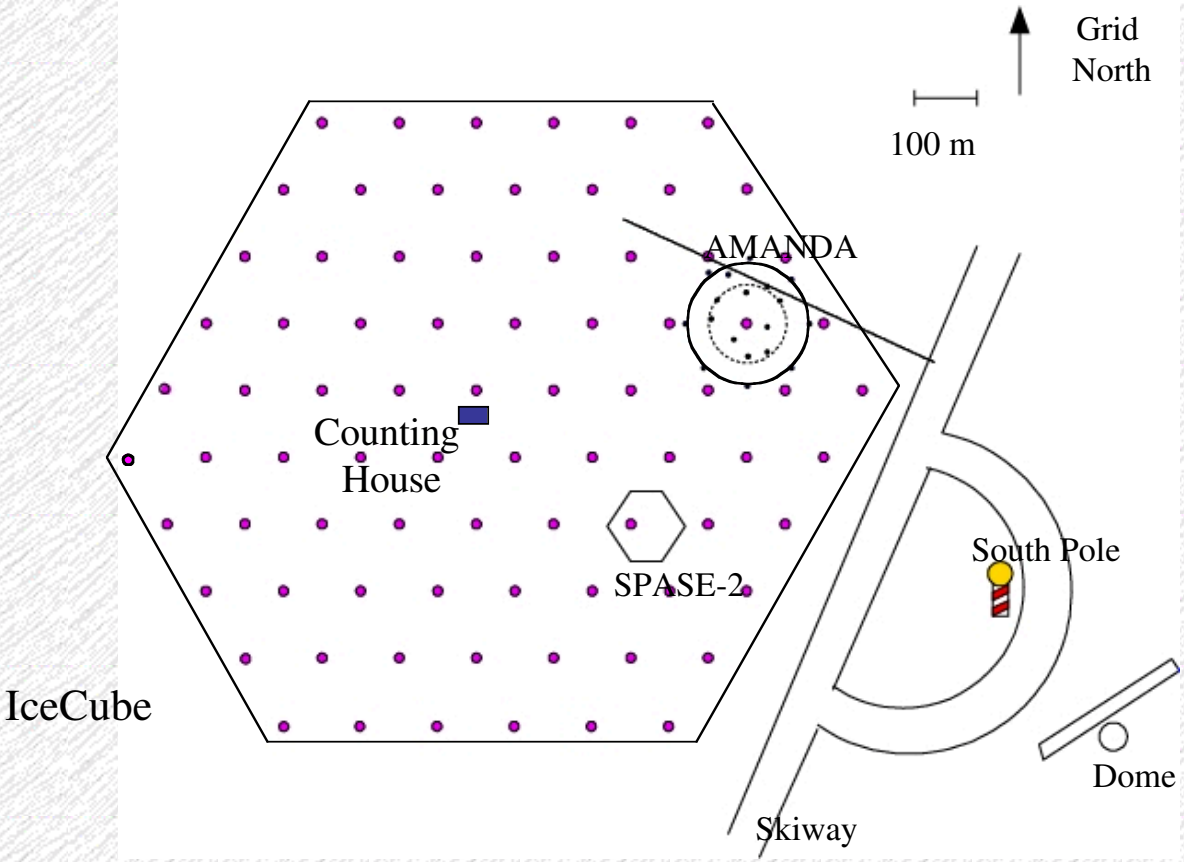
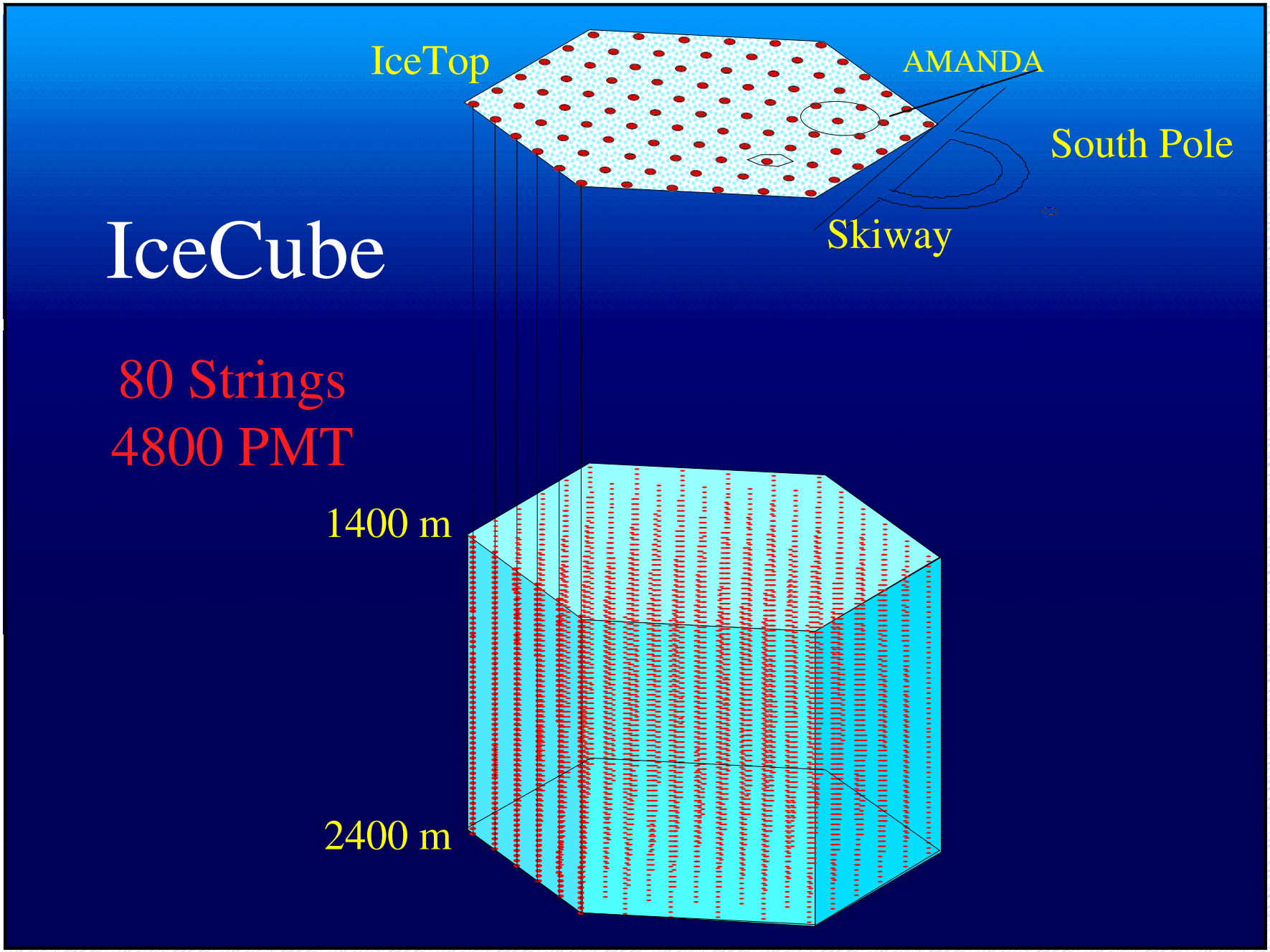
IceCube

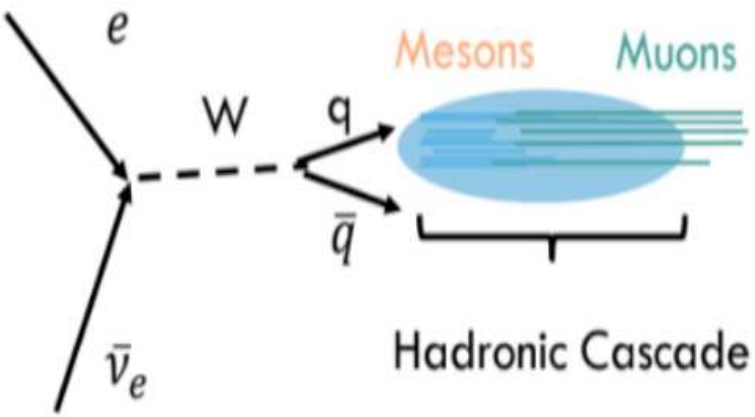
IceCube:Top View

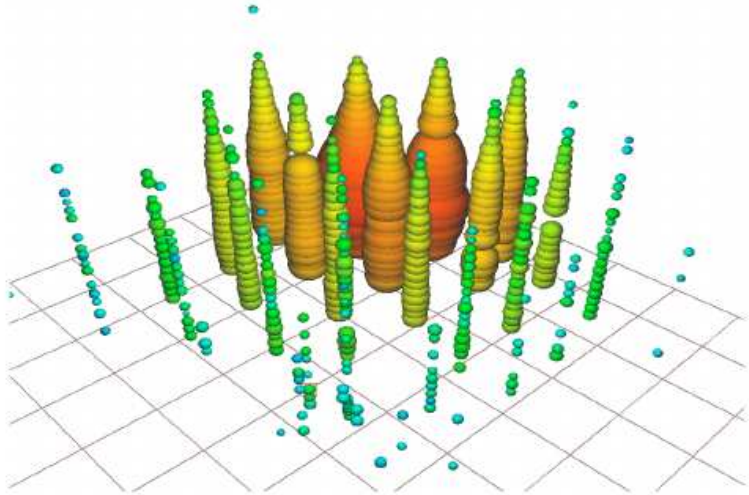


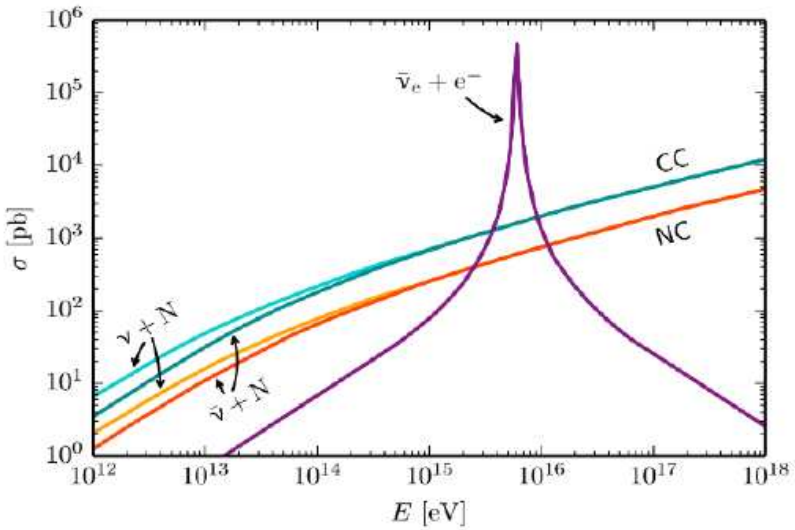

IceTop
AMANDA
South Pole
Skiway
IceCube
80 Strings
4800 PMT
1400 m
2400 m

IceCube events:

Glashow resonance: anti-ν_e + atomic electron → real W





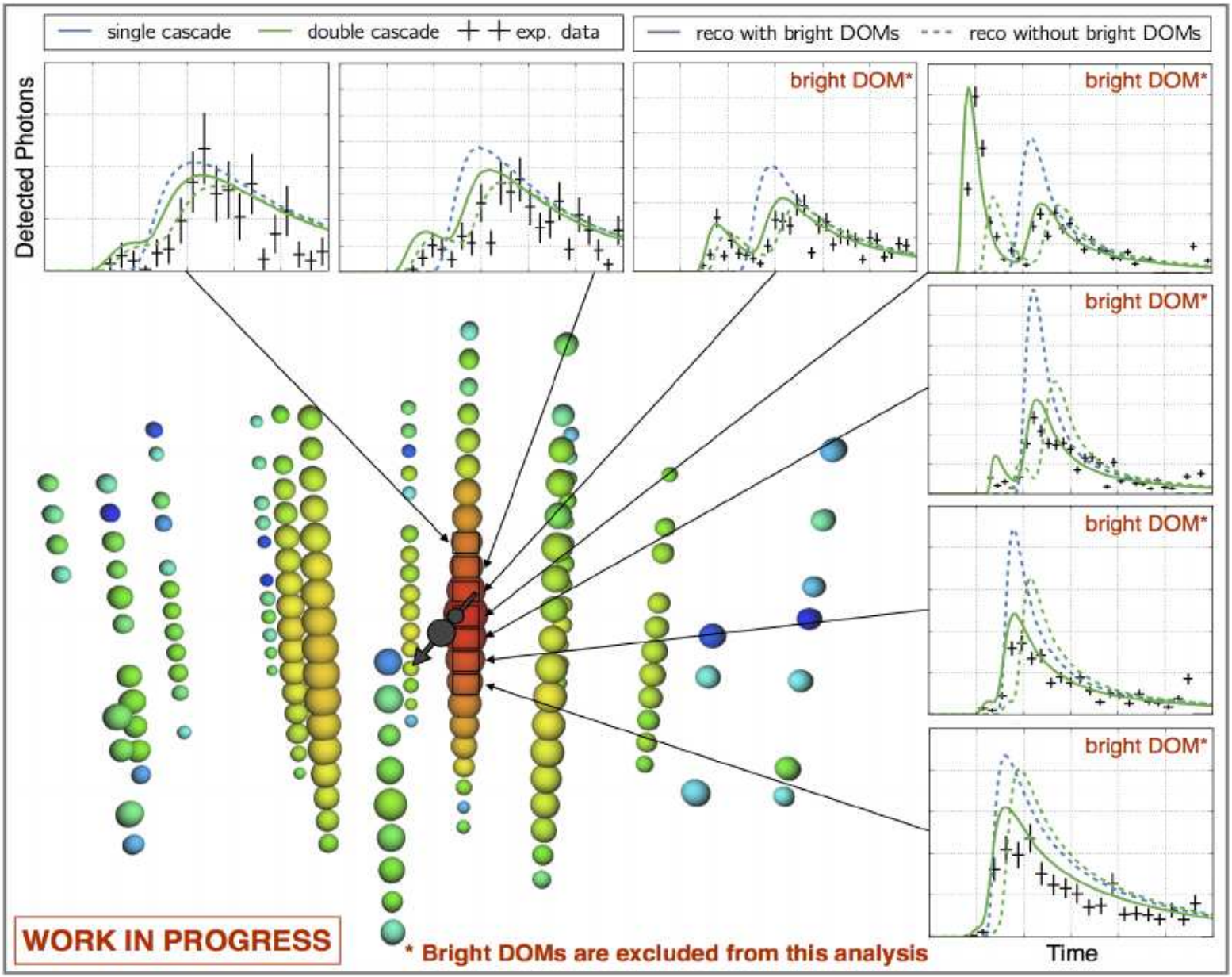


- partially-contained PeV search
- deposited energy: 5.9±0.18 PeV
- typical visible energy is 93%

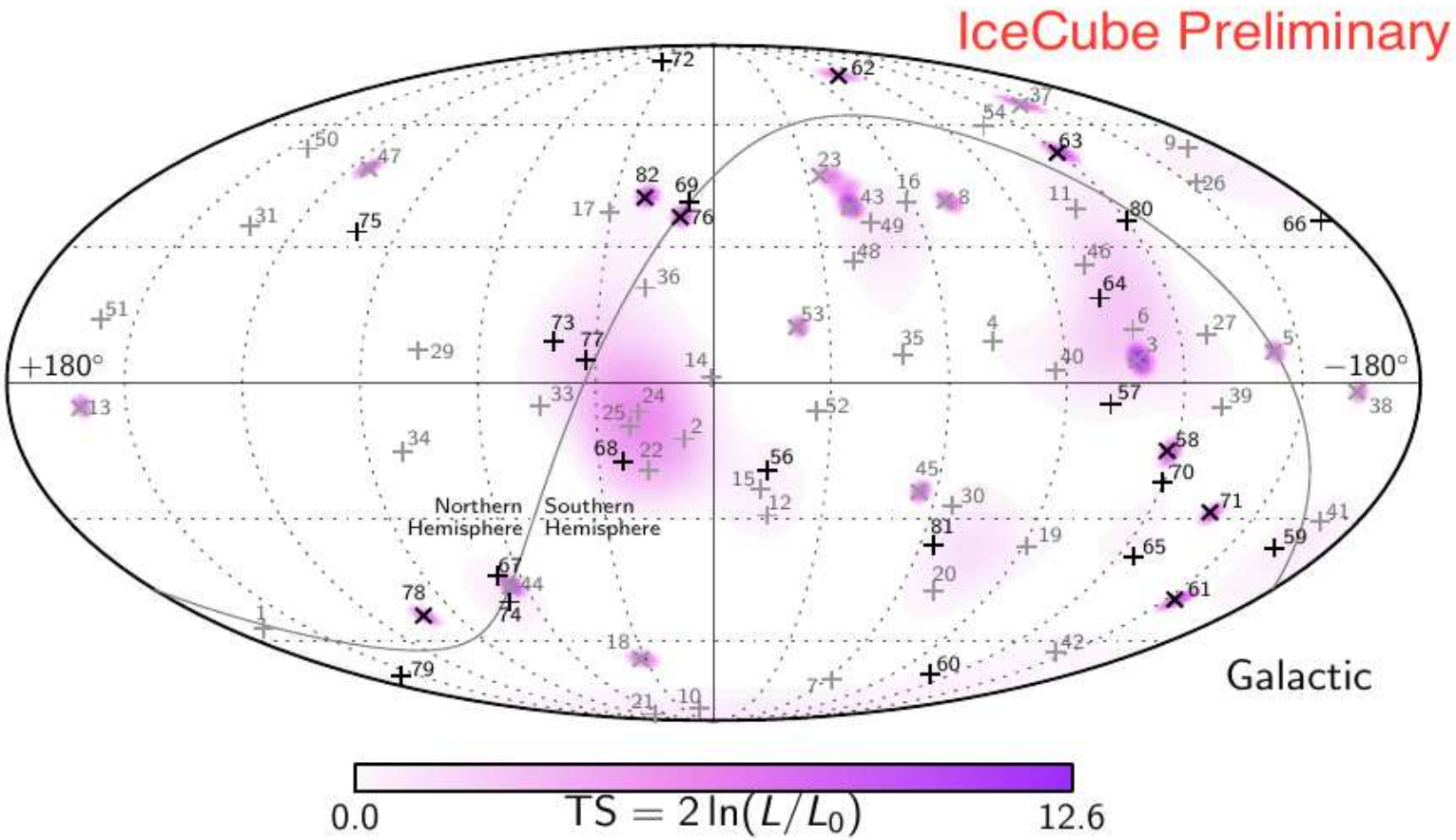
- → resonance: E_ν = 6.3 PeV

work on-going

IceCube events:Tau neutrino lifetime 17m



IceCube events: 6 years 82 events



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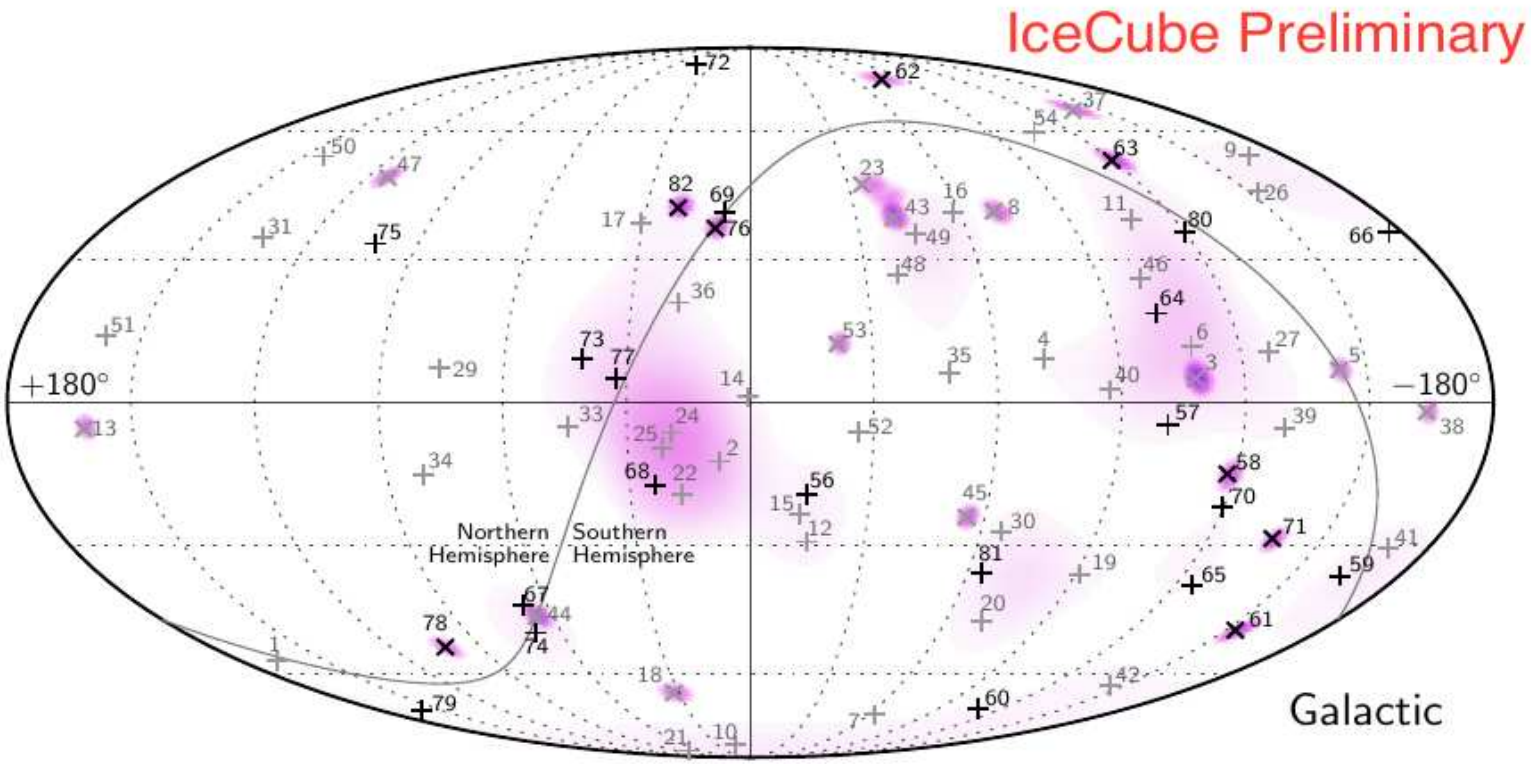

- consistent with isotropy

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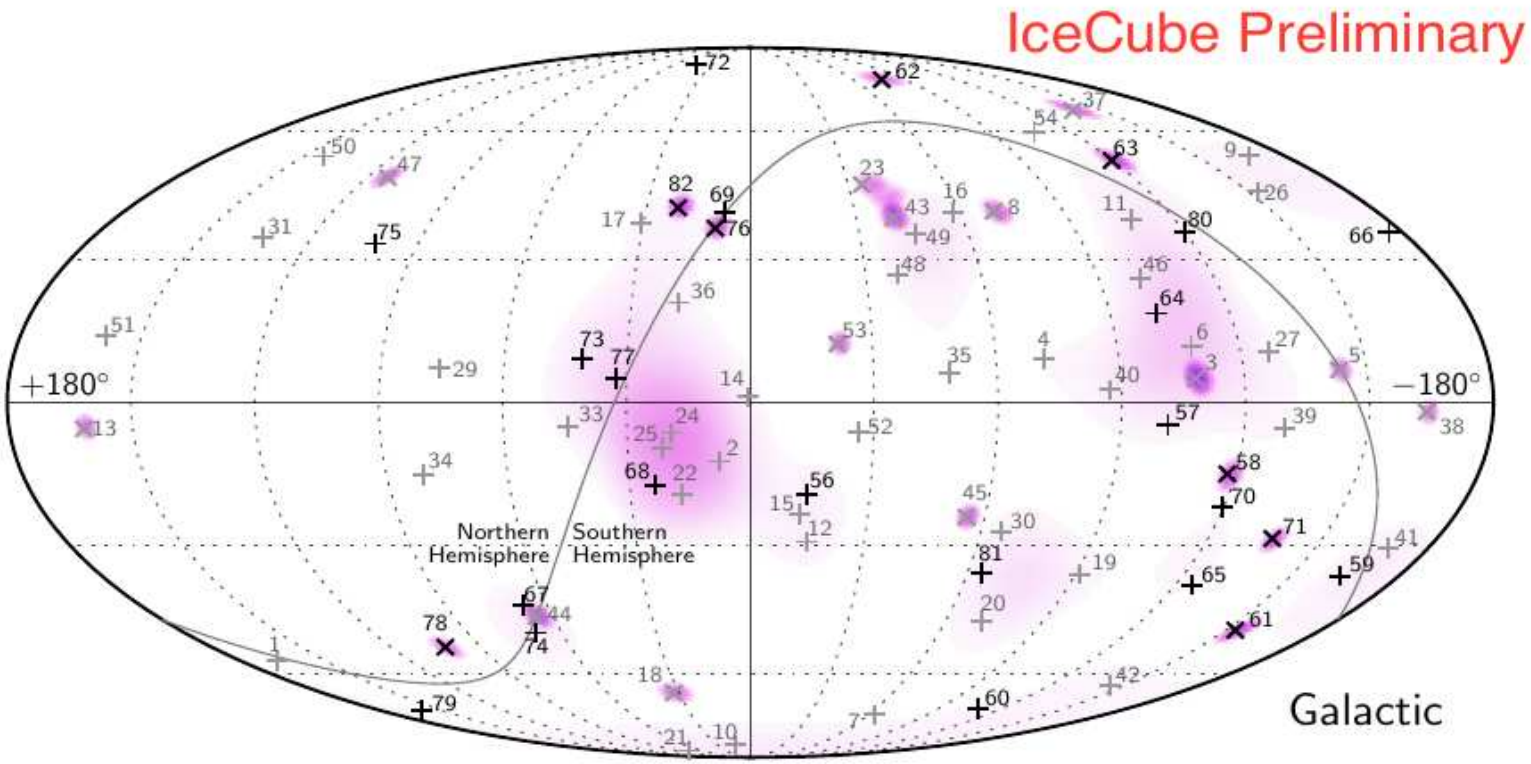
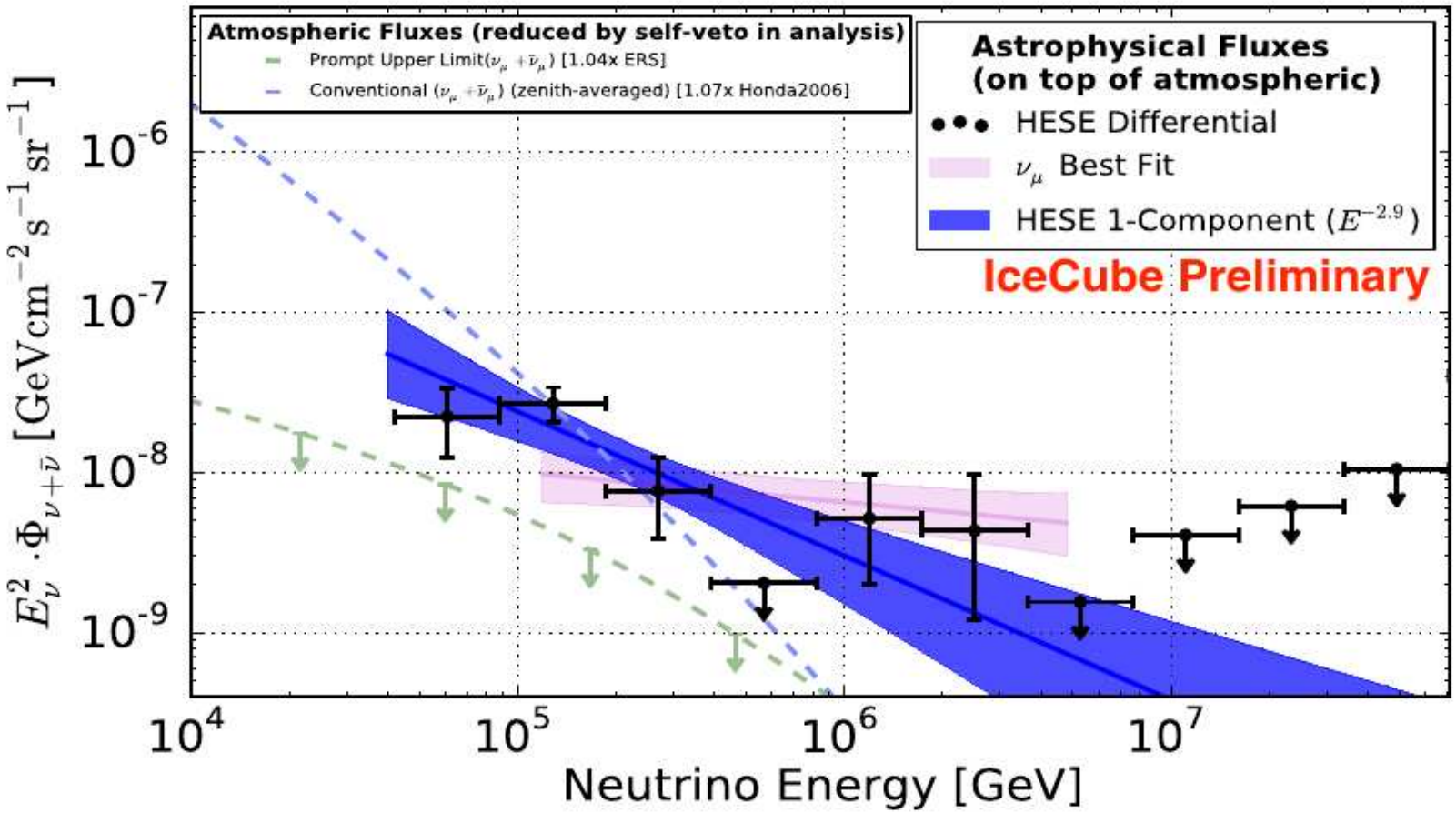


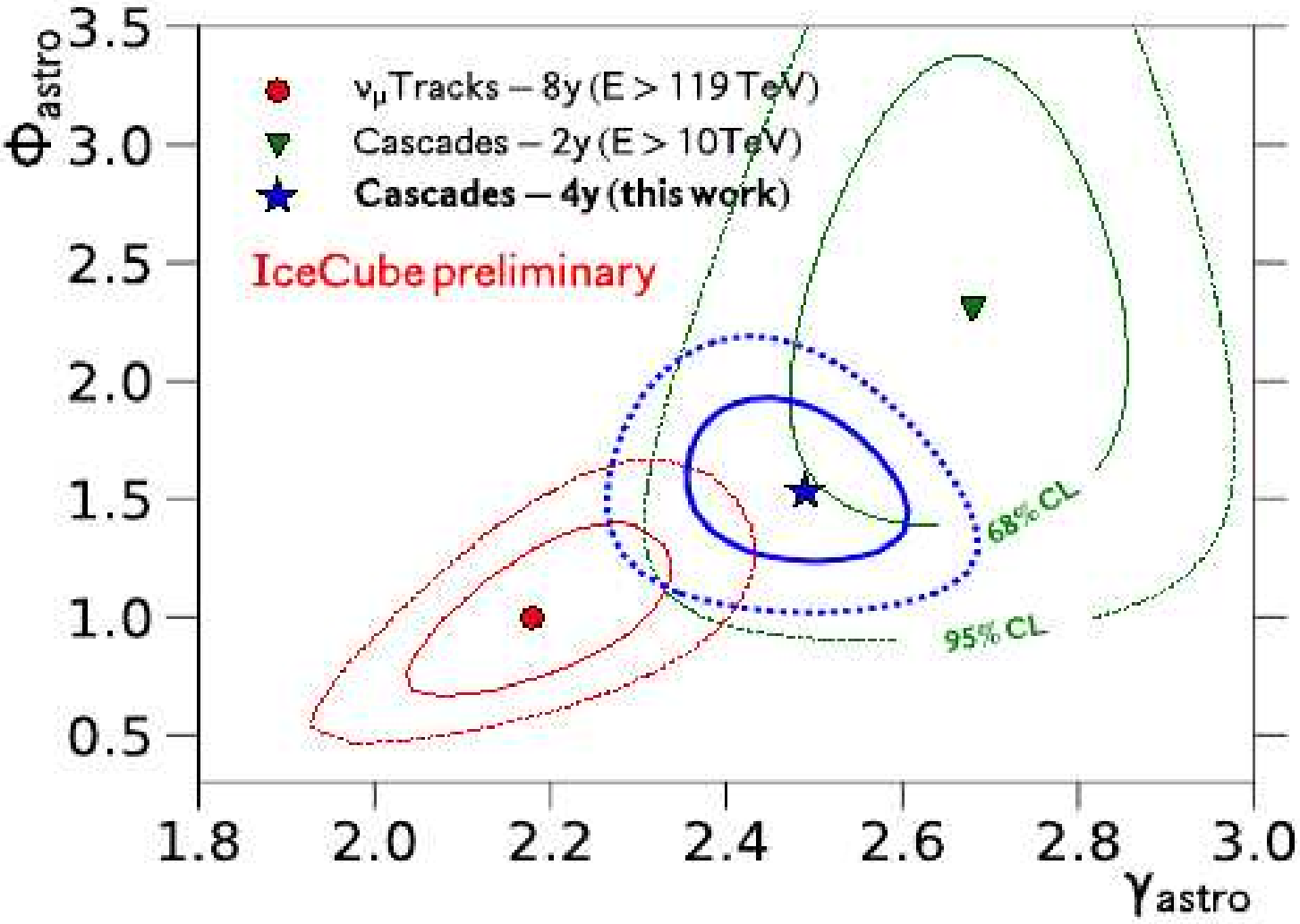
- consistent with isotropy

$\Rightarrow$ extragalactic neutrinos

IceCube events: Soft "low-energy" spectrum?



IceCube events: power-law fit of energy spectrum



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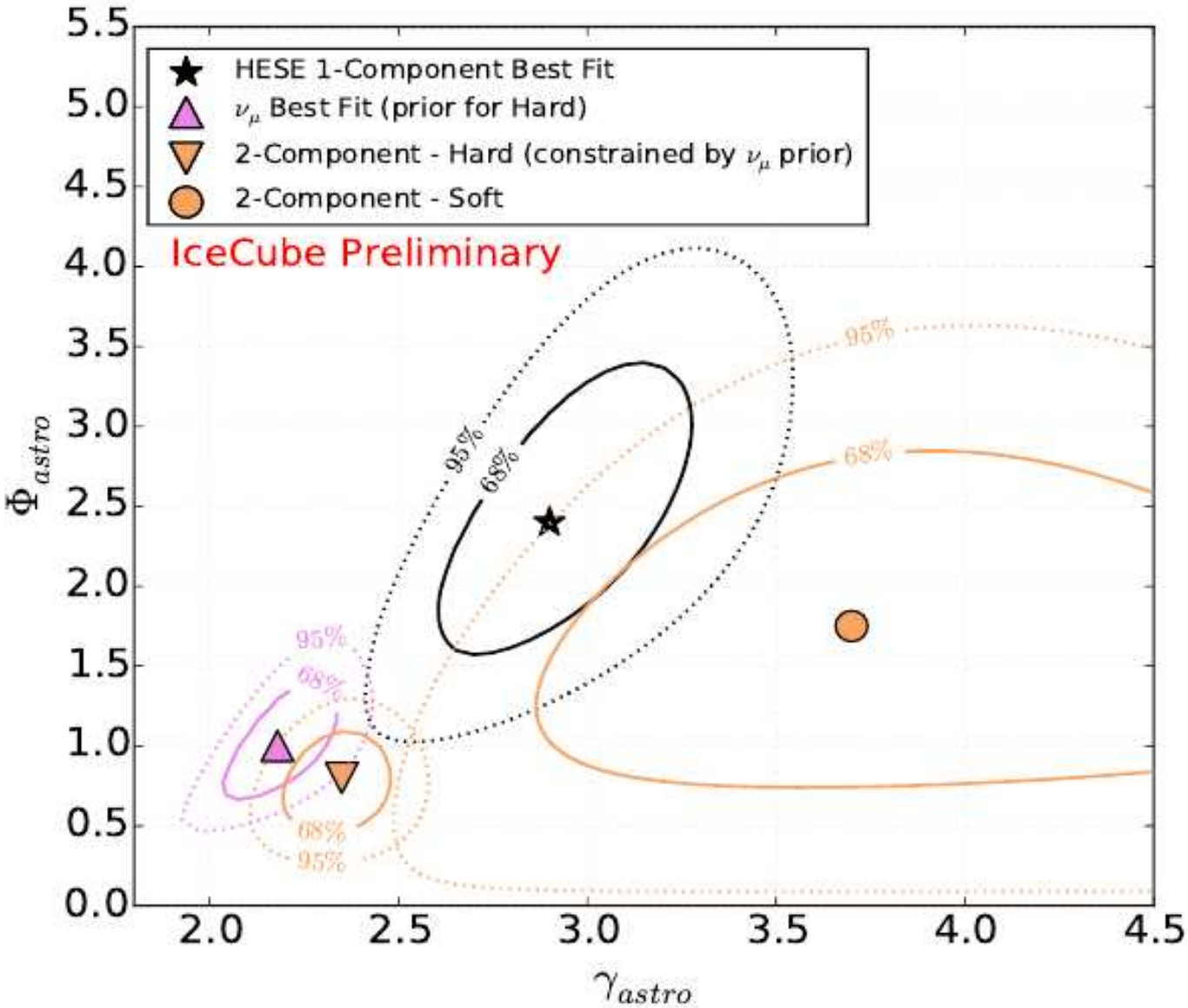
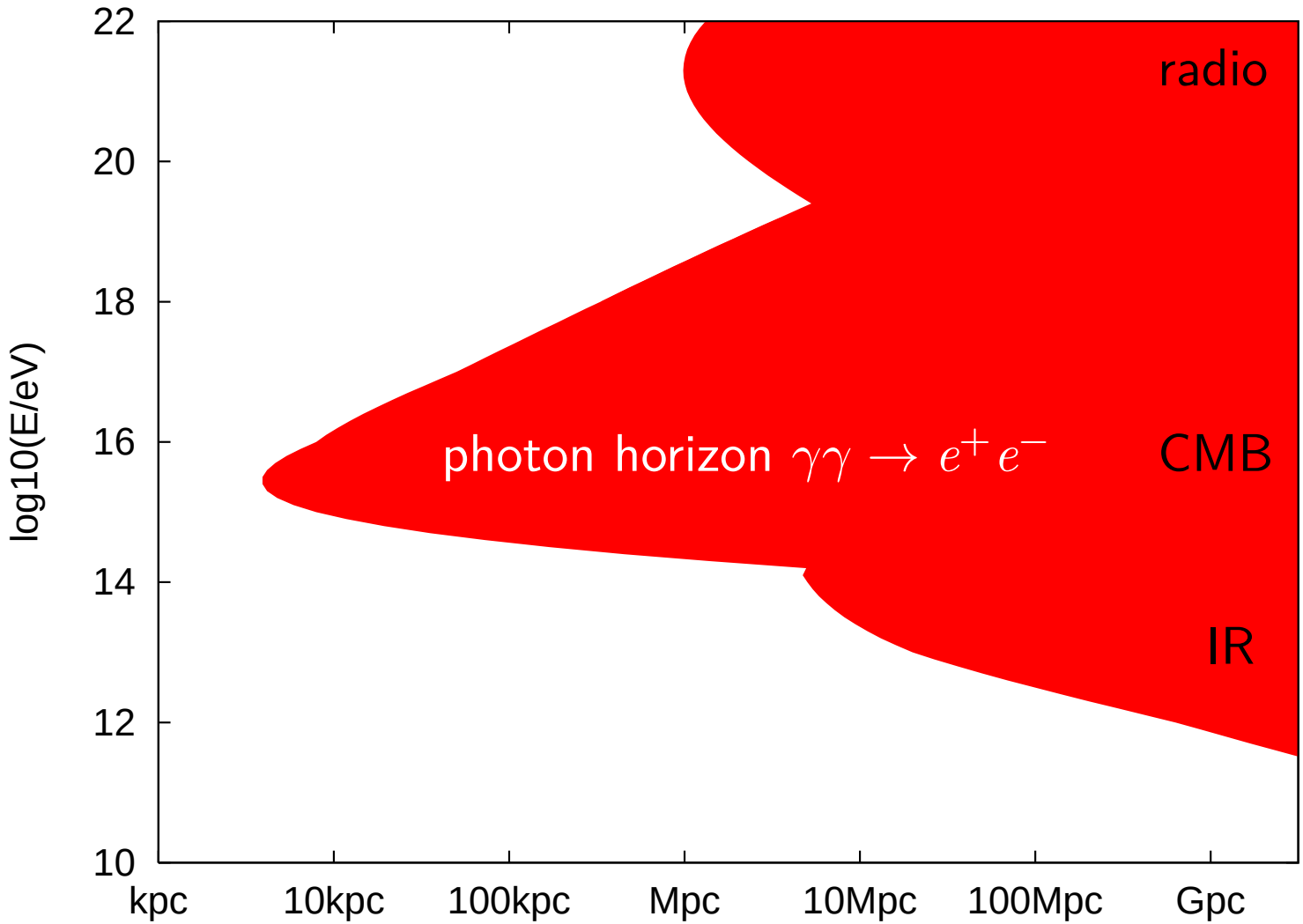
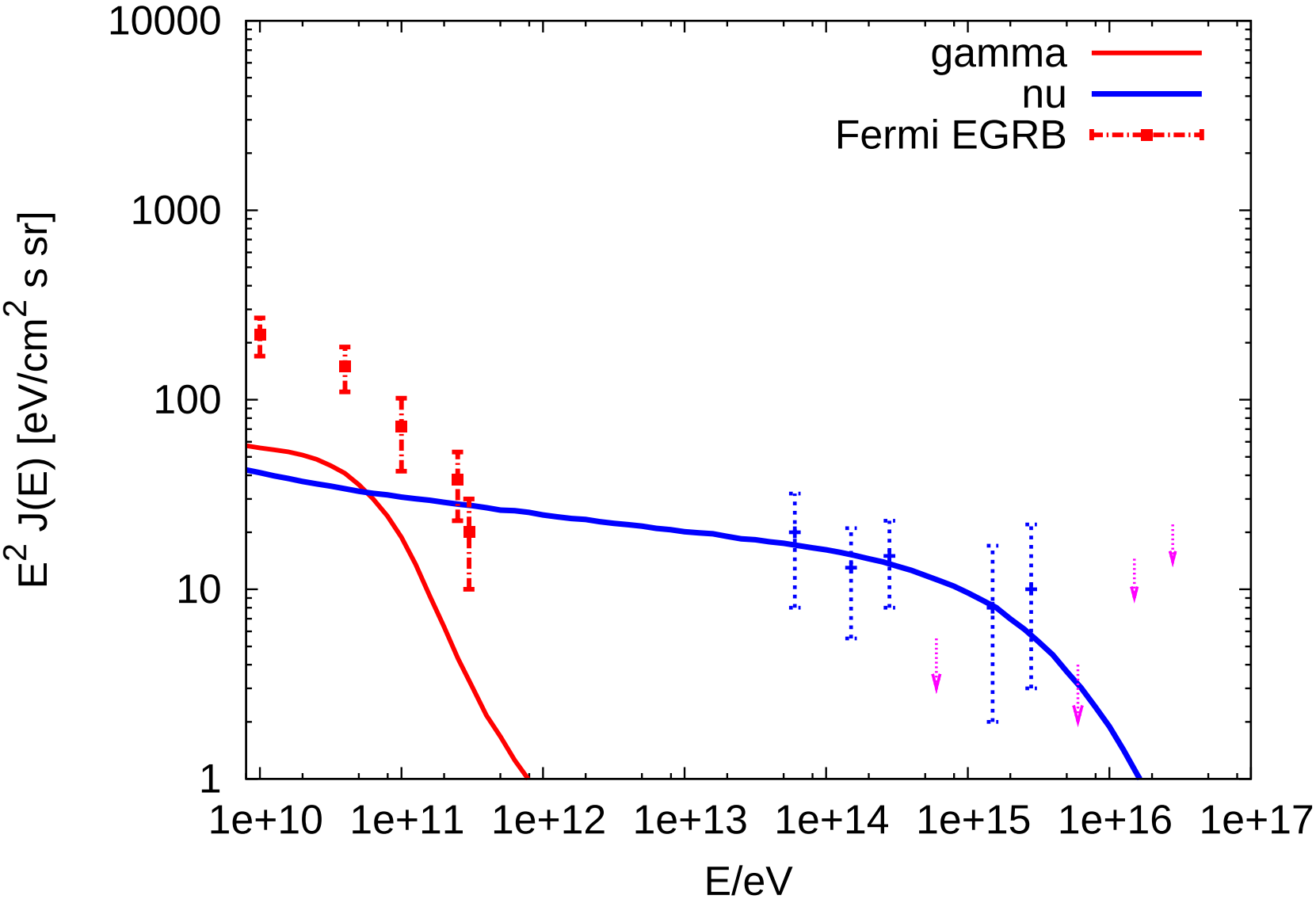


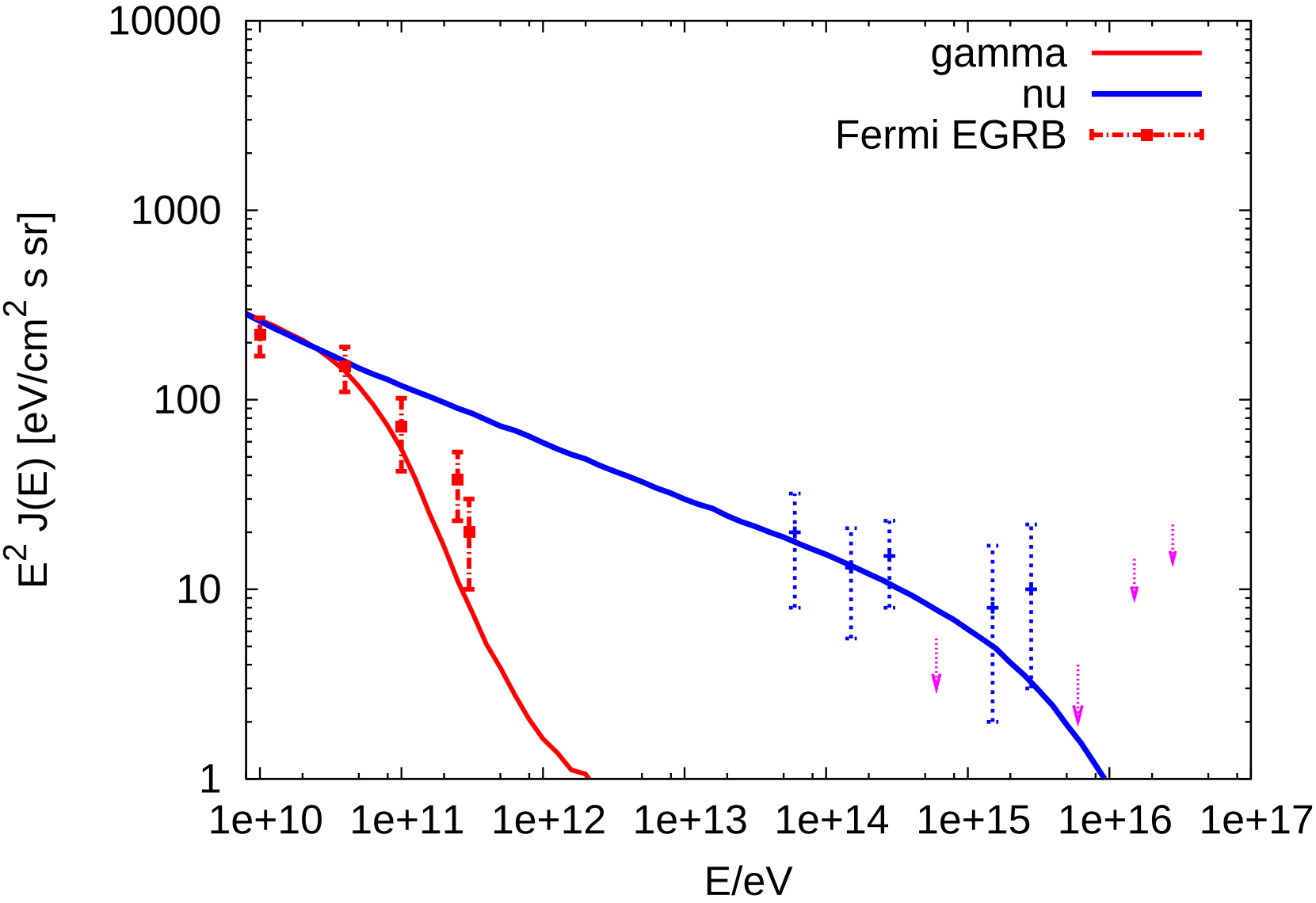
Recall: Photon horizon and cascades



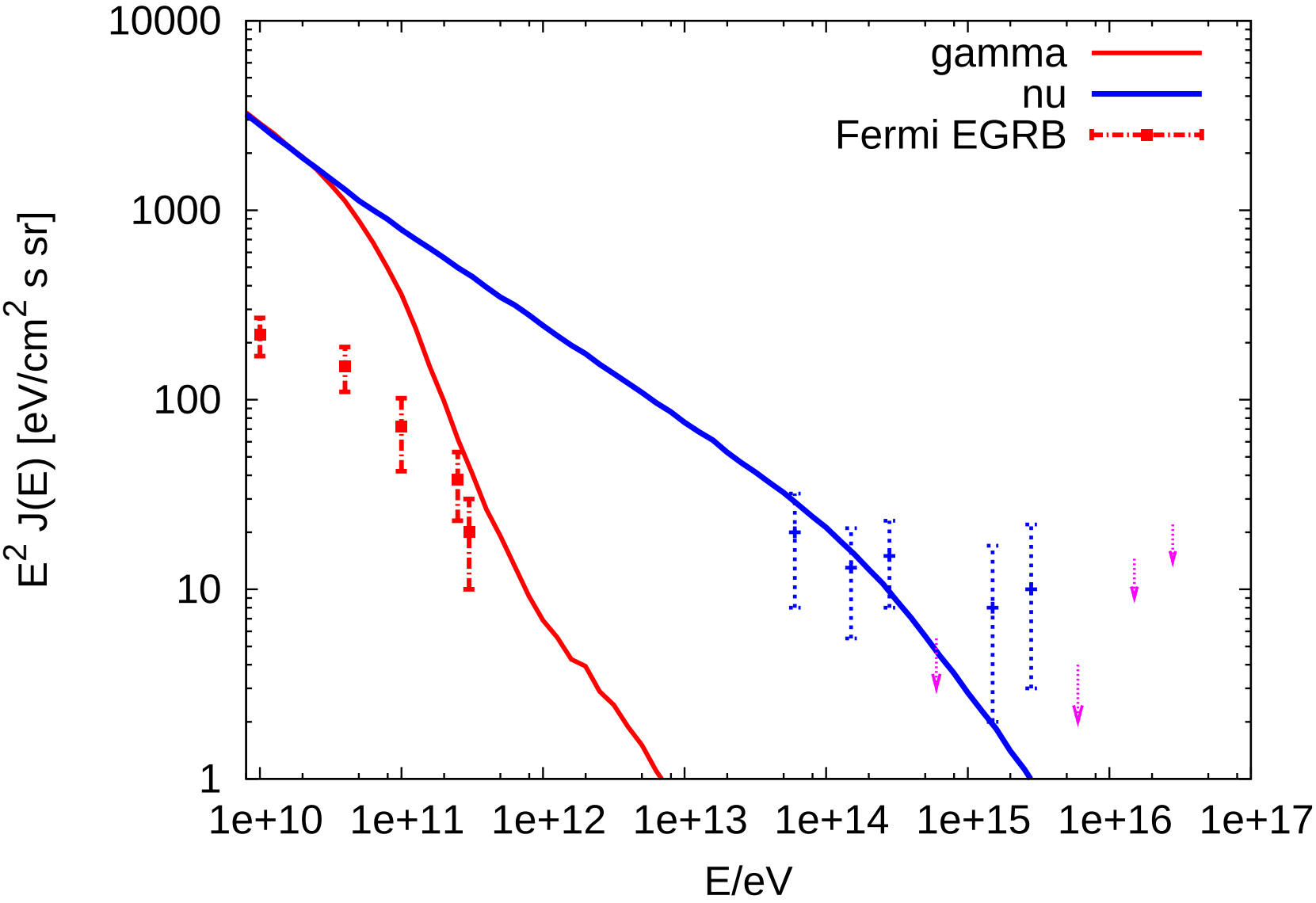
Cascade limit: $\alpha = 2.1$



Cascade limit: $\alpha = 2.3$



Cascade limit: $\alpha = 2.5$



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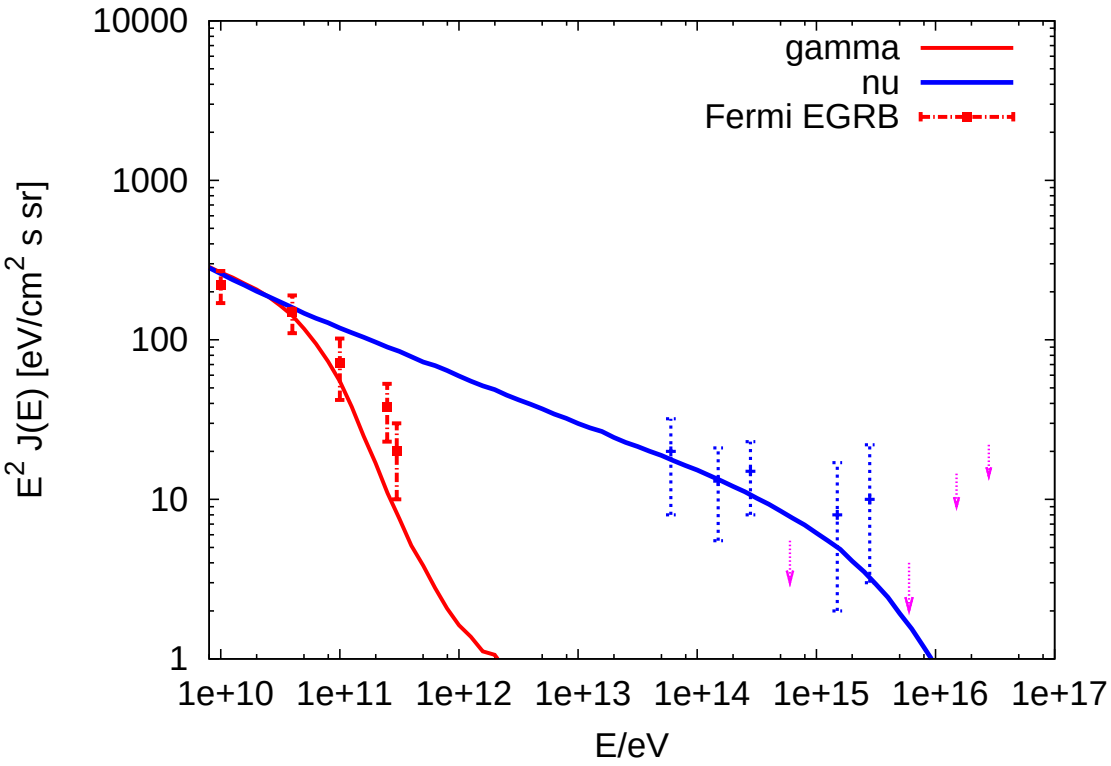
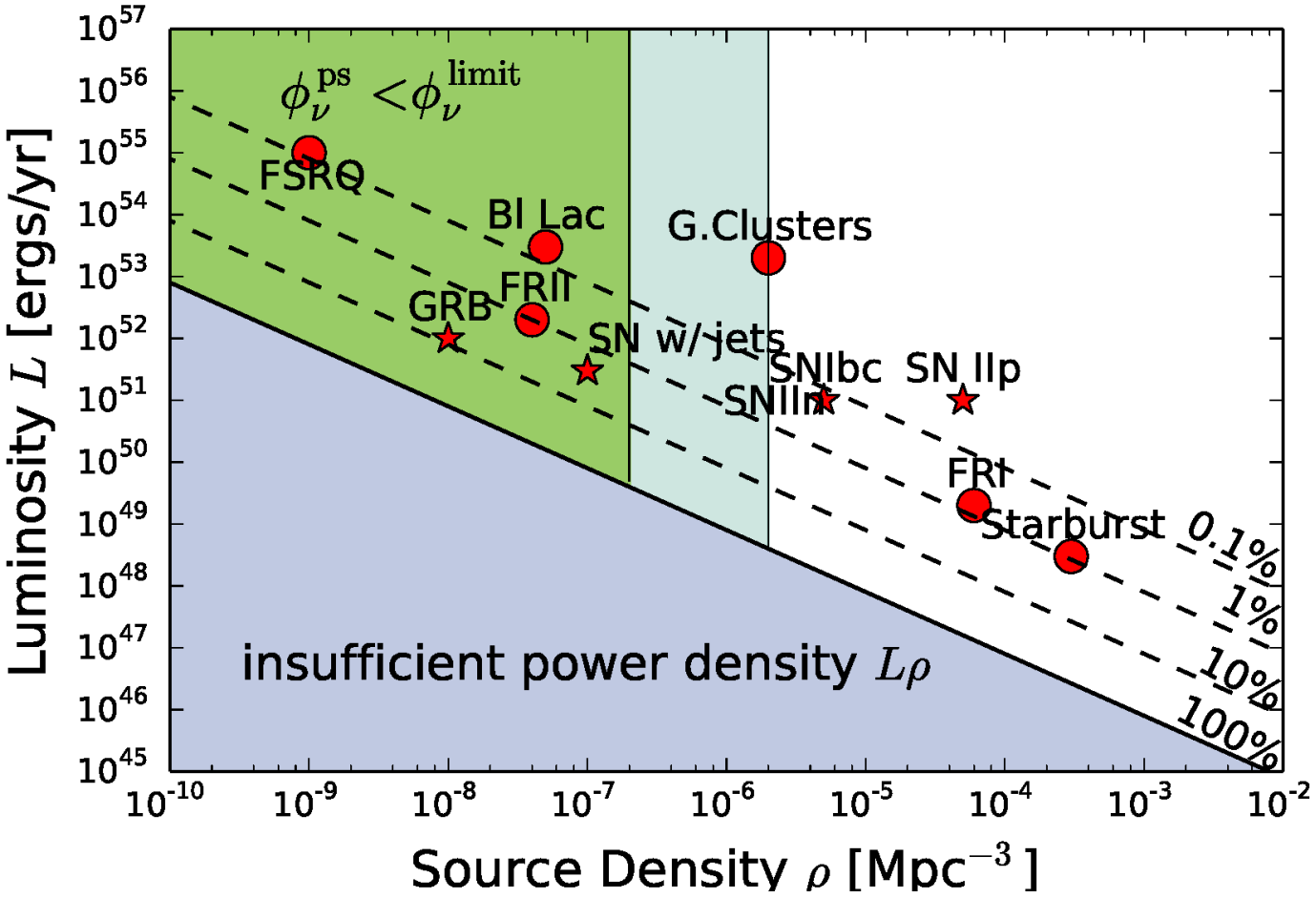


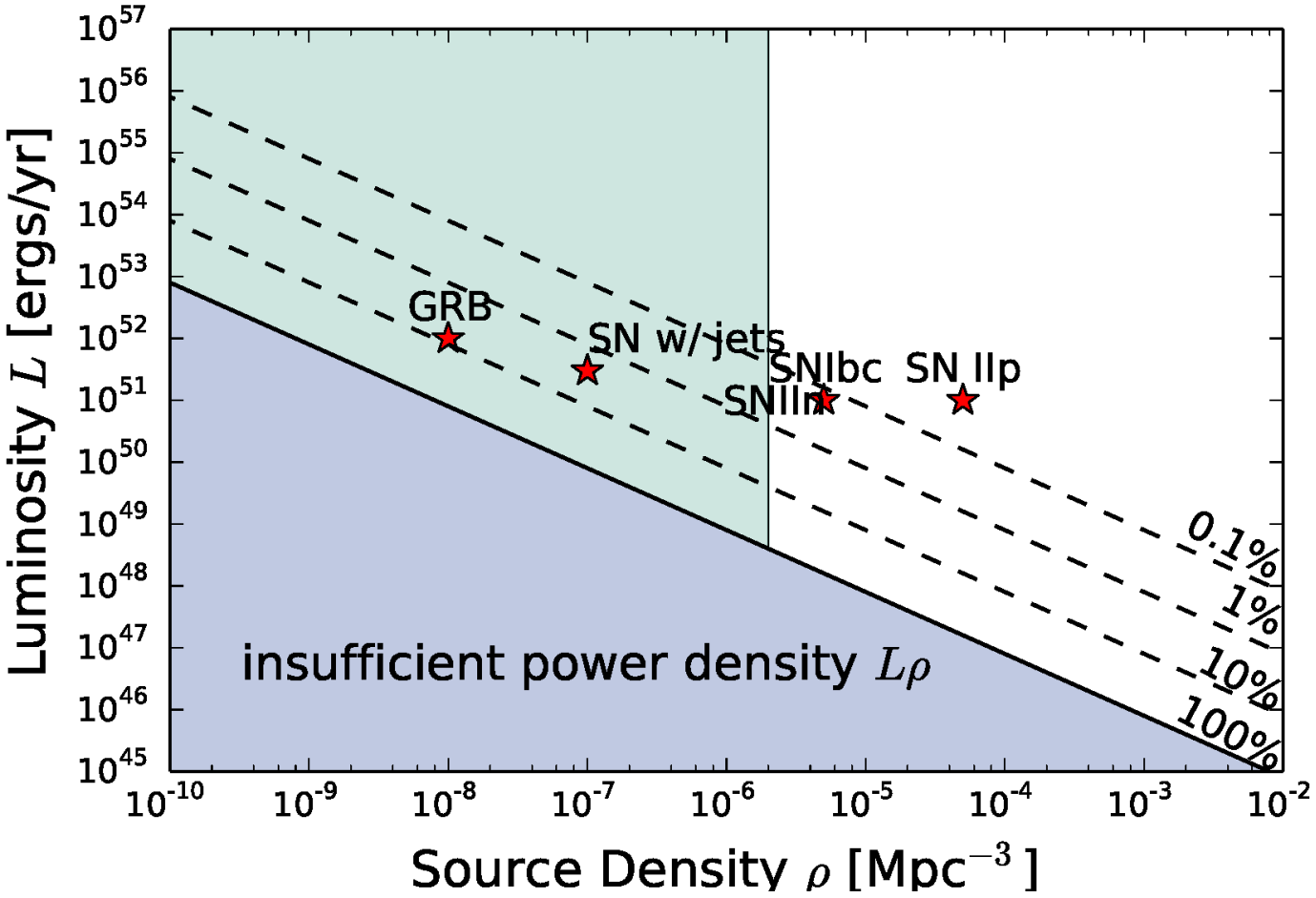
Slope $\alpha \gtrsim 2.2$

- requires "hidden sources" or
- Galactic origin

IceCube searches for sources: stationary sources



IceCube searches for sources: transient sources



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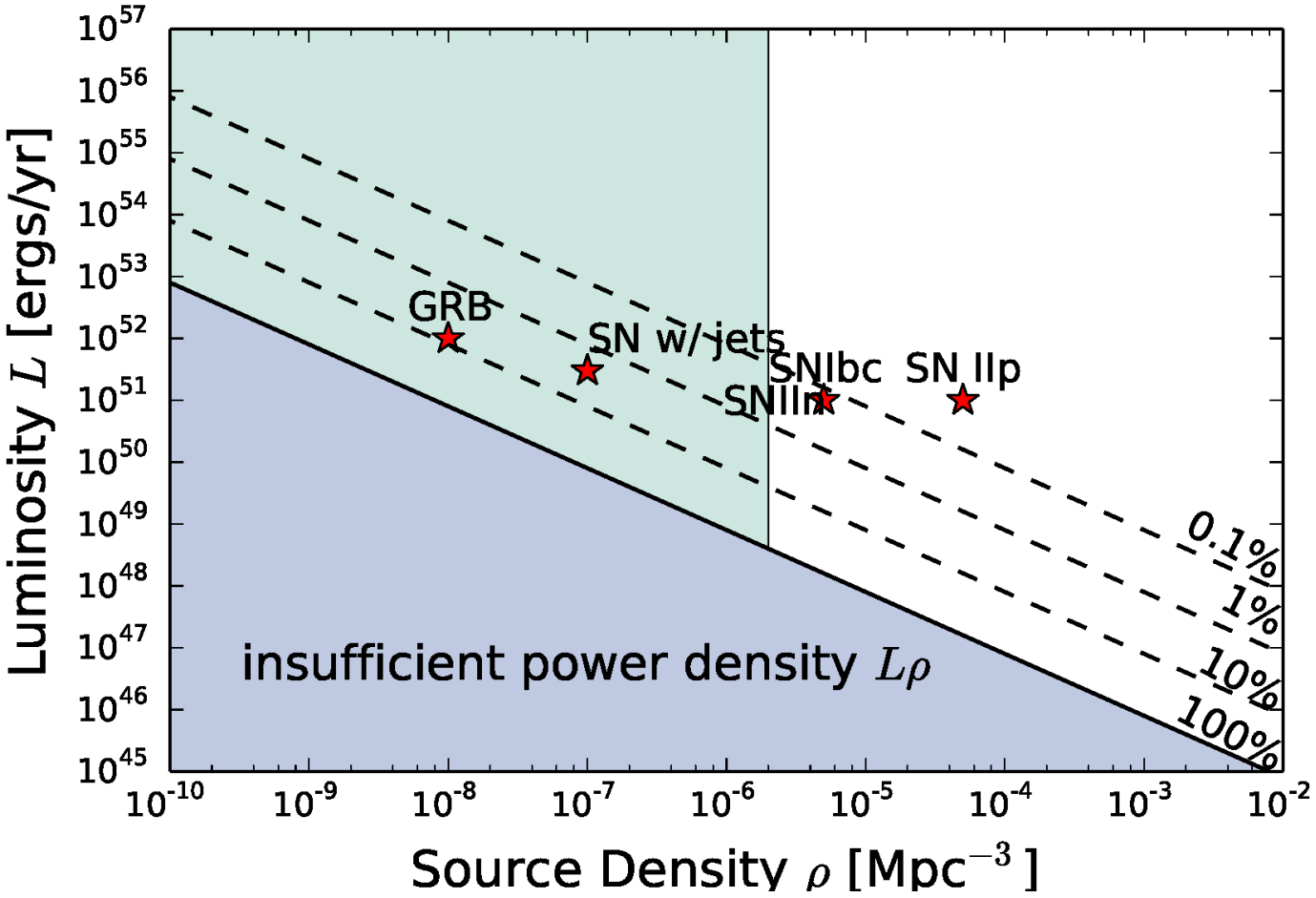
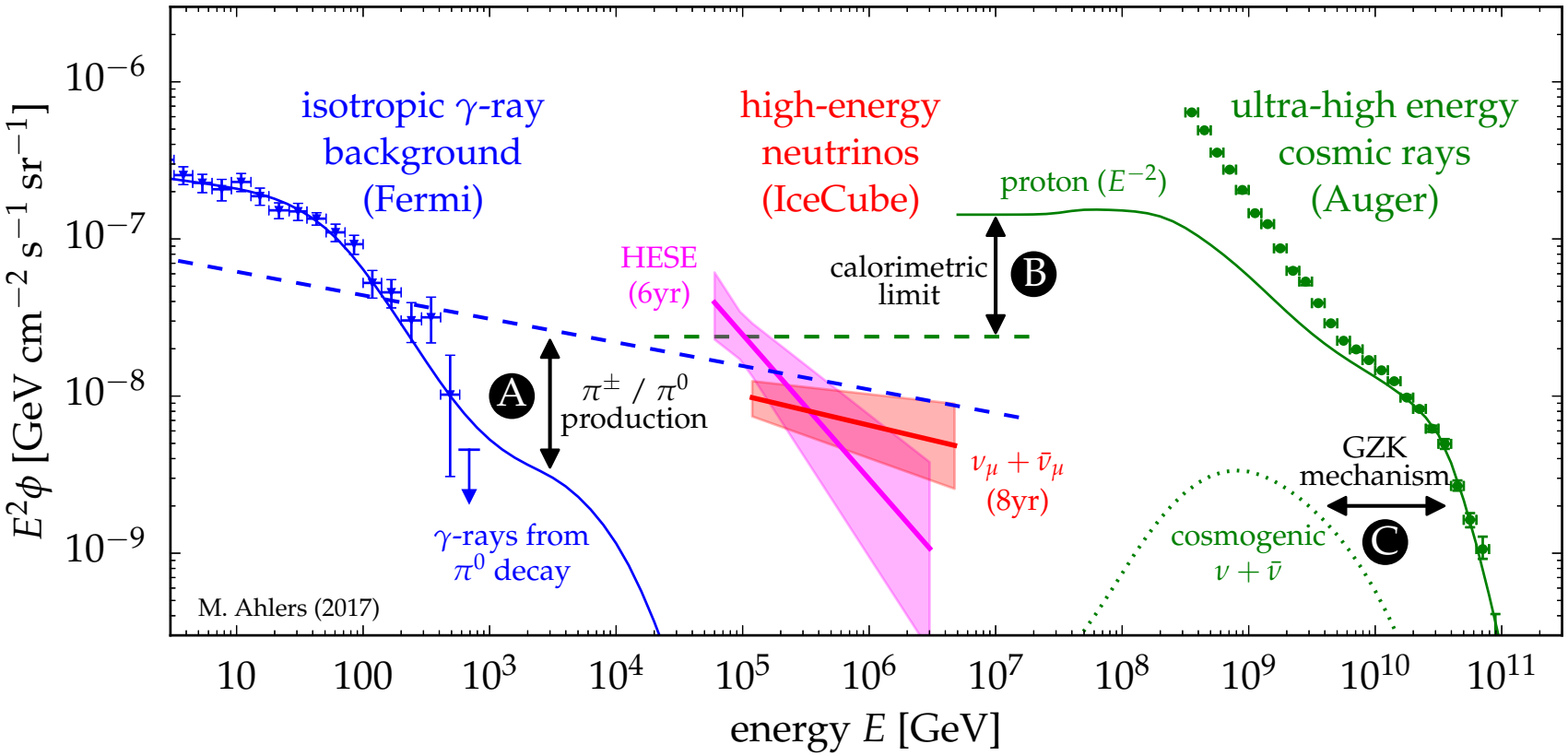
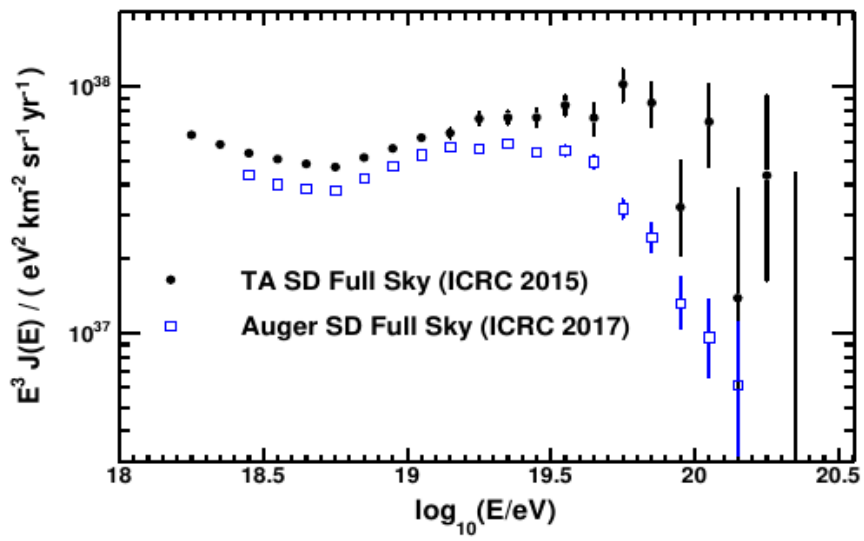


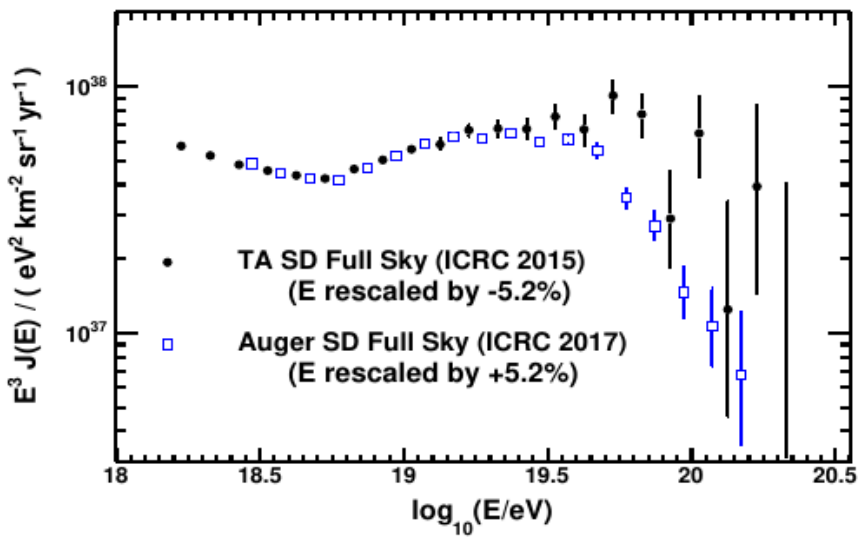
- add. constraint: angular correlations of photons
- add. constraint: diffuse γ-ray bound

Multi-messenger picture



Spectrum


E^3 J(E) / (eV^2 km^{-2} sr^{-1} yr^{-1})
10^{38}
10^{37}
TA SD Full Sky (ICRC 2015)
Auger SD Full Sky (ICRC 2017)
18
18.5
19
19.5
20
20.5
log$_{10}$(E/eV)


E^3 J(E) / (eV^2 km^{-2} sr^{-1} yr^{-1})
10^{38}
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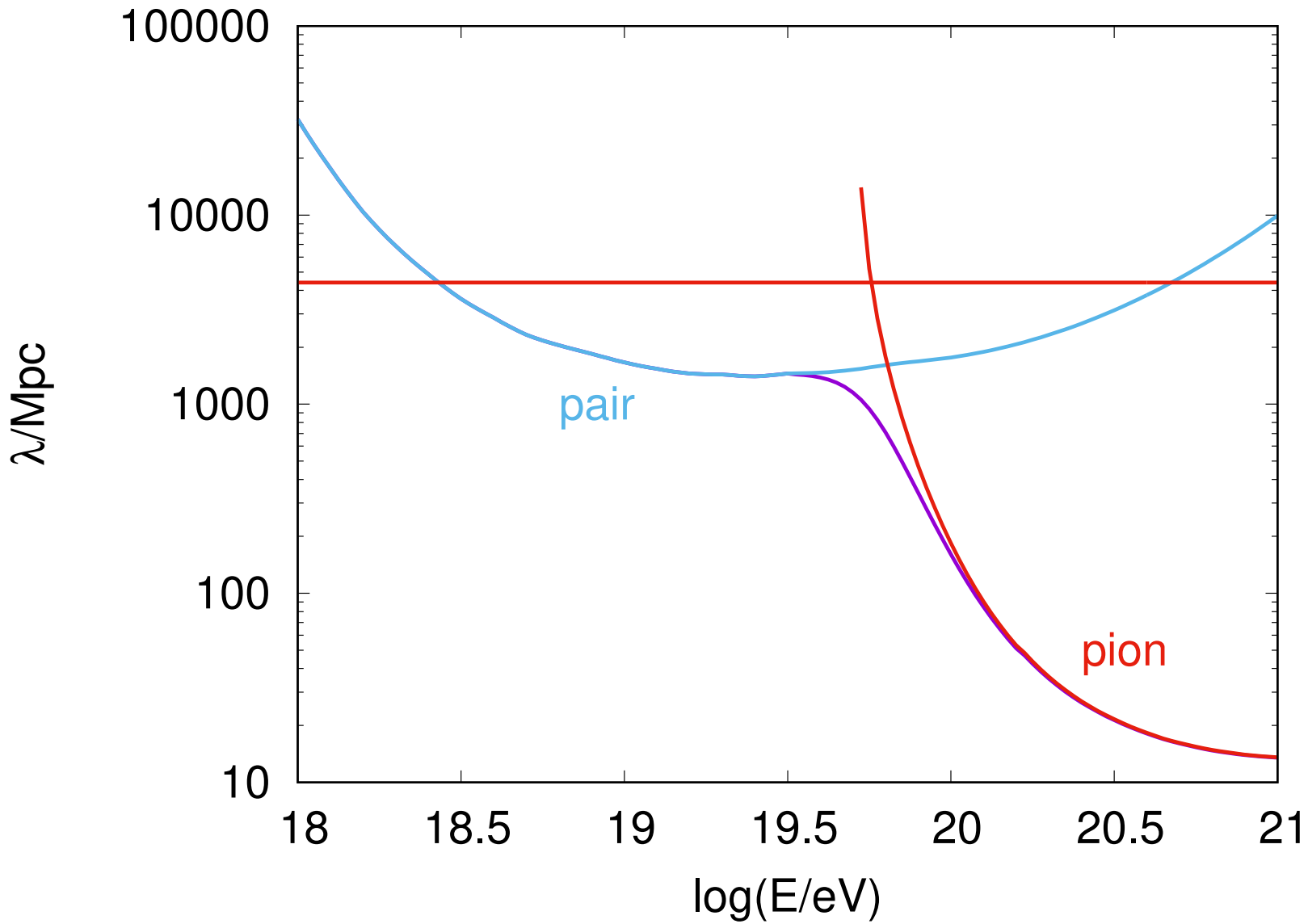
TA SD Full Sky (ICRC 2015)
(E rescaled by -5.2%)
Auger SD Full Sky (ICRC 2017)
(E rescaled by +5.2%)
18
18.5
19
19.5
20
20.5
log$_{10}$(E/eV)

Energy losses and GZK cutoff



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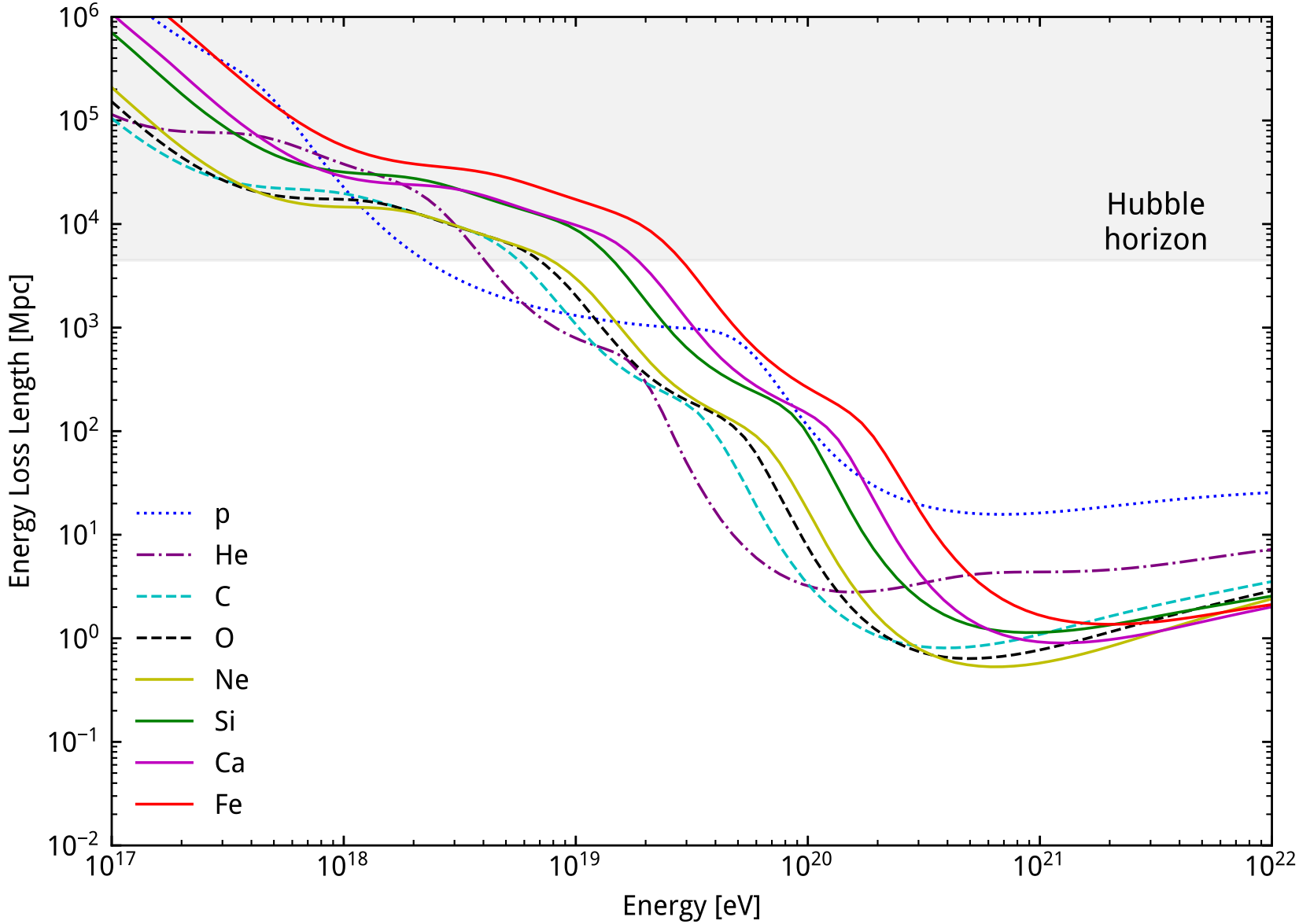
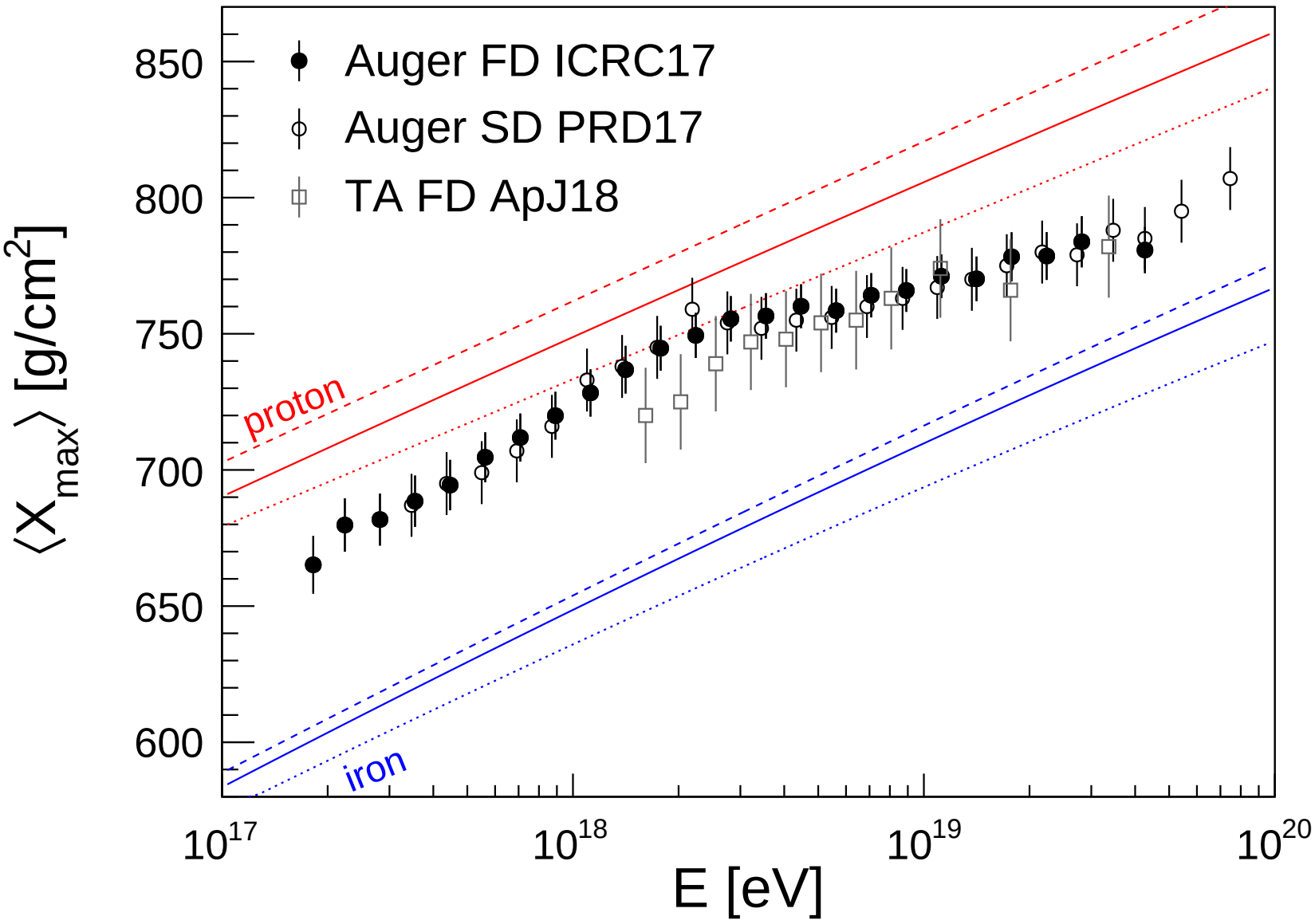


Composition



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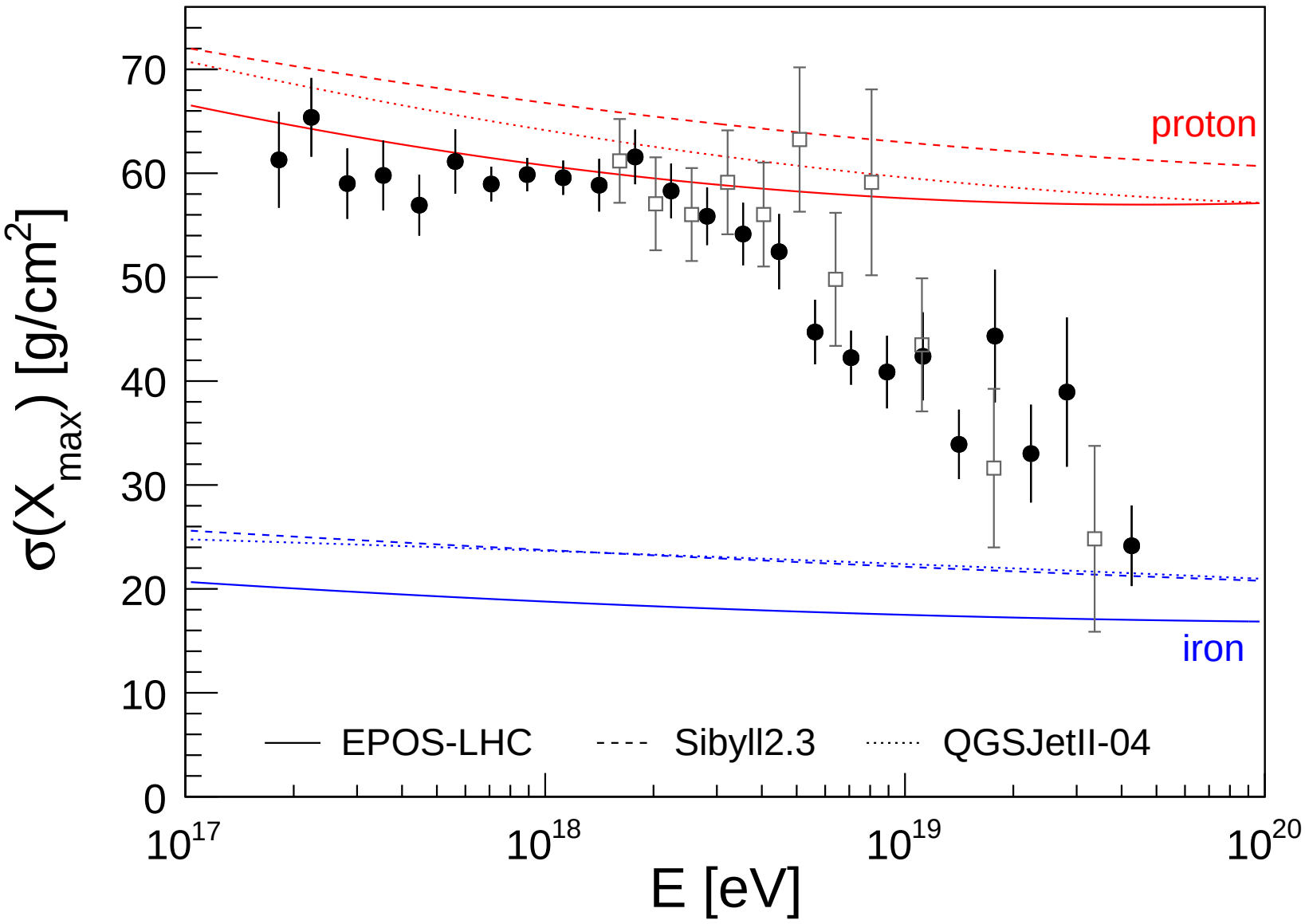
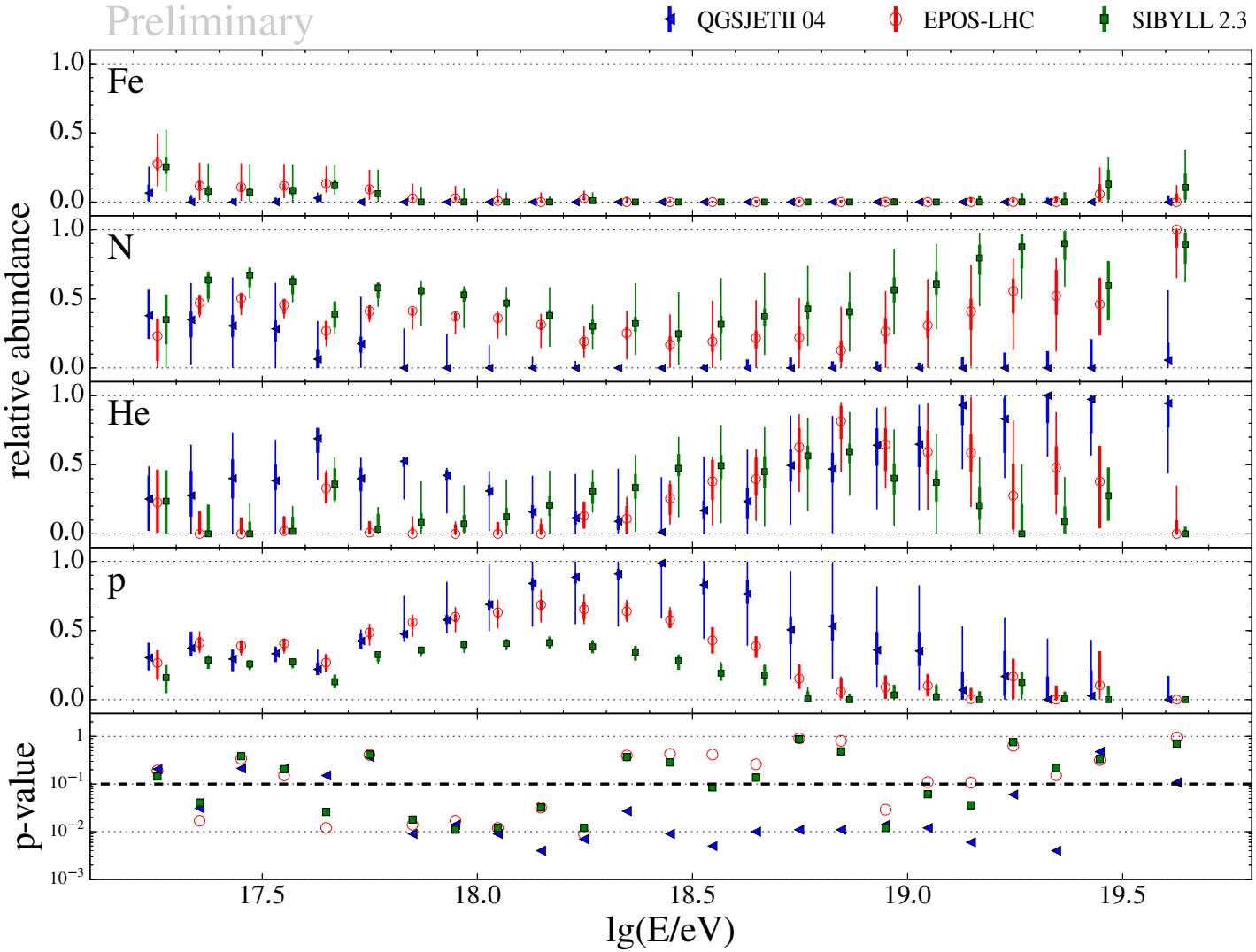


Composition of CRs:



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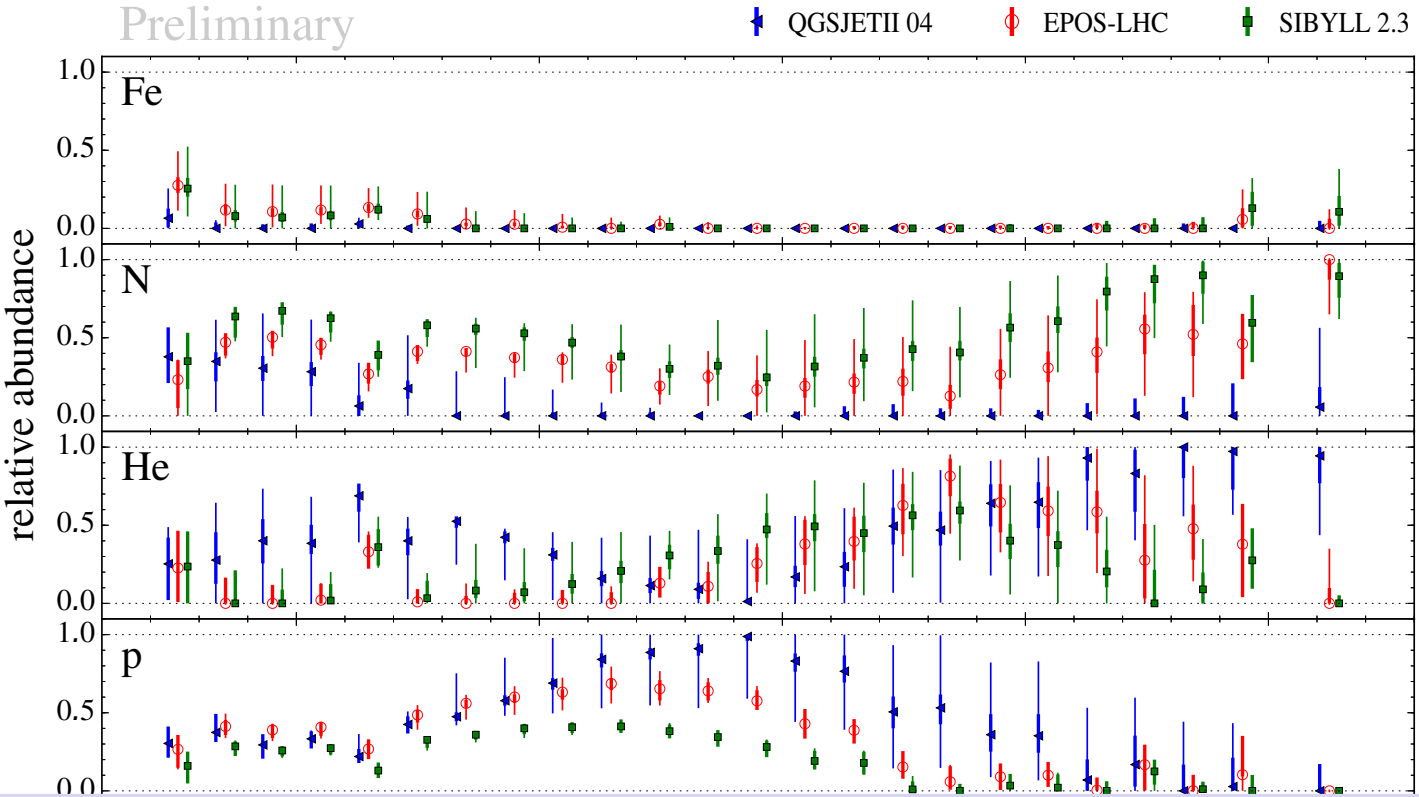

composition $6 \times 10^{17} - 5 \times 10^{18}$ eV consistent with

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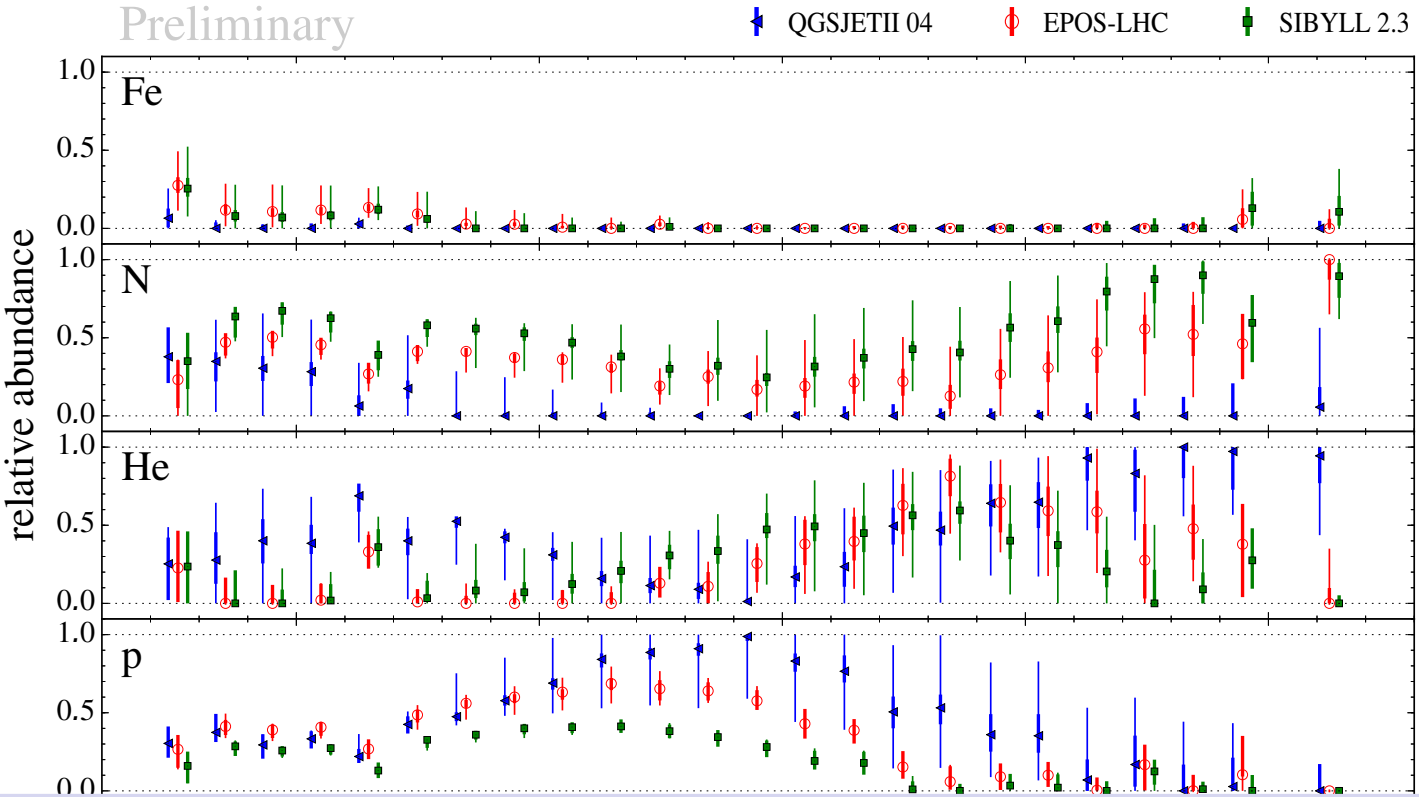

composition $6 \times 10^{17} - 5 \times 10^{18}$ eV consistent with

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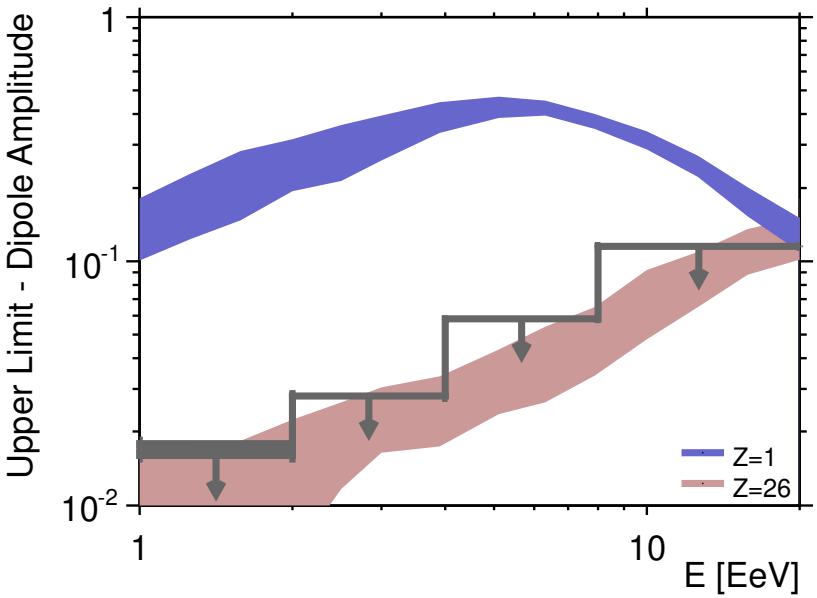
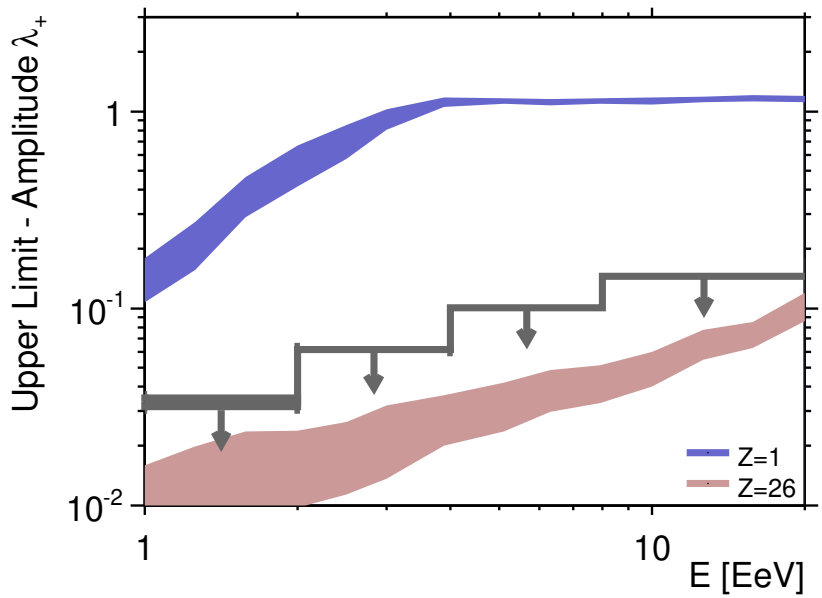
- early transition from Galactic to extragalactic CRs

Transition to extragalactic CRs – anisotropy limits

dipole



quadrupole



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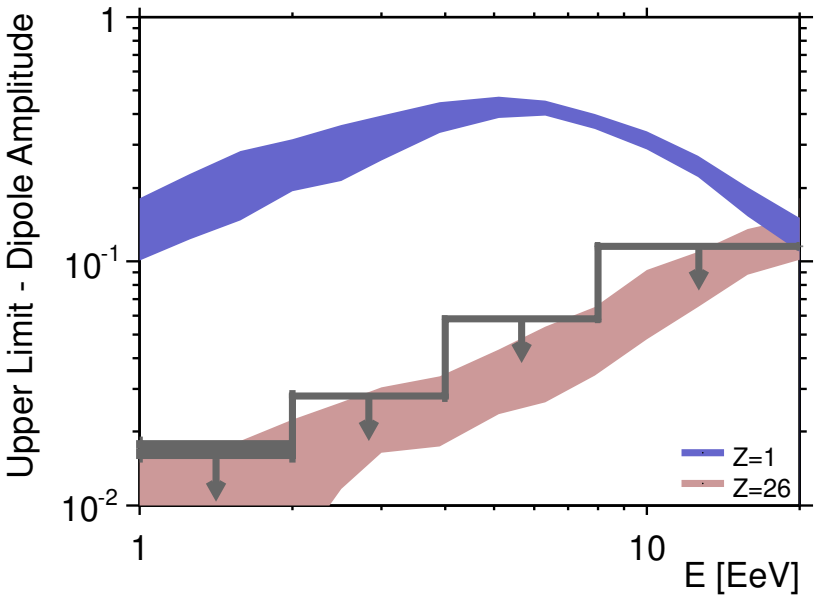

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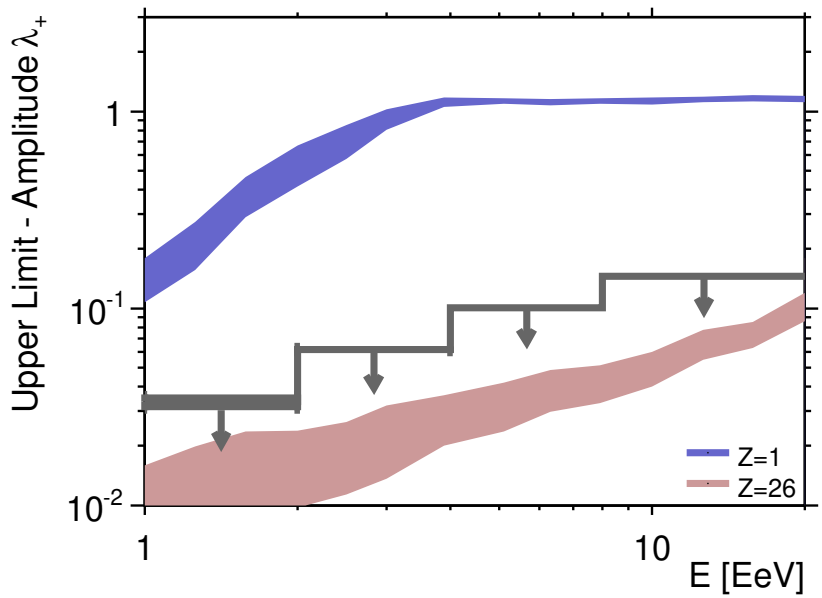
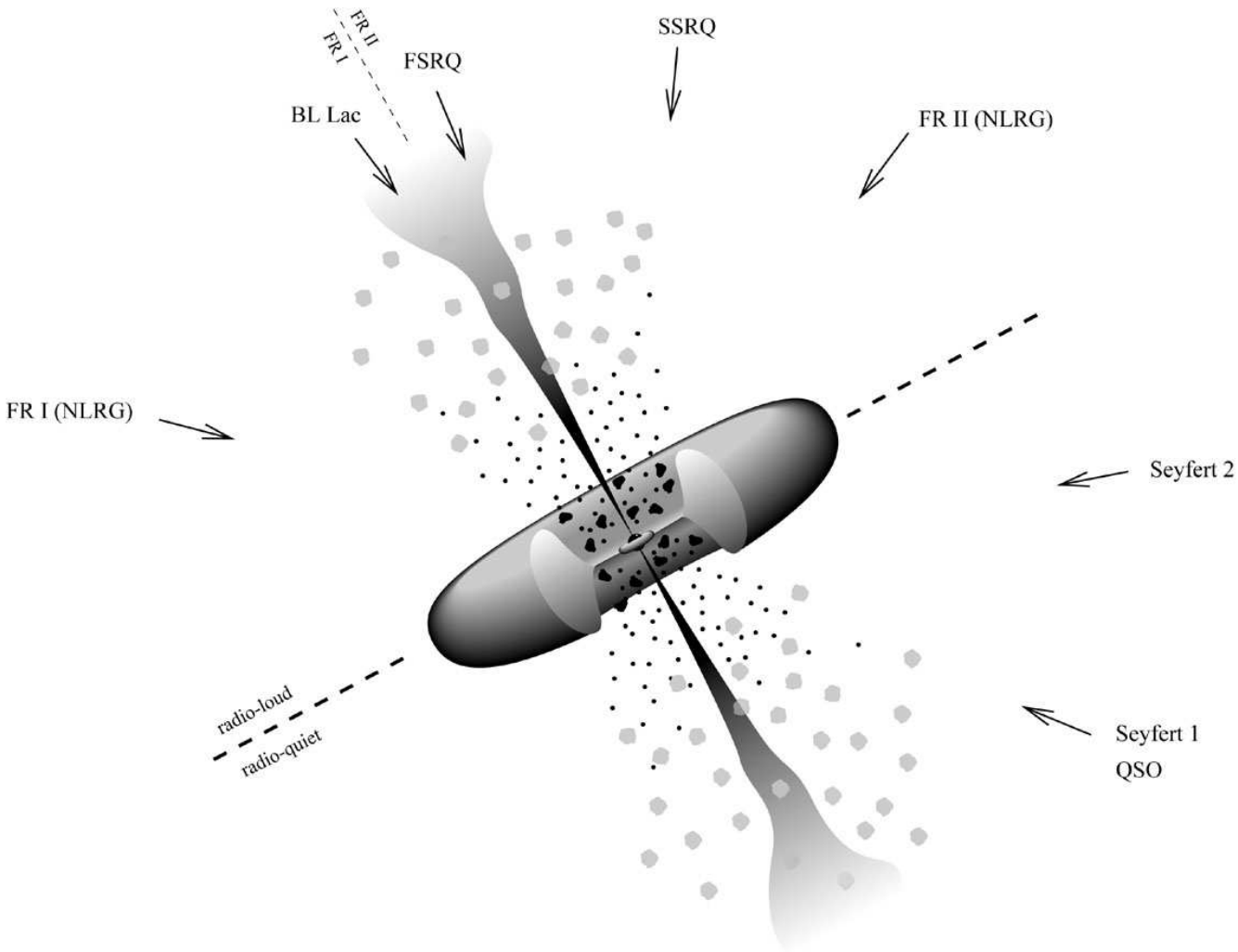


dominant light Galactic composition around $E = 10^{18}$ eV excluded

[*Giacinti et al. '12, PAO '13*]

Unified AGN picture



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- leptonic blazar models favored to explain EGRB
- neutrino sources should give sub-dominant contribution to EGRB

Constraints on a minimal model:

a single source class that

- fits the extragalactic UHECR flux and composition
- fits the (extragalactic) neutrino flux

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a single source class that

- fits the extragalactic UHECR flux and composition
- fits the (extragalactic) neutrino flux
- gives subdominant contribution to EGRB
- consistent with early Galactic to extragalactic transition

$\Rightarrow$ ankle has to be a feature of source spectrum

Mixed models

- Peter's cycle: $E_{\mathrm{max},A} = ZE_{\mathrm{max},p}$
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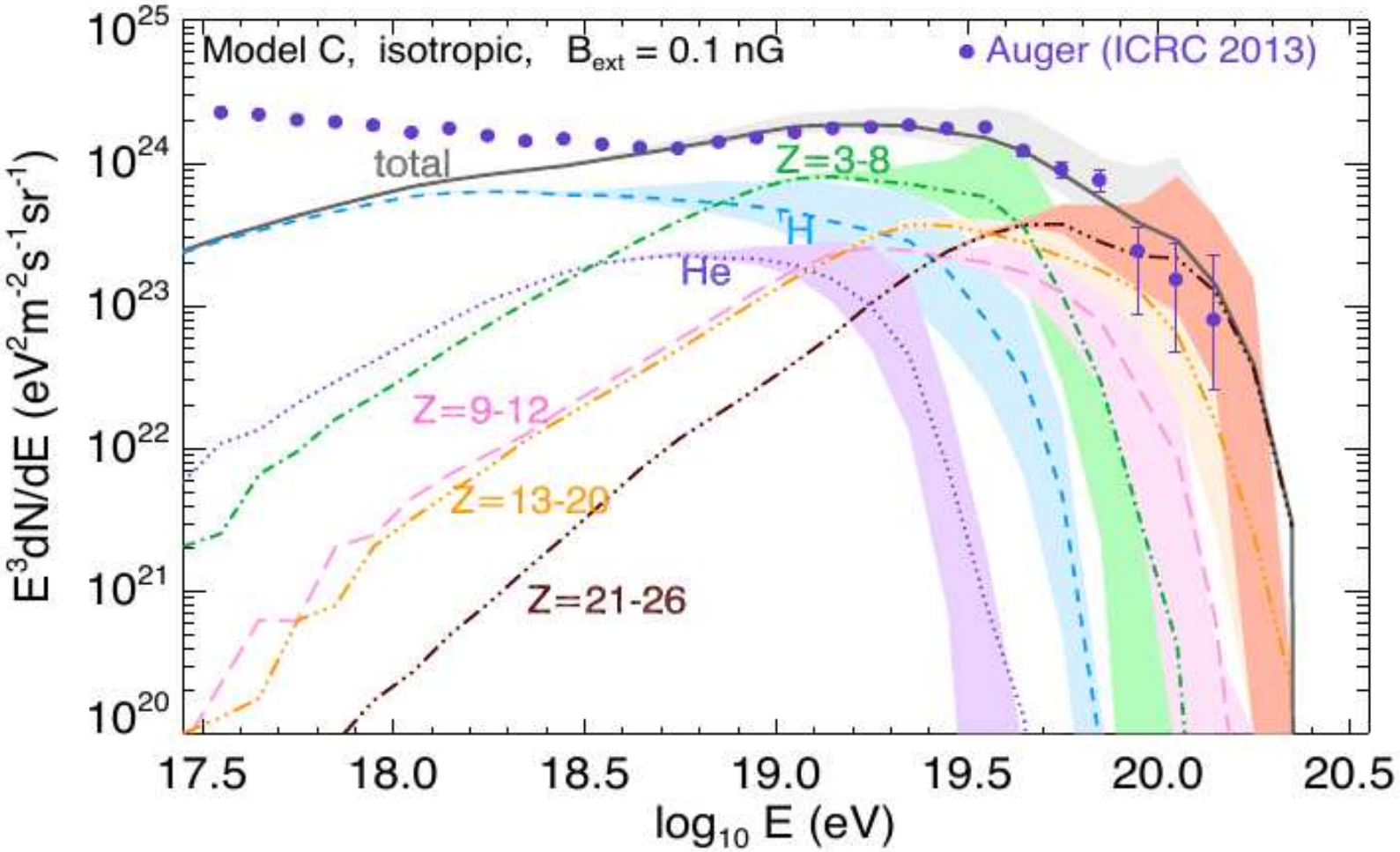
  $=$ transition: requires $E^p_{\mathrm{max}} \simeq 60\,\mathrm{PeV}$
  $=$ feature of extragalactic spectrum
- neutrino flux from $p\gamma$ suppressed, at too high E

GRB inspired ankle model

[*Globus et al. '15, '17*]

- spectrum:



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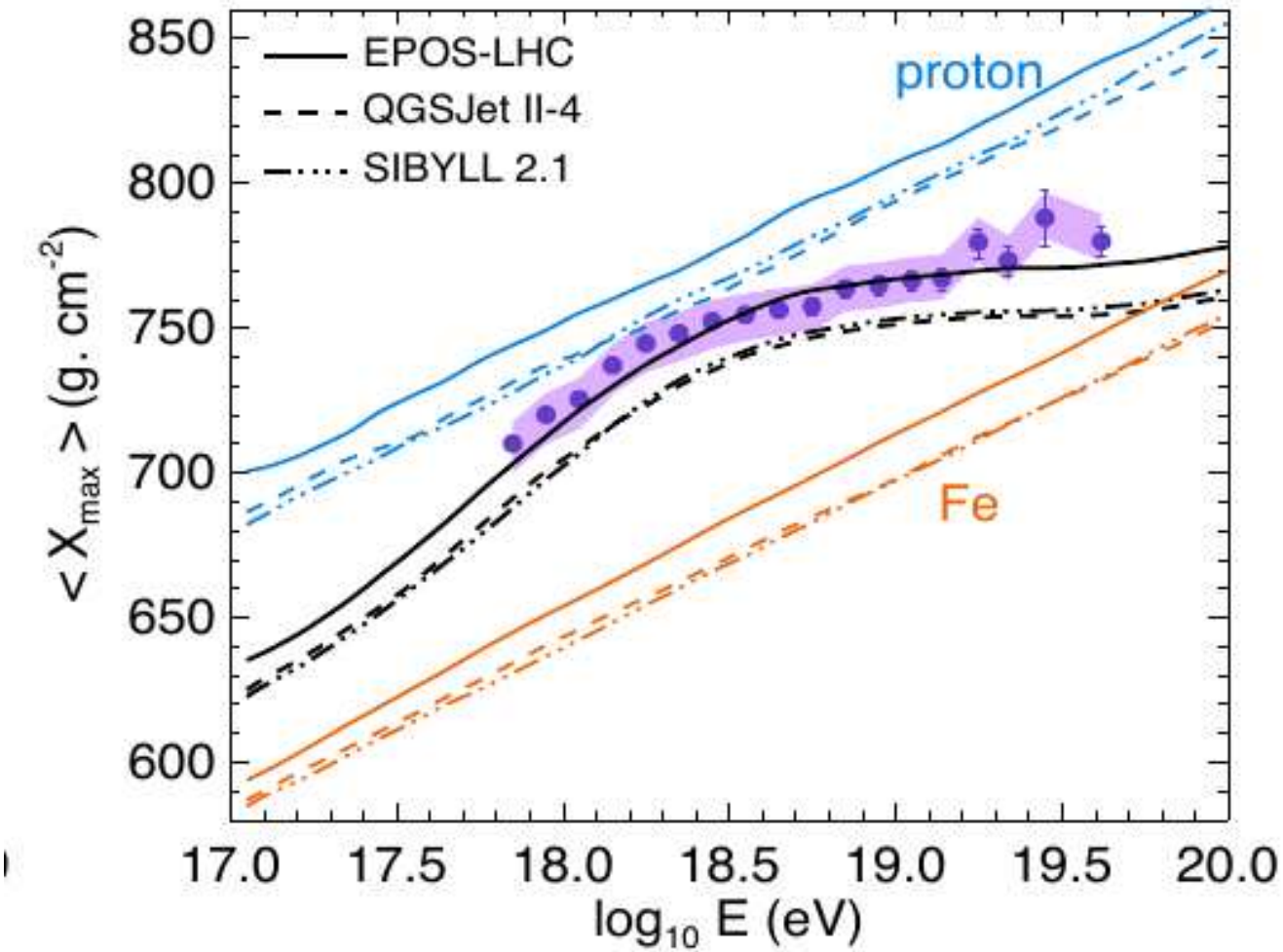

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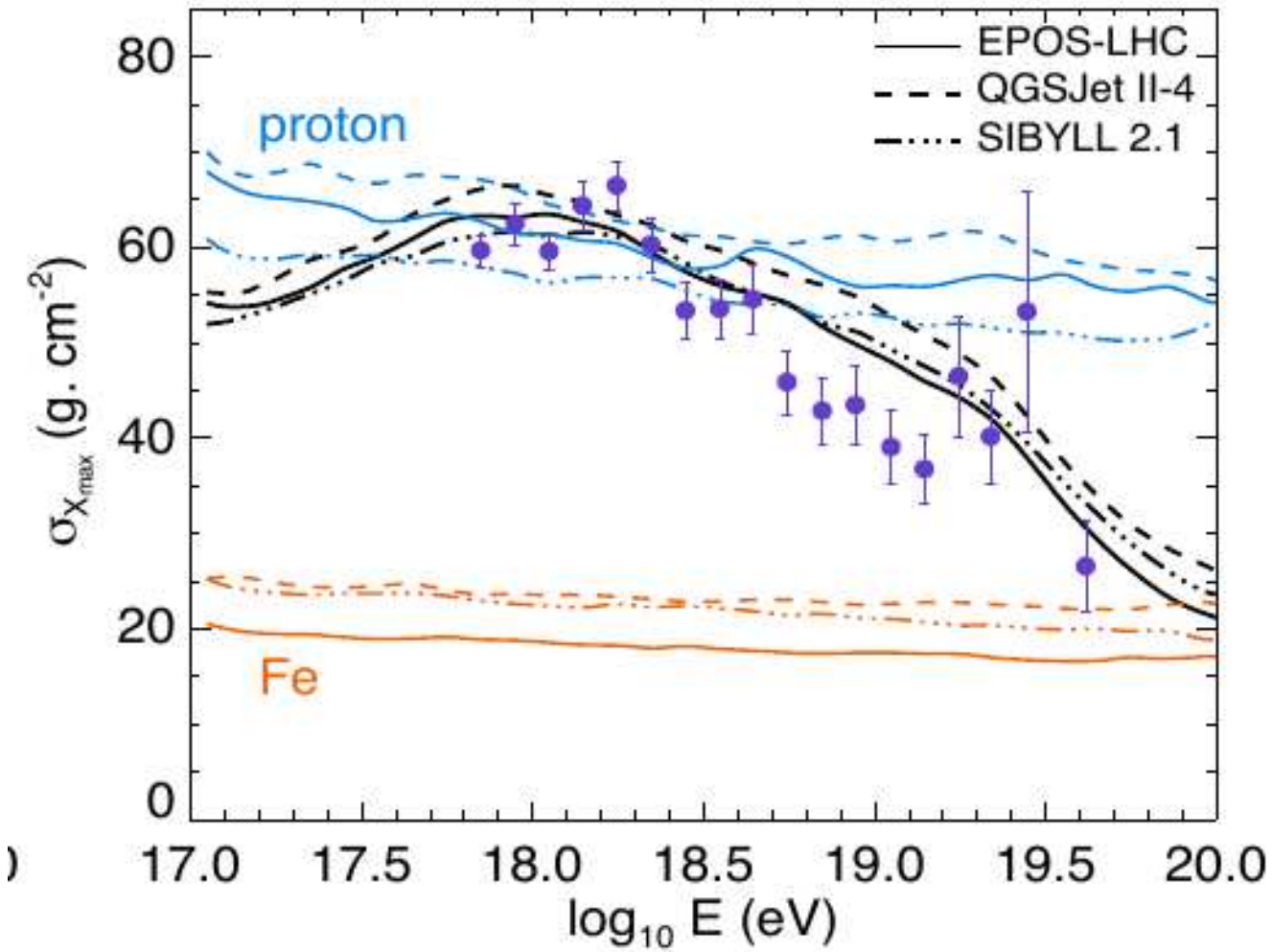

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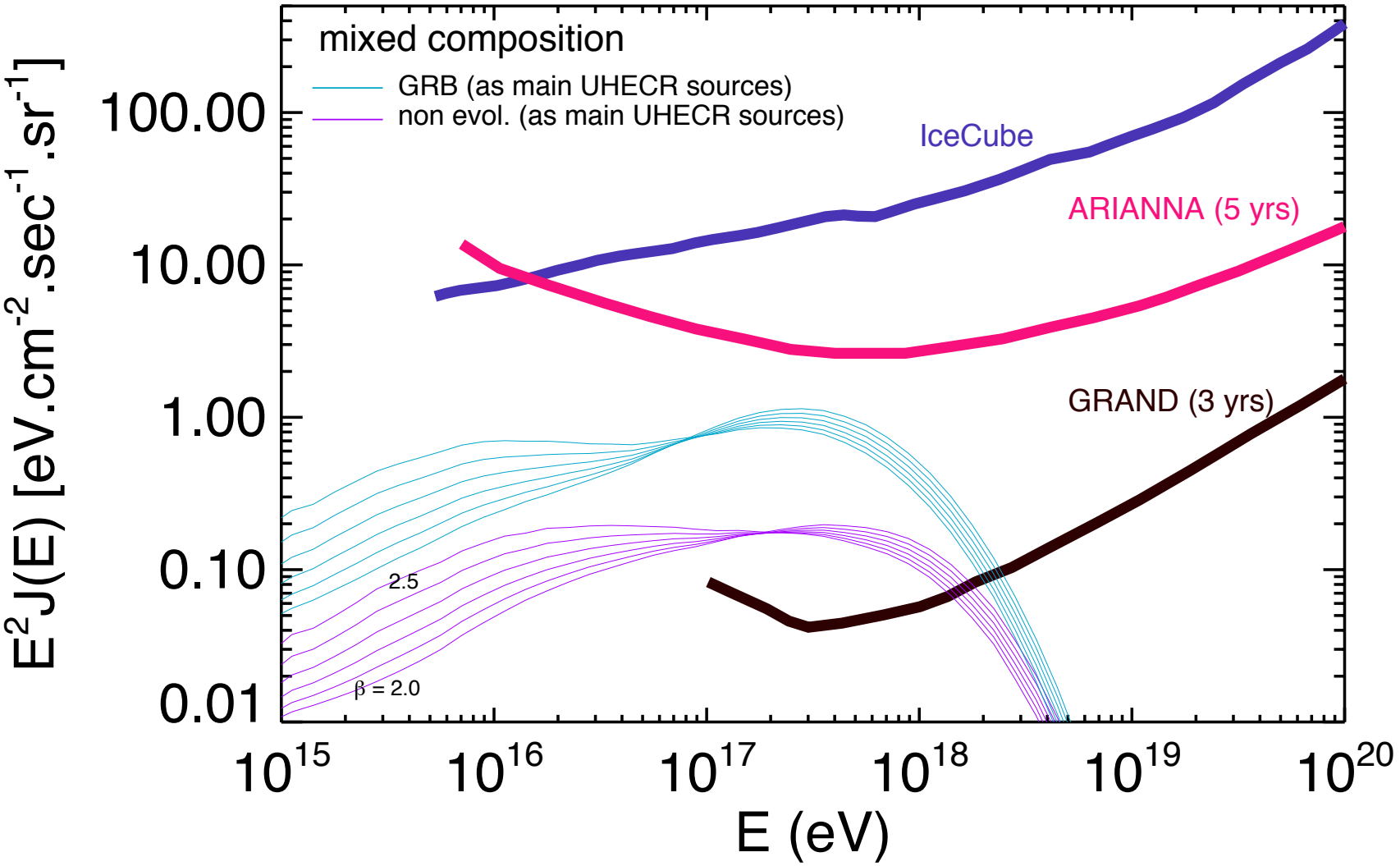
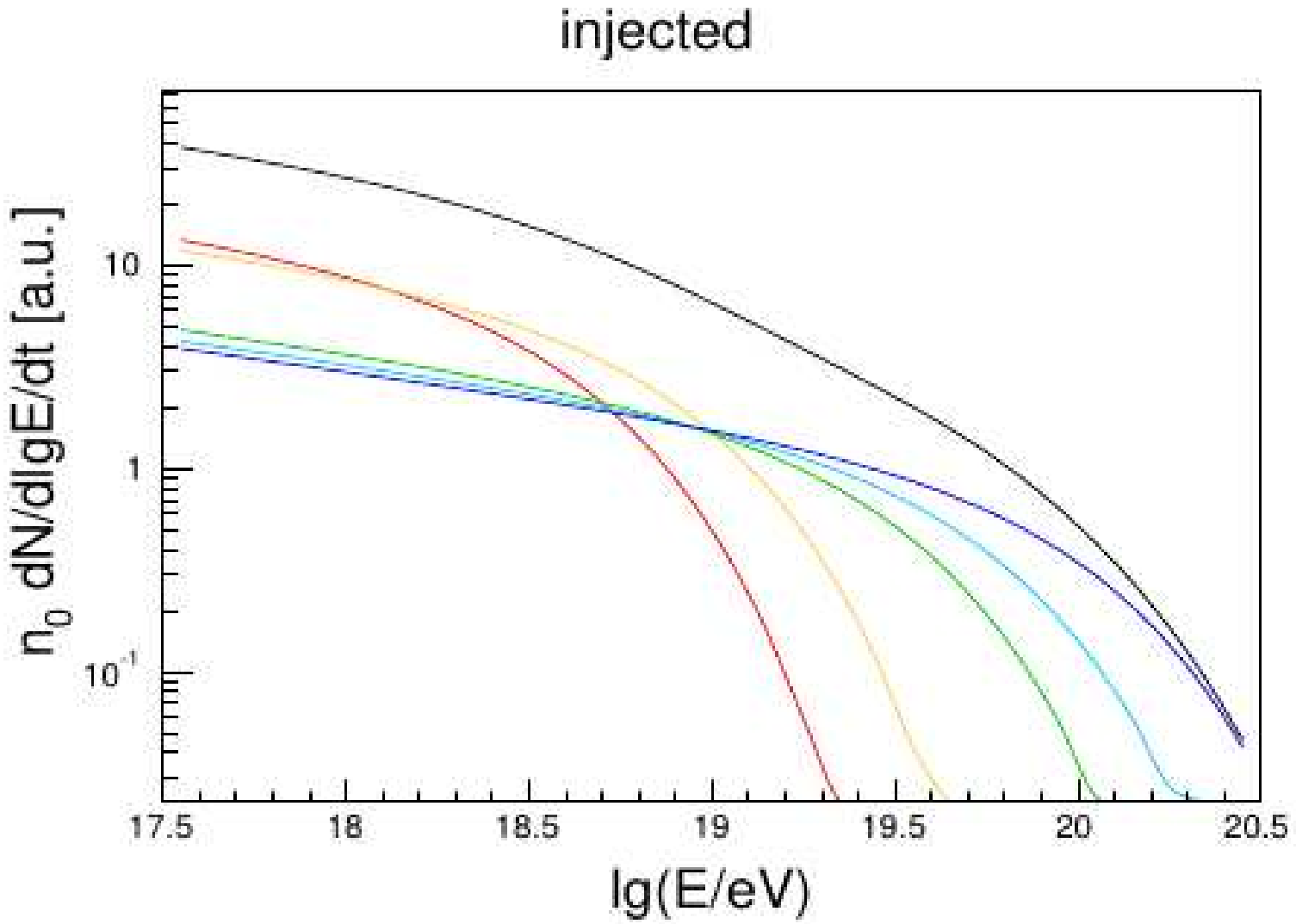
- neutrinos:



Phenomenological AGN model

[*Unger, Farrar, Anchordoqui '15*]



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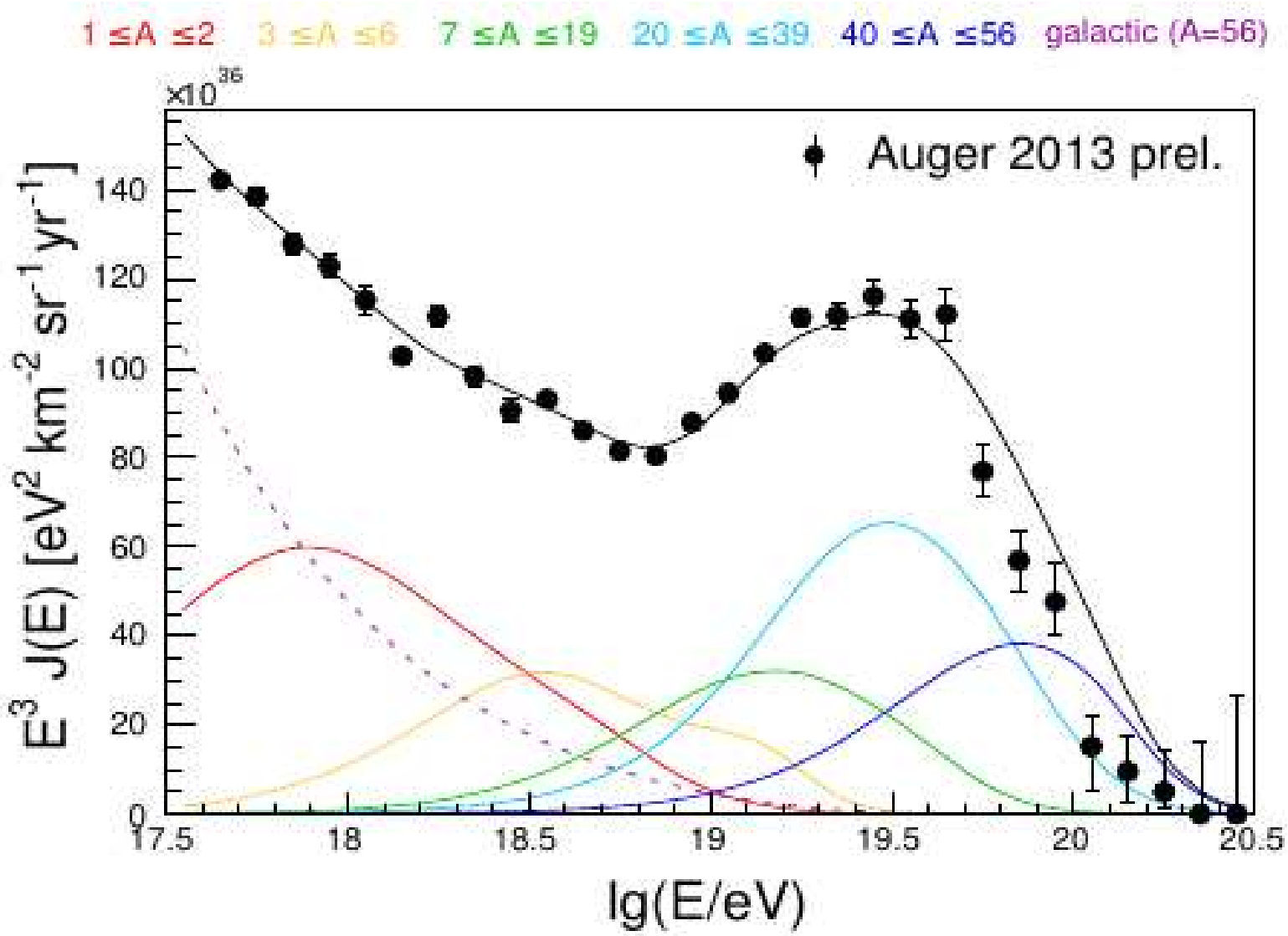

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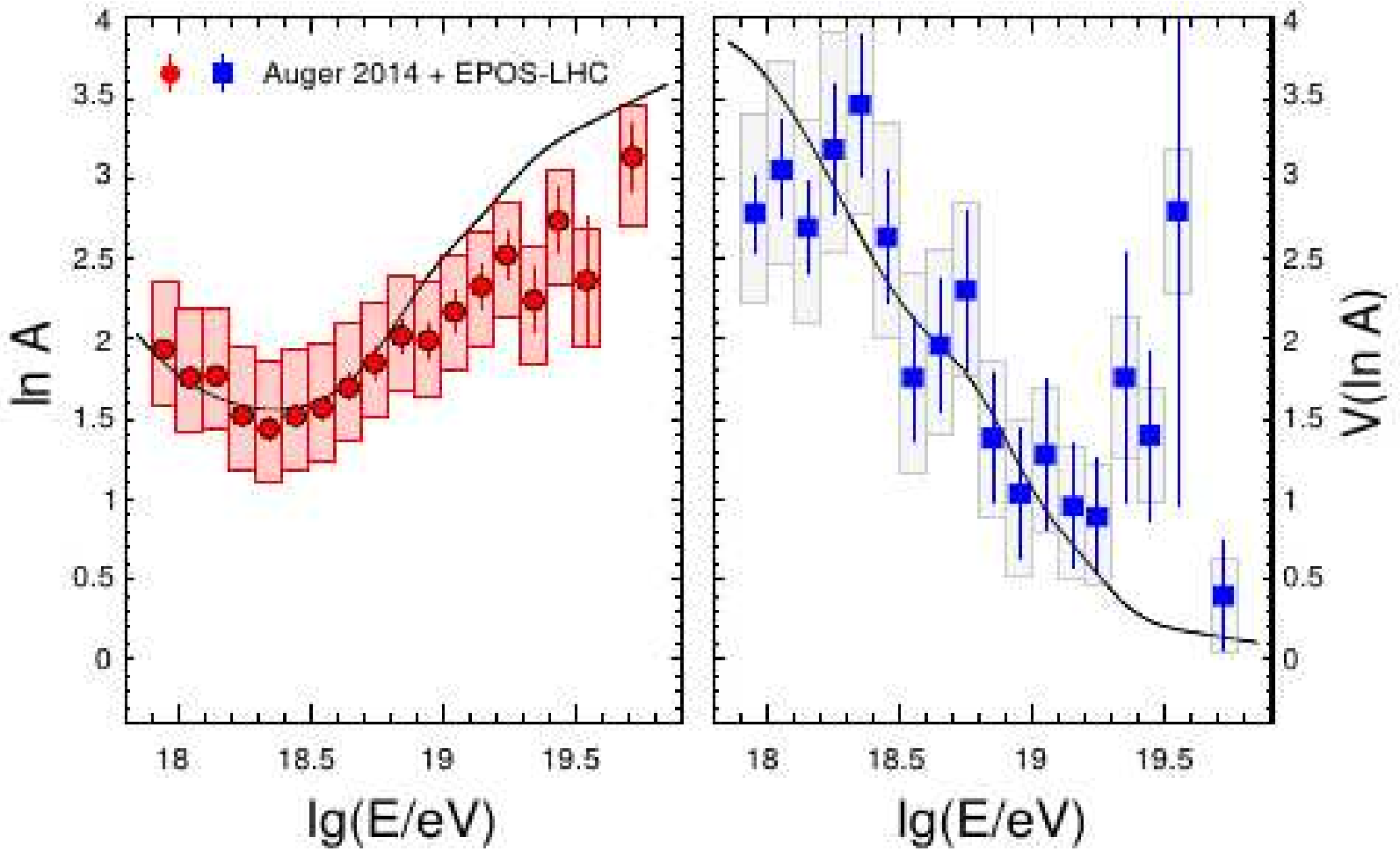

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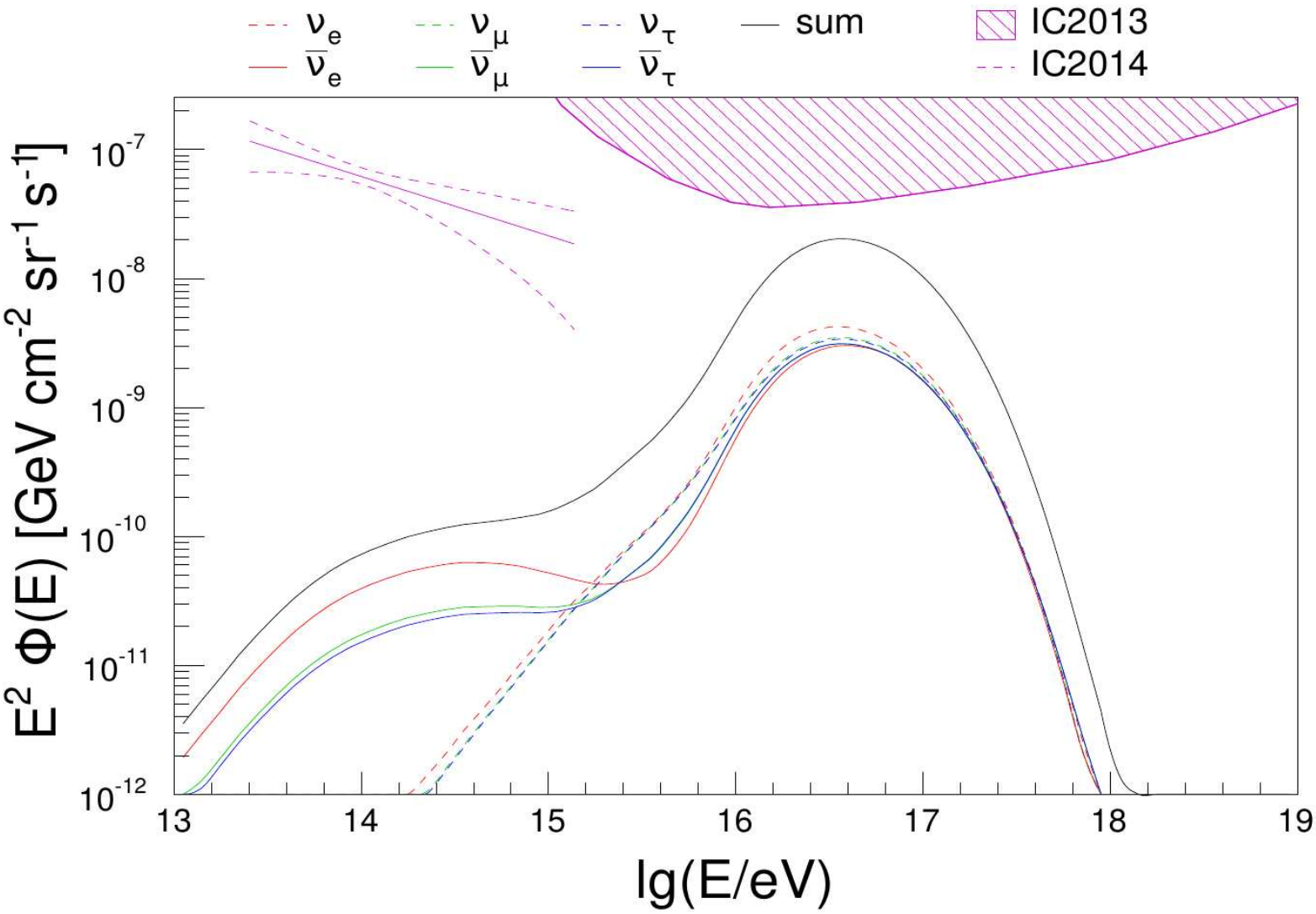

Minimal model: add neutrinos

- 3 zones
  - core: rigidity dependent acceleration $dN/dR \propto R^{-\alpha} \exp(-R/R_{\rm max})$
  - inner zone: $A\gamma$ interactions
  - outer zone: Ap interactions
- diffusion: increase of effective $\tau_{\rm int}$
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  - BL Lac $\simeq$ peaked at late times
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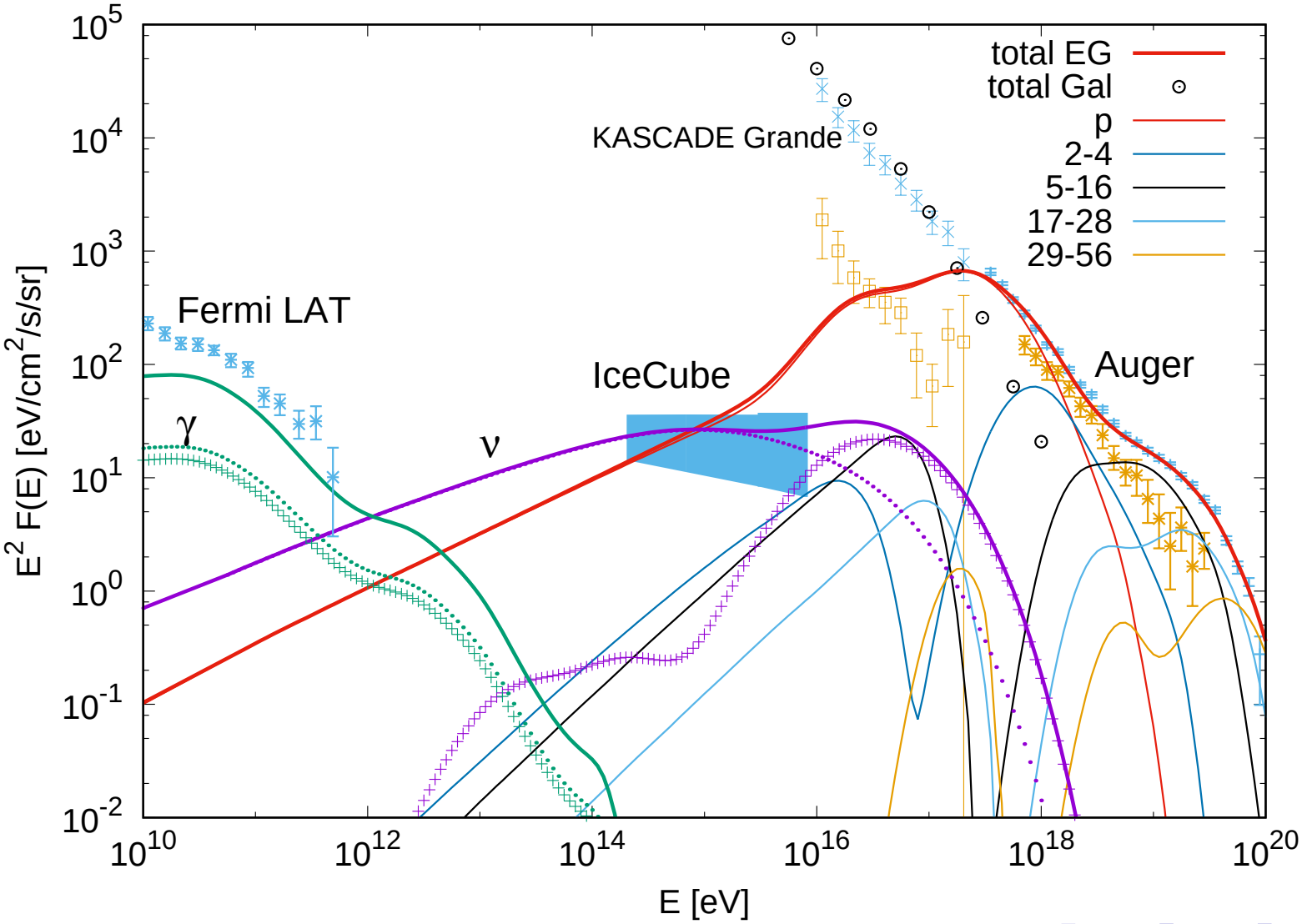
AGN evol., gas and photons: $\alpha = 1.5$, $\tau_0^{pp} = 0.035$ and $\tau_0^{p\gamma} = 0.29$



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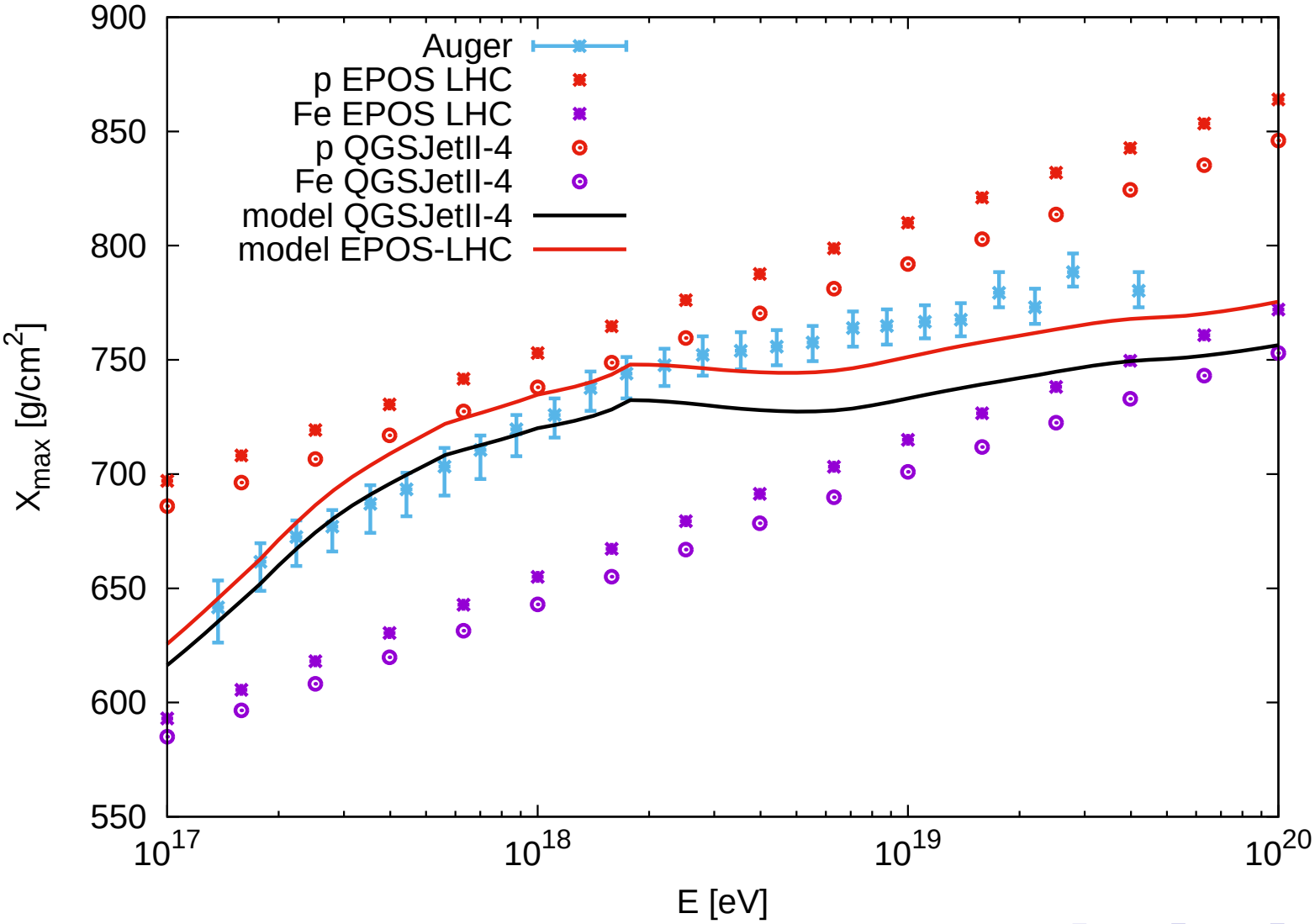

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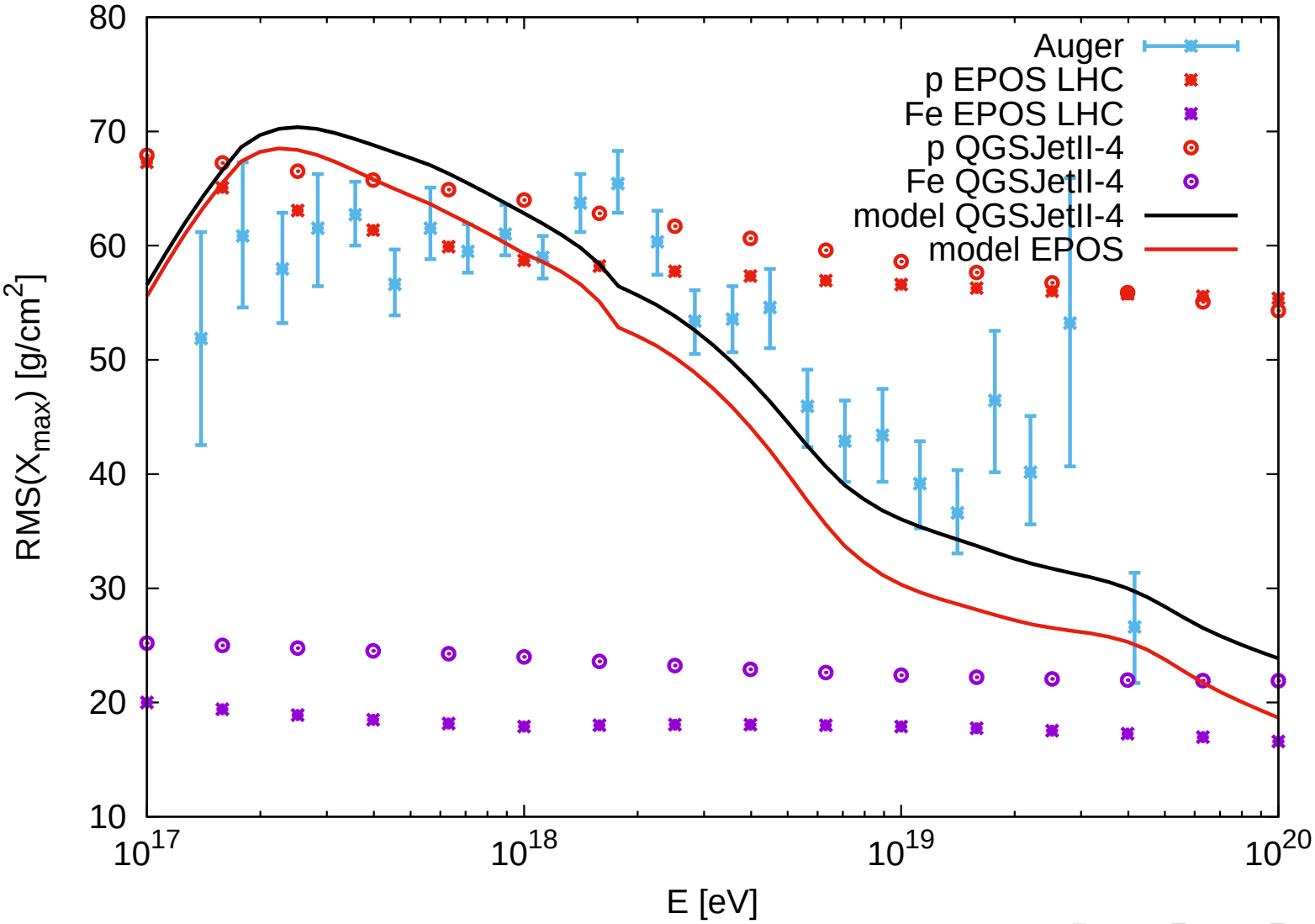
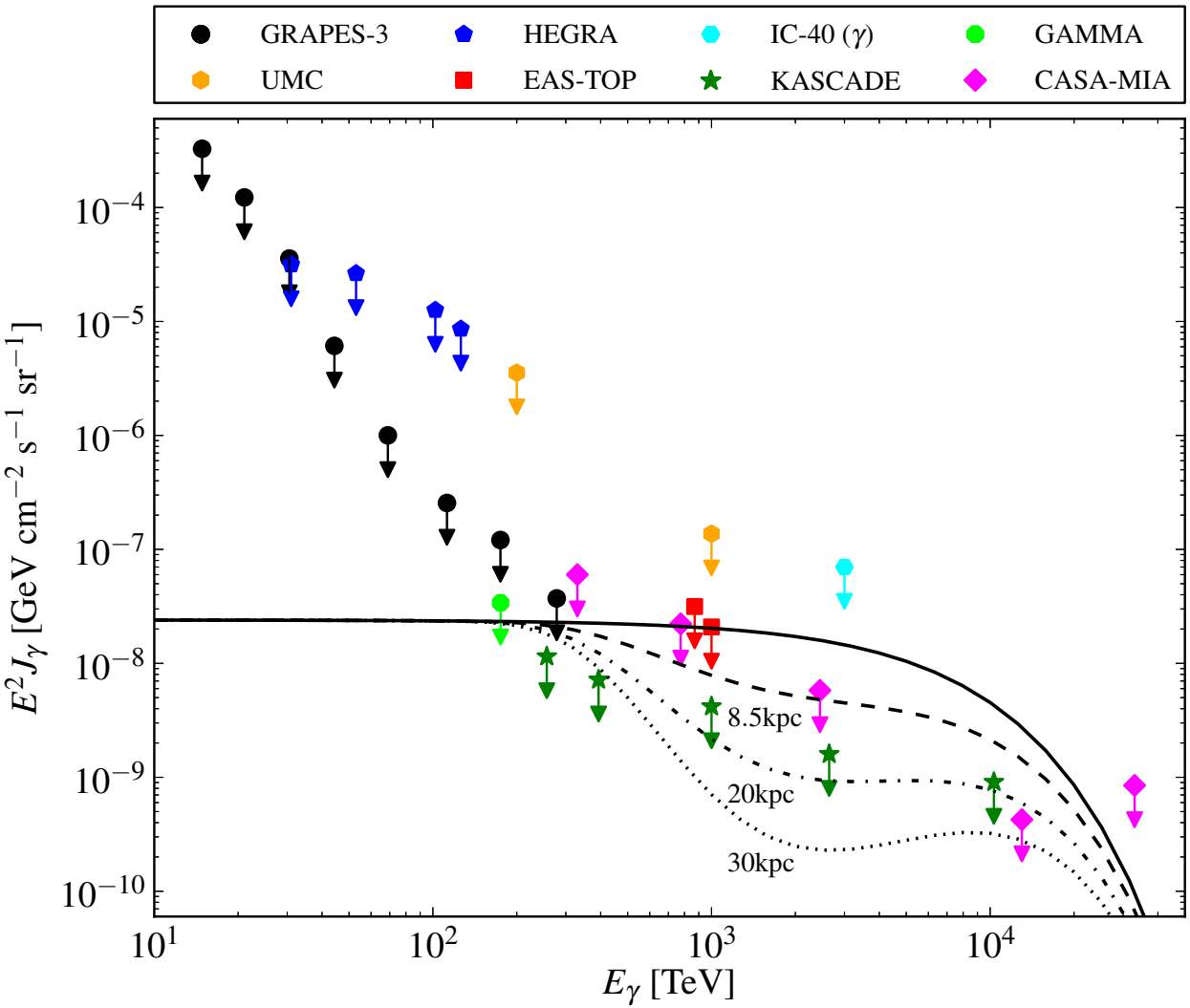


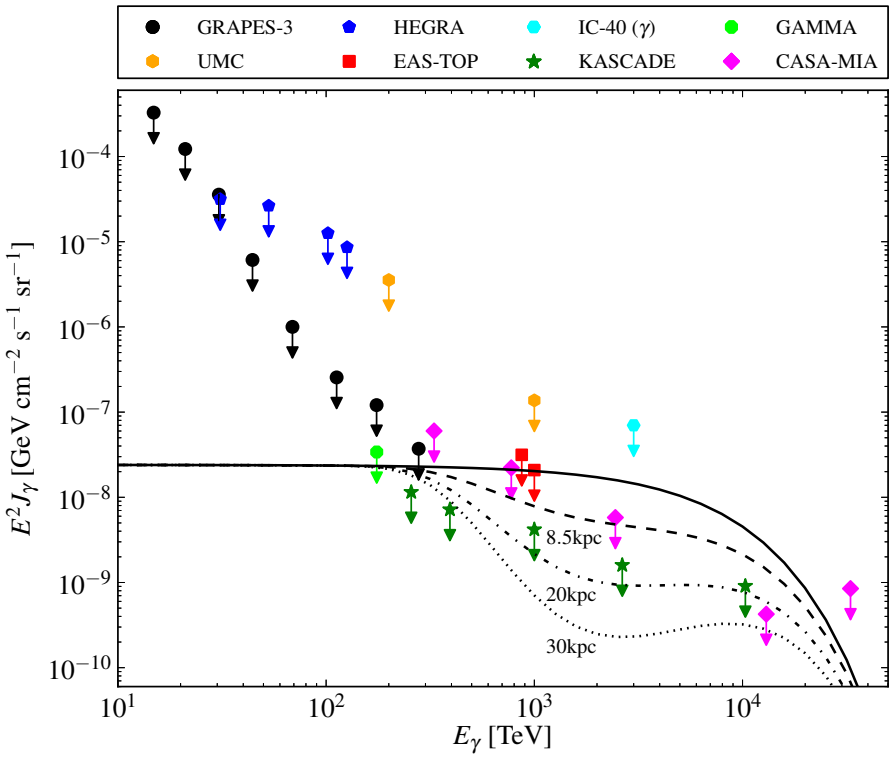
(Isotropic) photon limits

[*Ahlers, Murase '13*]



(Isotropic) photon limits

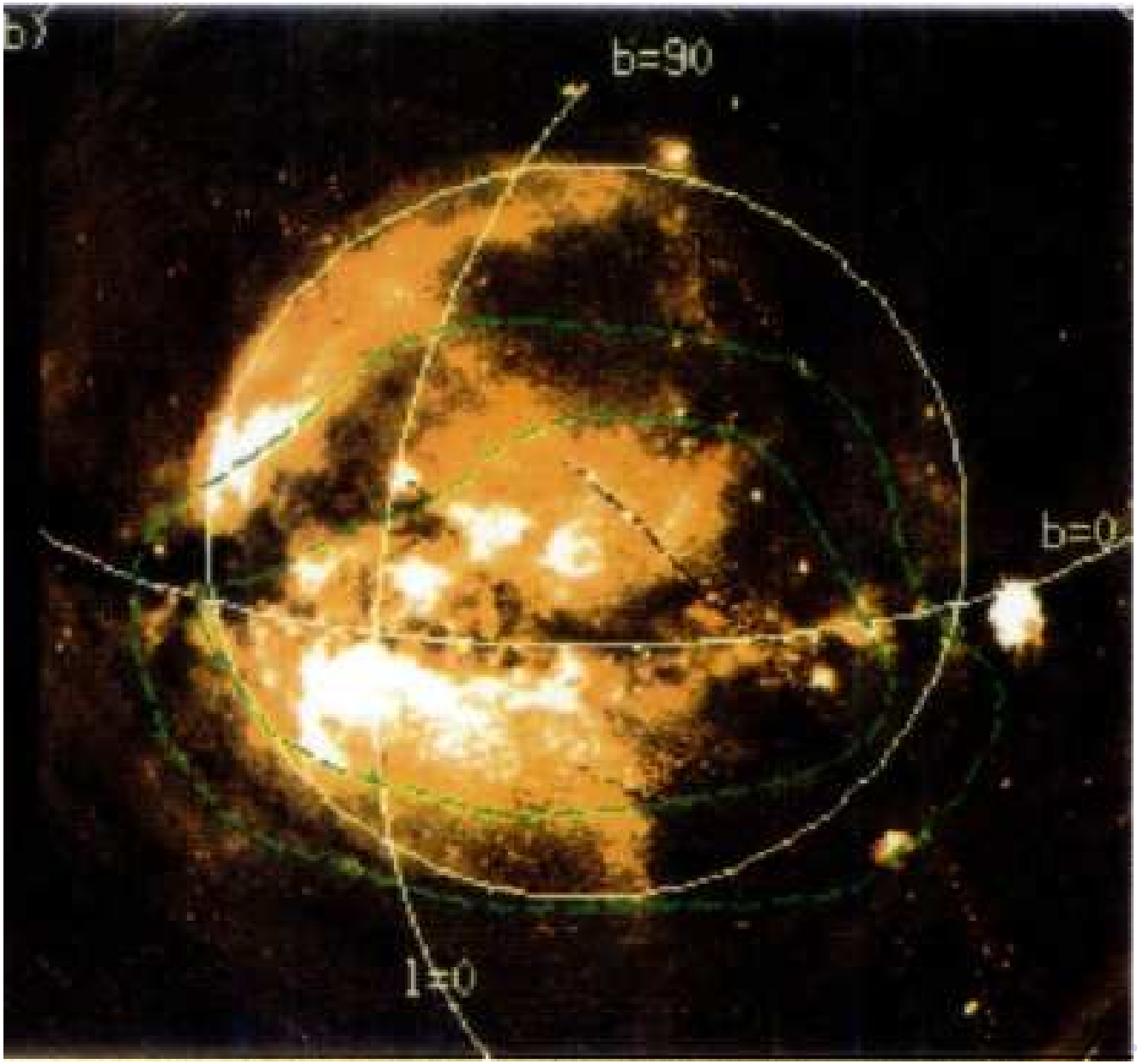
[*Ahlers, Murase '13*]



KASCADE limits

- reanalysed '17 and increased limit

Sources in Local & Loop I superbubble



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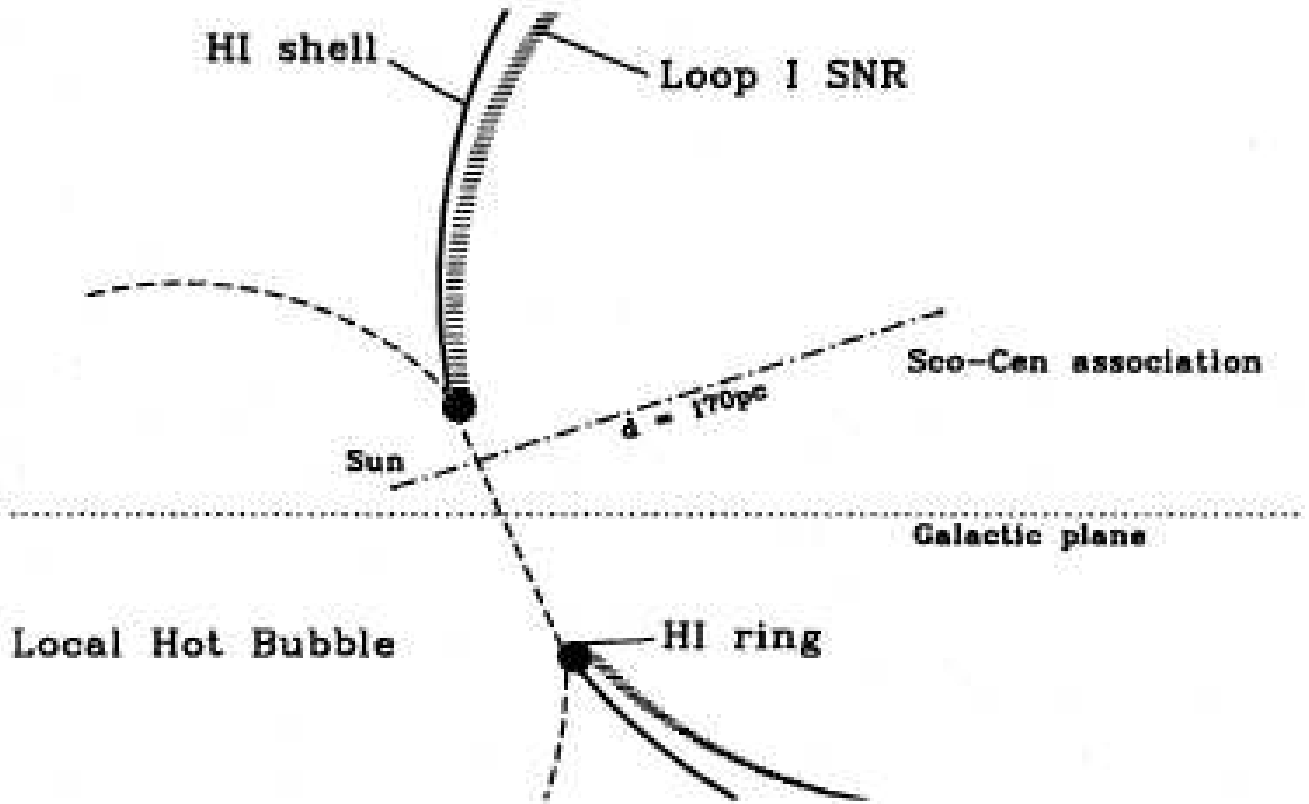

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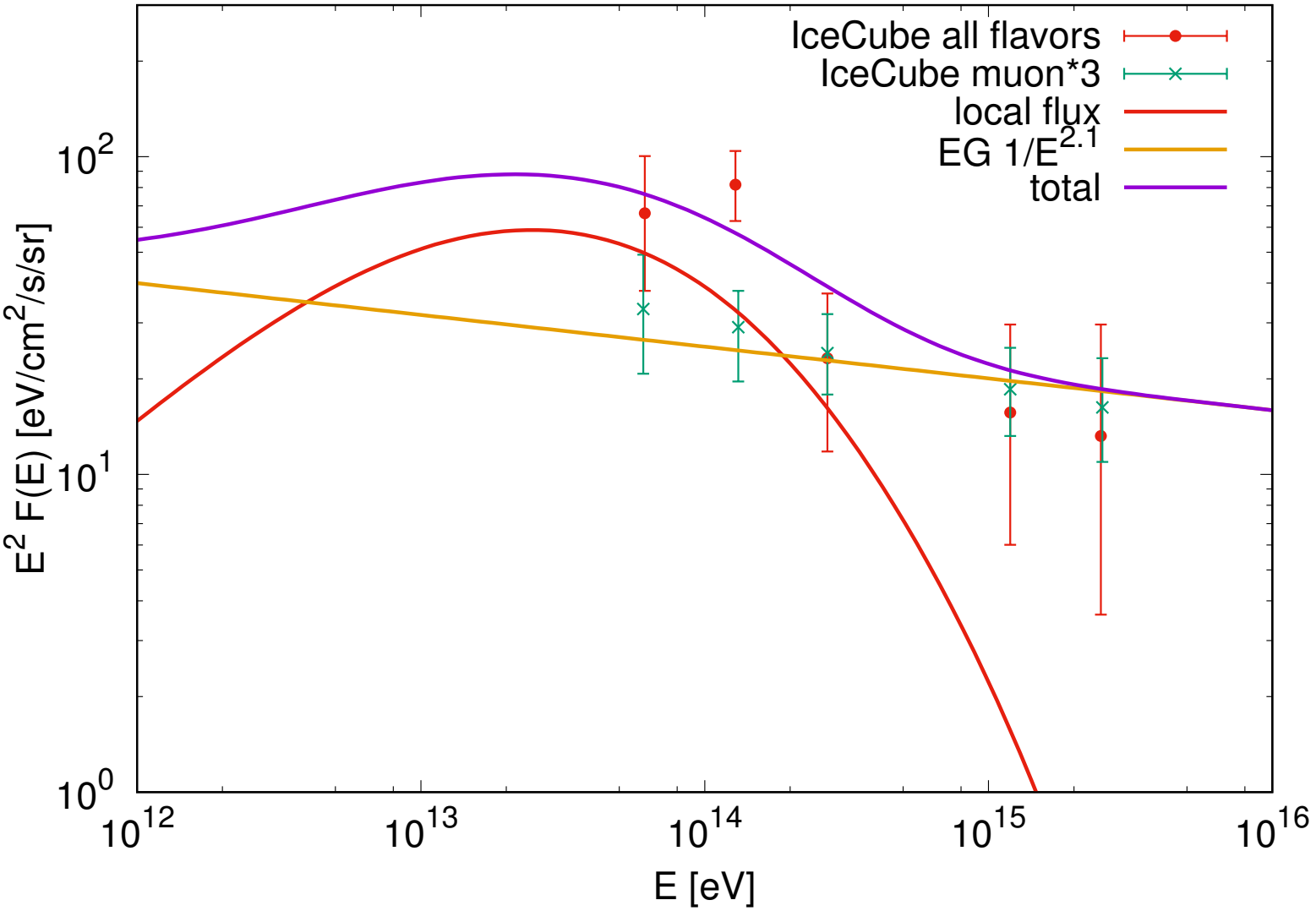

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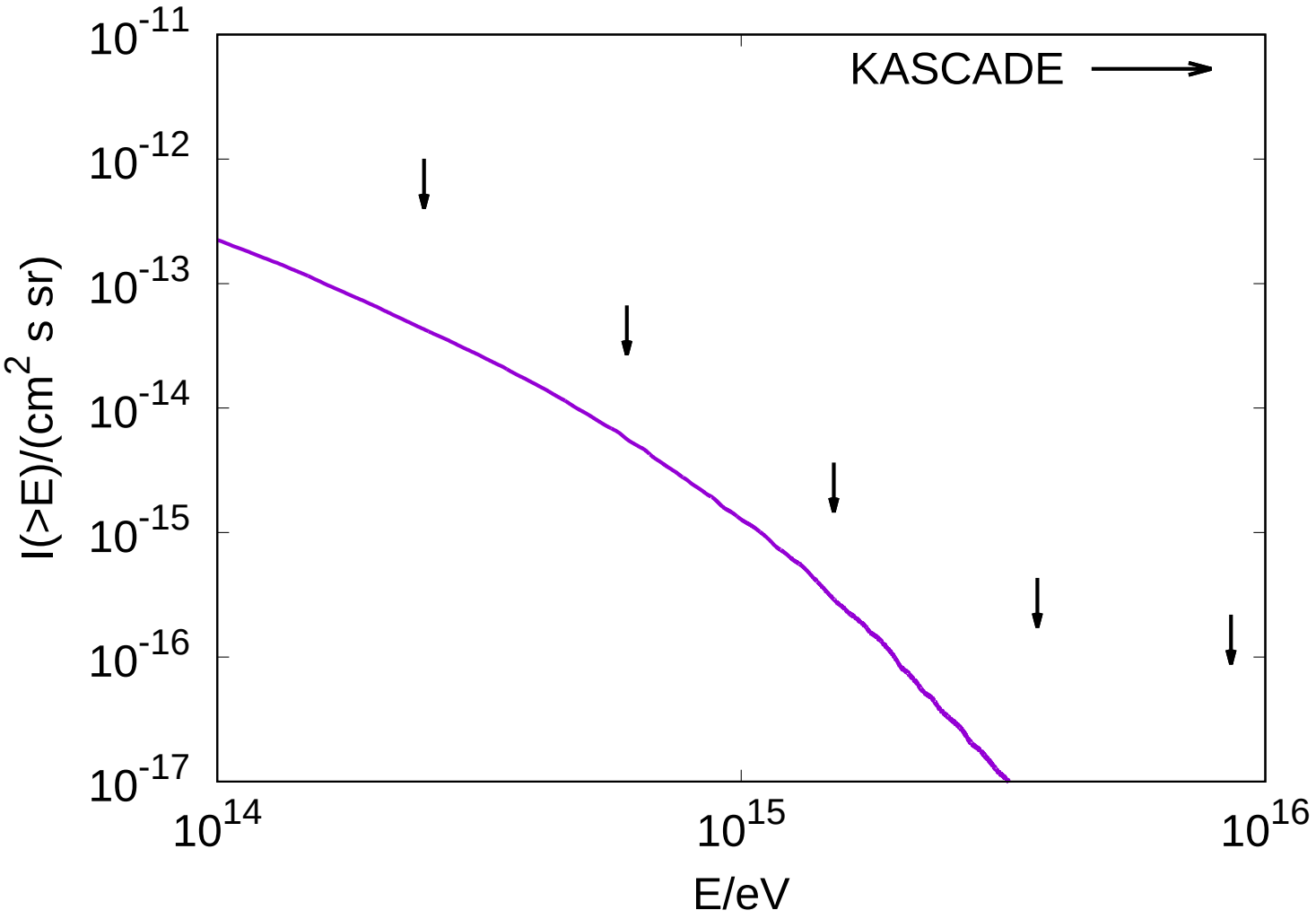
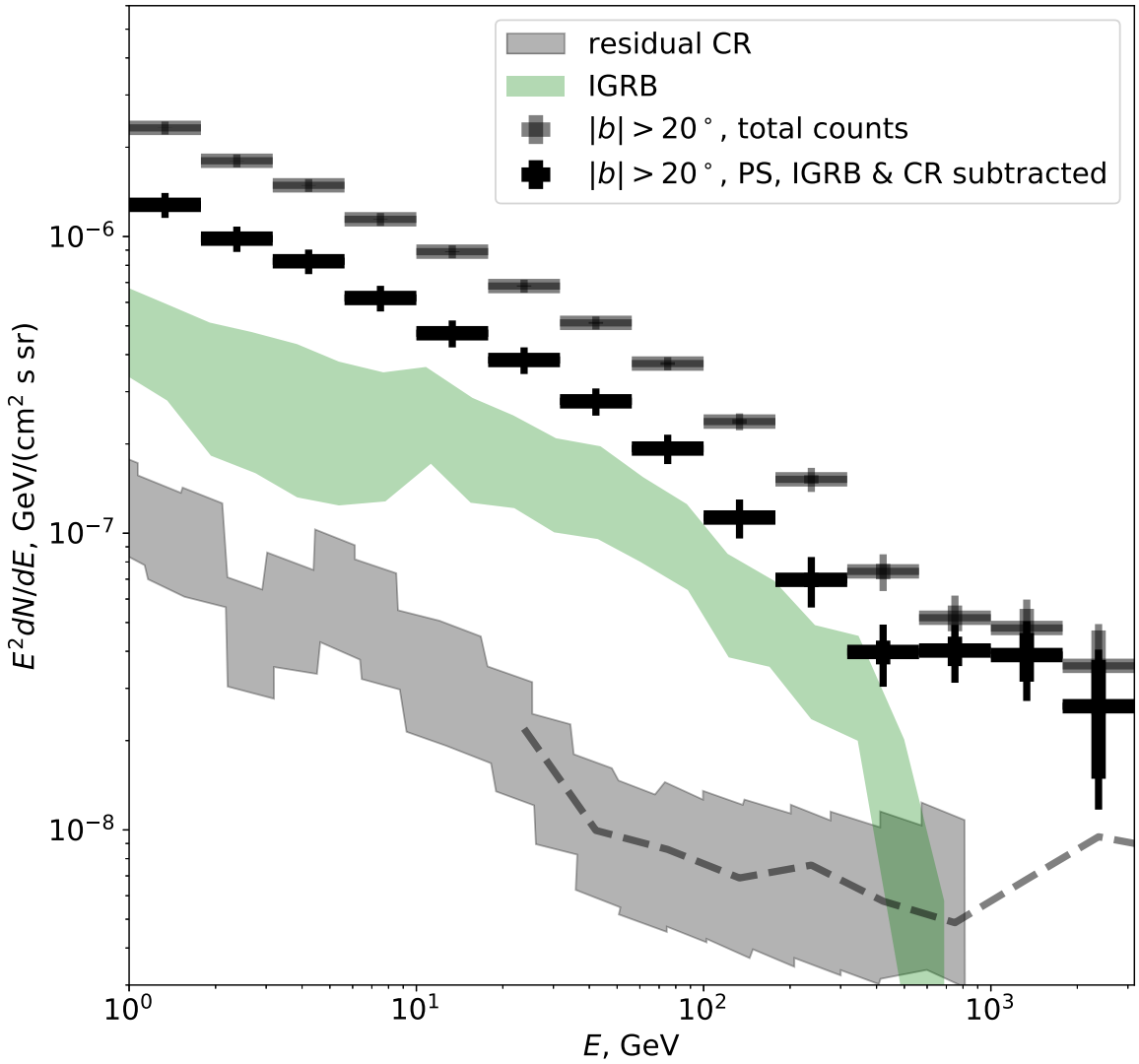


Are multi-TeV photons in the Fermi data? For $|b| > 20°$:



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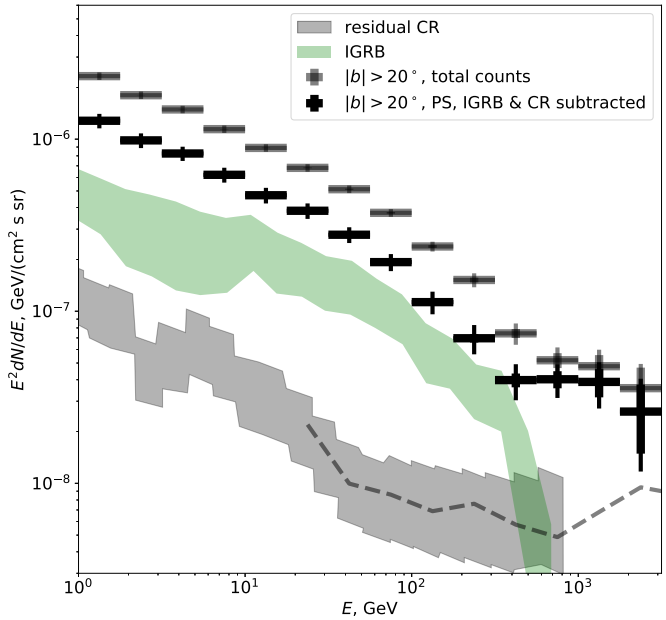
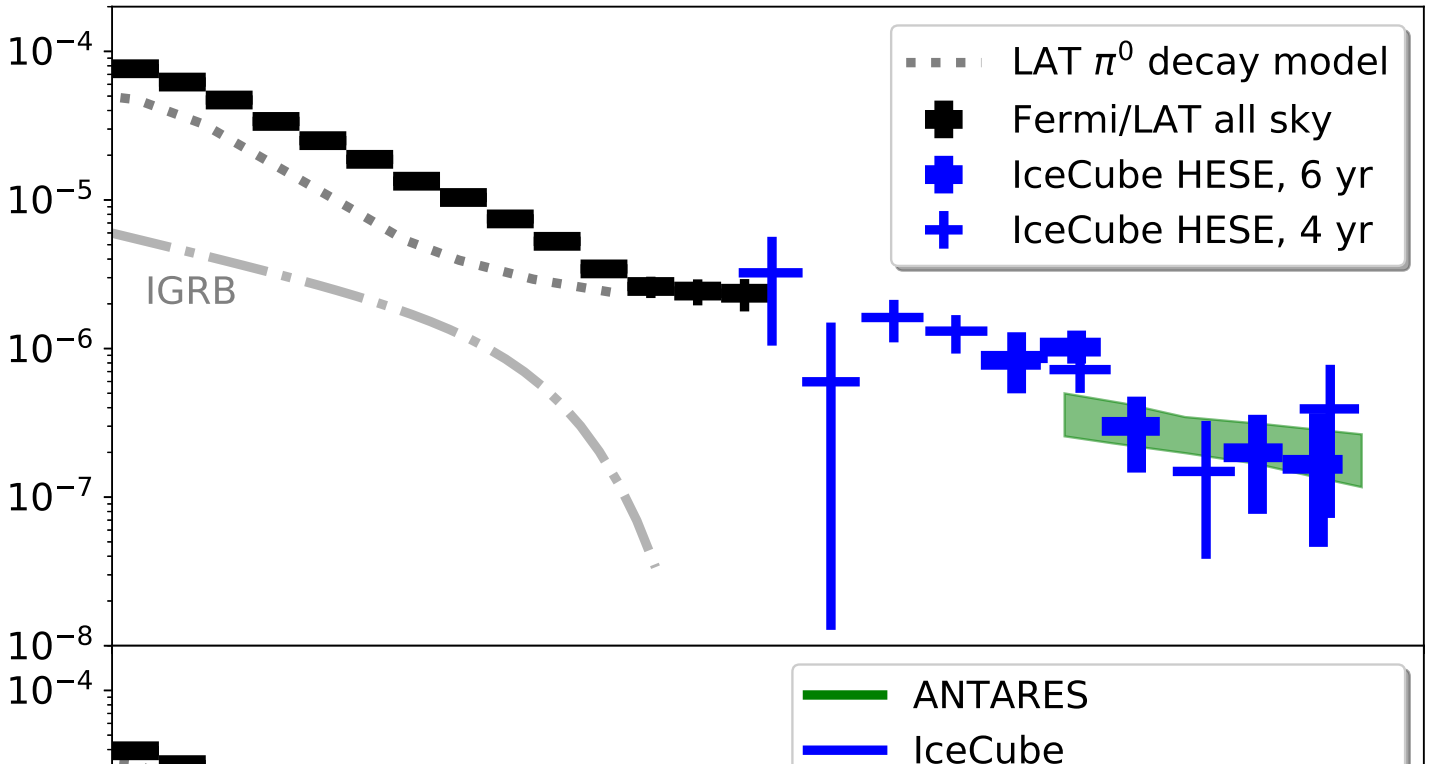


- bin 1–1.7 TeV: expected 14 (18.5) for nominal (renormalised) exposure
  observed (after subtr. CR): 47
- bin 1.7–3 TeV: expected 2.4 (3.5.5), observed 17

Adding neutrinos:



Possible explanations:

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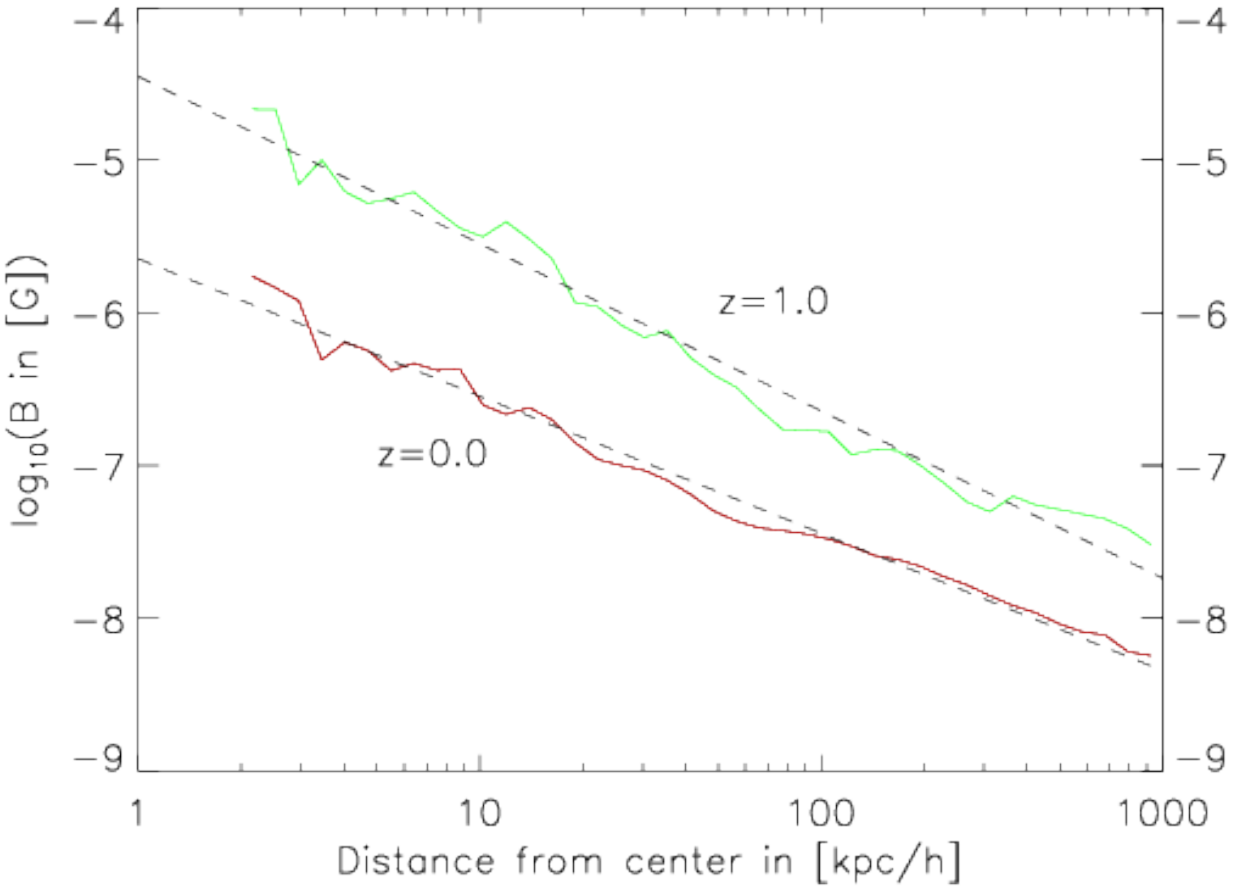
[*Taylor, Gabici, Aharonian '14*]



[*Dolag '02*]

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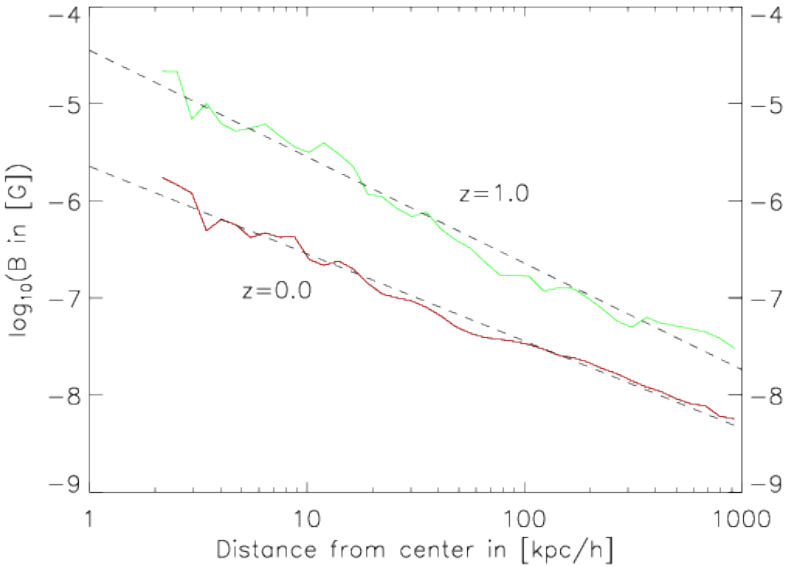


[*Dolag '02*]

- for $B \sim 0.01\mu$ G and $L_{\rm coh} \sim 100$ pc:

$\Rightarrow$ CR with $E_* = 100$ TeV is in large-angle scattering regime

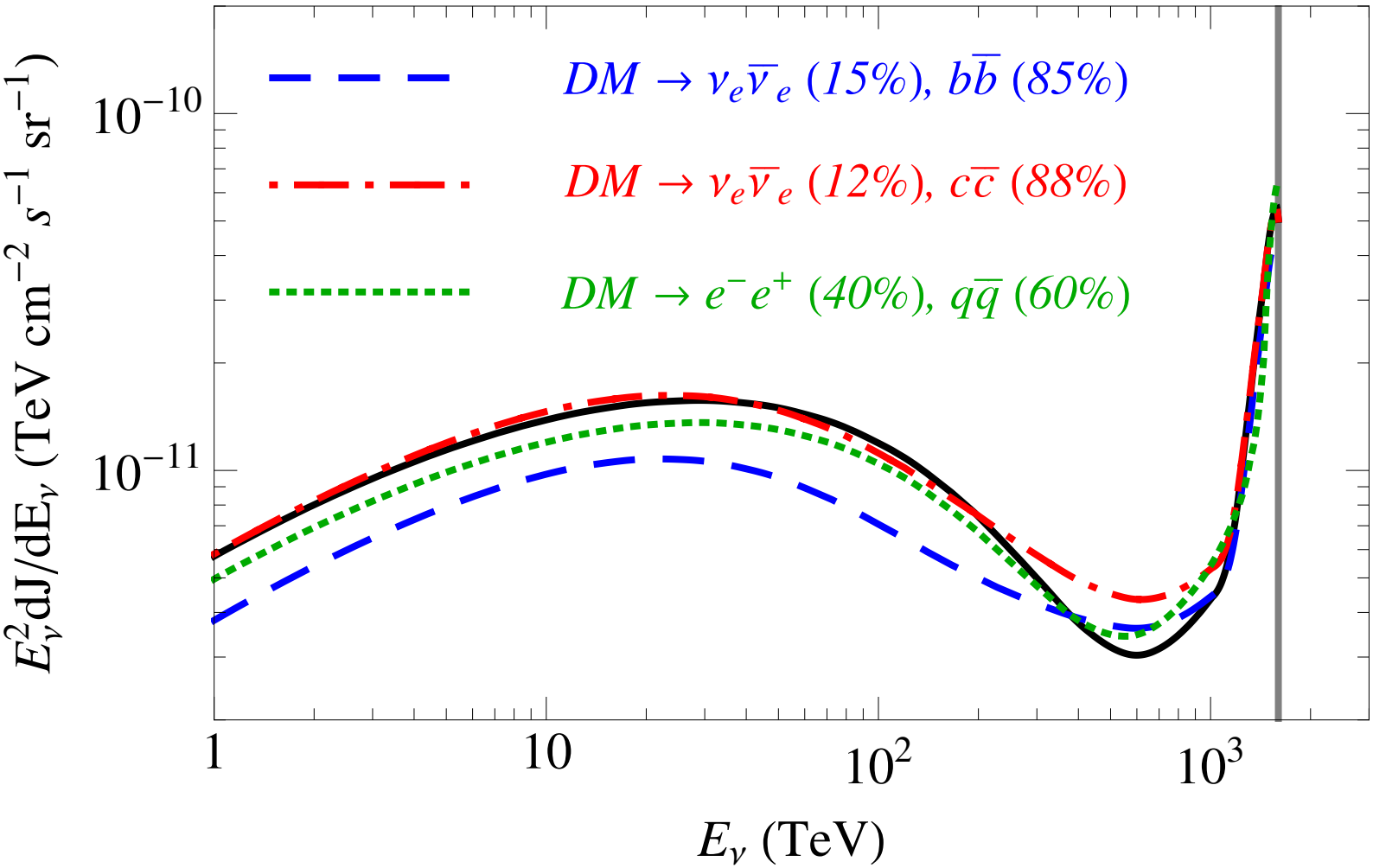
$\Rightarrow$ $D(E_*) \sim 10^{29} \mathrm{cm}^2/\mathrm{s}$

$\Rightarrow$ escape time $\tau = H^2/2D \sim t_0$

Possible explanations:

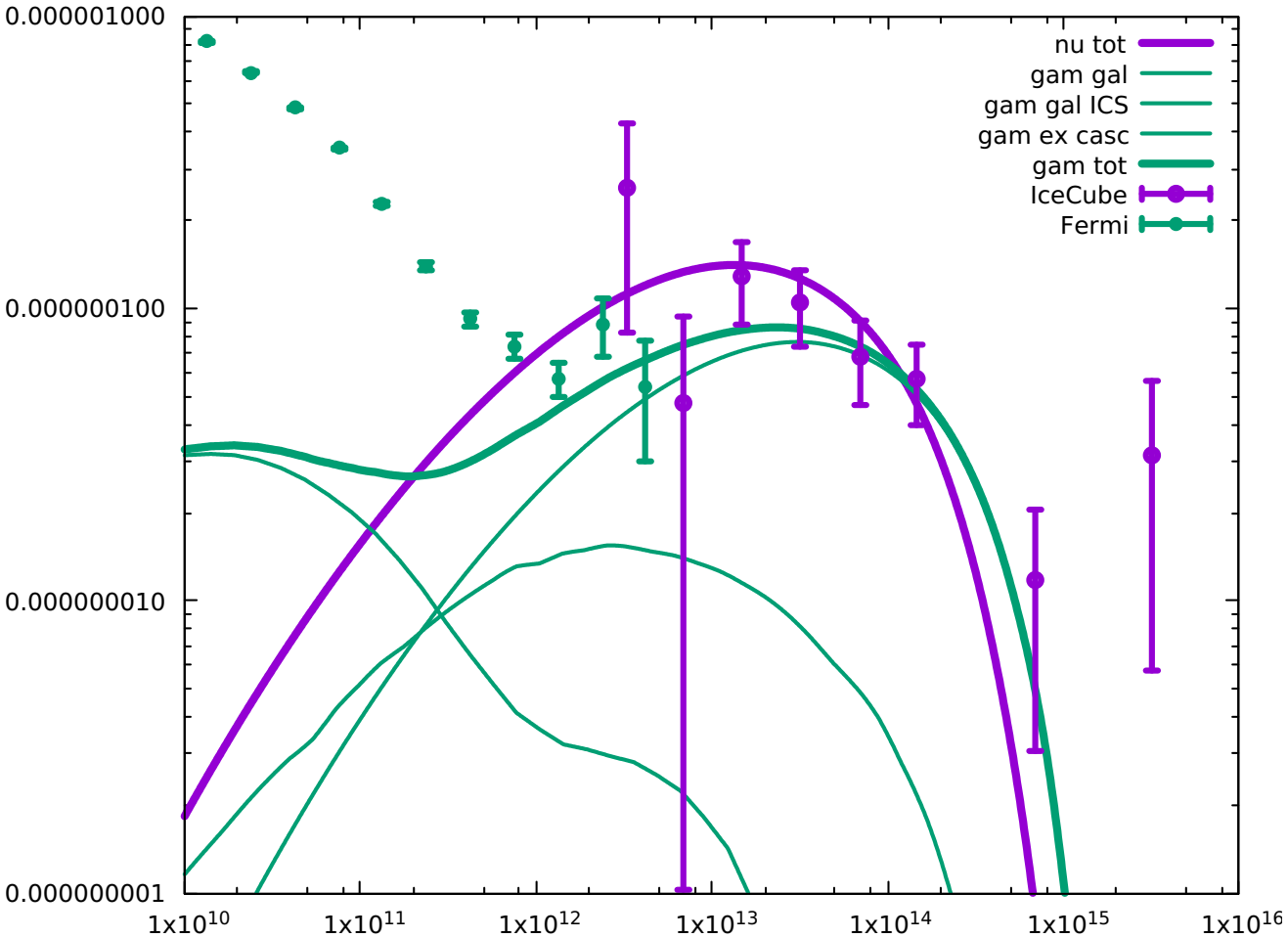
- interface Loop I/local superbubble: strong dipole?
- extended CR halo
- PeV dark matter: re-incarnation of SHDM idea for AGASA excess:
  - non-hermal DM
  - avoids cascacde limit
  - Galactic anisotropy

PeV dark matter

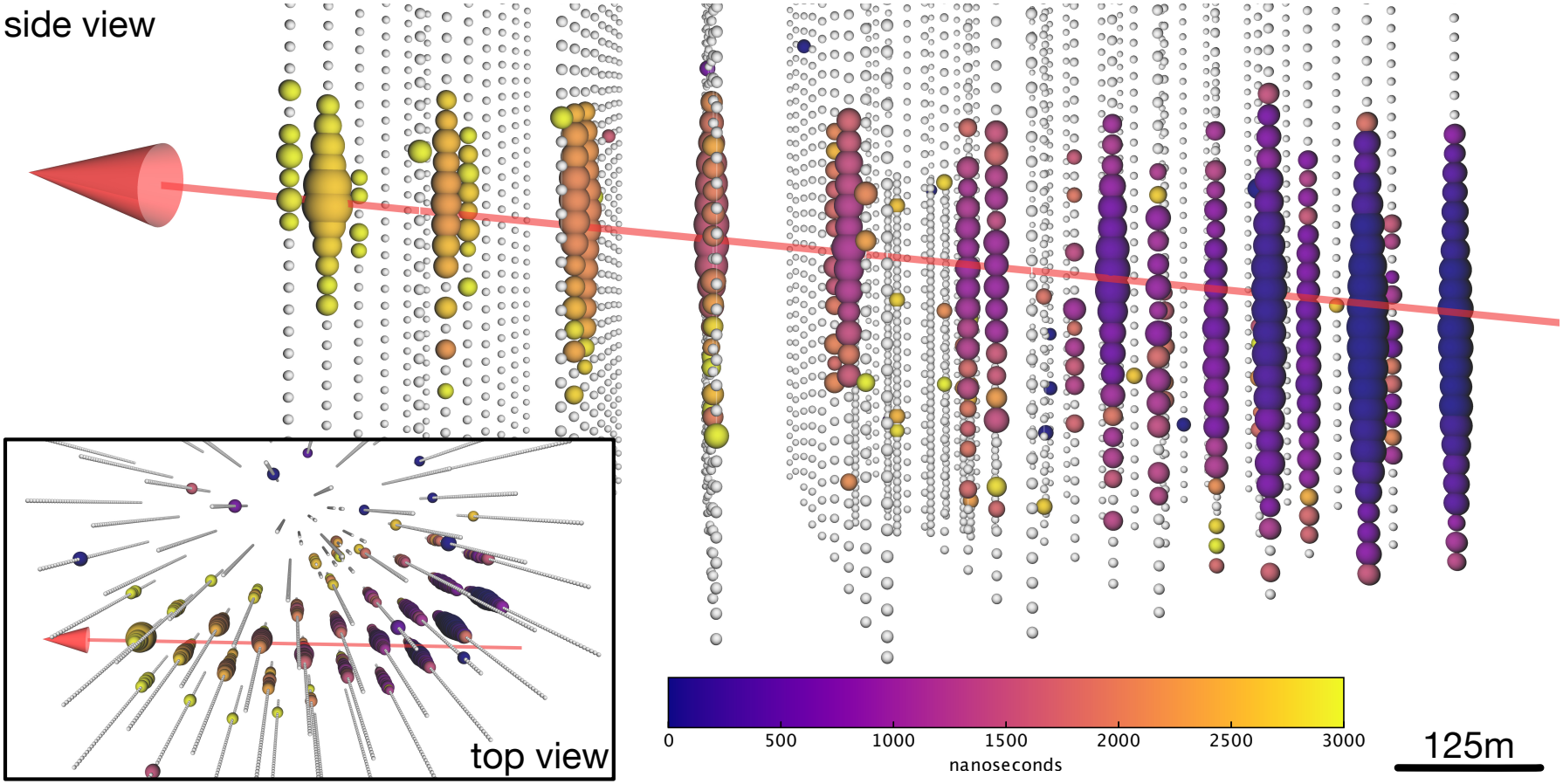


[*Kusenko et al. '13, Esmaili, Serpico '13*]

Possible explanations: heavy dark matter



IC170922A event



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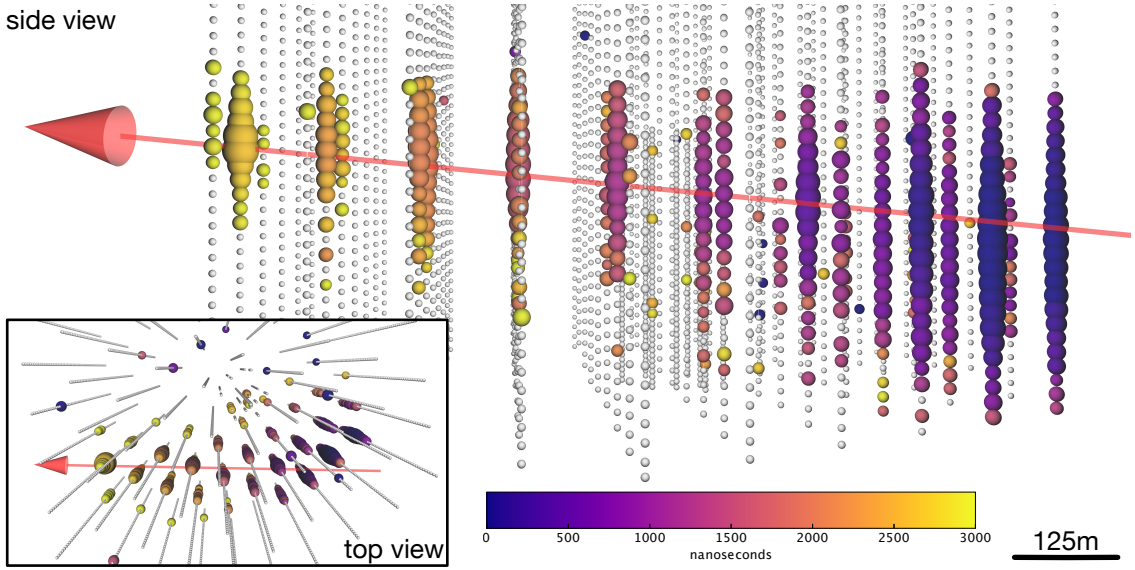
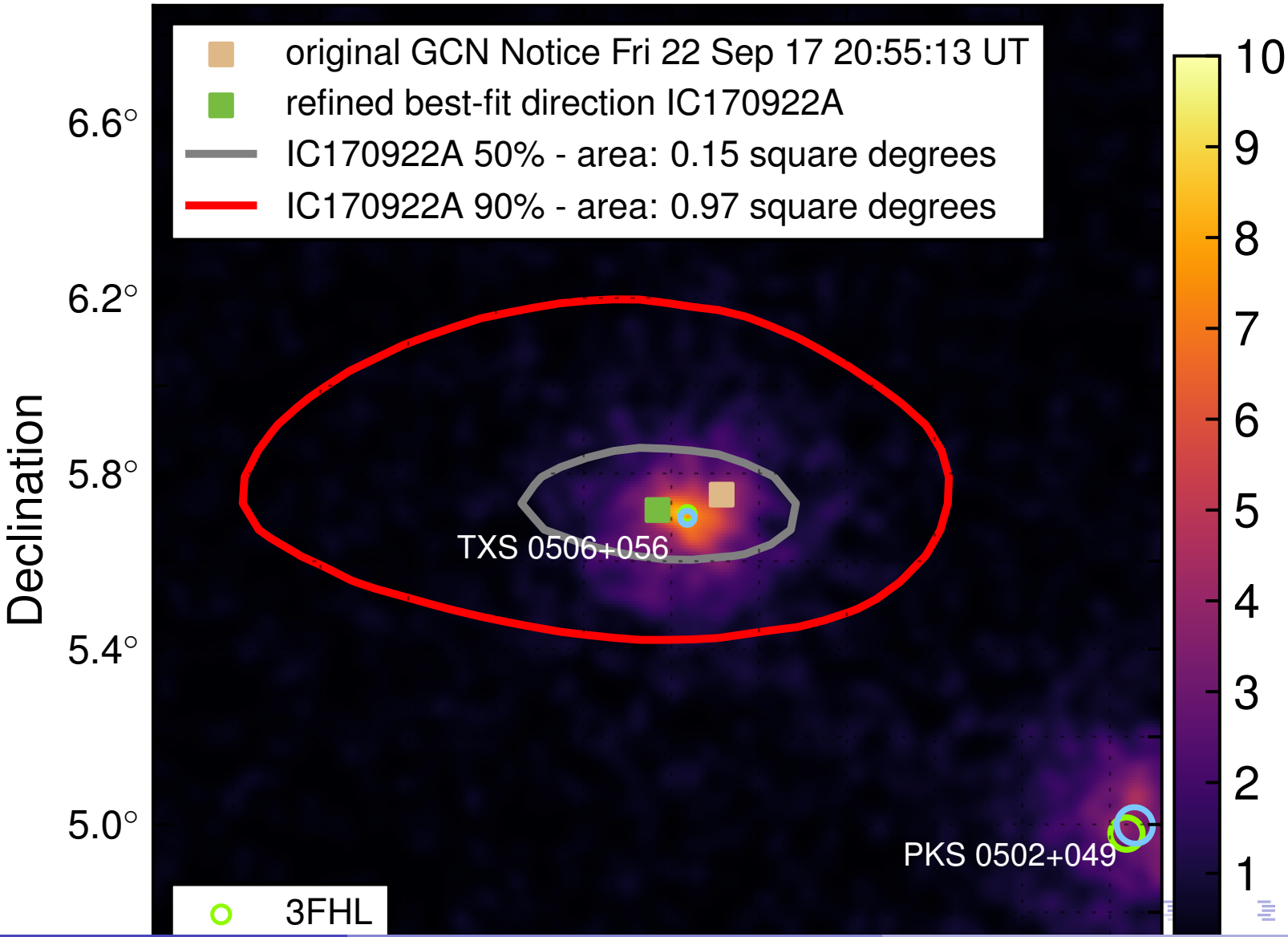
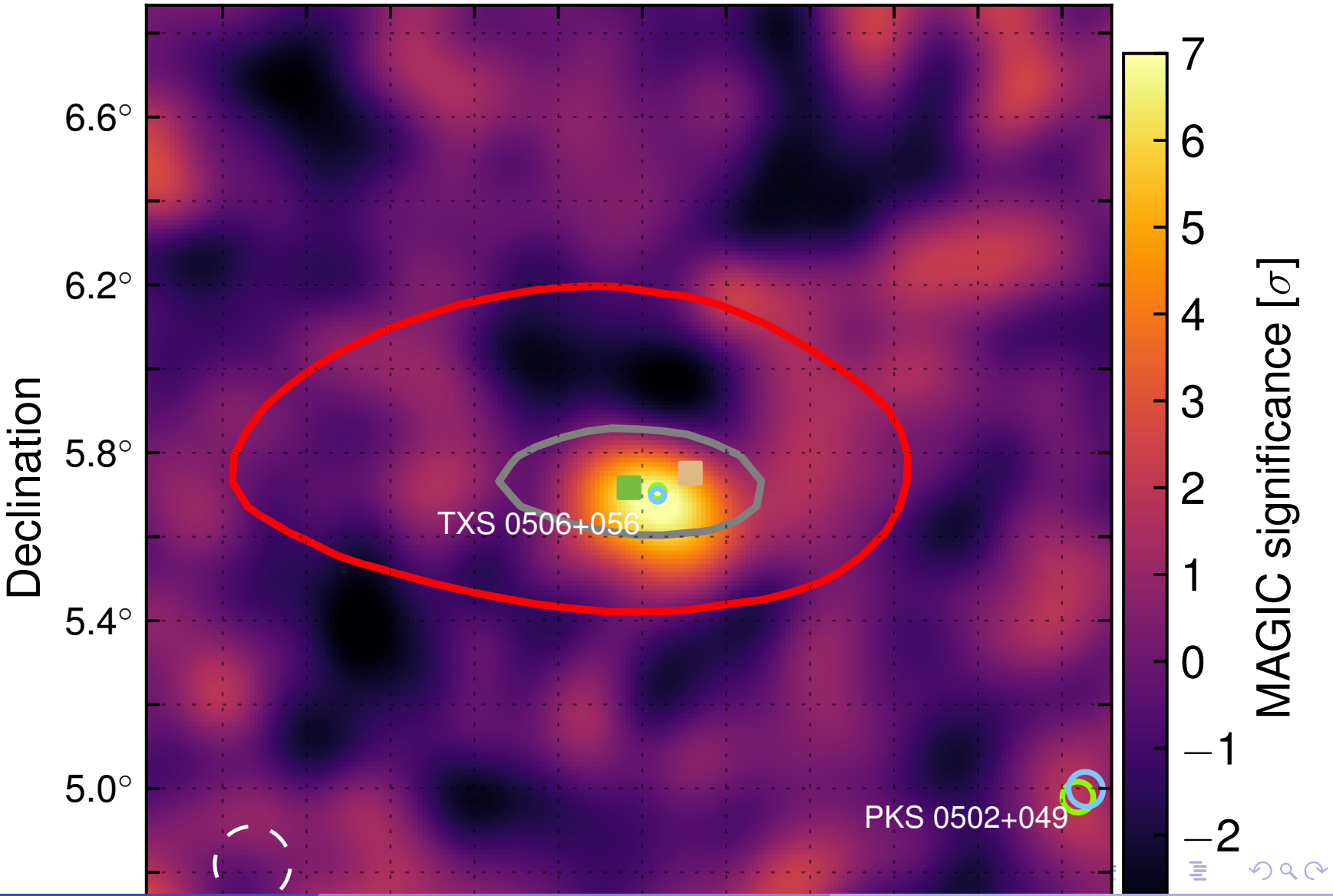


- direction RA $77.43^{+0.95}_{-0.65}$ and Dec $+5.72^{+0.50}_{-0.30}$
- coincides with blazar TXS 0506+056
- energy deposited 23.7 ± 2.8 TeV, $E_\nu \sim 290$ TeV

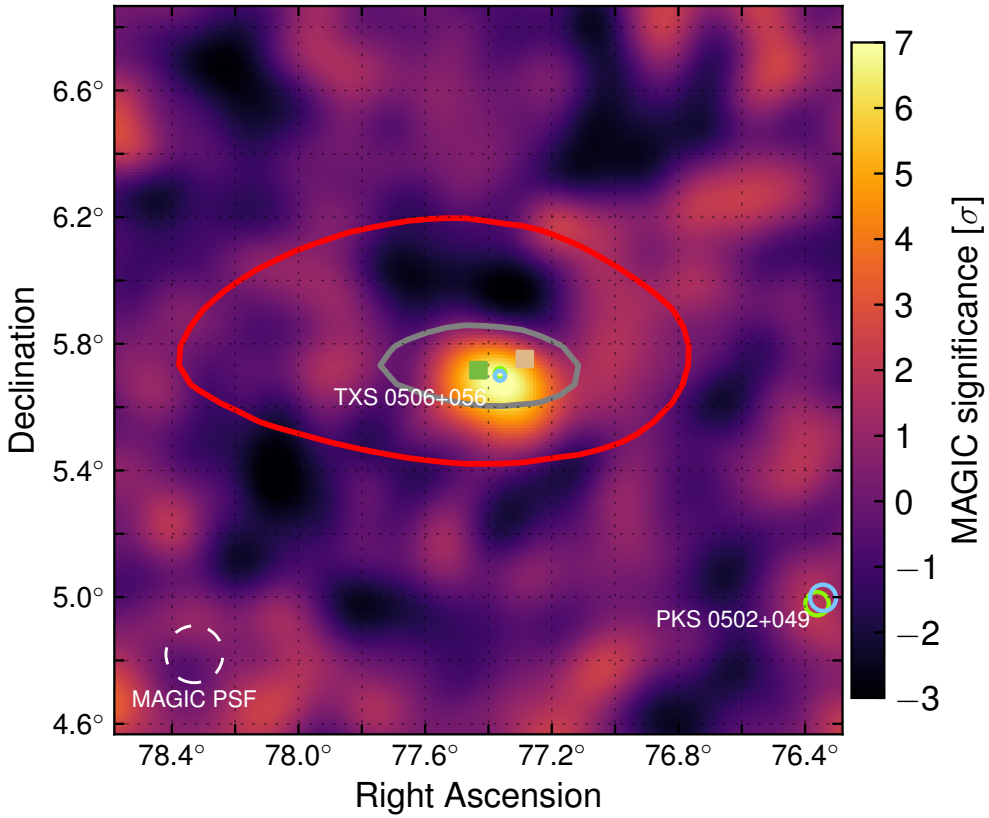
IC170922A event: Fermi-LAT observations



IC170922A event: MAGIC observations

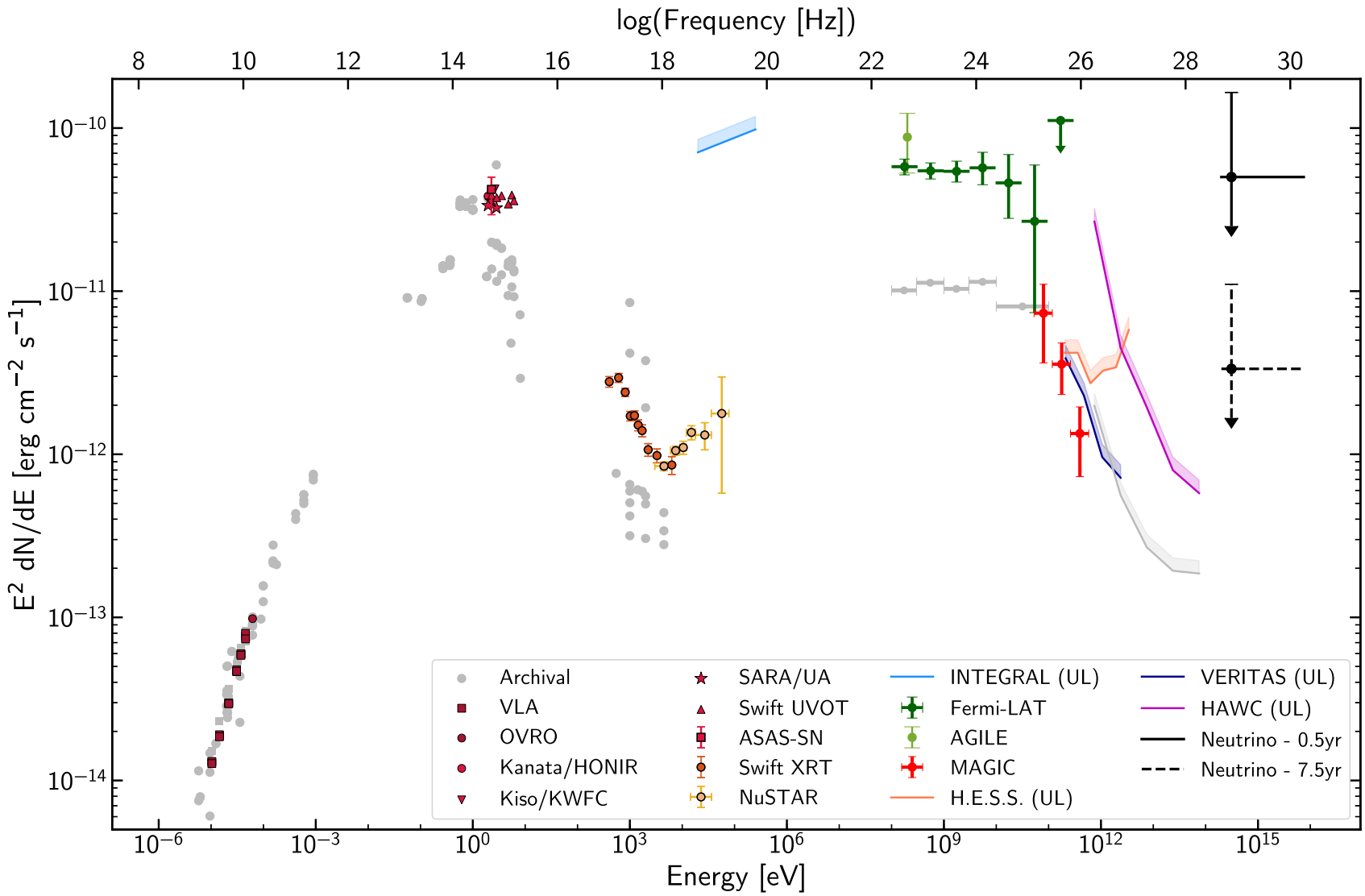


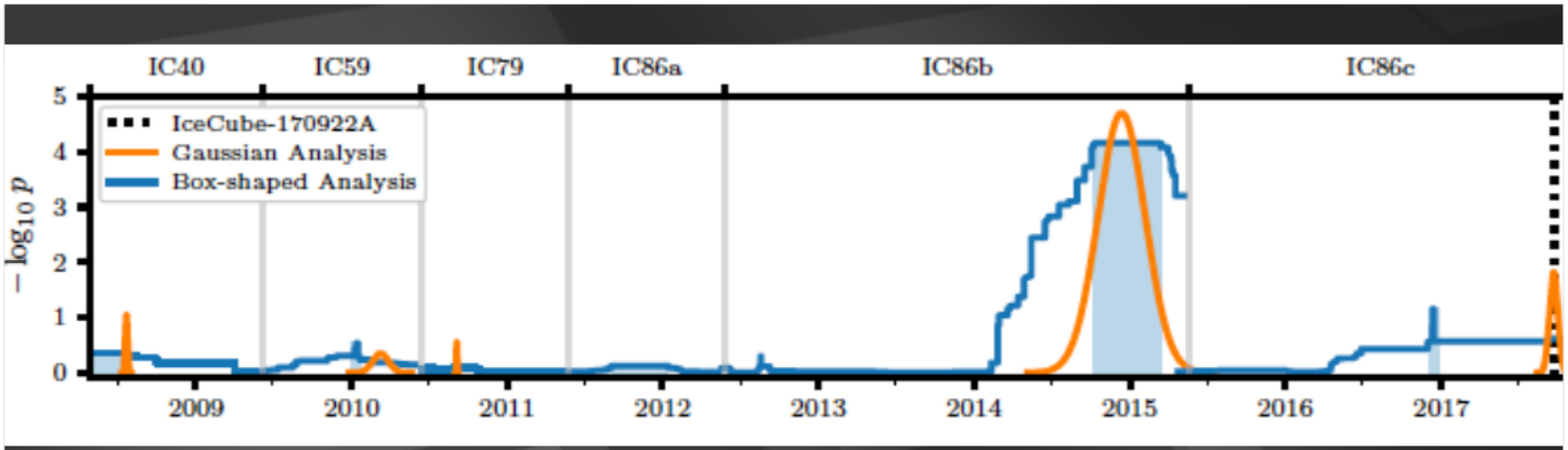
IC170922A event: observations



- chance coincidence of neutrino and gamma flare: $\sim 3\sigma$

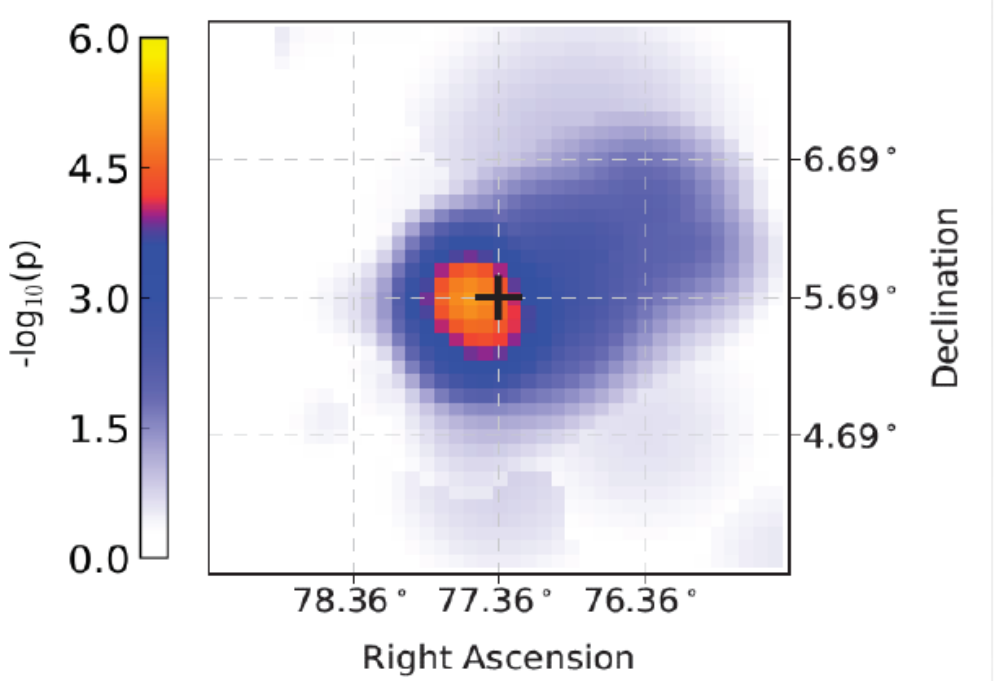
IC170922A event: multi-wavelength picture



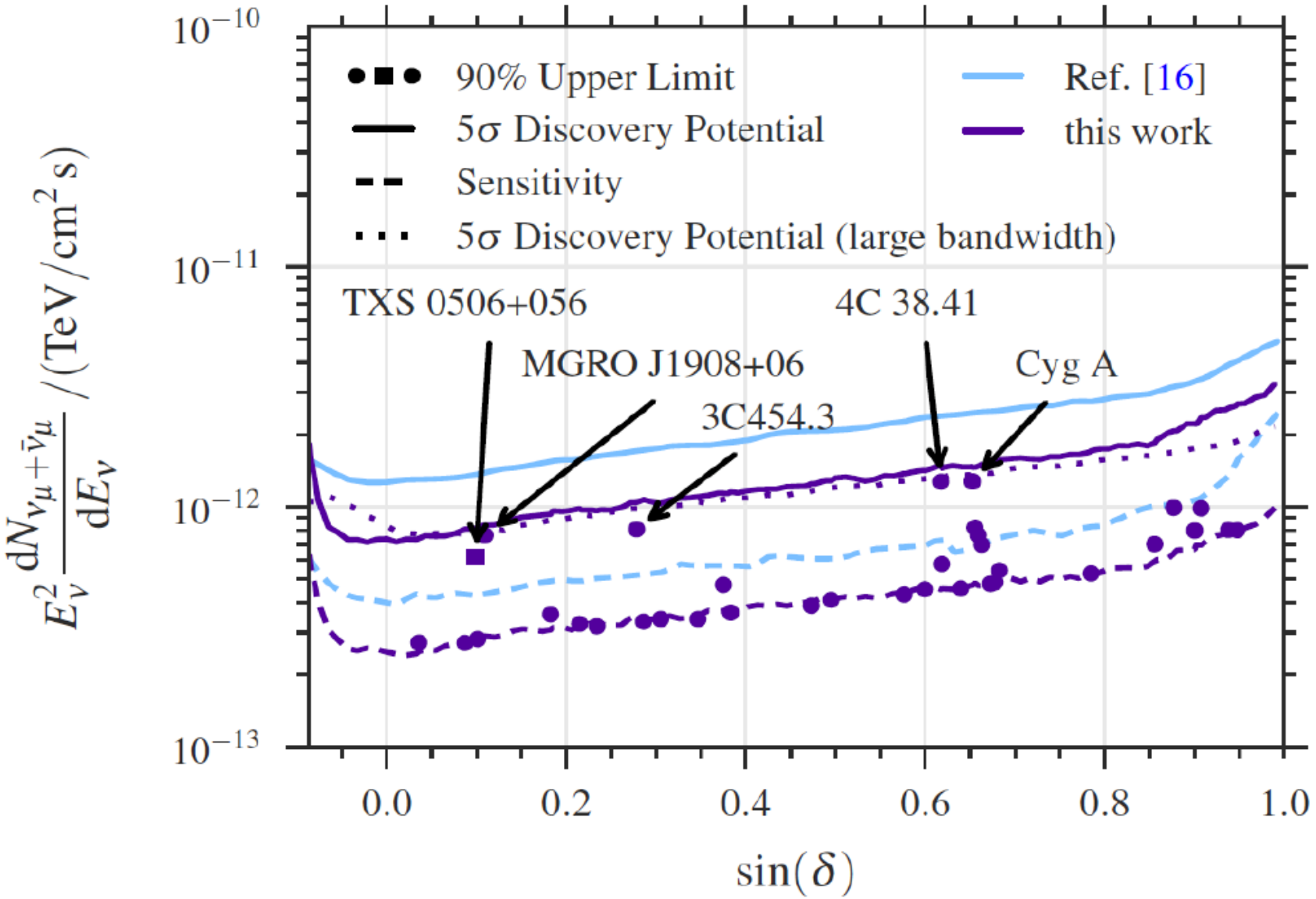


search in archival IceCube data:

- 150 day flare in December 2014 of 19 events (bkg <6)
- 10^{-5} bkg. probability
- accompanied by hardest Fermi spectrum in the 10 years of data ($E^{-1.7}$).

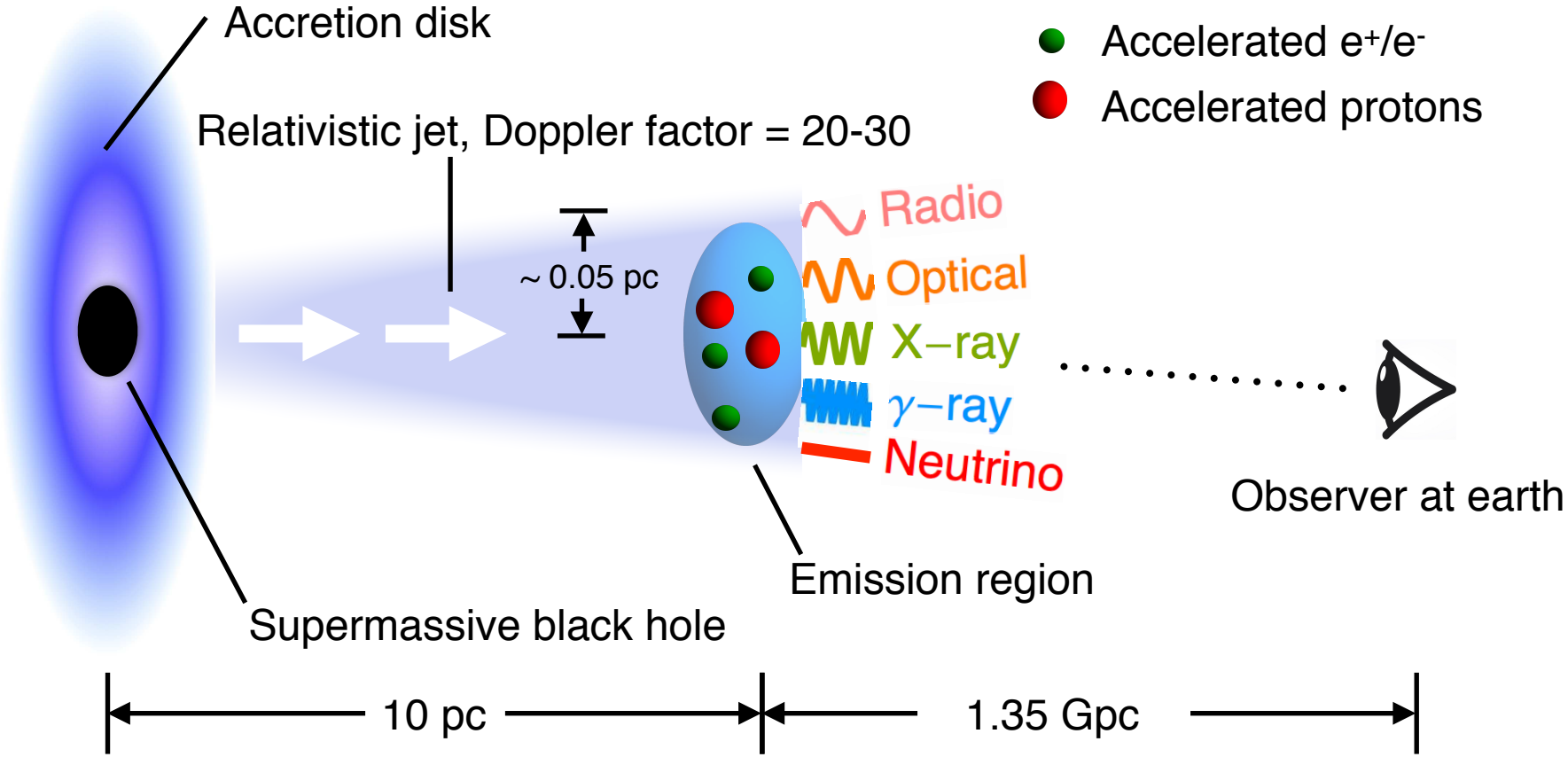


Why not seen before?

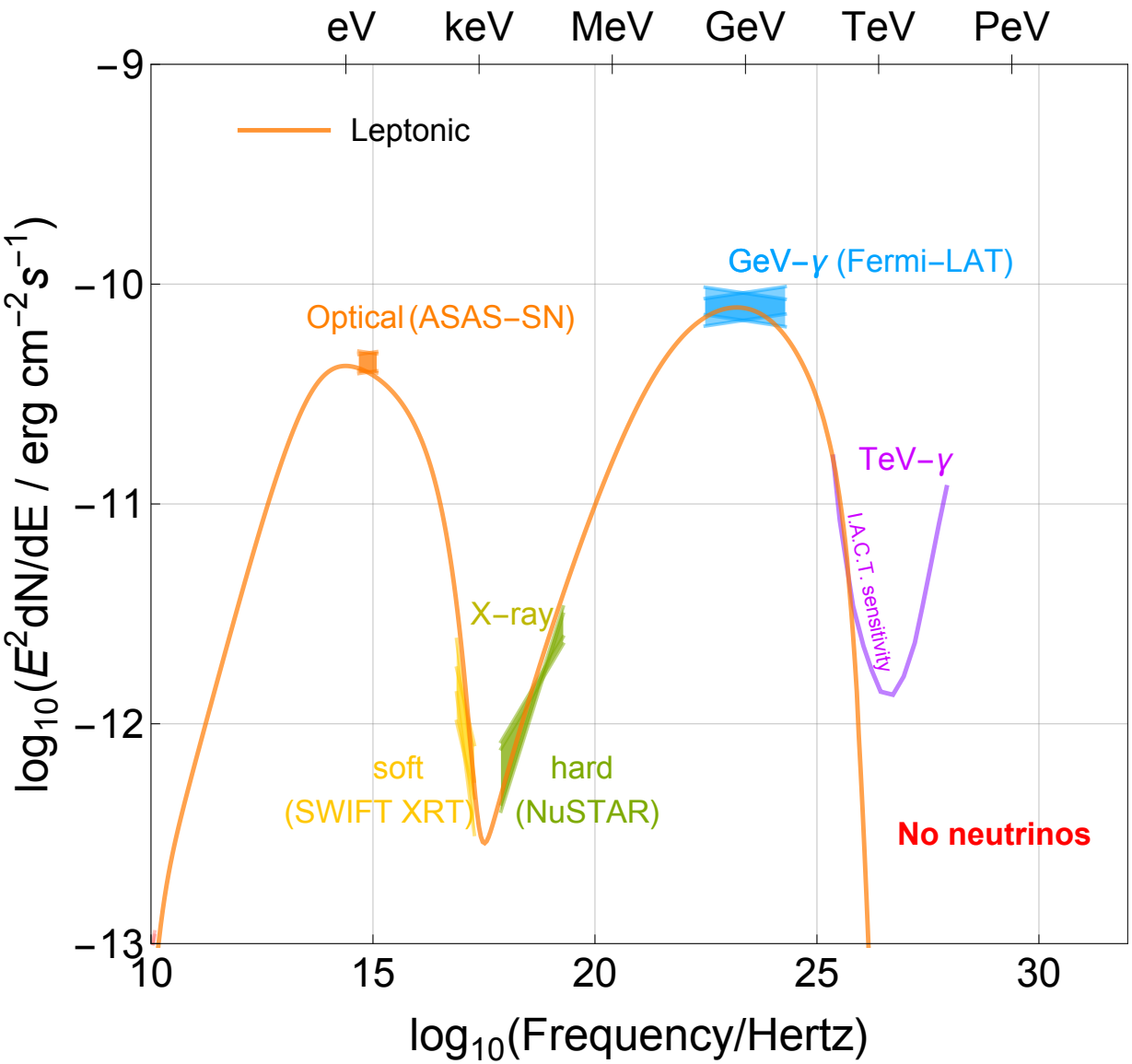


Texas blazar

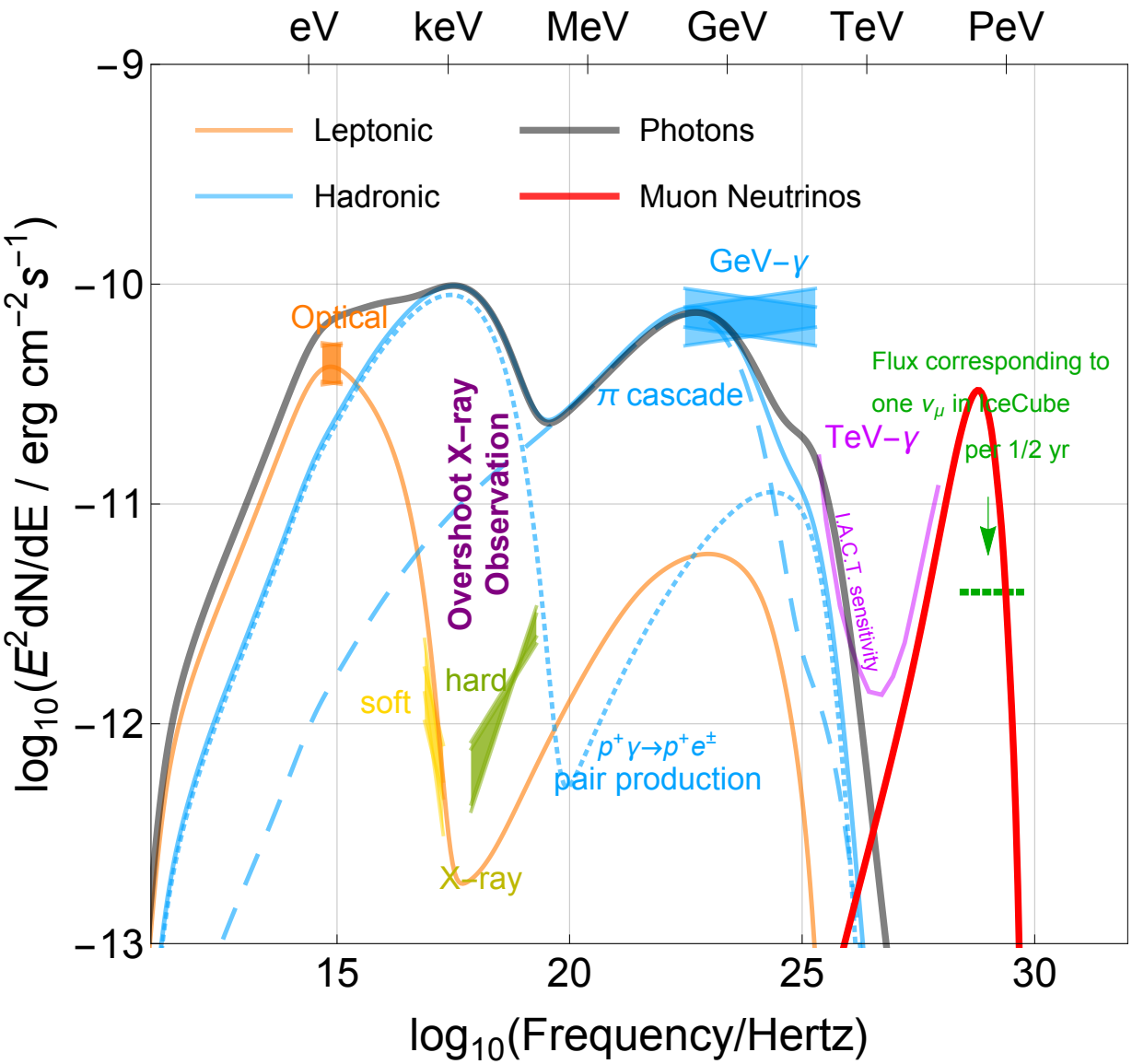
[Gao et al. 1807.04275]



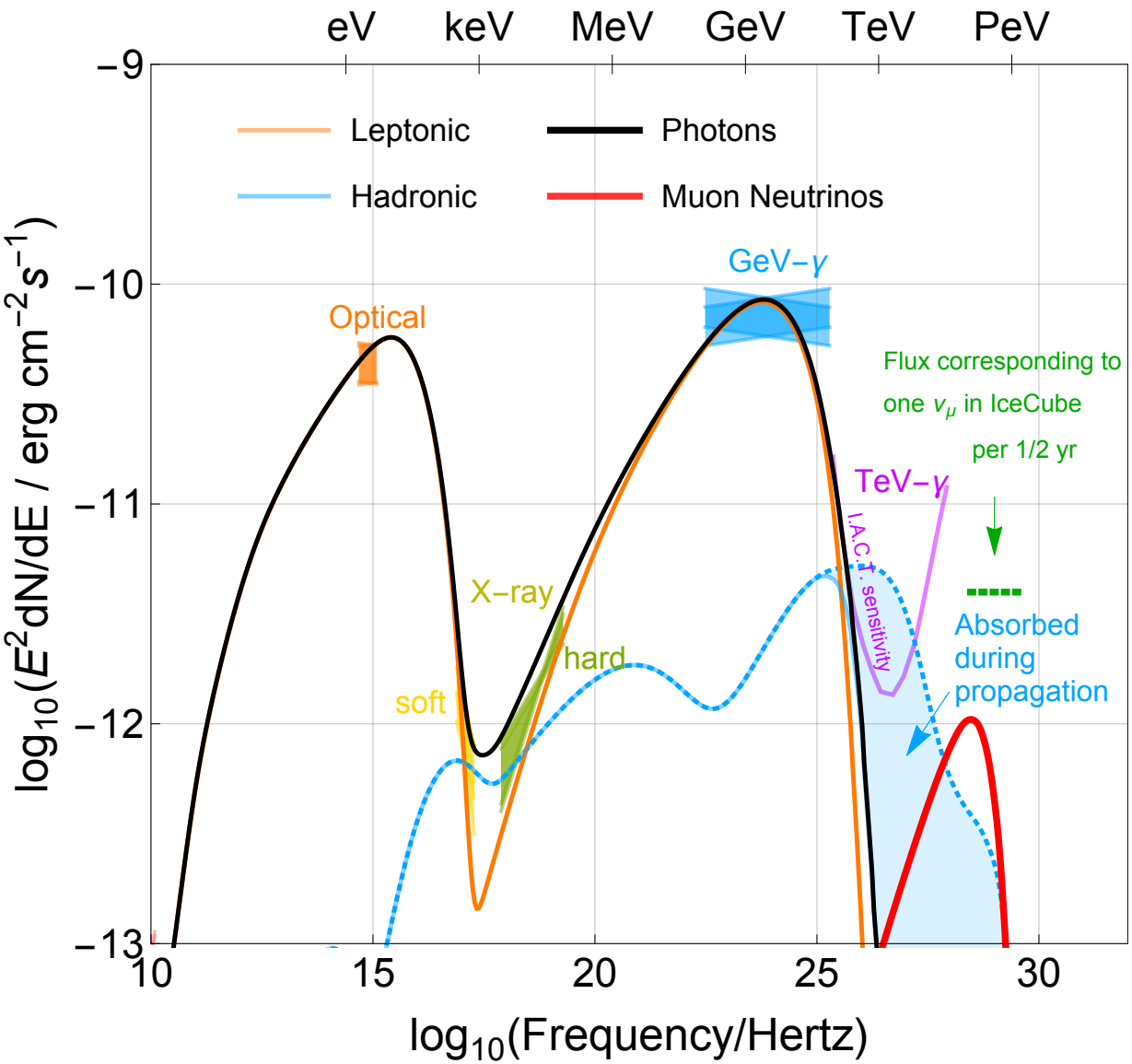
Texas blazar: leptonic model



Texas blazar: hadronic model



Texas blazar: hybrid model



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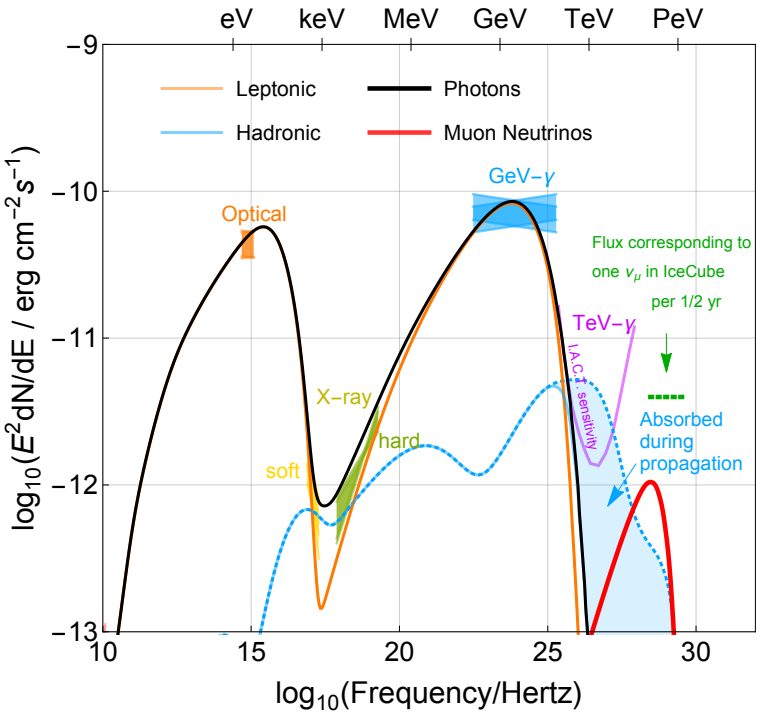
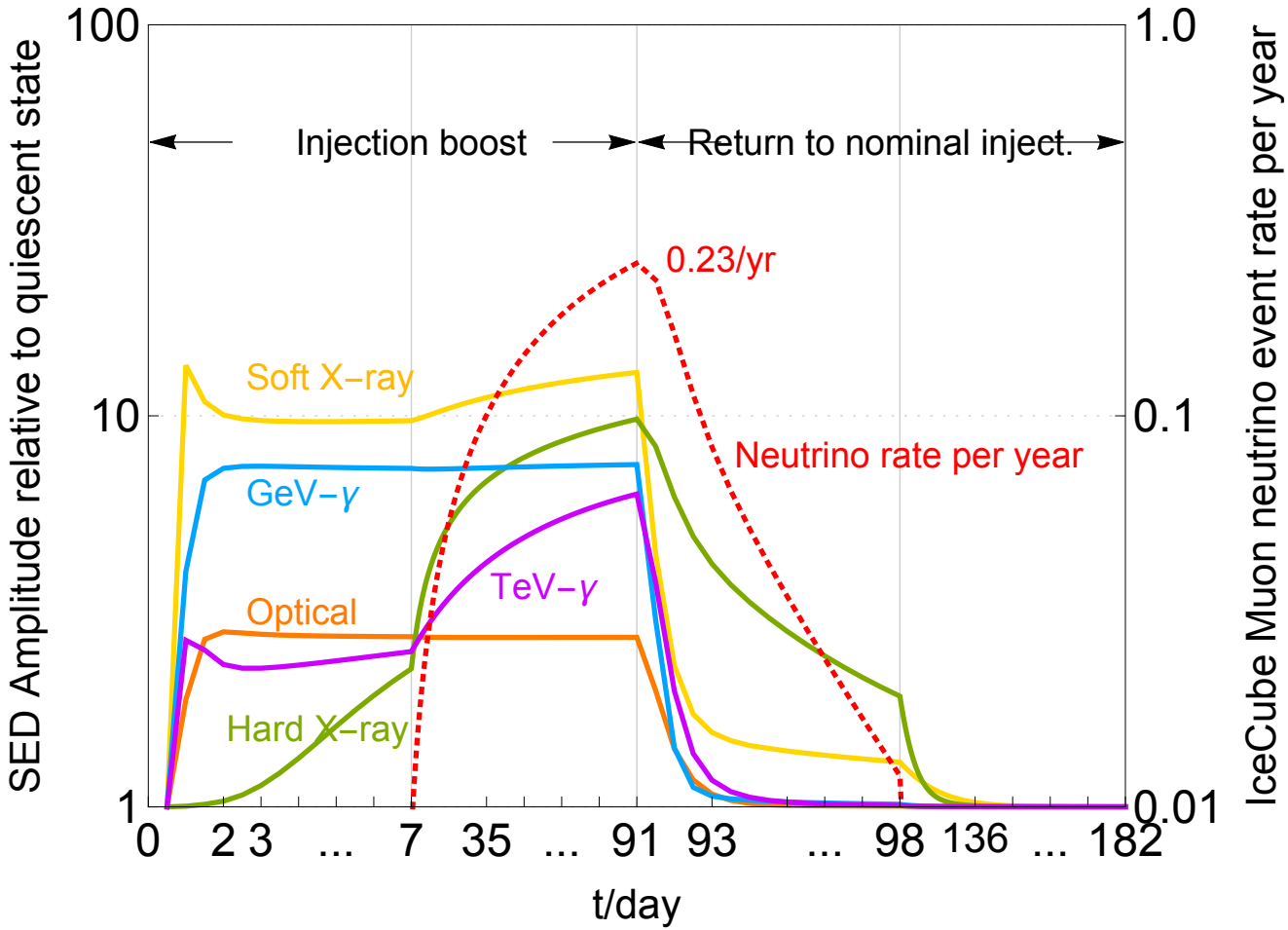


problems

- jet power 10^3 in excess of Eddington luminosity
- requires 2-zone model
- 0.1 neutrino/yr in IceCube during flare

Texas blazar: time-dependence model



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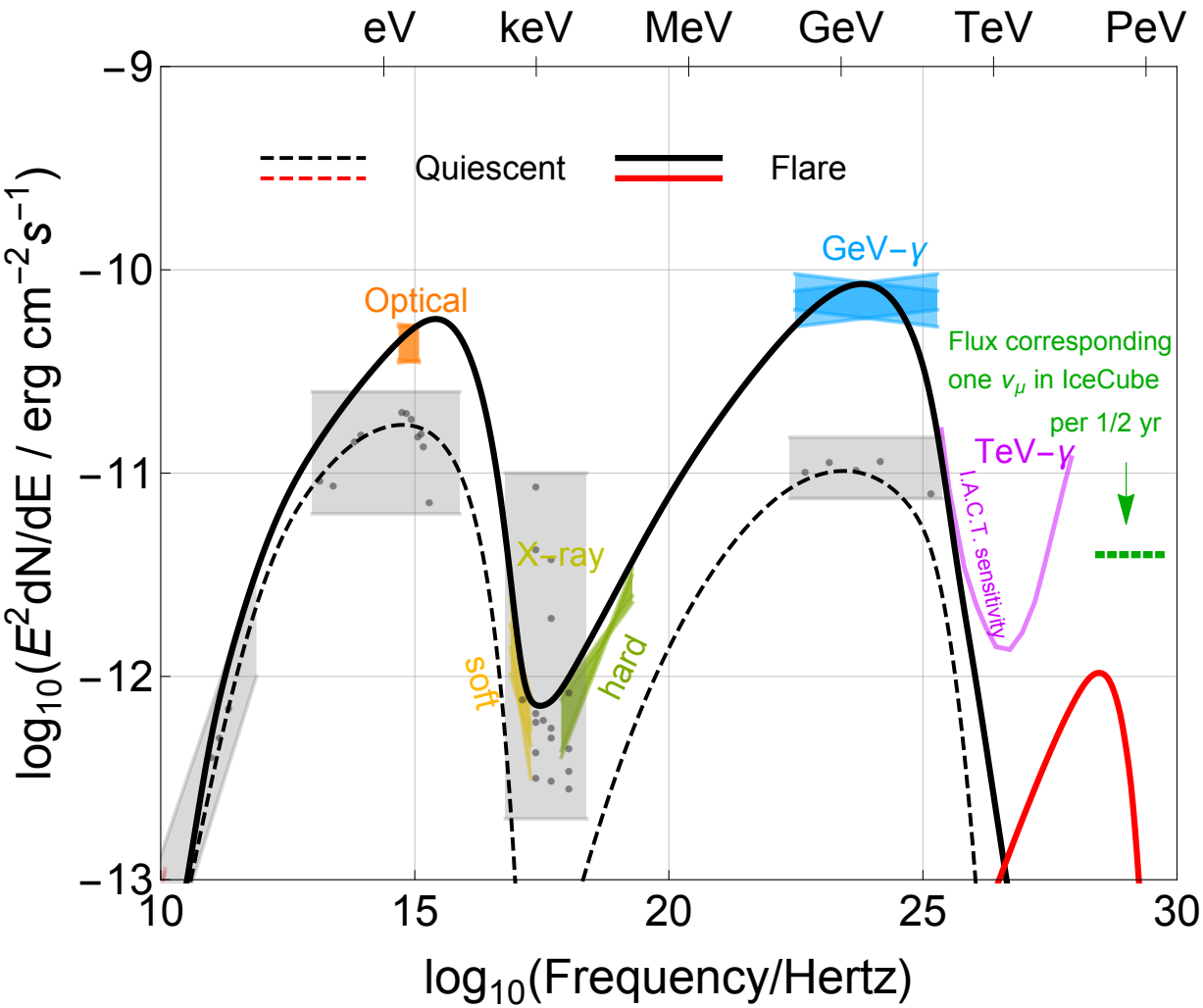

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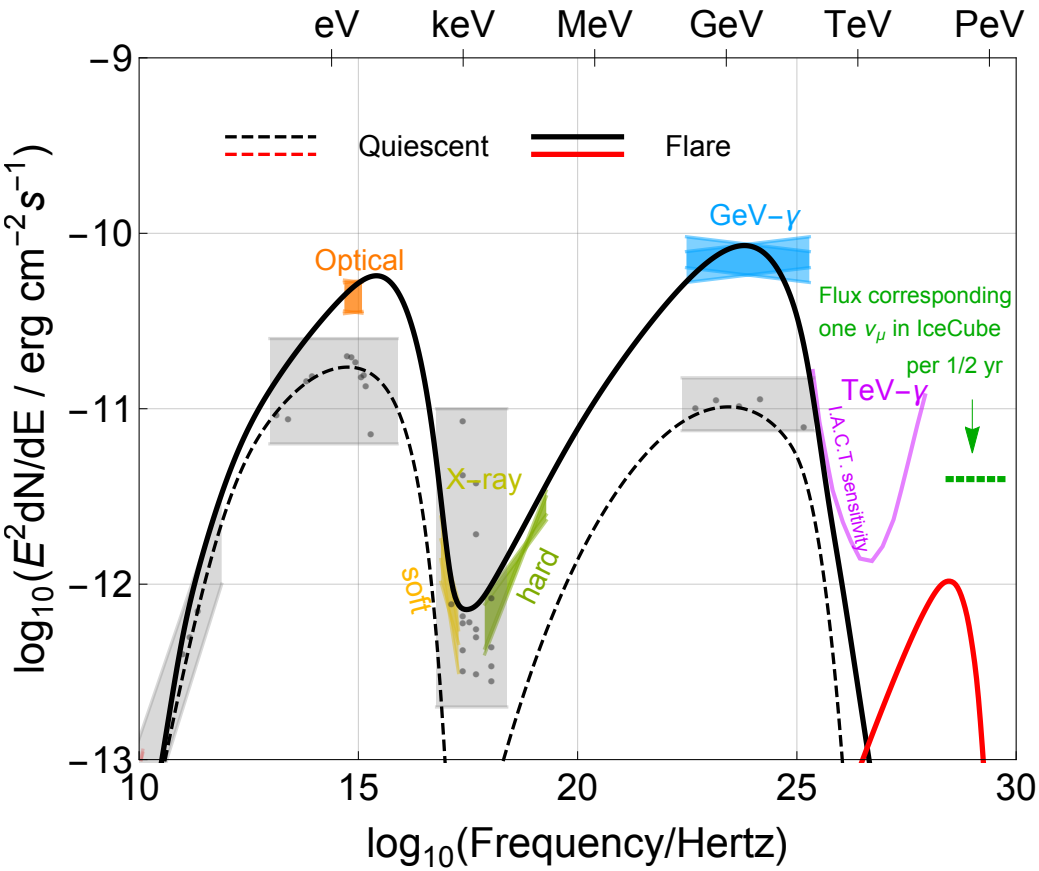

additional problem:

- no orphane neutrino signal expected

From Coulomb's law to wave equation

- Poisson law for charge and mass density

$$\Delta\varphi = -4\pi\rho \qquad\qquad \Delta\varphi = 4\pi G\rho$$

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- can set $A^0 = 0 \Rightarrow$ tranverse wave

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- consider it as gauge transformation in Minkowski space

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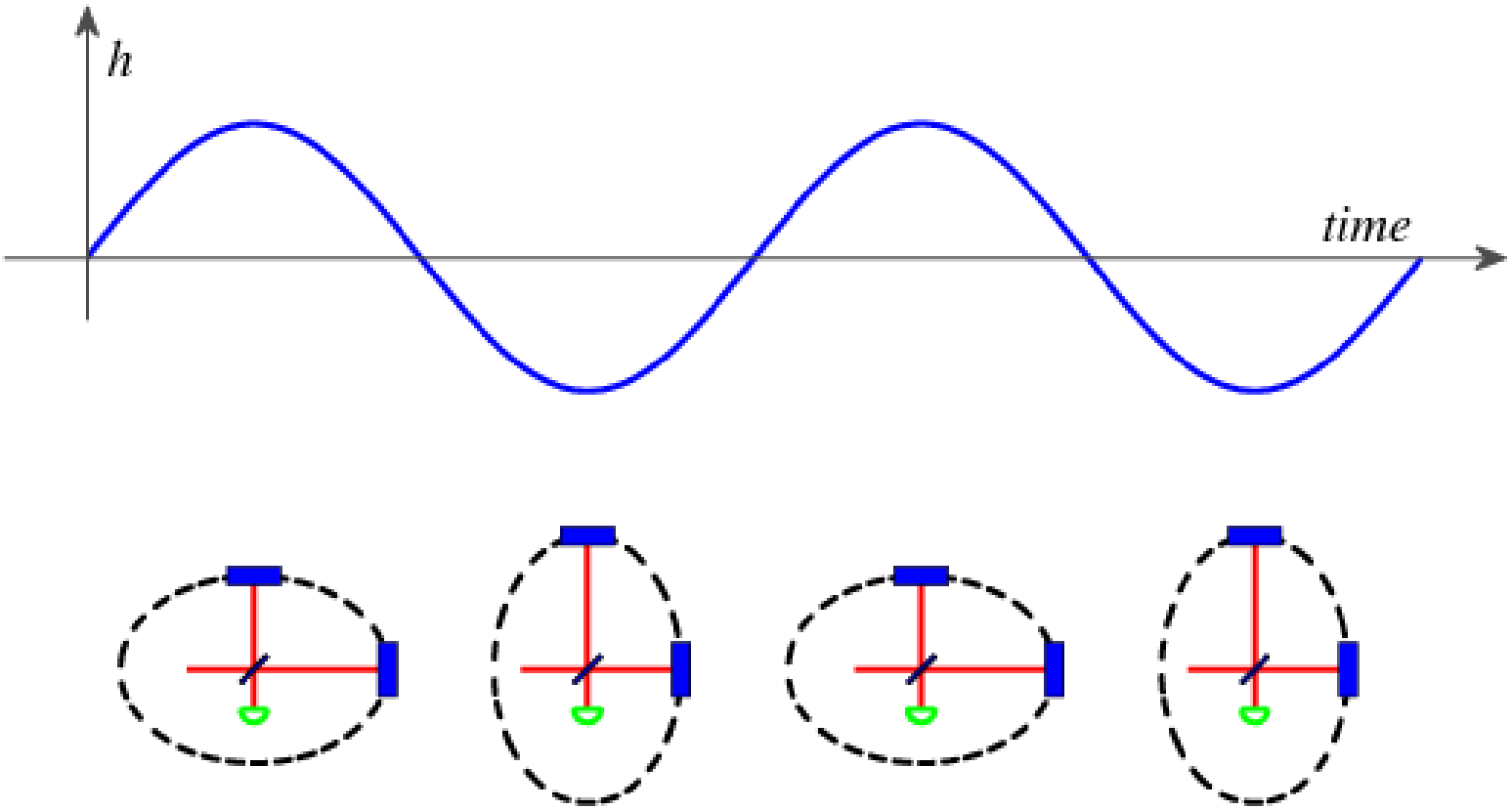
- energy loss

$$L_{\rm em} = -\frac{2}{3} \ddot{d}_\alpha \ddot{d}^\alpha \qquad\qquad L_{\rm gr} = -\frac{1}{5} \dddot{Q}_{\alpha\beta} \dddot{Q}^{\alpha\beta}$$

Gravitational wave: Spin-2 and tidal effect:



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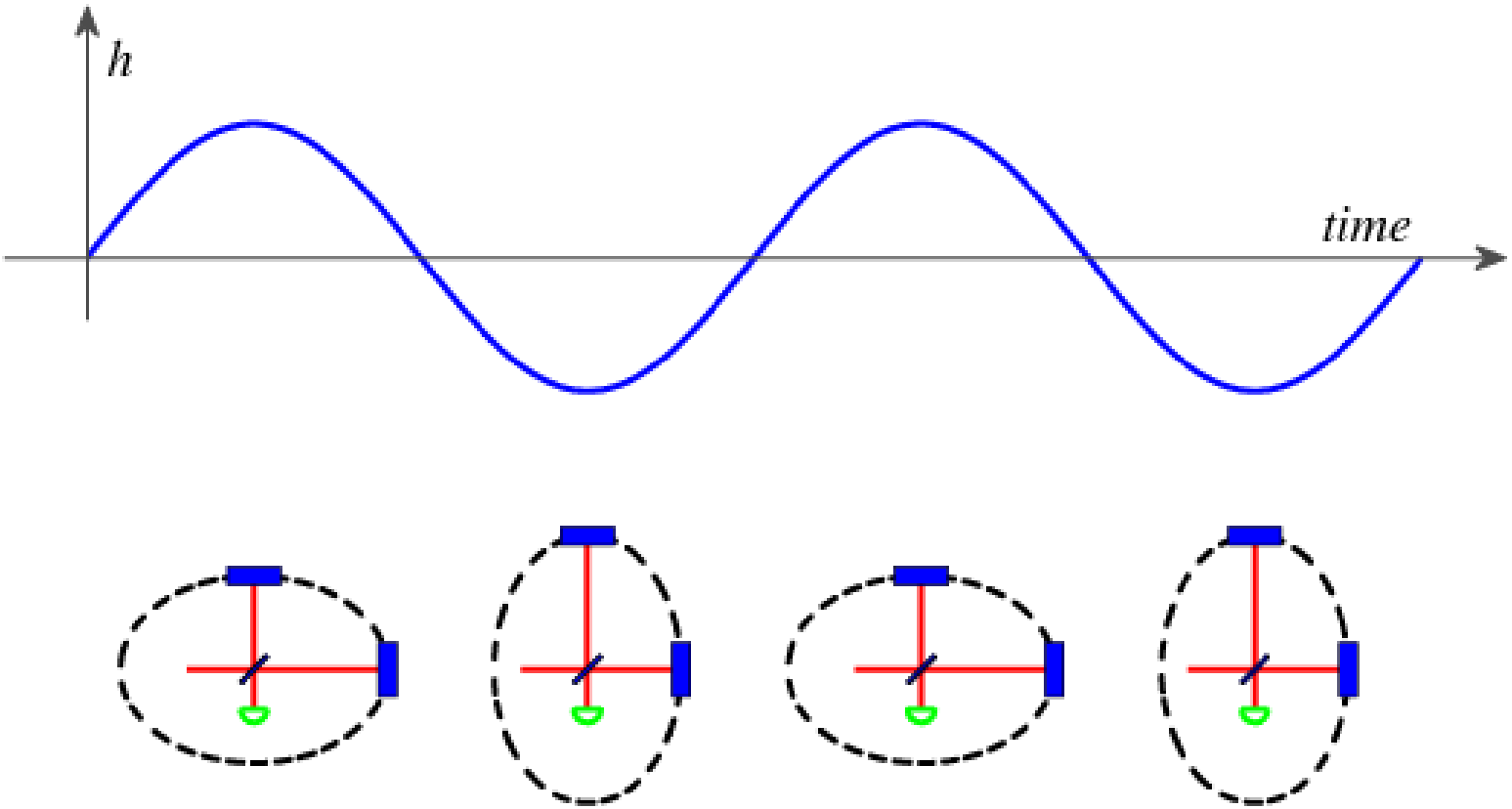

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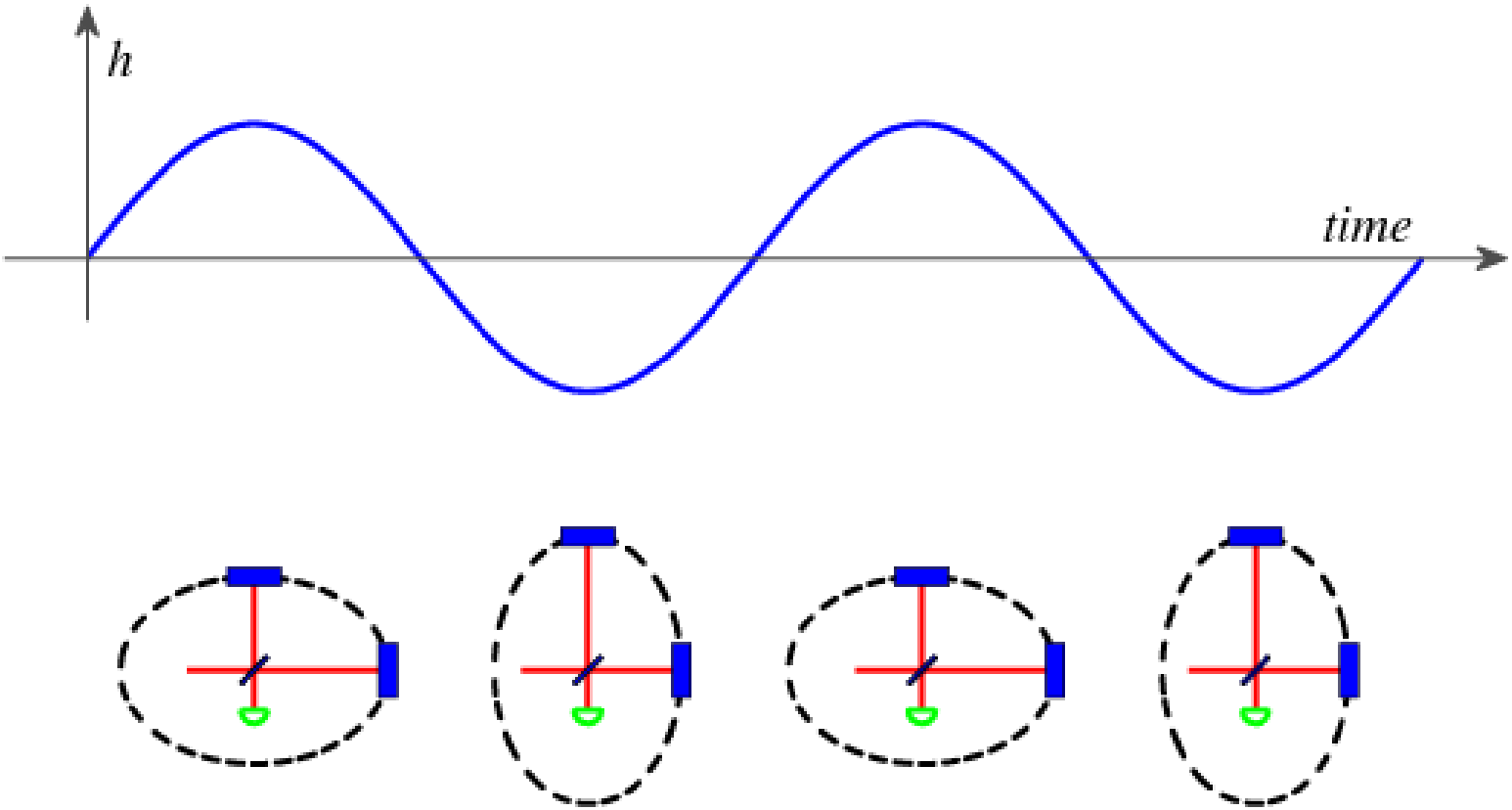

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sensitivity scales as $1/r$ compared to $1/r^2$!

Emission of radiation

system of N moving masses $m^{(k)}$ [or charges $q^{(k)}$]:

- $\dot{\boldsymbol{d}} = \sum_{i=1}^{N} m^{(k)} \boldsymbol{v}^{(k)} = \boldsymbol{P}_{\rm tot} = \text{const} \Rightarrow$ no grav. dipole radiation

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$$I_{ij} = \sum_{i=1}^{N} m^{(k)} x_i^{(k)} x_j^{(k)}$$

- use dimensional analysis to fix powers a and b:

$$L_{\rm gw} \propto G c^a \left[\frac{d I_{ij}^b}{d t^c} \right]^2$$

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for 2 rotating stars: $L_{\rm gw} \simeq -G R^4 M^2 \omega^6$

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- $\dot{\boldsymbol{d}} = \sum_{i=1}^{N} m^{(k)} \boldsymbol{v}^{(k)} = \boldsymbol{P}_{\rm tot} = \text{const} \Rightarrow$ no grav. dipole radiation
- have to us quadrupole:

$$I_{ij} = \sum_{i=1}^{N} m^{(k)} x_i^{(k)} x_j^{(k)}$$

- use dimensional analysis to fix powers a and b:

$$L_{\rm gw} \propto G c^a \left[\frac{d I_{ij}^b}{dt^c} \right]^2$$

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$$L_{\rm gw} \propto \frac{G}{c^5} \dddot{Q}_{ij}^2$$

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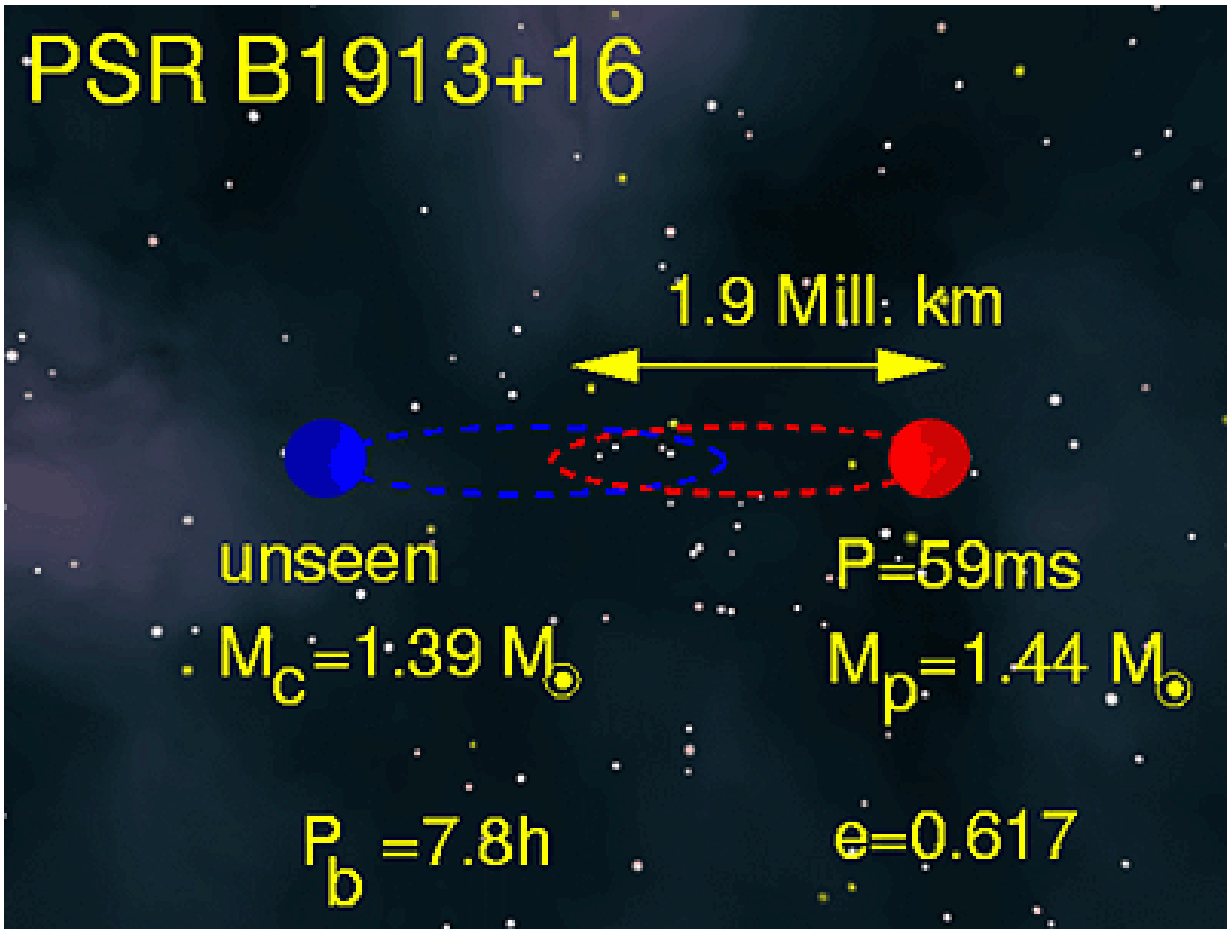
- frequency of grav. wave: 2ω

Hulse-Taylor pulsar: discovered 1974, Nobel prize 1993



- pulsar in binary system
- 2 million km wide orbit shrinks by 4mm/day

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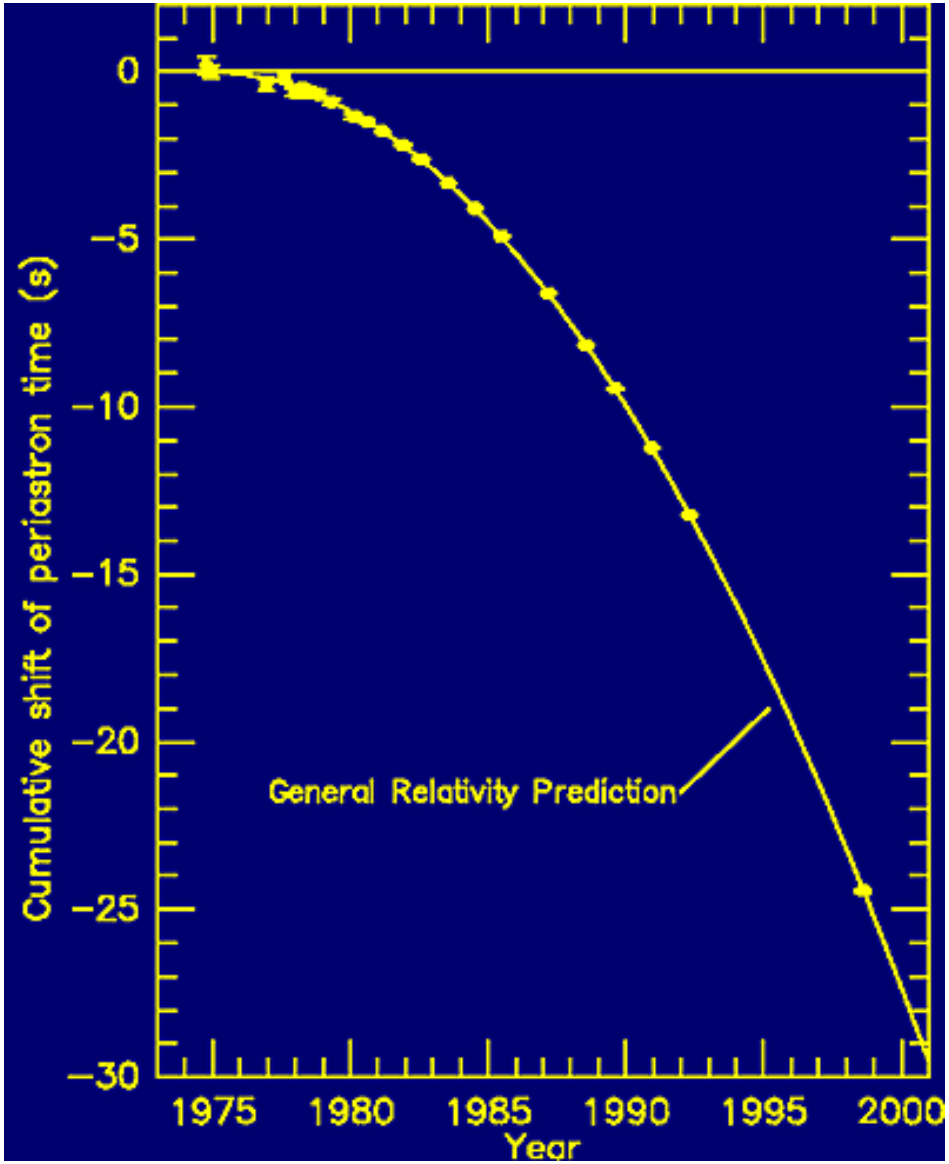

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- for $r = 300\,\mathrm{Mpc} \simeq 10^{22}$ km and $R \simeq R_s \simeq 100$ km: $h \simeq 10^{-20}$

Coalesence time

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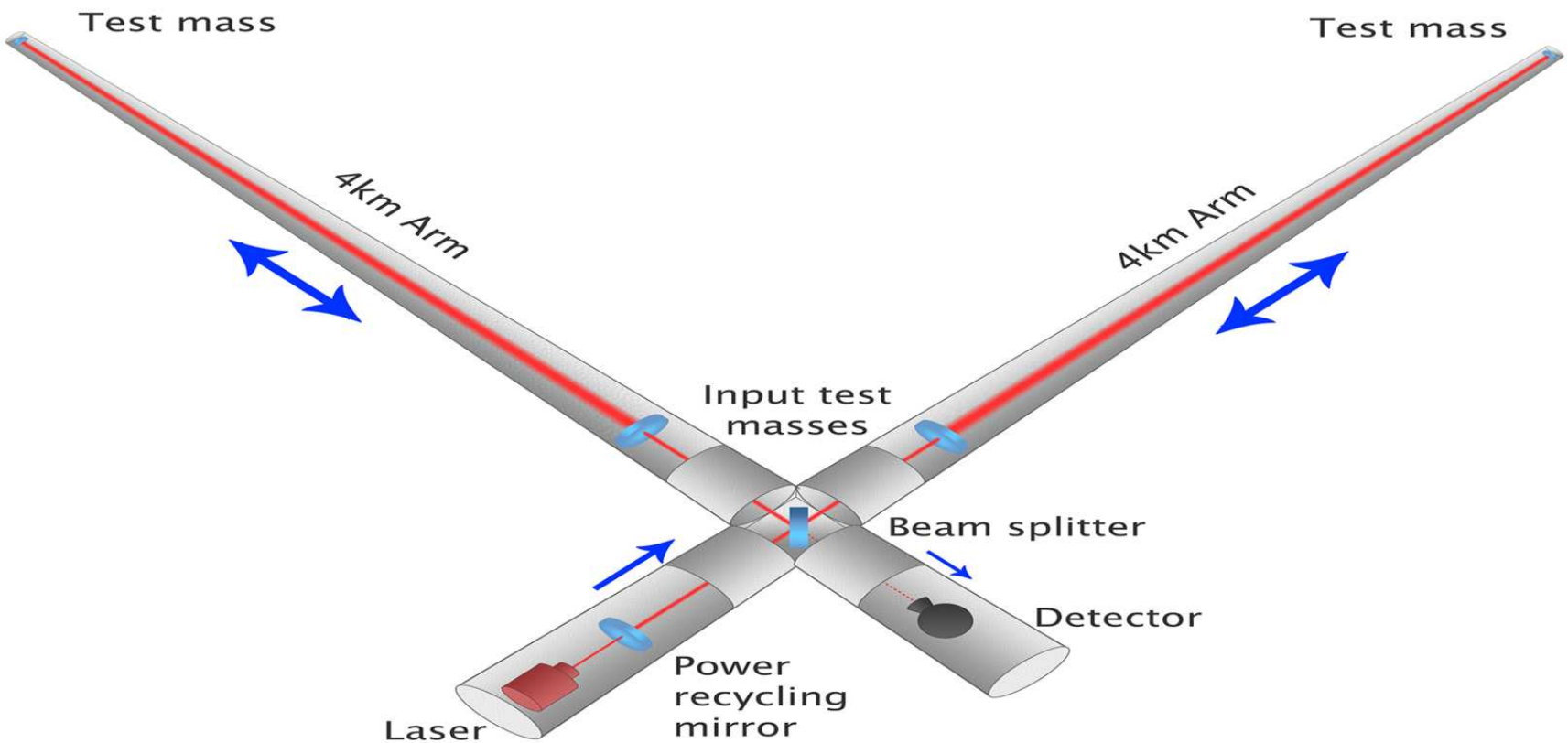
- LIGO/VIRGO events: $M = (10 + 10)M_\odot$, $r_0 \sim 500\,\text{km}$: $\Delta\tau \sim 1\text{s}$
- LISA events: $M = (10^6 + 10^6)M_\odot$, $r_0 \sim 10^8\,\text{km}$: $\Delta\tau \sim 1\text{yr}$

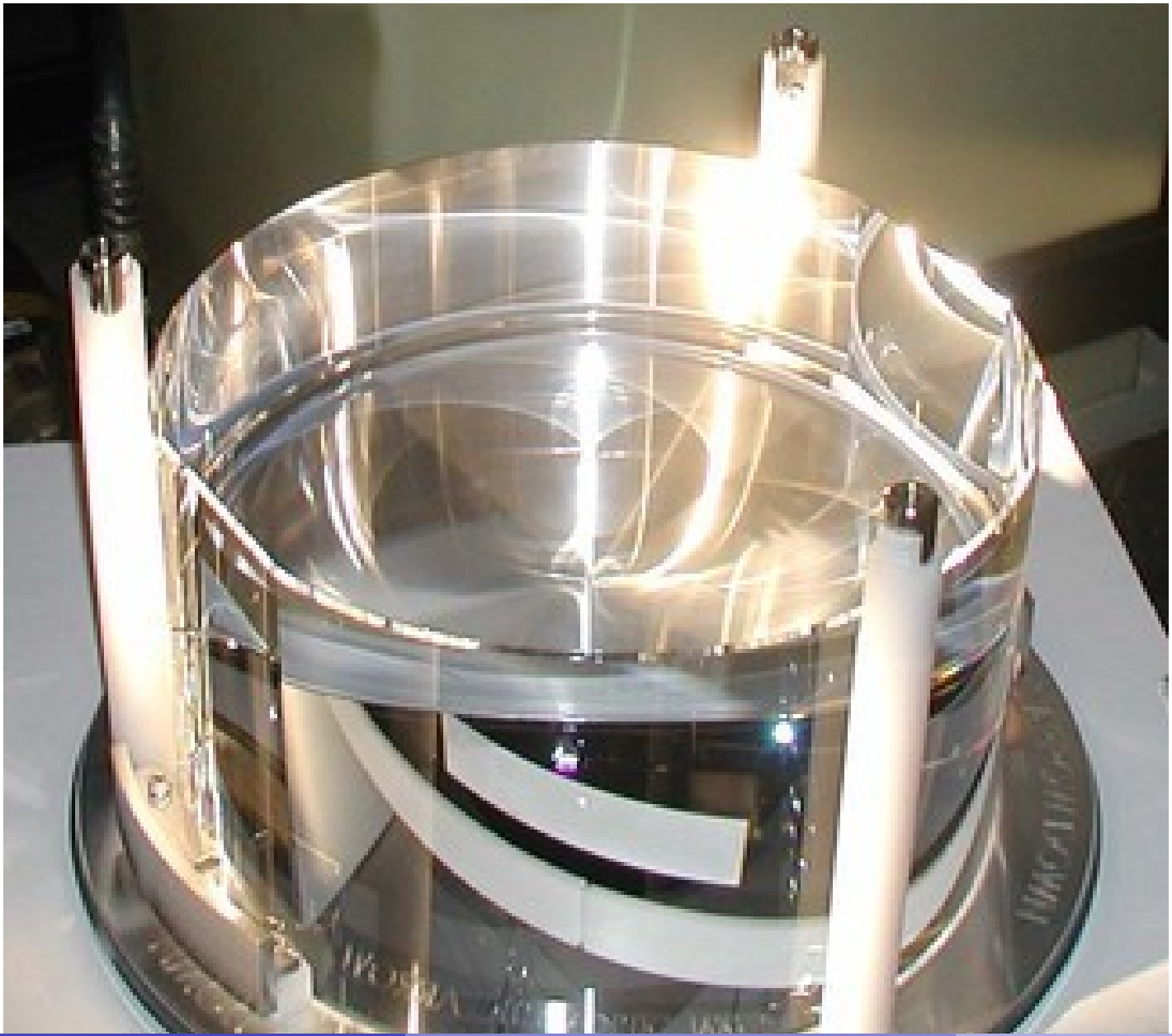
Optical interferometer:



LIGO detector – Livingstone site

LIGO detector – Hanford site

LIGO detector – "test mass"



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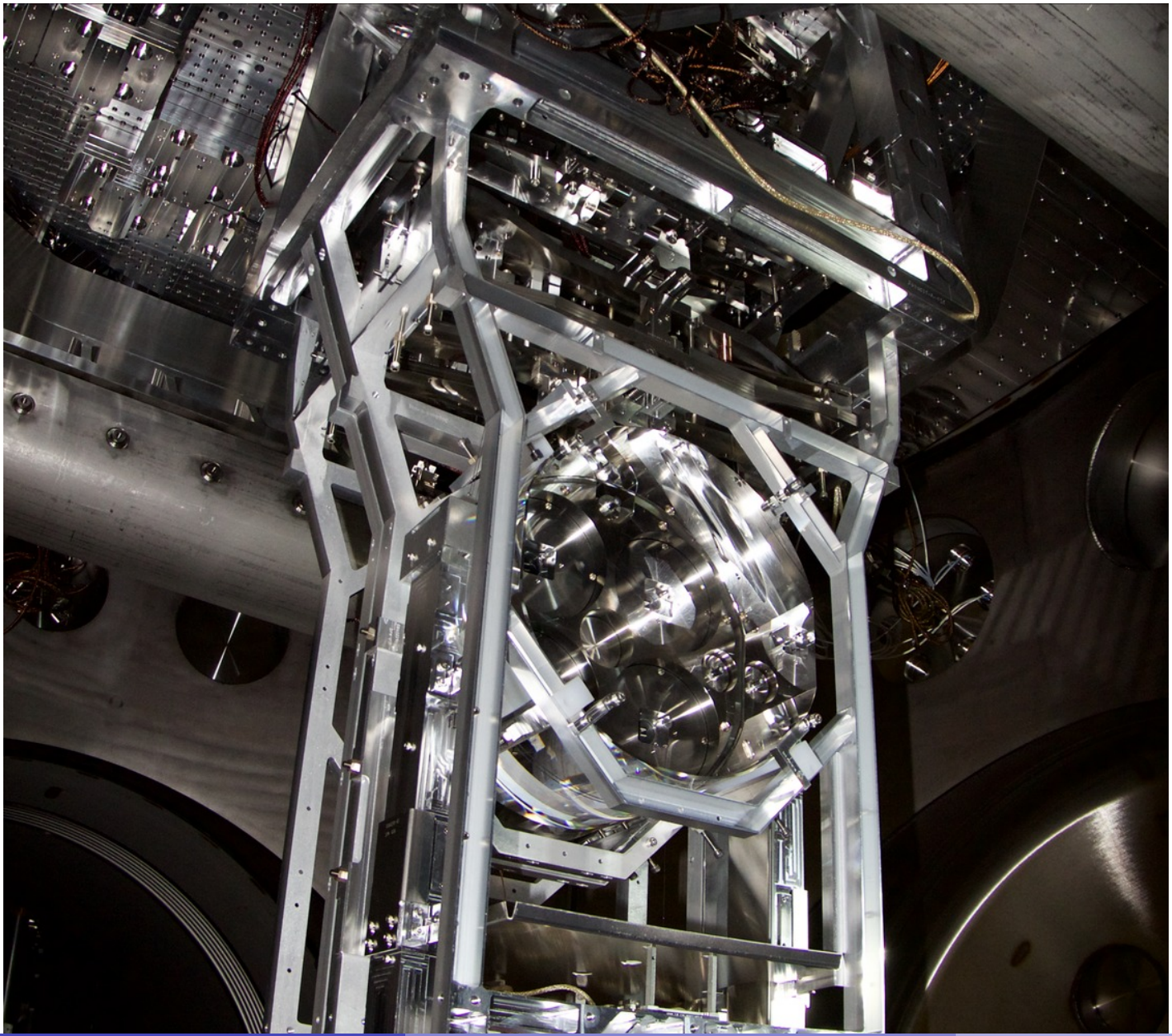
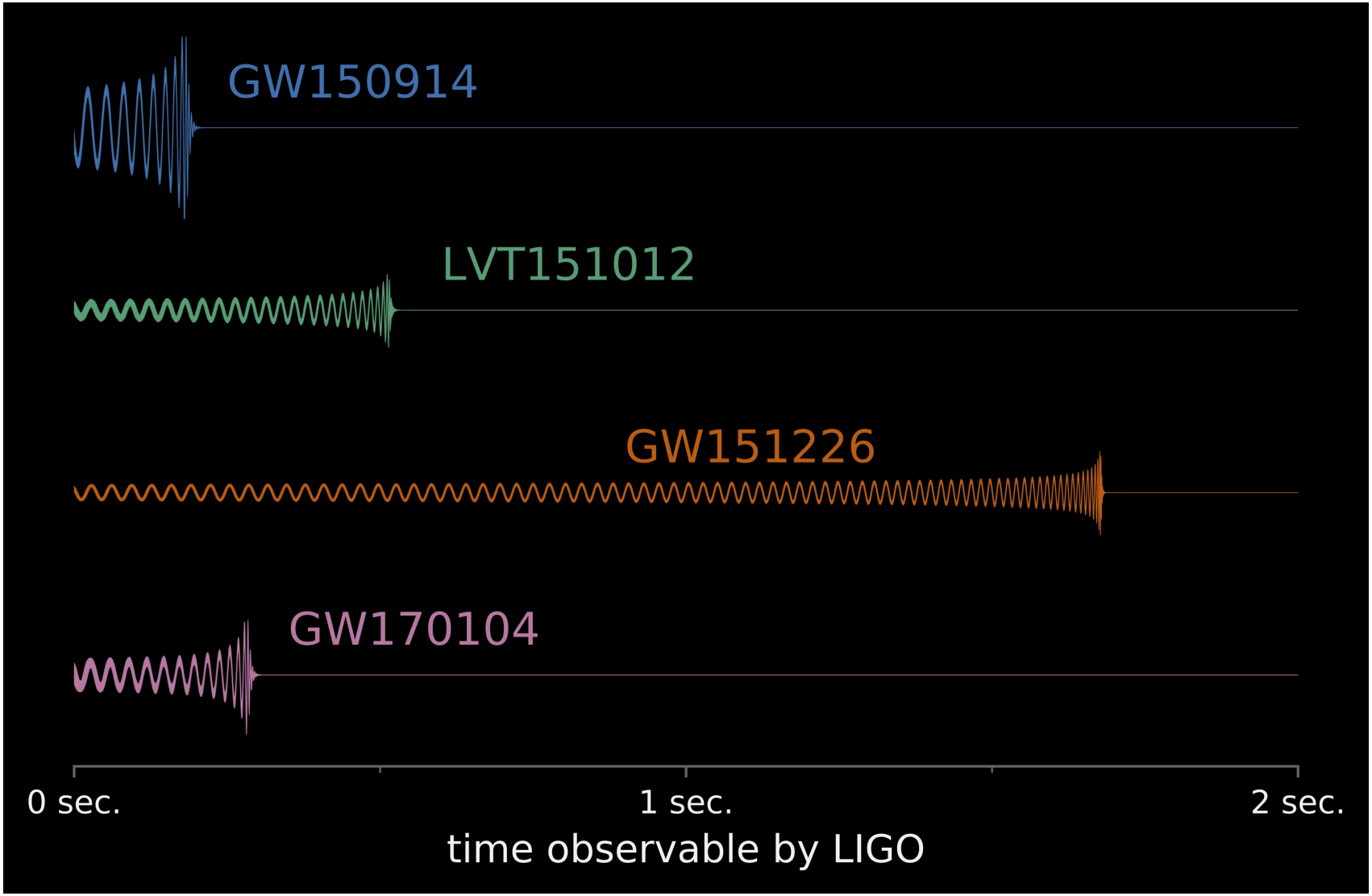
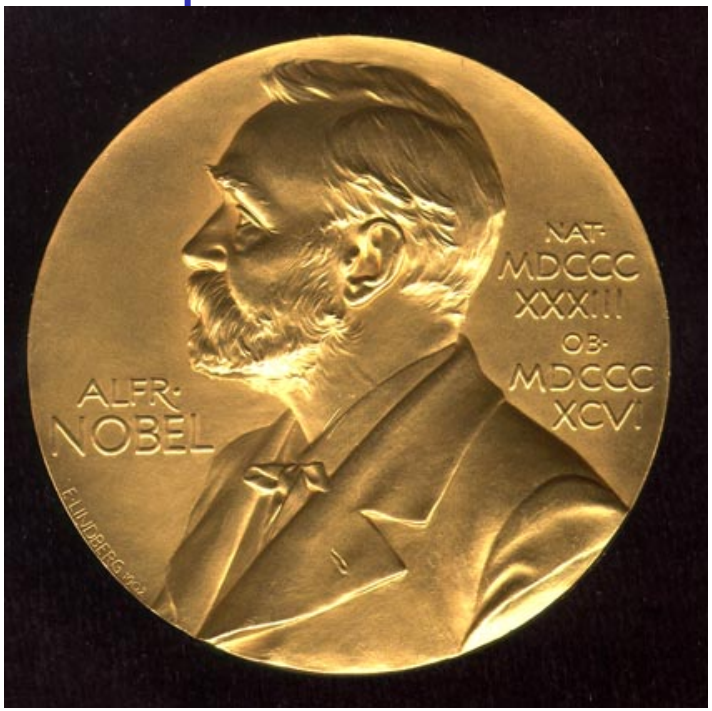


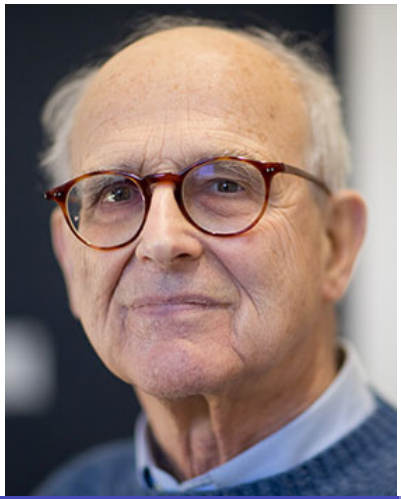
"Nobel prize detections:"

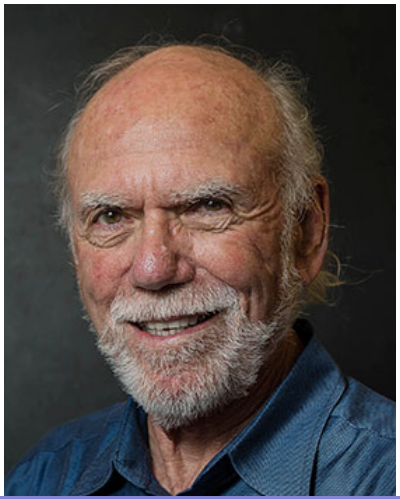


Nobelprize laudatio 2017

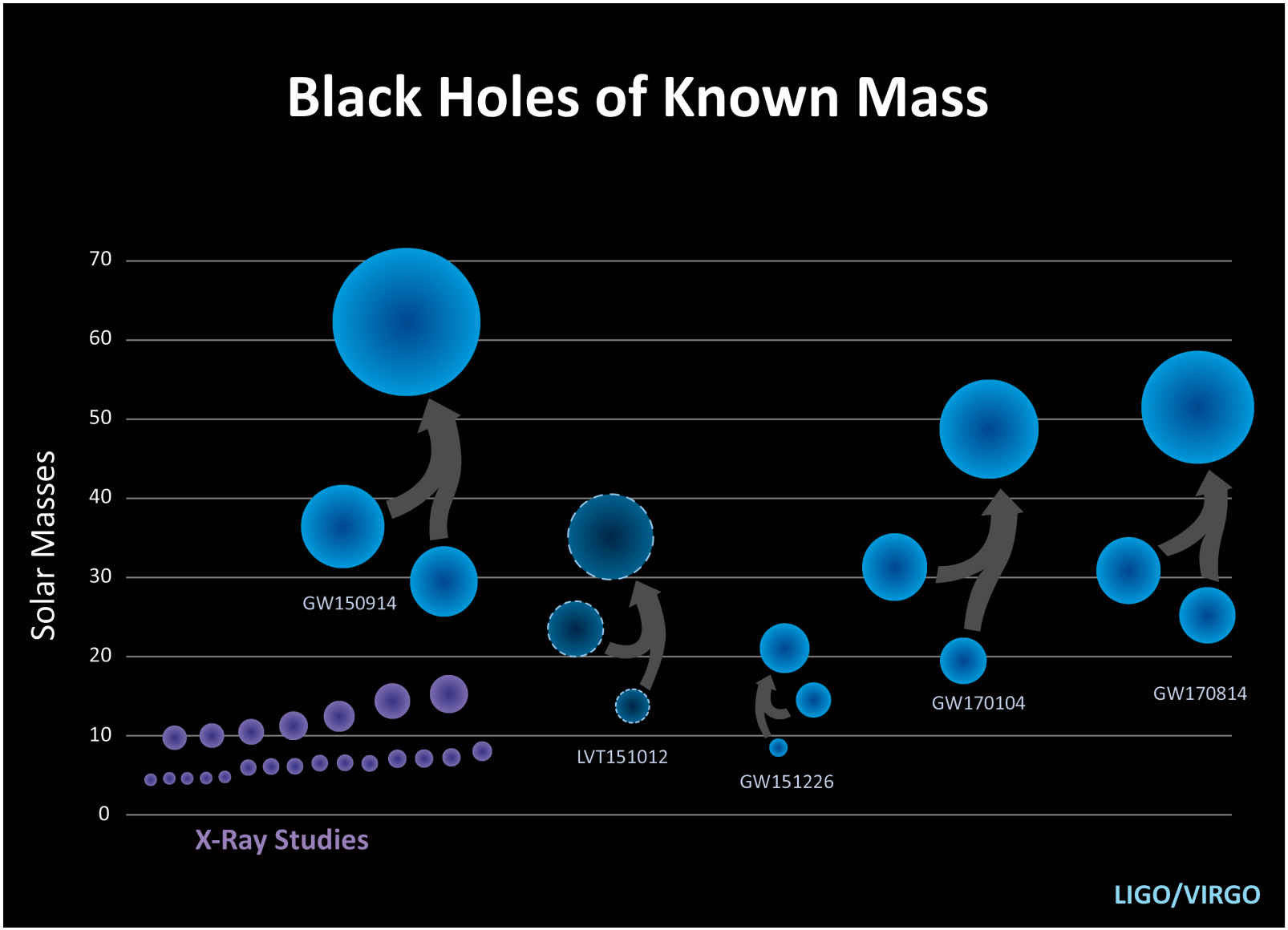


The Nobel Prize in Physics for 2017 is one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

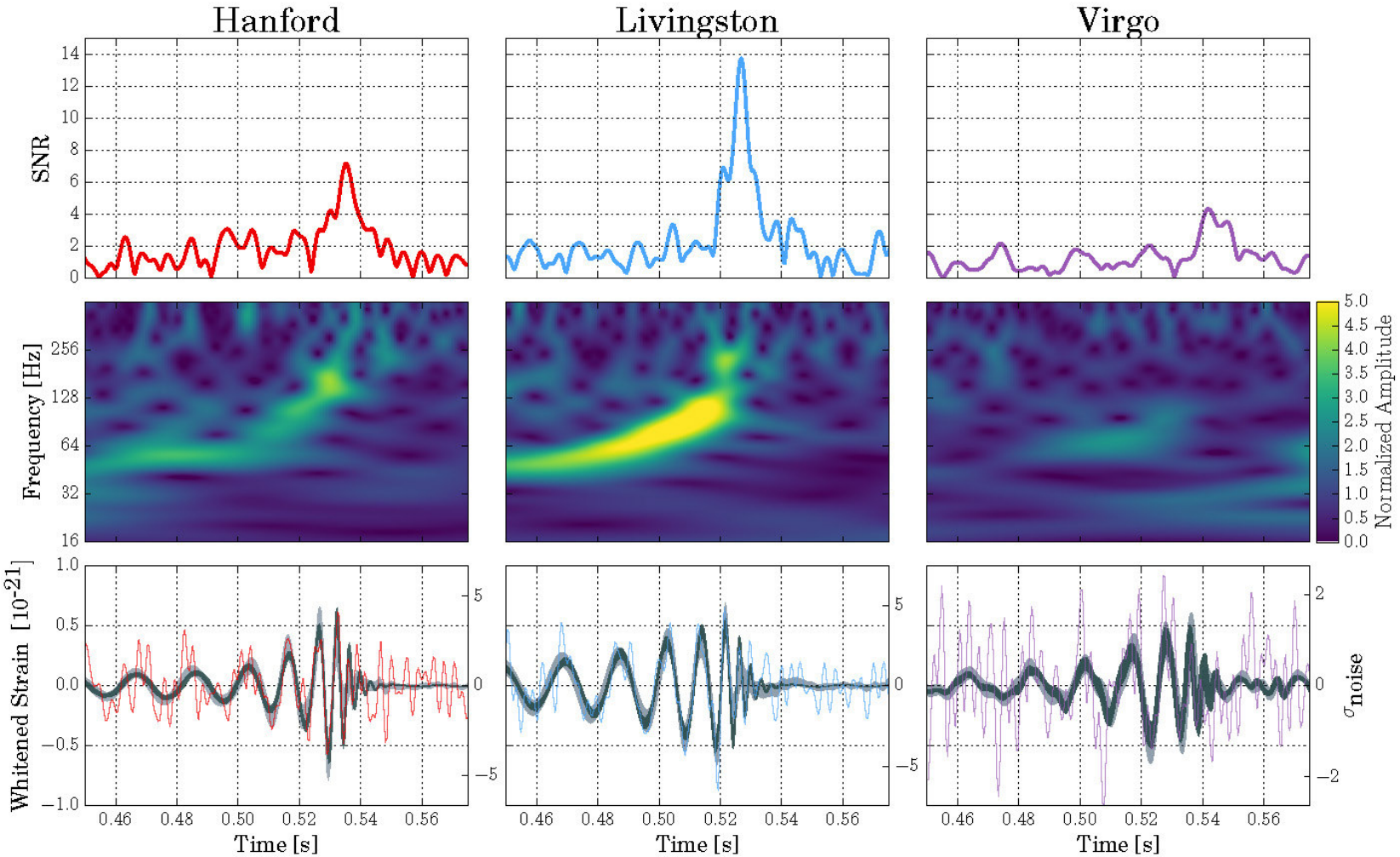




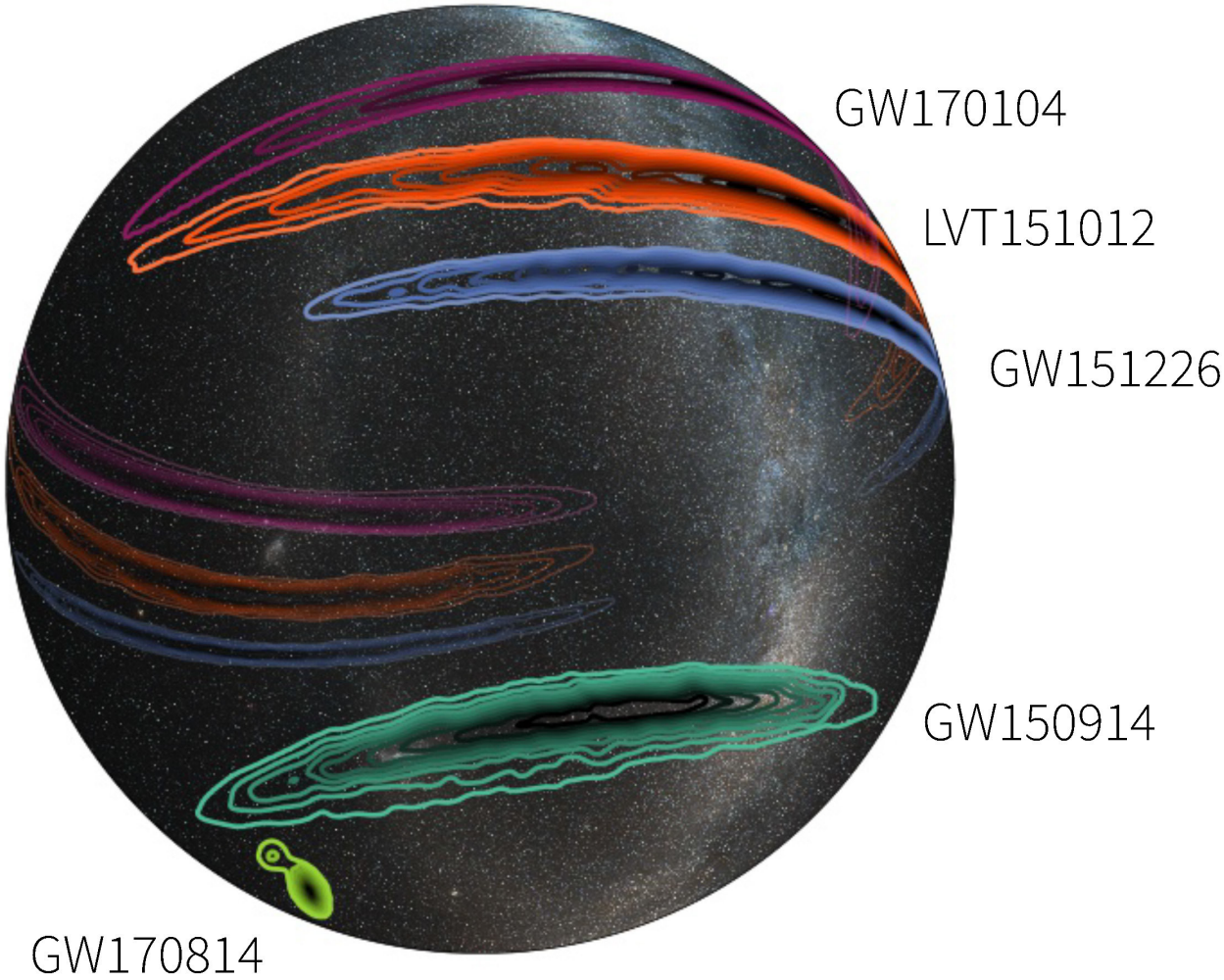
Black Holes


Black Holes of Known Mass
Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170814
X-Ray Studies
LIGO/VIRGO

GW170817


Hanford
Livingston
Virgo
SNR
Frequency [Hz]
Normalized Amplitude
Whitened Strain [10^-21]
σnoise
Time [s]

GW170817



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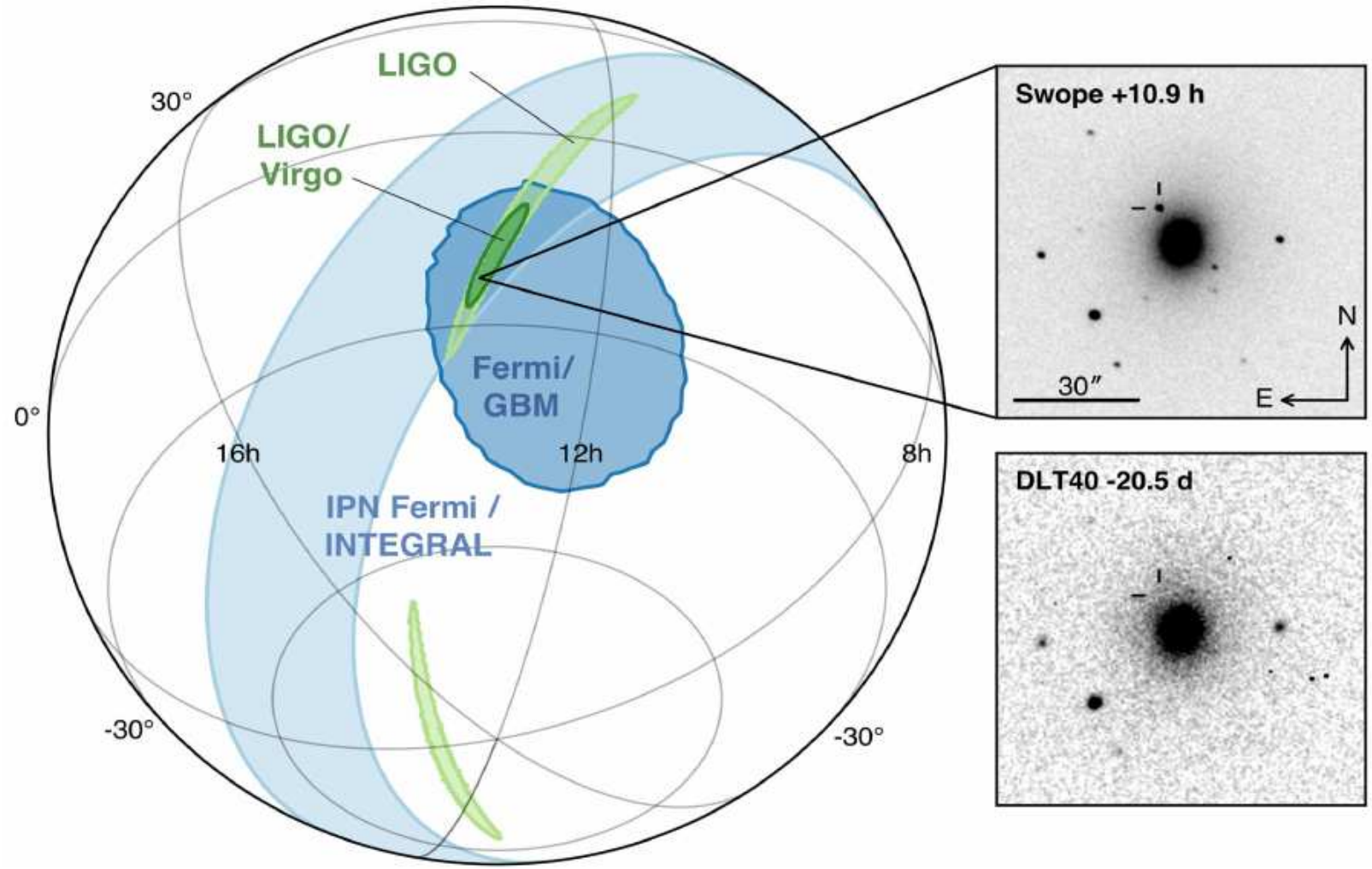
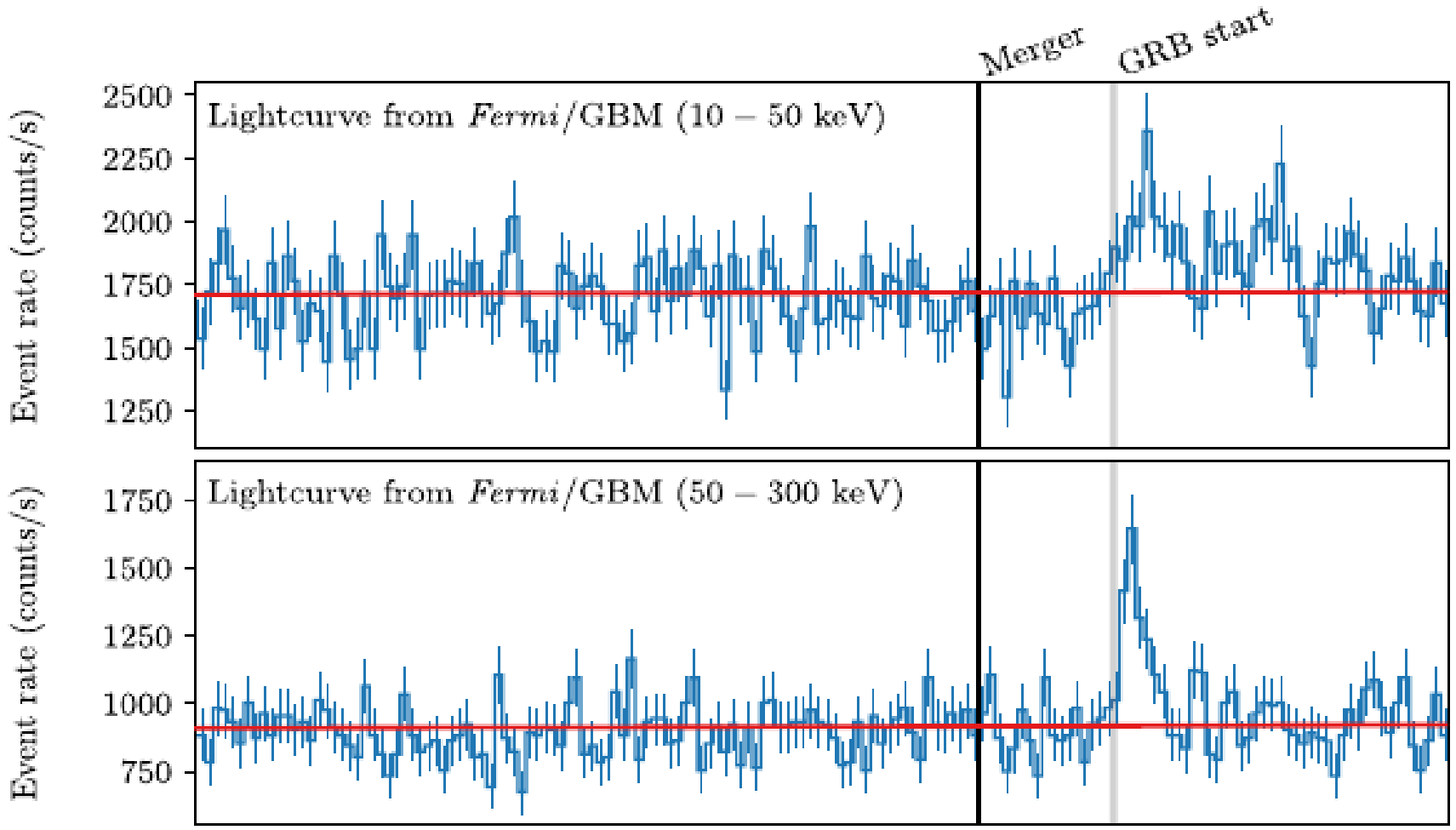
- elements heavier than Fe created
- constrains EoS of neutron stars
- ...

GW170817: Locating it



GW170817: Observing with Fermi and Integral



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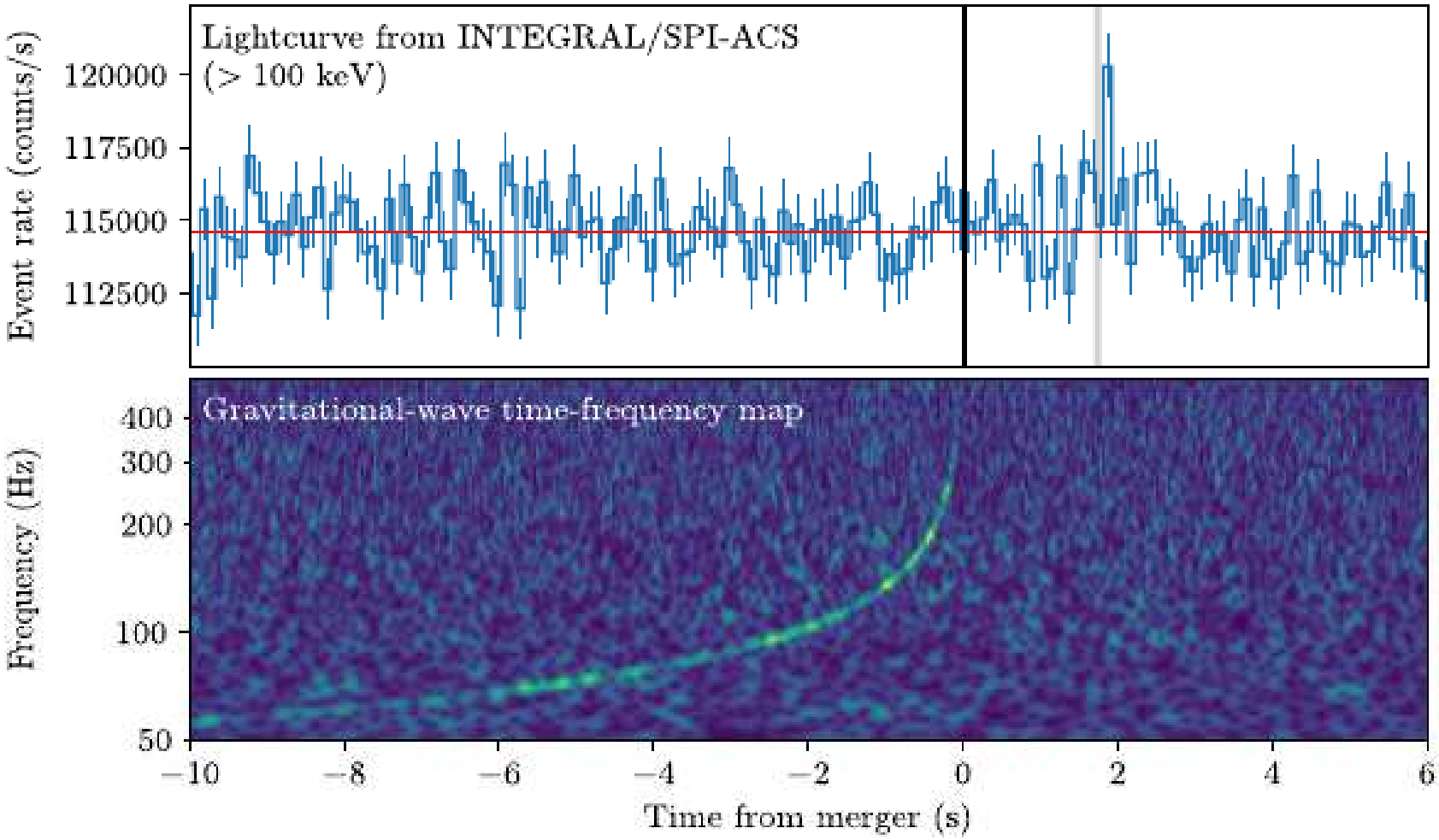
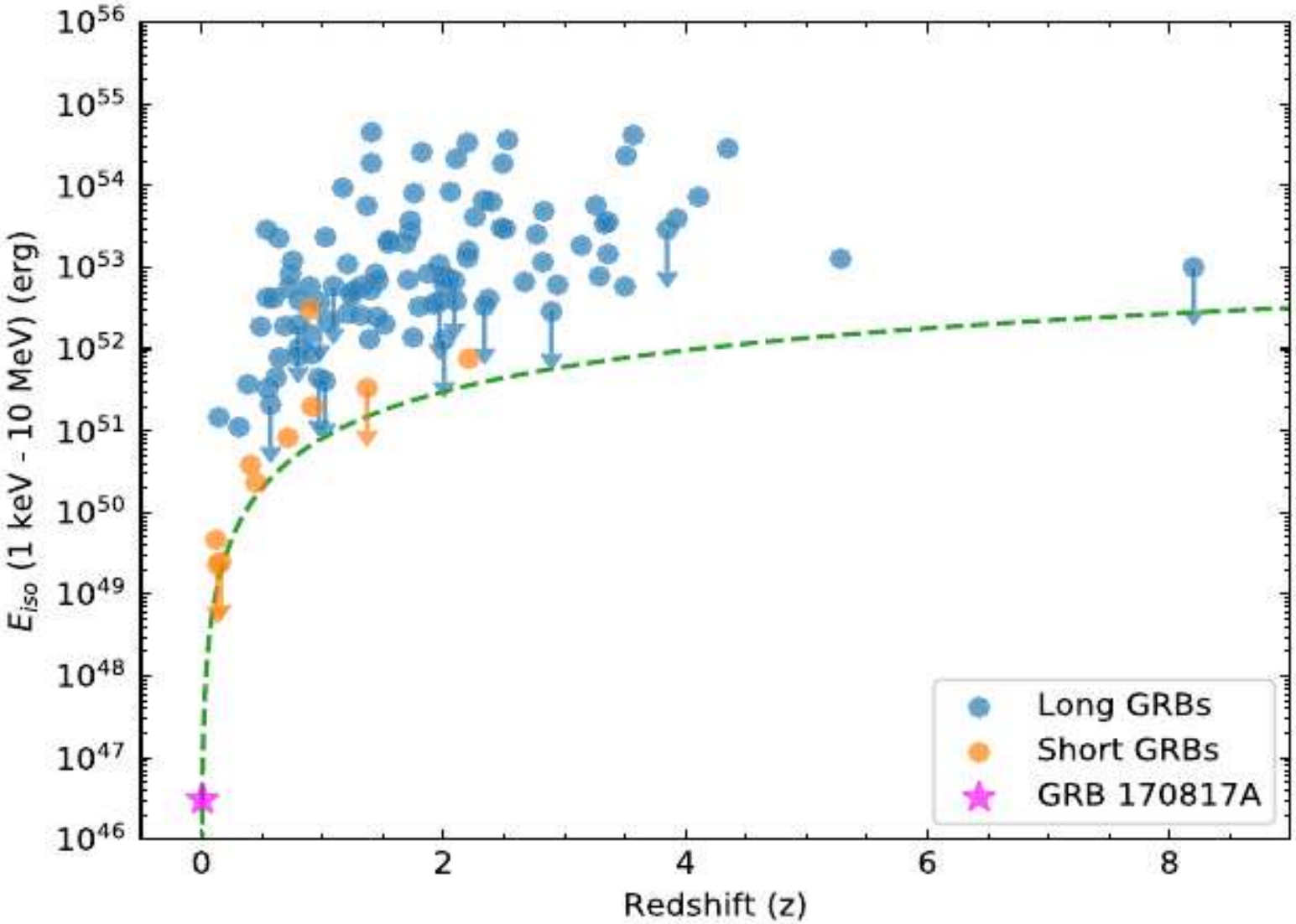


GW170817: a "strange" SGRB



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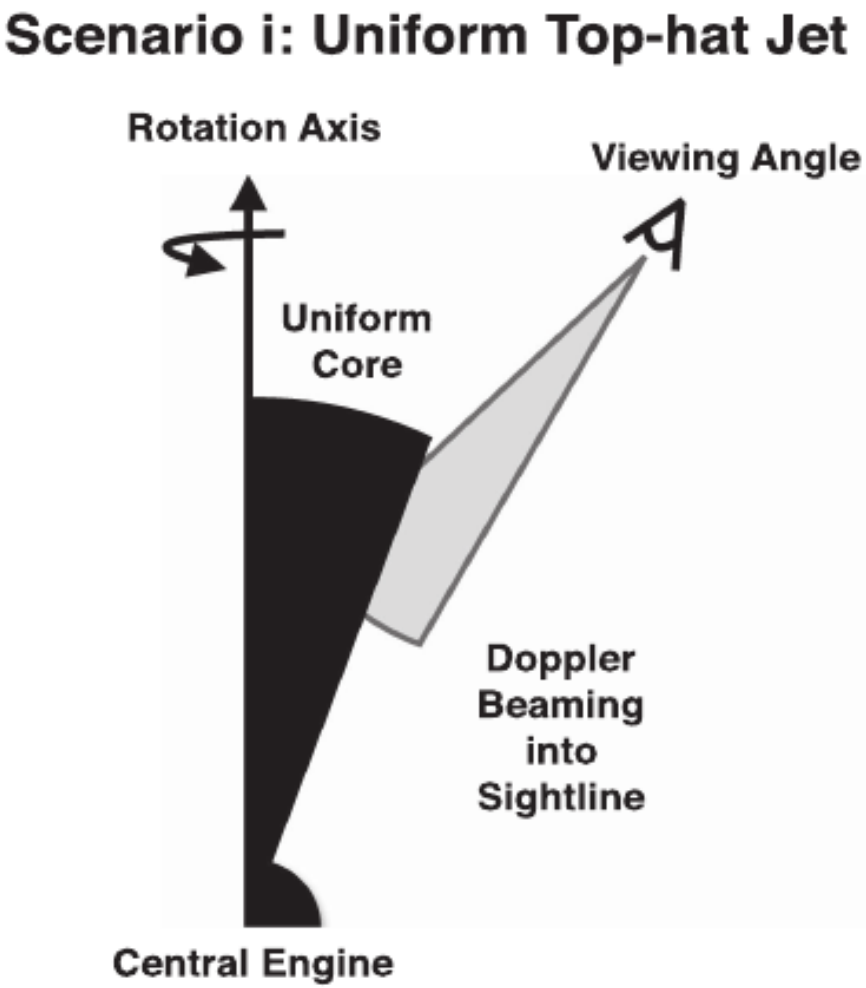
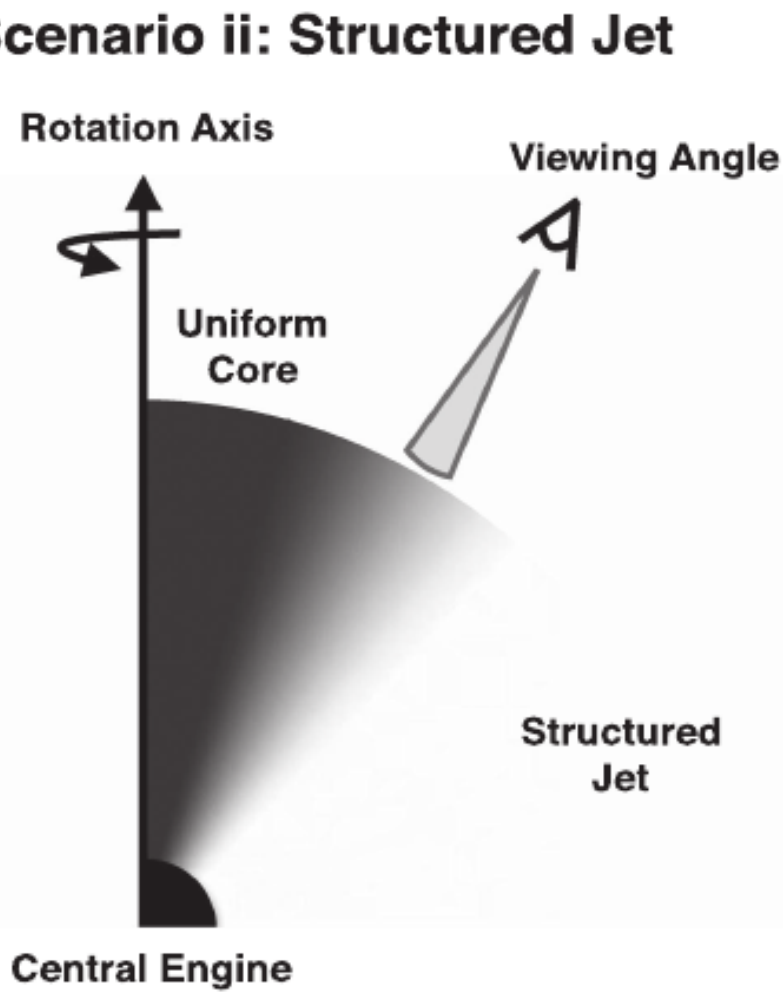
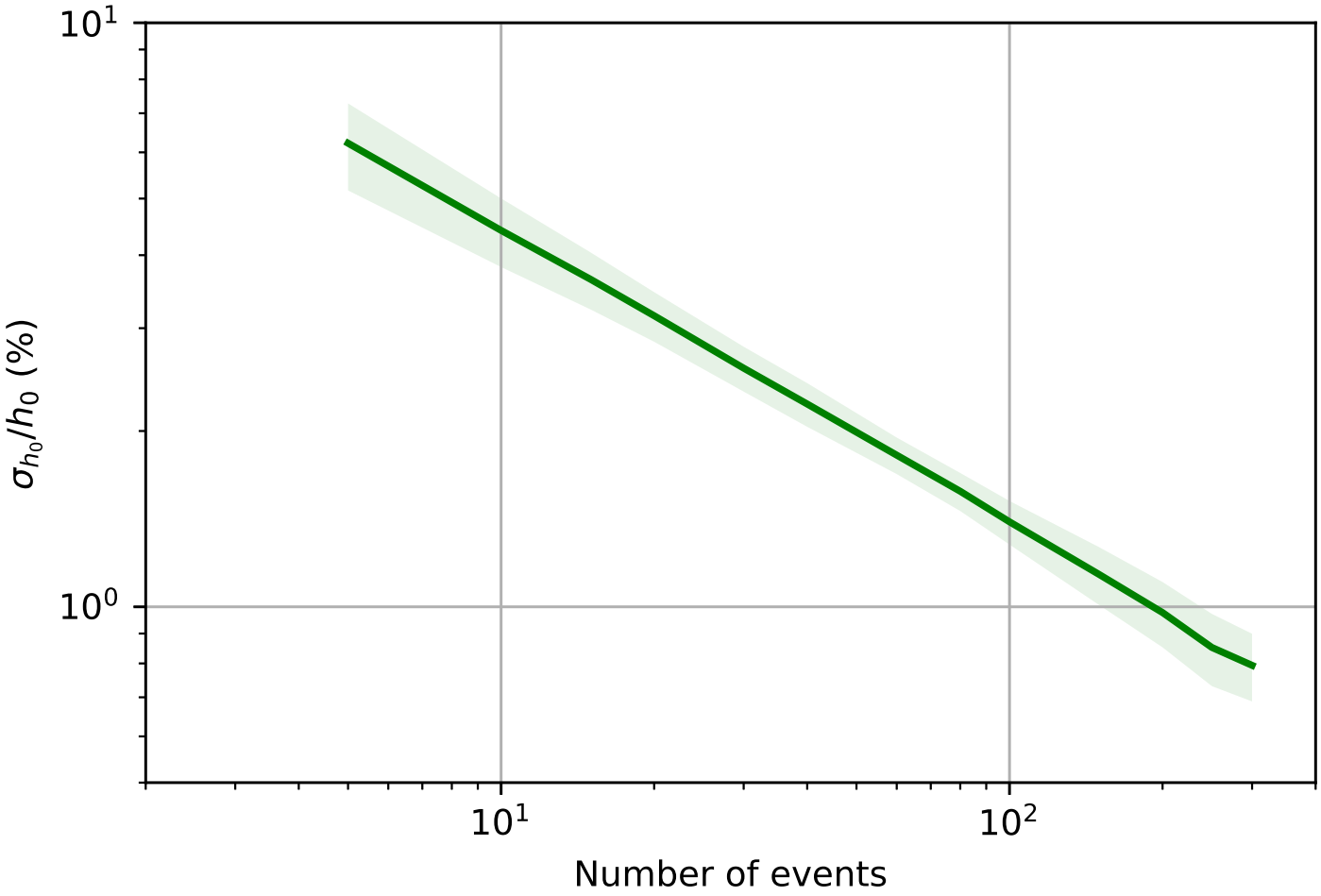




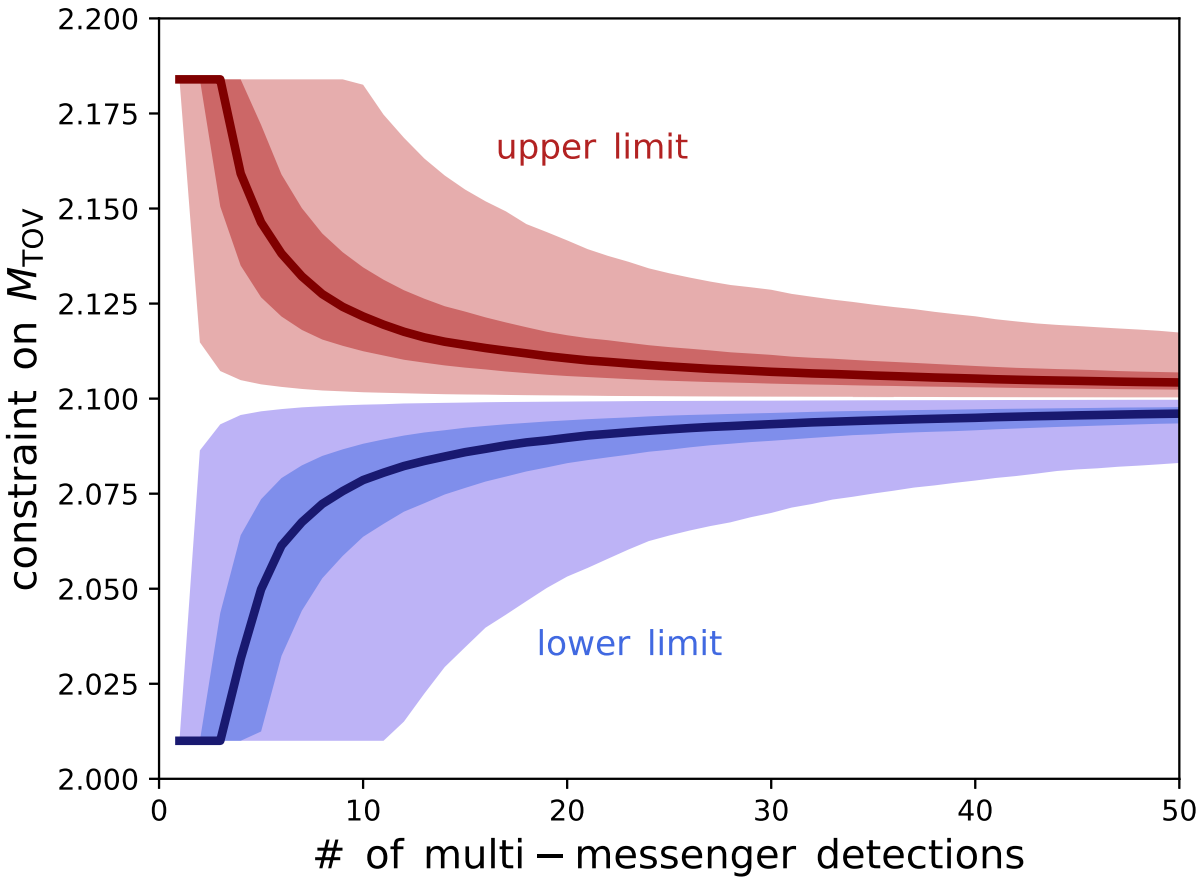
Measuring H_0:

- GW signal $\Rightarrow$ luminosity distance
- Photon observation $\Rightarrow$ redshift

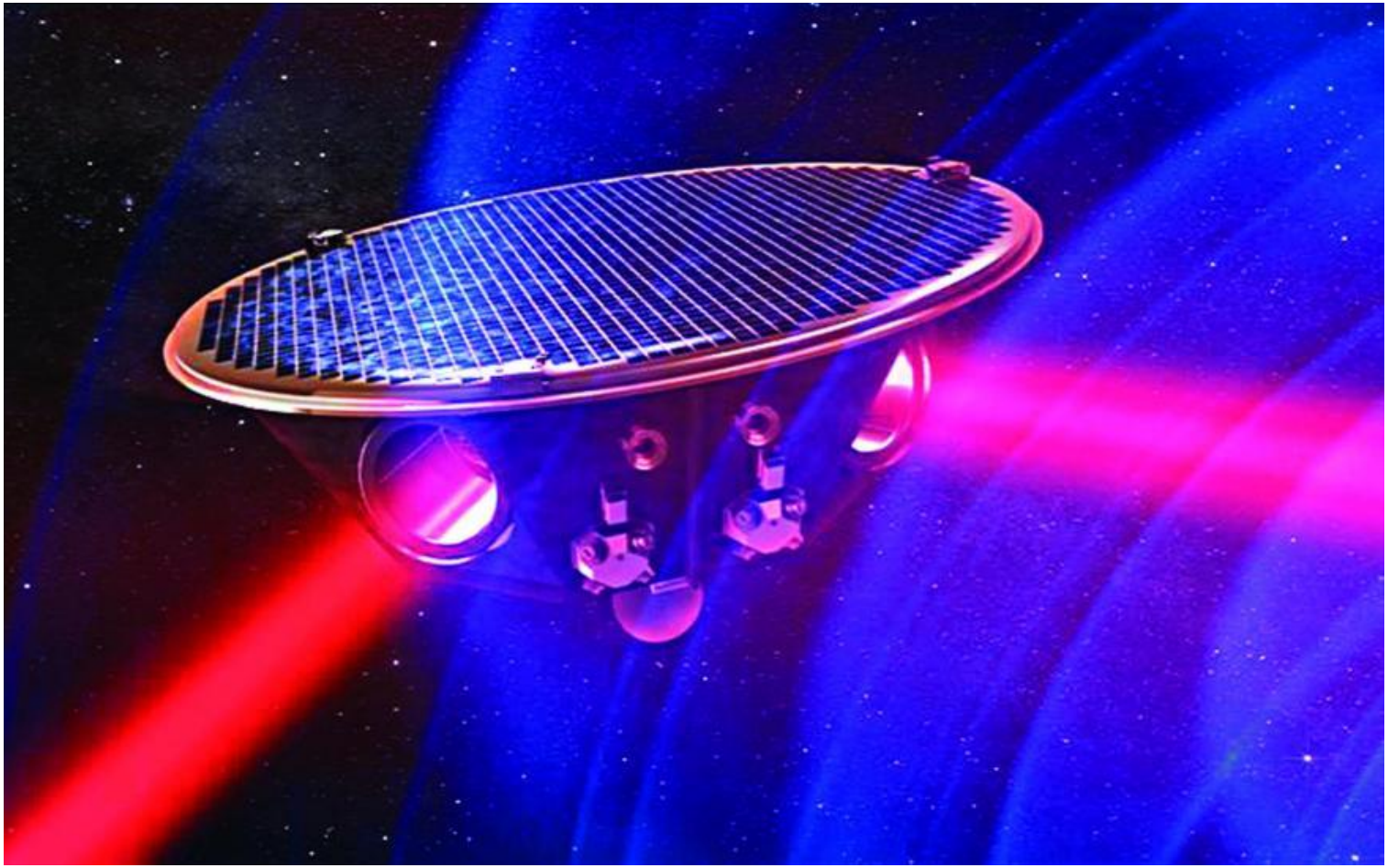


Limit on $M_{\max}$ for NS:

- GW signal $\Rightarrow$ cirp mass
- Photon observation $\Rightarrow$ fate of remnant



Outlook: (e)LISA



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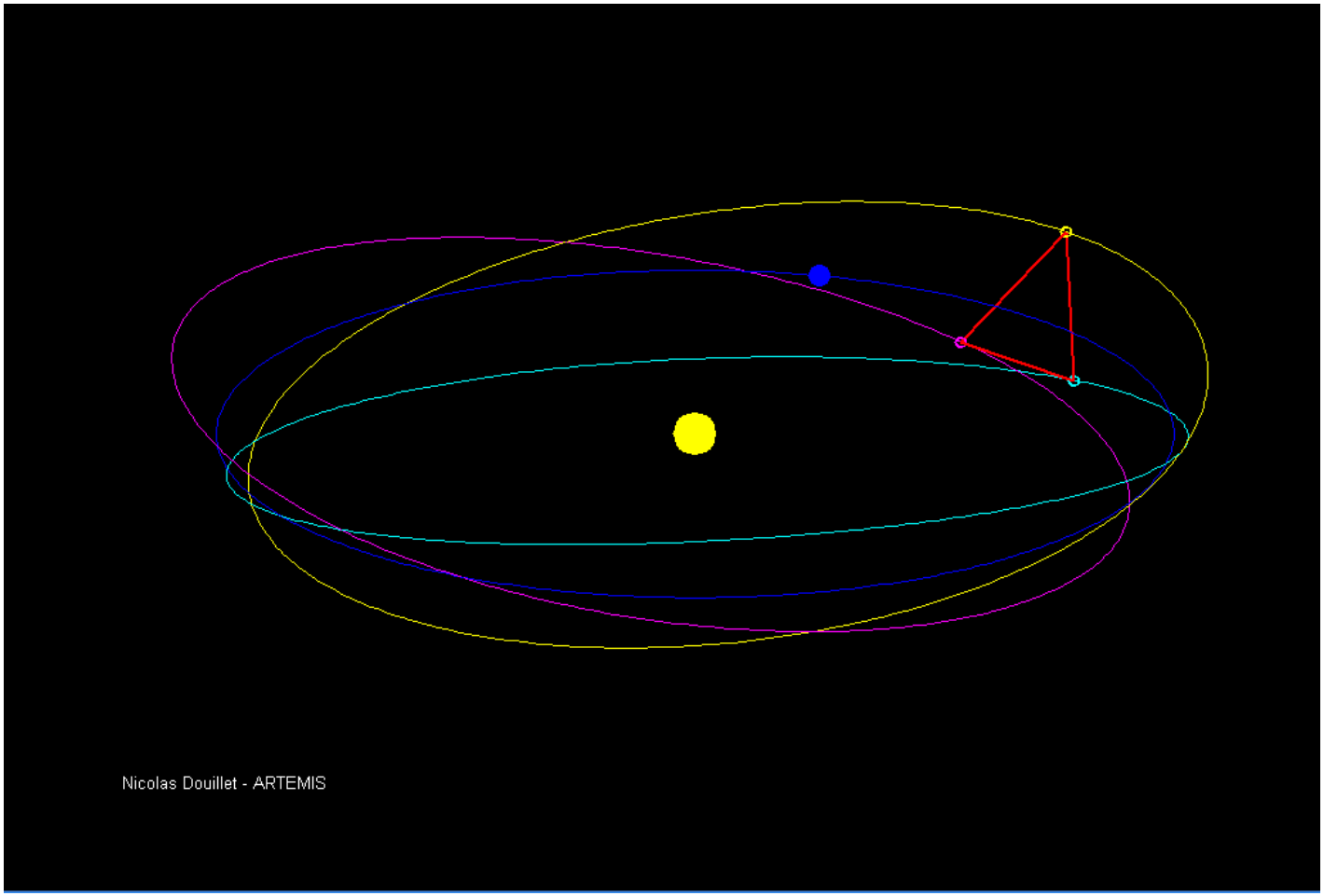

Outlook: (e)LISA and others: