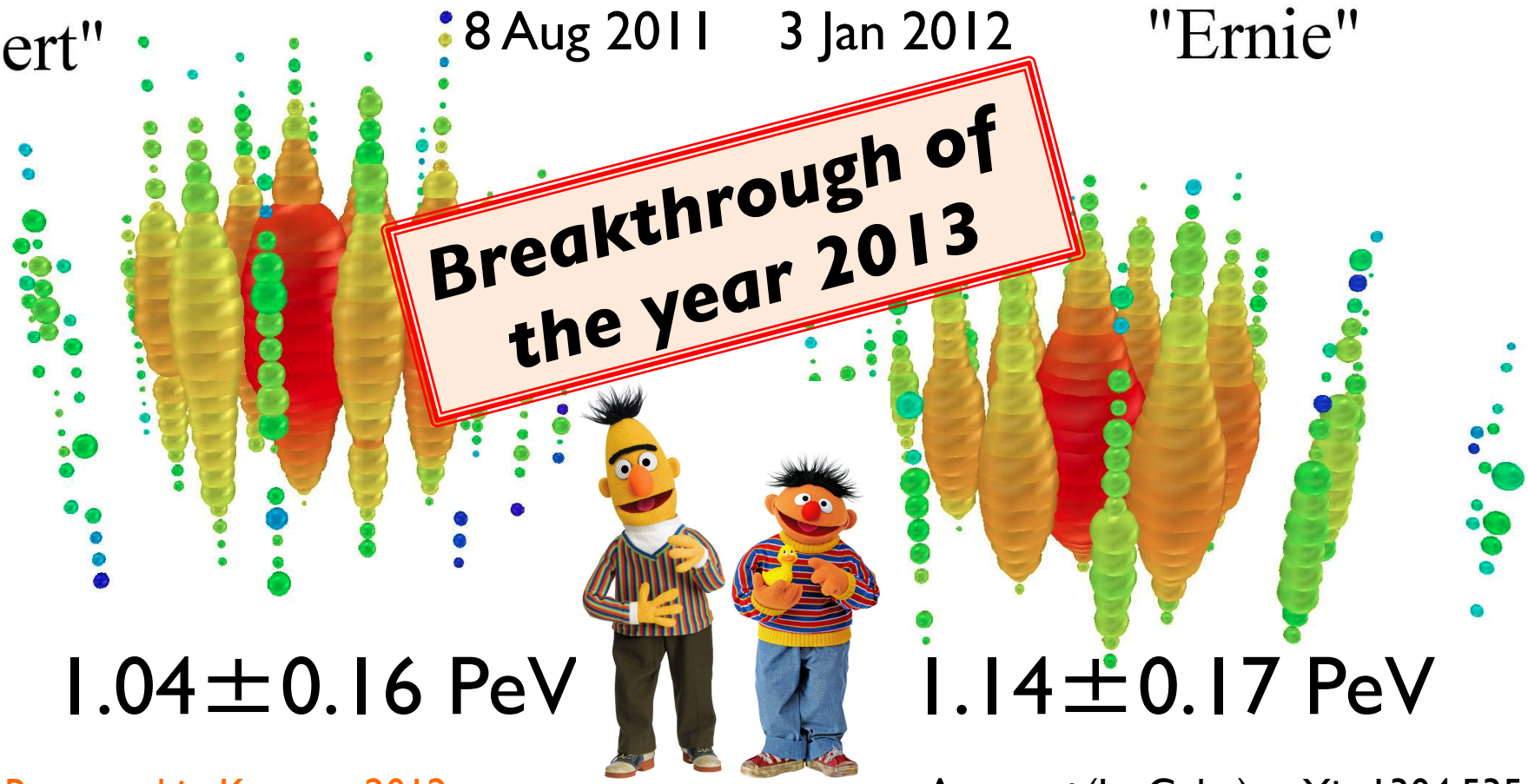
p



First 2 PeV νs

PeV=10^{15}eV

"Bert" 8 Aug 2011 3 Jan 2012 "Ernie"



Breakthrough of the year 2013

1.04±0.16 PeV 1.14±0.17 PeV

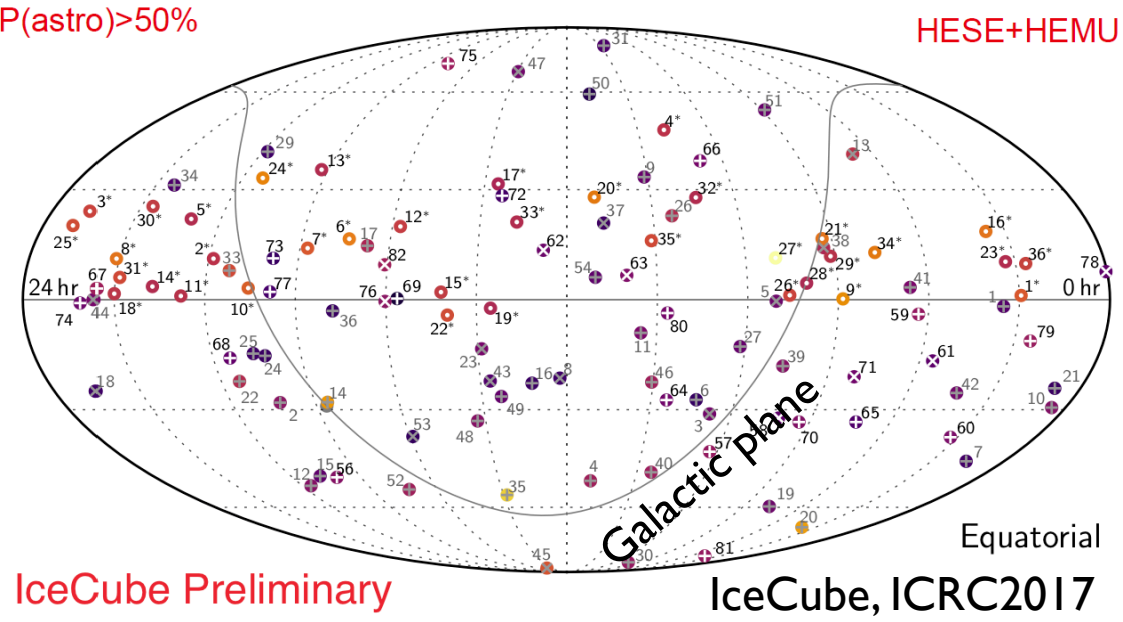
Reported in Kyoto ν 2012

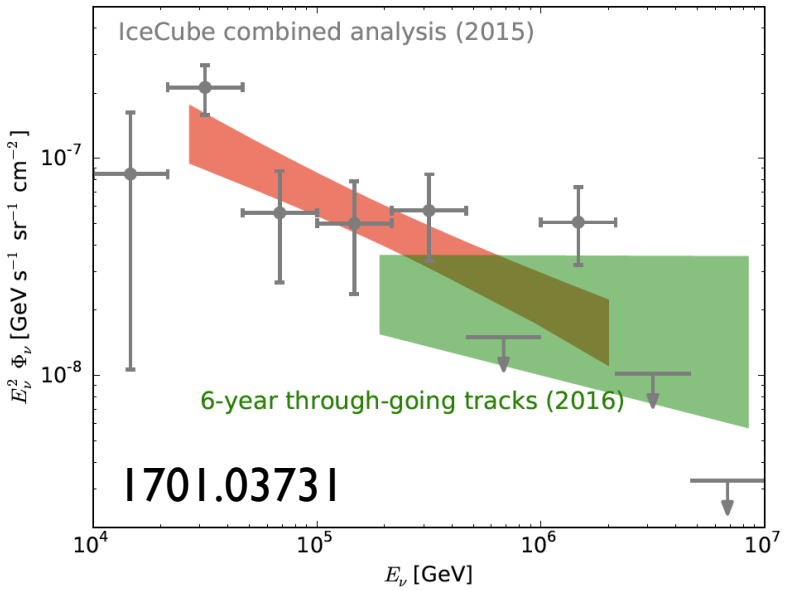
Aartsen+(IceCube), arXiv:1304.5356

Dawn of High-Energy ν Astronomy!!!

More Events

More than >100 events by IceCube
Origin still unknown

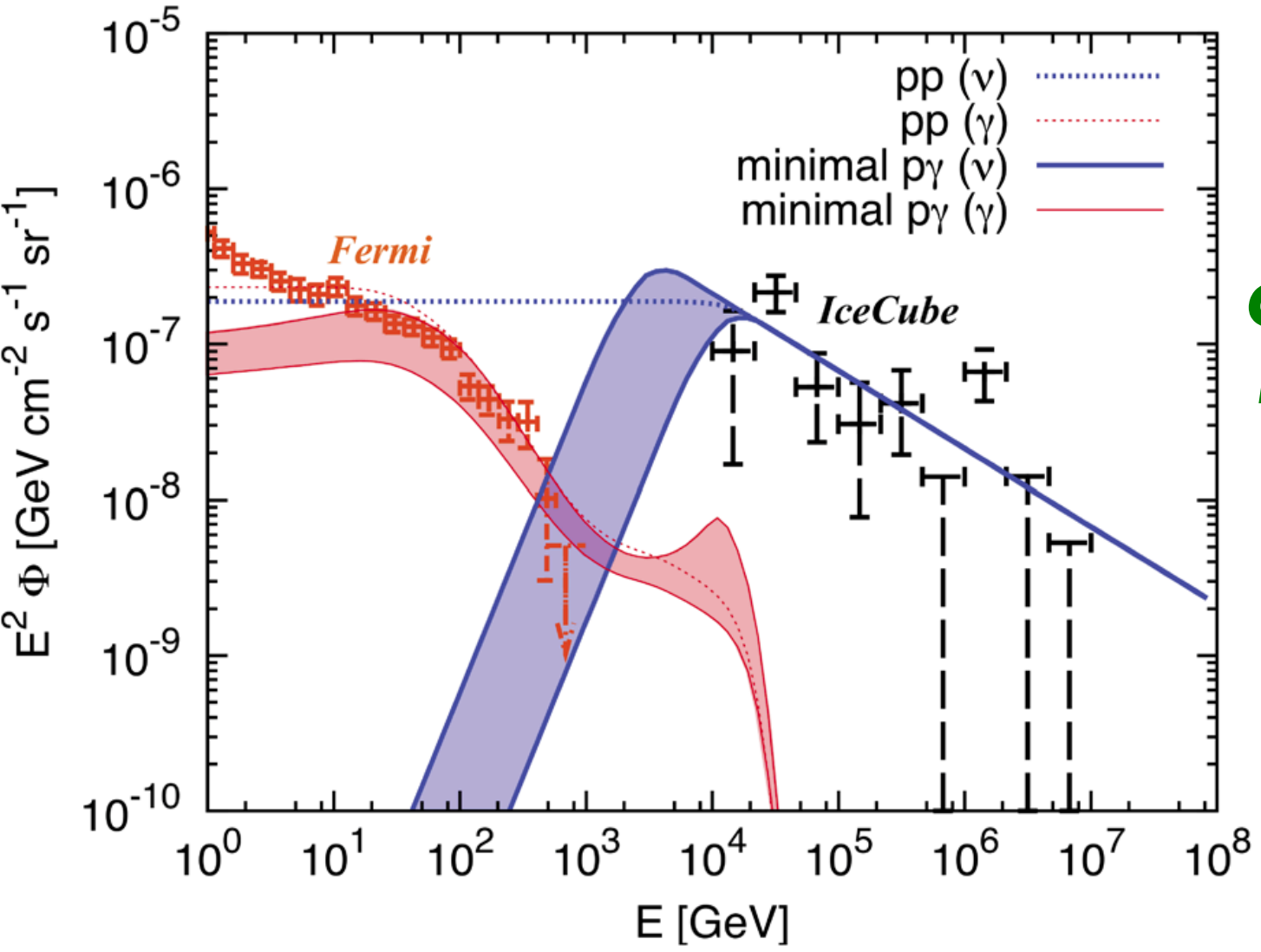




No significant clustering ⇒ ***Extragalactic***

Spectral break @~100TeV or Inconsistency?

Tension with CγB?



$\pi^0 \rightarrow \gamma\gamma$

PeV → TeV

Cosmic γ-ray Background

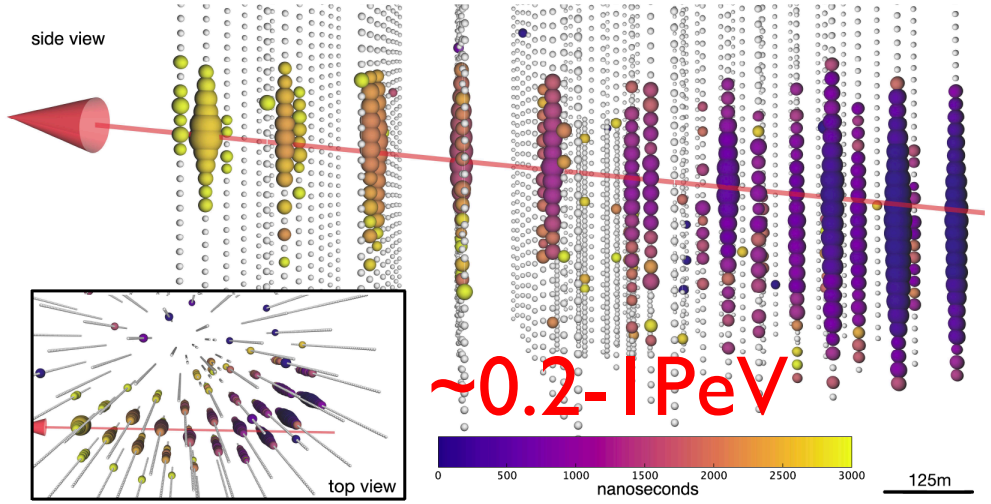
(from blazars, not ν-source)

Hidden ν-sources?

Murase+ 13

Murase+ 16

IceCube-170922A

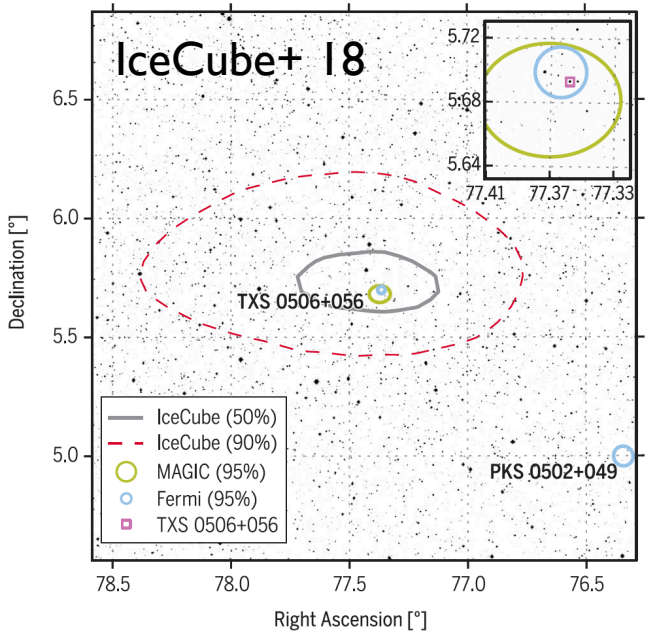


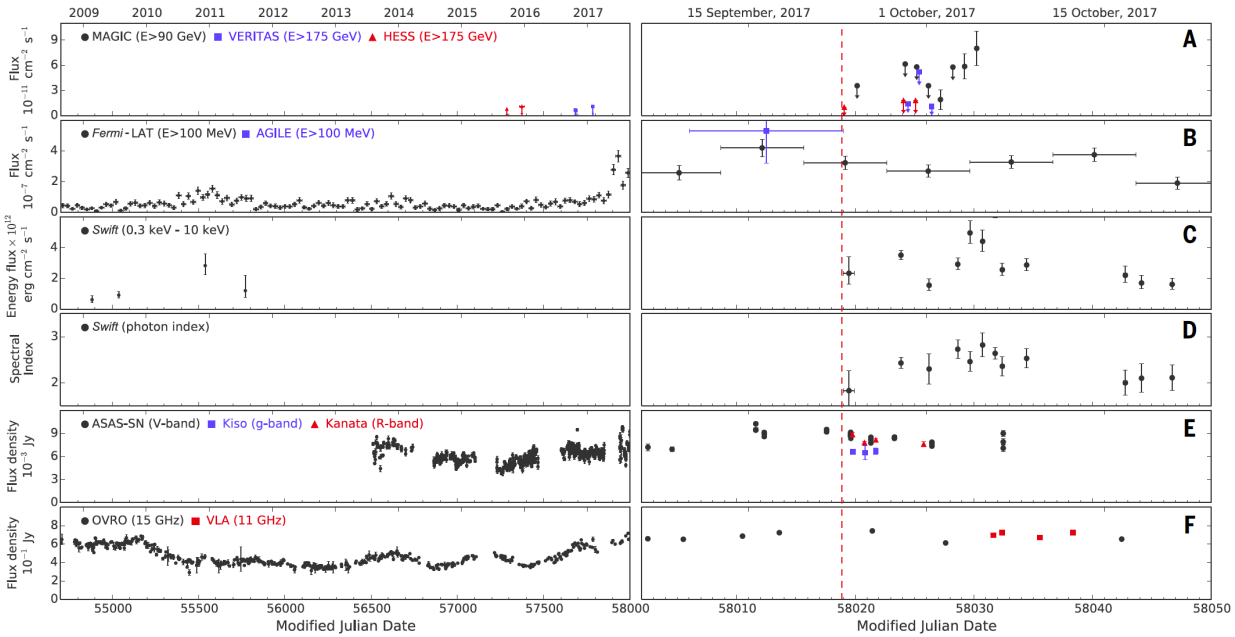
Multimessenger source

Blazar TXS 0506+056

~3σ coincidence

But the others are ν-dim



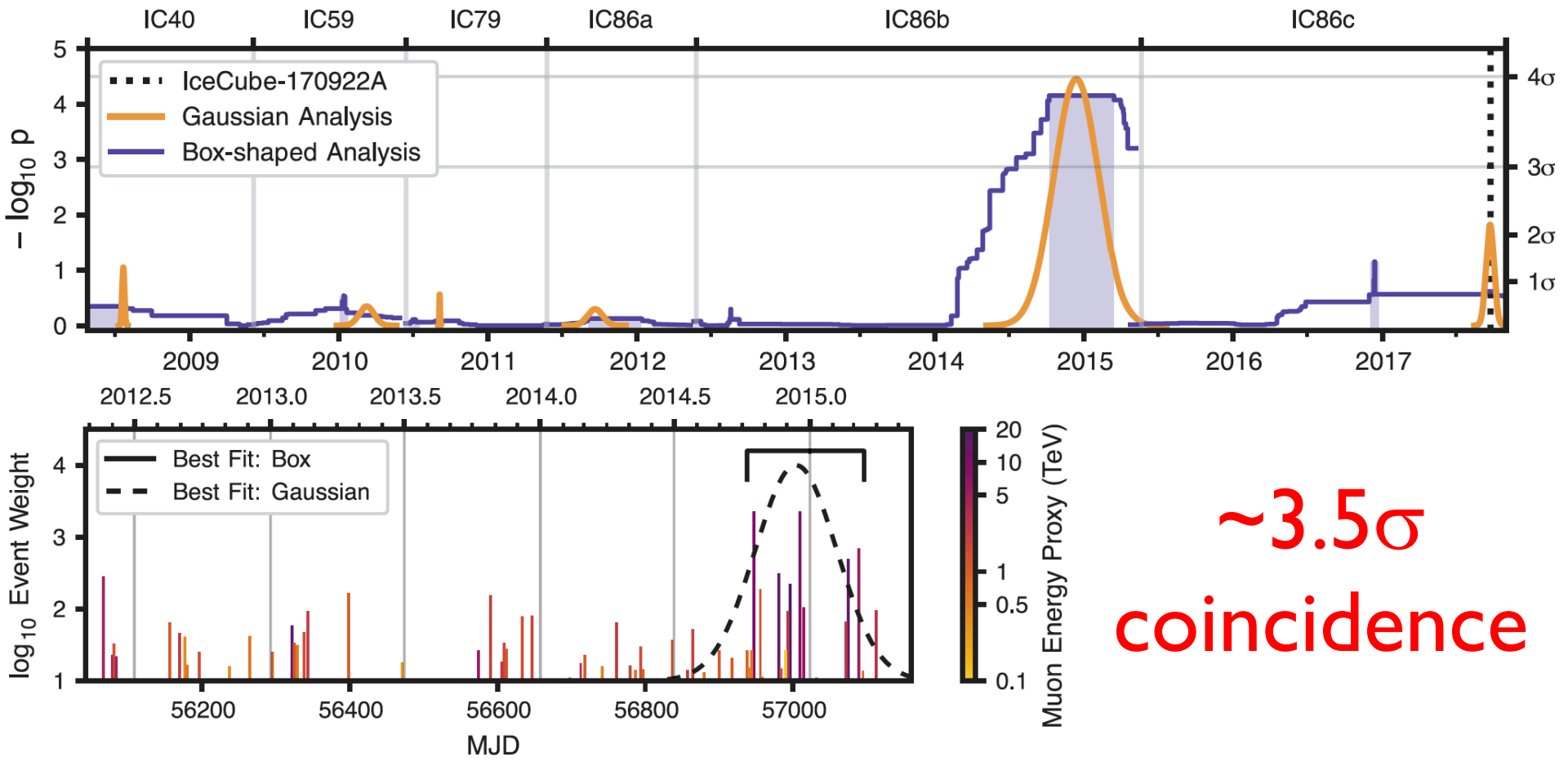


Before IceCube-170922A

13±5 ν_μ during 158 days (BG: 5.8 ν_μ)

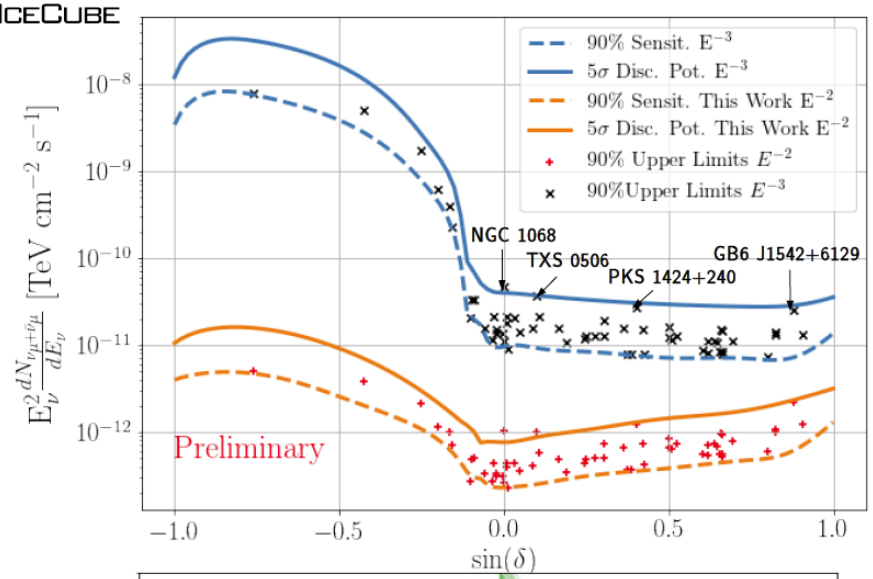
9.5 yr data of blazar TXS 0506-056

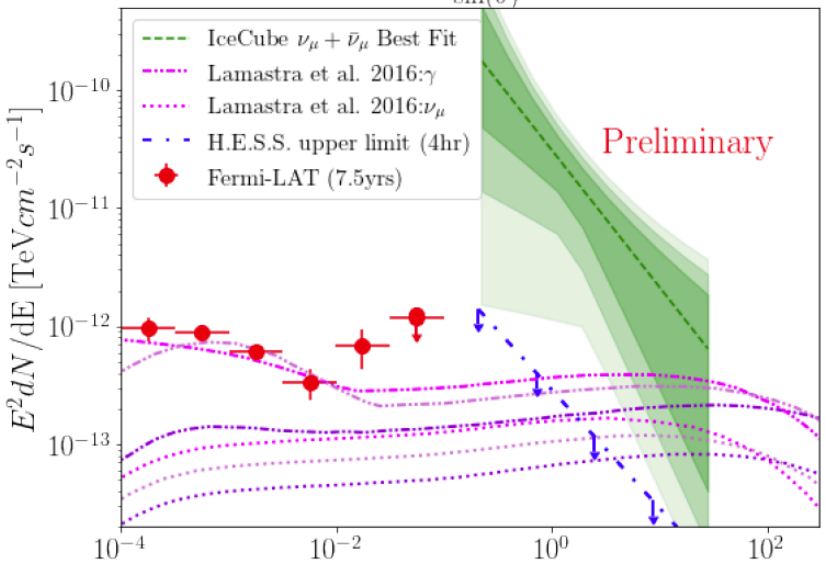
IceCube+ 18



~3.5σ coincidence

Outlook on Results





Multi-wavelength Observations around NGC 1068

- NGC 1068 alone shows a 2.9σ deviation from background.

  → all-sky hotspot ~ 1^0 diameter : its center is offset 0.35° from coords of NGC 1068.

  → this offset and size of hotspot is consistent with simulated tests for a soft flux at a point source.

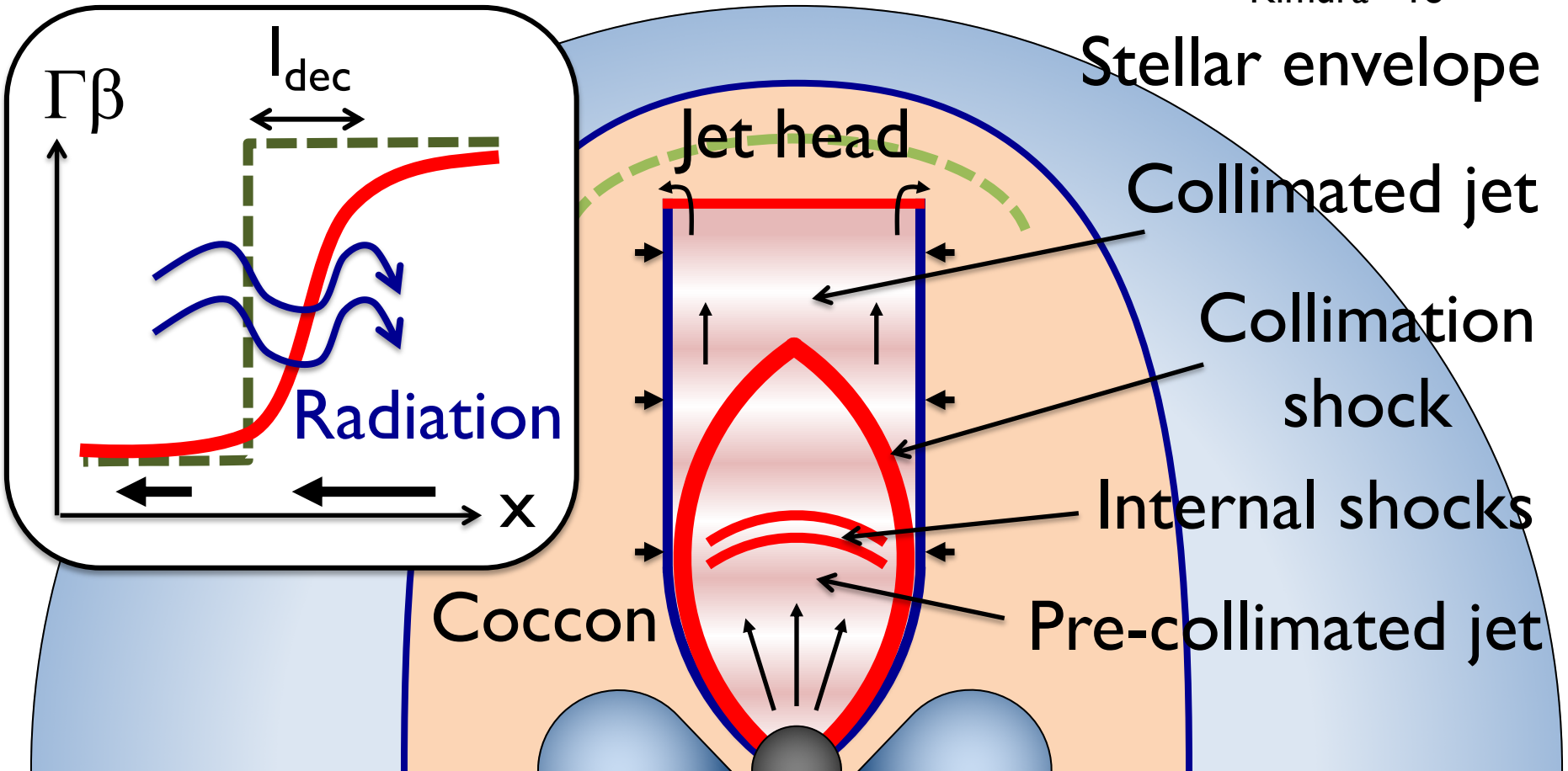
- Best fit normalisation is greater than current Gamma-ray observations.
- Best fit spectrum ∝ $E^{-3.16}$

Failed Gamma-Ray Burst?

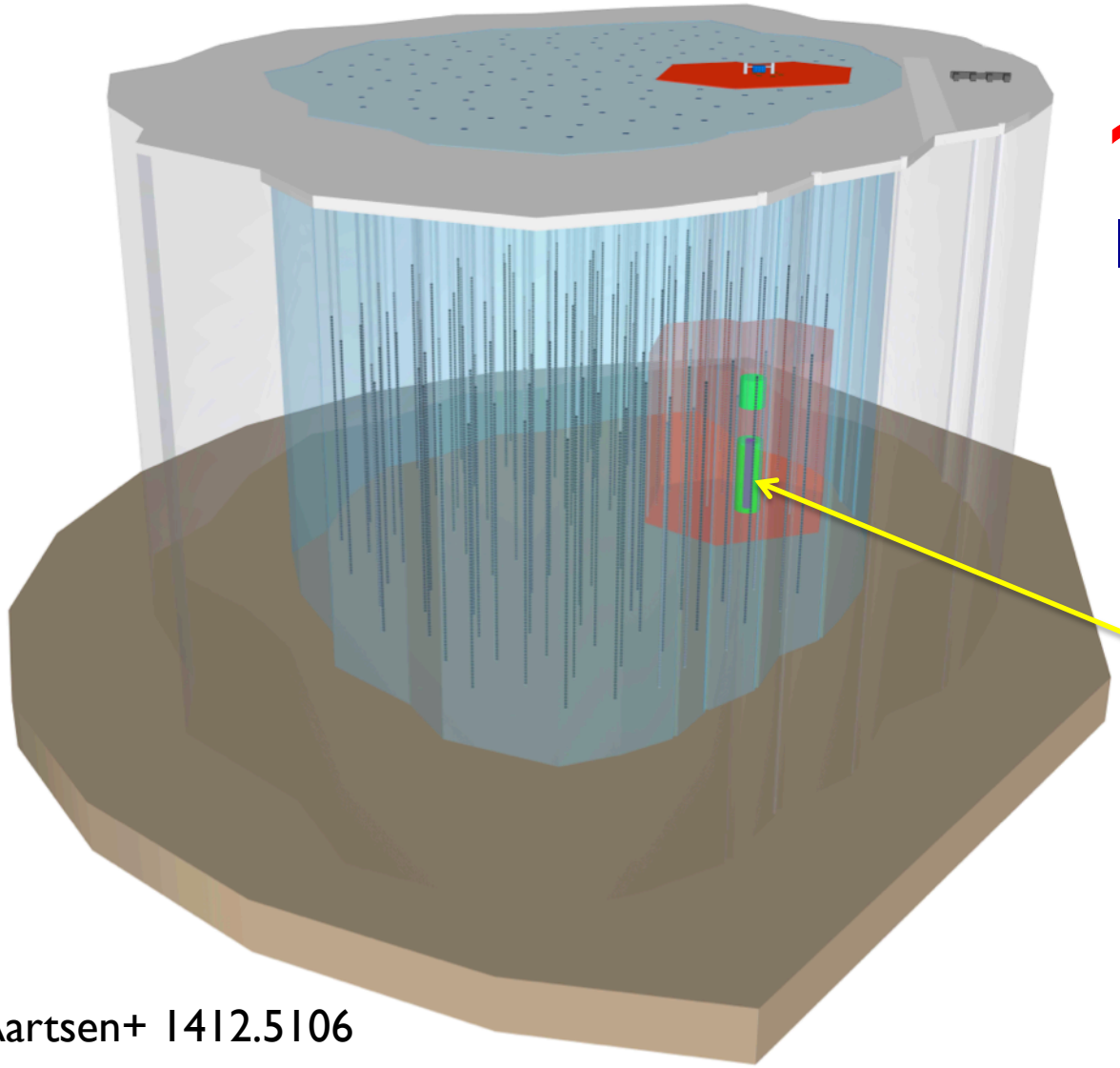
TeV-PeV ν from Low-power GRB Jets inside Stars

Not γ-ray sources

Murase & KI 13
Kimura+ 18



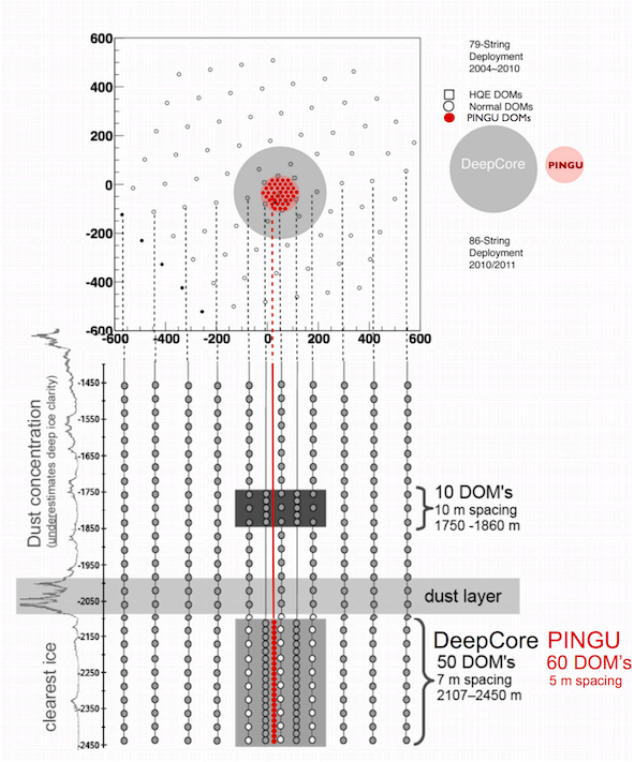
IceCube-Gen2



Aartsen+ 1412.5106

~10 km³

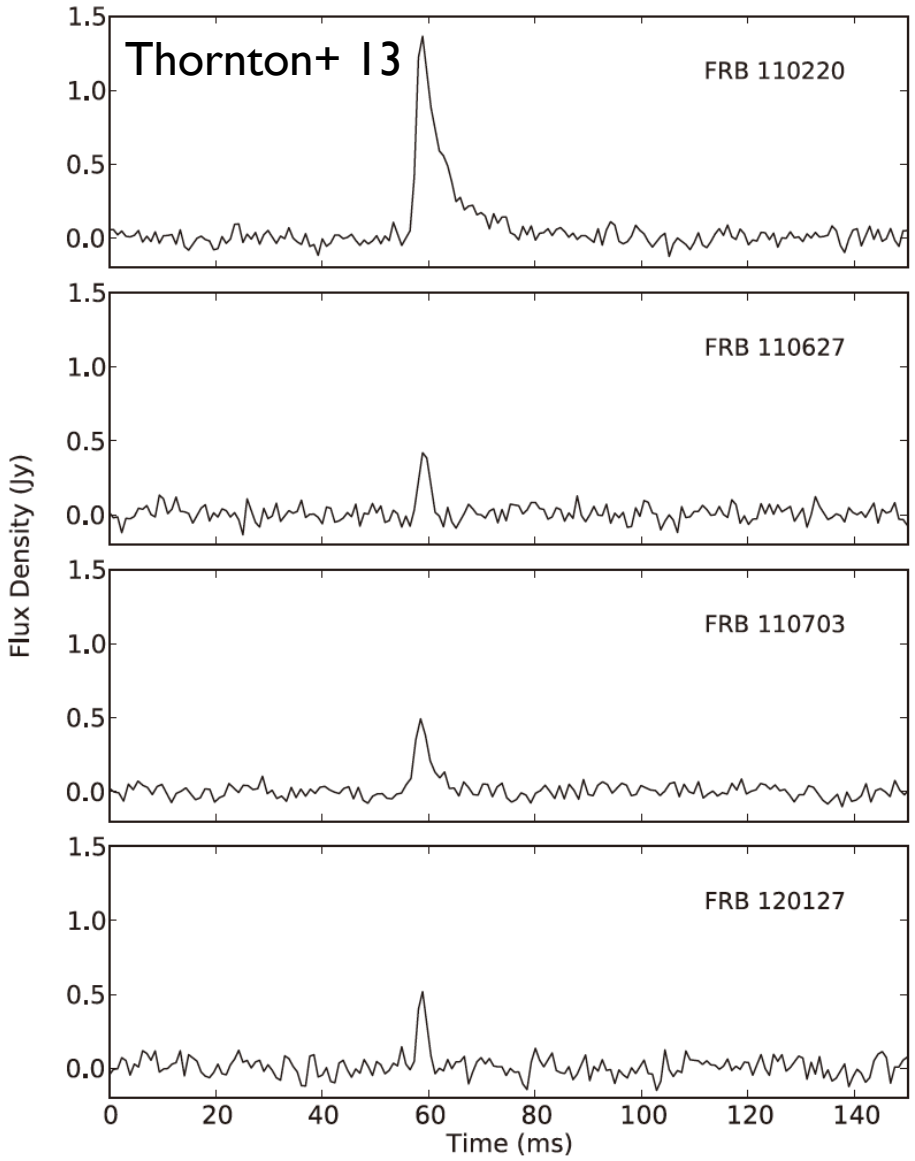
125m→250m spacing



Multi-Messenger Era

21th Century: Multi-Messenger Era

Fast Radio Bursts



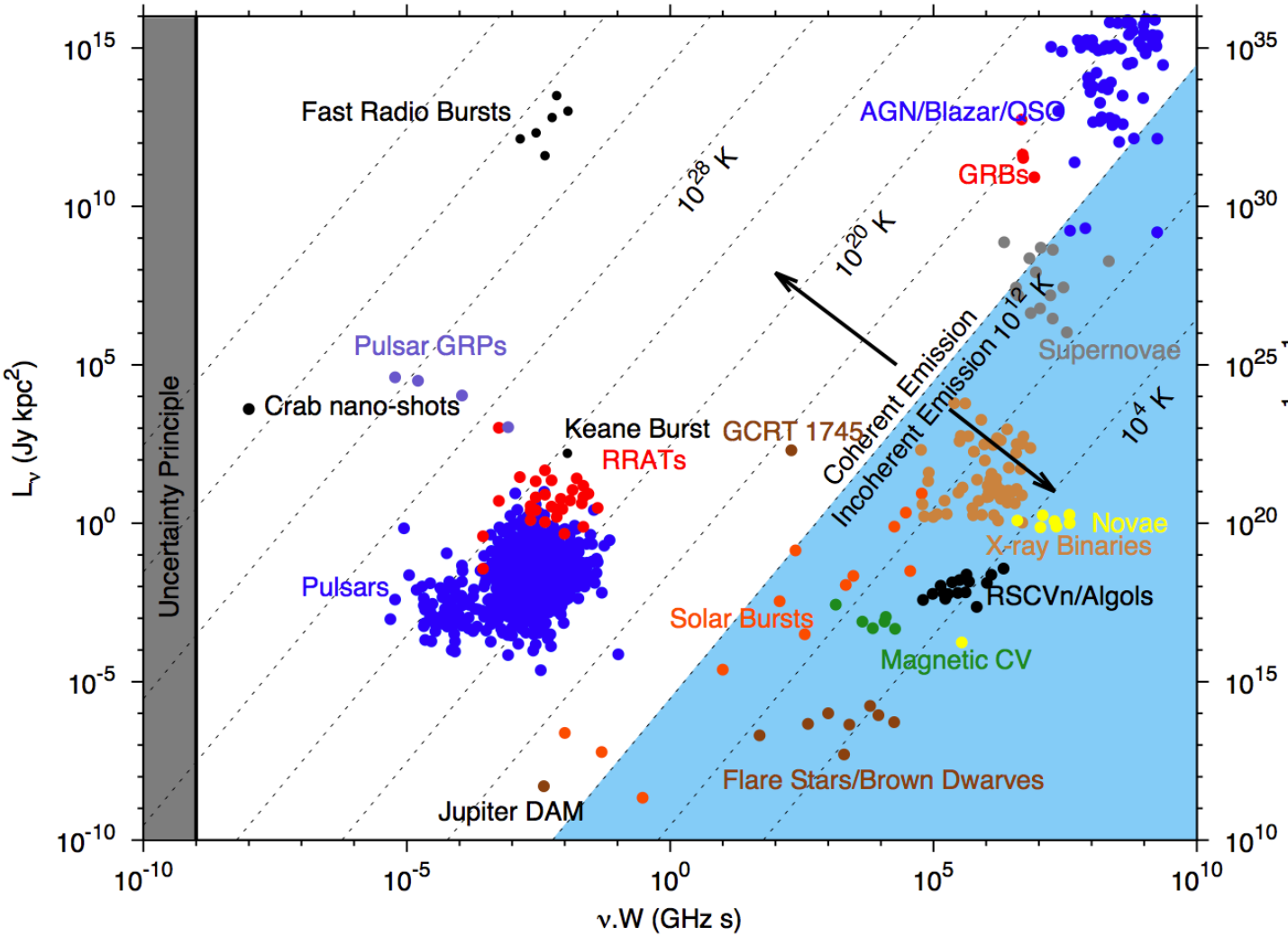
F=0.6-8.0 Jy ms !!!

Most luminous radio transients if cosmological

Brightness Temperature

$$T_{\rm B} \simeq 10^{36}{\rm K}\left(\frac{S_{\rm peak}}{\rm Jy}\right)\left(\frac{\rm GHz}{\nu}\right)^2\left(\frac{\rm ms}{\Delta t}\right)^2\left(\frac{d}{\rm Gpc}\right)^2\frac{(1+z)^4}{\gamma^2}$$

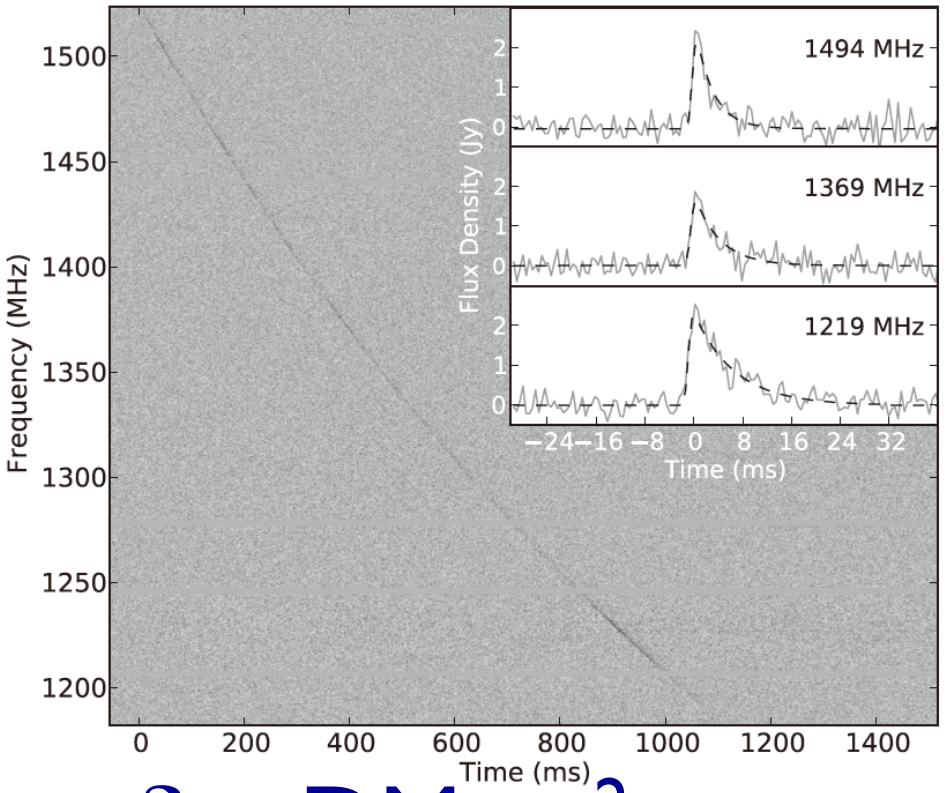
d: comoving distance



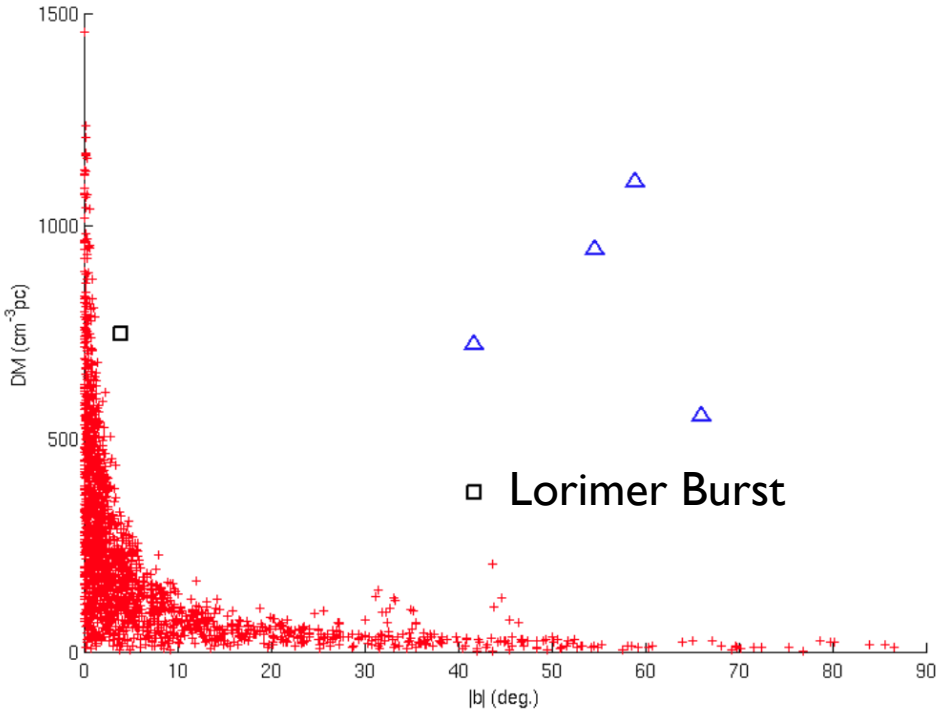
$P \sim |E|^2$
$\sim |E_1 + \ldots + E_N|^2$
$\sim N|E_1|^2$
(incoherent)
$\sim N^2|E_1|^2$
(coherent)

Pietka+ 14

Dispersion Measure



Thornton+ 13



$\delta t \propto DM \cdot \nu^{-2}$

Galactic latitude

DM (column density of electron) = 500-1000 cm^{-3} pc ⇒ z~1

Possible Origins

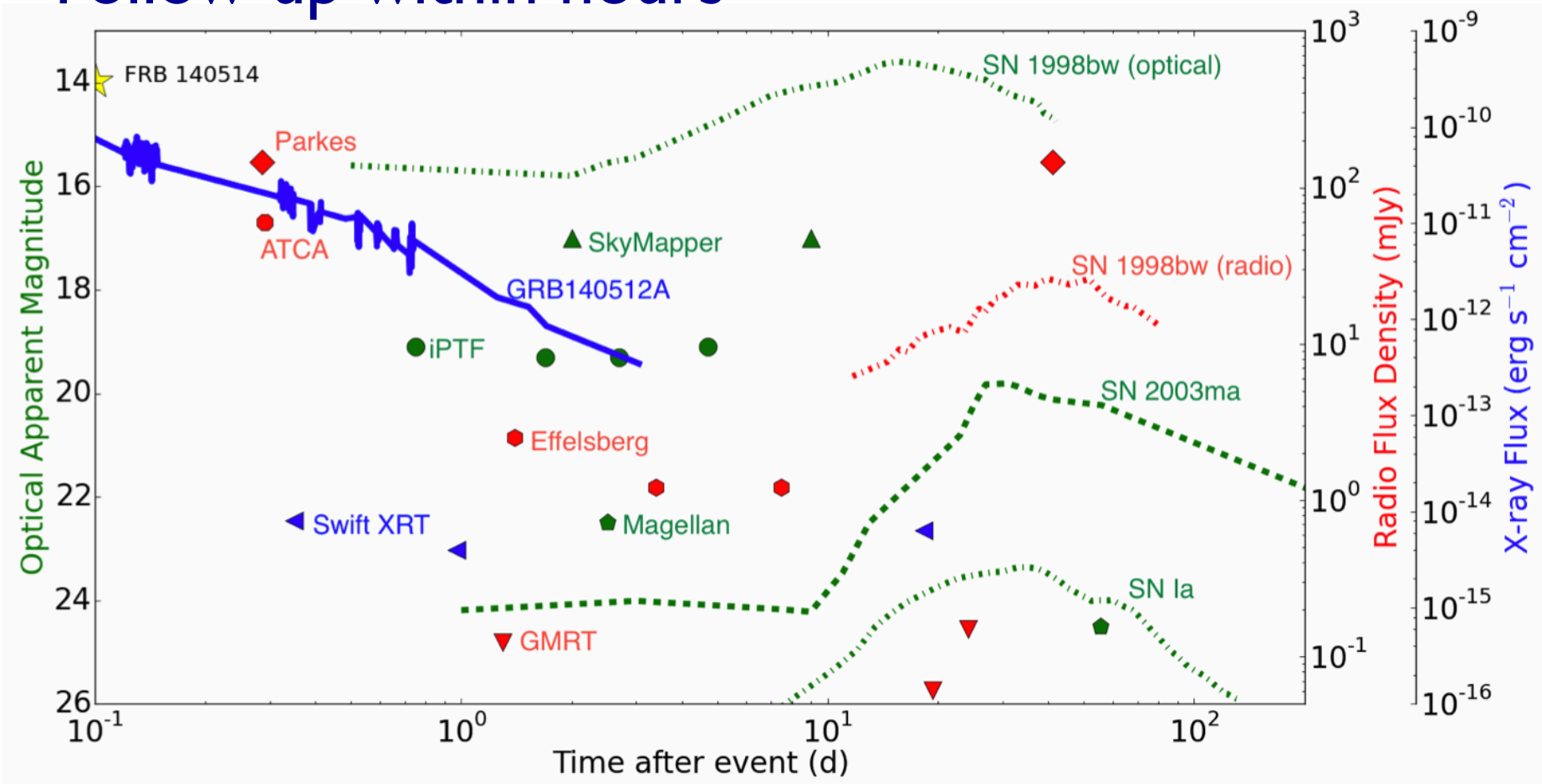
- ***Perytons*** Burke-Spolaor+ 11; Kulkarni+ 14
- ***Galactic***
  - Nearby flaring star Loeb, Shvartzvald & Maoz 13
  - RRAT (Rotating Radio Transient; intermittent pulsar)
- ***Extragalactic***
  - Magnetar giant flare Popov & Postnov 07; Thornton+ 13; Lyubarsky 14; Penn & Conner 15
  - NS-NS merger Hansen & Lyutikov 01; Totani 13
  - WD-WD merger Kashiyama, KI+ 13
  - Collapse of hypermassive NS Falcke & Rezzolla 13; Zhang 13
  - Supernova into a nearby star Colgate+ 71,75; Egorov & Postnov 09
  - Supergiant pulse Cordes & Wasserman 15
  - Pulsar-orbiting bodies Mottez & Zarka 14

Possible Exotics

- Evaporation of BH Rees 77; Blandford 77; Kavic+ 08; Keane+ 12
- PBH to white hole Barrau+ 14
- Superconducting cosmic strings Cai+ 12; Yu+ 14
- Axion stars Iwazaki+ 14; Tkachev+ 14
- …

No Counterpart Transients

Follow-up within hours

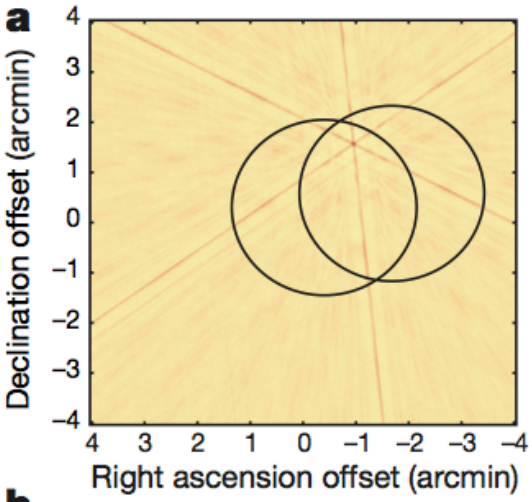


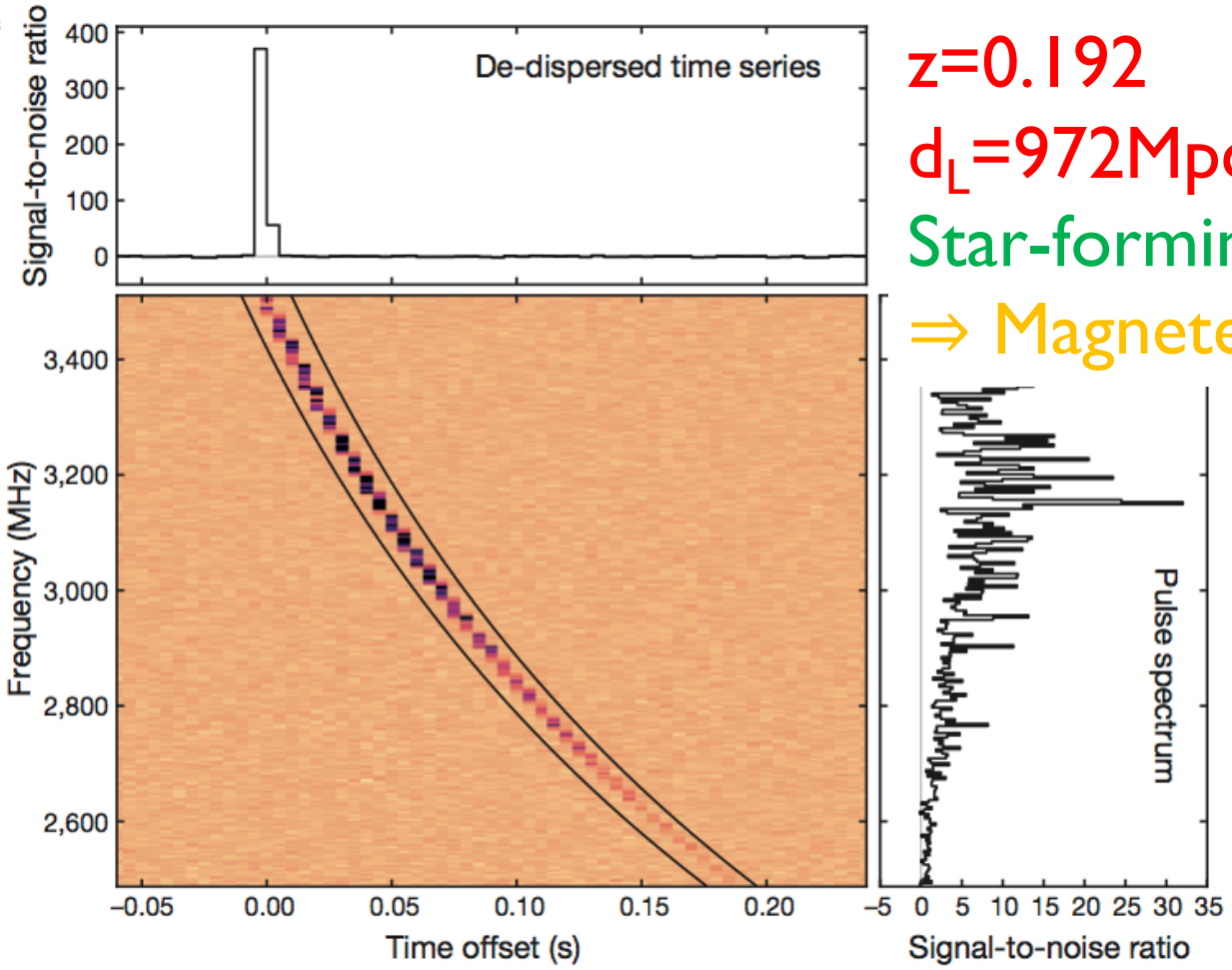
Rule out supernovae and long GRBs

Petroff+ 14

A FRB is Cosmological!

Repeating FRB 121102 ⇒ Radio interferometry





z=0.192

d_L=972Mpc

Star-forming

⇒ Magneter?

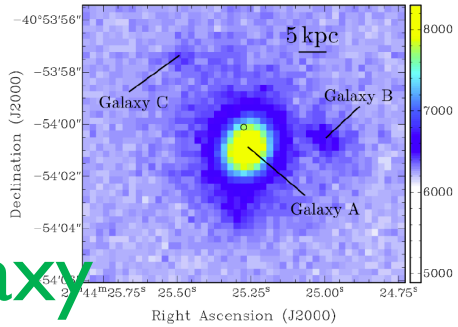
Chatterjee+ 17; Tendulkar+ 17; Marcote+ 17

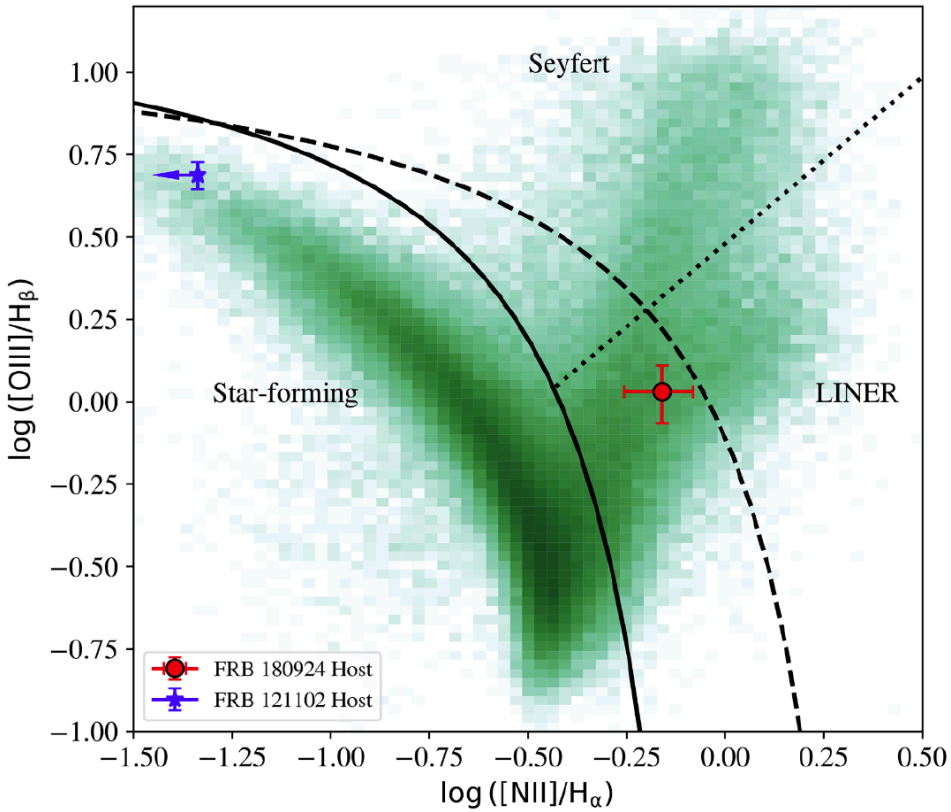
More Host Galaxies

FRB 180924

z=0.3214

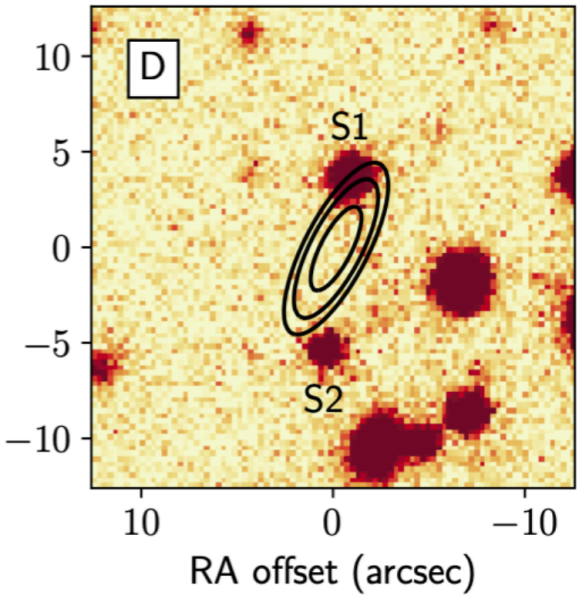
Old, clean galaxy





FRB 190523

z=0.66, old galaxy



⇒ NS-NS?

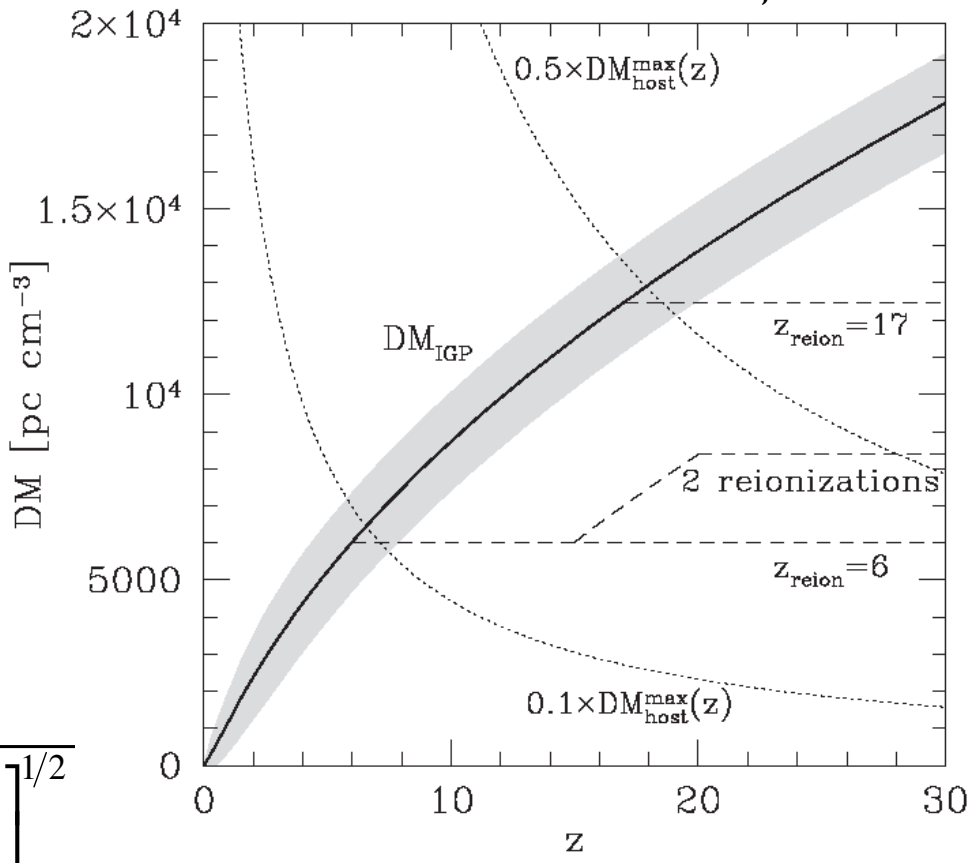
WD→NS?

Host galaxy redshift	0.660(2)
Host galaxy luminosity distance (Gpc)	4.08(1)
Burst energy (erg Hz^{-1})	5.6×10^{33}
Host galaxy stellar mass ($M_\odot$)	$10^{11.07(6)}$
Host galaxy star-formation rate ($M_\odot$ yr^{-1})	<1.3

FRB Cosmology

- Reionization
- Missing baryon
- Dark energy, cosmological para.
  ⇒ Swapland?

KI 03, Inoue 04

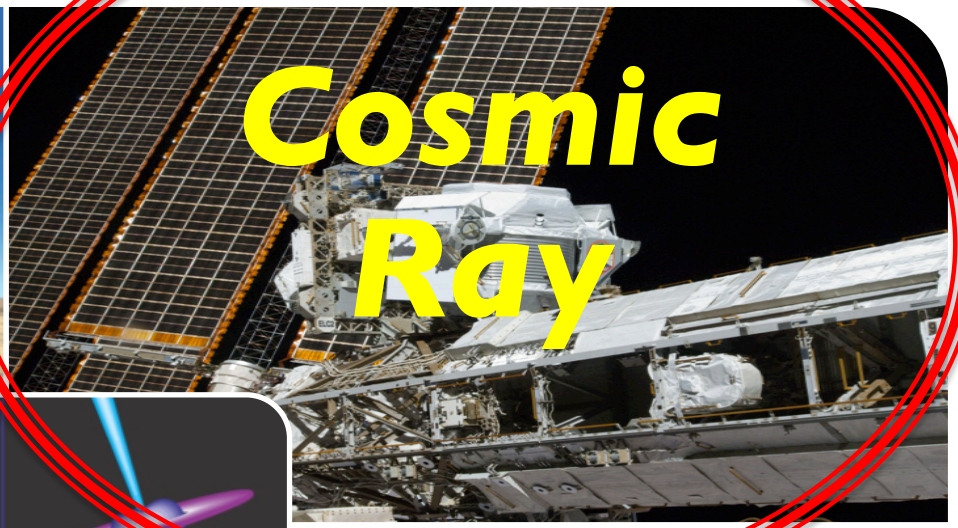


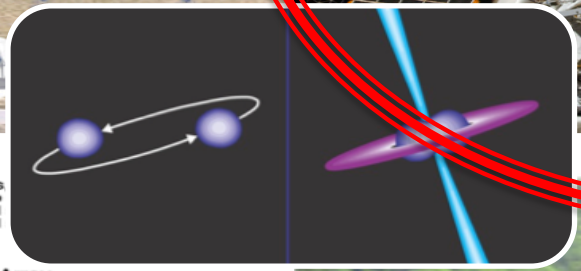
$$\mathrm{DM_{IGP}} = \frac{3cH_0\Omega_b}{8\pi G m_p}\int_0^z \frac{(1+z)\,dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

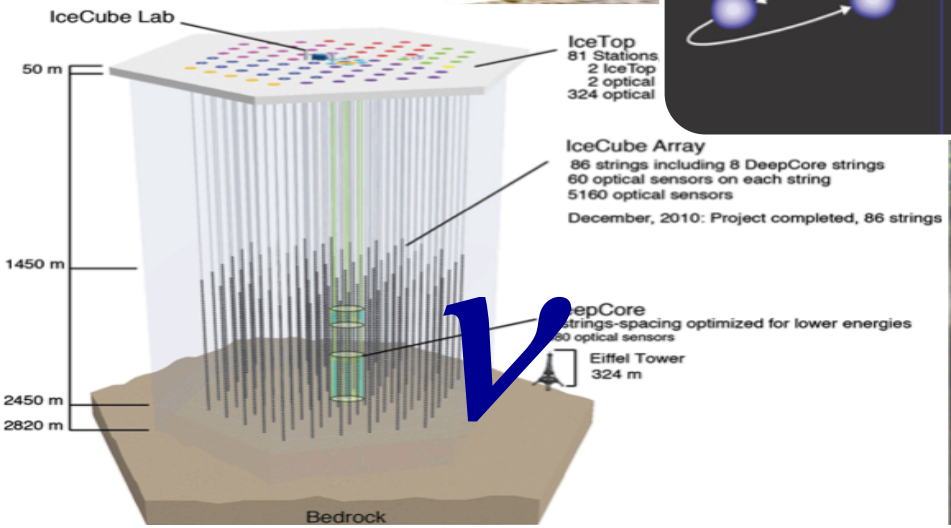
$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz}{\left[\Omega_m(1+z)^3+\Omega_\Lambda\right]^{1/2}}$$

Fast radio bursts as cosmological tools
New frontier?

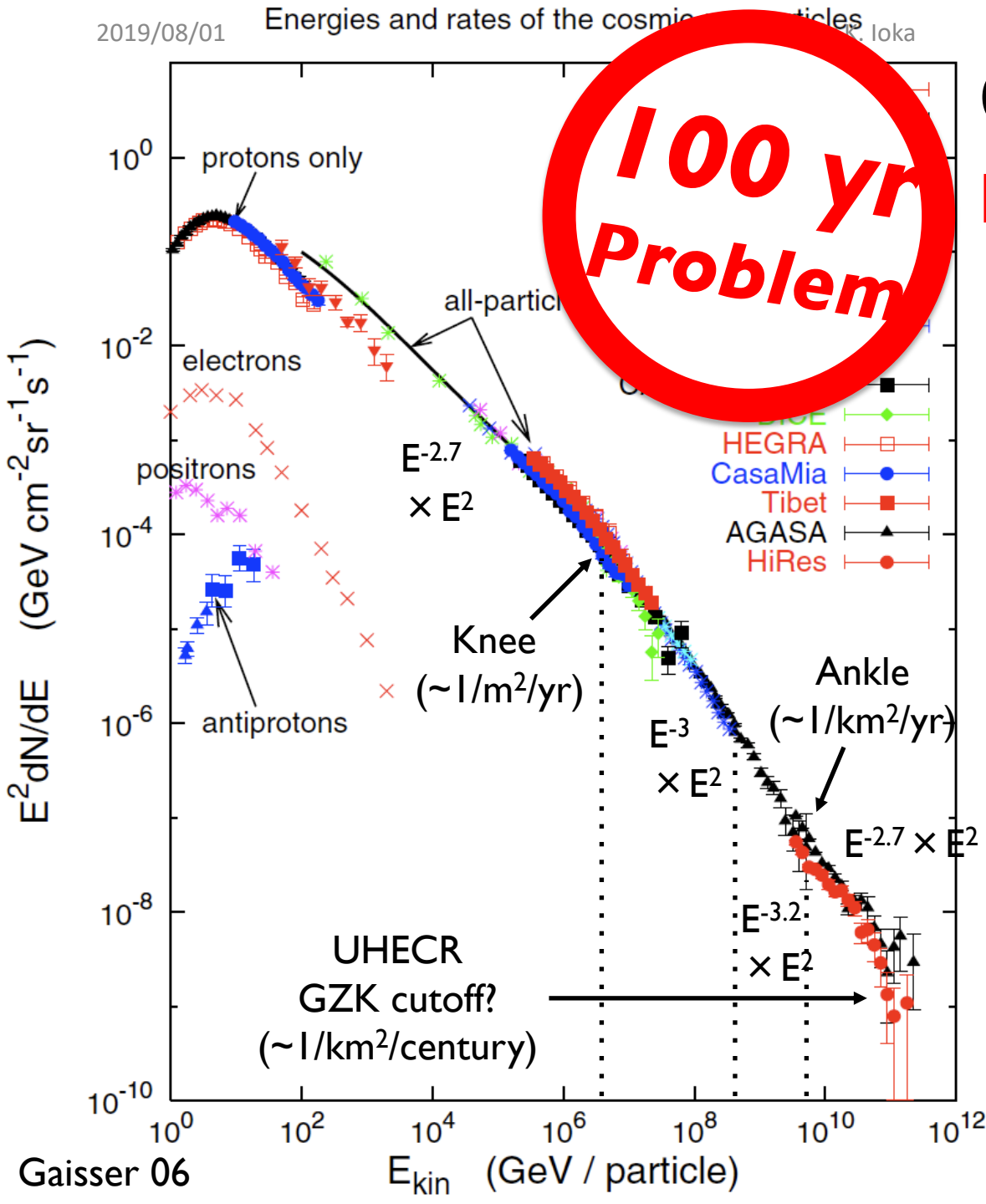
Multi-Messenger Era







21th Century: Multi-Messenger Era



Cosmic Ray

$E<10^{15\text{-}16}$eV (Knee)

$F \propto E^{-2.7}$

Supernova remnant(?)

$L_{CR} \sim 10^{41}$erg/s

$\sim 0.1 E_{SN}/t_{SN}$

$10^{15\text{-}16}<E<10^{18}$eV (Ankle)

$F \propto E^{-3\text{-}3.2}$

Galactic origin?

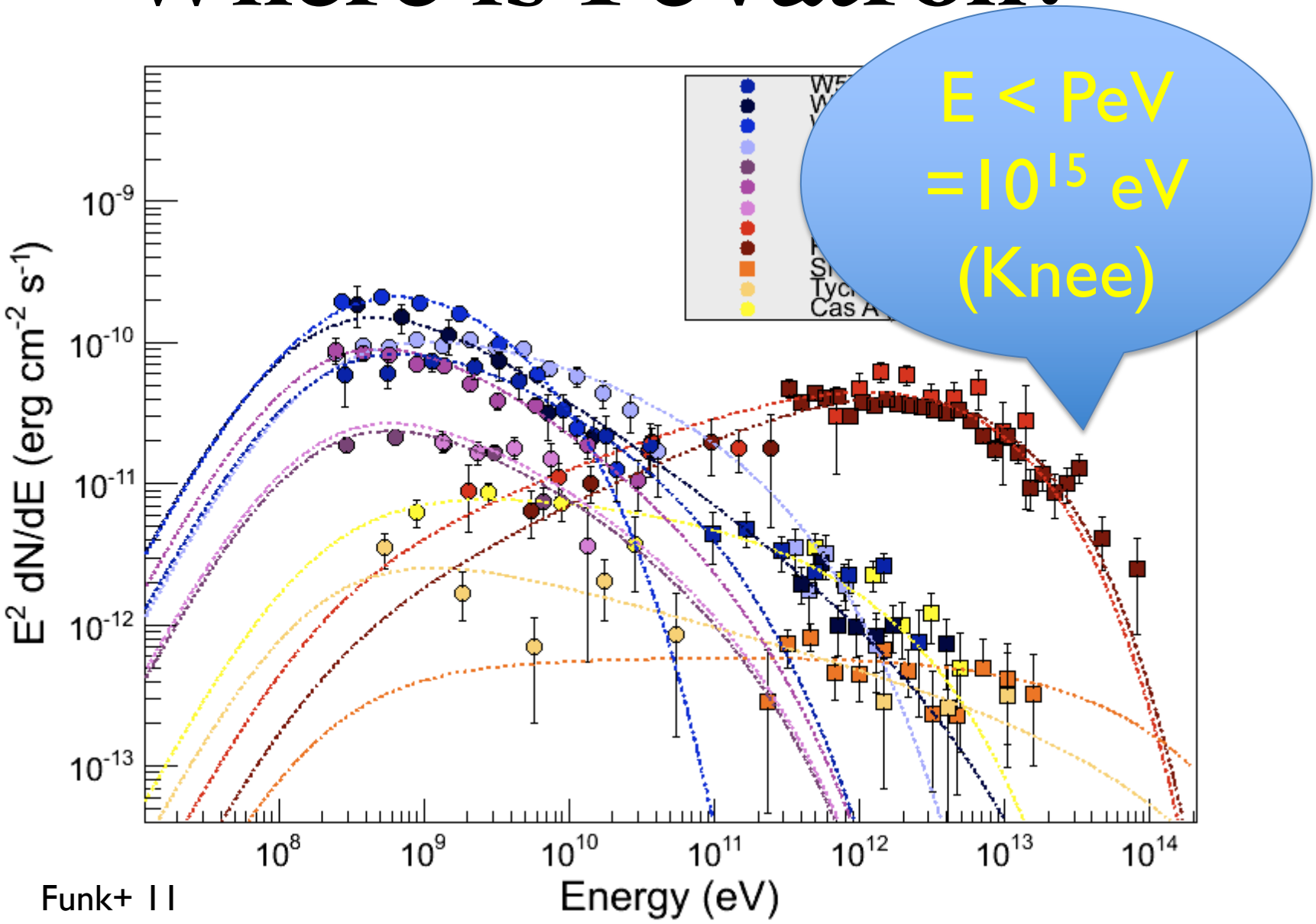
$<10^{14\text{-}15}$eV by SNR

$10^{18}\text{eV}<E$

$F \propto E^{-2.7}$

Extra-Gal. AGN? GRB?

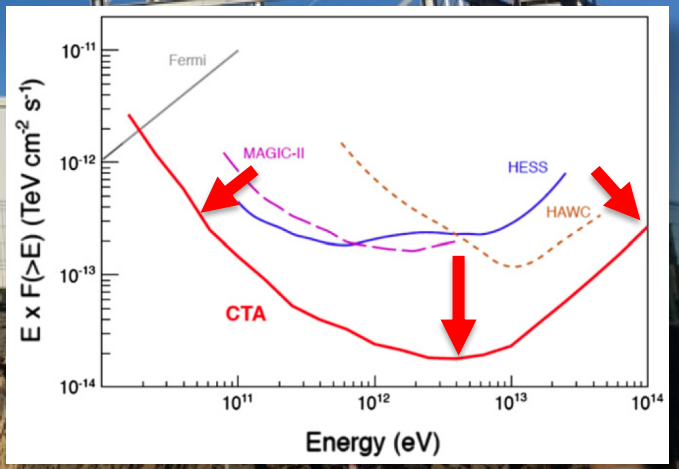
Where is PeVatron?



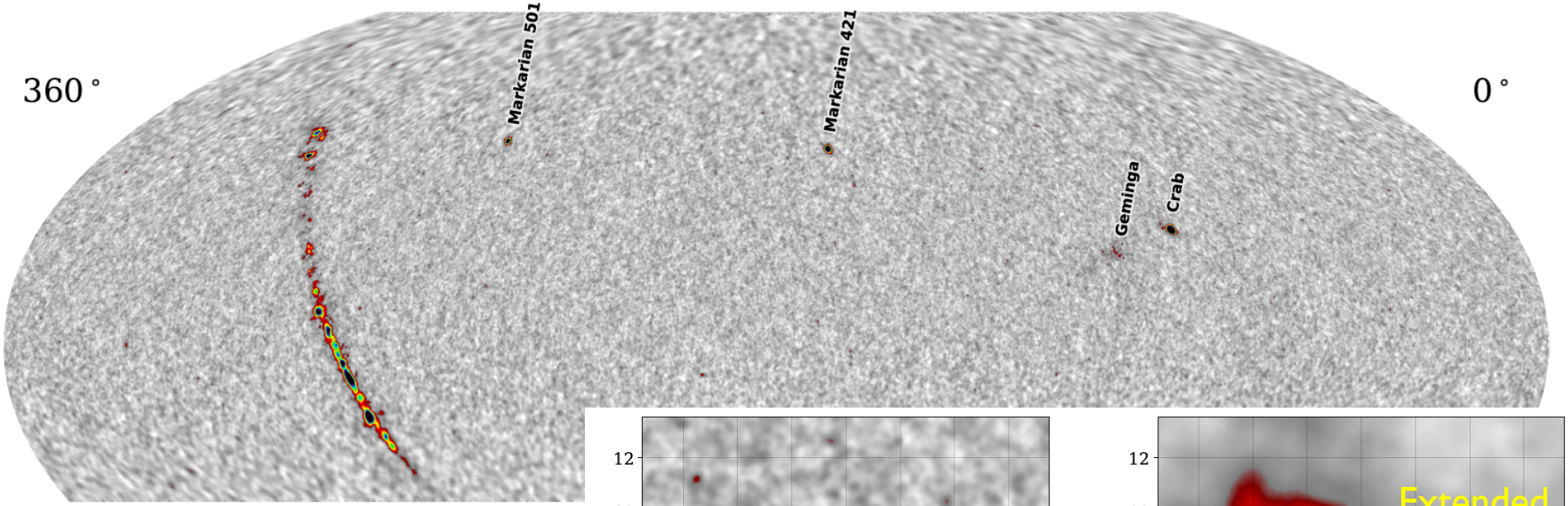
Funk+ 11

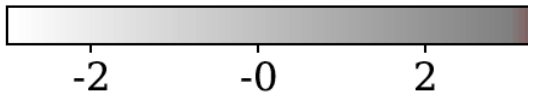
CTA

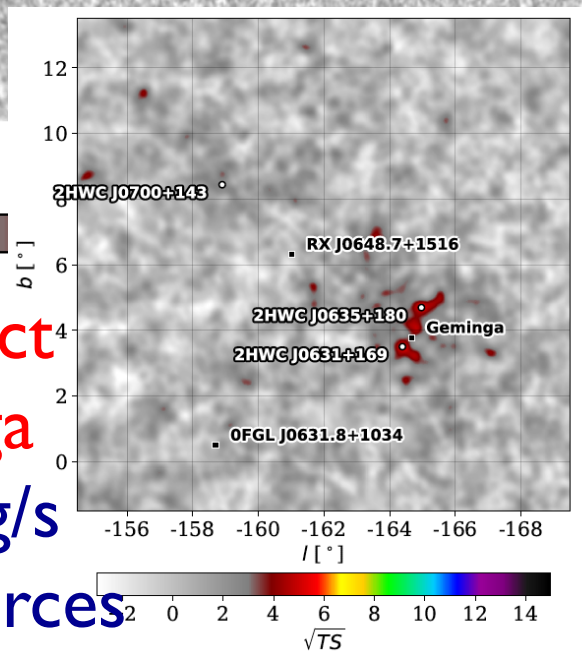
LST (Large Size Telescope)
@La Palma

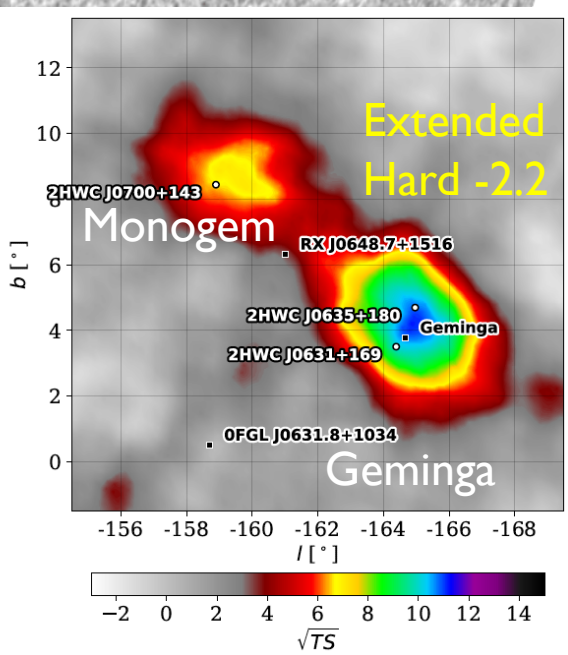


HAWC



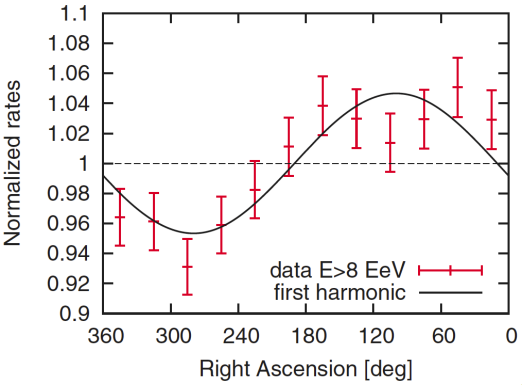






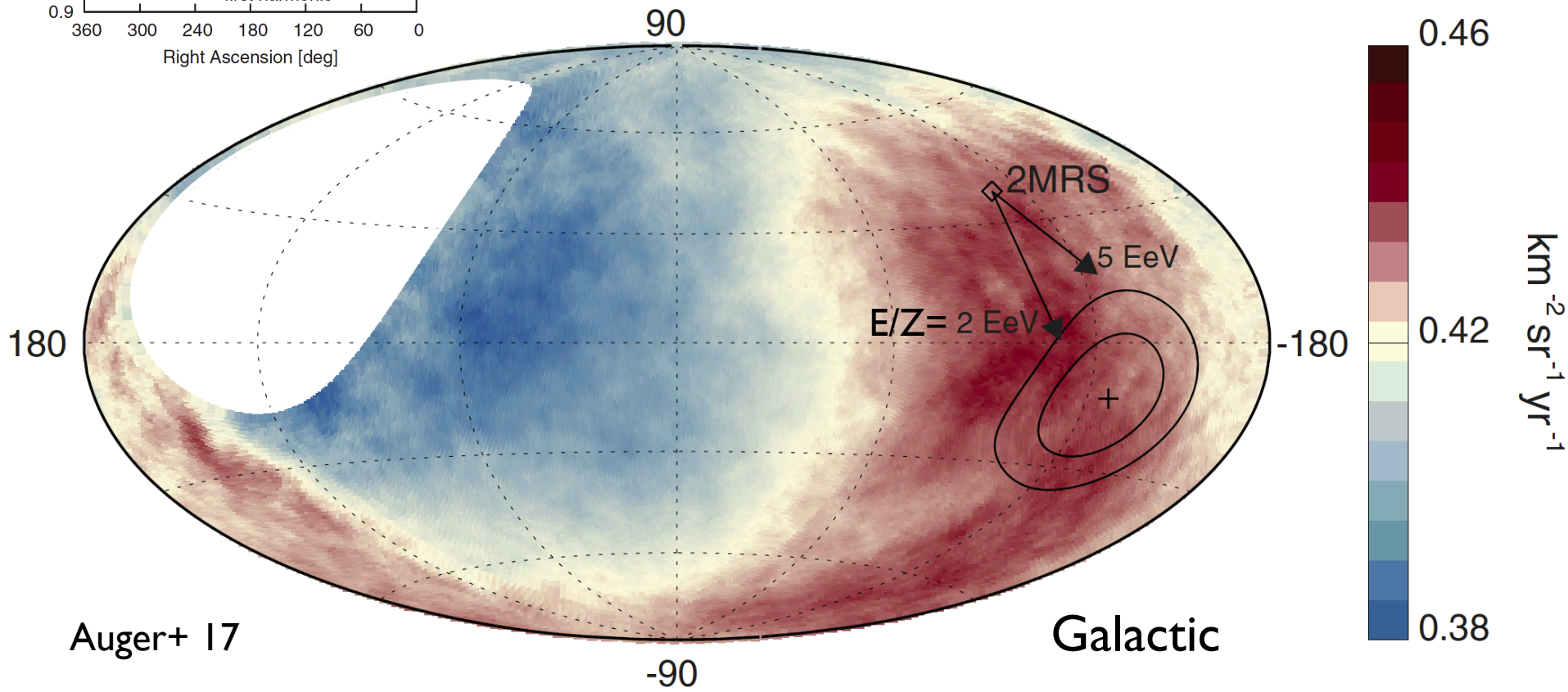
HAWC & Milagro detect
TeV γ-ray from Geminga
250pc, 342kyr, 3e34 erg/s
Slow diffusion near sources

Dipole Anisotropy >8EeV

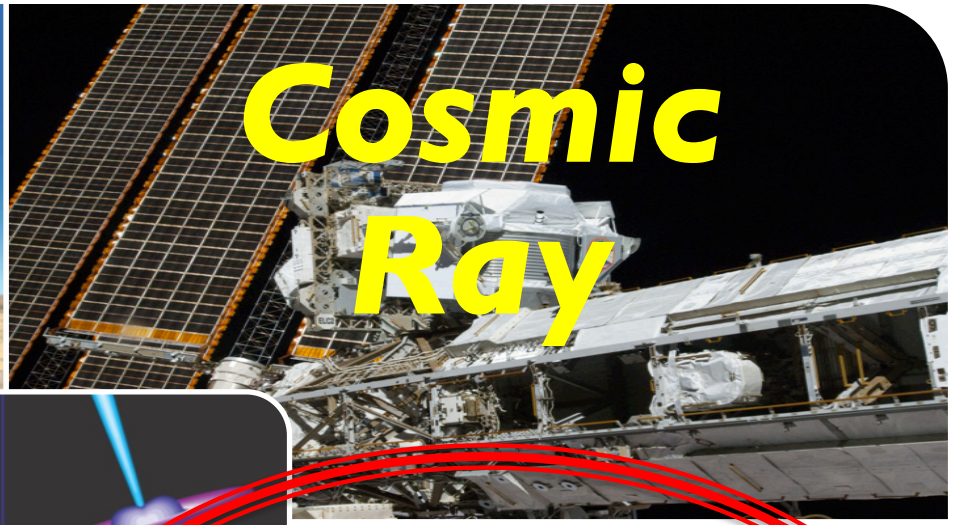


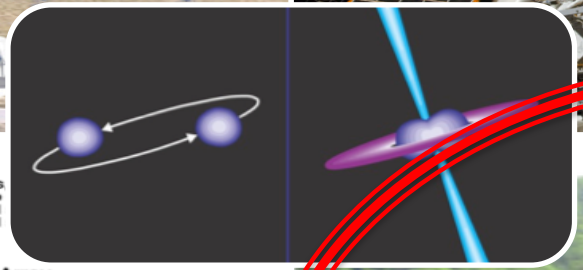
$\delta=6.5^{+1.3}_{-0.9}\%$ (>5.2σ) using 3e4 CRs

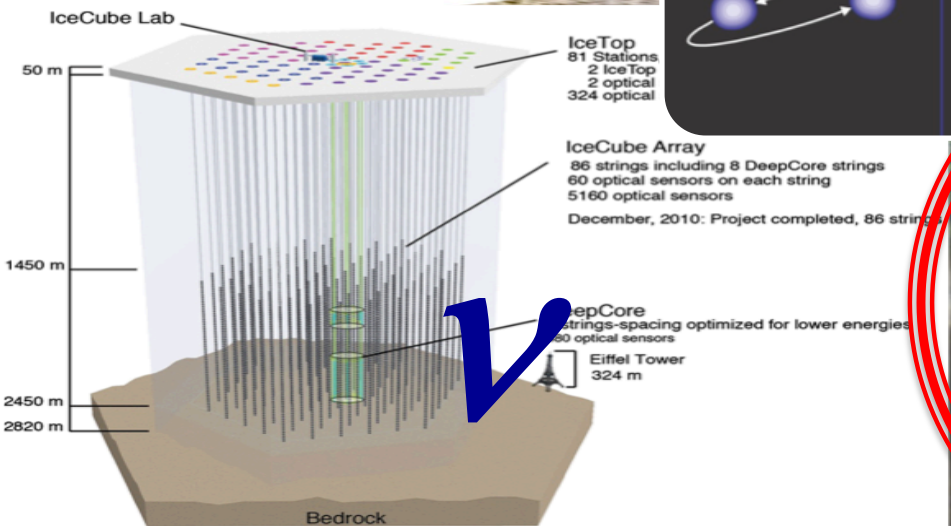
⇒ Extragalactic origin



Multi-Messenger Era

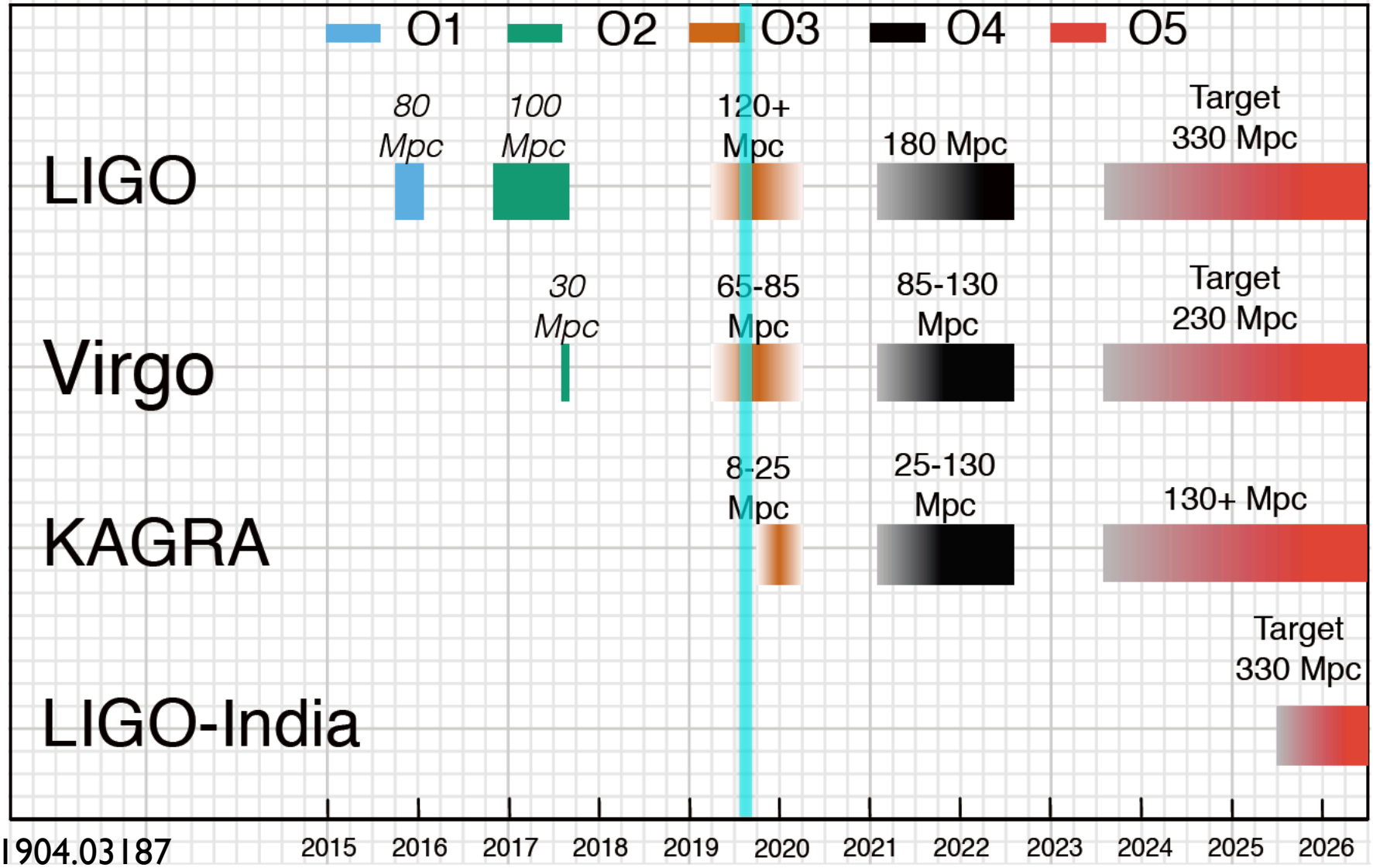




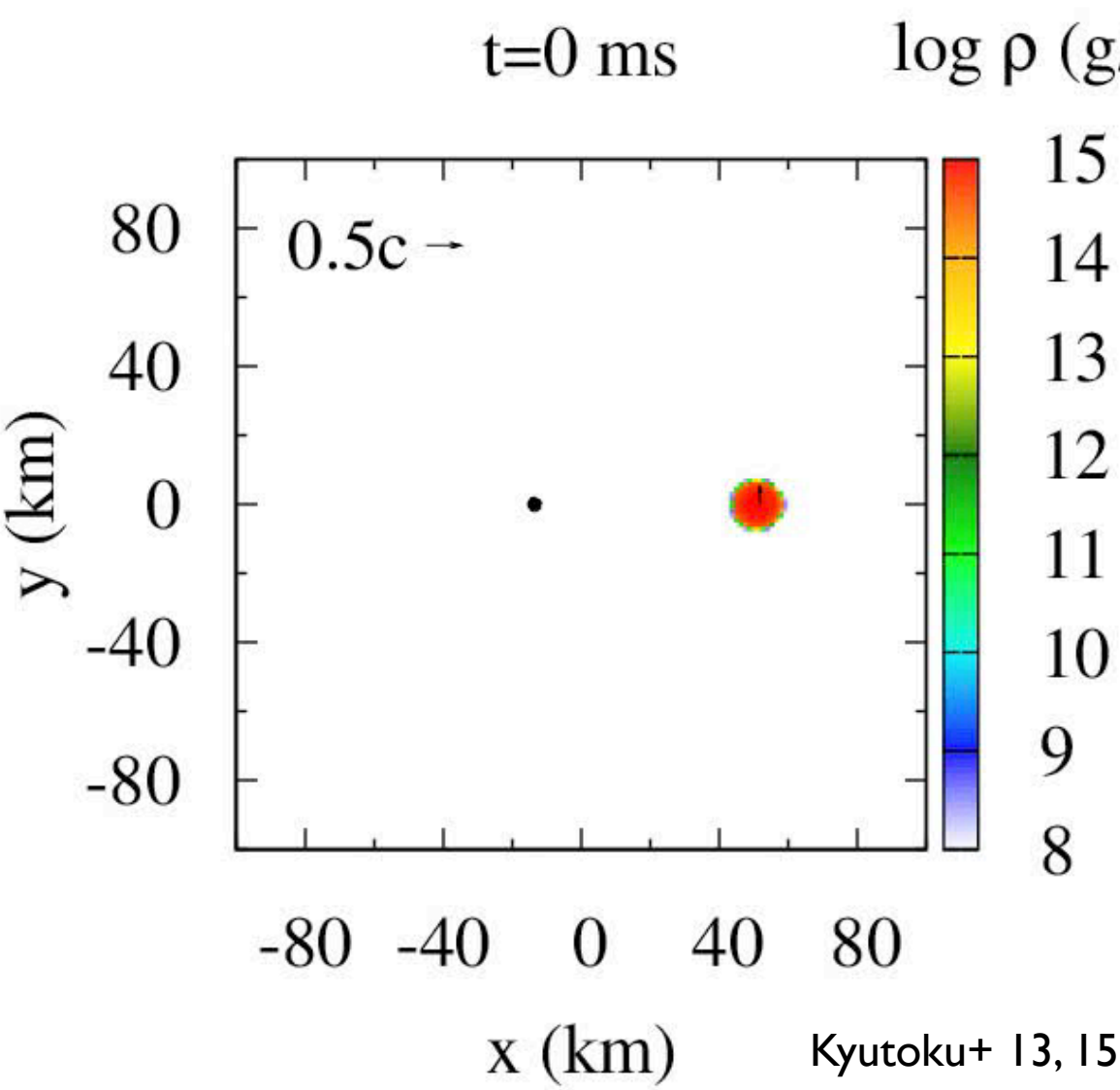


21th Century: Multi-Messenger Era

KAGRA is joining



BH-NS



Kyutoku+ 13, 15

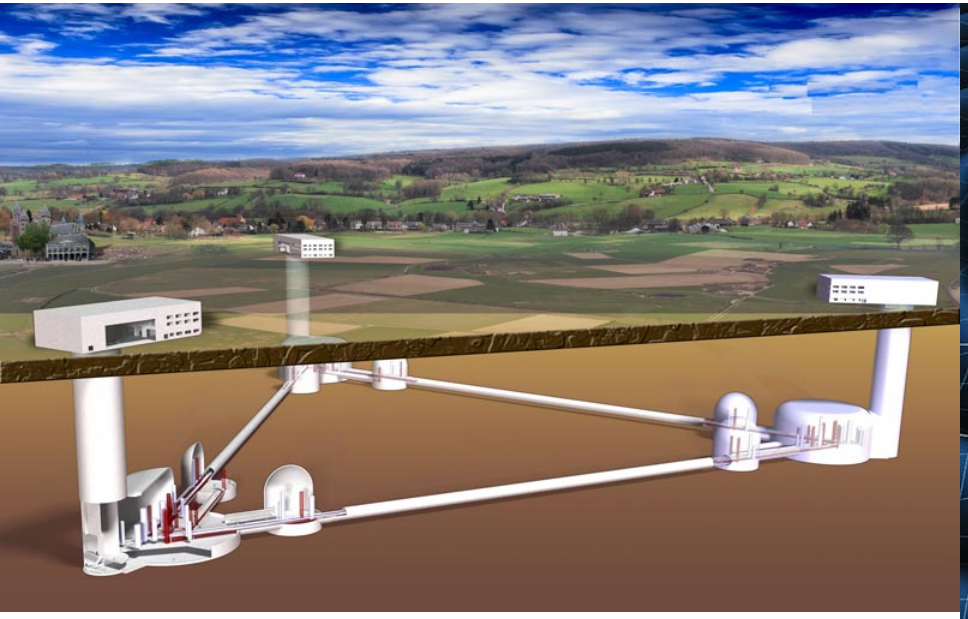
Numerical relativity

Low Y_e ejecta
M~0.01-0.1$M_\odot$
v~0.1-0.3c
E~10^{49}-10^{51} erg

BH-NS: Anisotropic
NS-NS: Spherical

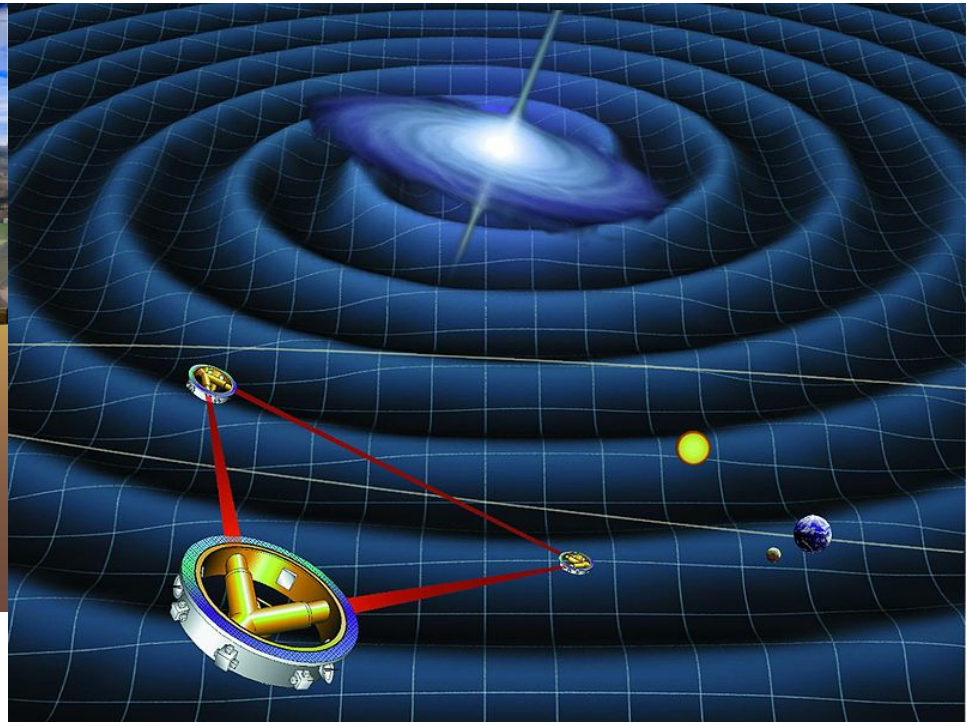
Near Future

3rd Generation



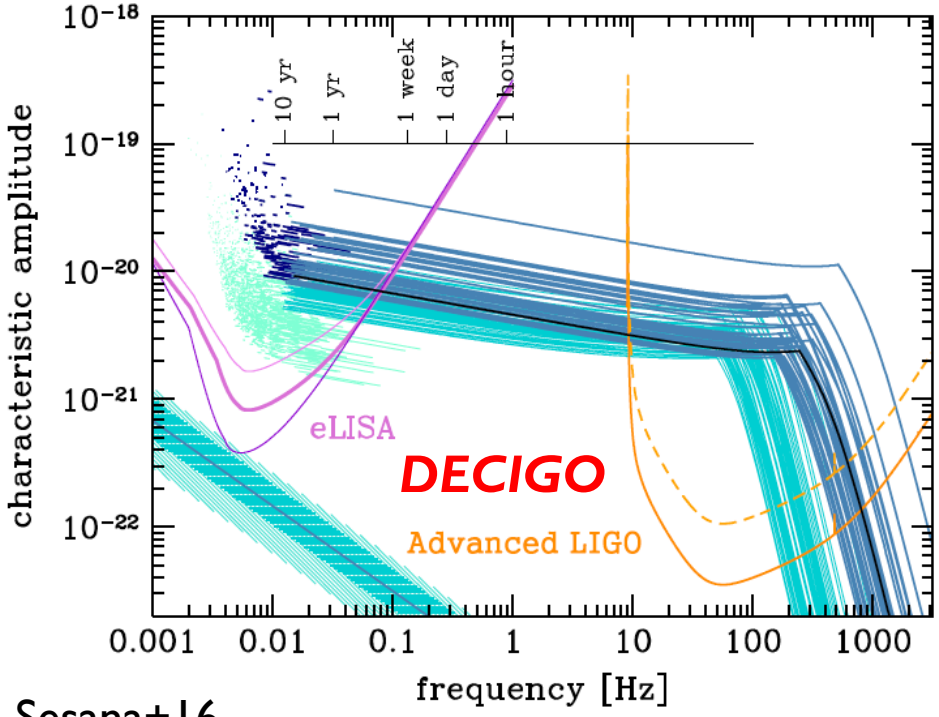
~10 times sensitivity
>1000 events/yr

Space



Massive black hole
Inflation

Space GW Observatories



Sesana+16

Low frequency band

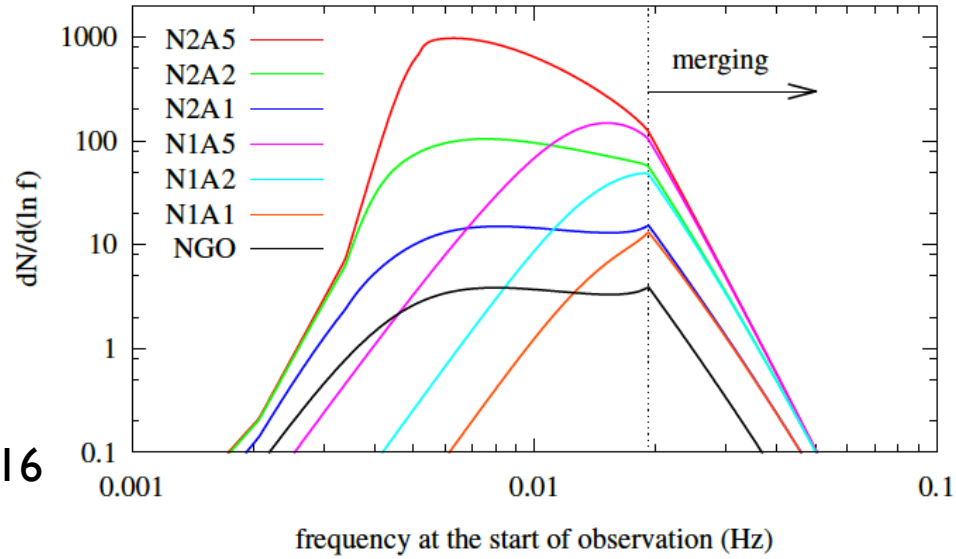
LISA ~0.01Hz

DECIGO ~0.1Hz

→ Ground ~100Hz

Guaranteed sources

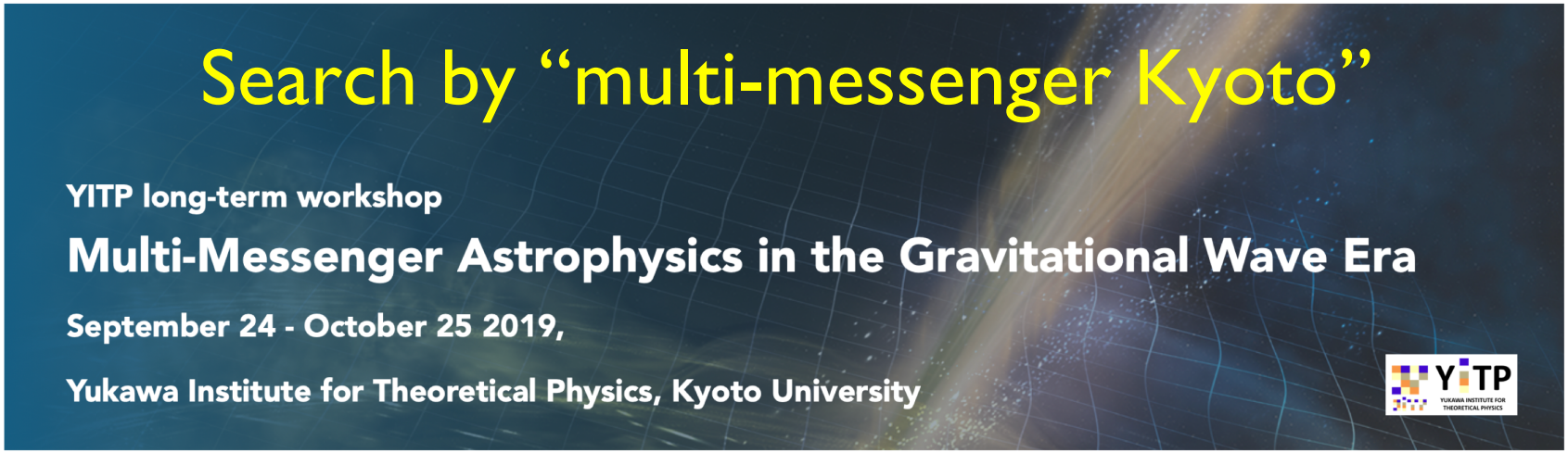
Good localization



Kyutoku & Seto 16

Seto 16

YITP Long-term Workshop



YKIS 2019

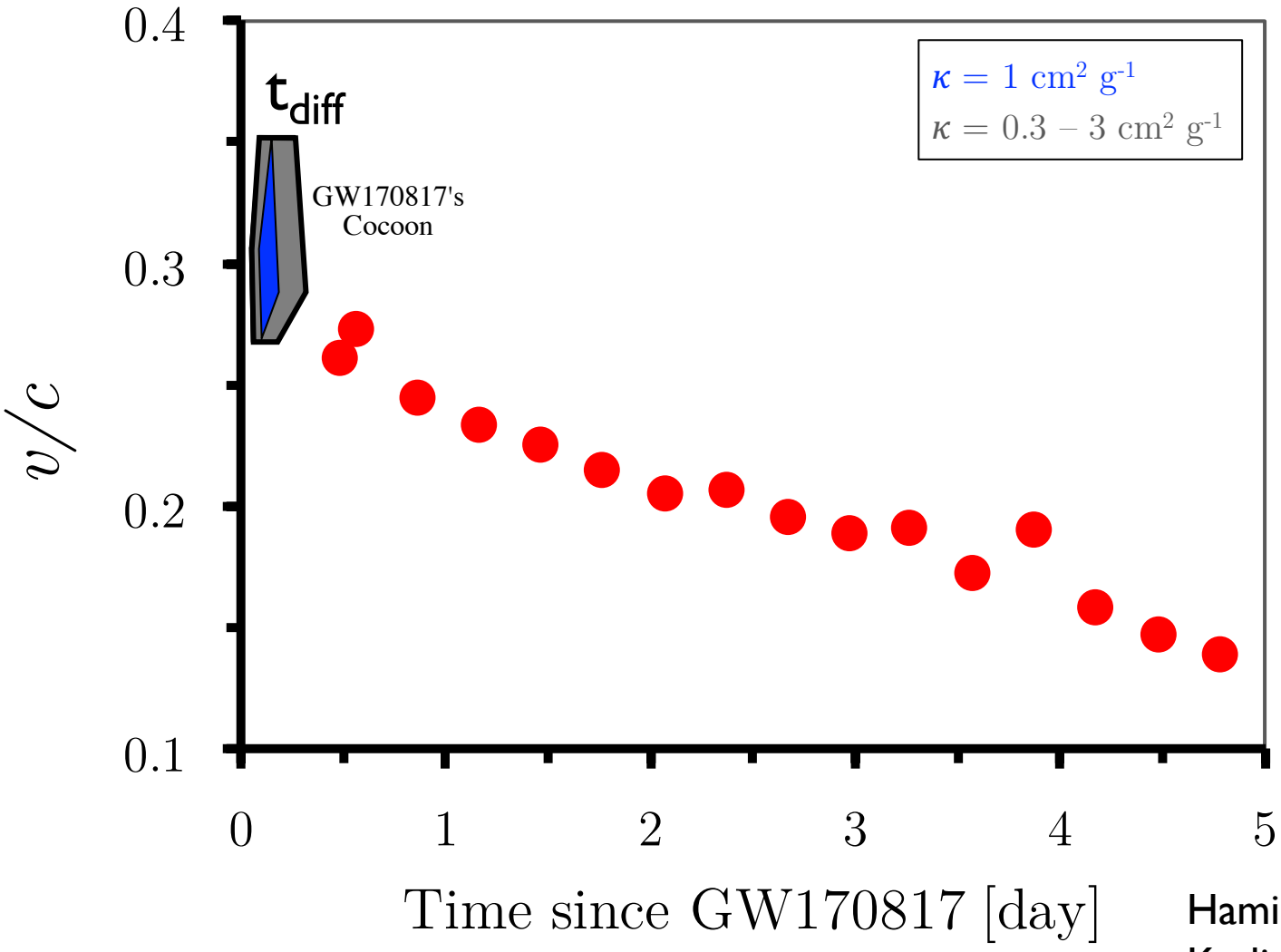
7-11 Oct.

5 days

symposium

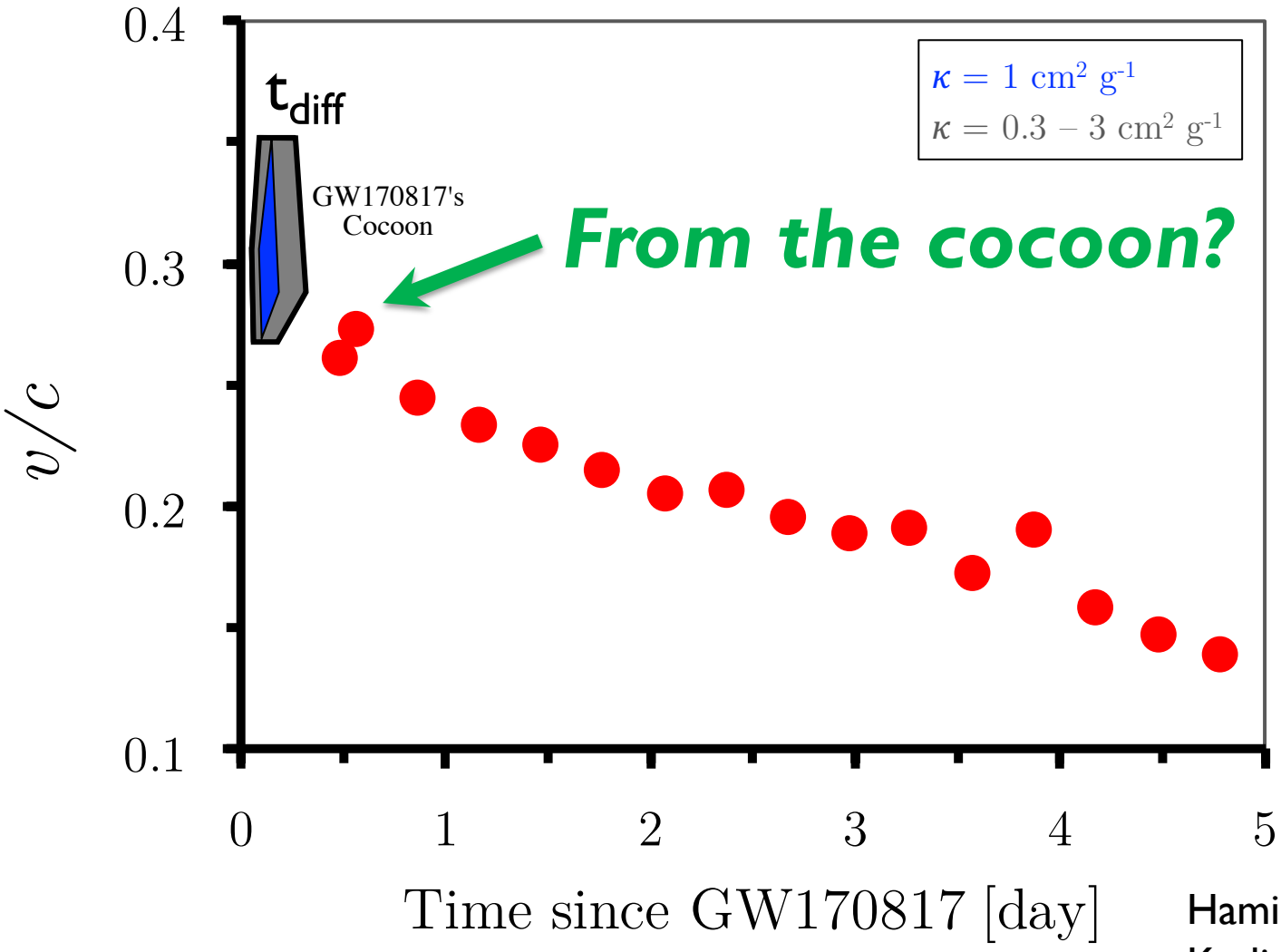
Thank You

Typical Cocoon Velocity



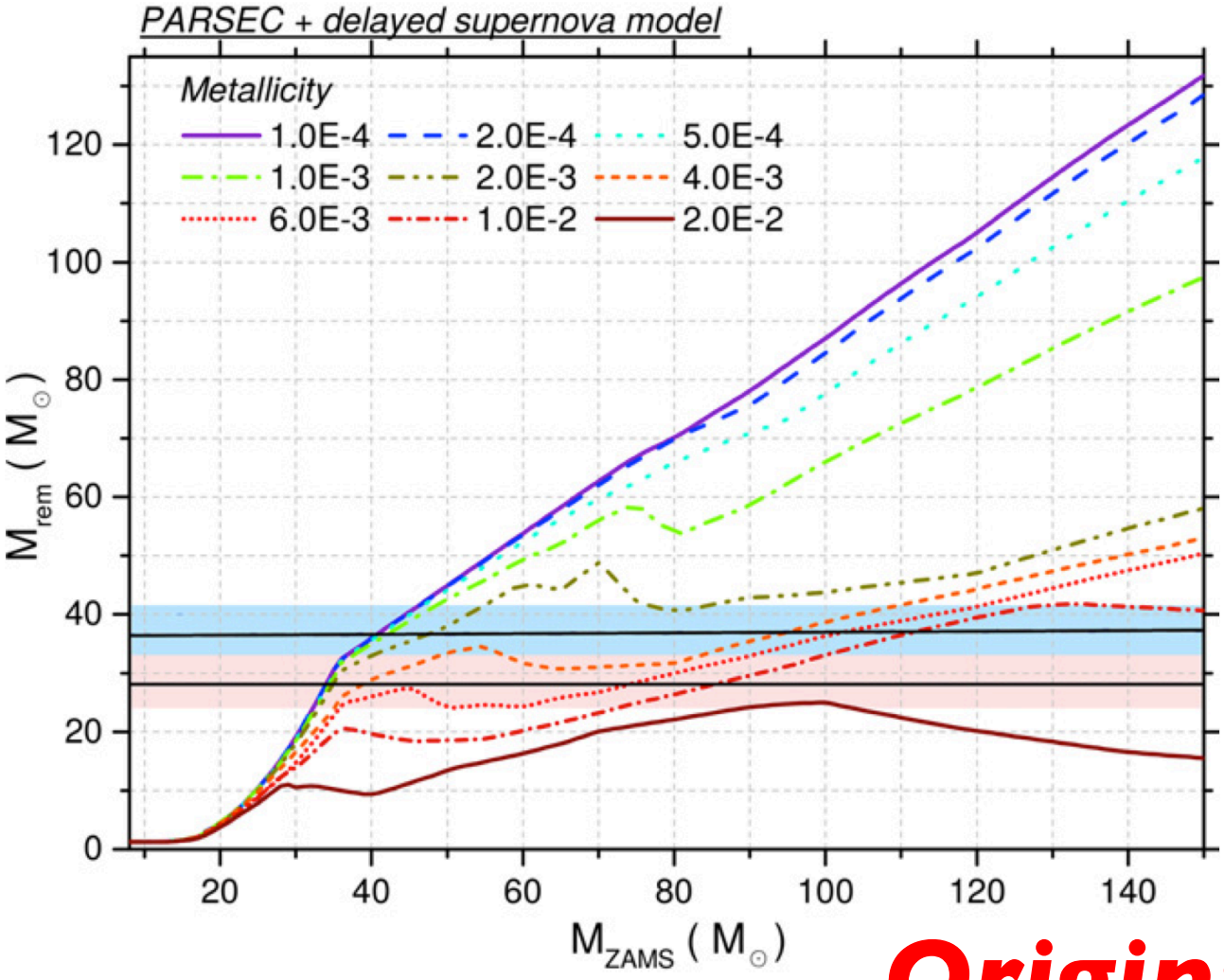
Hamidani+ in prep.
Kasliwal+ 17

Typical Cocoon Velocity



Hamidani+ in prep.
Kasliwal+ 17

Low Metallicity



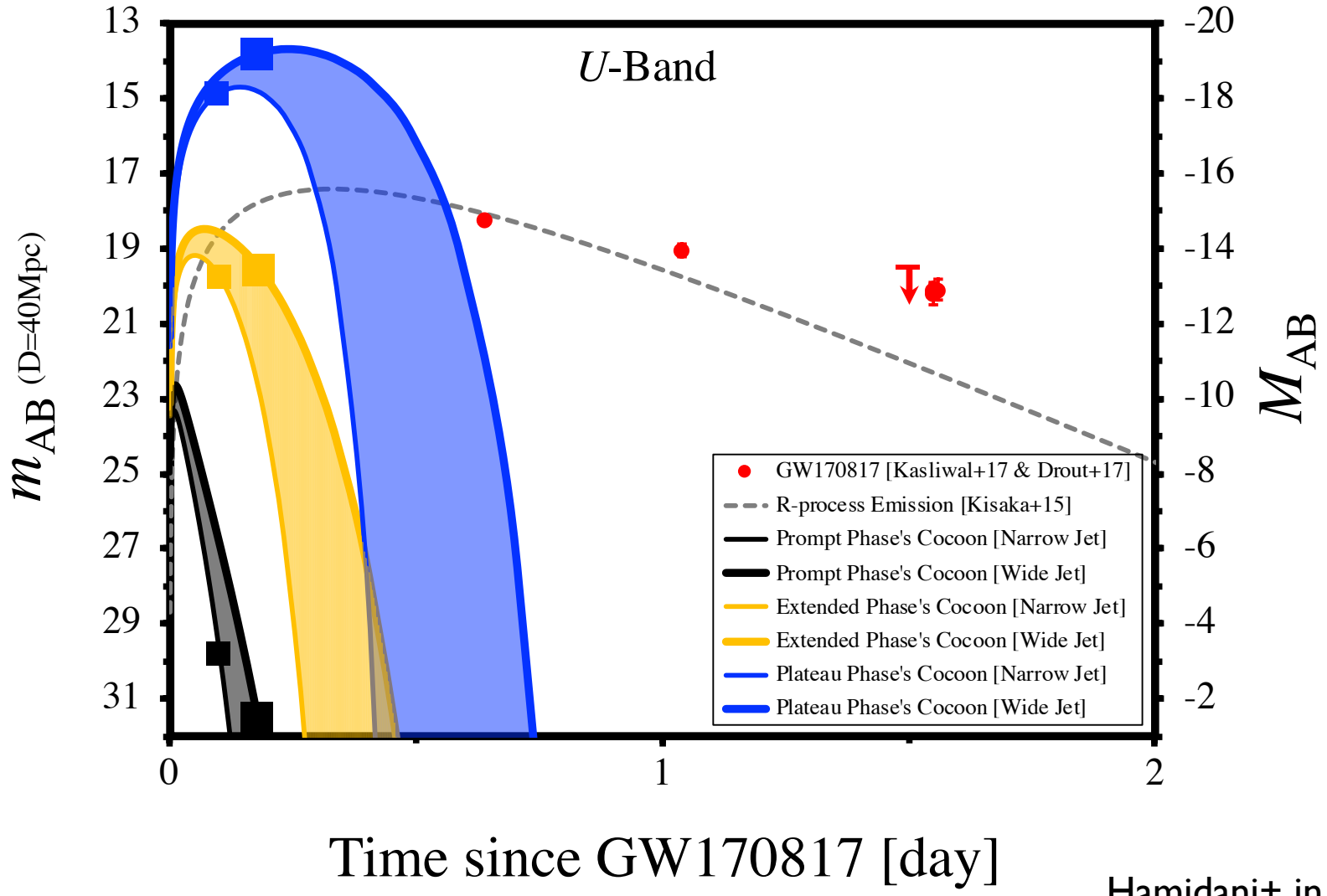
Heavy elements like C should be little in the star

Otherwise stellar wind
⇒ mass loss
⇒ too small M

Origin: Old stars

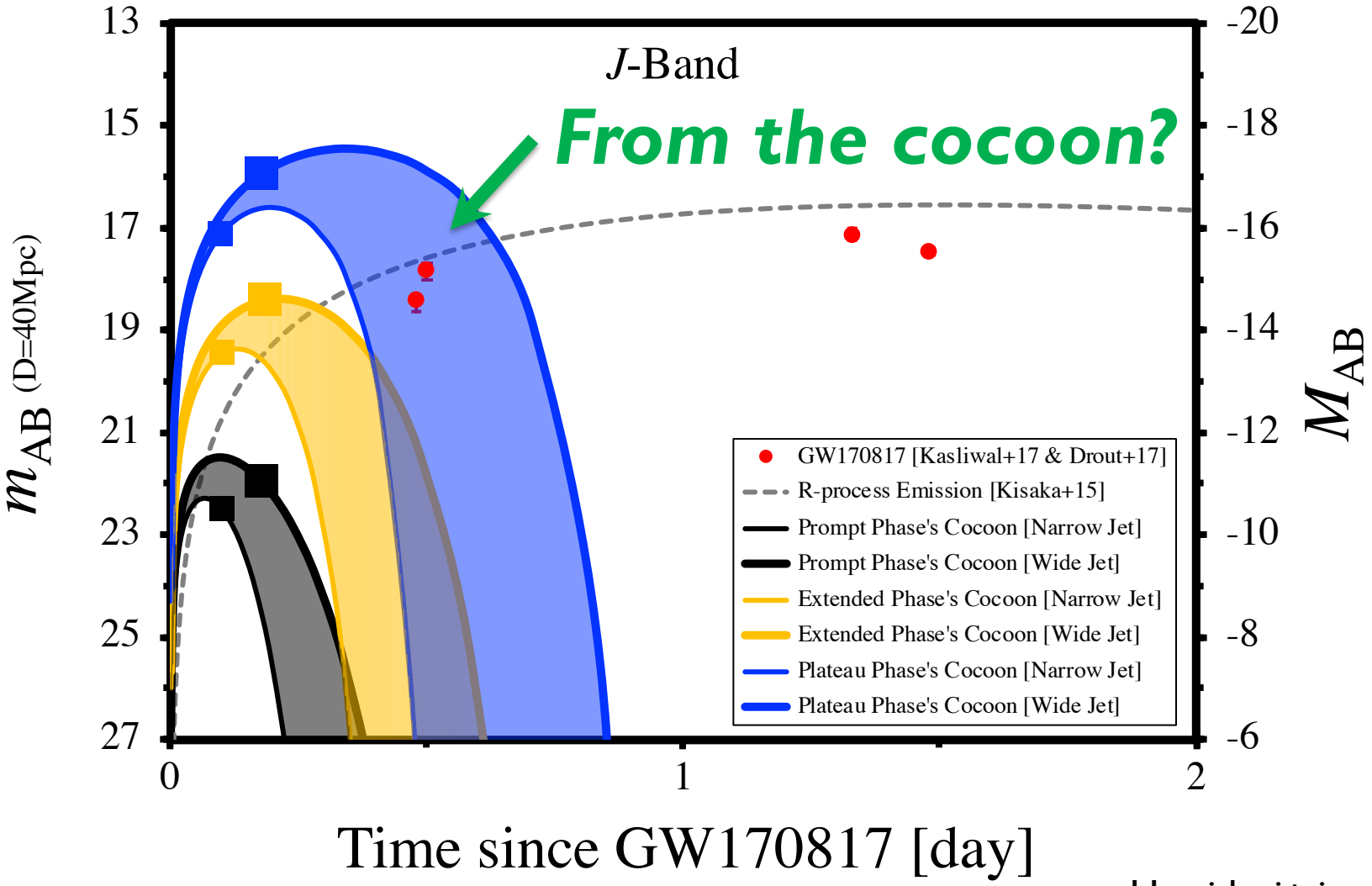
LIGO(astro) 16

Cocoon Emission



Hamidani+ in prep.

Cocoon Emission



Hamidani+ in prep.

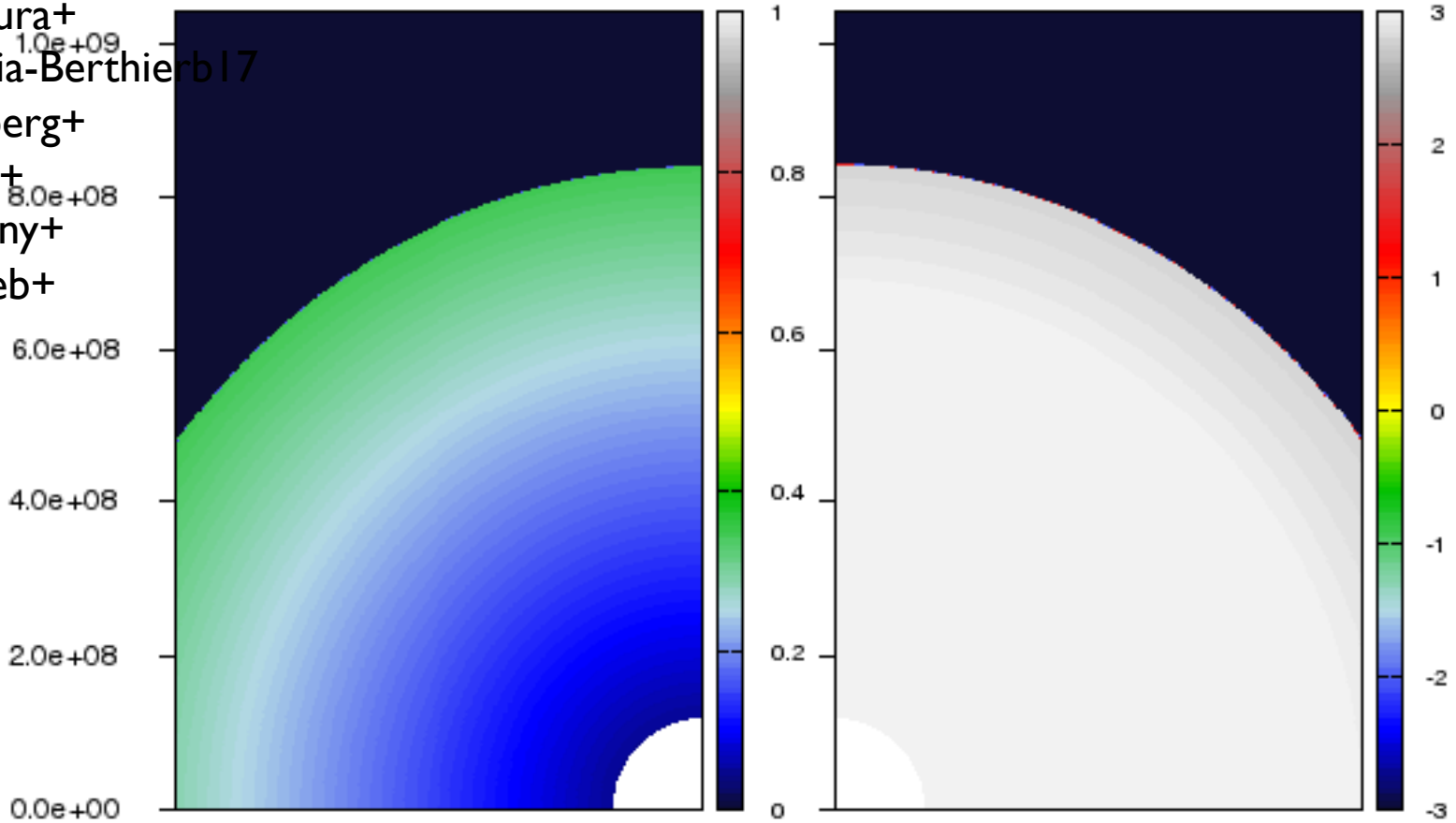
Breakout & Cocoon

Hamidani+ in prep.
Nagakura+
Murguia-Berthier+17
Bromberg+
Mizuta+
Morsony+
Gottlieb+

$\beta = \sqrt{\beta_r^2 + \beta_\theta^2}$

$log_{10}(\rho)$

Lazzati, Gottlieb, Geng, Gill's talk

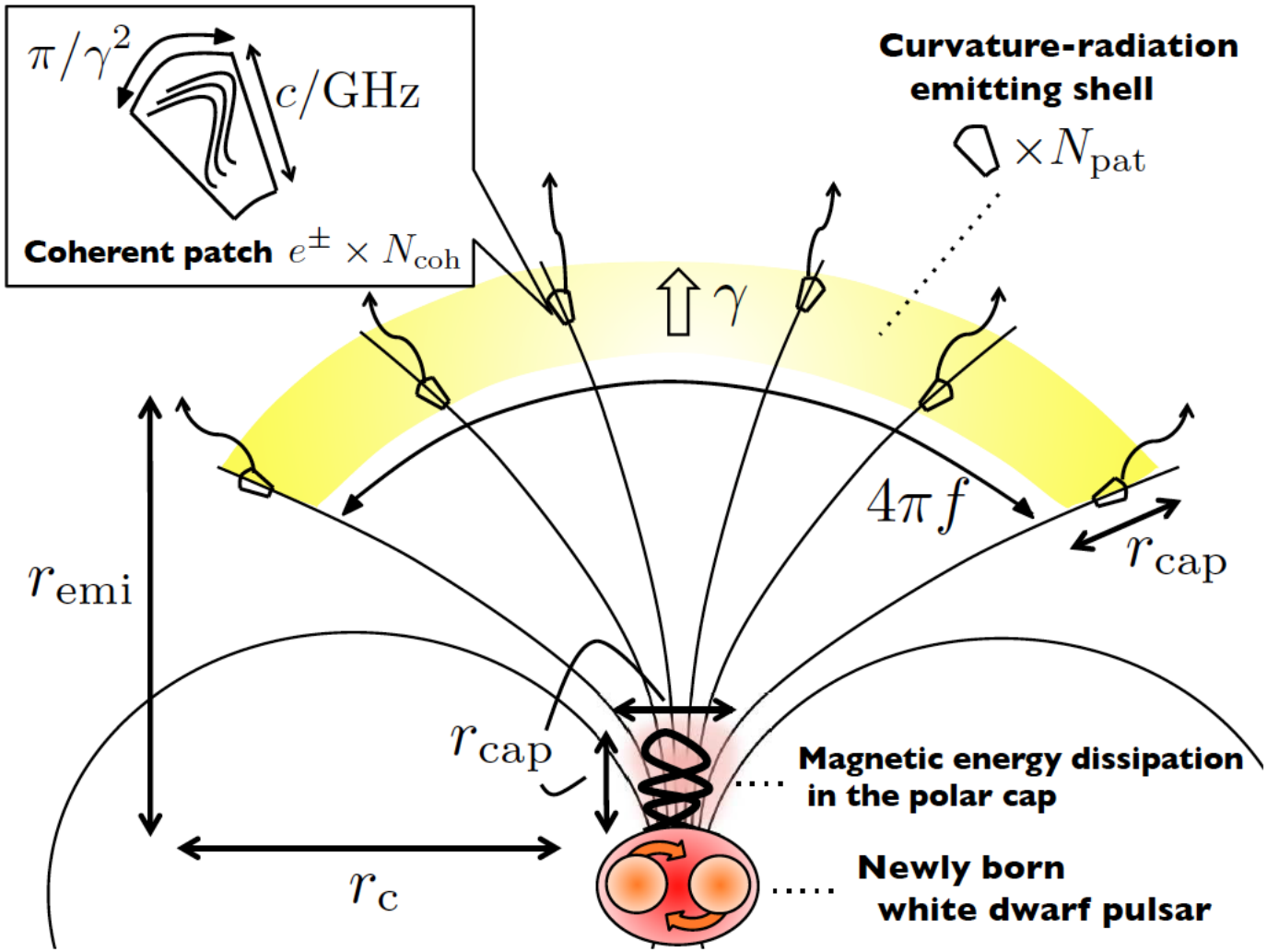


Velocity at t = 0.00 s

Density at t = 0.00 s

White Dwarf Mergers?

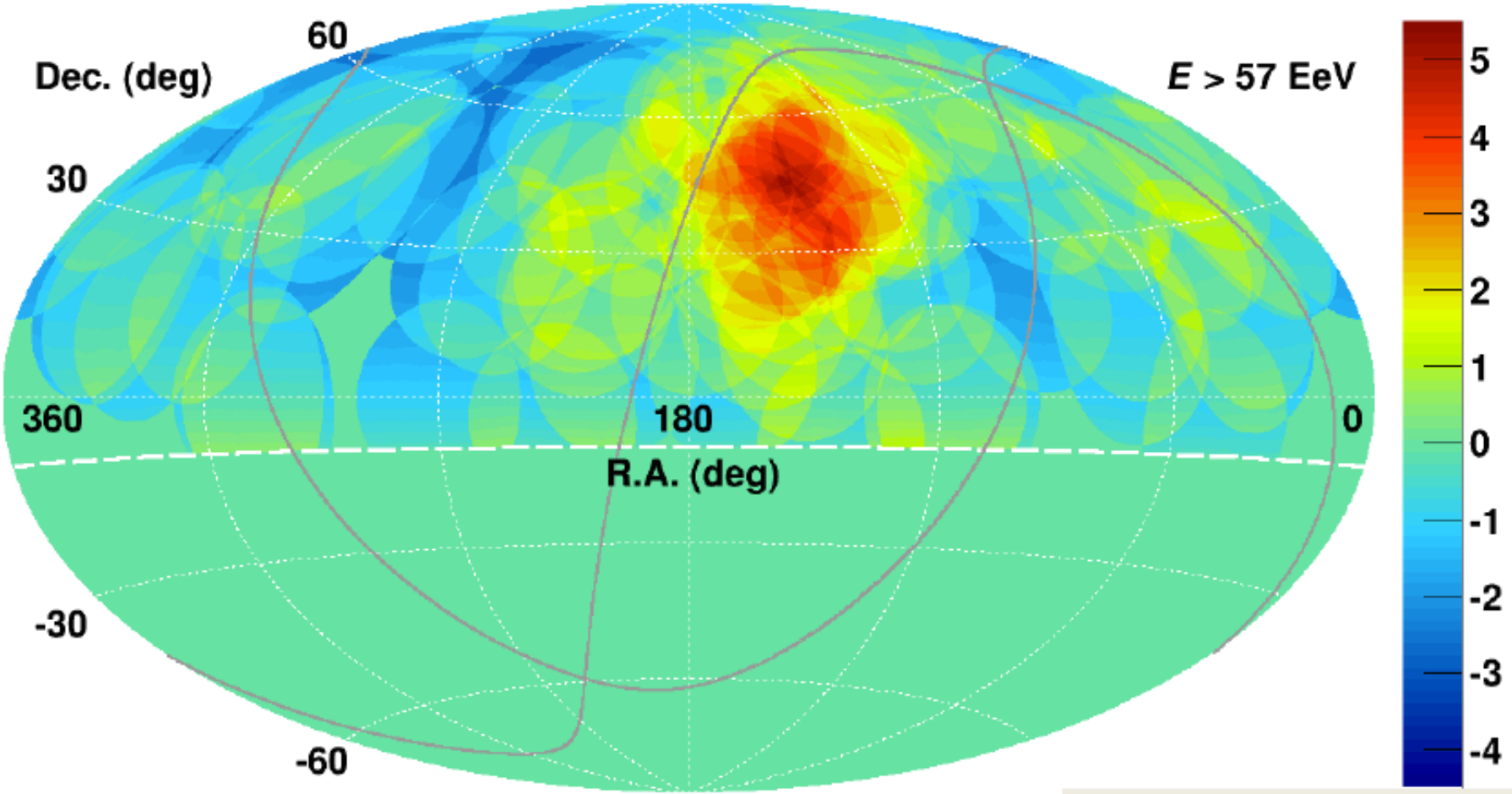
Kashiyama, KI & Meszaros 13



- Energetics $E_B \sim 10^{40}$erg
- Timescale $r_{cap}/c \sim$ms
- Event rate ~SN Ia
- SN Ia as a counterpart?

Significance Map 6 years

Oversampling with 20° -radius circle

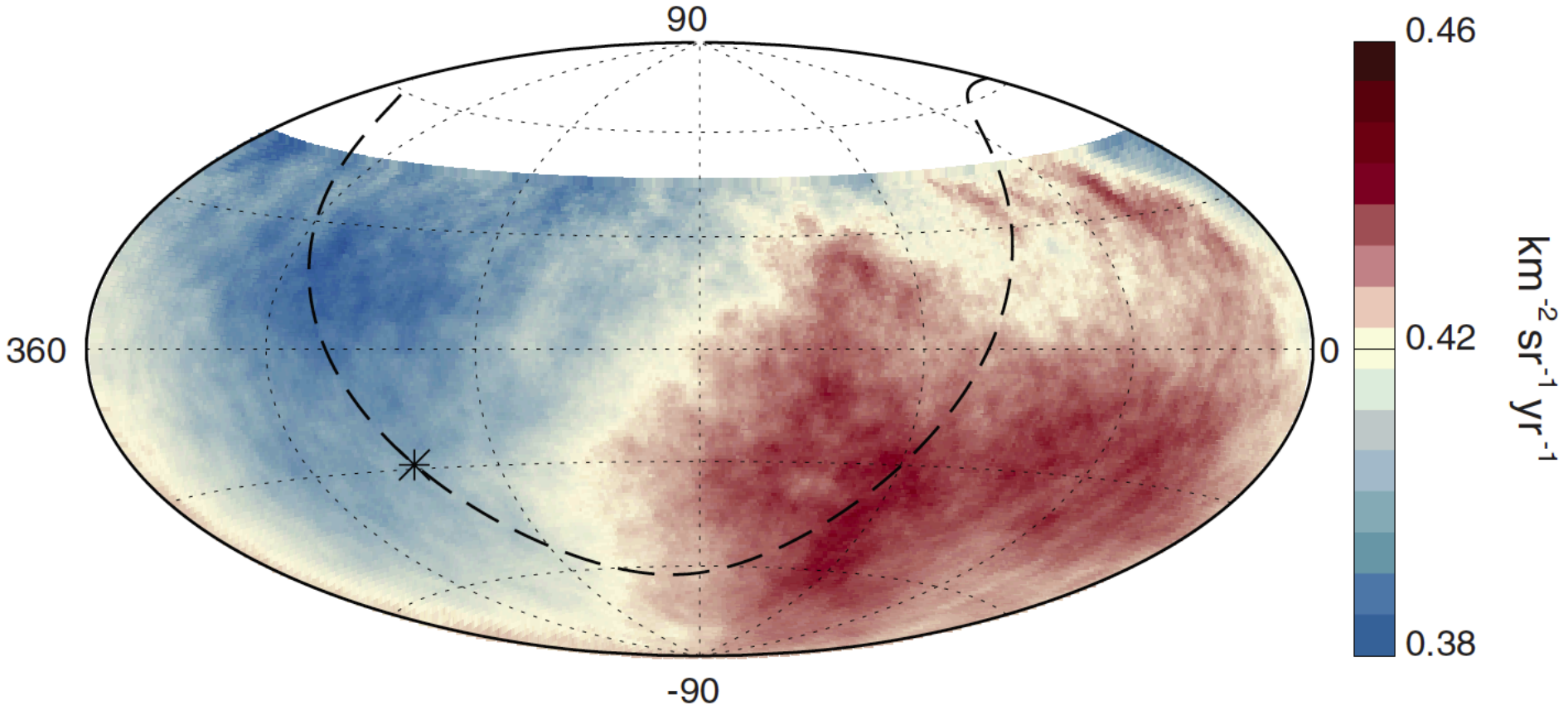


Slide K.Kawata @ ICRR seminar

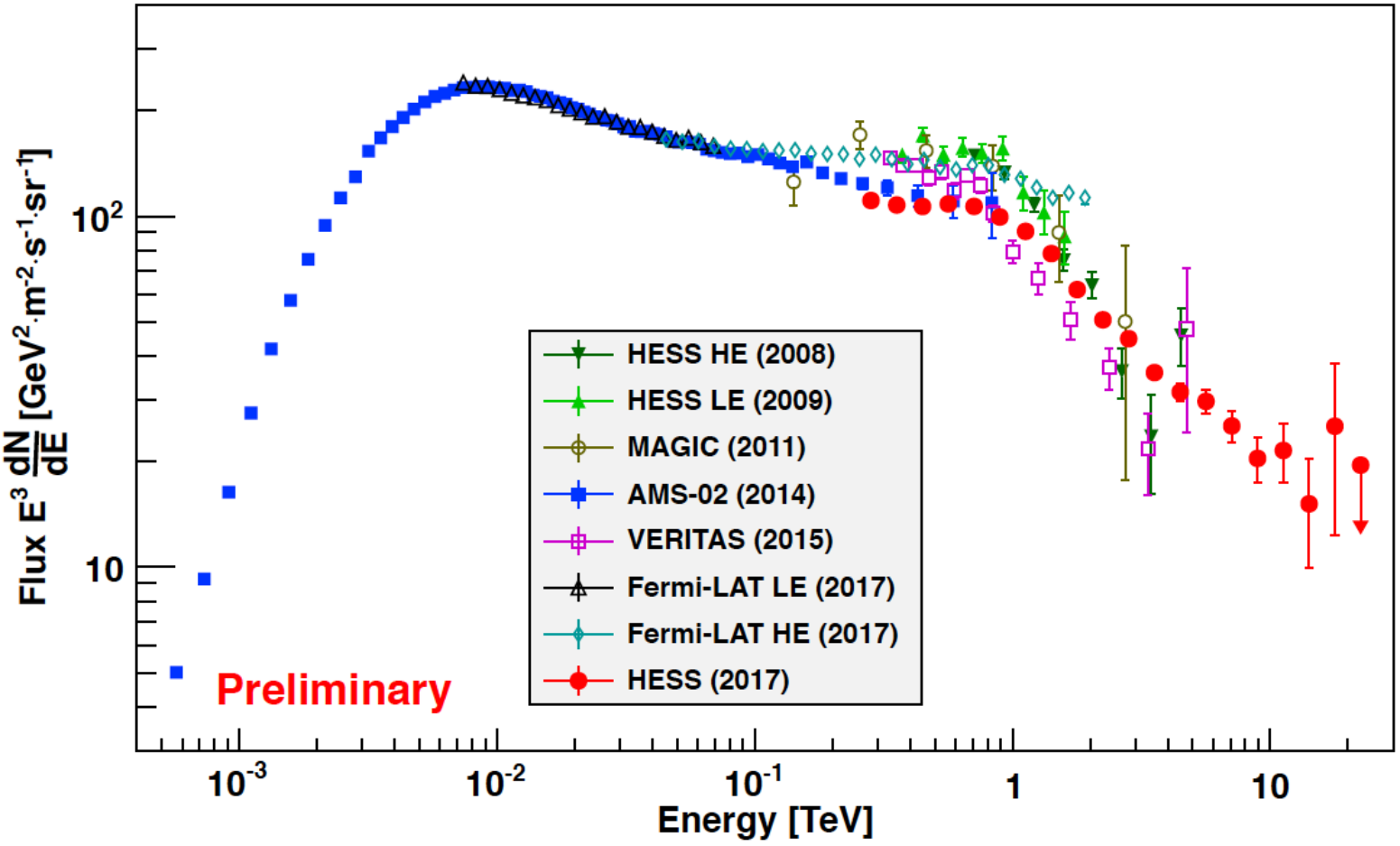
Max significance **5.55σ** (N_{on} = 23, N_{bg}=5.49)

Centered at R.A=148.4° , Dec.=44.5° (shifted from SGP by 17°)

Chance probability of appearing in isotropic sky → **4.0σ**


90
360
0
-90
0.46
0.42
0.38
km-2 sr-1 yr-1

New H.E.S.S. cosmic-ray electron spectrum



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