High-Energy Cosmic Particle Sources I
- Neutrinos and Gamma Rays from Jets -

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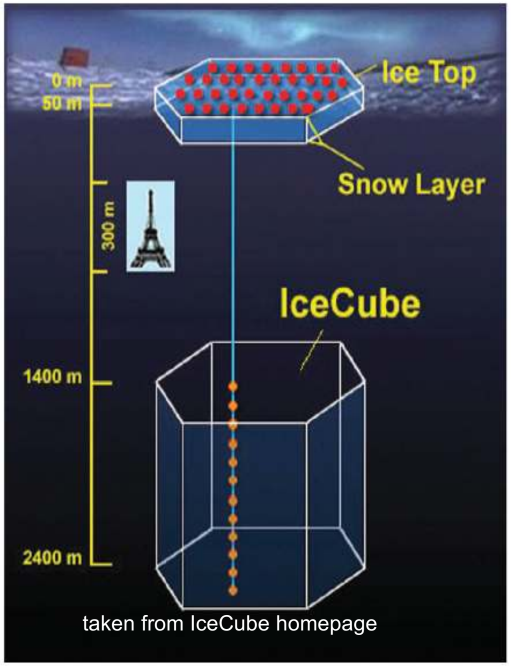
Era of Multi-Messenger Astroparticle Physics

Gamma Rays
Fermi, HAWC,
HESS, MAGIC, VERITAS, CTA etc.

Neutrinos
IceCube, KM3Net
Super-K etc.

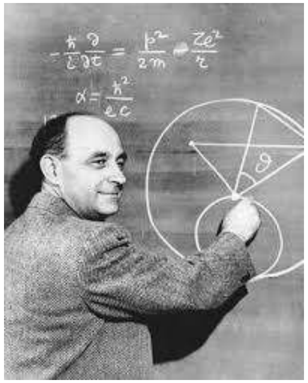


taken from IceCube homepage

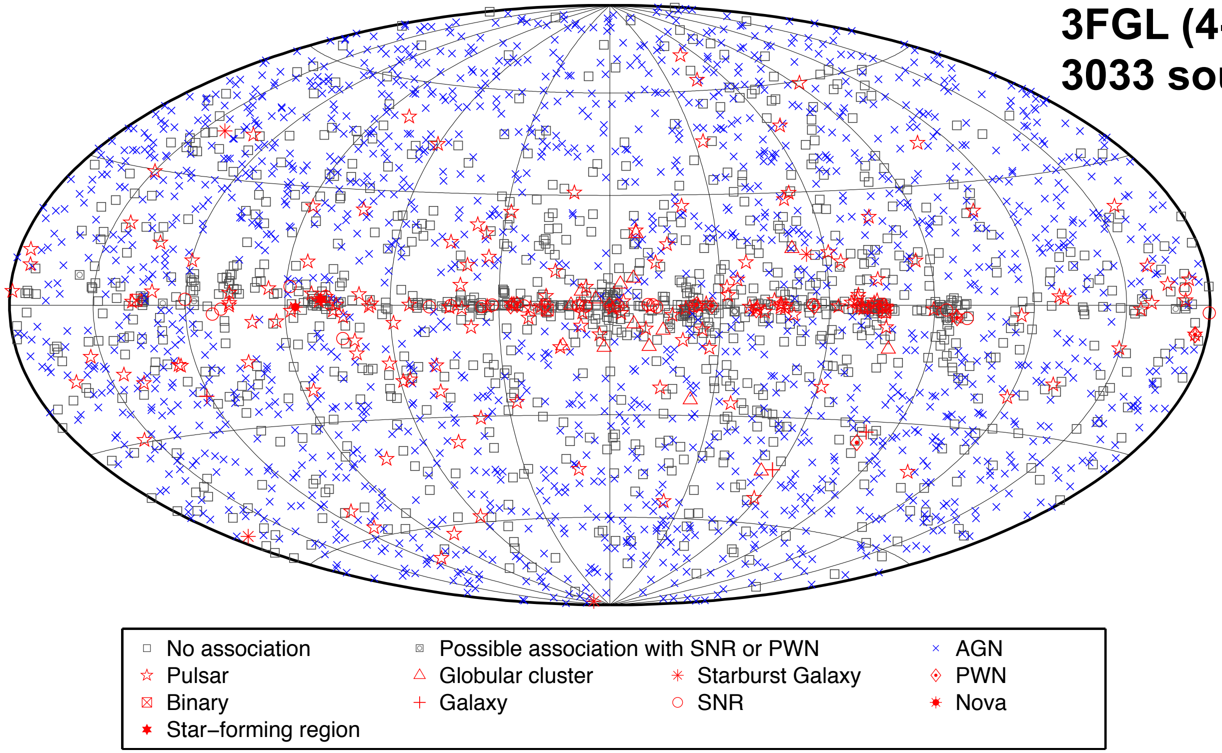
Cosmic Rays
PAMELA, AMS-02
Auger, TA etc.

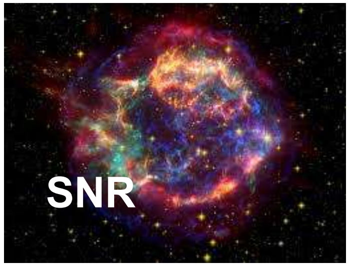
Gravitational Waves
LIGO, Virgo, KAGRA

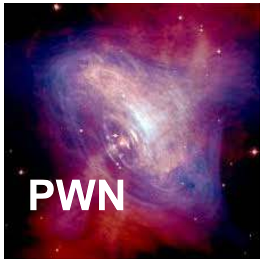
Gamma-Ray Astrophysics in the Fermi Era (2008-)



3FGL (4-year)
3033 sources



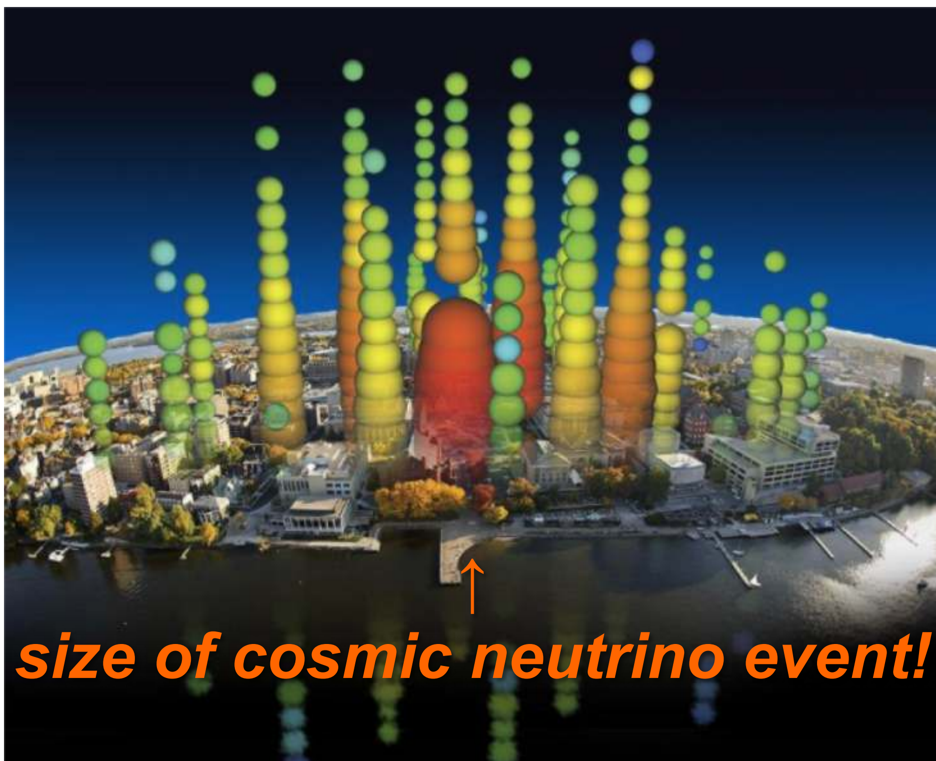


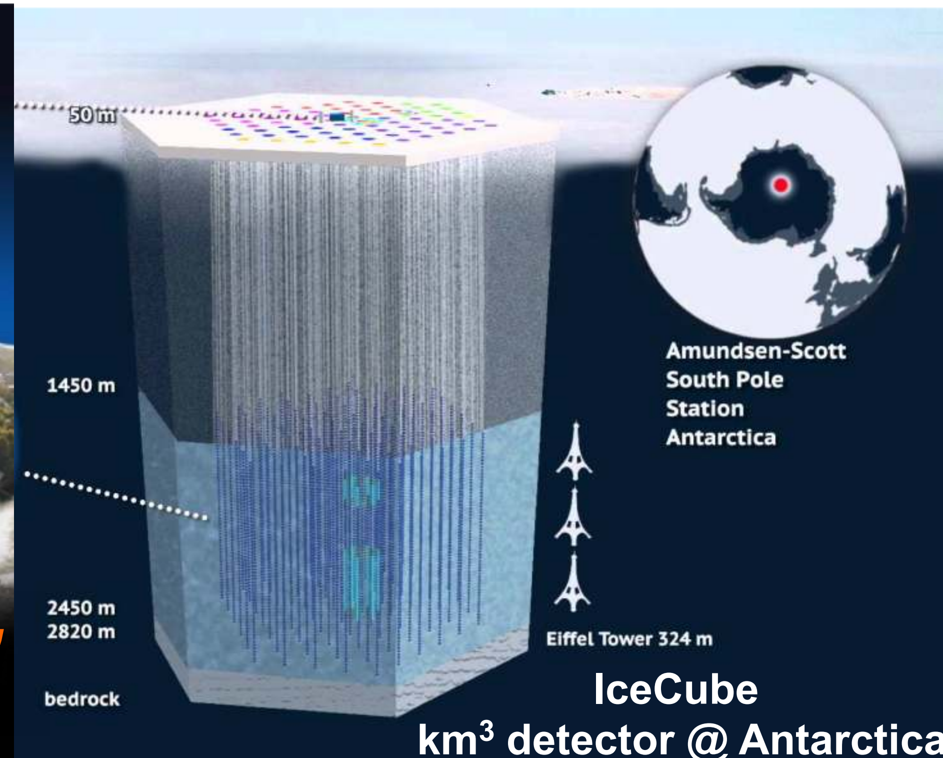


Discovery of High-Energy Neutrinos (2013)

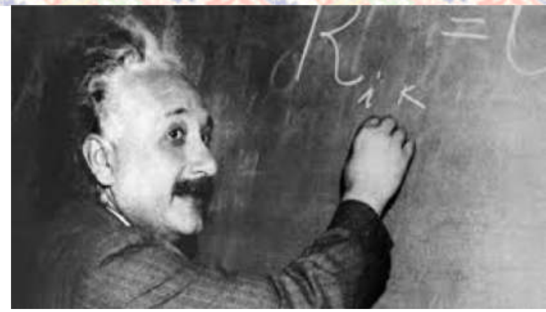
Neutrino (ν): mysterious subatomic particle w. tiny mass

- Discovery of neutrino mass (2015 Nobel prize)
  ↑ found in observations of neutrinos from cosmic rays
- "Ghost particle": interaction is 10,000 weaker than electromagnetic force
- High-energy ν from space: discovered by the IceCube experiment



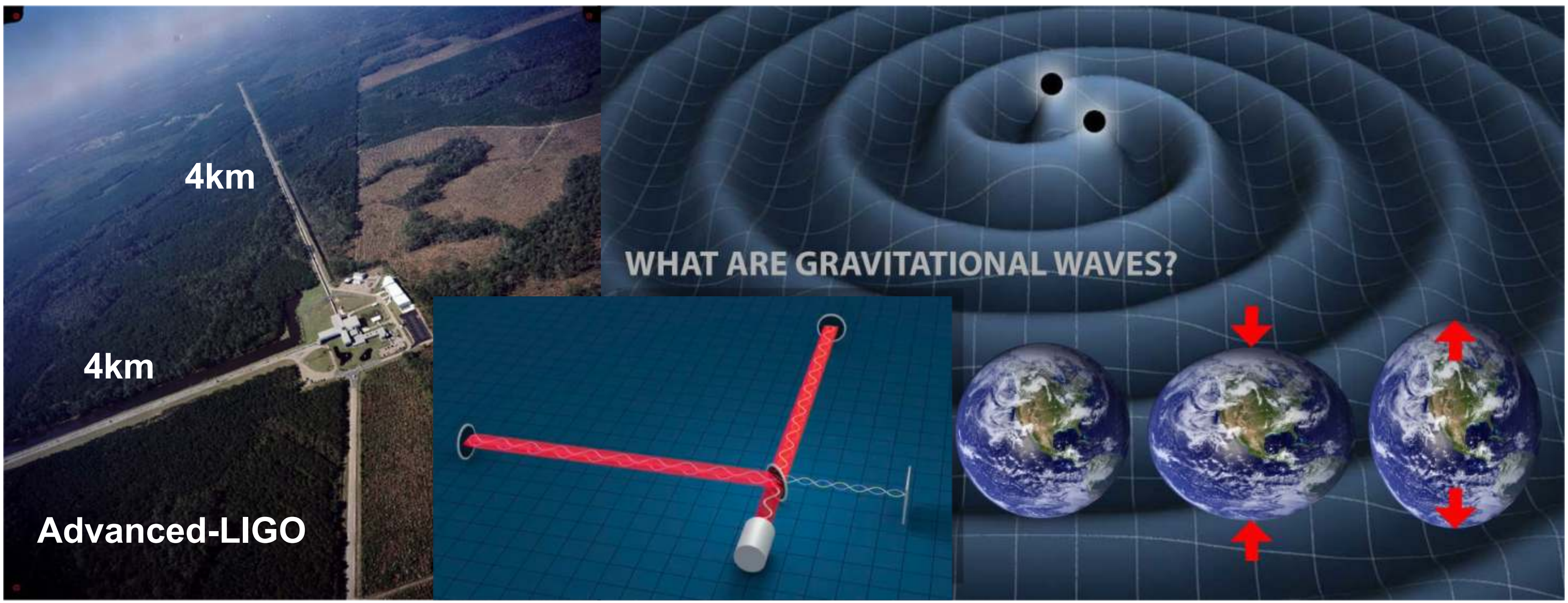


Discovery of Gravitational Waves (2016)

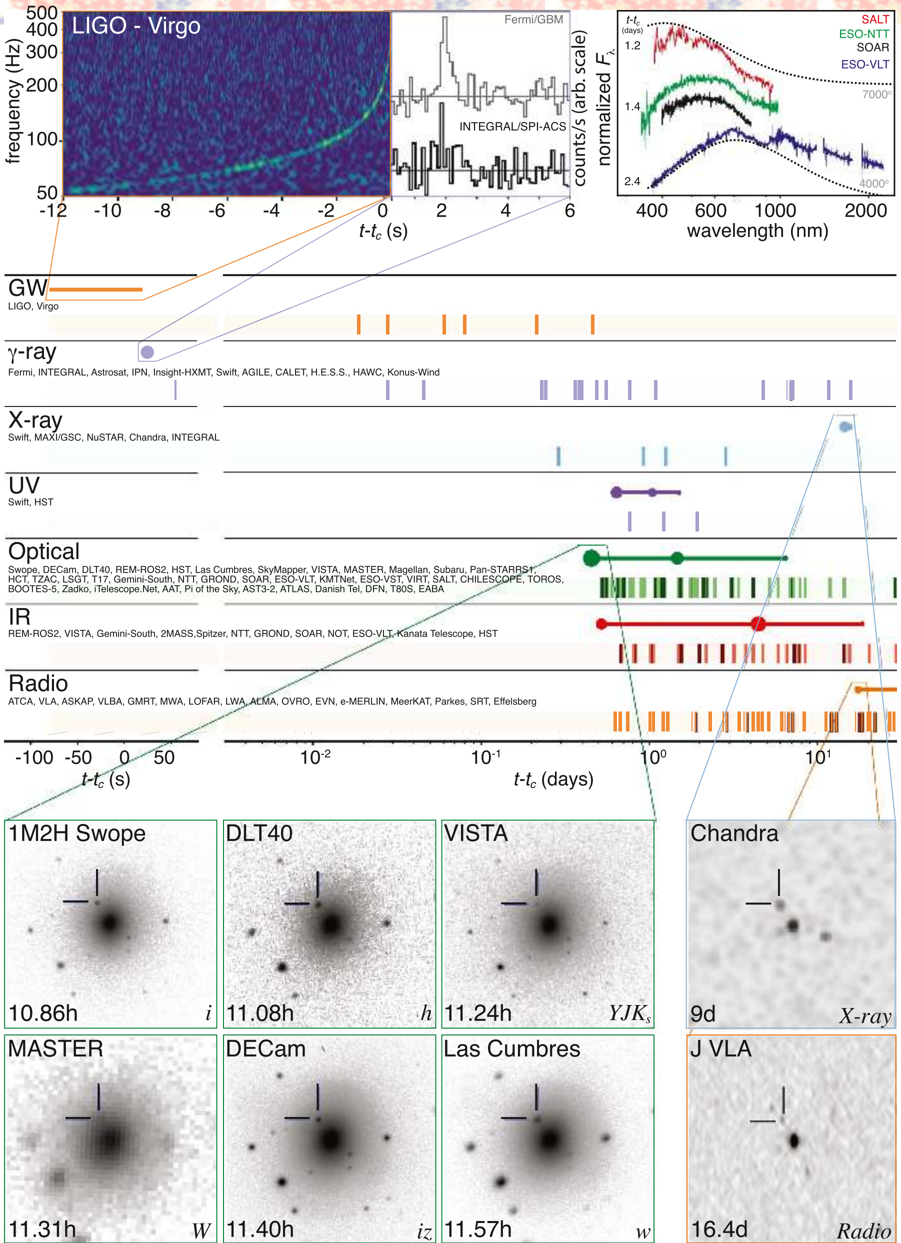


Gravitational wave (GW): ripples of spacetime

- Very tiny distortion: gravitational force is much weaker
  → source: neutron star, black hole (1993 Nobel Prize)
- "Einsteins' 100-yr homework":
  distortion is 1/10,000 of the atomic size for the entire Earth
- GWs from black hole mergers: discovered by Advanced-LIGO



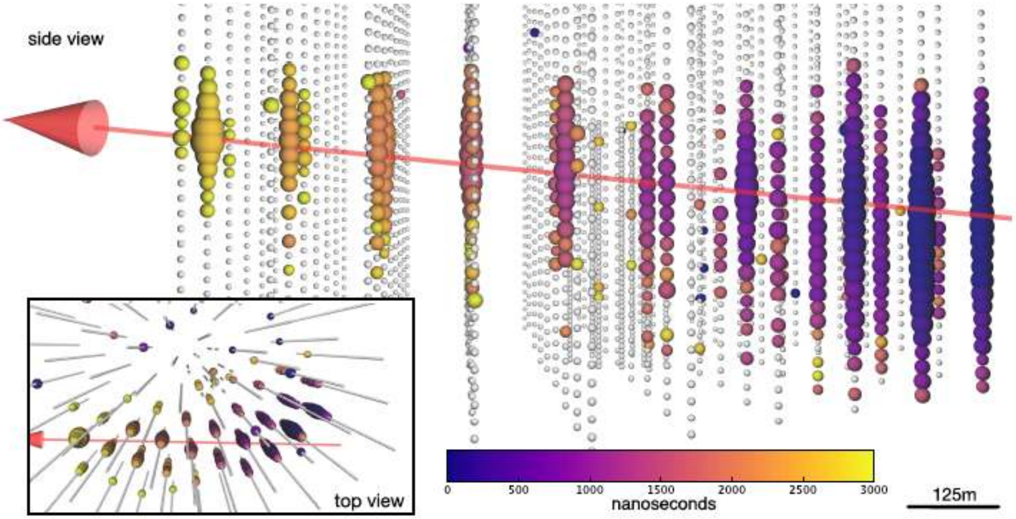
Discovery of Binary Neutron Star Merger (2017)



"concordance" picture

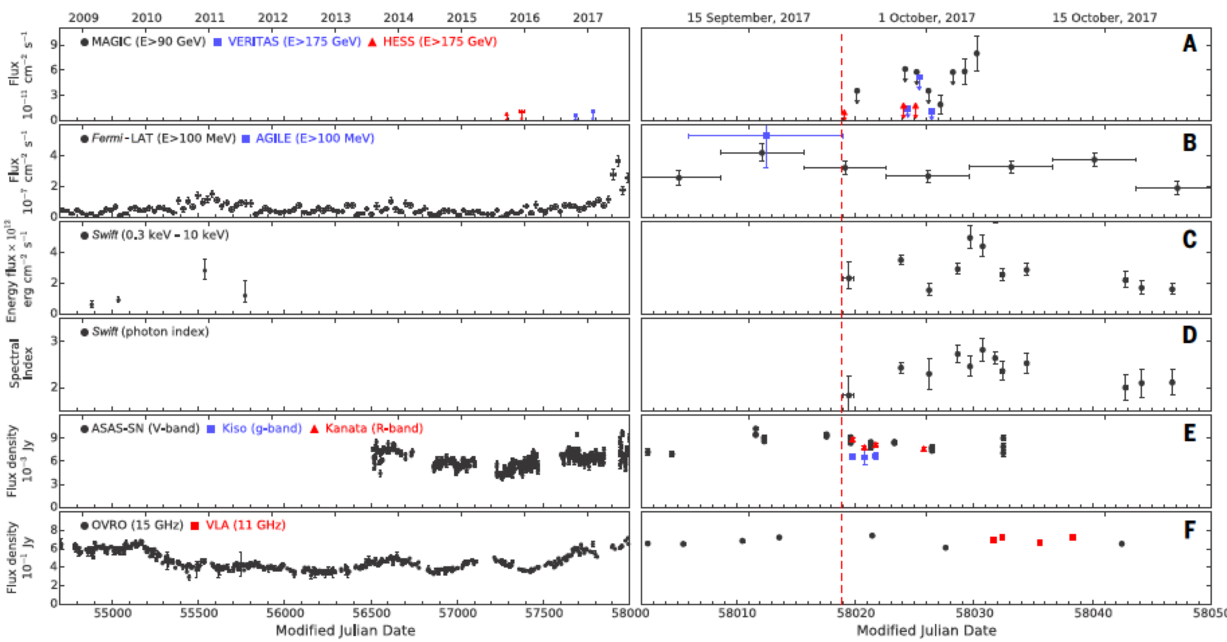
- gravitational wave
- gamma-ray burst
- kilonova/macronova
- X-ray/radio afterglow

(Evidence) of Blazar Neutrino Flare (2018)

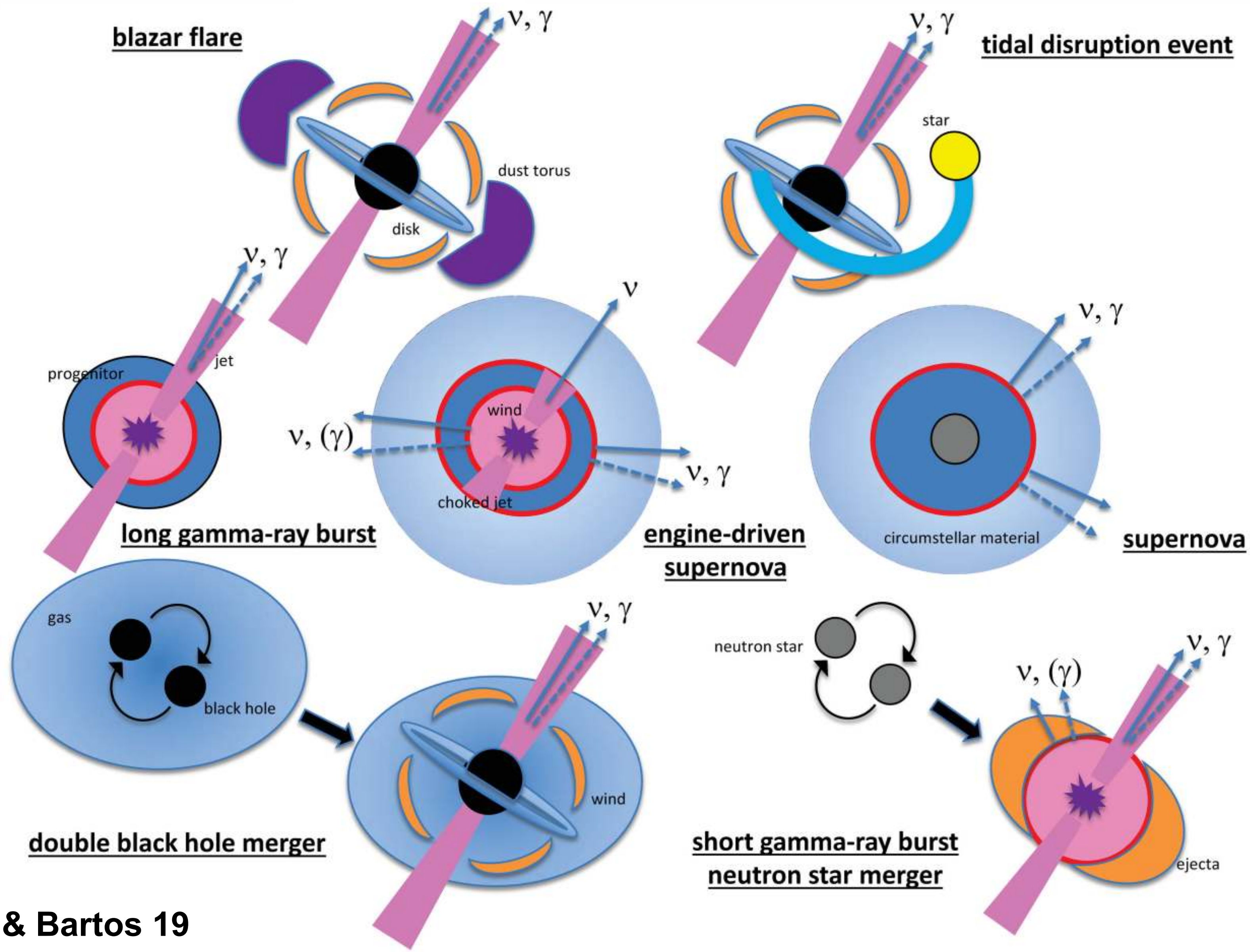


no simple picture

- neutrino
- gamma ray
- X-ray
- optical/UV
- radio



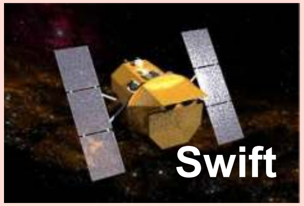
Diversity of High-Energy Transients



from KM & Bartos 19

Real-Time Alerts & Follow-Up Observations

Light (elemag)

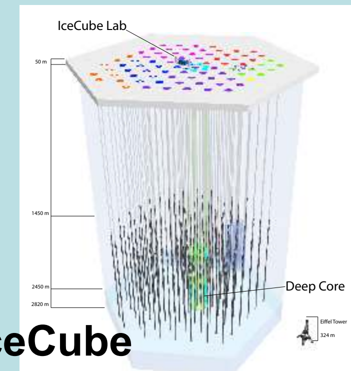


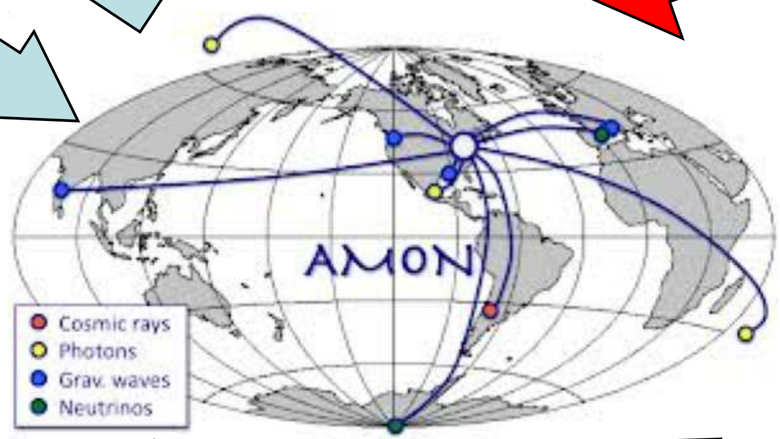
DO NOT miss interesting ν & GW events!

Astrophysical Multimessenger Observatory Network (AMON)

- pipelines to send "public" alerts
- ν–γ subthreshold events (in near future)

Neutrino (weak force)





Cosmic-ray (strong force)

PENNSTATE

Gravitational wave (gravity)

Importance of Source Modeling

1. Dynamics (hydro scale)
   outflow launch & propagation (energetics, velocity)
   composition (baryon, pair, magnetic field)
   dissipation (shocks, reconnection etc.)

2. Particle acceleration (plasma scale)
   shock acceleration, reconnection, electric field etc.

3. Particle interactions (elementary processes)
   leptonic process
   hadronic processes
   heating & thermal radiation

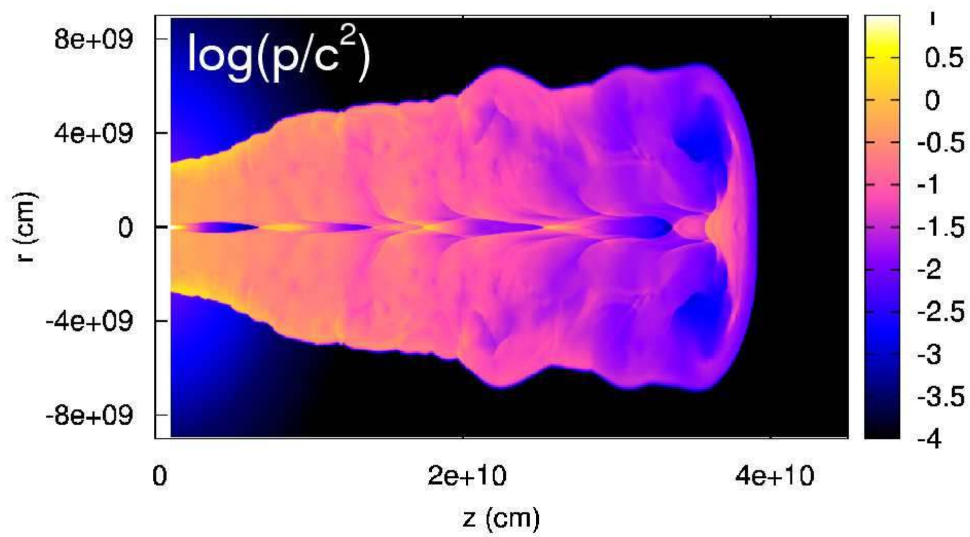
Rich astrophysical EM data are often available

Source Dynamics?

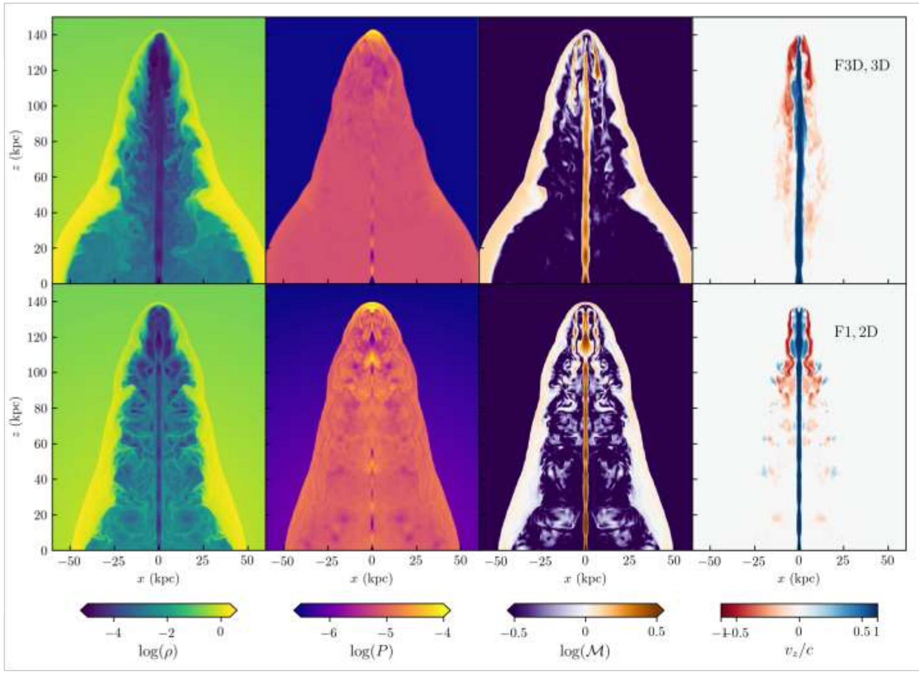
- HD, MHD, RHD, RMHD
  (H: hydro, M: magneto, R: radiation)

  ex. supernova remnants – Sedov-Taylor solution
  ex. GRB afterglow – Blandford-McKee solution
- Single zone model is often used for HE sources

GRB jet (Mizuta & Ioka 13)



AGN jet (Matthew+ 18)



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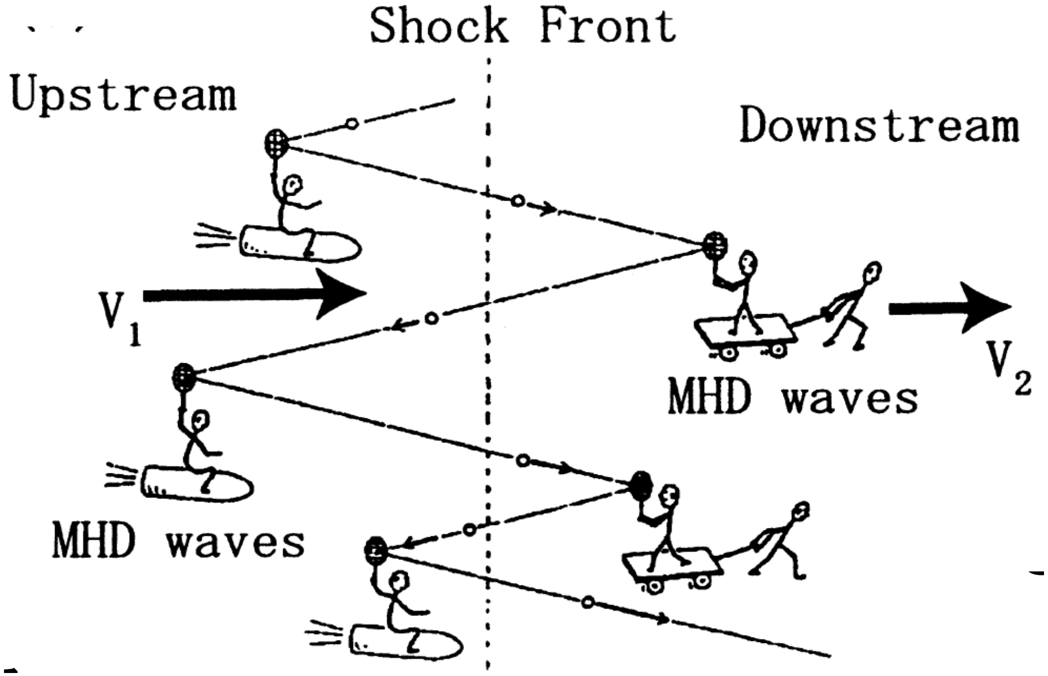
How are Cosmic Rays Accelerated?

stochastic acceleration

"Fermi mechanism"

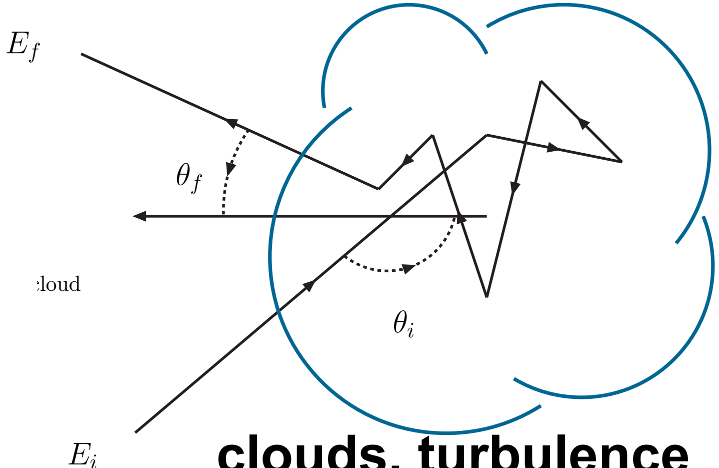
(Fermi 1949 PR)

first-order Fermi



shock=converging flows of plasma

second-order Fermi (original)

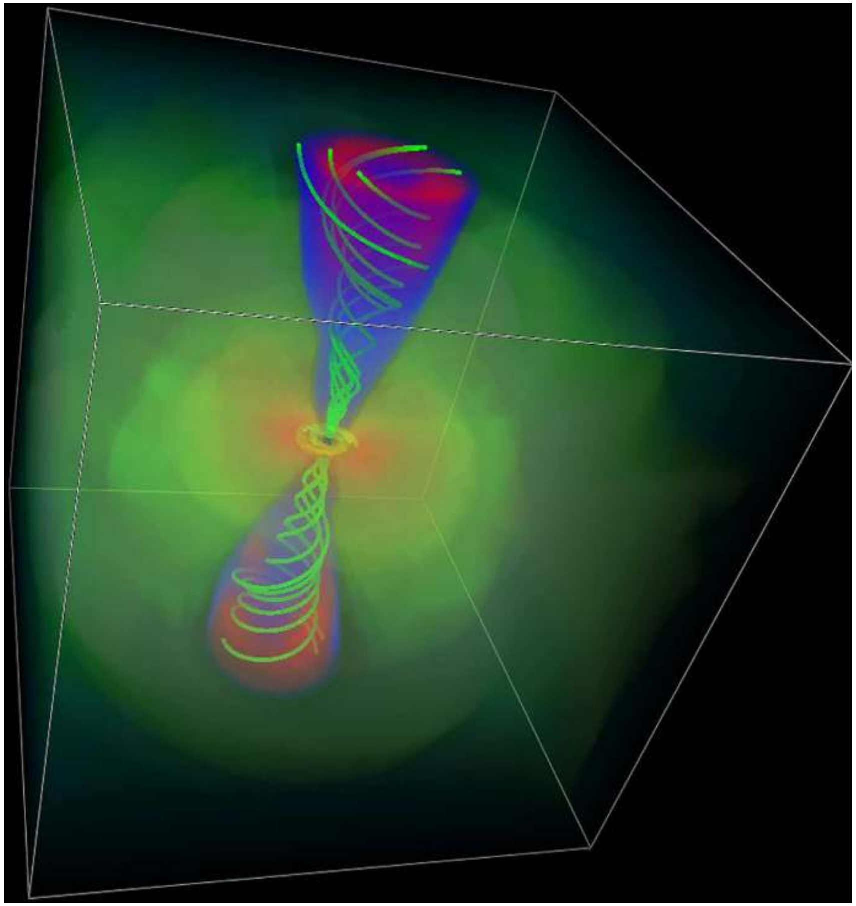


clouds, turbulence

power-law spectrum: $dN/dp \propto p^{-s}$ (s~2 for shock acc.)

Particle Acceleration in Jets?

Origin of relativistic particles inside jets is under debate



McKinney & Blandford 09

- Jet: launched as Poynting-dominated (e.g., Blandford-Znajek mechanism)
- Maybe many pairs ($1<n_e/n_p<1000$)
- Toroidal-dominated at larger distances -> quasi-perpendicular shocks
- Emission region: particle-dominated but magnetized
- Inefficient shock acceleration for relativistic magnetized shocks (Sironi et al. 13, Bell et al. 18 etc.)

magnetic reconnection?

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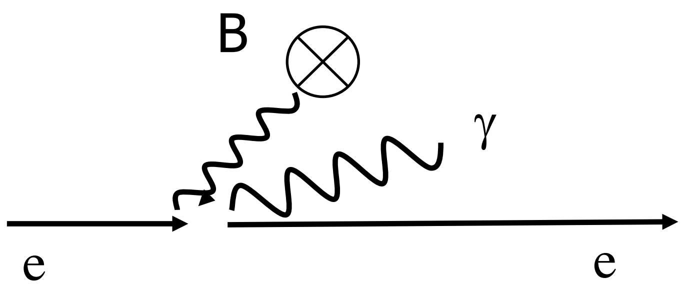
Radiation Processes

- Leptonic (electron/pair-induced) processes

synchrotron process

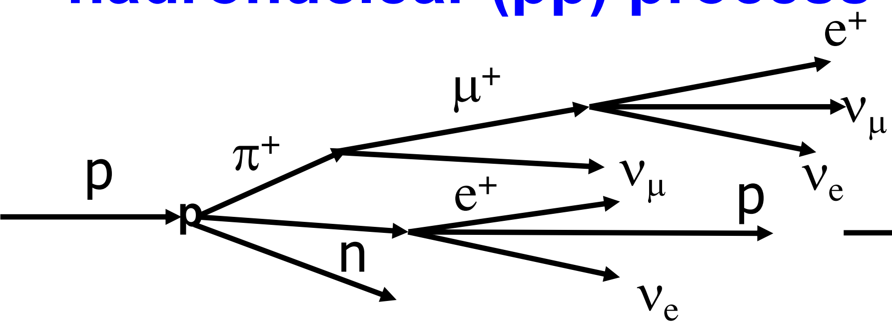


Inverse-Compton process

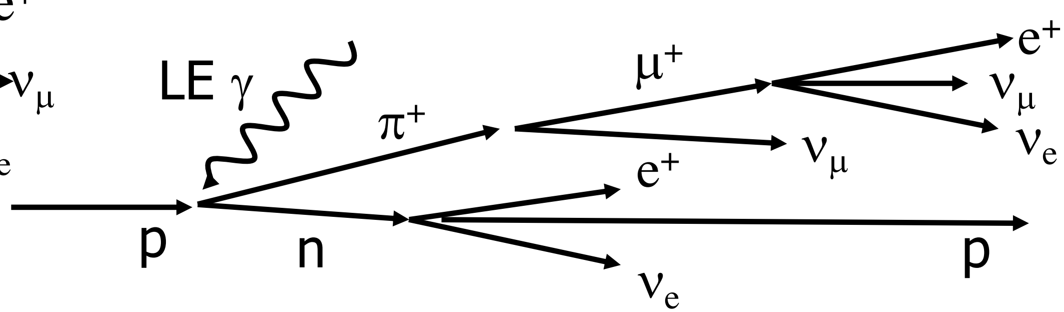
(two-photon annihilation, pair creation, bremsstrahlung etc.)

- Hadronic (ion-induced) processes

hadronuclear (pp) process



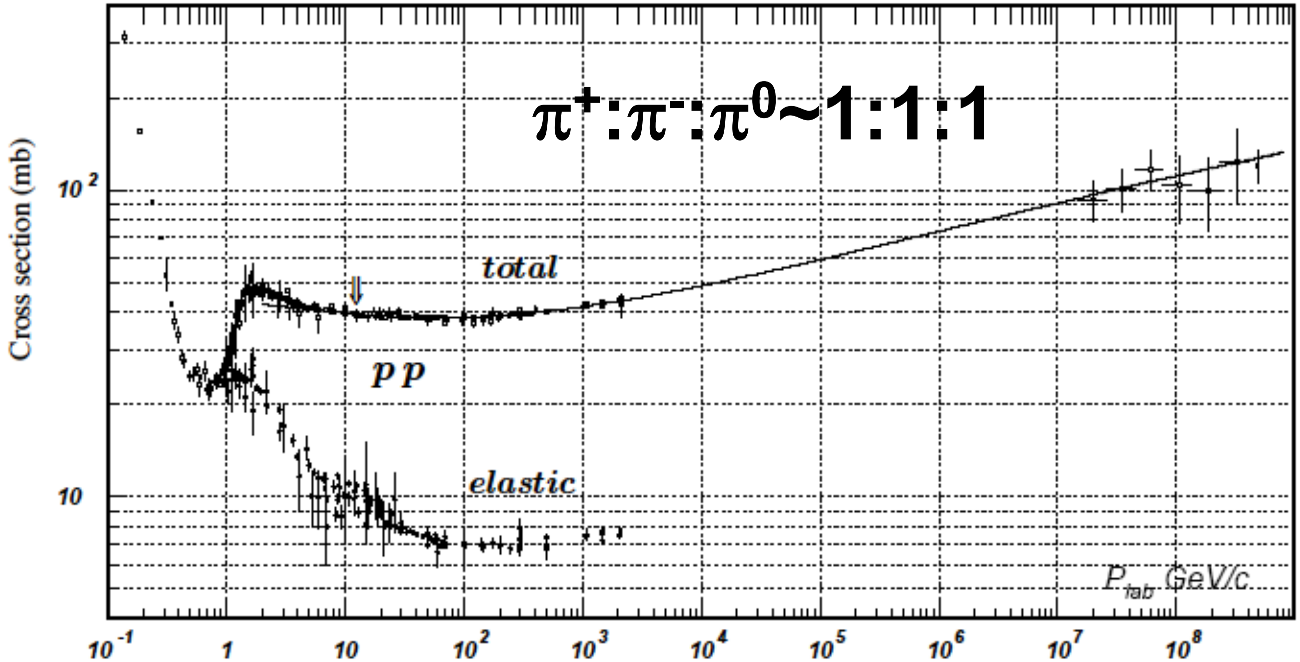
photohadronic (pγ) process



(proton synchrotron, Bethe-Heitler, photodisintegration etc.)

$p + p \rightarrow \text{mesons} + \ldots$

$\sigma_{pp} \sim 1/m_\pi^2 \sim 30$ mb



proton energy in the rest frame of the other proton

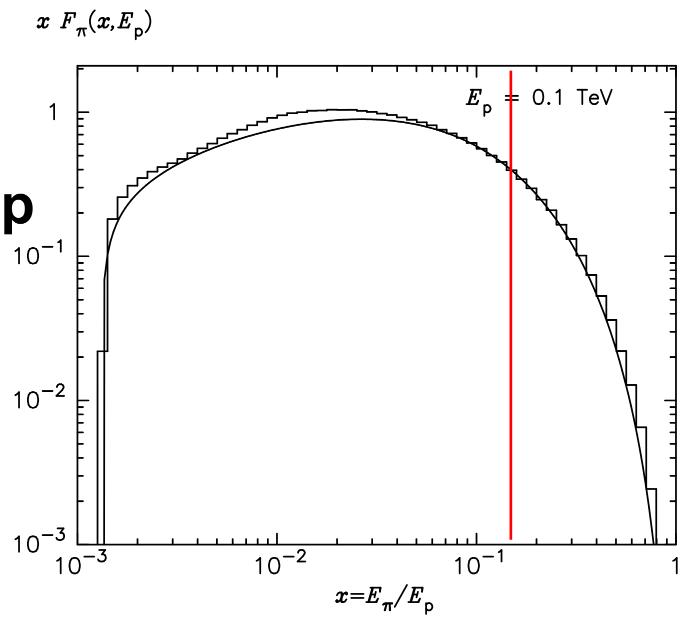
E_p>>TeV

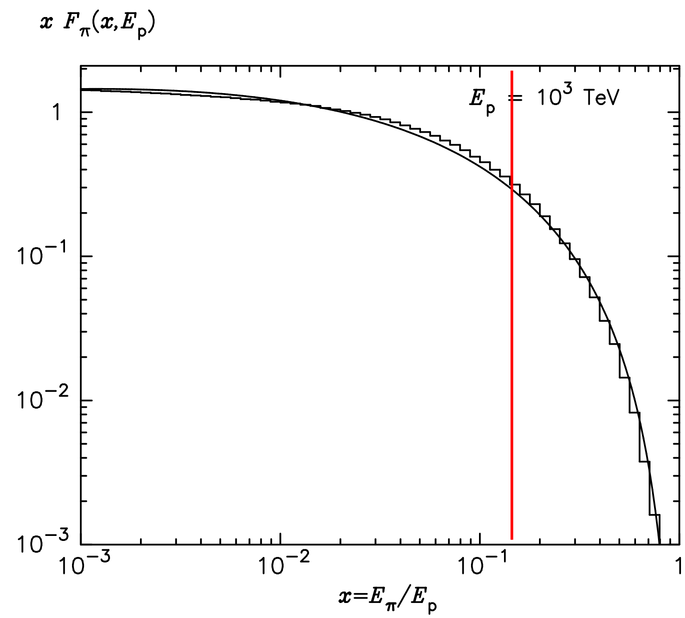
Inelasticity: $\kappa \sim 0.5$

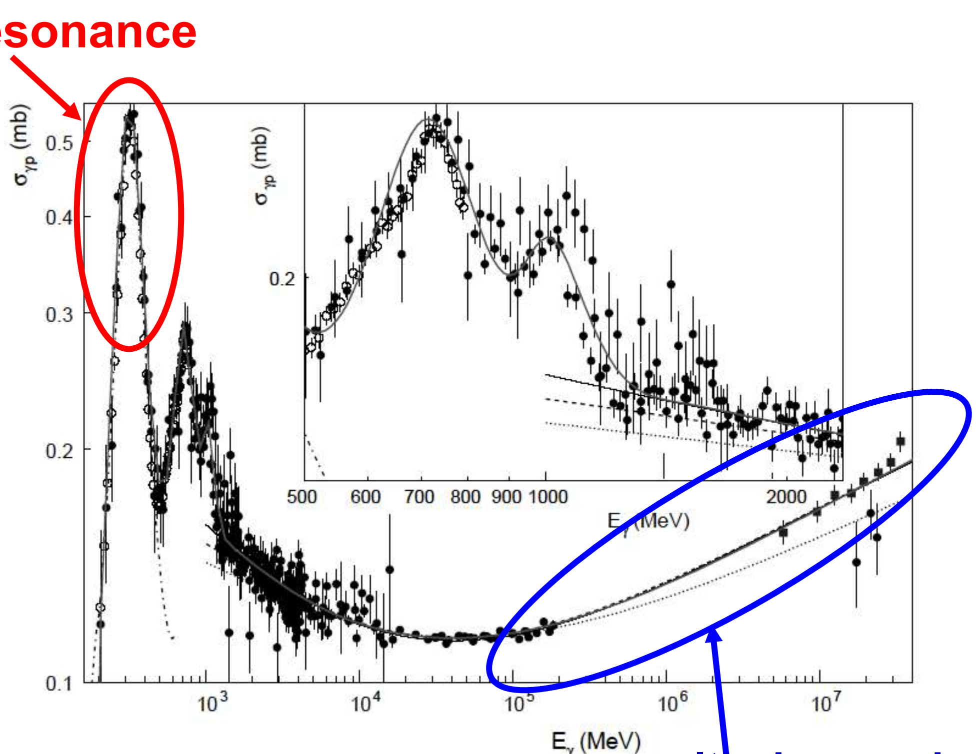
(energy-transfer fraction)

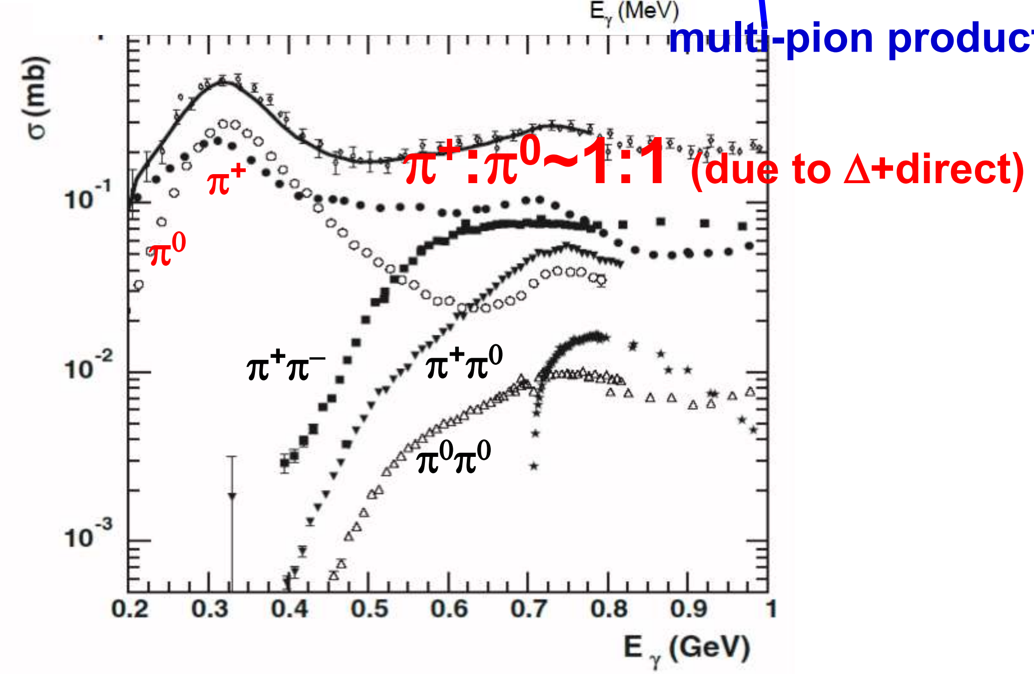
High multiplicity but in energy flux

$\varepsilon_\pi \sim 0.1\text{-}0.2\varepsilon_p$









$$p + \gamma \longrightarrow \text{mesons} + \ldots$$

$\sigma_{p\gamma} \sim \alpha\sigma_{pp} \sim 0.5$ mb

- **Threshold**

proton rest $m_\pi + \frac{m_\pi^2}{2m_p} \approx 145\,\text{MeV}$

- **Δ-resonance**

$$\bar{\varepsilon}_\Delta = \frac{m_\Delta^2 - m_p^2}{2m_p} \approx 340\,\text{MeV}$$

$\varepsilon_p\, \varepsilon_\gamma \sim 0.2$ GeV^2

$\varepsilon_\pi = \kappa\, \varepsilon_p \sim 0.2\, \varepsilon_p$

- **multi-pion production**

$\langle \xi_\pi\, \varepsilon_\pi \rangle \sim 0.5\, \varepsilon_p$

$\pi^+:\pi^-:\pi^0 \sim 1:1:1$

Neutrinos & Gammas from Pion Decay

$\pi^0 \to \gamma + \gamma$ **lifetime: 8.4x10^{-17} s**

$$\frac{dn_\gamma}{d\varepsilon_\gamma} = \frac{m_\pi c}{2\varepsilon_\gamma^*}\int_{\varepsilon_\pi^{\min}}^{\infty} d\varepsilon_\pi \frac{1}{p_\pi}\frac{dn_\pi}{d\varepsilon_\pi} \qquad \varepsilon_\gamma^* = \frac{1}{2}m_\pi c^2 \quad \varepsilon_\pi^{\min} = \frac{(\varepsilon_\gamma/\varepsilon_\gamma^* + \varepsilon_\gamma^*/\varepsilon_\gamma)m_\pi c^2}{2}$$

$\pi^\pm \to \mu^\pm + \upsilon_\mu(\overline{\upsilon}_\mu)$ **lifetime: 2.6x10^{-8} s**

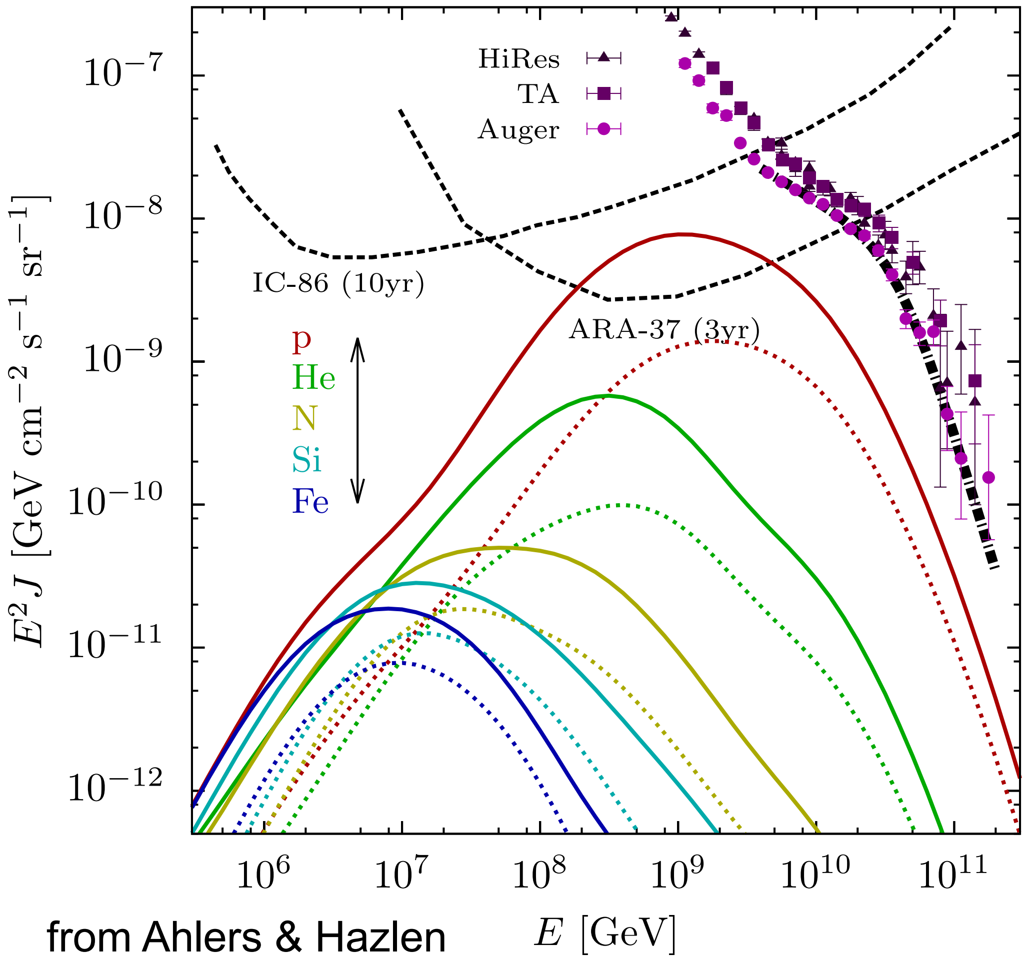
$$\frac{dn_\nu}{d\varepsilon_\nu} = \frac{m_\pi c}{2\varepsilon_\nu^*}\int_{\varepsilon_\pi^{\min}}^{\infty} d\varepsilon_\pi \frac{1}{p_\pi}\frac{dn_\pi}{d\varepsilon_\pi} \qquad \varepsilon_\nu^* = \frac{(m_\pi^2 - m_\mu^2)c^2}{2m_\pi}, \ \varepsilon_\pi^{\min} = \frac{(\varepsilon_\nu^*/\varepsilon_\nu + \varepsilon_\nu/\varepsilon_\nu^*)m_\pi c^2}{2}$$

$\mu^\pm \to \overline{\upsilon}_\mu(\upsilon_\mu) + \upsilon_e(\overline{\upsilon}_e) \ + e^\pm$ **lifetime: 2.2x10^{-6} s**

$$\frac{dn_\nu}{d\varepsilon_\nu} = \int_0^1 dy \frac{1}{y}\int_{\varepsilon_\nu/y}^{(m_\pi^2/m_\mu^2)\varepsilon_\nu/y} d\varepsilon_\pi \frac{m_\pi c}{2\varepsilon_\nu^*}\frac{1}{p_\pi} n_{\varepsilon_\pi}\left[g_0(y) \mp P_\mu(y) g_1(y)\right]$$

$\varepsilon_\nu \sim \varepsilon_e \sim \varepsilon_\pi/4$, $\varepsilon_\gamma \sim \varepsilon_\pi/2$ (in absence of meson/muon cooling)

Example: Cosmogenic Neutrinos



from Ahlers & Hazlen

"Cosmogenic" neutrinos
(Berezinsky & Zatsepin 69 PLB)

Resonance condition:
$E_0\ \varepsilon_{CMB} \sim 0.2\ GeV^2$
Resonance energy: $E_0 \sim 10^{20}$ eV
-> $E_\nu \sim 0.05\ E_0 \sim$ 5×10^{18} eV

Spectrum:
$E_\nu^2\ \Phi_\nu \sim E_\nu^2$ ($E<E_0$)
(due to decay kinematics)
$E_\nu^2\ \Phi_\nu \sim$ const ($E>E_0$)
(due to multi-pion production)

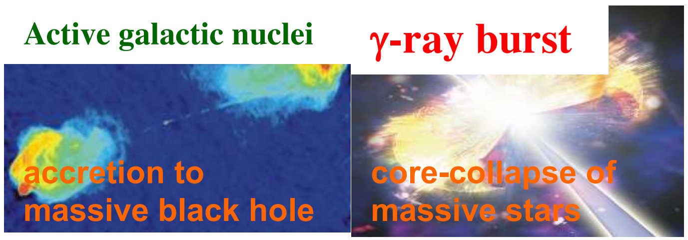
Nuclei lead to lower cosmogenic neutrino fluxes

(e.g., KM & Beacom 10)

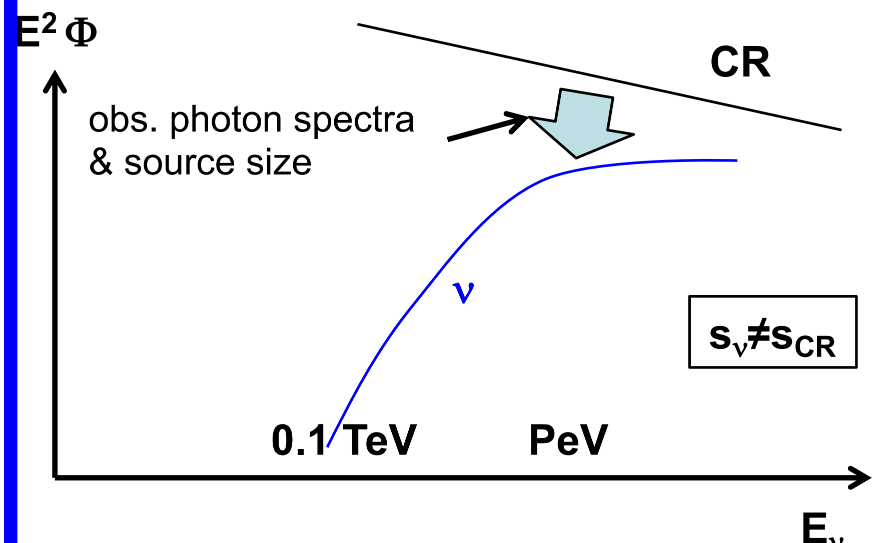
Astrophysical Extragalactic Scenarios

$E_\nu \sim 0.04\, E_p$: PeV neutrino ⇔ 20-30 PeV CR nucleon energy

Cosmic-ray Accelerators (ex. UHECR candidate sources)

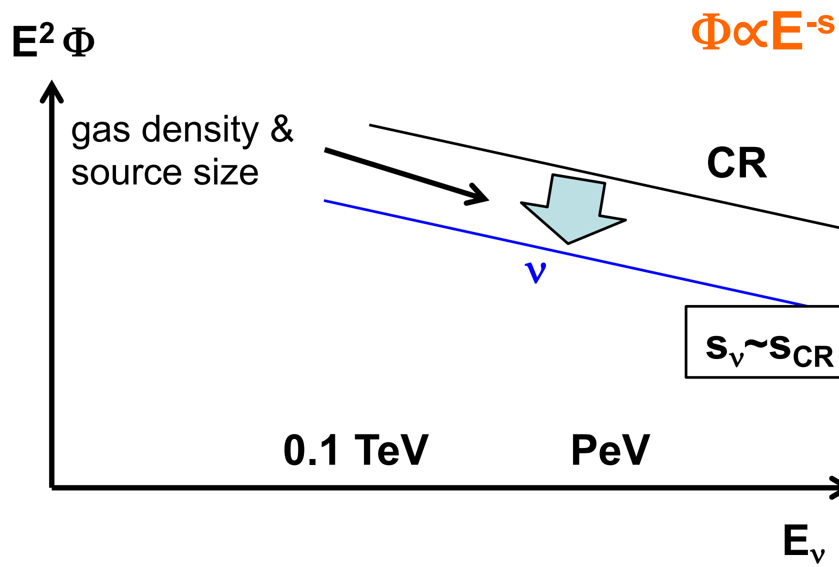


$$p + \gamma \rightarrow N\pi + X$$

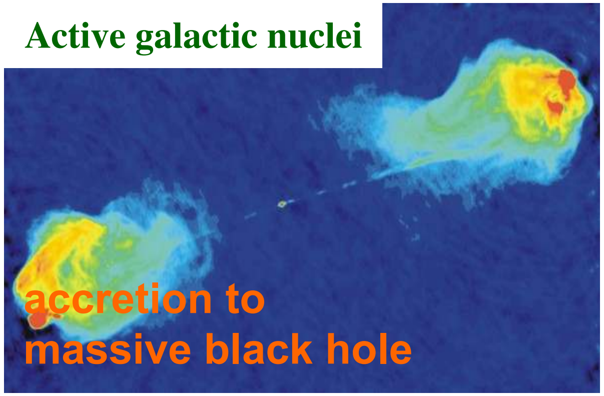


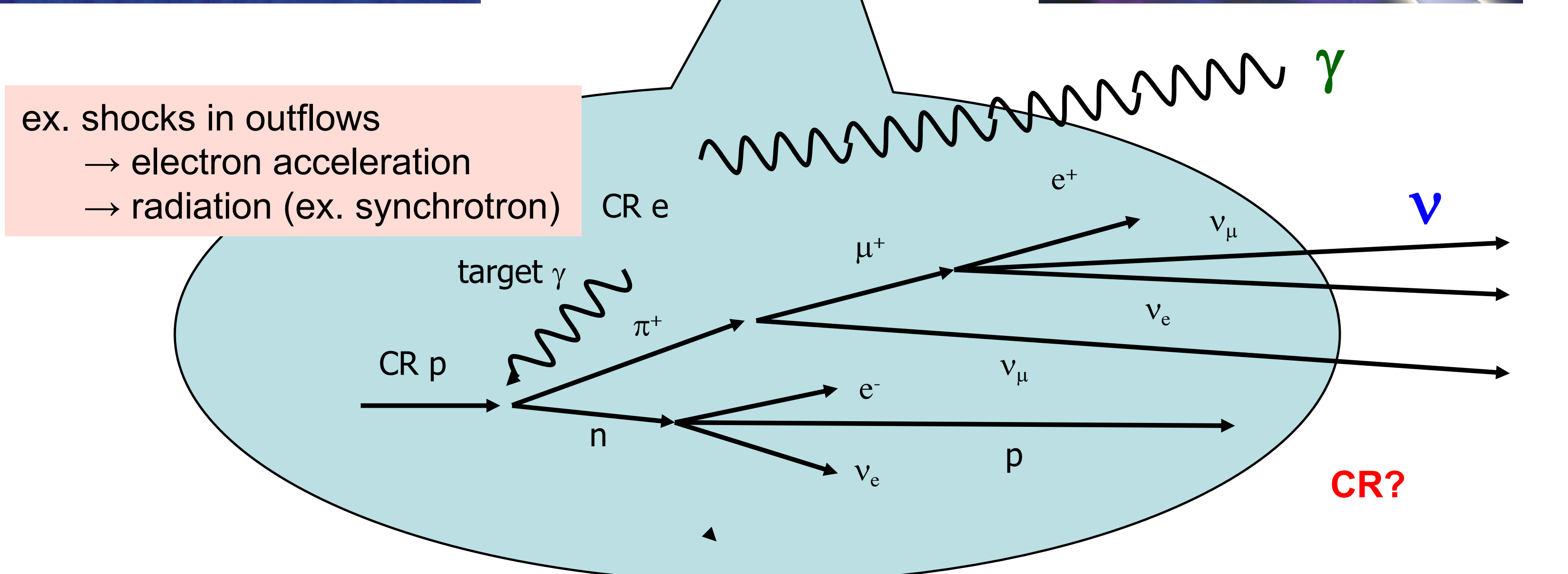
Cosmic-ray Reservoirs

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



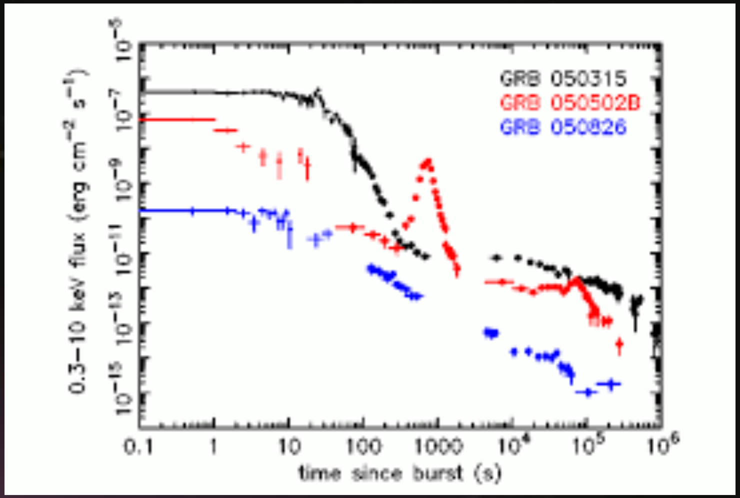
Cosmic-Ray Accelerators





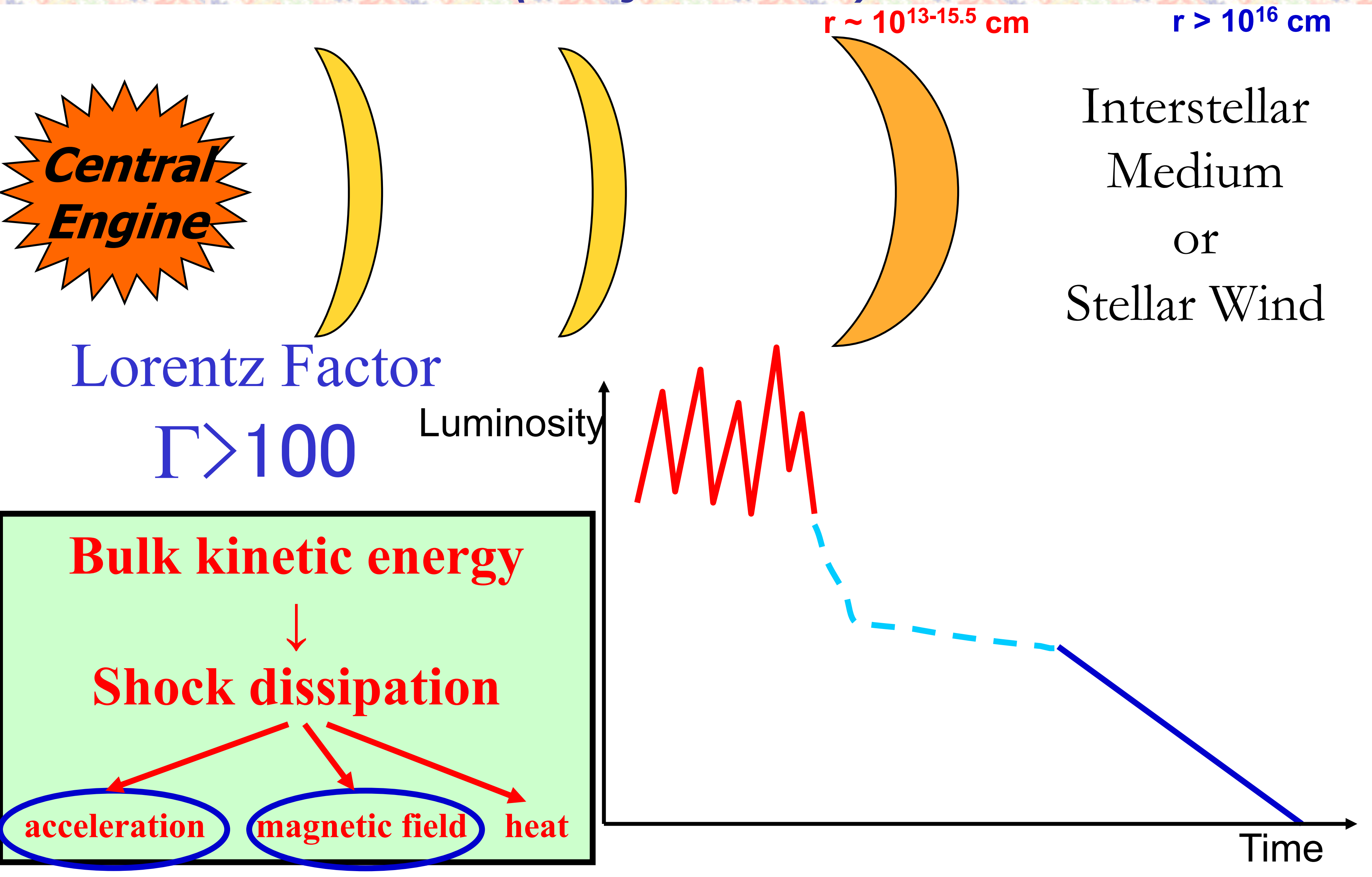
CRs may or may not escape

Gamma-Ray Bursts

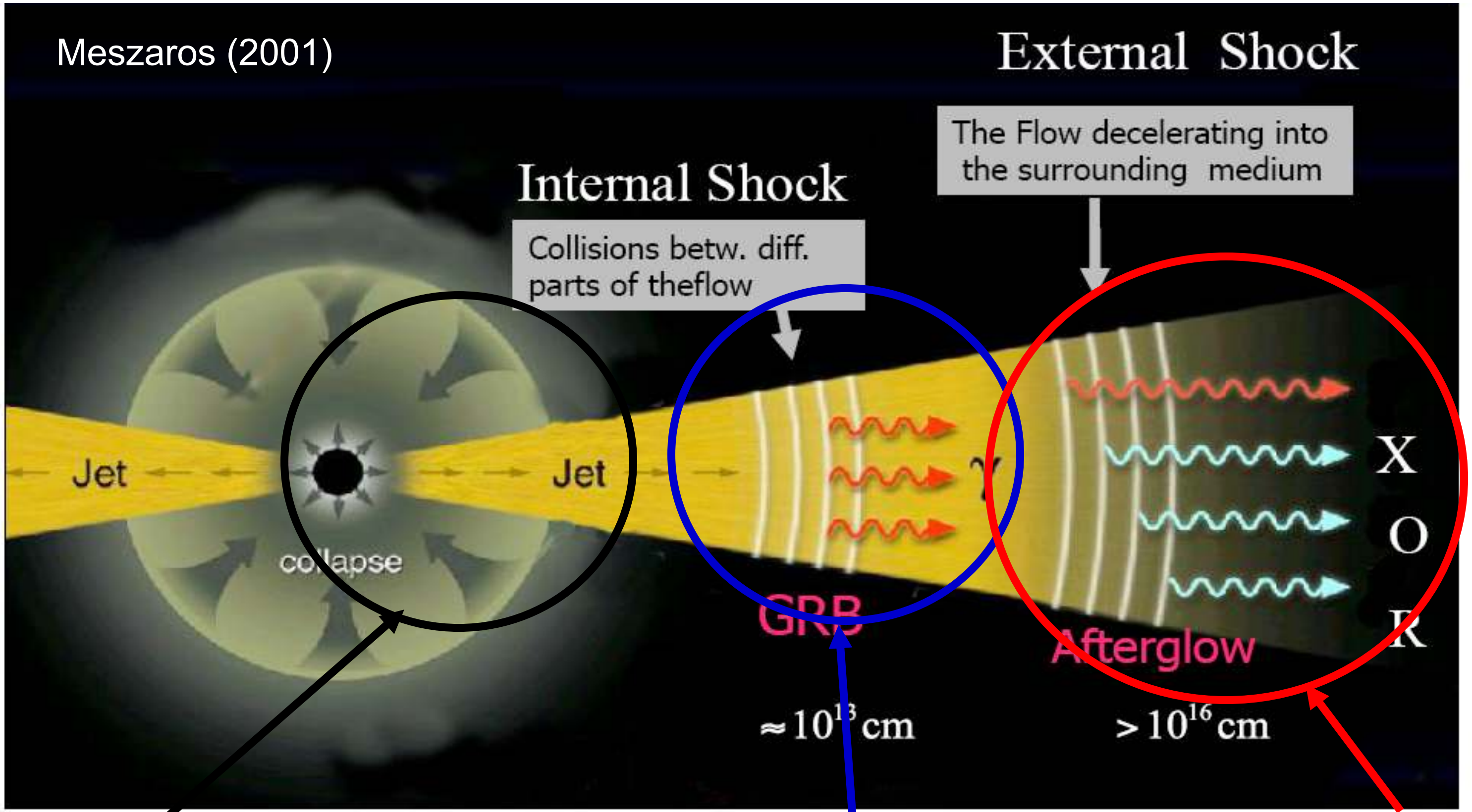


- ~10^{51} erg/s in γ rays
- Relativistic jets
- Massive star deaths (long)
  Compact object mergers (short)

"Classical" Internal-External Shock Scenario (Baryonic Jet)



HE Particle Production Sites



Inner jet inside a star

$r < 10^{12}$ cm, $B > 10^{6}$ G

TeV-PeV ν, no γ

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

Inner jet (prompt/flare)

$r \sim 10^{12}$-10^{16} cm $B \sim 10^{2-6}$ G

PeV ν, GeV-TeV γ

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

Afterglow

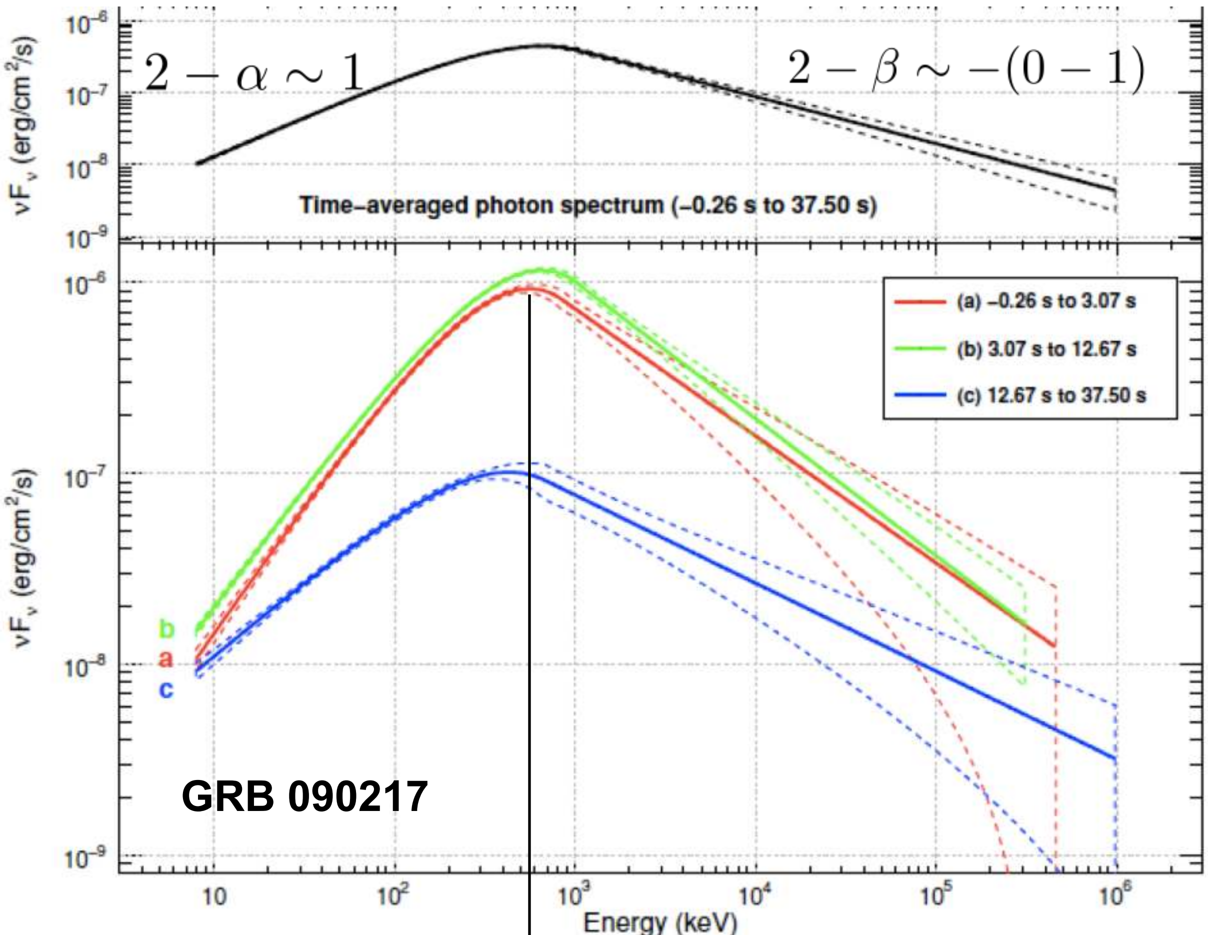
$r \sim 10^{14}$-10^{17} cm $B \sim 0.1$-100 G

EeV ν, GeV-TeV γ

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

GRB Prompt Emission

Fermi collaboration 10 ApJ



$\varepsilon_{\gamma,\mathrm{pk}} \sim 0.1\text{–}1$ MeV

Band function
~ broken power-law
$F_\nu \propto \nu^{-\beta+1}$

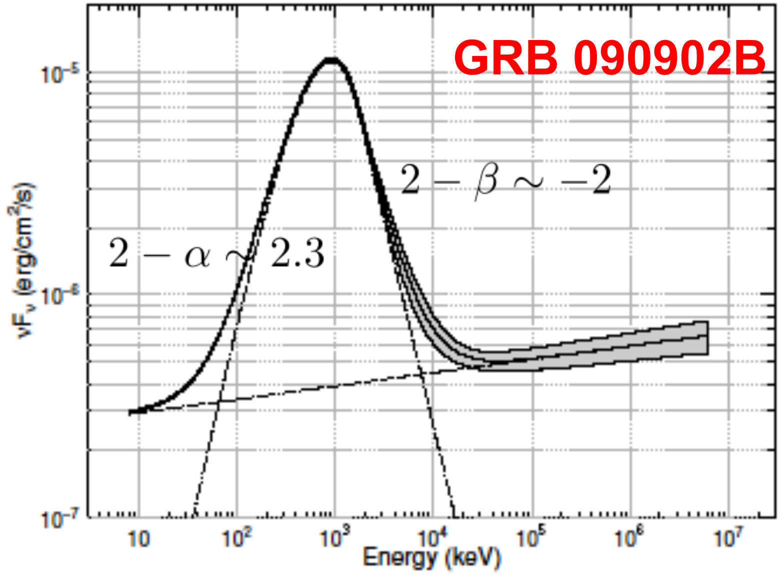
"classical scenario"
= internal shock
+ synchrotron origin

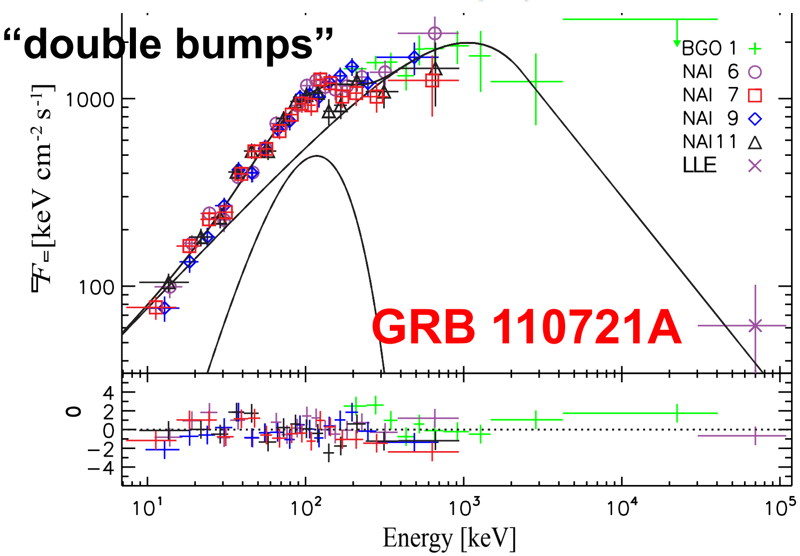
$$\varepsilon_{\gamma,\mathrm{pk}} = \Gamma \hbar \gamma_{ei}^2 \frac{eB}{m_e c}$$

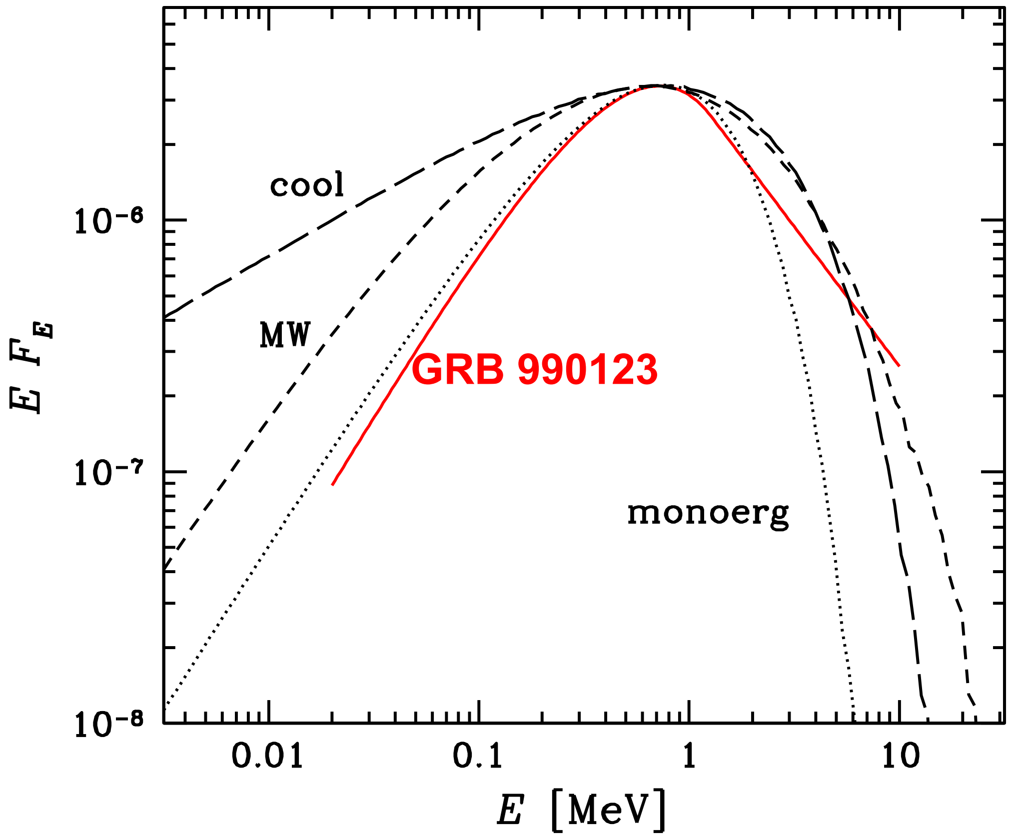
For $U_e \sim U_B \equiv B^2/8\pi$
If emission radius
$r \sim 10^{14}$cm → $B \sim 10^{4.5}$ G
r: model-dependent

Evidence for Thermal Components

"modified" thermal emission or possible black-body in broken power law

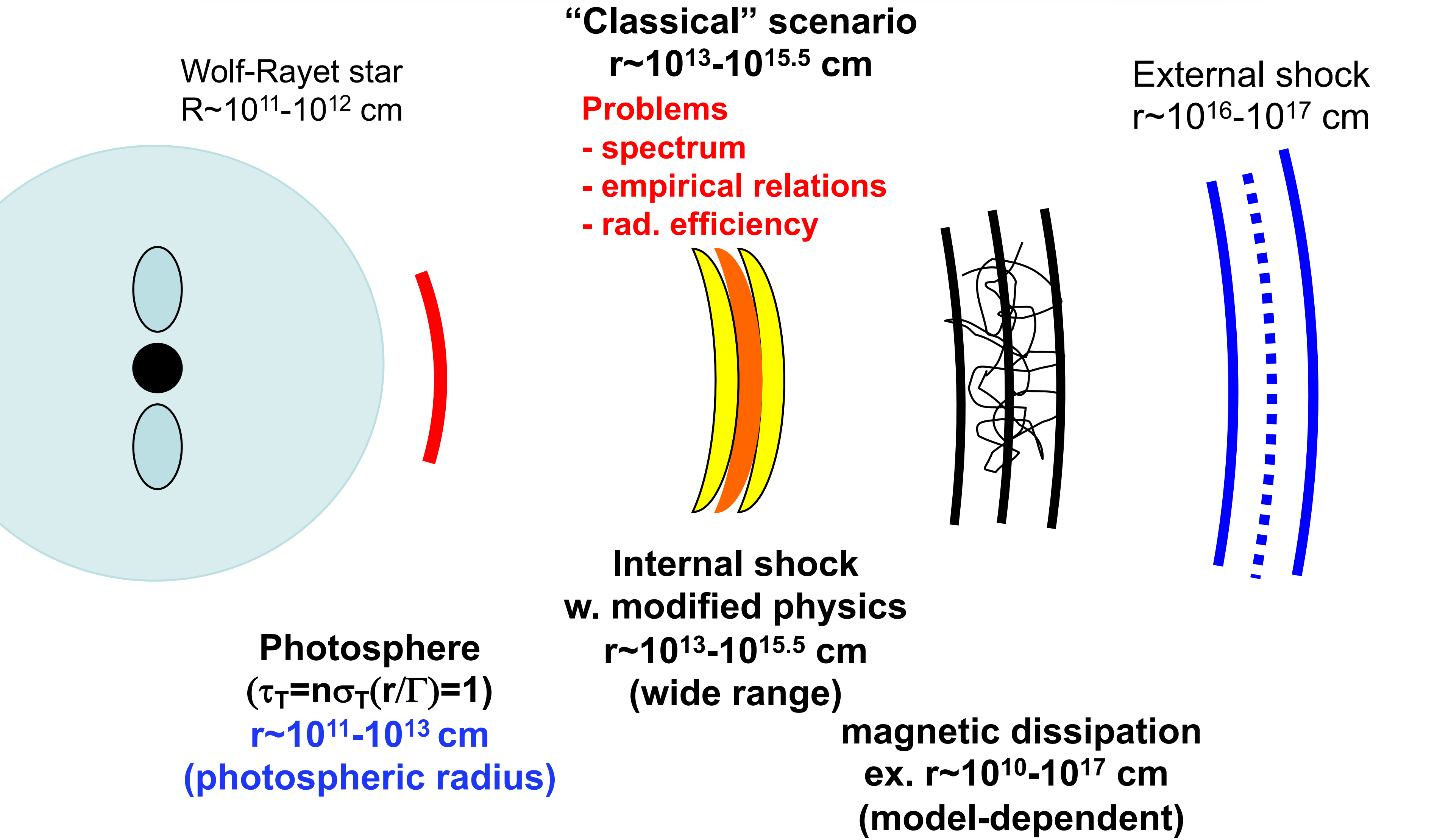






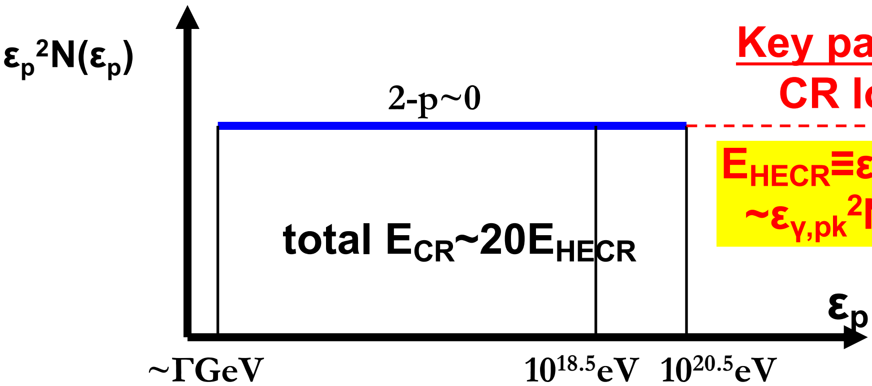
Peer & Ryde 16, Beloborodov & Meszaros 17

Prompt Emission Models



Basics of ν and γ-ray Emission

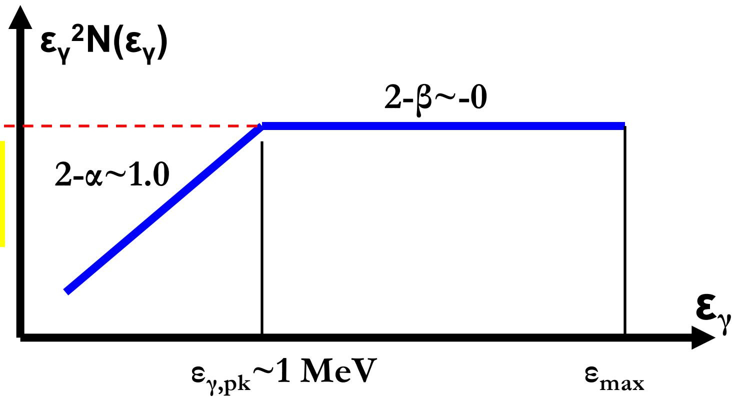
CR Spectrum (Fermi mechanism)

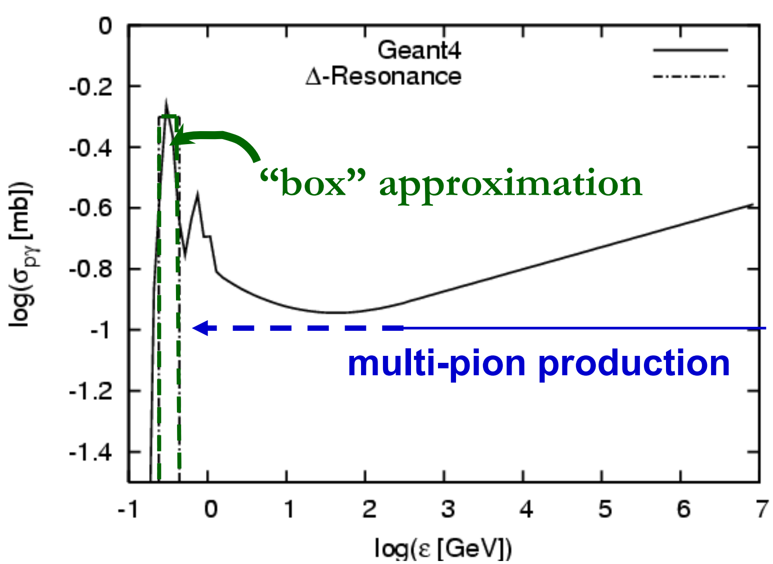


Key parameter
CR loading

$E_{HECR} \equiv \varepsilon_p^2 N(\varepsilon_p) \sim \varepsilon_{\gamma,pk}^2 N(\varepsilon_{\gamma,pk})$

Photon Spectrum (observed)





(in proton rest frame)

Photomeson Production

$$p + \gamma \rightarrow n + \pi^+ \qquad \kappa_p \sim 0.2$$

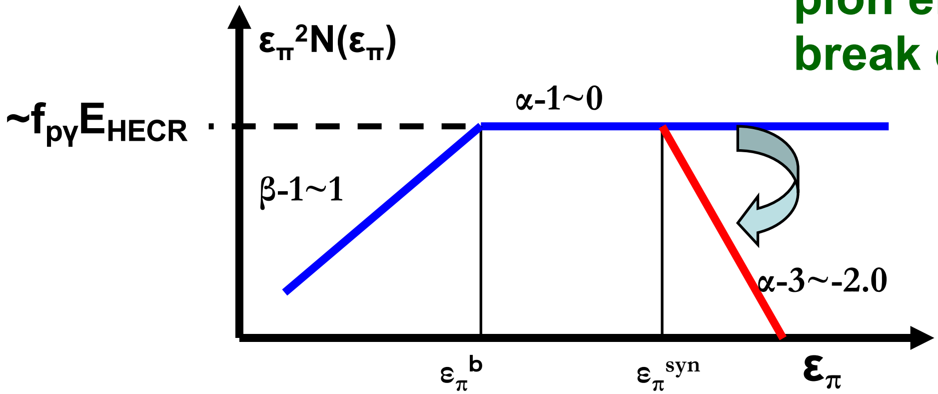
$$p + \gamma \rightarrow N\pi + X \qquad \kappa_p \sim (0.4 - 0.6)$$

at Δ-resonance ($\varepsilon_p \varepsilon_\gamma \sim 0.2\ \Gamma^2$ GeV^2)
$\varepsilon_p^b \sim 0.2$ GeV $\Gamma^2/\varepsilon_{\gamma,pk} \sim 20$ PeV

Photomeson production efficiency
~ effective optical depth for pγ process

$f_{p\gamma} \sim 0.2\ n'_\gamma \sigma_{p\gamma}\ (r/\Gamma) \propto r^{-1}\ \Gamma^{-2}$
$\propto \Gamma^{-4}\ \delta t^{-1}$ (if $r \sim \Gamma^2\ \delta t$)

Meson Spectrum



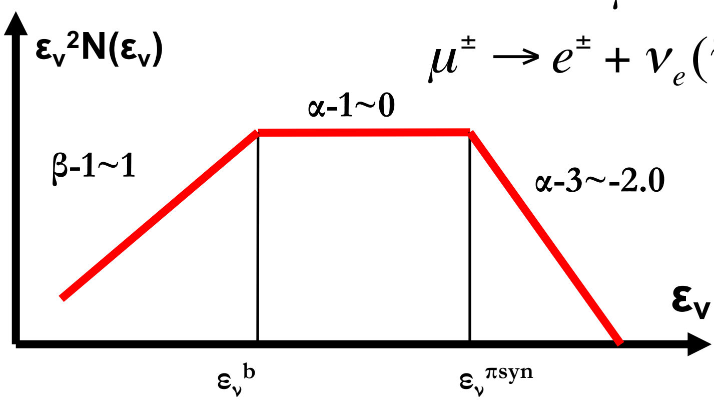
pion energy $\varepsilon_\pi \sim 0.2\ \varepsilon_p$
break energy $\varepsilon_\pi^b \sim 0.04\ \mathrm{GeV}^2\ \Gamma^2/\varepsilon_{\gamma,pk} \sim 4$ PeV

HE charged mesons
(meson cooling time) < (meson life time)
→ suppression at high energies

Waxman & Bahcall, PRL (1997)

Neutrino Spectrum

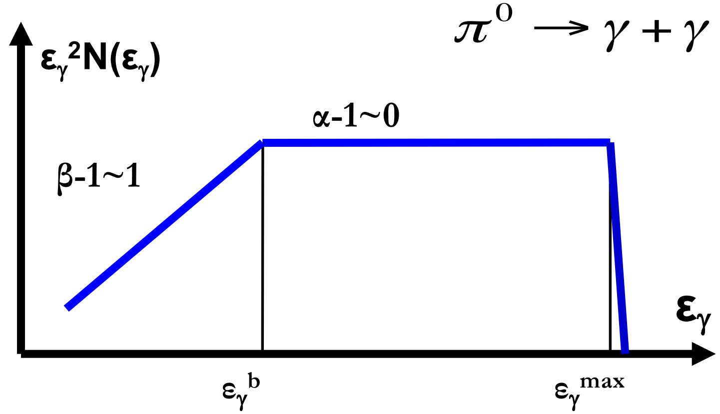
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu)$$
$$\mu^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$$



neutrino energy $\varepsilon_\nu \sim 0.25\ \varepsilon_\pi \sim 0.05\ \varepsilon_p$
•ν lower break energy $\varepsilon_\nu^b \sim 1$ PeV
•ν higher break energy $\varepsilon_\nu^{\pi syn} \sim 25$ PeV

Gamma-Ray Spectrum

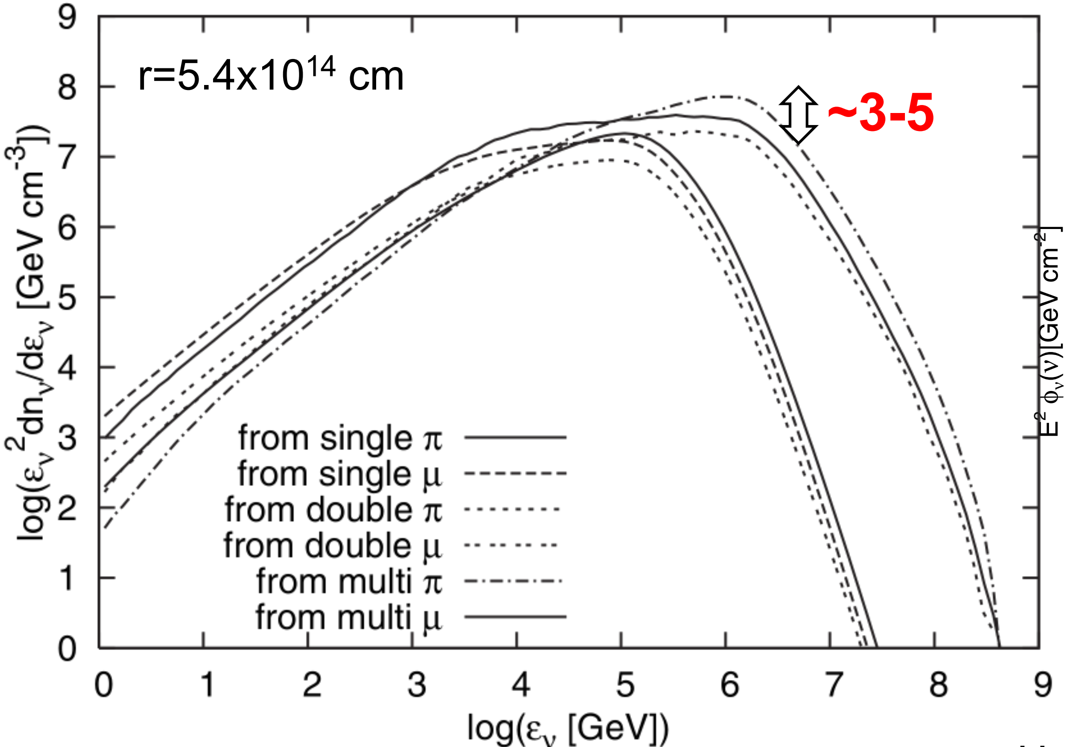
$$\pi^0 \rightarrow \gamma + \gamma$$



γ-ray energy $\varepsilon_\gamma \sim 0.5\ \varepsilon_\pi \sim 0.1\ \varepsilon_p$
•γ lower break energy $\varepsilon_\gamma^b \sim 2$ PeV
•γ maximum energy $\varepsilon_\gamma^{max} \sim 0.1\ \varepsilon_p^{max}$

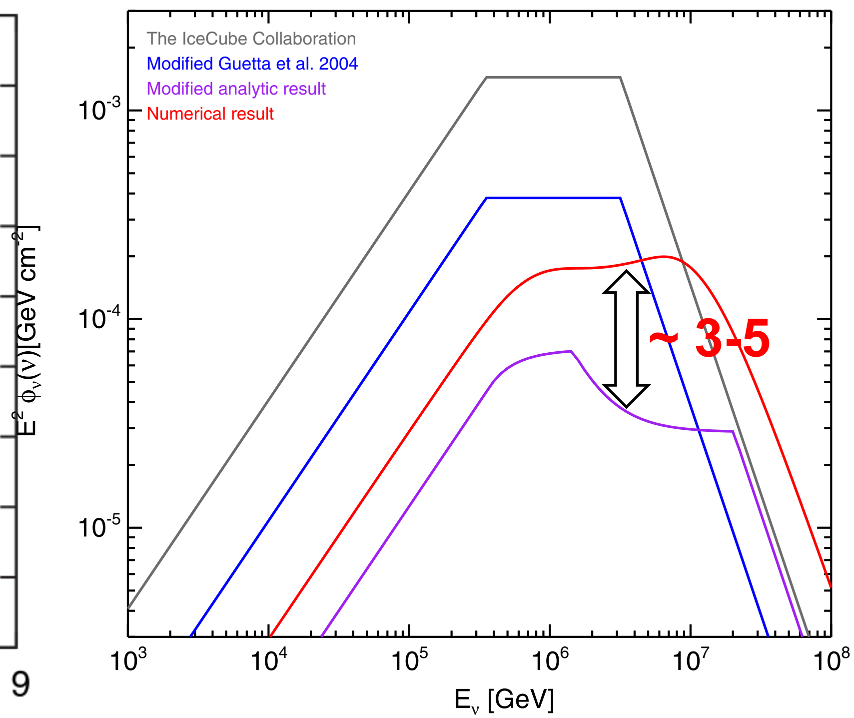
Single-Zone Analytic vs Numerical Modeling

before neutrino mixing



KM & Nagataki 06 PRD

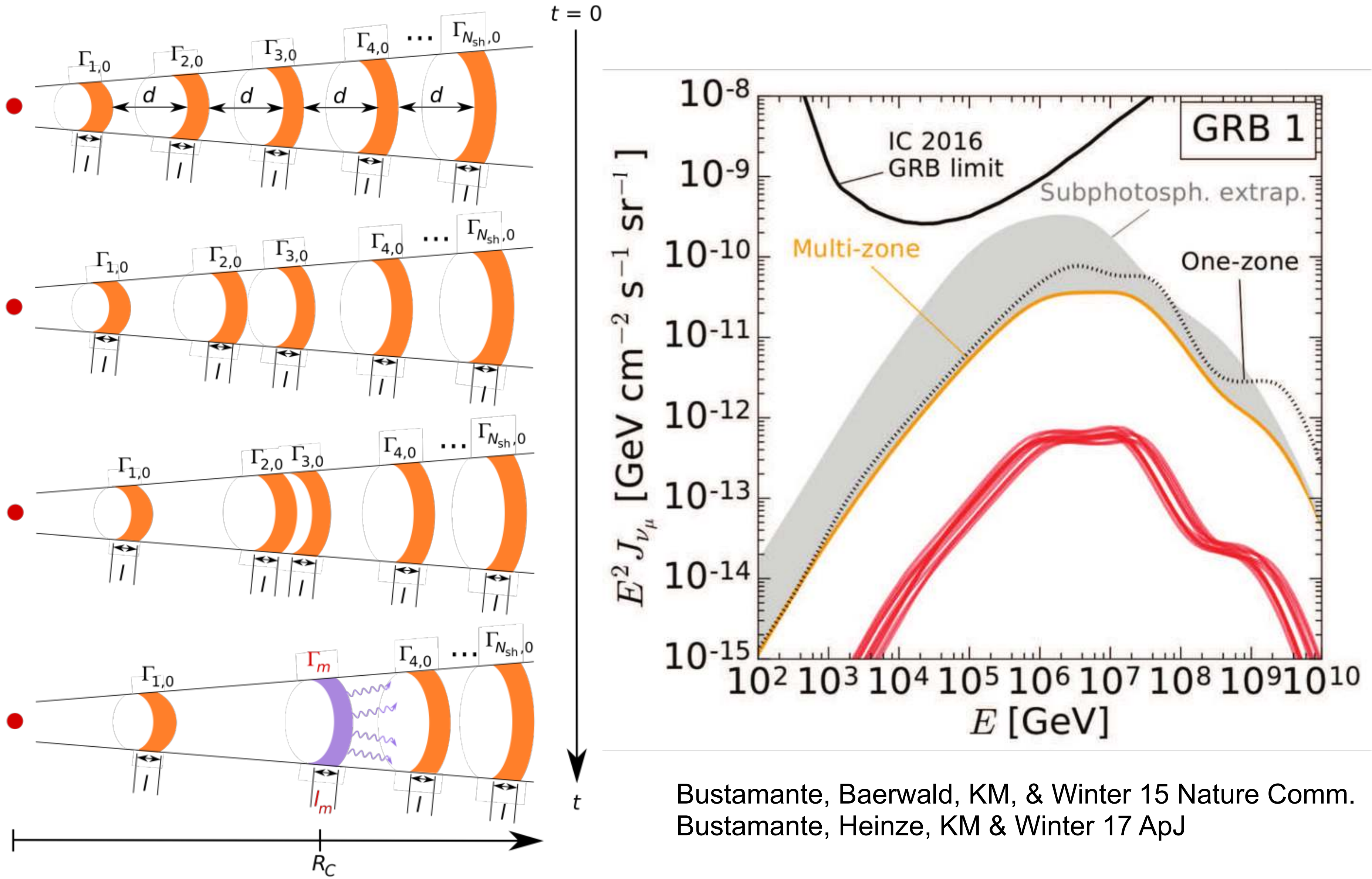
after neutrino mixing



He, Liu, Wang, Nagataki, KM & Dai 12 ApJ
see also Hummer, Baerwald & Winter 12 PRL

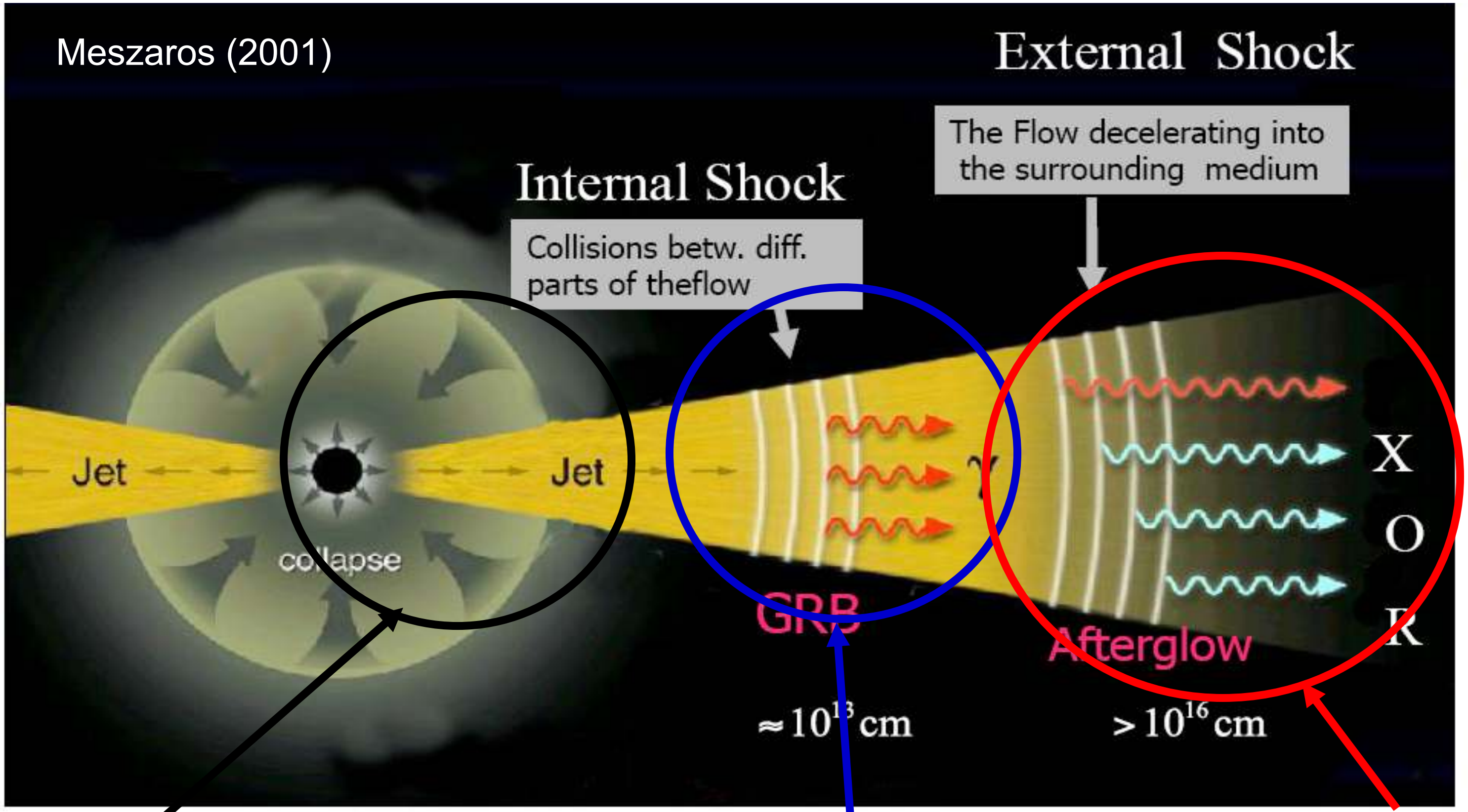
Multipion/higher resonances are relevant for hard spectra (β<1)
(more important for thermal spectra)

One-Zone vs Single Zone Modeling



Bustamante, Baerwald, KM, & Winter 15 Nature Comm.
Bustamante, Heinze, KM & Winter 17 ApJ

HE Particle Production Sites



Inner jet inside a star
r < 10^{12} cm, B > 10^{6} G
TeV-PeV ν, no γ

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

Inner jet (prompt/flare)
r ~ 10^{12}-10^{16} cm B ~ 10^{2-6} G
PeV ν, GeV-TeV γ

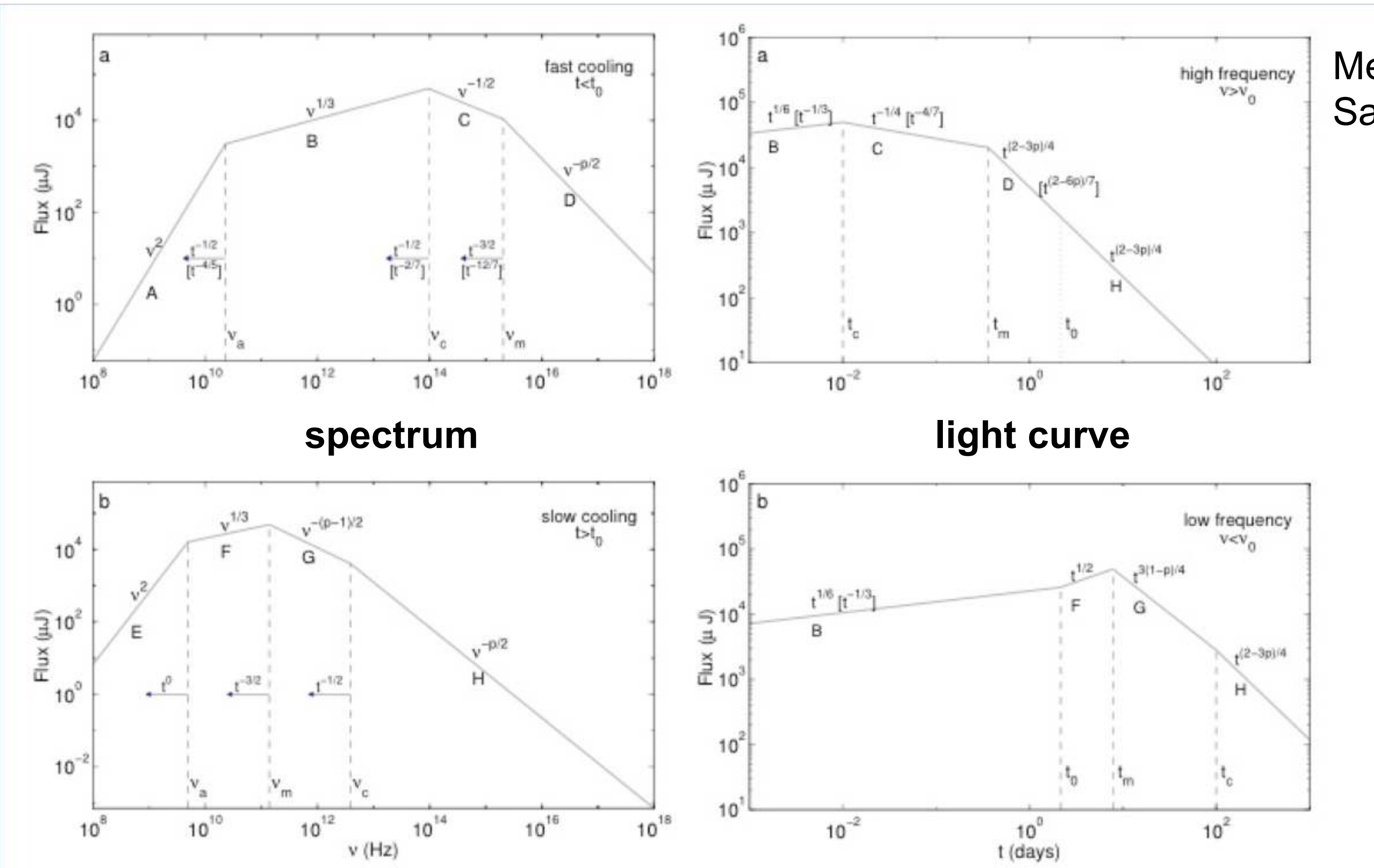
Waxman & Bahcall 97 PRL
Dermer & Atoyan 03 PRL
KM & Nagataki 06 PRL

Afterglow
r ~ 10^{14}-10^{17} cm B ~ 0.1-100 G
EeV ν, GeV-TeV γ

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

Afterglow Theory

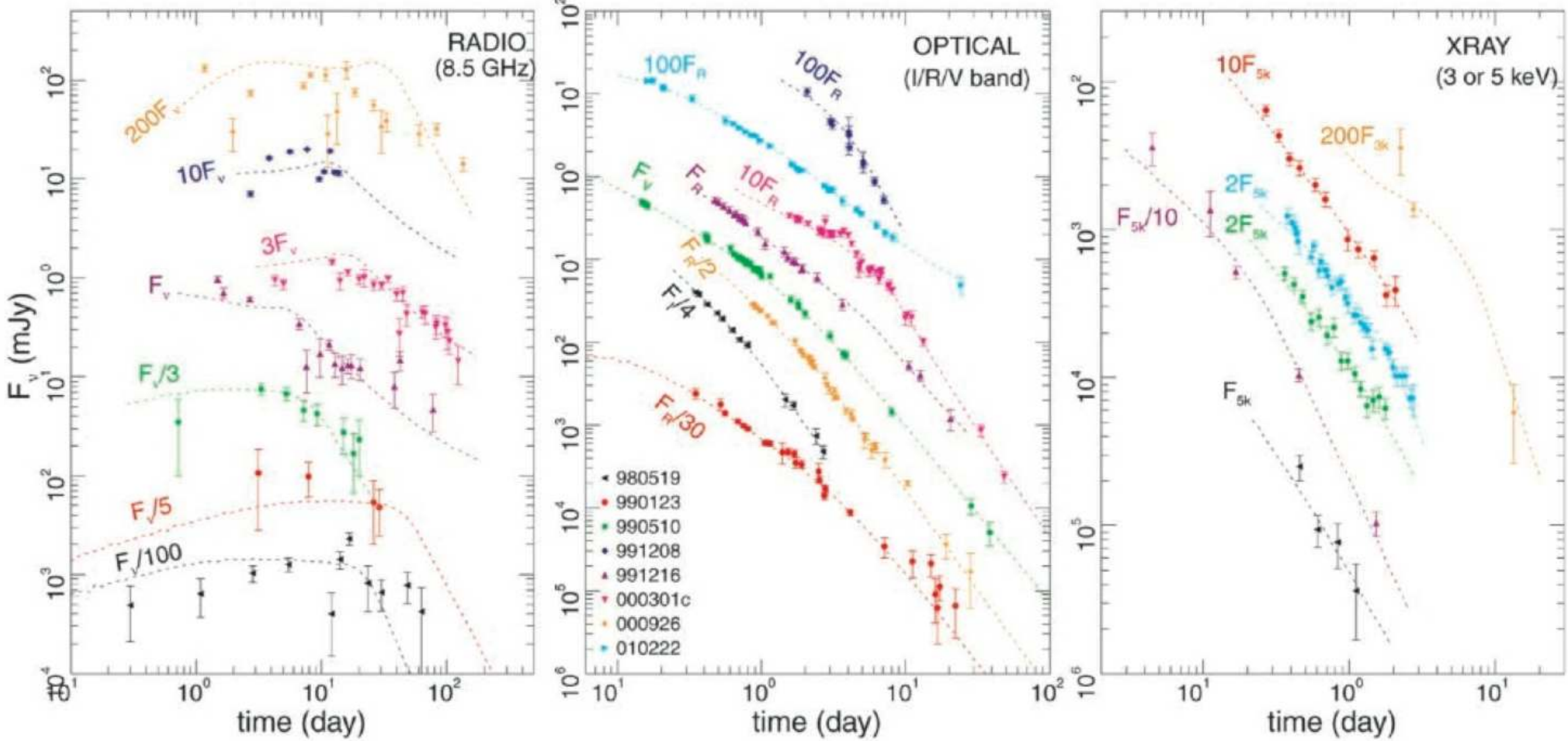
1. Dynamics – Blandford-McKee solution
2. Acceleration – power-law (shock acceleration of electrons)
3. synchrotron (+ inverse Compton)



Meszaros & Rees 97
Sari+ 98

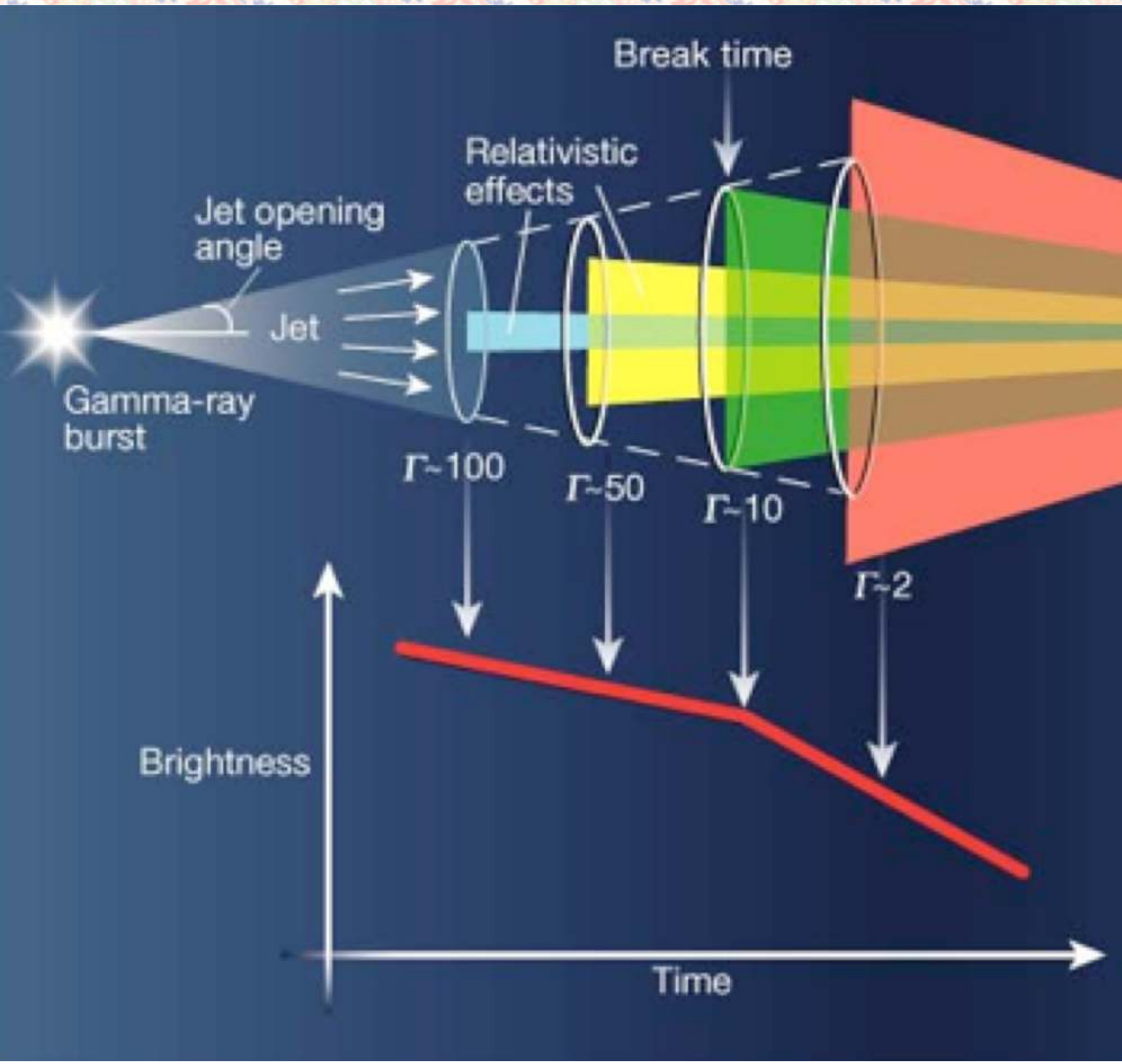
Observational Confirmation

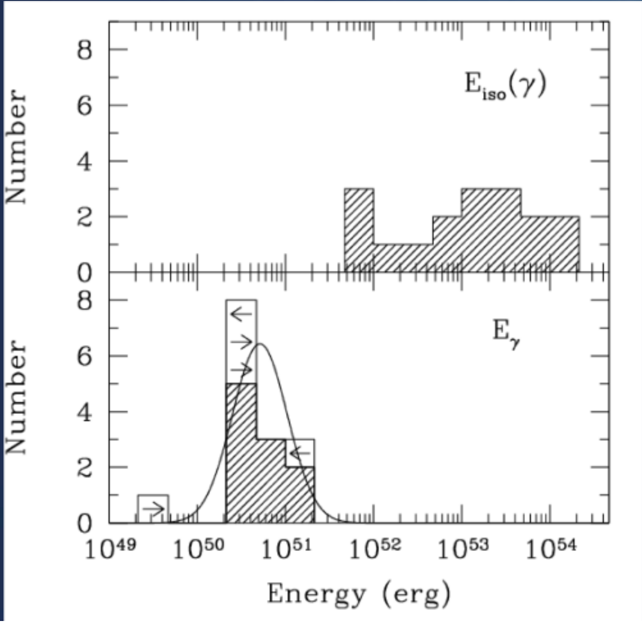
Panaitescu & Kumar 01



- Fitting parameters: (E_k^{iso}, ε_e, ε_B, n; s)
- LGRB: E_k^{iso}~10^{53}-10^{54} erg, ε_e~0.01-0.1, ε_B~10^{-4}-10^{-3}, s~2.2

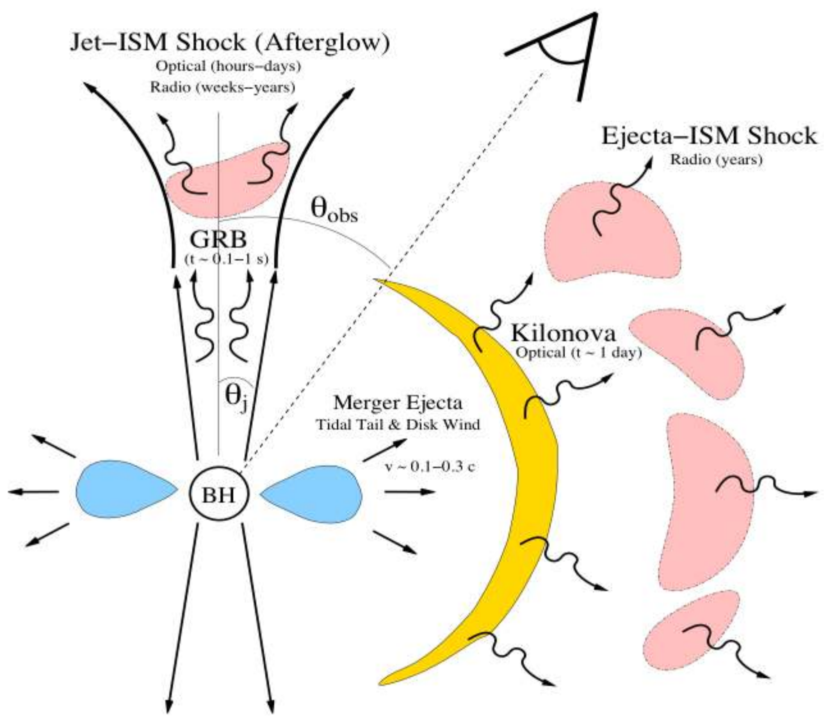
Evidence for Jets

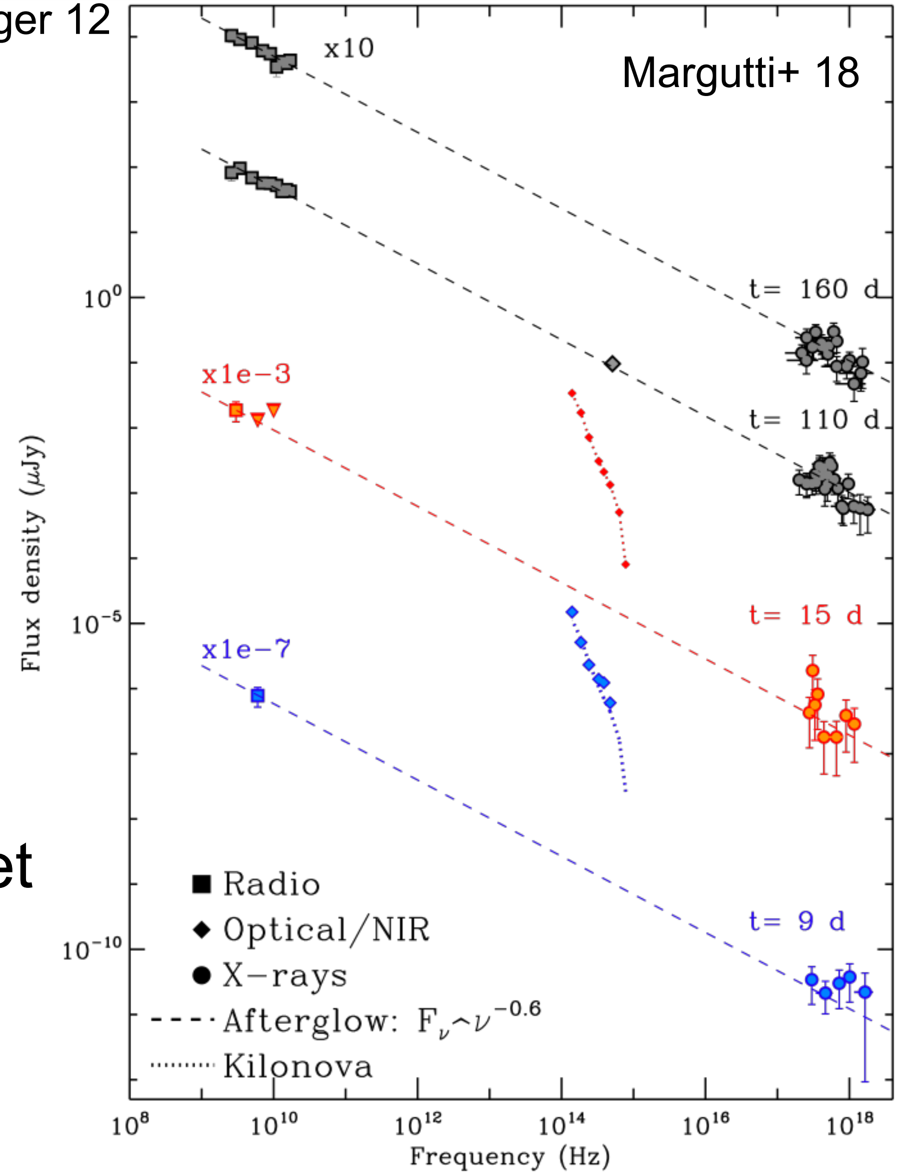




Golden Example: GW170817

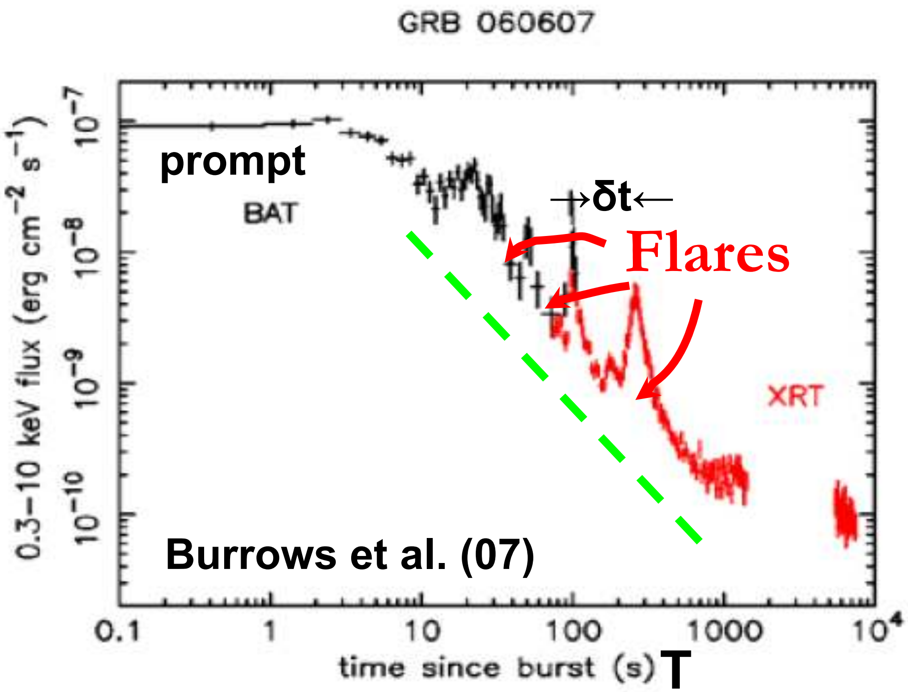
Metzger & Berger 12

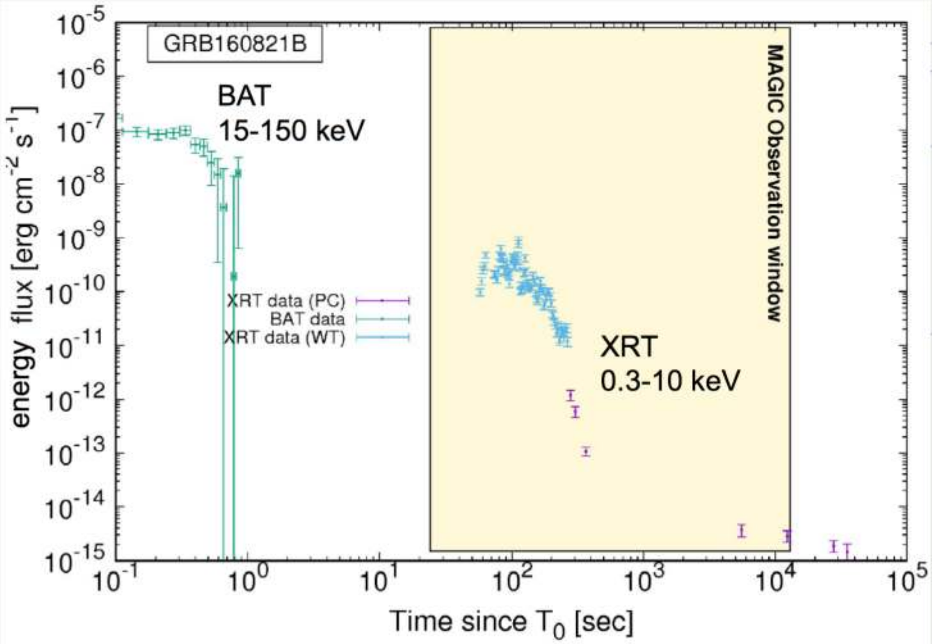




- Strong evidence for off-axis jet
- Beautiful synchrotron (Lorentz factor: Γ~3-10)
- s~2.2, n~10^{-5}-10^{-4} cm^{-3}

Evidence for Long-Lasting Central Engines





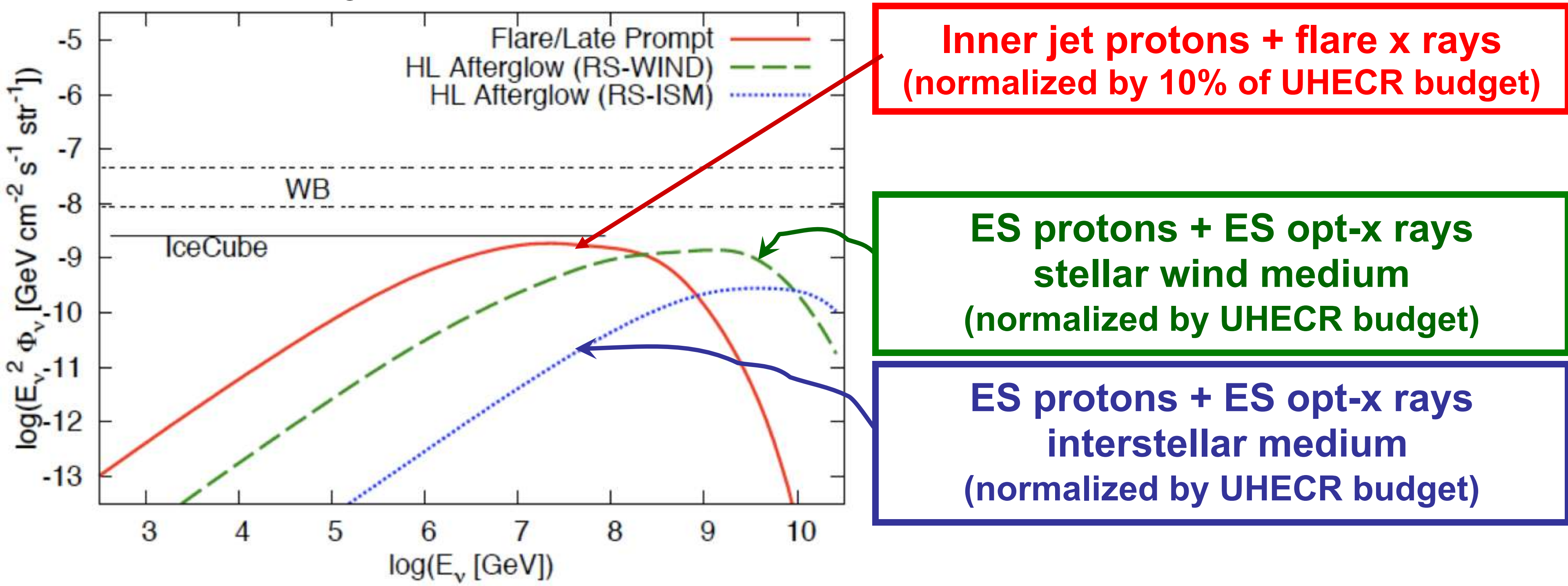
- Energetic (E_{flare} ~ 0.1-1 $E_{GRB\gamma}$)
- δt >~ 10^{2-3} s, δt/T < 1 → internal dissipation
- Flaring in the softer energy range (far-UV/X-ray/γ-ray)
- Lower Lorentz factors (maybe)
- Common (at least 1/3-1/2 of LGRBs) (also seen in SGRBs)
- Mechanism: fallback disk or long-lived magnetar

Neutrino Afterglow Emission

- Afterglows are typically explained by external shock scenario
- Flares and early afterglows may come from internal dissipation

UHECRs may be accelerated during the afterglow phase

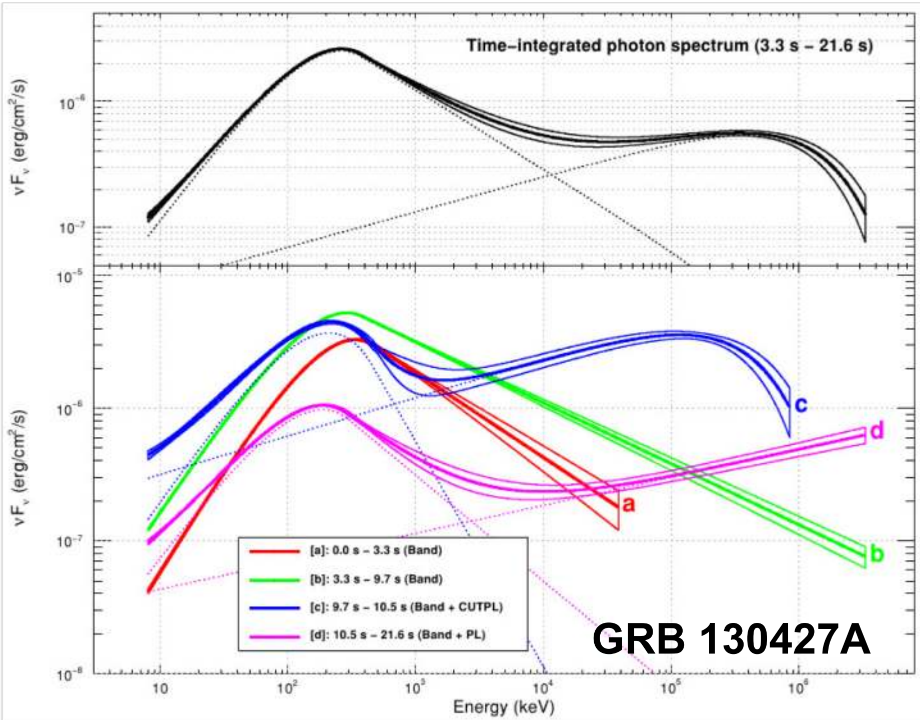
KM & Nagataki 06 PRL, KM 07 PRD

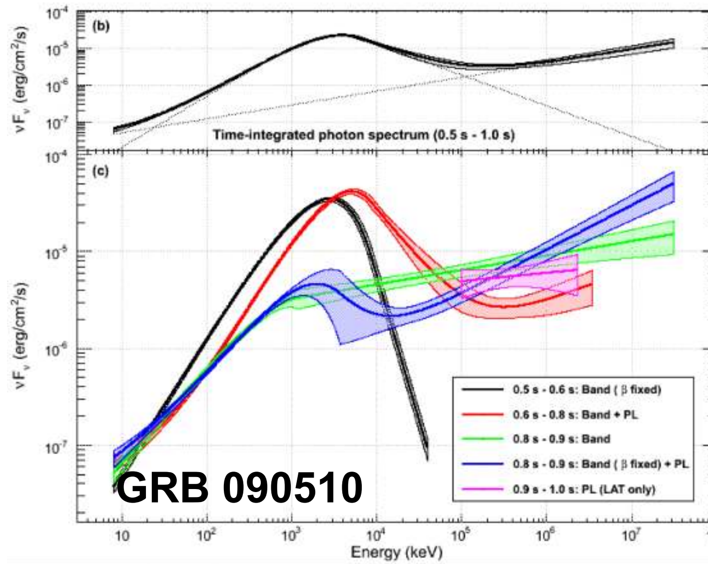


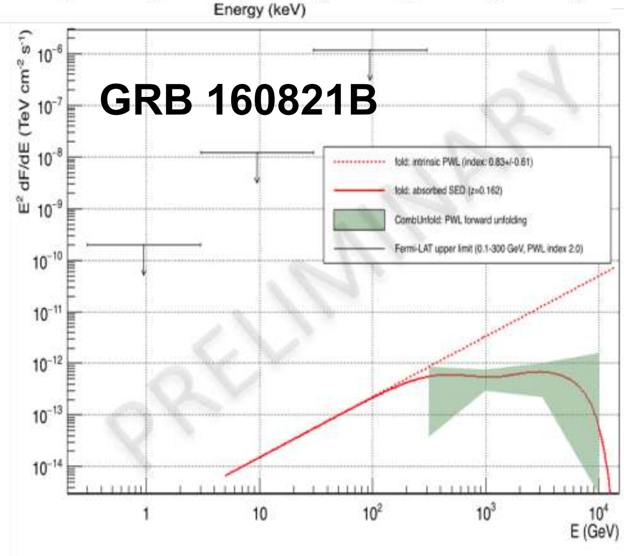
Forward shock is unlikely to accelerate CRs up to UHECR energies
Reverse shock emission is mildly relativistic and feasible

GeV-TeV Gamma Rays?

Hard component comes later (external shock component?)







First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

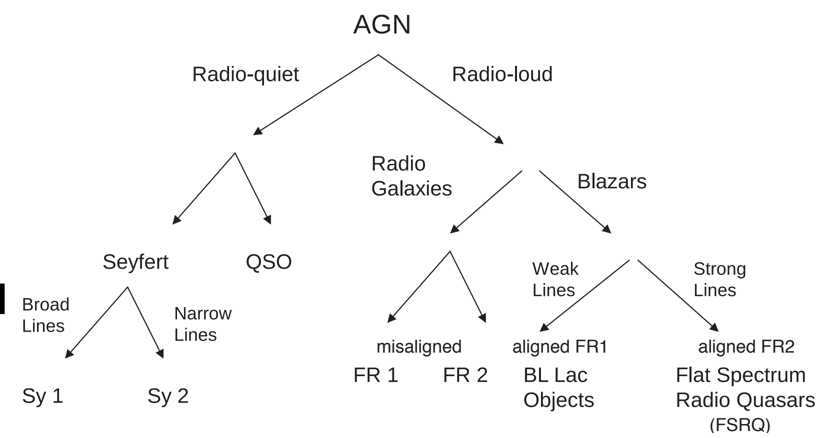
ATel #12390; ***Razmik Mirzoyan on behalf of the MAGIC Collaboration***
on 15 Jan 2019; 01:03 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

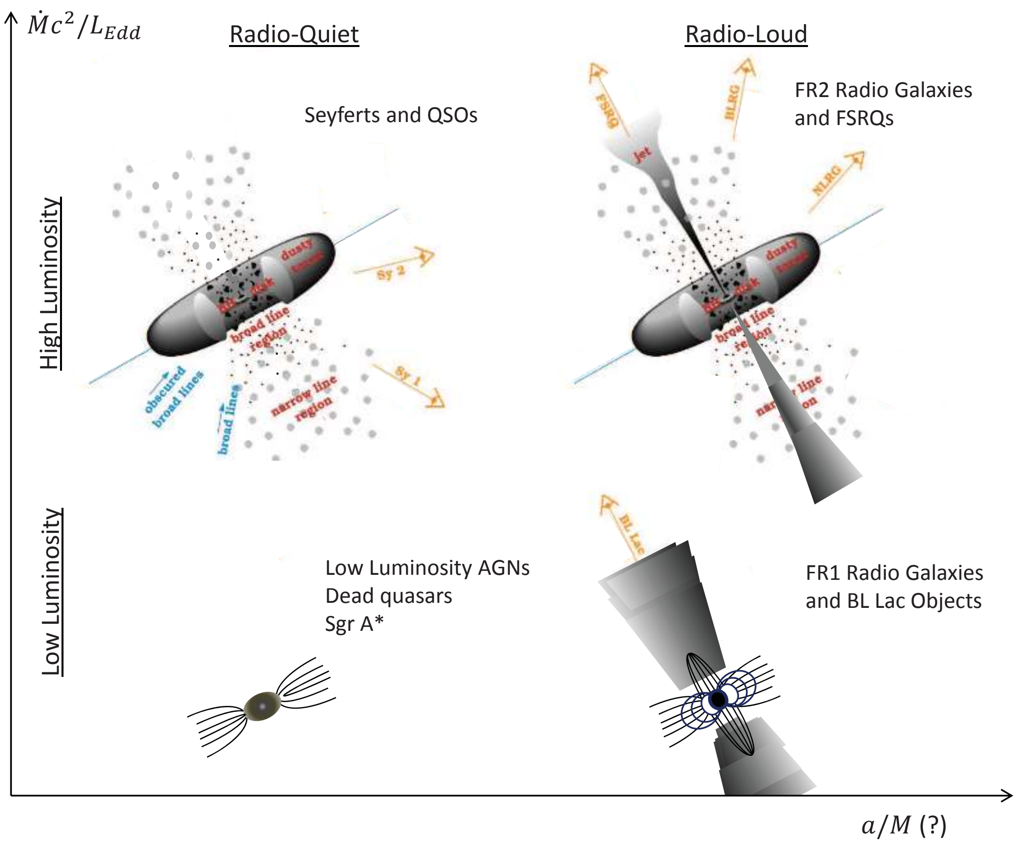
Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

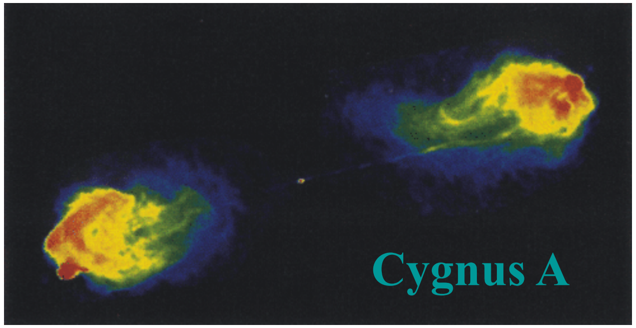
Referred to by ATel #: 12395, 12475

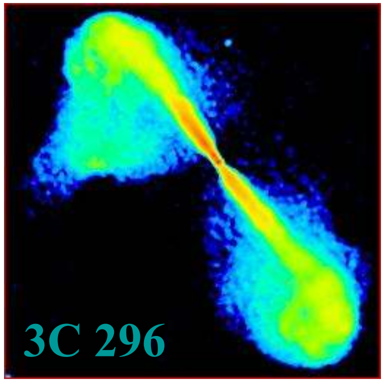
Active Galactic Nuclei

- jets of radio-loud AGN (including blazars)
- weak jets of radio-quiet AGN
- knots, cocoon & hotspot of radio galaxies
- accretion disk/coronae of AGN
- disk-driven outflows
- black hole magnetosphere of low-luminosity AGN





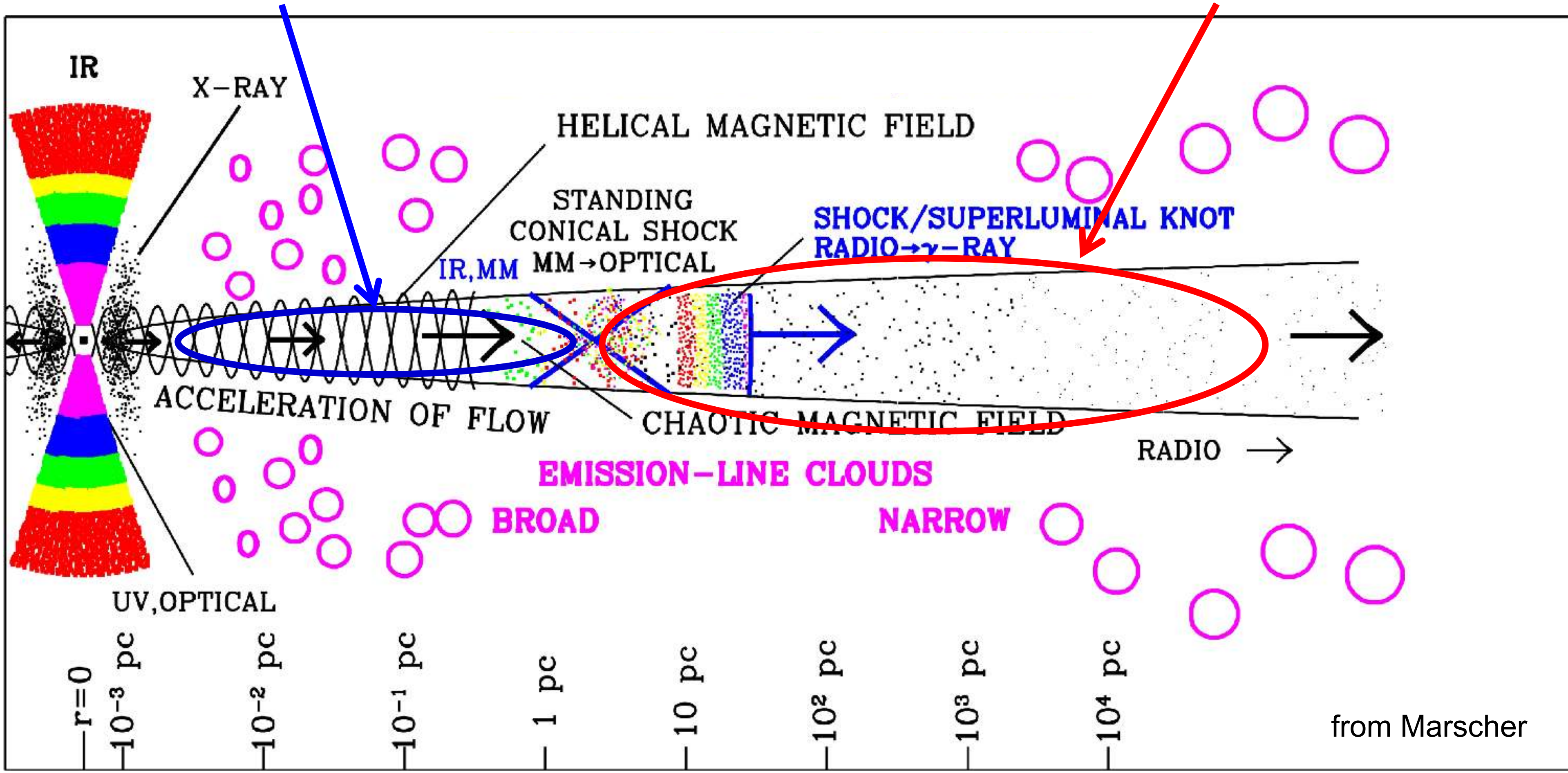




Particle Acceleration in AGN Jets?

Inner jet (blazar zone)
r ~ 10^{16}-10^{17} cm, B ~ 0.1-100 G, Γ ~ 10

Large-scale jet, cocoon, hot spot
r ~ 10^{20}-10^{21} cm, B ~ 1μG -1 mG, Γ ~ 1



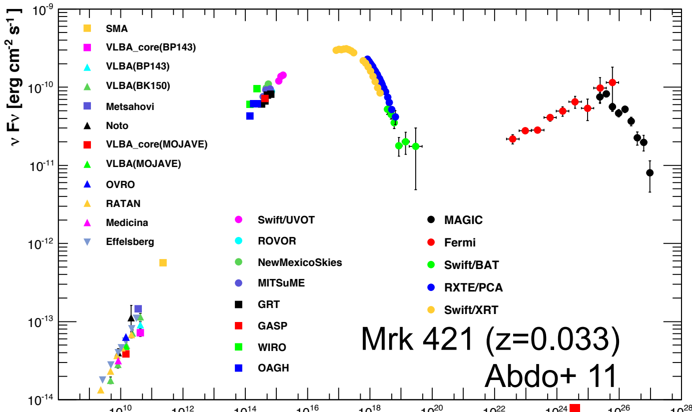
Hillas condition: E_{max} ~ZeBrΓ ~ 3x10^{19} eV Z (Γ/10) (B/0.1 G) (r/10^{17} cm)

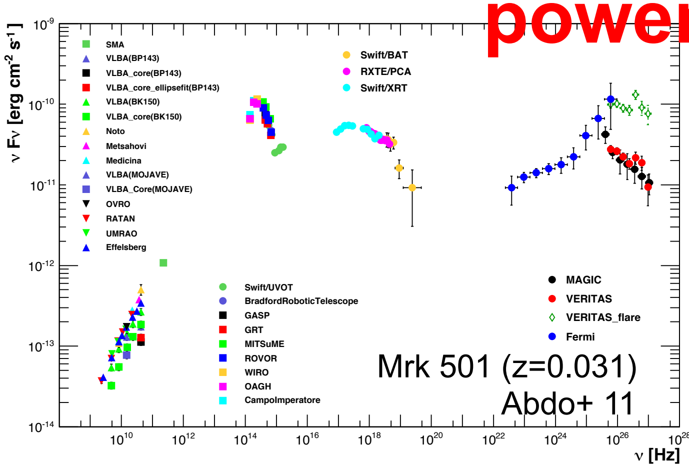
Blazars: Success of Multiwavelength Observations

Spectral energy distribution (SED): typically "two hump" structure

BL Lac objects (BL Lacs)

γ emission up to TeV energies

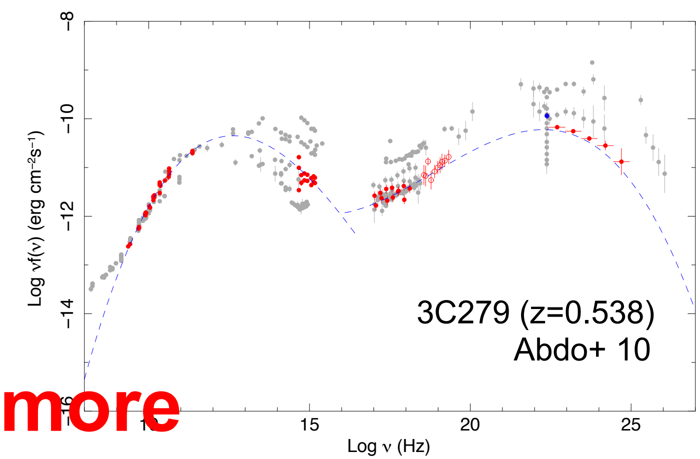


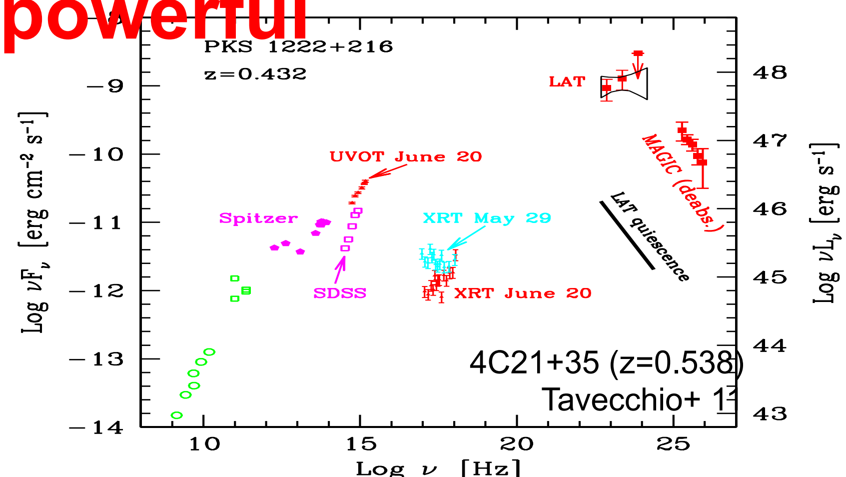


less powerful ⟺ **more powerful**

Flat-spectrum quasars (FSRQs)

mostly $\nu_{syn}<10^{14}$ Hz, GeV break





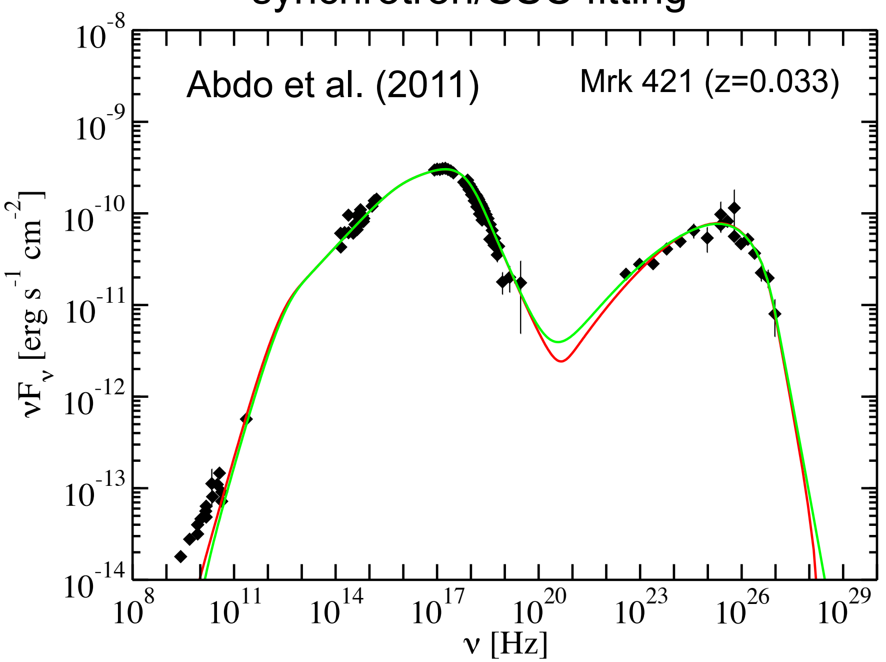
Leptonic Scenario

Broadband HE radiation: relativistic electrons accelerated in magnetized jets

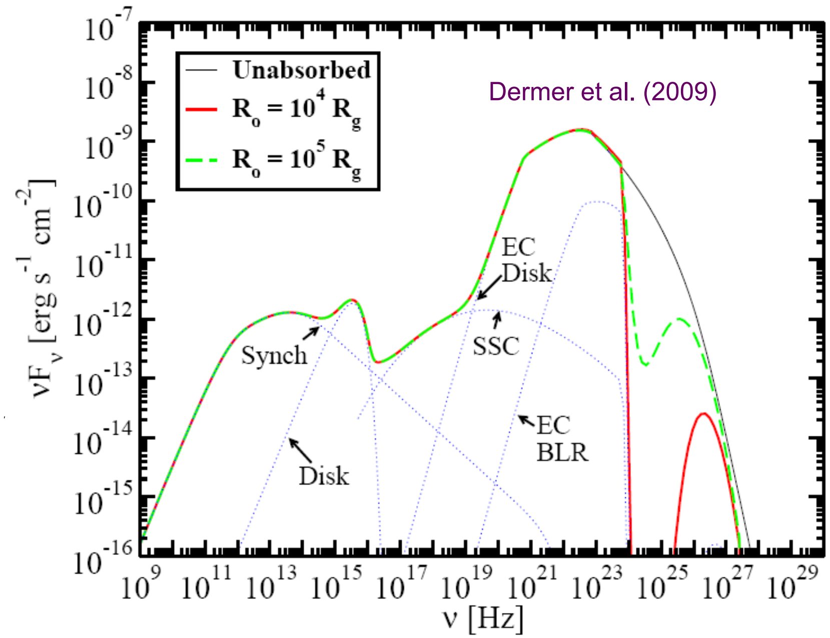
LE hump = synchrotron emission (B' ~ 0.1-1 G)

HE hump = synchrotron self-Compton (SSC) or external inverse-Compton (EIC)

BL Lacs
synchrotron/SSC fitting



FSRQs
synchrotron/SSC+EIC model fits

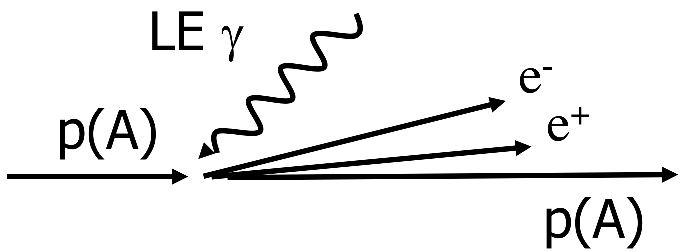


- Basic tool: one-zone syn./SSC model w. syn. self-absorption and internal $\gamma\gamma$
- EIC target: bloadline regions (BLR), dust torus, (scattered) accretion disk

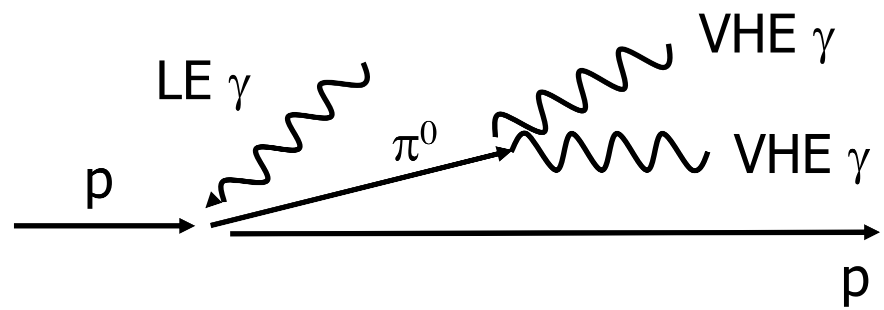
Intra-Source Cascades

VHE γ/e injection by cosmic rays

Bethe-Heitler process



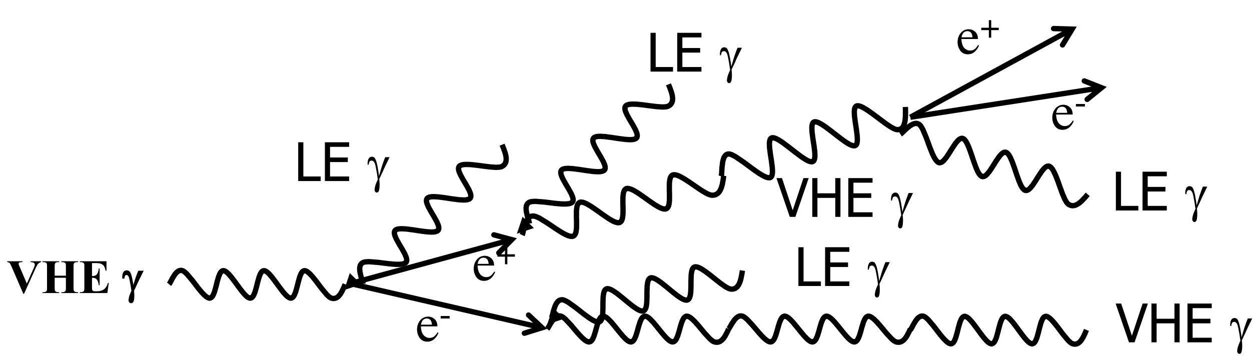
pγ meson production



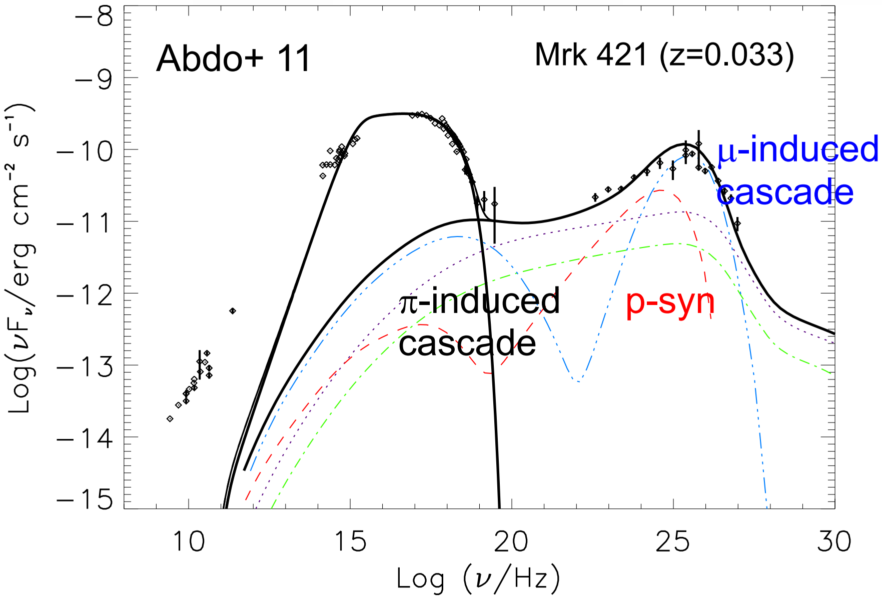
$$\gamma + \gamma \rightarrow e^{+} + e^{-}$$

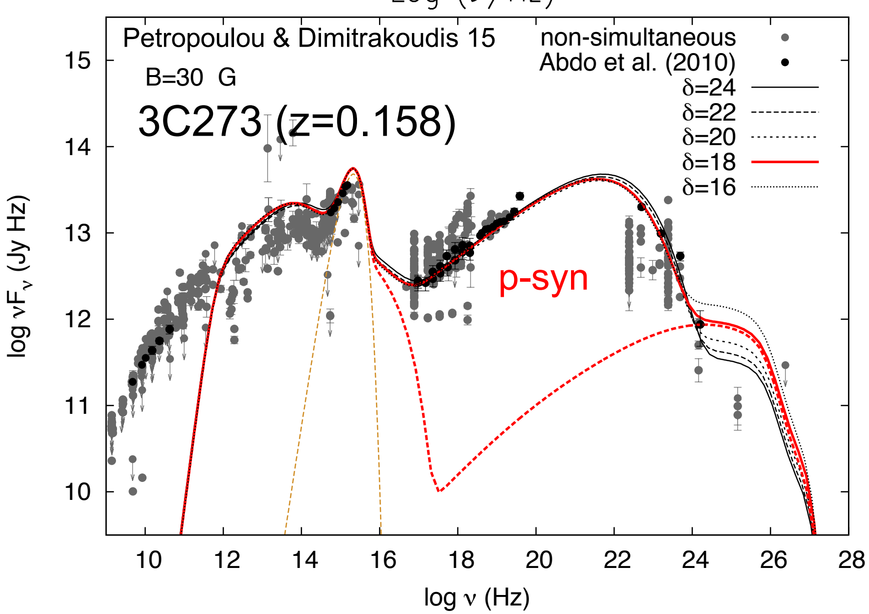
$$e + \gamma \rightarrow e + \gamma \ (\mathrm{IC})$$

$$e + B \rightarrow e + \gamma \ (\mathrm{syn})$$



(Lepto-)Hadronic Scenario?





- Nonthermal synchrotron radiation from primary electrons for radio through optical (low-energy hump)

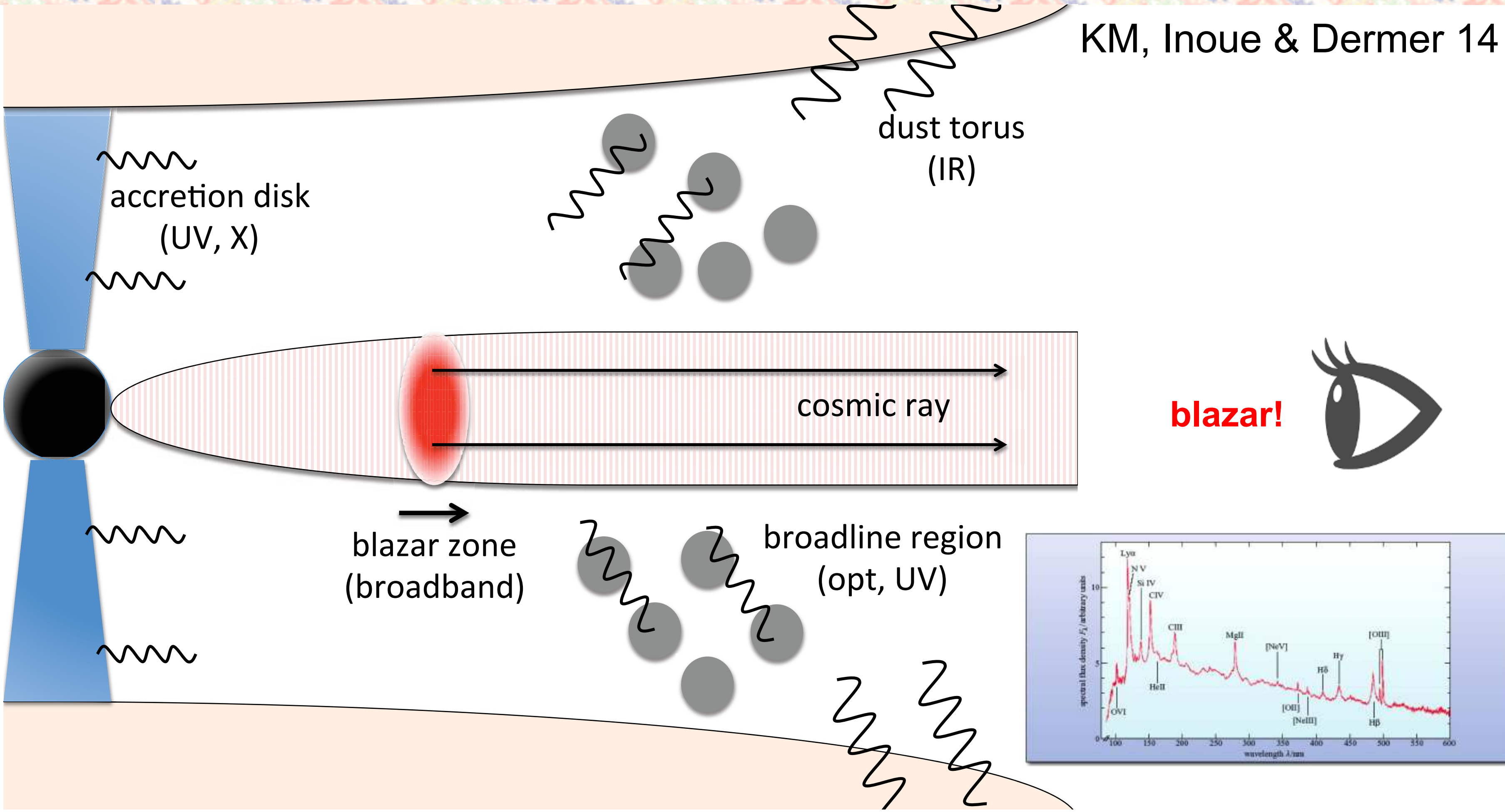
- Cascades via photomeson production
  $p+\gamma \rightarrow p/n, \pi \rightarrow p/n, \nu, \gamma, e$
- Proton and ion synchrotron radiation
  $p+B \rightarrow p+\gamma$

"SEDs can usually be fitted by both leptonic and leptohadronic scenarios"

caveats:
- large CR power is necessary ($L_p \sim 10^{47}$-10^{49} erg/s ~ 10^3-10^6 L_e)
- much more free parameters

smoking gun? -> neutrinos!

Photomeson Production in AGN Jets



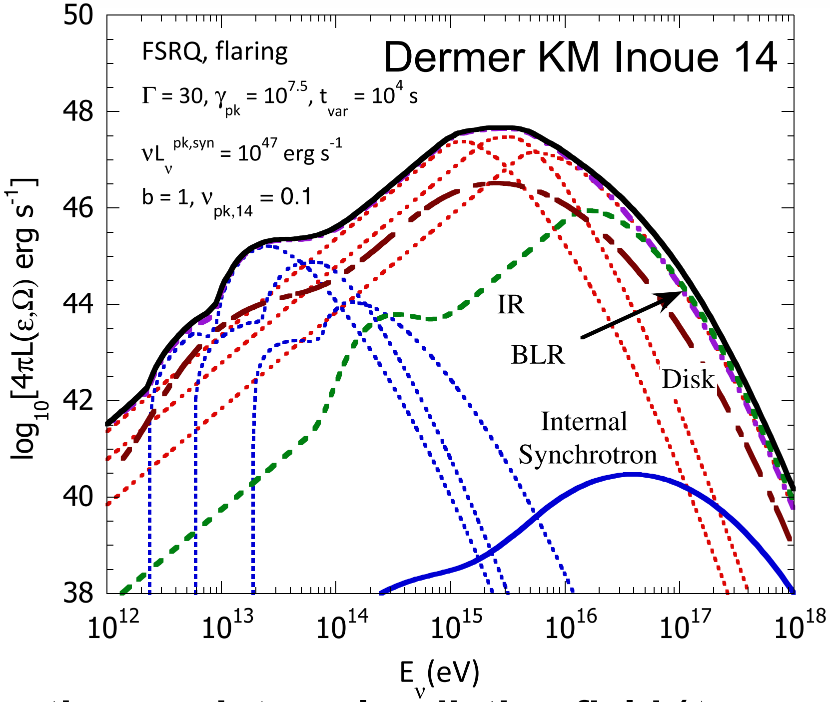
$p\gamma \rightarrow \Delta^+ \rightarrow \pi + N$

$E'^b_\nu \approx 0.05 E'^b_p \simeq 80\ \mathrm{PeV}\ \Gamma_1^2 (E'_s/10\ \mathrm{eV})^{-1}$ **inner jet photons**

$E'^b_\nu \approx 0.05(0.5 m_p c^2 \bar{\varepsilon}_\Delta / E'_{\mathrm{BL}}) \simeq 0.78\ \mathrm{PeV}$ **BLR photons**

$E'^b_\nu \simeq 0.066\ \mathrm{EeV}(T_{\mathrm{IR}}/500\ \mathrm{K})^{-1}$ **IR dust photons**

Ex. Neutrinos from FSRQs



effective optical depth for pγ:

$$f_{p\gamma} \sim n_\gamma(\kappa_p \sigma_{p\gamma})(\Gamma c \delta t)$$

interactions w. internal radiation field (Δ-res.+direct prod.)

$$f_{p\gamma}(E'_p) \simeq 7.8\times10^{-4} L^{s}_{\mathrm{rad},45}\Gamma_1^{-4}\delta {t'}_5^{-1}(E'_s/10\ \mathrm{eV})^{-1}\begin{cases}(E'_\nu/{E'}^b_\nu)^{\beta_h-1}\\(E'_\nu/{E'}^b_\nu)^{\beta_l-1}\end{cases}$$

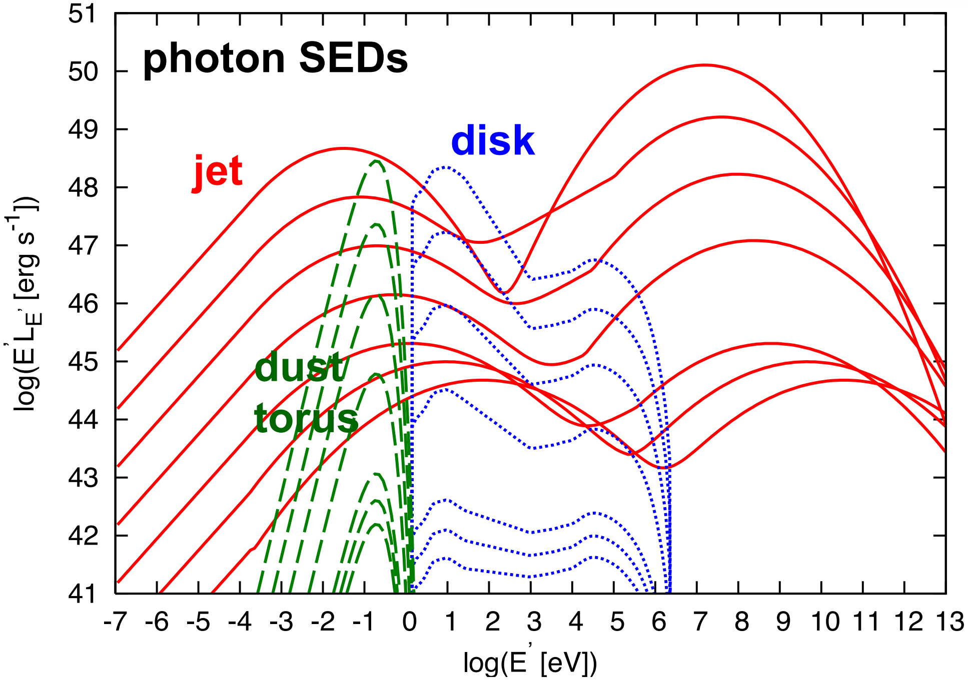
interactions w. external radiation fields (Δ-res.+multi-pion)

$$f_{p\gamma} \approx \hat{n}_{\mathrm{BL}}\sigma^{\mathrm{eff}}_{p\gamma} r_{\mathrm{BLR}} \simeq 5.4\times10^{-2}\ f_{\mathrm{cov},-1}L^{1/2}_{\mathrm{AD},46.5}$$

$$f_{p\gamma} \simeq 0.89\ L^{1/2}_{\mathrm{AD},46.5}(T_{\mathrm{IR}}/500\ \mathrm{K})^{-1}$$

independent of Γ

Brighter is Better



"Blazar sequence" (Fossati+ 98)

softer spectra at higher L

LSP: powerful ⇆ HSP: weak

external radiation fields

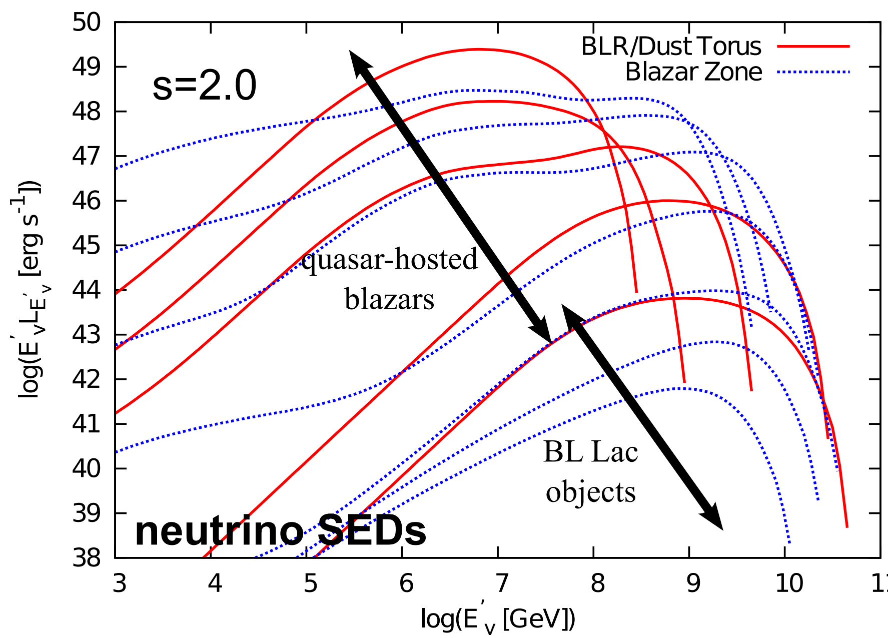
$L_\nu \propto L_\gamma^{1.5}$

internal radiation fields

ex. $L_\nu \propto L_\gamma^2$

cf. hadronic scenario (saturated)

$L_\nu \propto L_\gamma$



Relativistic Jet Sources: Summary

Source physics is important

Rich EM data are available: do not ignore

GRBs and blazars - motivated by GW170817 & IceCube-170922A

<u>HE neutrino & gamma-ray emissions</u>

GRB?

Prompt: internal dissipation – thermal + heating/acceleration

Afterglow: external shock emission – successful theory

Evidence for long-lasting central engines

Blazar?

Blazar emission: internal dissipation - leptonic vs hadronic

FSRQs: external radiation fields relevant

Problems for Discussion

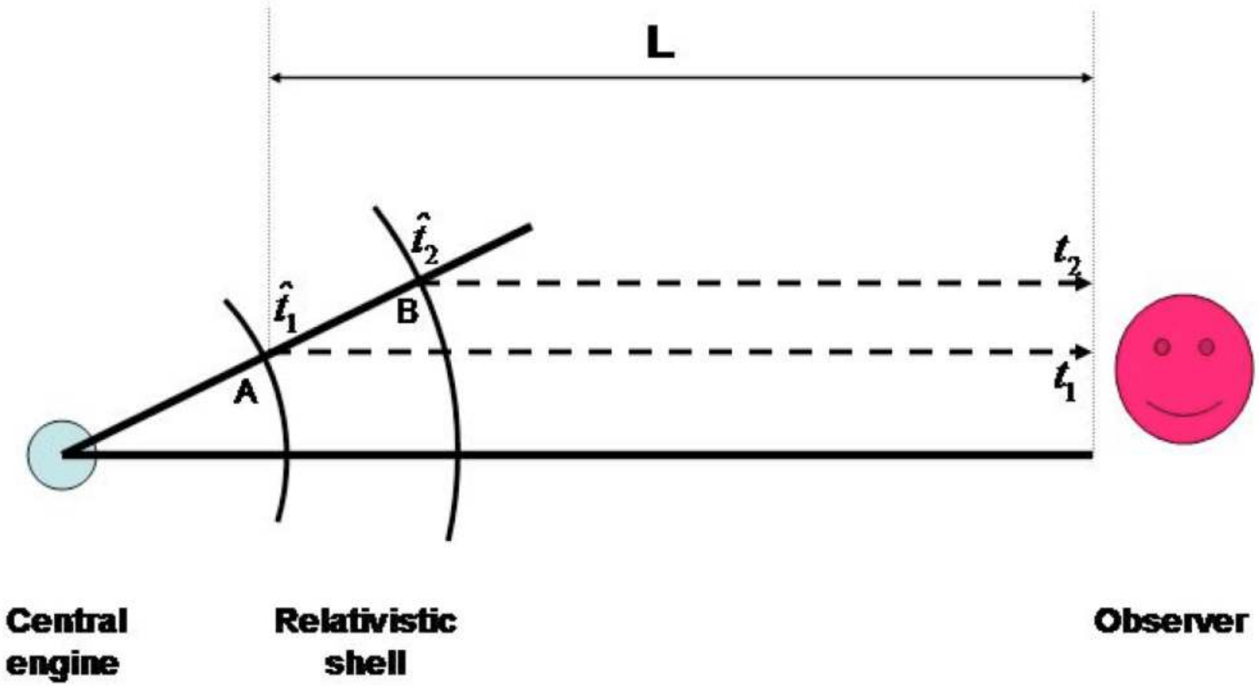
1. How likely can we detect HE neutrinos from GW170817 if on-axis

   (suppl.1): check the afterglow theory
   (suppl.2): check the relevance of pp

2. Estimate photomeson production efficiency for TXS 0506+056 and required power of CRs

   (suppl.1): check the $\gamma\gamma$ optical depth
   (suppl.2): check the Bethe-Heitler optical depth

2 Frames, 3 Time Scales



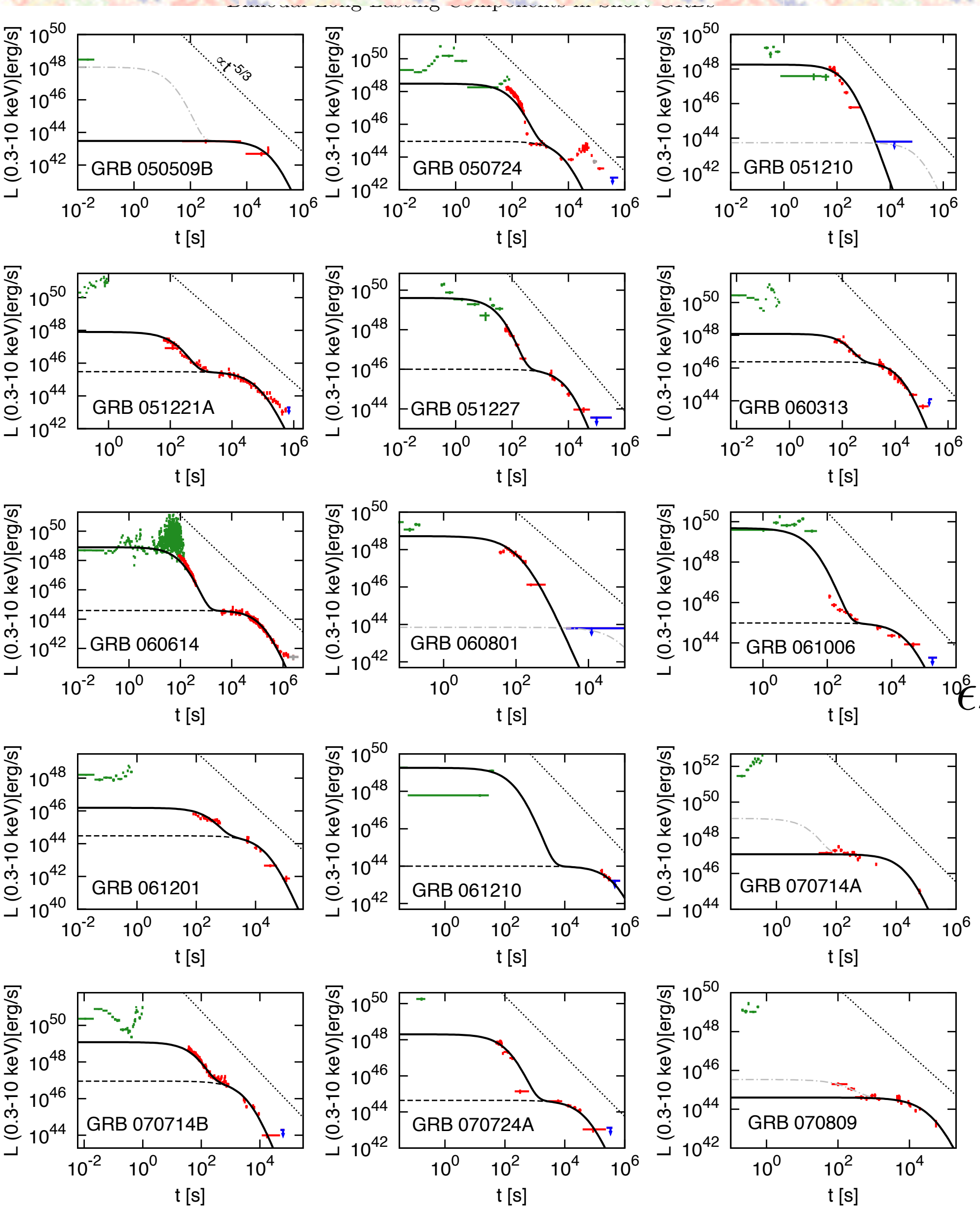
$$dt = (1-\beta\mu)d\hat{t} \simeq d\hat{t}/2\Gamma^2 = dr/(2\Gamma^2 c)\,,$$

$$dt' = d\hat{t}/\Gamma = dt/\Gamma(1-\beta\mu) = \mathcal{D}dt \simeq 2\Gamma dt$$

$$\mathcal{D} = [\Gamma(1-\beta\mu)]^{-1}$$

GW170817

Long-Lasting Emission from Short GRBs



short GRB plateau emission

fall-back activity?
magnetar activity?

$$L = \epsilon_\gamma \eta_j \dot{M} c^2 / f_b,$$

$$\dot{M} \simeq 5.6 \times 10^{-9} \ M_\odot \ \mathrm{s}^{-1} \ f_{b,-2} \epsilon_{\gamma,-1}^{-1} \eta_j^{-1} L_{47}$$

$\epsilon_\gamma \sim 1$ and $\eta_j \sim 1$

$$\dot{M}_0 \sim 3 \times 10^{-3} \ M_\odot \ \mathrm{s}^{-1}$$

at t ~ 1 sec

Kisaka+

Parameters

Parameters	Γ	$L^*_{\gamma,\rm iso}$ (erg s^{-1})	$\mathscr{E}^*_{\gamma,\rm iso}$ (erg)	$r_{\rm diss}$ (cm)	$E_{\gamma,\rm pk}$ (keV)	Energy Band (keV)
EE-mod	30	3×10^{48}	10^{51}	10^{14}	1	0.3–10
EE-opt	10	3×10^{48}	10^{51}	3×10^{13}	10	0.3–10
Prompt	10^3	10^{51}	10^{51}	3×10^{13}	500	$10–10^3$
Flare	30	10^{48}	3×10^{50}	3×10^{14}	0.3	0.3–10
Plateau	30	10^{47}	3×10^{50}	3×10^{14}	0.1	0.3–10
Quantities	B (G)	$L_{\gamma,\rm iso}$ (erg s^{-1})	$\mathscr{E}_{\gamma,\rm iso}$ (erg)	$E_{p,M}$ (EeV)	$E_{\nu,\mu}$ (EeV)	$E_{\nu,\pi}$ (EeV)
EE-mod	2.9×10^3	1.2×10^{49}	3.8×10^{51}	21	0.020	0.28
EE-opt	5.0×10^4	3.4×10^{49}	1.1×10^{52}	6.0	3.9×10^{-4}	5.4×10^{-3}
Prompt	6.7×10^3	6.1×10^{51}	6.1×10^{51}	60	0.29	4.0
Flare	5.3×10^2	3.5×10^{48}	1.0×10^{51}	25	0.11	1.5
Plateau	1.8×10^2	3.8×10^{47}	1.1×10^{51}	13	0.33	4.6

$$E_{\nu_\mu}^2 \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} \approx \frac{1}{8} f_{p\gamma} f_{\sup\pi} E_p^2 \frac{dN_p}{dE_p}$$

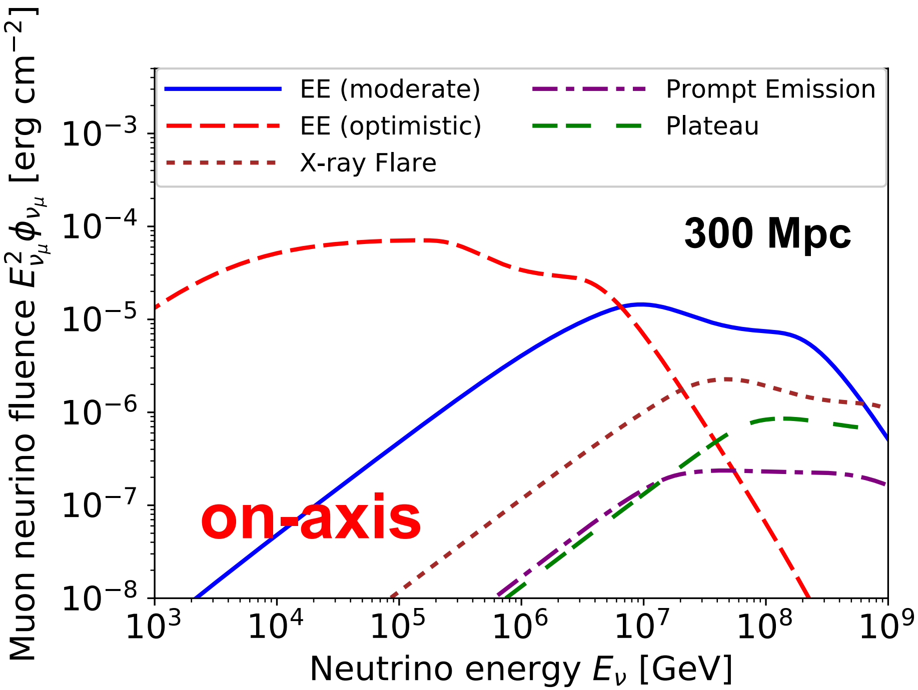
$$E_{\nu_e}^2 \frac{dN_{\nu_e}}{dE_{\nu_e}} \approx E_{\bar{\nu}_\mu}^2 \frac{dN_{\bar{\nu}_\mu}}{dE_{\bar{\nu}_\mu}} \approx \frac{1}{8} f_{p\gamma} f_{\sup\pi} f_{\sup\mu} E_p^2 \frac{dN_p}{dE_p},$$

$$\phi_{\nu_e+\bar{\nu}_e} = \frac{10}{18}\phi^0_{\nu_e+\bar{\nu}_e} + \frac{4}{18}(\phi^0_{\nu_\mu+\bar{\nu}_\mu} + \phi^0_{\nu_\tau+\bar{\nu}_\tau})$$

$$\phi_{\nu_\mu+\bar{\nu}_\mu} = \frac{4}{18}\phi^0_{\nu_e+\bar{\nu}_e} + \frac{7}{18}(\phi^0_{\nu_\mu+\bar{\nu}_\mu} + \phi^0_{\nu_\tau+\bar{\nu}_\tau})$$

Neutrinos Coinciding w. Gravitational Waves?

GW170817: supporting the NS merger origin of short GRBs



Kimura, KM, Meszaros & Kiuch 17 ApJL
used in ANTARES-IceCube-Auger-LIGO-VIRGO

The Detection Probabilities within a Given Time Interval, $\mathcal{P}_{\Delta T}$

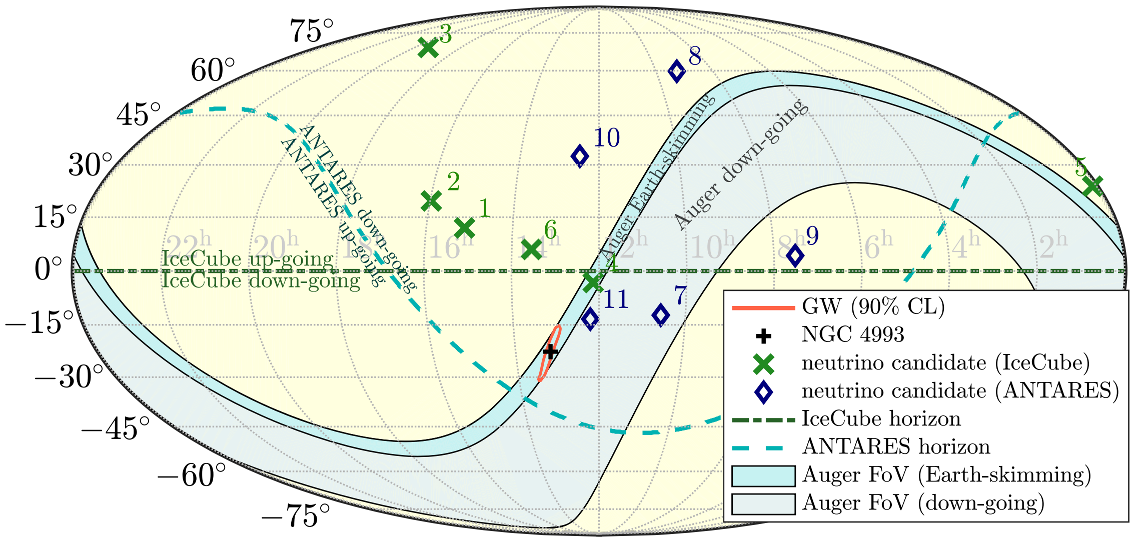
NS–NS (ΔT = 10 years)	IC (all)	Gen2 (all)
EE-mod-dist-A	0.11–0.25	0.37–0.69
EE-mod-dist-B	0.16–0.35	0.44–0.77
EE-opt-dist-A	0.76–0.97	0.98–1.00
EE-opt-dist-B	0.65–0.93	0.93–1.00
NS–BH (ΔT = 5 years)	**IC (all)**	**Gen2 (all)**
EE-mod-dist-A	0.12–0.28	0.45–0.88
EE-mod-dist-B	0.18–0.39	0.57–0.88
EE-opt-dist-A	0.85–0.99	1.00–1.00
EE-opt-dist-B	0.77–0.97	0.99–1.00

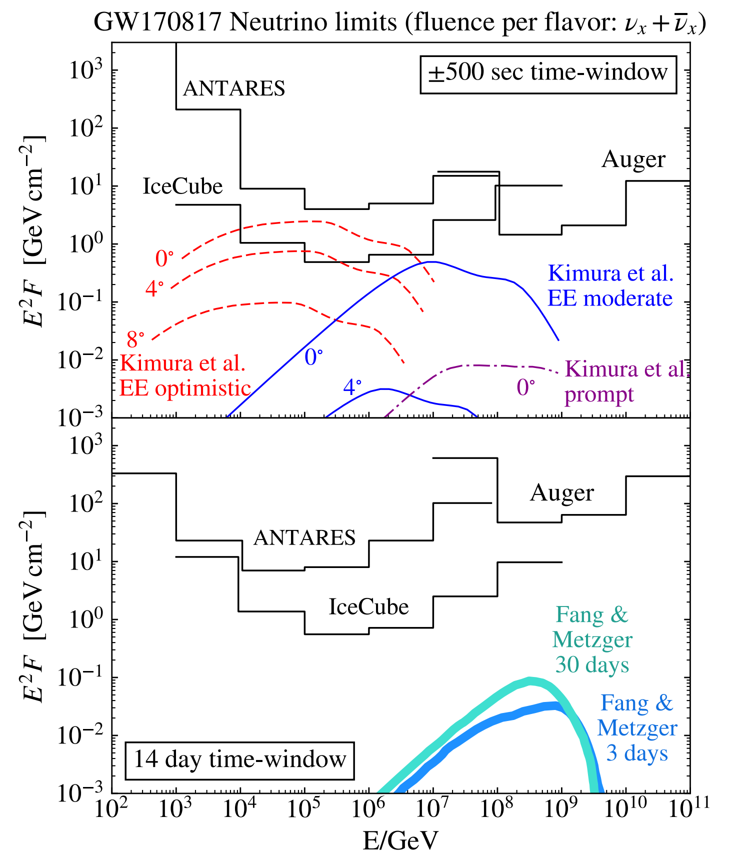
- GW170817: off-axis (~30 deg) so SGRB models are OK (unlikely to be a long-lived fast-spinning magnetar)
- Gen-2 can see ~a few events/decade coinciding w. GW signals
- UHE ν detectors should look (~1/yr for $A_{eff}=10^{11}$ cm^2 at EeV)

Neutrinos Coinciding w. Gravitational Waves?

GW170817: supporting the NS merger origin of short GRBs

ANTARES, IceCube, Auger, & LIGO-Virgo ApJL 17

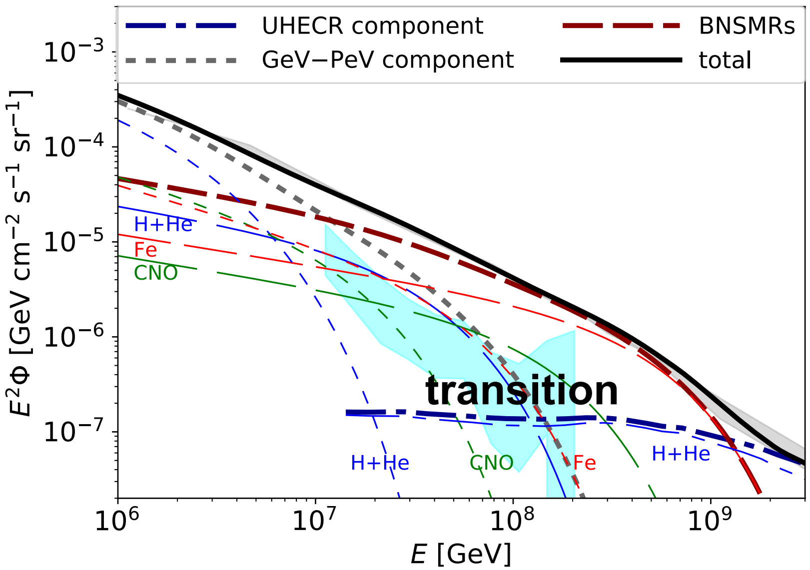


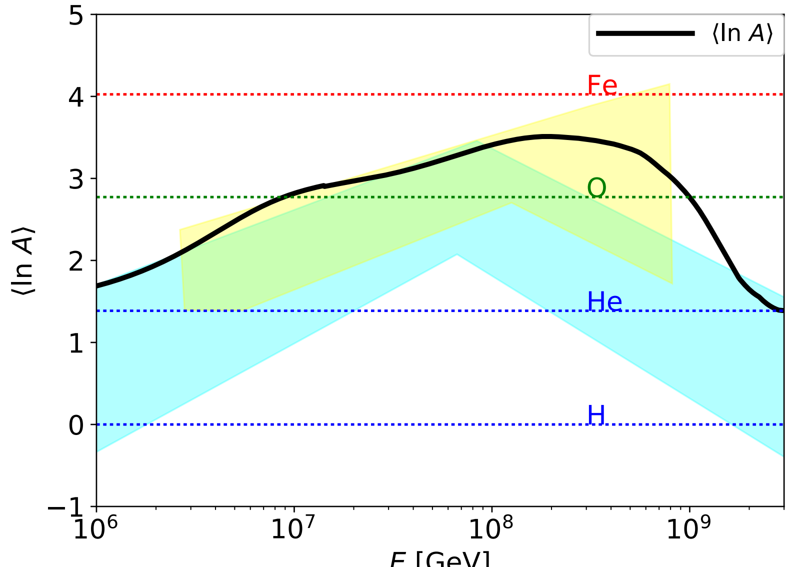


theoretical models
short GRB jets (Kimura, KM, Meszaros & Kiuchi 17)
magnetar in the ejecta (Fang & Metzger 17)
(see also KM, Zhang & Meszaros 09)

- GW170817: off-axis (~30 deg): the models are still consistent
- On-axis events coinciding w. GW signals could be seen

“Tale” of Past Galactic Neutron Merger Remnants?

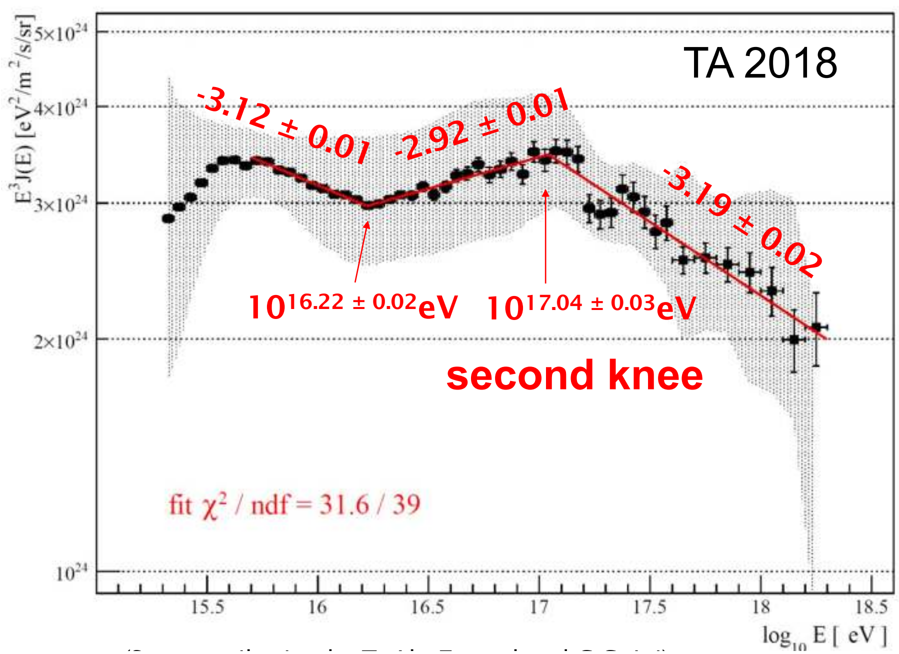




Kimura, KM & Meszaros 18 ApJ

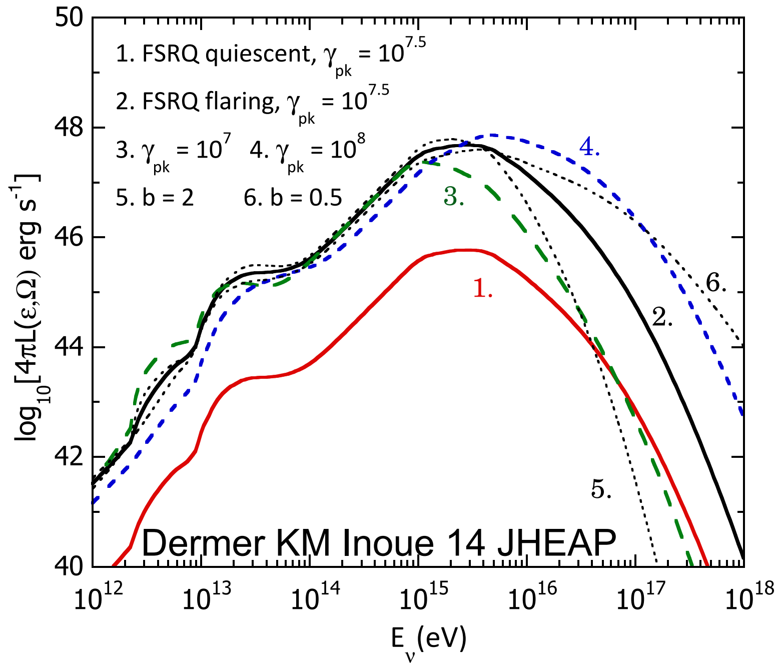
GW170817 confirmed
transrelativistic ejecta w. V~0.2-0.3c
-> E_p^{max} ~ 30 PeV >> knee

TALE spectrum:
second knee at ~10^{17} eV
break at ~$10^{16.2}$ eV



IceCube-170922A

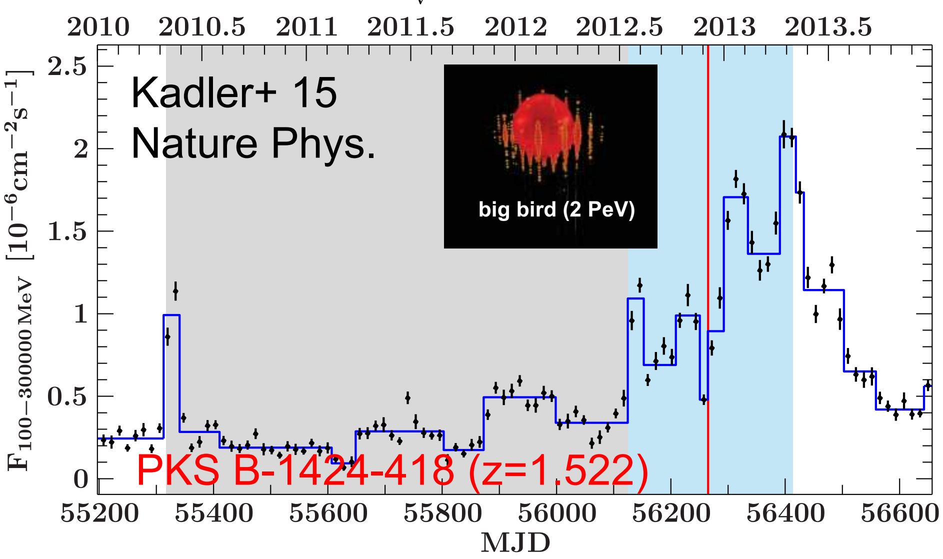
Blazar Flares?

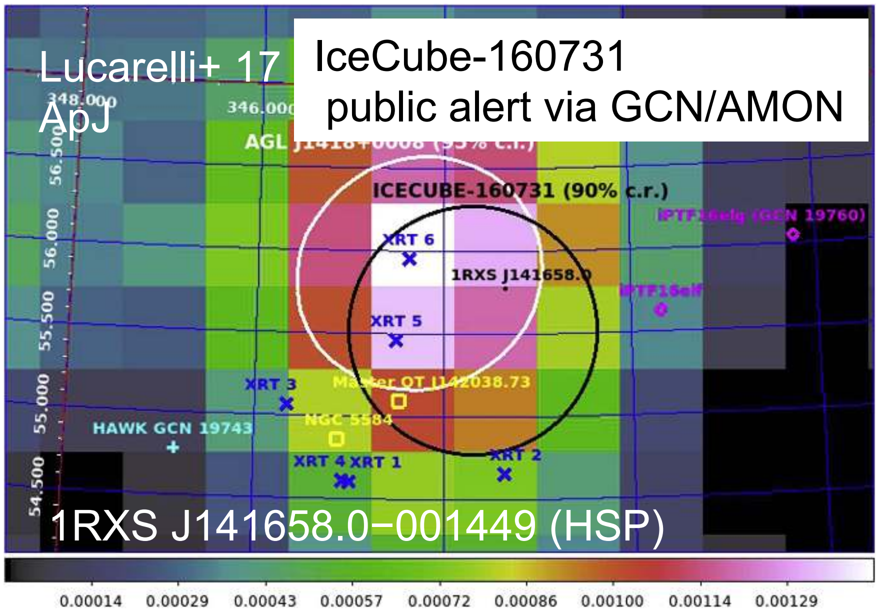


Good chances to detect them even if subdominant in the diffuse ν sky

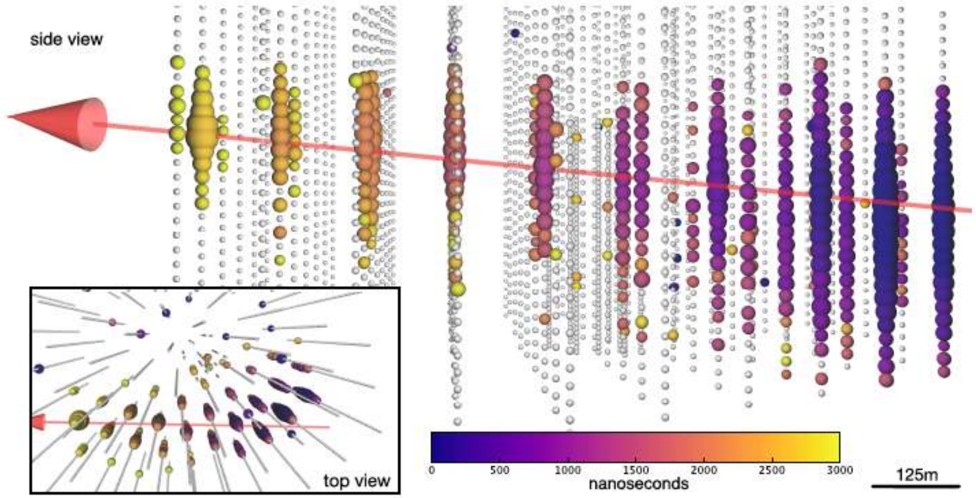
1. Observational reason:
   temporal & spatial coincidence
2. Theoretical reason
   "enhanced" jet power + target photons

(see e.g., KM & Waxman 16, KM et al.18)

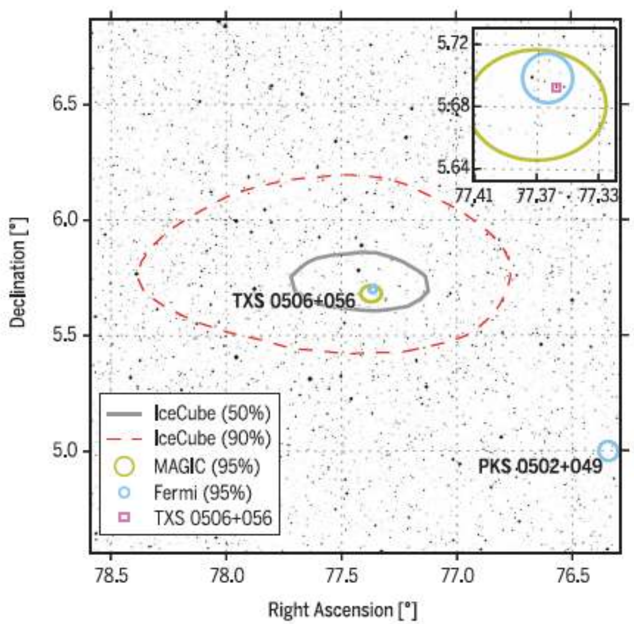




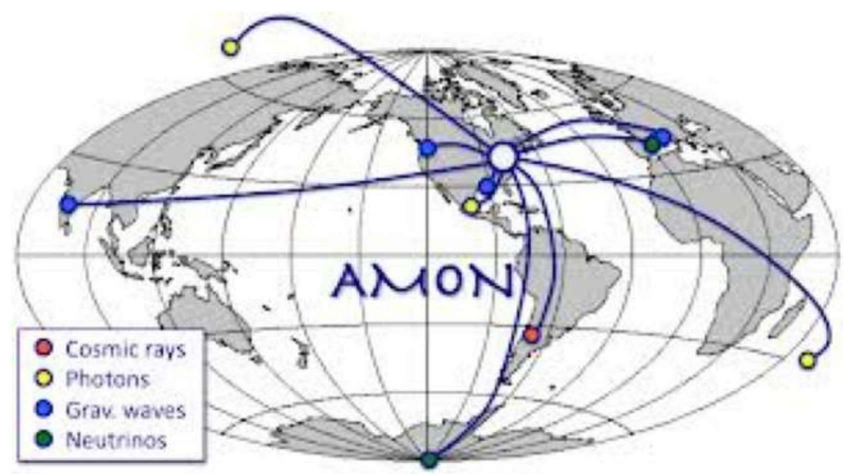
IceCube 170922A & TXS 0506+056



IceCube 2018 Science

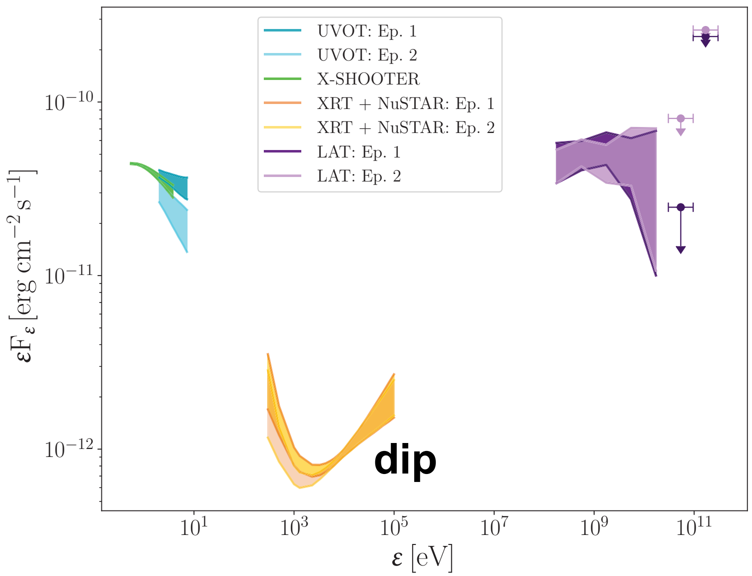


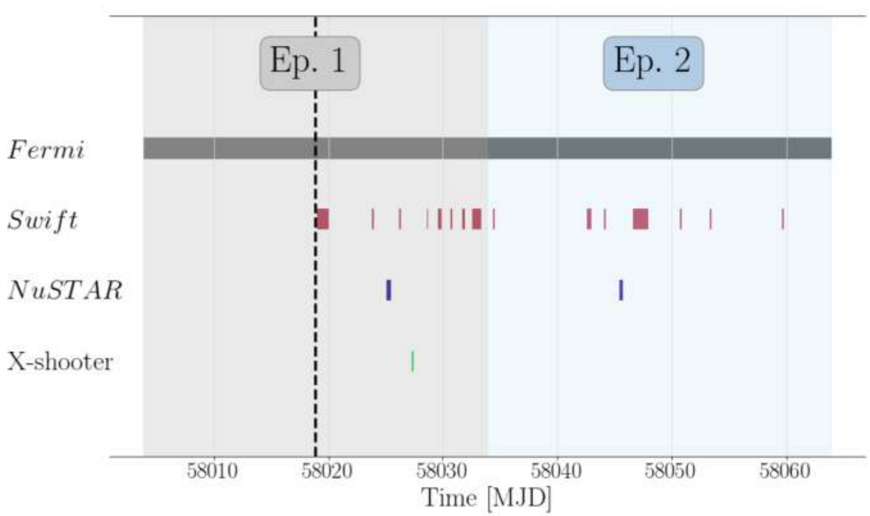
- IceCube EHE alert pipeline
- Automatic public alert (through AMON/GCN)
- Kanata observations of blazars -> Fermi-LAT (Tanaka et al.) ATel #10791 (Sep/28/17)
- X-ray observations reported by members of Penn State people
- Swift (Keivani et al.) GCN #21930, ATel #10942 NuSTAR (Fox et al.) ATel #10861



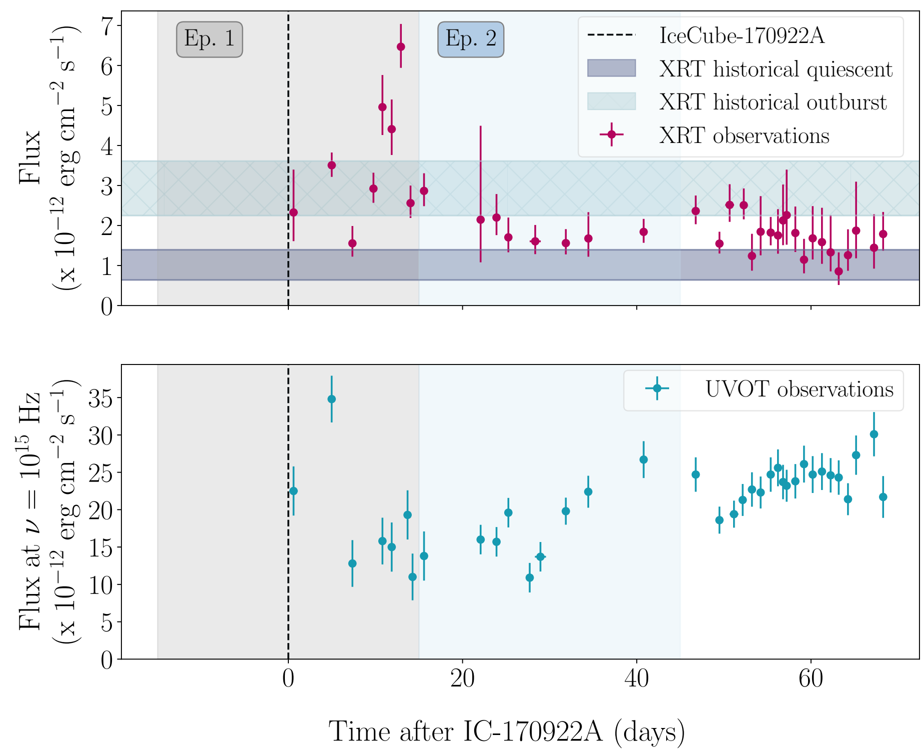
Our Observations of TXS 0506+056

Quasi-simultaneous SED





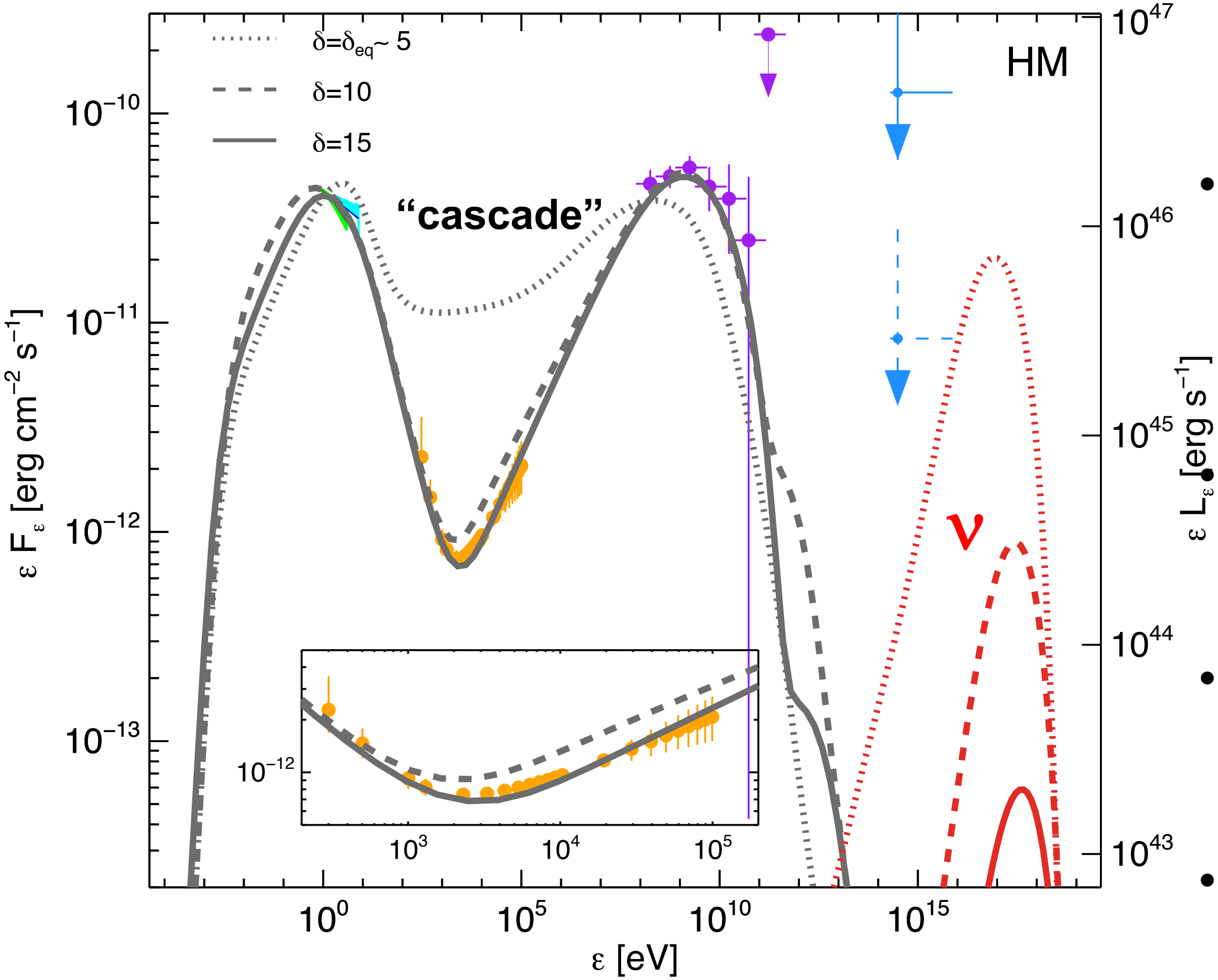
XRT & UVOT light curves



Keivani, KM, Petropoulou, Fox et al. 2018

TXS 0506+056 SED Modeling: Hadronic

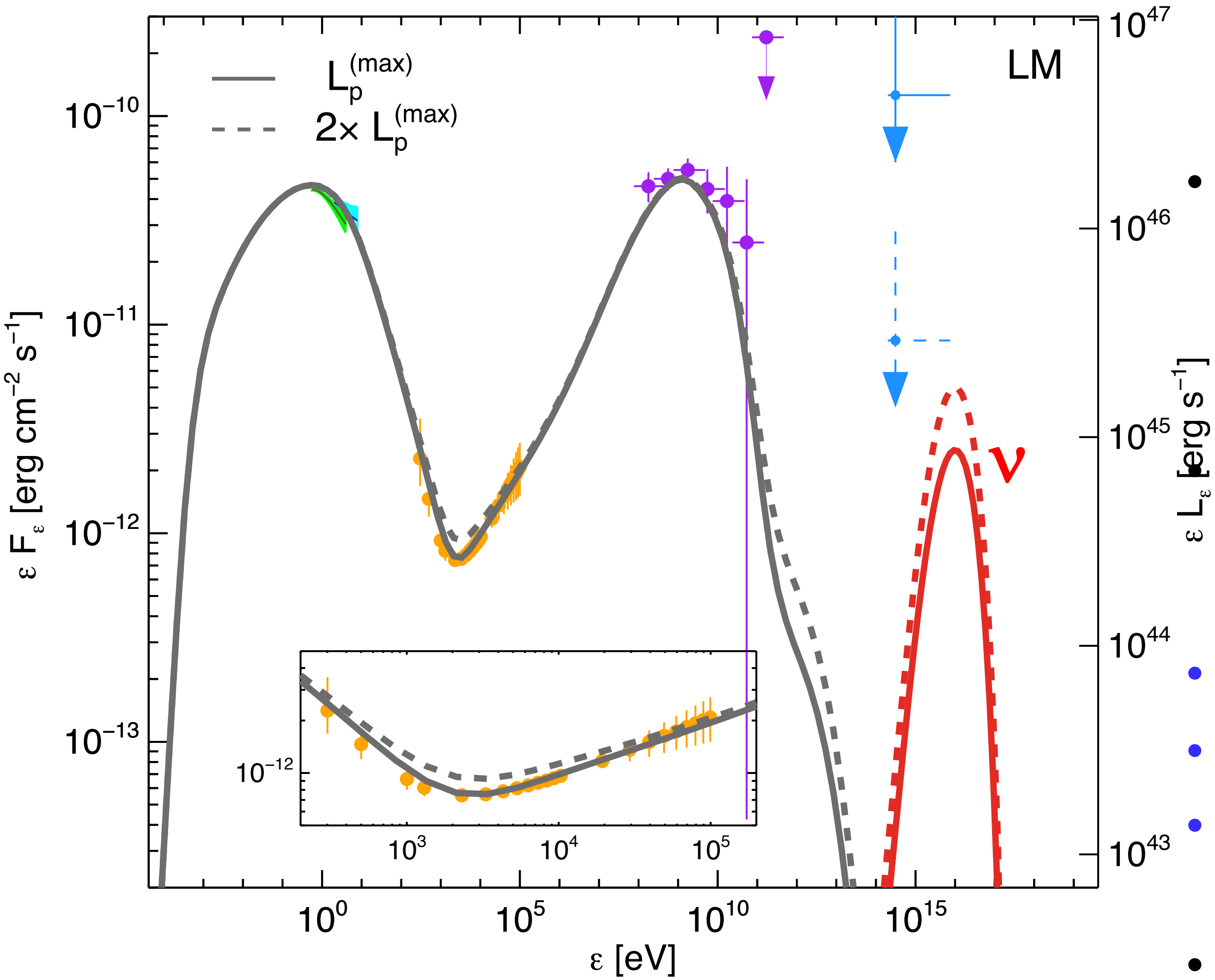
Keivani, KM, Petropoulou, Fox et al. 2018 ApJ



- Swift-UVOT/X-Shooter, Swift-XRT/NuSTAR Fermi-LAT data
- UVOT/X-Shooter ν_{syn}<3x10^{14} Hz: ISP/LSP
- 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
- IC-170922A event CANNOT be explained by the hadronic scenario

TXS 0506+056 SED Modeling: Leptonic

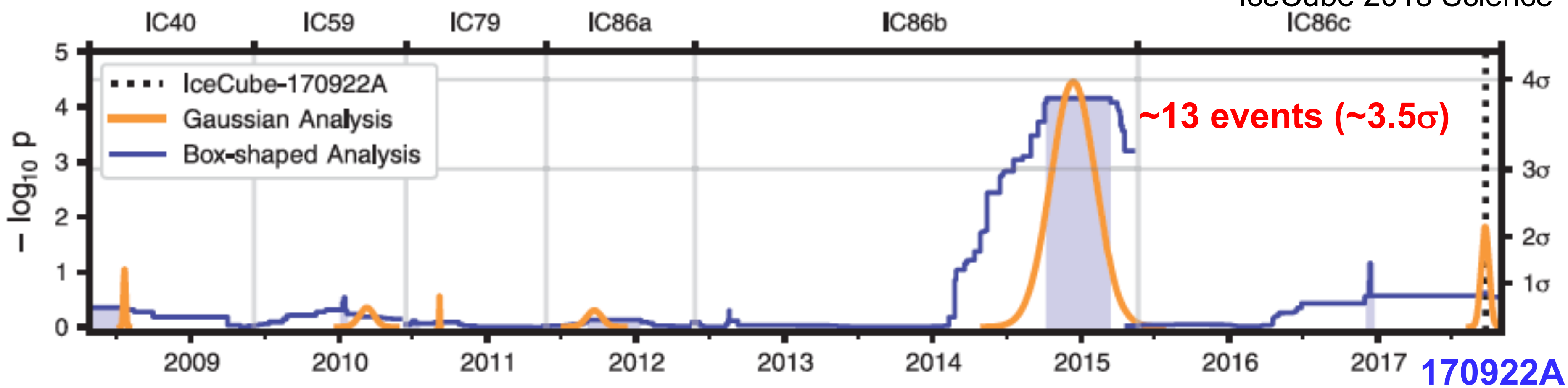
Keivani, KM, Petropoulou, Fox et al. 2018 ApJ



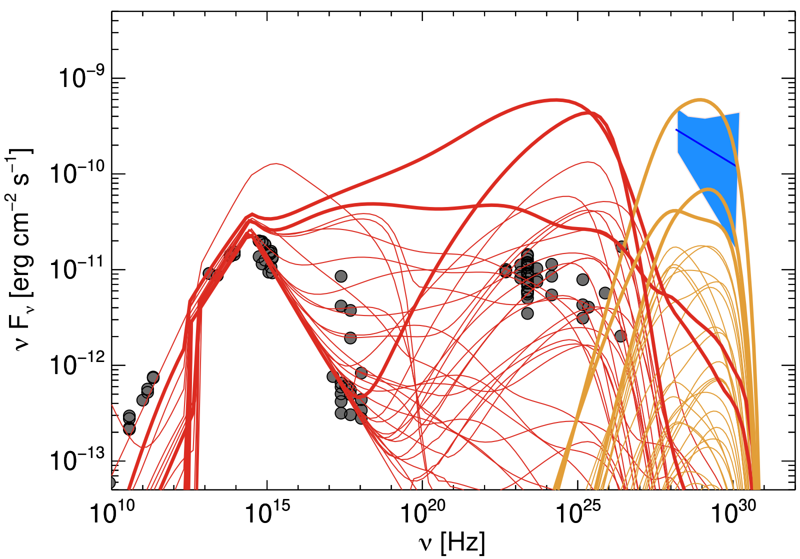
- Swift-UVOT/X-Shooter, Swift-XRT/NuSTAR Fermi-LAT data
- UVOT/X-Shooter $\nu_{syn}<3\times10^{14}$ Hz: ISP/LSP
- Leptonic scenario γ = external IC emission
- $F_\nu < (1\text{-}2)\times10^{-12}$ erg/cm²/s
- $\varepsilon_p/\varepsilon_e > 300$
- $E_{max} < 0.3$ Z EeV
- N_ν~0.02/yr (real-time) N_ν~0.2/yr (point-source)

2014-2015 Neutrino Flare

IceCube 2018 Science



Single-zone models predict **F_x~10^{-10} erg/cm²/s** **by cascades**
(violating Swift-BAT limit)



Petropoulou, KM+ in prep.

KM, Oikinomou & Petropoulou 18 ApJ

confirmed by numerical studies:

Rodrigues et al. 18

Reimer et al. 18

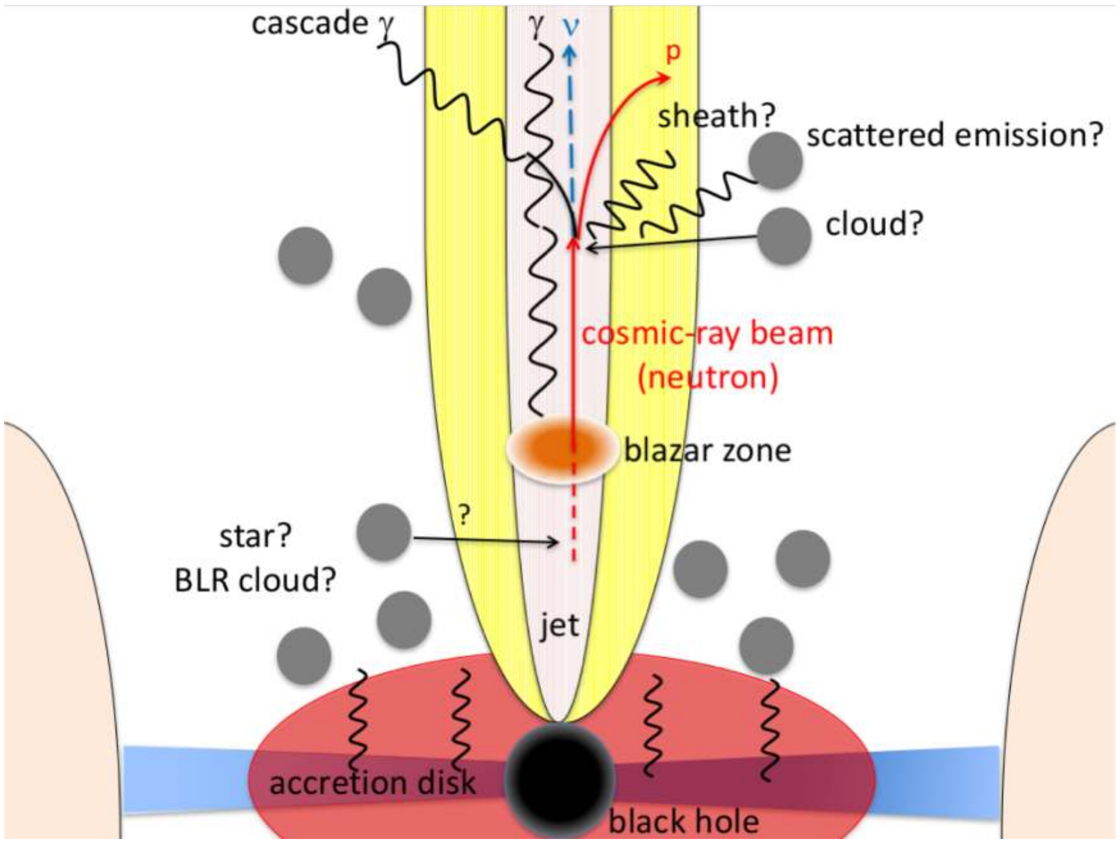
Petropoulou, KM et al. in prep.

No simple picture

Multi-Zone Picture?

Problems

- Severe X-ray constraints on the maximum neutrino flux
- Severe CR power requirement for low ν production efficiency



Relaxing X-ray suppression?

1. Anisotropic cascades
   (isotropization & time delay)
2. Avoiding Bethe-Heitler
   (for neutron beams)
3. Scattering ($N_H > 10^{25}$ cm^{-2})

Efficient ν production?

1. External radiation fields
2. pp interactions w. clouds

see
KM, Oikinomou & Petropoulou 18 ApJ

Need more information: X-ray/γ-ray monitoring, X-ray/γ-ray polarization

Open Questions

<u>Source physics</u>

- Gamma-ray origin: leptonic vs hadronic?
- CR acceleration process & magnetic fields?
- Jet properties (total power composition etc.)
- What can we learn about engines (jet-disk connection)?

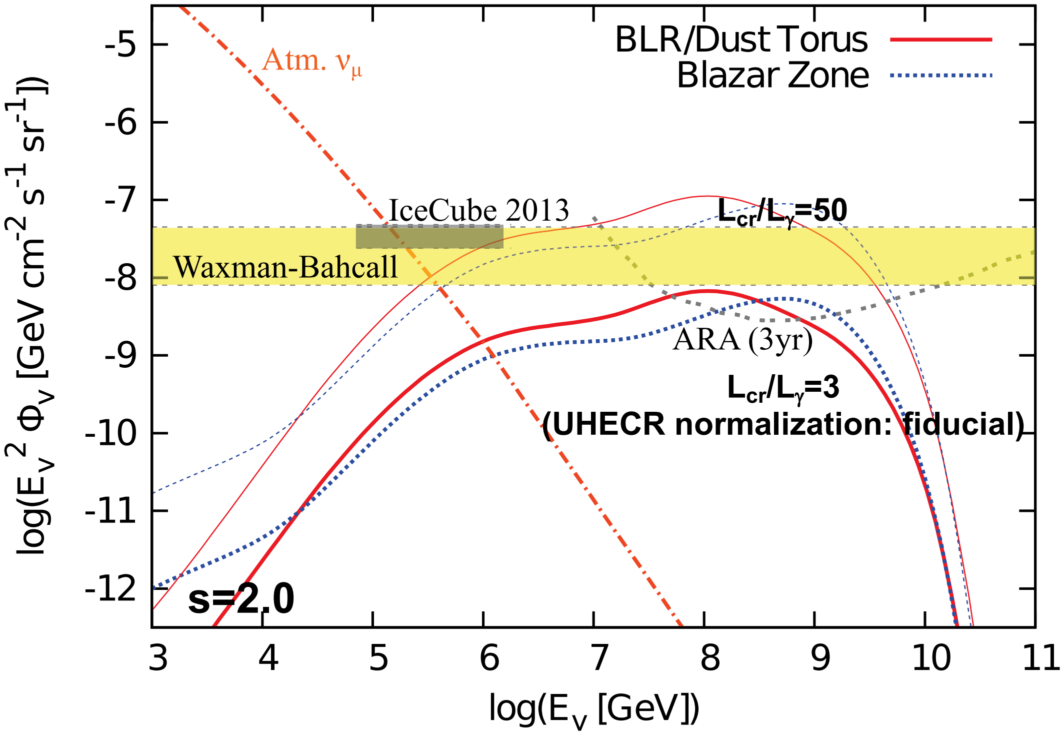
<u>Origins of extragalactic background emissions</u>

- Can AGN jets be the dominant origin of UHECRs?
- Can be blazars be the dominant origin of HE neutrinos?
- Interplay of BL Lacs, FSRQs, FR I galaxies & FR galaxies etc.?

Blazars as Powerful EeV ν Sources

Blazar (radio galaxy) = BL Lacs (FR-I) + FSRQs (FR-II)

- FSRQs: efficient ν production, dominant in the neutrino sky
- BL Lacs: inefficient ν production, dominant in the UHECR sky as FR-I



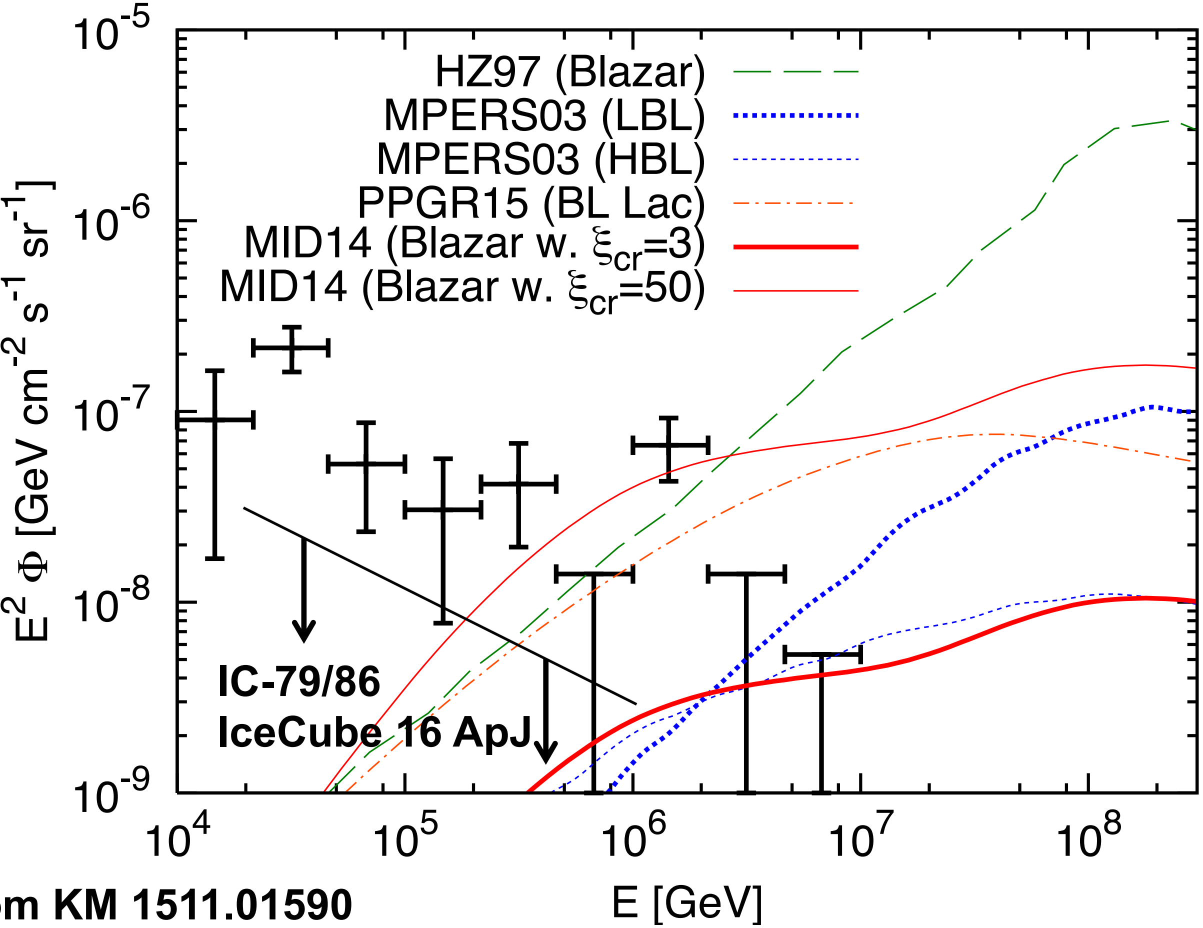
KM, Inoue & Dermer 14 PRD

- Unique ν spectrum: PeV ν by BLR photons & EeV ν by dust IR photons
- Only bright FSRQs are dominant -> promising source identification
- Consistent w. IceCube (1-10% at PeV), UHECRs are isotropized at kpc-Mpc

HE Neutrinos from AGN Jets: Constraints

Standard simplest jet models as UHECR accelerators: many constraints…

- Blazars: power-law CR spectra & known SEDs→ hard spectral shape



leptonic w, neutrino norm, BL Lacs + FSRQs

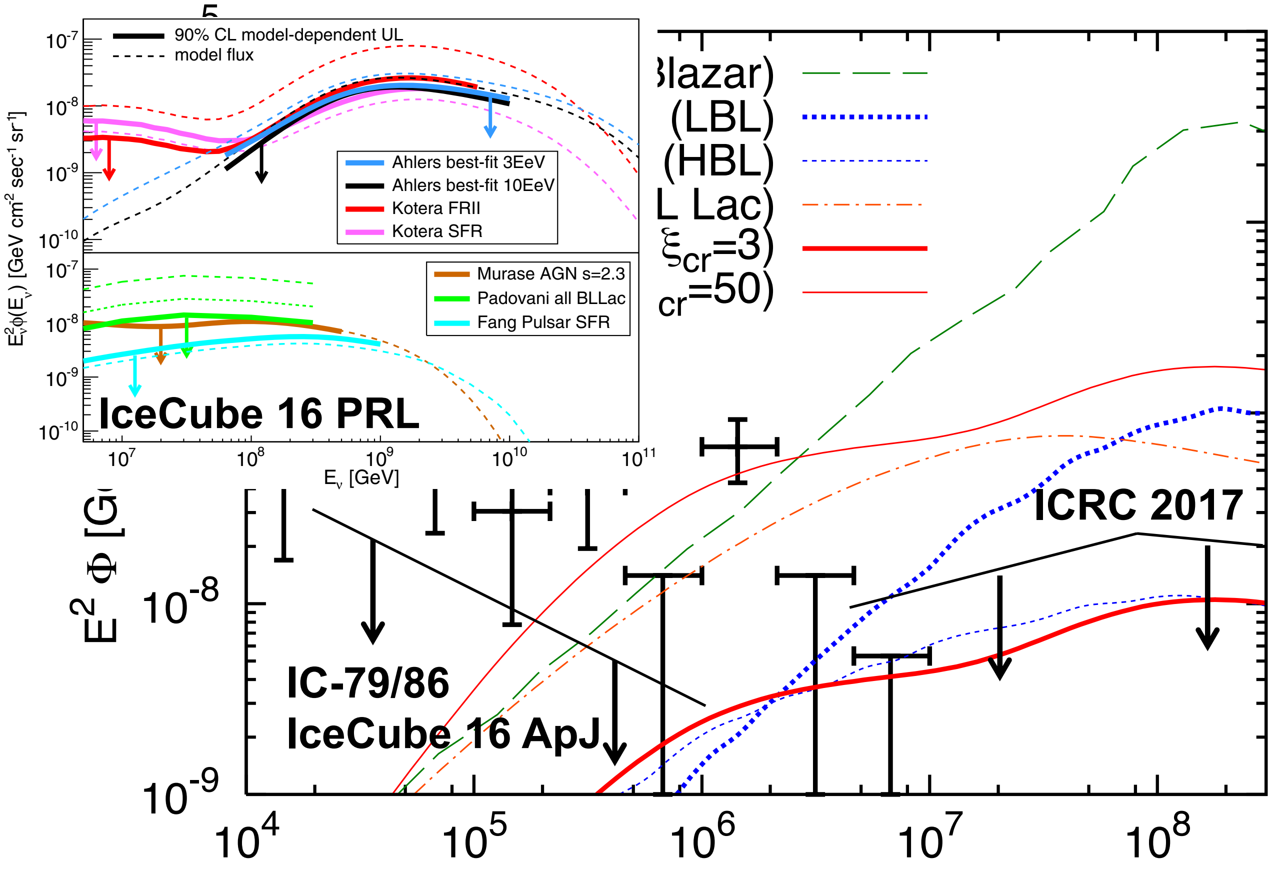
lepto-hadronic w. γ-ray norm. BL Lacs (w.o. external fields)

leptonic w. UHECR norm. BL Lacs + FSRQs

from KM 1511.01590

HE Neutrinos from AGN Jets: Constraints

Standard simplest jet models as UHECR accelerators: many constraints…
- Blazars: power-law CR spectra & known SEDs→ hard spectral shape
  IceCube 9-yr EHE analyses give a limit of $<10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} at 10 PeV



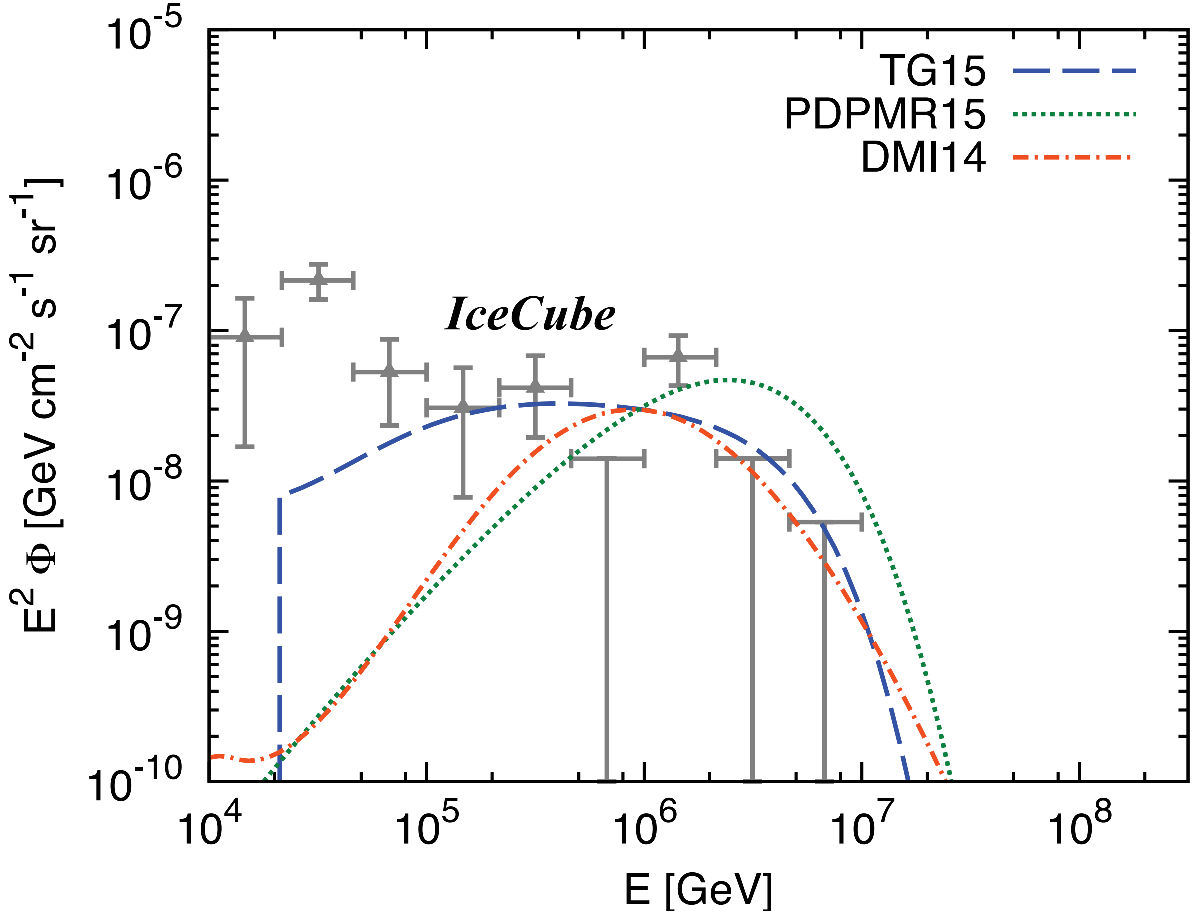
leptonic w, neutrino norm,
BL Lacs + FSRQs

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

leptonic w. UHECR norm.
BL Lacs + FSRQs
(This model is still OK!)

from KM 1511.01590

Can Blazars Explain the IceCube Data?



BL Lac – two-zone
BL Lac – one-zone
FSRQ – external field

KM & Waxman 16 PRD

- Cutoff or steepening around a few PeV (ex. stochastic acceleration) But the models give up the simultaneous explanation of UHECRs
- Neutrino data at <~100 TeV are not explained by proposed models and there are constraints from stacking and clustering analyses

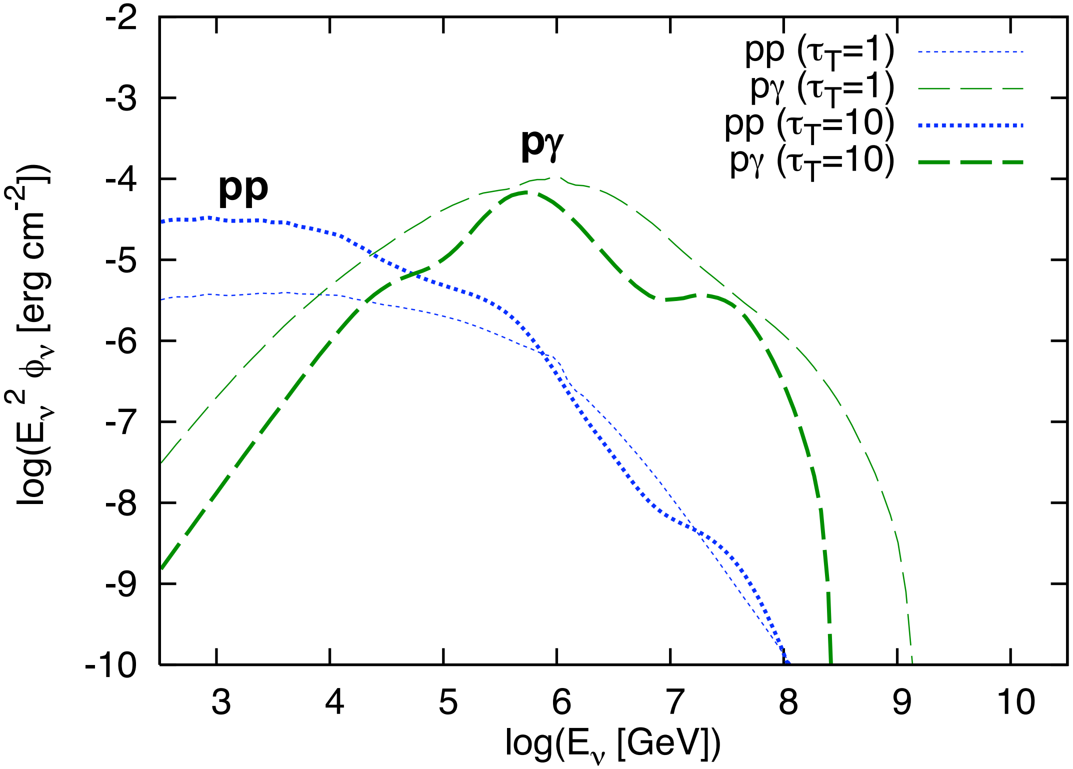
Subphotospheric GRB Emission

Non-Thermal Photospheric Neutrinos

- **Dissipative baryonic photosphere** (e.g., Rees & Meszaros 05 ApJ)

$\tau_T = n_e \sigma_T (r/\Gamma) \sim 1\text{-}10 \Leftrightarrow f_{pp} = (\kappa_{pp}\sigma_{pp}/\sigma_T)\tau_T \sim 0.05\text{-}0.5$

collisionless shocks require $\tau_T < 1\text{-}10 \rightarrow f_{p\gamma} > f_{pp}$



τ_T=1-10 (r ~ 10^{12}-$10^{12.5}$ cm)
$\Gamma = 10^{2.5}$, $U_e = U_B$

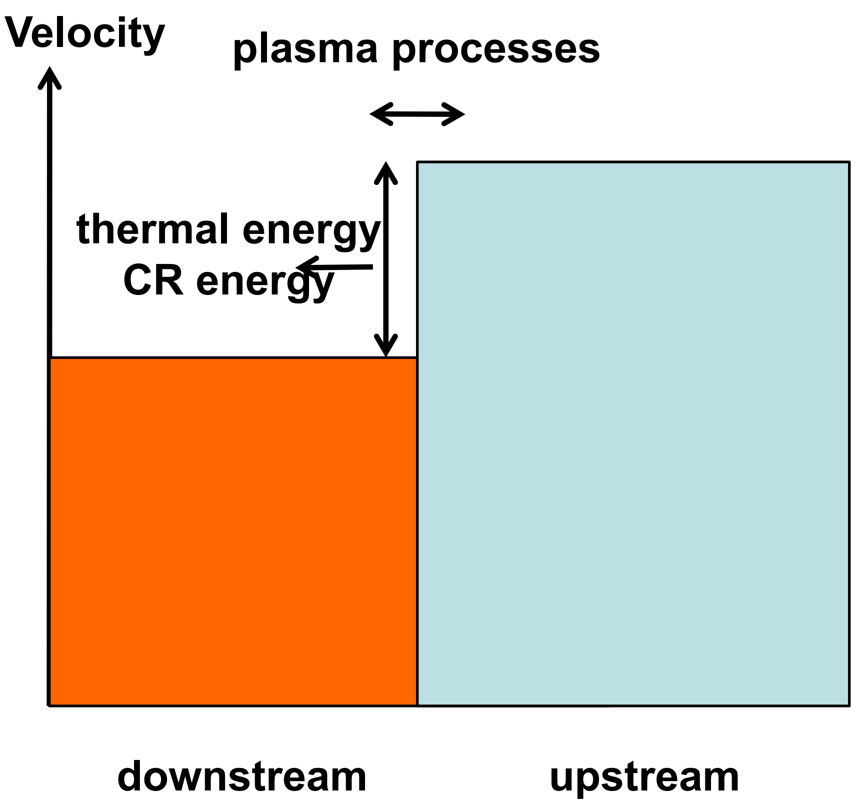
If $E_{CR}^{iso} \sim E_\gamma^{iso} \sim 10^{53.5}$ erg
→ # of μs ~ 1-2 for GRB @z=0.1

KM, PRD(R), 78, 101302 (2008)

$f_{p\gamma} > 1$ (calorimetric) & UHECR acceleration is not necessary

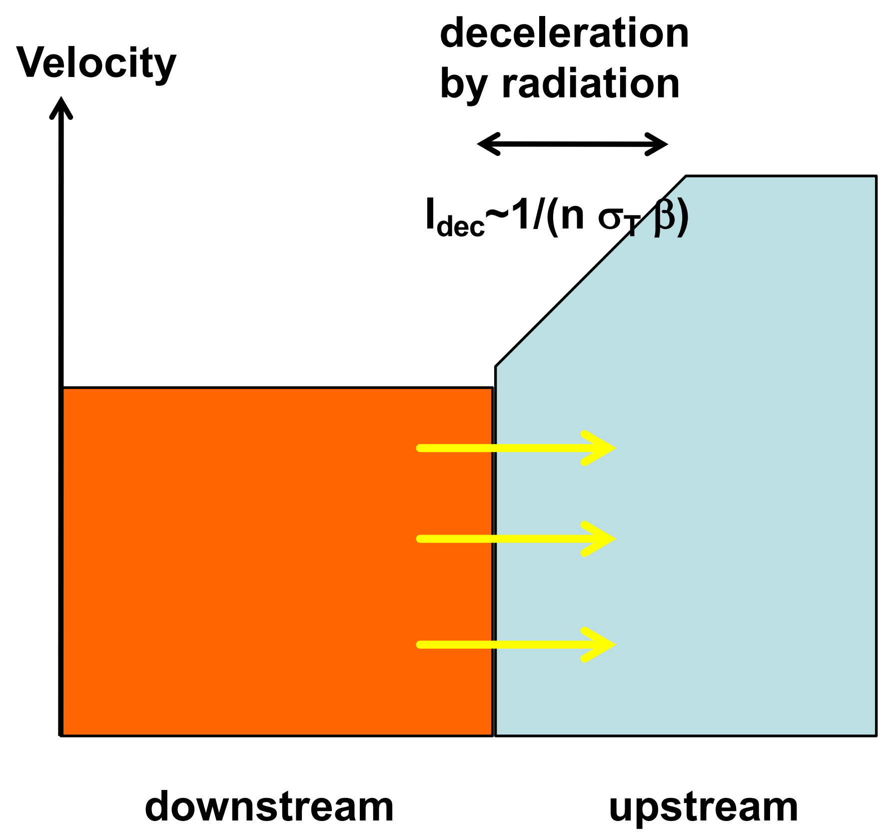
Limitation of Shock Acceleration

Collisionless shock



(m.f.p.) ~ $r_L(\varepsilon_p)$ > (shock width)

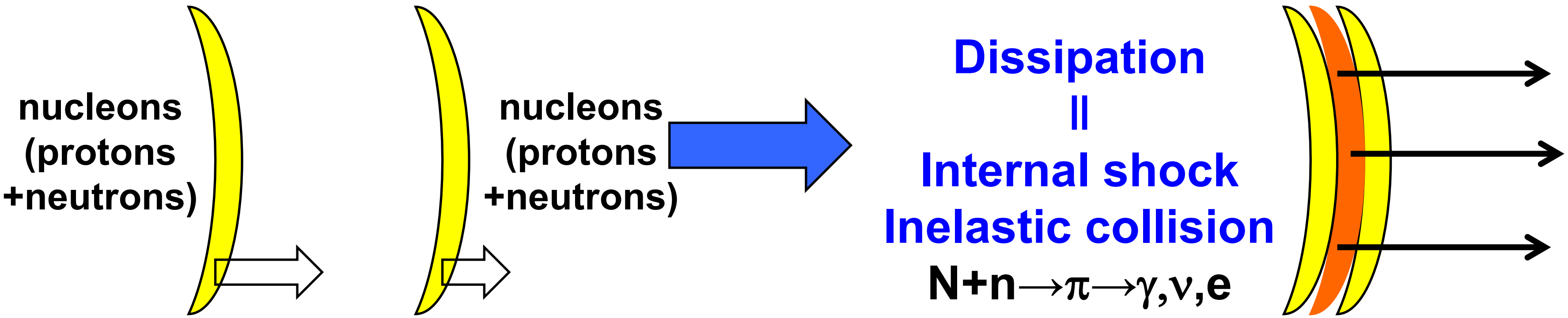
Radiation-mediated shock



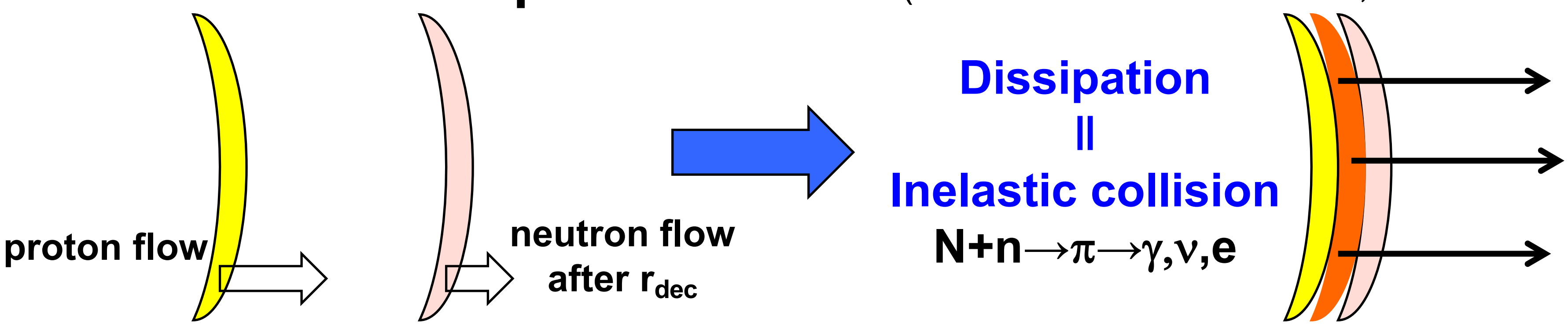
(m.f.p.) ~ $r_L(\varepsilon_p)$ < (shock width)

Neutrinos Probe Dissipation Mechanisms

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

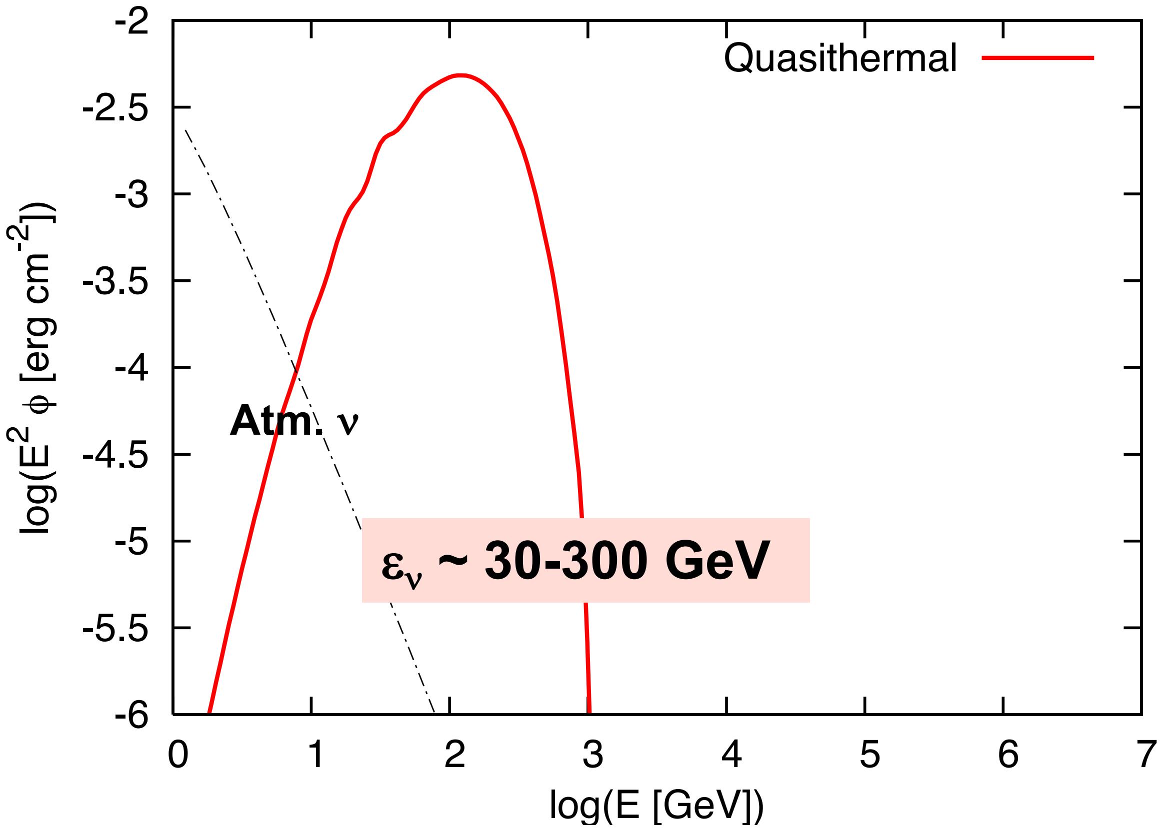


Collision w. decoupled neutrons (ex. Bahcall & Meszaros 00, Beloborodov 10)



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



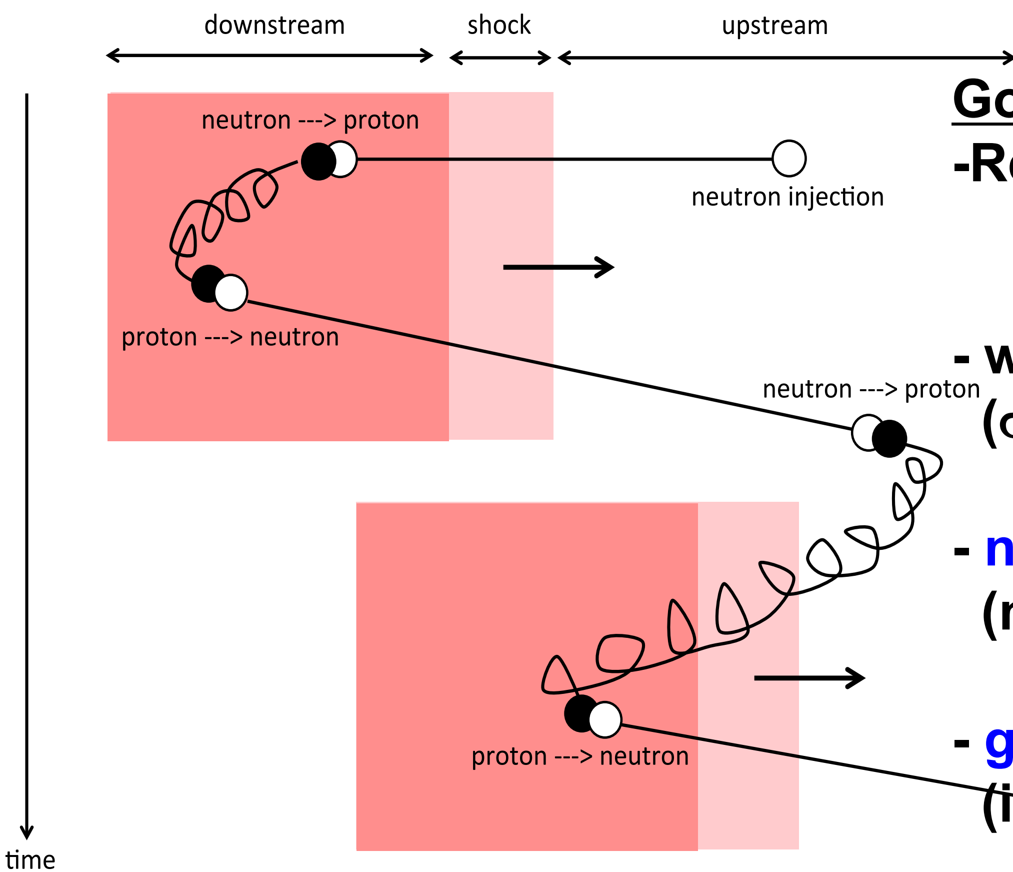
$E_k^{iso}/E_\gamma^{iso}=4$
$E_\gamma^{iso}=10^{53.5}$ erg
$\Gamma=600$, $z=0.1$

KM, Kashiyama & Meszaros 13 PRL

Novel Acceleration Process in Neutron-Loaded Jets

"Neutron-Proton-Converter Acceleration" (Derishev+ 03 PRD)

another Fermi acceleration mechanism without diffusion



Good news

-Relevance in GRB jets inside stars

(KM, Kashiyama & Meszaros 13 PRL)

- works even if radiation mediated ($\sigma_{np} < \sigma_T$)

- naturally injected (neutron m.f.p. > shock width)

- guaranteed for n-loaded flows (insensitive to plasma physics)

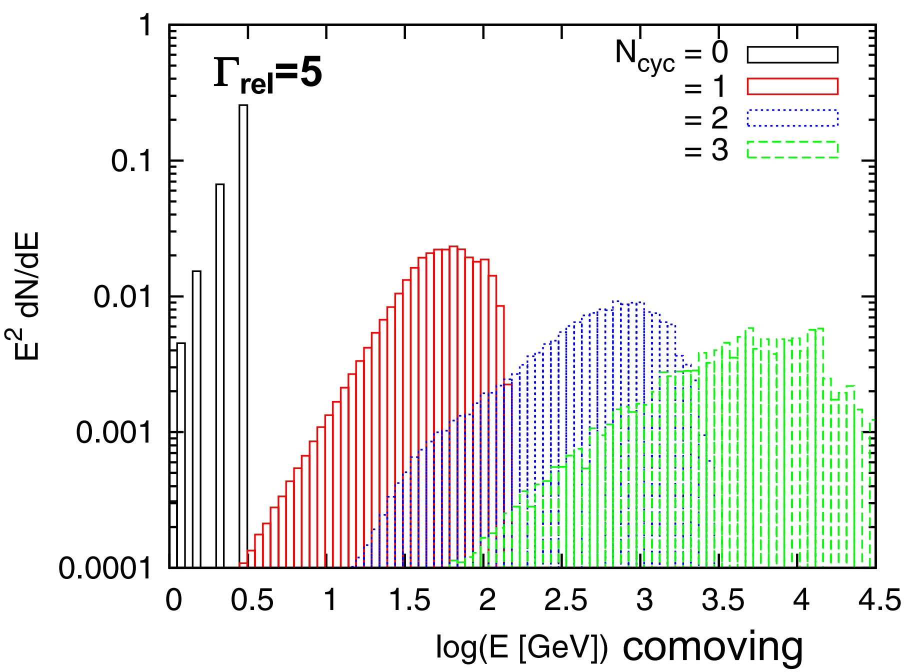
- slow process → TeV ν

NPC Acceleration: Spectra & Effects

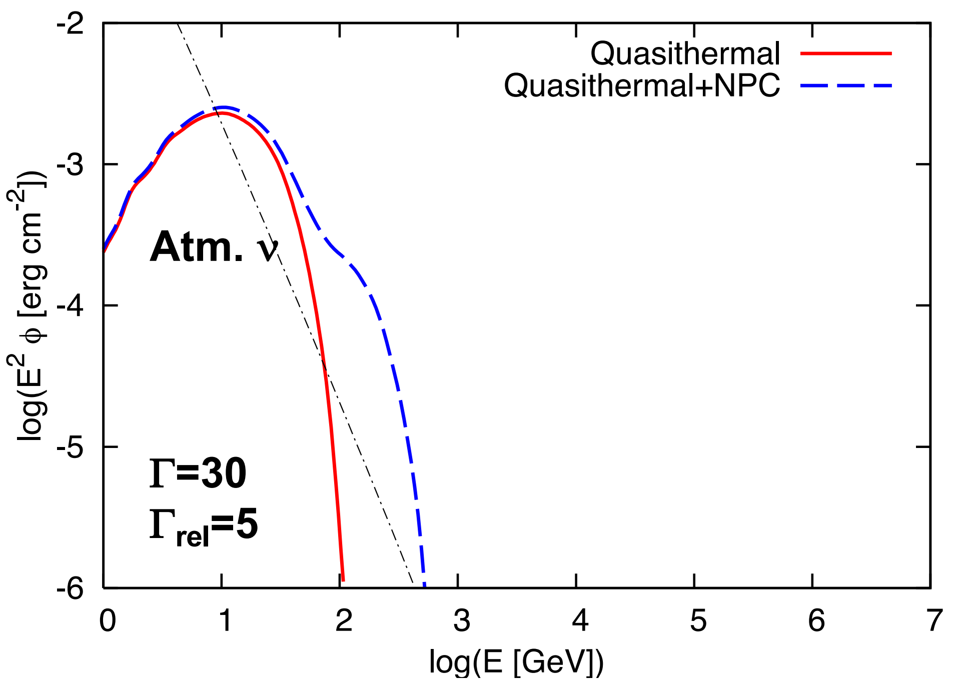
We first performed Monte Carlo simulations for test particles

- Nucleon spectra consisting of bumps rather than a power law
- >10% of incoming neutron energy can be used for NPC acc.
- Enhancement of the detectability of GeV-TeV neutrinos

Kashiyama, KM & Meszaros 13 PRL



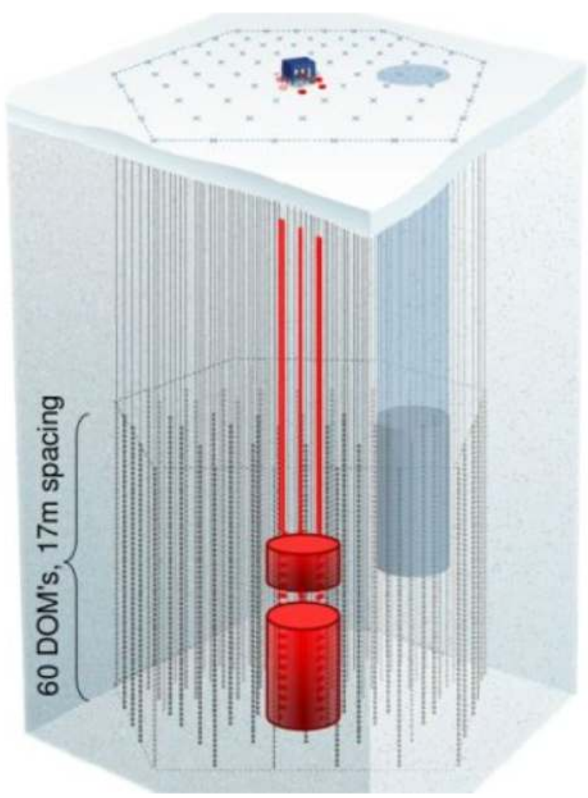
nucleon spectra w.o. cooling

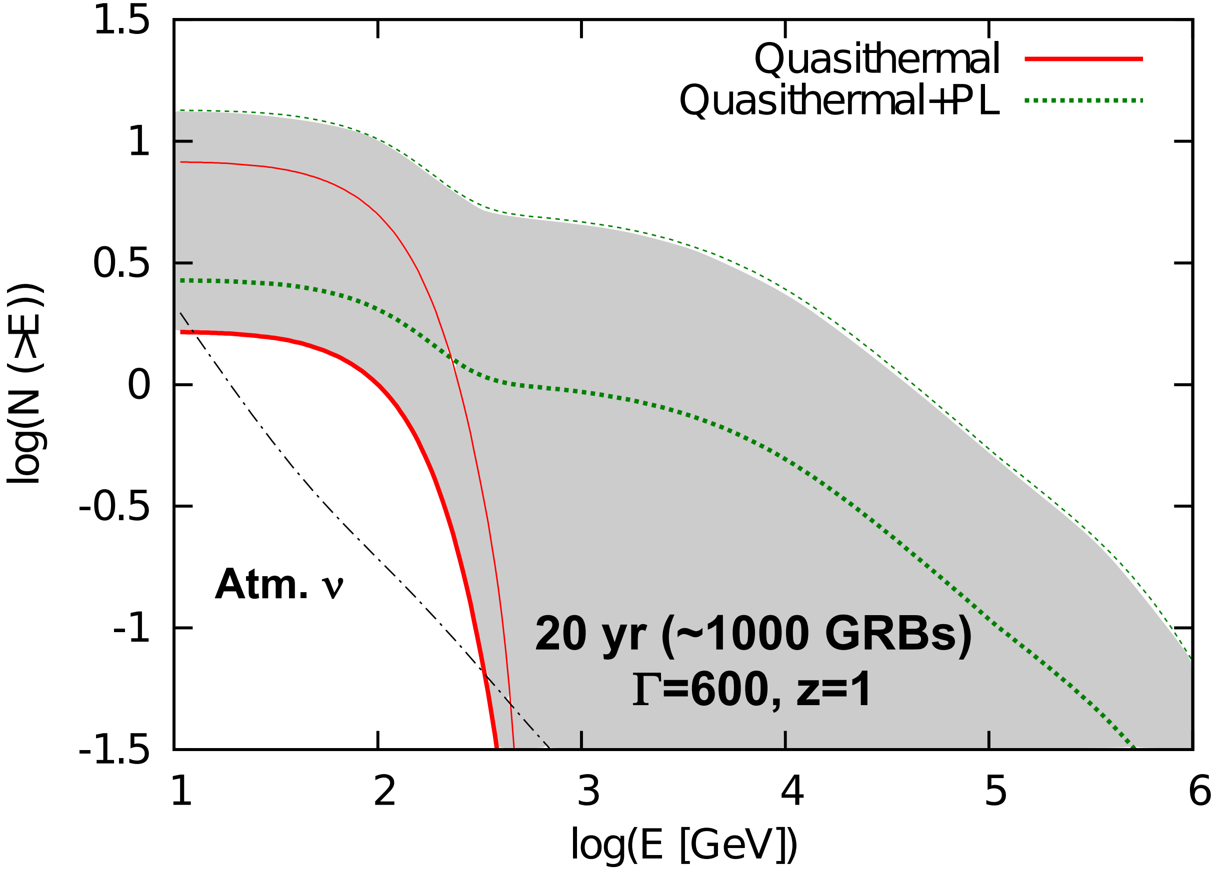


neutrino spectra

Prospects for DeepCore+IceCube

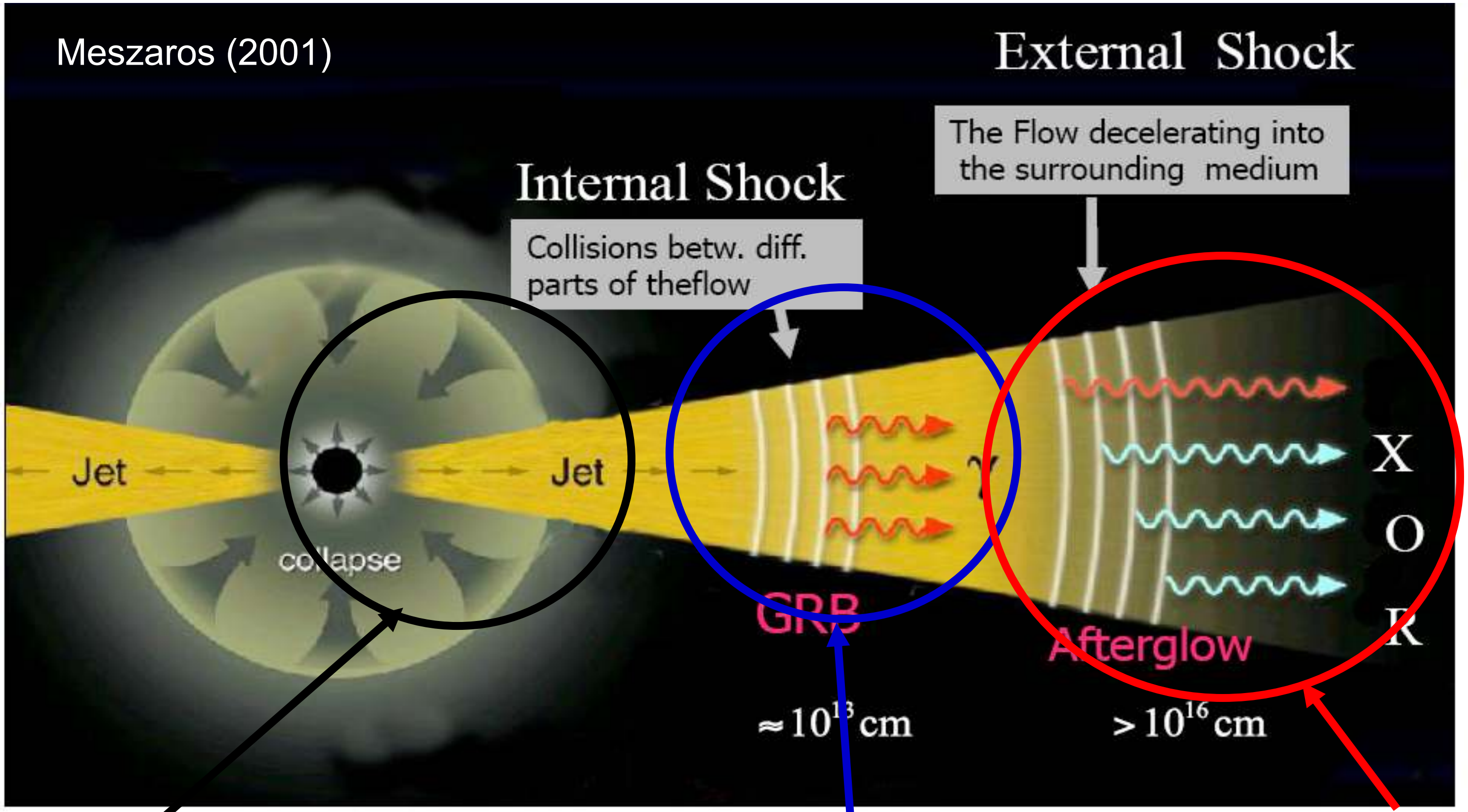
- Including DeepCore is essential at 10-100 GeV
- Reducing atmospheric ν background is essential
  → select only bright GRBs w. > 10^{-6} erg cm^{-2}





KM, Kashiyama & Meszaros 13 PRL

Possible Neutrino Production Sites



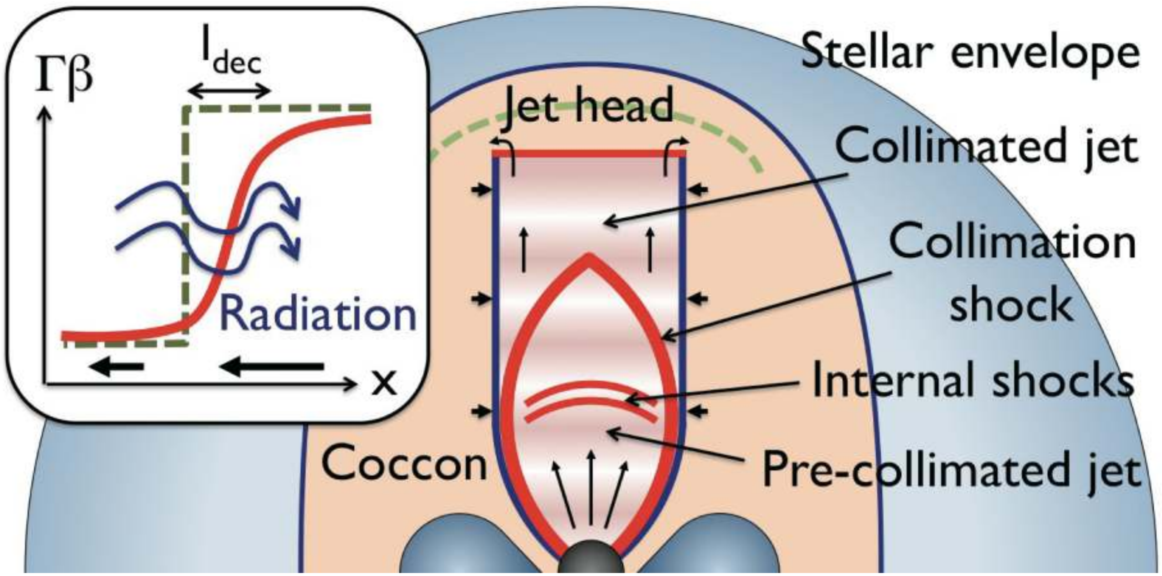
Inner jet inside a star
$r < 10^{12}$ cm, $B > 10^6$ G
TeV-PeV ν, no γ
Meszaros & Waxman 01 PRL
Razzaque et al. 03 PRL
KM & Ioka 13 PRL

Inner jet (prompt/flare)
$r \sim 10^{12}$-10^{16} cm $B \sim 10^{2\text{-}6}$ G
PeV ν, GeV-TeV γ
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
EeV ν, GeV-TeV γ
e.g., Waxman & Bahcall 00 ApJ
Dermer 02 ApJ
KM 07 PRD

Realistic Picture

Two pieces of important physics were overlooked

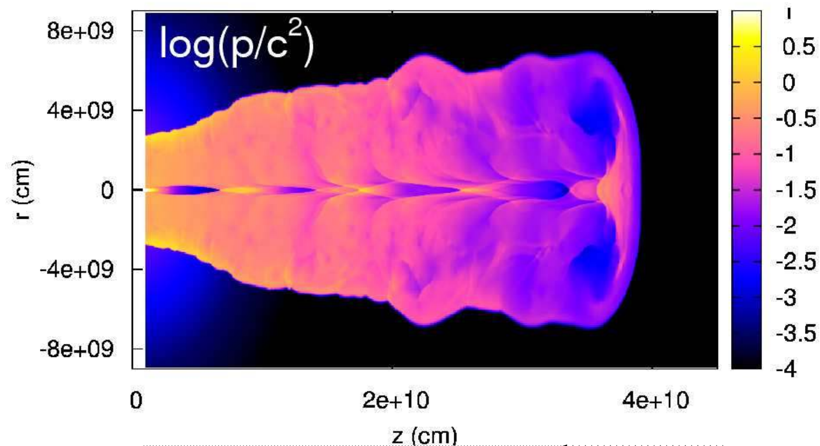


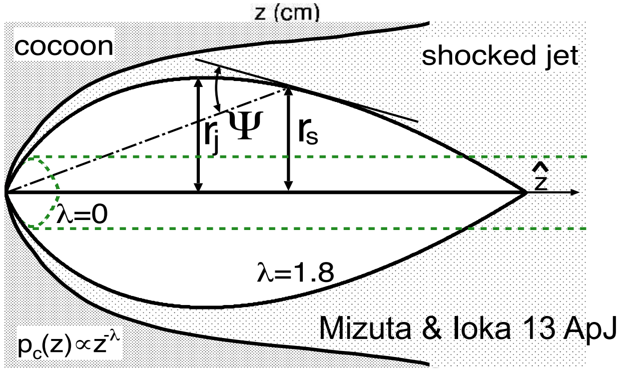
KM & Ioka 13 PRL

1. Ballistic jets inside stars
   → collimation shock & collimated jet
2. CR acceleration at collisionless shocks
   → inefficient at radiation-mediated shocks

Jet Propagation inside a Star

- Jet propagation has been understood (cannot be ignored) controlled by luminosity, duration, opening angle, and ρ(r)





1. ram pressure balance at jet head
2. cocoon dynamics
3. collimation shocks

(Bromberg+ 11 ApJ, Mizuta & Ioka 13 ApJ)

jet head radius

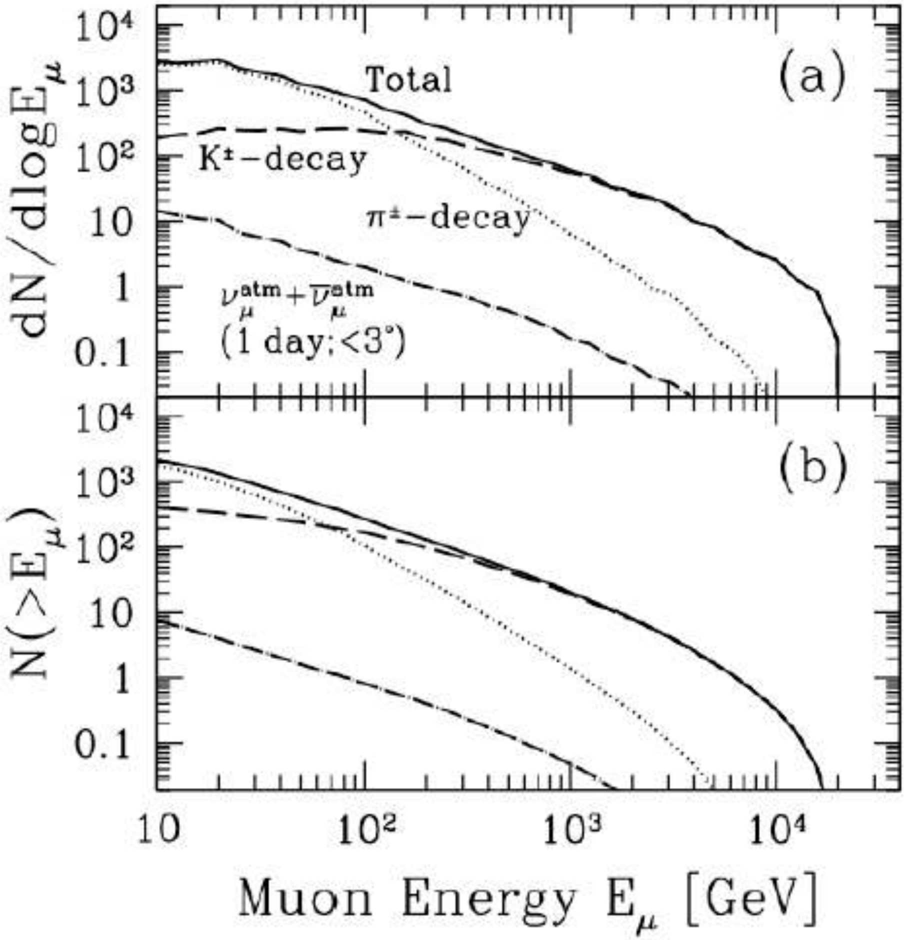
$$r_h \approx 8.0 \times 10^9\ \mathrm{cm}\ t^{3/5} L_{j0,52}^{1/5} (\theta_j/0.2)^{-4/5} \varrho_{a,4}^{-1/5}$$

cf. uncollimated shock

$$r_h \approx 2\Gamma_h^2 ct \simeq 2.3 \times 10^{13}\ \mathrm{cm} L_{0,52}^{1/2} \rho_{\mathrm{ext}}^{-1/2} r_{\mathrm{ext},13.5}^{-1} t_{1.5}$$

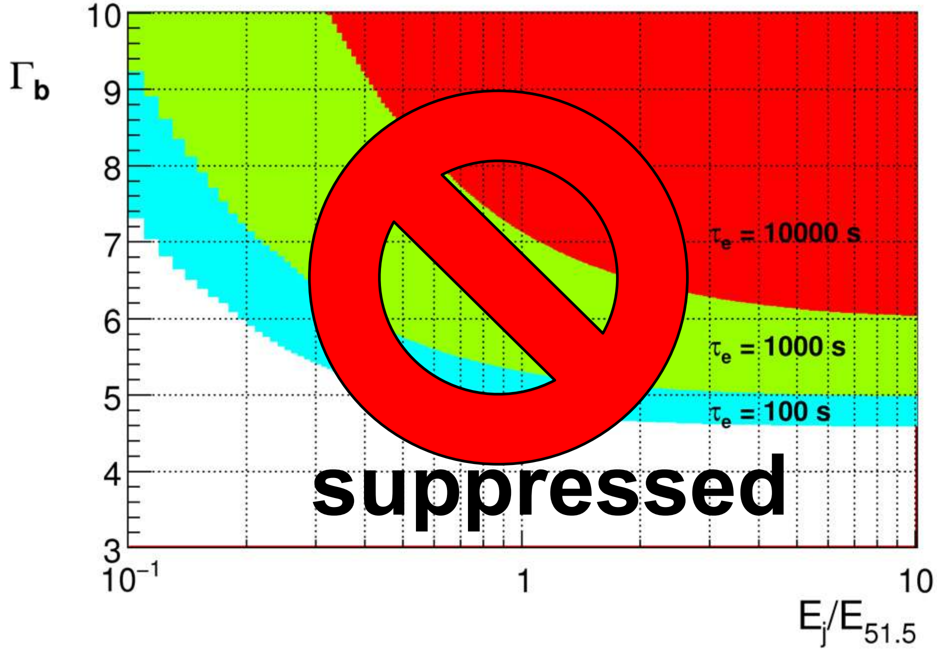
- Collimation is crucial for jets propagating in high-density environments
- **Must be taken into account for neutrino emission from choked jets**
  jet-stalling condition $L < L_{JS}$: change by many order of magnitudes

SNe with Slow Jets (Failed GRBs)



Ando & Beacom 05 PRL

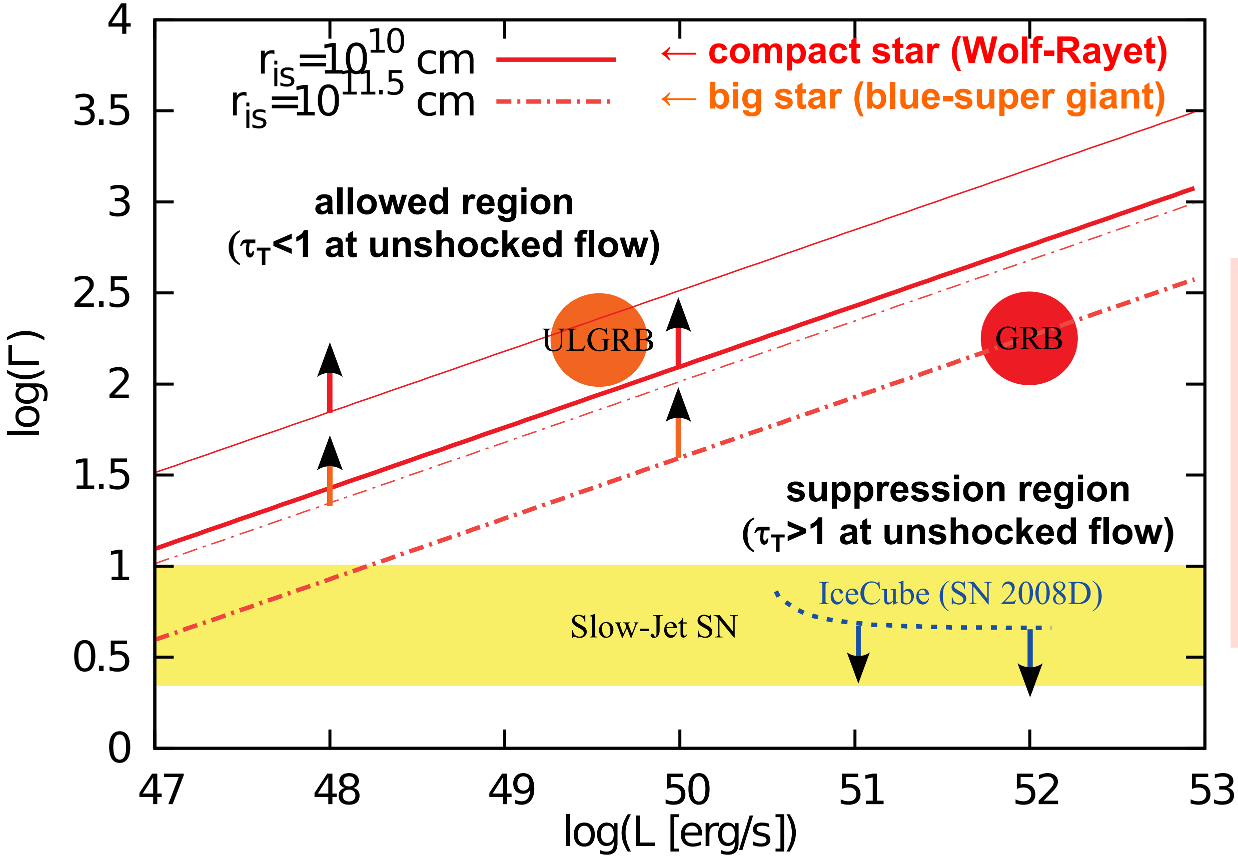
SN 2008D
constraints on Γ and E_j



IceCube 11 A&A

If CRs carry E_{CR}^{iso}~0.5x10^{53} erg (GRB)
→ # of μs ~ **0 events (due to radiation mediated shocks)**

"Radiation Constraints" on Non-thermal Neutrino Production



KM & Ioka 13 PRL

Thomson optical depth

$$\tau_T = n_e \sigma_T \Delta \propto L\Gamma^{-2}$$

L: kinetic luminosity

Γ: Jet Lorentz factor

- Lower-power is better
- Bigger progenitor is better

⇒

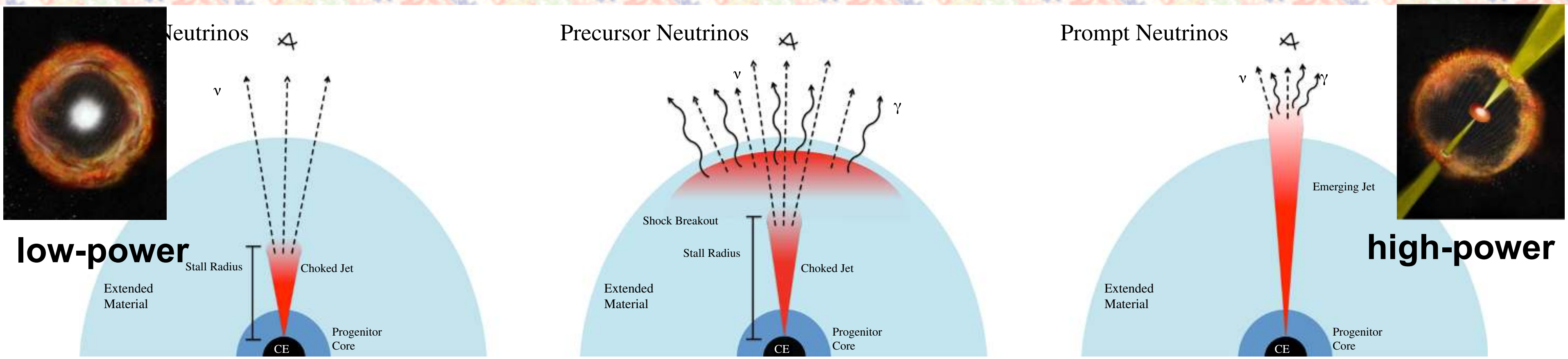
- **suppressed in typical GRBs and powerful slow-jet SNe**
- **favoring choked jets (difficulty of penetration)**

Basic Picture

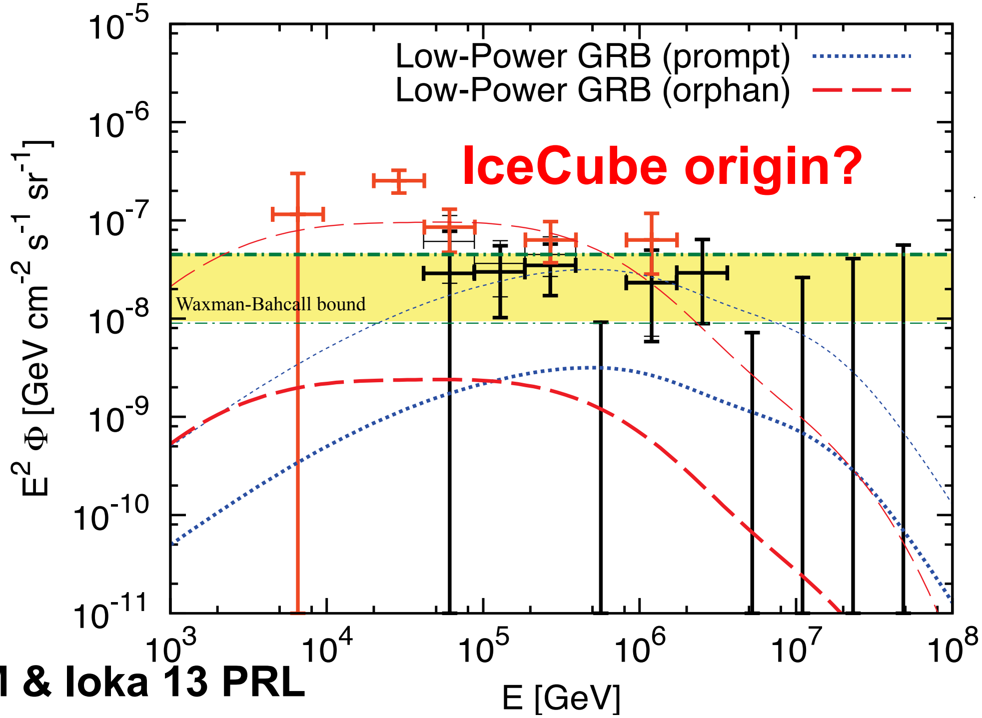
Story of high-energy neutrino production

- Internal shock scenario
  maybe CR acceleration (if collisionless)
  pγ interactions in inner jets, pp interactions are inefficient $f_{pp} \lesssim \frac{\kappa_{pp}\sigma_{pp}}{\sigma_T} \simeq 0.04$
  target photons by collimation-shocked jet (w. screening) & inner jets
  adiabatic losses during the expansion of the emission region and
  will not interact w. stellar material (hot spot and cocoon)
- Collimation shock scenario
  possible CR acceleration (if collisionless)
  pγ interactions in collimation-shocked jets
  target photons by collimation-shocked jet
  little adiabatic losses due to the collimation and
  pp interactions should occur during the advection
- Reverse shock scenario
  CR acceleration is usually difficult
- Forward shock scenario
  No CR acceleration (collisional)

Choked Jets as Hidden Neutrino Factories?

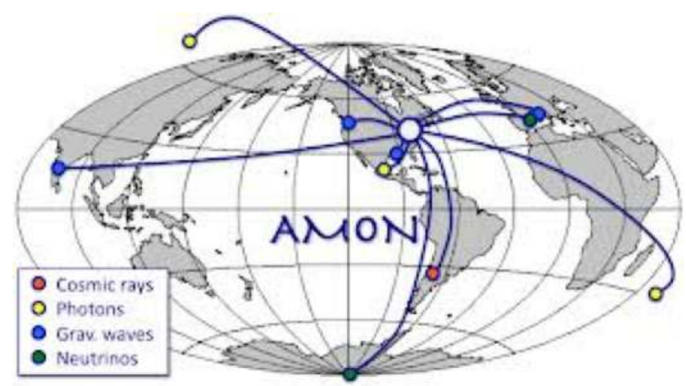


Senno, KM & Meszaros 16 PRD



KM & Ioka 13 PRL

Multi-messenger targets!




Thanks!