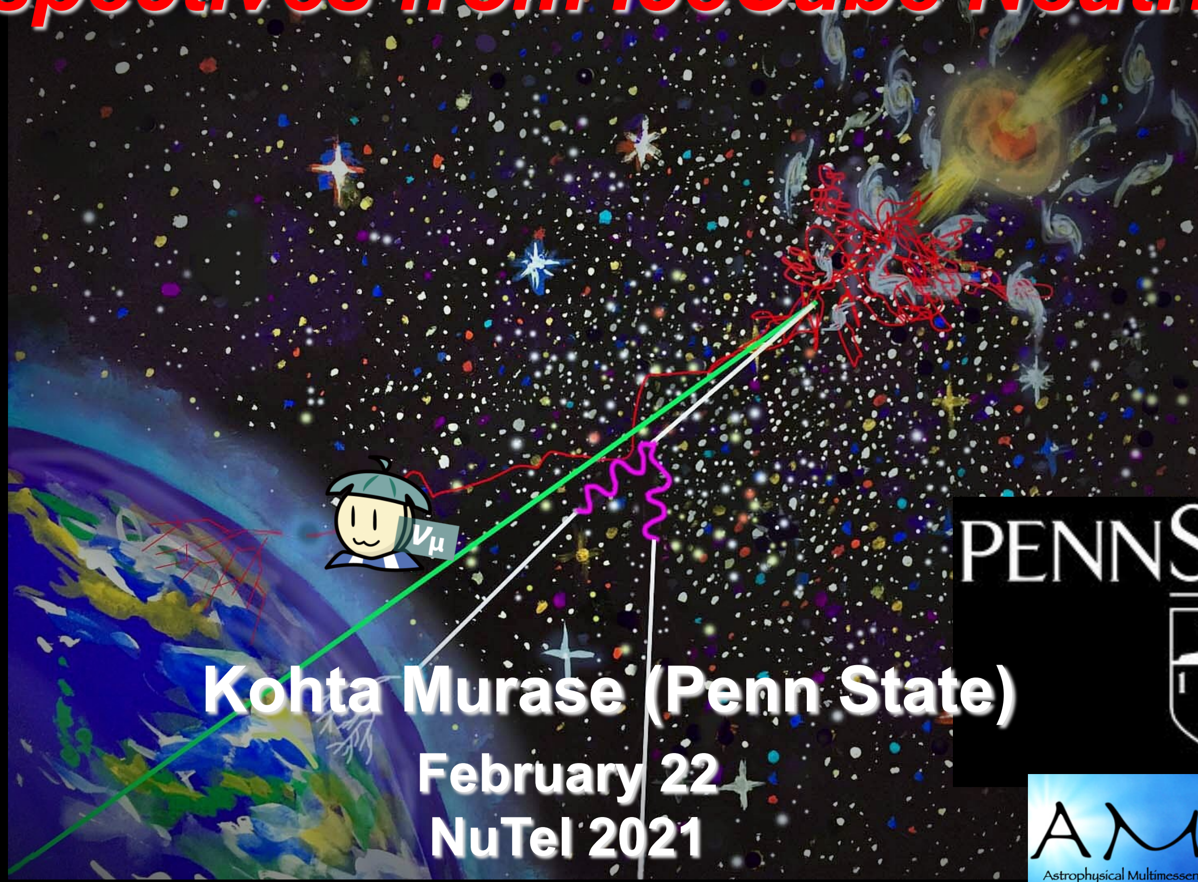
Multi-Energy Neutrino Sources: Perspectives from IceCube Neutrinos



Kohta Murase (Penn State)

February 22
NuTel 2021

PENNSTATE
1855

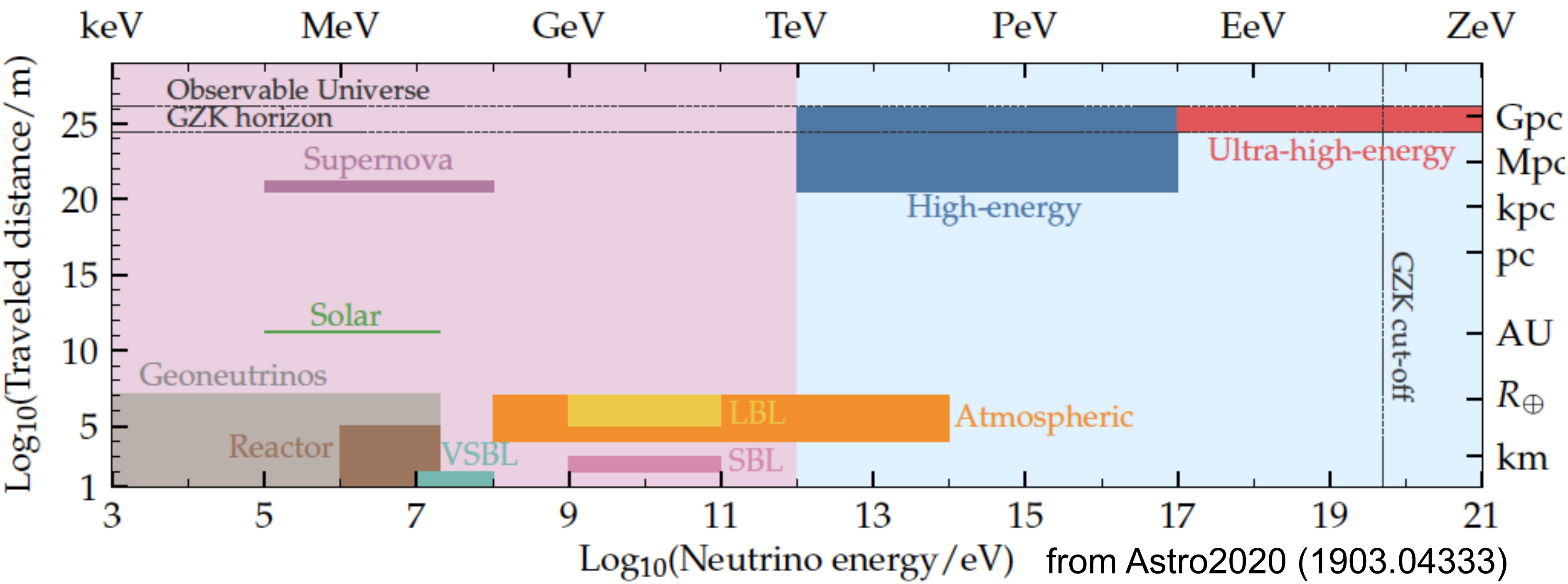
AMON
Astrophysical Multimessenger Observatory Network

NSF

Multi-Energy Neutrino Sources?

Cosmic rays are observed over 10 orders of magnitude in energy

Nonthermal spectra are generally broad (→ EM multi-wavelength)



from Astro2020 (1903.04333)

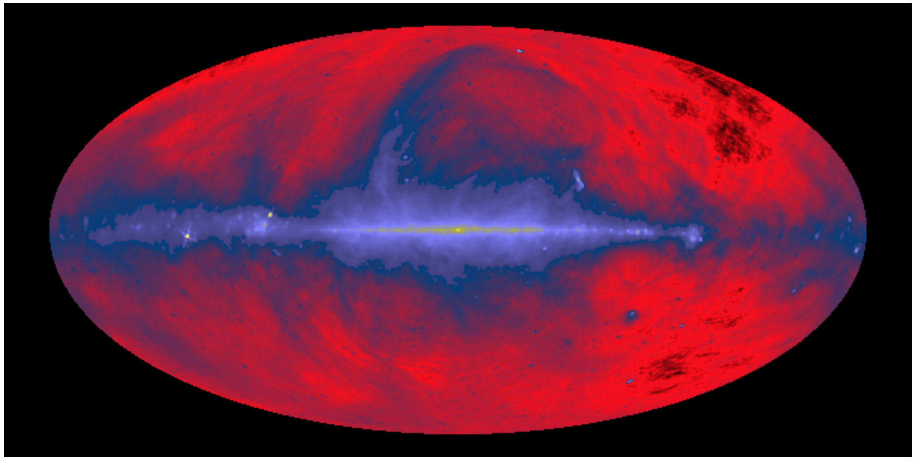
Greening the deserts

- Experimental challenges (limited by signal and/or background)
- Crucial for addressing key questions in particle astrophysics (ex. UHECR origin, CR & ν production mechanisms, BSM searches)

Multi-Wavelength Astronomy

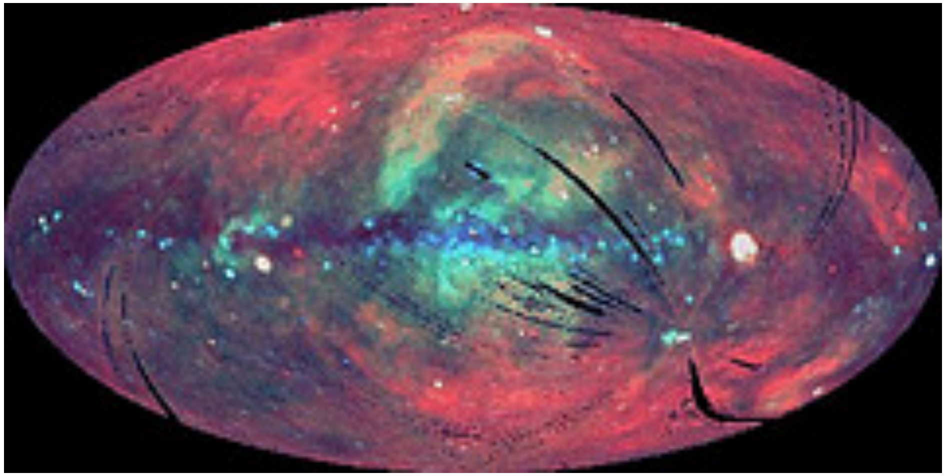
multi-wavelength astrophysics was established and is developing

Radio

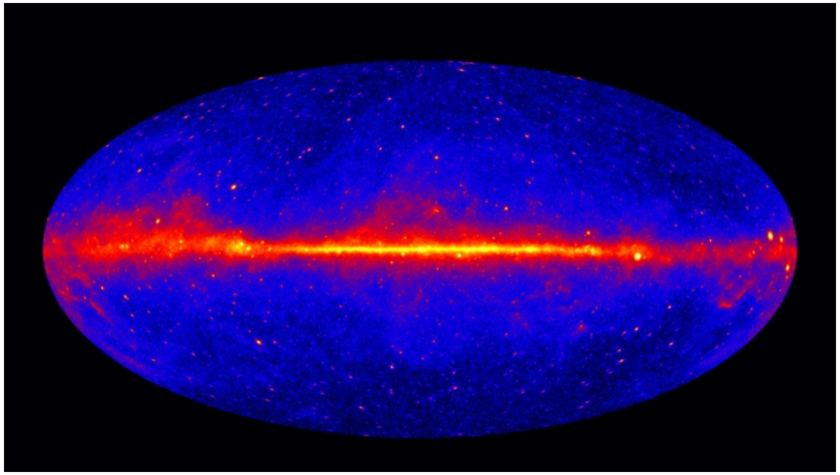


Optical

X-ray



Gamma-ray



Now: Multi-Messenger Era

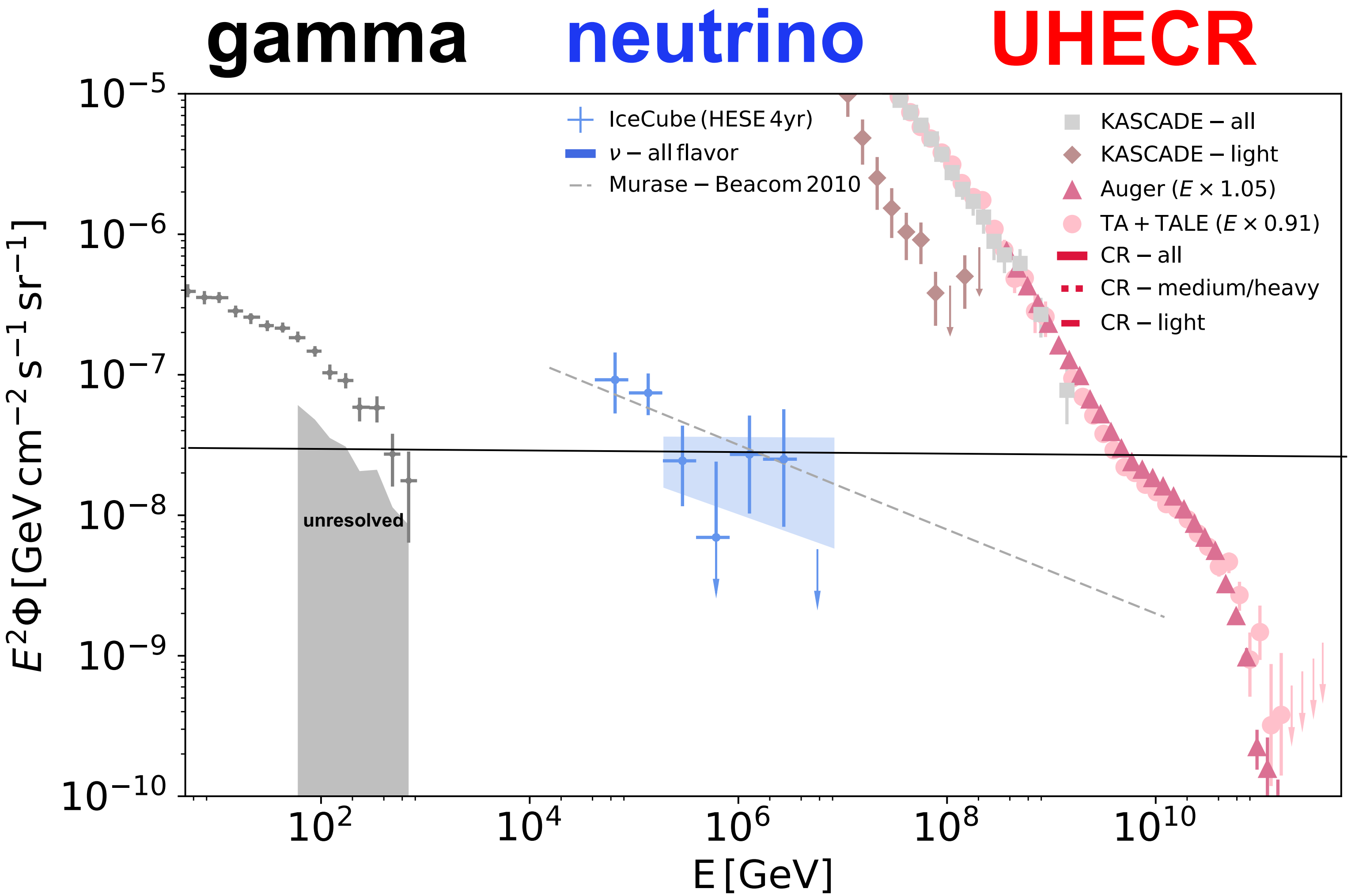
Neutron star merger
GW170817
GRB 170817A

"concordance"

Blazar flare
IceCube-170922A
TXS 0506+056

"puzzling"

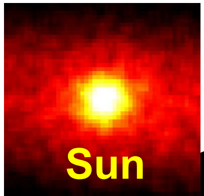
Multi-Messenger Astro-Particle "Backgrounds"



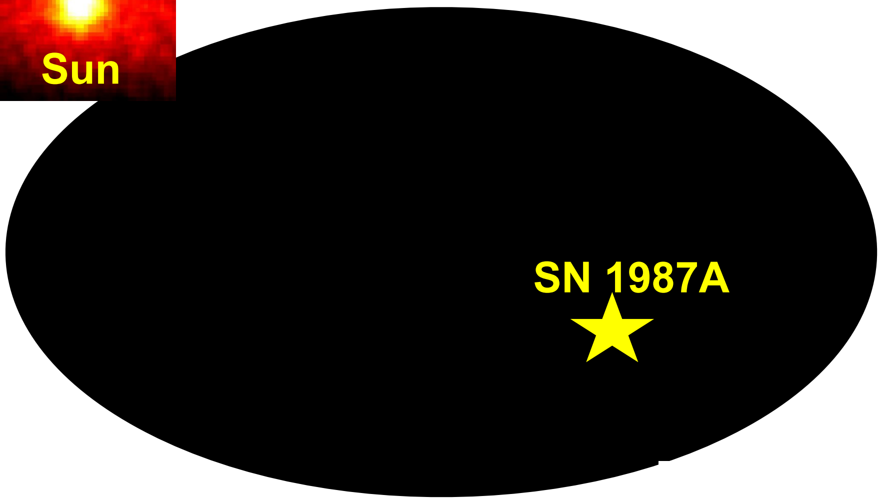
Energy generation rates of 3 messengers are comparable (ex. KM & Fukugita 19)

→ **multi-messenger & multi-energy connection**

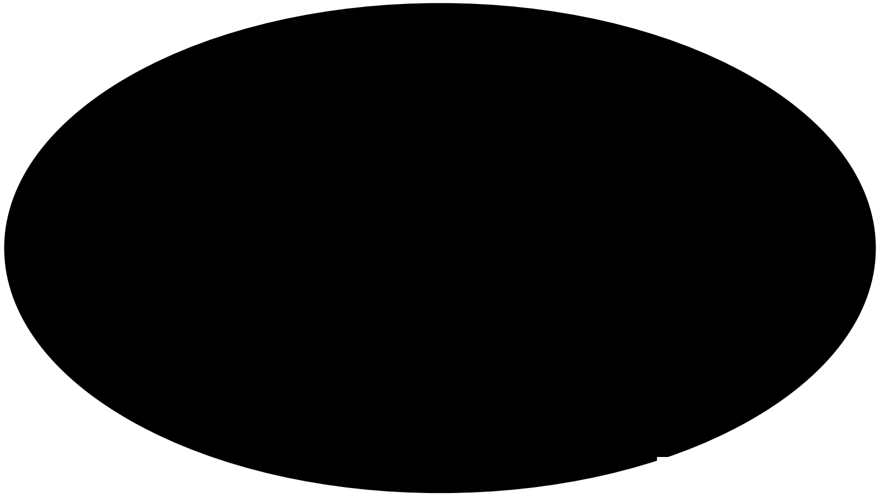
Next: Multi-Energy Neutrino Astronomy?



MeV-GeV

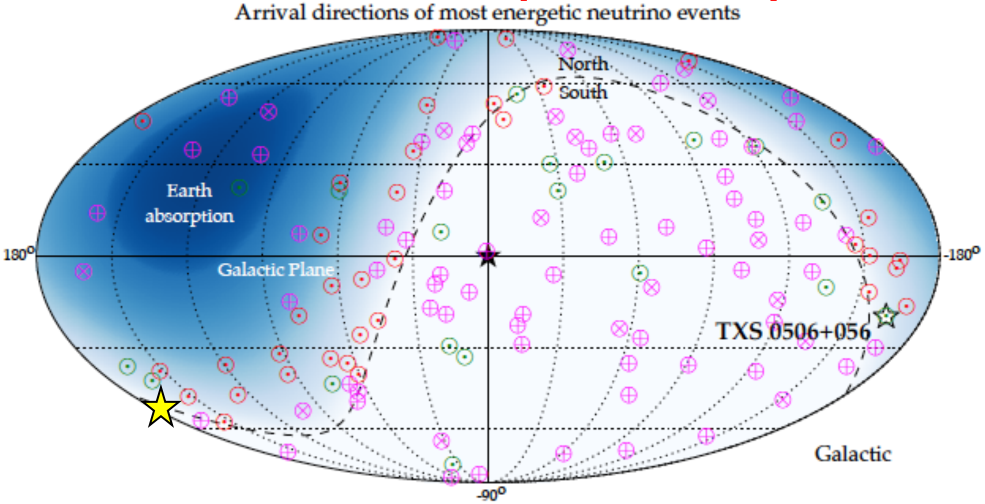


GeV-TeV

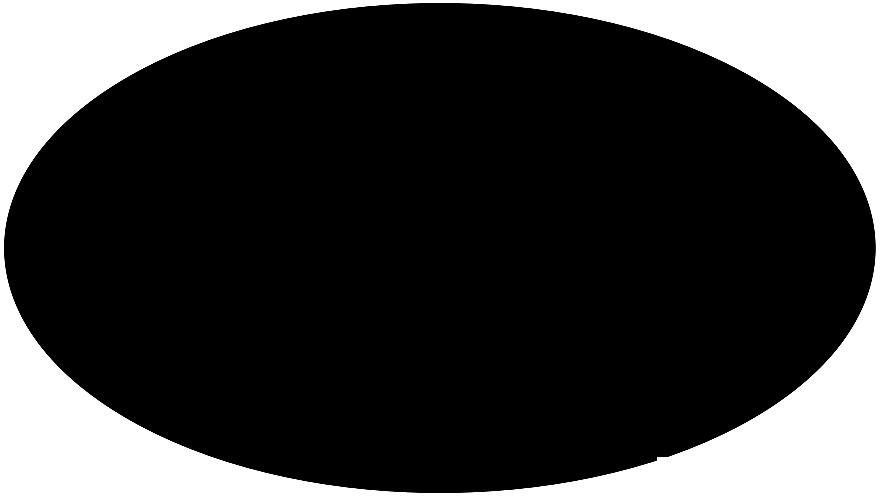


TeV-PeV (>60 TeV)

Arrival directions of most energetic neutrino events

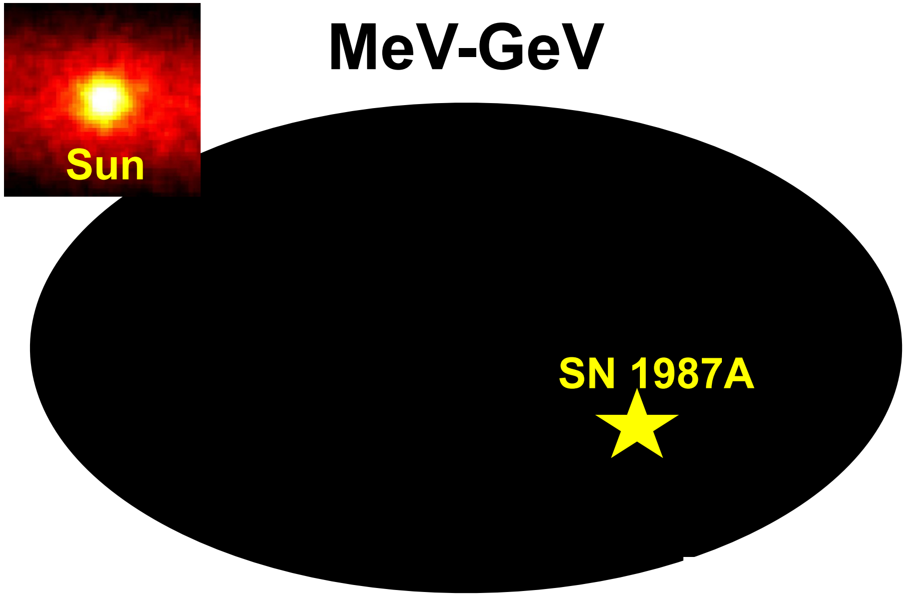


PeV-EeV

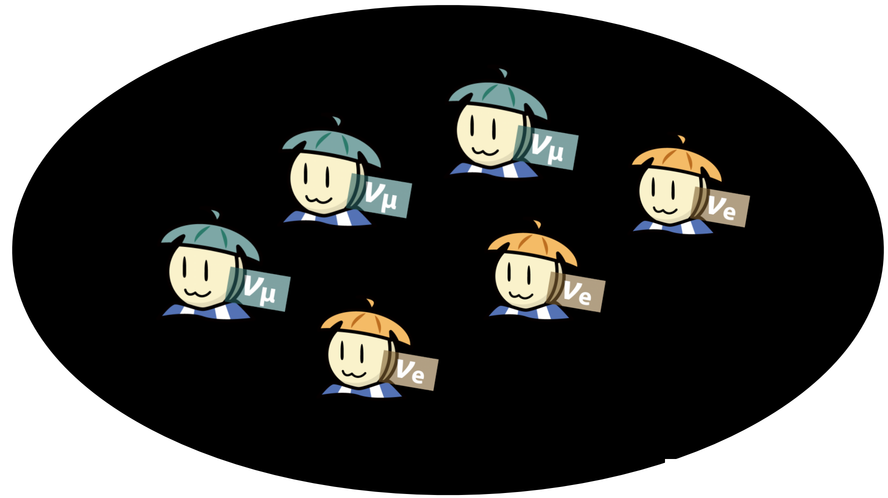


Dreaming Multi-Energy Neutrino Astronomy…

MeV-GeV

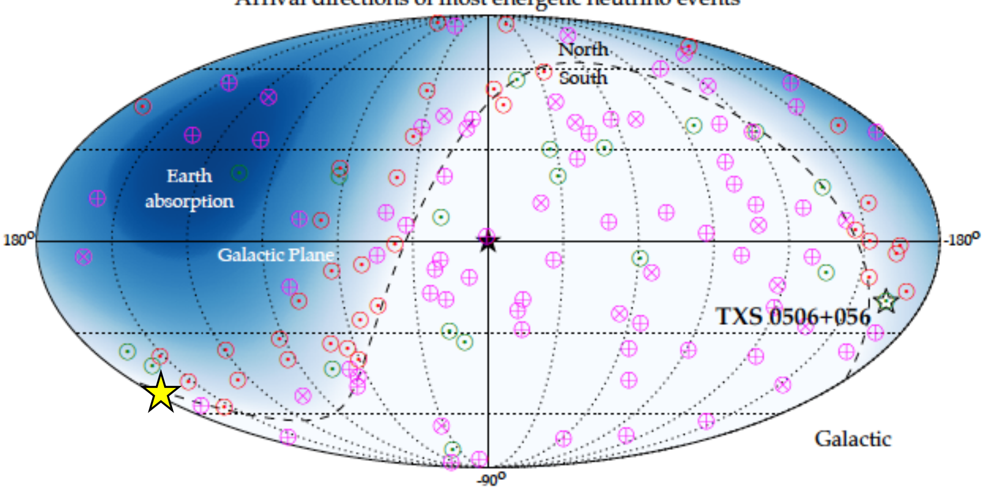


GeV-TeV

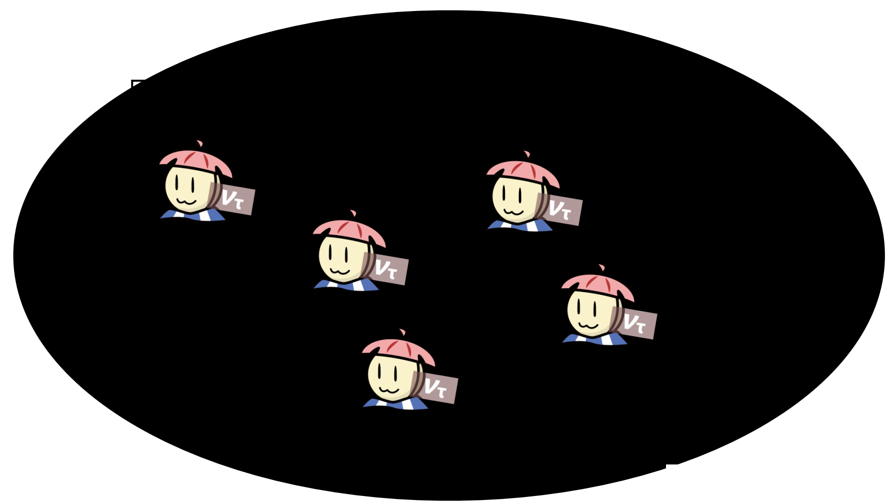


TeV-PeV (>60 TeV)

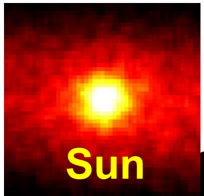
Arrival directions of most energetic neutrino events



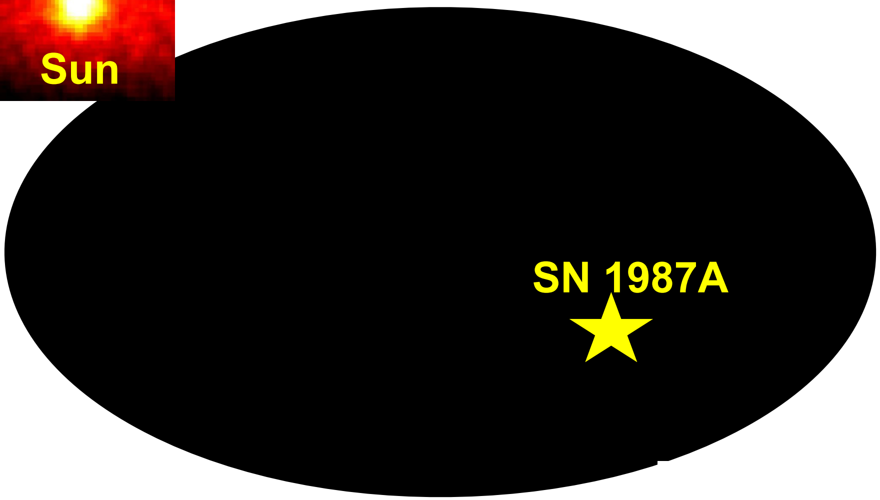
PeV-EeV



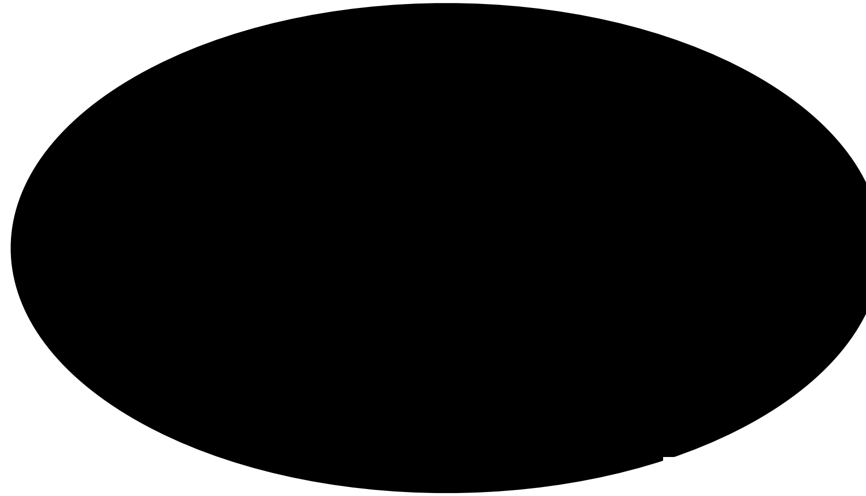
Dreaming Multi-Energy Neutrino Astronomy…



MeV-GeV

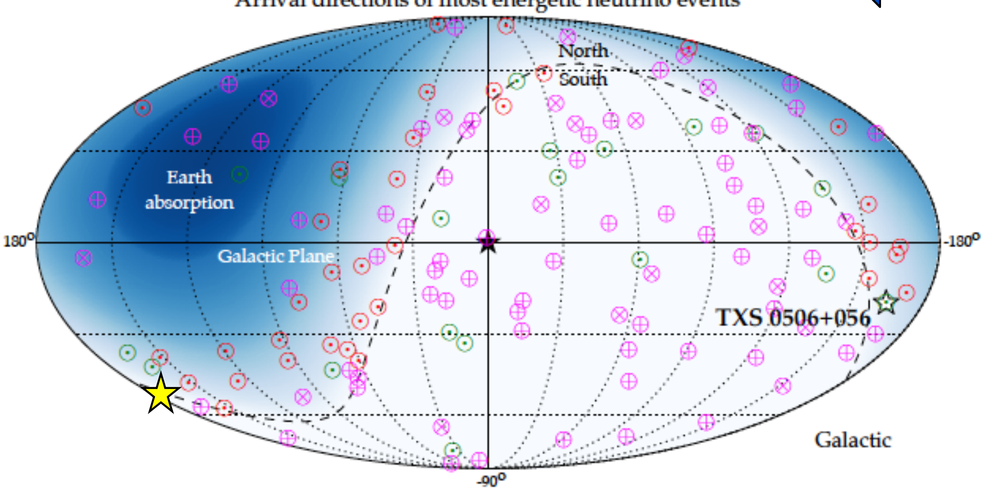


GeV-TeV



TeV-PeV (>60 TeV)

Arrival directions of most energetic neutrino events

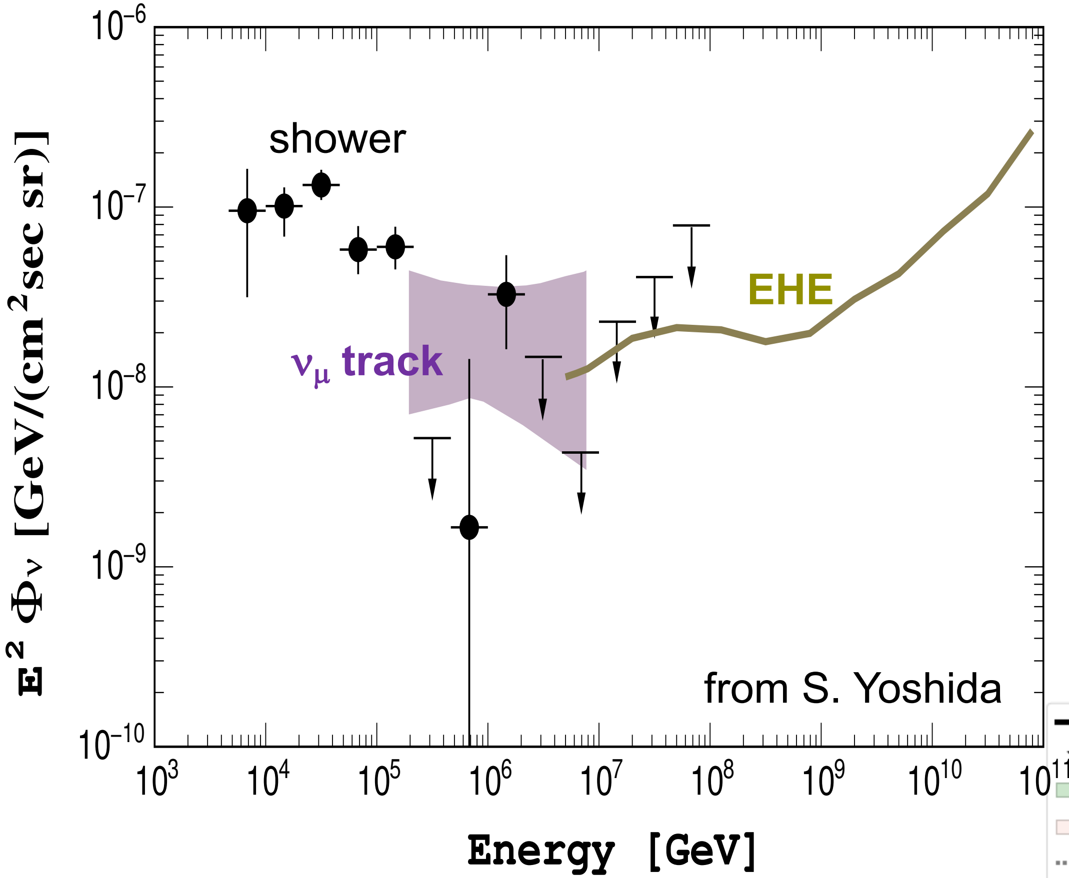


PeV-EeV

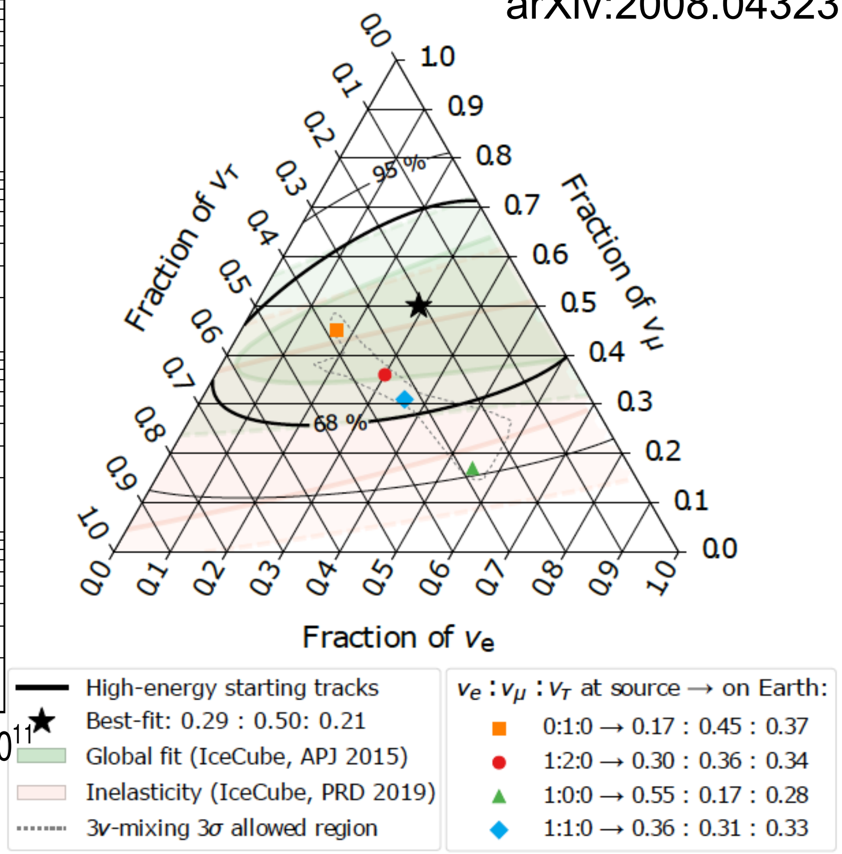
"UHECR" connection

All-Sky Neutrino Spectra and Flavors

IceCube Collaboration @ Neutrino 2020
IceCube Collaboration 20 PRL



arXiv:2008.04323



$E_\nu^2\Phi_\nu$ ~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} @~200 TeV
structure? consistent w. a power law

consistent w.
$\nu_e:\nu_\mu:\nu_\tau$ ~ 1:1:1

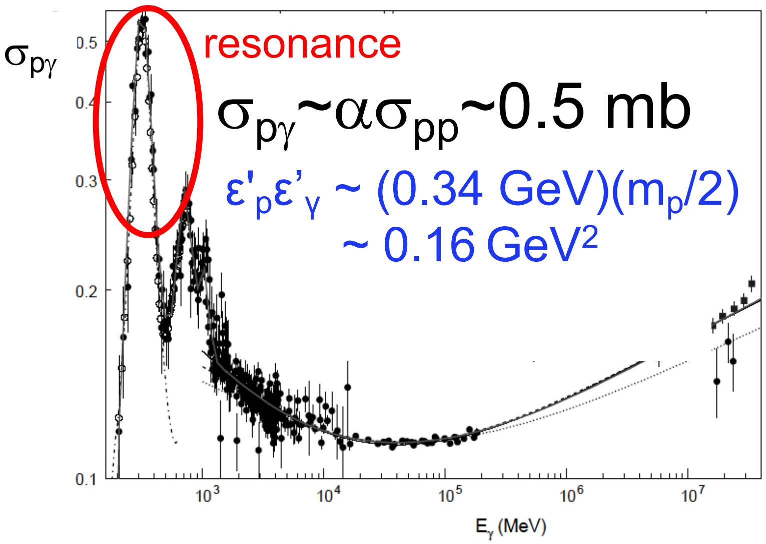
High-Energy Neutrino Production

Cosmic-ray Accelerators

Active galaxy

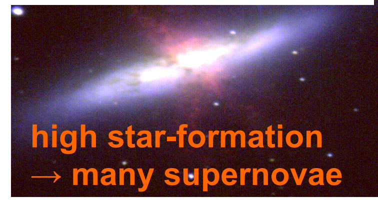
γ-ray burst

$$p + \gamma \rightarrow N\pi + X$$



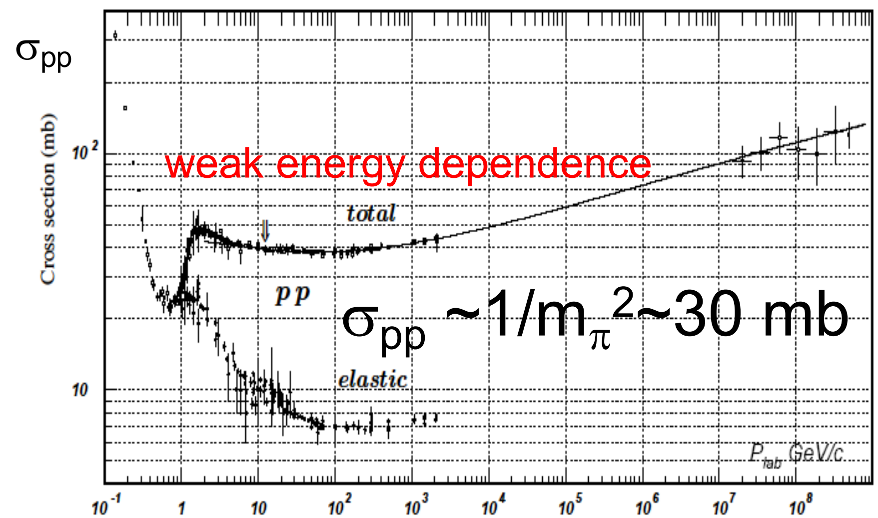
Cosmic-ray Reservoirs

Starburst galaxy



Galaxy cluster

$$p + p \rightarrow N\pi + X$$

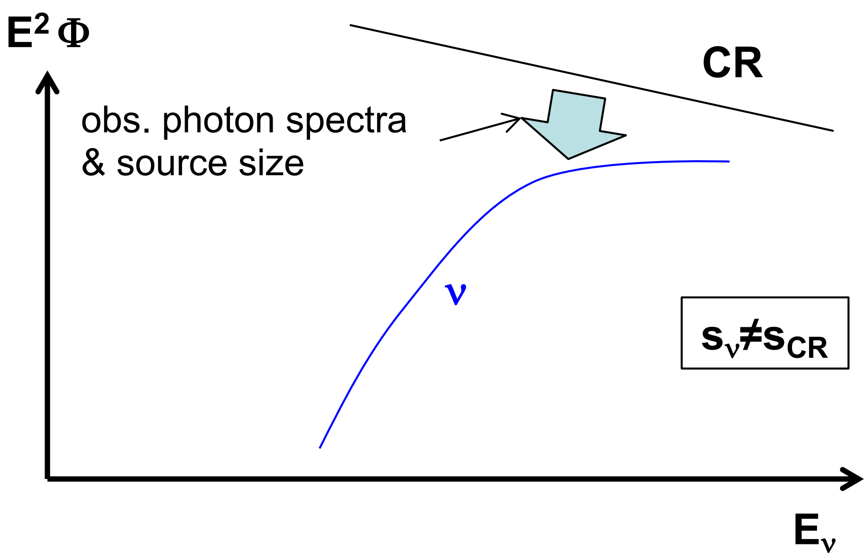


$$\pi^{\pm} \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e\ (\text{or}\ \bar{\nu}_e) + e^{\pm}$$

High-Energy Neutrino Production

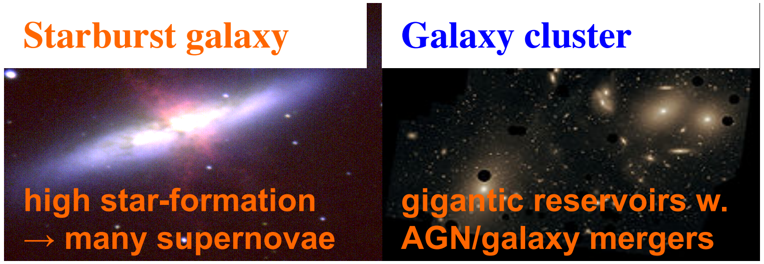
Cosmic-ray Accelerators

$$p + \gamma \rightarrow N\pi + X$$

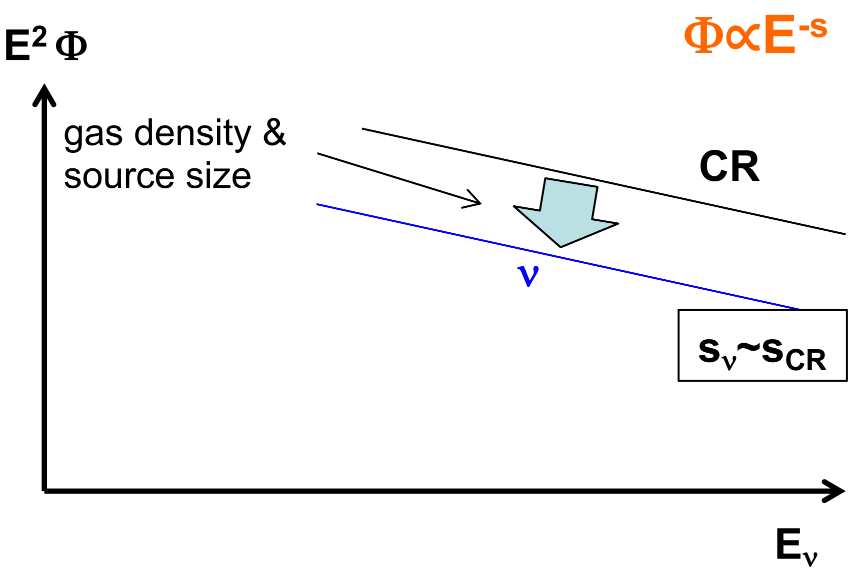


NOT power-law in multi-energies

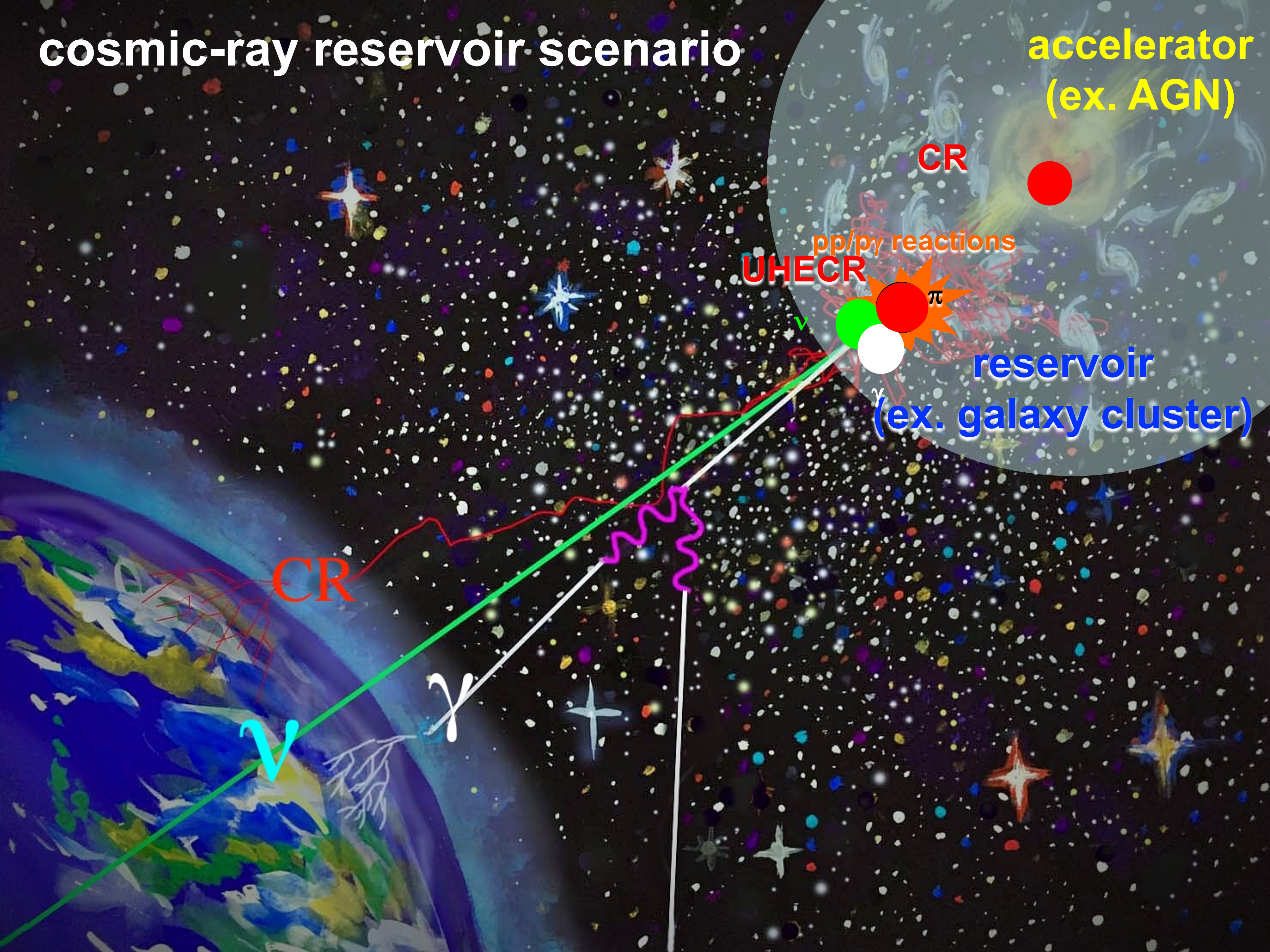
Cosmic-ray Reservoirs



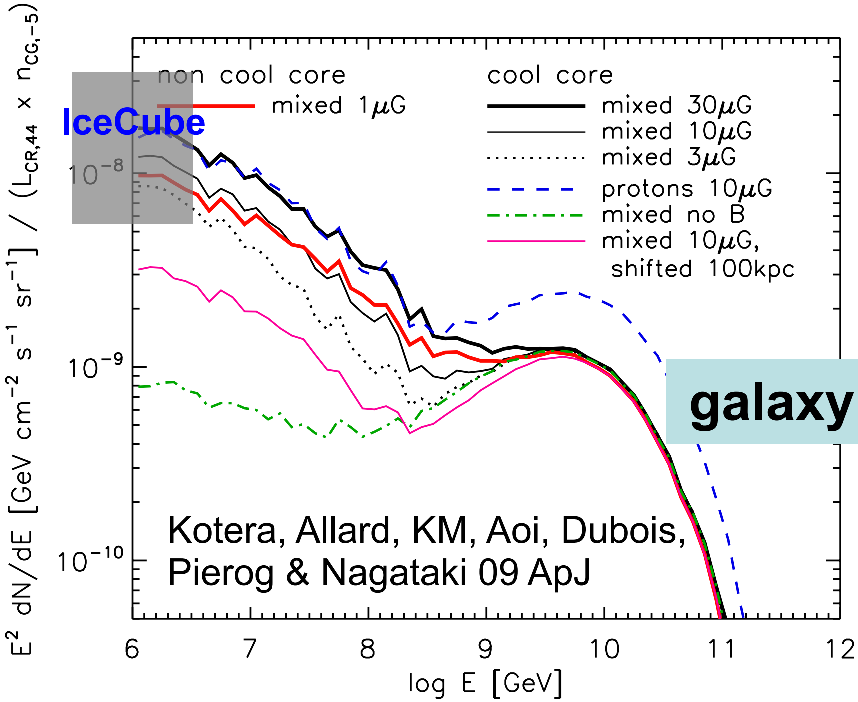
$$p + p \rightarrow N\pi + X$$

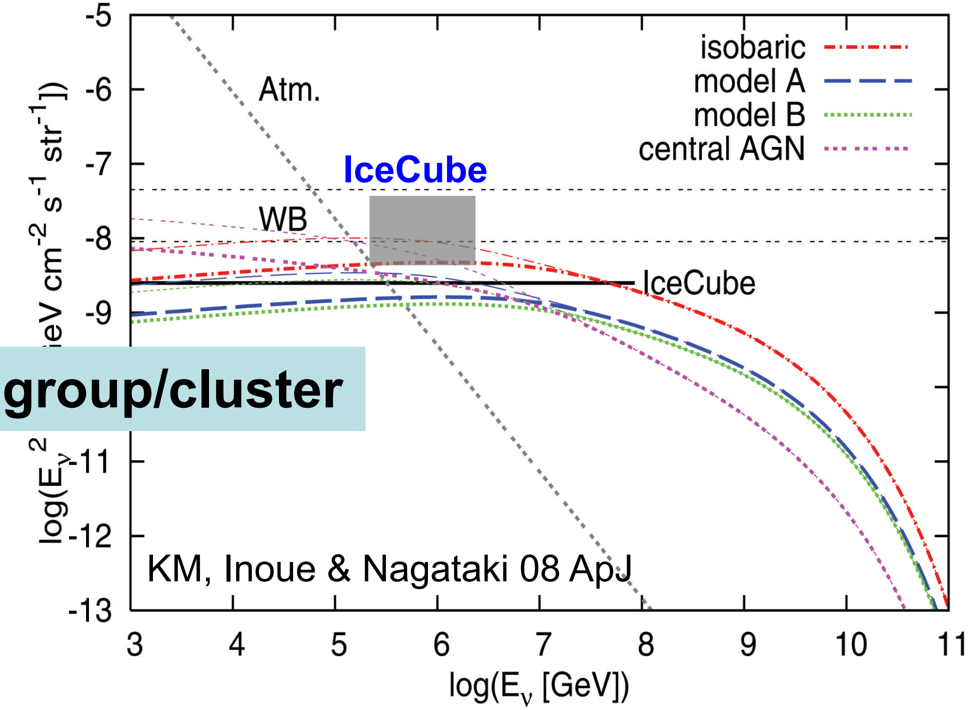


can be a smoothened power law

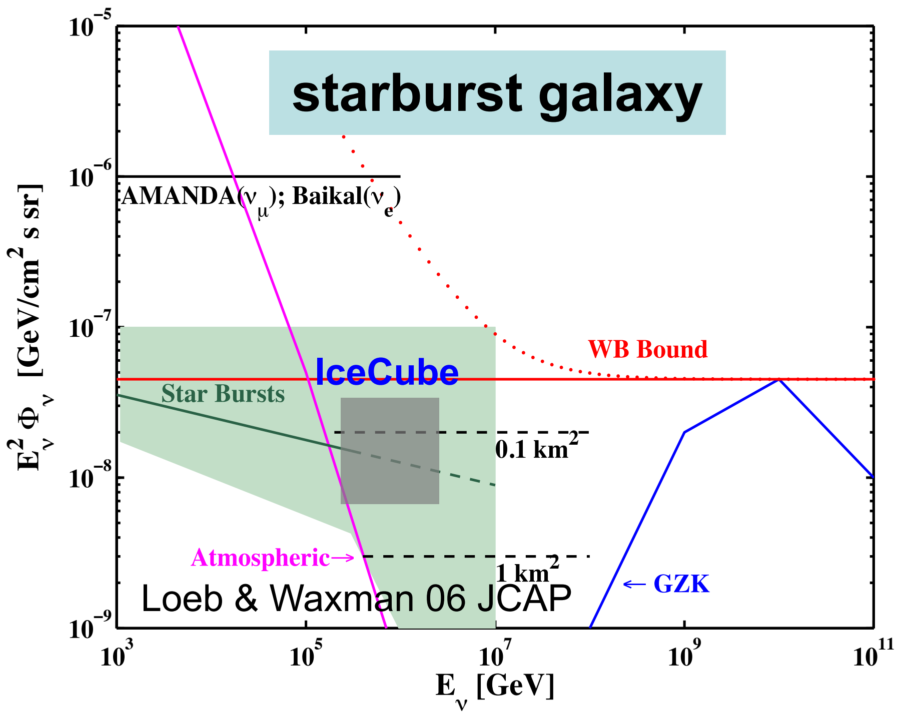


cosmic-ray reservoir scenario
accelerator
(ex. AGN)
CR
pp/pγ reactions
UHECR
π
ν
γ
reservoir
(ex. galaxy cluster)
CR
γ
ν





galaxy group/cluster

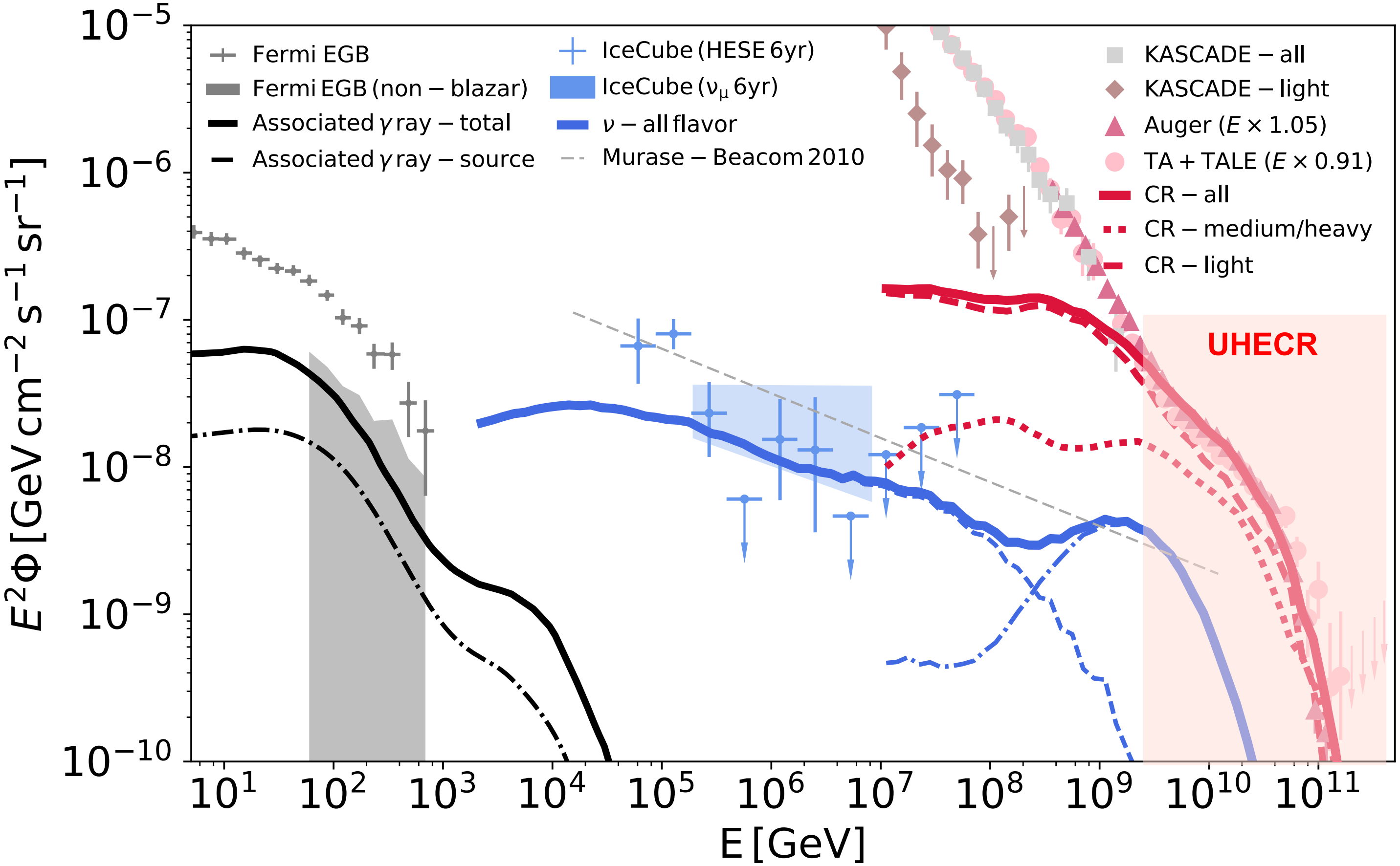


>0.1 PeV IceCube data: consistent w. earlier theoretical predictions

High-Energy Astro-Particle Grand-Unification

example of AGN as "UHECR" accelerators

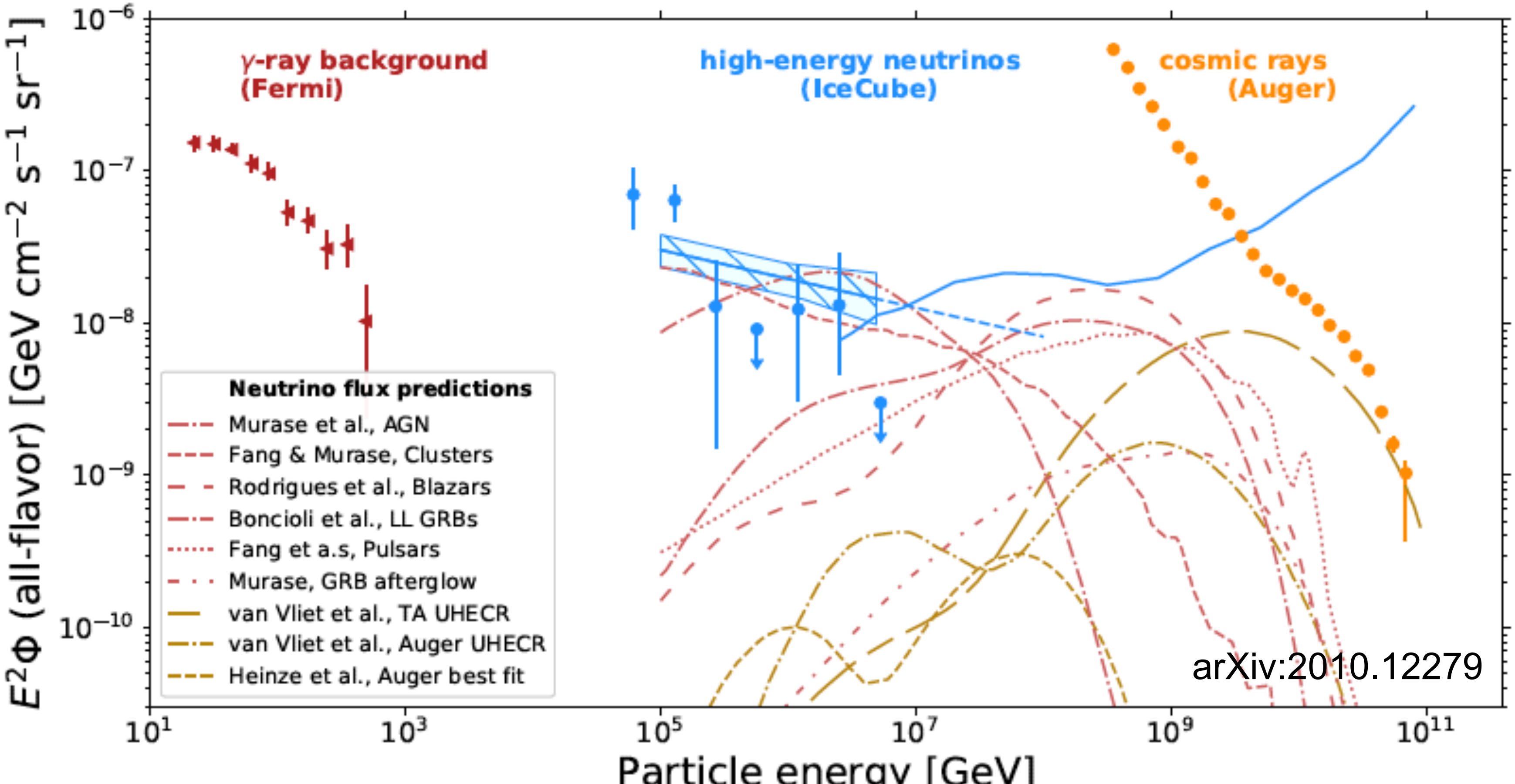
Fang & KM 18 Nature Phys. (1704.00015)
see also 1607.01601 and 1704.06893



- hard ν spectrum by confined CRs & hard UHECR spectrum by escaping CRs
- smooth transition from source ν (at PeV) to cosmogenic ν (at EeV)

Or Coincidence or Conspiracy?

- pγ scenarios explaining IceCube νs (GRBs/AGN) → cutoff/sharp decline
- AGN/pulsar models for UHECRs -> hard component around 10-100 PeV



multi-energy connection is a key: smooth spectra? decline? hardening? bump?

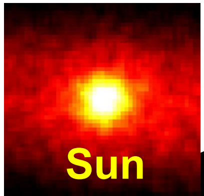
Beyond 10 PeV ν: Signal "Challenge"

- ν spectral features around 10 PeV and beyond?
  benchmark flux: $E_\nu^2\Phi_\nu \sim 3\times10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} @ 10 PeV

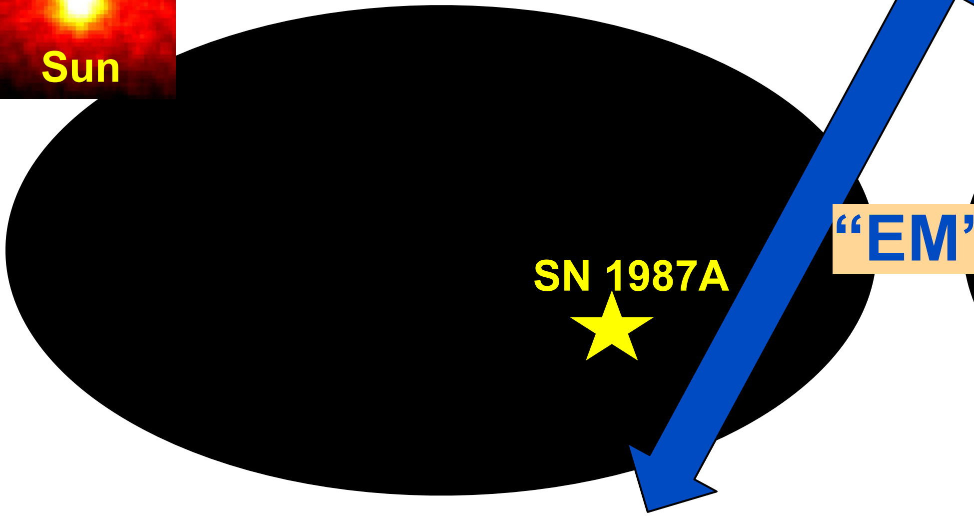
- EeV ν sources are uncertain but crucial for UHECRs
  $E_\nu \sim 0.04\ E_p$: 1 PeV neutrino $\Leftrightarrow$ 20-30 PeV per CR nucleon
  400 PeV neutrino $\Leftrightarrow$ 10 EeV per CR nucleon
  benchmark flux? $\rightarrow$ "nucleus-survival" bound (KM & Beacom 10)
  $E_\nu^2\Phi_\nu <(1\text{-}3)\times10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1} @ EeV

- Bigger exposures needed; various ideas have been proposed!
  In-ice optical – IceCube-Gen2, KM3Net-ARCA, Baikal-GVD, P-One
  In-ice radio – ARA, ARIANNA, Gen2 radio, RNO-G
  Air-shower radio – ANITA, PUEO, GRAND, BEACON etc.
  Air-shower Cherenkov – Trinity, NTA, POEMMA, TAMBO

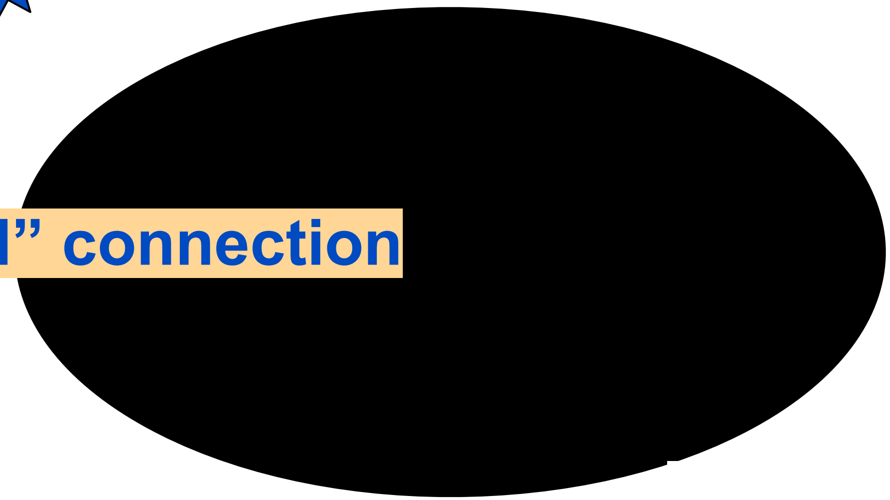
Multi-Energy Neutrino Astronomy?



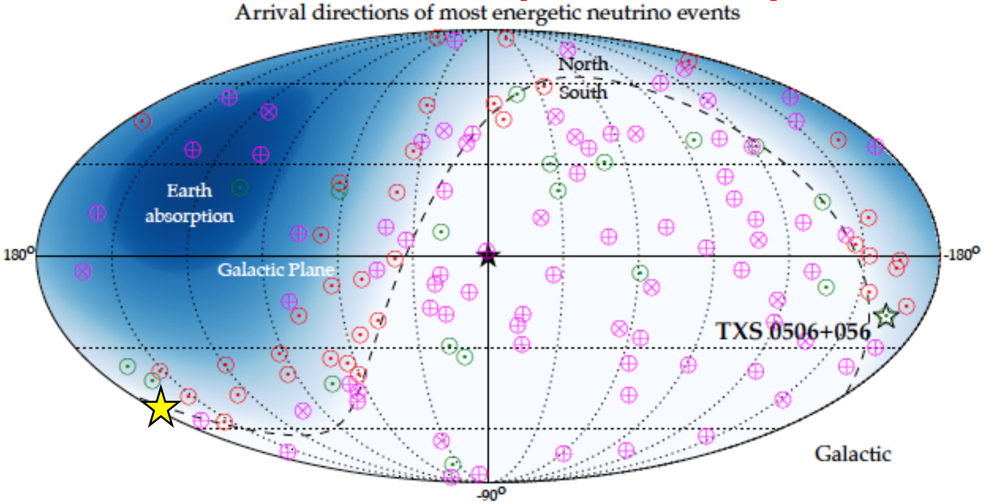
MeV-GeV



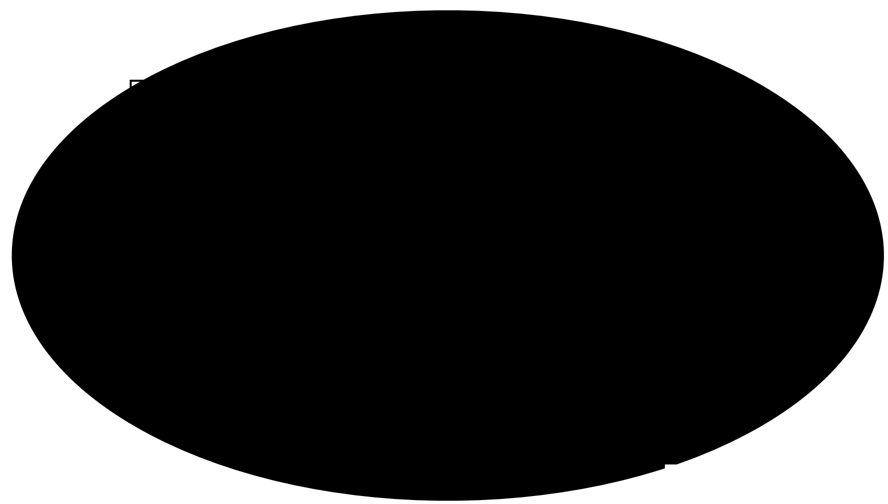
GeV-TeV



TeV-PeV (>60 TeV)

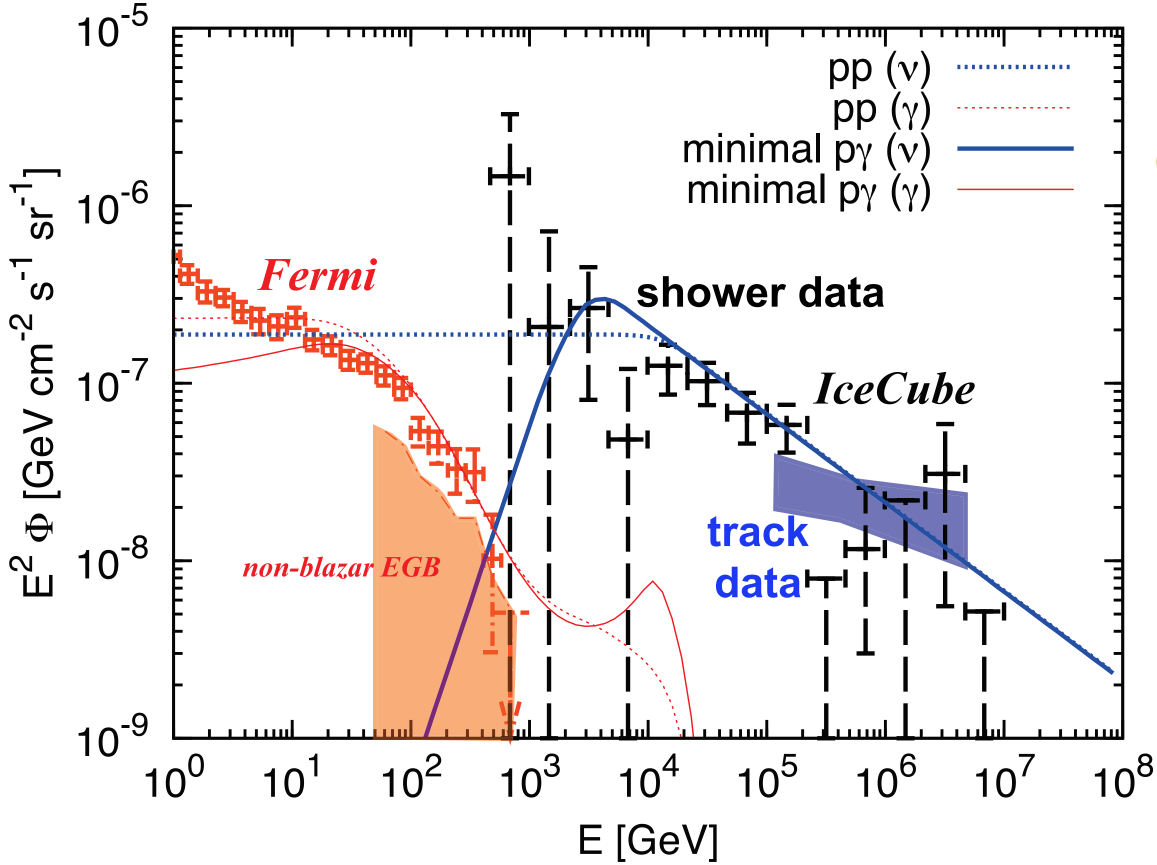


PeV-EeV



Multi-Messenger Implications of 10-100 TeV ν Data

- 10-100 TeV shower data: large fluxes of ~10^{-7} GeV cm^{-2} s^{-1} sr^{-1}



$$\varepsilon_\gamma Q_{\varepsilon_\gamma} \approx \frac{4}{3K}(\varepsilon_\nu Q_{\varepsilon_\nu})|_{\varepsilon_\nu=\varepsilon_\gamma/2}$$

K=1 (pγ), K=2 (pp)

KM, Guetta & Ahlers 16 PRL
see also
KM, Ahlers & Lacki 13 PRDR
Capanema, Esmaili & KM 20 PRD
Capanema, Esmaili & Serpico 20

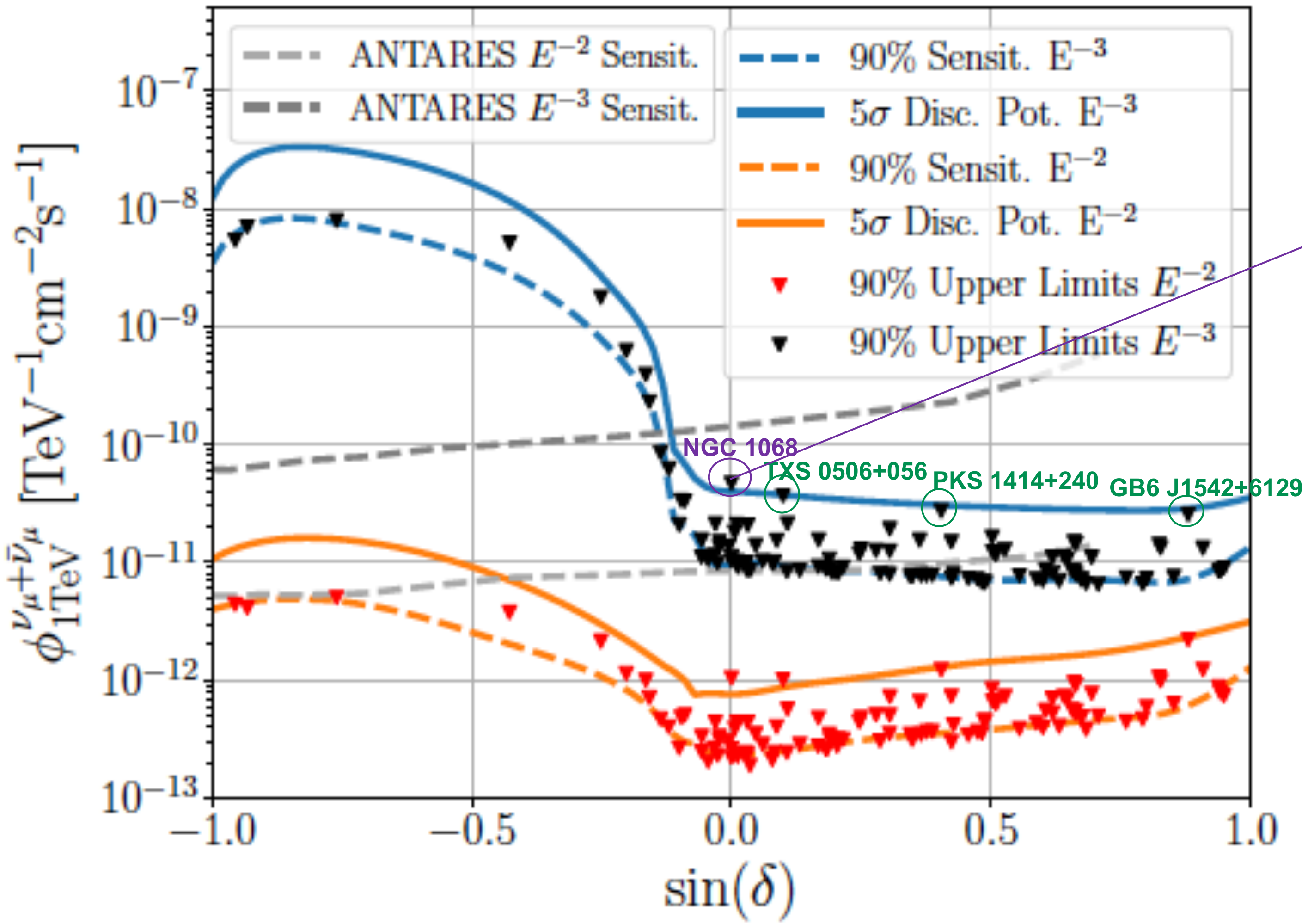
Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent

→ existence of "hidden (i.e., γ-ray opaque) neutrino sources"

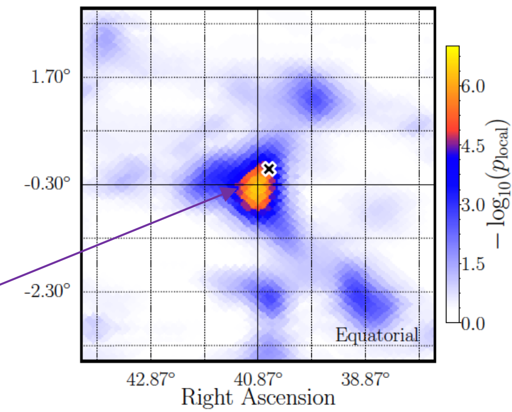
(ν data above 100 TeV can be explained by γ-ray transparent sources)

Other Hints in Neutrino Point Sources?

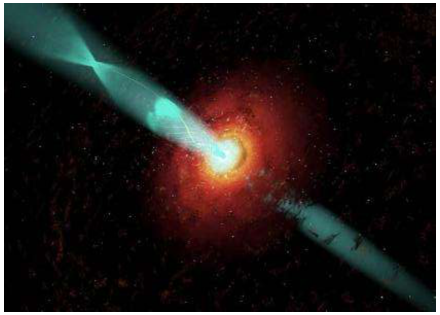
IceCube Collaboration 20 PRL



starburst galaxy/AGN



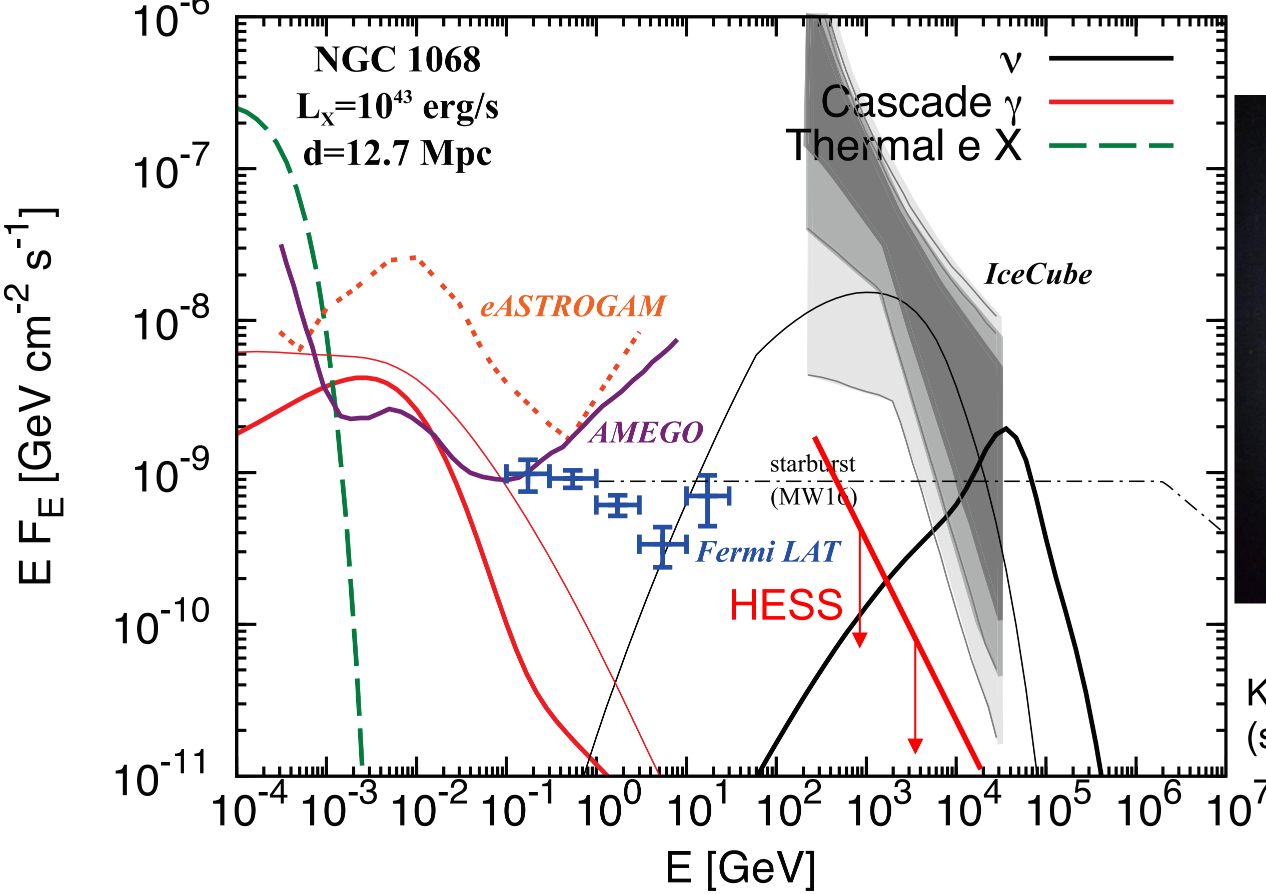
Jetted AGN (blazar)



"Catches" (~3σ) exist; need more data to reach the discovery level

NGC 1068 as Hidden ν Sources

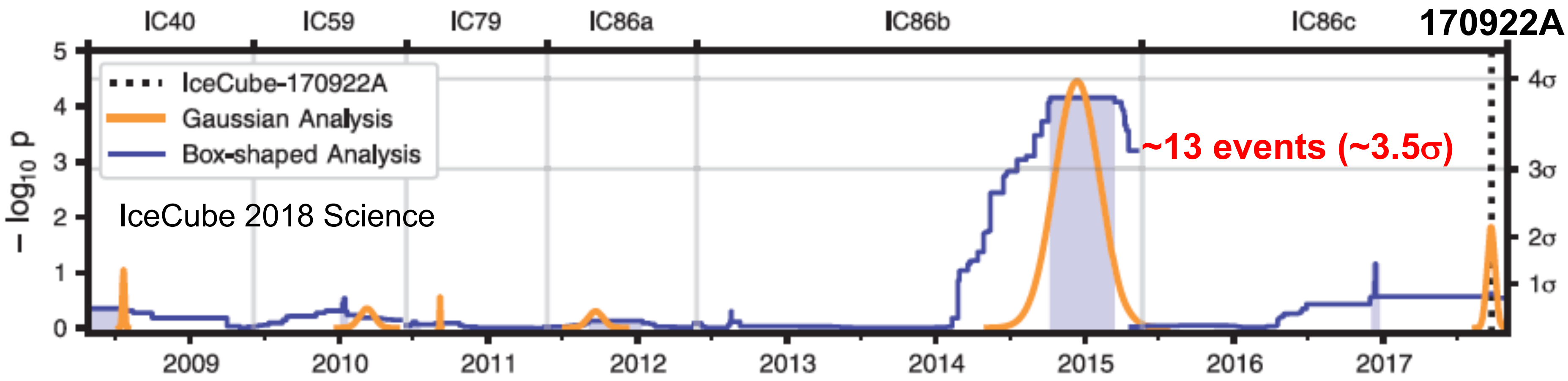
NGC 1068 is a Seyfert galaxy w. starburst activities (not jetted AGN)



KM, Kimura & Meszaros 20 PRL
(see also Inoue+ 20 ApJ)

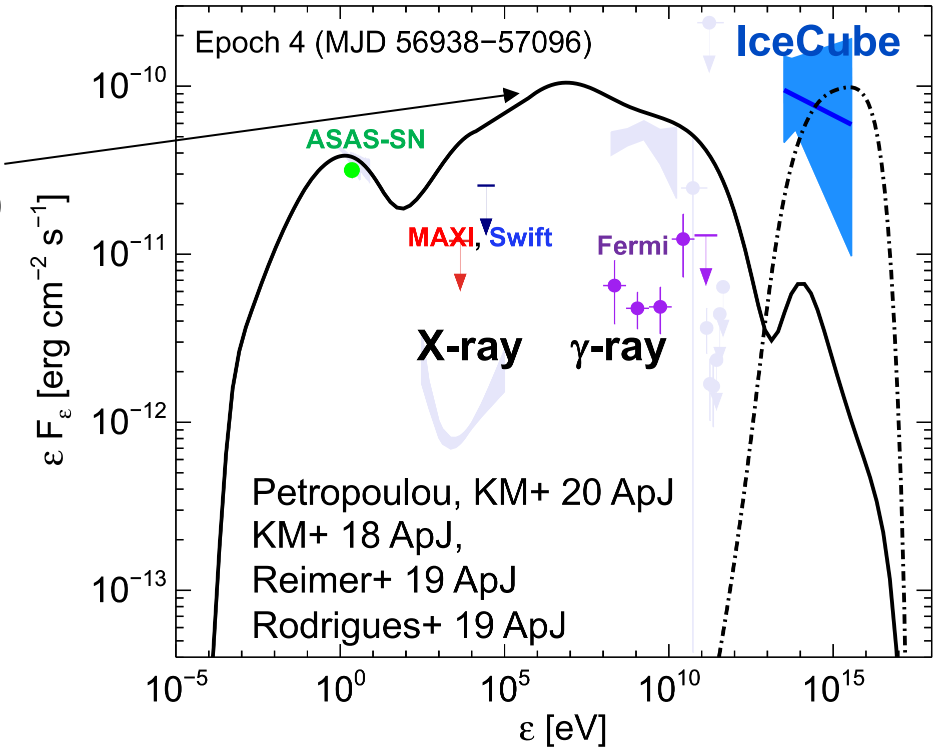
Black hole "corona" model
- NGC 1068: predicted to be the brightest in the northern sky
- GeV-TeV γ rays must be hidden but should appear in MeV γ rays
- Suppressed ν spectra below TeV? (cannot be extrapolated w. steep spectra)

2014-2015 Neutrino Flare from TXS 0506+056



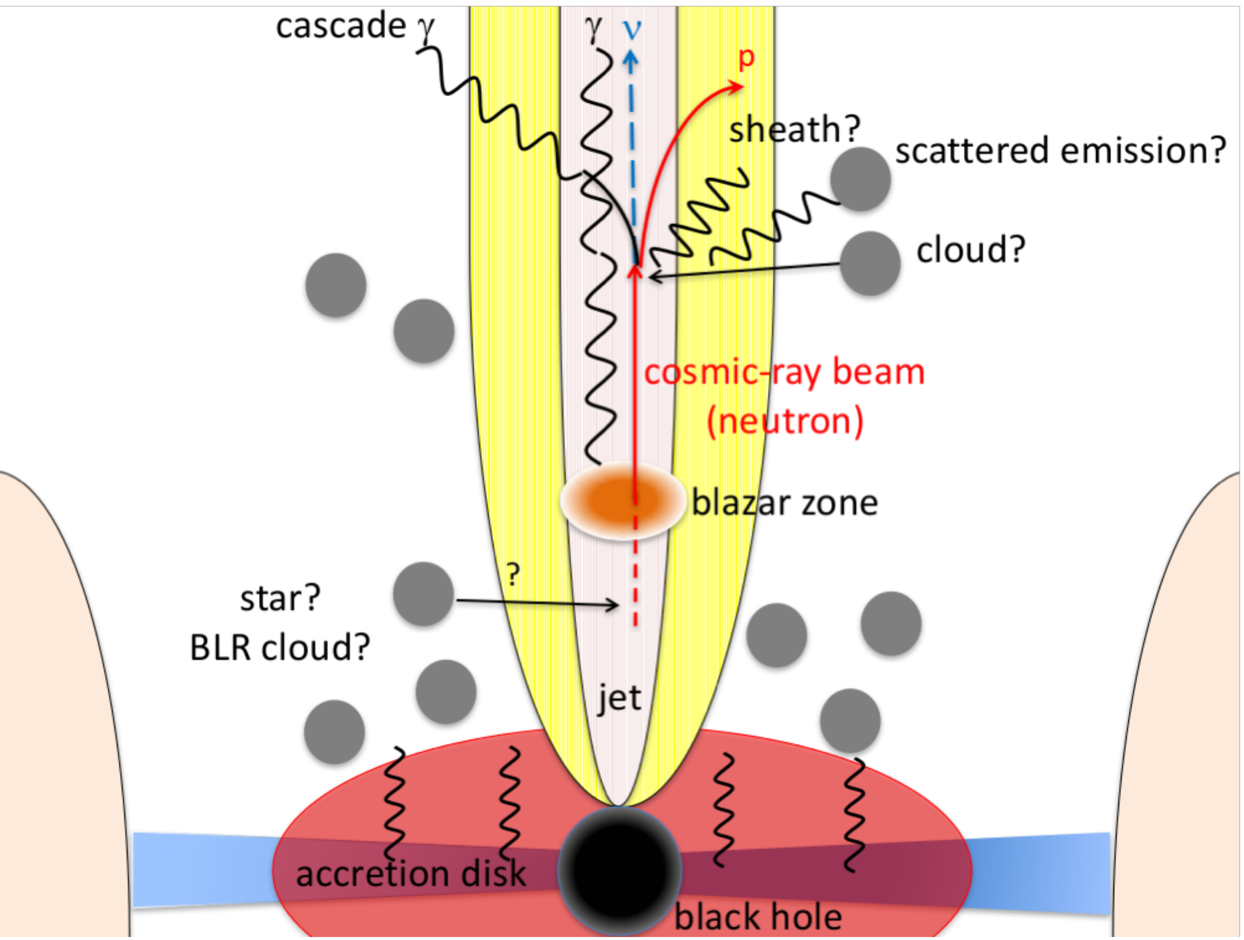
- CR-induced cascade emission from the Bethe-Heitler process ($p\gamma \rightarrow p\ e^+e^-$)
- unpleasantly large energetics

one-zone models do not work

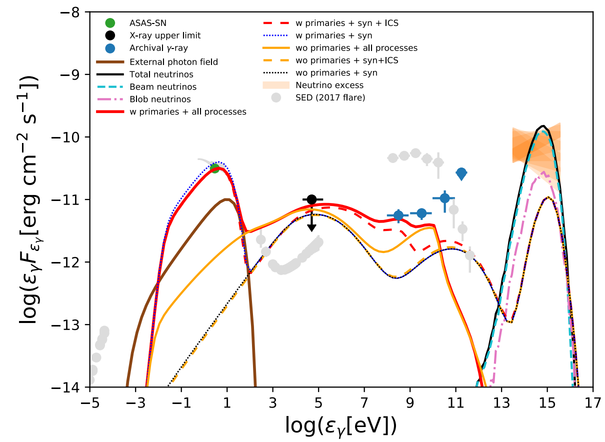


How to Hide Gamma Rays from Blazars?

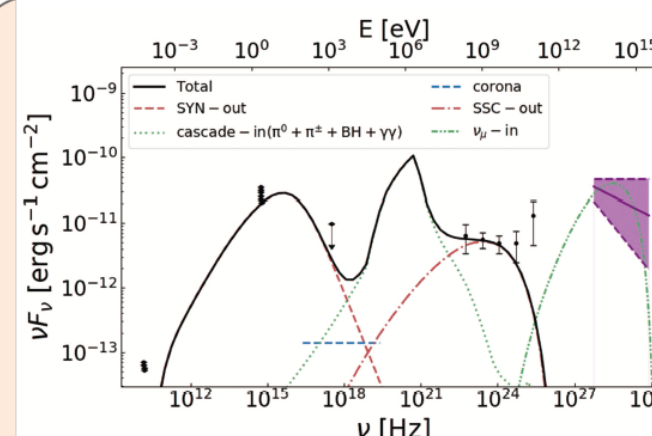
- Blazar (at least radio-emitting) zones are typically transparent for <GeV γ rays
- Suppressed ν spectra below 10-100 TeV?



KM, Oikonomou & Petropoulou 18



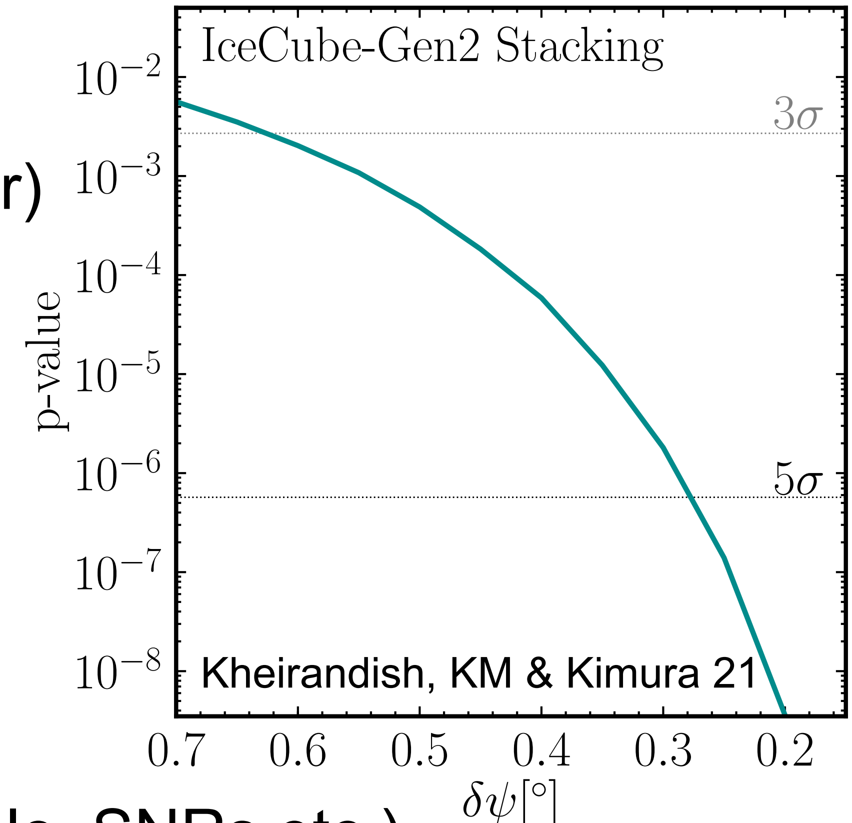
CR beam model
(Zhang+KM 20, KM+ 18)



Blazar core model
(Xue+ 21, Rodrigues+ 19)

Below 10 TeV ν: Background "Challenge"

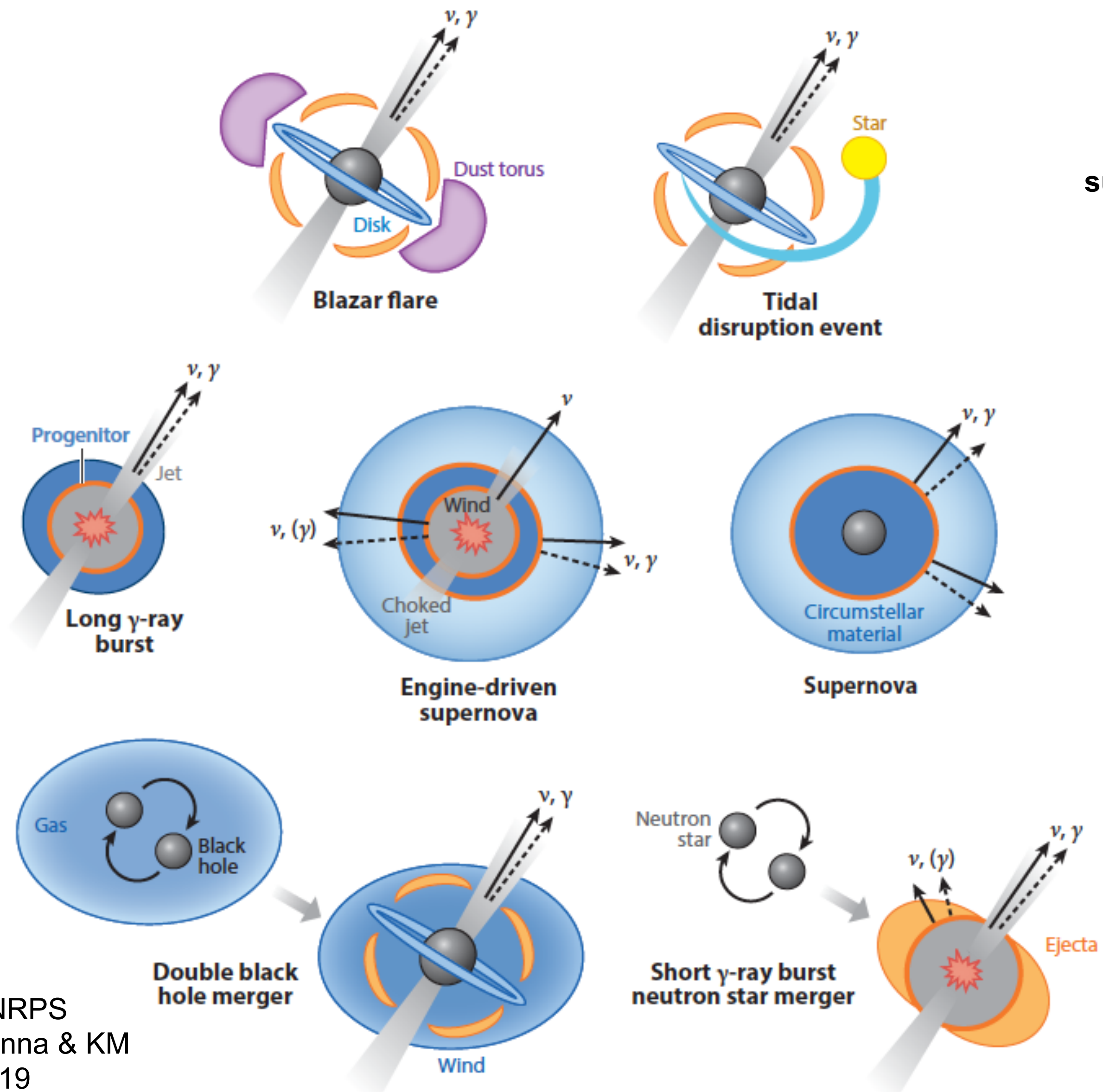
ν spectra features below 10 TeV?
- excellent angular resolution
- good shower reconstruction (water)
- presumably bigger than IceCube



Many motivations
- Testing hidden ν scenarios
- pp vs pγ
- GeV-TeV sources "exist"
  Galactic contribution (MW disk, halo, SNRs etc.)

May be challenging and need ideas (to have x10 better sensitivity)
but good news, atm. backgrounds can be reduced for transients

Diversity of Multi-Messenger Transients



supermassive black holes

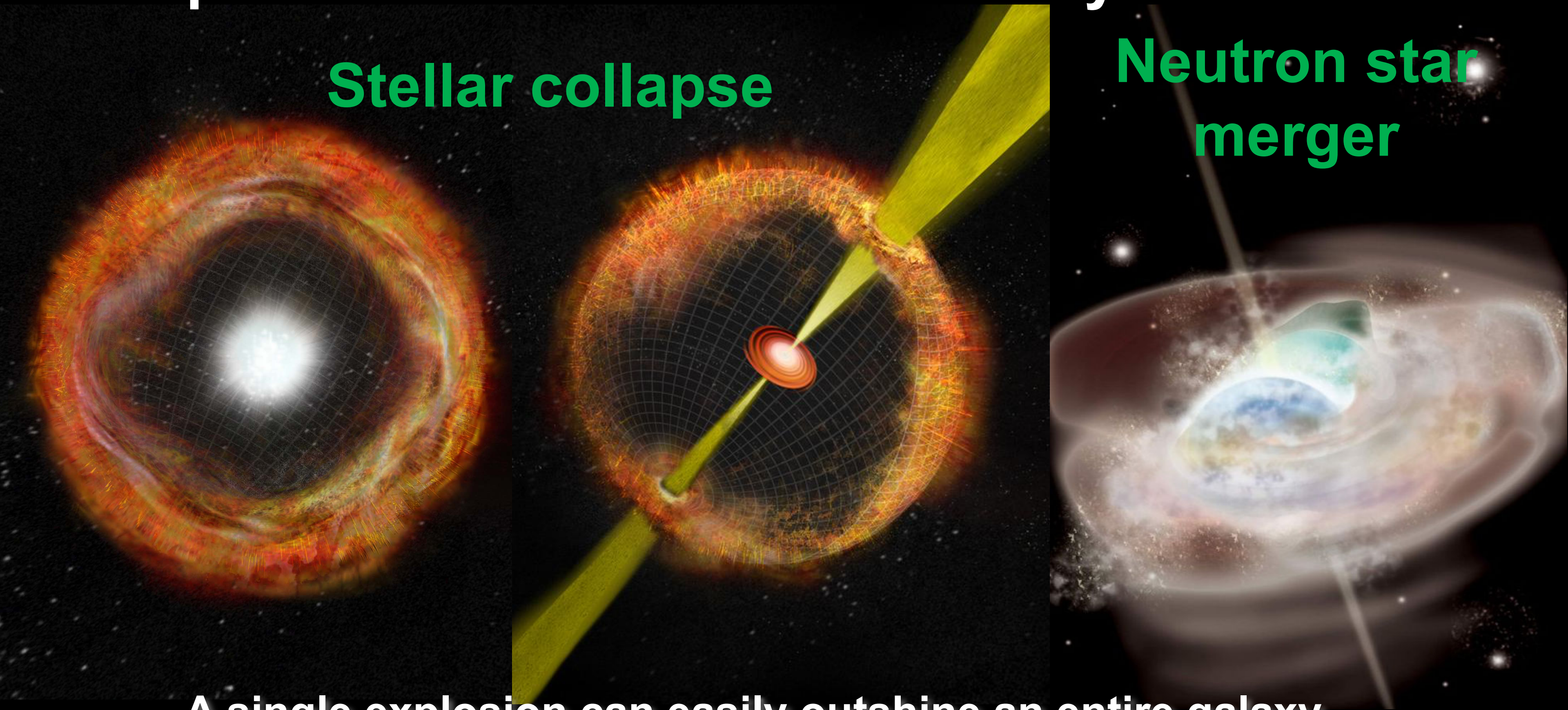
massive stellar deaths

compact mergers
(promising GW sources)

KM & Bartos 19 ANRPS
Meszaros, Fox, Hanna & KM
Nature Rev. Phys. 19

Powerful Cosmic Explosions as Multi-Messenger Transients

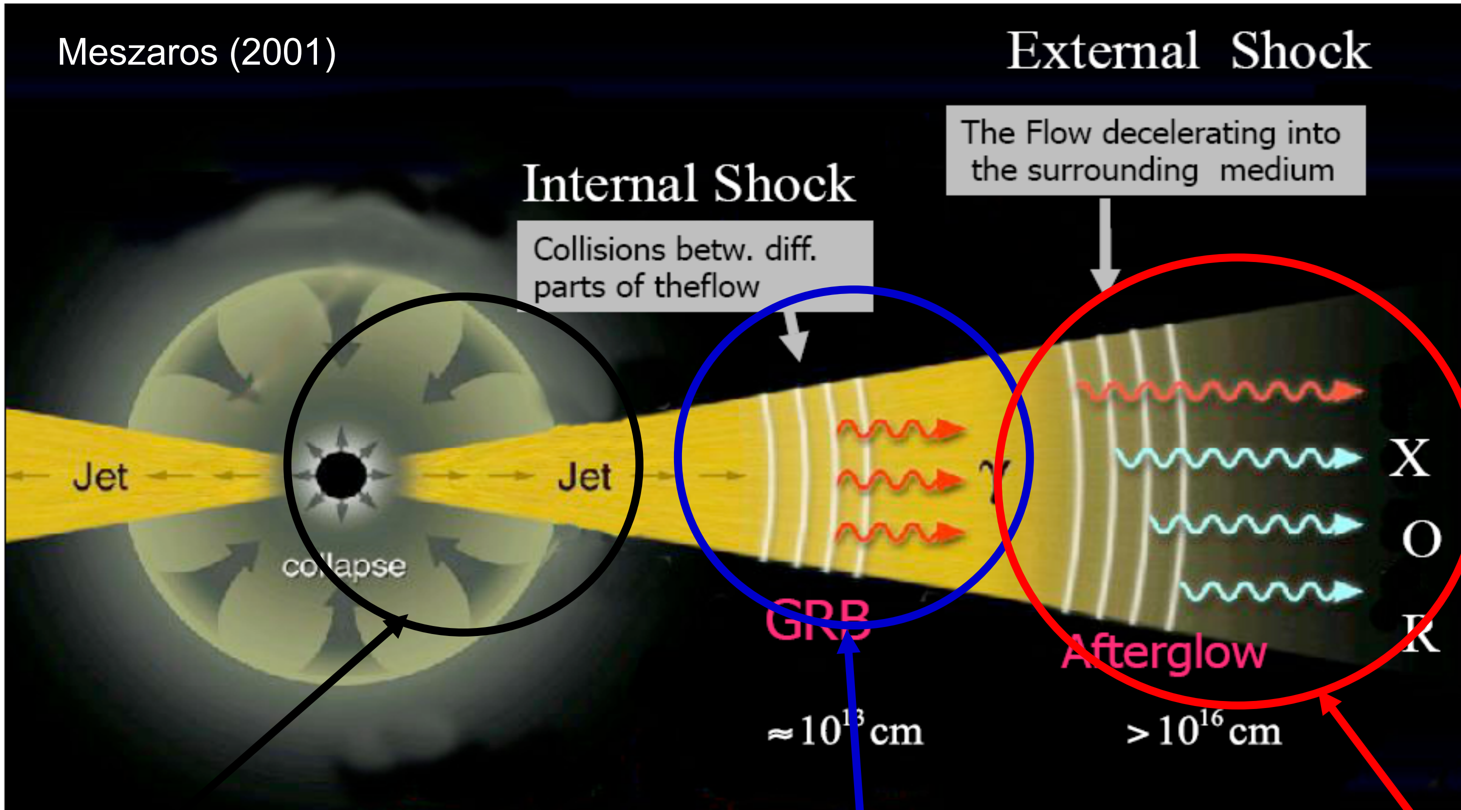
Supernova **Gamma-ray burst**



A single explosion can easily outshine an entire galaxy containing hundreds of billions of stars.

ν & GWs - smoking gun

GRBs as Multi-Energy Neutrino Sources



Inner jet inside a star
$r < 10^{12}$ cm, $B > 10^{6}$ G
GeV-PeV ν

Meszaros & Waxman 01 PRL
Razzaque et al. 03 PRL
KM & Ioka 13 PRL

Inner jet (prompt/flare)
$r \sim 10^{12}$-10^{16} cm $B \sim 10^{2\text{-}6}$ G
TeV-PeV ν,

Waxman & Bahcall 97 PRL
Dermer & Atoyan 03 PRL
KM & Nagataki 06 PRL

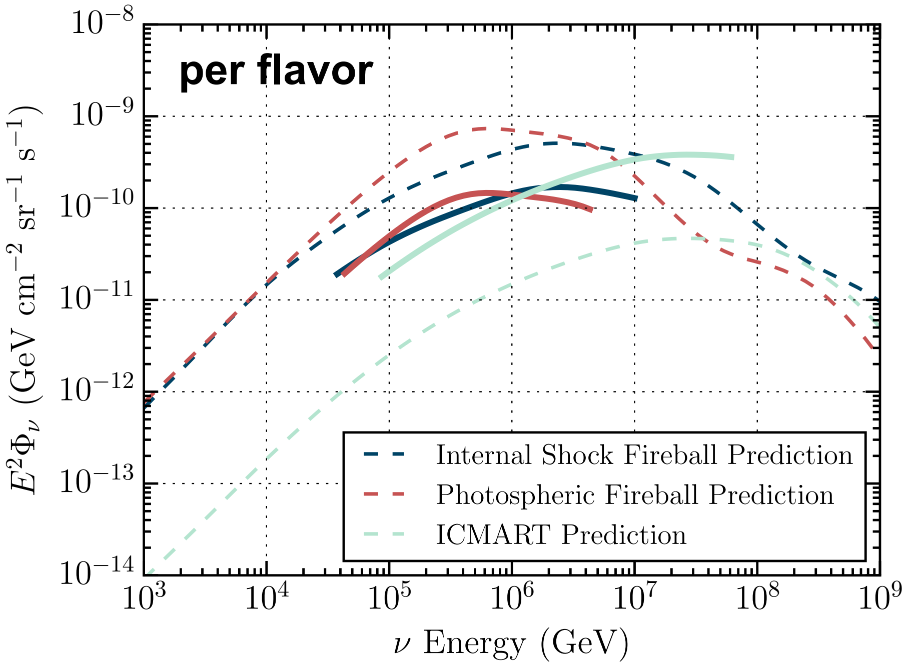
Afterglow
$r \sim 10^{14}$-10^{17} cm $B \sim 0.1$-100 G
PeV-EeV ν

e.g., Waxman & Bahcall 00 ApJ
Dermer 02 ApJ
KM 07 PRD

HE Neutrinos from GRBs: Constrained?

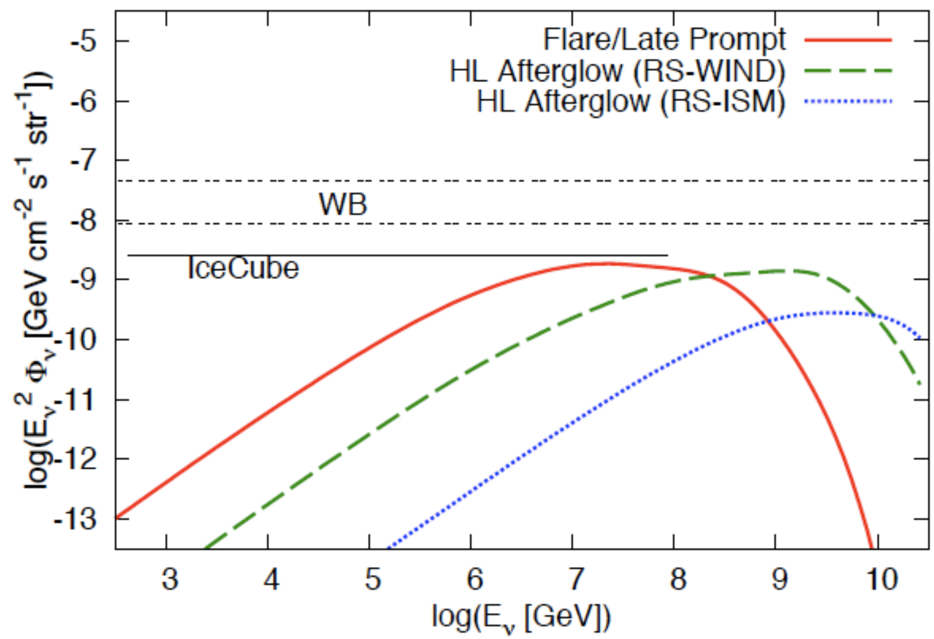
GRB prompt: constrained by stacking analyses **<~ 3x10^{-10} GeV cm^{-2} s^{-1} sr^{-1}**
→ only subdominant (<~1%) contribution to IceCube neutrinos
However…
- Both prompt and afterglow models can still be viable as the UHECR origin
- Low-power GRBs (including choked jets) are viable as the IceCube ν origin

GRB prompt



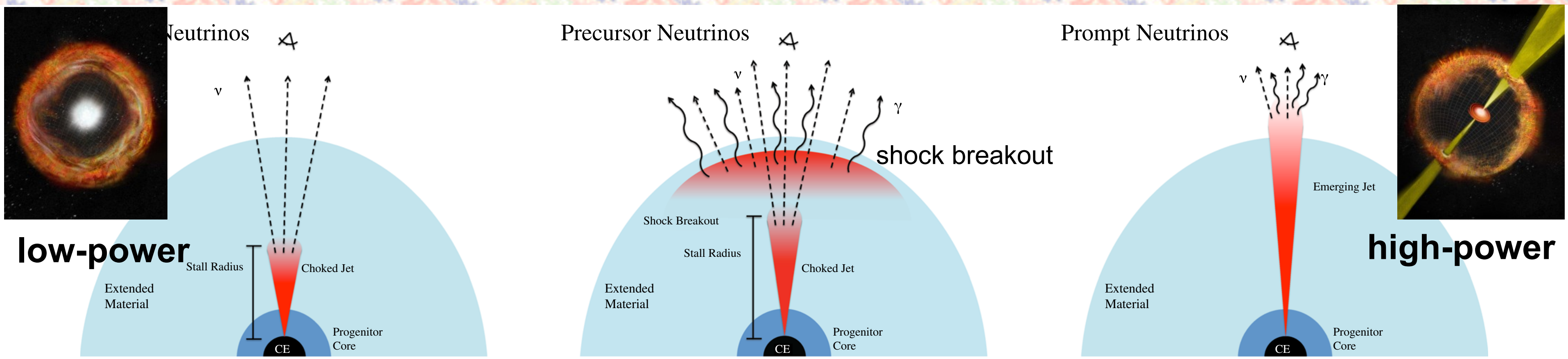
IceCube 2017 ApJ

GRB flare/afterglow

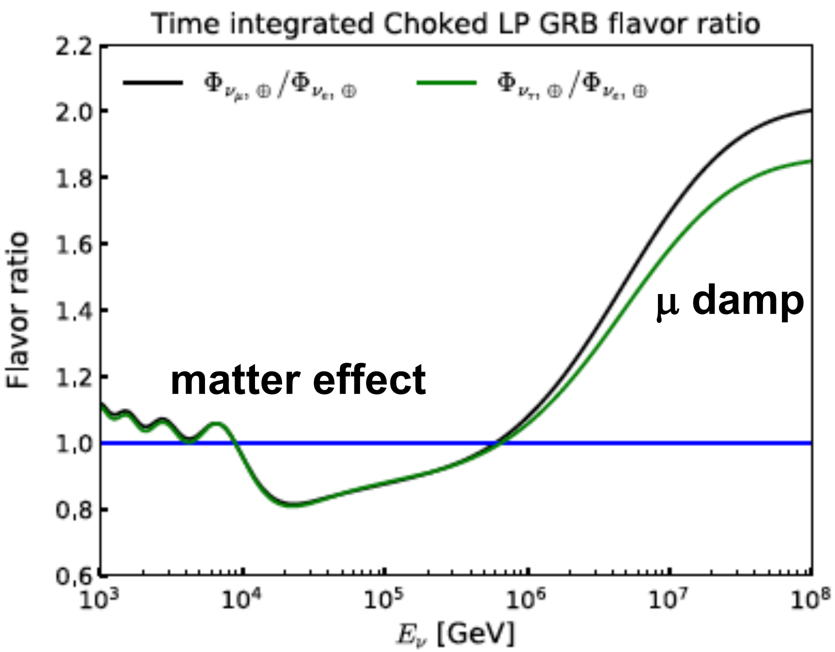


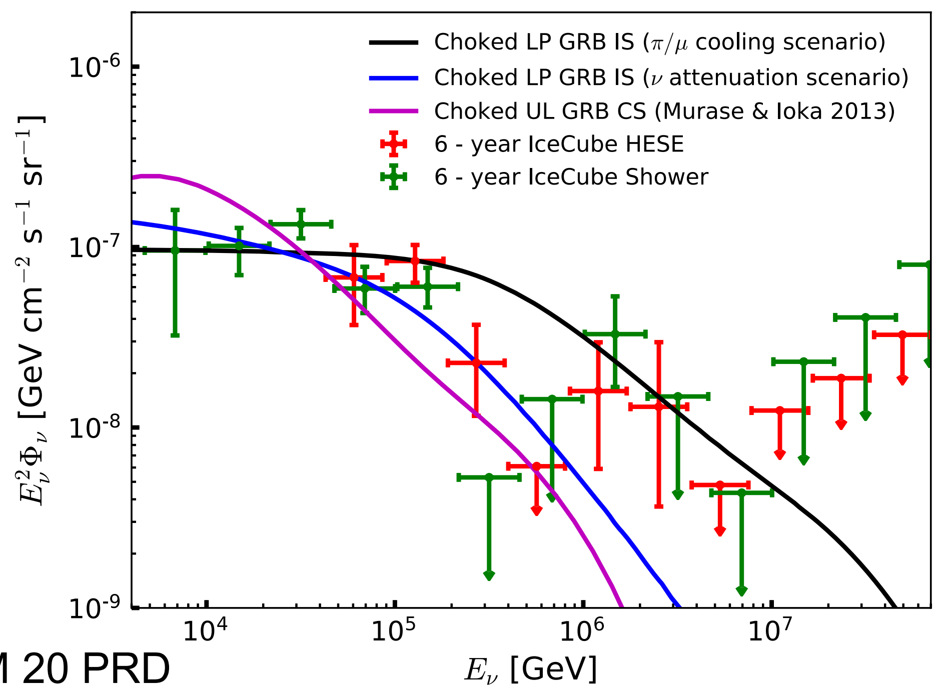
KM & Nagataki 06 PRL, KM 07 PRD

Low-Power GRB Jets Embedded in Massive Stars



KM & Ioka 13 PRL, Senno, KM & Meszaros 16 PRD, Tamborra & Ando 16 PRD, Denton & Tamborra 18 JCAP

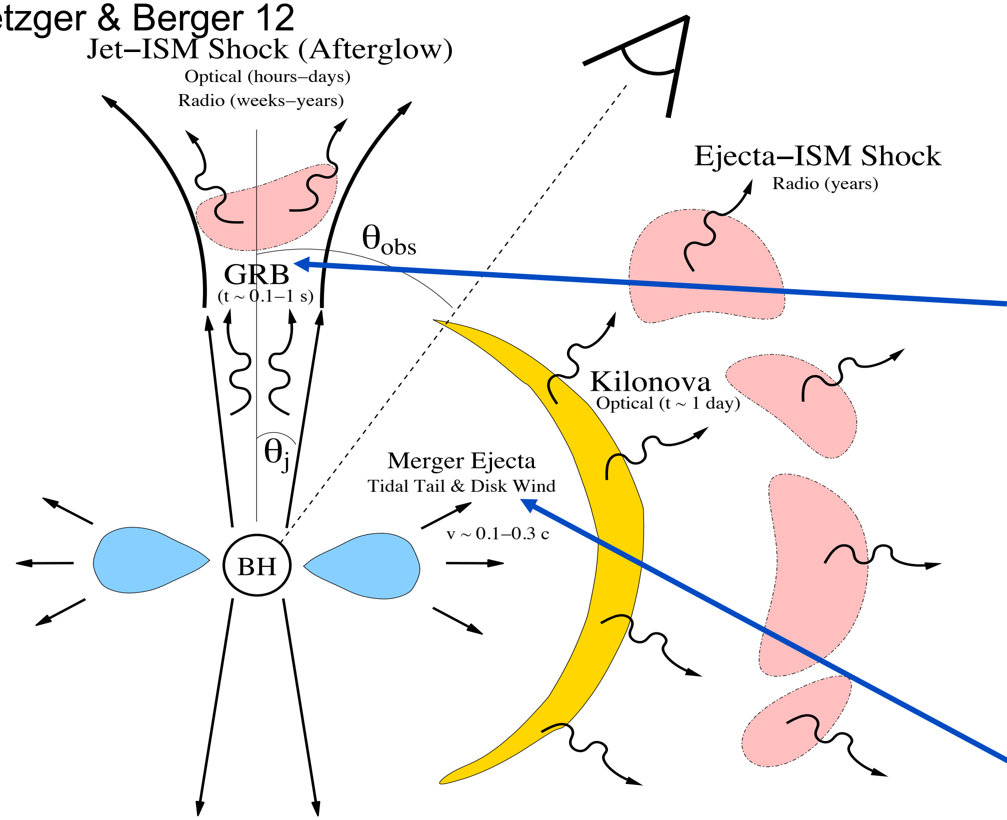




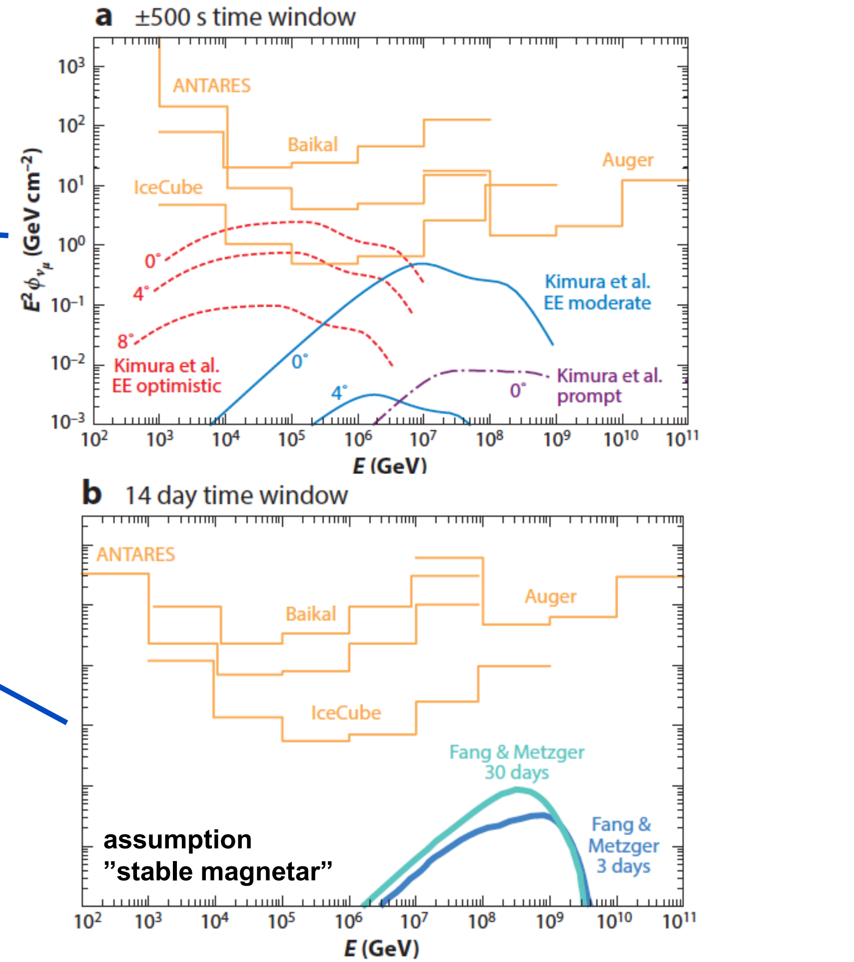
Carpio & KM 20 PRD

Short GRB Jets from Neutron-Star Mergers

Metzger & Berger 12



next: neutrinos?



from KM & Bartos 19

see also Kimura, KM+ 18, Kyutoku & Kashiyama 18, Biehl+ 18, Ahlers & Halser 19, Decoene+ 20

GW170817-GRB 170817A

success of multi-messenger & multi-wavelength observations

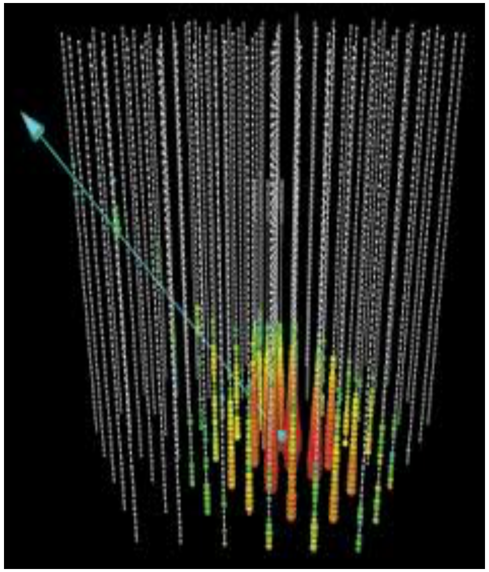
- GRB afterglow from off-axis jet
- Kilonovae from merger ejecta

Core-Collapse Supernovae and Neutrinos

~10 MeV neutrinos from supernovae
thermal: core's grav. binding energy

- supernova explosion mechanism
- progenitor, nucleosynthesis
- neutrino properties, BSM physics

Super-K detect ~8,000 ν at ~10 MeV (at 8.5 kpc)



GeV-PeV neutrinos from supernovae?
non-thermal: shock dissipation

- cosmic-ray origin and acceleration
- progenitor, mass-loss mechanism
- neutrino properties, BSM physics

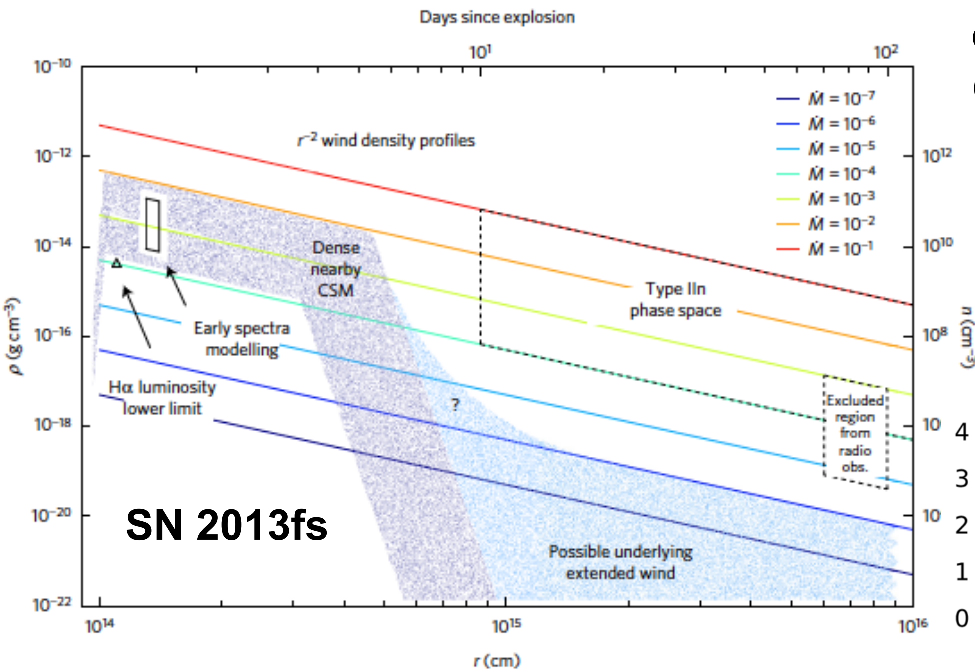
How many GeV-PeV νs can be detected?

CR Acceleration and ν Production in Early Supernovae?

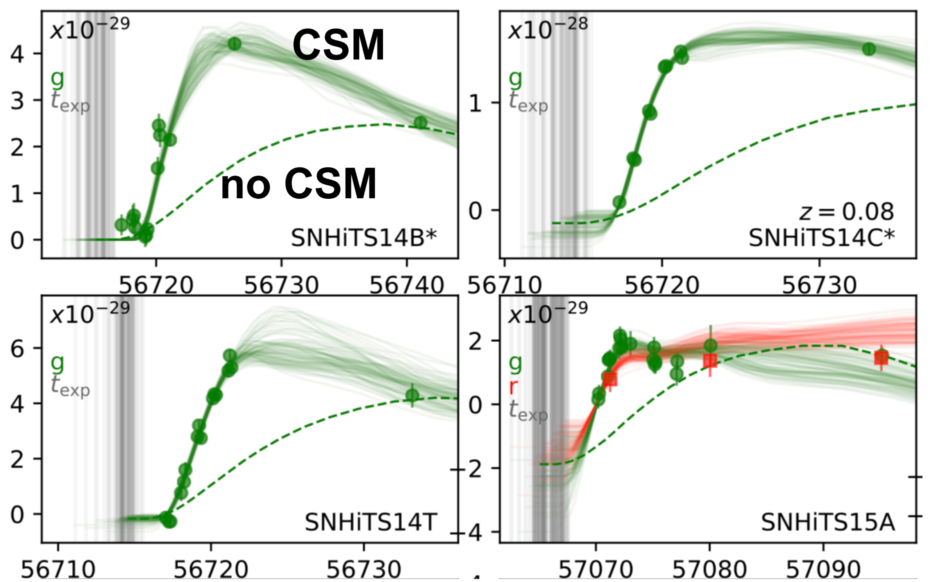
- Young supernova “remnants”:
  believed to be responsible for CRs up to the knee energy
  diffusive shock (Fermi) acceleration
- However, naively, early CR and HE ν production is negligible
  mostly kinetic energy until the Sedov time
  ex. dissipation energy ∝ t^3 for uniform medium
- But the situation is different
  when circumstellar material (CSM) exists

$$\mathcal{E}_d = \frac{M_{\rm cs}}{M_{\rm ej}+M_{\rm cs}}\mathcal{E}_{\rm ej}$$

New: Evidence for Dense Material around Progenitor



early spectroscopy
(Yaron+ 16 Nature Phys.)

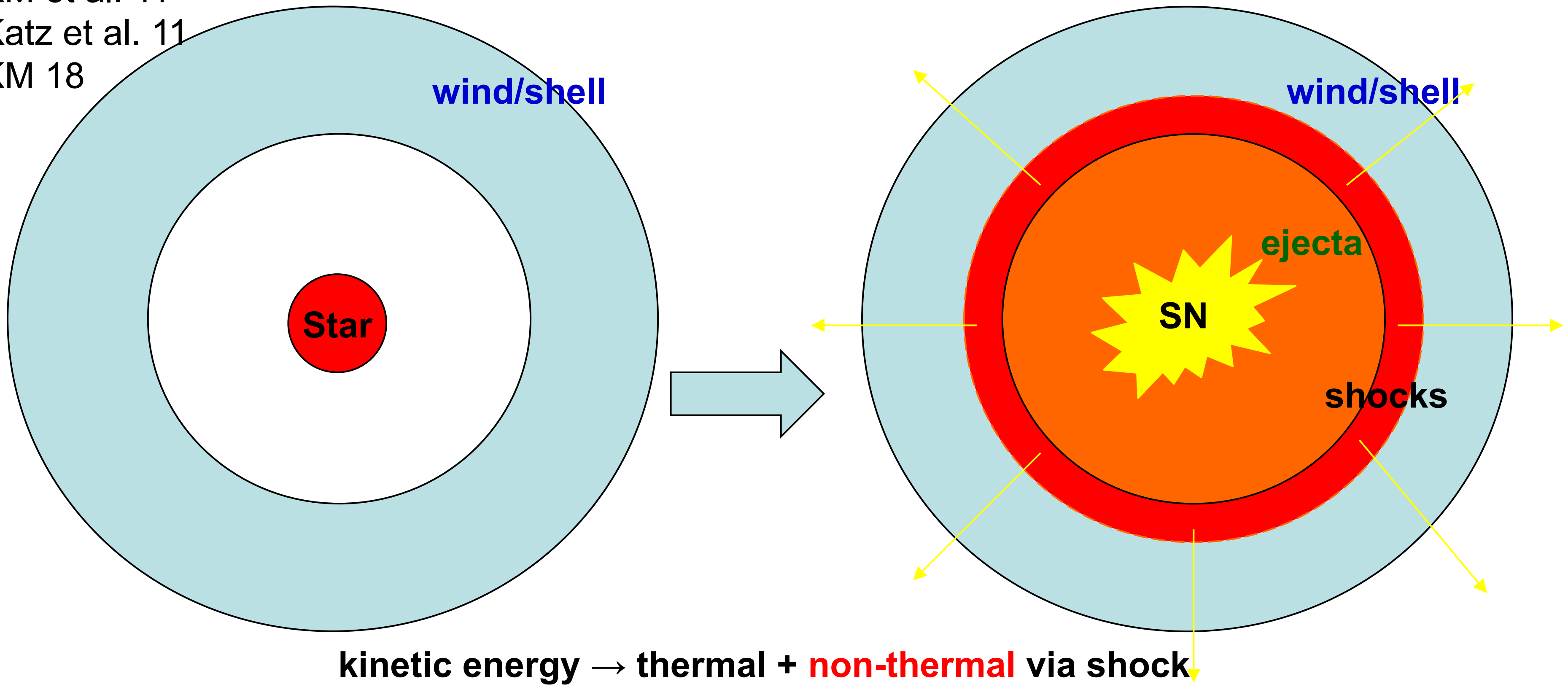


light curve modeling
Forster+ 18 Nature Astronomy
see also Morozova+ 17 ApJ

- **Apparently common for Type II SNe**
  $dM_{cs}/dt \sim 10^{-3}\text{-}10^{-1}\ M_{sun}\ yr^{-1}$ ($\gg 3\times10^{-6}\ M_{sun}\ yr^{-1}$ for typical red supergiants)

Supernovae with Interactions with CSM

KM et al. 11
Katz et al. 11
KM 18



kinetic energy → thermal + non-thermal via shock

$$p + p \rightarrow N\pi + X$$

$$\pi^{\pm} \rightarrow \nu_{\mu} + \bar{\nu}_{\mu} + \nu_{e}(\bar{\nu}_{e}) + e^{\pm}$$

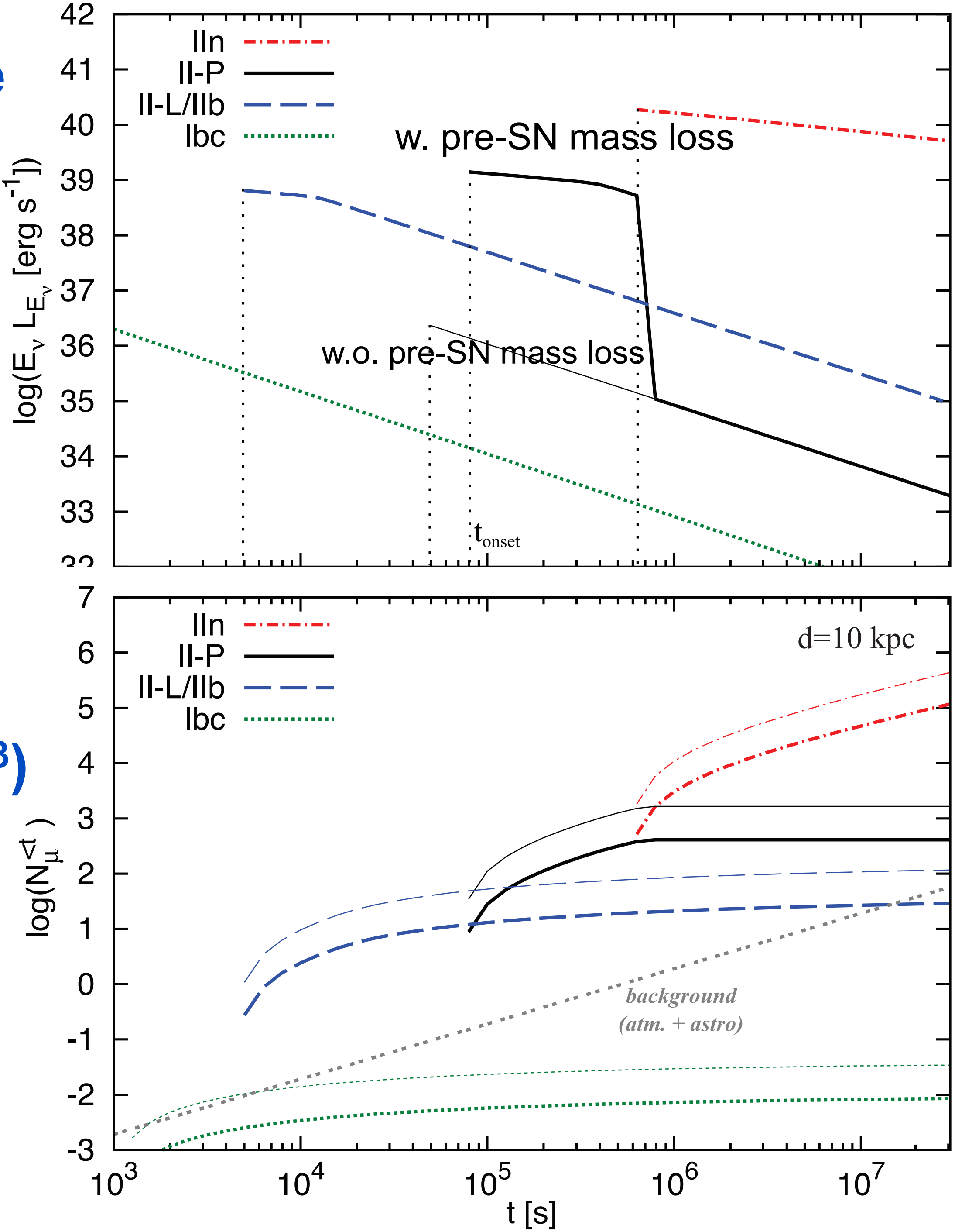
$$\pi^{0} \rightarrow \gamma + \gamma$$

dense environments = efficient ν emitters (calorimeters)

light curve

KM 18 PRDR

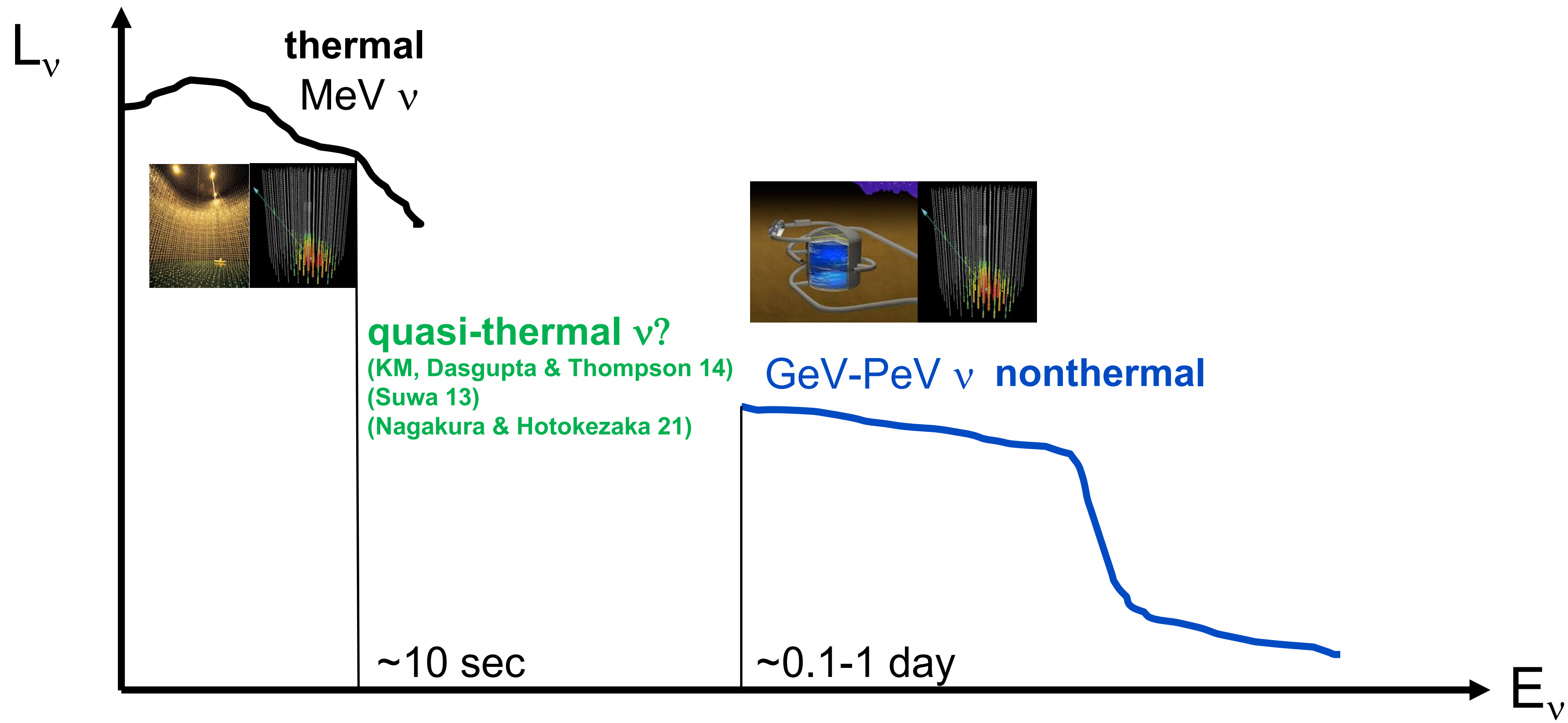
expected # of ν_μ tracks (w. V=1 km^3)



~100-1000 events for typical CCSNe

Next Galactic SN: Multi-Messenger & Multi-Energy ν Source

- Not only MeV νs but also GeV νs could be detected by Hyper-K & IceCube
- TeV-PeV νs will be detected by IceCube-like detectors w. large statistics
  ex. Betelgeuse: ~10^3-3×10^6 events, Eta Carinae: ~10^5-3×10^6 events
  → real-time observation of cosmic-ray ion acceleration
  testing the cosmic-ray origin & applications to neutrino physics



Summary

Green the deserts toward the multi-energy ν astrophysics era

From TeV-PeV to PeV-EeV

Important to reveal the origin of UHECRs and test the astro-particle unification
Many experimental proposals to enlarge effective volumes

From TeV-PeV to GeV-TeV

Important to reveal the connection to γ rays and test hidden ν scenarios
Nearby GeV-TeV (Galactic) sources and transients (GRBs/SNe/TDEs)

GRBs & SNe (Stellar Collapse & Compact Mergers)

ν-UHECR connection? ν-GW coincident? Possible but w. Gen2-like detectors
Galactic SN: promising multi-messenger & multi-energy ν source

Large statistics at different energies will help us test various neutrino physics
Lorentz invariance, neutrino oscillation, neutrino decay, ν-ν/ν-DM/other NSI etc.
(e.g., 1404.0622, 1404.7025, 1512.07228, 1610.02096, 1404.2279, 1404.2288,1408.3799 & 1903.04333)

Thank you very much!

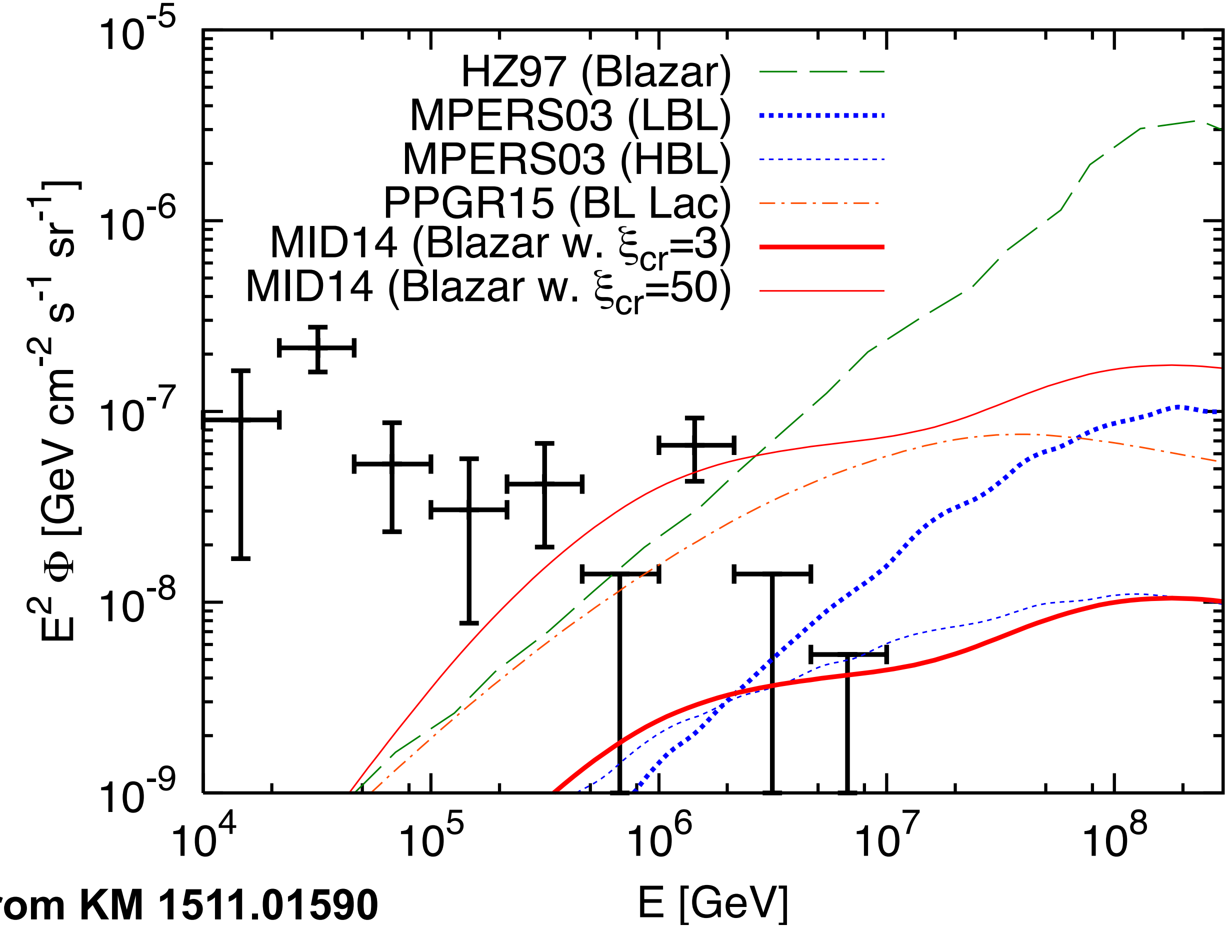
Masatoshi Koshiba
(1926 - 2020)

U. Tokyo in Dec 2002

Backup

Diffuse Neutrino Intensity?

Blazars: if UHECR accelerators → promising EeV neutrino emitters



various diffuse ν predictions

leptonic (w. IceCube ν norm.)
BL Lacs + FSRQ

hadronic (w. Fermi γ-ray norm.)
BL Lacs (w.o. external fields)

leptonic (w. "UHECR" norm.)
BL Lacs + FSRQ

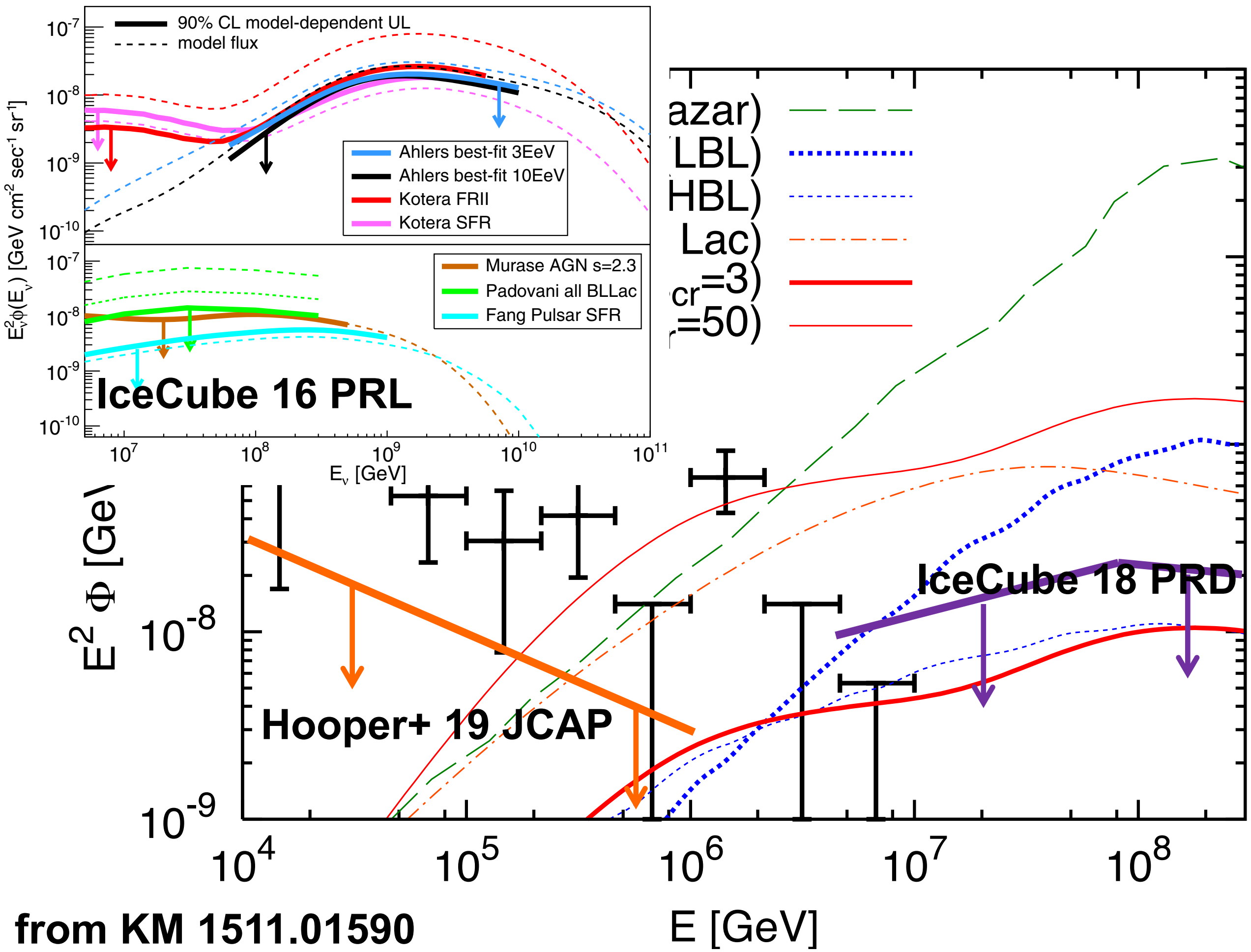
from KM 1511.01590

Diffuse Neutrino Intensity?

Blazars: if UHECR accelerators → promising EeV neutrino emitters

IceCube 9-yr EHE analyses give a limit of $<10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} at 10 PeV

many existing models have been constrained



various diffuse ν predictions

leptonic (w. IceCube ν norm.)
BL Lacs + FSRQ

hadronic (w. Fermi γ-ray norm.)
BL Lacs (w.o. external fields)

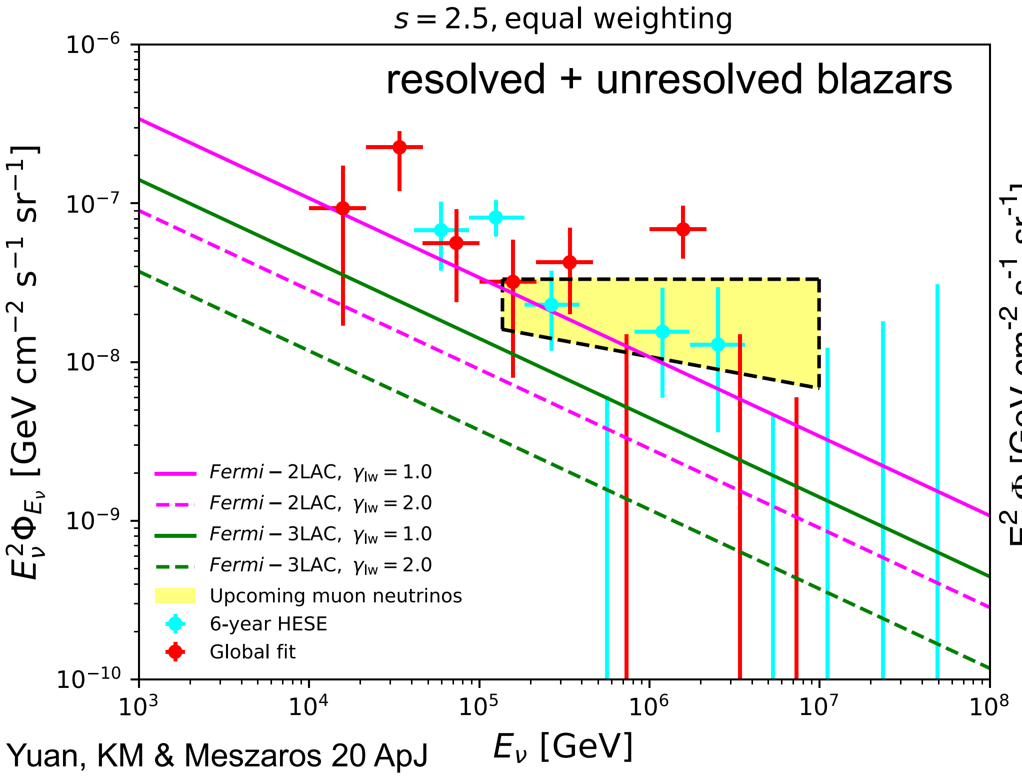
leptonic (w. "UHECR" norm.)
BL Lacs + FSRQ

from KM 1511.01590

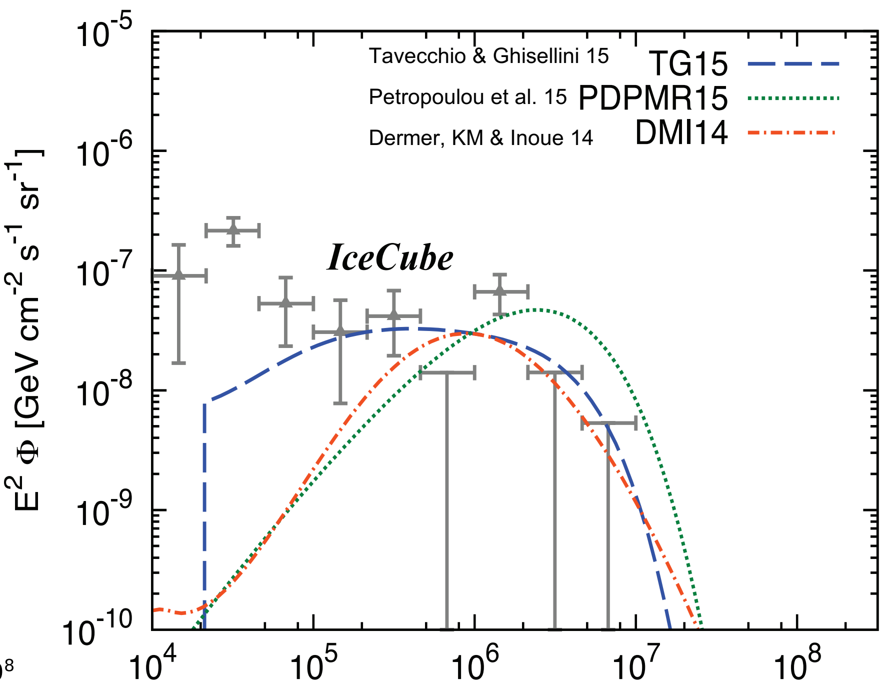
Can Blazars be the Origin of IceCube Neutrinos?

γ-ray bright blazars are largely resolved -> stacking analyses are powerful

(IceCube 17 ApJ, Hooper+ 19 JCAP)



Yuan, KM & Meszaros 20 ApJ



KM & Waxman 16 PRD

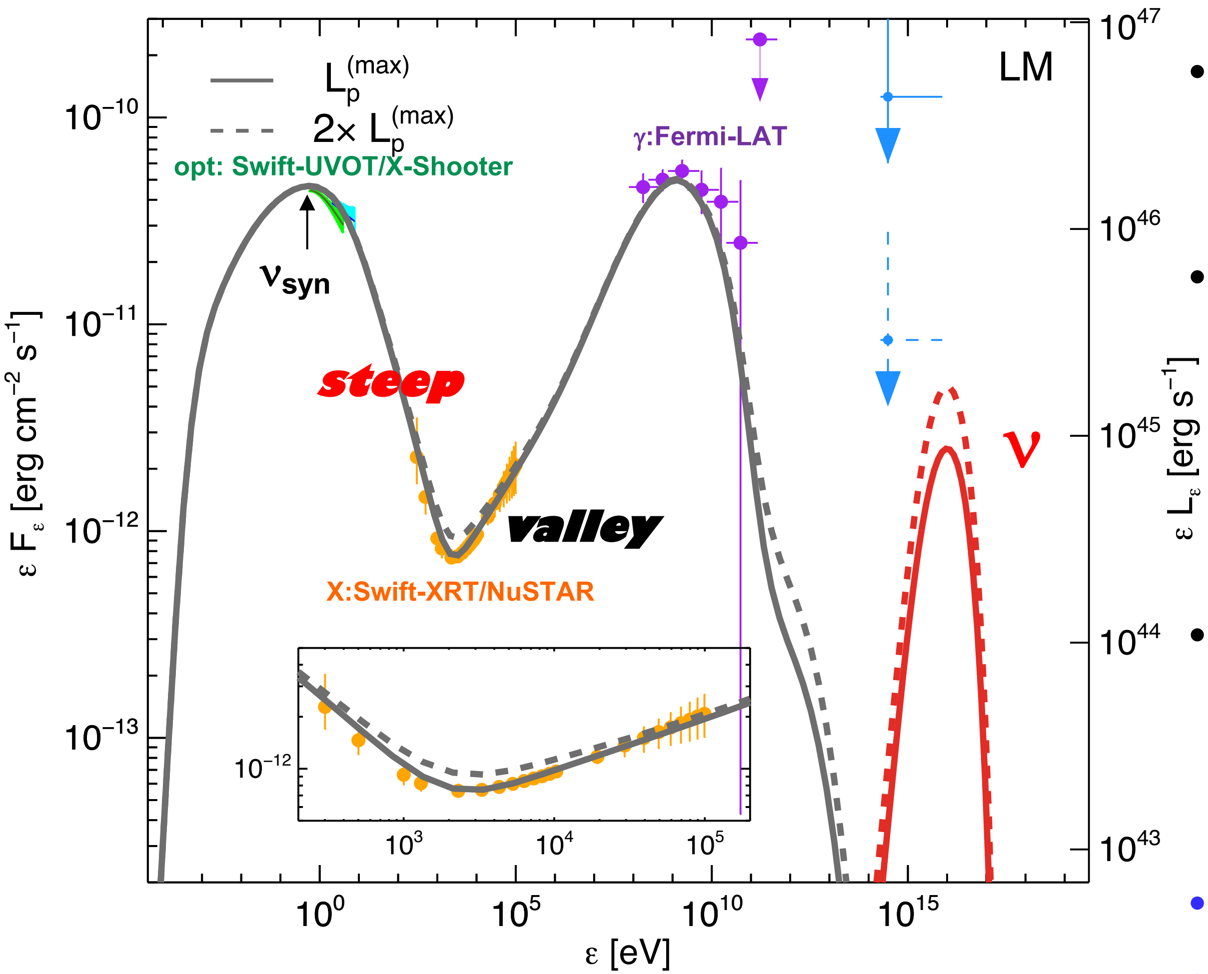
- Comprehensive analysis considering uncertainty from "unresolved" blazars (complementary to neutrino anisotropy limits by e.g., KM & Waxman 16)

  → blazars are subdominant in the diffuse ν sky (most likely <~ 30%)

- Possible to partially account for the ν data by giving up UHECR explanation

Modeling of the 2017 Multimessenger Flare

Keivani, KM, Petropoulou, Fox et al. 2018 ApJ



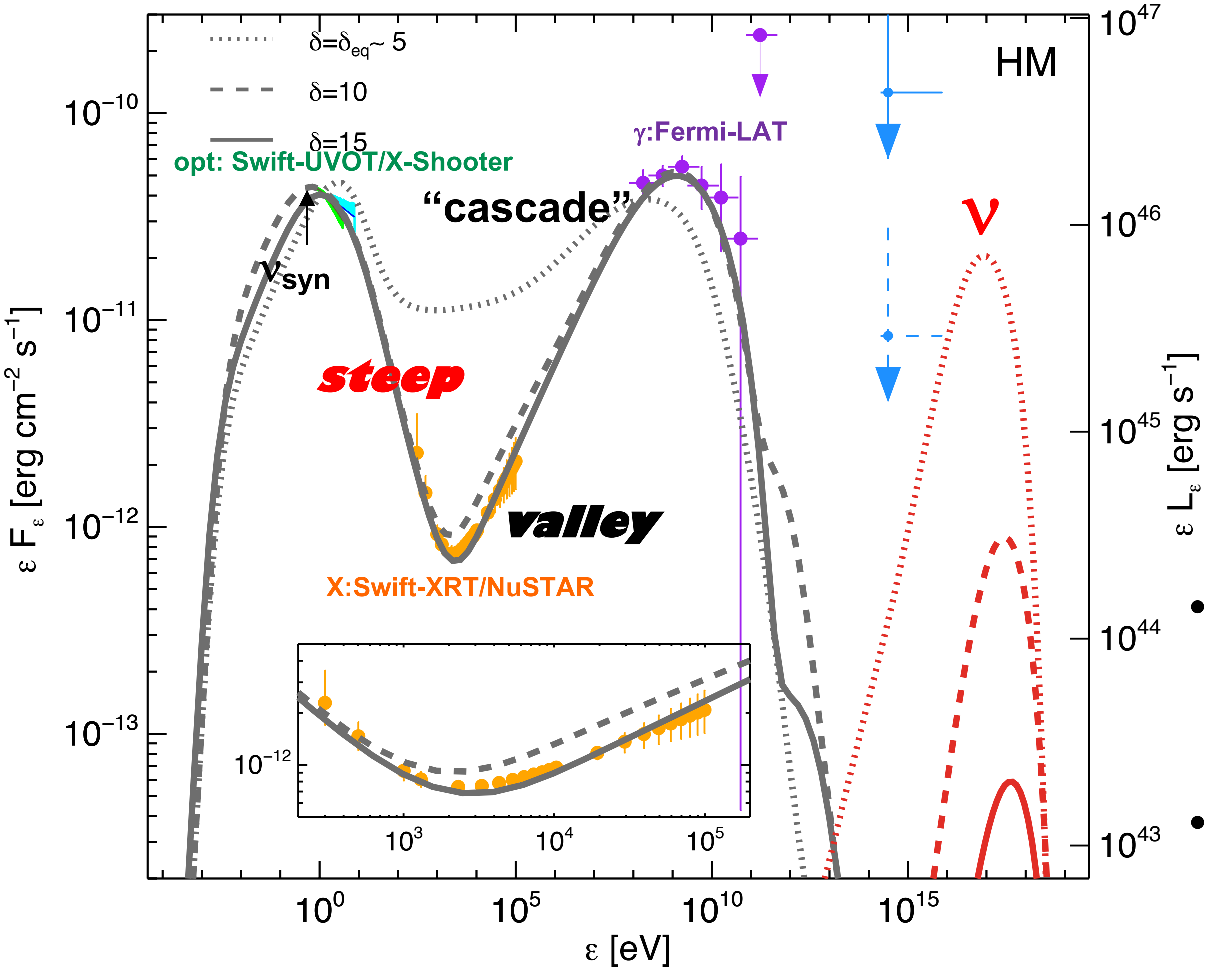
- Low synchrotron peak ν_{syn}<3x10^{14} Hz (infrared)
- Leptonic scenario γ rays = inverse-Compton (external radiation needed)
- Hadronic γ rays: cascaded "inside" the sources

Implications

- γ-ray cascade bounds on neutrino fluxes imply: N_ν<0.02/yr (real-time) N_ν<0.2/yr (point-source)
- No UHECR (<0.3 EeV)
- Extremely large jet power $\varepsilon_p/\varepsilon_e$ >300 needed

Hadronic Scenarios: Unlikely to Explain the IceCube Data

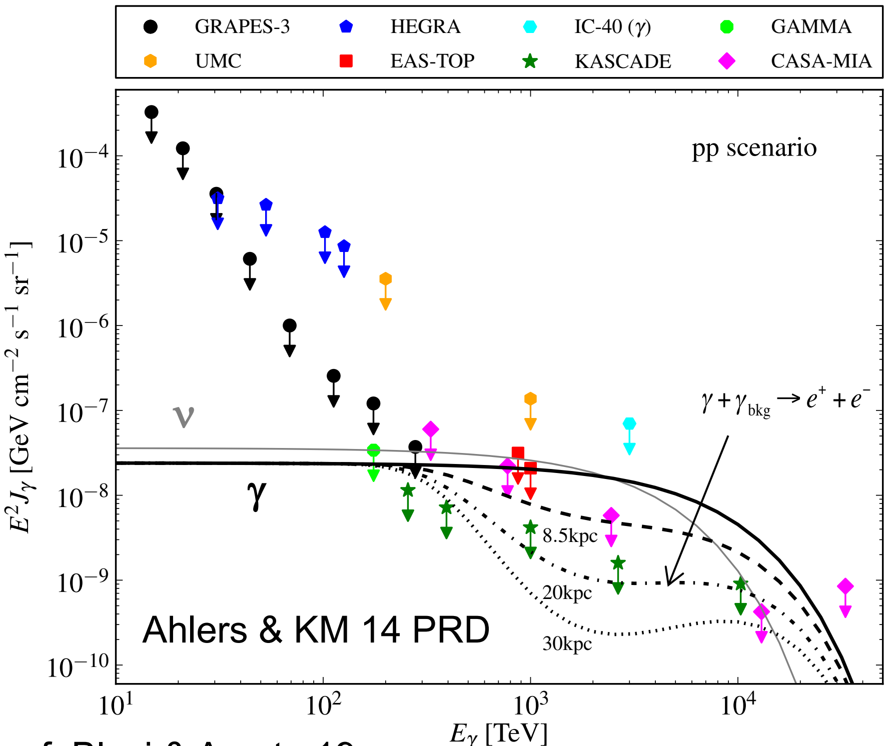
Keivani, KM, Petropoulou, Fox et al. 2018 ApJ



- Low synchrotron peak ν_{syn}<3x10^{14} Hz (infrared)
- γ = π-induced cascade
  $F_\nu \sim F_\gamma$: ruled out
- γ = p-syn. from UHECRs
  very low F_ν at 0.1-1 PeV due to the peak at ~1 EeV
  (γ rays can be explained)

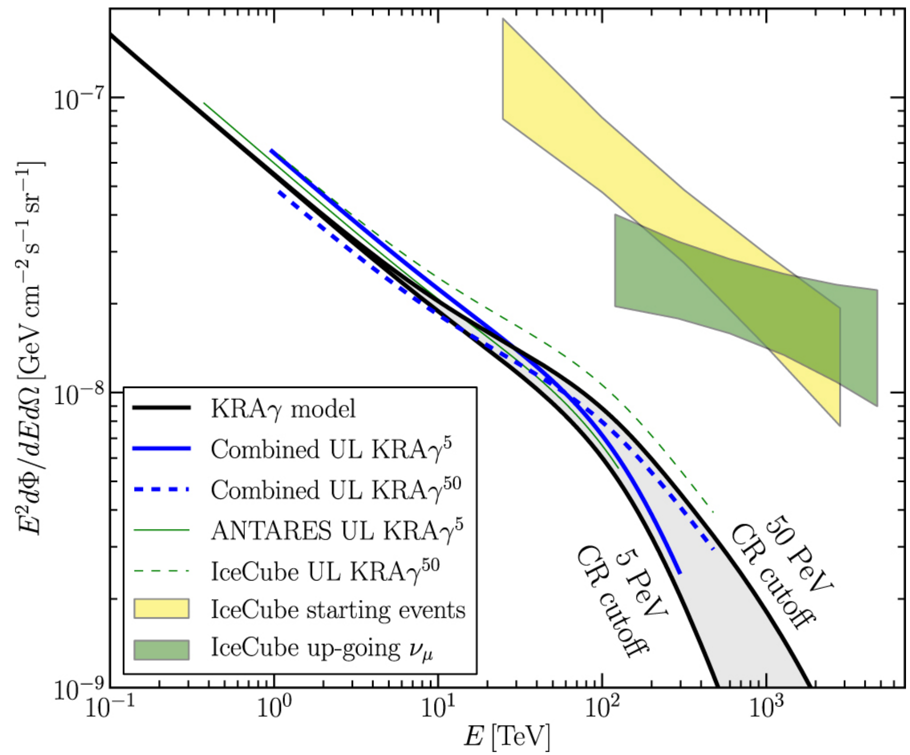
Constraints on Galactic Sources

Isotropic emission
(ex. Galactic halo CRs)



cf. Blasi & Amato 19

Galactic plane emission
(ex. diffuse CRs, supernova remnants)

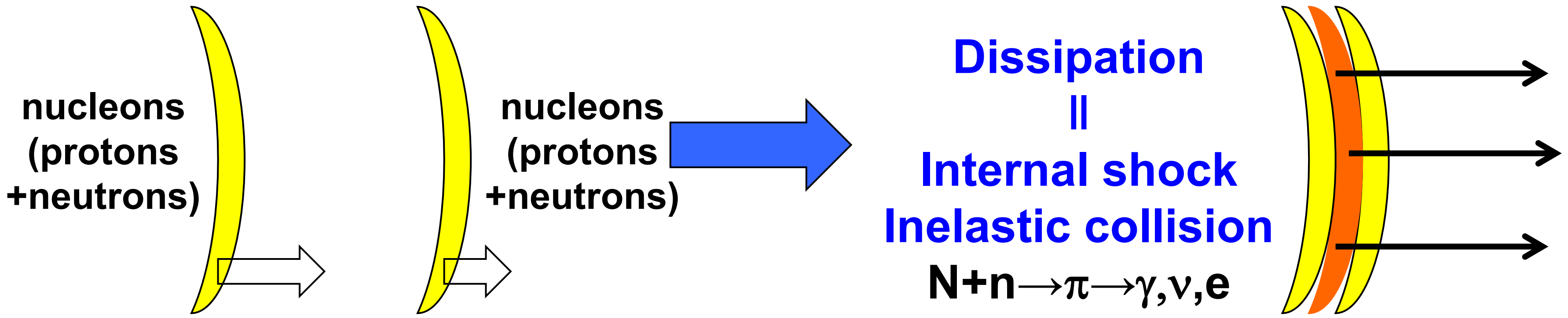


IceCube Collabooration 18 ApJL

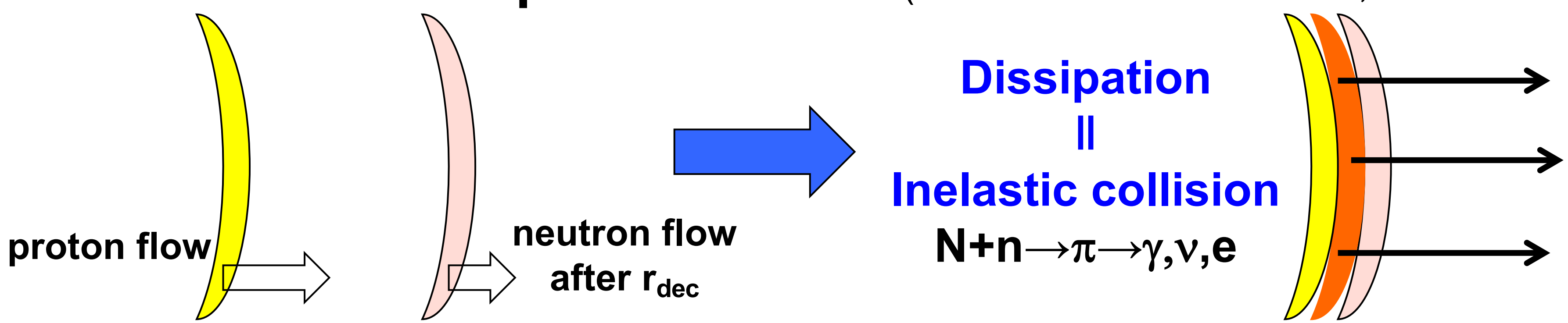
- IceCube+ANTARES: Galactic plane contribution should be subdominant
- Quasi-isotropic emission: tension w. existing TeV-PeV γ-ray limits
  need deeper TeV-PeV γ-ray obs. (ex. Fermi, HAWC, Tibet-AS+MD, SGSO)

Neutrinos Probe Dissipation Mechanisms

Collision w. compound flow (ex. Meszaros & Rees 00)

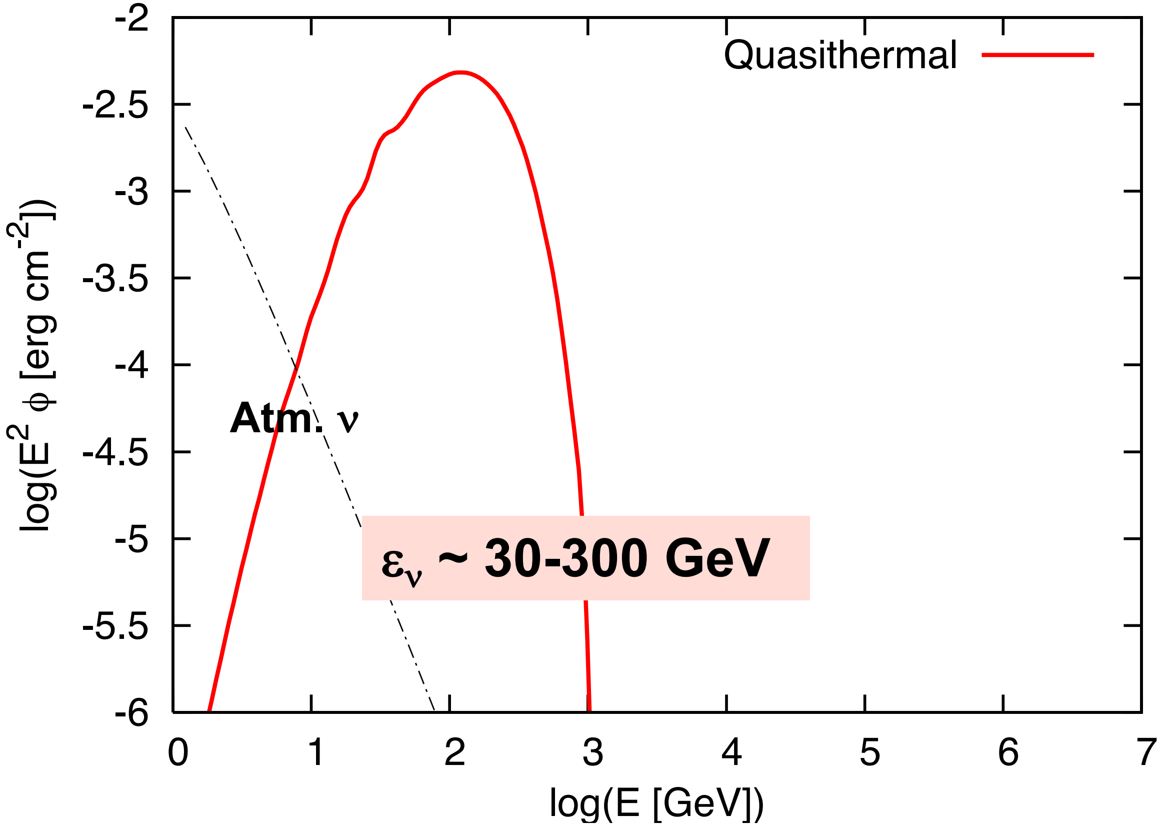


Collision w. decoupled neutrons (ex. Bahcall & Meszaros 00, Beloborodov 10)



Quasi-Thermal Neutrinos from pn Collisions

- $\varepsilon_\nu \sim 0.1\Gamma\Gamma_{rel} m_p c^2 \sim 100$ GeV$(\Gamma/500)(\Gamma_{rel}/2)$: quasithermal
- pn collisional dissipation is unavoidable
  $\varepsilon_\nu^2\phi_\nu \sim \varepsilon_\gamma^2\phi_\gamma$: required to explain prompt emission
  much less uncertainty in meson production efficiency

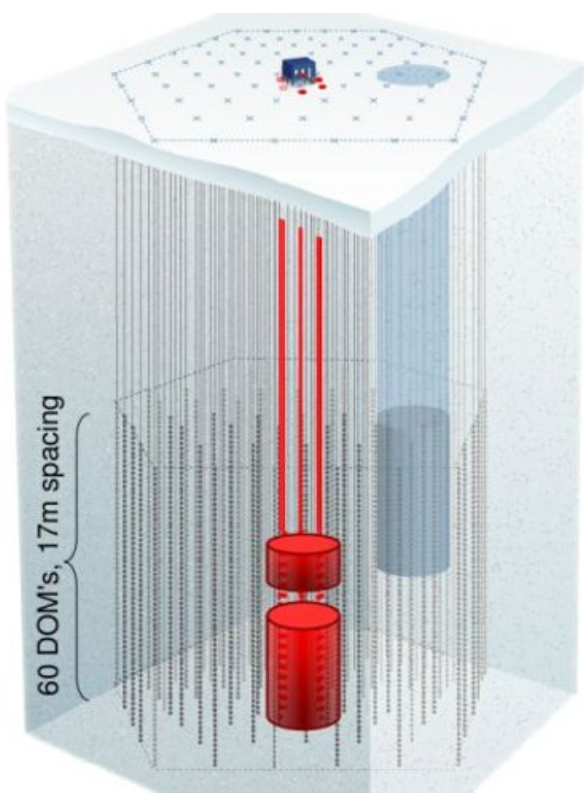


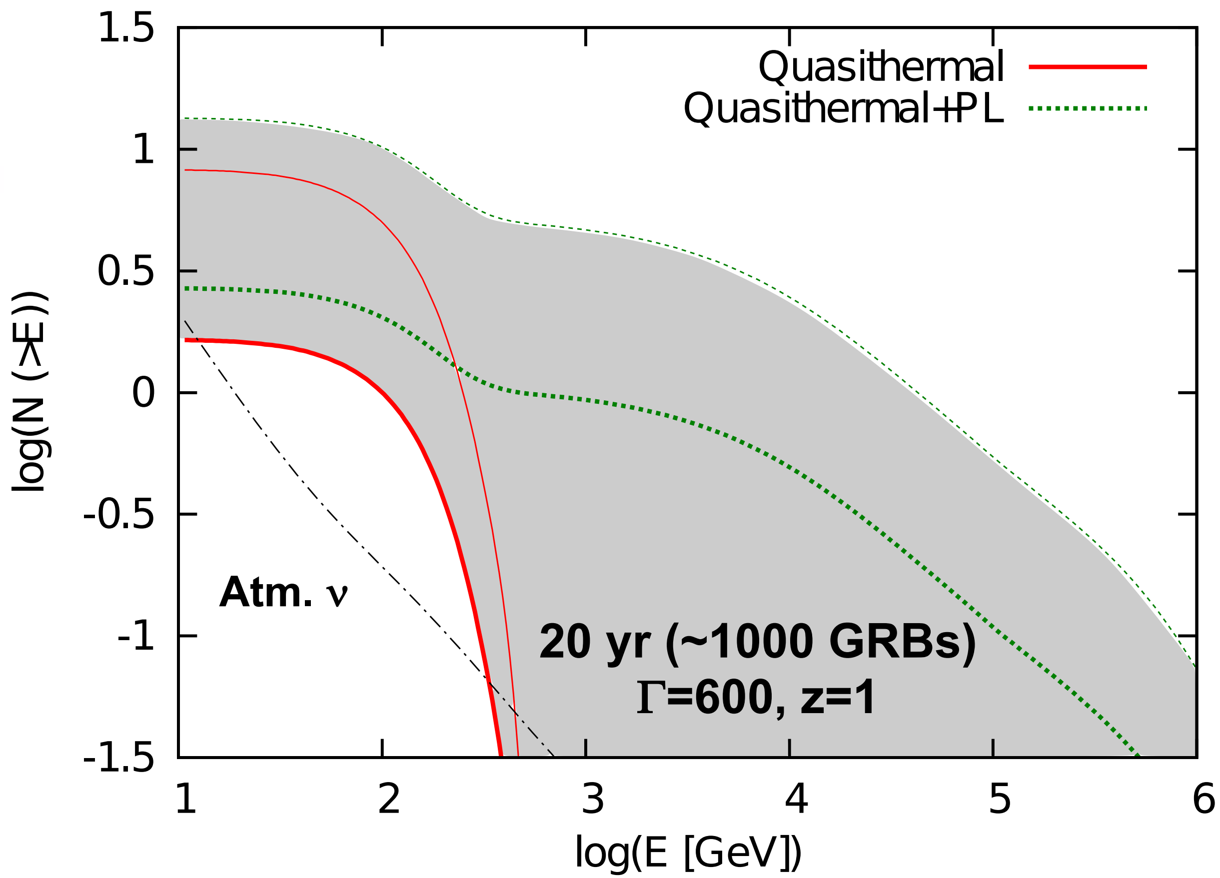
$E_k^{iso}/E_\gamma^{iso}=4$
$E_\gamma^{iso}=10^{53.5}$ erg
$\Gamma=600$, $z=0.1$

KM, Kashiyama & Meszaros 13 PRL

Prospects for DeepCore+IceCube

- Including DeepCore is essential at 10-100 GeV
- Reducing atmospheric ν background is essential
  → select only bright GRBs w. > 10^{-6} erg cm^{-2}

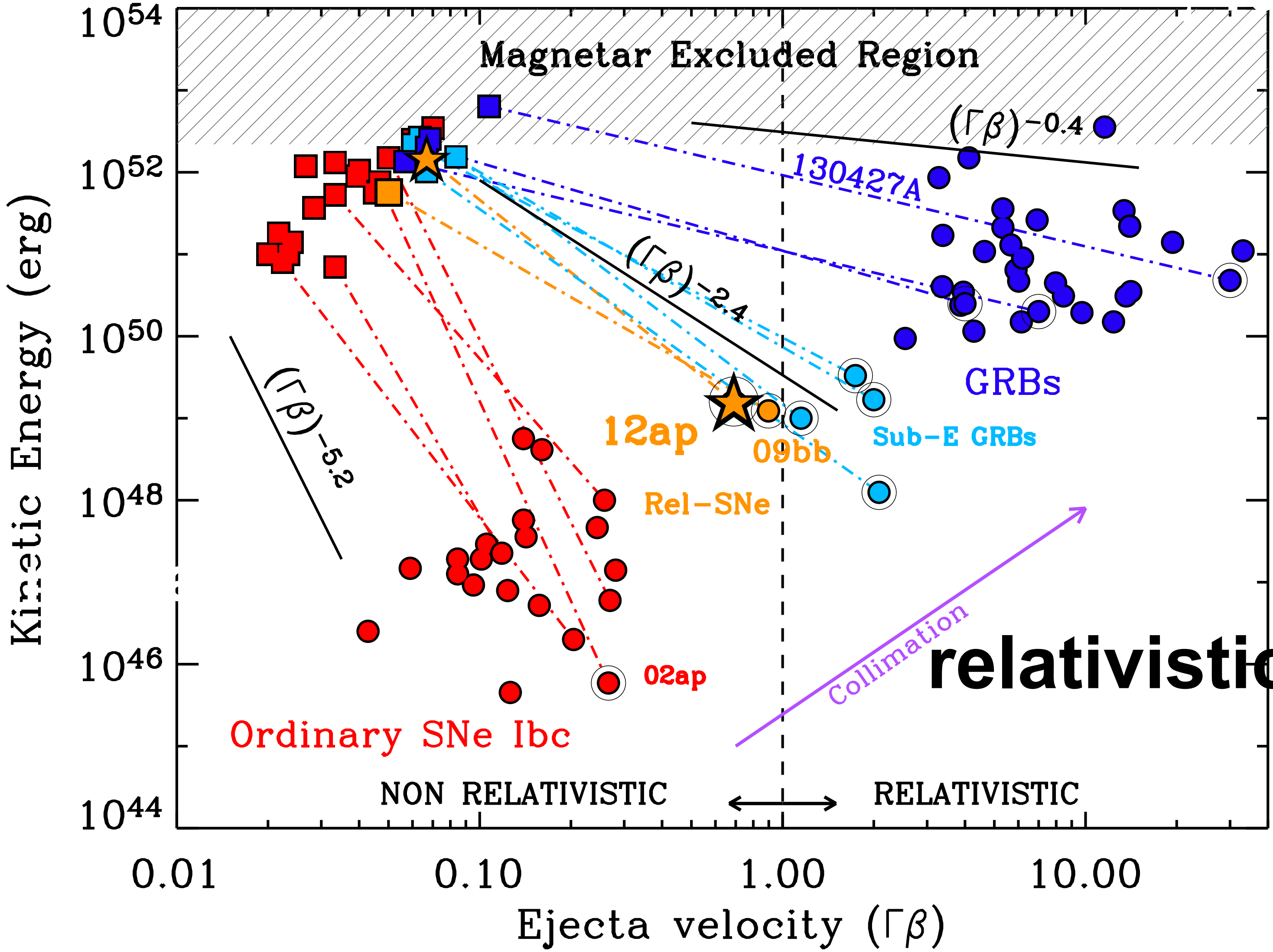




KM, Kashiyama & Meszaros 13 PRL

GRB-SN Connection

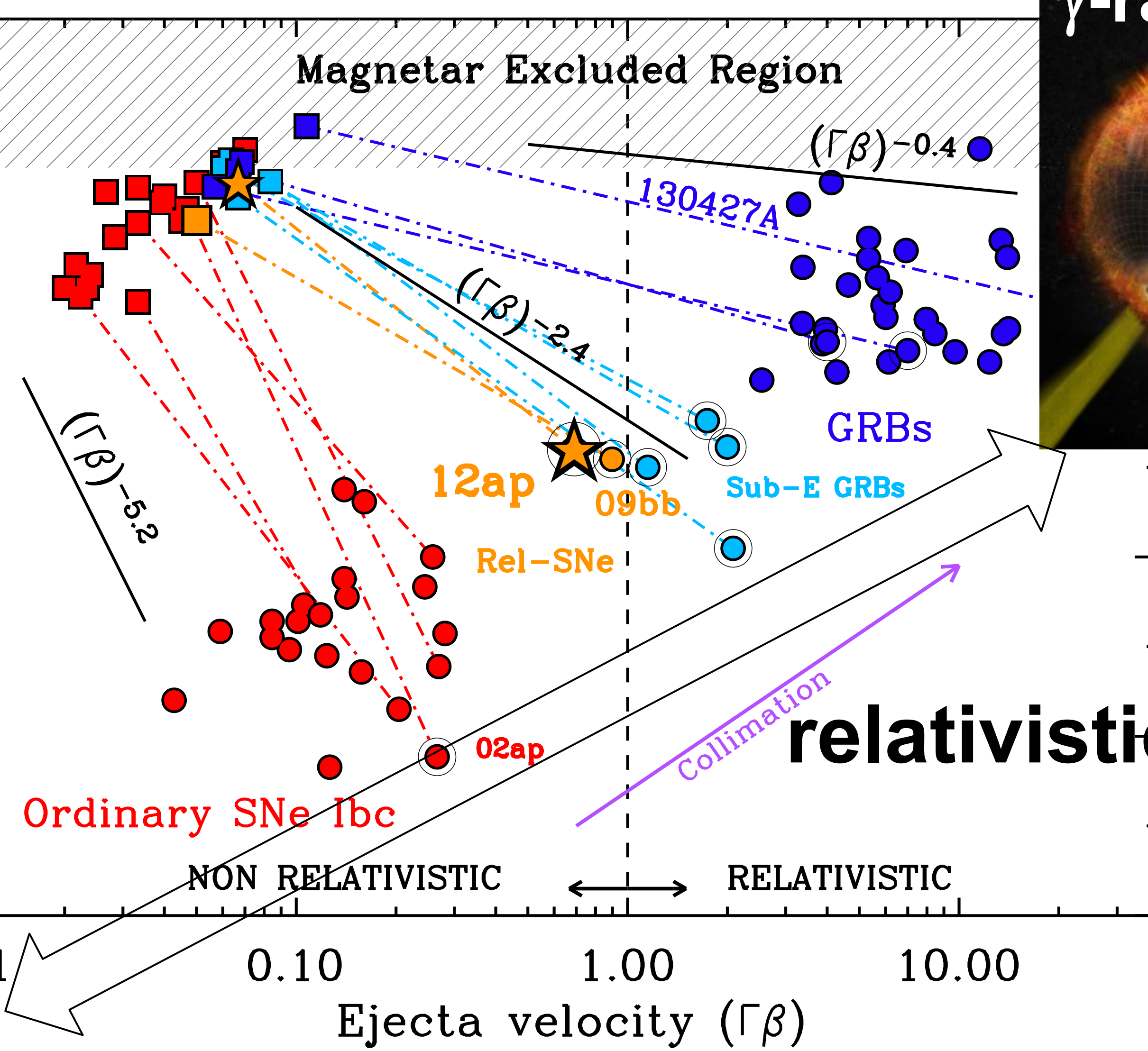
Margutti+ 14



relativistic jet?

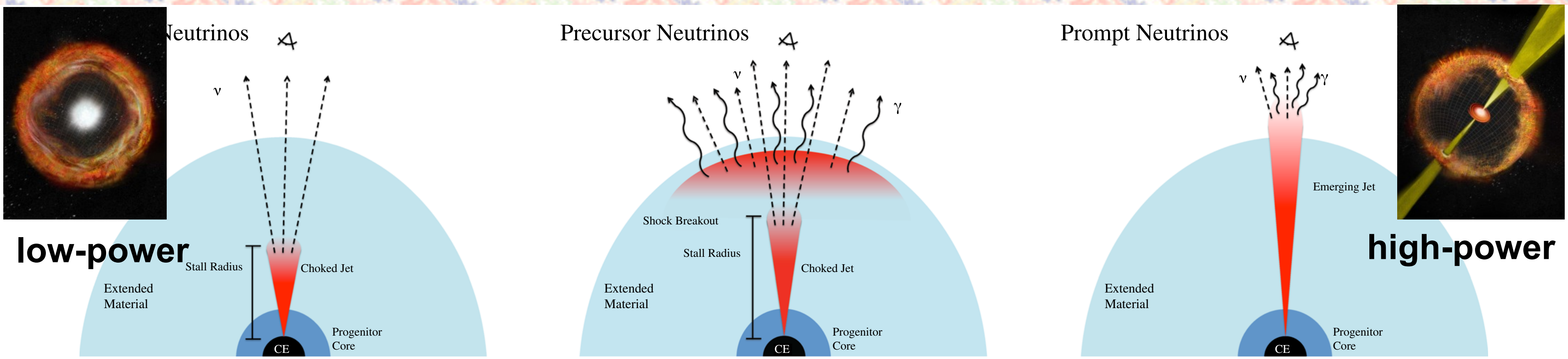
GRB-SN Connection

Margutti+ 14

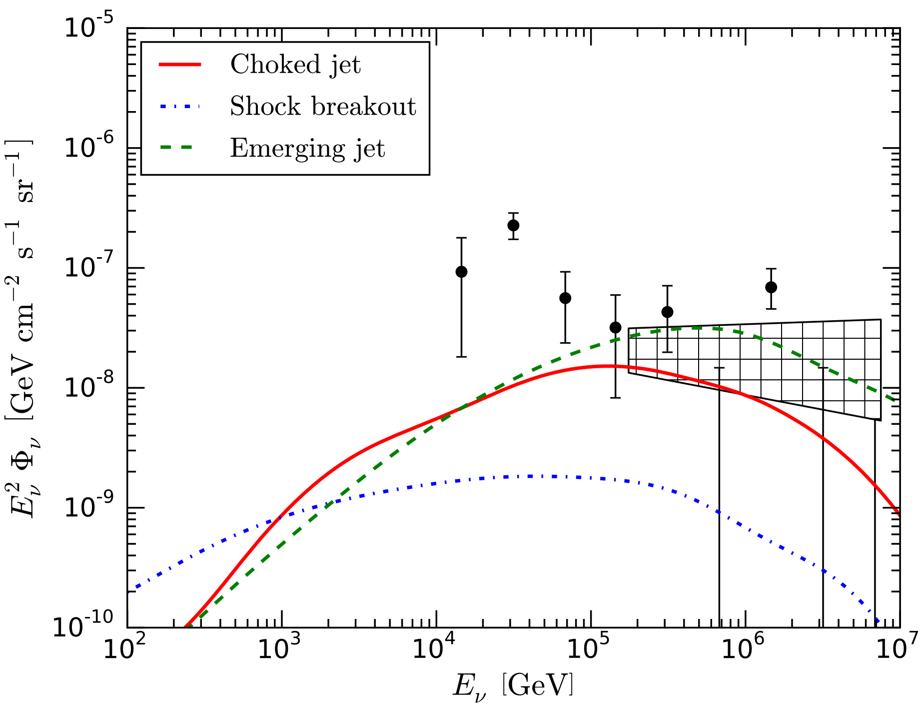


relativistic jet?

HE Neutrinos from LL GRBs and Type Ibc SNe



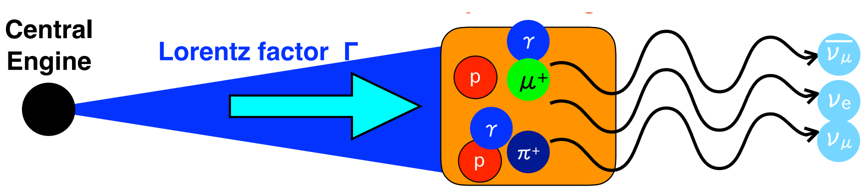
from Senno, KM & Meszaros 16 PRD

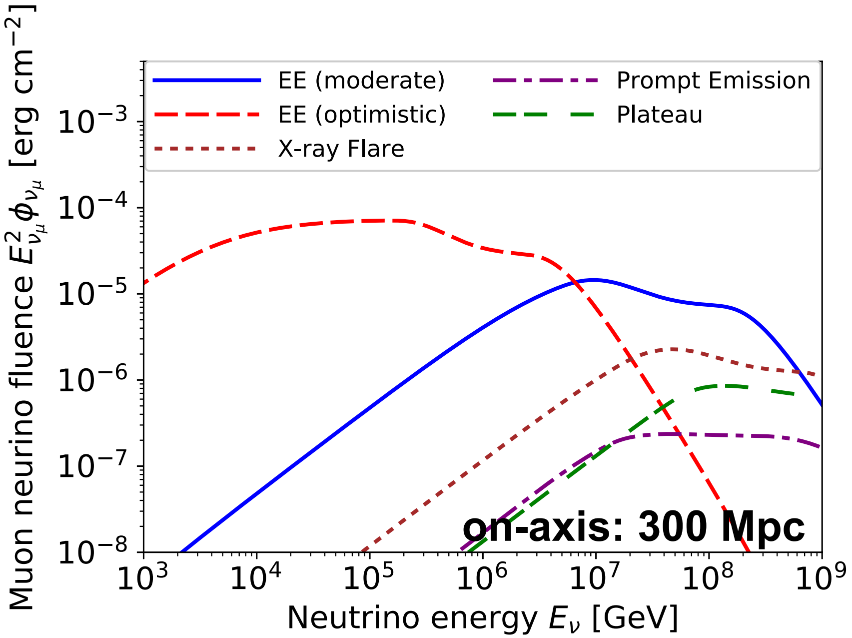


- Trans-relativistic SNe such as may come from shock breakout (Campana+ 07, Waxman+ 07)
- Jet: successful or failed? (Toma+07, Nakar 15, Irwin & Chevalier 16)
- They could significantly contribute to the IceCube flux (usual stacking limits are not applied) (KM+ 06, KM & Ioka 13, Senno, KM+ 16)

Coincident Detection w. Gravitational Waves?

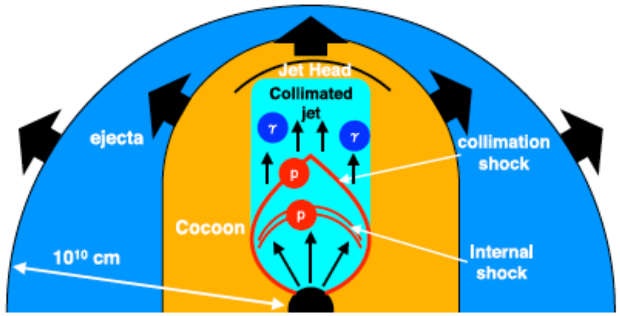
Kimura, KM, Meszaros & Kiuchi 17 ApJL
(cf. Waxman & Bahcall 97 PRL for prompt
KM & Nagataki 06 PRL for X-ray flares)

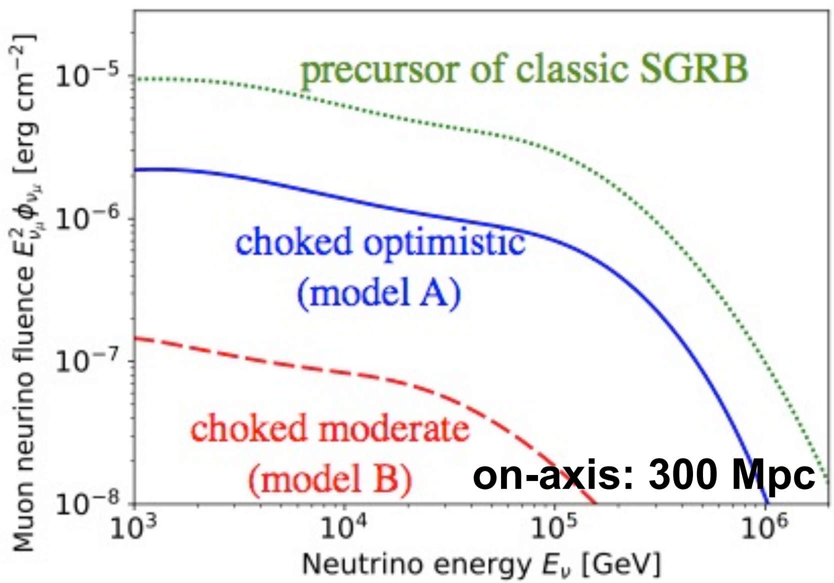




extended emission:
< 2-5 events in 10 years w. Gen2

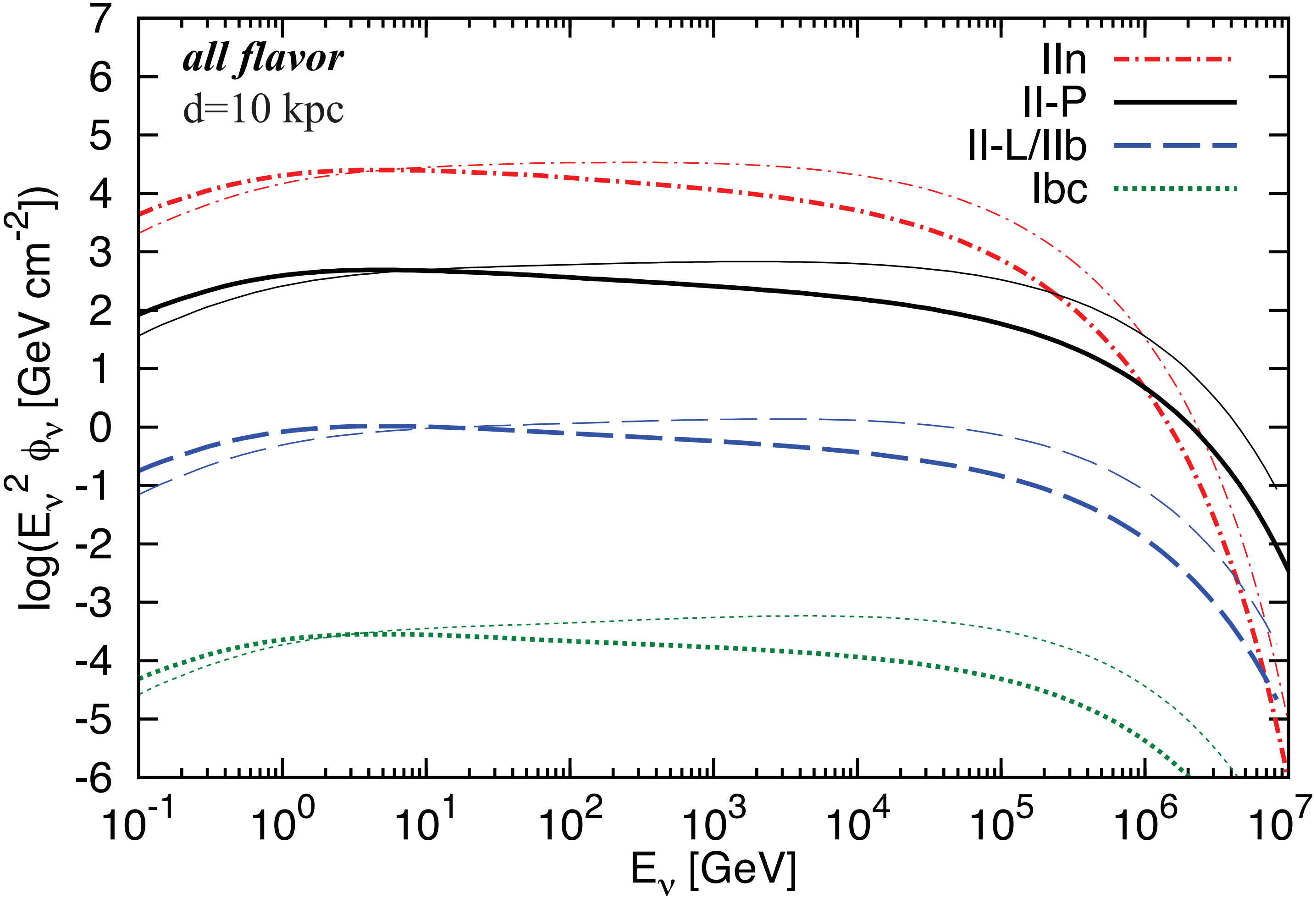
Kimura, KM, Bartos, Ioka+ 18 PRD
(cf. KM & Ioka 13 PRL for massive stars)





< 1-3 bursts in 10 years w. Gen2

Multi-Energy Neutrino Spectra



thick: s=2.2

thin: s=2.0

KM 18 PRDR

Fluence for an integration time when $S/B^{1/2}$ is maximal
(determined by the time-dependent model due to atm. bkg.)