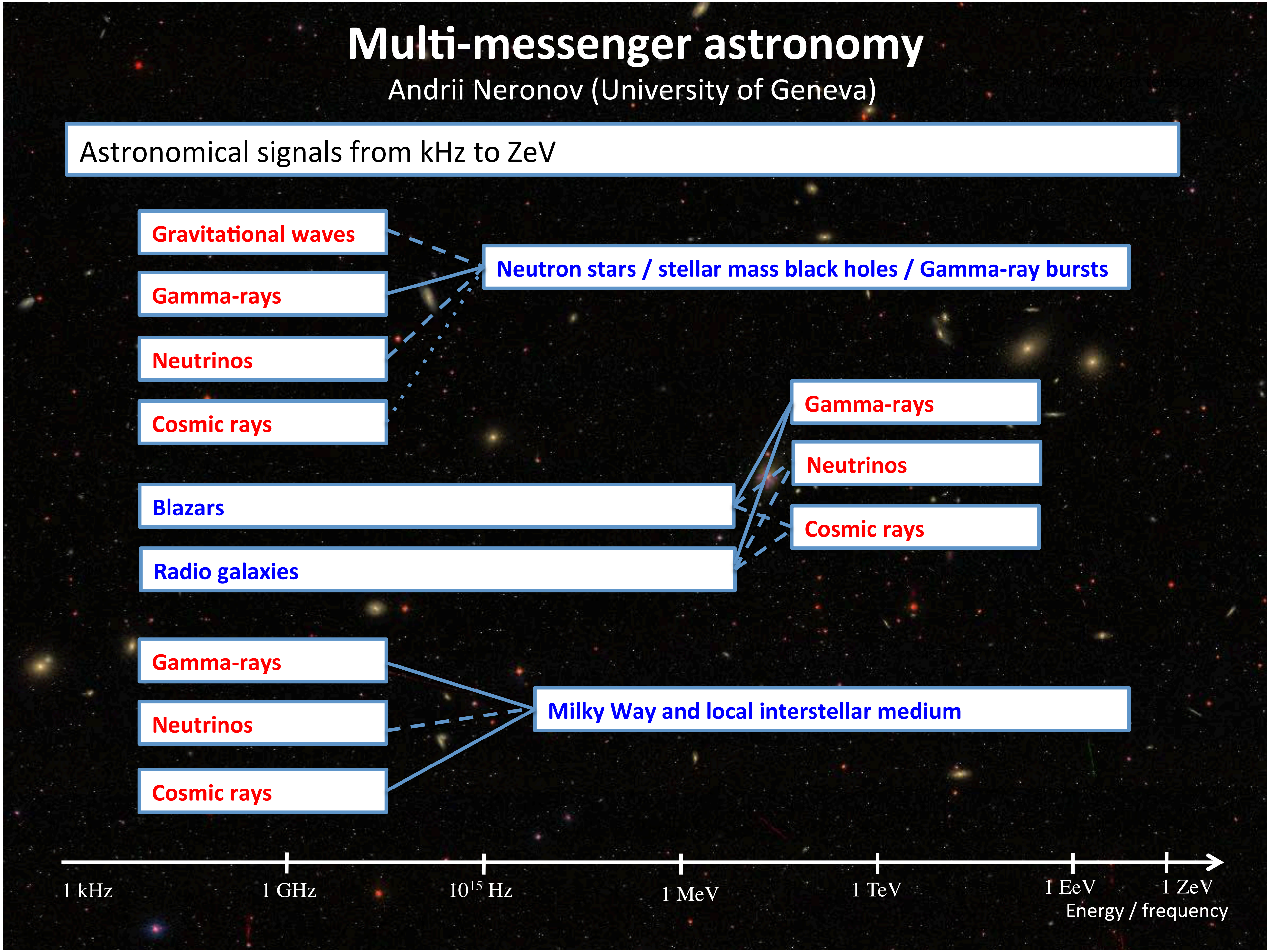
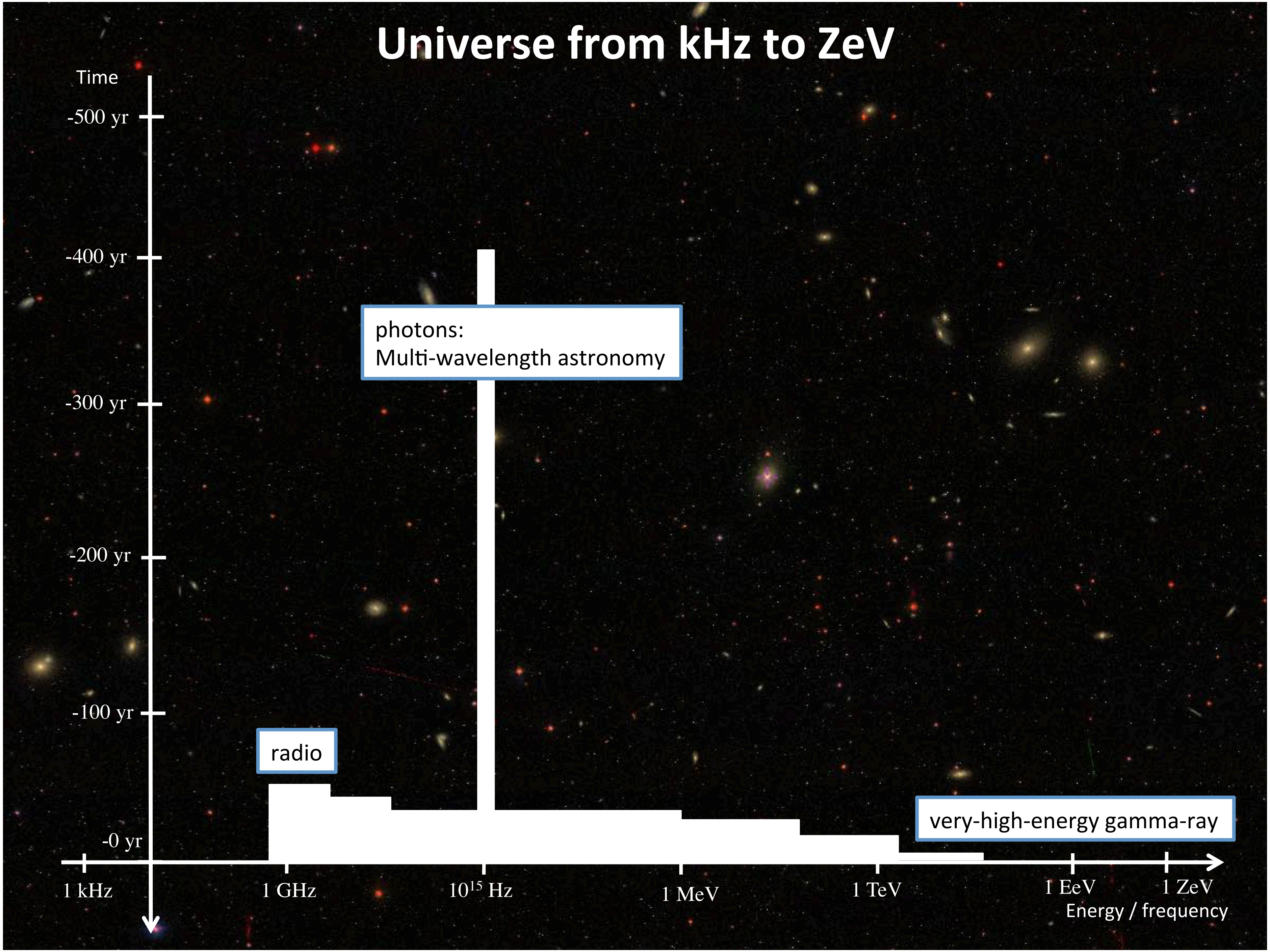
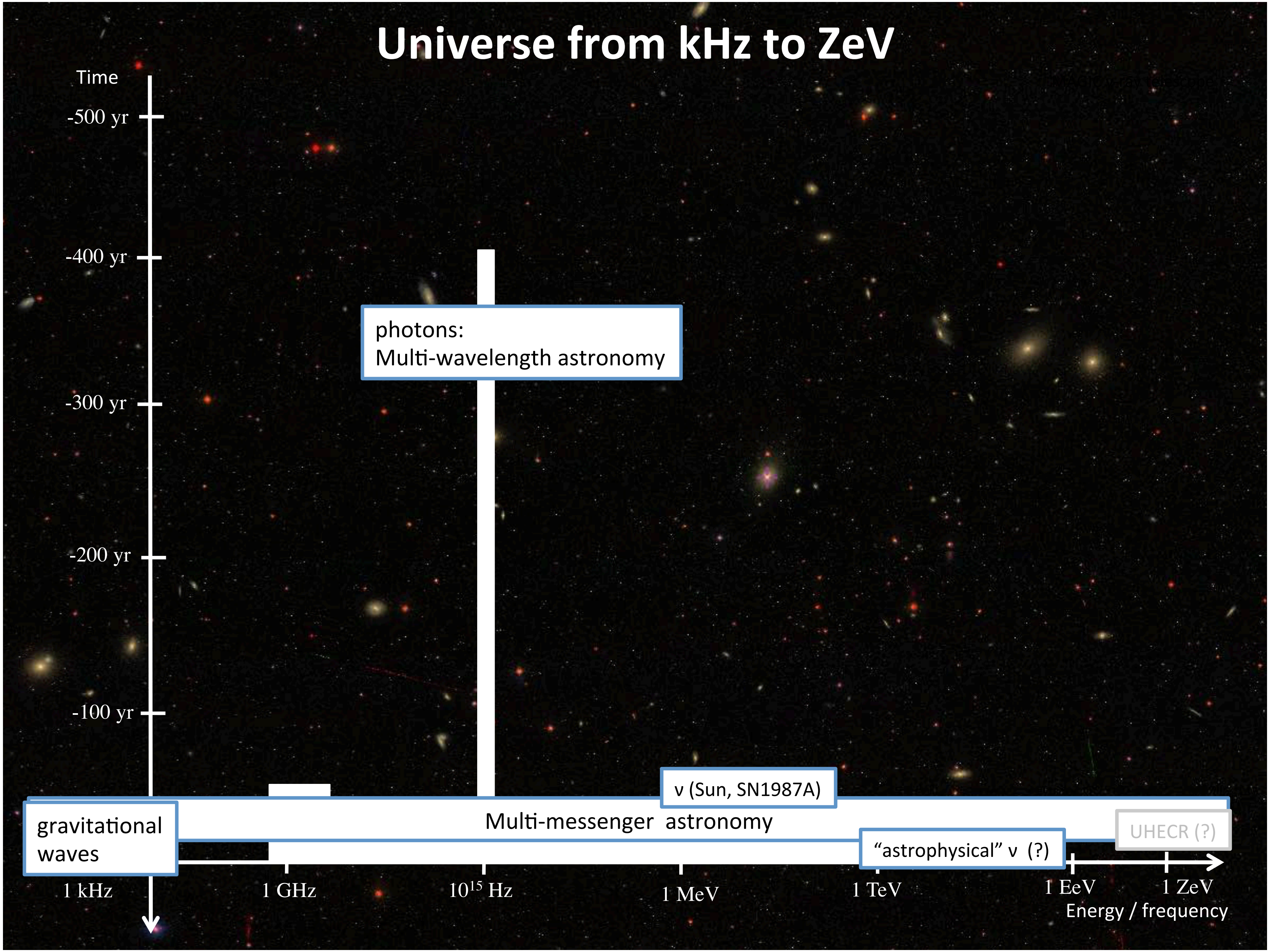
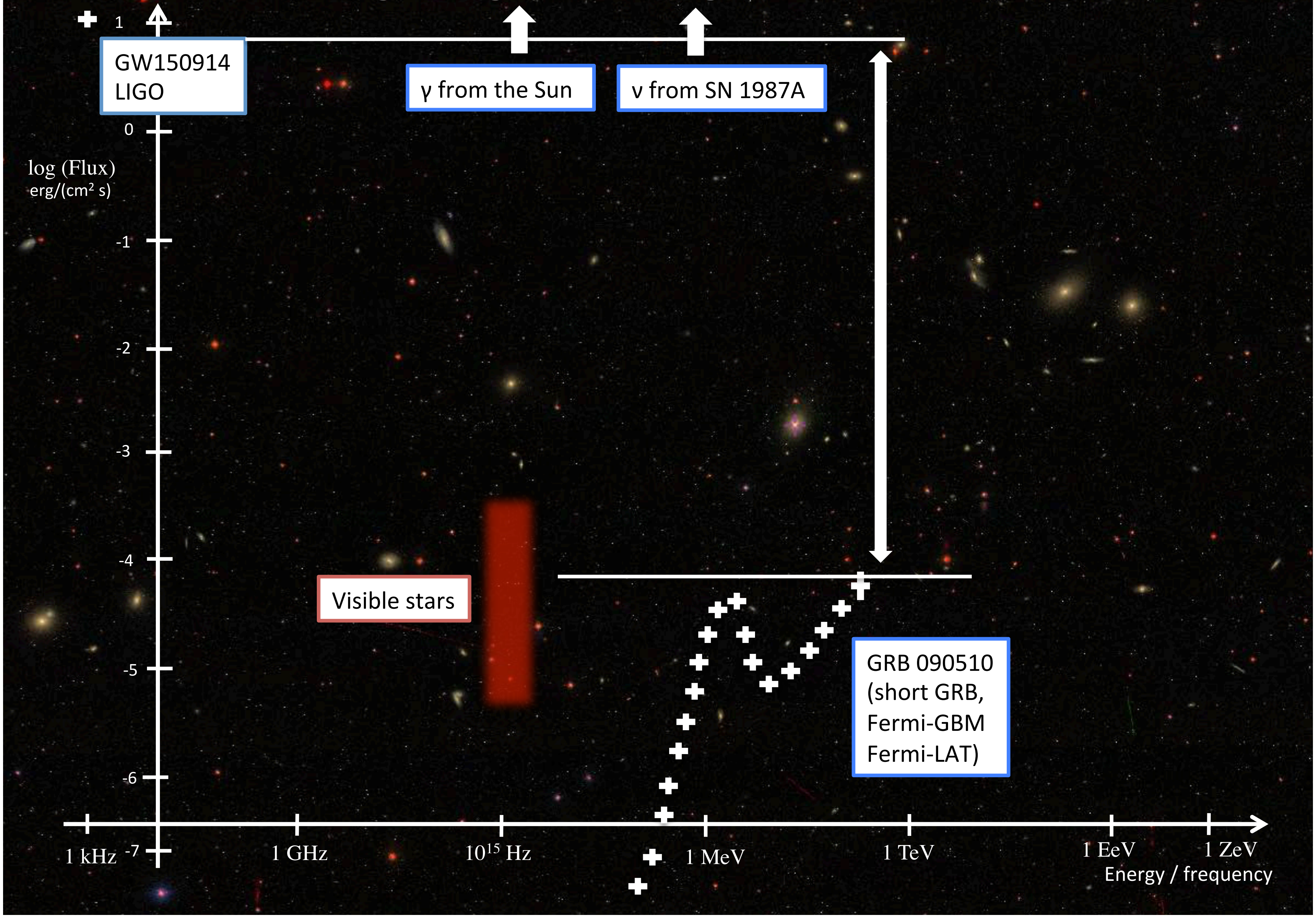
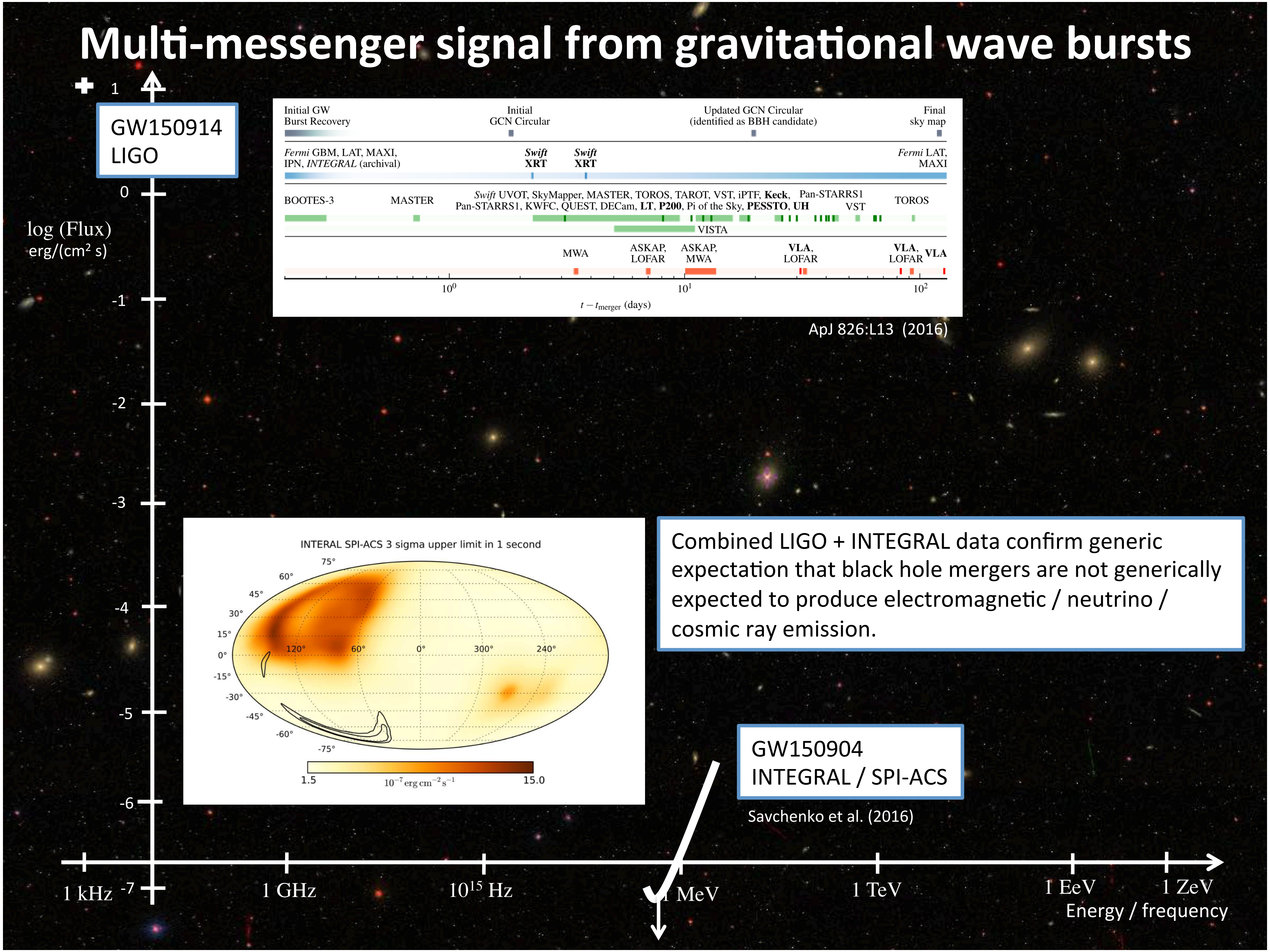

Multi-messenger astronomy
Andrii Neronov (University of Geneva)
Astronomical signals from kHz to ZeV
Gravitational waves
Gamma-rays
Neutrinos
Cosmic rays
Neutron stars / stellar mass black holes / Gamma-ray bursts
Gamma-rays
Neutrinos
Cosmic rays
Blazars
Radio galaxies
Gamma-rays
Neutrinos
Cosmic rays
Milky Way and local interstellar medium
1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency


Universe from kHz to ZeV
Time
-500 yr
-400 yr
-300 yr
-200 yr
-100 yr
-0 yr
photons:
Multi-wavelength astronomy
radio
very-high-energy gamma-ray
1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency

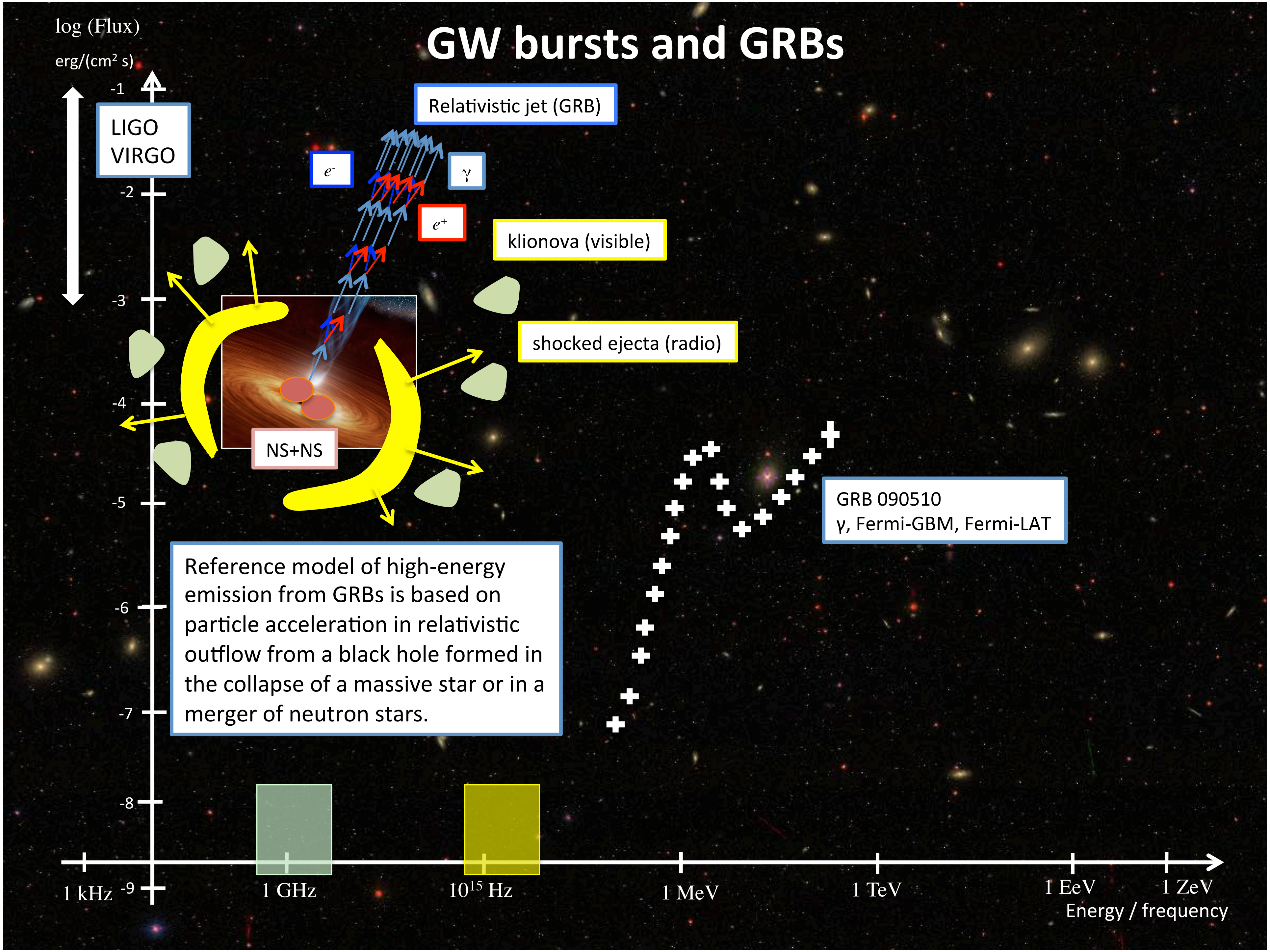

Universe from kHz to ZeV
Time
-500 yr
-400 yr
-300 yr
-200 yr
-100 yr
photons:
Multi-wavelength astronomy
ν (Sun, SN1987A)
gravitational waves
Multi-messenger astronomy
UHECR (?)
“astrophysical” ν (?)
1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency

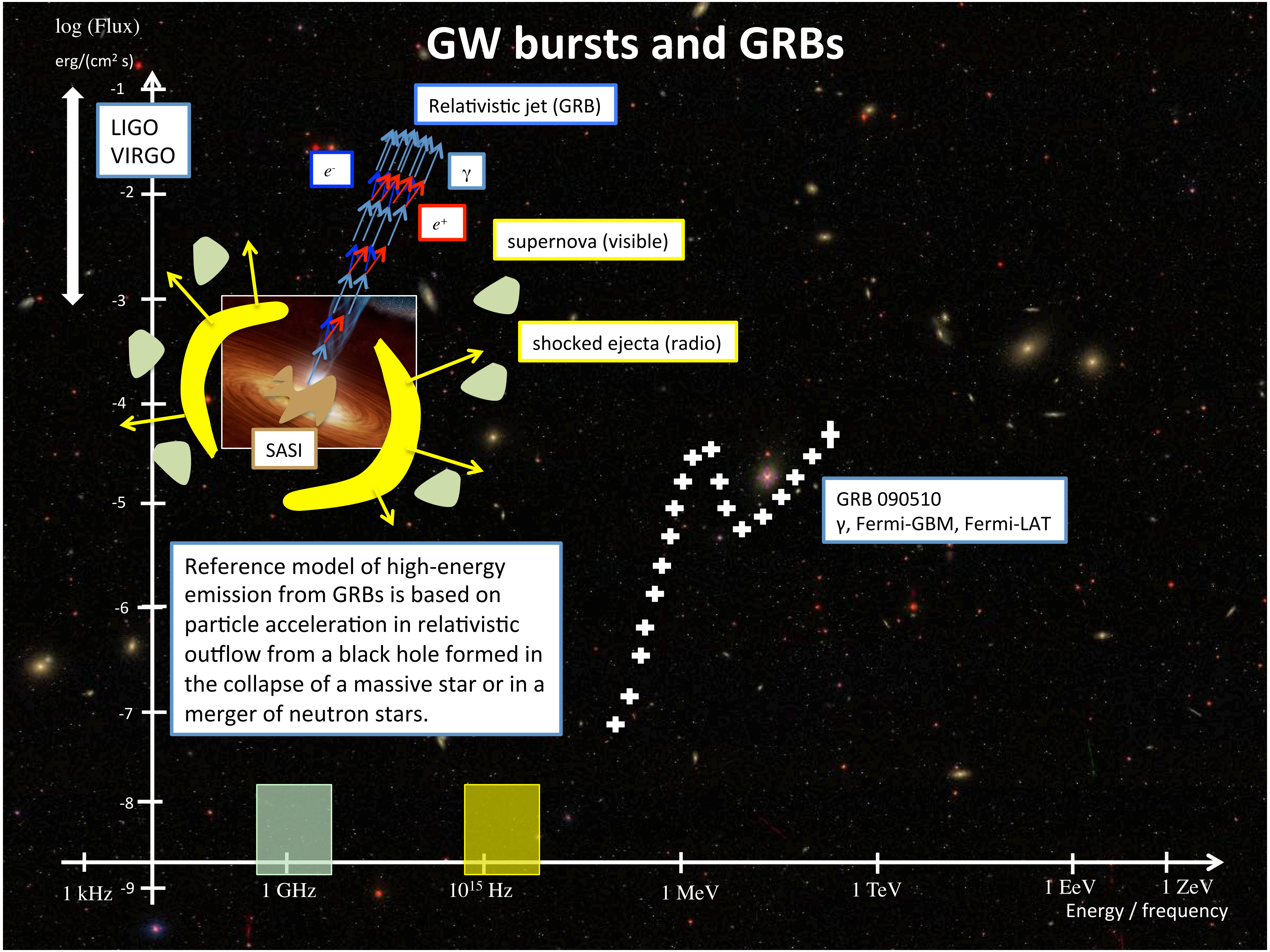
Multi-messenger signal from gravitational wave bursts



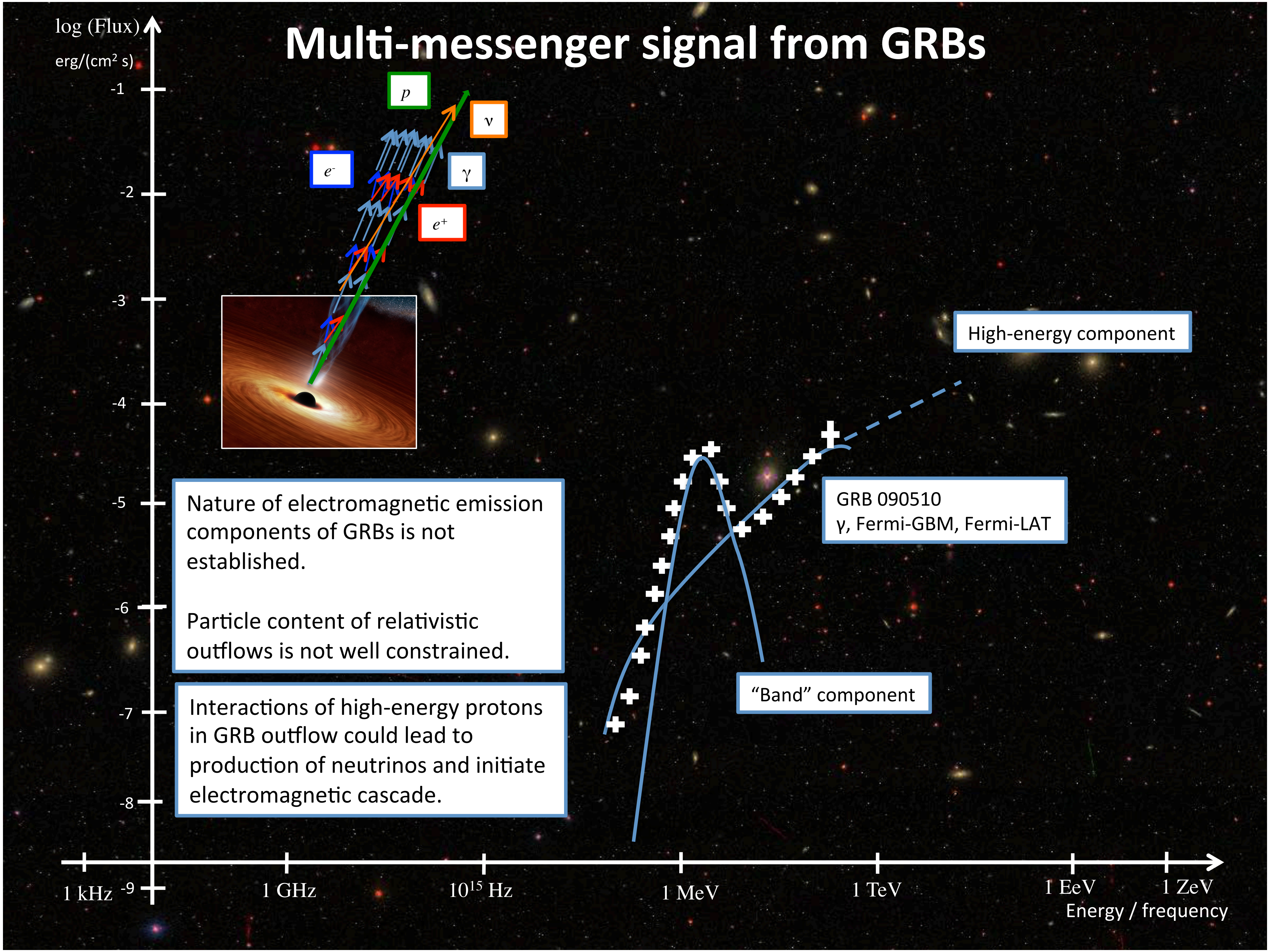


Multi-messenger signal from gravitational wave bursts
1
GW150914
LIGO
0
log (Flux)
erg/(cm² s)
-1
-2
-3
-4
-5
-6
-7
Initial GW Burst Recovery
Initial GCN Circular
Updated GCN Circular (identified as BBH candidate)
Final sky map
Fermi GBM, LAT, MAXI, IPN, INTEGRAL (archival)
Swift XRT
Swift XRT
Fermi LAT, MAXI
BOOTES-3
MASTER
Swift UVOT, SkyMapper, MASTER, TOROS, TAROT, VST, iPTF, Keck, Pan-STARRS1, KWFC, QUEST, DECam, LT, P200, Pi of the Sky, PESSTO, UH
Pan-STARRS1
VST
TOROS
VISTA
MWA
ASKAP, LOFAR
ASKAP, MWA
VLA, LOFAR
VLA, LOFAR
VLA
10^0
10^1
10^2
$t - t_{merger}$ (days)
ApJ 826:L13 (2016)
INTERAL SPI-ACS 3 sigma upper limit in 1 second
1.5
10^{-7} erg cm^{-2} s^{-1}
15.0
Combined LIGO + INTEGRAL data confirm generic expectation that black hole mergers are not generically expected to produce electromagnetic / neutrino / cosmic ray emission.
GW150904
INTEGRAL / SPI-ACS
Savchenko et al. (2016)
1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency

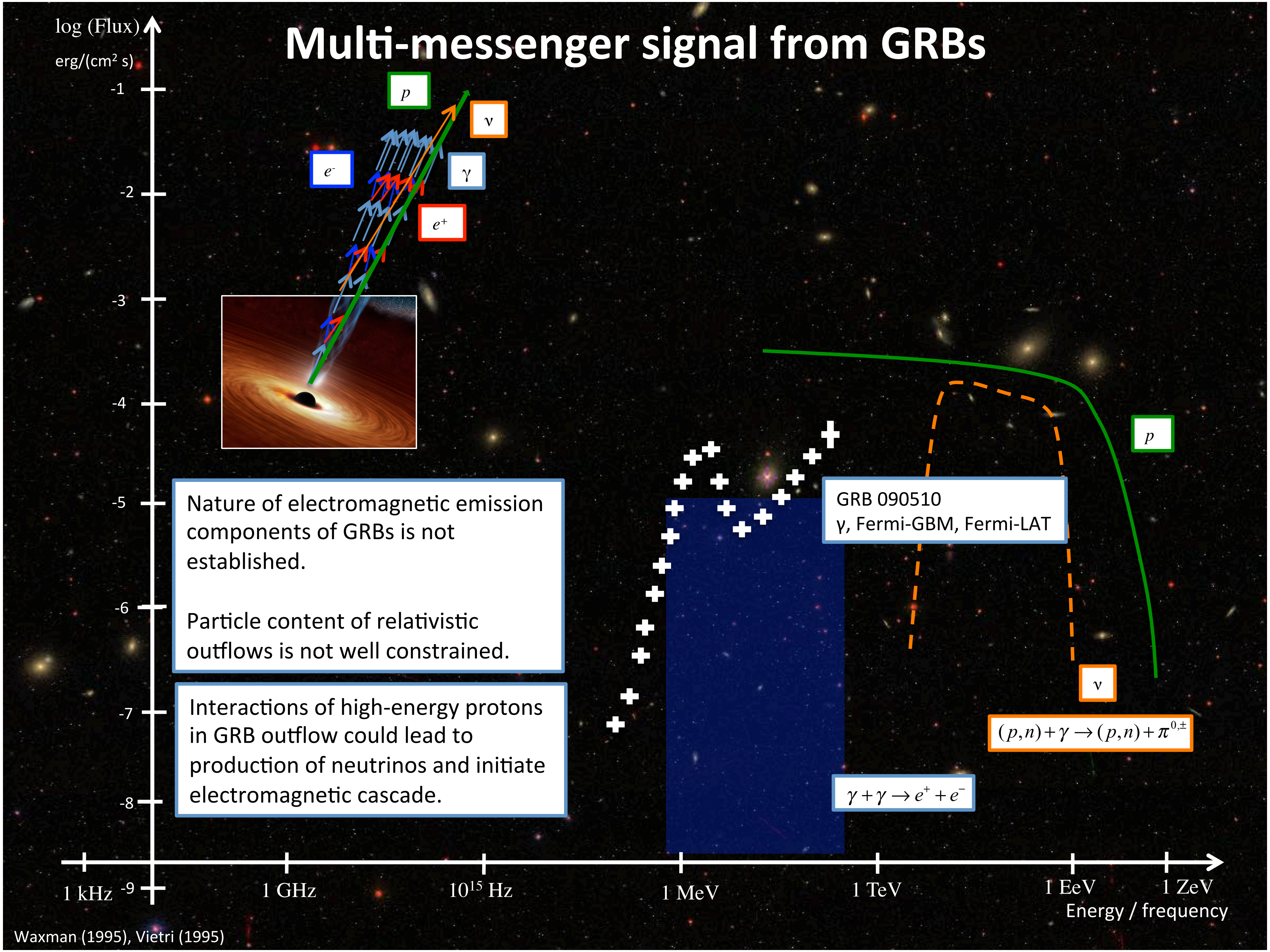

GW bursts and GRBs
log (Flux)
erg/(cm² s)
-1
-2
-3
-4
-5
-6
-7
-8
-9
LIGO
VIRGO
Relativistic jet (GRB)
e⁻
γ
e⁺
klionova (visible)
shocked ejecta (radio)
NS+NS
GRB 090510
γ, Fermi-GBM, Fermi-LAT
Reference model of high-energy emission from GRBs is based on particle acceleration in relativistic outflow from a black hole formed in the collapse of a massive star or in a merger of neutron stars.
1 kHz
1 GHz
10¹⁵ Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency



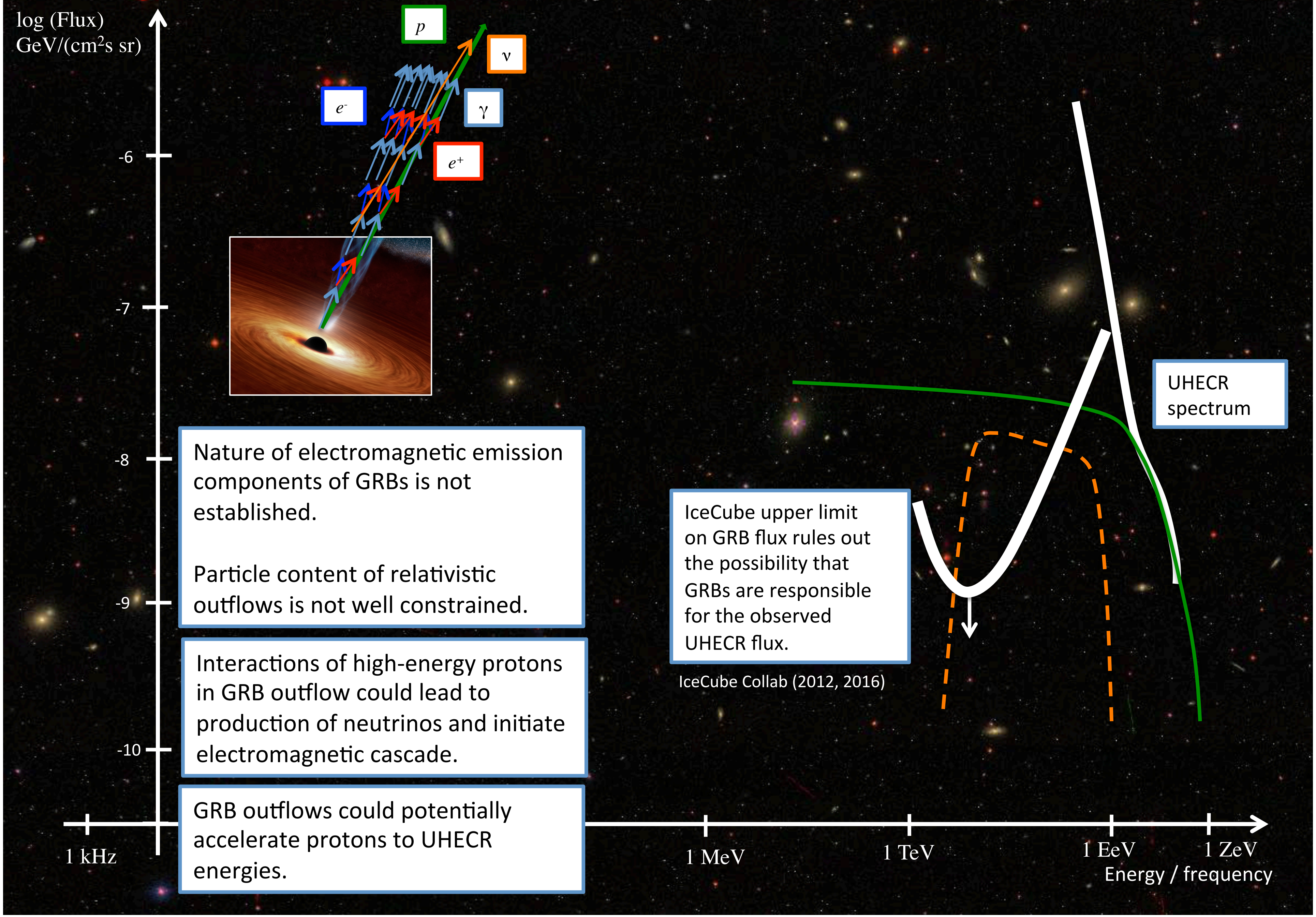
GW bursts and GRBs
log (Flux)
erg/(cm² s)
-1
-2
-3
-4
-5
-6
-7
-8
-9
LIGO
VIRGO
Relativistic jet (GRB)
e-
γ
e+
supernova (visible)
shocked ejecta (radio)
SASI
GRB 090510
γ, Fermi-GBM, Fermi-LAT
Reference model of high-energy emission from GRBs is based on particle acceleration in relativistic outflow from a black hole formed in the collapse of a massive star or in a merger of neutron stars.
1 kHz
1 GHz
10¹⁵ Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency

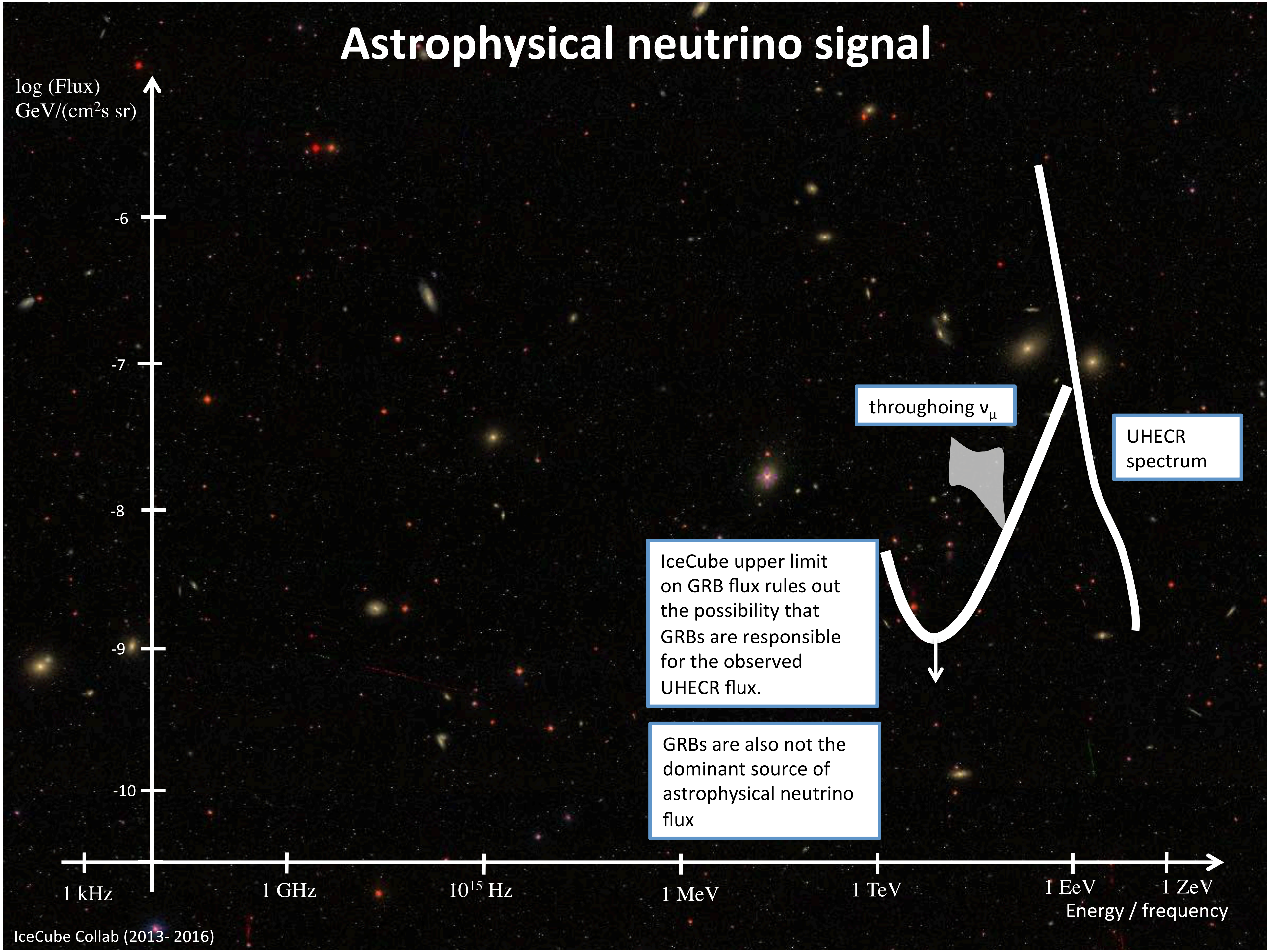


Multi-messenger signal from GRBs
log (Flux)
erg/(cm² s)
-1
-2
-3
-4
-5
-6
-7
-8
-9
p
ν
e⁻
γ
e⁺
High-energy component
Nature of electromagnetic emission components of GRBs is not established.
Particle content of relativistic outflows is not well constrained.
GRB 090510
γ, Fermi-GBM, Fermi-LAT
"Band" component
Interactions of high-energy protons in GRB outflow could lead to production of neutrinos and initiate electromagnetic cascade.
1 kHz
1 GHz
10¹⁵ Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency


Multi-messenger signal from GRBs
log (Flux)
erg/(cm² s)
-1
-2
-3
-4
-5
-6
-7
-8
-9
p
ν
e-
γ
e+
Nature of electromagnetic emission components of GRBs is not established.
Particle content of relativistic outflows is not well constrained.
Interactions of high-energy protons in GRB outflow could lead to production of neutrinos and initiate electromagnetic cascade.
GRB 090510
γ, Fermi-GBM, Fermi-LAT
$\gamma + \gamma \rightarrow e^{+} + e^{-}$
p
ν
$(p,n) + \gamma \rightarrow (p,n) + \pi^{0,\pm}$
1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency
Waxman (1995), Vietri (1995)

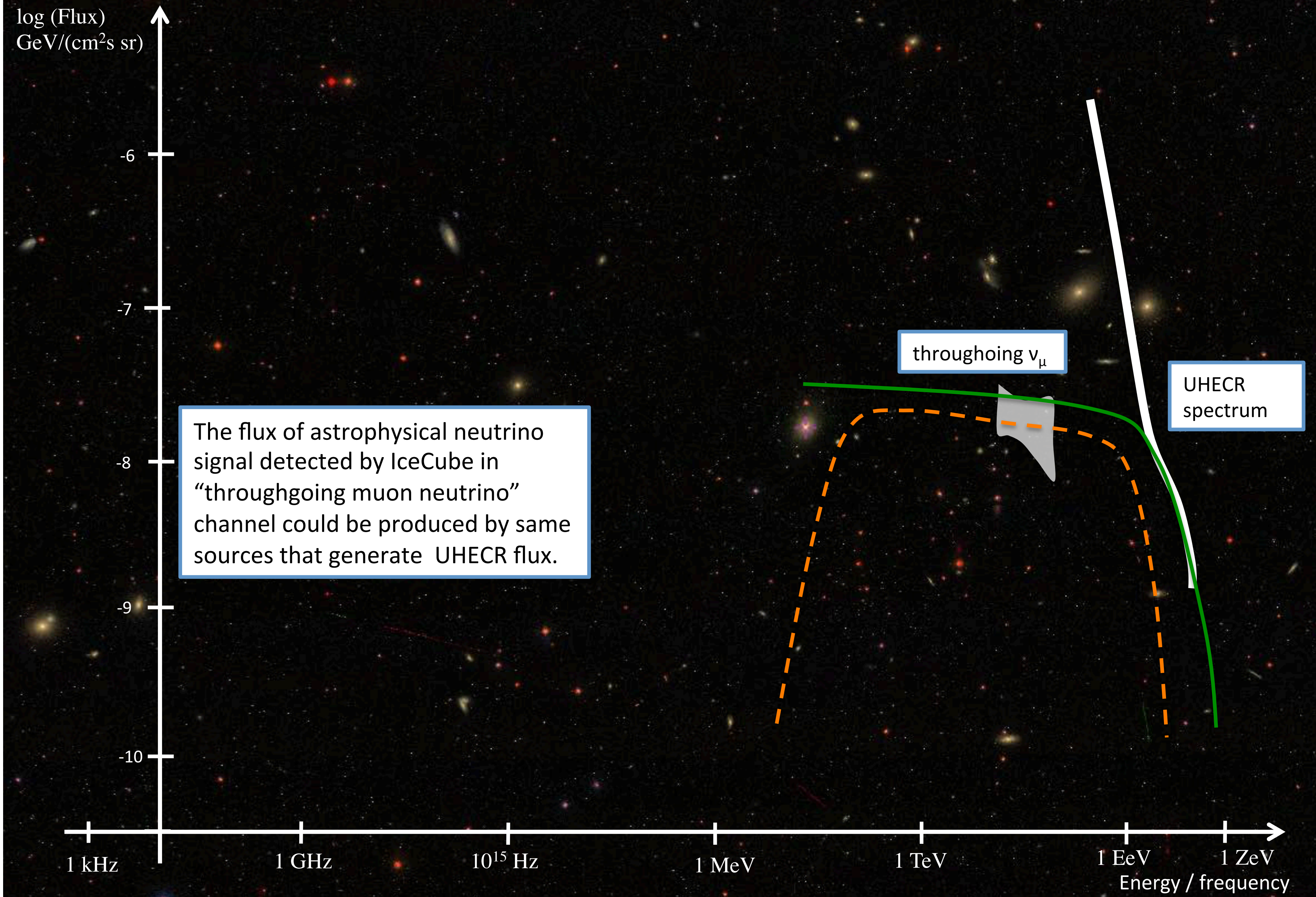
Multi-messenger signal from GRBs





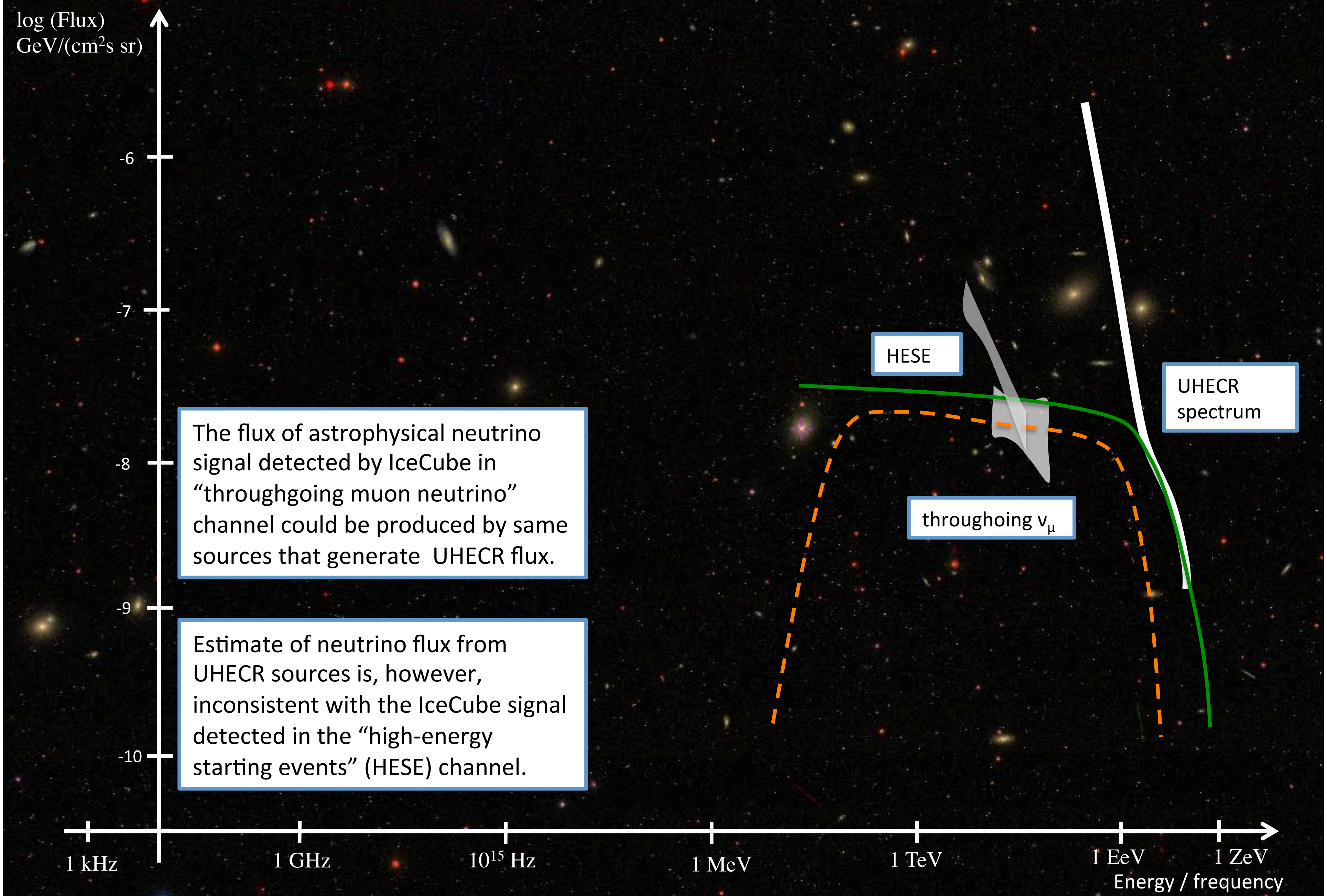
Astrophysical neutrino signal
log (Flux)
GeV/(cm^{2}s sr)
-6
-7
-8
-9
-10
1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency
throughgoing ν_μ
UHECR spectrum
IceCube upper limit on GRB flux rules out the possibility that GRBs are responsible for the observed UHECR flux.
GRBs are also not the dominant source of astrophysical neutrino flux
IceCube Collab (2013- 2016)

Astrophysical neutrino signal



IceCube Collab (2013- 2016), Waxman & Bahcall (1999)

Astrophysical neutrino signal

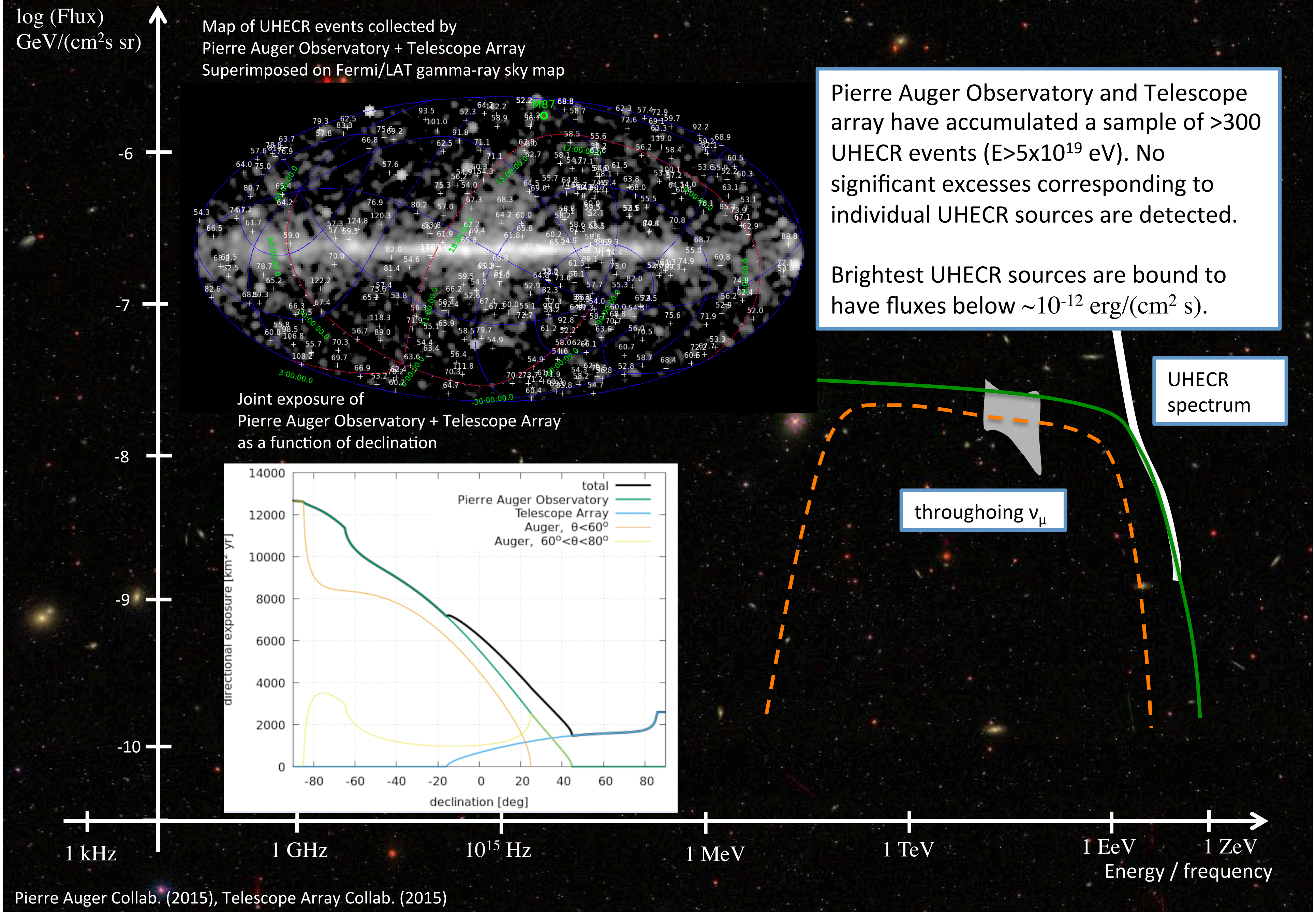


The flux of astrophysical neutrino signal detected by IceCube in "throughgoing muon neutrino" channel could be produced by same sources that generate UHECR flux.

Estimate of neutrino flux from UHECR sources is, however, inconsistent with the IceCube signal detected in the "high-energy starting events" (HESE) channel.

IceCube Collab (2013- 2016), Waxman & Bahcall (1999)

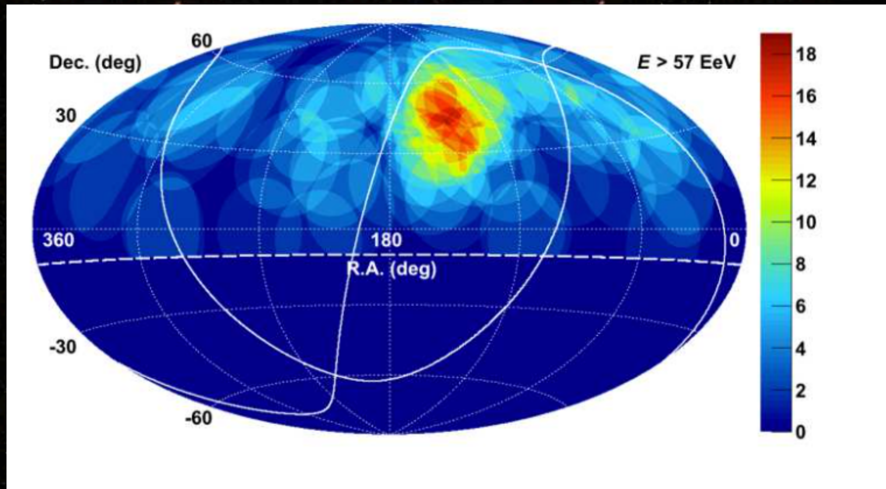
UHECR sources



UHECR sources

log (Flux)
GeV/(cm^{2}s sr)

Telescope Array sky map smoothed with 20 degrees



The most significant anisotropy feature observed is a 3.4 sigma (post-trial) 20-degree-wide "hot spot" reported by Telescope array.

This is the first possibly first astronomical UHECR source.
Large angular width of the hotspot has to be explained:
- Galactic/intergalactic magnetic field?
- UHECR particle electric charge?

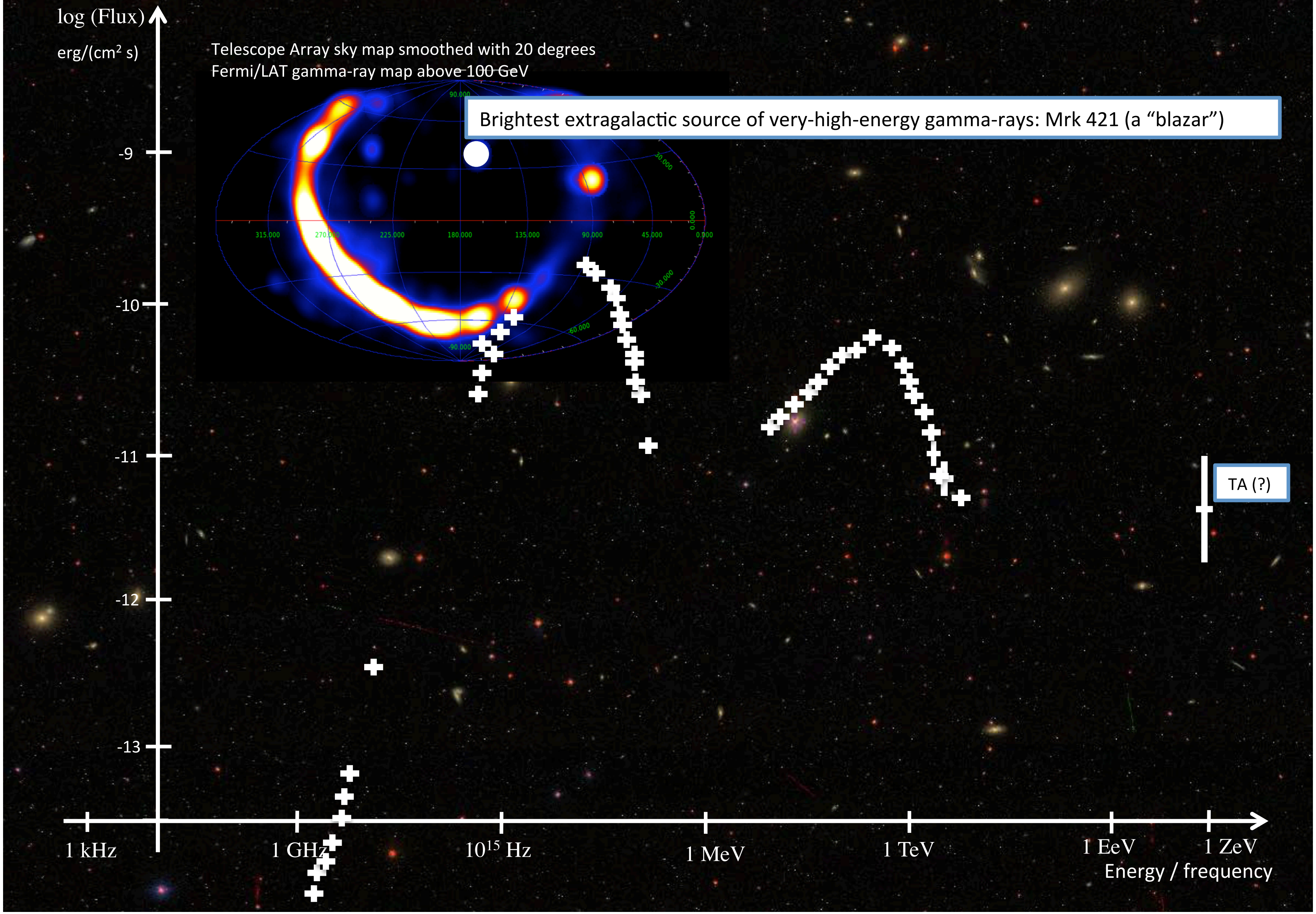
-9
-10
-11
-12
-13

1 kHz | 1 GHz | 10^{15} Hz | 1 MeV | 1 TeV | 1 EeV | 1 ZeV

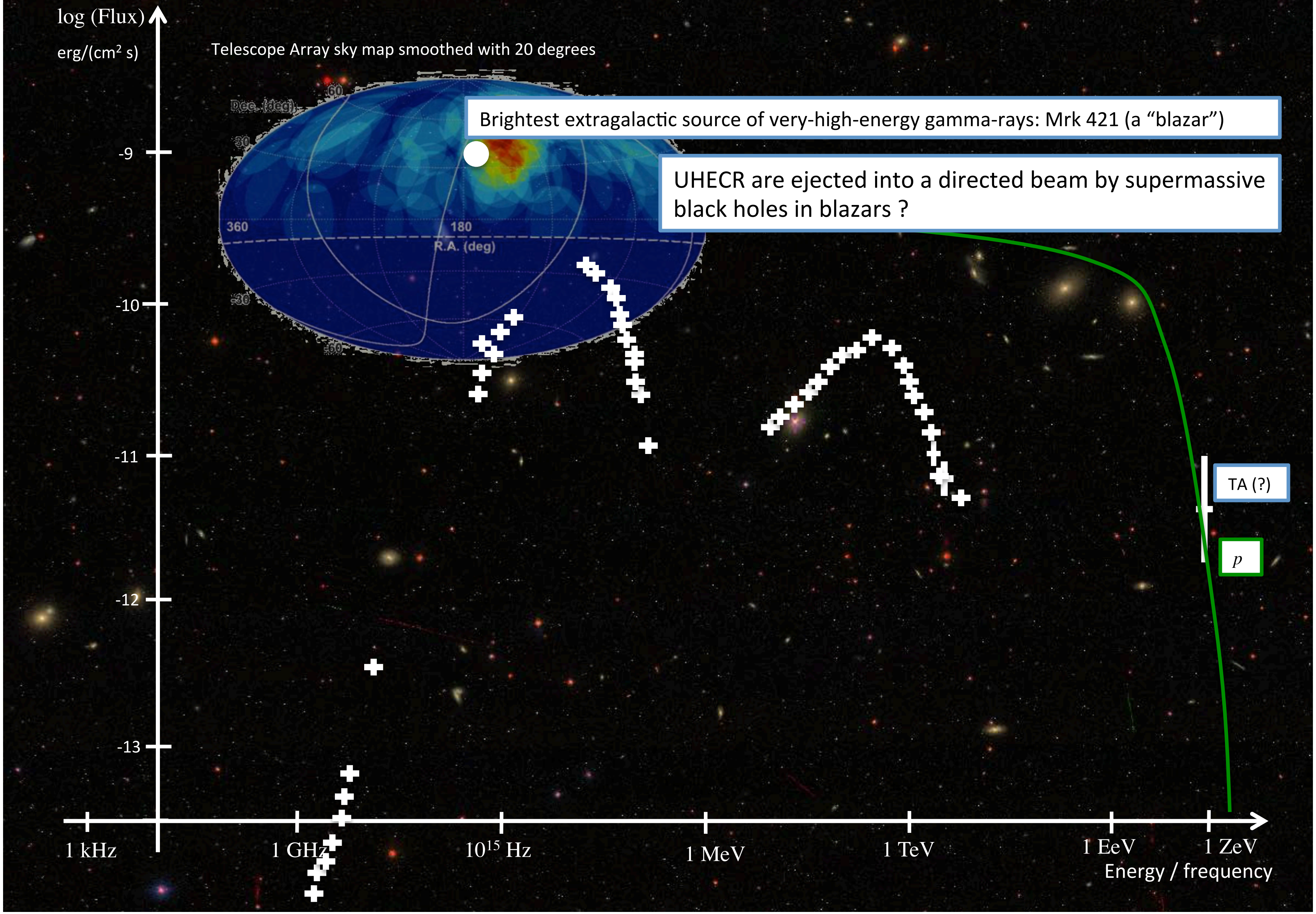
Energy / frequency

Telescope Array Collab. (2014)

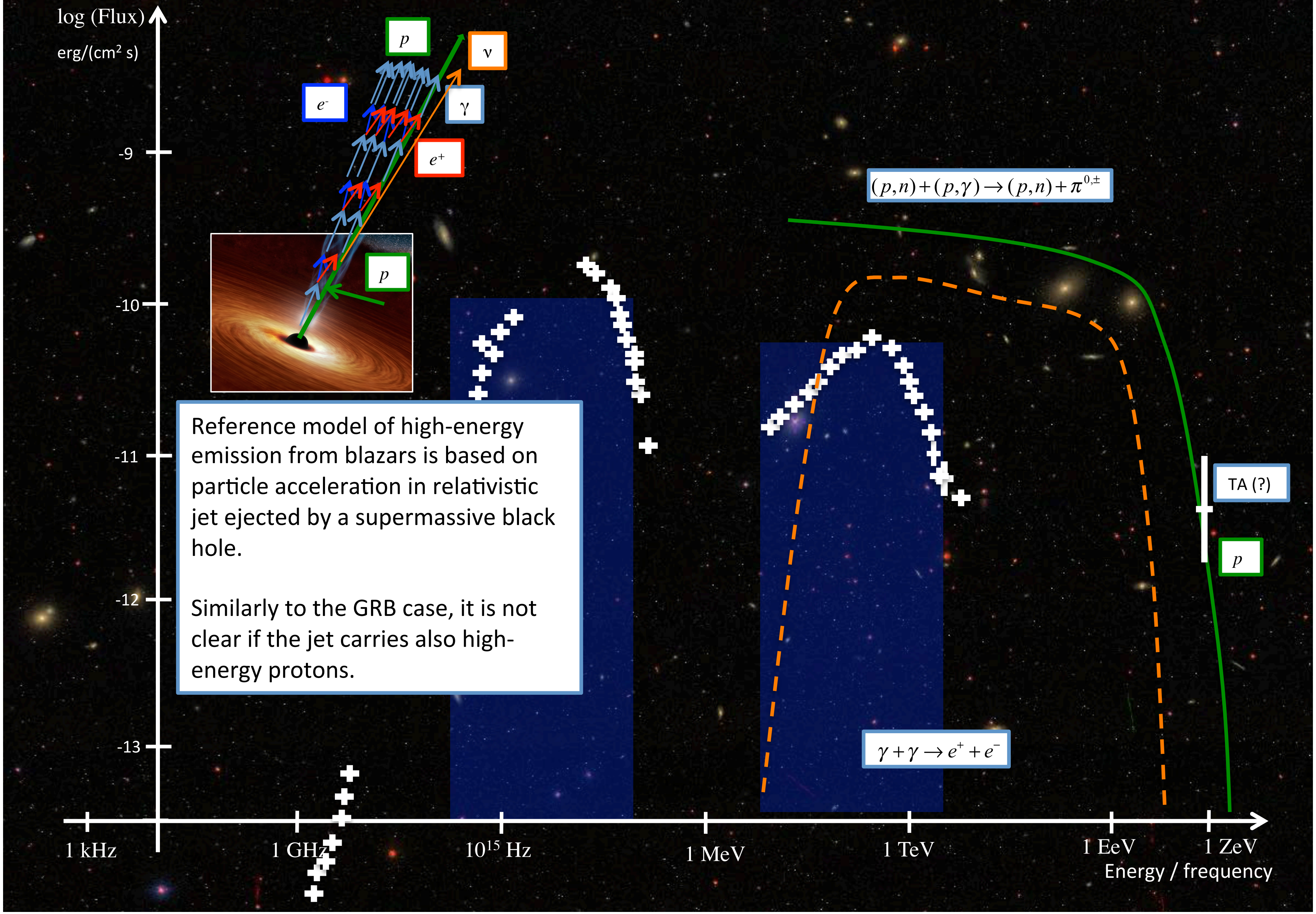
Multi-messenger signal from blazars



Multi-messenger signal from blazars



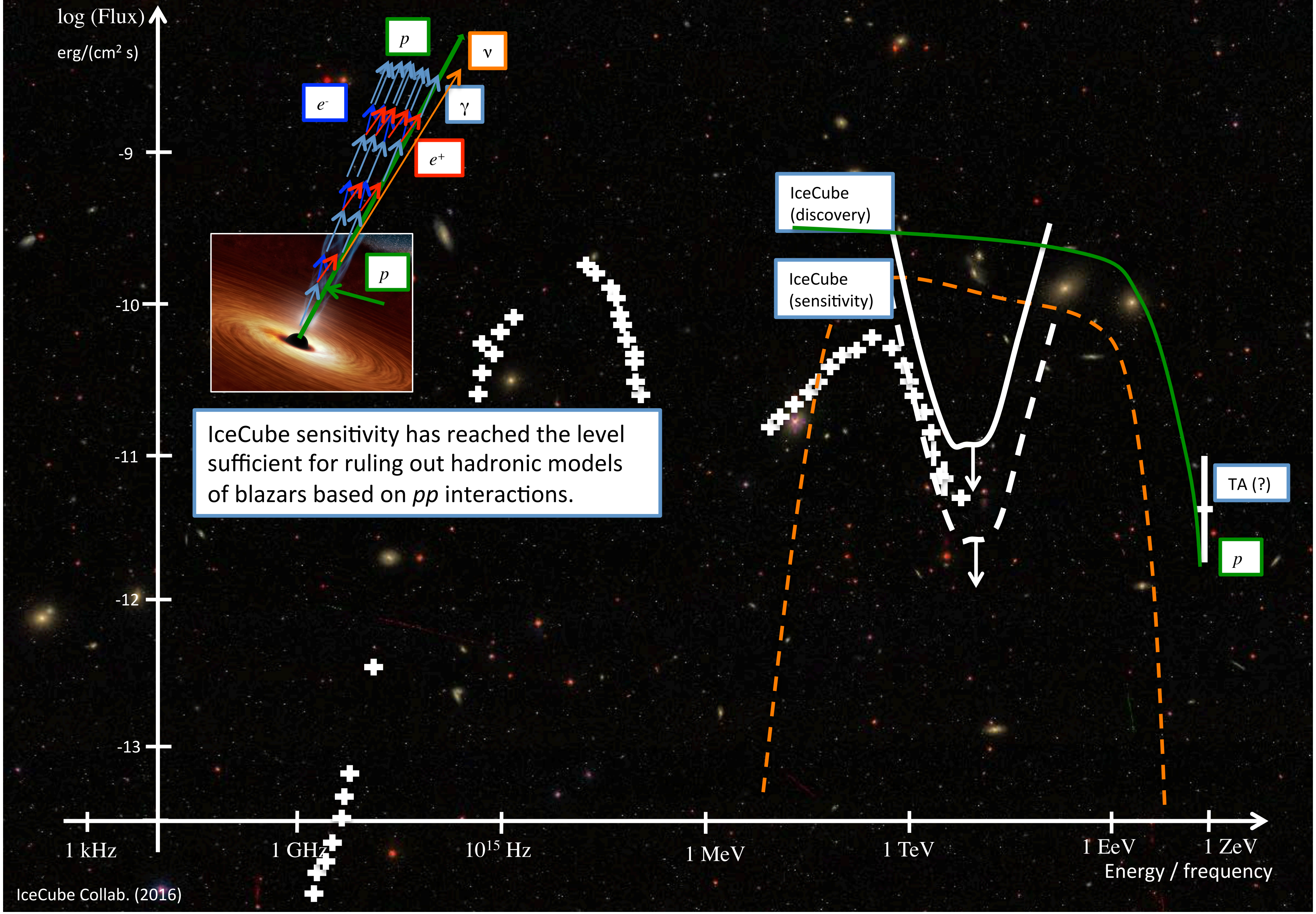
Multi-messenger signal from blazars



Reference model of high-energy emission from blazars is based on particle acceleration in relativistic jet ejected by a supermassive black hole.

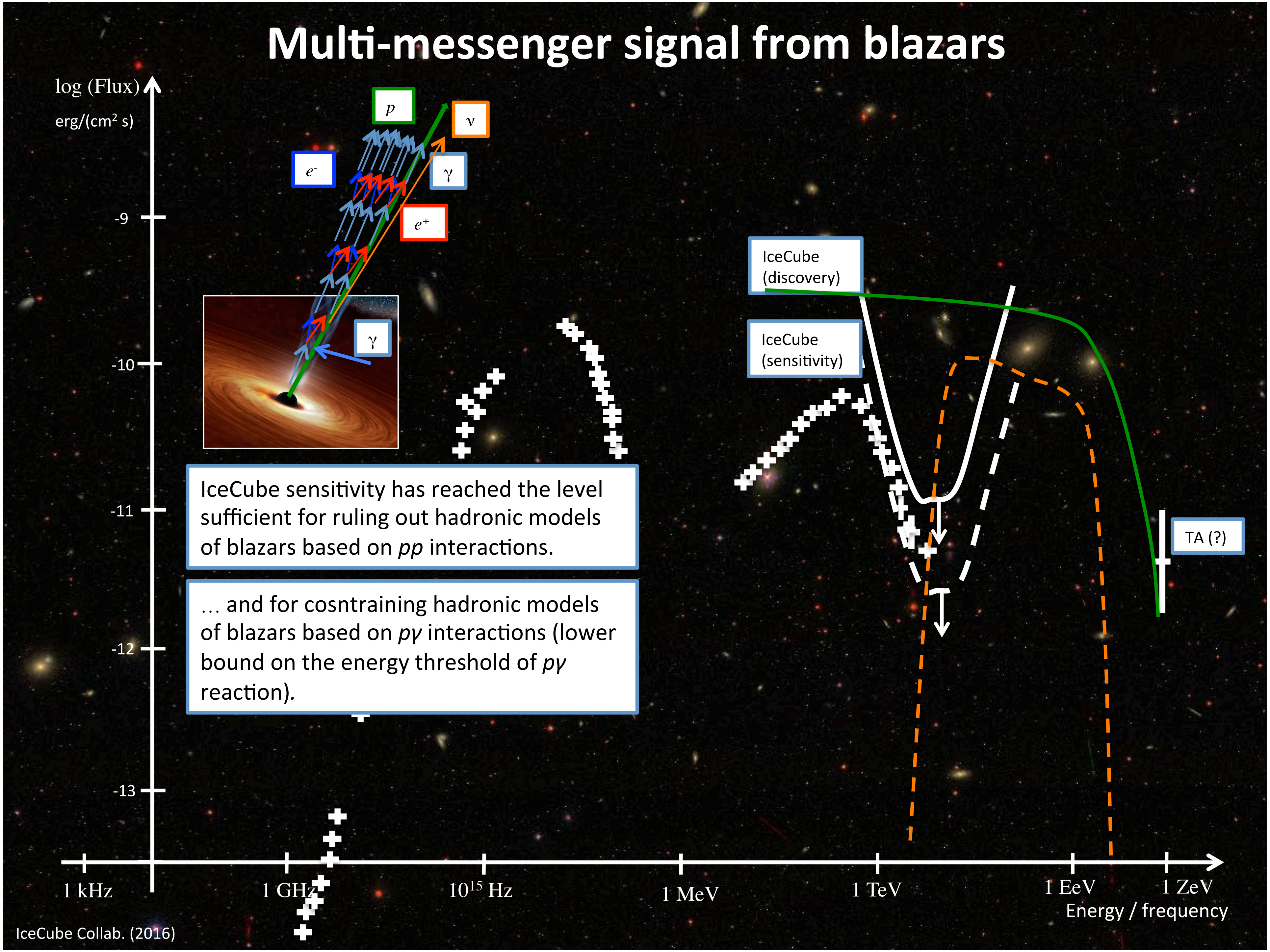
Similarly to the GRB case, it is not clear if the jet carries also high-energy protons.

Multi-messenger signal from blazars



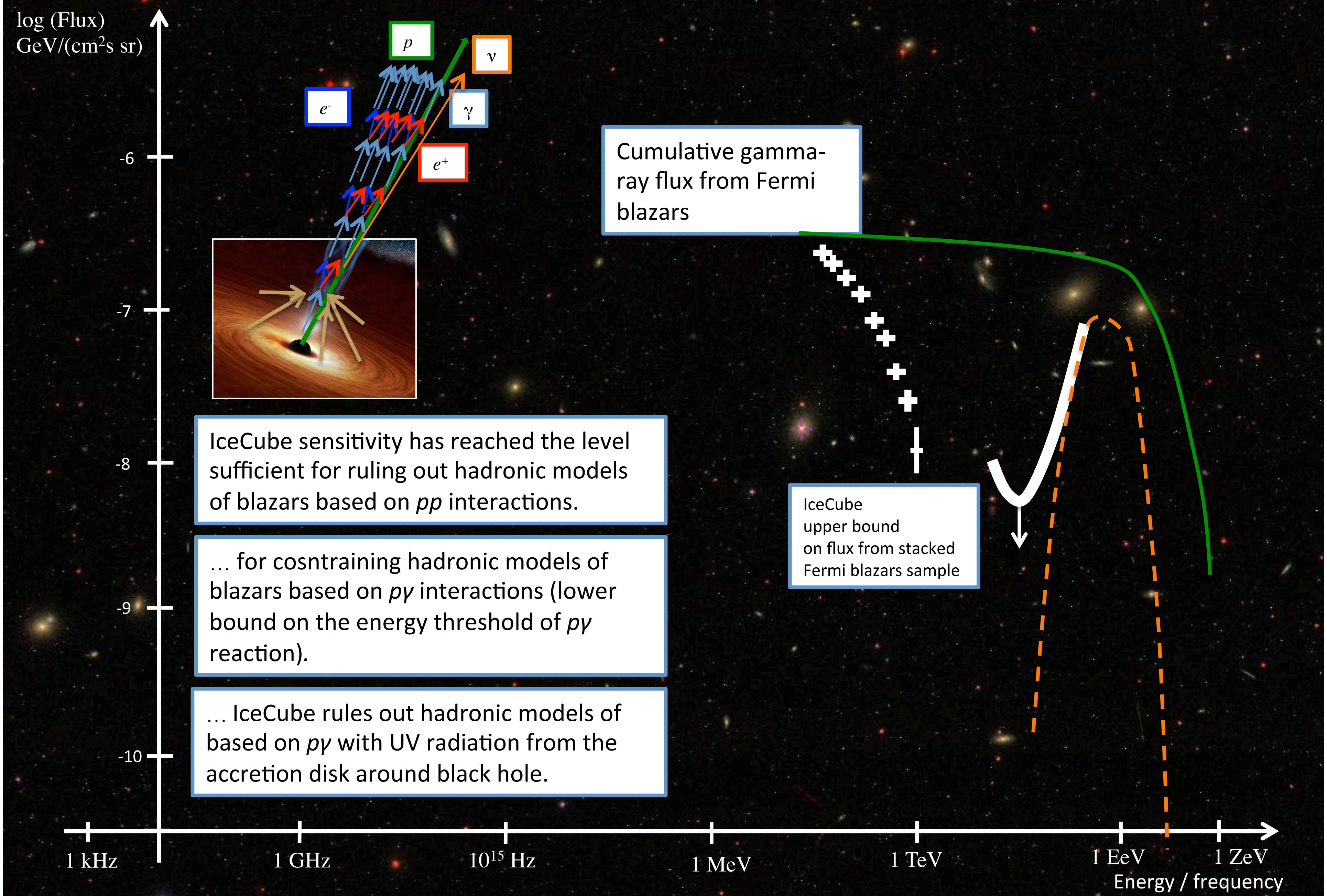
IceCube sensitivity has reached the level sufficient for ruling out hadronic models of blazars based on *pp* interactions.

IceCube Collab. (2016)



Multi-messenger signal from blazars
log (Flux)
erg/(cm² s)
-9
-10
-11
-12
-13
p
ν
e⁻
γ
e⁺
γ
IceCube (discovery)
IceCube (sensitivity)
TA (?)
IceCube sensitivity has reached the level sufficient for ruling out hadronic models of blazars based on *pp* interactions.
… and for cosntraining hadronic models of blazars based on *pγ* interactions (lower bound on the energy threshold of *pγ* reaction).
1 kHz
1 GHz
10¹⁵ Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency
IceCube Collab. (2016)

Multi-messenger signal from blazars

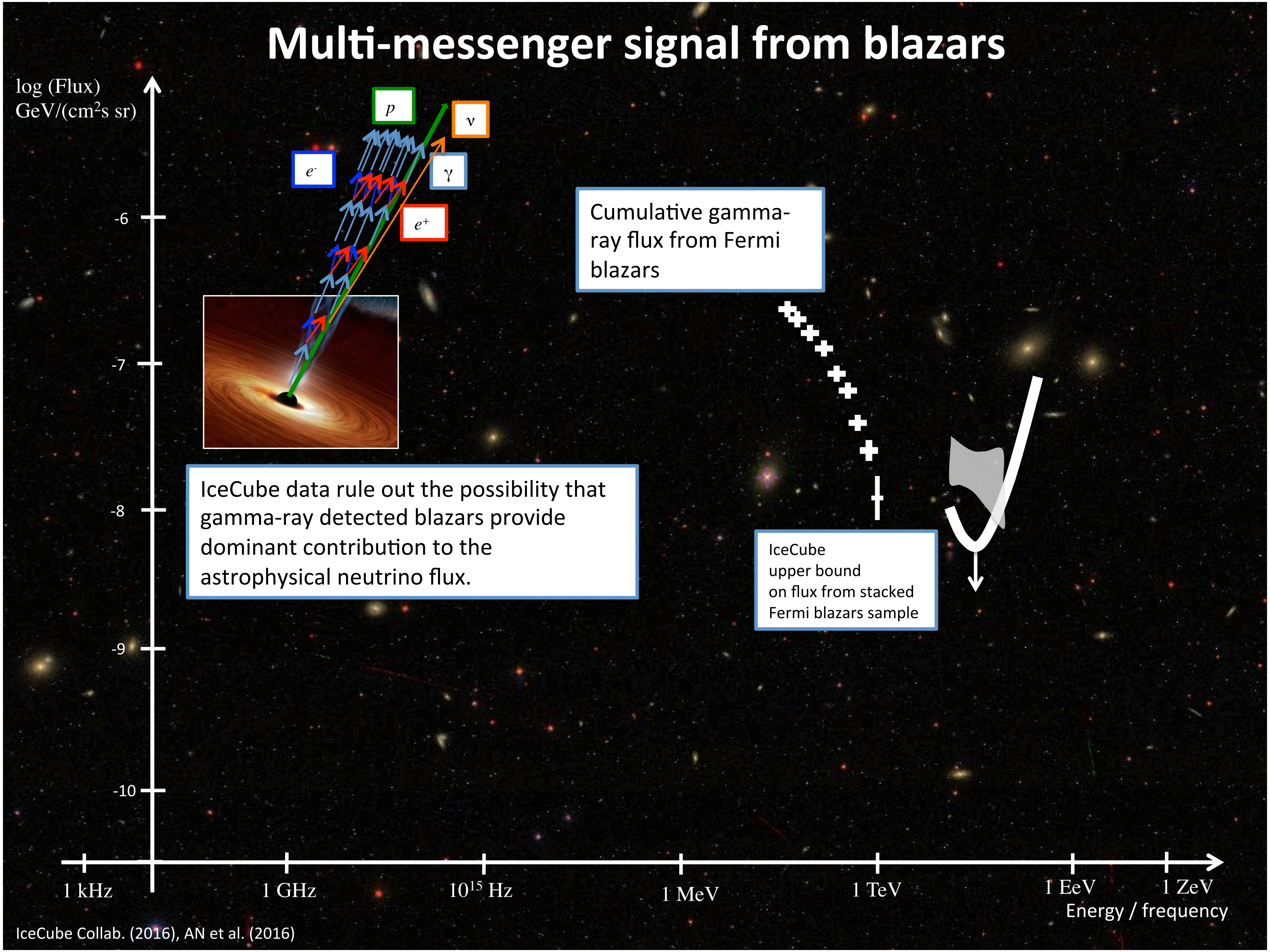


IceCube sensitivity has reached the level sufficient for ruling out hadronic models of blazars based on *pp* interactions.

… for cosntraining hadronic models of blazars based on *pγ* interactions (lower bound on the energy threshold of *pγ* reaction).

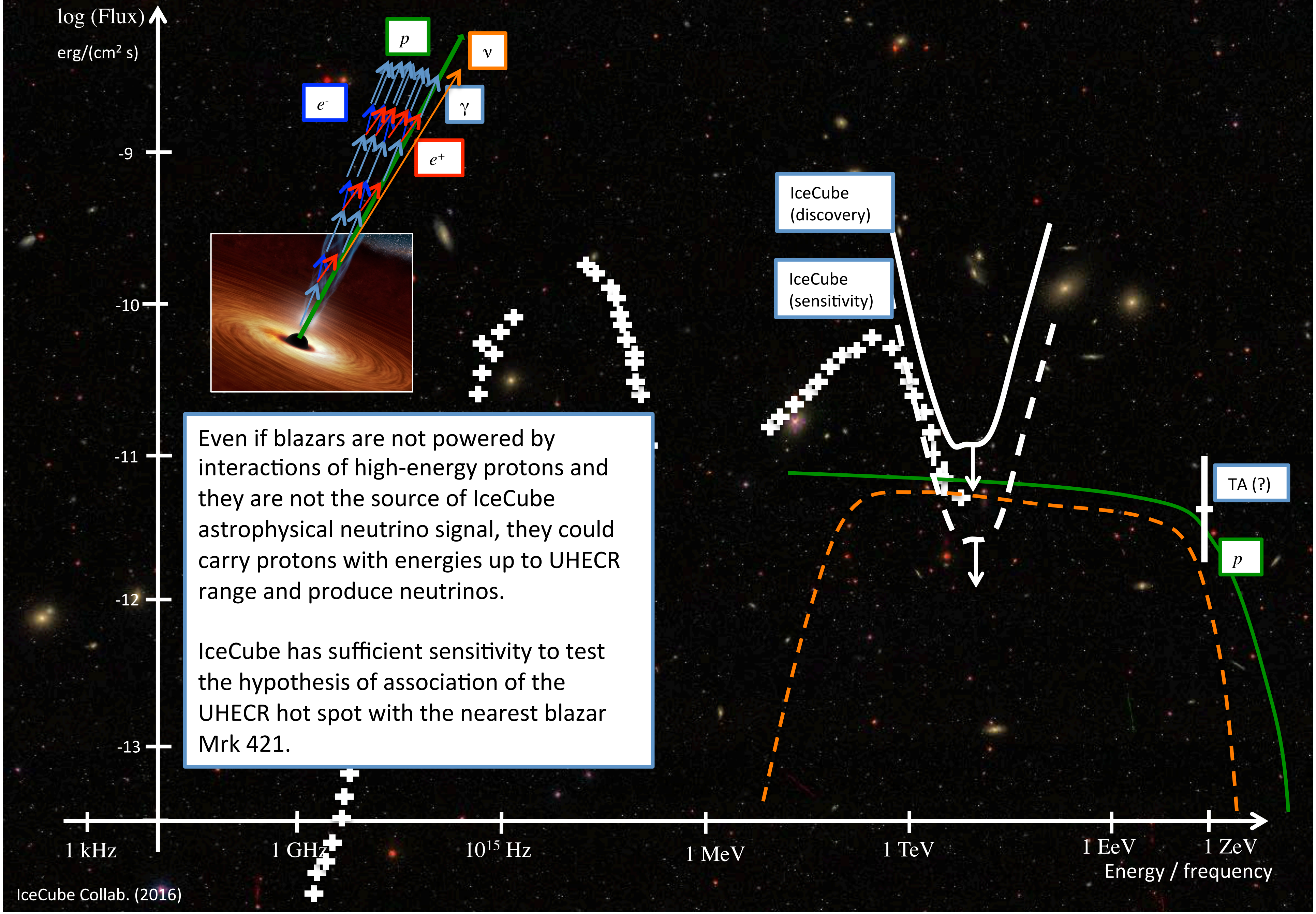
… IceCube rules out hadronic models of based on *pγ* with UV radiation from the accretion disk around black hole.

IceCube Collab. (2016), AN et al. (2016)



Multi-messenger signal from blazars
log (Flux)
GeV/(cm²s sr)
-6
-7
-8
-9
-10
p
ν
e⁻
γ
e⁺
Cumulative gamma-ray flux from Fermi blazars
IceCube data rule out the possibility that gamma-ray detected blazars provide dominant contribution to the astrophysical neutrino flux.
IceCube upper bound on flux from stacked Fermi blazars sample
1 kHz
1 GHz
10¹⁵ Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency
IceCube Collab. (2016), AN et al. (2016)

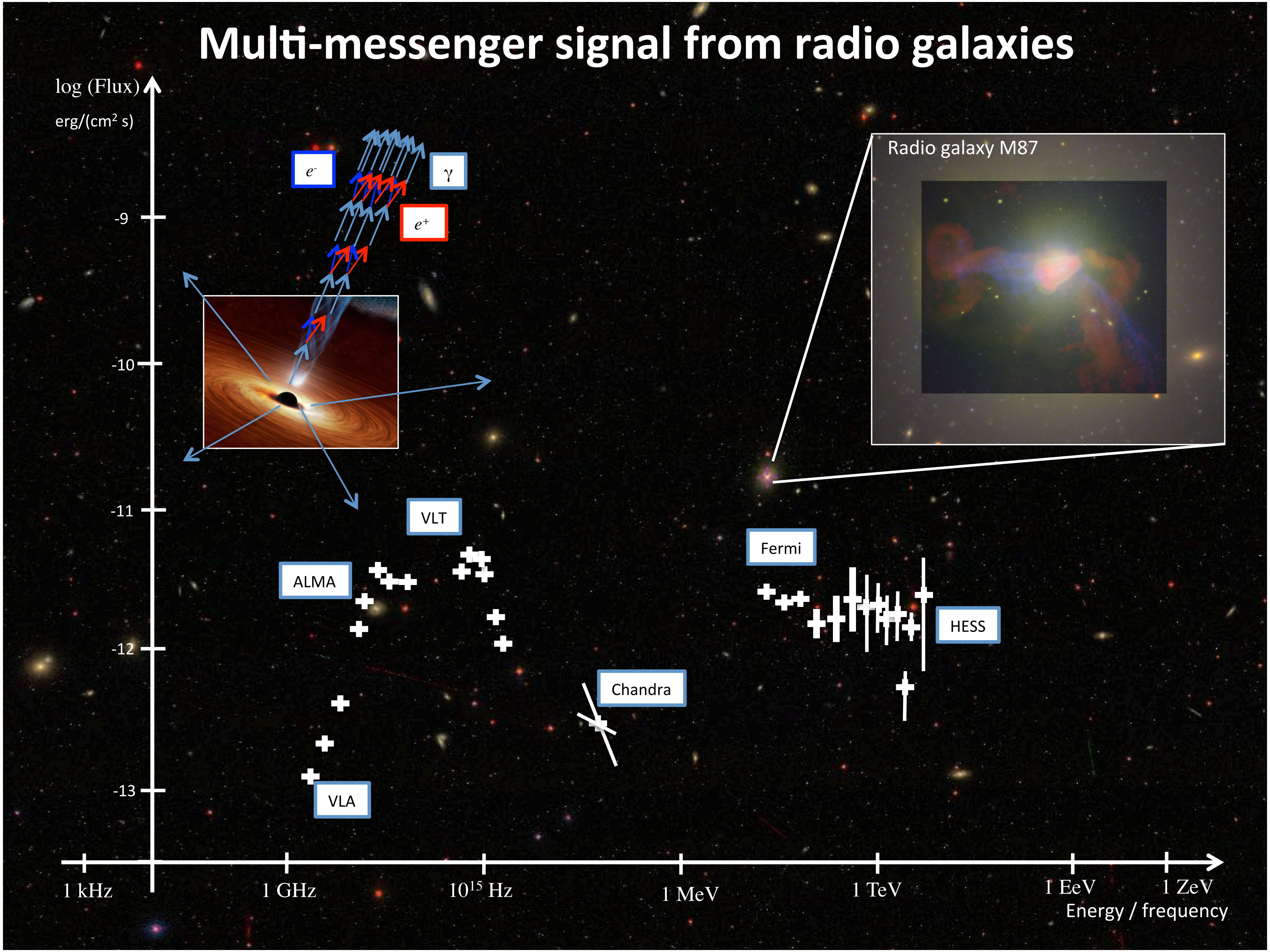
Multi-messenger signal from blazars

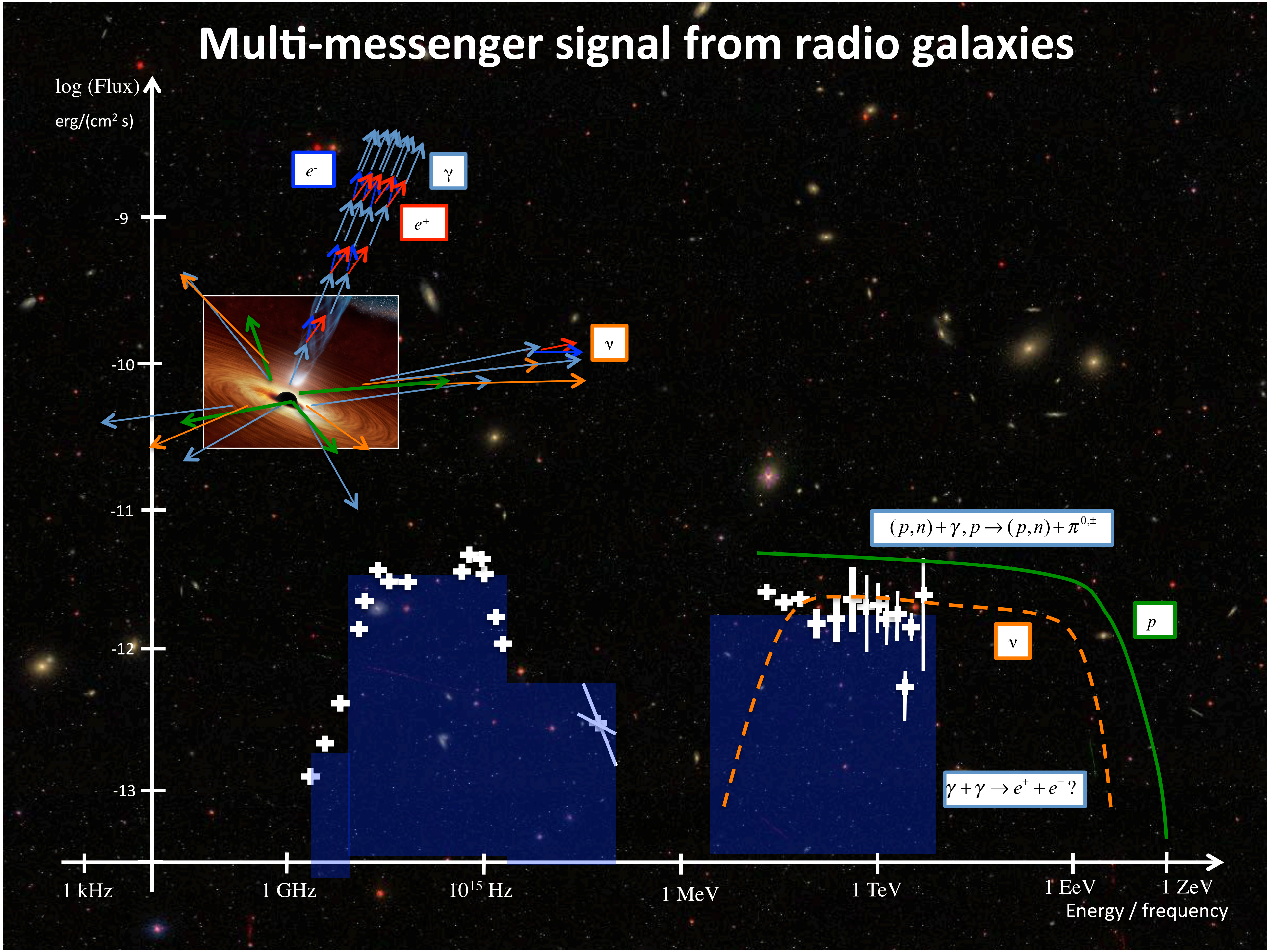


Even if blazars are not powered by interactions of high-energy protons and they are not the source of IceCube astrophysical neutrino signal, they could carry protons with energies up to UHECR range and produce neutrinos.

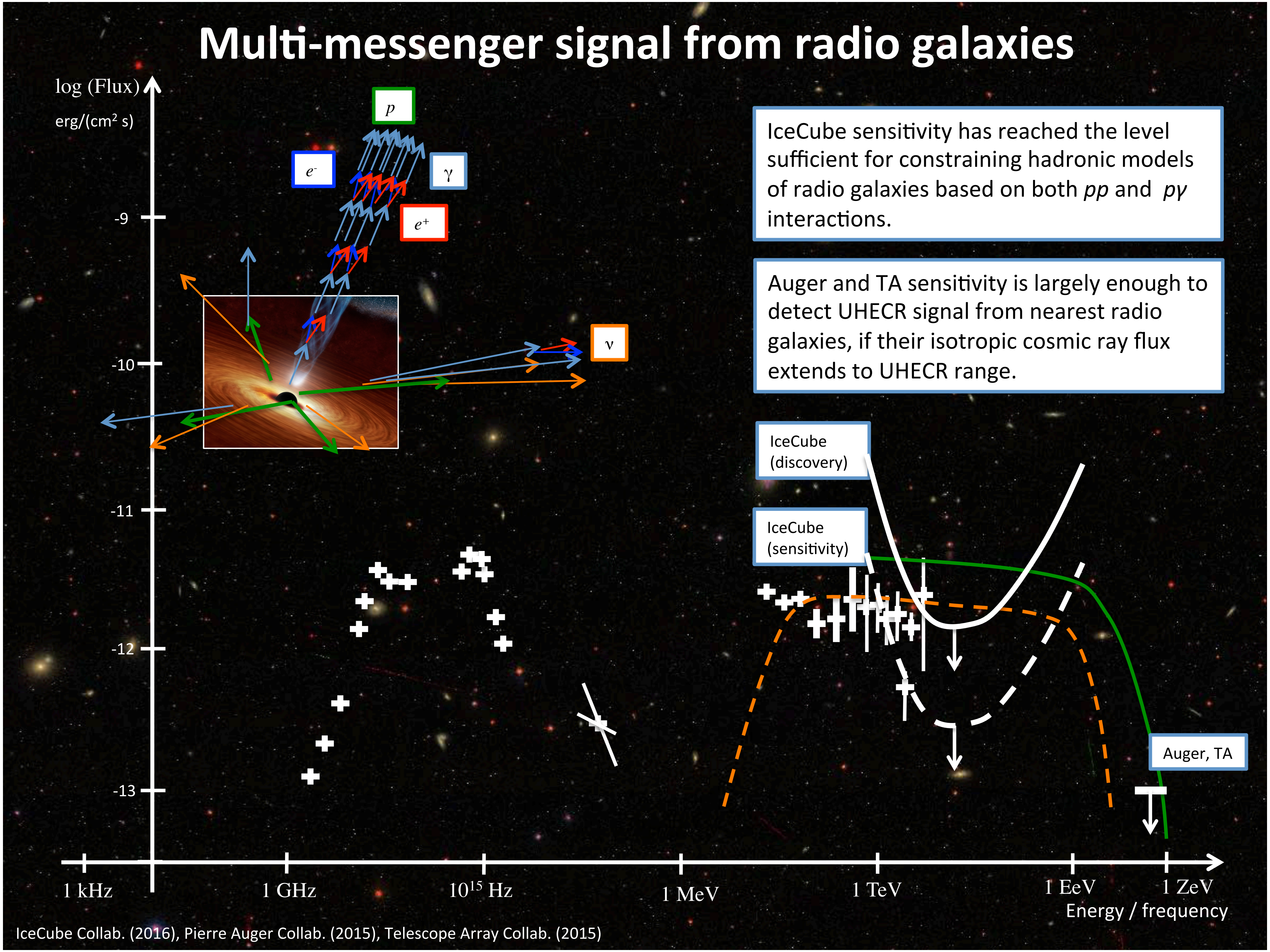
IceCube has sufficient sensitivity to test the hypothesis of association of the UHECR hot spot with the nearest blazar Mrk 421.

IceCube Collab. (2016)

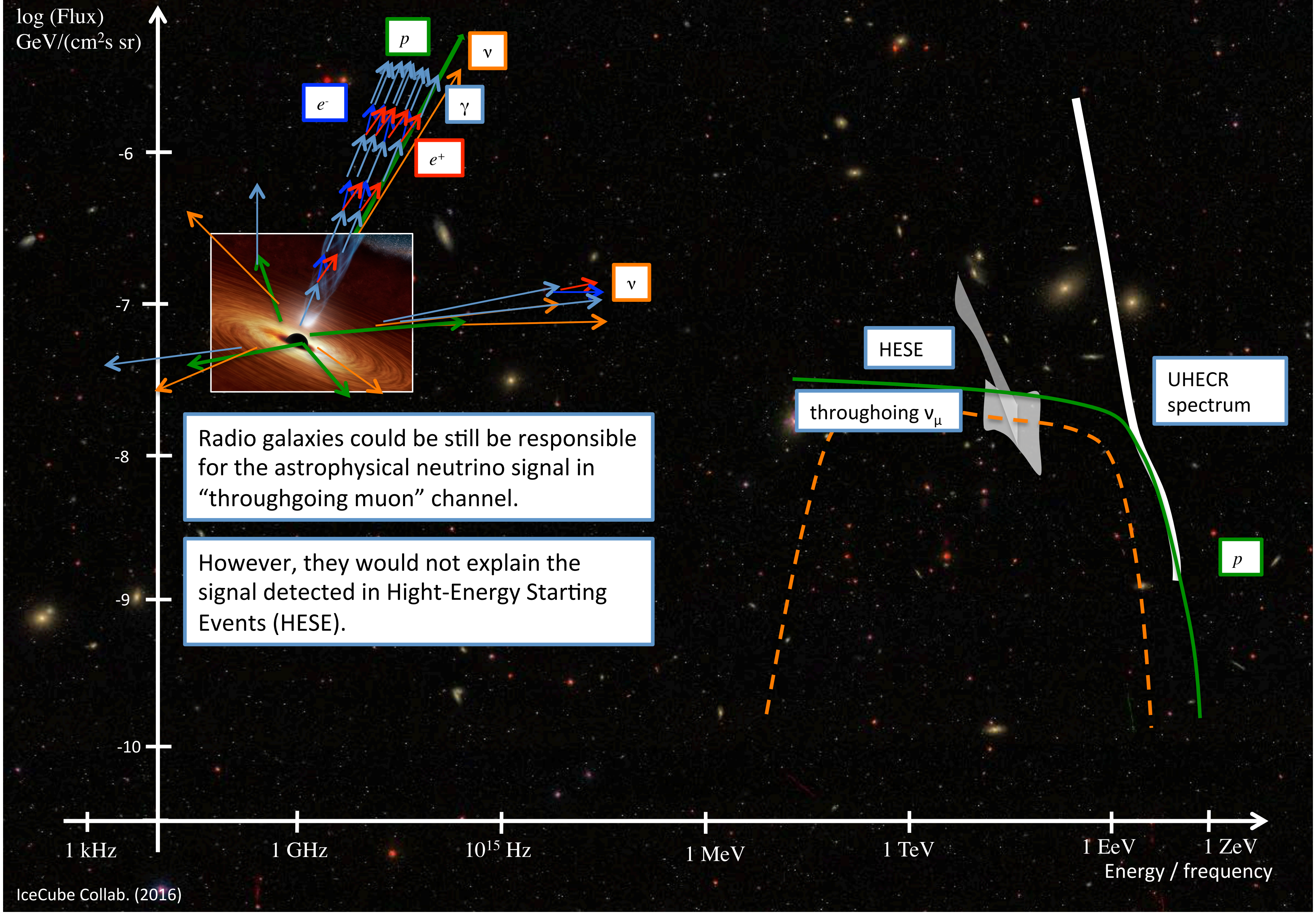

Multi-messenger signal from radio galaxies
log (Flux)
erg/(cm² s)
-9
-10
-11
-12
-13
e⁻
γ
e⁺
Radio galaxy M87
VLT
ALMA
Fermi
HESS
Chandra
VLA
1 kHz
1 GHz
10¹⁵ Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency



Multi-messenger signal from radio galaxies
log (Flux)
erg/(cm² s)
-9
-10
-11
-12
-13
e⁻
γ
e⁺
ν
$(p,n)+\gamma, p \rightarrow (p,n)+\pi^{0,\pm}$
ν
p
$\gamma+\gamma \rightarrow e^{+}+e^{-}$?
1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency

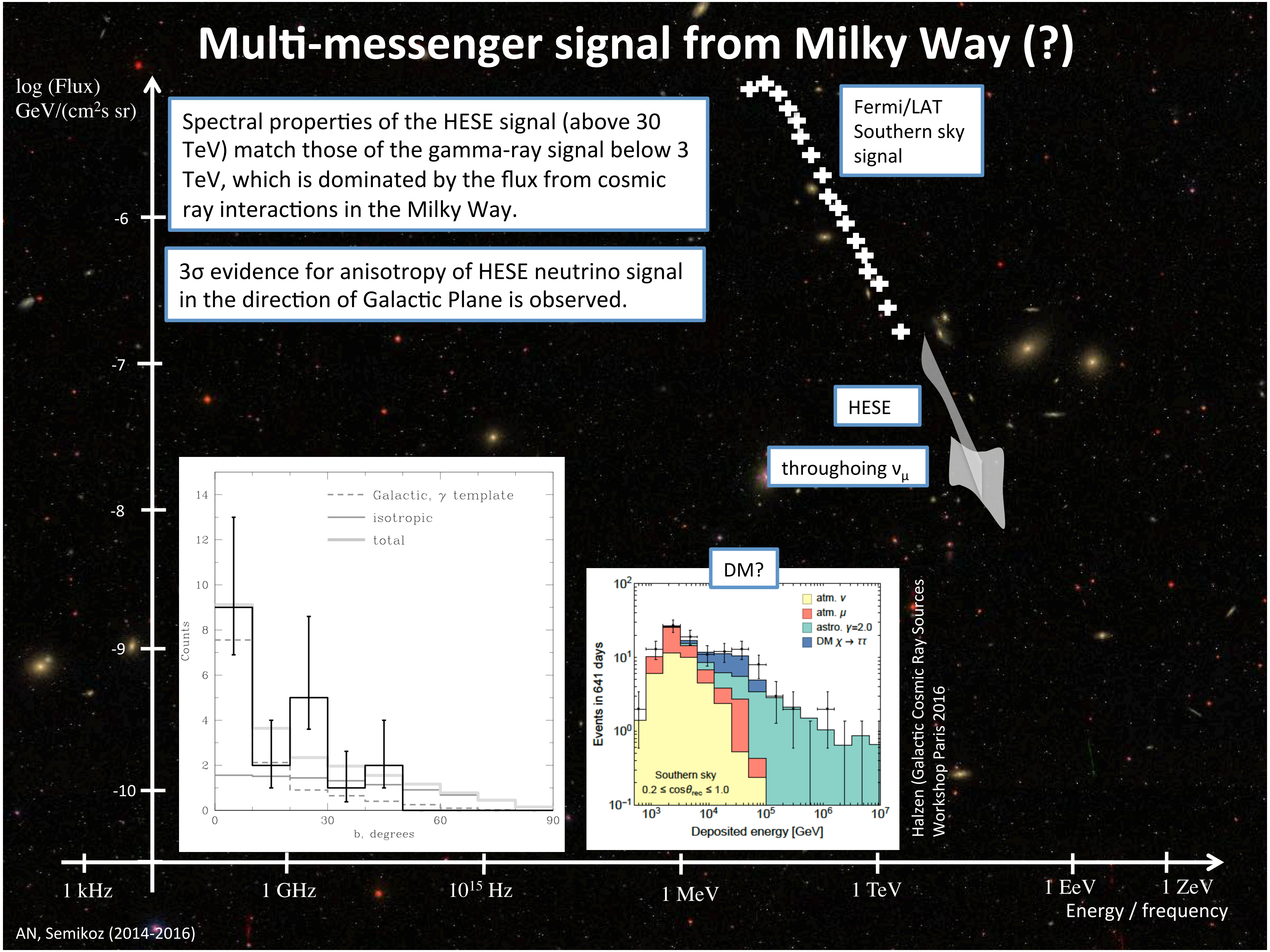

Multi-messenger signal from radio galaxies
log (Flux)
erg/(cm² s)
-9
-10
-11
-12
-13
p
e-
γ
e+
ν
1 kHz
1 GHz
10^15 Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency
IceCube sensitivity has reached the level sufficient for constraining hadronic models of radio galaxies based on both pp and pγ interactions.
Auger and TA sensitivity is largely enough to detect UHECR signal from nearest radio galaxies, if their isotropic cosmic ray flux extends to UHECR range.
IceCube (discovery)
IceCube (sensitivity)
Auger, TA
IceCube Collab. (2016), Pierre Auger Collab. (2015), Telescope Array Collab. (2015)

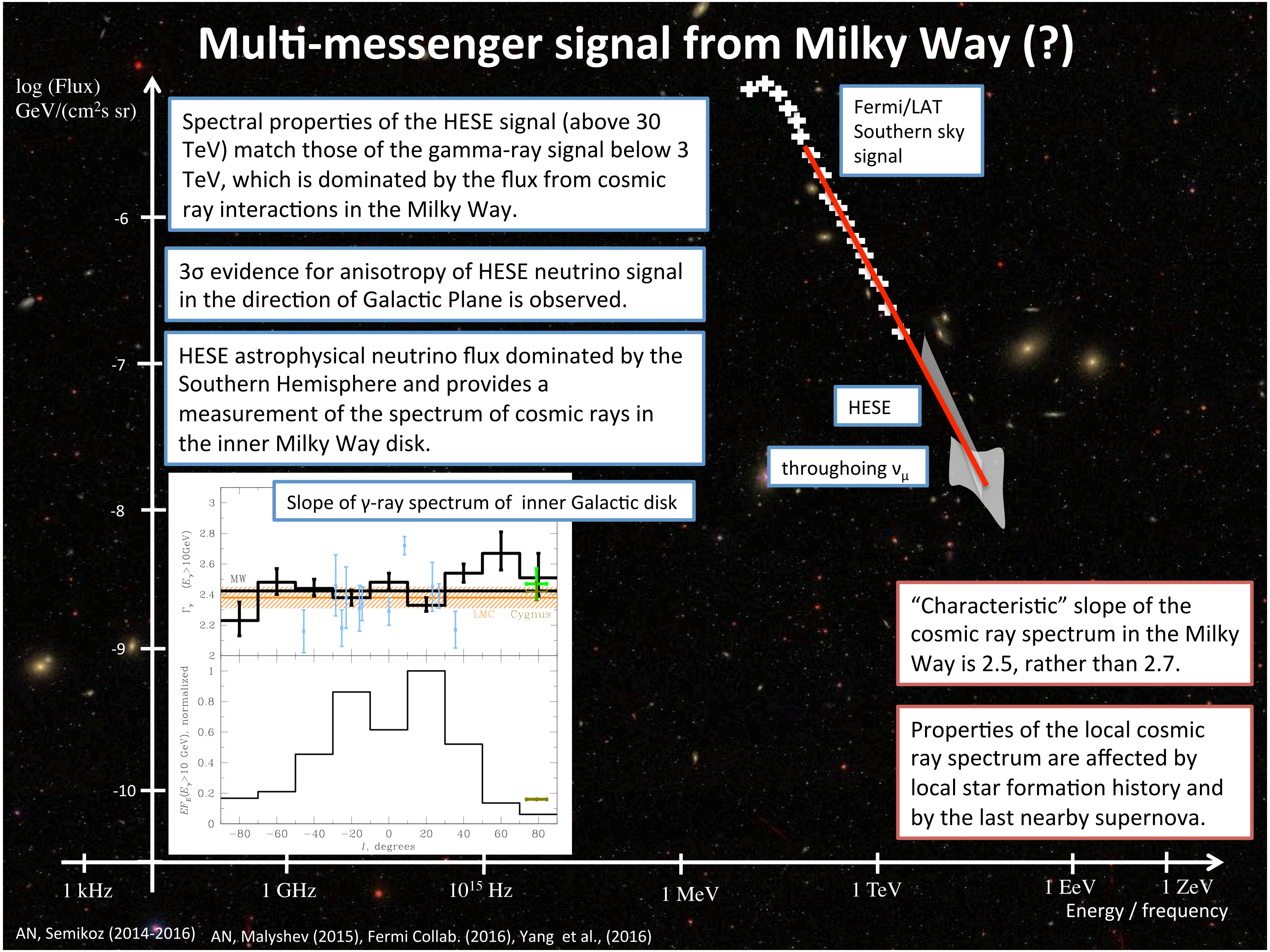
Multi-messenger signal from radio galaxies



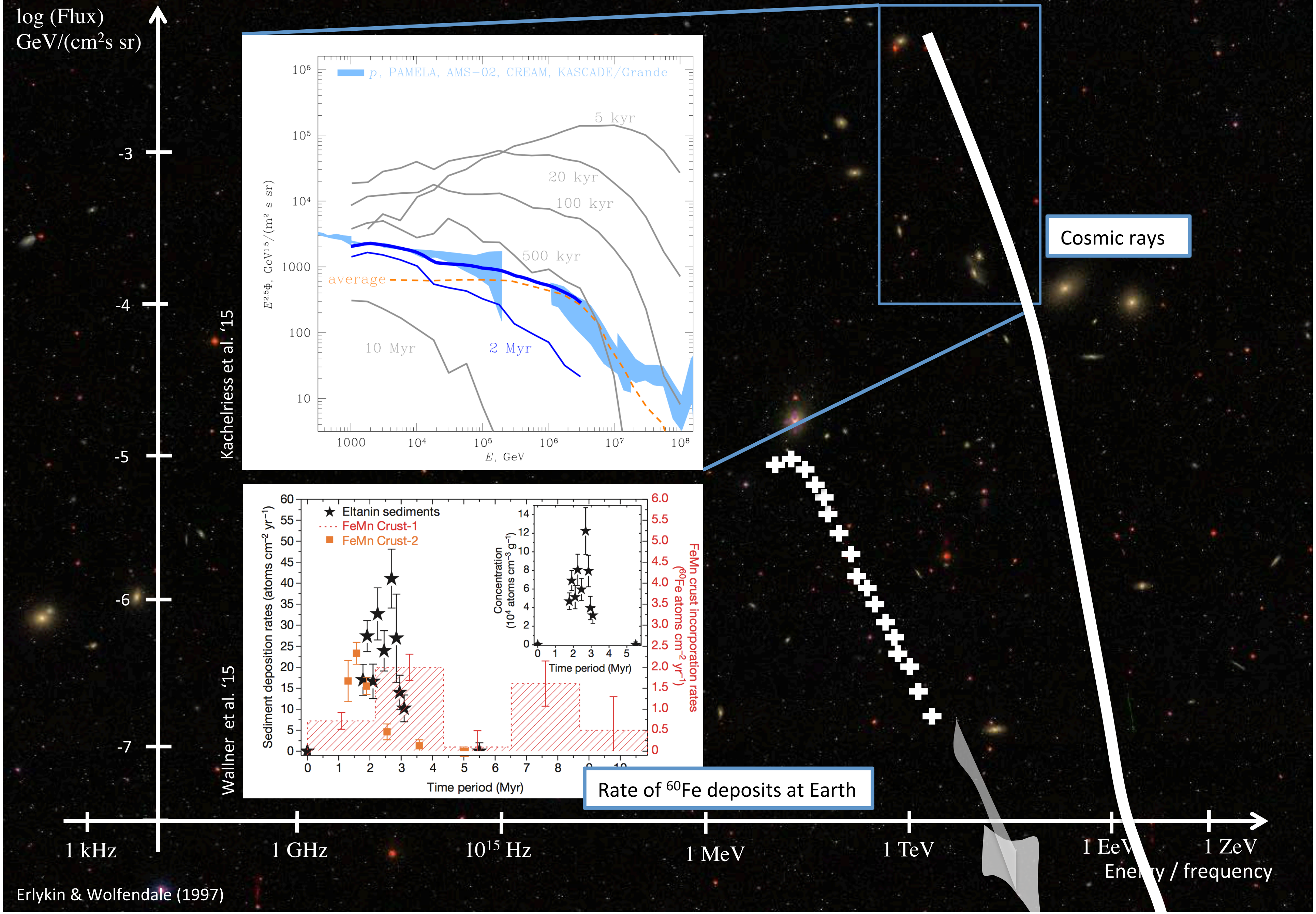
Radio galaxies could be still be responsible for the astrophysical neutrino signal in "throughgoing muon" channel.

However, they would not explain the signal detected in Hight-Energy Starting Events (HESE).


Multi-messenger signal from Milky Way (?)
log (Flux)
GeV/(cm²s sr)
Spectral properties of the HESE signal (above 30 TeV) match those of the gamma-ray signal below 3 TeV, which is dominated by the flux from cosmic ray interactions in the Milky Way.
3σ evidence for anisotropy of HESE neutrino signal in the direction of Galactic Plane is observed.
Fermi/LAT Southern sky signal
HESE
throughoing ν_μ
DM?
-6
-7
-8
-9
-10
Galactic, γ template
isotropic
total
Counts
b, degrees
atm. ν
atm. μ
astro. γ=2.0
DM χ → ττ
Events in 641 days
Southern sky
0.2 ≤ cosθ_rec ≤ 1.0
Deposited energy [GeV]
Halzen (Galactic Cosmic Ray Sources
Workshop Paris 2016
1 kHz
1 GHz
10^15 Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency
AN, Semikoz (2014-2016)

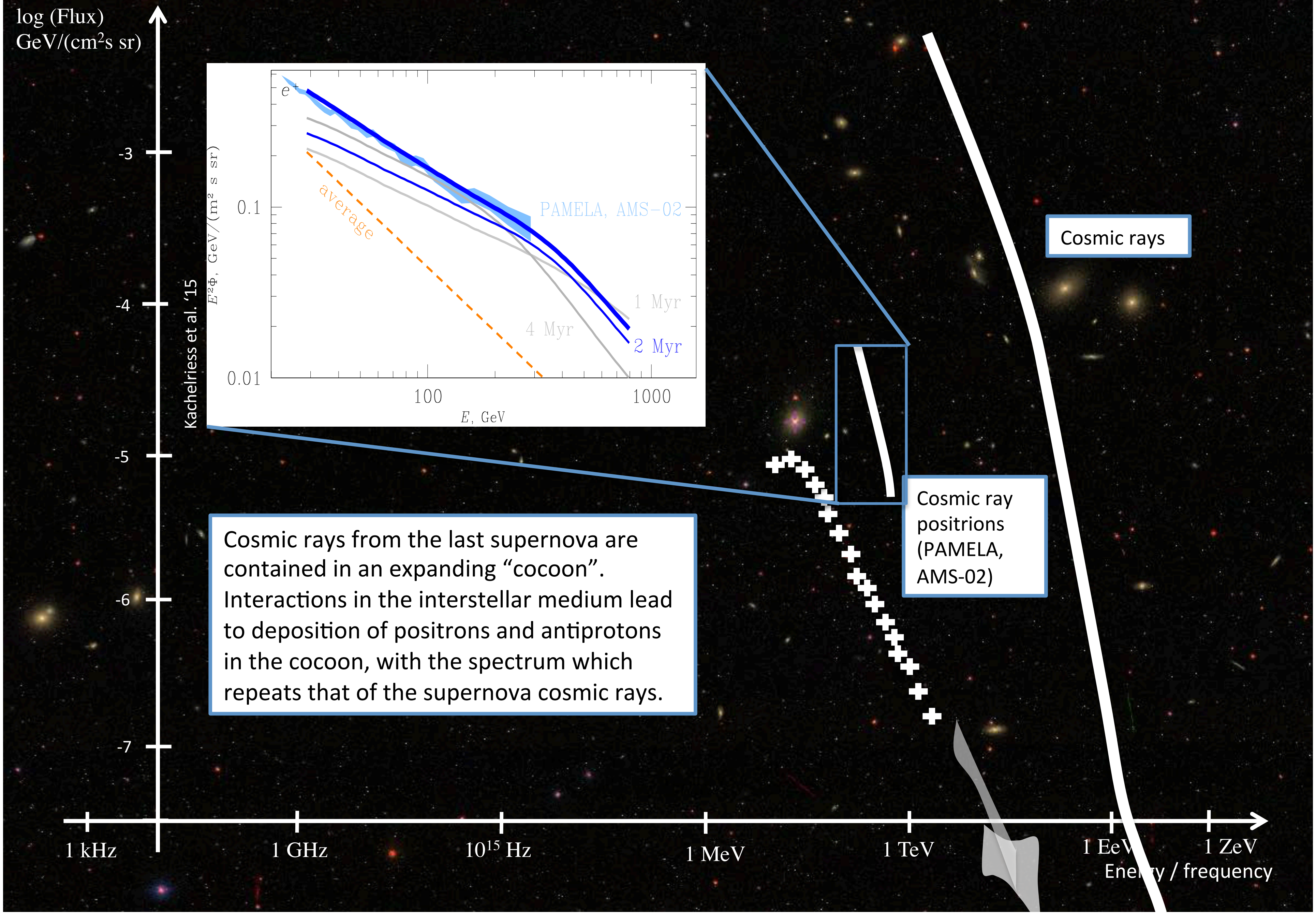

Multi-messenger signal from Milky Way (?)
log (Flux) GeV/(cm²s sr)
-6
-7
-8
-9
-10
Spectral properties of the HESE signal (above 30 TeV) match those of the gamma-ray signal below 3 TeV, which is dominated by the flux from cosmic ray interactions in the Milky Way.
3σ evidence for anisotropy of HESE neutrino signal in the direction of Galactic Plane is observed.
HESE astrophysical neutrino flux dominated by the Southern Hemisphere and provides a measurement of the spectrum of cosmic rays in the inner Milky Way disk.
Slope of γ-ray spectrum of inner Galactic disk
MW
LMC
Cygnus
Γ_γ (E_γ>10GeV)
EF_E(E_γ>10 GeV), normalized
l, degrees
Fermi/LAT Southern sky signal
HESE
throughoing ν_μ
"Characteristic" slope of the cosmic ray spectrum in the Milky Way is 2.5, rather than 2.7.
Properties of the local cosmic ray spectrum are affected by local star formation history and by the last nearby supernova.
1 kHz
1 GHz
10^{15} Hz
1 MeV
1 TeV
1 EeV
1 ZeV
Energy / frequency
AN, Semikoz (2014-2016)
AN, Malyshev (2015), Fermi Collab. (2016), Yang et al., (2016)

Multi-messenger signal from local cosmic ray source

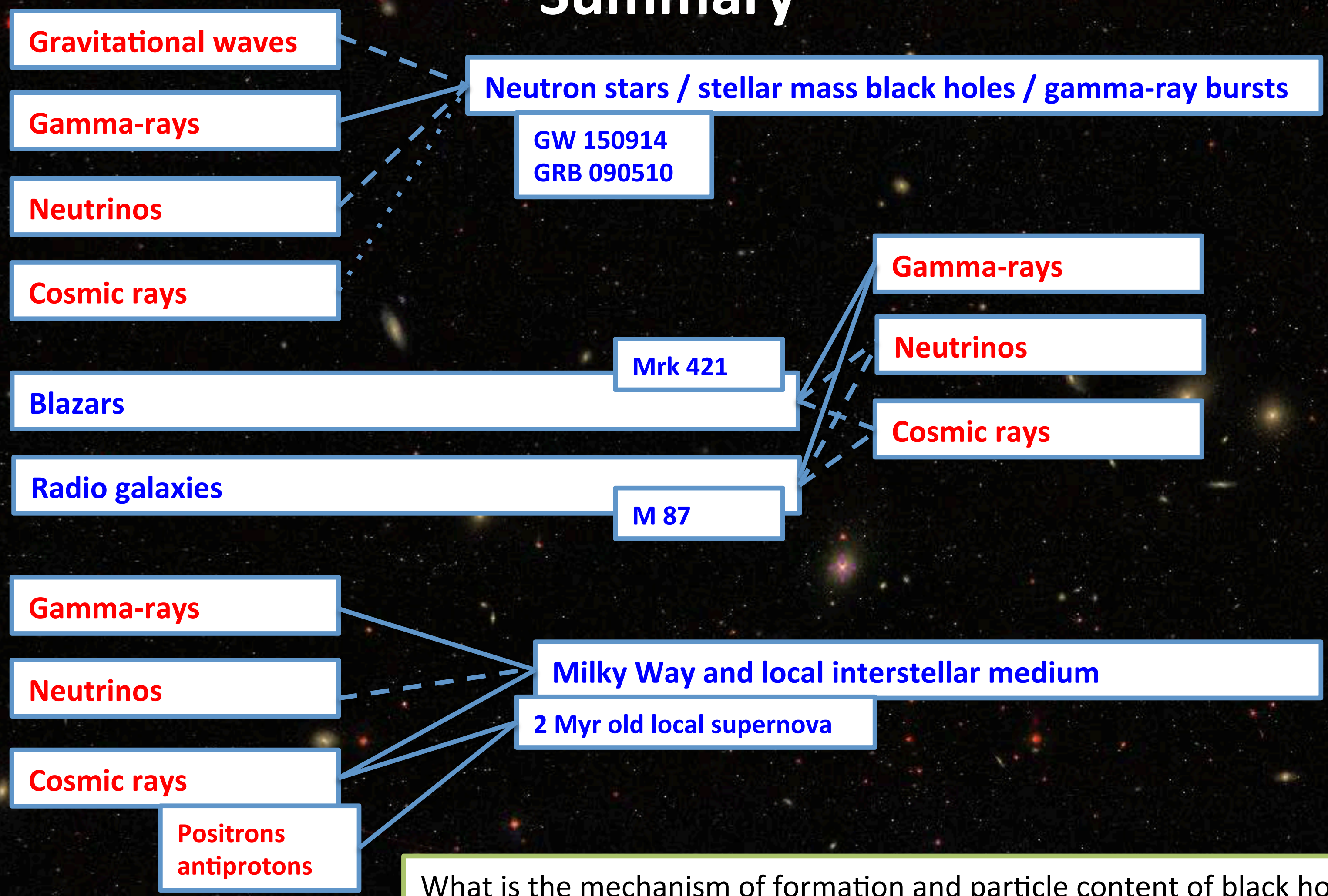


Erlykin & Wolfendale (1997)

Multi-messenger signal from local cosmic ray source



Summary



What is the mechanism of formation and particle content of black hole jets?

What extragalactic sources produce UHECR?

What Galactic source(s) produces GeV-PeV cosmic rays?

What sources produce astrophysical TeV-PeV neutrinos?

Is there unexplained multi-messenger signal which could be attributed to DM?