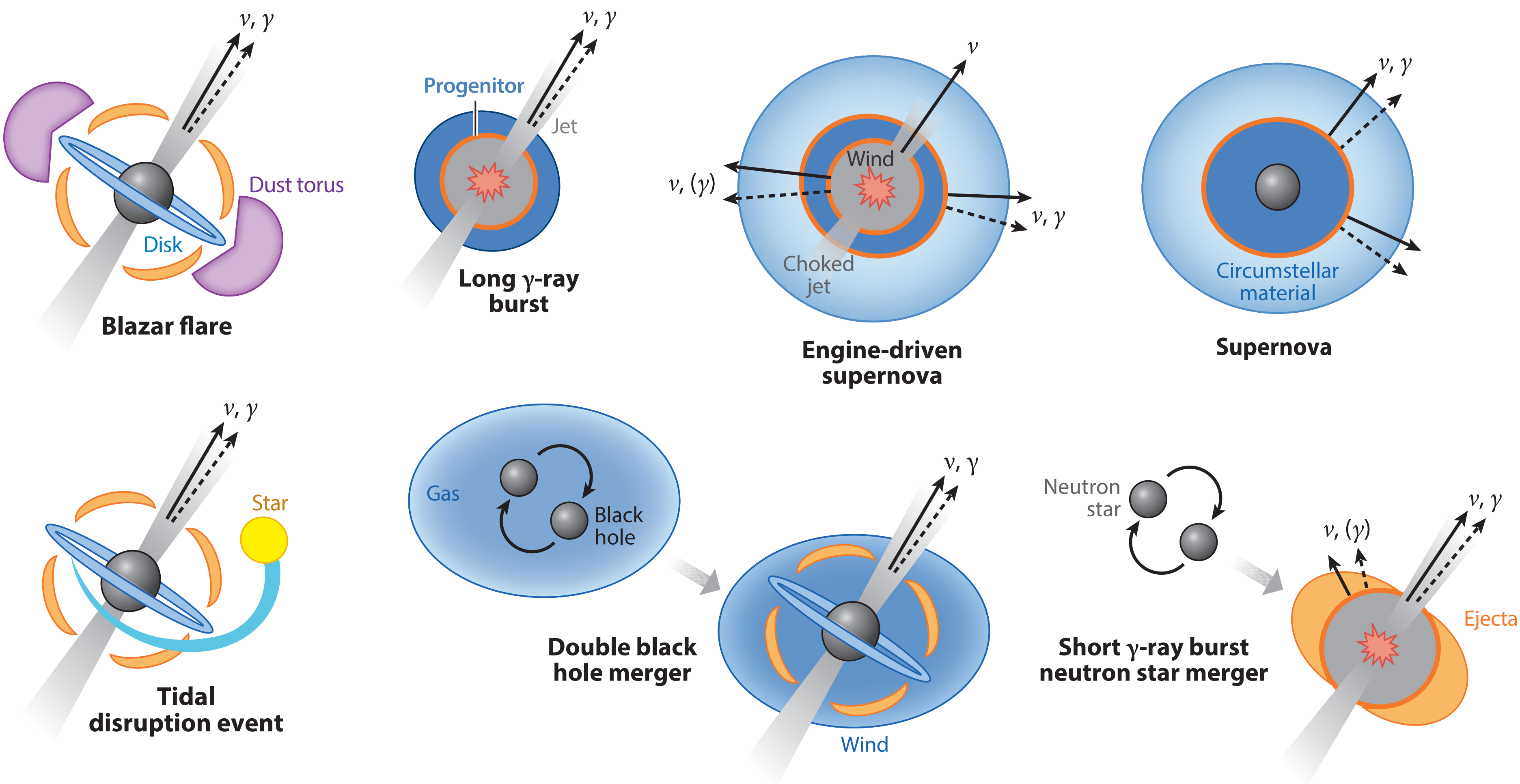
High-Energy Neutrinos from Choked Jets and Supernovae & (High-Energy Neutrinos from AGN Coronae)

Kohta Murase (Penn State)

December 17 @ Marseille

Diversity of High-Energy Transients

from KM & Bartos 19 ARNPS



Diversity of High-Energy Transients

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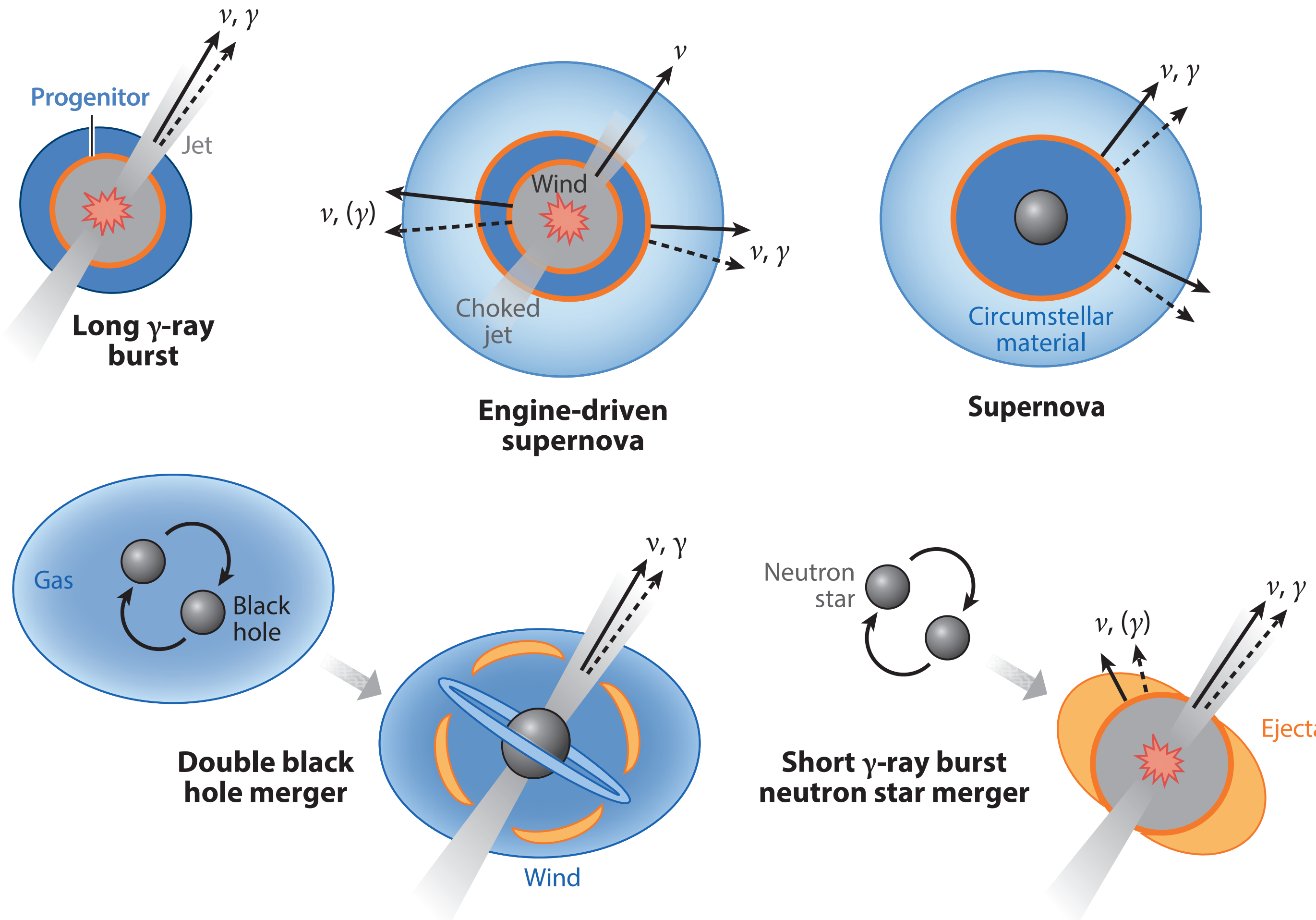

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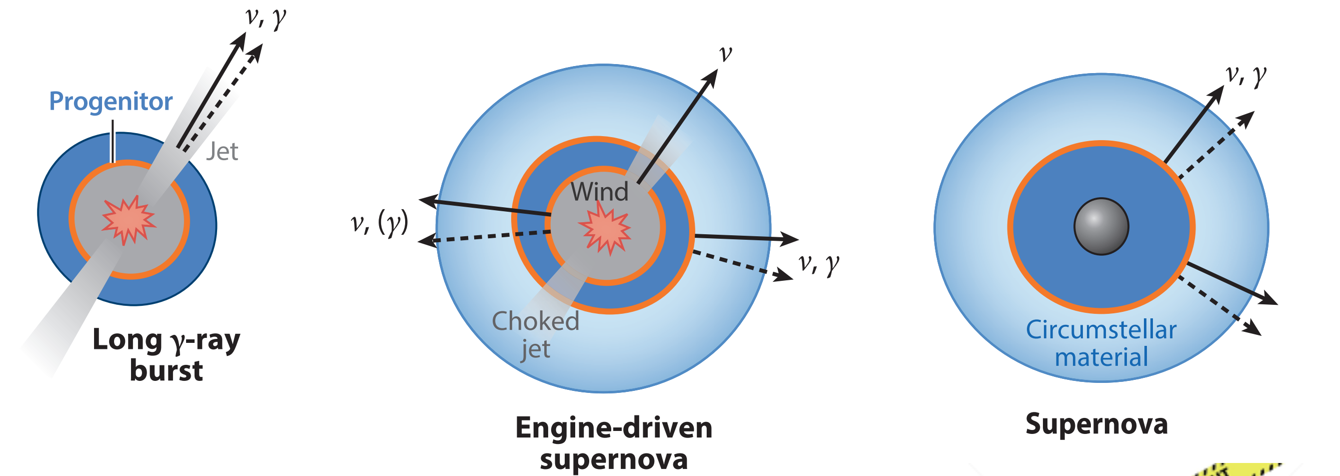
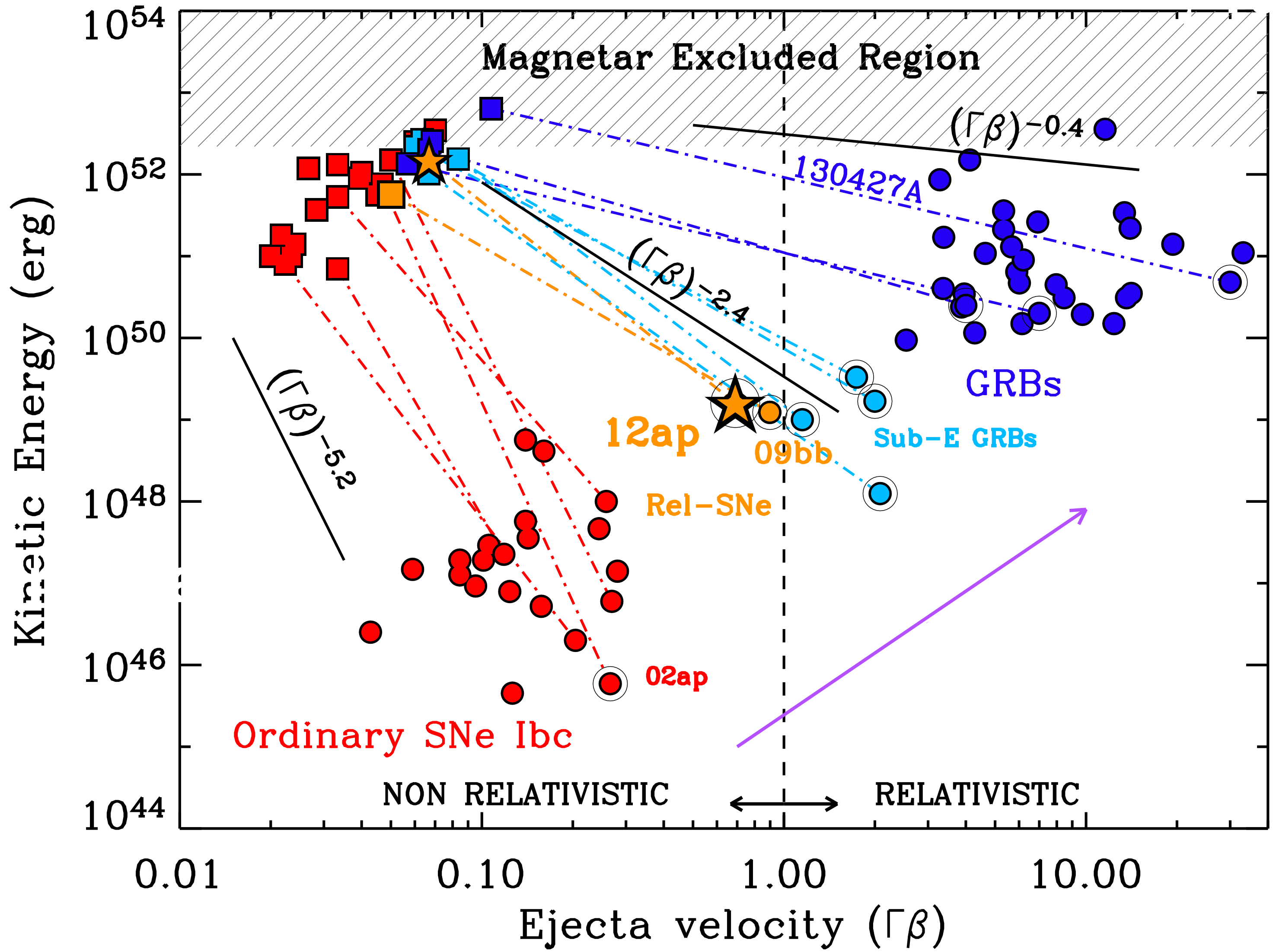


Gamma-Ray Burst-Supernova Connection

Margutti+ 14



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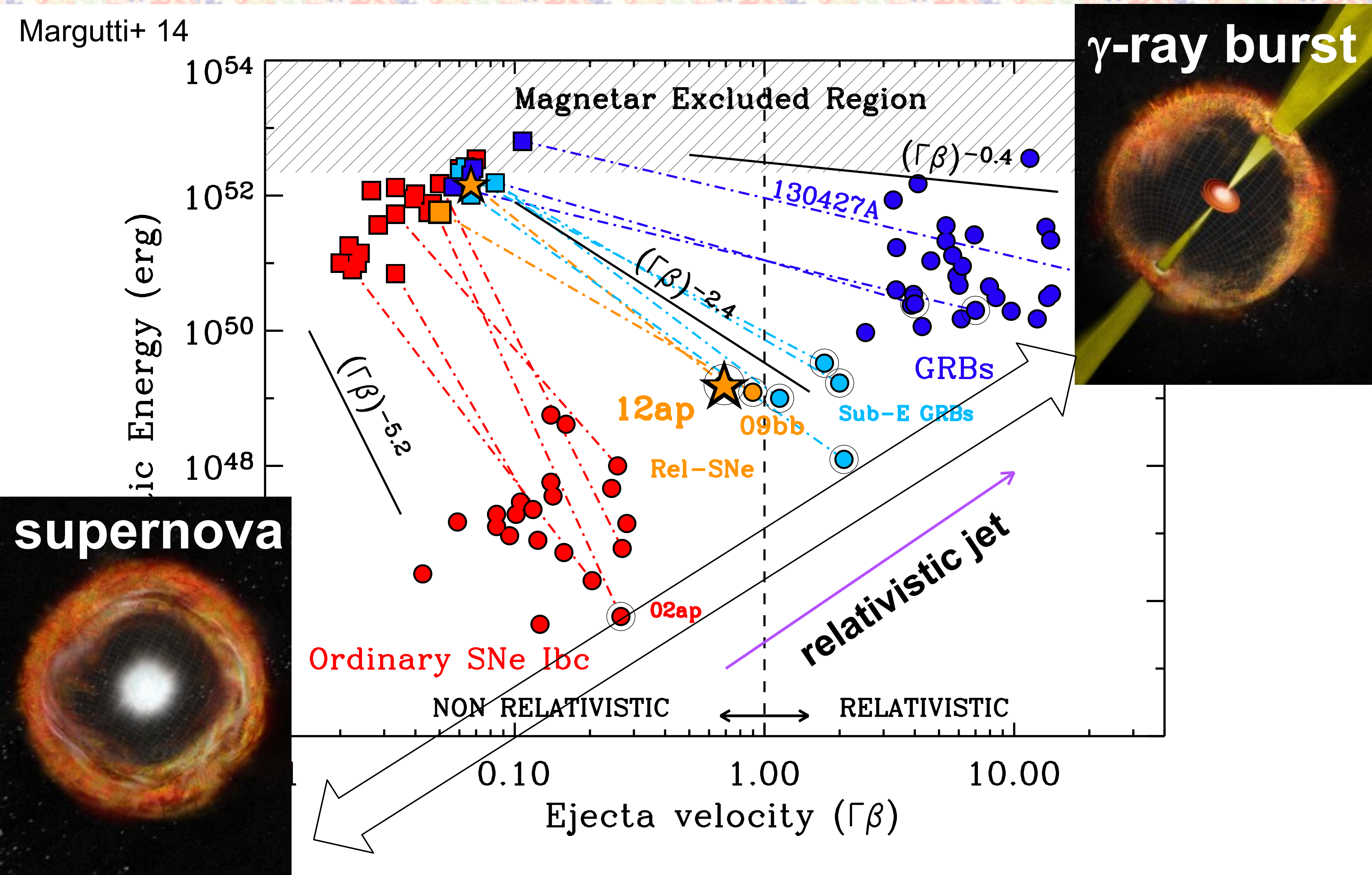
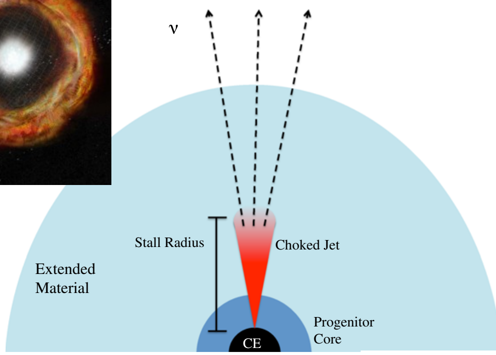
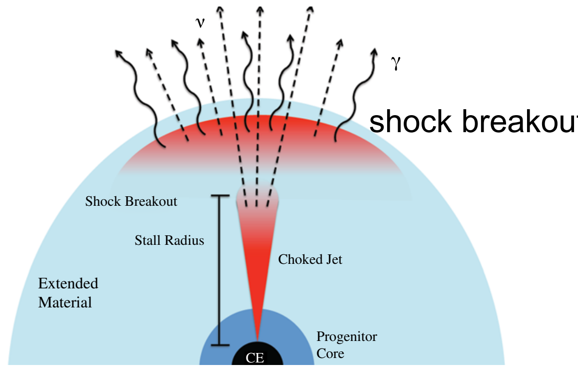


Diversity of Gamma-Ray Bursts

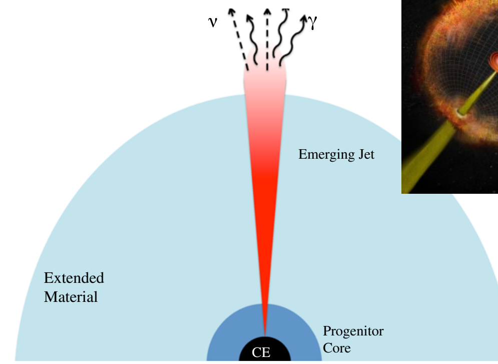
supernovae w. choked jets

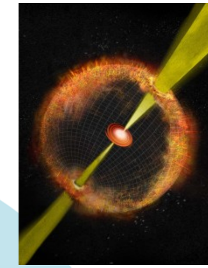


Trans-relativistic SNe w. choked/successful jets

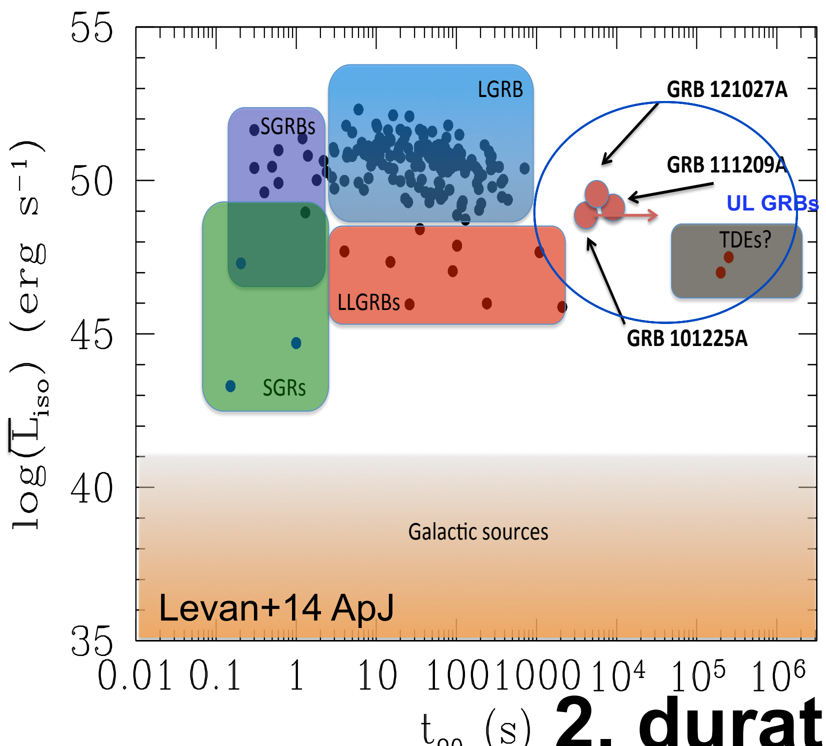


GRBs w. successful jets





from Senno, KM & Meszar

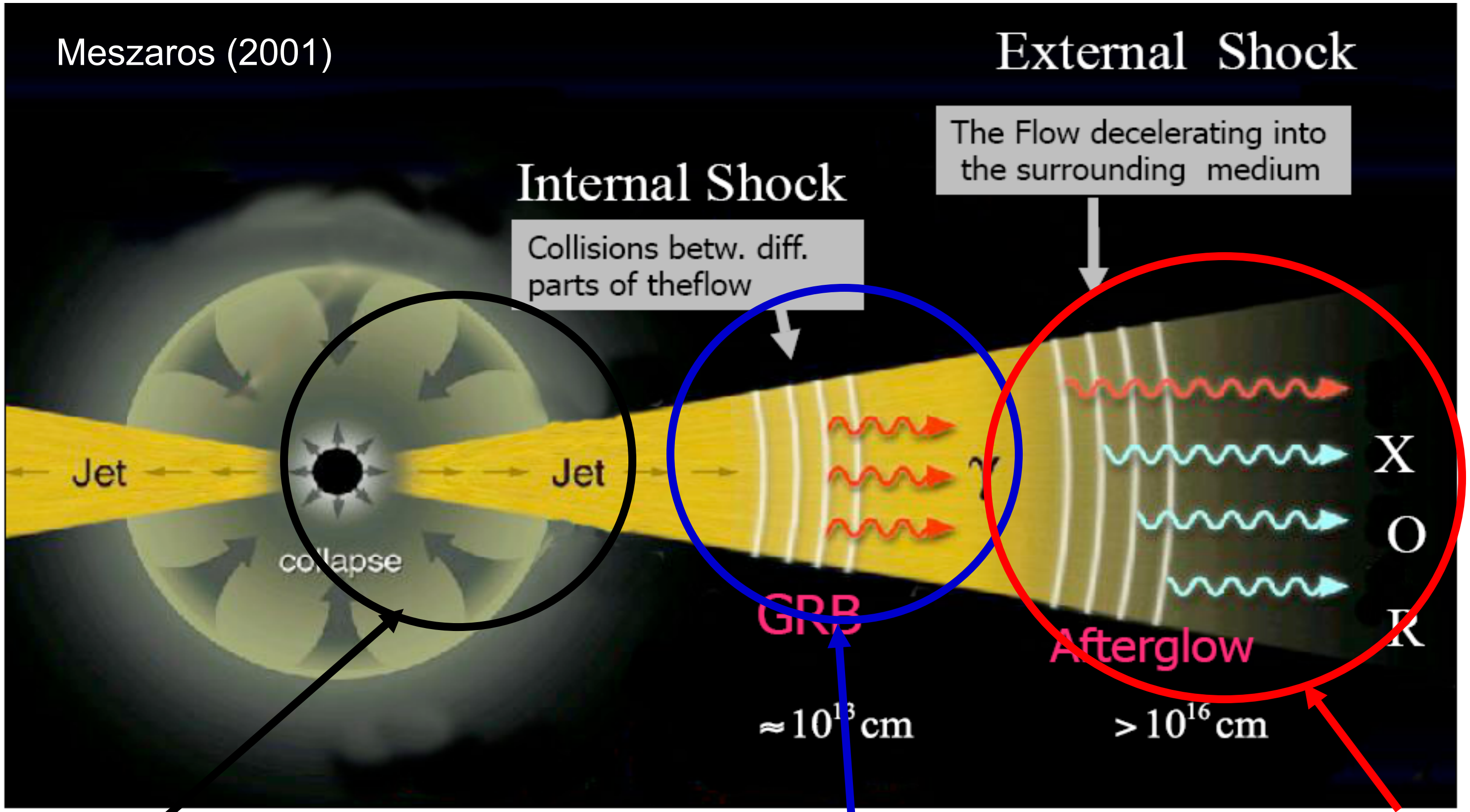


1. jet power

2. duration

3. progenitor

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

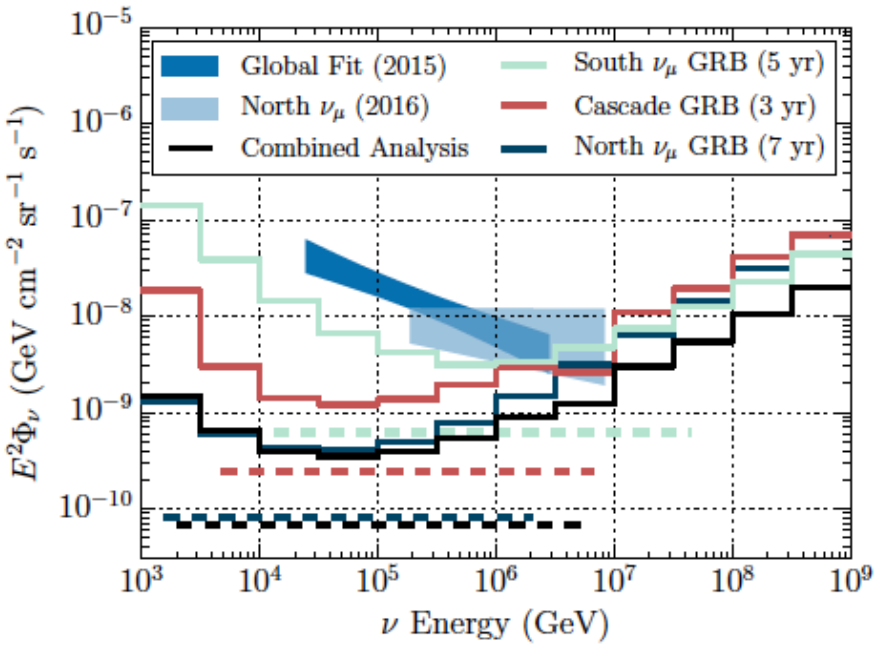
EeV ν, GeV-TeV γ

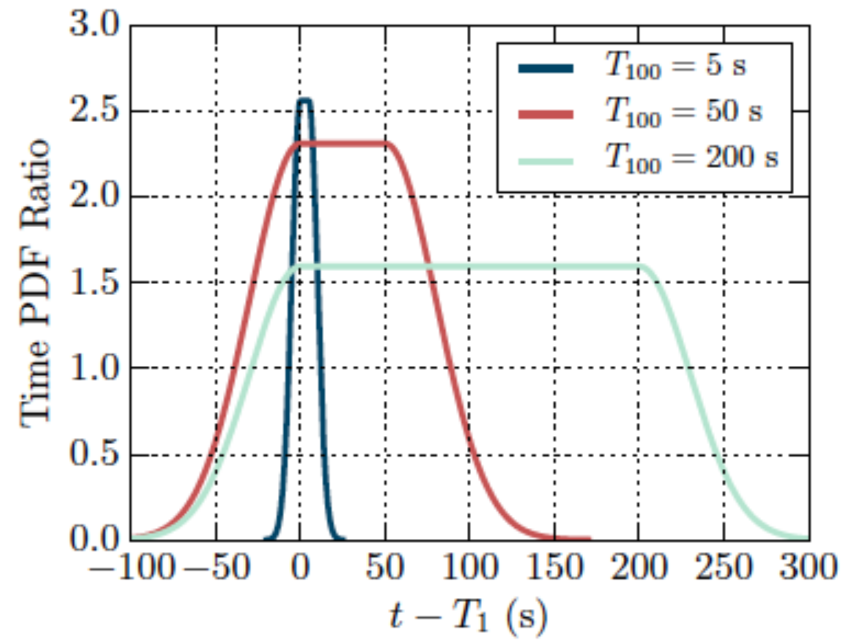
e.g., Waxman & Bahcall 00 ApJ
Dermer 02 ApJ
KM 07 PRD

Implications of GRB Stacking Search

1172 GRB samples

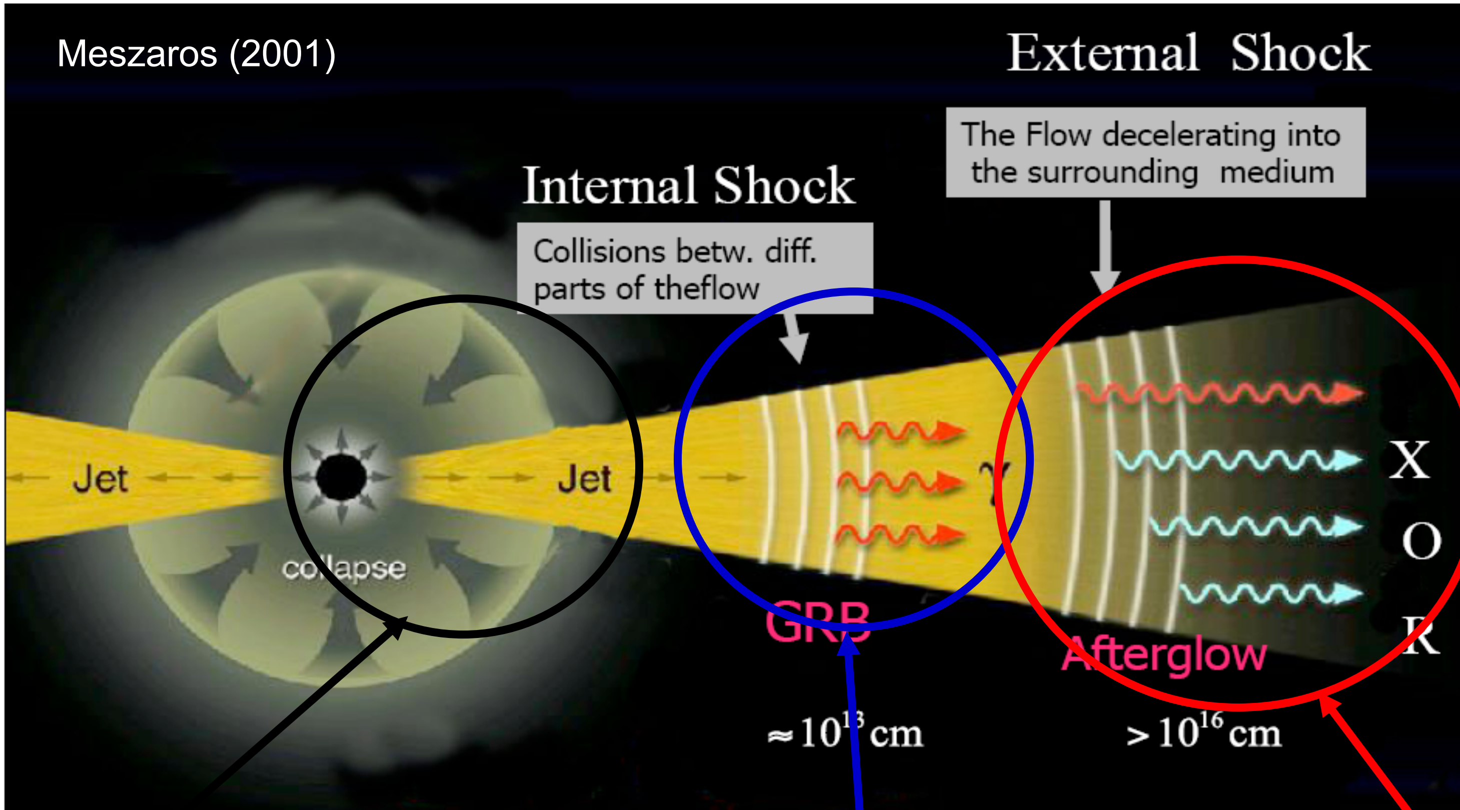
IceCube 2017 ApJ





- Classical GRB: <~1% of the diffuse IceCube flux
- DO NOT overinterpret results:
  - Constraints are much weaker at EeV (ex. ν afterglow models)
  - Constraints are much weaker at GeV-TeV (ex. sub-photospheric models)
  - Constraints are weaker for longer-lasting emission (ex. flares/afterglows)
  - Not applied to other transients (ex. low-luminosity GRBs, choked jets)

Possible Neutrino Production Sites



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Afterglow

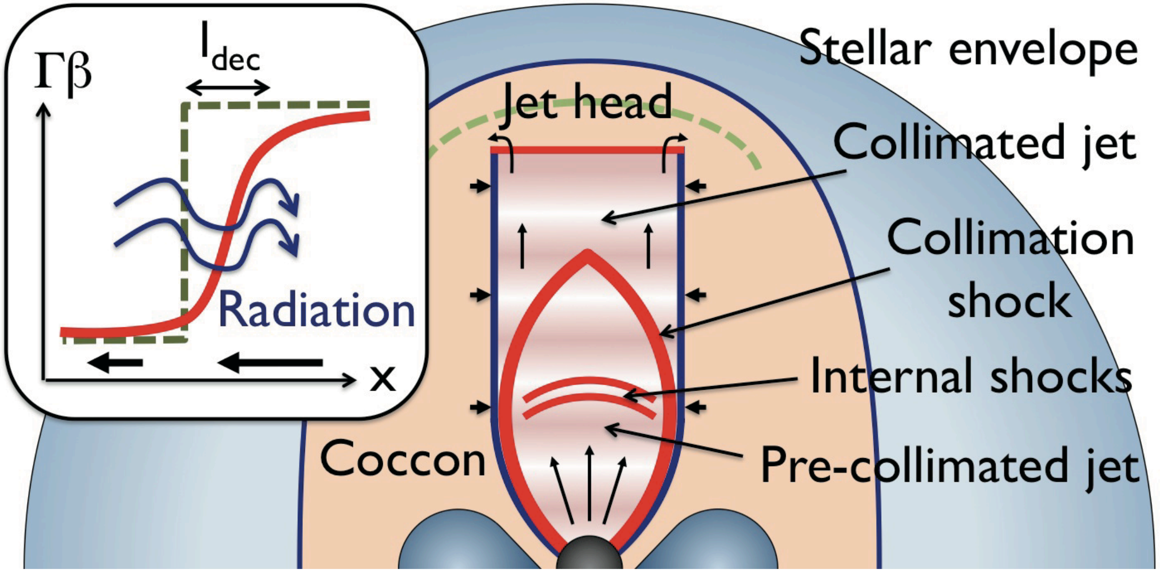
r ~ 10^{14}-10^{17} cm   B ~ 0.1-100 G

EeV ν, GeV-TeV γ

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

High-Energy Neutrinos from Choked Jets?

all cosmic-ray energy can be used for π production!



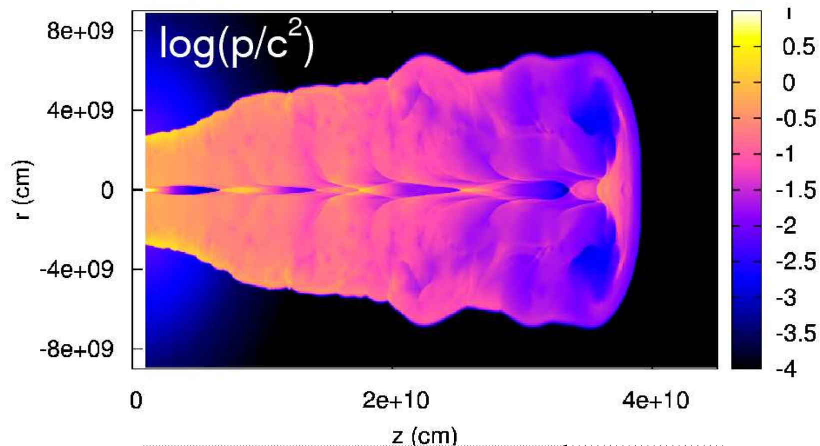
KM & Ioka 13 PRL

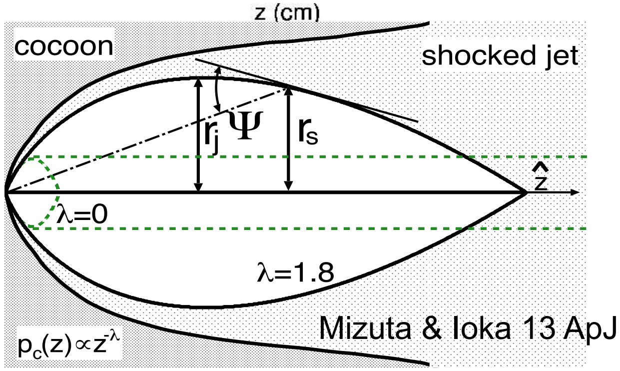
two pieces of important physics were overlooked

1. Jet propagation:
   jets may not be conical but collimated
2. Collisionless vs radiation-mediated shocks:
   efficient CR acceleration may be prohibited

Jet Propagation

- Jet propagation in a star has been understood controlled by luminosity, duration, opening angle, and $\rho(r)$





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

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

jet head radius if collimated

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

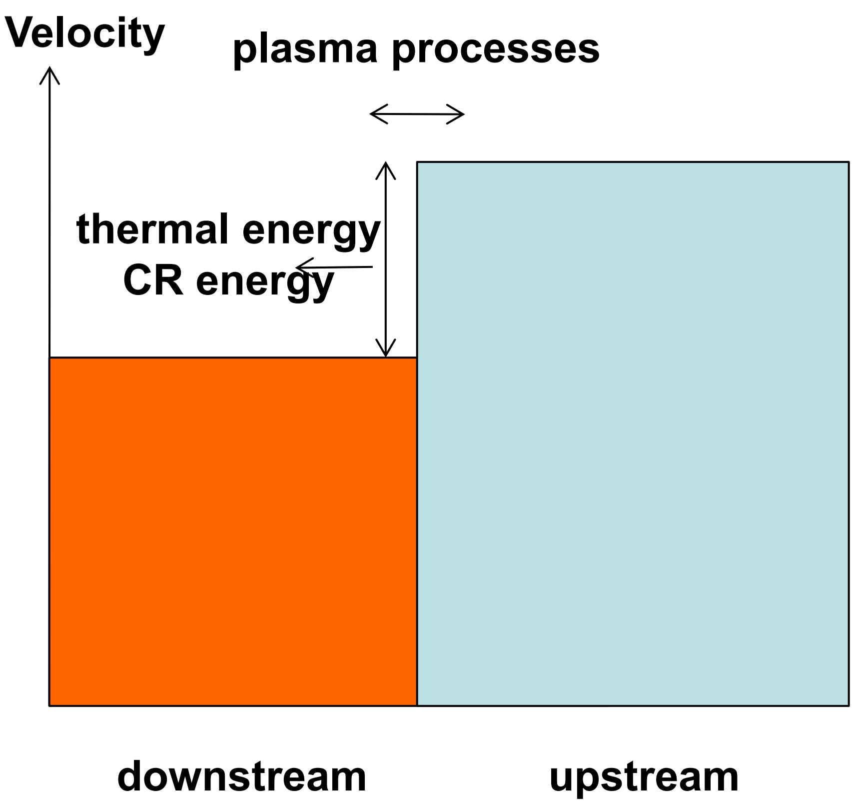
cf. uncollimated jet

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

- Collimation is crucial for jets propagating in high-density environments
- **Relevant to determine whether jets are “choked” or “successful”**

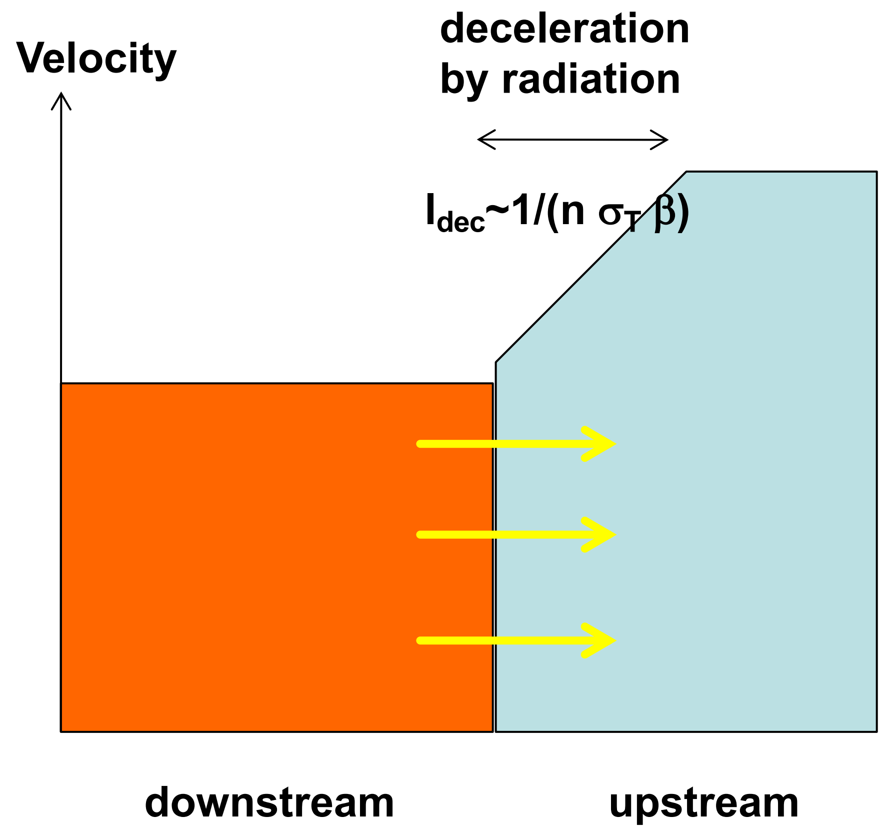
Collisionless vs Radiation-Mediated shocks

Collisionless shock



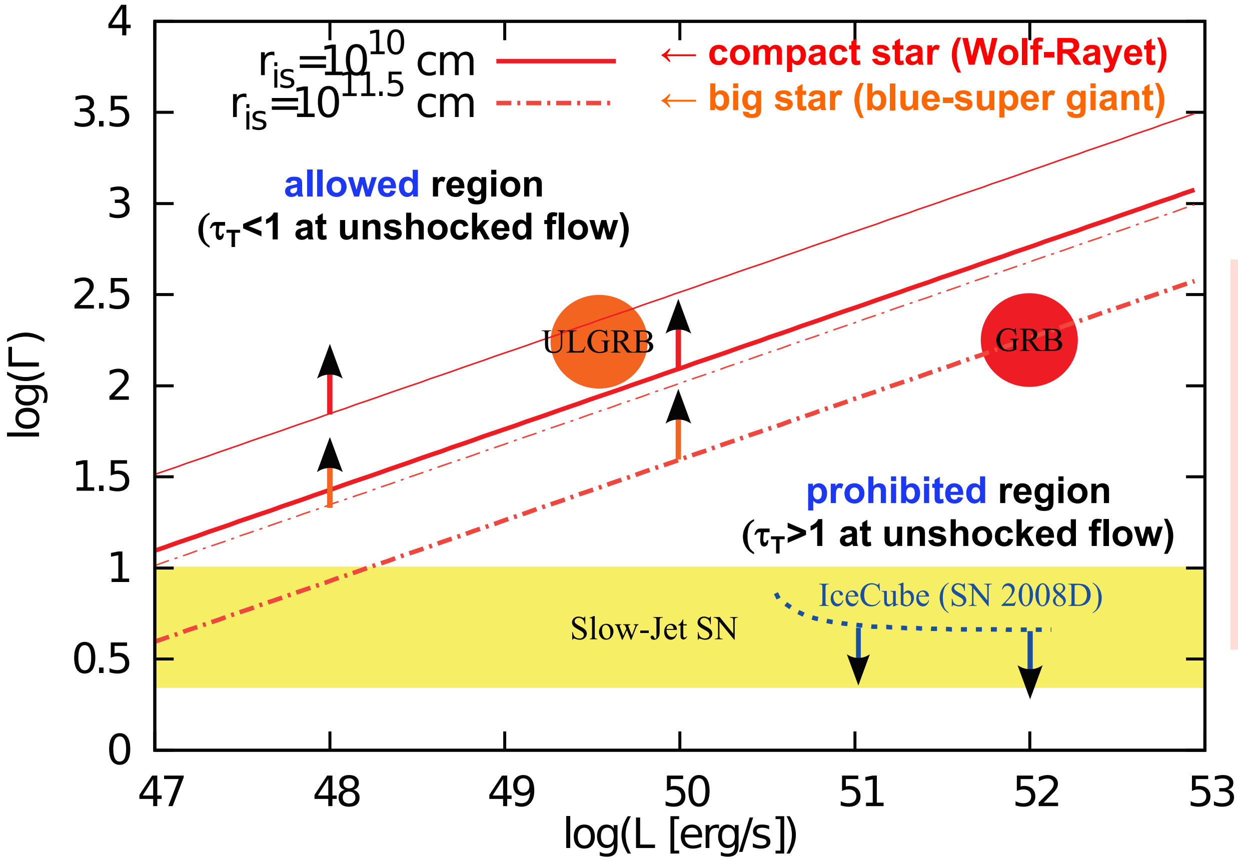
(m.f.p.) ~ $r_L(\varepsilon_p)$ > (shock width)

Radiation-mediated shock



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

"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

⇨ **favoring "choked jets"**
(both conditions make jet penetration difficult)

Implications

- Good news:
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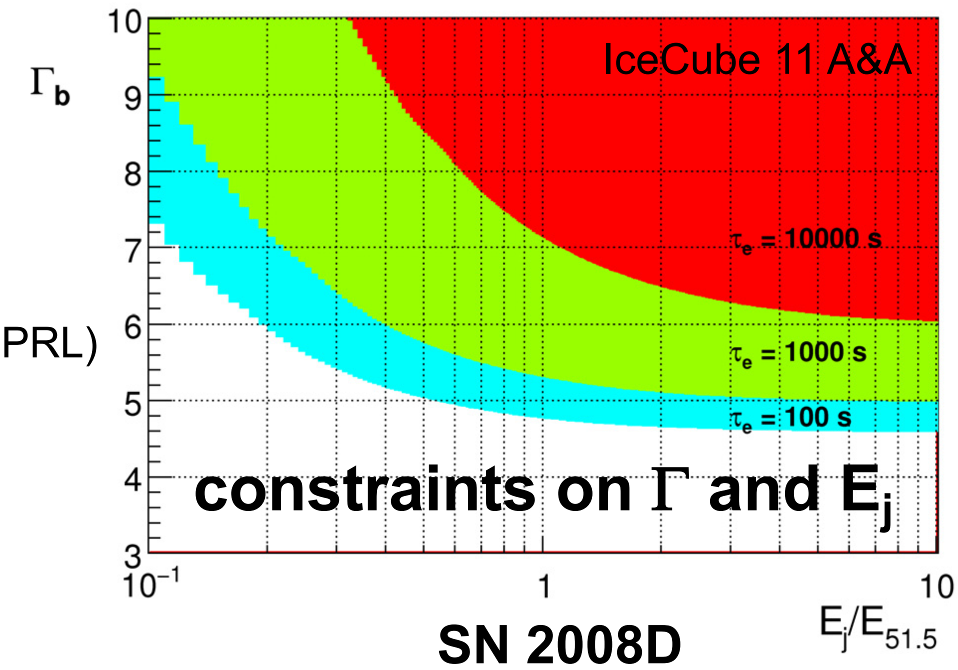
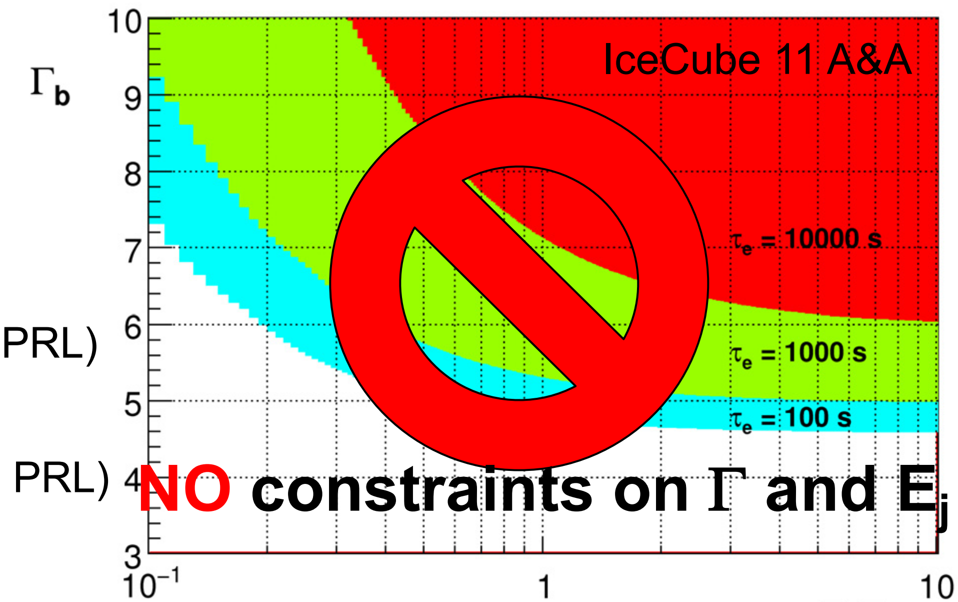
- <u>Bad news</u>
  ex. slow-jet SN model
  SN @ 10 Mpc
  # of νs: >~100 events!
  (Razzque+ 04 PRL, Ando & Beacom 05 PRL)



Implications

- <u>Good news:</u>
  non-detections of HE "precursor" neutrinos from canonical GRBs are naturally explained

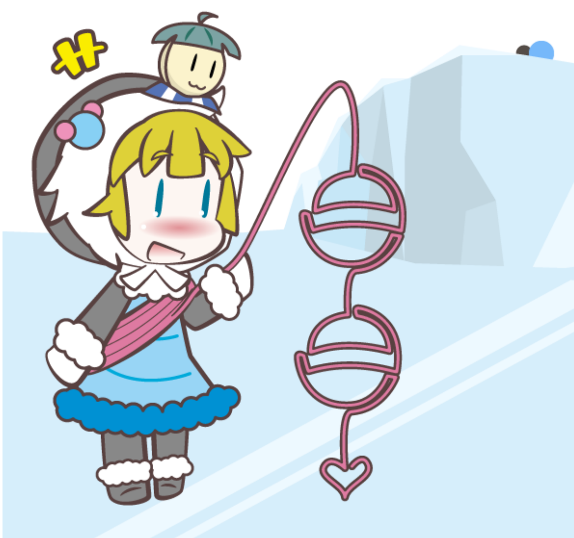
- <u>Bad news</u>
  ex. slow-jet SN model
  SN @ 10 Mpc
  ~~# of νs: $>\sim$100 events!~~
  (Razzque+ 04 PRL, Ando & Beacom 05 PRL)
  # of νs: **~0** events…
  (w. radiation constraints by KM & Ioka 13 PRL)

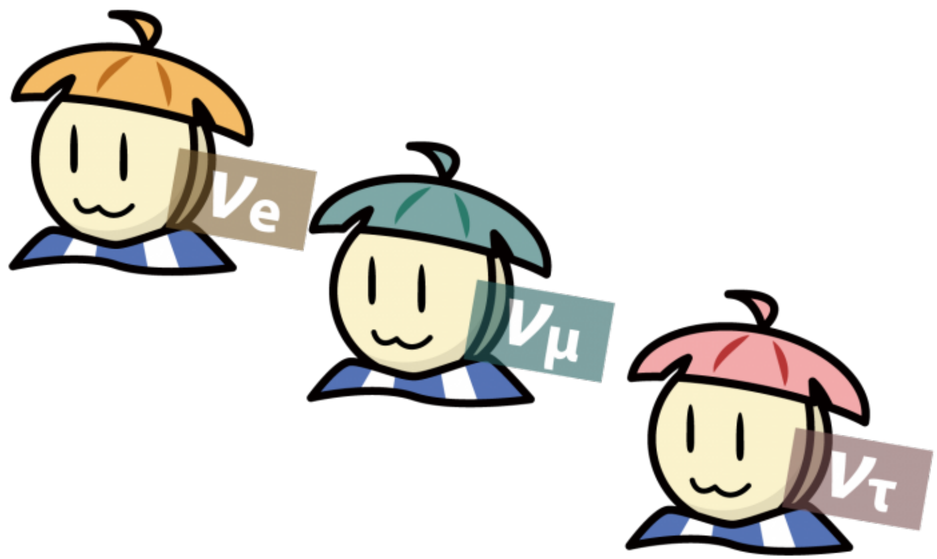


SN 2008D

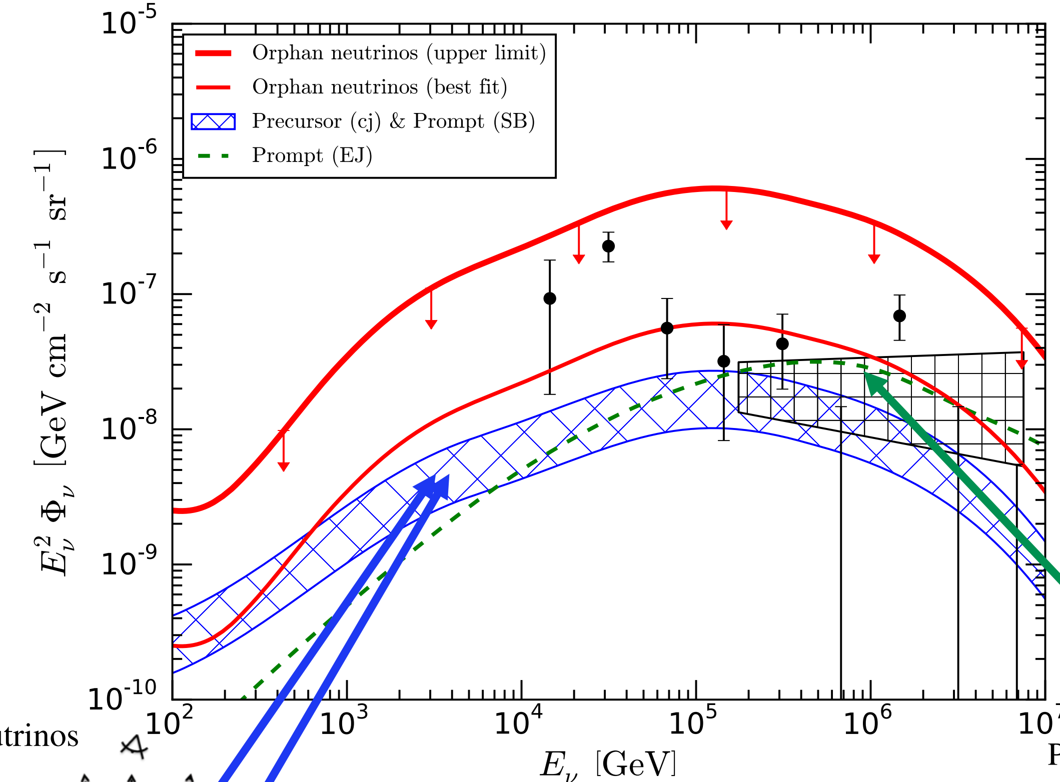
Where Should We Hunt (Fish)?

1. Nonthermal neutrinos from **low-power** jets
   - transrelativistic SNe (low-luminosity GRBs)
   or SN Ibc-BL (hypernovae) or even SNe Ibc
   - GRB jets in blue supergiants (failed UL GRBs)
   - GRB jets in red supergiants (SNe II)
2. **Quasithermal** neutrinos from high-power jets
   - neutron-loaded outflows

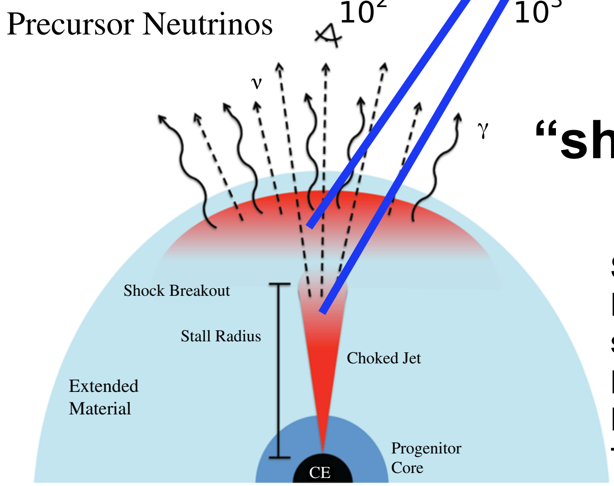




Low-Luminosity Gamma-Ray Bursts



Senno, KM & Meszaros 16 PRD

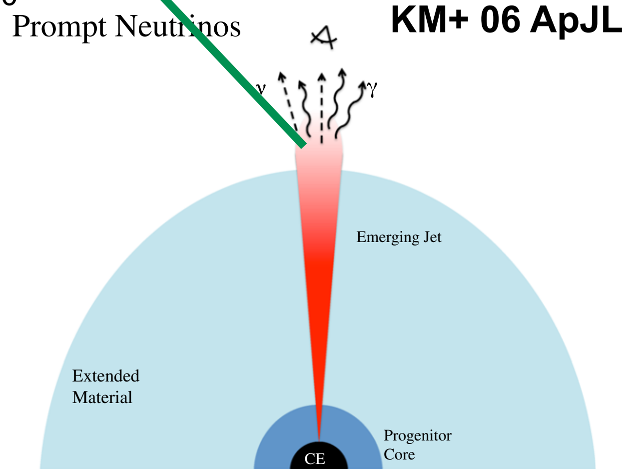


"shock breakout" scenario

Senno, KM & Meszaros 16 PRD
Kashiyama, KM+ 13 ApJL
see also
KM & Ioka 13 PRL
Nakar 15 ApJ
Tamborra & Ando 16 PRD

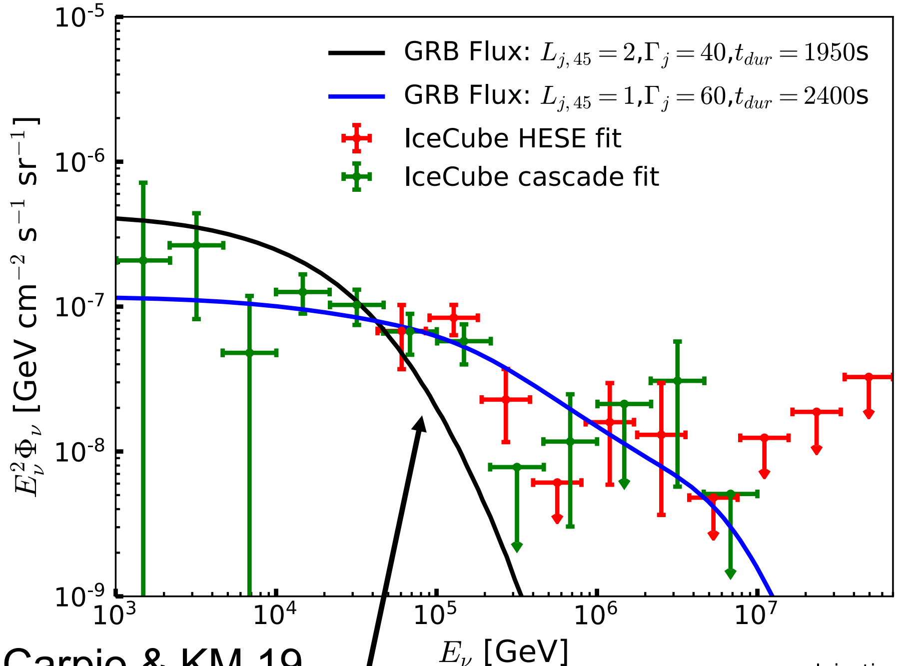
"successful jet" scenario

KM+ 06 ApJL



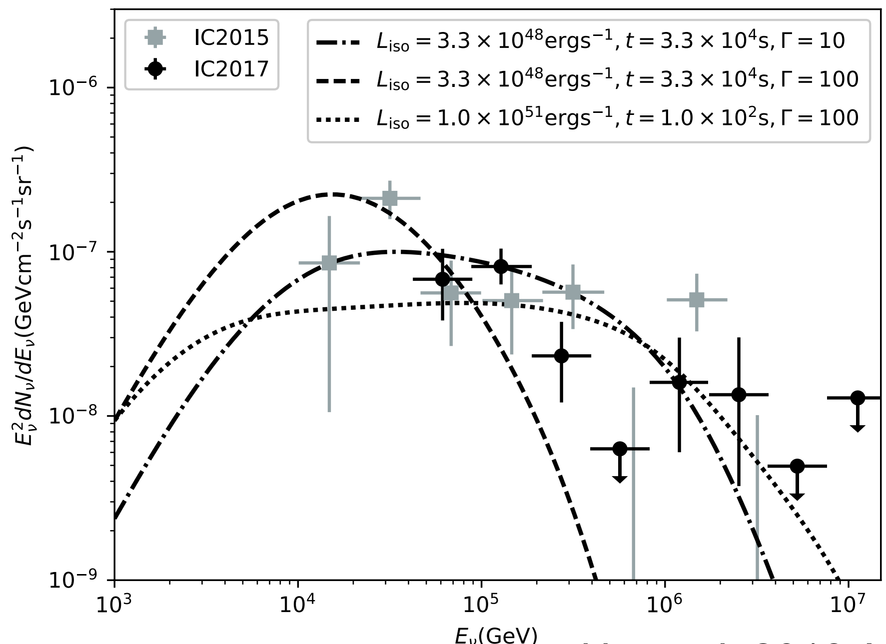
Choked Jets Embedded in BSGs/RSGs

blue supergiants (failed UL GRBs)



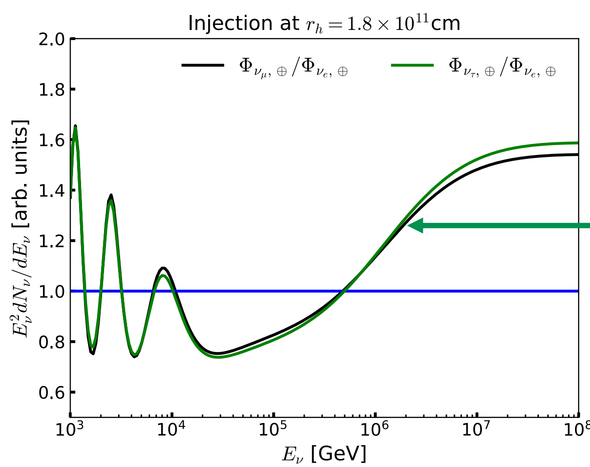
Carpio & KM 19
(see also KM & Ioka 13)

red supergiants (SNe II)



He et al. 2018 ApJ

ν attenuation by matter

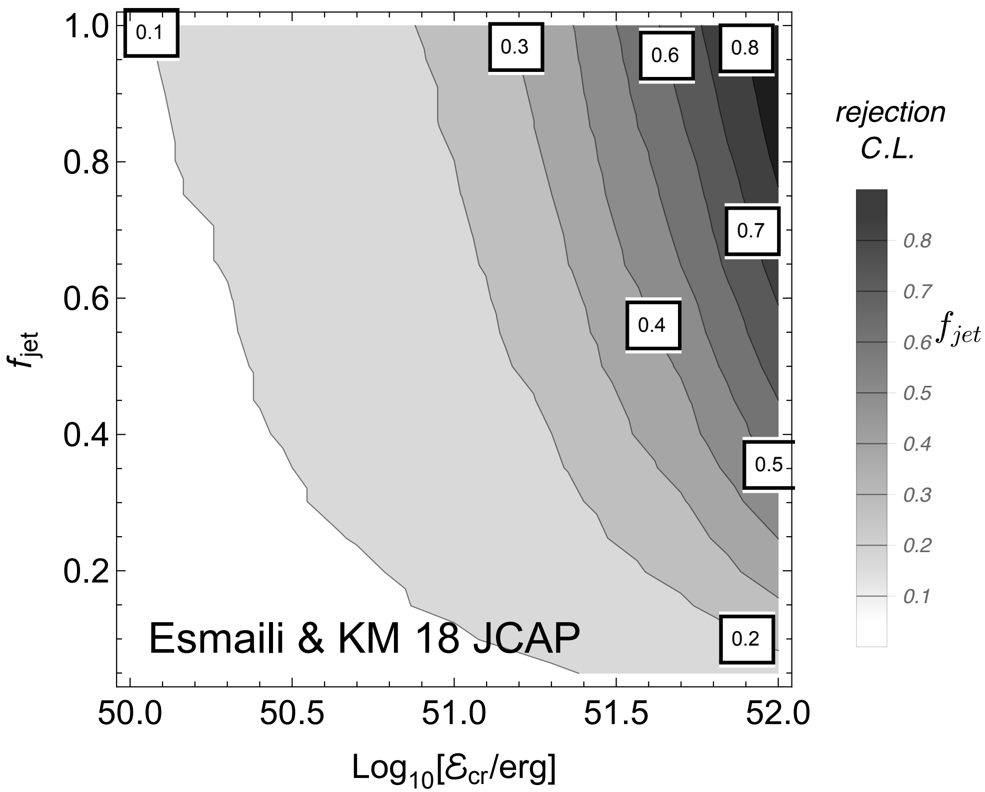


ν oscillation w. matter effects

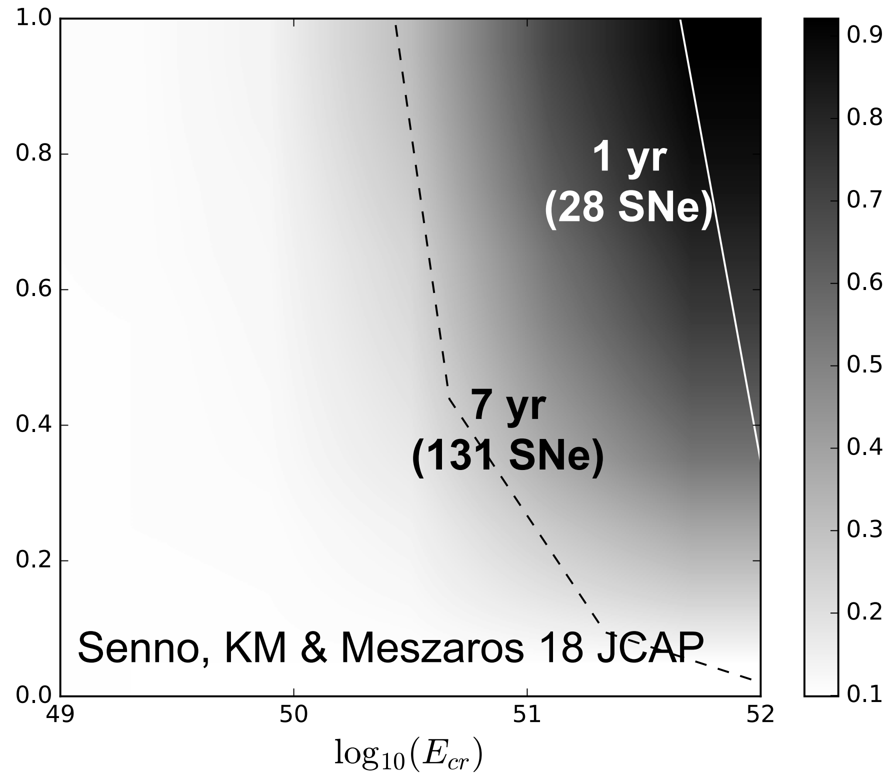
Searches for HE Neutrinos from Supernovae

Stacking analyses on SNe (~week) w. open SN catalogue

public 6 yr HESE data w. 222 SNe Ibc



public 1 yr upgoing ν_μ data w. 28 SNe Ibc



- Present constraints: $E_{cr}<10^{51}$-10^{52} erg (if all SNe emit νs)
- Future multimessenger searches: improved w. more SNe (ZTF, LSST etc.)
- Angular resolution is crucial (Gen2 & KM3Net for both showers & tracks)

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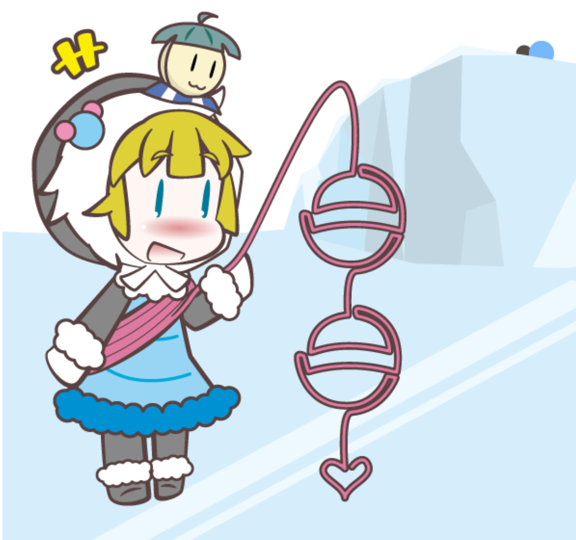
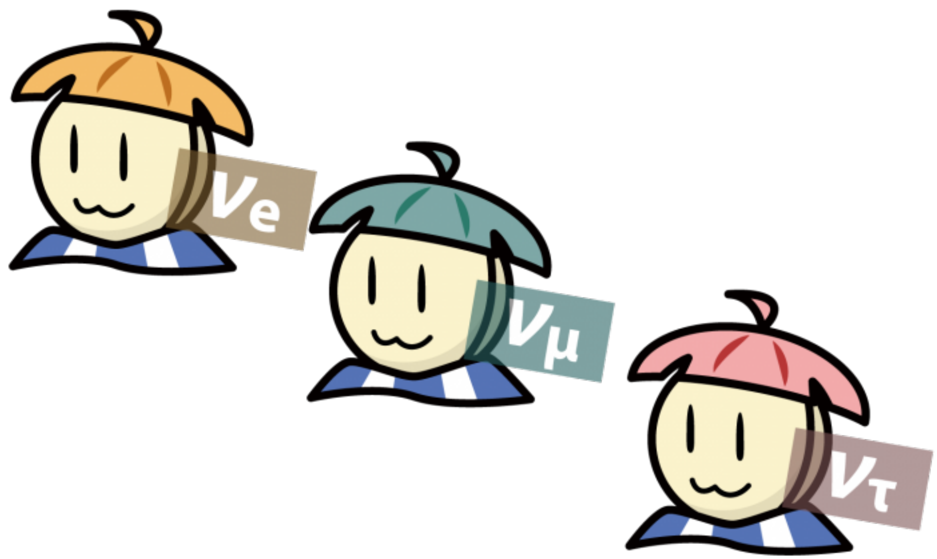
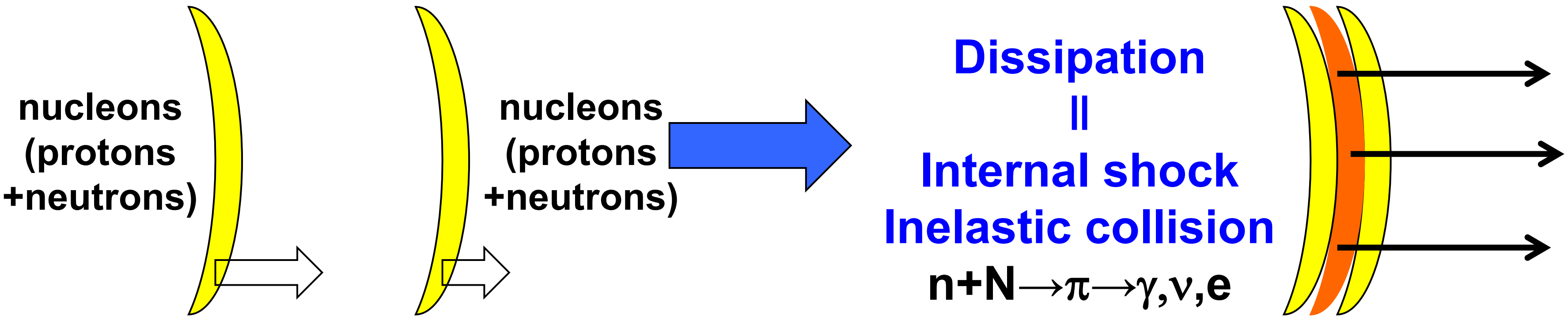


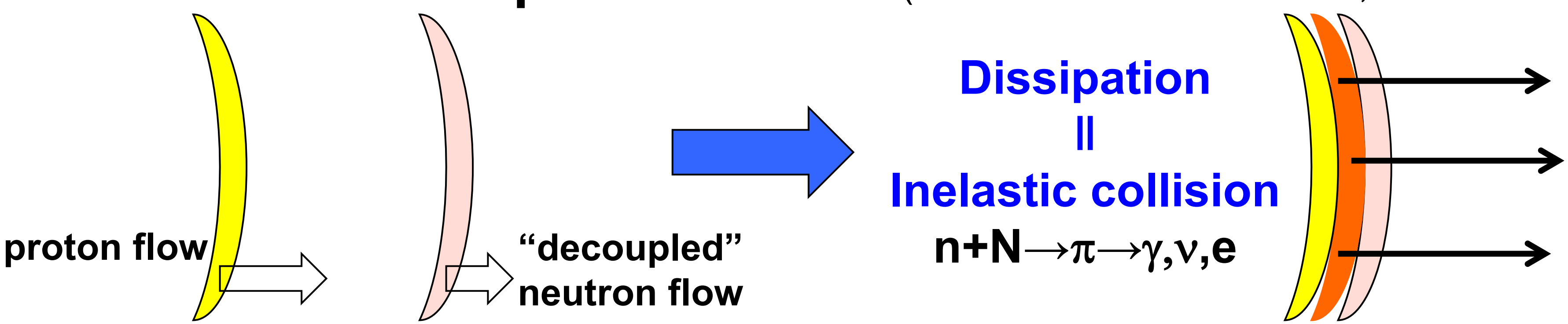


Fate of Neutron-Loaded Outflows

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

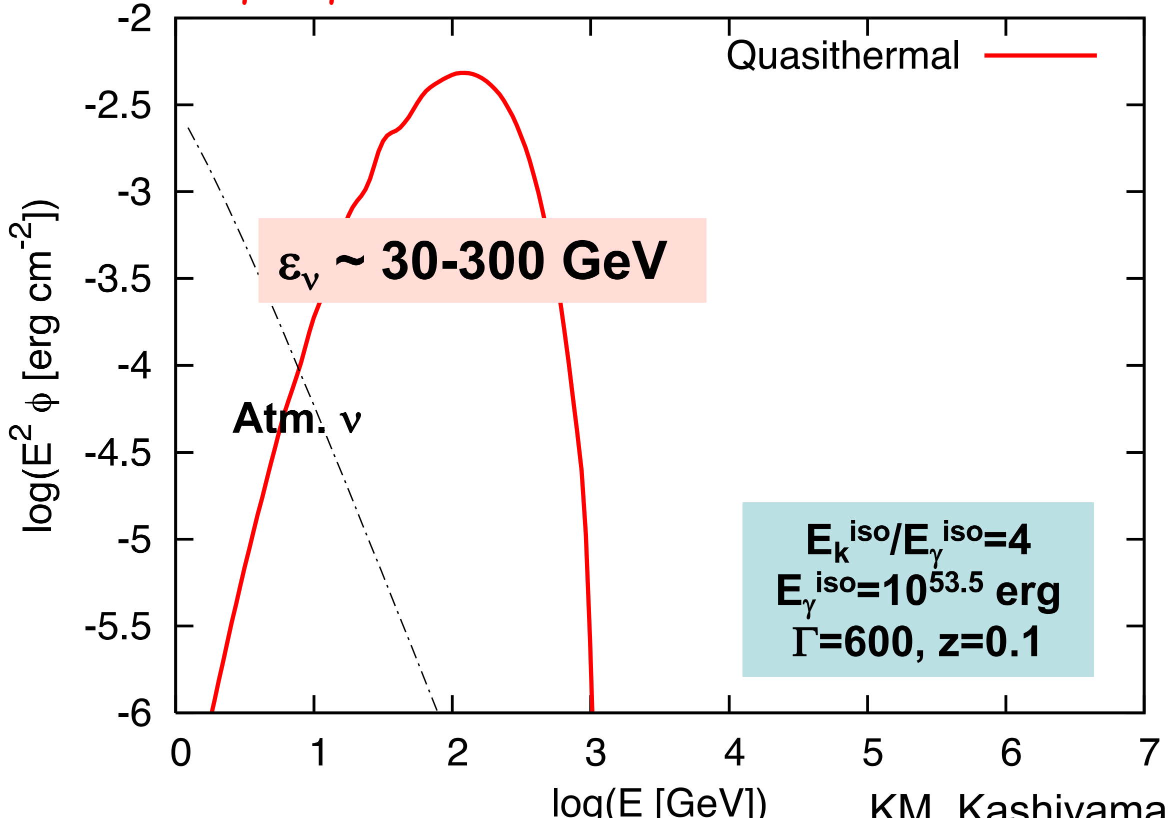


Collision w. decoupled neutrons (ex. Bahcall & Meszaros 00, Beloborodov 10)



Quasi-Thermal Neutrinos from Neutron Collisions

- Quasithermal (nonthermal CRs unnecessary)
  ν energy: $\varepsilon_\nu \sim 0.1\Gamma\Gamma_{rel} m_p c^2 \sim$ 100 GeV$(\Gamma/500)(\Gamma_{rel}/2)$
- Efficient π production (inelastic dissipation of ns)
  ν flux: $\varepsilon_\nu^2\phi_\nu \sim \varepsilon_\gamma^2\phi_\gamma$: calibrated by prompt emission

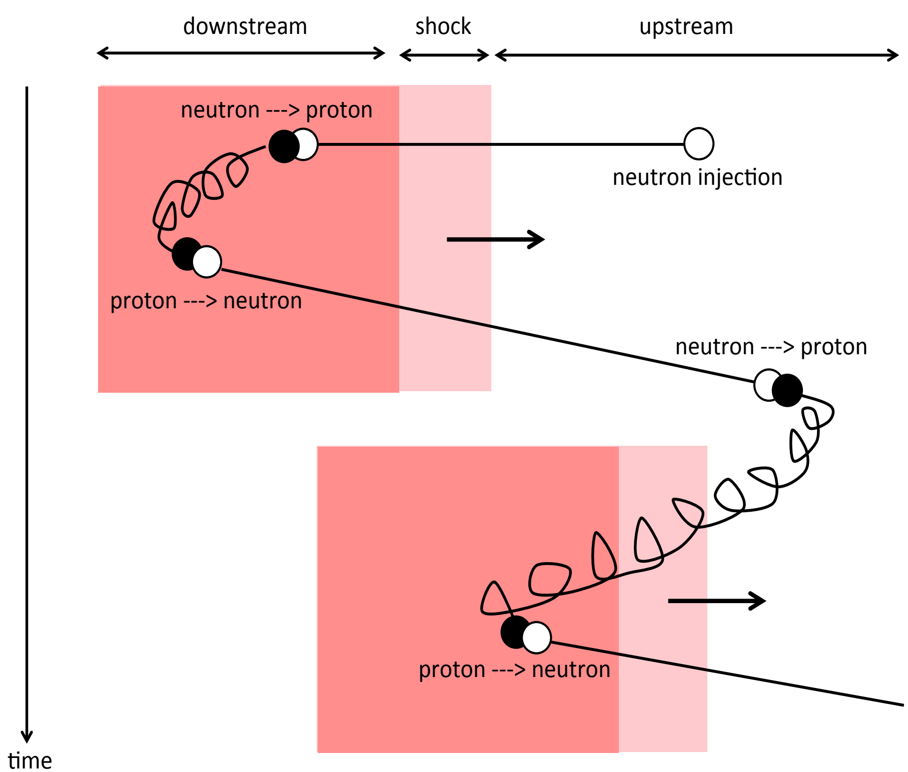


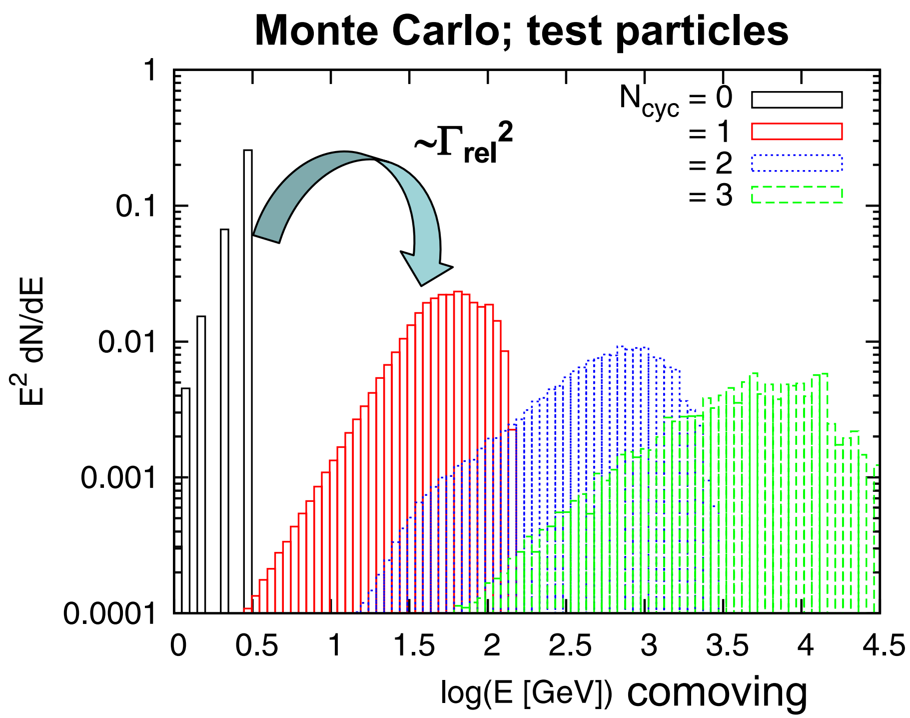
KM, Kashiyama & Meszaros 13 PRL

Particle Acceleration in Radiation-Dominated Regions?

Neutron-proton-converter acceleration ("**NPCA**") (Derishev+ 03 PRD)
- Naturally occurs at radiation-mediated shocks
- Multi-TeV ν emission is enhanced by an additional boost $\sim\Gamma^2$

(KM, Kashiyama & Meszaros 13 PRL)

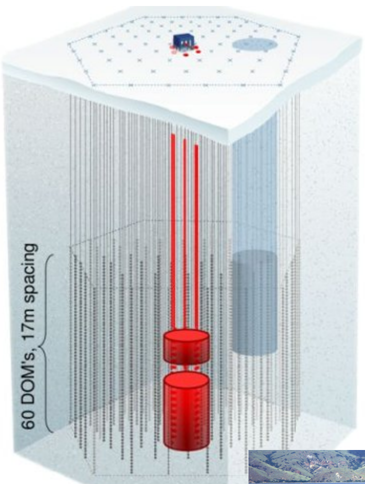


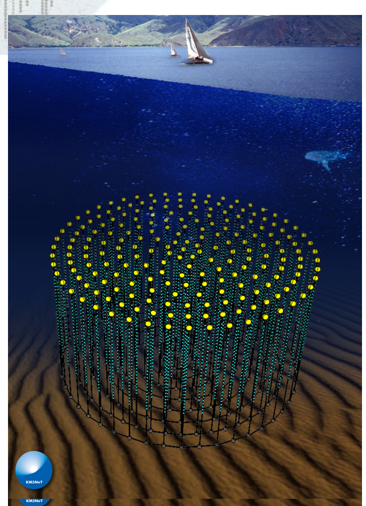


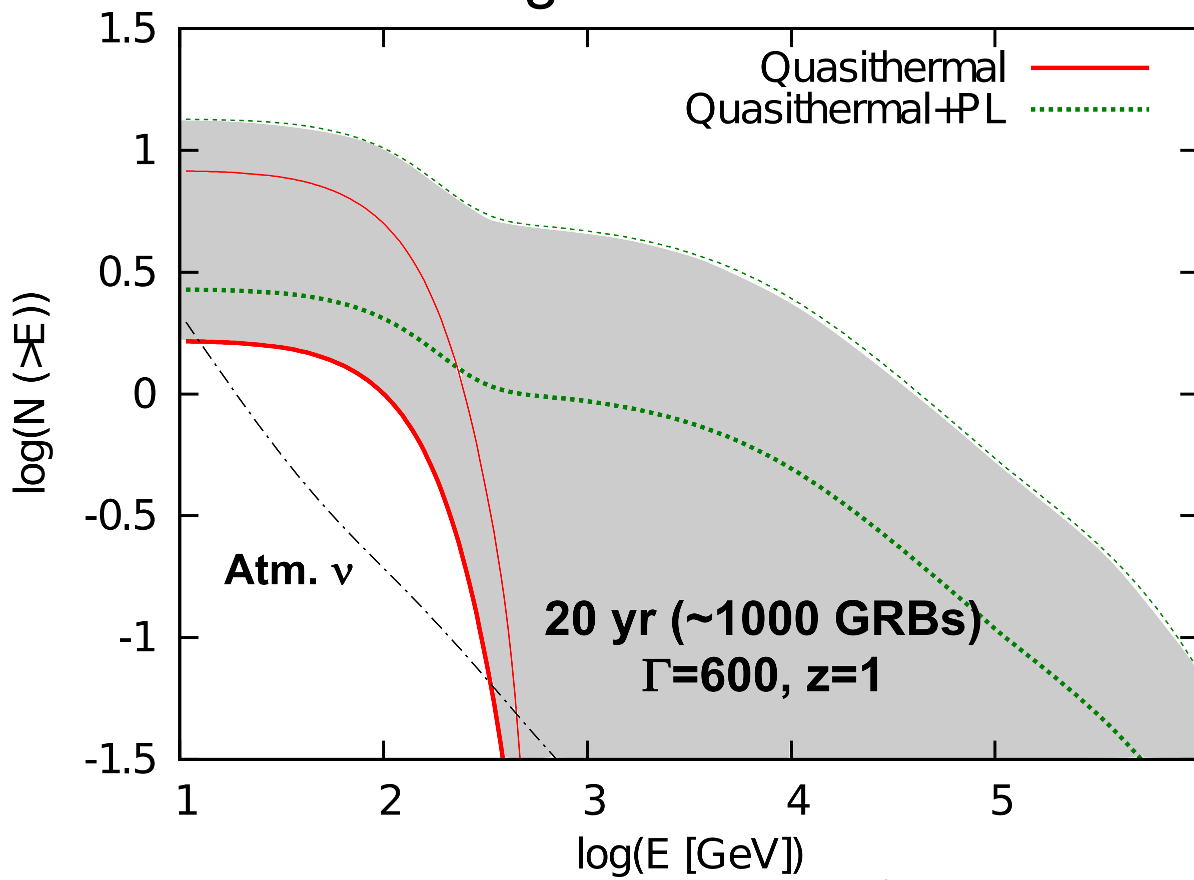
Kashiyama, KM & Meszaros 13 PRL

Prospects for IceCube & KM3Net

- Dedicated searches **below 100 GeV:** crucial (DeepCore,ORCA)
- Reducing atmospheric ν background is essential
  $\rightarrow$ select only bright GRBs w. > 10^{-6} erg cm^{-2}



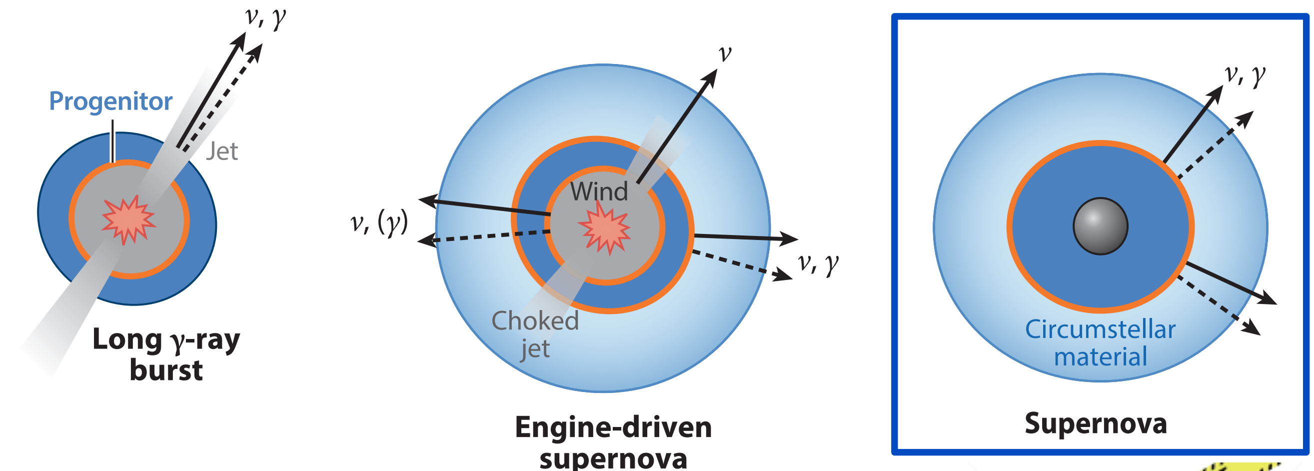


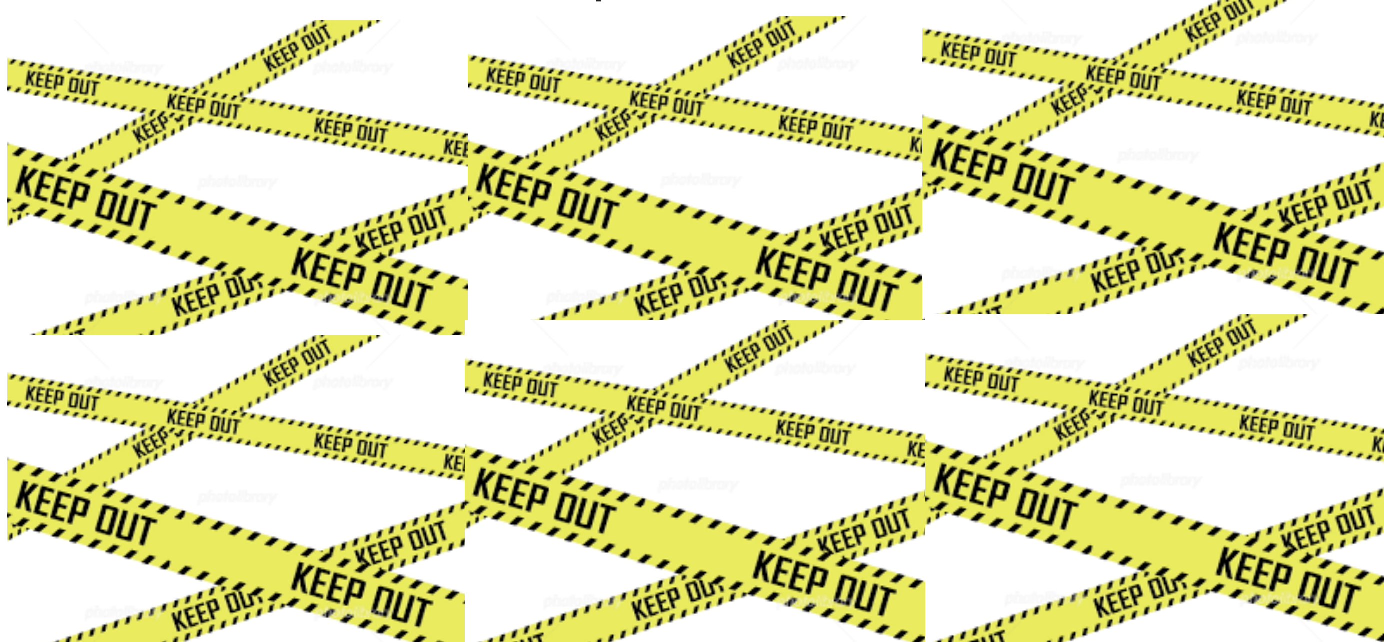


KM, Kashiyama & Meszaros 13 PRL
see also Bartos, Beloborodov, Hurley & Marka 13 PRL

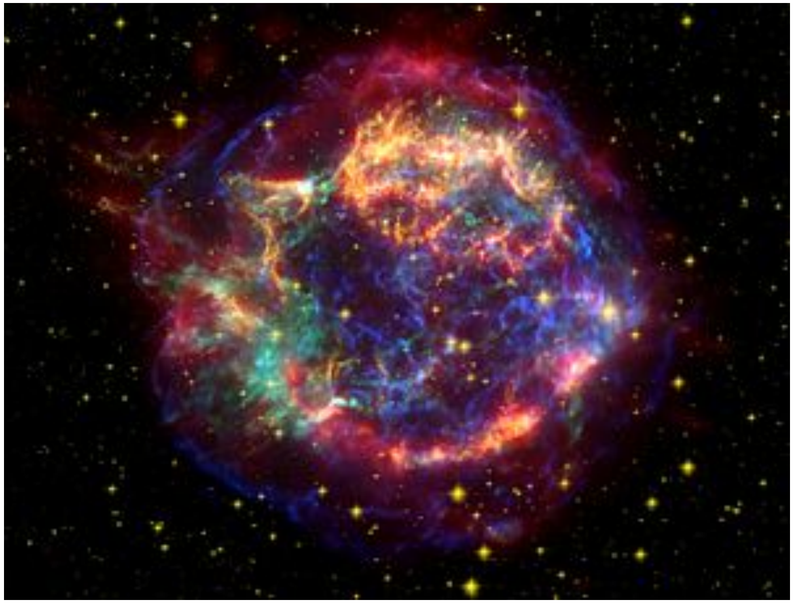
Diversity of High-Energy Transients

from KM & Bartos 19 ARNPS



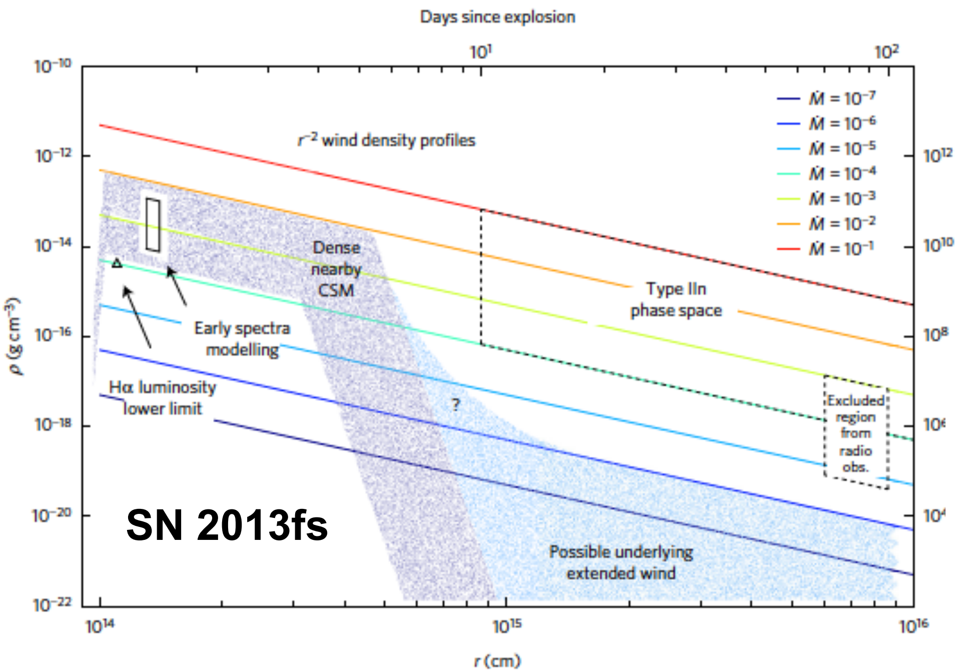


Diffusive Shock Acceleration in Supernovae?

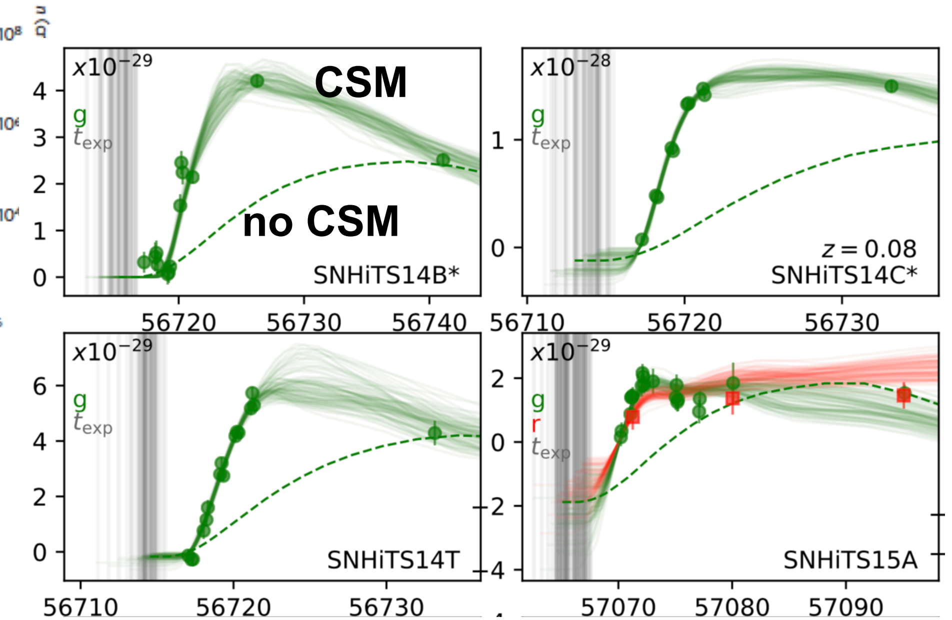


- Young supernova "remnants":
  diffusive shock (Fermi) acceleration: supported by simulations
- Naively, early CR and HE neutrino production is negligible
  most of energy is in a kinetic form until deceleration (~300 yrs)
- But situations are different
  when circumstellar material (CSM) exists $\mathcal{E}_d = \frac{M_{\rm cs}}{M_{\rm ej} + M_{\rm cs}} \mathcal{E}_{\rm ej}$

Evidence for Dense Material around Progenitor



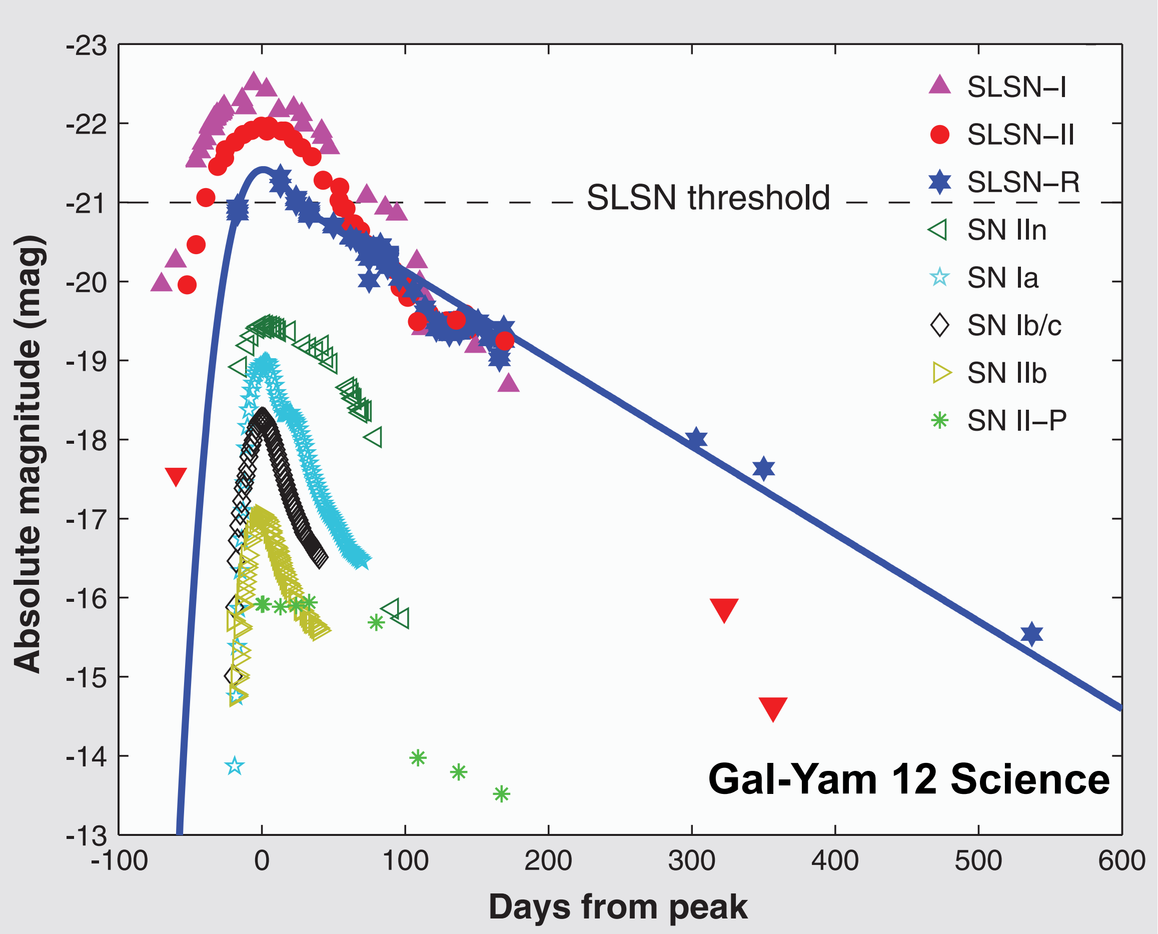
early spectroscopy
(Yaron+ 16 Nat. Phys.)



light curve modeling
Forster+ 18 Nat. Ast.
see also Morozova+ 17 ApJ

- **Known to exist for Type IIn SNe** (M_{cs}~0.1-10 M_{sun})
- **May be common even for Type II-P SNe**
  dM_{cs}/dt~10^{-3}-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)

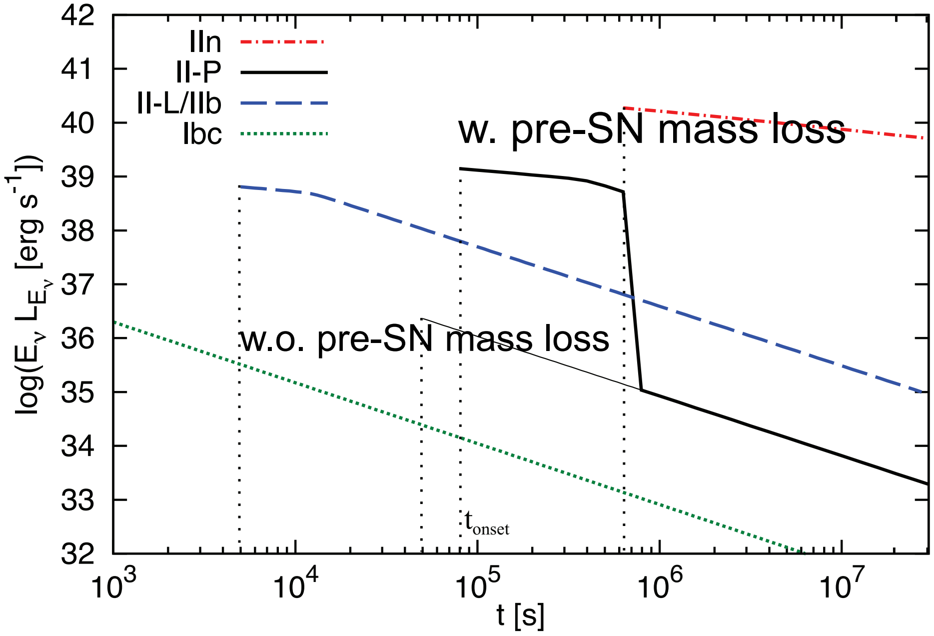
Luminous Supernovae as Long-Duration Transients



Luminous SNe explanations w. radioactivity for I and II often have difficulty

- SLSN-I (hydrogen poor) – enegy injection by engine?
- SLSN-II (hydrogen) – circumstellar material interaction

High-Energy Neutrino "Light Curves"

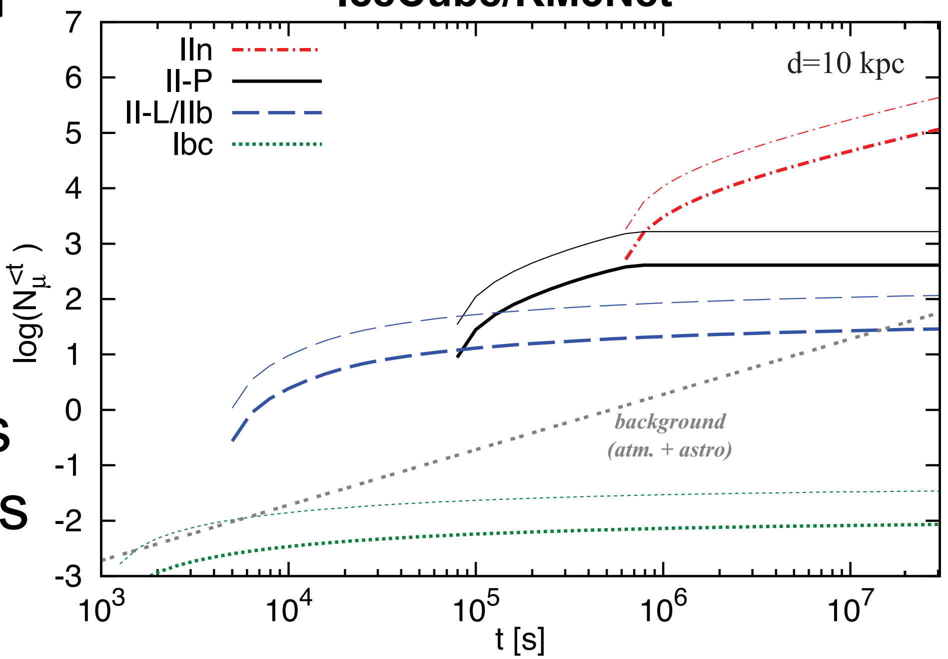


Murase 18 PRDR

"first time-dependent calculation of high-energy neutrinos from various types of supernovae"

(S/B$^{1/2}$ can be calculated only via the dynamical model)

IceCube/KM3Net

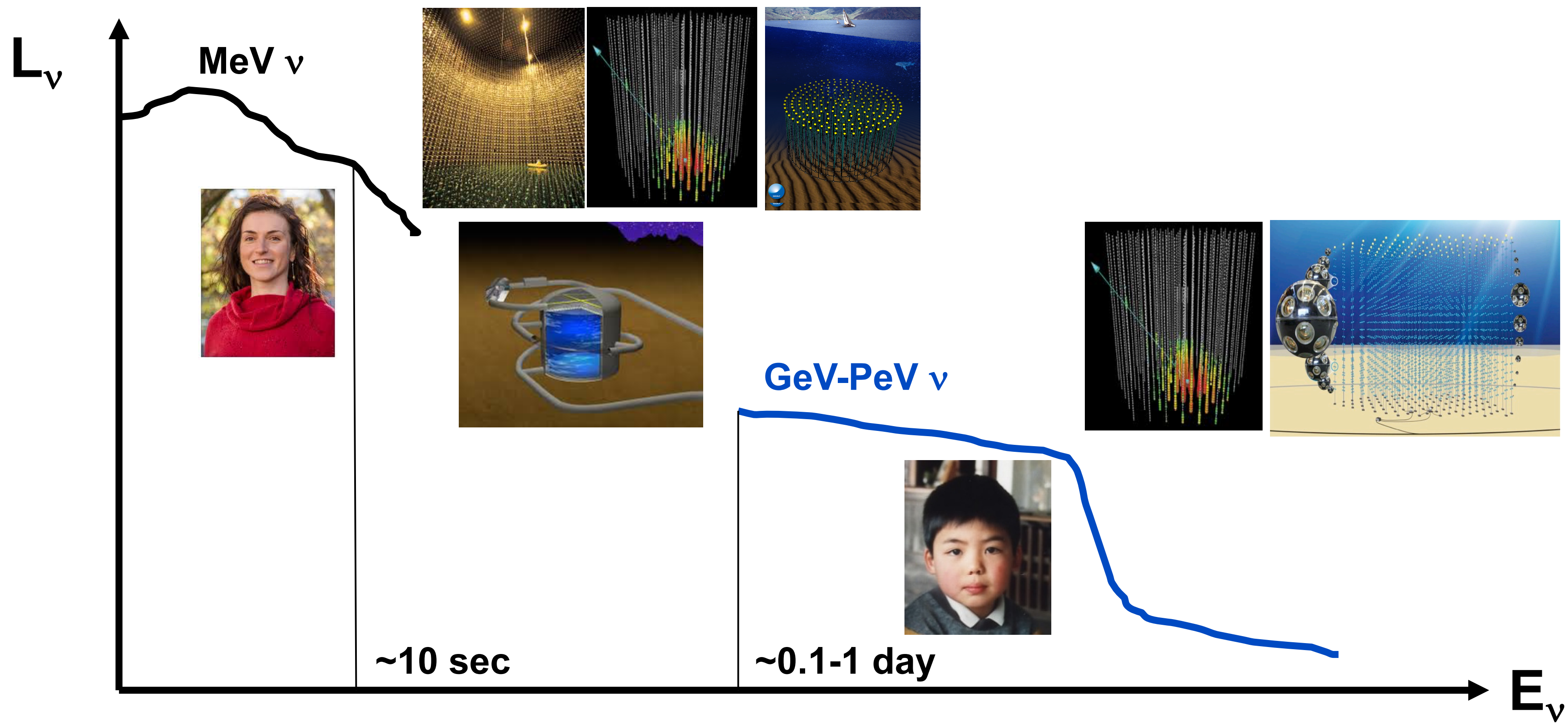


Next Galactic SN?

- SN II @ 10 kpc
  ~100-1000 events of TeV ν
- Betelgeuse: ~10^3-3×10^6 events
- Eta Carinae: ~10^5-3×10^6 events

Global Neutrino View of Supernovae

- Galactic SN: first "multi-messenger" & "multi-energy" ν source
- Real-time measurement of CR acceleration & testing Pevatrons
- KM3Net is the most relevant for HE ν from the next Galactic SN



Summary I

"Canonical" Gamma-Ray Bursts:

<1% of diffuse neutrino flux, but many related transients UNCONSTRAINED

Choked-Jet Supernovae:

Radiation constraints favor low-power jets that are more likely to be "choked"
low-luminosity GRBs, failed ultralong GRBs, choked jet SNe II
stacking searches by **KM3Net** & IceCube-Gen2 are crucial

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Neutron-loaded outflows & TeV ν signals enhanced by the NPCA mechanism
Searches below 1 TeV that will not be covered by Gen-2 → **KM3Net!**

Core-Collapse Supernovae:

Dense CSM guaranteed by optical observations & important for PeVatrons
Next Galactic SN: >10-100 HE ν events from a normal SN II → **KM3Net!**

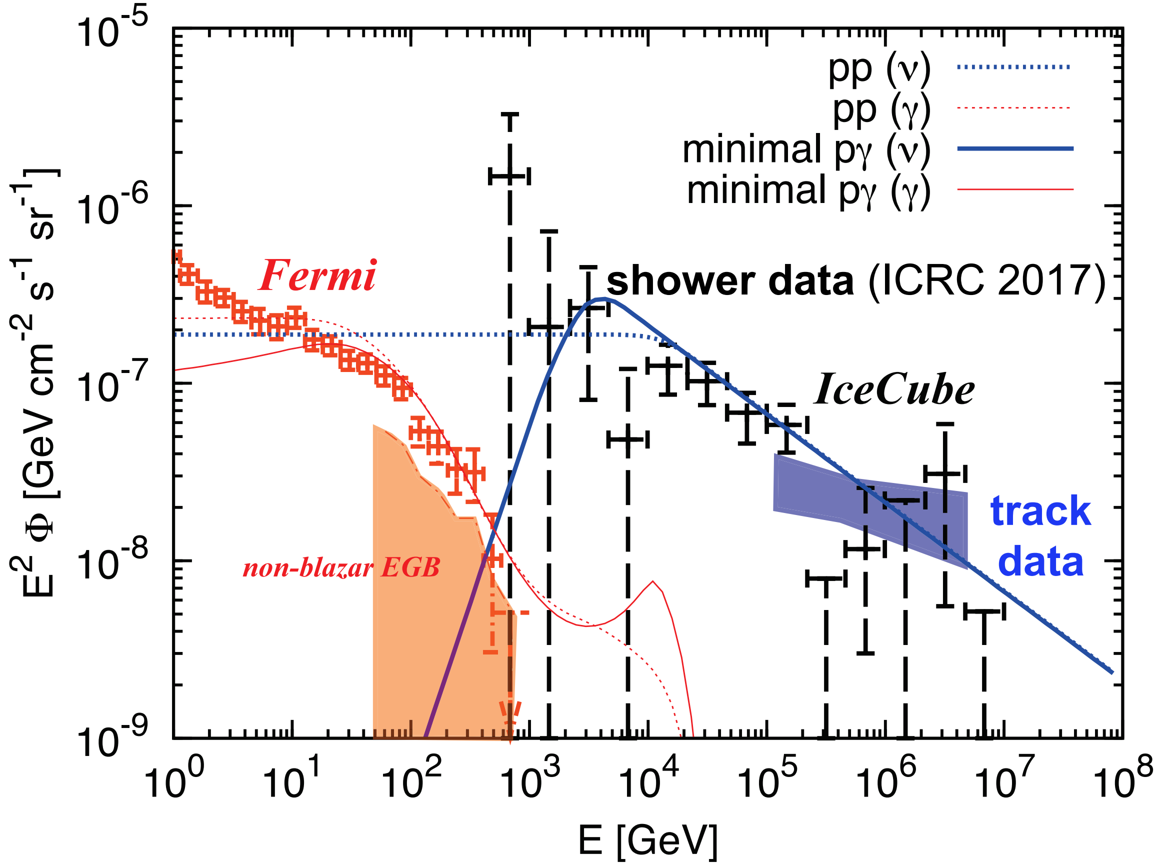
High-Energy Neutrinos from Choked Jets and Supernovae
&
(High-Energy Neutrinos from AGN Coronae)

Kohta Murase (Penn State)

December 17 @ Marseille

Medium-Energy Excess Problem

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



KM, Guetta & Ahlers 16 PRL

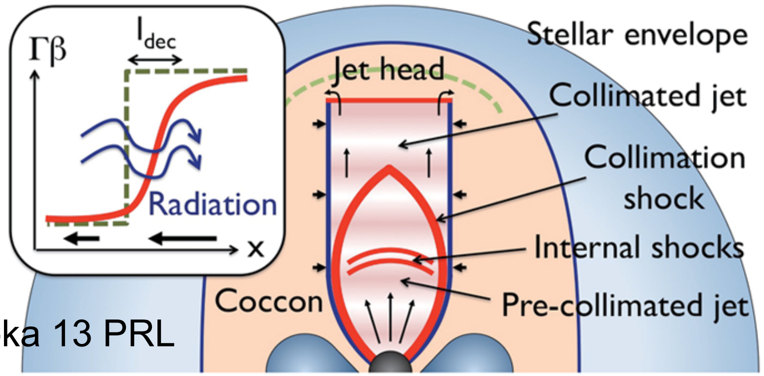
Fermi diffuse γ-ray bkg. is violated (>3σ) if ν sources are γ-ray transparent

→ **existence of "hidden (γ-ray dark) sources"**

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

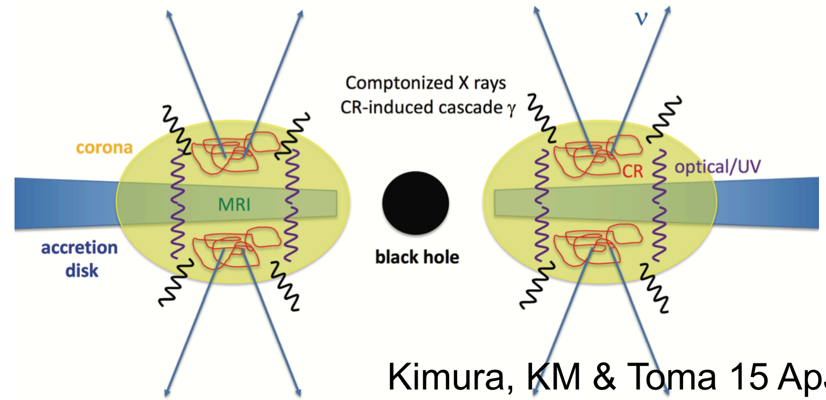
Hidden Cosmic-Ray Accelerators?

Low-power GRBs (choked jets)

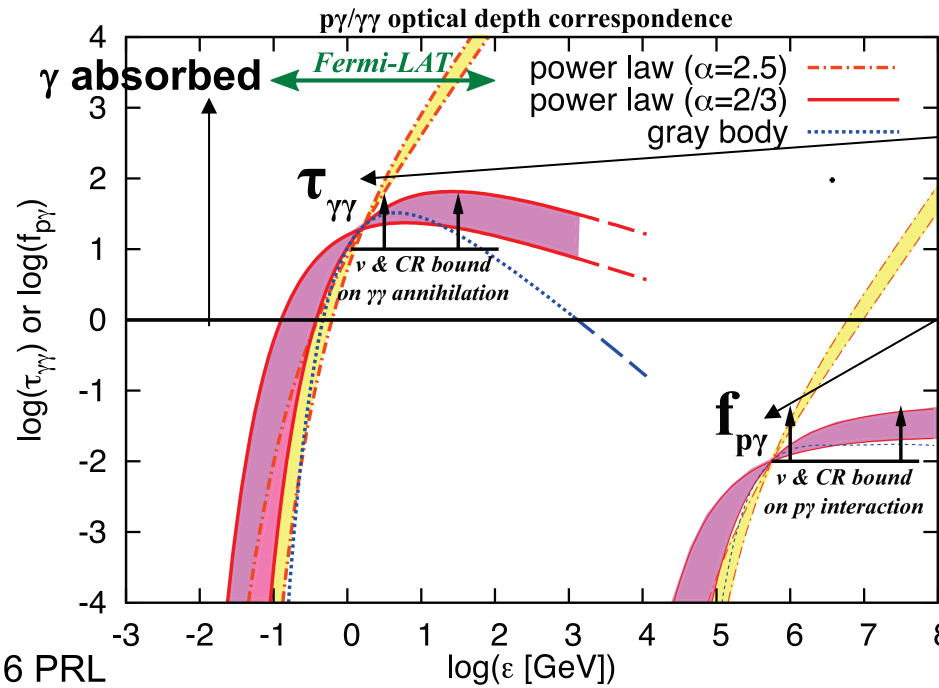


KM & Ioka 13 PRL

Supermassive black hole cores



Kimura, KM & Toma 15 ApJ



KM+ 16 PRL

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

$$\parallel$$

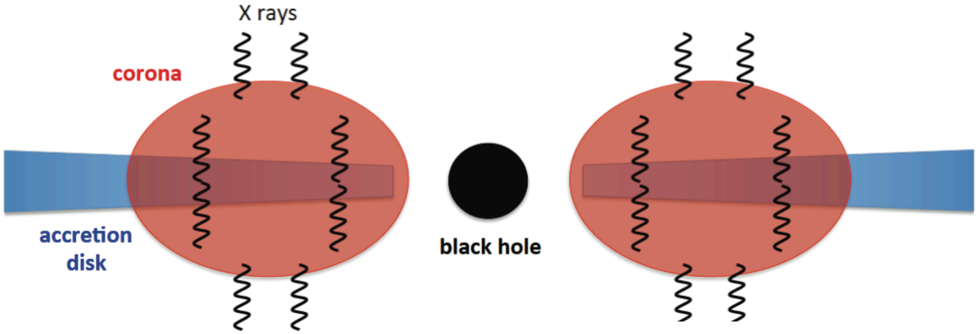
$$p + \gamma \rightarrow N\pi + X$$

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

Interaction probability of γγ ~ 1000 x (effective) interaction probability of pγ collisions

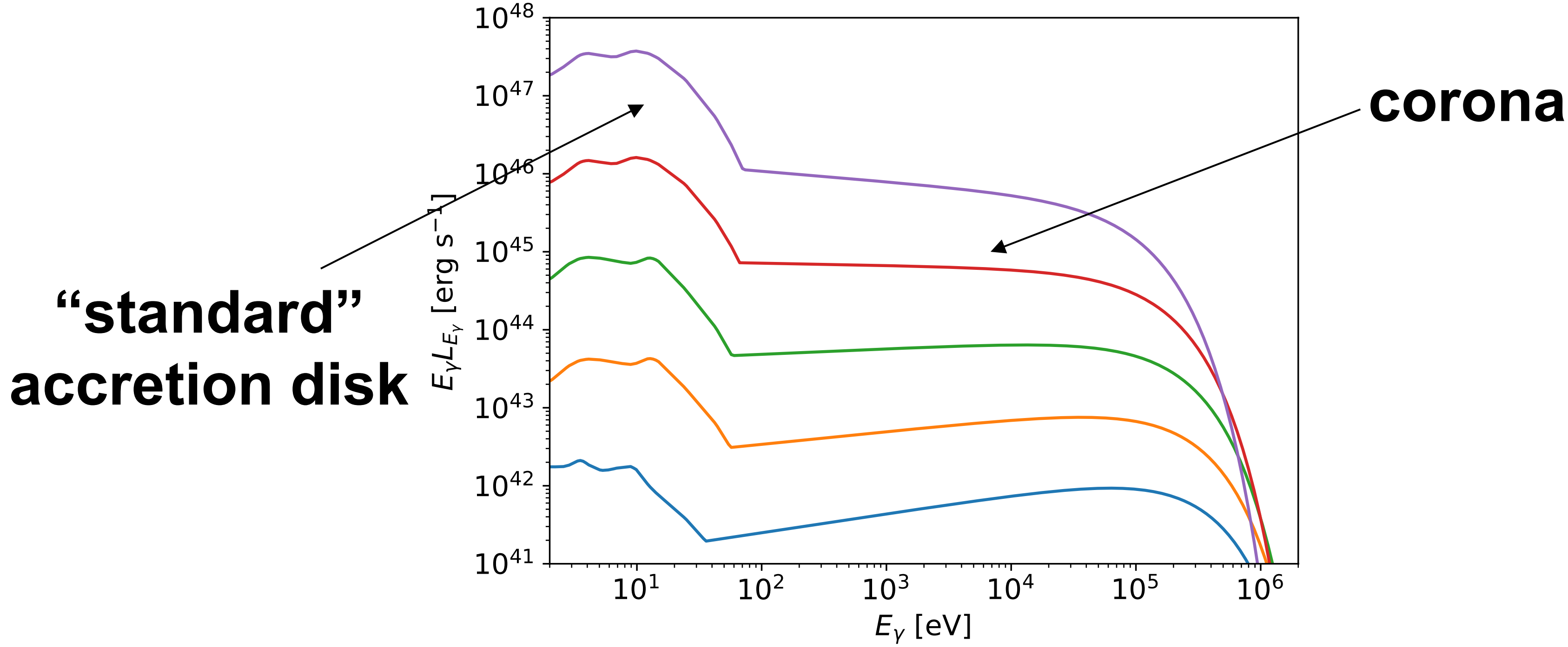
Vicinity of Supermassive Black Holes

Cores of active galactic nuclei (mainly radio-quiet AGNs)



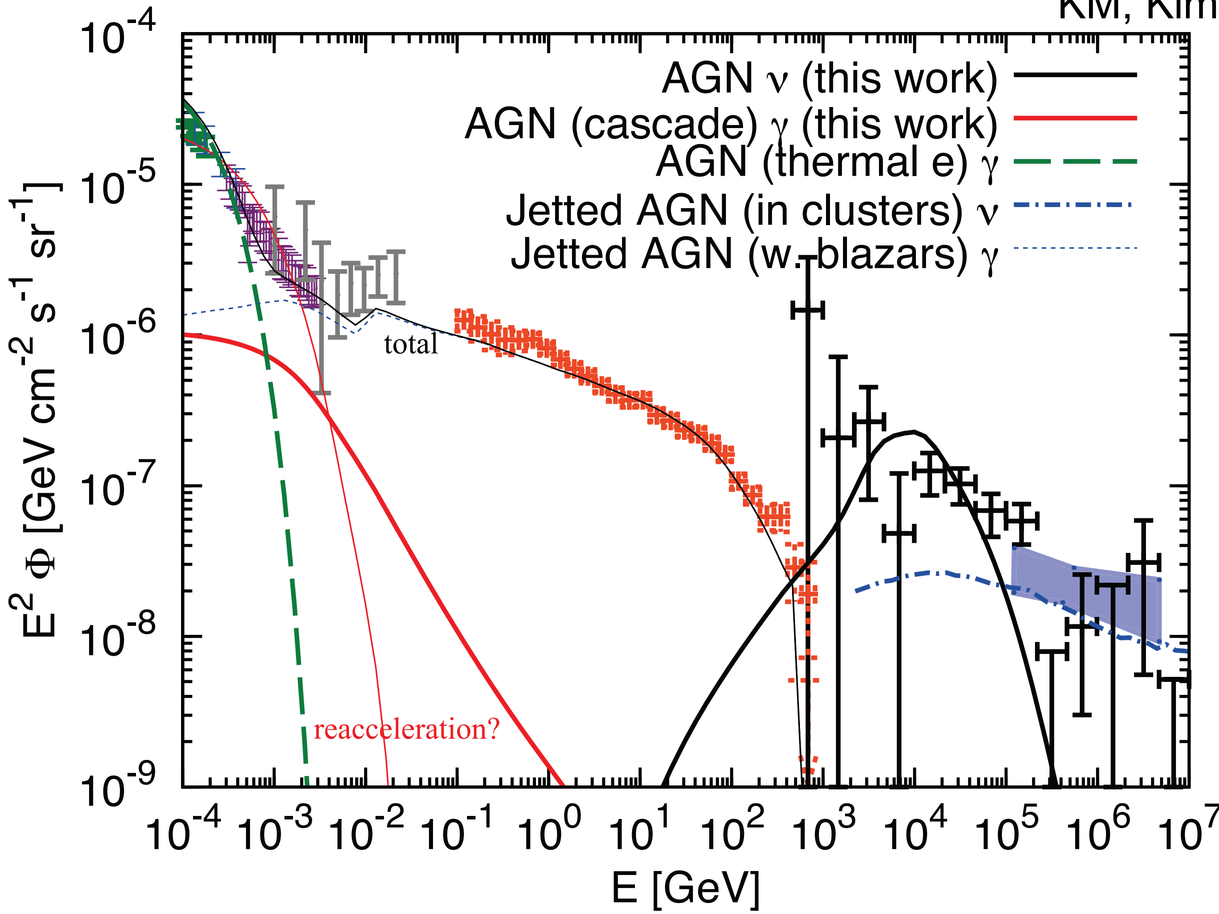
disk-corona model

X-rays=Compton by thermal e
(not accretion shocks)
supported by observations & theory (PIC/MHD simulations)



TeV-PeV Neutrino – "MeV" Gamma-Ray Connection

KM, Kimura & Meszaros 19



- Most economical for 10-100 TeV νs: only ~1% of thermal energy
- "Unique" physical consequences of observed disk-corona SEDs
  10-100 TeV ν by X rays from coronae & MeV γ by UV from accretion disks
- Dominance of Bethe-Heitler-induced cascades (ignored in previous work)

Detectability of Nearby Seyferts

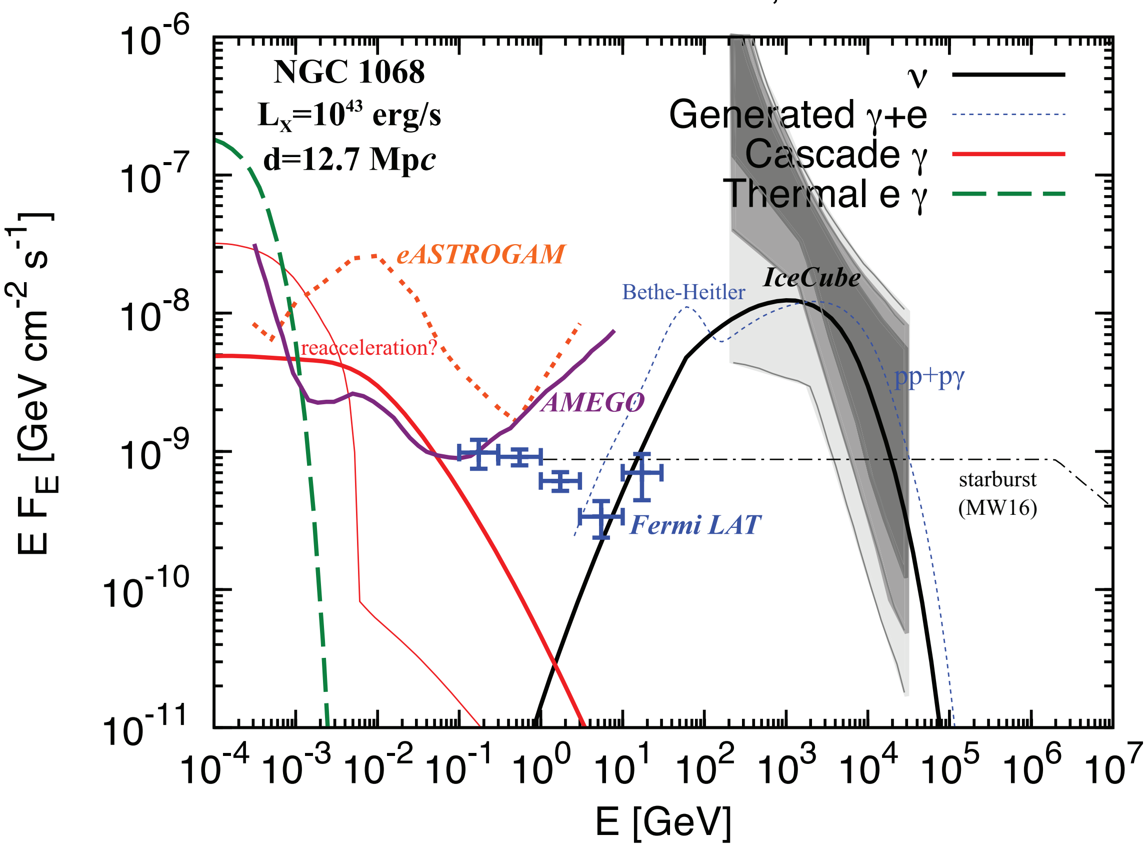
Strong prediction power: correlation w. X rays and MeV γ rays

Predicted Ranking

1. **Circinus Galaxy**
2. **ESO 138-G001**
3. NGC 7582
4. Cen A
5. **NGC 1068**
6. NGC 424
7. CGCG 164-019

blue: south
red: north

KM, Kimura & Meszaros 19



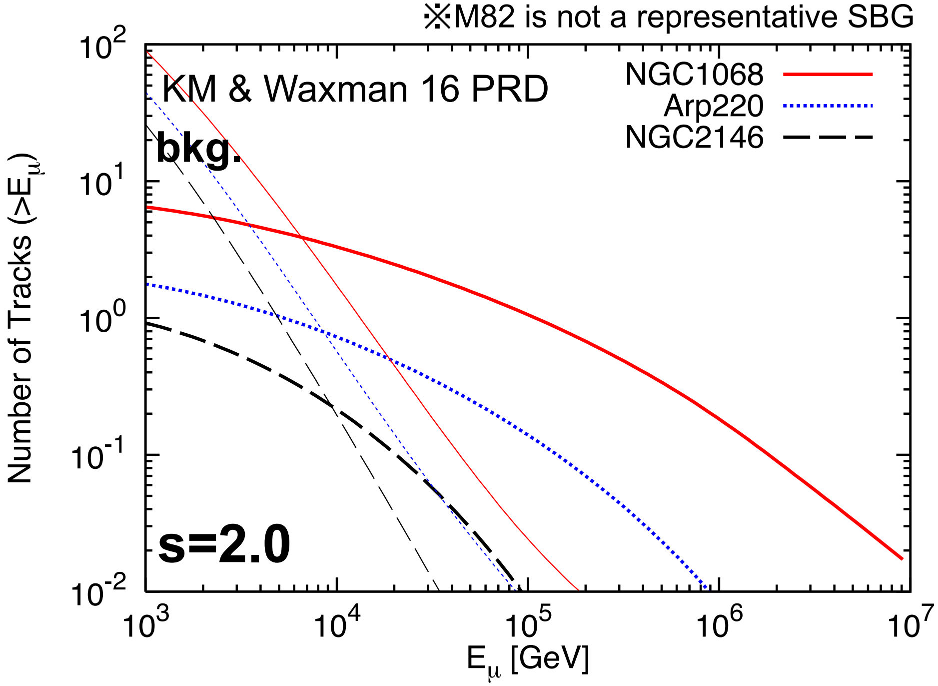
- Guaranteed MeV γ-ray counterparts: detectable by AMEGO etc.
- NGC 1068: top 1 in the north and consistent w. the multi-messenger data
- Importance of shower search (<100 TeV), many in the south → KM3Net!!!

Comparison w. the Starburst Galaxy Scenario

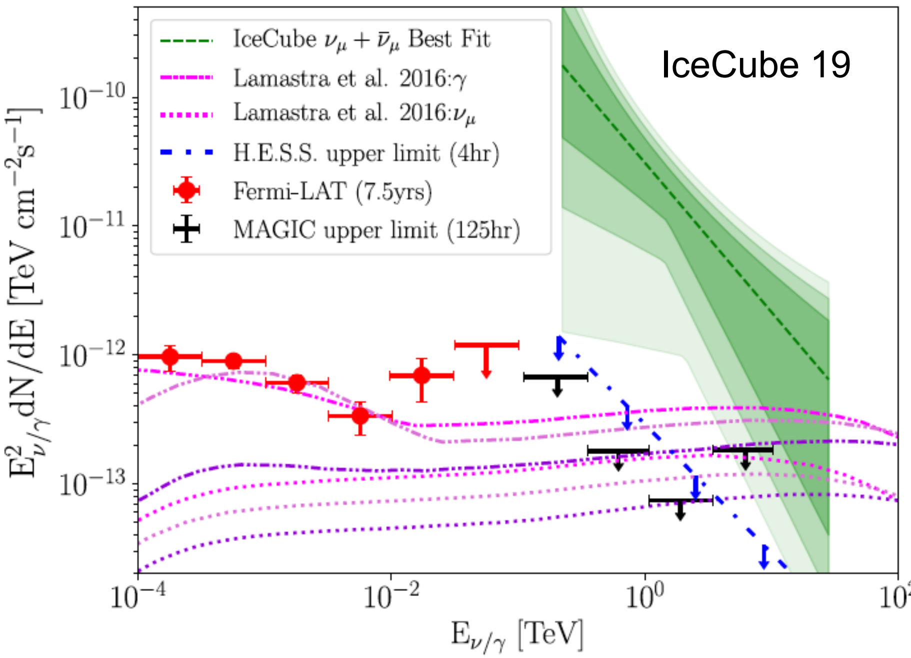
ν and γ-ray spectra of pp sources: **s<2.1-2.2** (KM, Ahlers & Lacki 13 PRDR)
→ "representative" sources should have **s~2.0-2.1: promising**

nearby starburst galaxies (north) IceCube 10 year observations

※M82 is not a representative SBG



IceCube 10 year point-source NGC 1068: ~3σ (post-trial)



- Prediction: IceCube may see ~2-3σ fluctuations (ex. NGC 1068)
- But… spectrum is too soft & contradiction w. MAGIC γ-ray limits

Summary II

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Core-Collapse Supernovae:

Dense CSM guaranteed by optical observations & important for PeVatrons
Next Galactic SN: >10-100 HE ν events from a normal SN II → **KM3Net!**

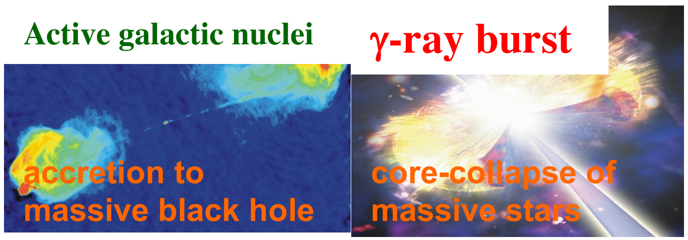
AGN Coronae:

AGN corona model: unique connection to X-ray and MeV γ-ray backgrounds
Strong prediction power: nearby Seyferts such as NGC 1068 are promising
Importance of shower search (<100 TeV), many in the south → **KM3Net!!!**

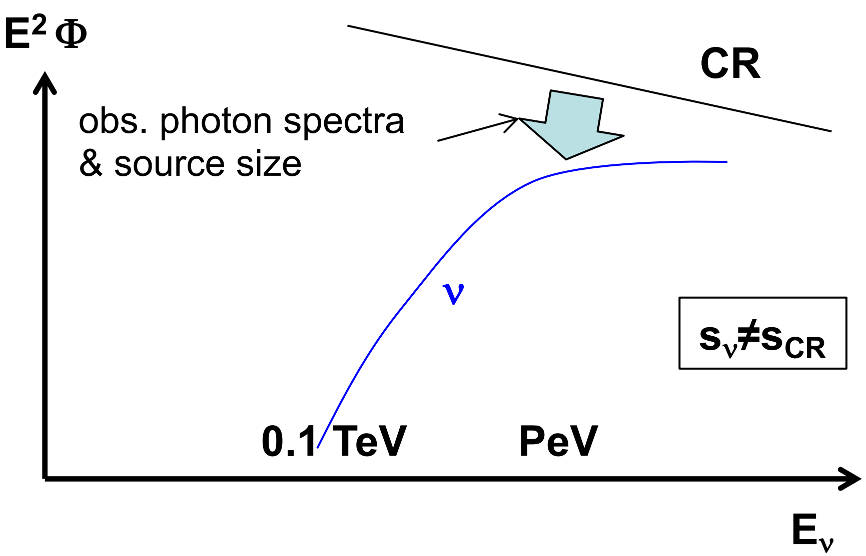
Astrophysical Extragalactic Scenarios

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

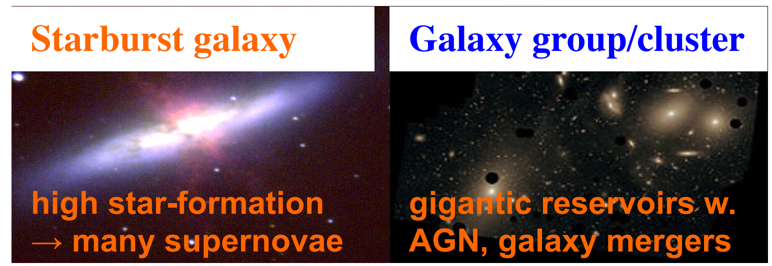
Cosmic-ray Accelerators (ex. UHECR candidate sources)



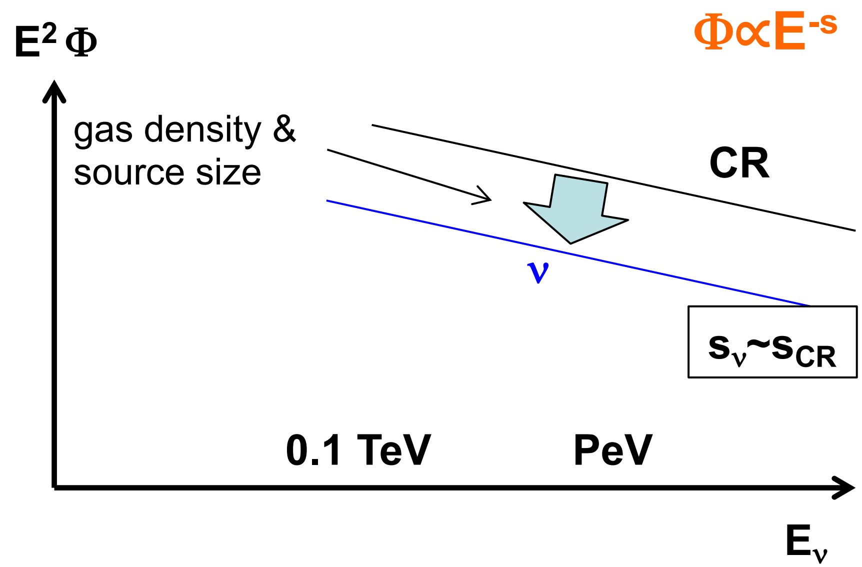
$$p + \gamma \rightarrow N\pi + X$$



Cosmic-ray Reservoirs



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



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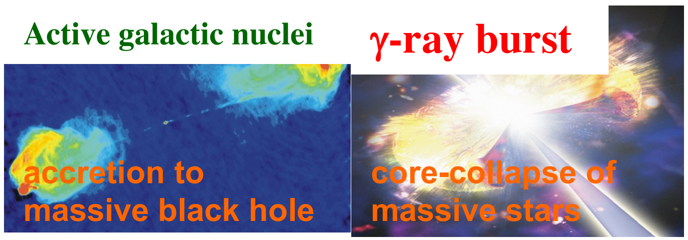
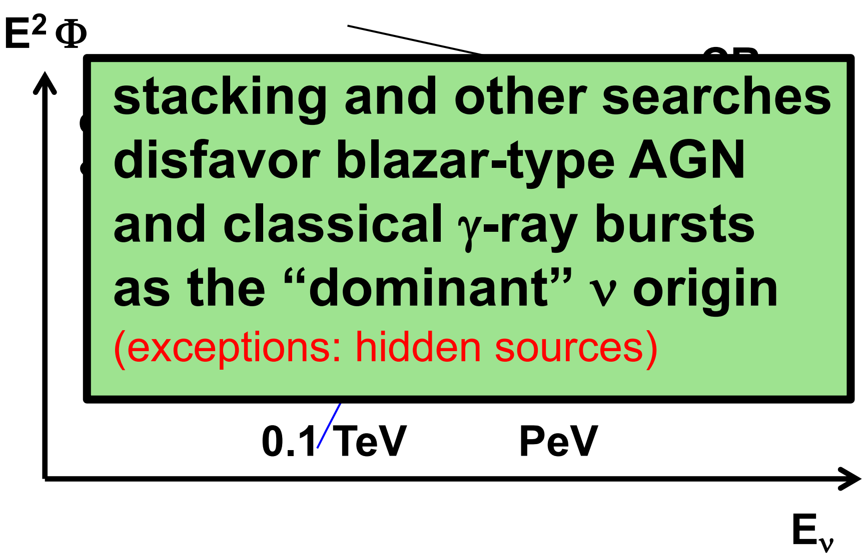


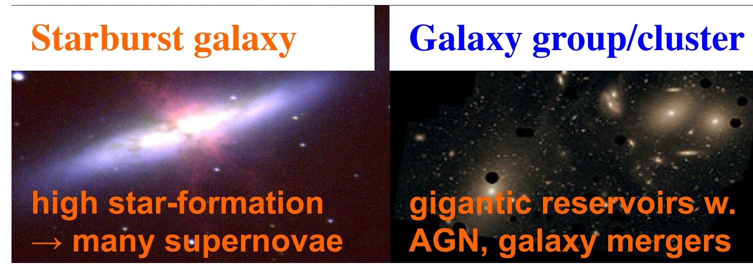
$$p + \gamma \rightarrow N\pi + X$$



stacking and other searches disfavor blazar-type AGN and classical γ-ray bursts as the "dominant" ν origin

(exceptions: hidden sources)

Cosmic-ray Reservoirs



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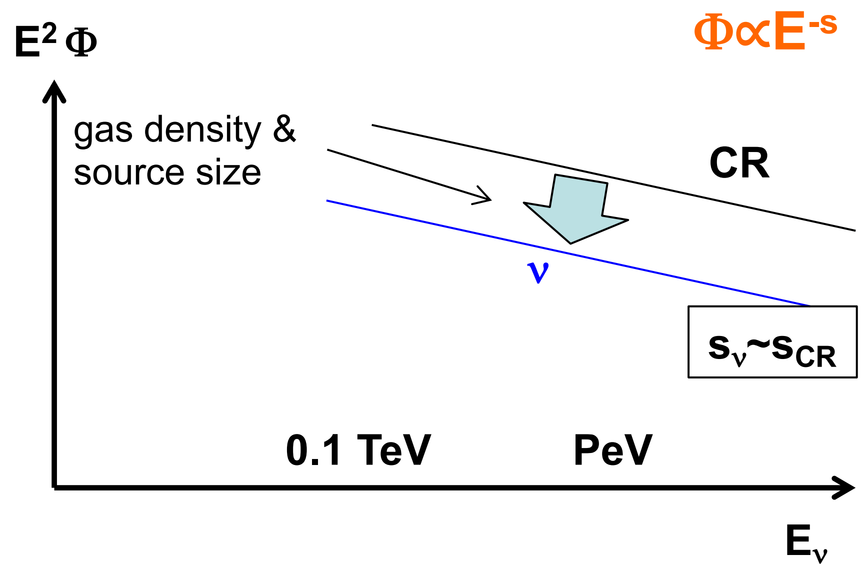
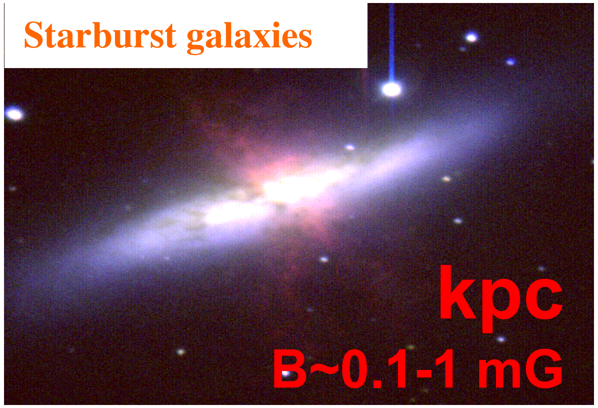
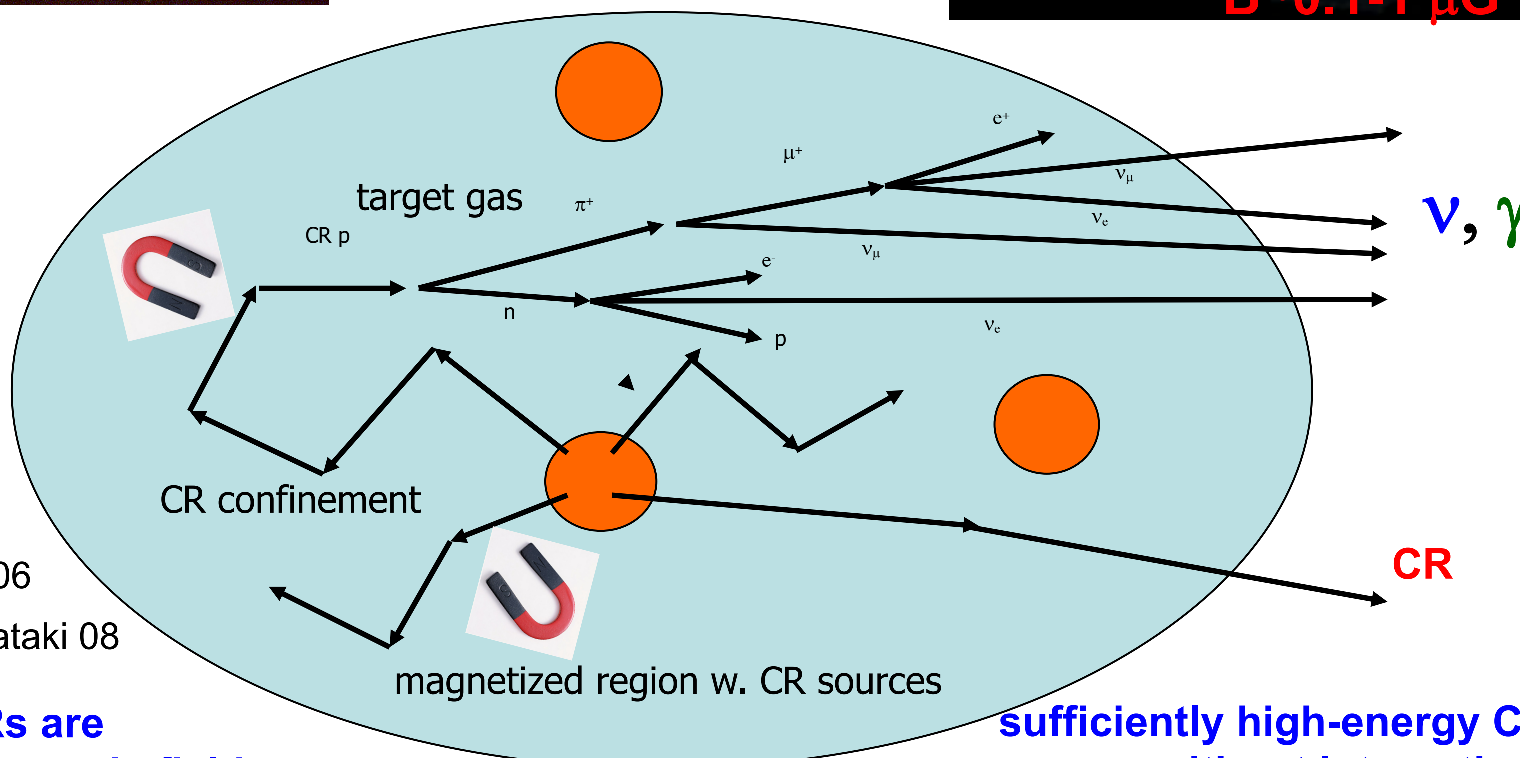


Cosmic-Ray Reservoirs



"cosmic-ray reservoirs"

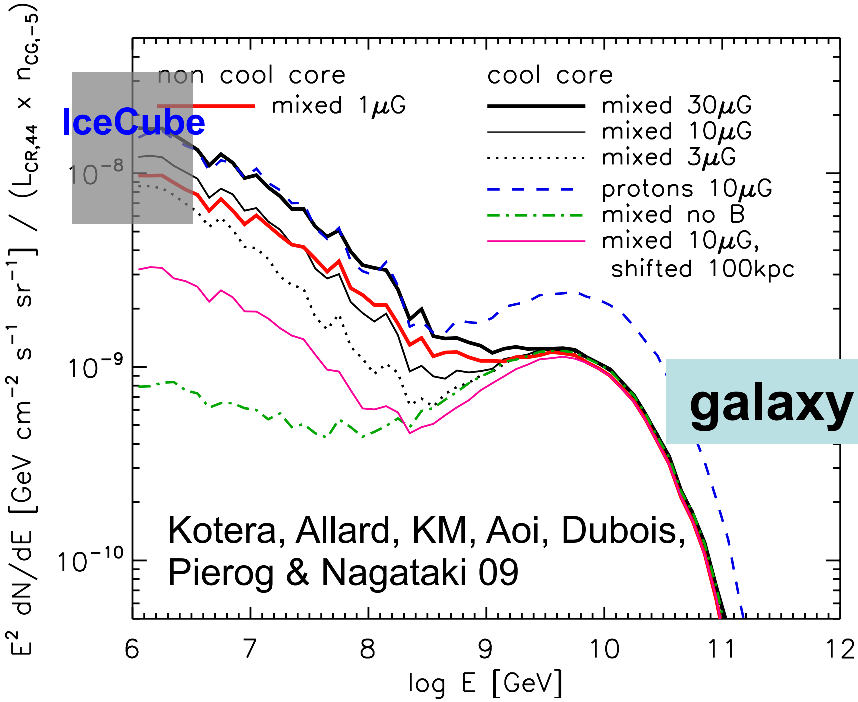


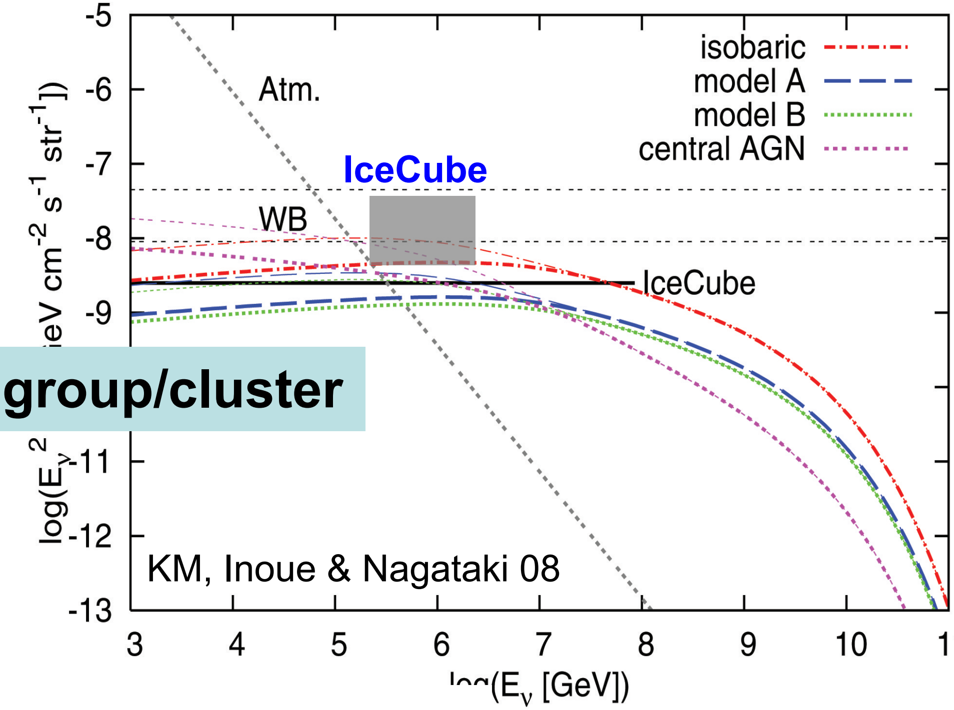
Loeb & Waxman 06

KM, Inoue & Nagataki 08

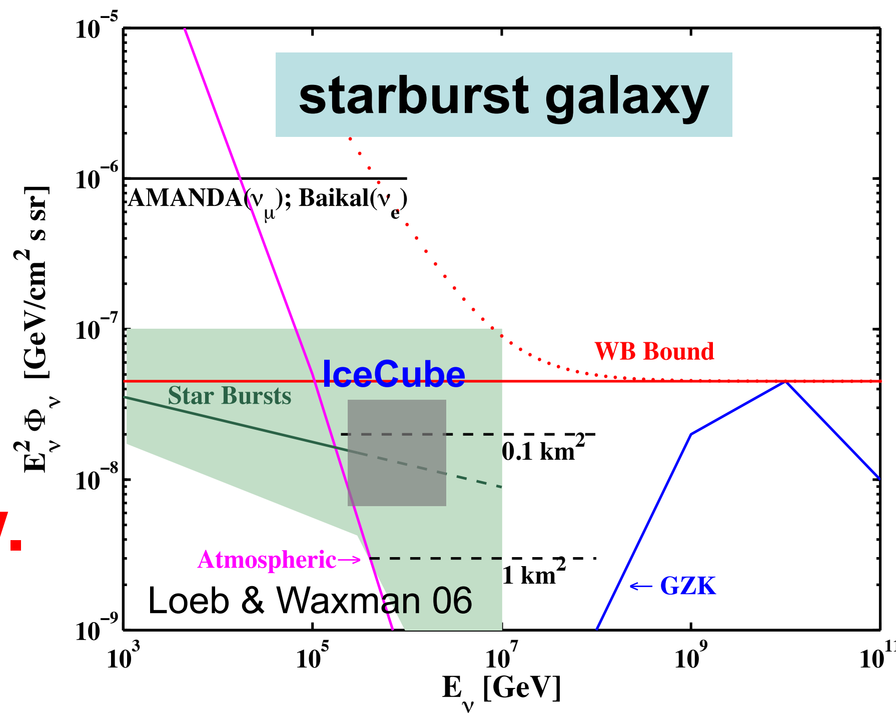
low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions





galaxy group/cluster

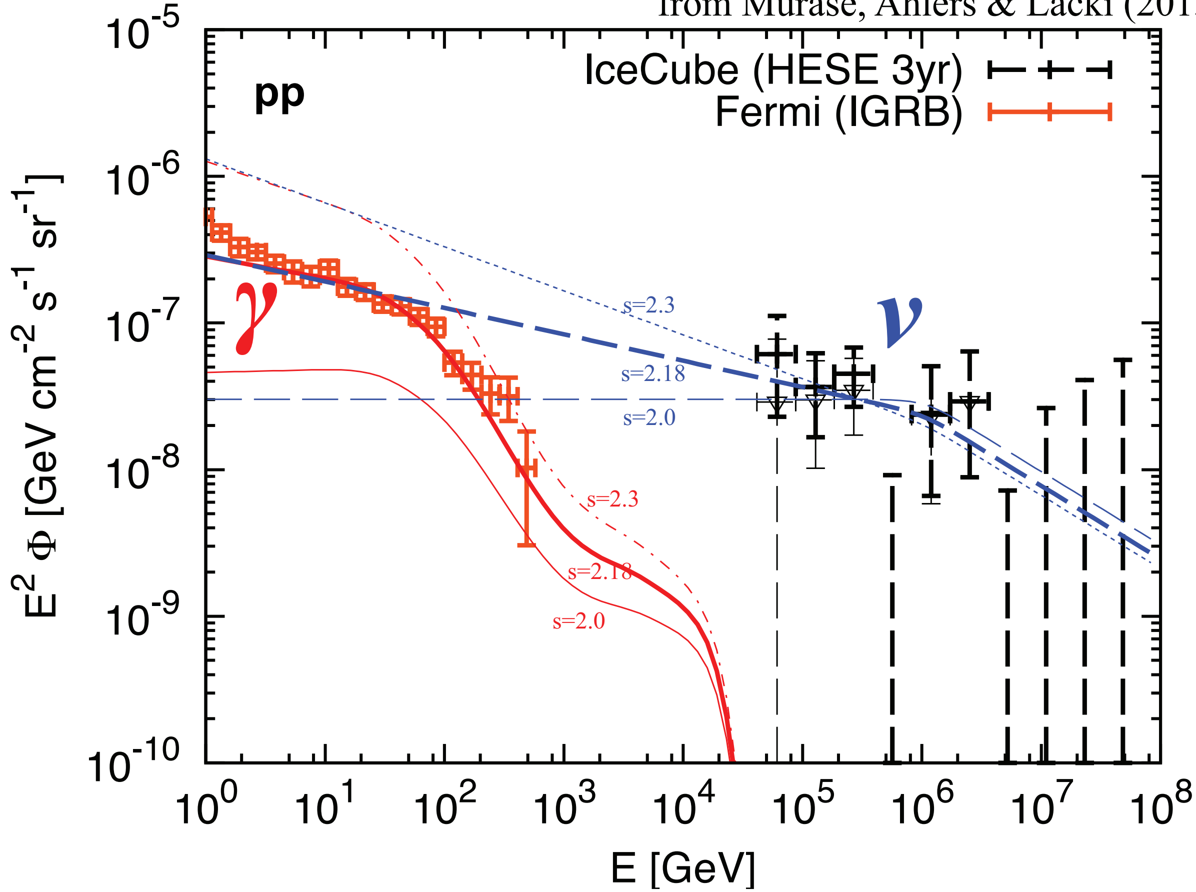


Consistent w. predictions

Neutrino-Gamma Connection

Generic power-law spectrum: $\propto \varepsilon^{2-s}$, transparent to GeV-TeV γ

from Murase, Ahlers & Lacki (2013)



- **s_ν<2.1-2.2 (for extragal.); insensitive to redshift evolution of sources**
- **physical connection between ν & γ backgrounds?**
  contribution to diffuse sub-TeV γ: >30%(SFR evol.)-40% (no evol.)

PHYSICAL REVIEW D **88,** 121301(R) (2013)

Testing the hadronuclear origin of PeV neutrinos observed with IceCube

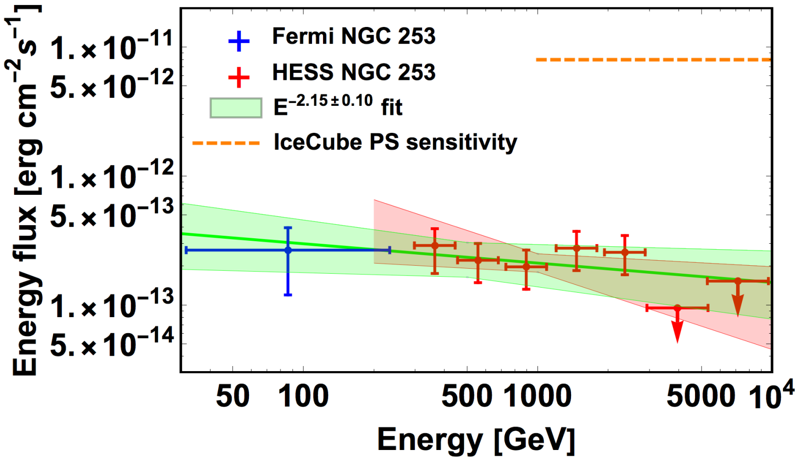
Kohta Murase,[1] Markus Ahlers,[2] and Brian C. Lacki[3]

We consider implications of the IceCube signal for hadronuclear (pp) scenarios of neutrino sources such as galaxy clusters/groups and star-forming galaxies. Since the observed neutrino flux is comparable to the diffuse γ-ray background flux obtained by *Fermi*, we place new, strong *upper* limits on the source spectral index, $\Gamma \lesssim 2.1$–2.2. In addition, the new IceCube data imply that these sources contribute *at least* 30%–40% of the diffuse γ-ray background in the 100 GeV range and even $\sim$100% for softer spectra. Our results, which are insensitive to details of the pp source models, are one of the first strong examples of the multimessenger approach combining the *measured* neutrino and γ-ray fluxes. The pp origin of the IceCube signal can further be tested by constraining Γ with sub-PeV neutrino observations, by unveiling the sub-TeV diffuse γ-ray background and by observing such pp sources with TeV γ-ray detectors. We also discuss specific pp source models with a multi-PeV neutrino break/cutoff, which are consistent with the current IceCube data.

Ex. Starburst Galaxies

Several starbursts are seen by γ rays
(M82, NGC253, NGC 1068, Arp 220 etc.)

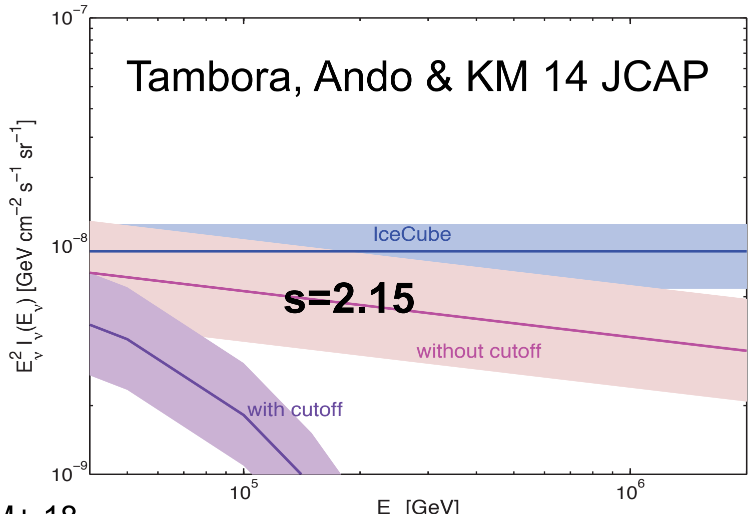
Palladino+ 19 JCAP



Two challenges:

1. **Confinement of CRs up to 100 PeV**
   D_{1GeV}~10^{25}-10^{26} cm^2/s
   << 10^{28} cm^2/s (for Milky Way)
   supernova-driven? CR-driven?

2. Necessity of 100 PeV accelerators
Milky Way: knee at ~3 PeV → ~100 TeV cutoff

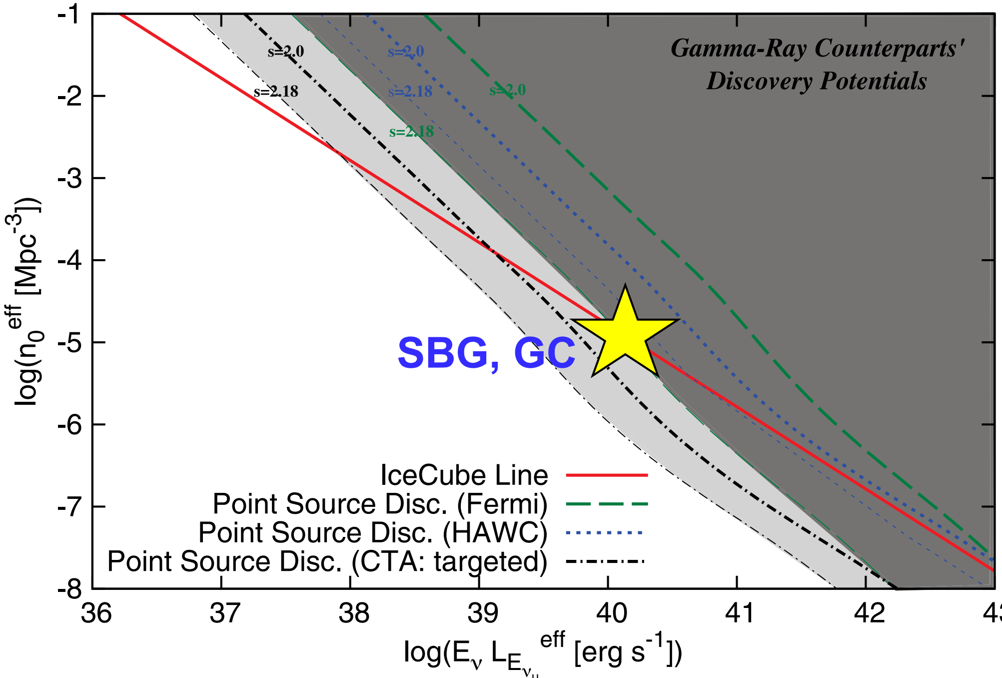


1. ~mG environments — KM+ 13, Peretti, Blasi+ 19
2. Hypernovae & GRBs — KM+ 13, Liu+ 14, Senno+ 15
4. Type IIn/IIb supernovae — Zirakashvilli & Ptuskin 16
5. Super-bubbles — Zhang, KM & Meszaros 19
6. AGN disk-driven flows — Tamborra+KM 14, Wang & Loeb 17
7. Galaxy mergers — Kashiyama & Meszaros 14, Yuan, KM+ 18

Gamma-Ray Tests: Importance of TeV Observations

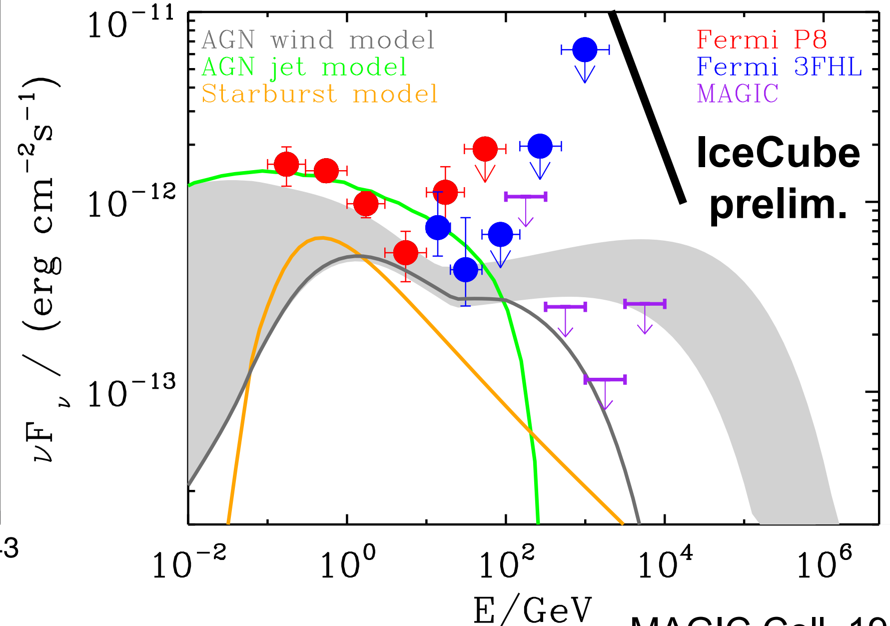
Starbursts & galaxy clusters/groups: γ-ray transparent up to ~1-100 TeV
s~2-2.1 → promising for γ-ray targeted (point-source & stacking) searches

γ-ray constraints on number density



KM & Waxman 16 PRD

NGC 1068



MAGIC Coll. 19

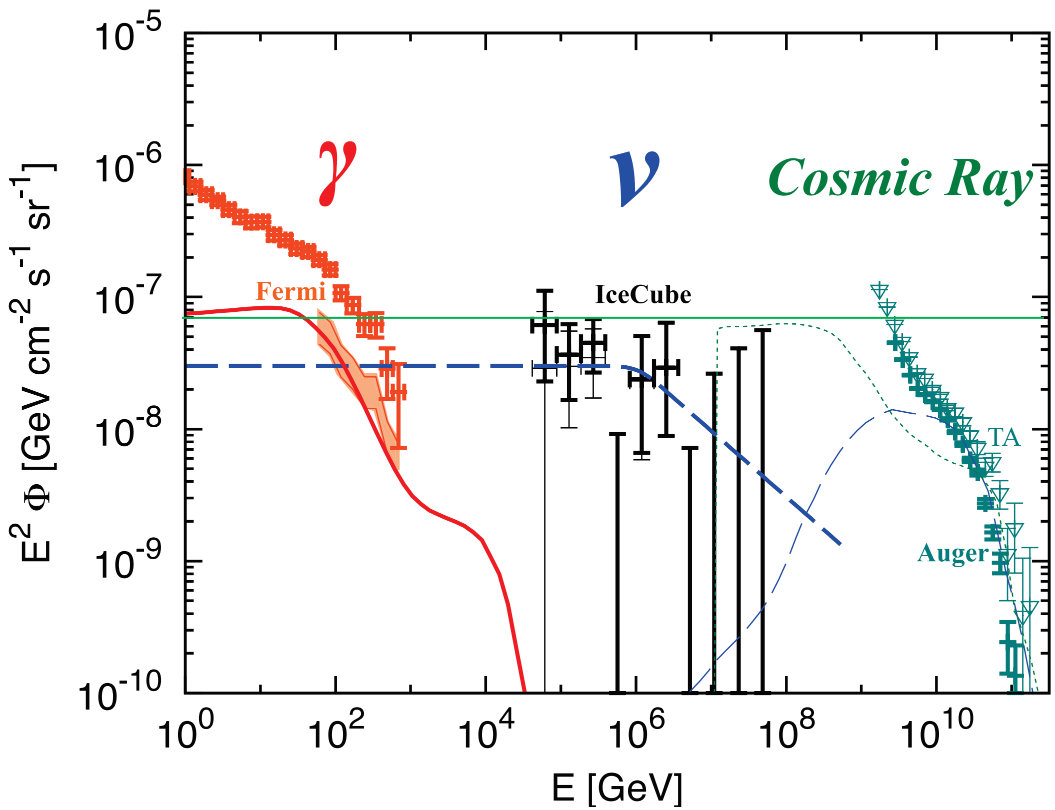
- About 10 representative sources should be seen by CTA
- Possible to have strong constraints even w. current IACTs

Neutrino-Gamma-UHECR Connection?

(grand-)unification of neutrinos, gamma rays & UHECRs

simple flat energy spectrum w. s~2 can fit all diffuse fluxes

- Explain >0.1 PeV ν data with a few PeV break (theoretically expected)
- Escaping CRs may contribute to the observed UHECR flux

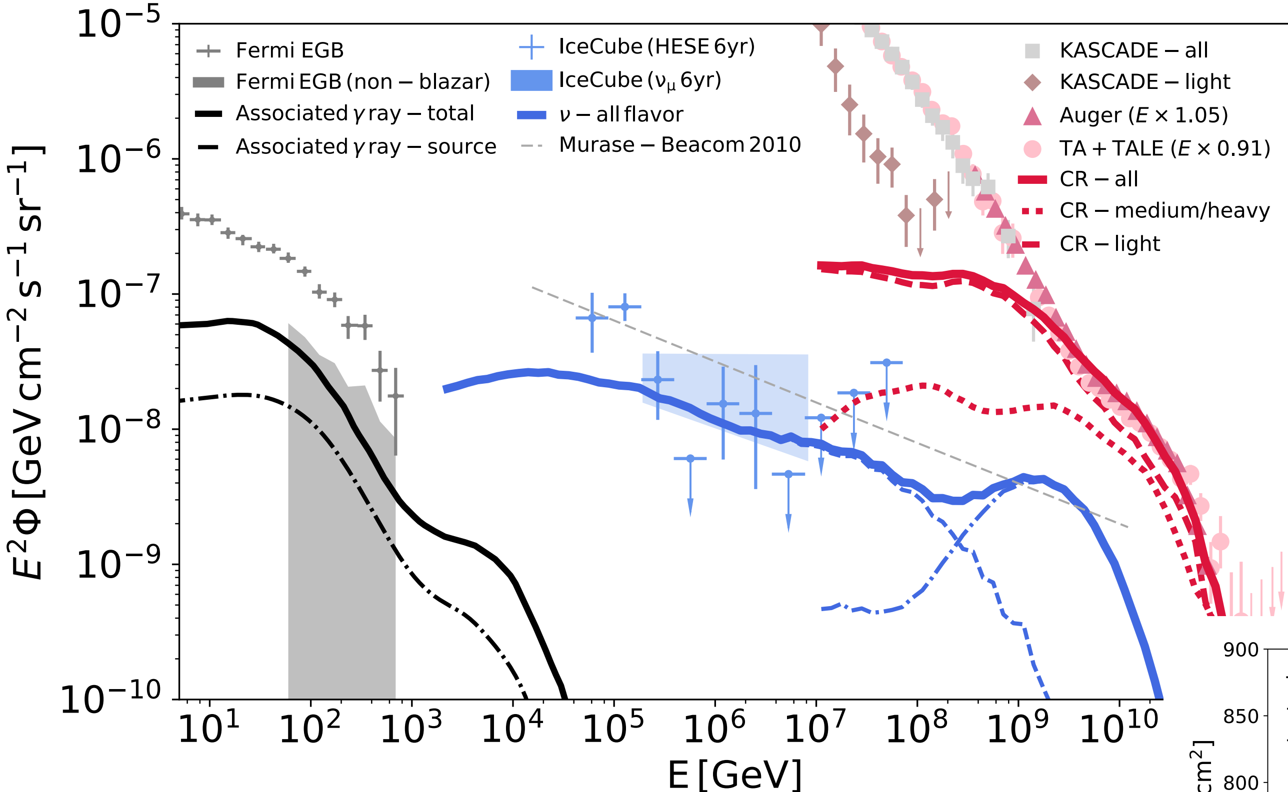


KM & Waxman 16 PRD

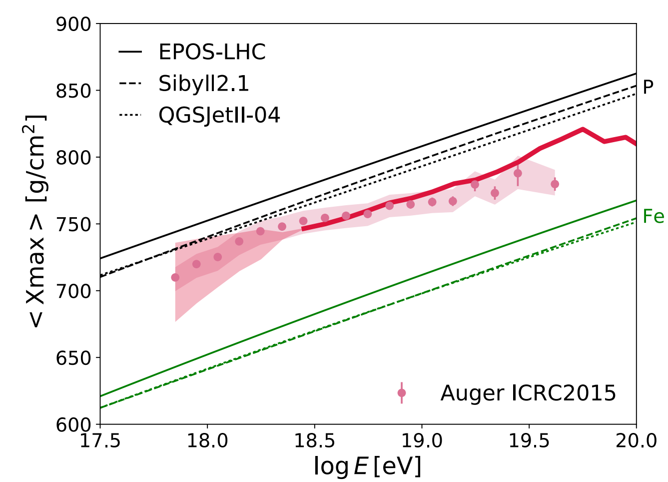
PeVν – confined CR
UHECR – escaping CR
sub-TeVγ – "sum"

Ex. AGN Embedded in Galaxy Clusters/Groups

"Unifying" >0.1 PeV ν, sub-TeV γ, and UHECRs (above 2[nd] knee at 10^{17} eV)



Fang & KM 18 Nature Phys.



- AGN as "UHECR" accelerators
- confinement in cocoons & clusters
- escaping nuclei → "hard" spectrum
- smooth transition to cosmogenic ν spectrum

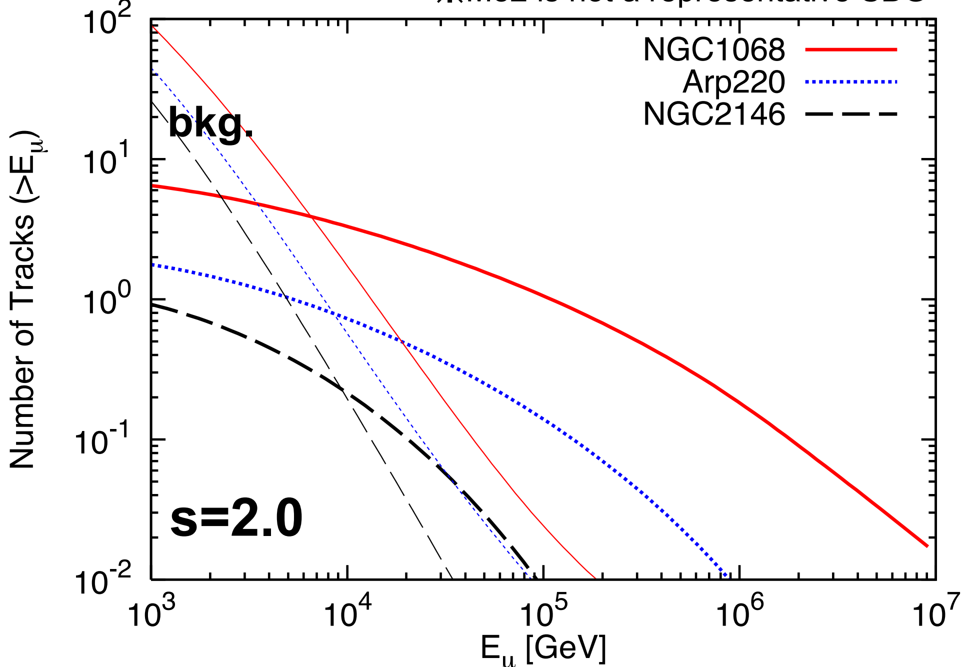
Neutrino Tests: Detectability of Neutrino Sources

γ-ray spectra of pp sources should be hard: **s<2.1-2.2** (KM, Ahlers & Lacki 13)
→ nearby "representative" sources w. **s~2.0-2.1 are promising**

nearby starburst galaxies (north)
IceCube 10 year observations

nearby galaxy clusters
IceCube 5 year observations

※M82 is not a representative SBG



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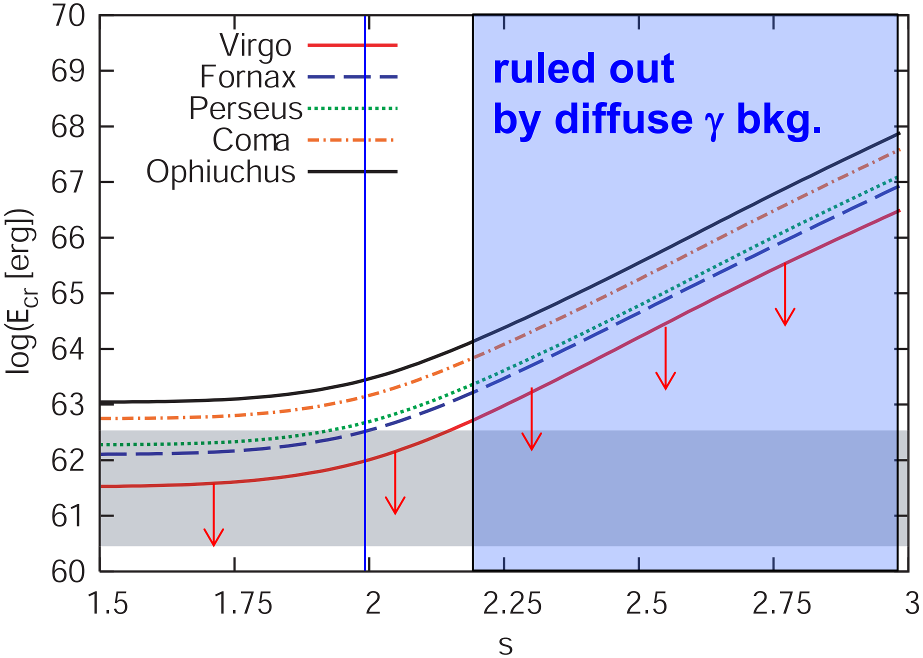

KM & Beacom 13 JCAP

- Current IceCube may see ~2-3σ fluctuations (ex. NGC 1068?)
- IceCube-Gen2 is necessary for discoveries anyway