Study of Black Holes and Multi-Messenger Astronomy with CTA

Kunihito Ioka

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

KYOTO UNIVERSITY FOUNDED 1897 KYOTO JAPAN

YITP YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

CGP Center for Gravitational Physics Yukawa Institute for Theoretical Physics

Talk 2015

CTAで迫る物理

CTA Physics Drivers

井岡　邦仁

Kunihito IOKA

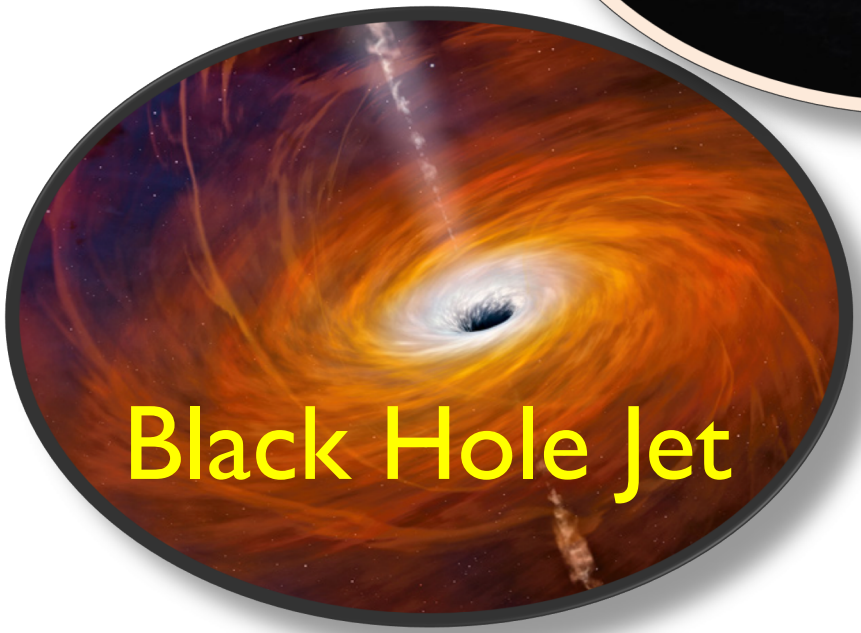
(KEK, SOKENDAI)

Talk 2015

Mysteries in 21th Century

?

• • •



Talk 2015

Mysteries in 21th Century

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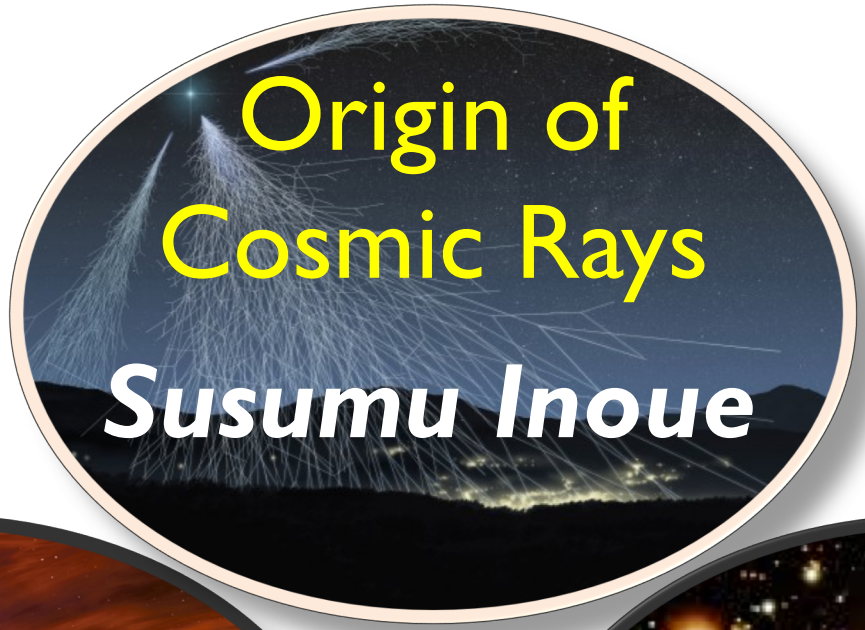

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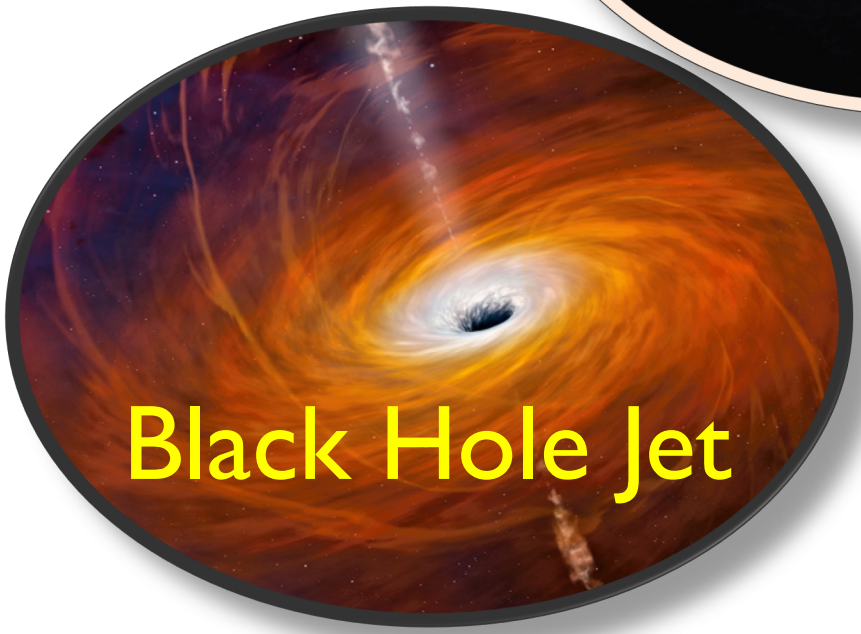
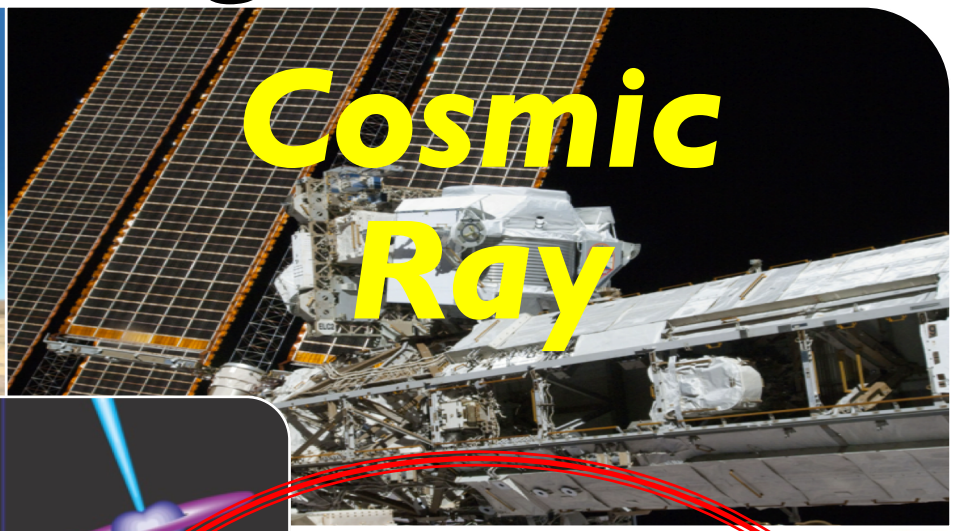
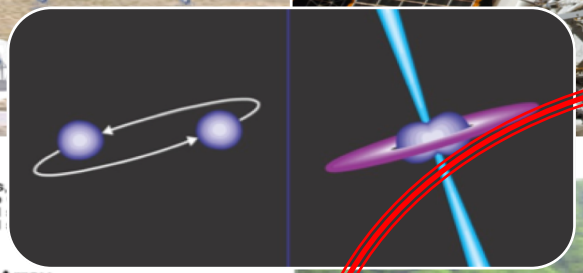
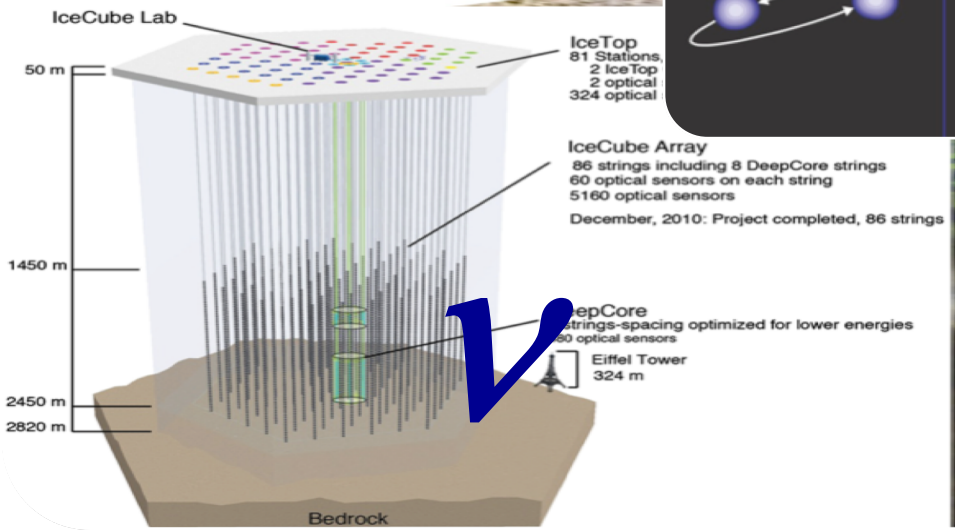


Multi-Messenger Era



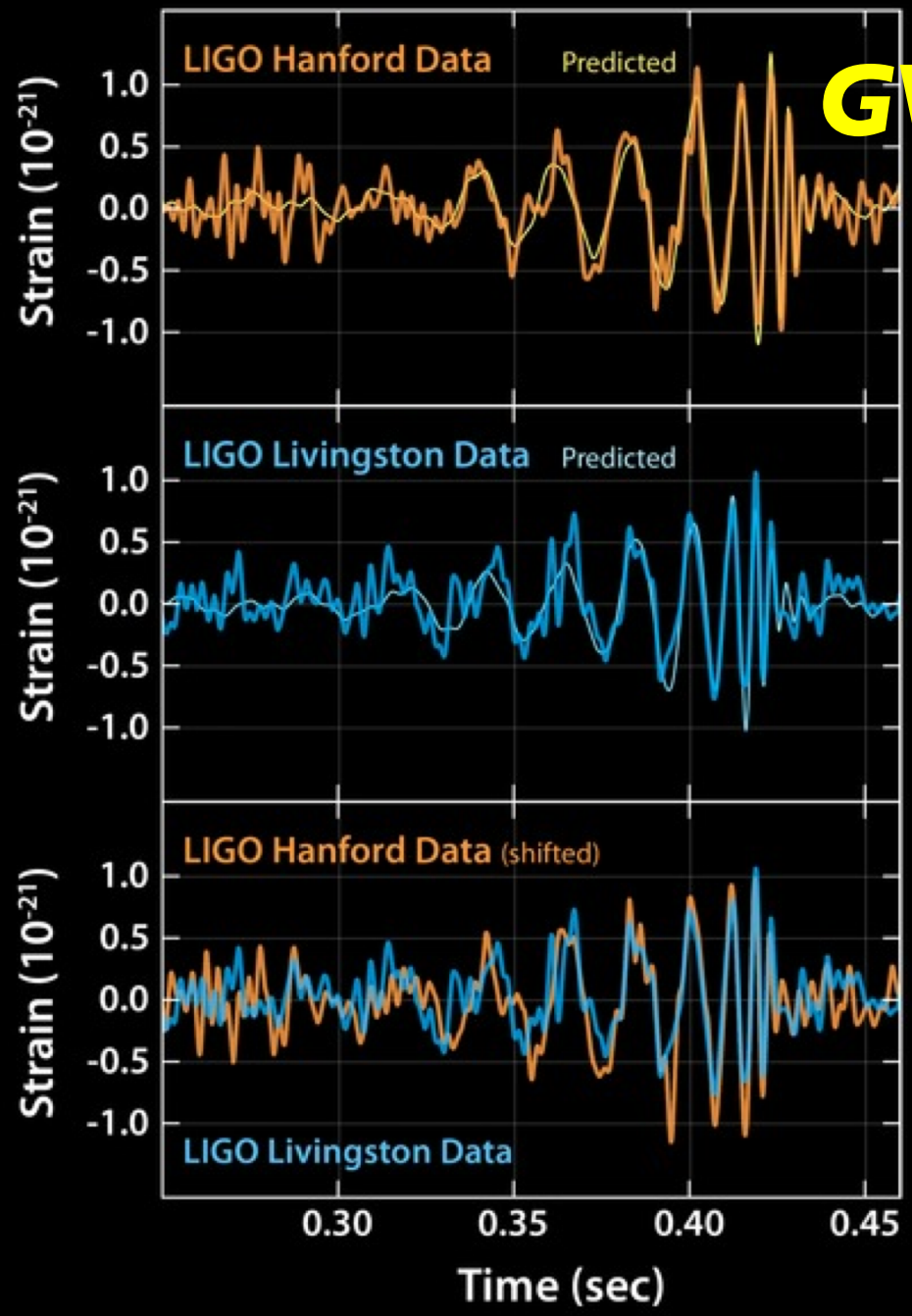




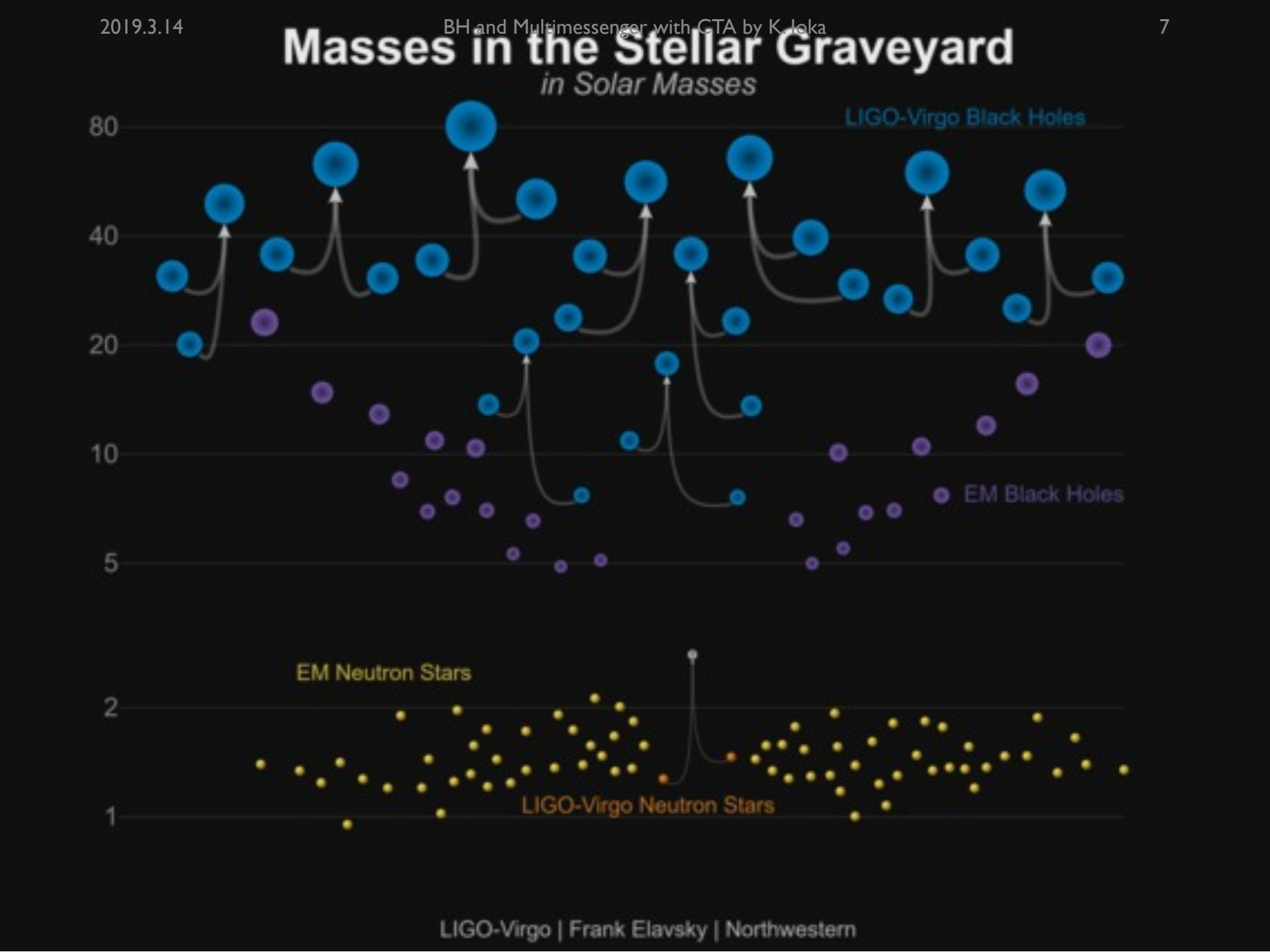
21th Century: Multi-Messenger Era

GW150914

Amplitude of Gravitational Waves

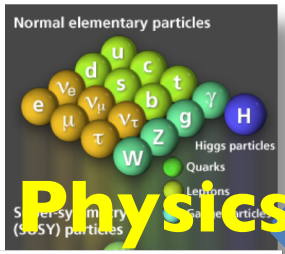


LIGO 16

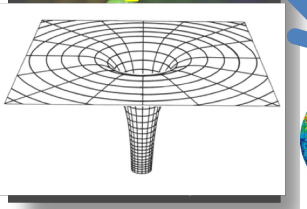

Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

Evolution to Black Holes

Gravity
Quantum



Physics



Star

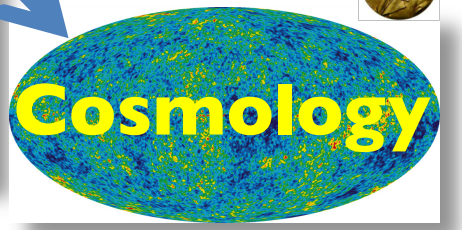
Supernova GRB

Supernova Remnant

W. A. Fowler

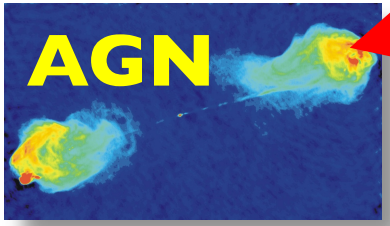
Chandrasekhar
Bethe

Davis
Koshiba



Cosmology

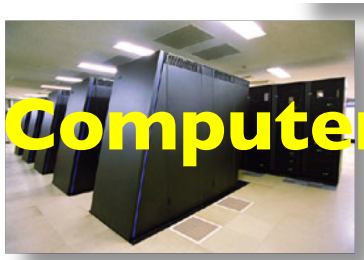
Weiss, Barish & Thorne



AGN

Compact Star

Cosmic Ray



Computer

Penzias, Wilson
Mather, Smoot
Perlmutter, Riess, Schmidt

Active galactic nuclei
Massive black hole
at the center of galaxy

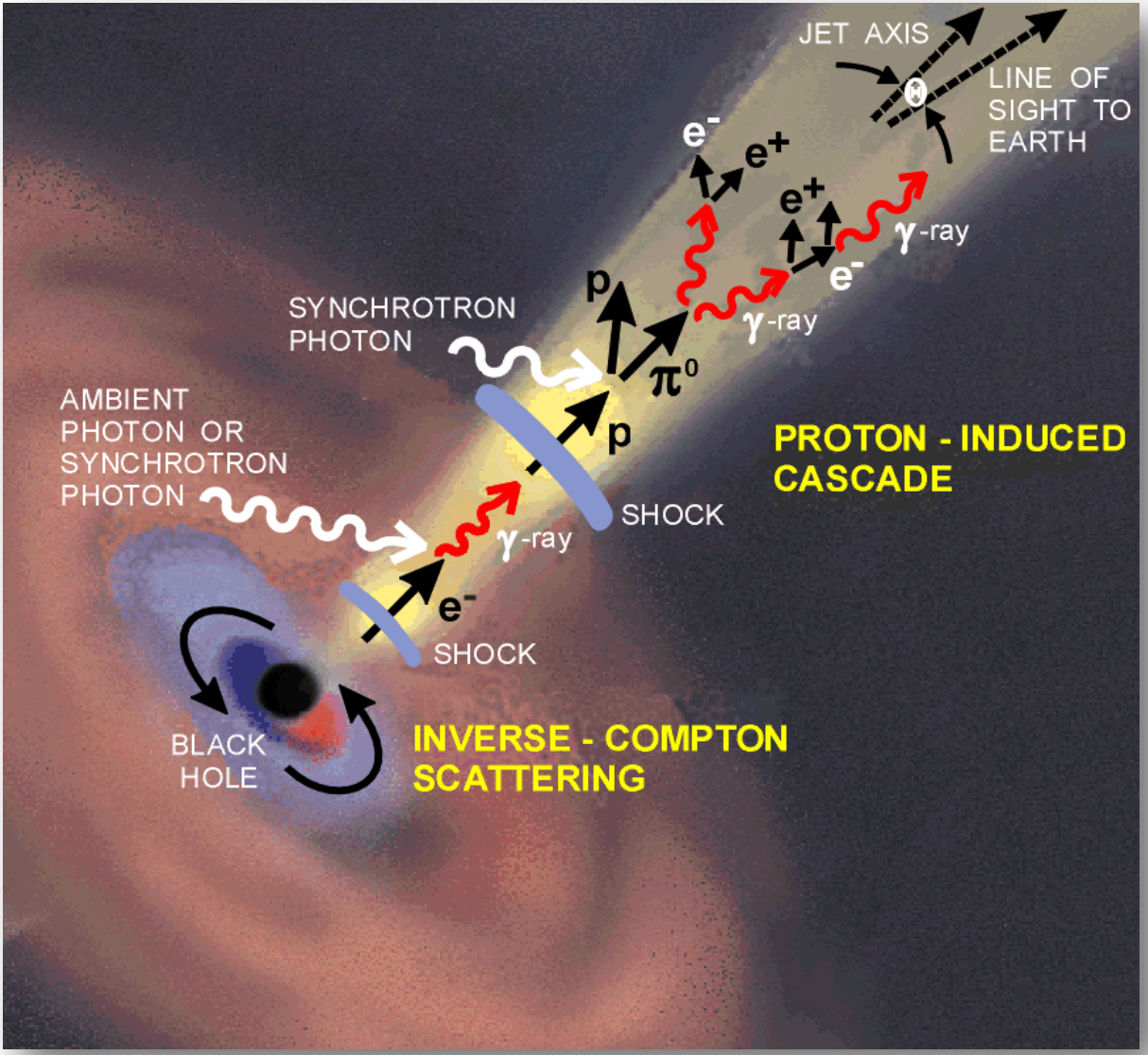
Black Hole
Neutron Star
White Dwarf

Giacconi
Hewish
Hulse, Taylor

Hess
Anderson
Yukawa
Powell
Kajita

High Energy Universe

How to Form a Jet?



B, e±, p, Fe?

Lorentz factor?

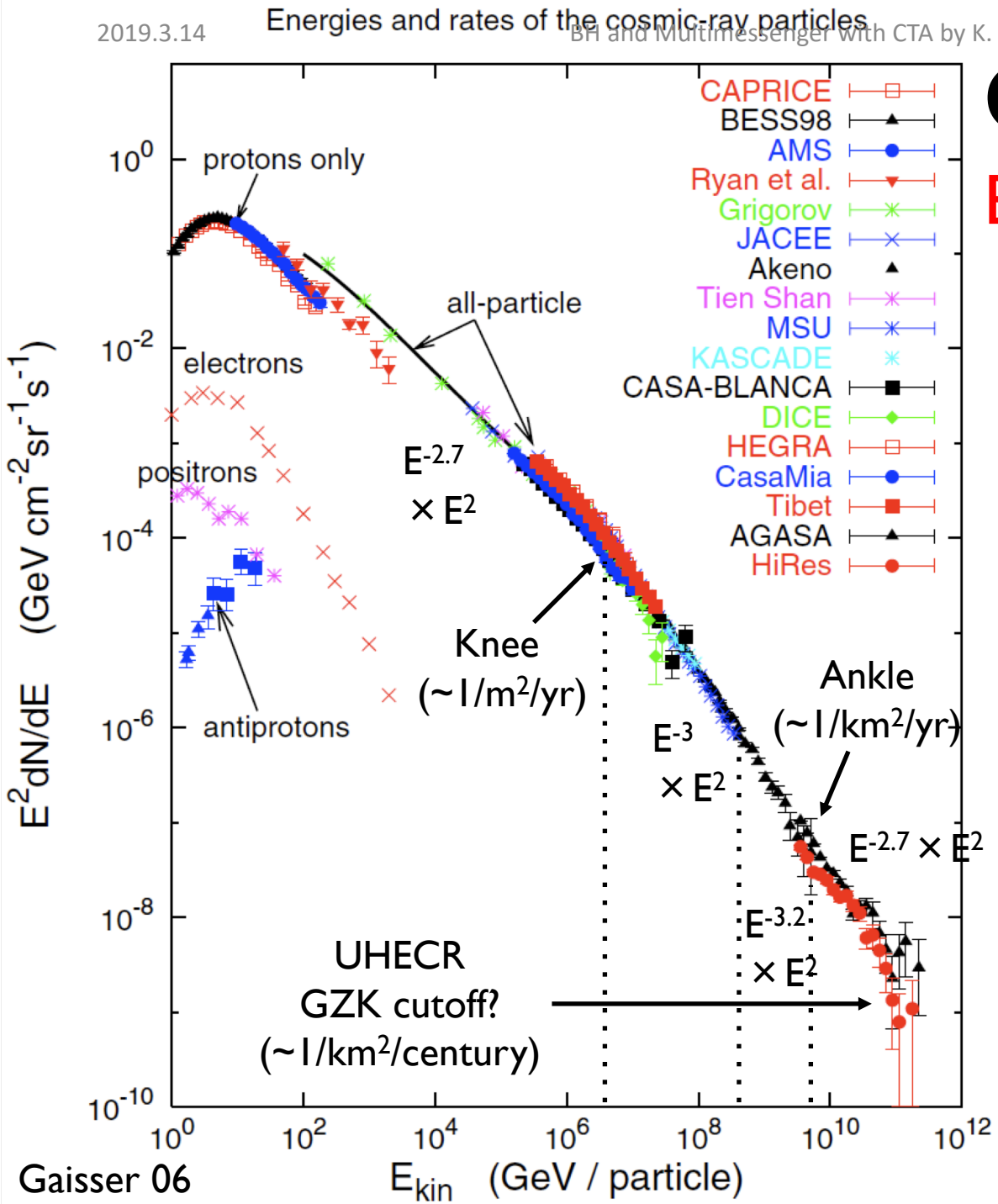
Dissipation?

p acceleration?

Jet? Disk wind?

has a jet

has no jet



Gaisser 06

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)

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

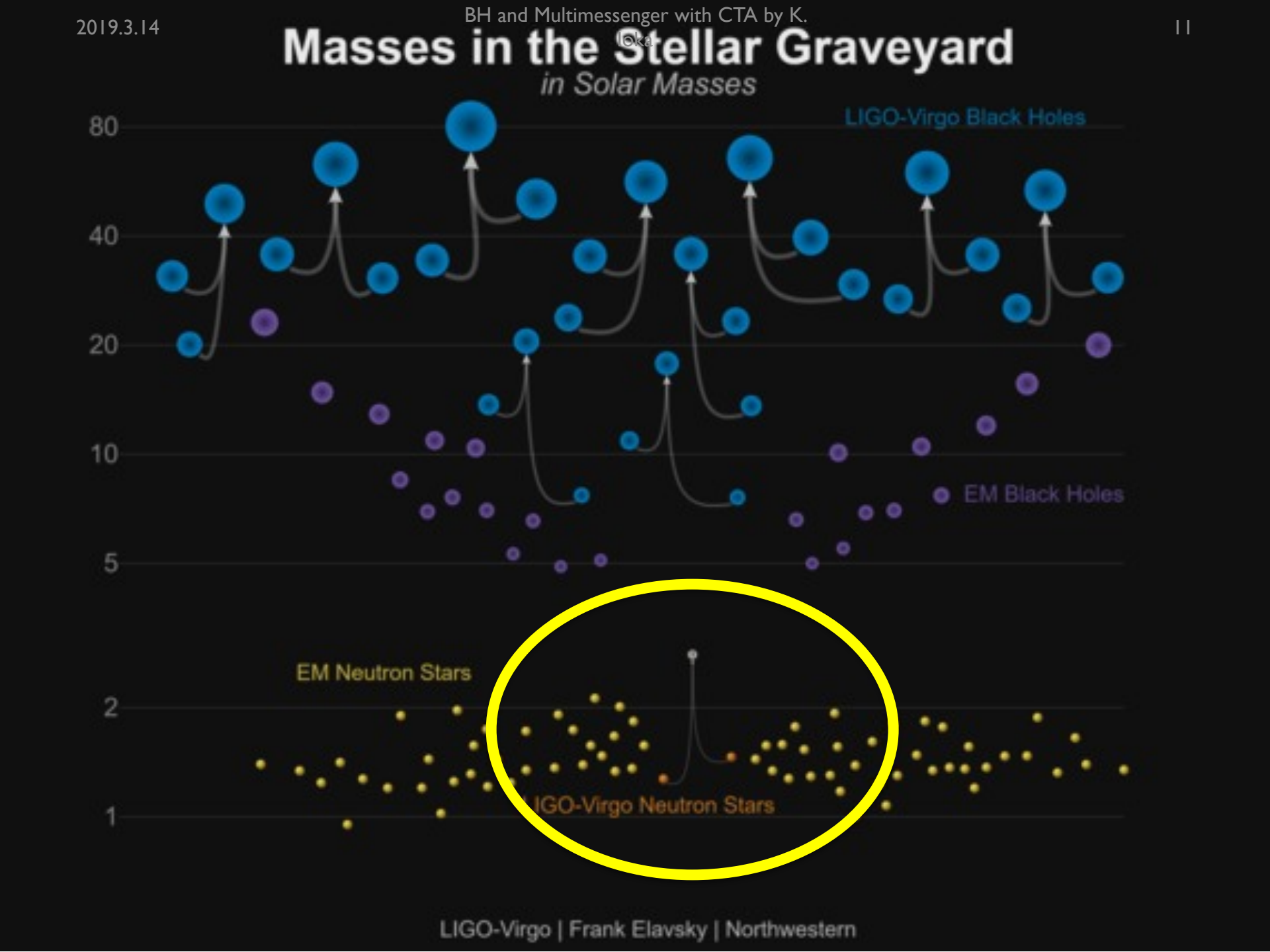
Galactic origin?

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

10^{18}eV$<E$

$F \propto E^{-2.7}$

Extra-Gal. AGN? GRB?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LIGO-Virgo Black Holes
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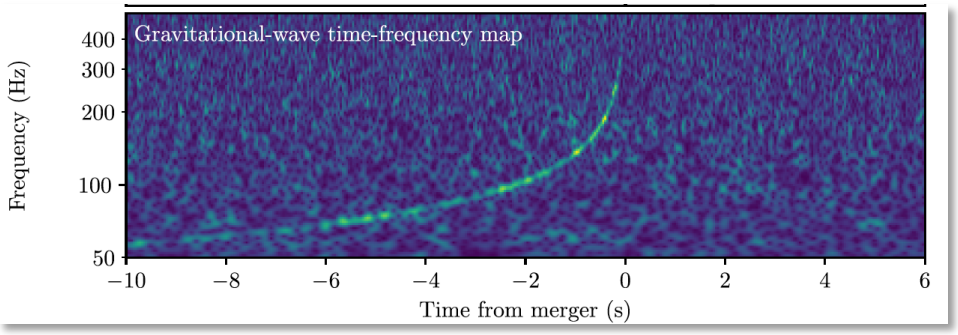
LIGO-Virgo | Frank Elavsky | Northwestern

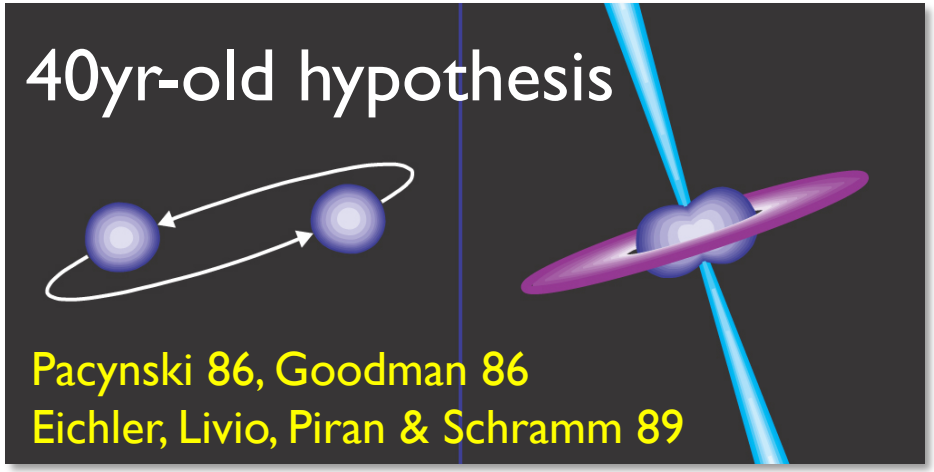
GW170817

1st GW from NS²



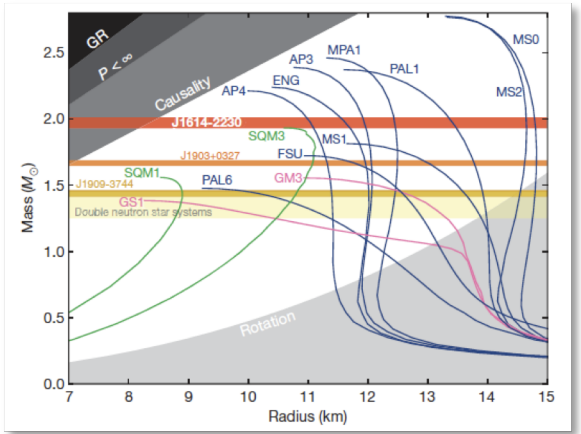
~100 sec chirp ⇒ NS-NS

NS² = Short GRB?

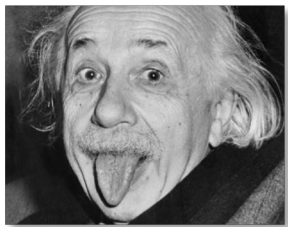


R-process elements

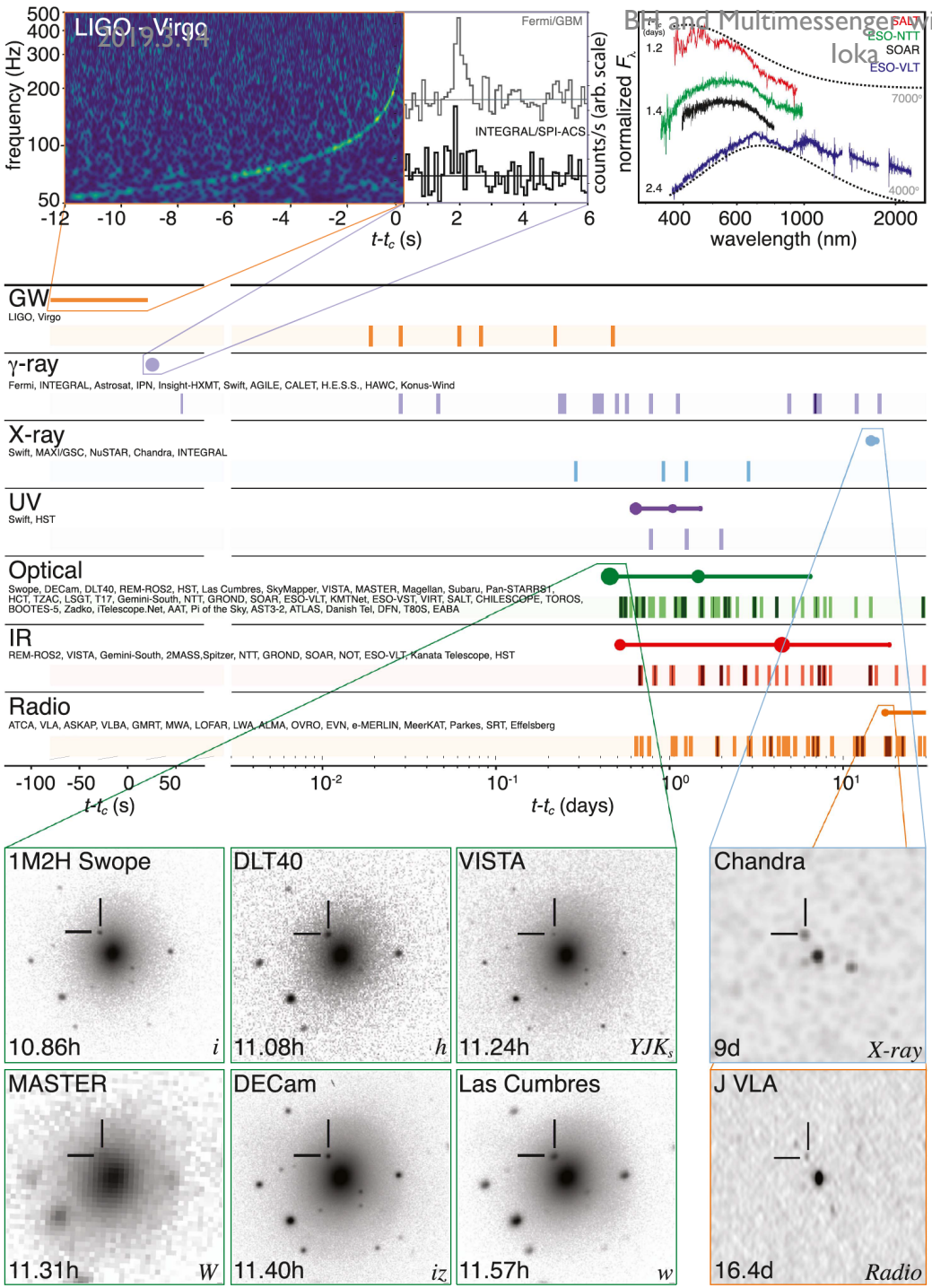
Equation of state



Relativity,
Cosmology,
…



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

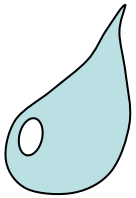
LVC-EM 17

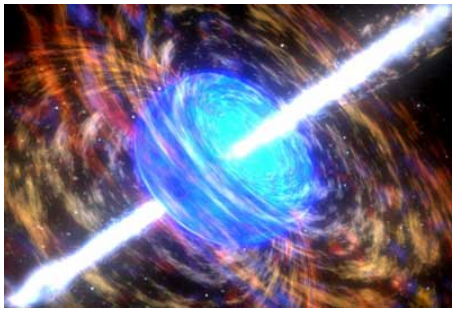
Band: GCN circ., Circles ∝ brightness

Gamma-Ray Burst

$E=mc^2$ (by Einstein)

=





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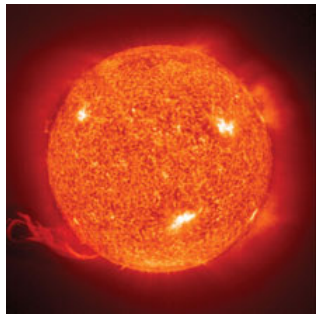


Atomic bomb ~1kg

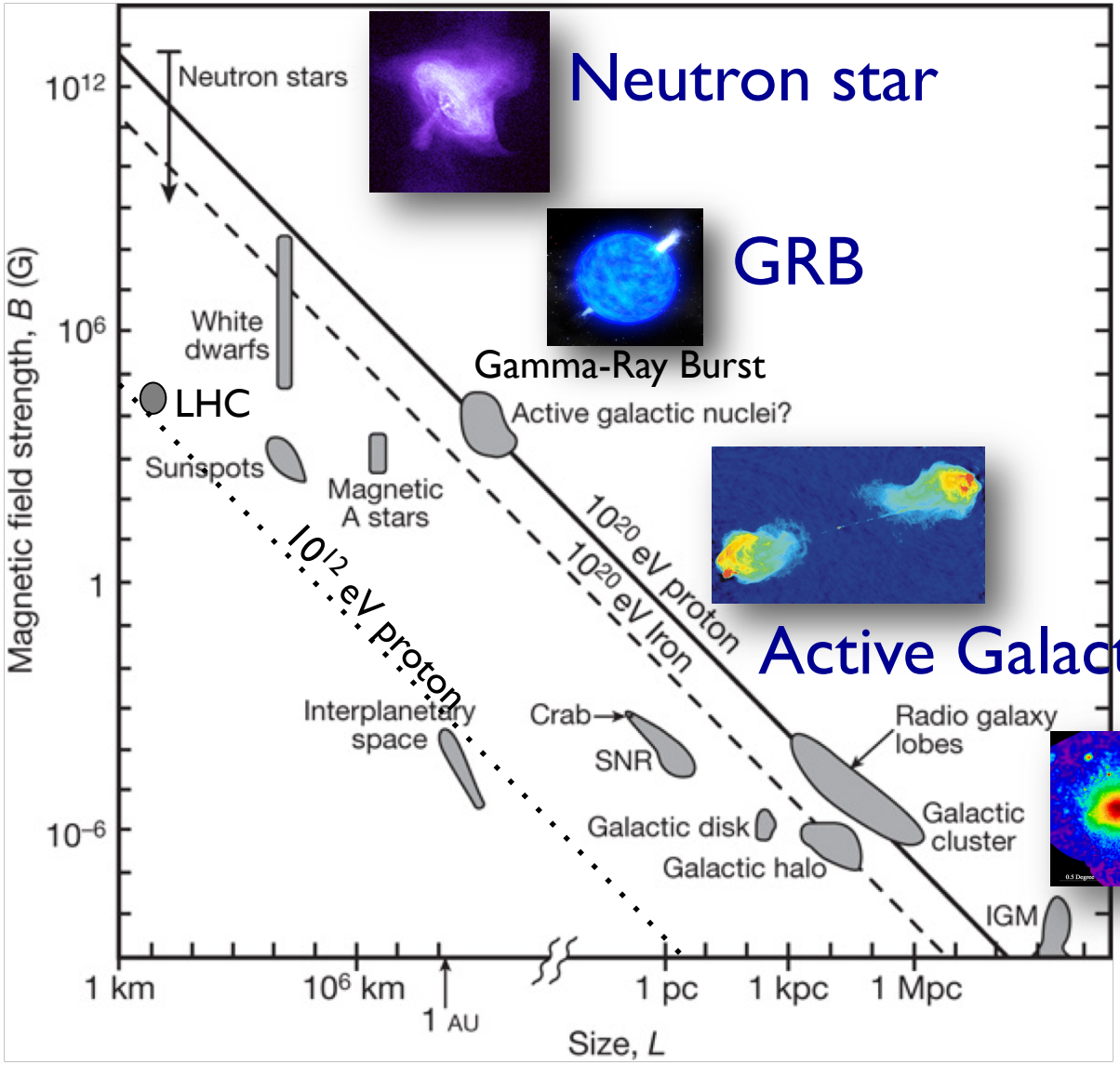
GRB ~10^{52}erg

Sun ~10^{33}g

In ~sec, GRB release energy Sun emit over lifetime

GRB is the most luminous object

Particle Acceleration



Neutron star

GRB

Active Galactic Nuclei

Galaxy Cluster

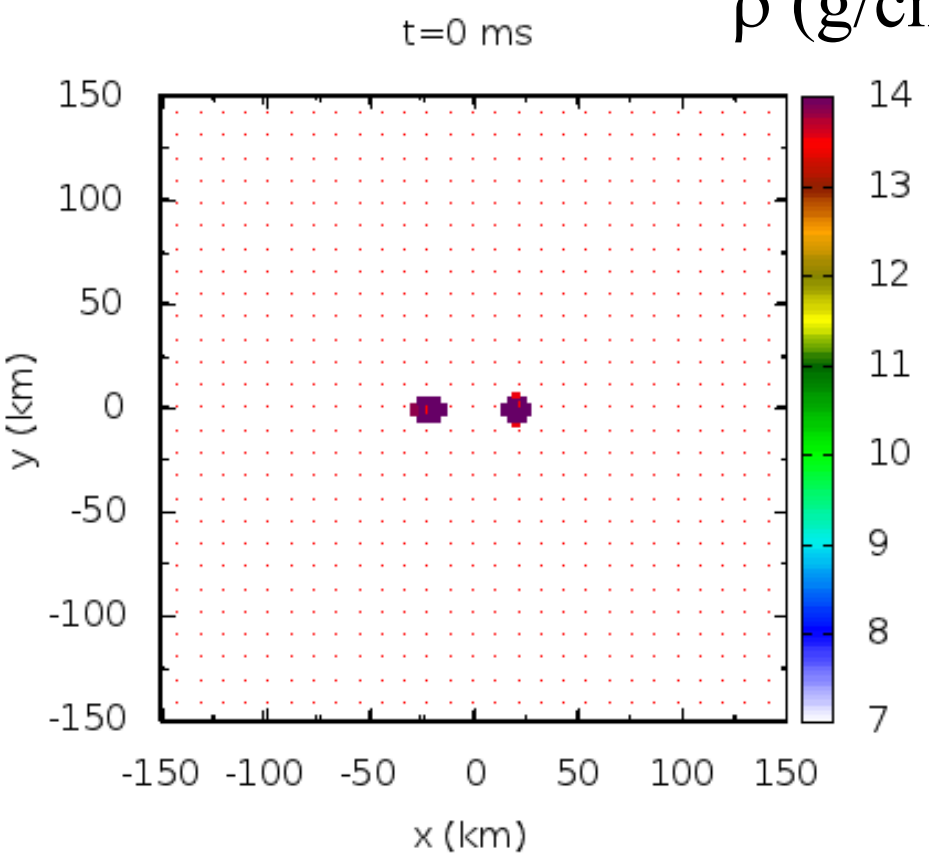
- Hillas condition
  $E<ZqBR$
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
  $\propto (BR)^2$ Blandford 00 Waxman 04
- E_{max}>EeV

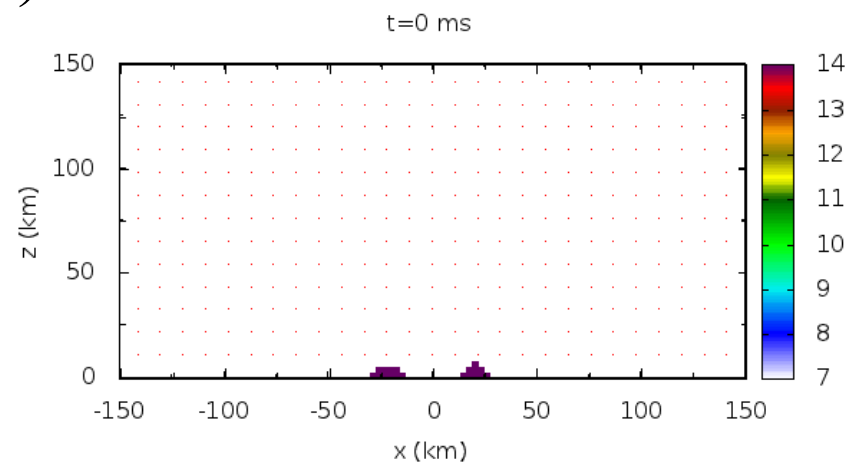
TeV sources

Dark Matter?

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

ρ (g/cm^3)



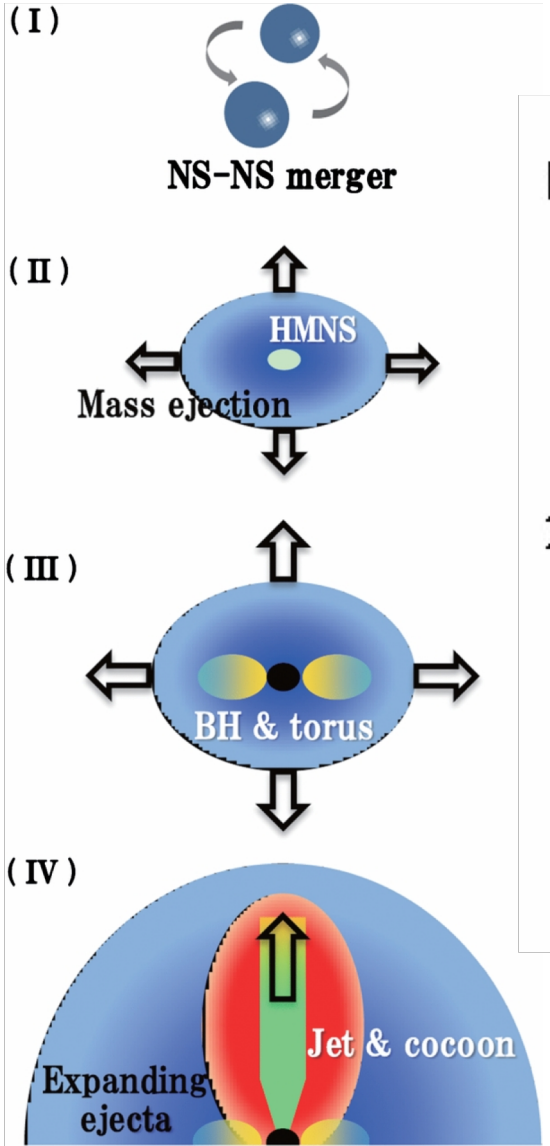


Relatively wider view

Orbital plane ***X-Z* plane**

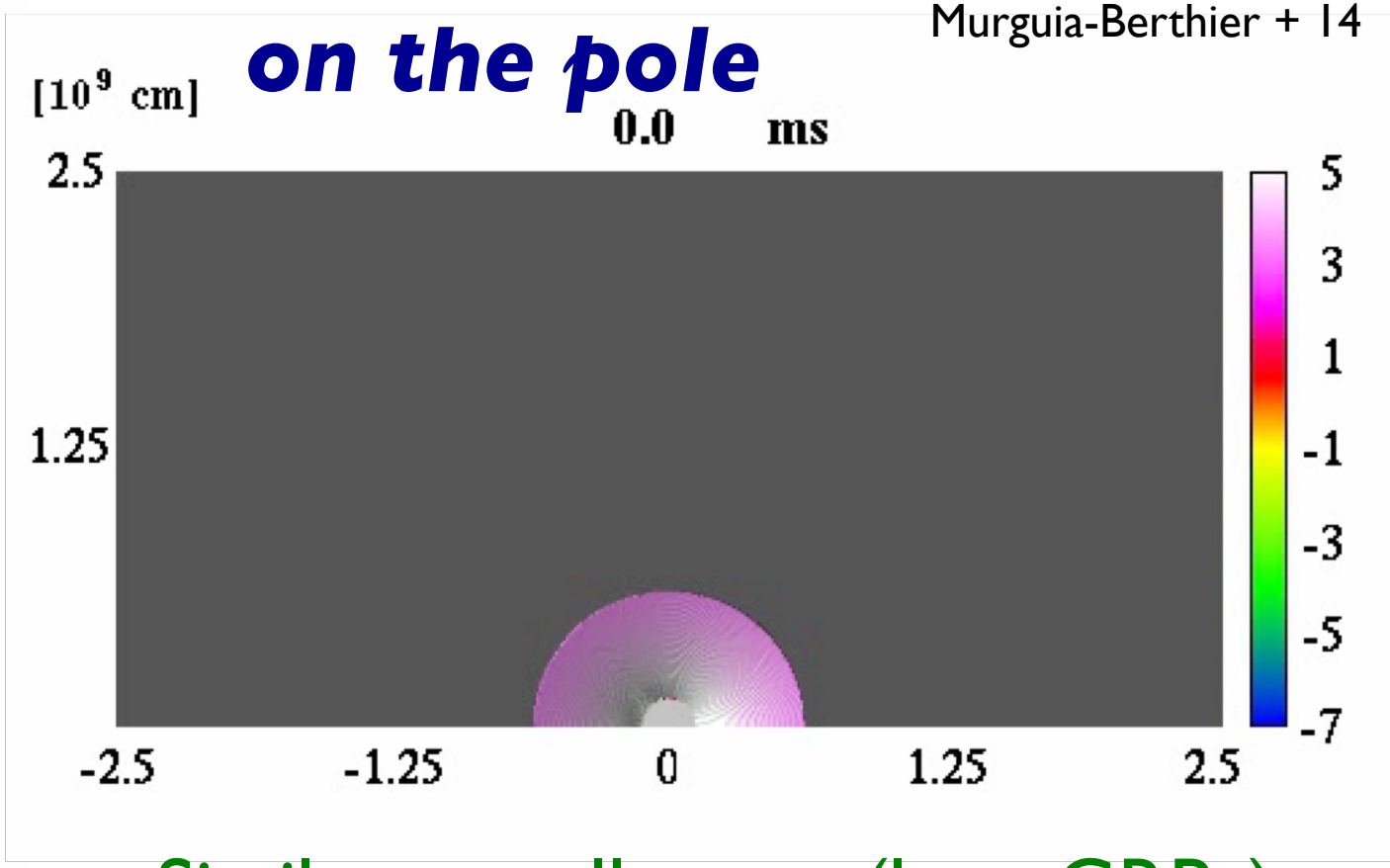
©Shibata, Hotokezaka

Jet Breakout from Ejecta



Ejecta is also on the pole

Nagakura+ 14
Murguia-Berthier + 14

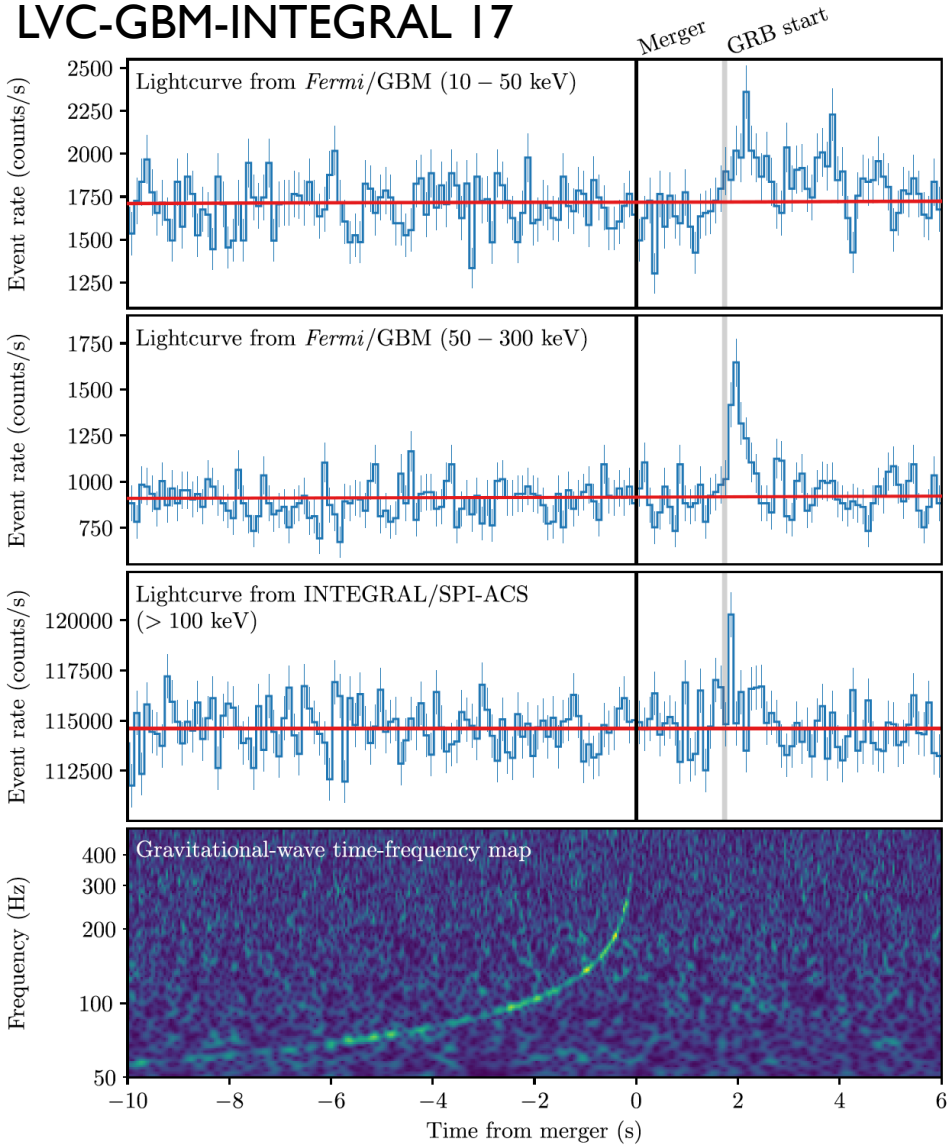


Similar to collapsars (long GRBs)

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

GW170817 & GRB 170817A

LVC-GBM-INTEGRAL 17

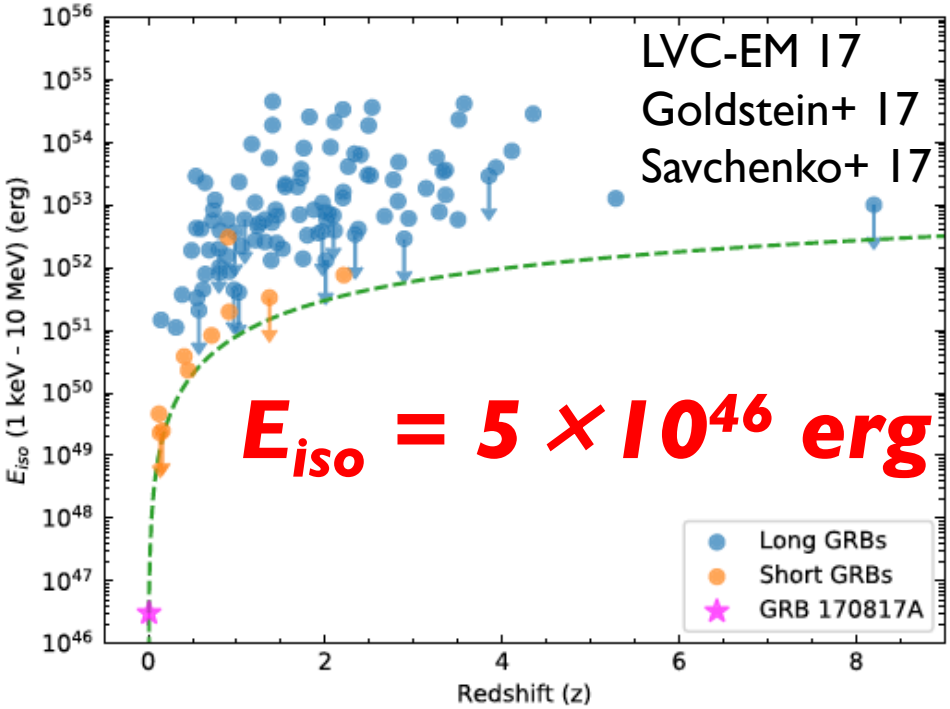


3 (of 12) GBM NaI detectors

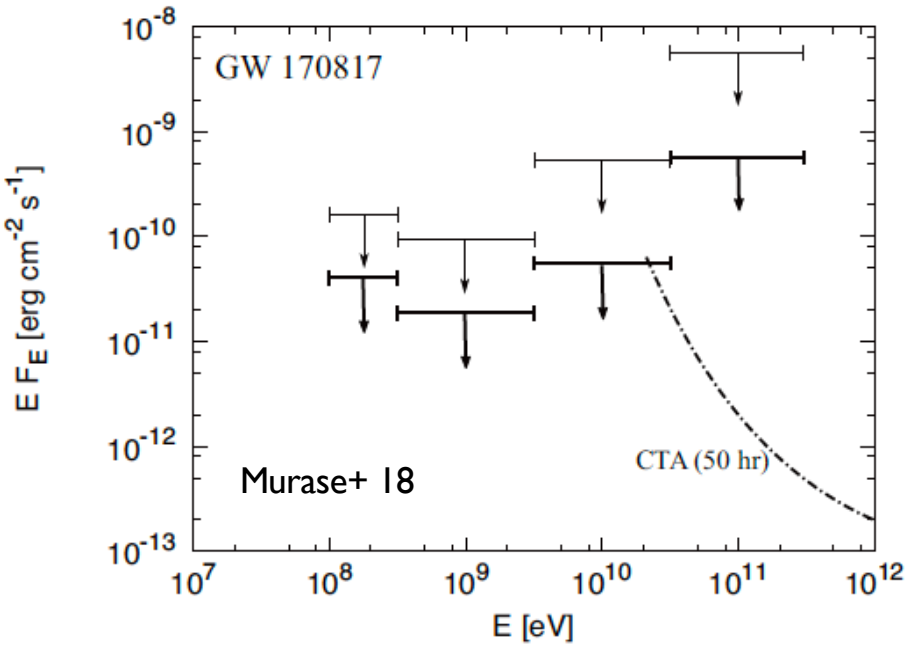
T_0=1.74±0.05 sec (68%)

T_{90}=2.0±0.5 sec

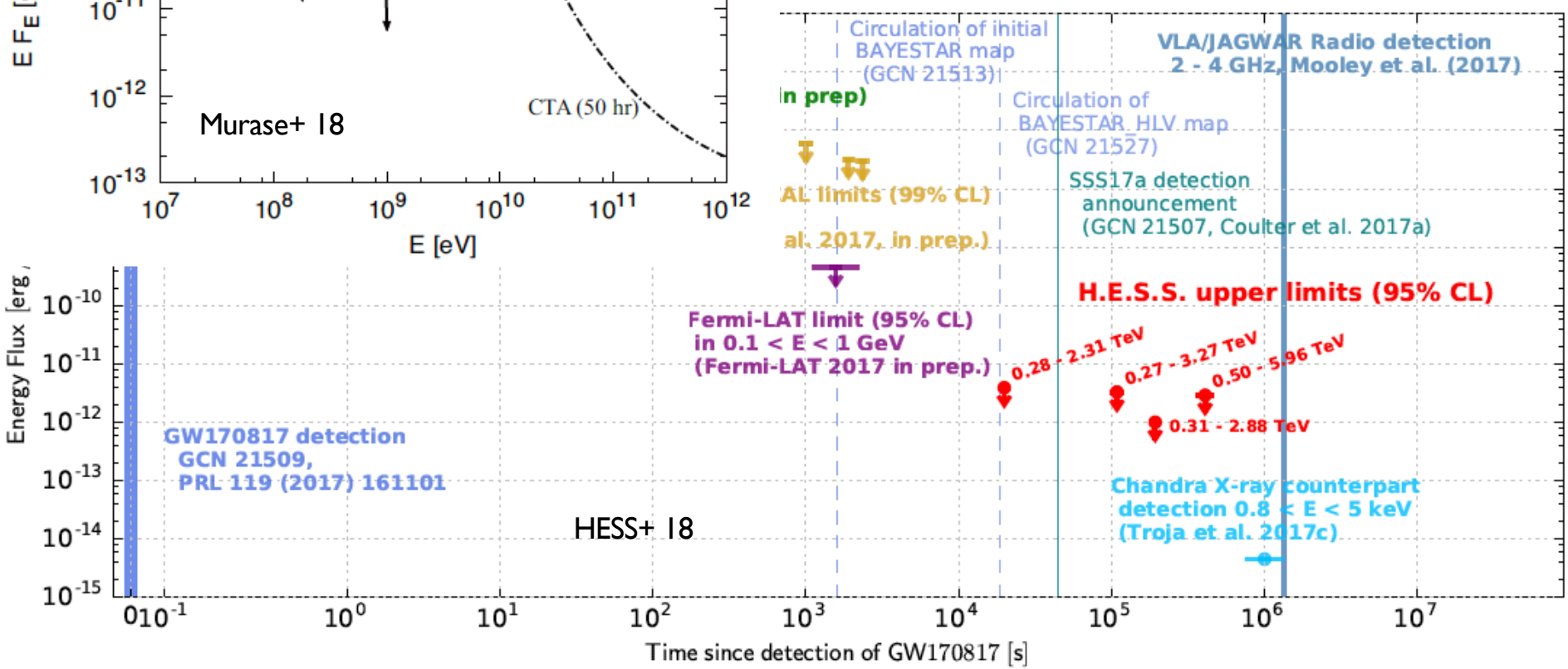
Weak but Detected



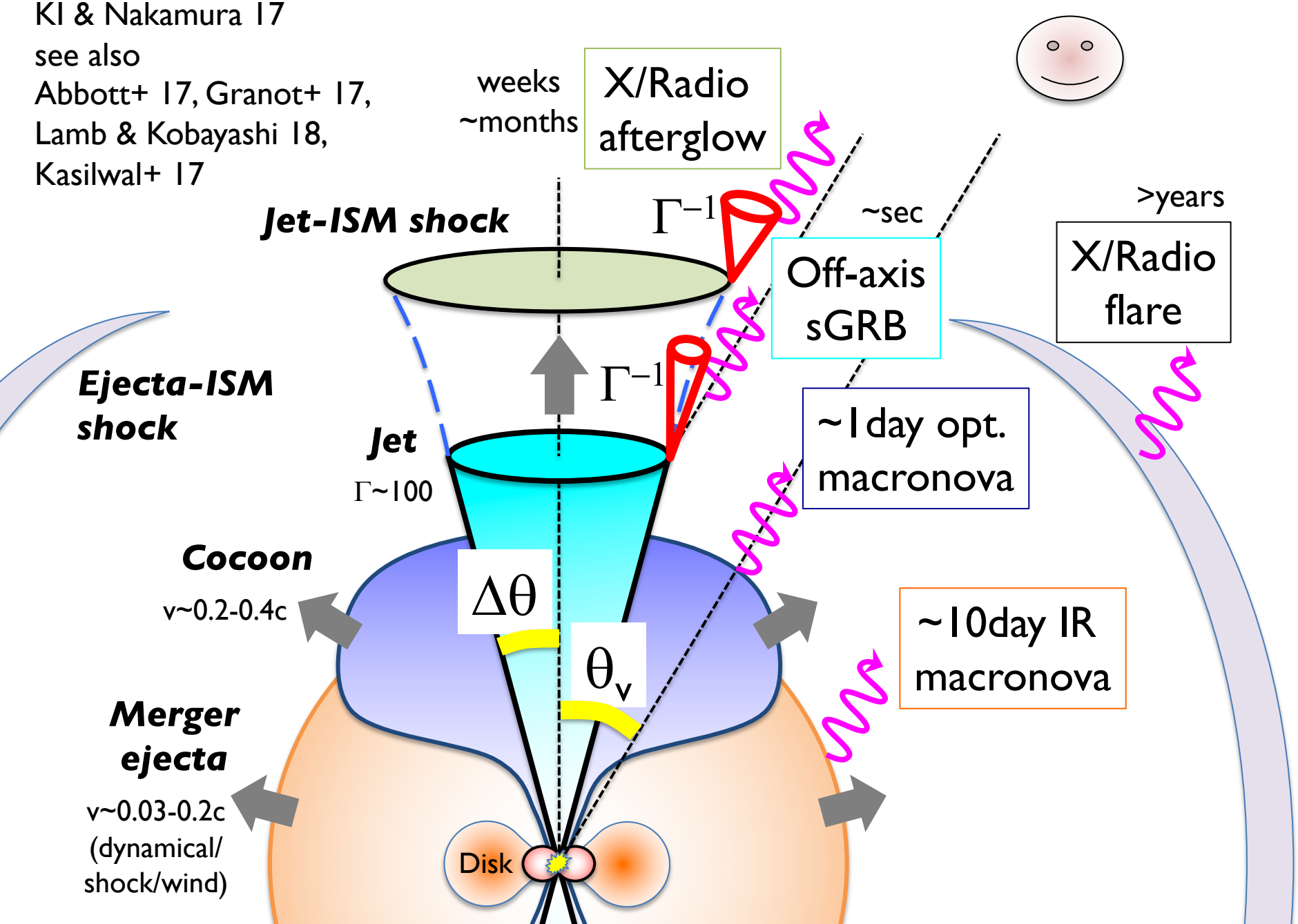
Limits on GW170817



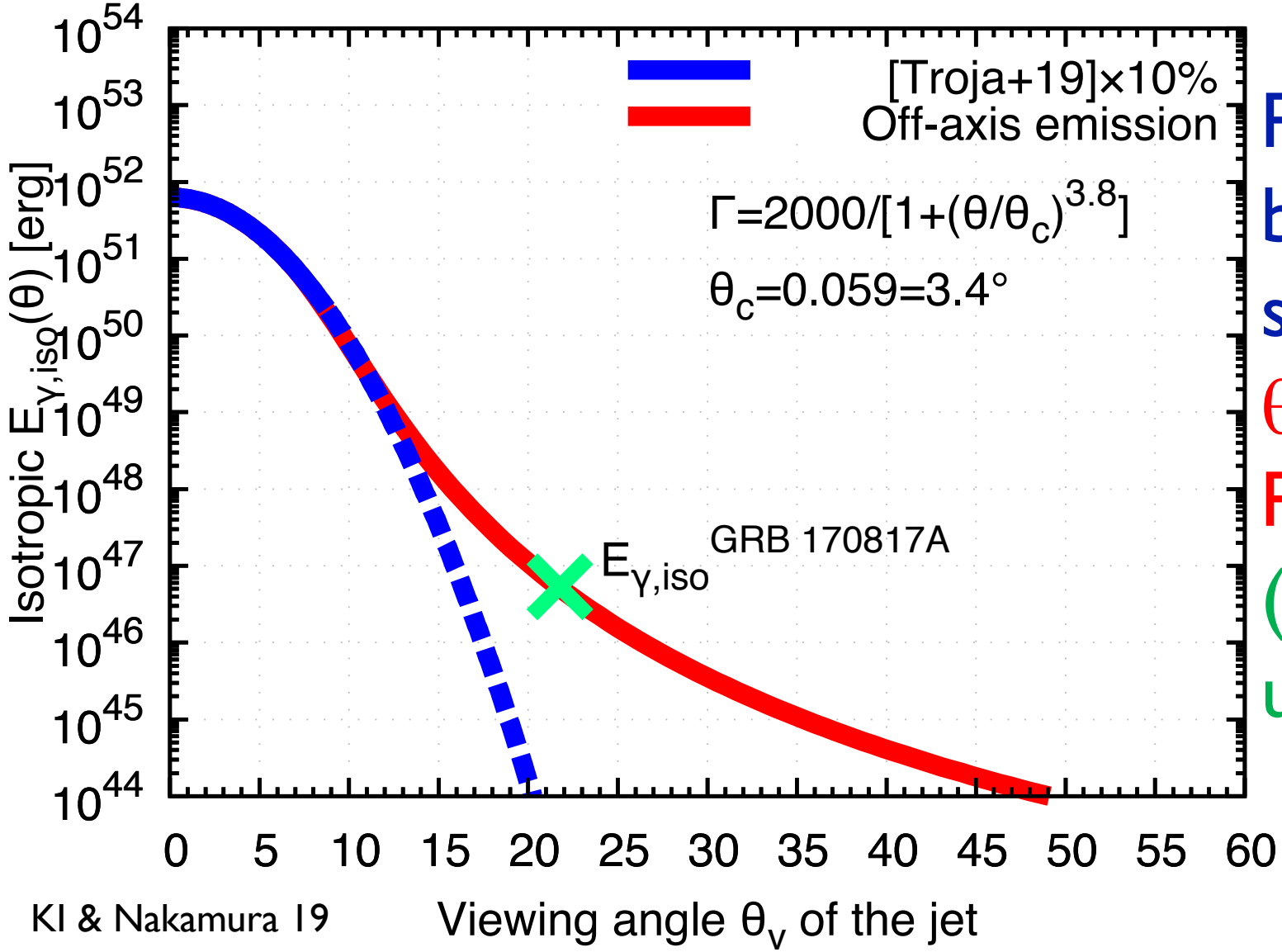
No detection so far
CTA is more powerful



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



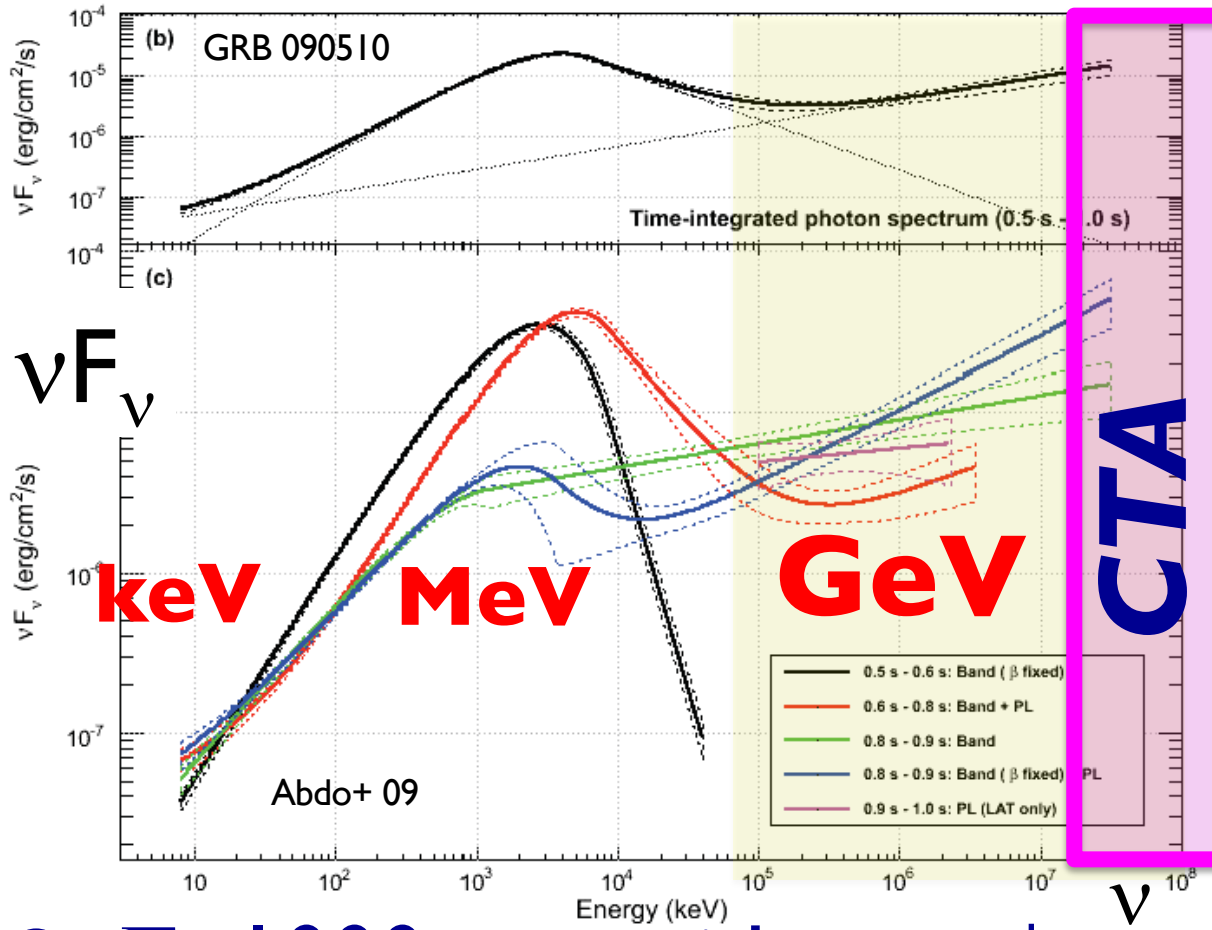
Off-Axis Emission



KI & Nakamura 19

Predict brighter sGRBs:
θ_v<20,10°
P~20, 5%
(still large uncertain)

>GeV γ-ray from GRBs

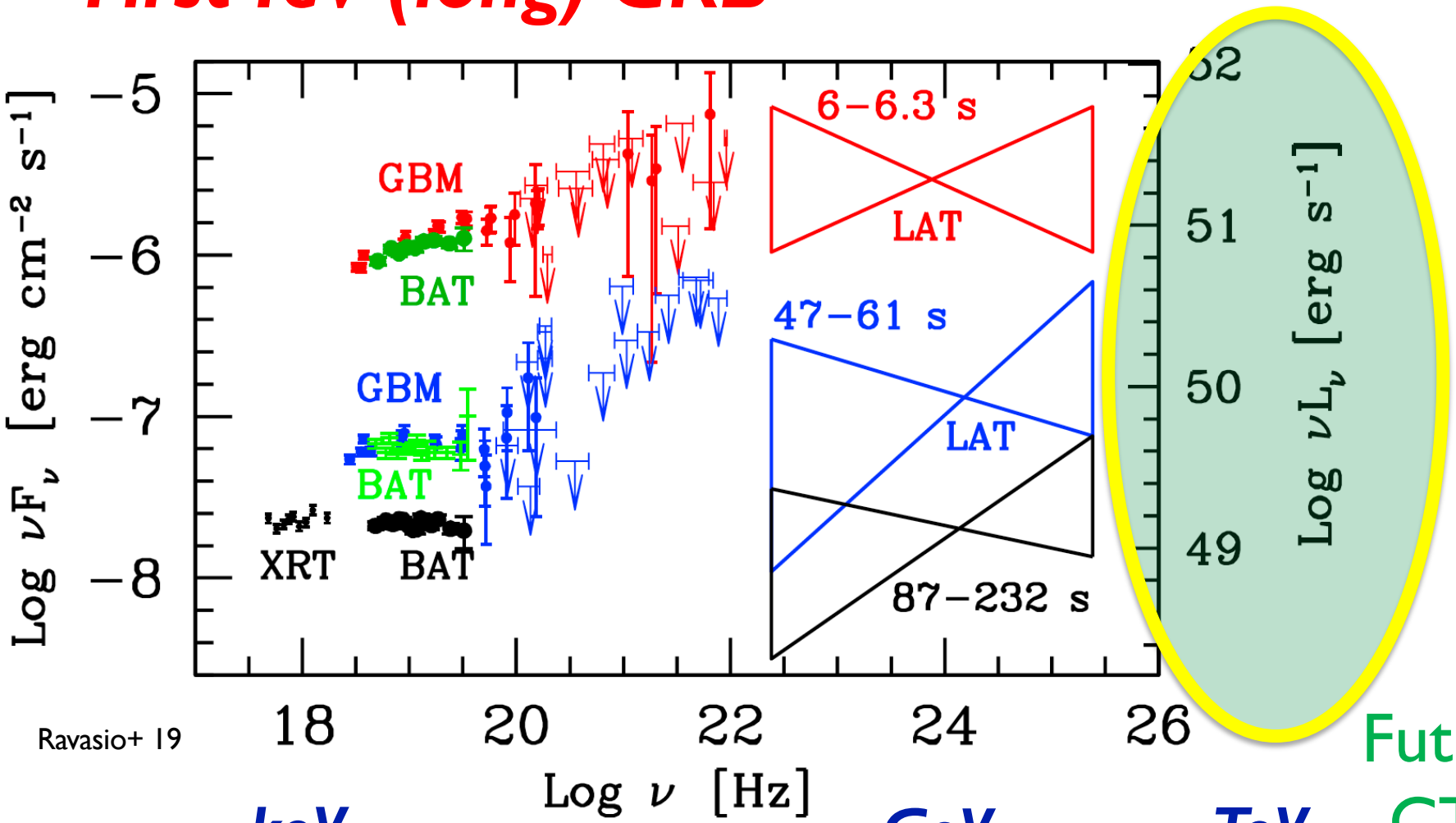


- Γ>1000 to avoid $\gamma\gamma \rightarrow e^+e^-$
- $>10^{17}$eV $p+\gamma \rightarrow \pi \rightarrow \gamma, e$?

GRB 190114C

First TeV (long) GRB

MAGIC

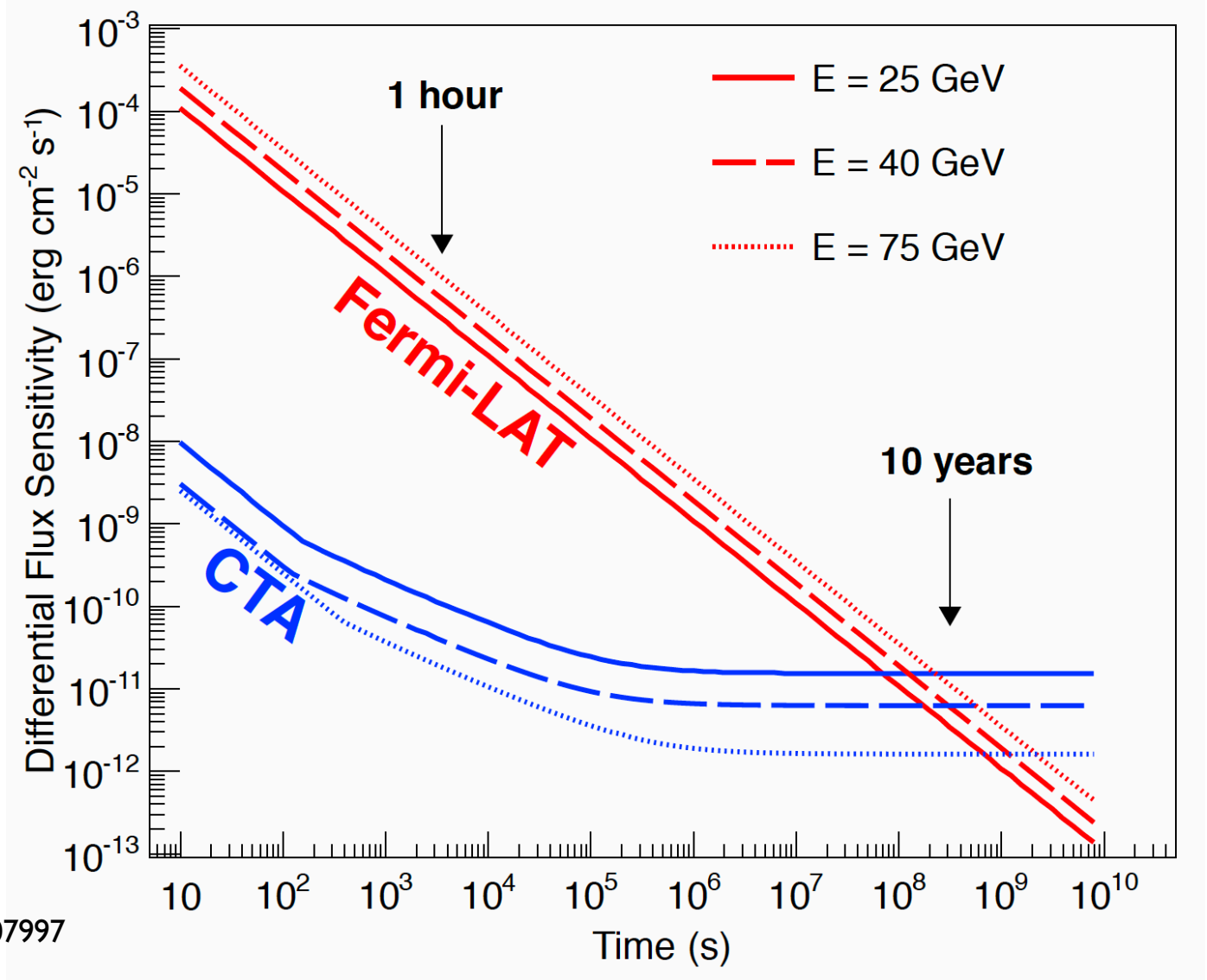


Ravasio+ 19

keV **GeV** **TeV**

Future CTA

Transient Observatory



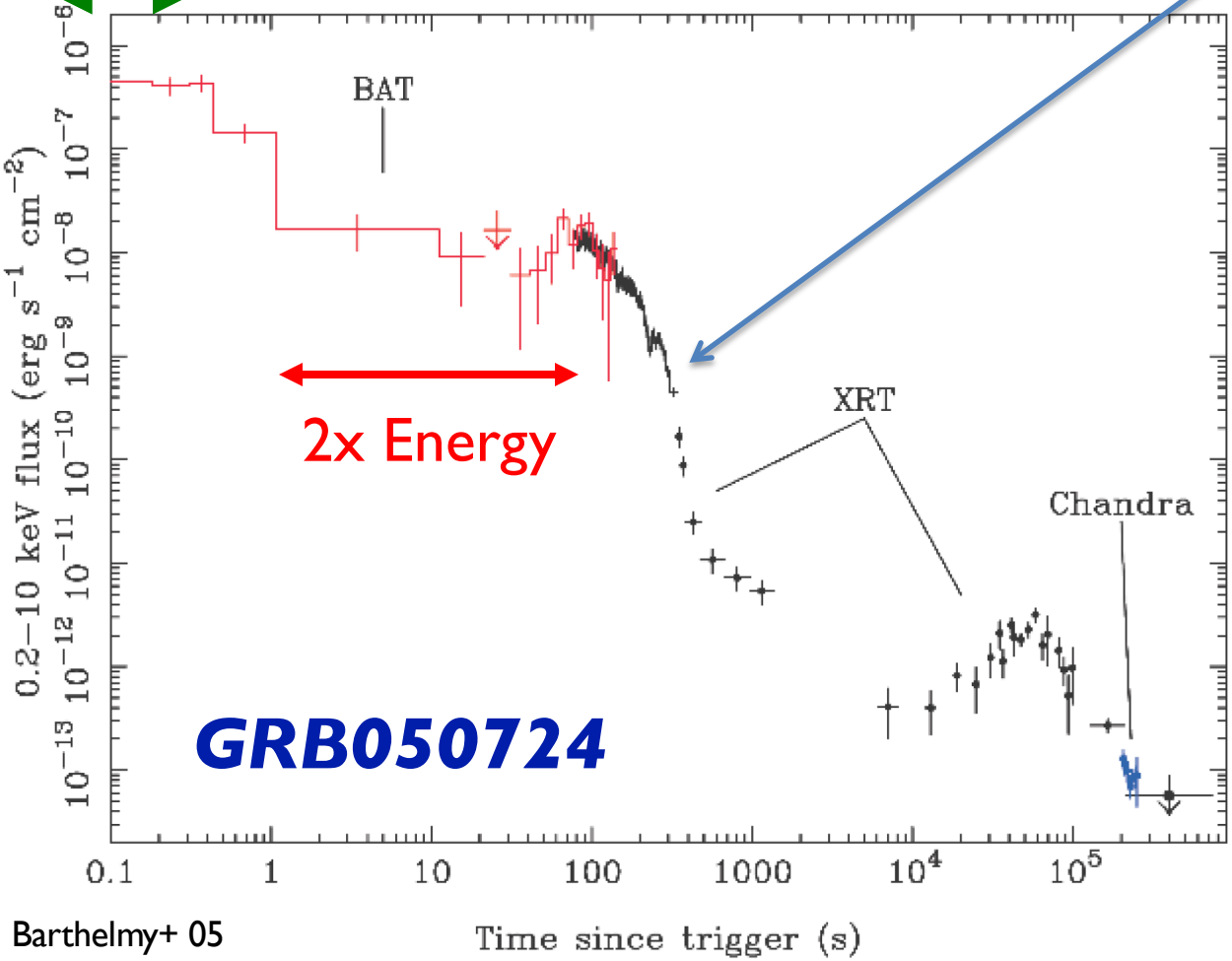
LST slew in **~20 s**

CTA 1709.07997

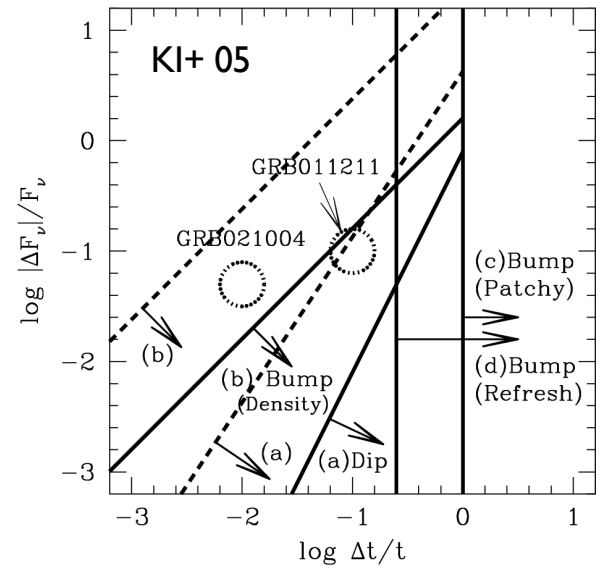
Extended Emission

Short GRB

Too rapid decline: NOT afterglow
BUT central engine

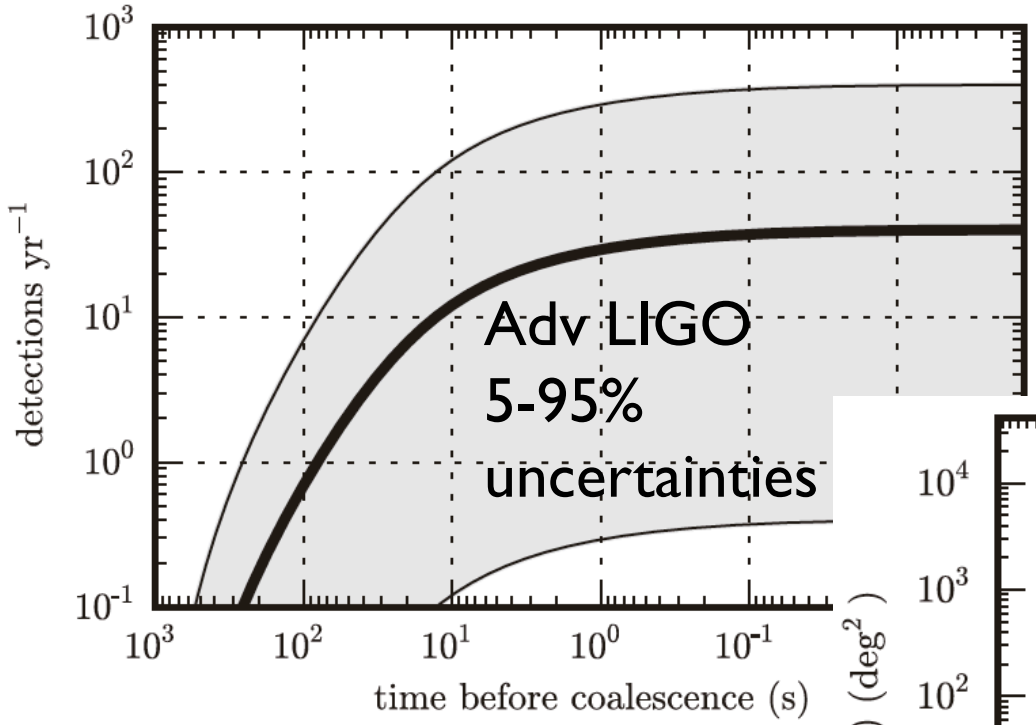


Barthelmy+ 05

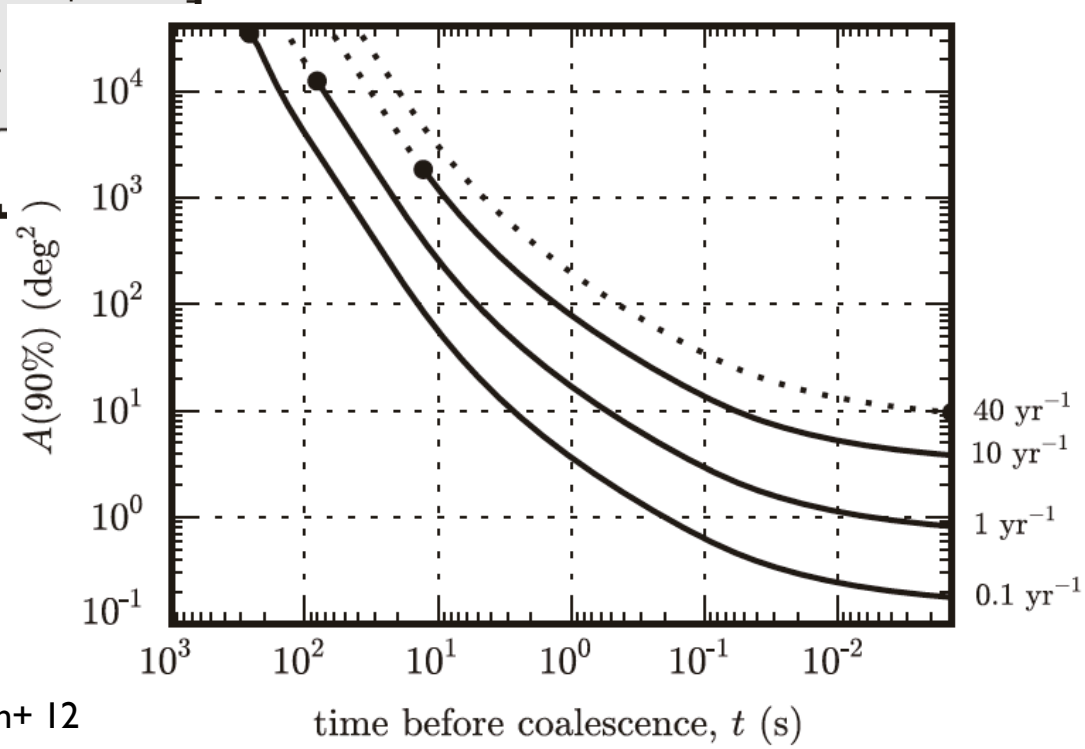


t >~20 sec
CTA can turn to the source

Real Time Search



Alert time
GW170817: ~5 hr
O3: minutes delay

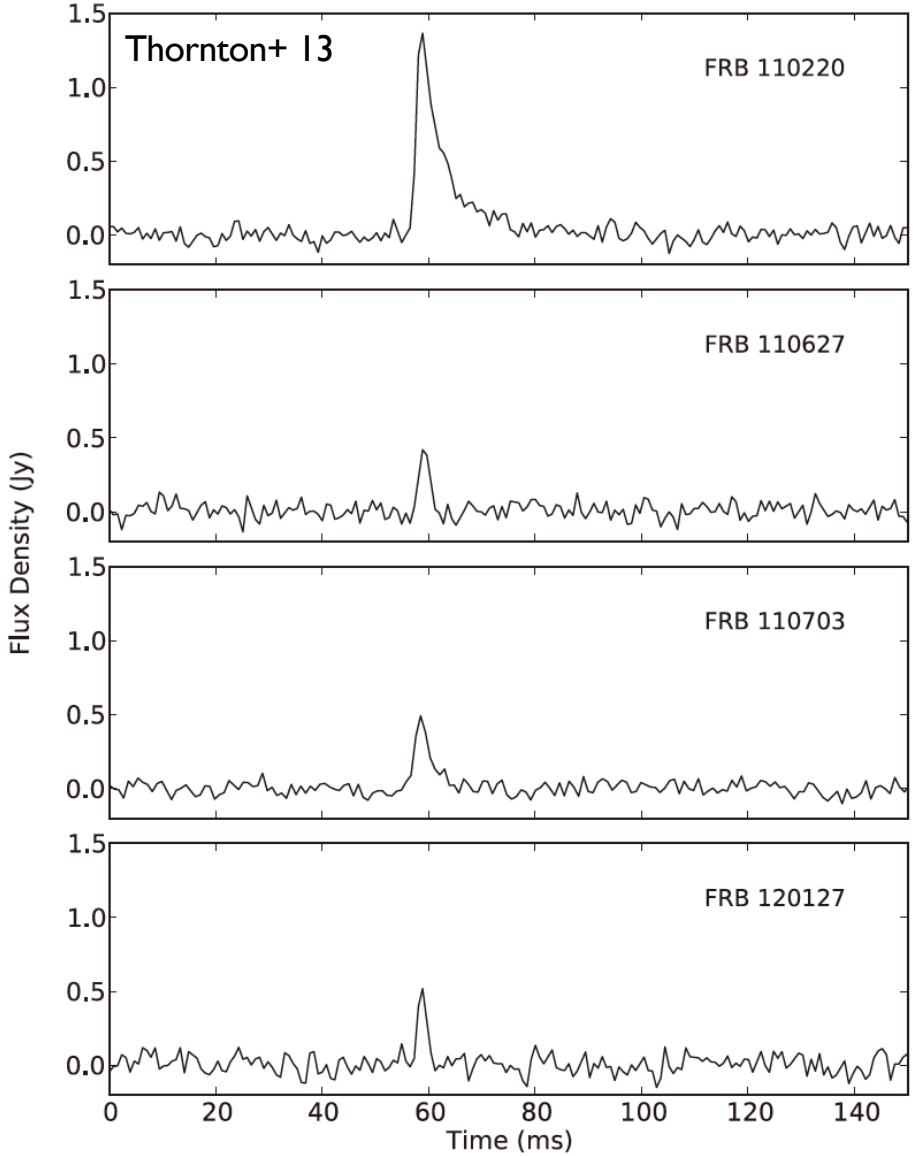


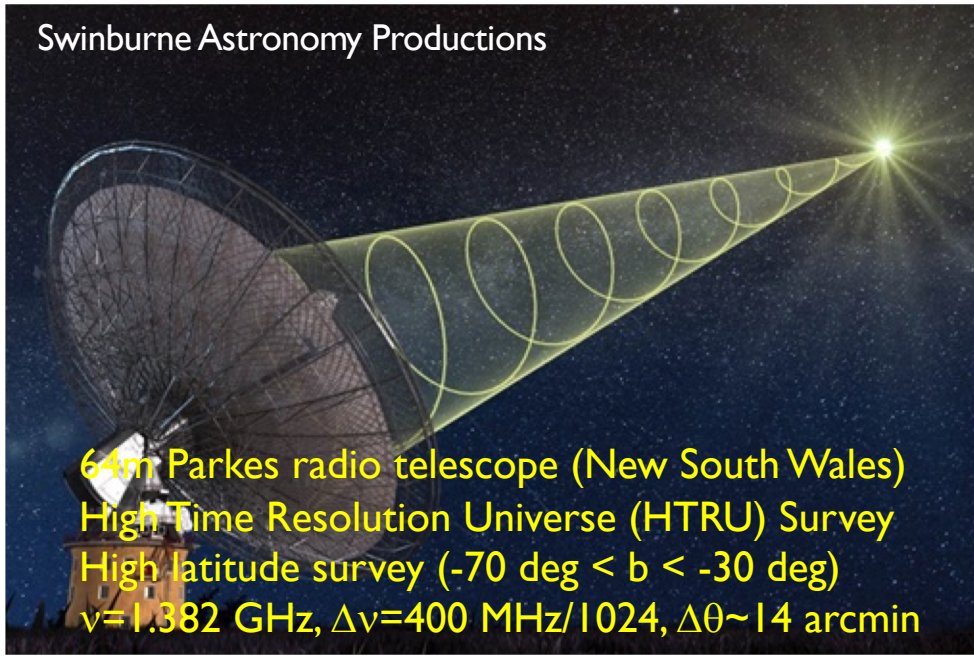
In the near future, alert time will be negative

Cannon+ 12

Fast Radio Bursts

Totani+ 13

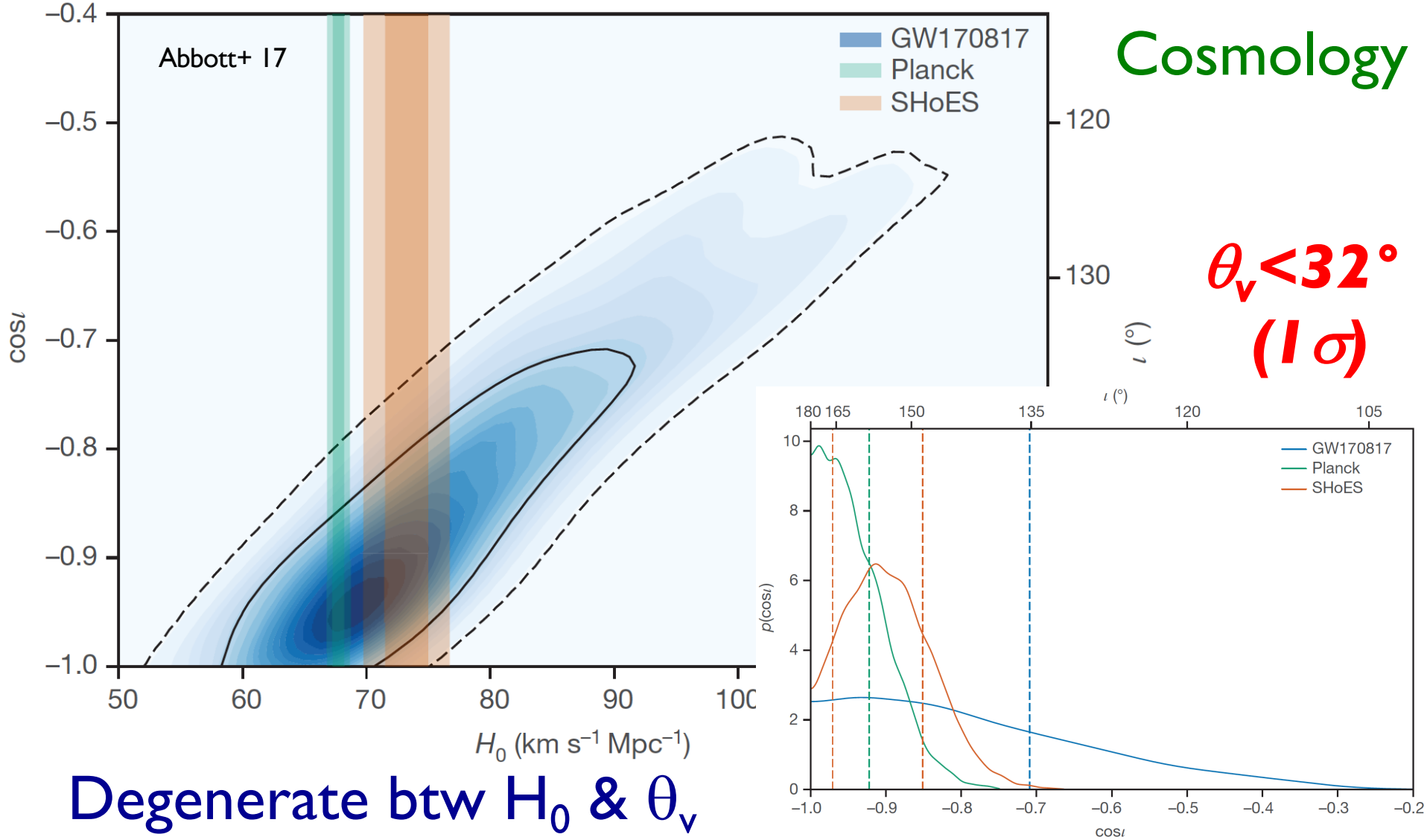




F=0.6-8.0 Jy ms !!!

Most luminous mysterious radio transients

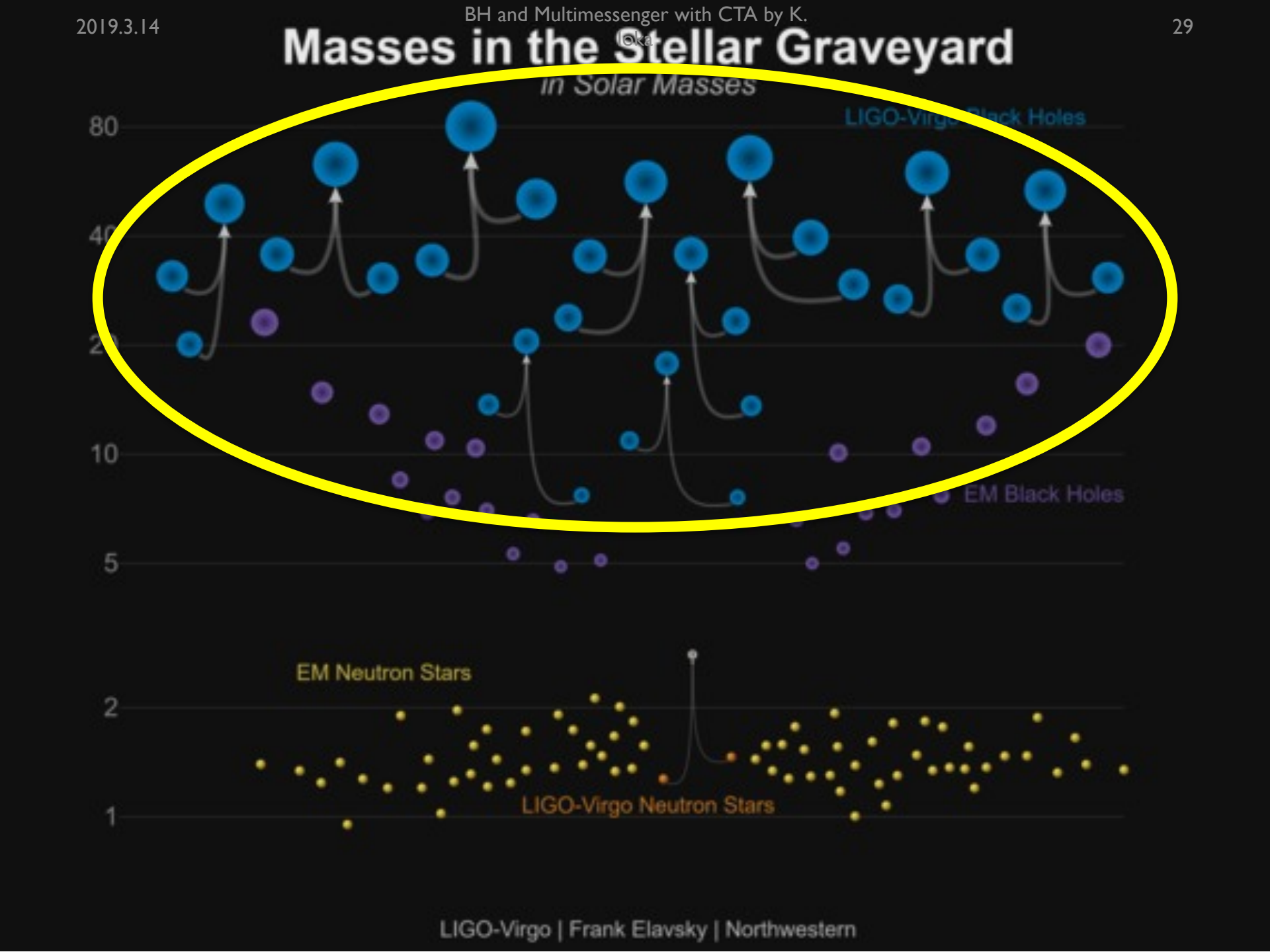
Cosmology



Cosmology

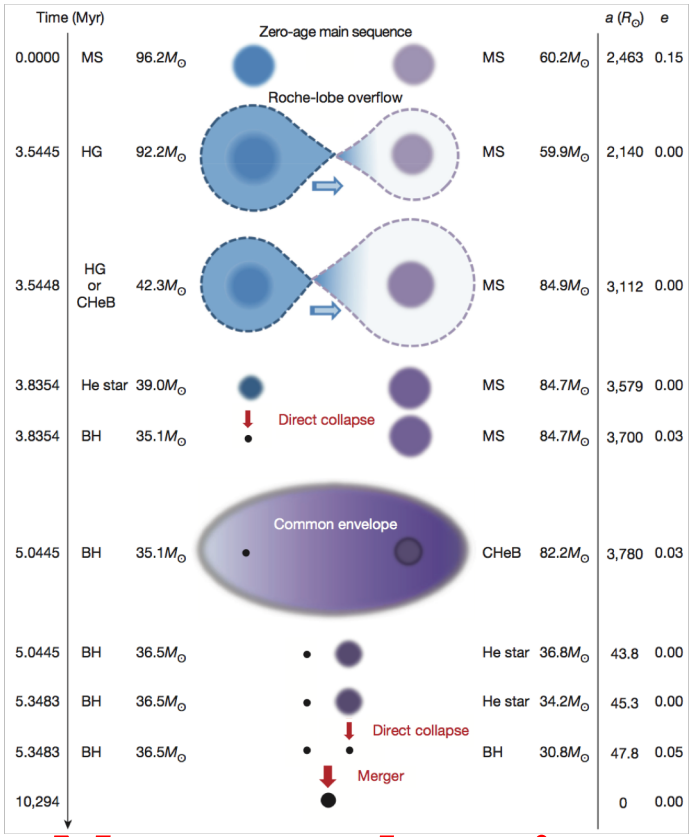
θ_v<32° (1 σ)

Degenerate btw H_0 & θ_v

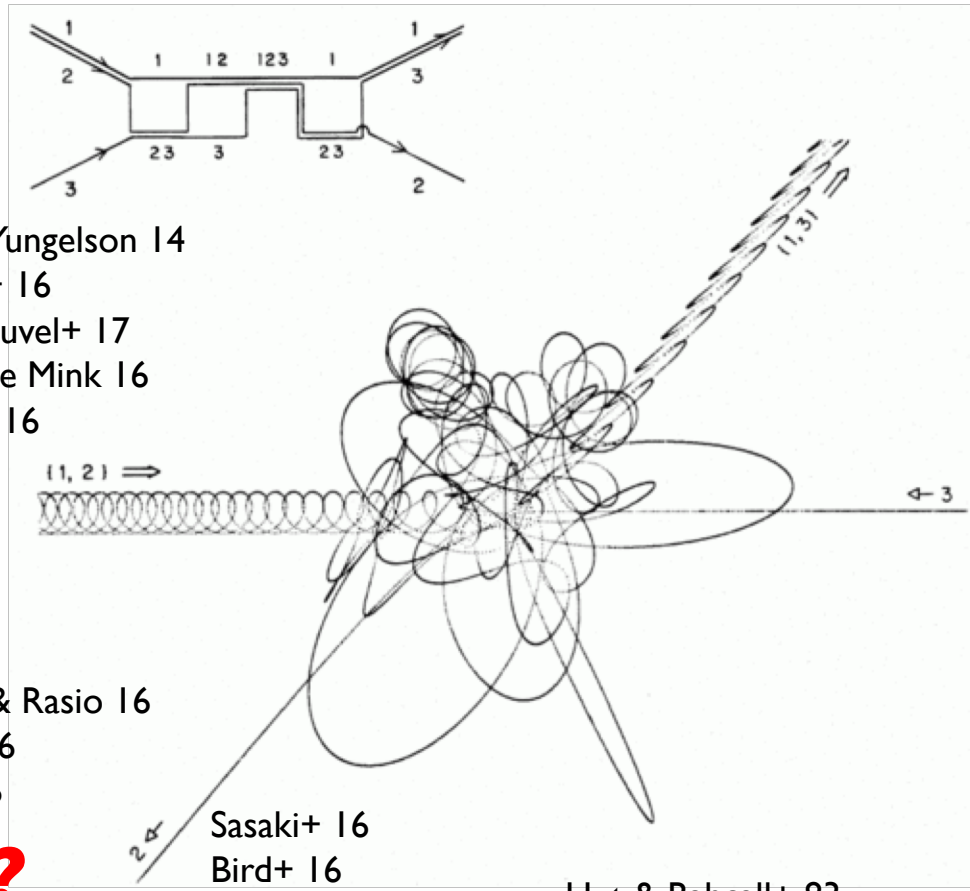

Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

What is the Origin?

Isorated binary?



Stellar cluster?



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

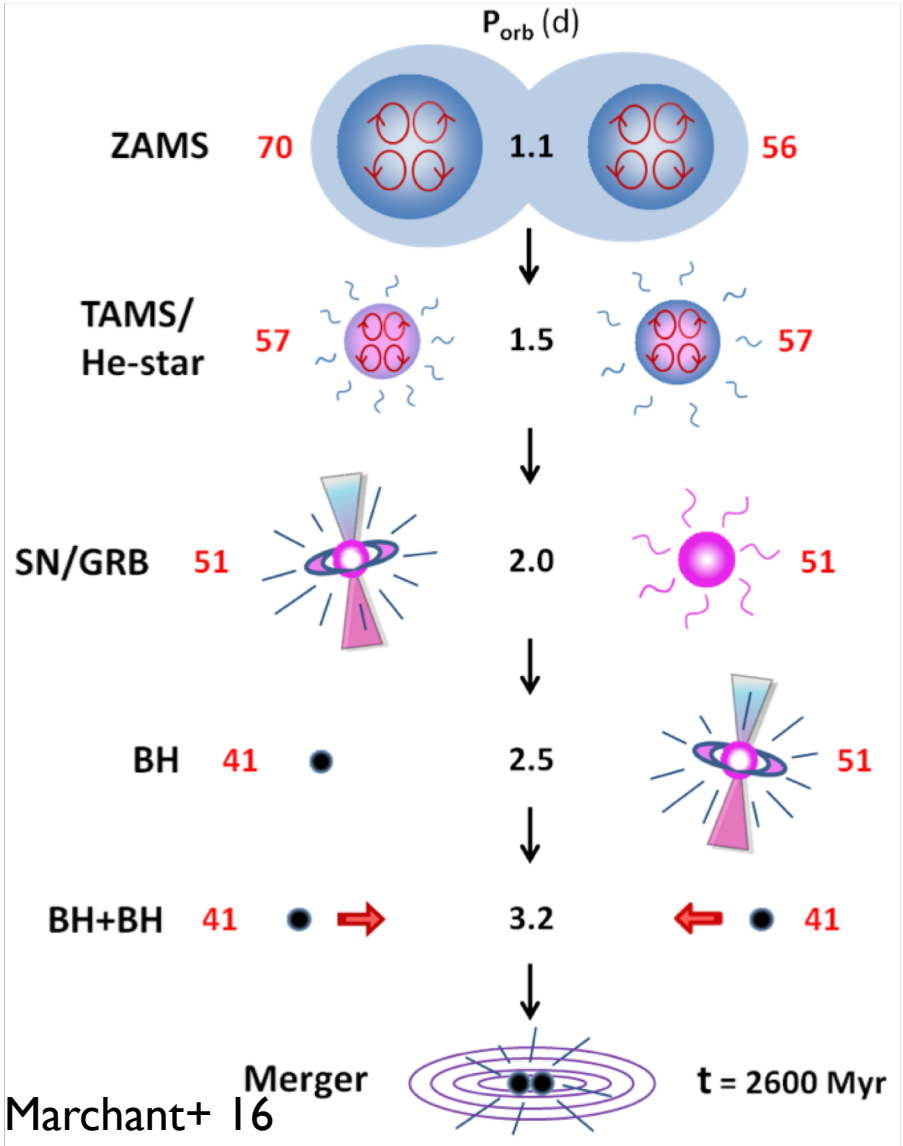
Antonini & Rasio 16
Bartos+ 16
Stone+ 16

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

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

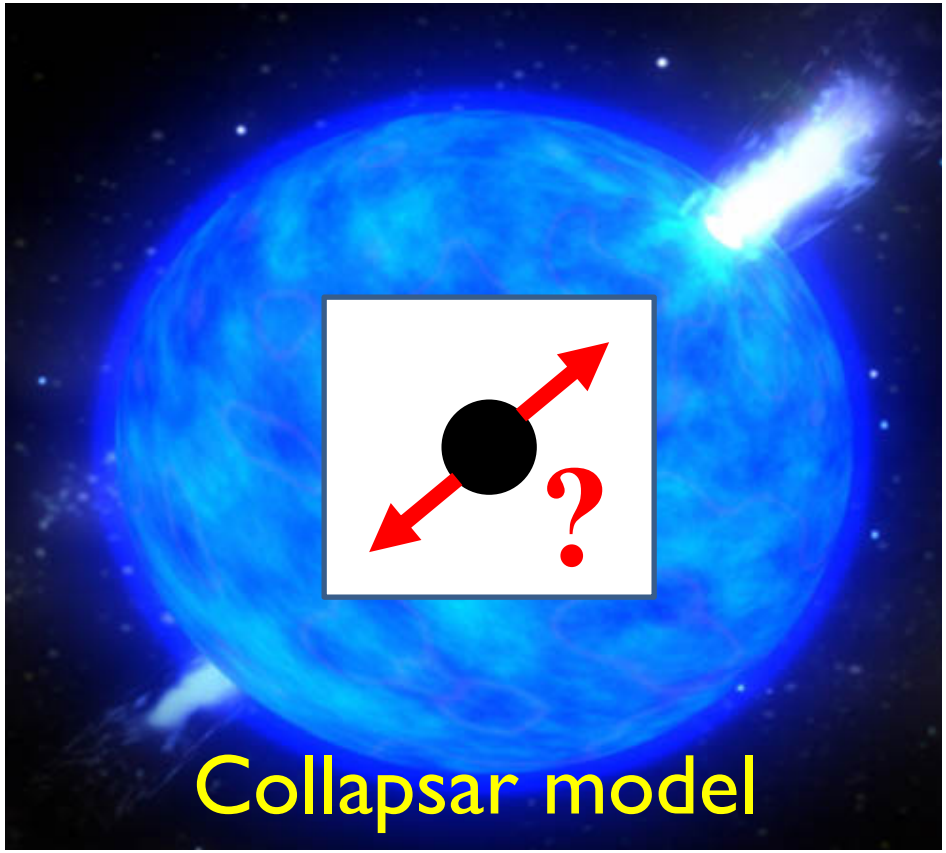
Near galactic nuclei?
Primordial black hole?

Gamma-Ray Bursts?



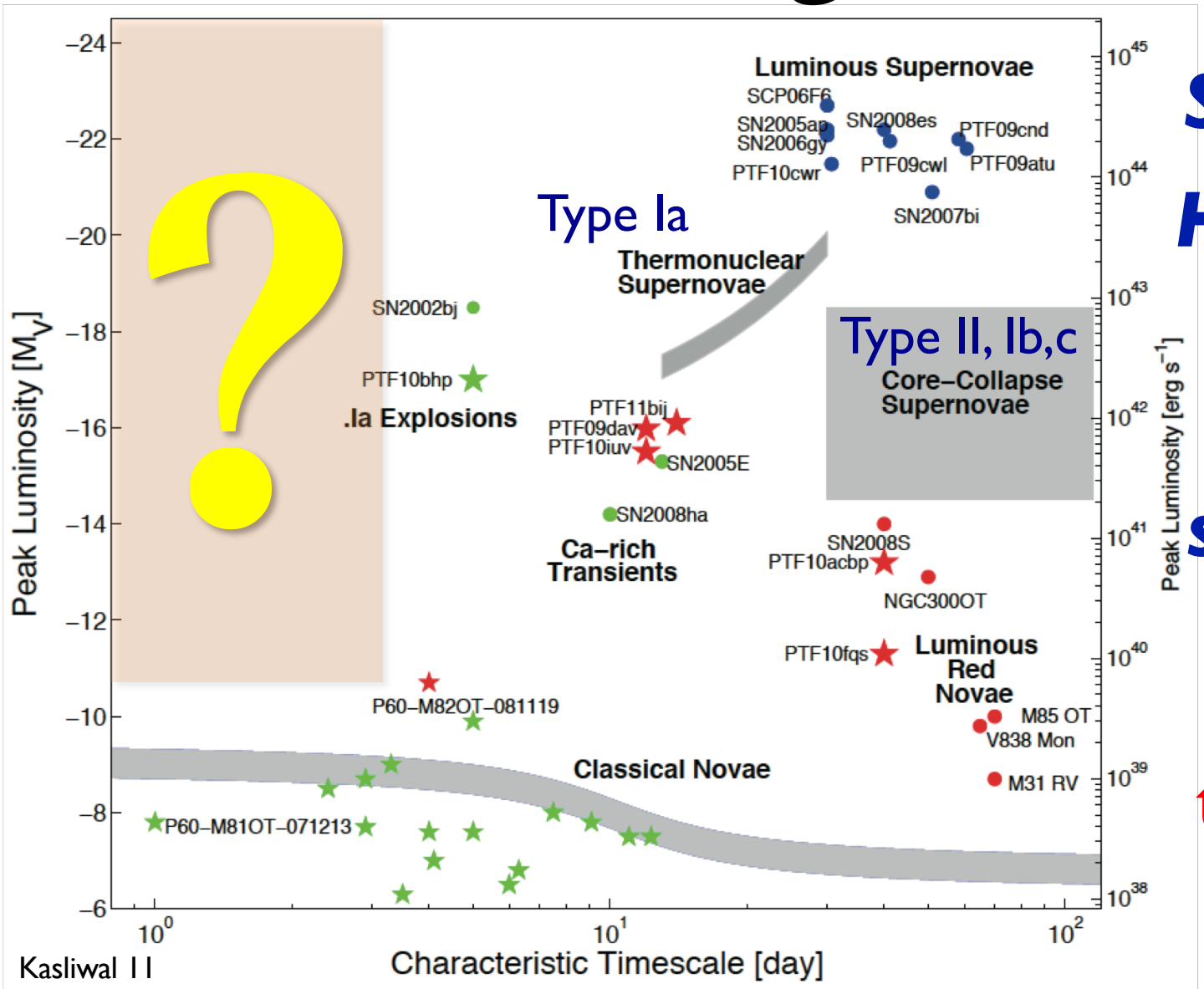
Marchant+ 16

~ BH formation



GW rate ~ GRB rate

BH Forming Transients



Supernova

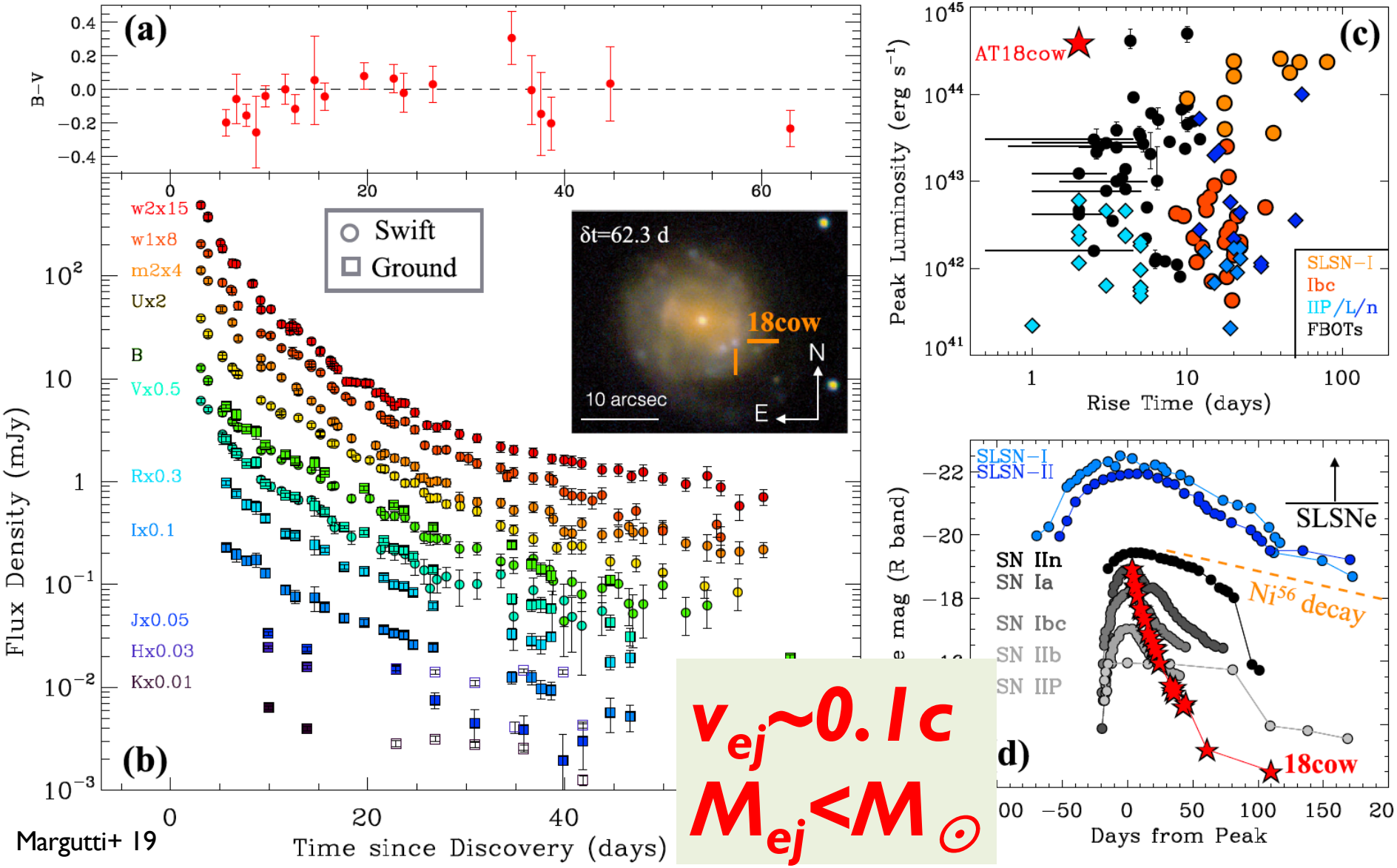
Hypernova

Super-luminous supernova

Other transients?

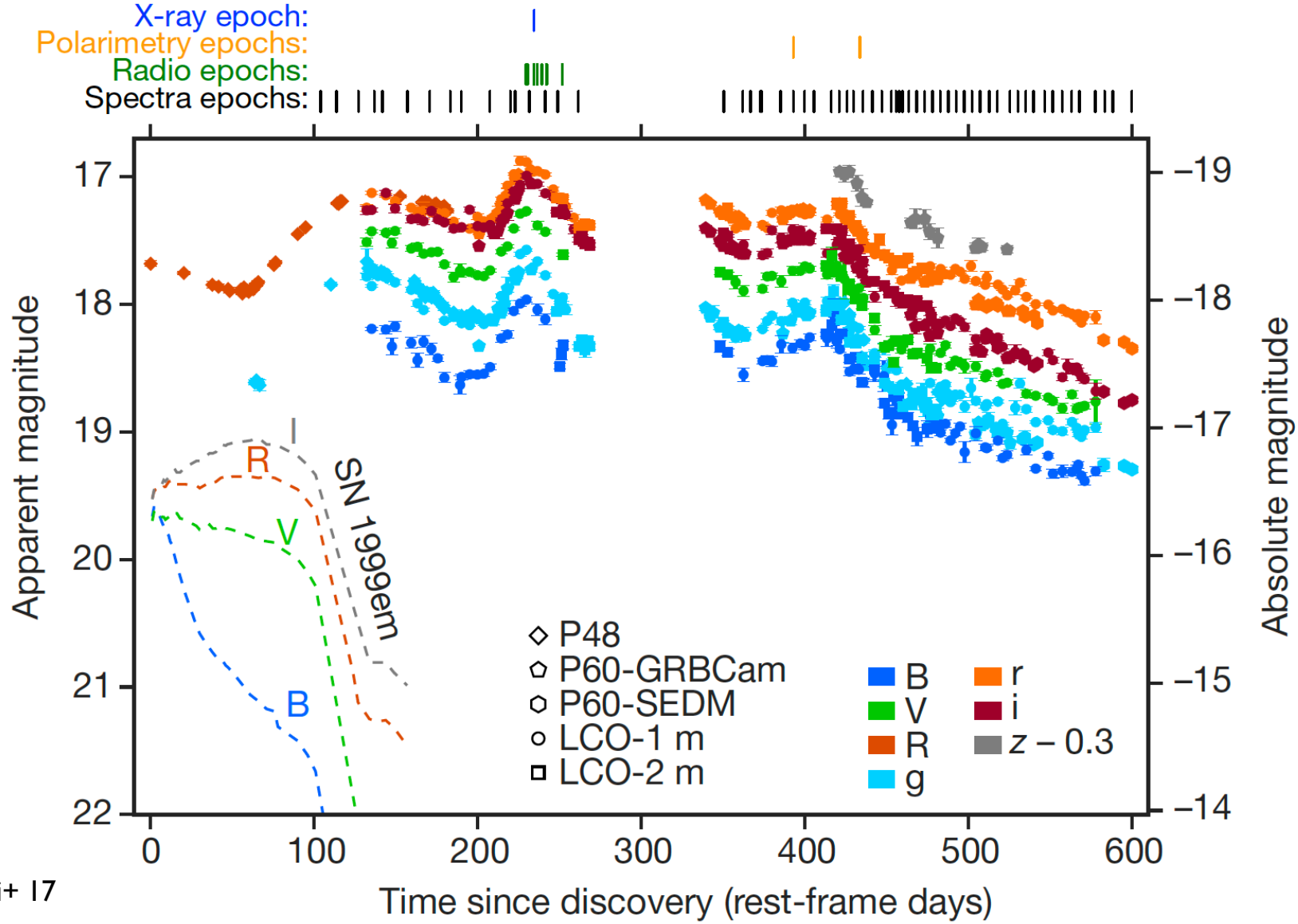
Short Δt

AT18cow: BH formation?



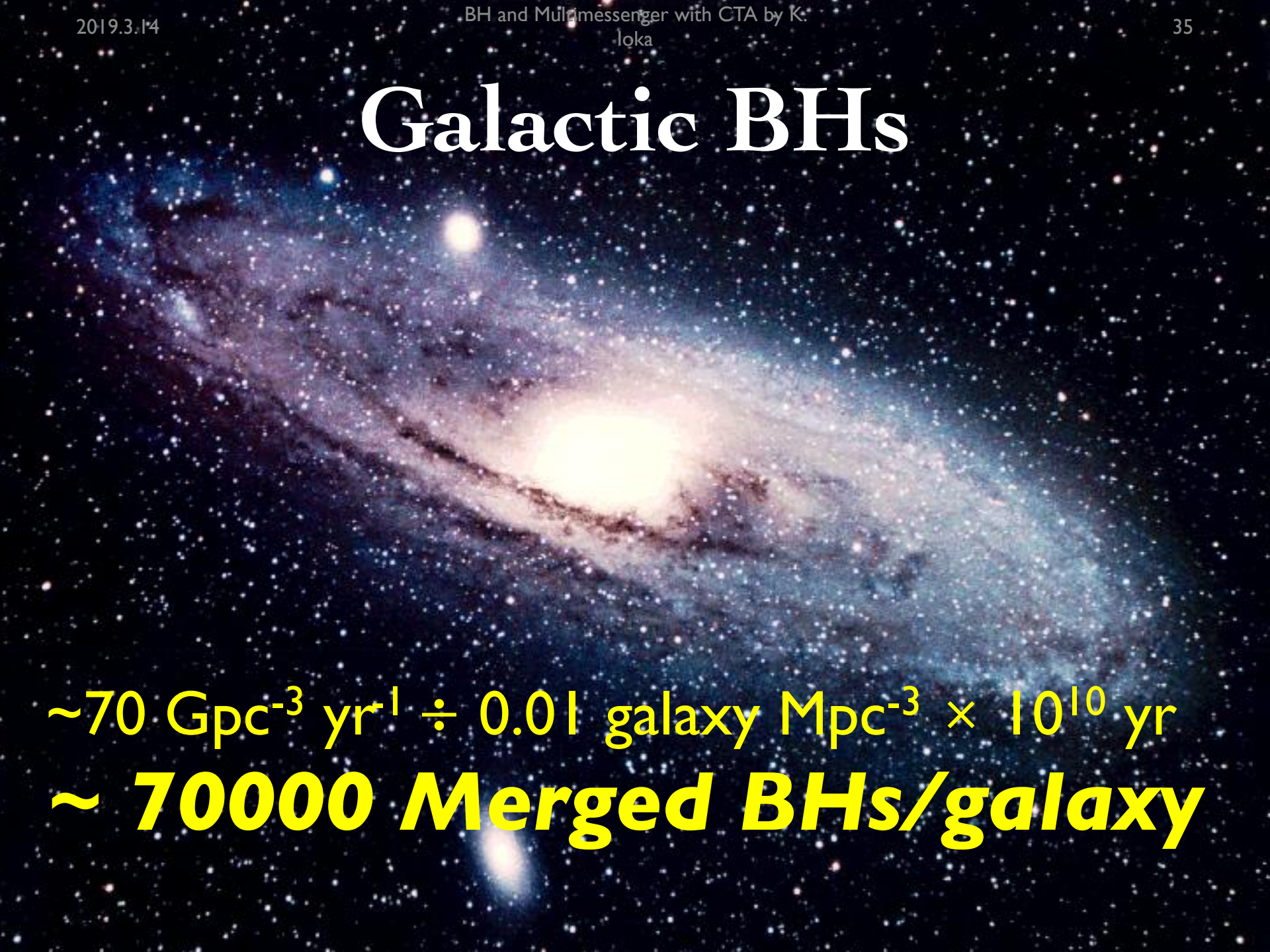
Margutti+ 19

iPTF14hls: >100M$_\odot$ SN?



Arcavi+ 17

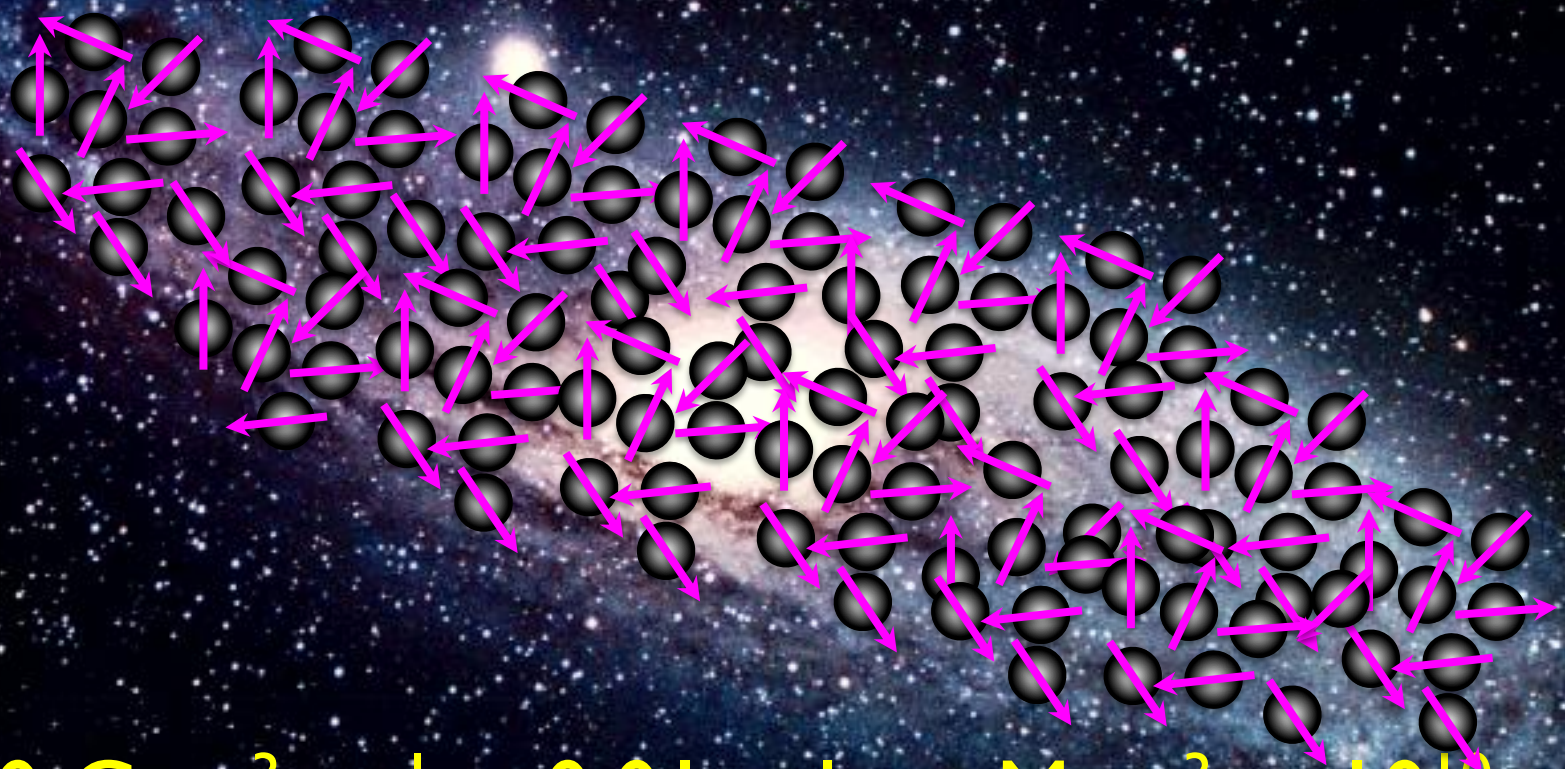
Galactic BHs



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

~ 70000 Merged BHs/galaxy

Galactic BHs



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

~ 70000 Merged BHs/galaxy

Spin Energy

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

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

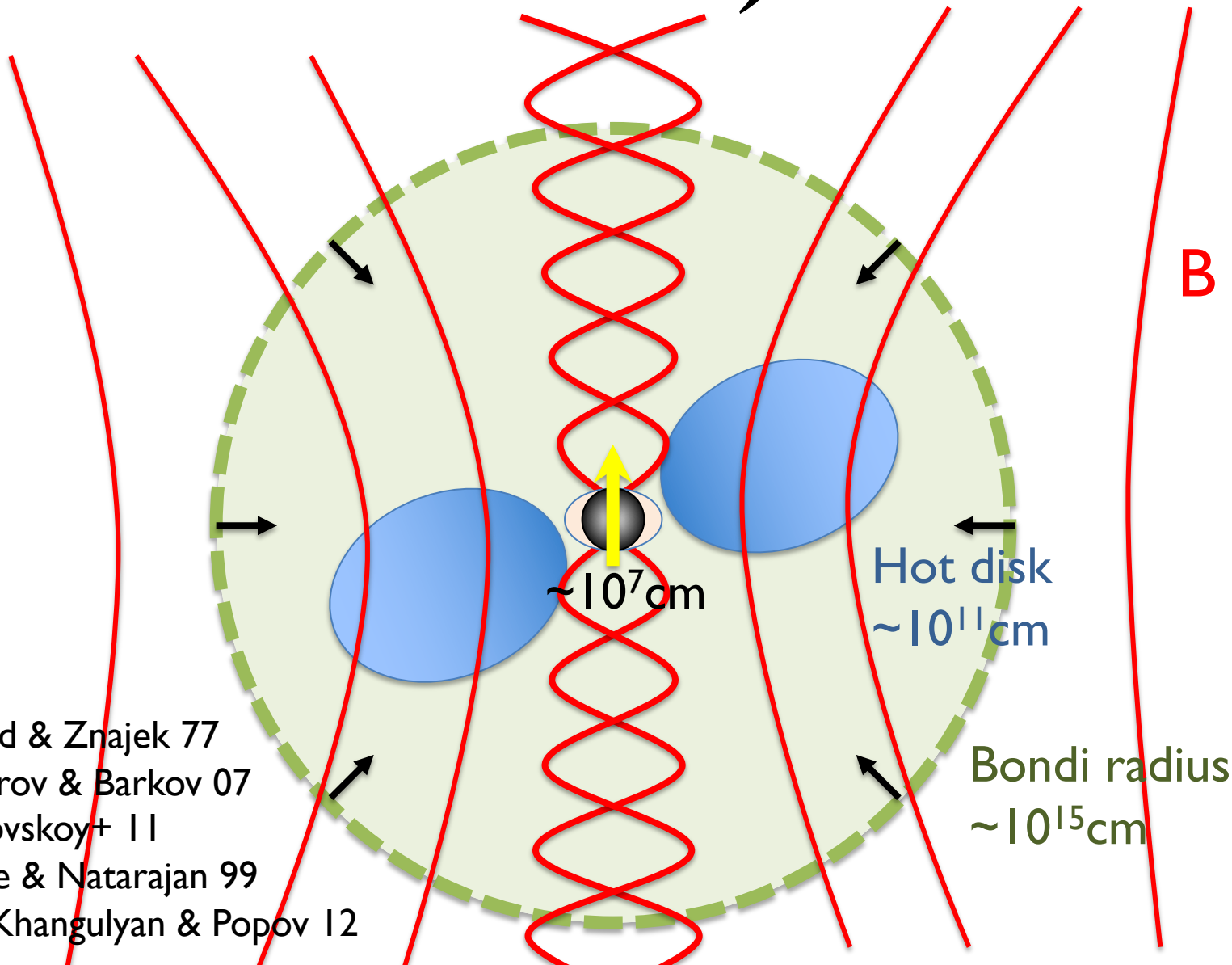
$$E_{\rm tot} \sim N_{BH} E_{\rm spin} \sim 7 \times 10^4\ {\rm BHs} \times 1 \times 10^{54}\,{\rm erg}$$

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

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

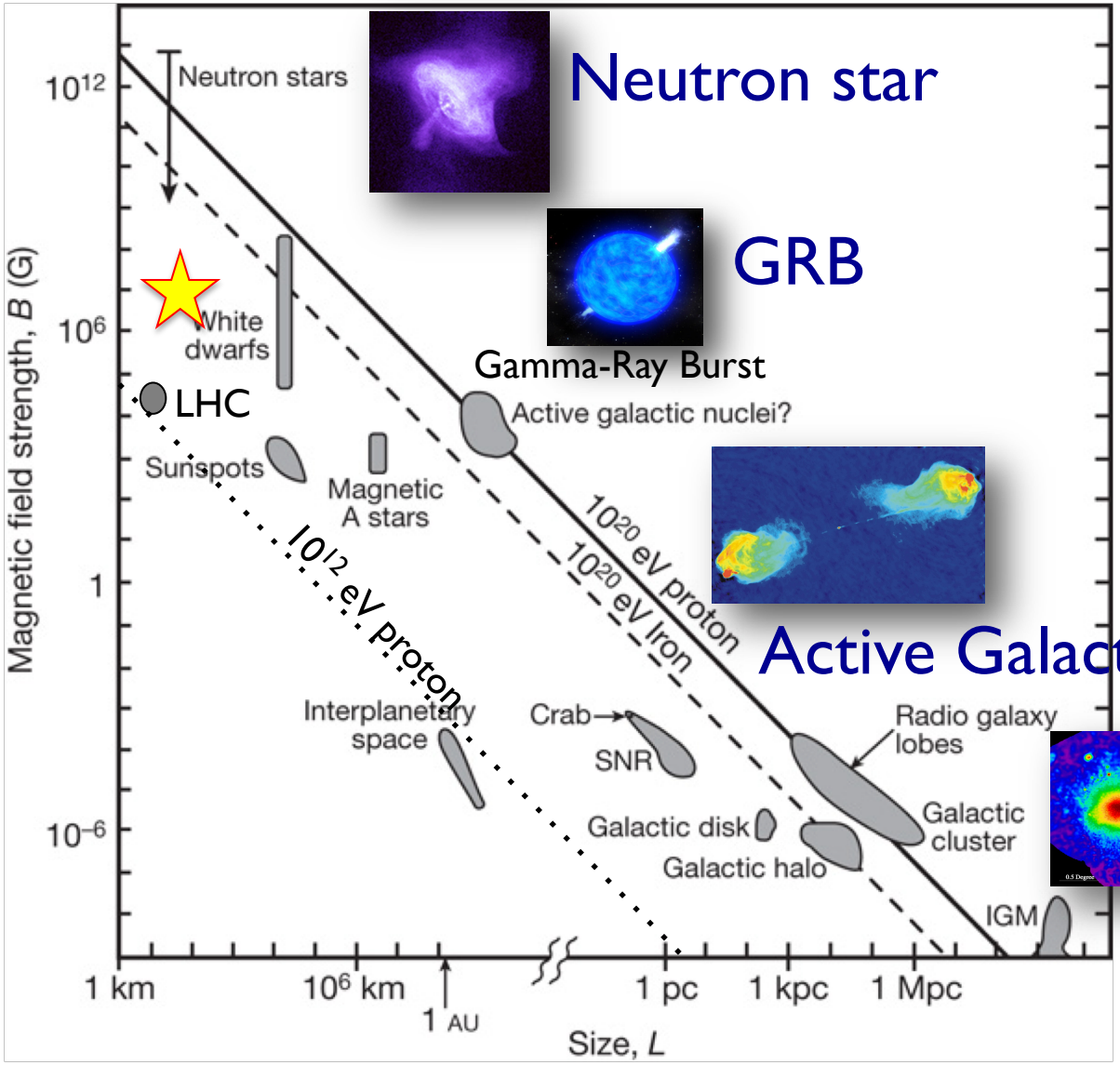
Comparable to supernovae ever happened!

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

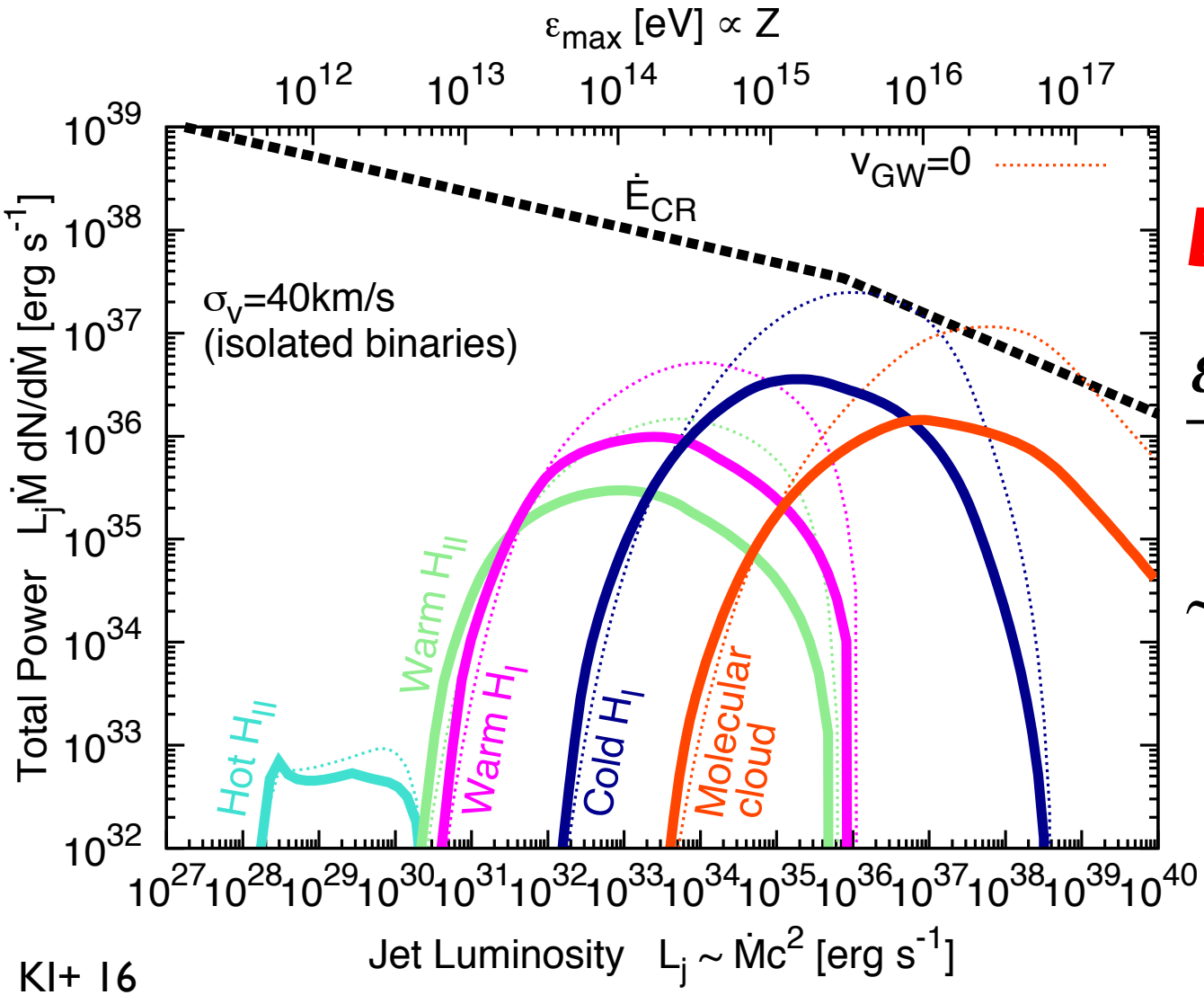
- Hillas condition
  $E<ZqBR$
- $L_B \sim 4\pi R^2 (B^2/8\pi) c$
  $\propto (BR)^2$ Blandford 00 Waxman 04
- E_{max}>PeV

PeVatron!!!

Barkov+ 12
KI+ 16

Dark Matter?

Total Power



KI+ 16

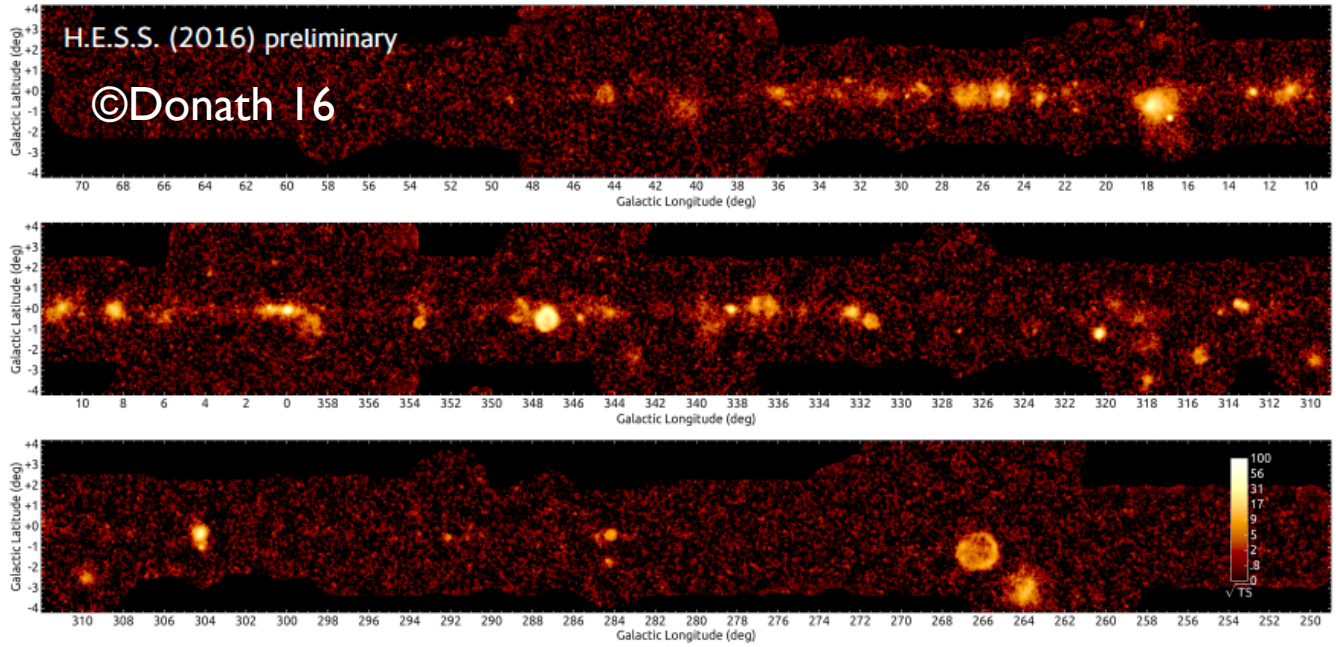
BHs ⇔ Cosmic rays beyond PeV?

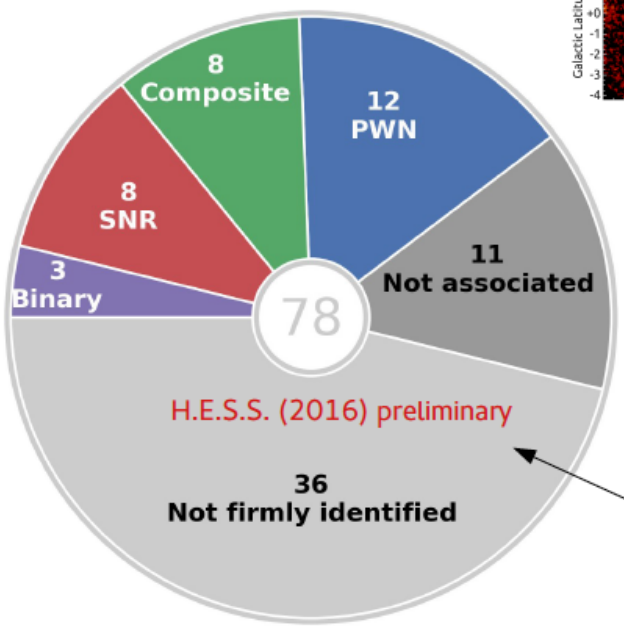
$$\frac{\varepsilon_{CR} E_{SN}}{100\,\mathrm{yr}} \sim 3\times10^{40}\ \mathrm{erg\ s^{-1}}$$

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

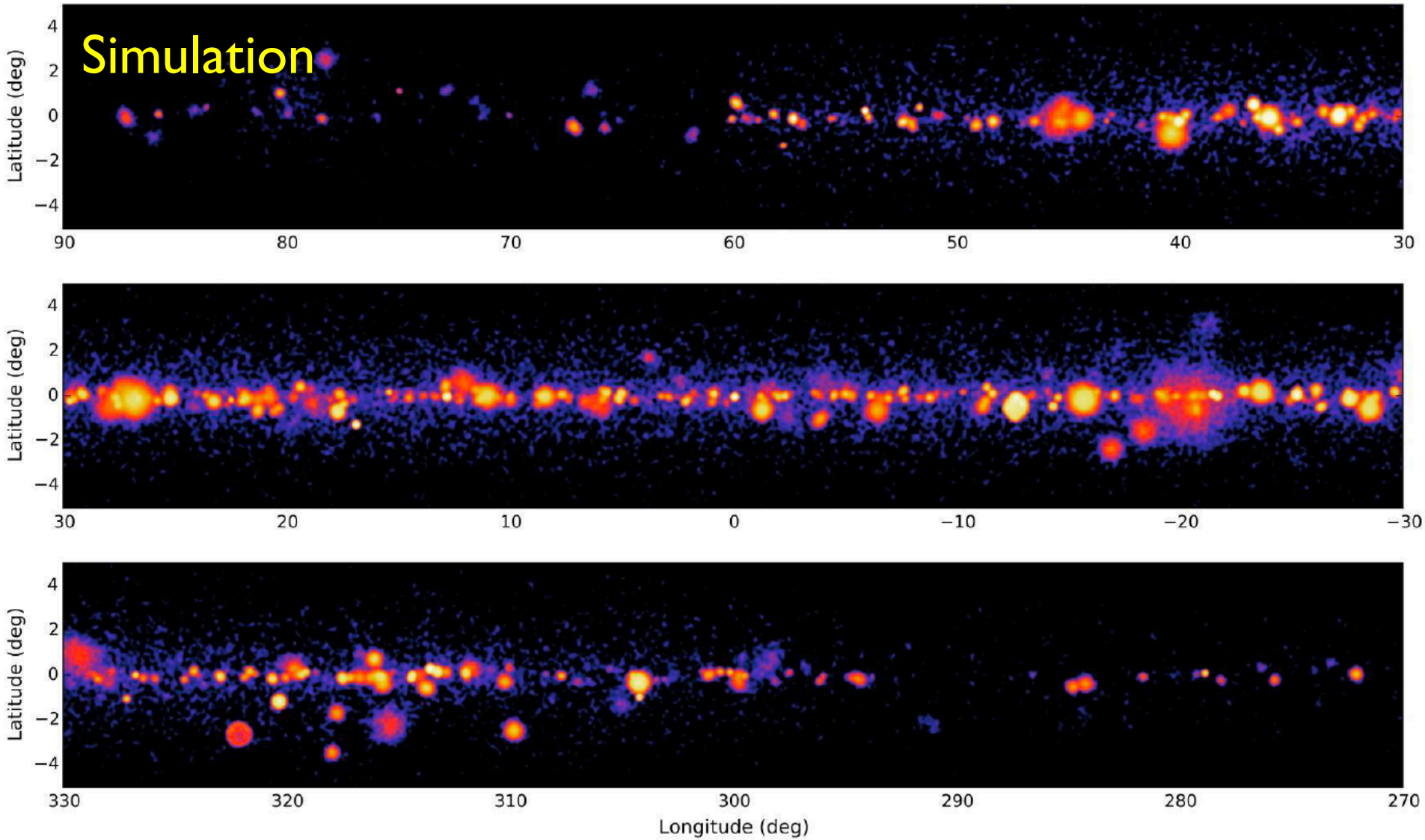
Some are dark accelerators

⇔ Accreting BHs?

KI, Matsumoto, Teraki, Kashiyama & Murase 16

Galactic Plane Survey

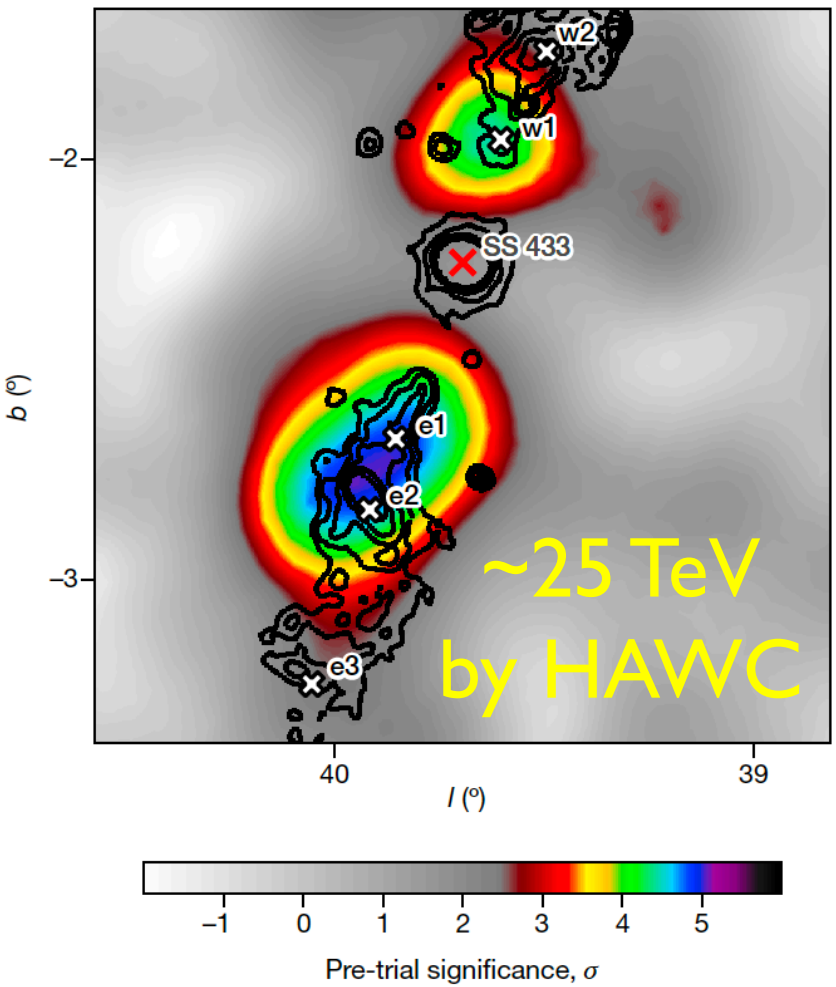
CTA 1709.07997



Galactic BHs

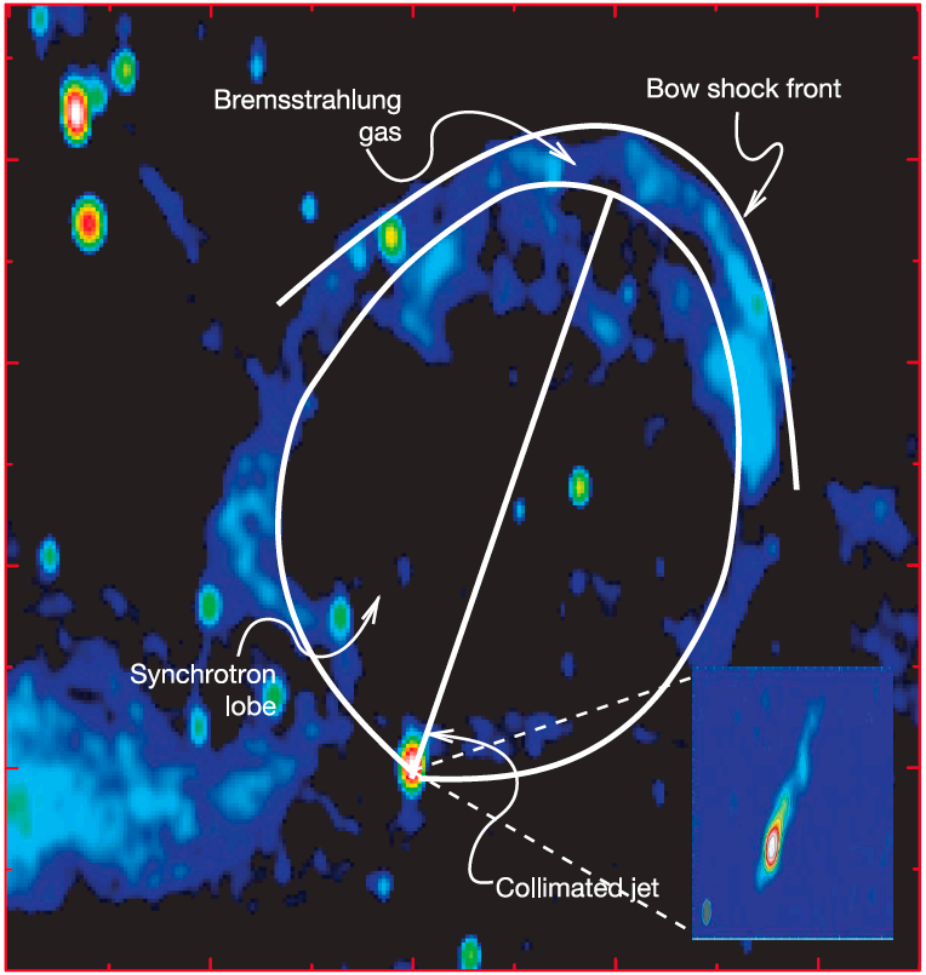
SS433

Abeysekara+ 18

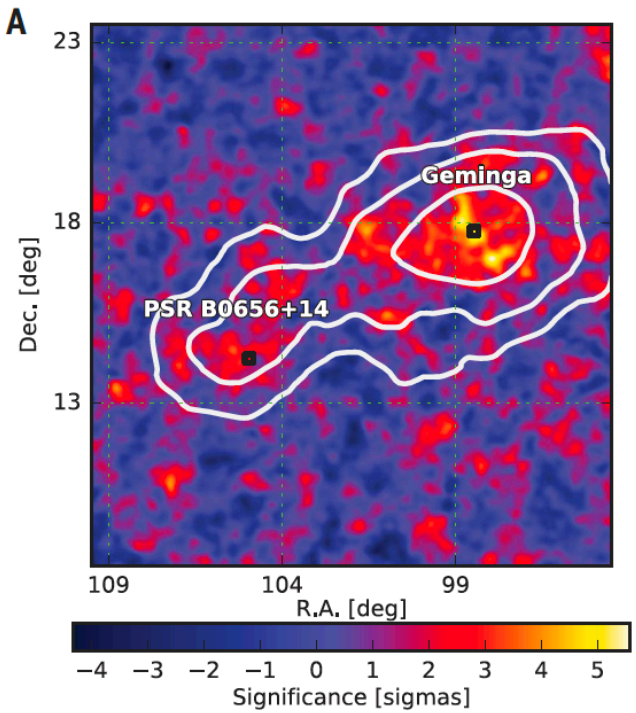


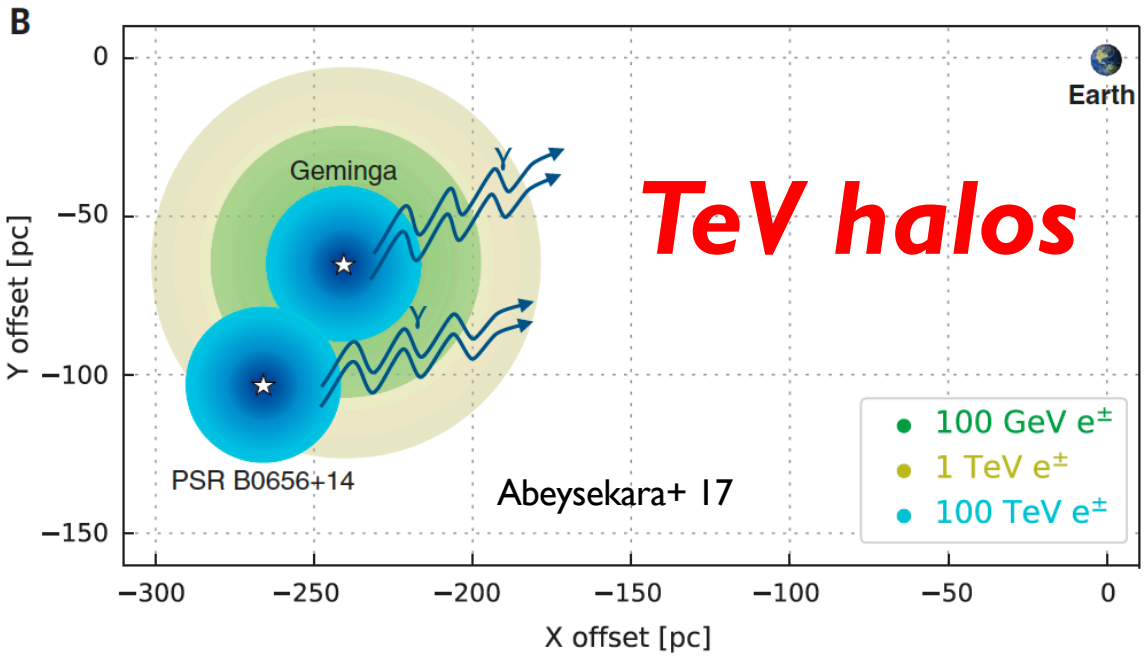
Cygnus X-1

Gallo+ 05



Cosmic-Ray Diffusion

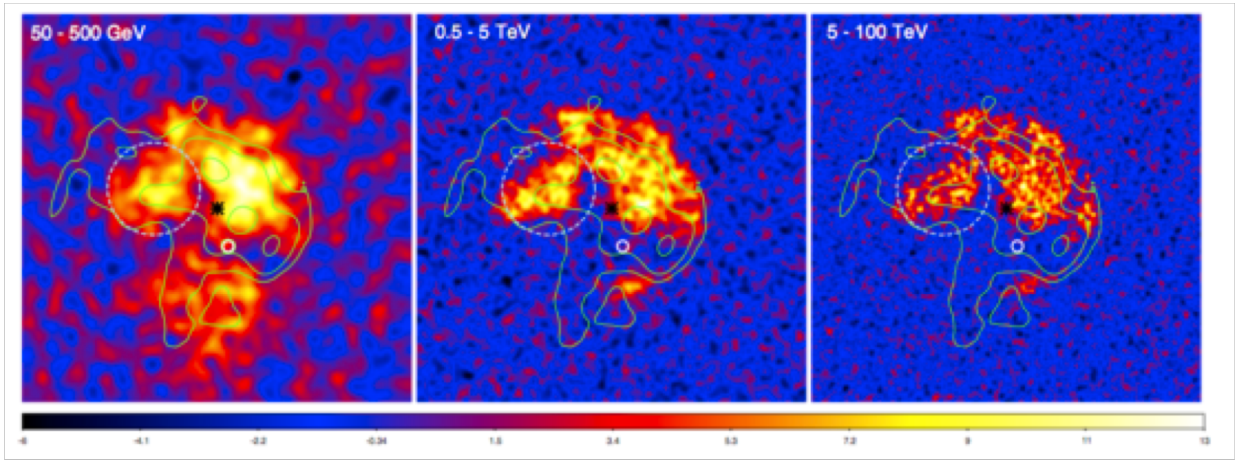




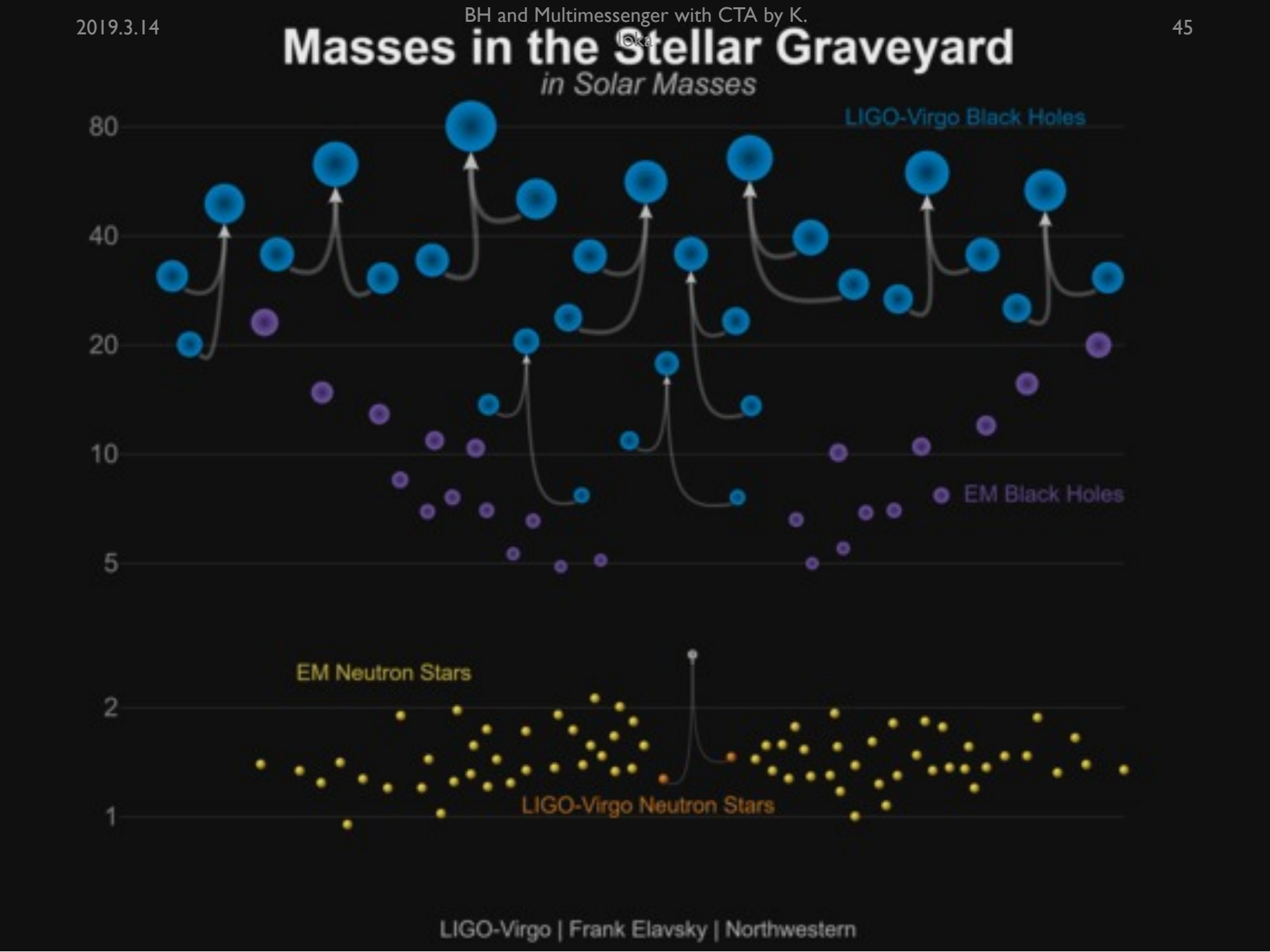
TeV halos

HAWC

CTA expects



CTA 1709.07997


Masses in the Stellar Graveyard
in Solar Masses
80
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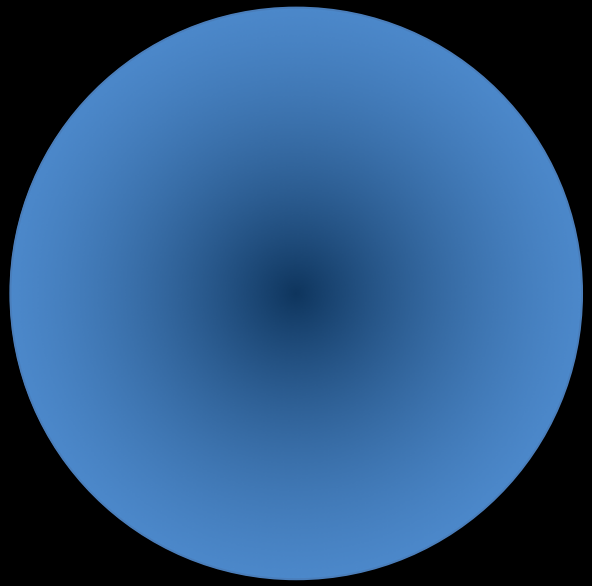
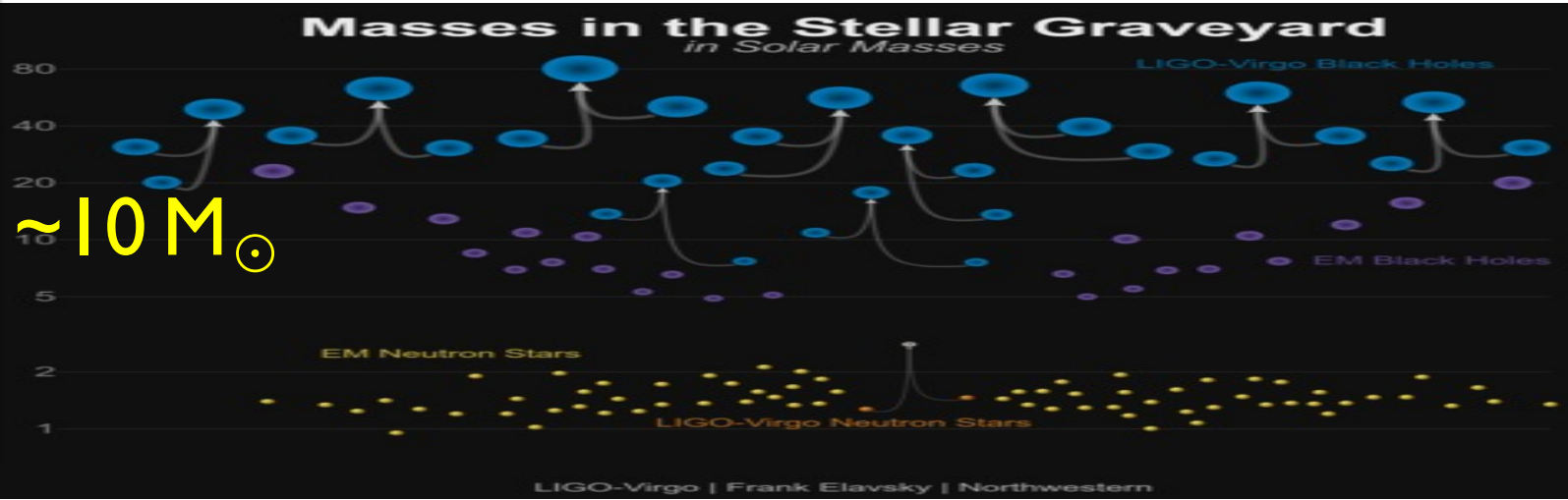
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
LIGO-Virgo | Frank Elavsky | Northwestern

$\sim 10^9\ M_\odot$



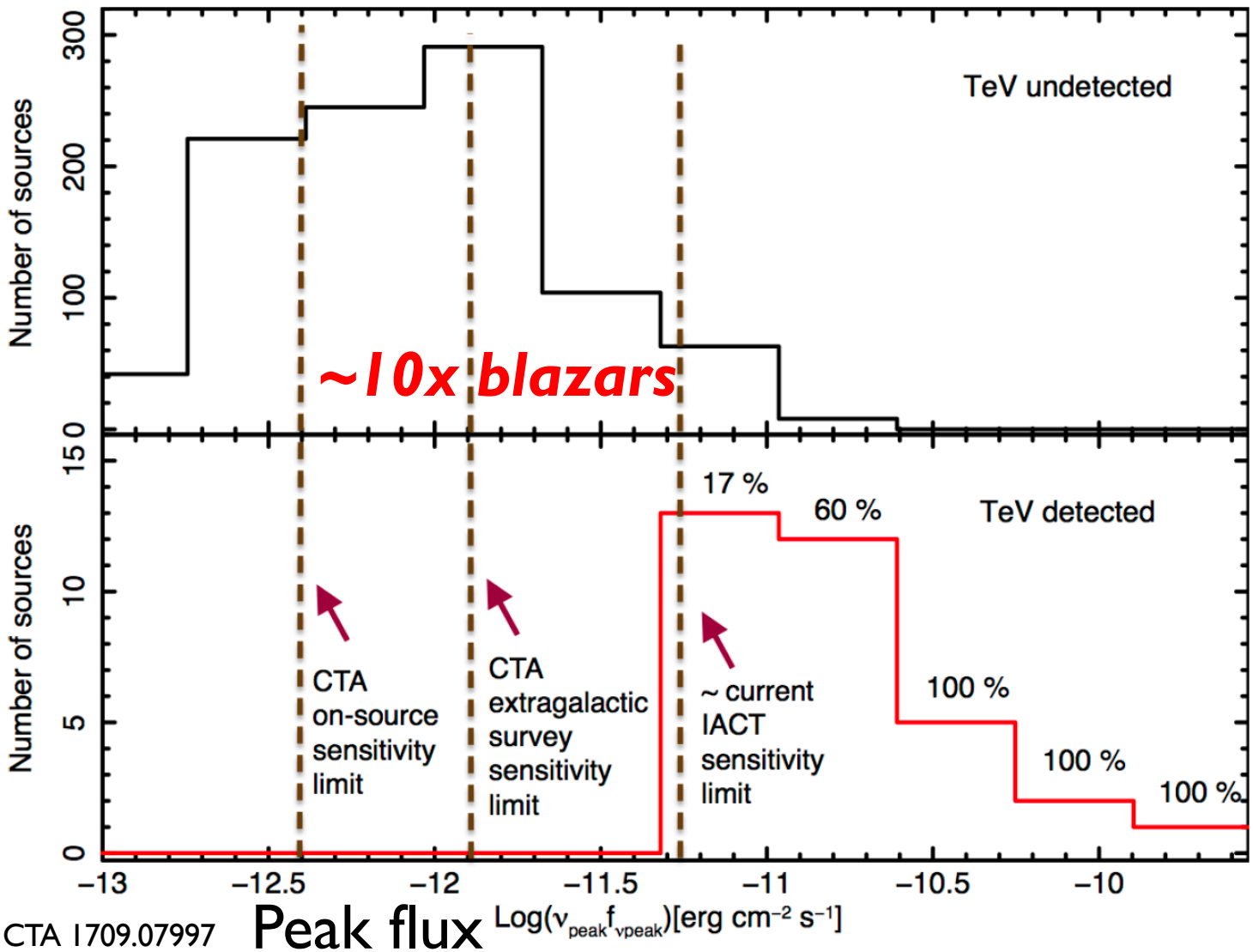
Supermassive Black Hole

$\sim 10^5\ M_\odot$



$\sim 10\ M_\odot$

CTA as AGN Factory

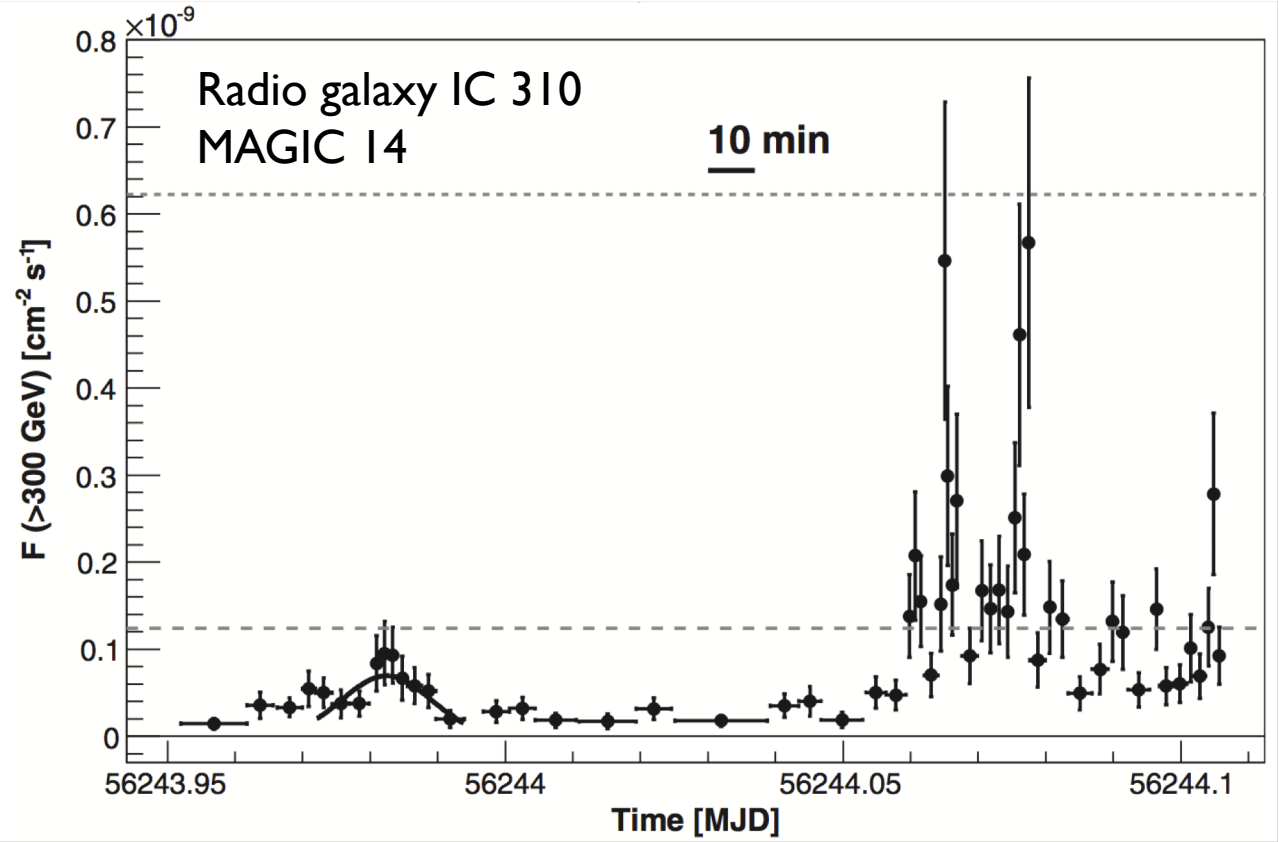


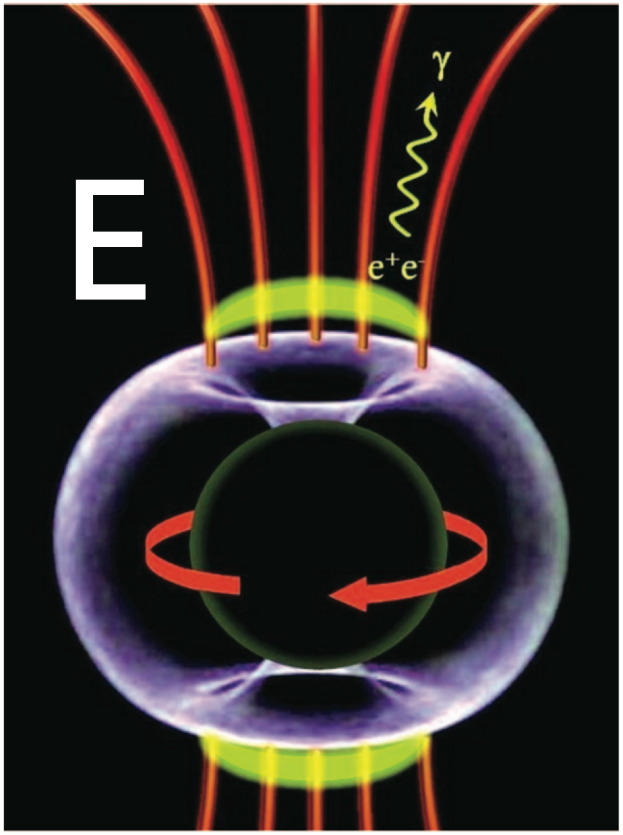
CTA 1709.07997 Peak flux

Active Galacitc Nuclei

On-axis jet → Blazar

Fast Variability

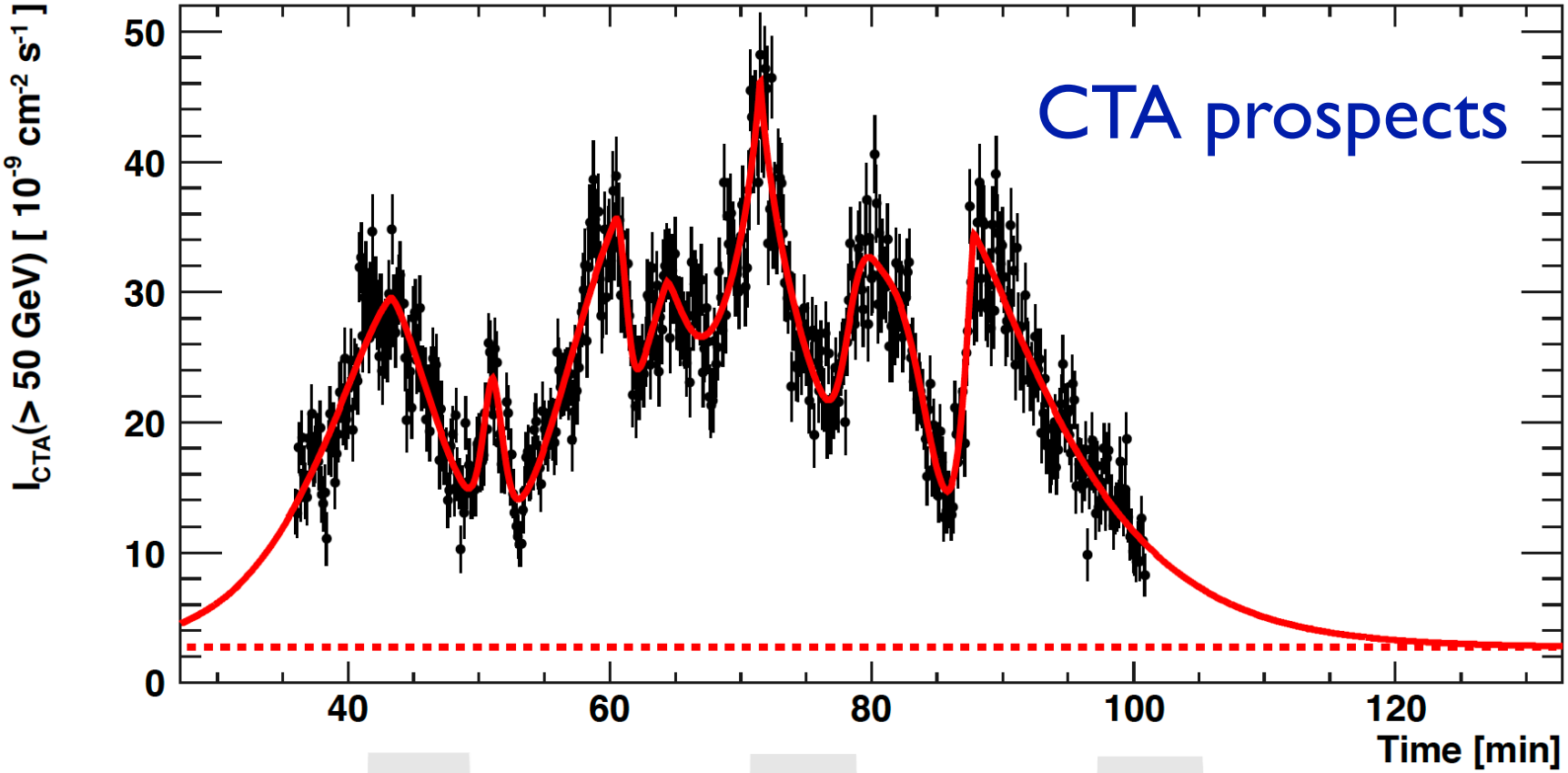


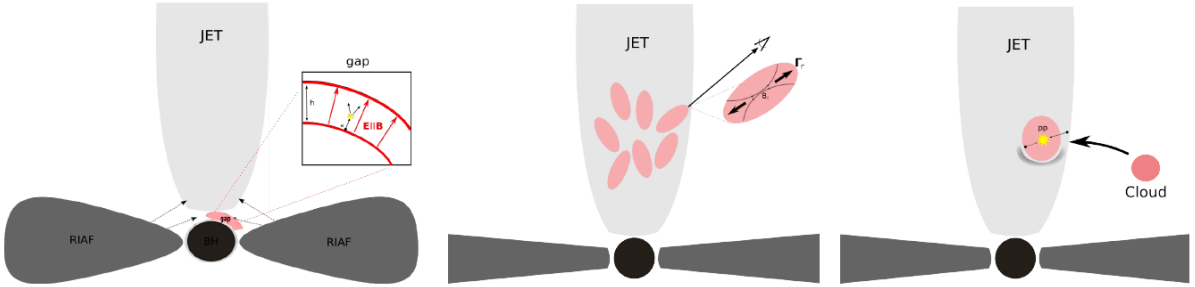


$\Delta t \sim 4.8$ min $\sim 20\%\ r_g$ (Sub-horizon)/c?

Probing BH Horizon

CTA 1709.07997

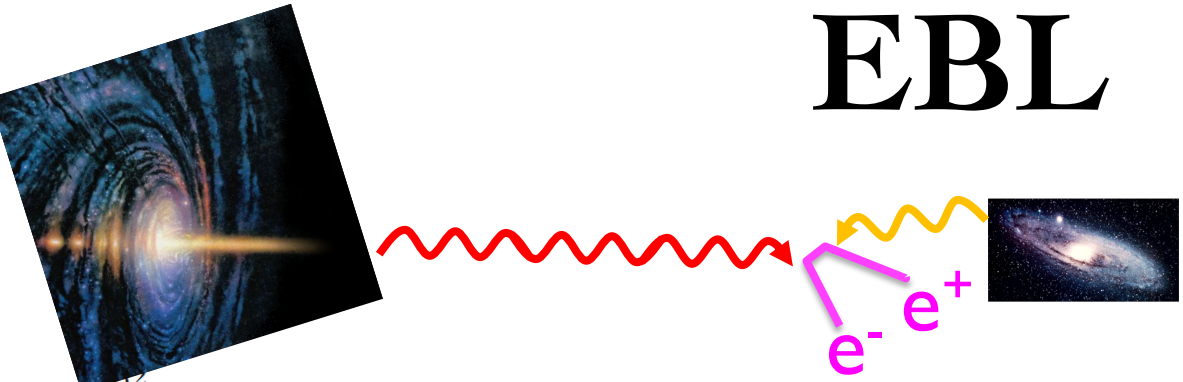




Rieger 19

EBL

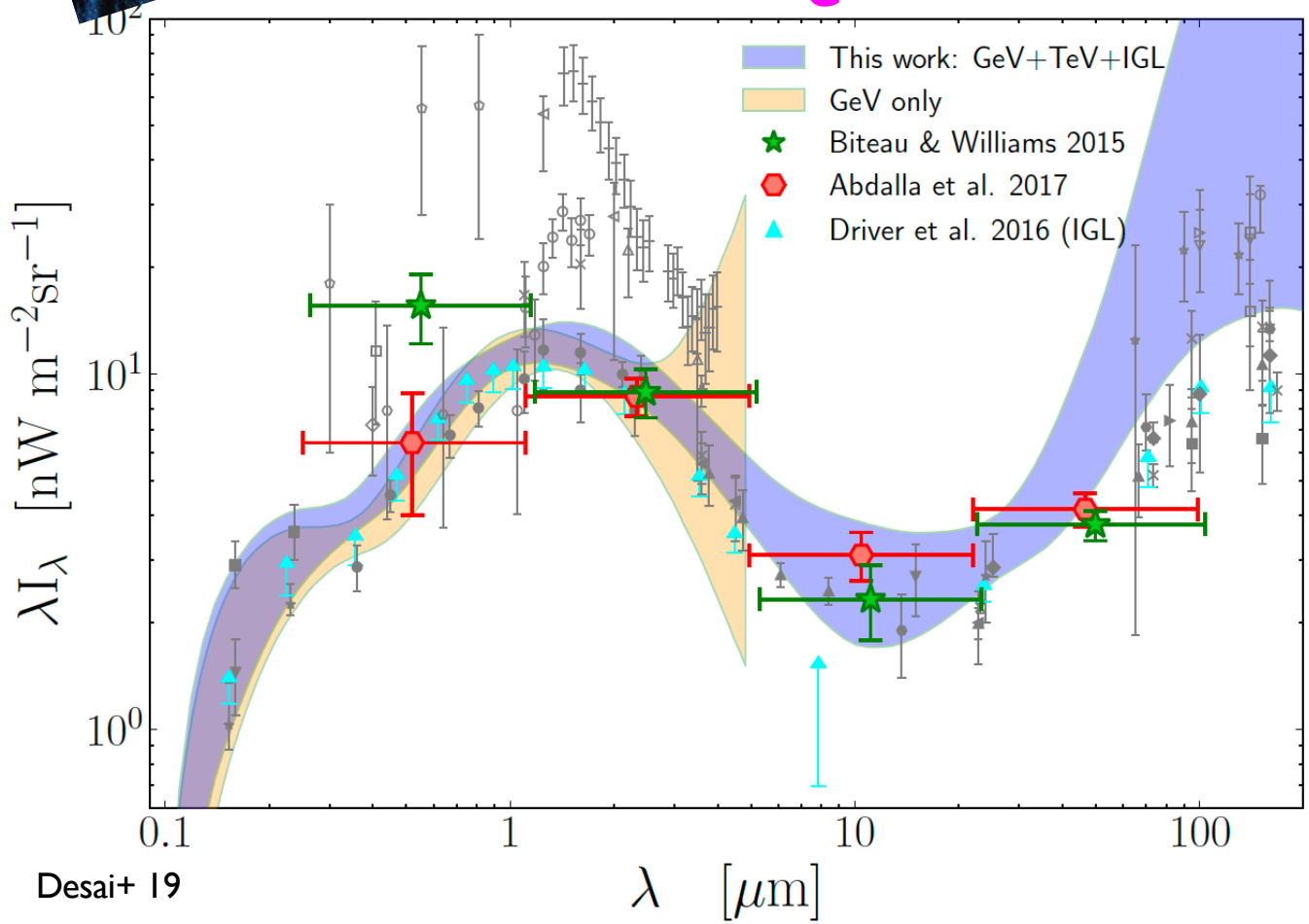
Extragalactic Background Light



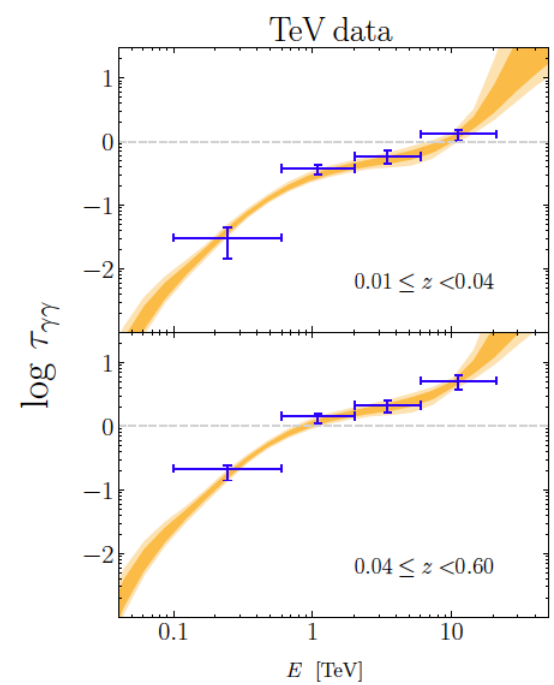
$$\mathrm{eV} \times \mathrm{TeV} \sim \left(m_e c^2\right)^2$$

$$l_{\gamma\gamma} \sim 1/\sigma_T n_{IR} \sim 10 n_{IR}^{-1}\mathrm{Mpc}$$

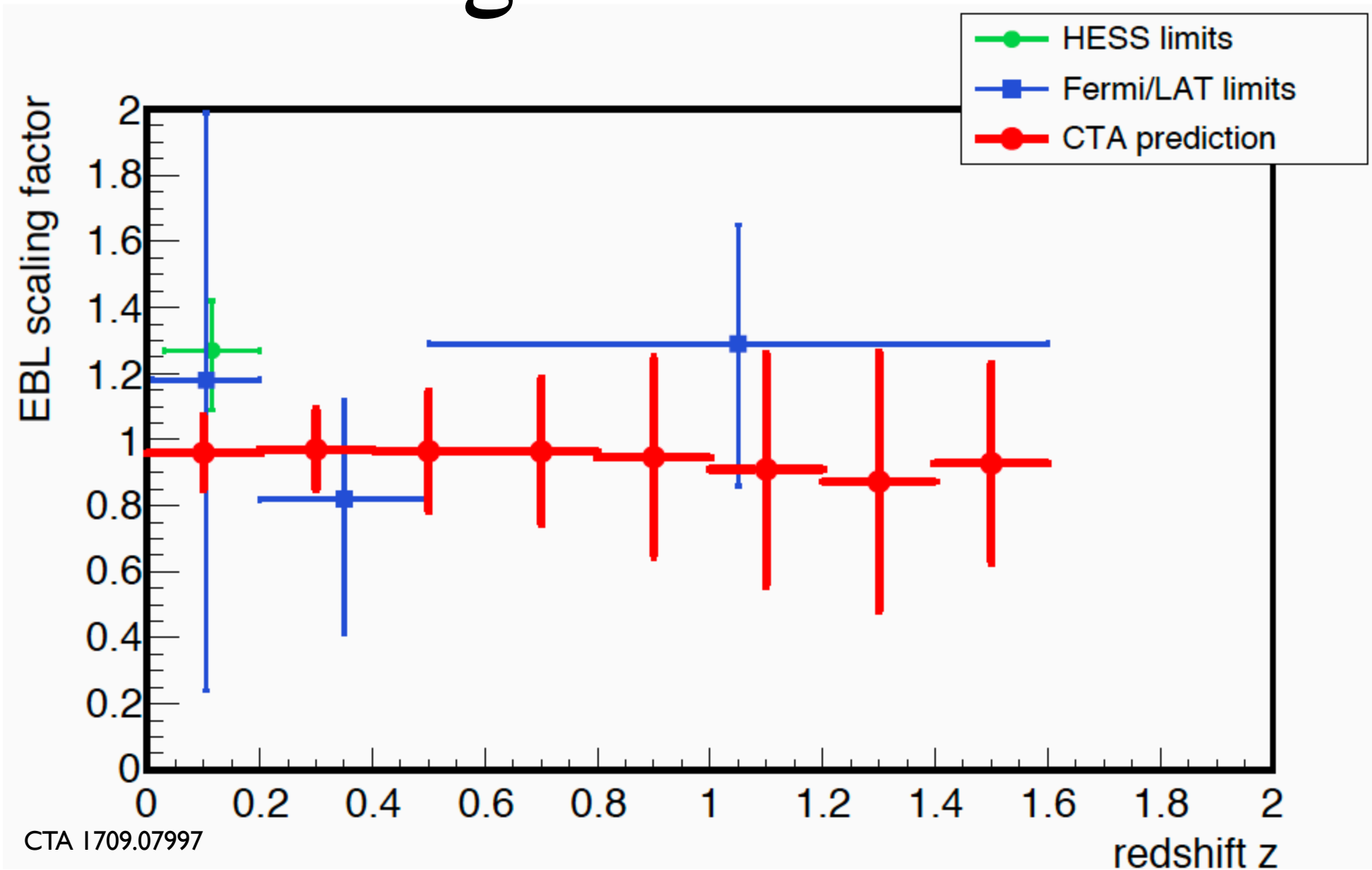
$$\frac{dN}{dE}_{\mathrm{obs}} = \frac{dN}{dE}_{\mathrm{int}} \cdot e^{-b\cdot\tau_{\mathrm{model}}}$$



Desai+ 19

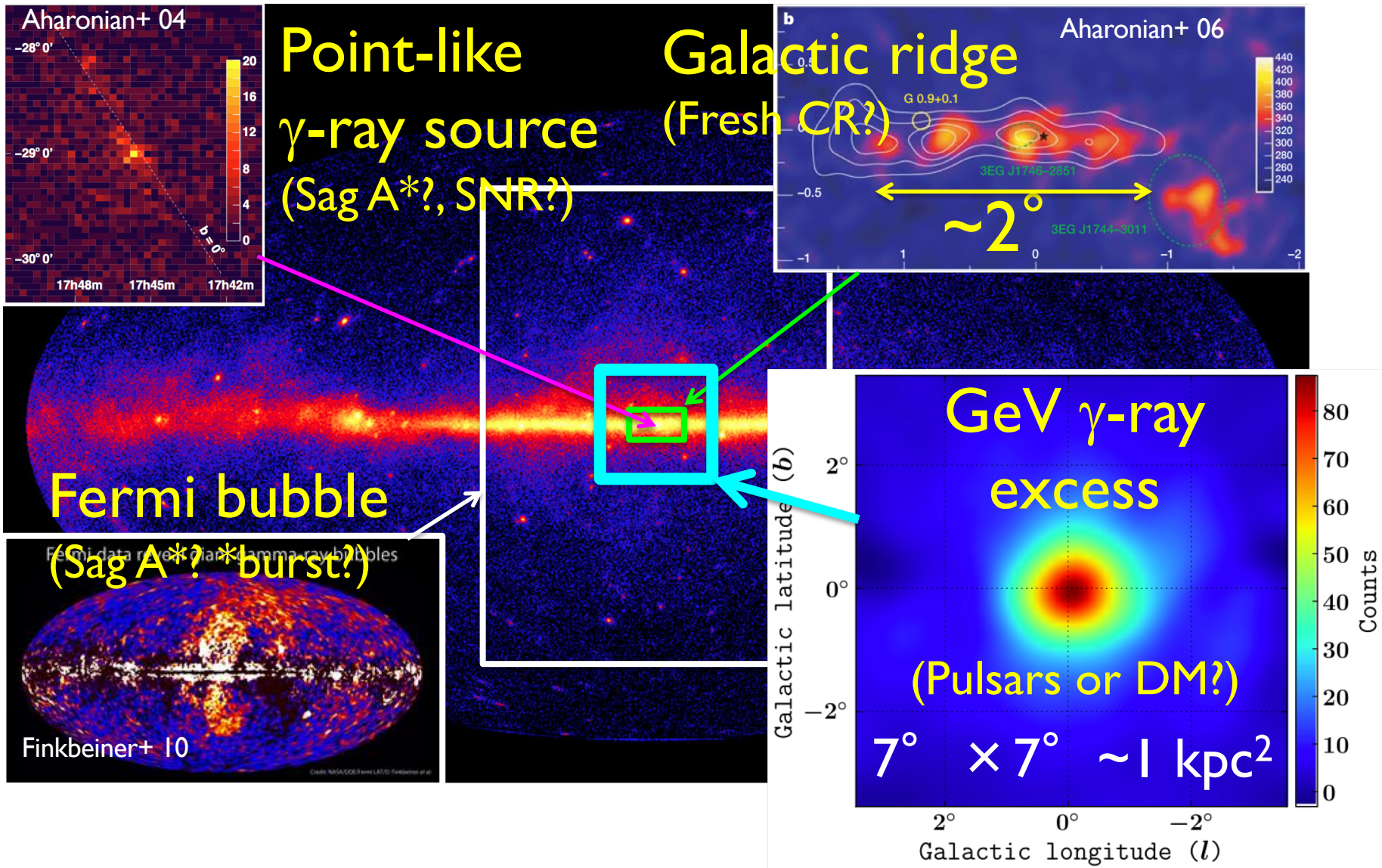


Probing EBL Evolution

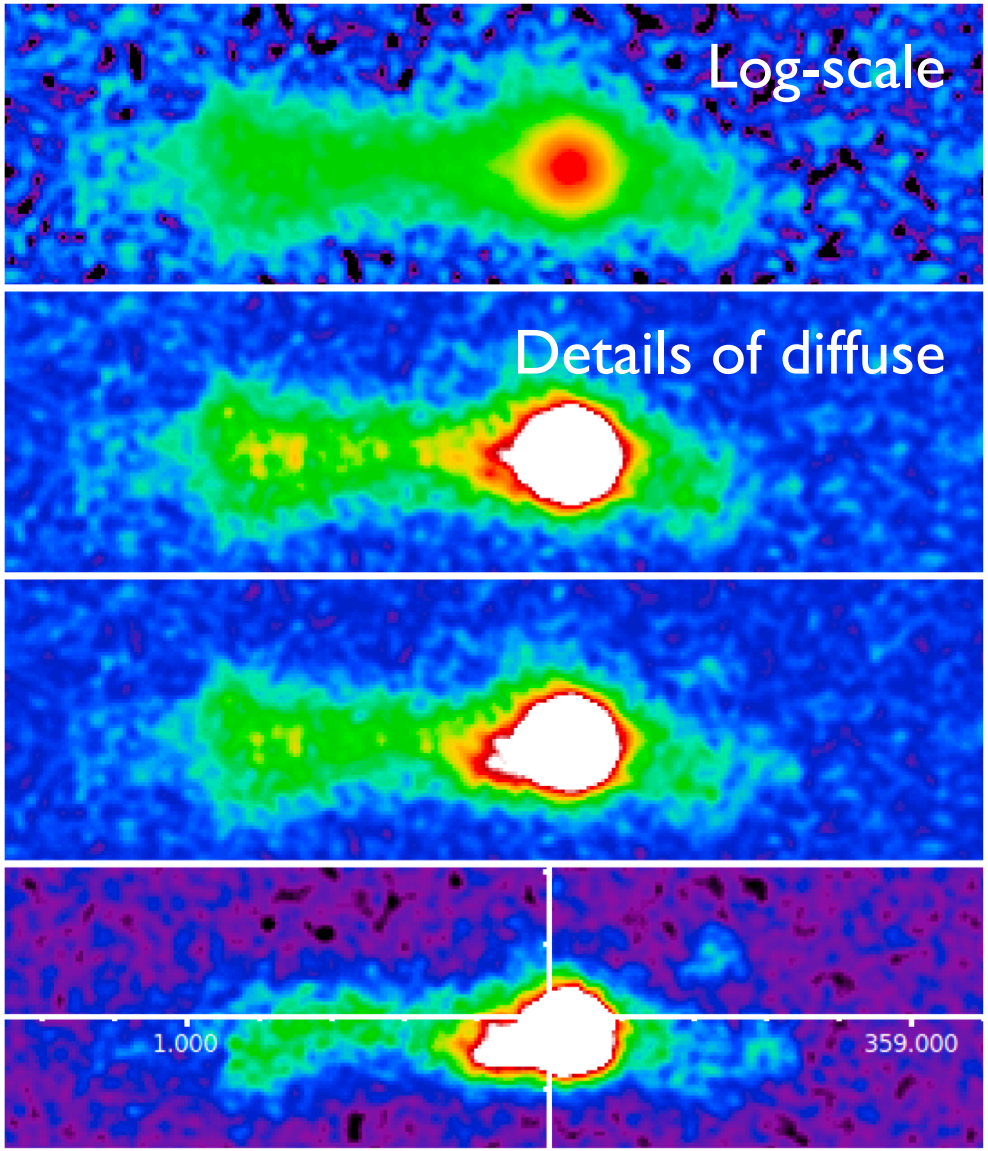


CTA 1709.07997

Galactic Center



Galactic Center by CTA



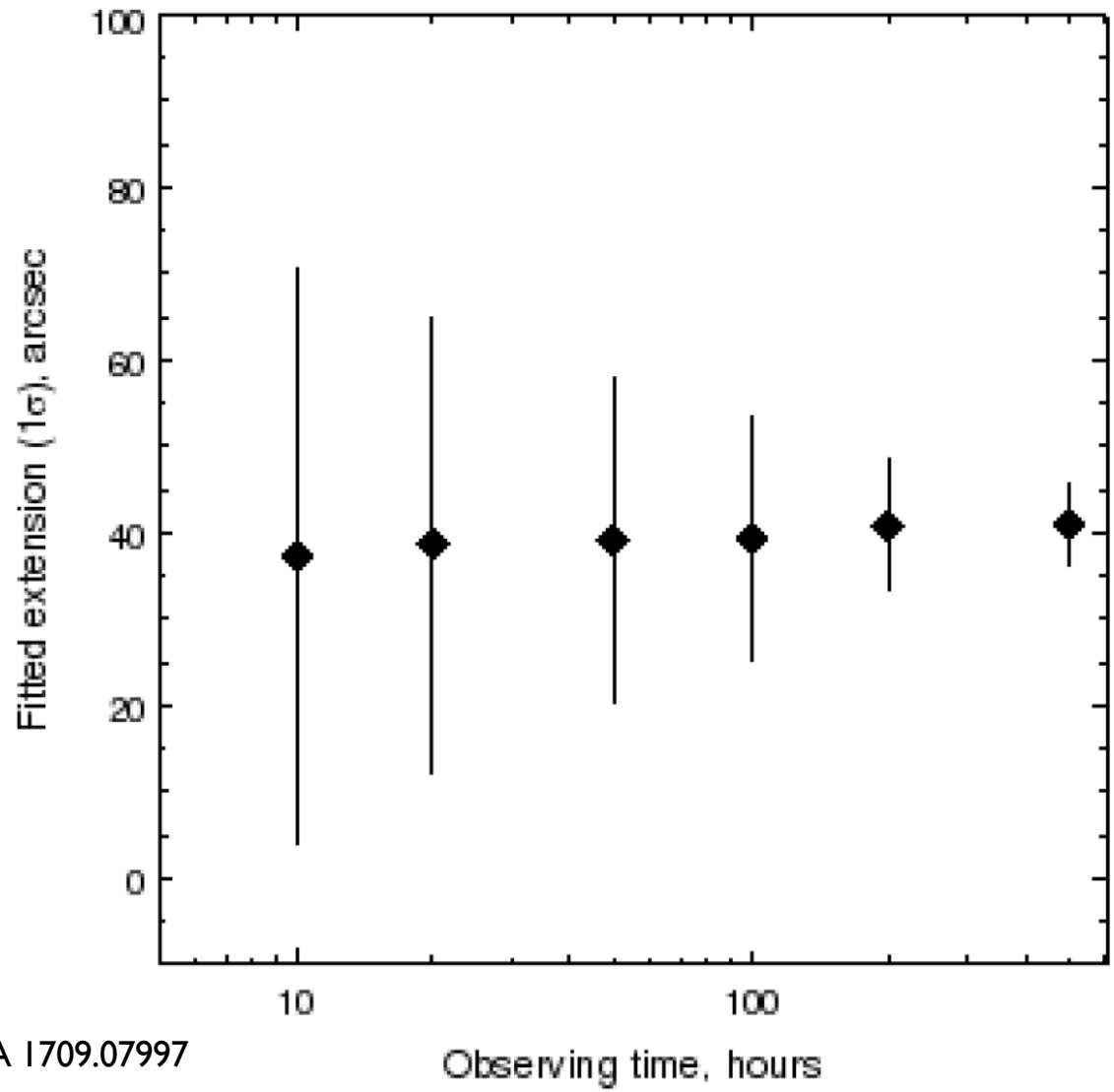
Point-like Sgr A*
+ SNR G0.9+0.1
+ diffuse emission
+ circum-nuclear ring

+ pulsar-wind-nebulae

- (Sgr A* and G0.9+0.1)

CTA 1709.07997

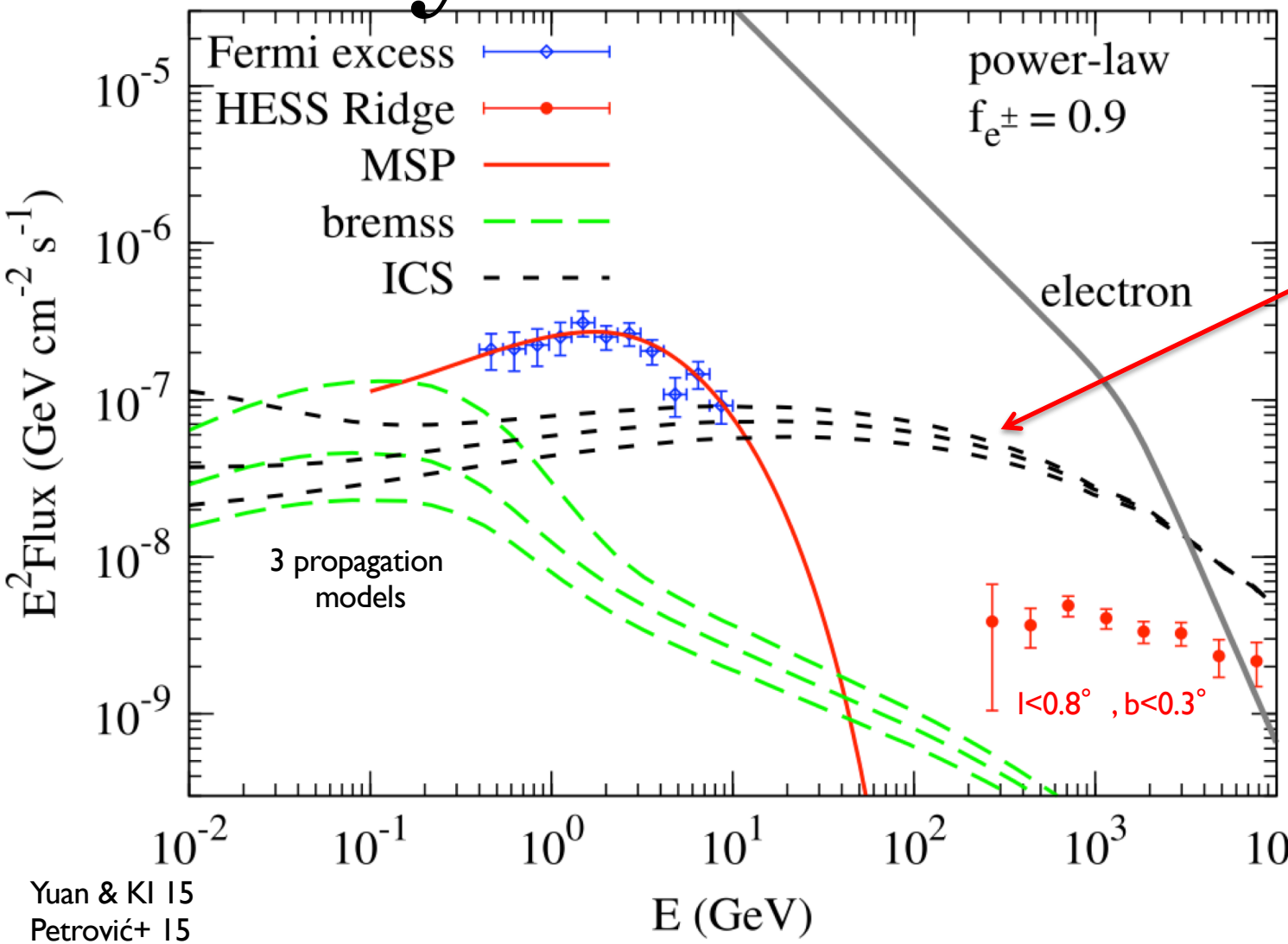
Super-Resolution in TeV



< 10 arcsec by CTA!!!

CTA 1709.07997

TeV Counterpart to Mysterious GeV Excess



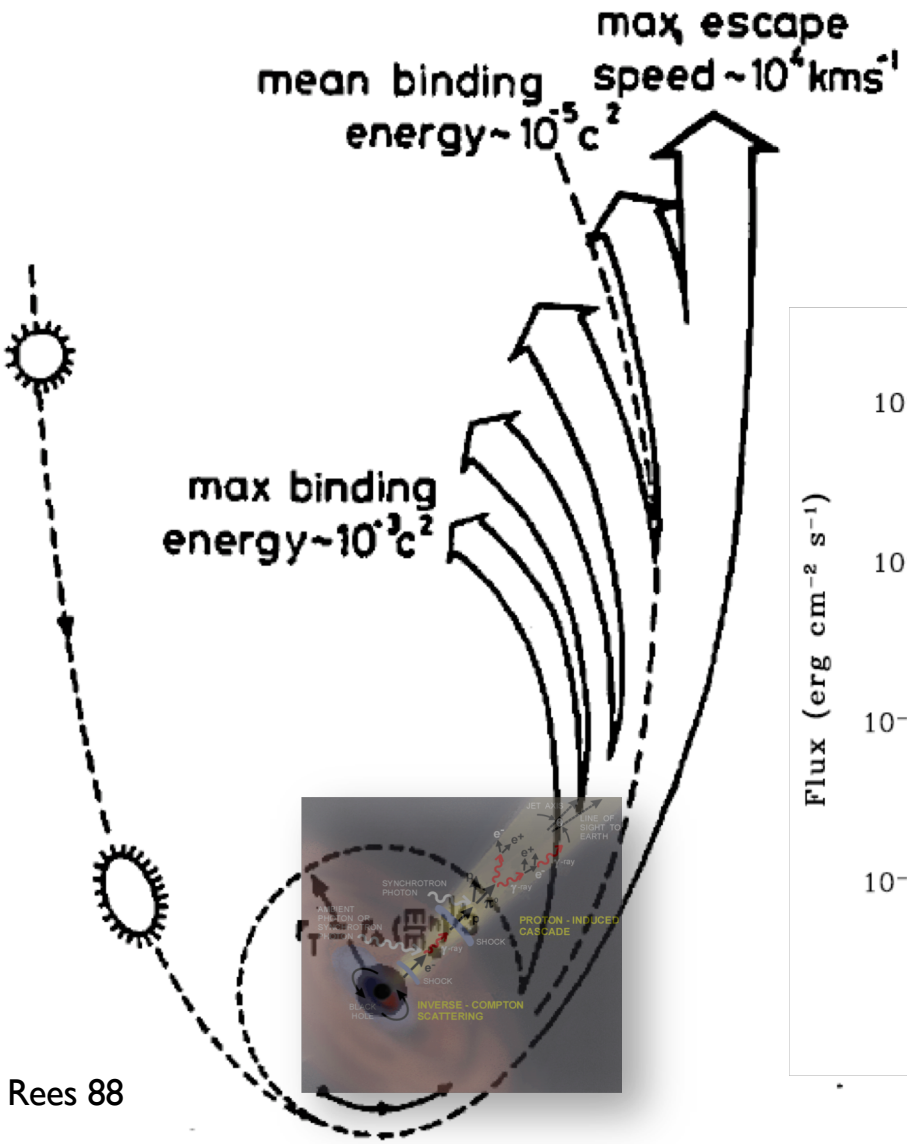
Yuan & KI 15
Petrović+ 15

Extended
7° × 7°
Power law E^{-2}
(E_{max}=50TeV)

Electron BG
(Isotropic)

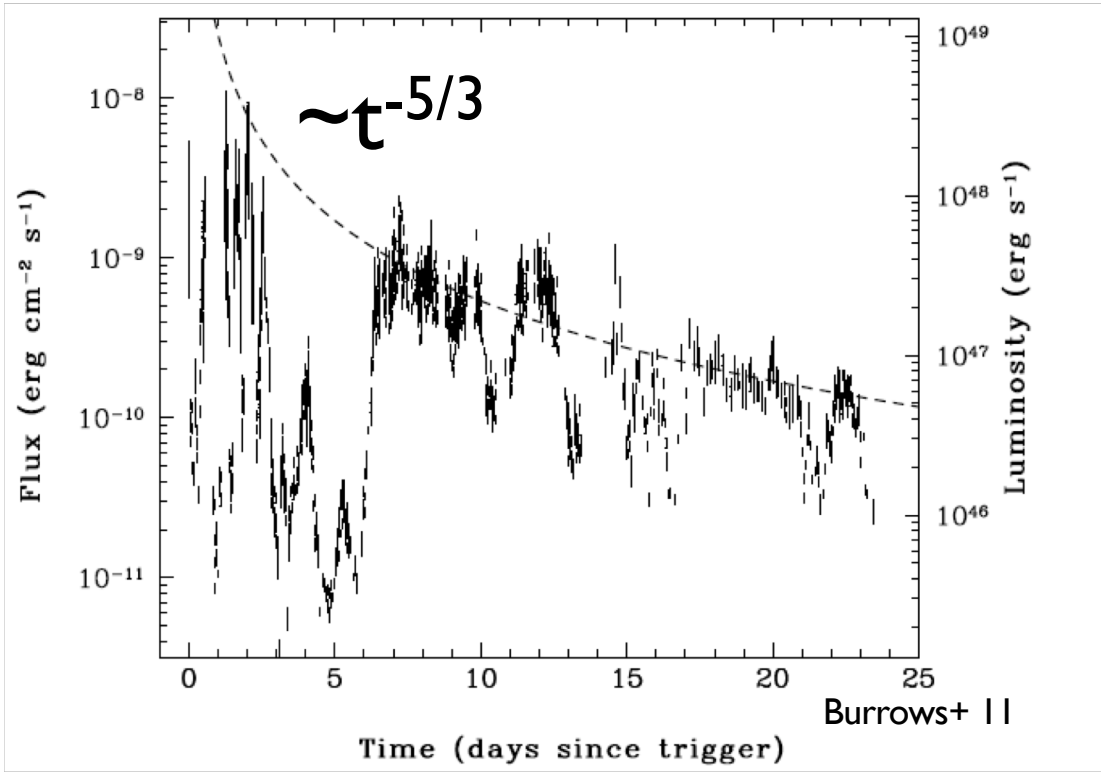
Pulsar model
$\gamma + e^+e^-$
Inverse
Compton

Tidal Disruption Jet



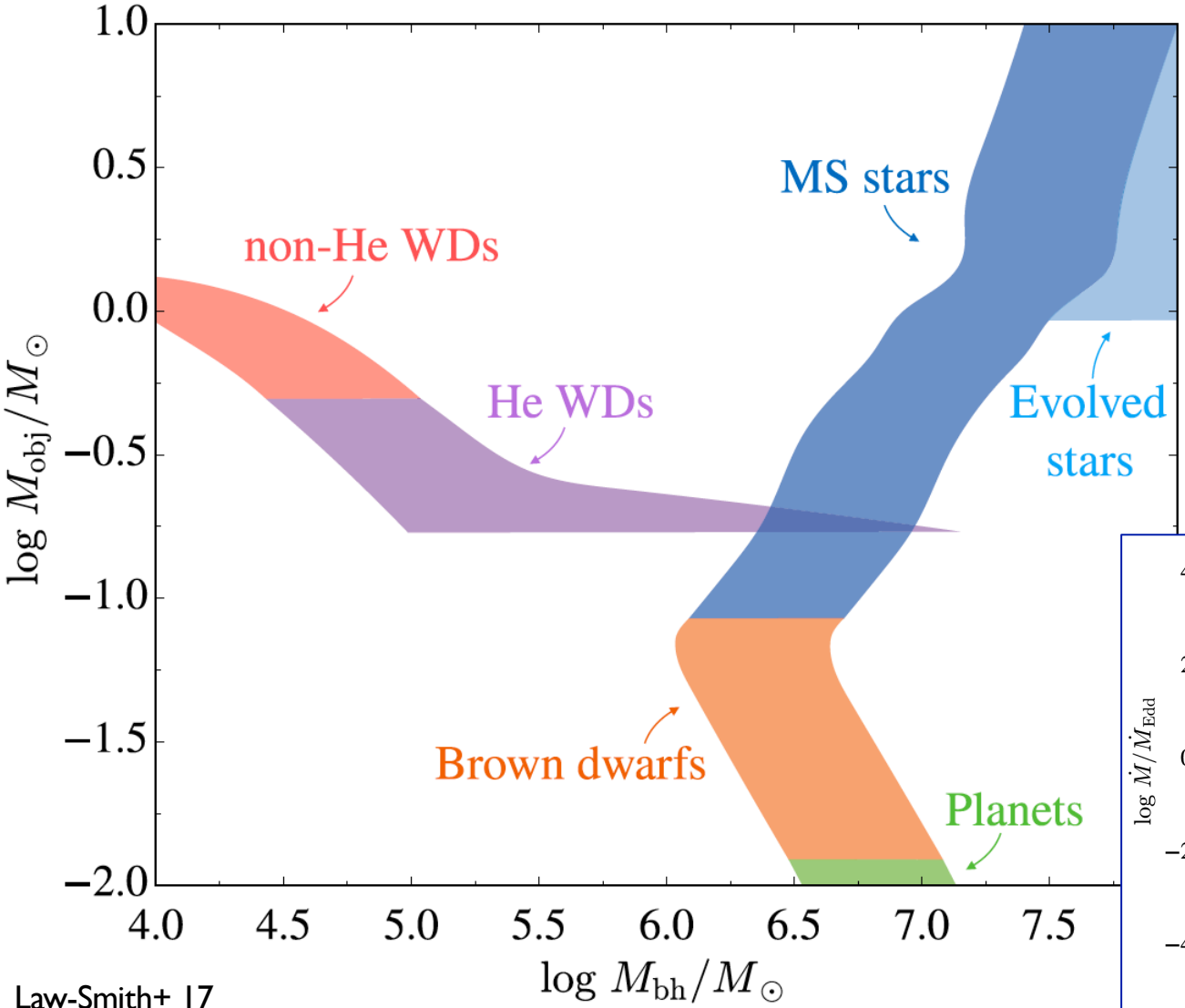
Rees 88

Supermassive BH disrupts a star ⇒ Jet



Burrows+ 11

Probing $M<10^5 M_\odot$ BH



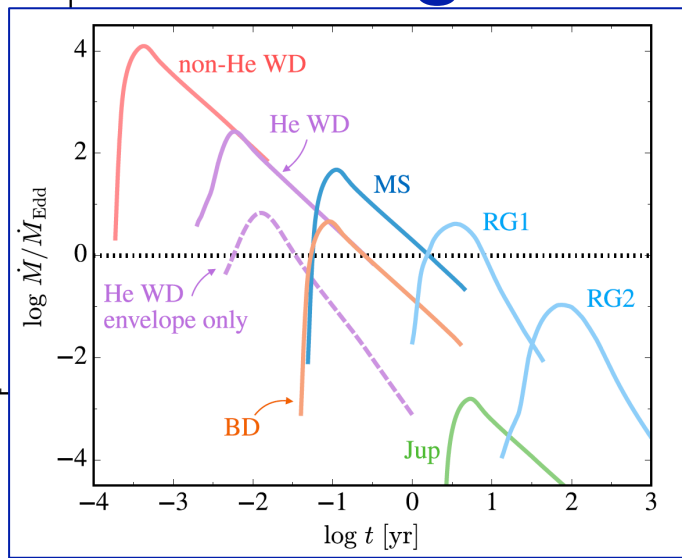
Law-Smith+ 17

$M<10^5 M_\odot$ BHs exist?

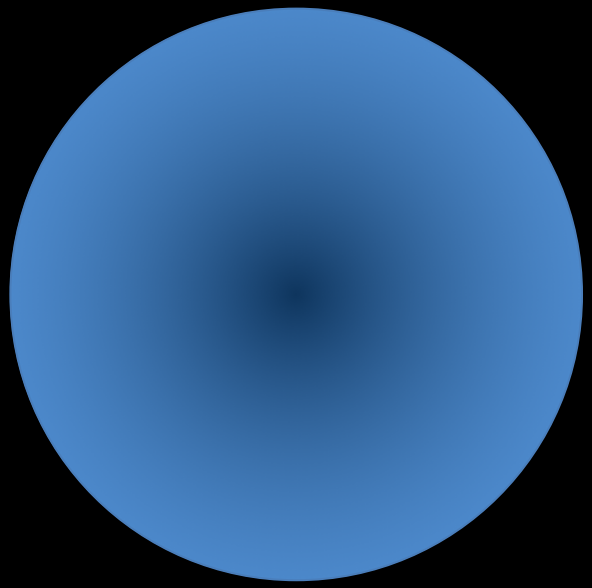
Short Δt

Bright TDE

Ultralong GRB

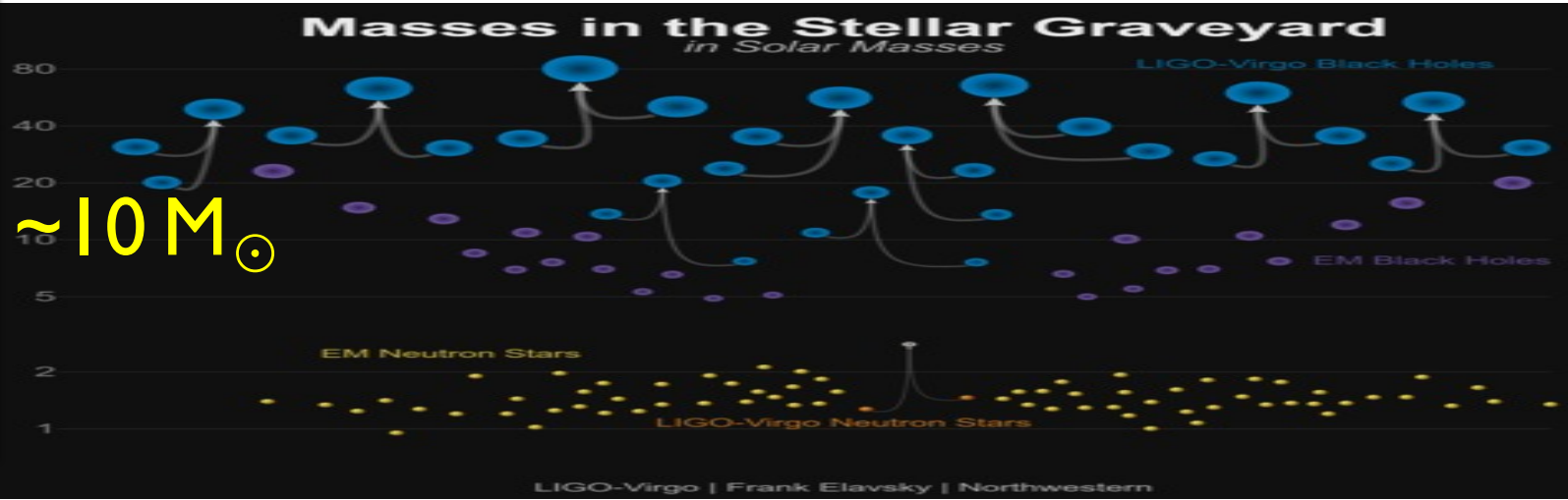


$\sim 10^9\ M_\odot$



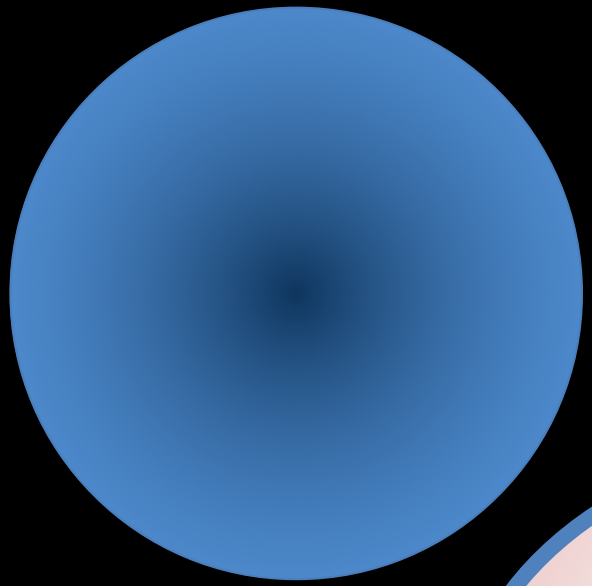
Supermassive Black Hole

$\sim 10^5\ M_\odot$



$\sim 10\ M_\odot$

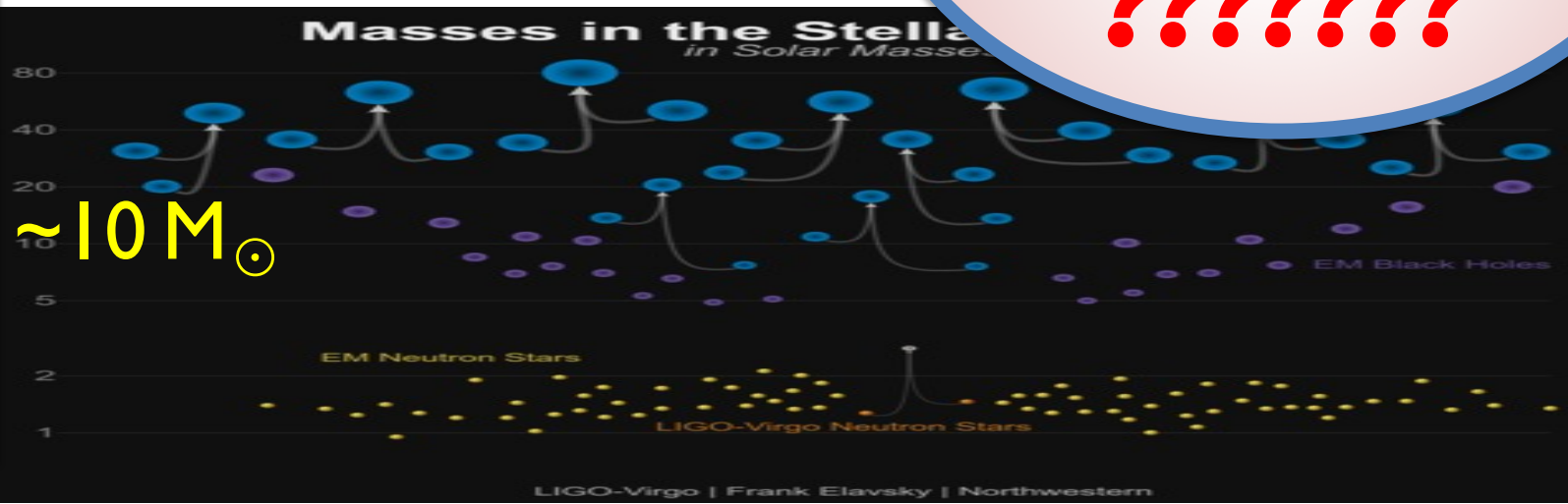
$\sim 10^9\ M_\odot$



Supermassive Black Hole

$\sim 10^5\ M_\odot$

Unknown unknowns ???????



$\sim 10\ M_\odot$

YITP Long-term Workshop

Search by "multi-messenger Kyoto"

YITP long-term workshop

Multi-Messenger Astrophysics in the Gravitational Wave Era

September 24 - October 25 2019,

Yukawa Institute for Theoretical Physics, Kyoto University

YKIS 2019

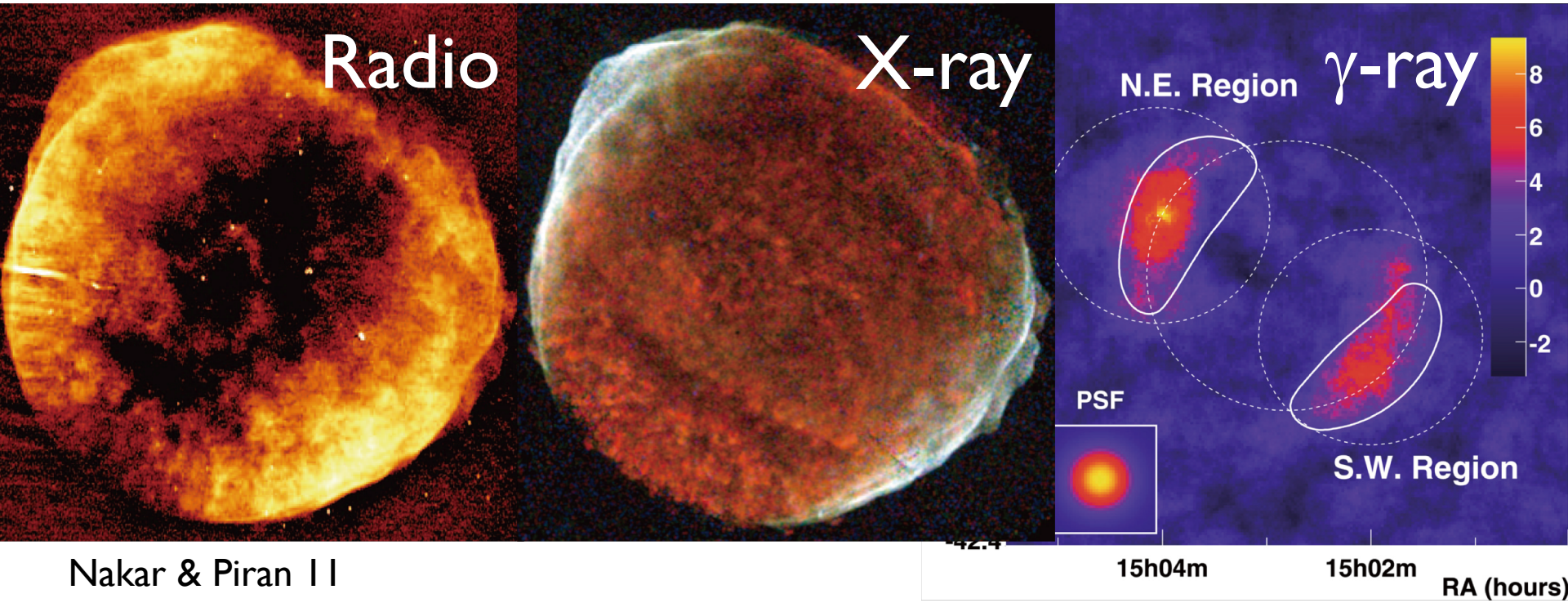
7-11 Oct.

5 days

symposium

Thank You

Like Supernova Remnant

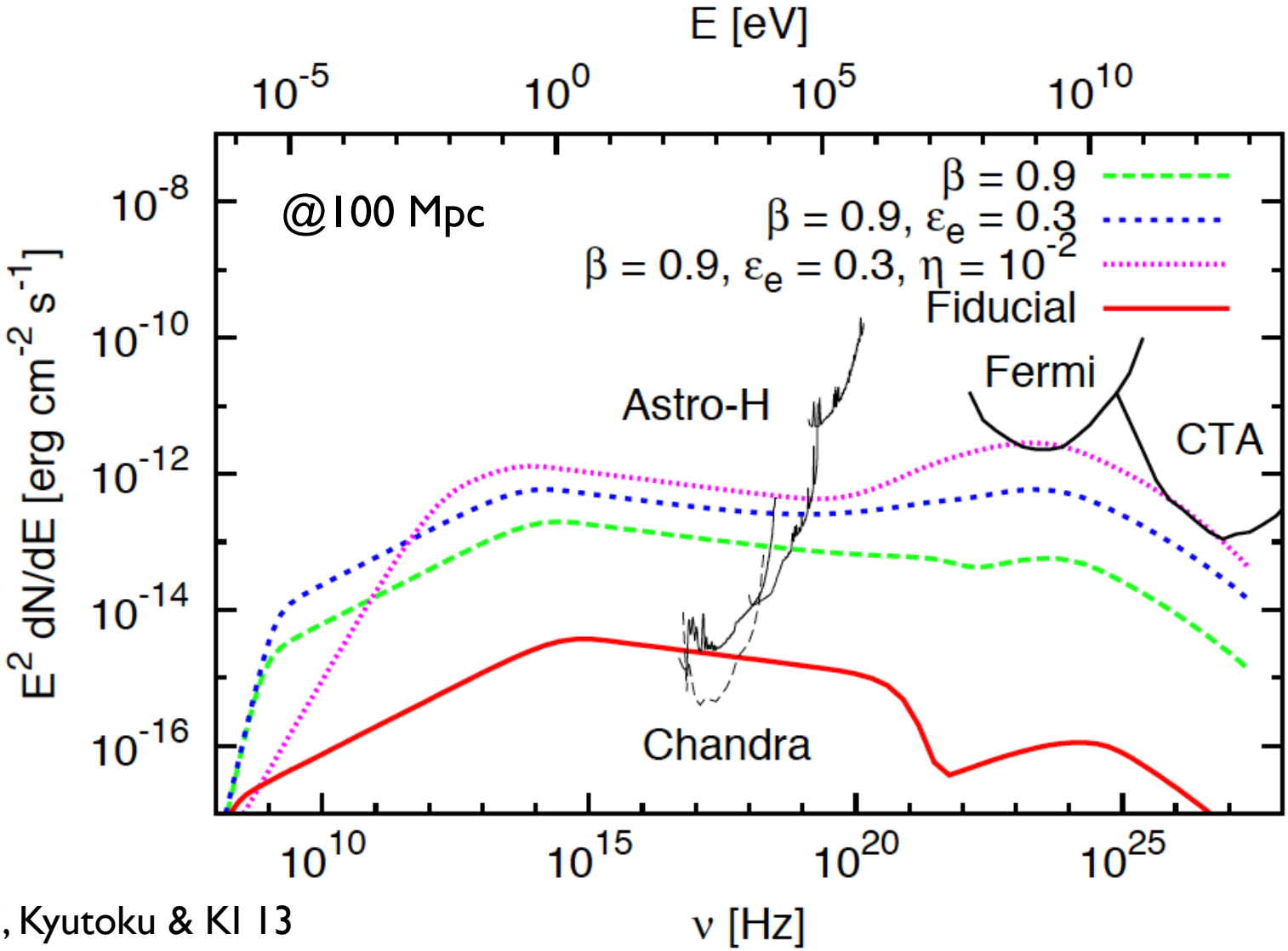


Nakar & Piran 11

NS merger remnant ~ Supernova remnant

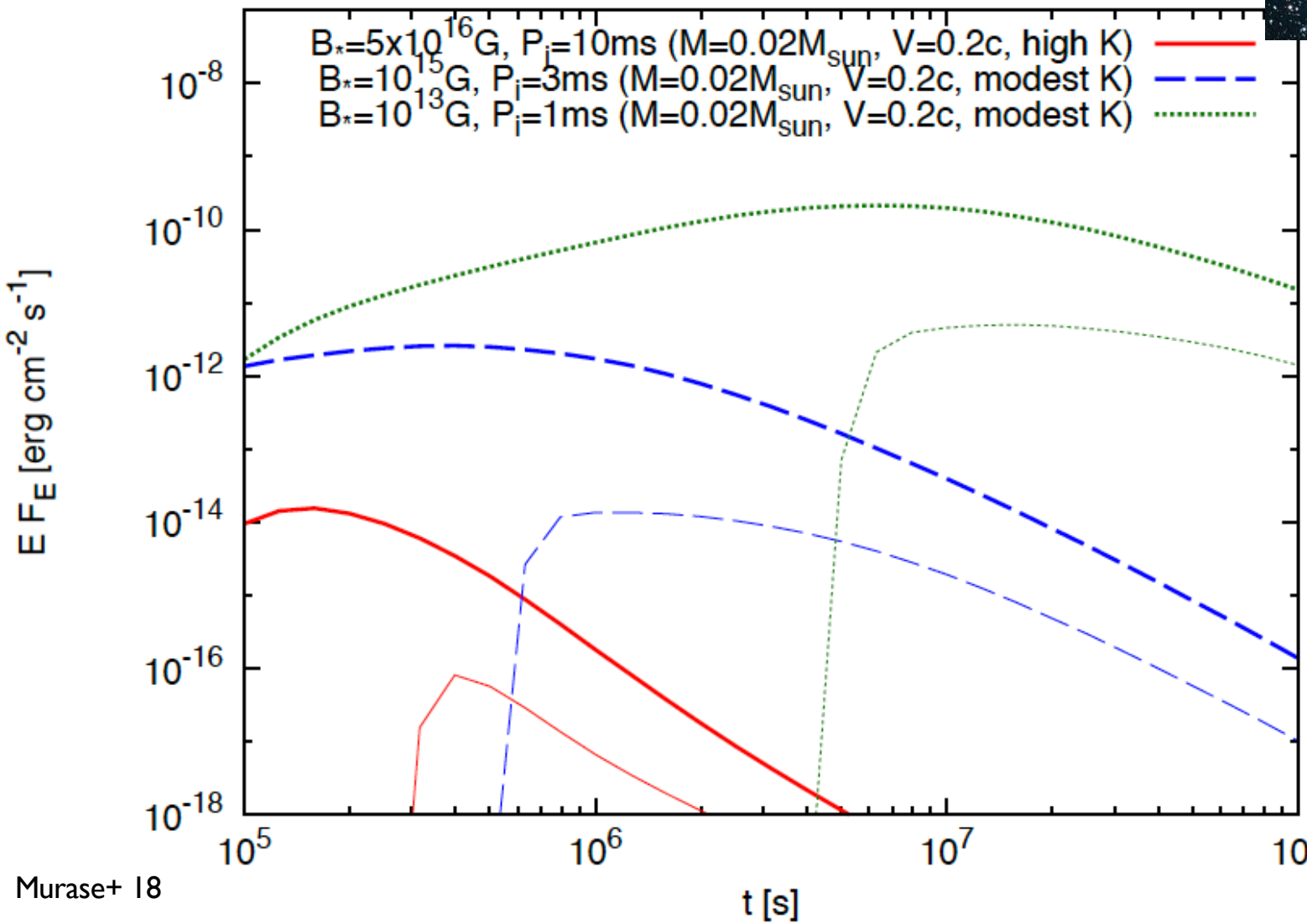
⇒ ***High energy remnant for NS merger?***

Merger Remnant Spectrum



Takami, Kyutoku & KI 13

Magnetar?



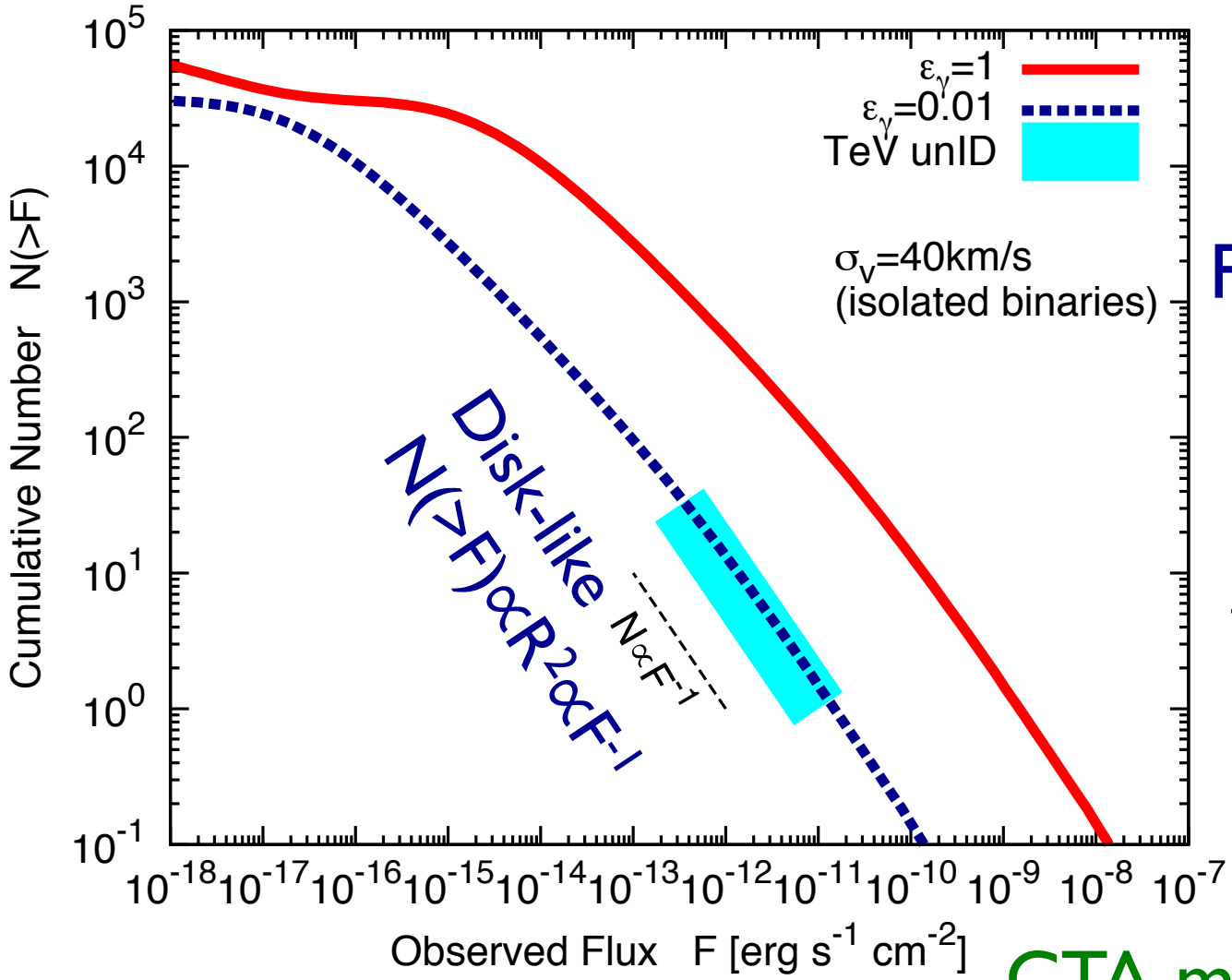
Ejected $M_{NS\text{-}NS} << M_{SN}$

$\Rightarrow \tau < 1$ earlier

Diversity of M_{NS}

Murase+ 18

Log N – Log F



KI+ 16

BHs ⇔ TeV unIDs?

Flux dis. is similar

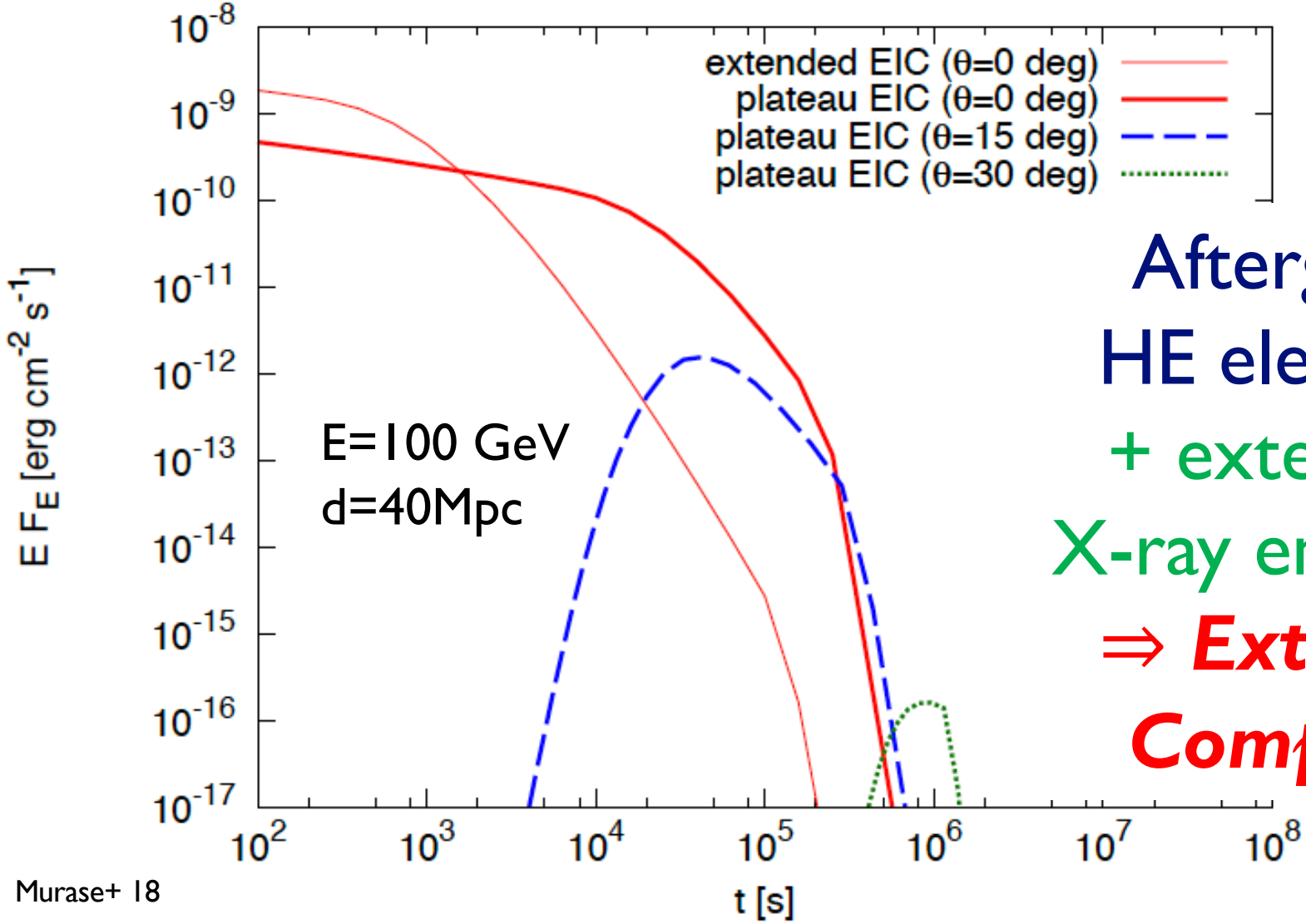
BH nebula size:

$$\frac{L_j}{4\pi r_h^2 \theta^2 c} \sim \rho V^2$$

$$\Rightarrow \; r_h \sim 3 \text{ pc}$$

CTA may see ~10^3 BHs

HE γ-ray from Afterglow

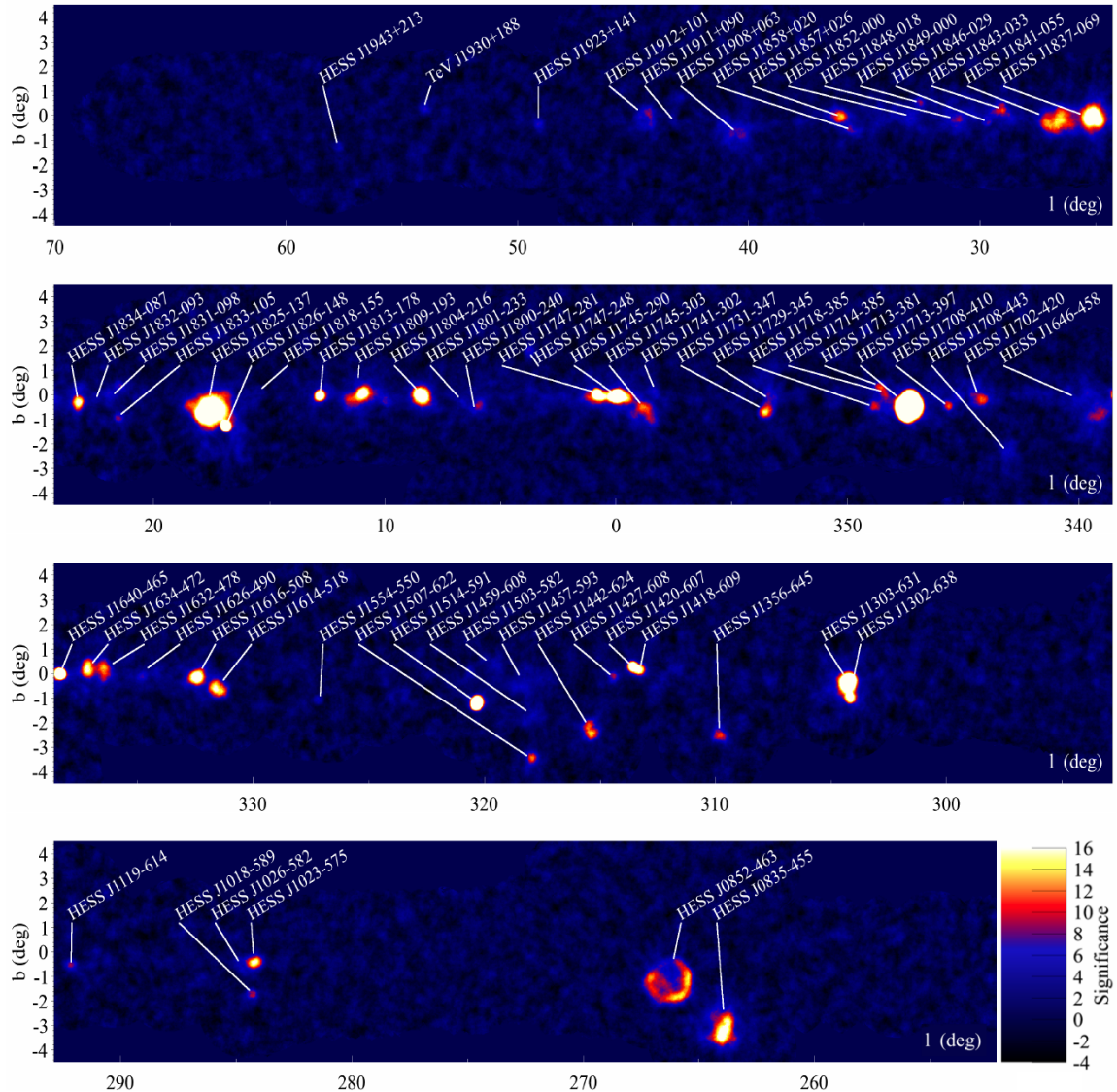


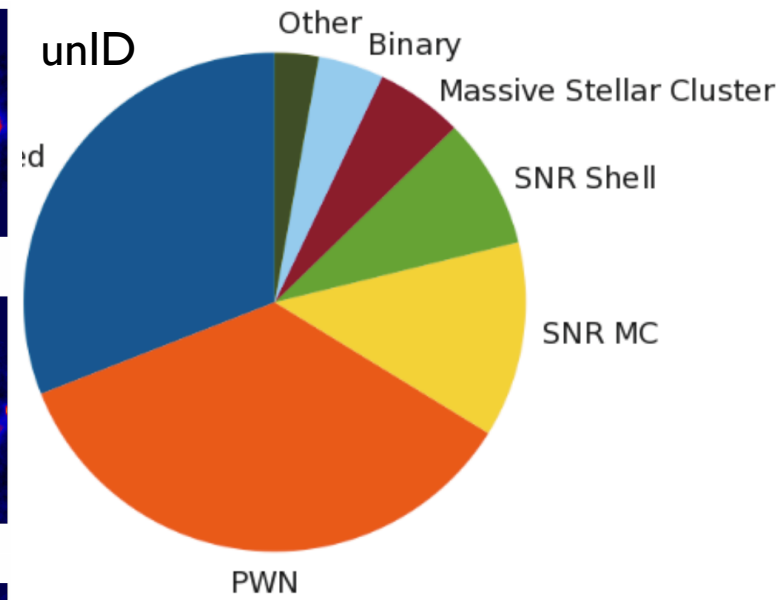
Afterglow
HE electron
+ extended
X-ray emission
⇒ ***External Compton***

Murase+ 18

TeV Gamma-Ray Sky

HESS 1307.4690



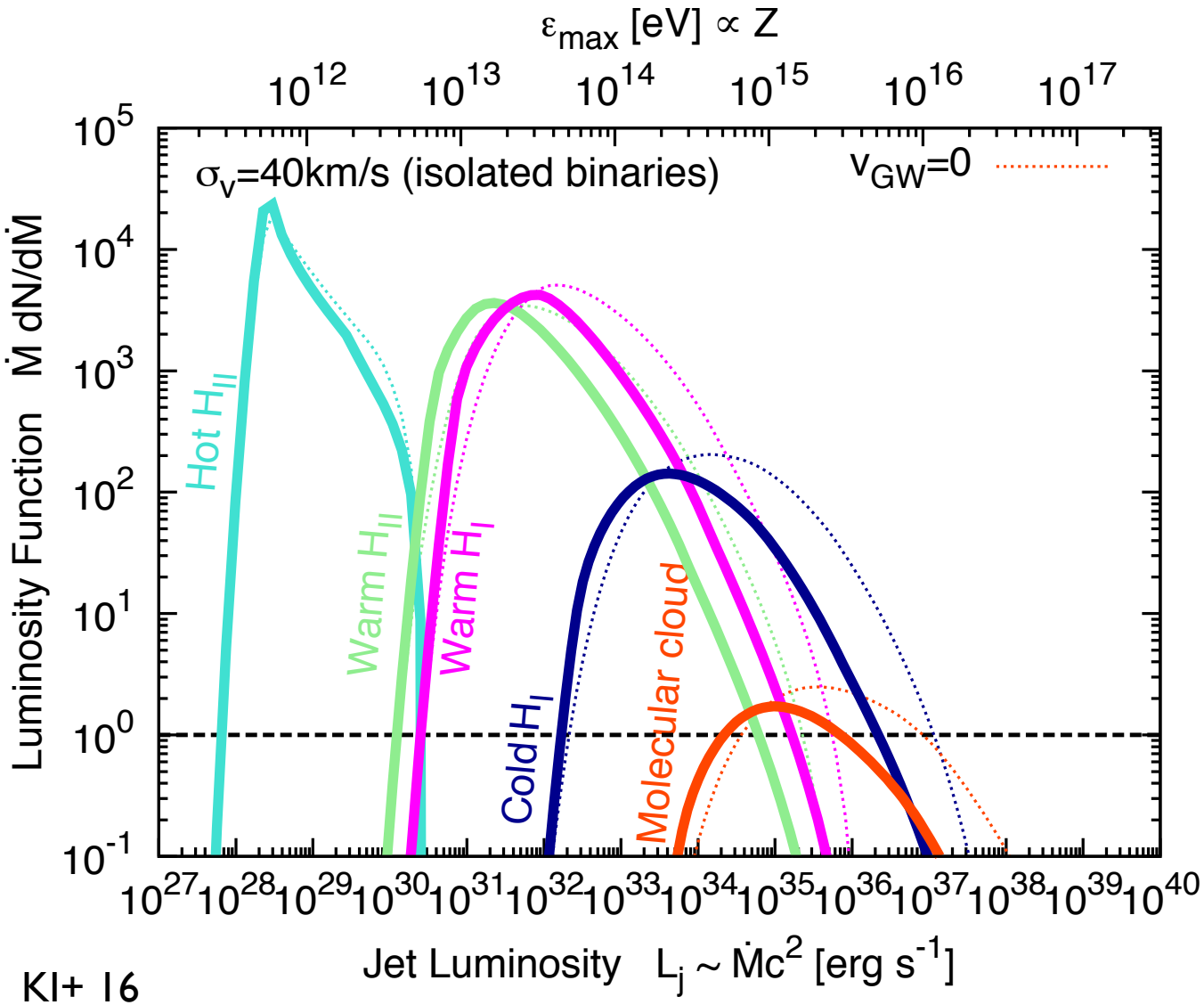


unIDs dominate TeV γ-ray sky

Spatially extended

$$R \sim \theta d \sim 3\mathrm{pc}\left(\frac{\theta}{0.2^\circ}\right)\left(\frac{d}{\mathrm{kpc}}\right)$$

Luminosity Function



KI+ 16

The most luminous BH jet is ~10^{36} erg/s in cold H_I

v_{GW} reduces L_j by ~10