High-Energy Cosmic Particle Sources II
- Supernovae & Cosmic-Ray Emission -

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PENNSTATE
1855

One Comment: Coincident Examples

Black hole merger

GW150914

GRB 150914

~3σ

No simple concordance

Blazar flare

IceCube-170922A

TXS 0506+056

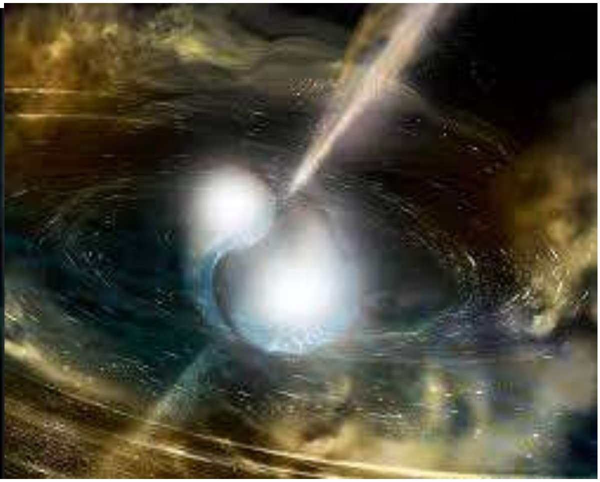
~3σ (~4σ w.o. γ)

No simple concordance

Neutron star merger

GW170817

GRB 170817A

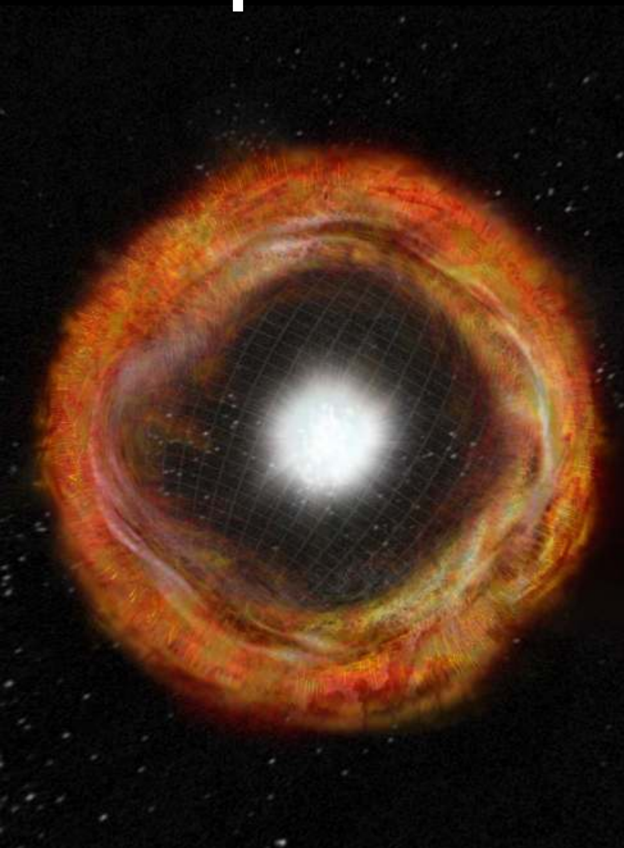


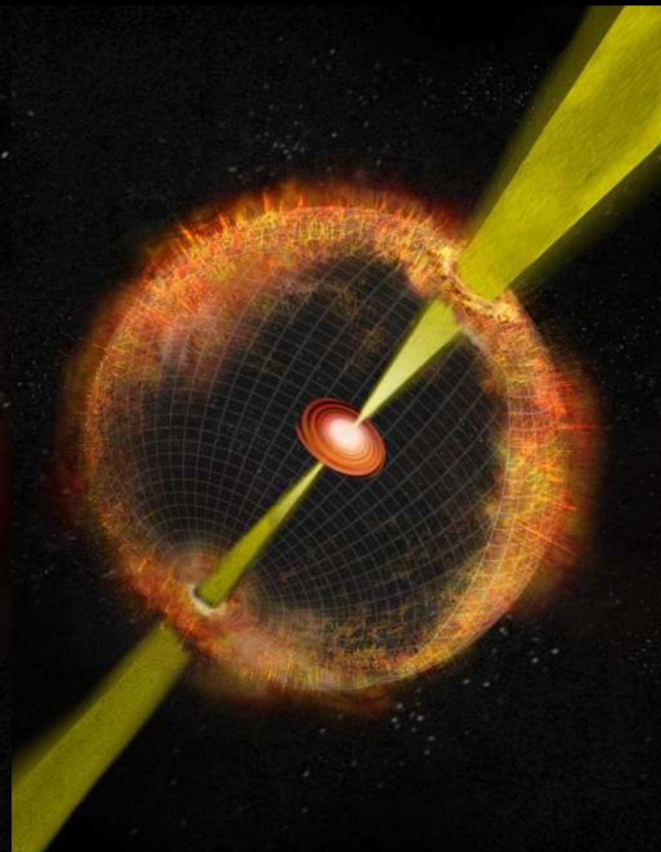
~5σ

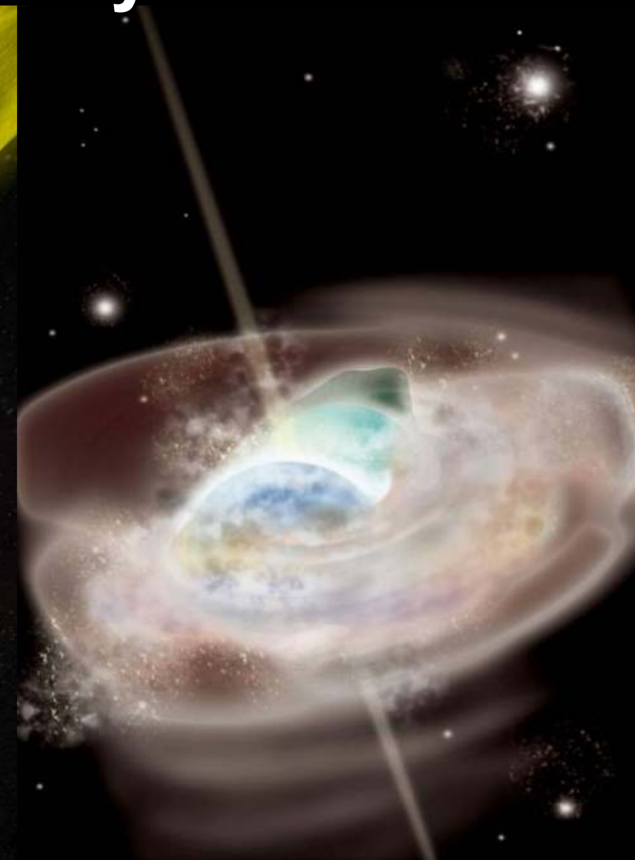
Concordance

What Can νs and GWs Tell Us?

Supernova **Gamma-ray burst**







“Cosmic explosions”

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

What Can νs and GWs Tell Us?

Supernova

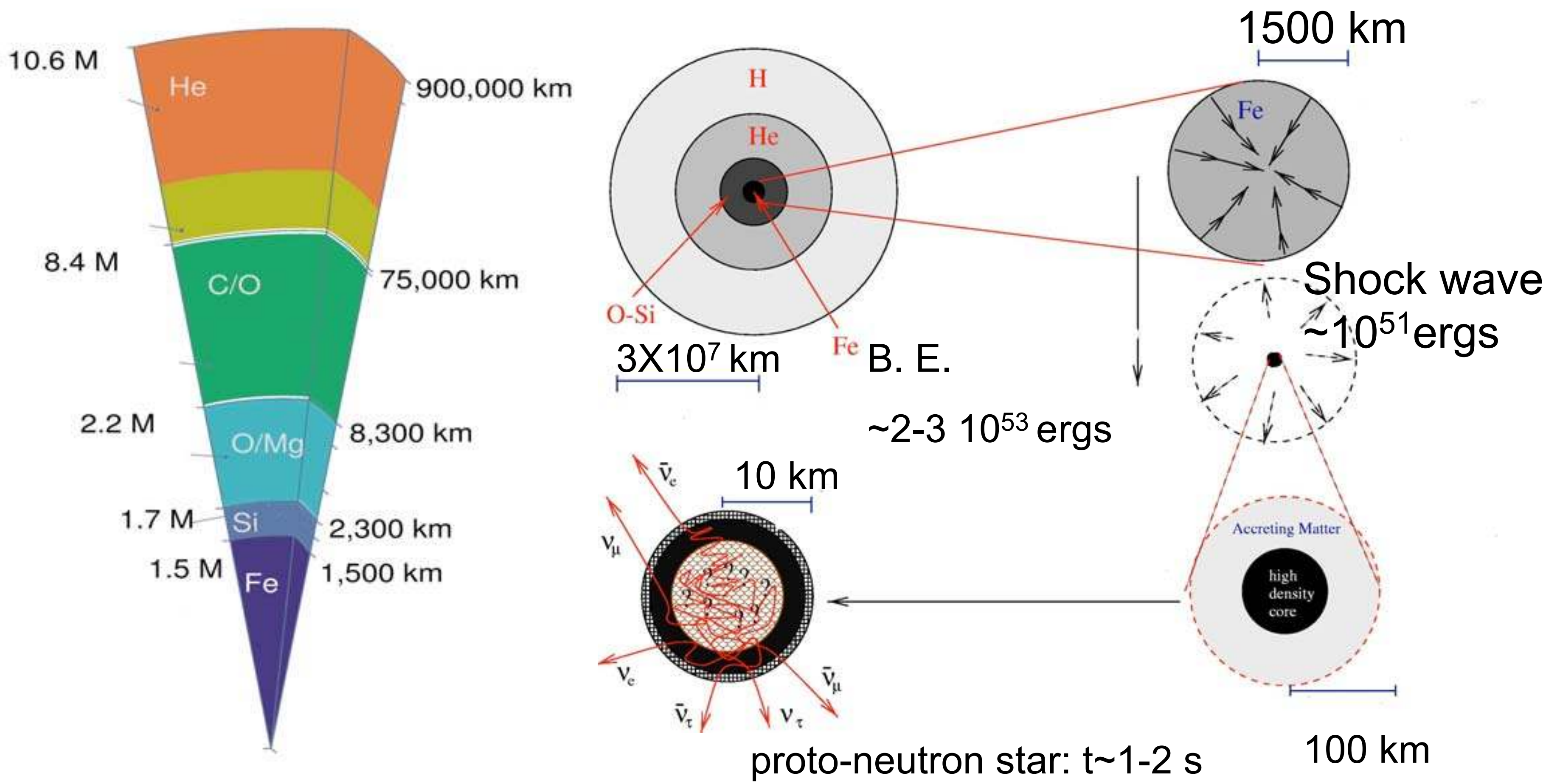
Gamma-ray burst

What are their mechanisms?

"Cosmic explosions"

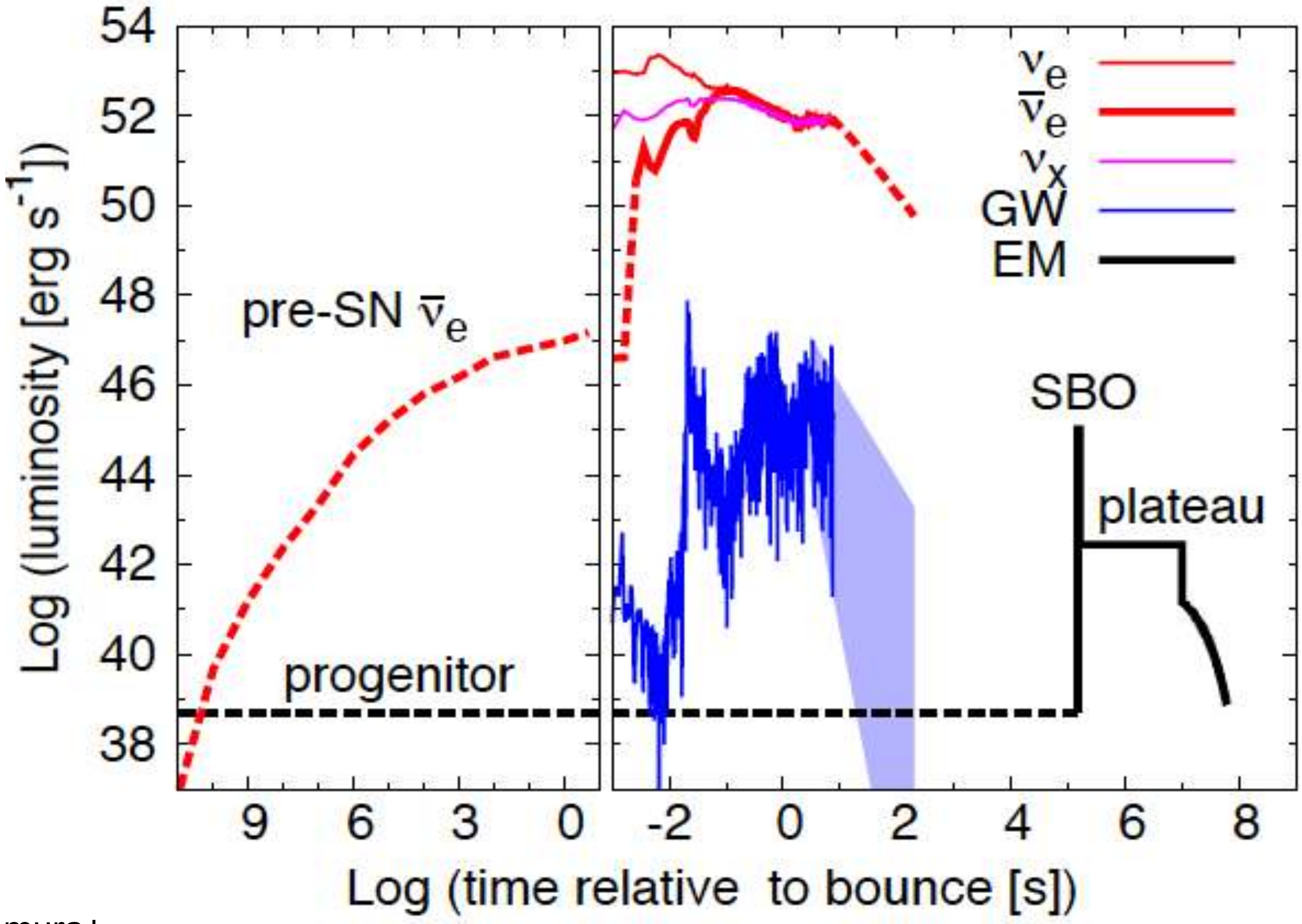
A single explosion can easily outshine an entire galaxy containing hundreds of billions of stars.

Path to Core-Collapse Supernova



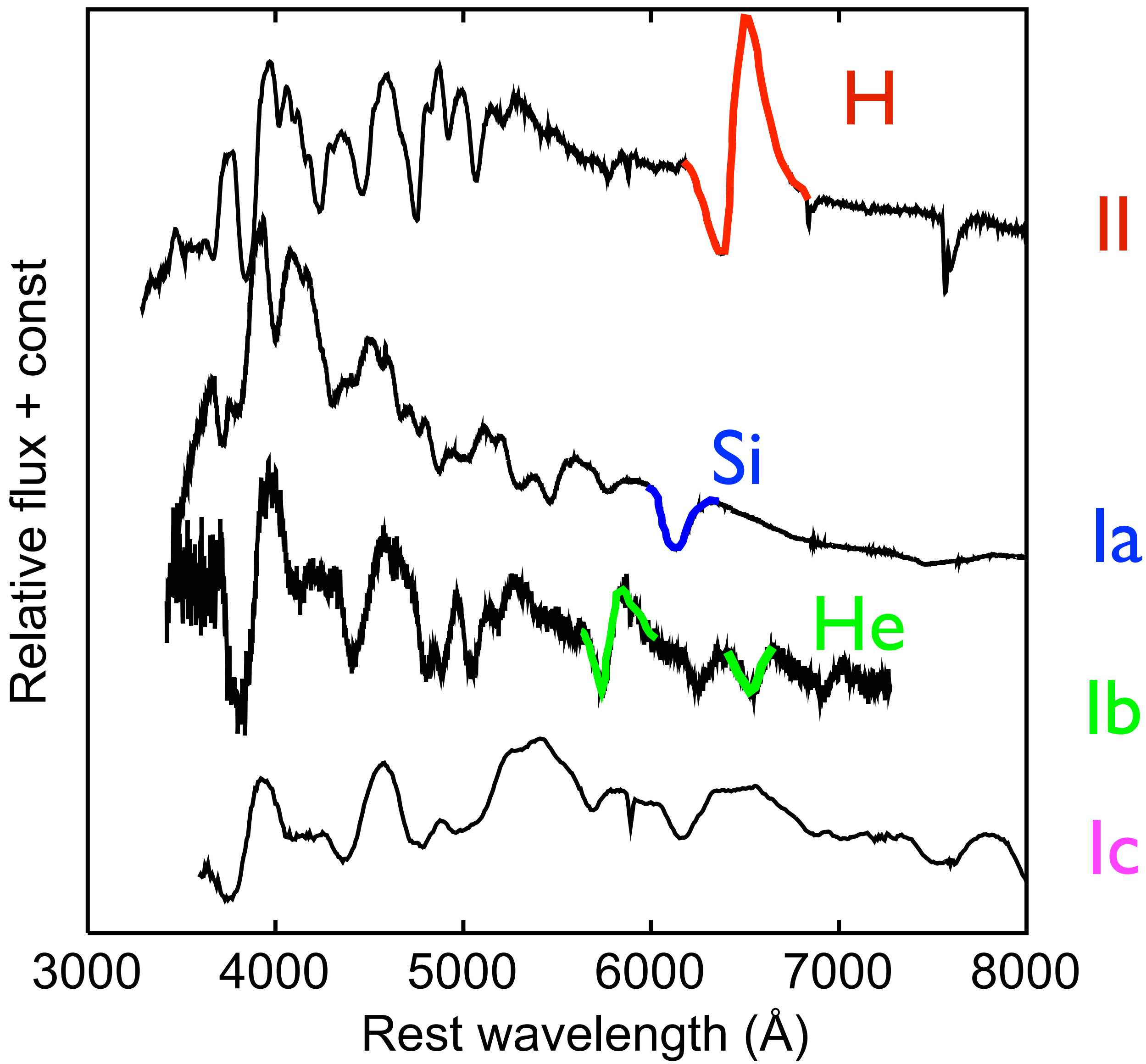
How is gravitational energy converted into kinetic energy?

Supernova as a Multi-Messenger Source

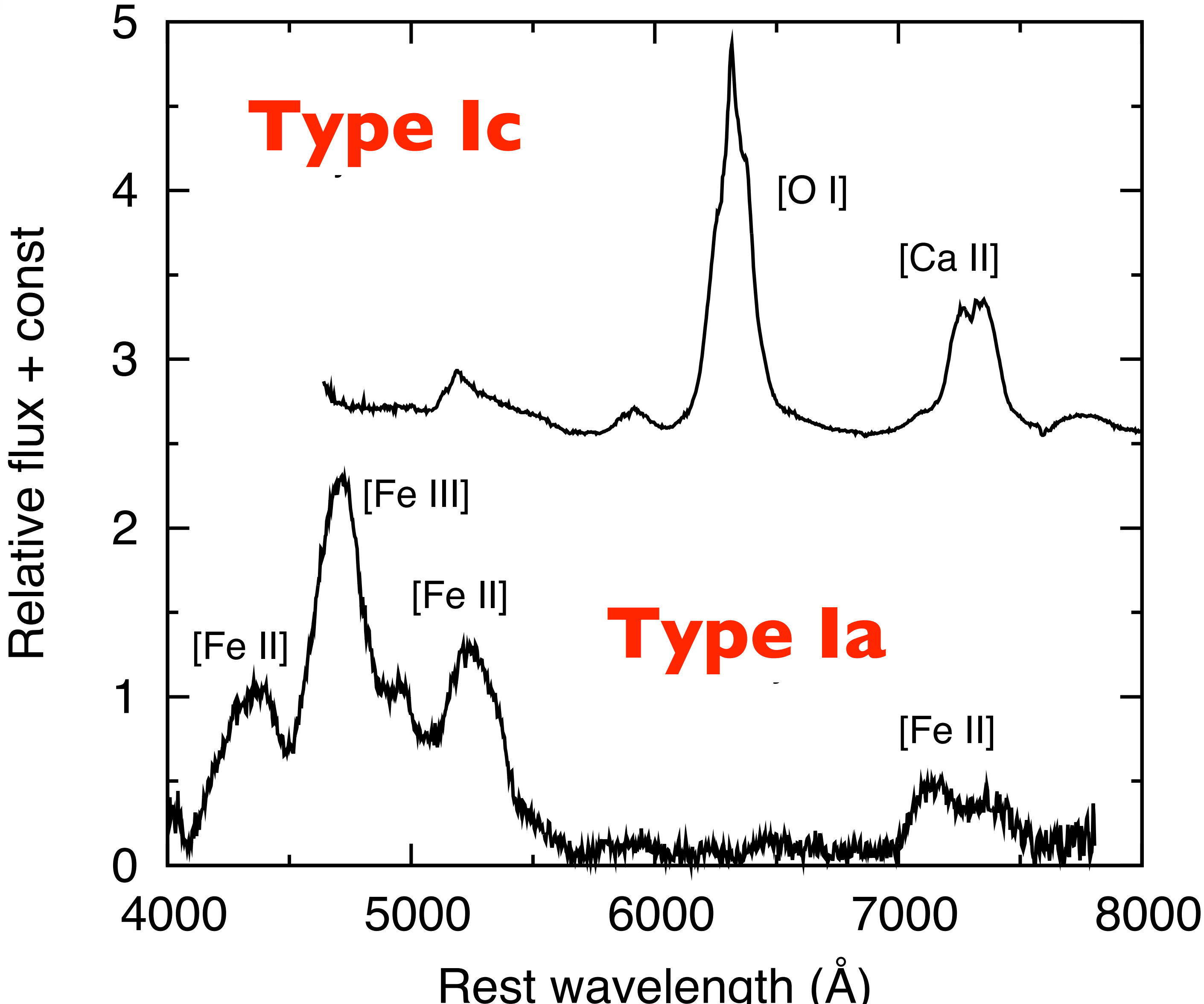


Nakamura+

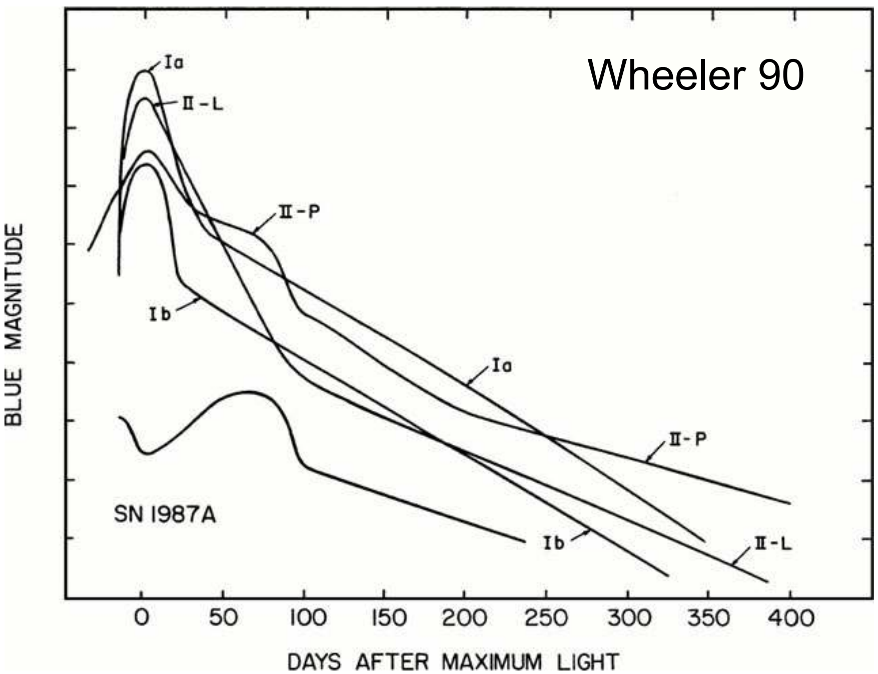
Optical Spectra



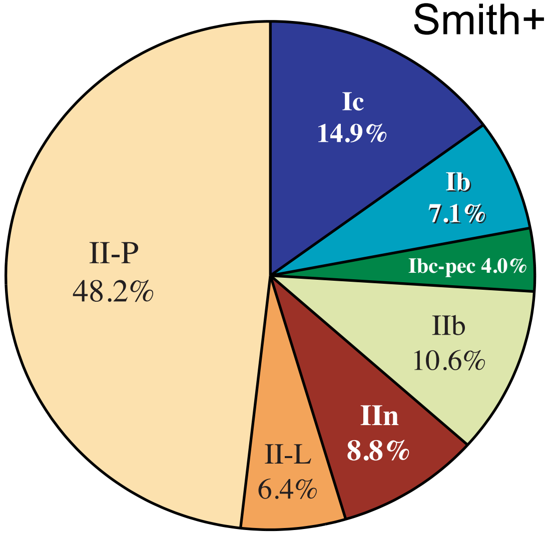
Late Time (Nebula Phase) Spectra



Diversity of Core-Collapse Supernovae



Smith+ 11 MNRAS



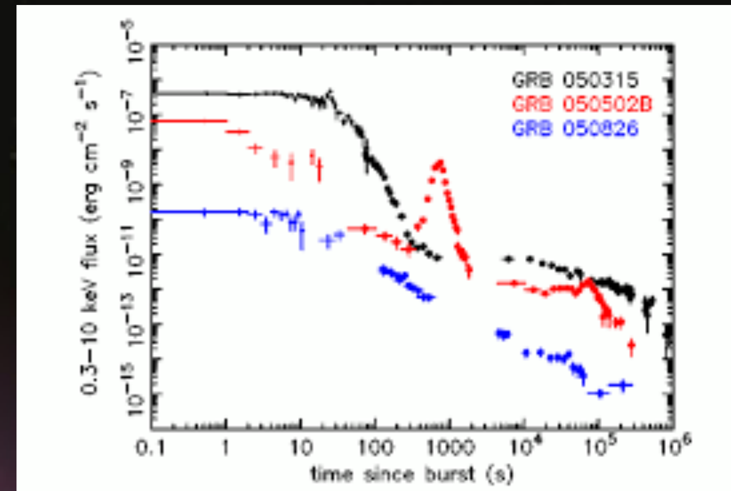
Core-Collapse SN Fractions

Type II: ~ 2/3 of CCSN

II-P/II-L – core-collapse supernovae from red/blue super giants
Ibc/IIb – core-collapse supernovae from binaries or WR stars
Ia – white dwarf merger or white dwarf – star binary

II/Ibc – found in star-forming galaxies
Ia – found in both star-forming and elliptical galaxies

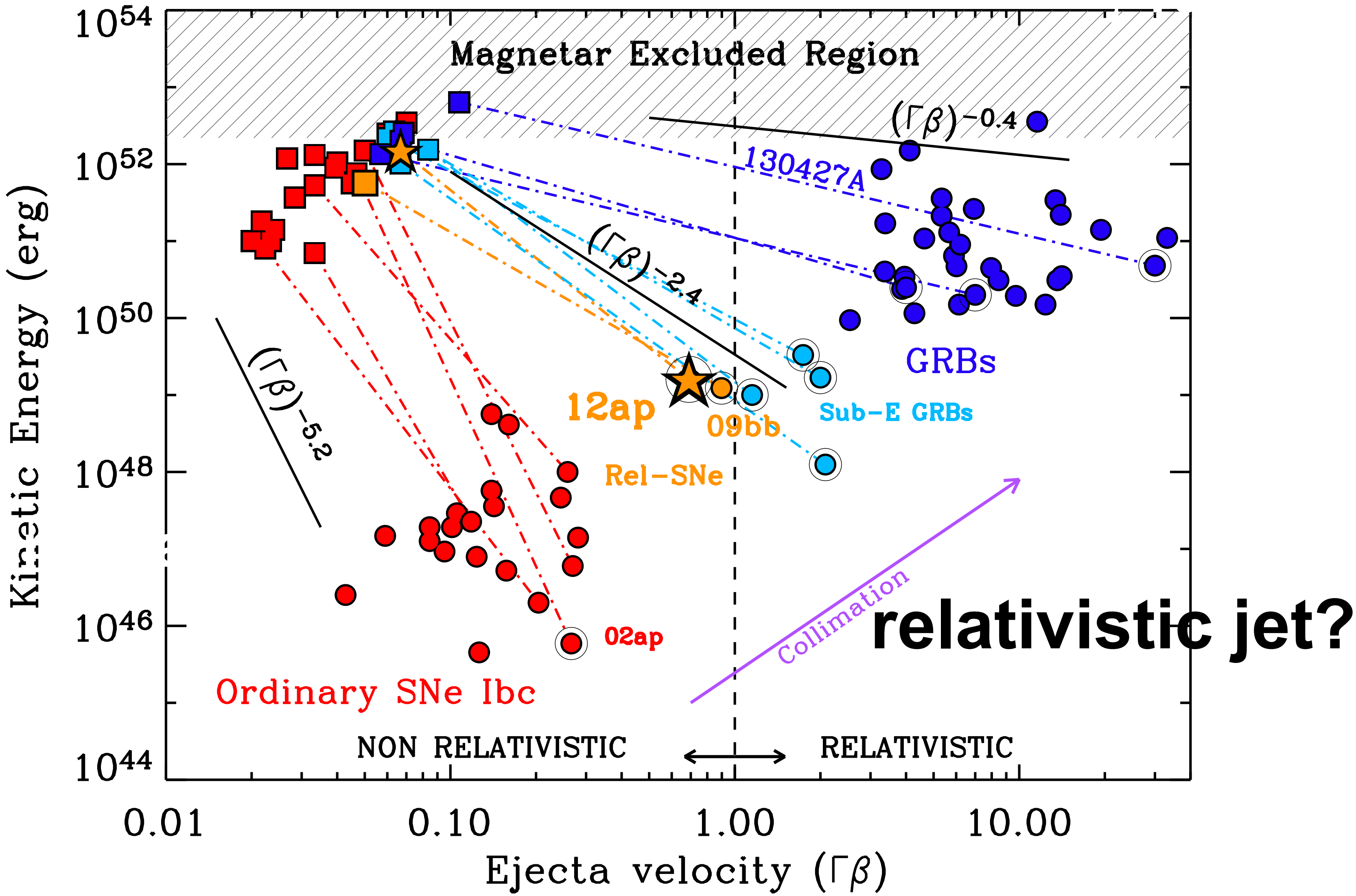
Long Gamma-Ray Bursts



- ~10^{51} erg in γ rays
- Relativistic jets
- Black hole w. accretion disk
  Fast-rotating magnetar
- Broadline Ic supernovae/hypernovae

Trans-Relativistic SNe (Low-Luminosity GRBs)

Margutti+ 14



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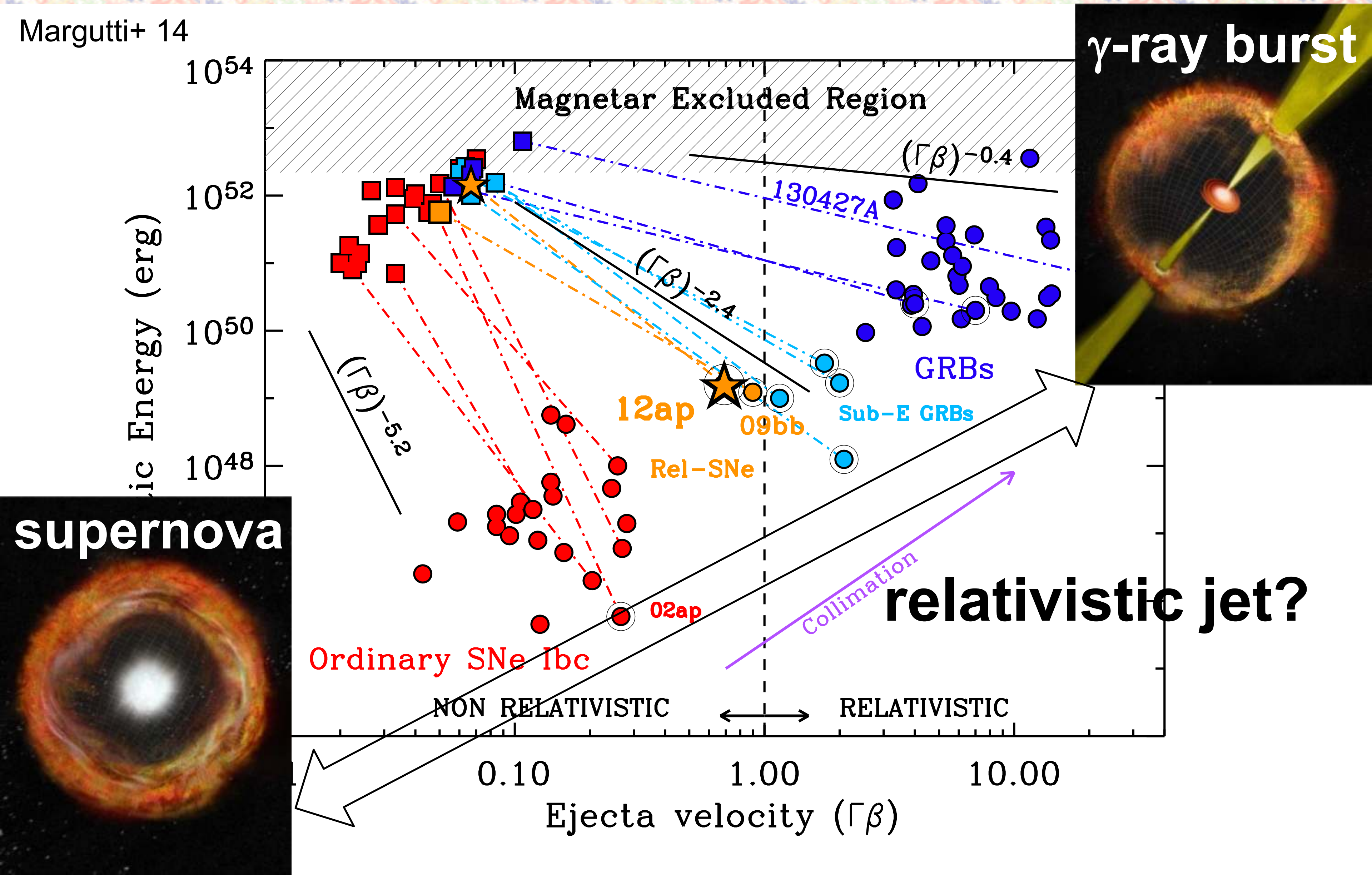
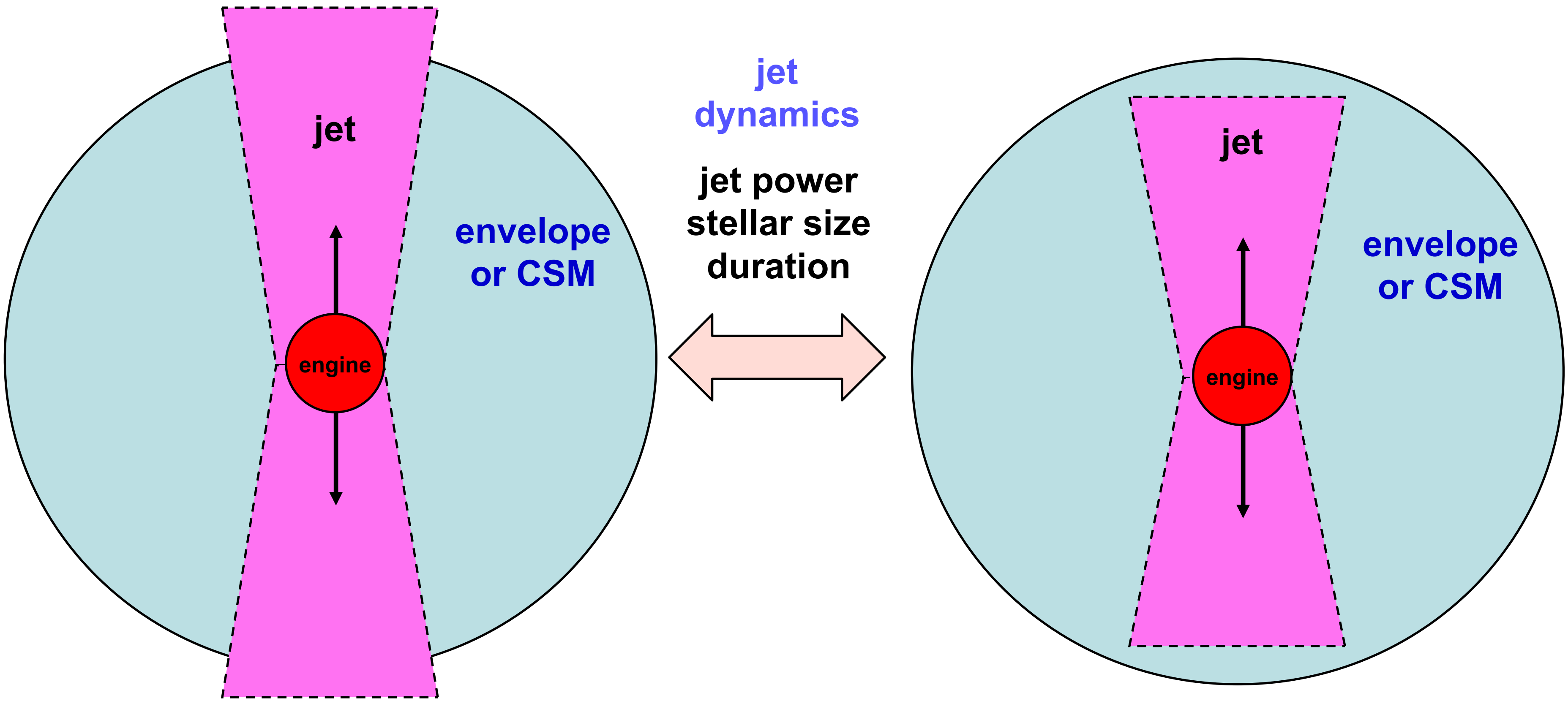


Jets: Key to GRB-SN Connection

"Successful" Jet | "Choked" Jet



long GRB

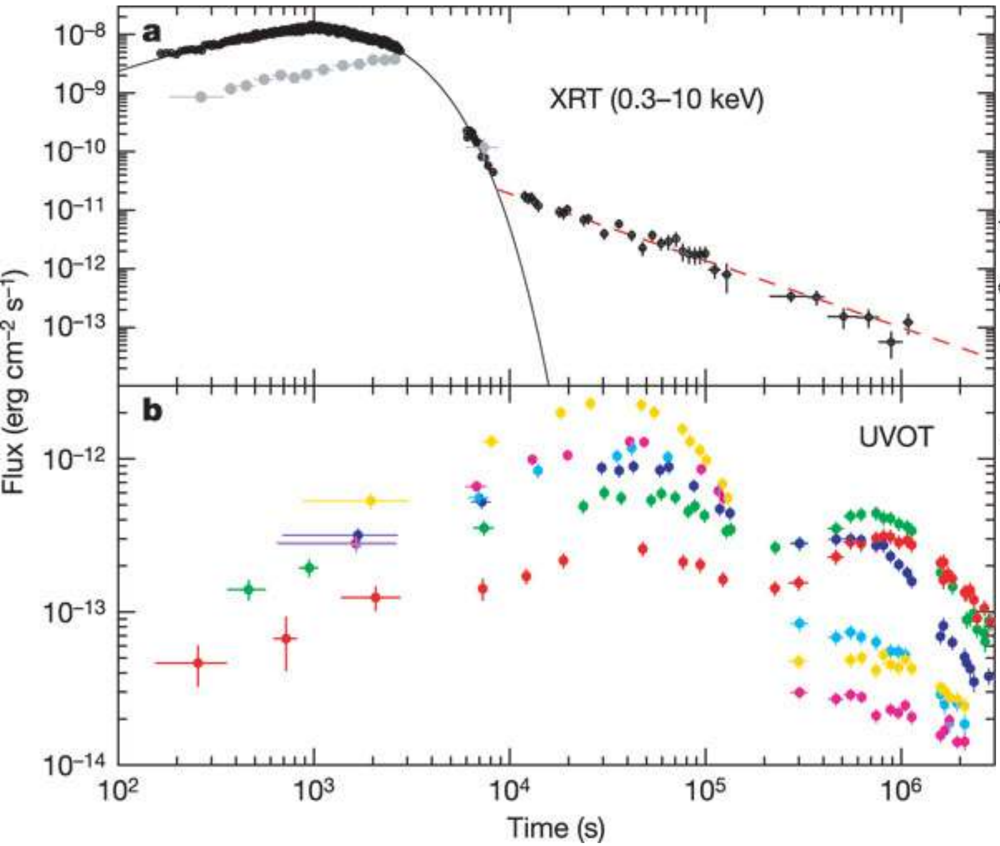
GRB before breakout
failed GRB or jet-powered SN
(trans-relativistic SN? hypernova?)

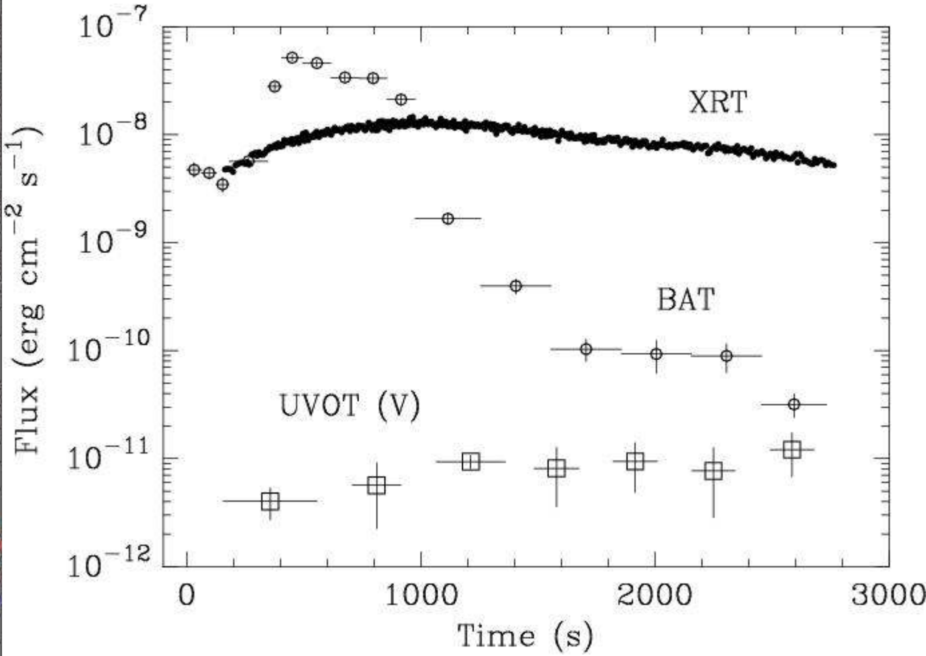
direct counterparts in e,g., γ rays

indirect counterparts in e,g., opt, X rays

GRB 060218: Shock Breakout?

Campana+ 06 Nature





Prompt emission: T ~ 3000 sec w. ε_γ^{pk} ~ 5 keV
long-lasting X-ray and UV (thermal) emission
intermediate nature between GRBs and SNe

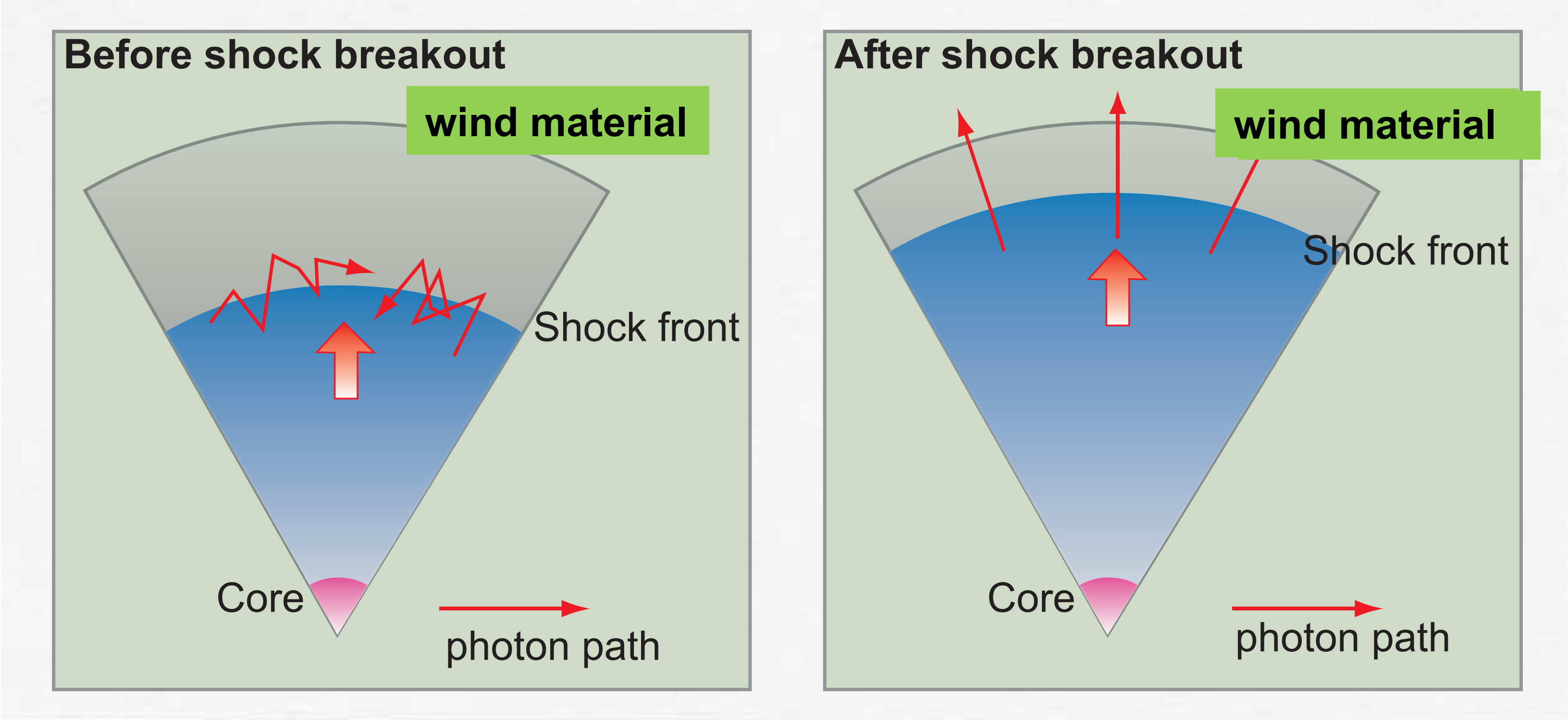
Shock Breakout from Dense Circumstellar Wind

photon diffusion time
$t_{diff} \sim R^2/\kappa_{rad} \sim n\sigma_T R^2/c$

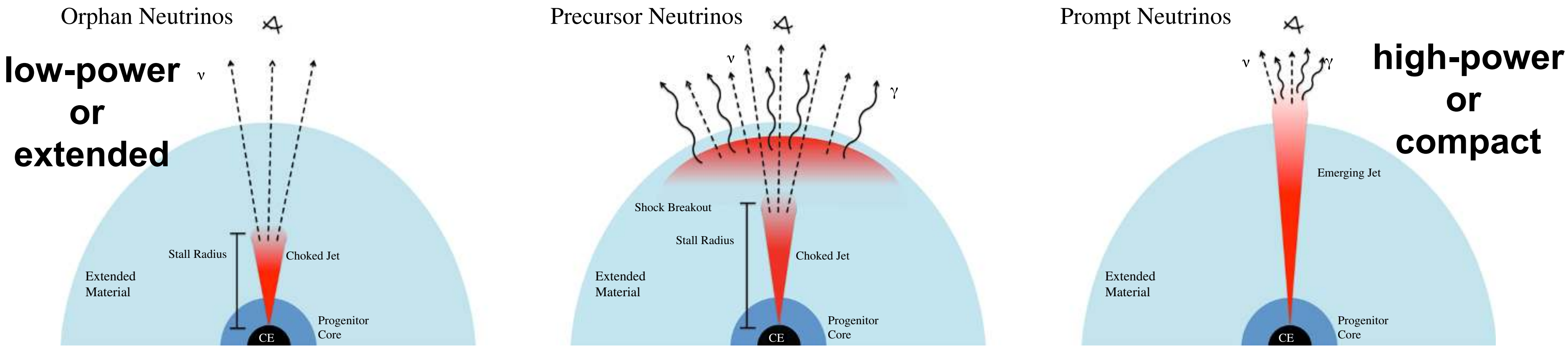
⇔

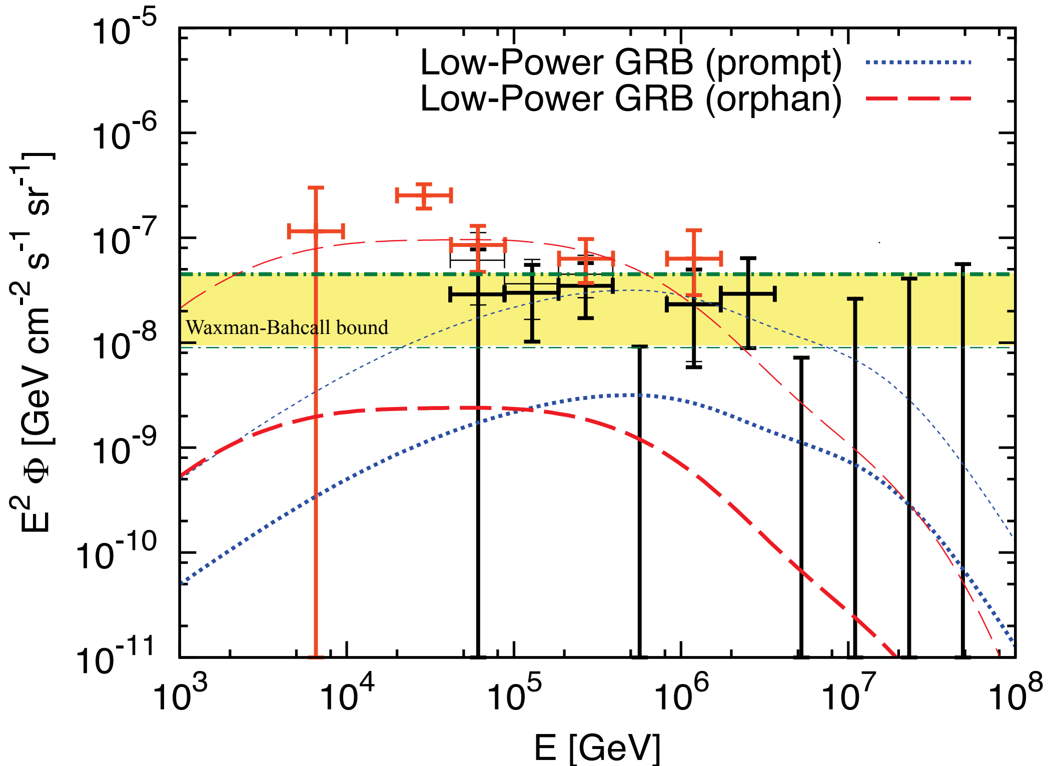
dynamical time:
$t_{dyn} \sim R/\beta c,\ \beta=V/c$

at breakout from wind
$t_{diff}=t_{dyn} \Leftrightarrow \tau_T=1/\beta=c/V$



Choked Jets as Hidden Neutrino Factories?

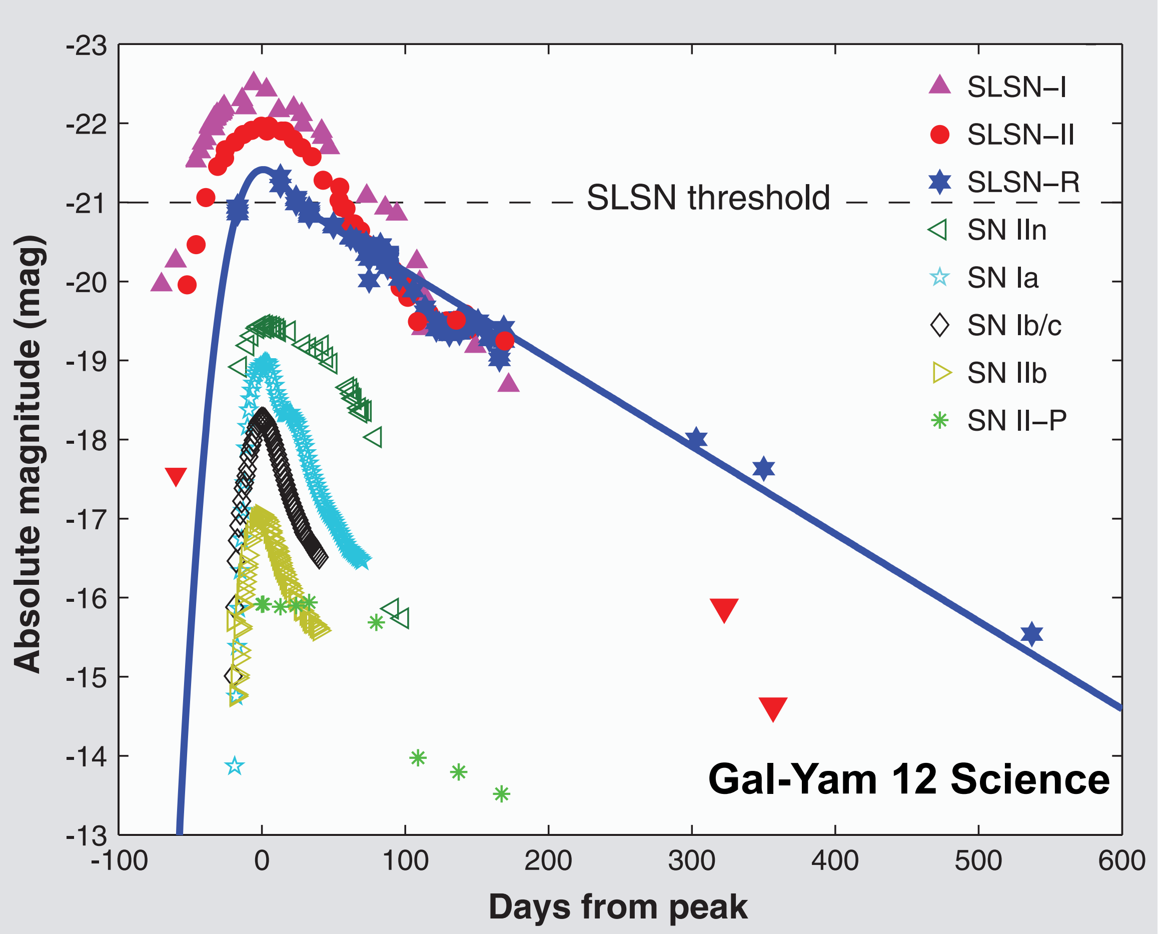




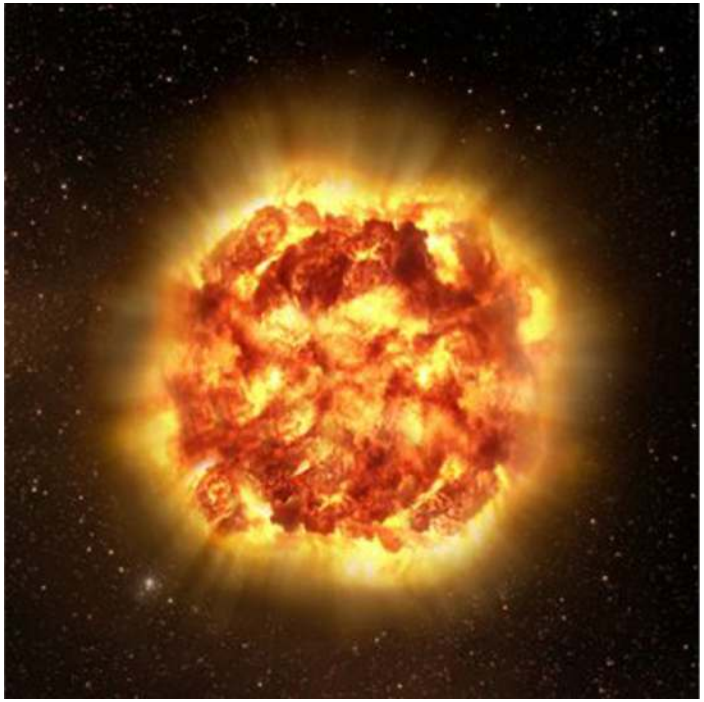
IceCube ν origin?

from KM & Ioka 13
Senno, KM & Meszaros 16

Luminous Supernovae as Long-Duration Transients



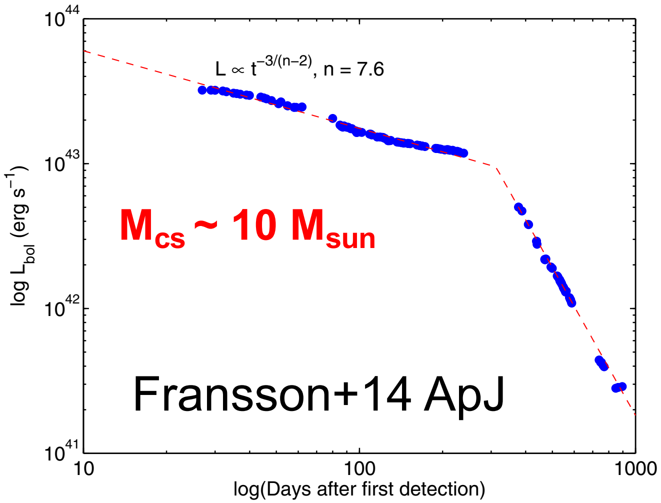
Luminous SNe explanations w. radioactivity for I and II often have difficulty

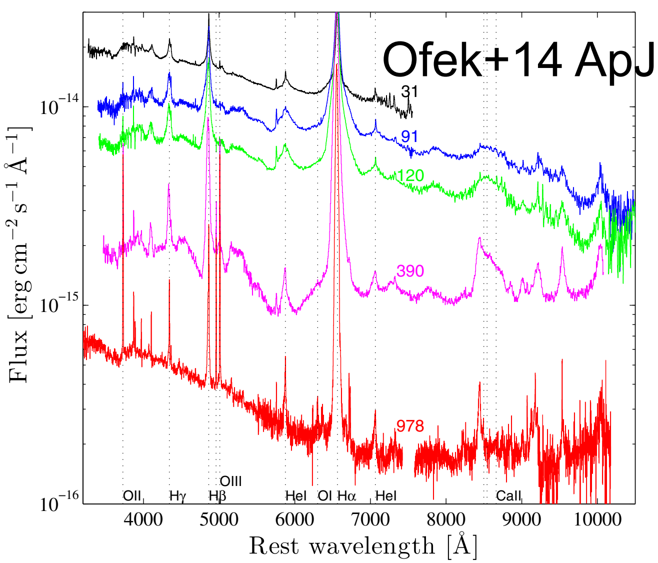


- SLSN-I (hydrogen poor) – enegy injection by engine?
- SLSN-II (hydrogen) – circumstellar material interaction

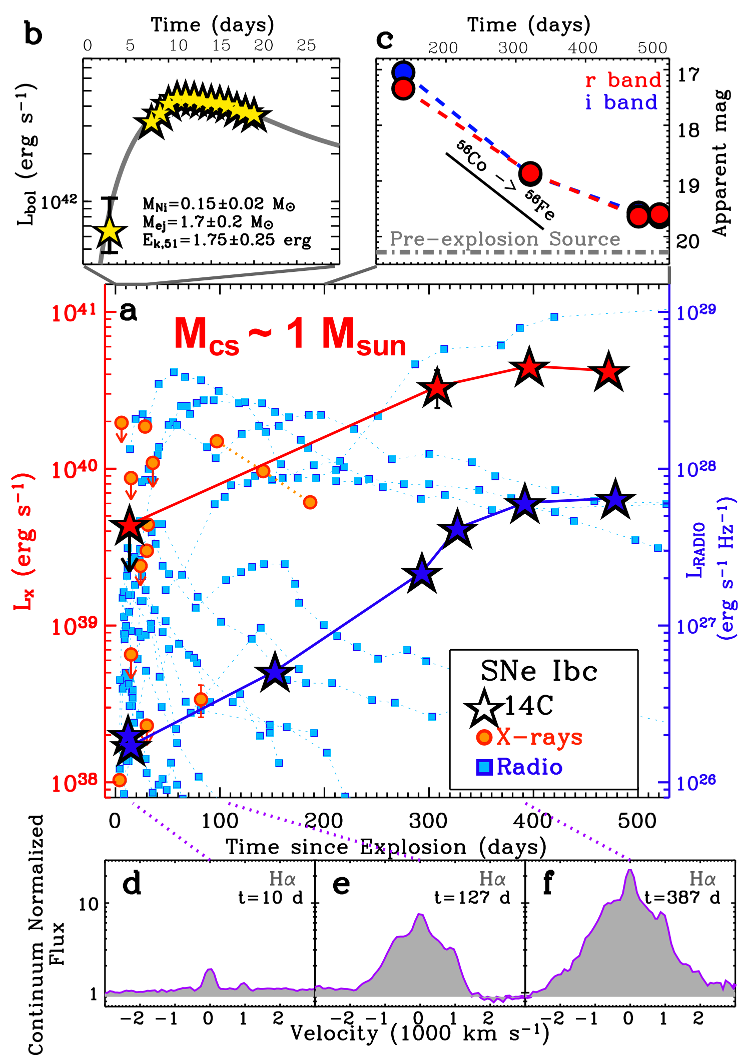
Type IIn: Interactions w. Dense CSM

SN 2010jl



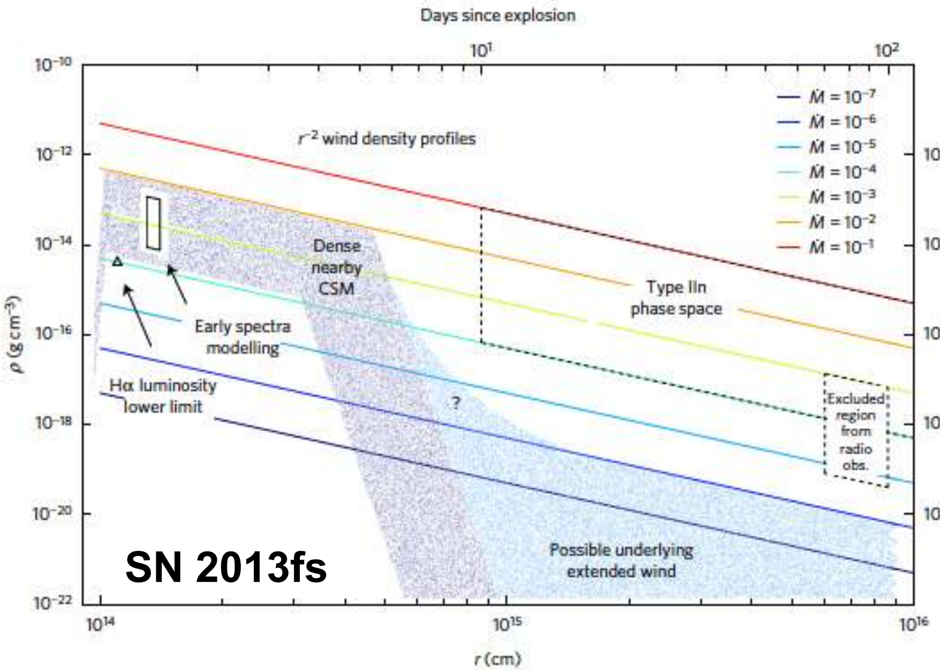


SN 2014C Margutti et al. 16

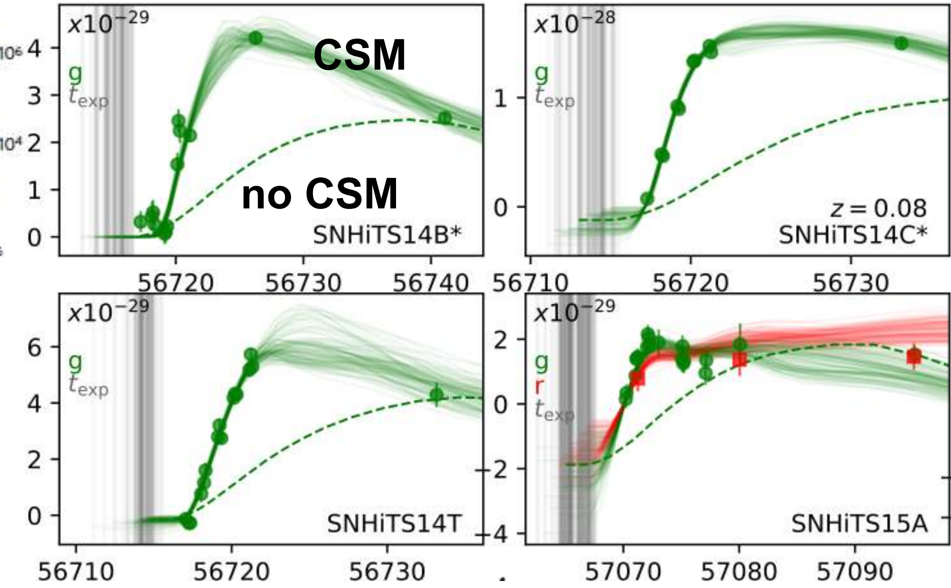


Interactions w. dense wind or CSM are common (SLSN-II, IIn, IIb)

Evidence for Dense Material in "Ordinary" SNe II



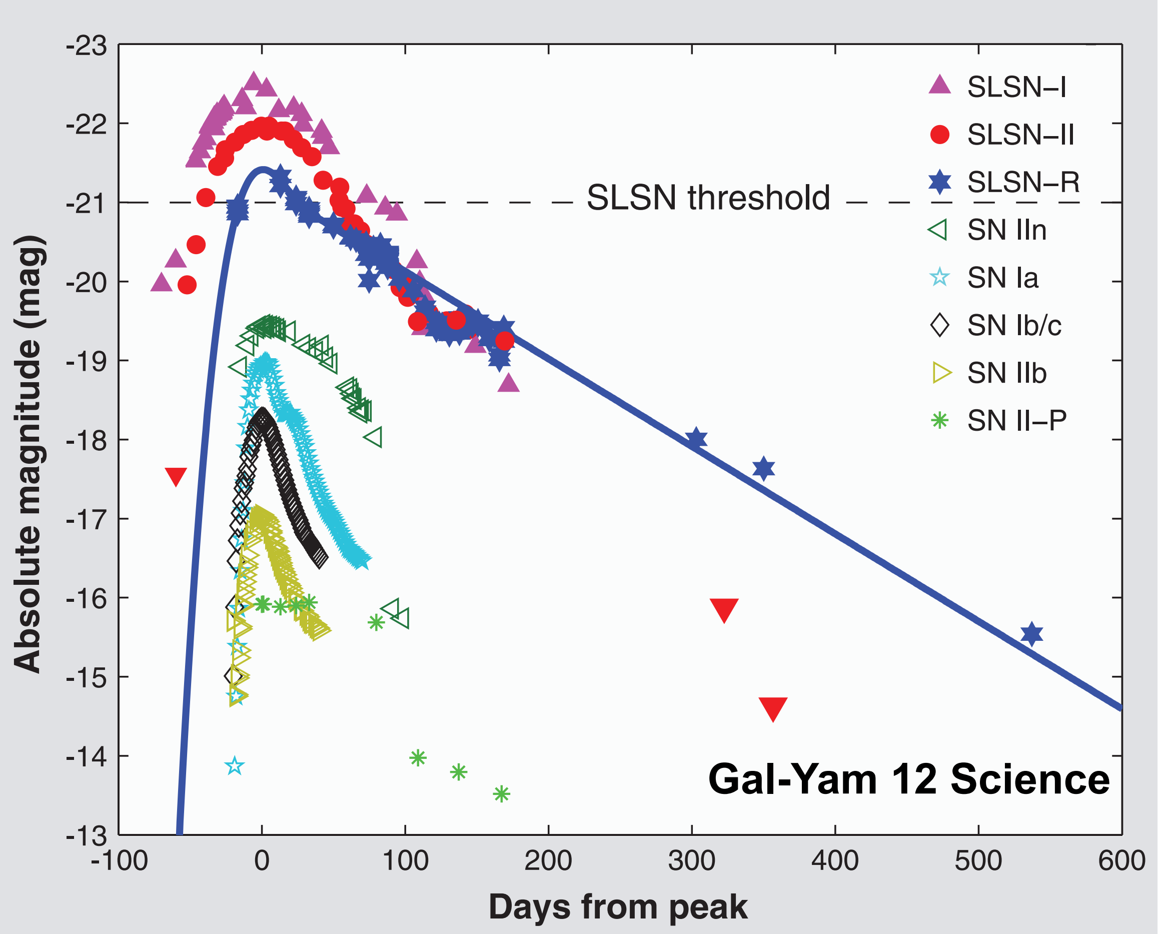
early spectroscopy
(Yaron+ 16 Nat. Phys.)



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

Extended material is common even for Type II-P SNe
$dM_{cs}/dt \sim 10^{-3}$-10^{-1} M_{sun} yr^{-1} (>> 3×10^{-6} M_{sun} yr^{-1} for RSG)

Luminous Supernovae as Long-Duration Transients



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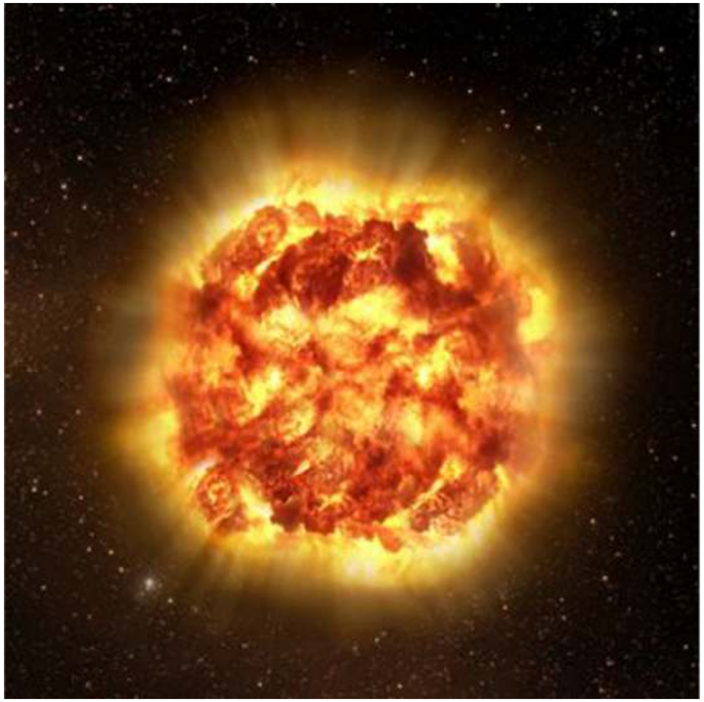
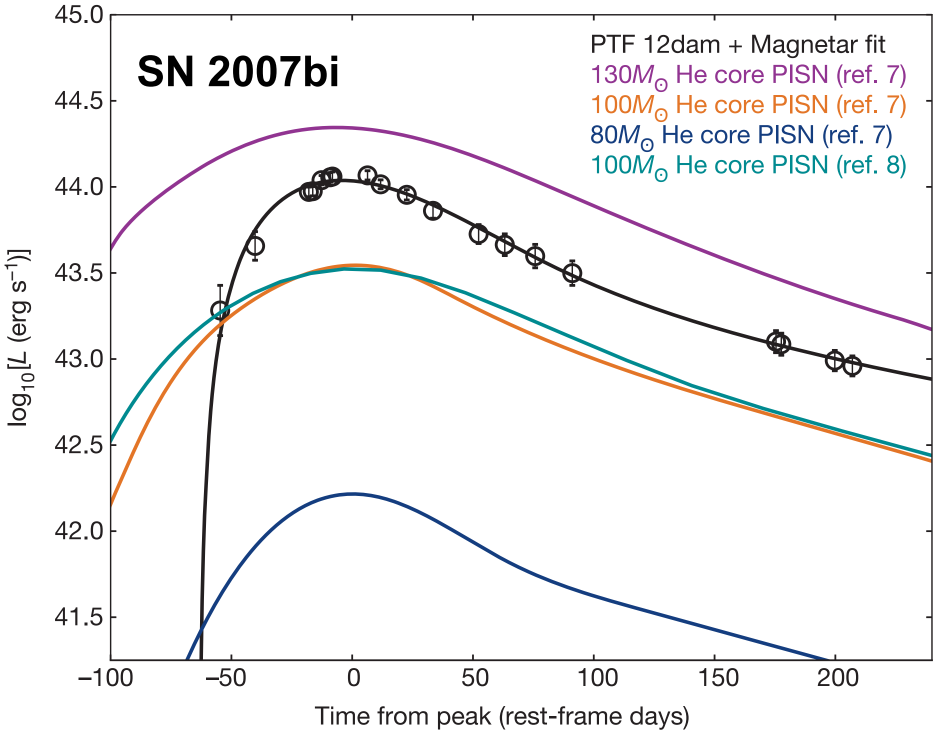
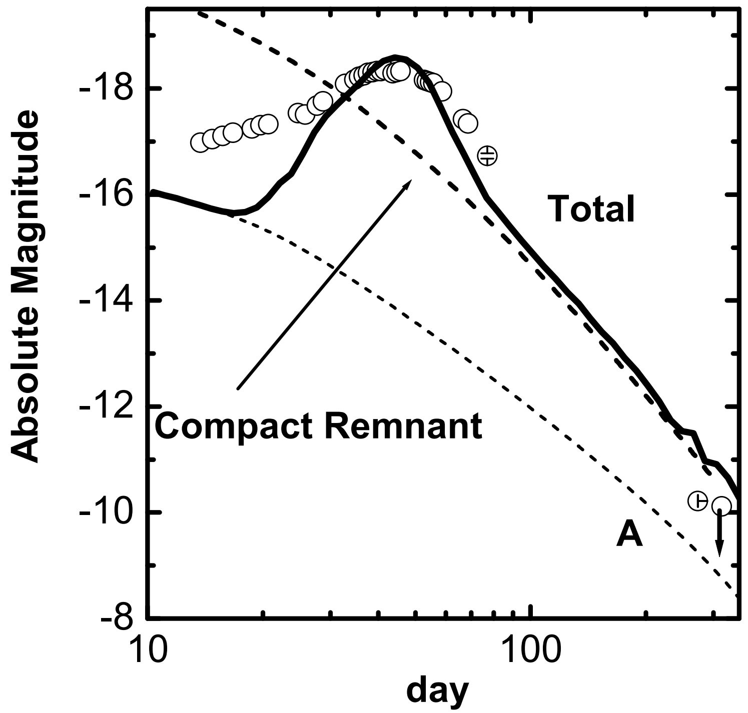


- SLSN-I (hydrogen poor) – energy injection by engine?
- SLSN-II (hydrogen) – circumstellar material interaction

Newborn Pulsar Scenario for Ibc/SLSNe I



Nicholl et al. 13 Nature

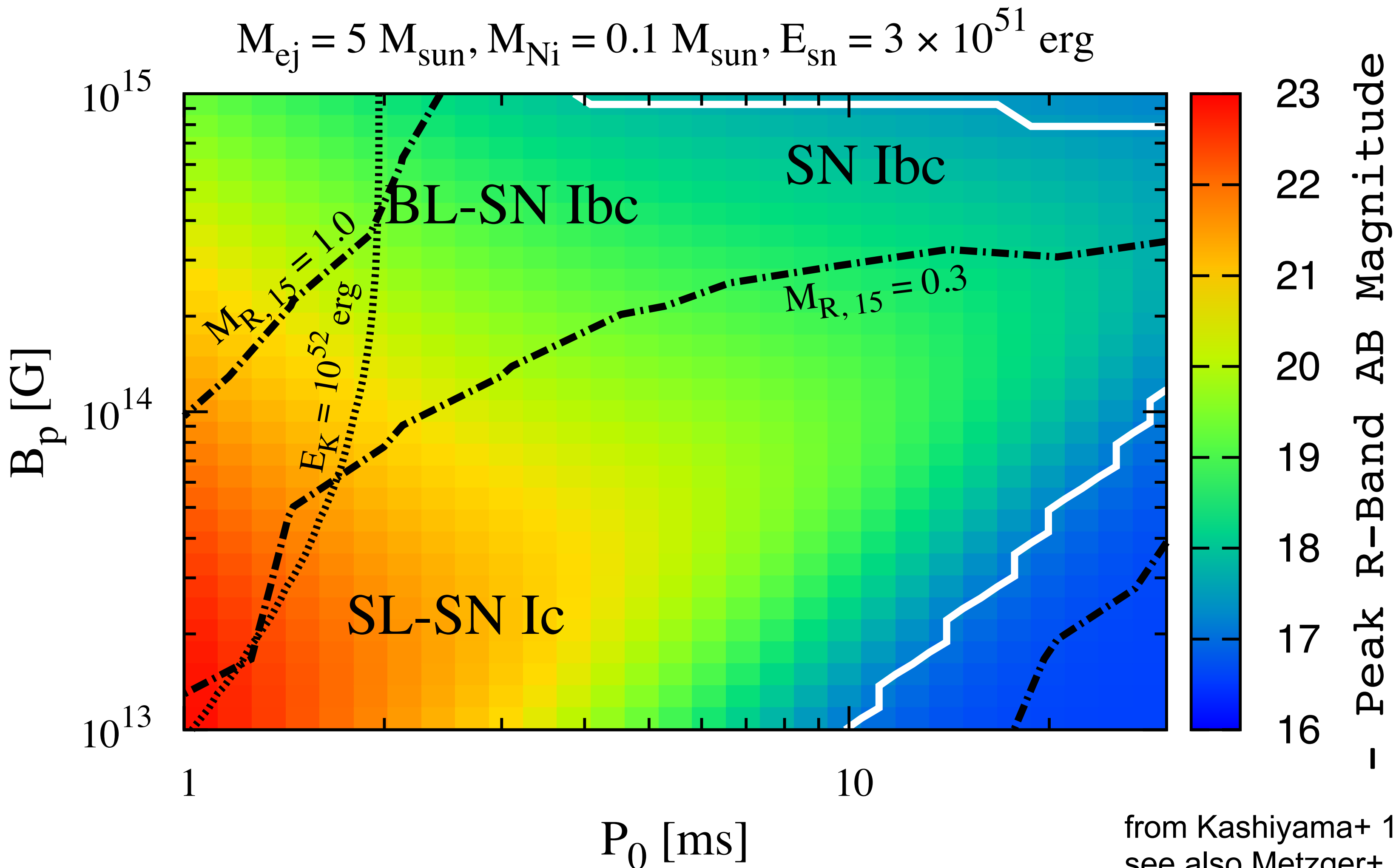


Maeda et al. 07 ApJ

- parameters: B_{dip} & P_i (or L_{em} & t_{em}), V_{ej}, M_{ej}
- assumption: all Poynting energy is converted into thermal energy

Origin of Supernova Diversity?

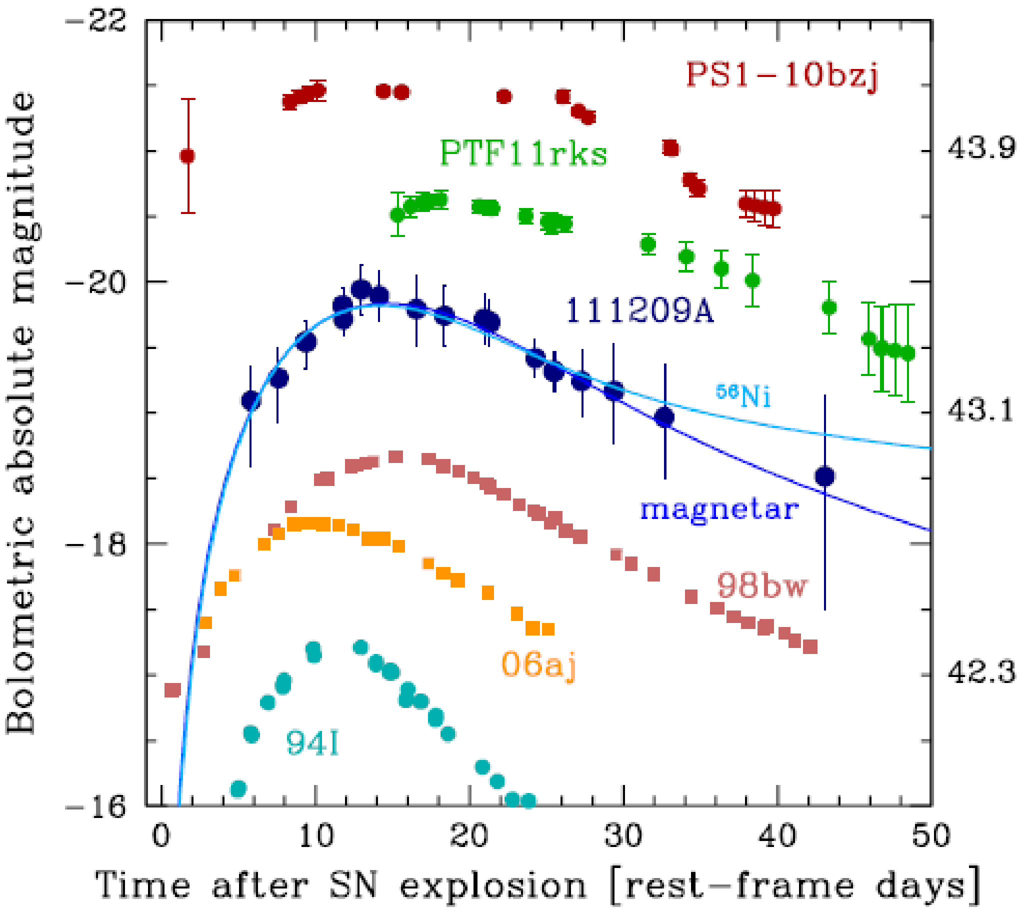
Newborn pulsars: luminosity governed by B (mag.) and P (period)



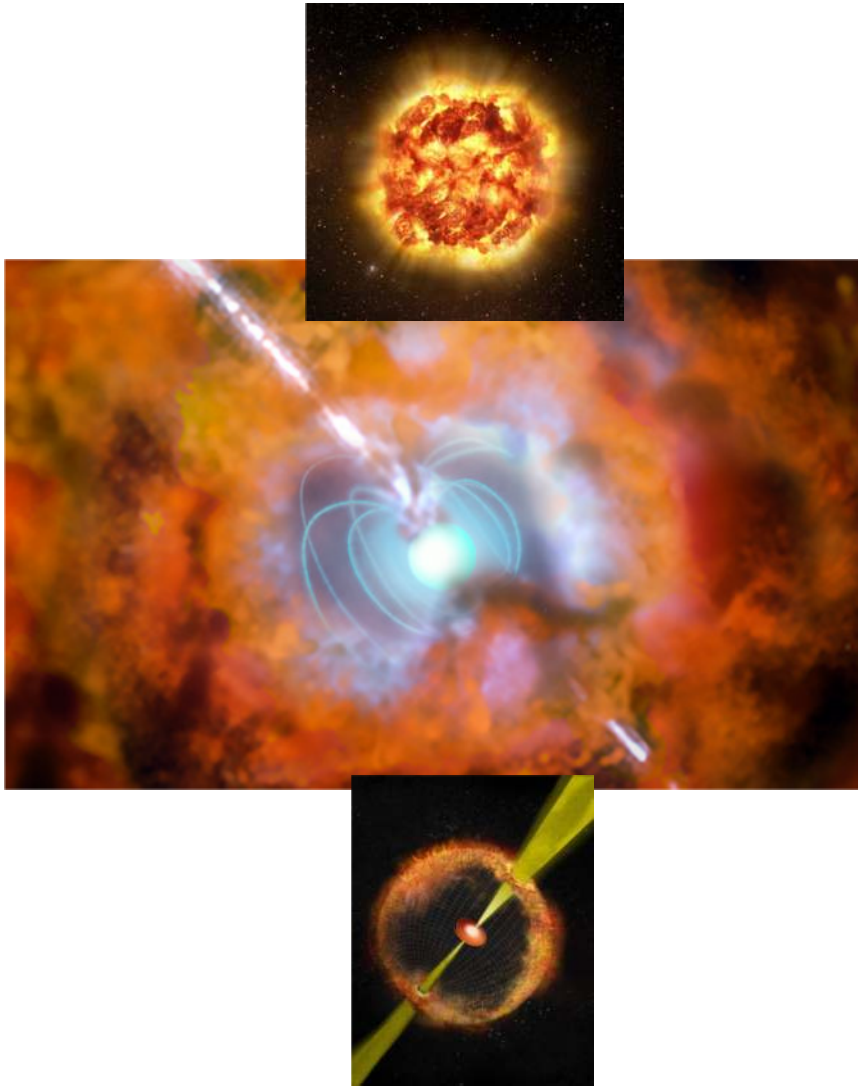
from Kashiyama+ 16
see also Metzger+ 15

GRB-SLSN Connection?

GRB 111209A: consistent w. SLSN-like SN



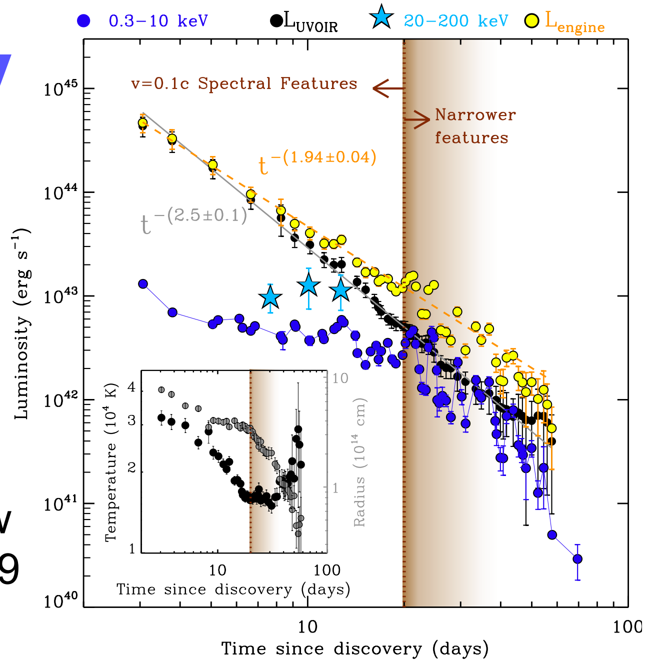
Greiner et al. 15 Nature



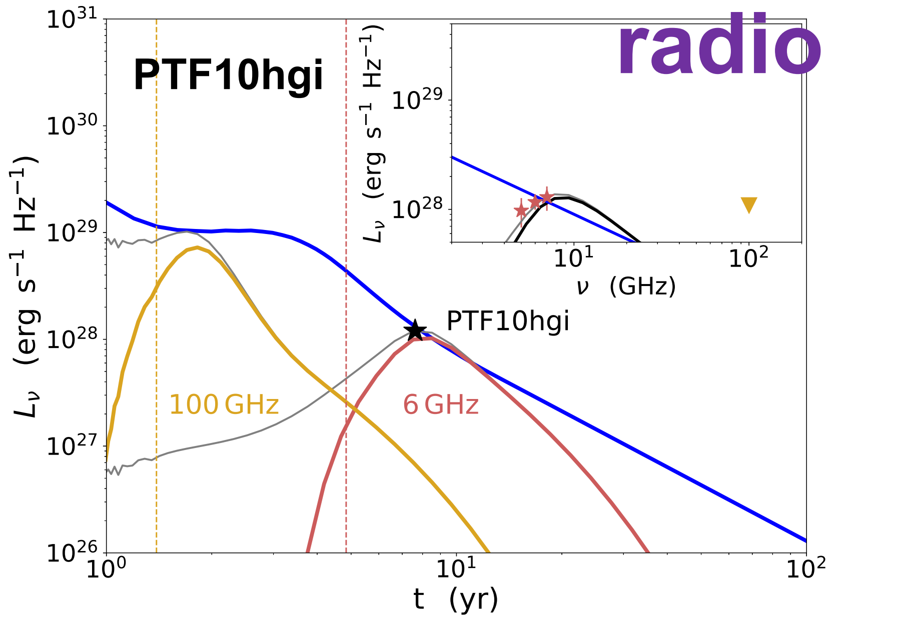
Nonthermal Nebular Emission?

Crab pulsar (age ~ 1240 yr)

X ray



AT2018cow
Margutti+ 19



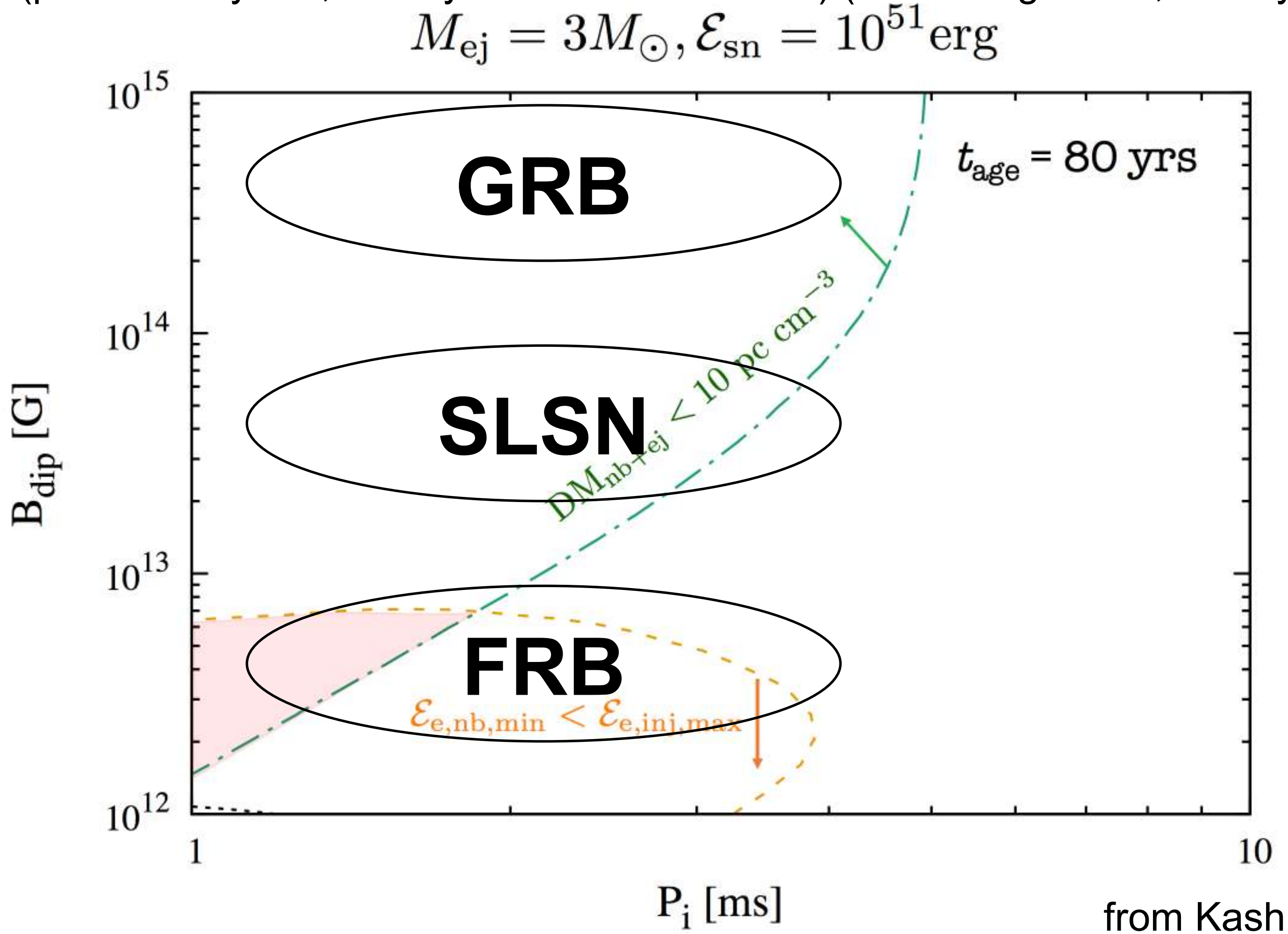
Eftekhari+ 19 (see Omand, Kashiyama & KM 18)

Connection to Fast Radio Bursts?

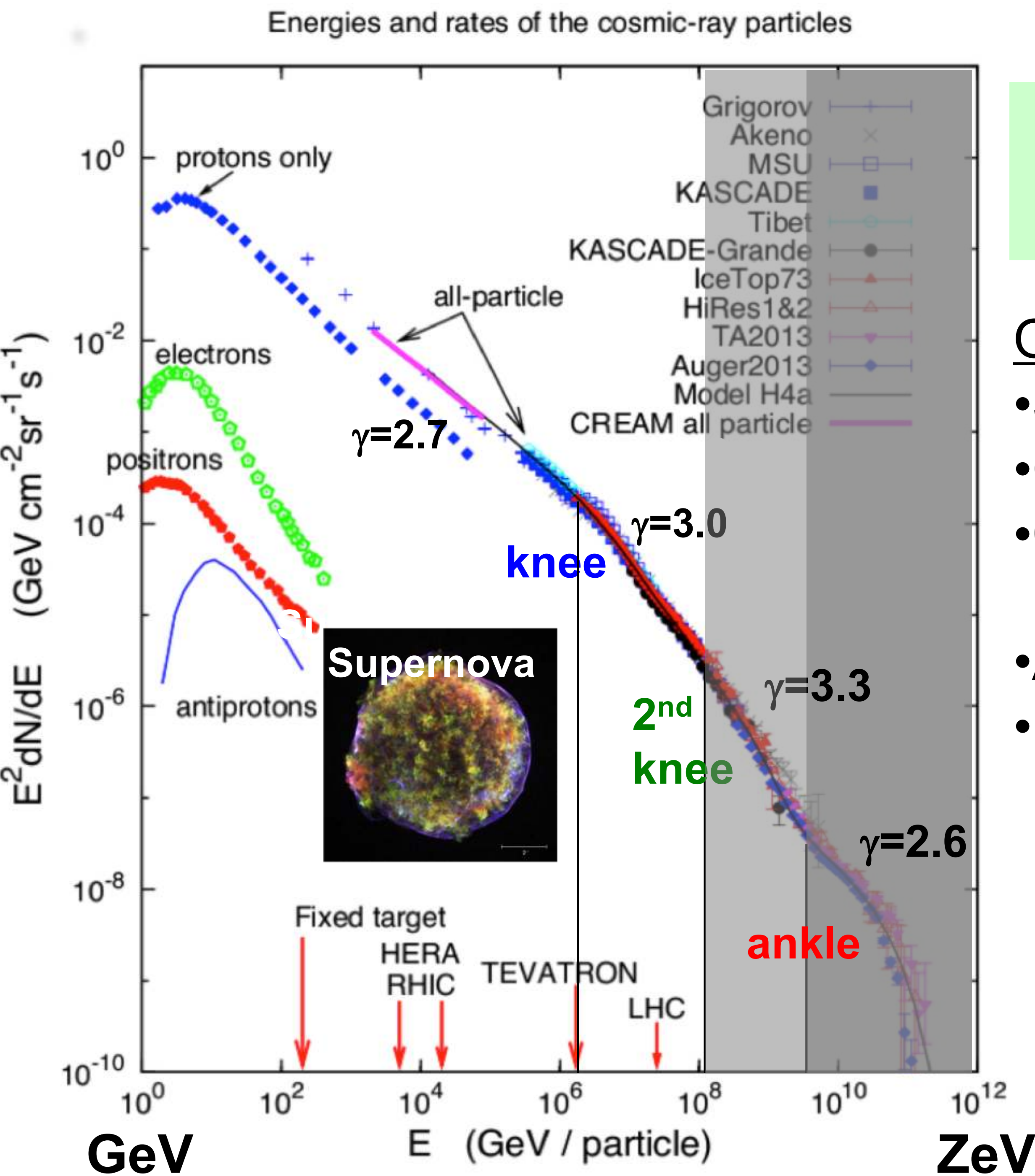
Persistent radio emission seen in FRB 121102

Associated with non-thermal emission from a young pulsar?

(predicted by KM, Kashiyama & Meszaros 16) (see Metzger+ 17, Kashiyama & KM 17)



from Kashiyama & KM 17



CR spectrum

$$\frac{dN_{\mathrm{CR}}}{dE} \propto E^{-s_{\mathrm{CR}}}$$

<u>Open problems</u>

- Sources?
- Galactic/extragalactic?
- Composition?

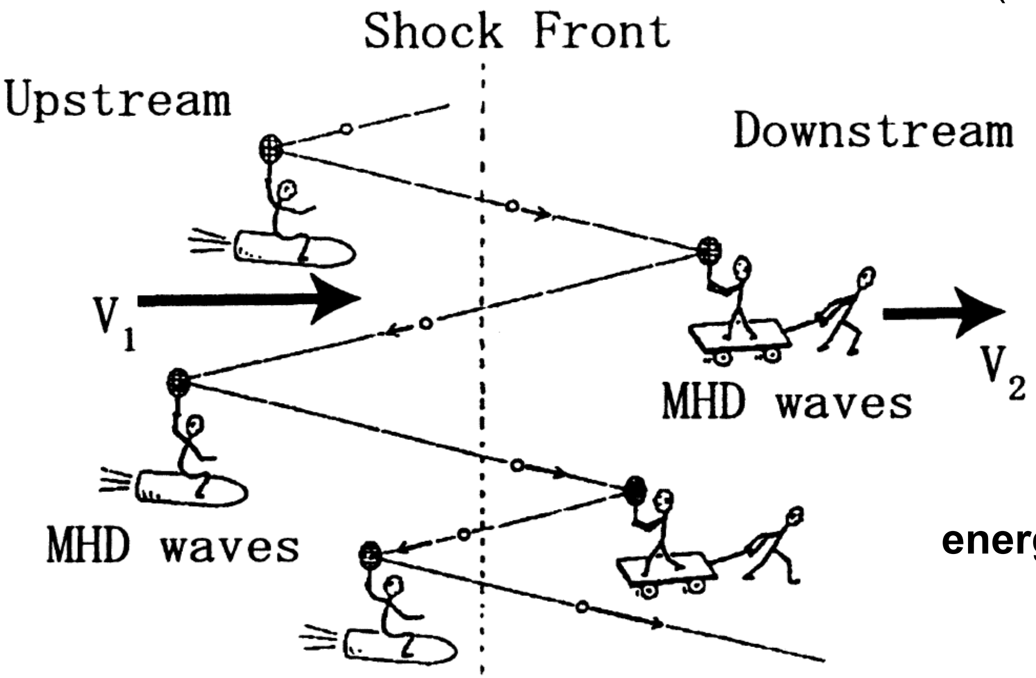
- Acceleration?
- Propagation?

※energy scale
MeV=10^6 eV, GeV=10^9 eV,
TeV=10^{12} eV, PeV=10^{15} eV,
EeV=10^{18} eV, ZeV=10^{21} eV

First Order Fermi Acceleration

Diffusive shock acceleration mechanism (DSA)

(Axford, Krymskii, Bell, Blandford & Ostriker)



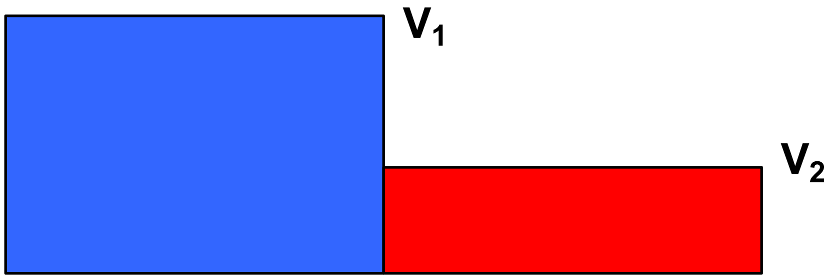
shock=converging flows

$$u = V_1 - V_2$$

$$E' = \gamma_u (E + u\, p \cos\theta)$$

energy gain per cycle $$\frac{\Delta E}{E} = 2\frac{u}{c}\cos\theta$$

collision rate ~ cosθ $$\langle \cos\theta \rangle = \frac{2}{3}$$



$$\frac{\langle \Delta E \rangle}{E} = 4\frac{V_1 - V_2}{3c}$$ **"first-order"**

Energy Gain vs Escape

energy gain after N crossings

$$p_N \propto \left(1 + \frac{\langle \Delta p \rangle}{p}\right)^N \sim \exp\left(\frac{4(V_1 - V_2)N}{3c}\right)$$

escape: determined by the incoming and outgoing fluxes

incoming from upstream: $R_{\rm in}(\mathrm{up} \to \mathrm{down}) = \int_{\mathrm{up}\to\mathrm{down}} dn_1\, v\, \cos\theta = \frac{v\, n_1}{4\pi} \int_0^{2\pi} d\phi \int_0^1 d\cos\theta = \frac{1}{4} v\, n_1$

outgoing from downstream: $R_{\rm out} = n_2 V_2$

escape probability

$$P_{\rm esc} = \frac{R_{\rm out}}{R_{\rm in}} = \frac{4V_2}{c}$$

residual number after N crossings

$$n_N \propto (1 - P_{\rm esc})^N \sim \exp\left(-\frac{4V_2 N}{c}\right)$$

final spectrum

$$\frac{dn}{dp} = \frac{dn}{dt}\frac{dt}{dp} \propto \exp\left(-\frac{4(V_1 - V_2)N}{3c}\left[1 + \frac{3V_2}{V_1 - V_2}\right]\right) \sim p^{-\underbrace{\left(1 + \frac{3V_2}{V_1 - V_2}\right)}_{s}}$$

Maximum Energy in DSA

- Strong adiabatic shock: $r_c = V_1/V_2 = 4$
  -> $s = 1 + 3V_2/(V_1 - V_2) = 2$ --- similar to the expected value
- Spectral index does not depend on details of turbulence but the maximum energy does
- Cycle/acceleration times depend on diffusion coefficient "κ"

$$t_{\rm cy} = t_u + t_d = \frac{4\kappa}{V_1 c} + \frac{4\kappa}{V_2 c} \qquad \kappa = \frac{1}{3} r_L c \left(\frac{B}{\delta B}\right)^2 \approx \frac{cE}{3Ze}\xi_B$$

acceleration time

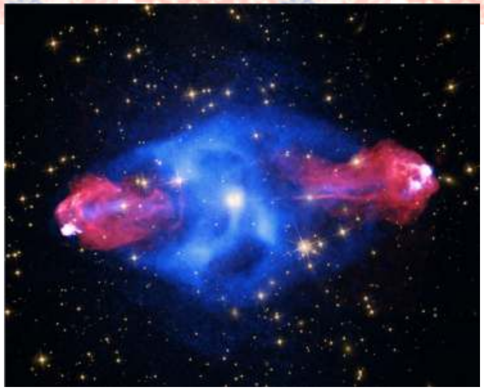
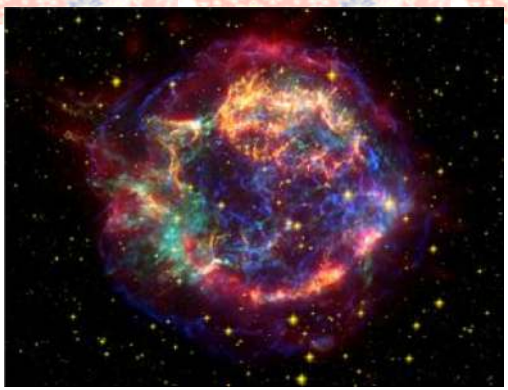
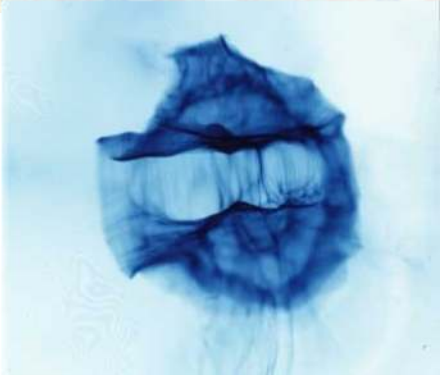
$$t_{\rm acc} = \frac{t_{\rm cy}}{\langle \Delta p \rangle / p} = \frac{3 r_c (r_c + 1)}{r_c - 1} \frac{\kappa}{V_1^2}$$

$$t_{\rm acc} < t_{\rm dyn} = \frac{R}{V}$$ **gives a necessary condition**

$$E < E_{\rm max} = \frac{3}{20} \xi_B ZeBR(V/c) \sim Z 10^{15}\ {\rm eV}\ \xi_B \left(\frac{B}{300\ \mu G}\right)\left(\frac{R}{3\ {\rm pc}}\right)\left(\frac{V}{3000\ {\rm km\ s^{-1}}}\right)$$

Hillas condition $$E < ZeBR\beta$$

Complications

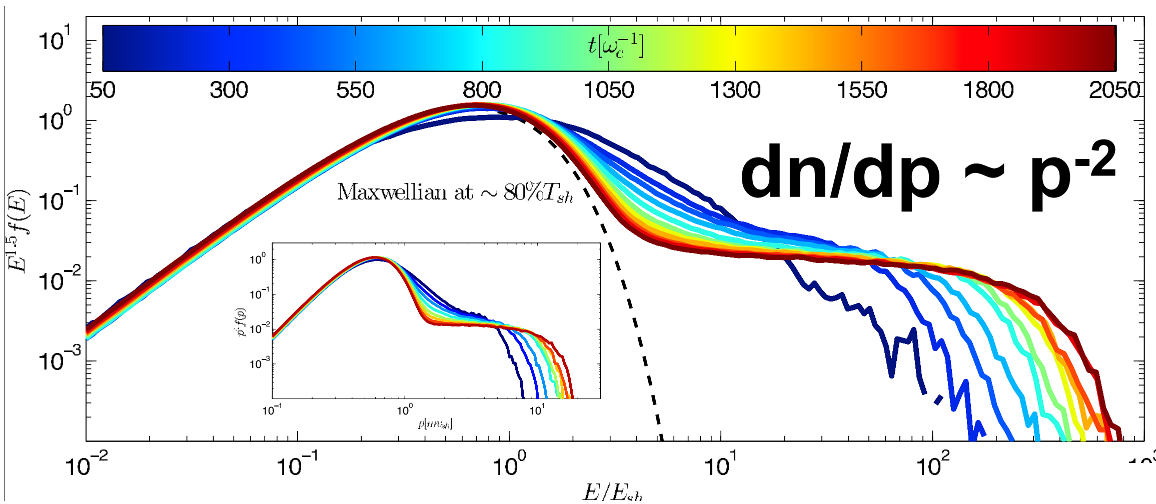





- Diversity among different astrophysical shocks?
- Magnetic field amplification mechanism
  and cosmic-ray feedbacks on dynamics & waves
- Shock obliquity: parallel vs perpendicular
- Relativistic shocks
- Roles of radiation (radiative, radiation-mediated)
- Electron acceleration & heating
- Many other acceleration mechanisms

Particle-In-Cell Simulations

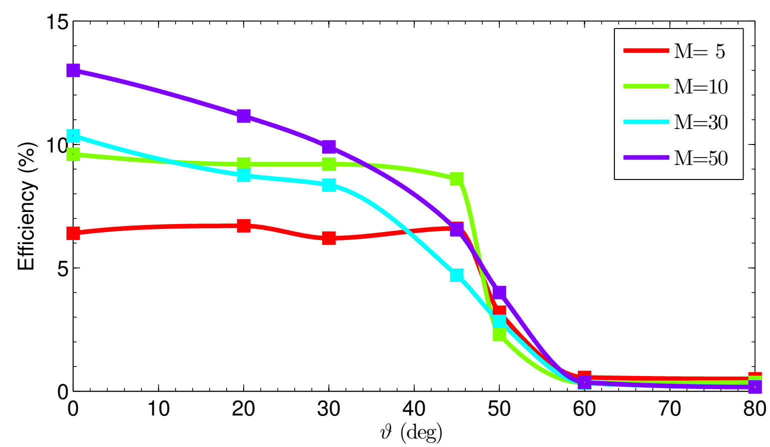
- Collisionless shock: plasma-mediated

  ν_{pl}, ν_c >> ν_{Coul} -> shocks are formed via plasma instabilities
- Injection & Energy fraction? Magnetic fields? CR feedbacks?



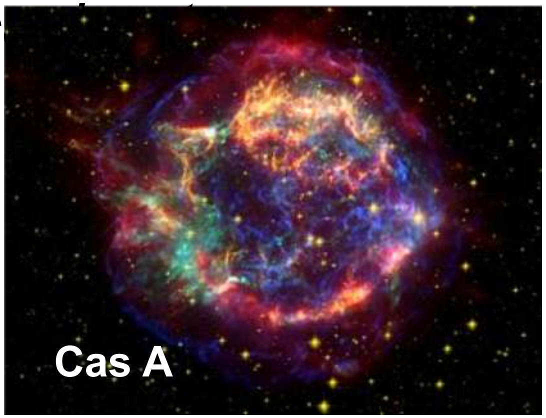
Caprioli & Spitkovsky 15 ApJ

CR energy fraction
~10%



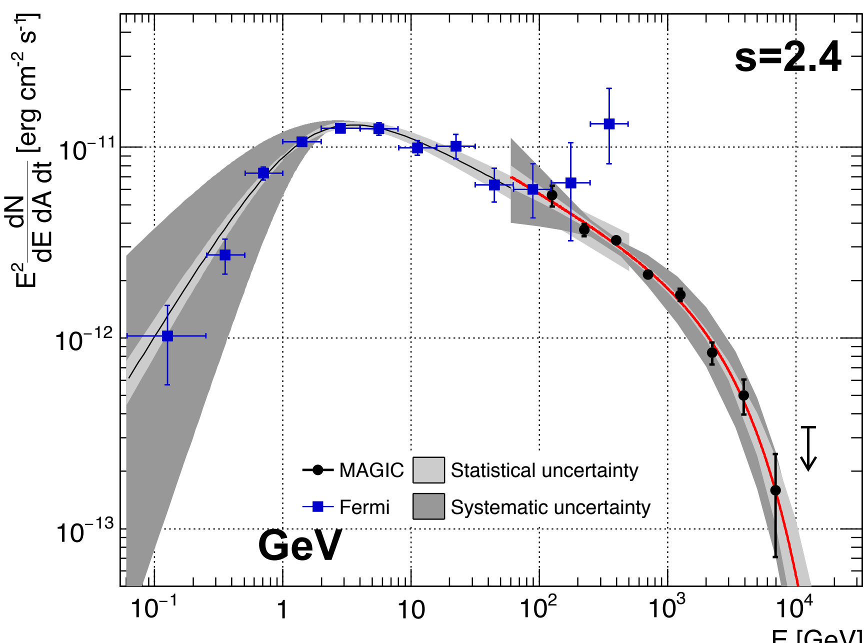
Galactic Supernova Remnants as CR Ion Sources

Fermi established supernova remnants as CR “ion” ac

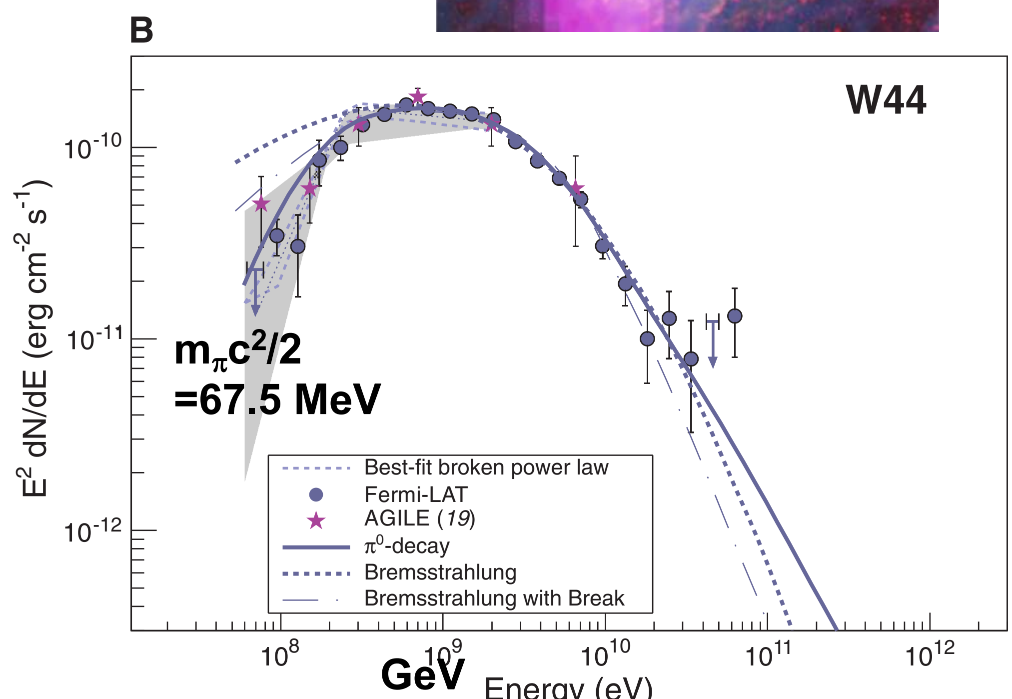


$$p + p \rightarrow N\pi + X$$

$$\pi^0 \rightarrow 2\gamma$$

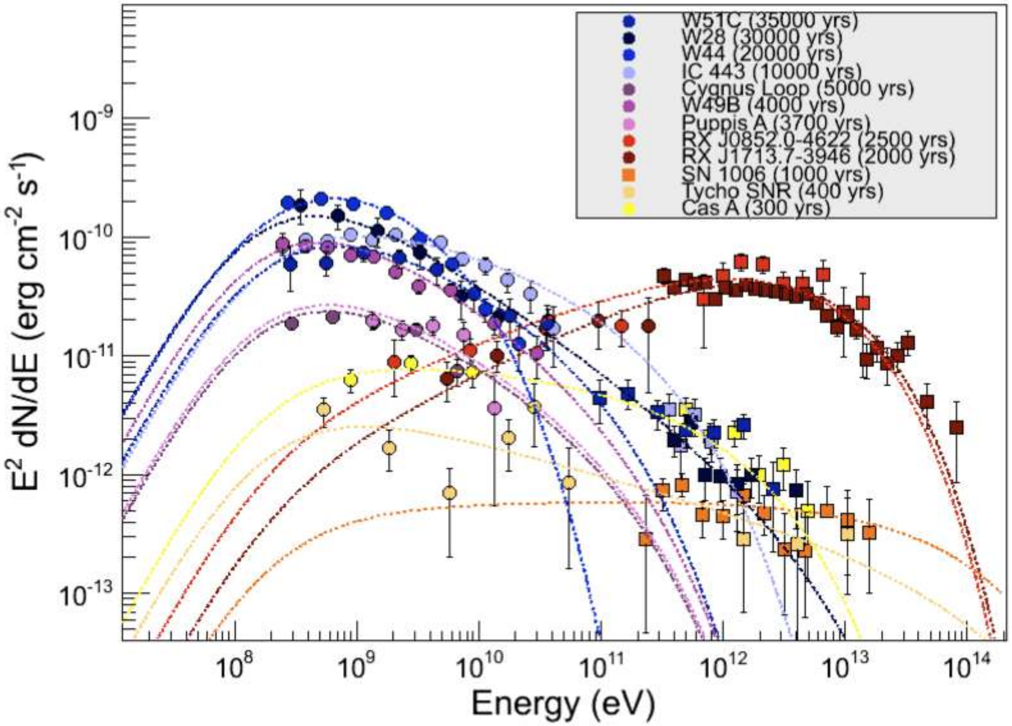


Ahnen+ 17 MNRAS



Ackermann+ 13 Science

Knee Accelerators?



No evidence for PeVatrons (so far)

-> targets for HAWC/CTA

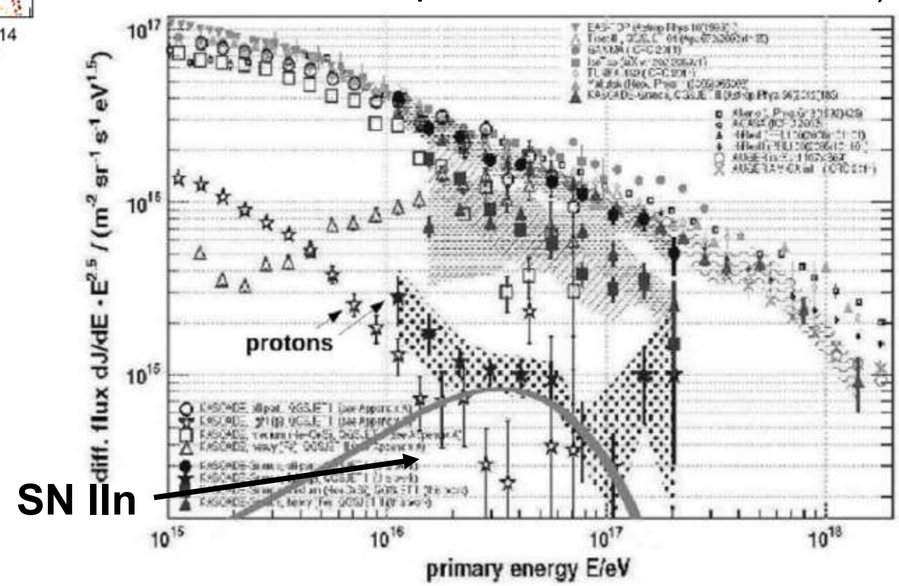
Theoretically challenging

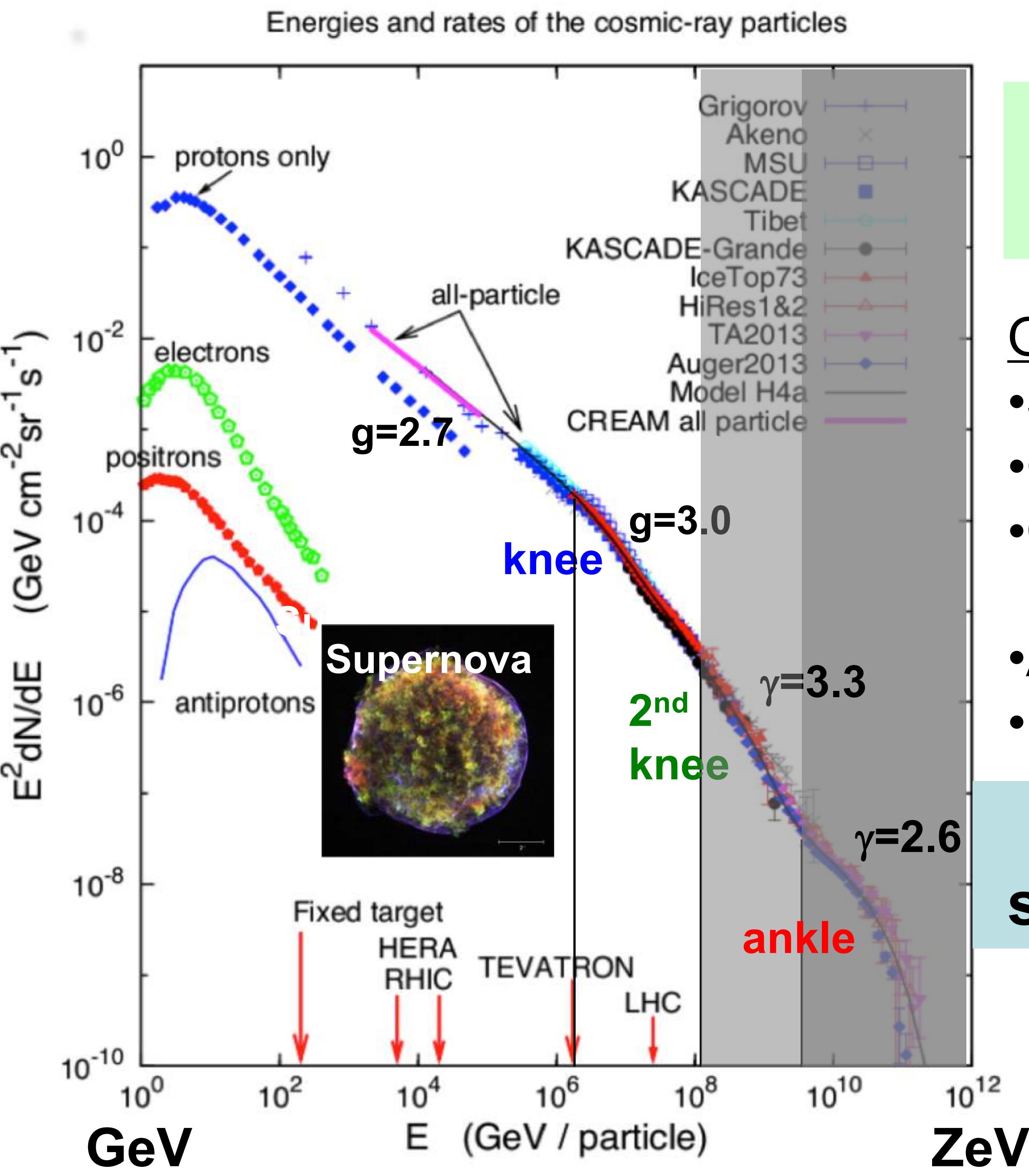
(upstream) B amplification: CR streaming instability

supernovae in dense winds?

ex. Bell+ 13 MNRAS

Zirakashvili & Ptuskin 16 APh
(cf. Sveshnikova 03 ApJ
KM, Thompson & Ofek 14 MNRAS)





CR spectrum

$$\frac{dN_{\rm CR}}{dE} \propto E^{-s_{\rm CR}}$$

Open problems

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- Propagation?

$\gamma = s + \delta$

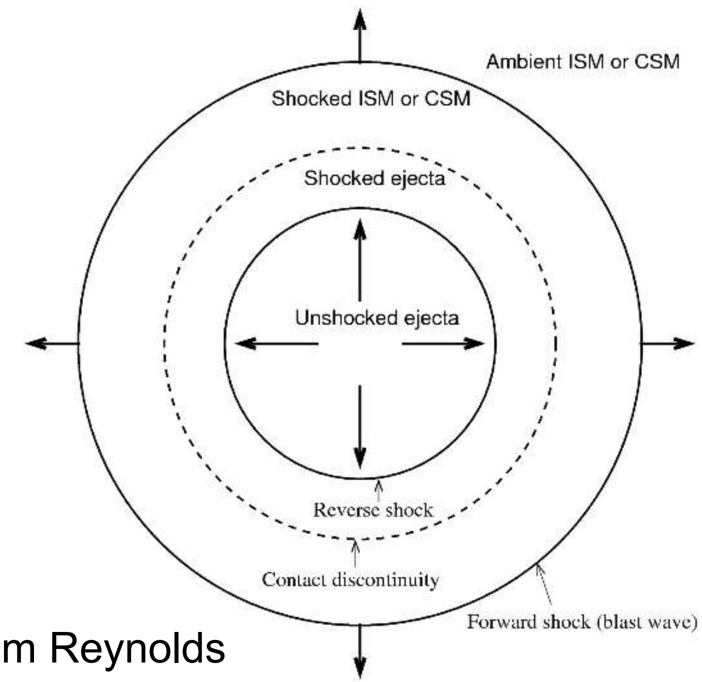
s ~2.2–2.4, δ~0.3–0.5

※energy scale

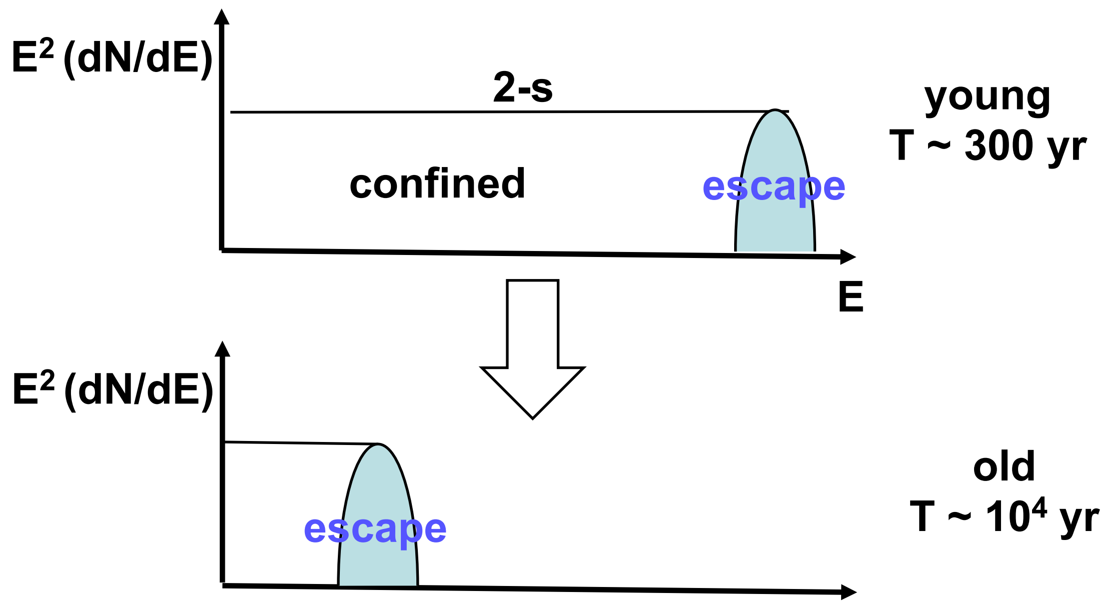
MeV=10^6 eV, GeV=10^9 eV, TeV=10^{12} eV, PeV=10^{15} eV, EeV=10^{18} eV, ZeV=10^{21} eV

"Simplified" View of Cosmic-Ray Escape

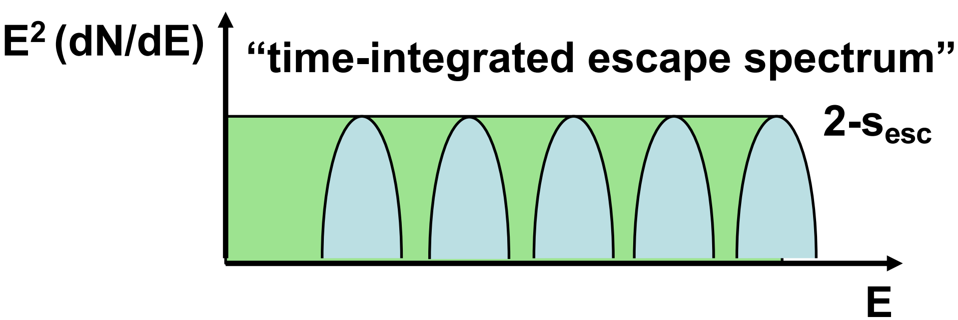
Escaping CR spectrum ≠ Accelerated CR spectrum



from Reynolds



$$E_{max} \propto R^{-\alpha} \quad E^2(dN/dE)|_{p=mc} \propto R^{\beta}$$

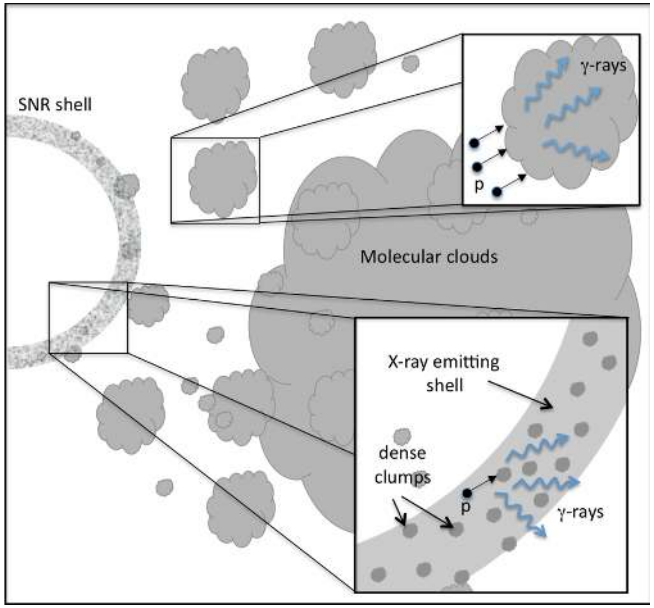


$$s_{esc} = s+\beta/\alpha$$

ex. Caprilori+ 10 Ohira, KM & Yamazaki 10

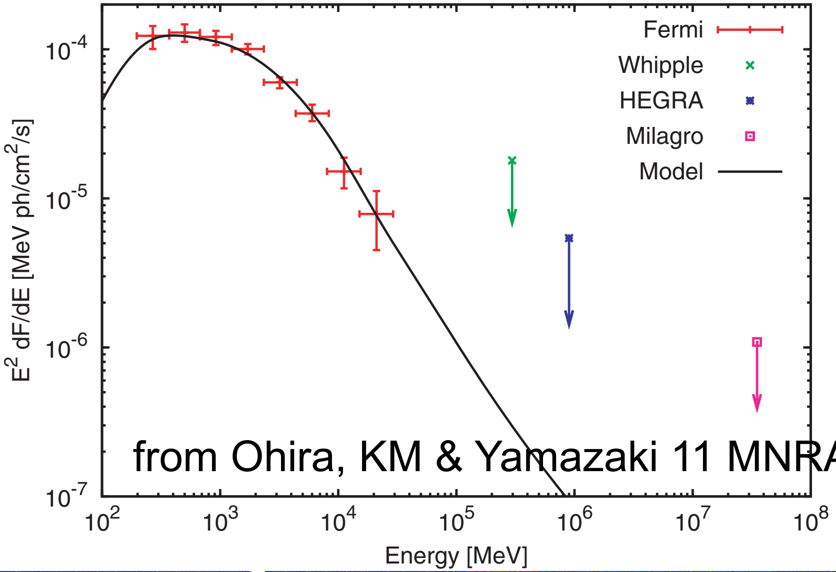
(SNR case: β~0)

Ex. Cosmic-Ray-Illuminated Molecular Clouds



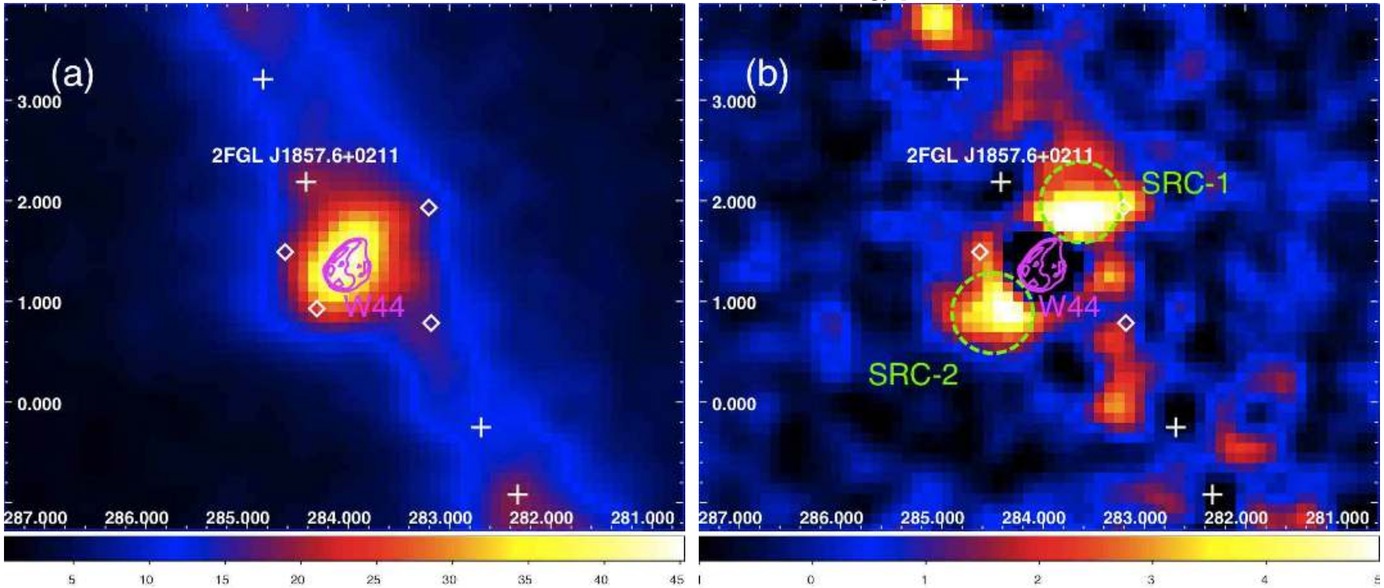
Slane+

see Gabici et al. 09 MNRAS



from Ohira, KM & Yamazaki 11 MNRAS

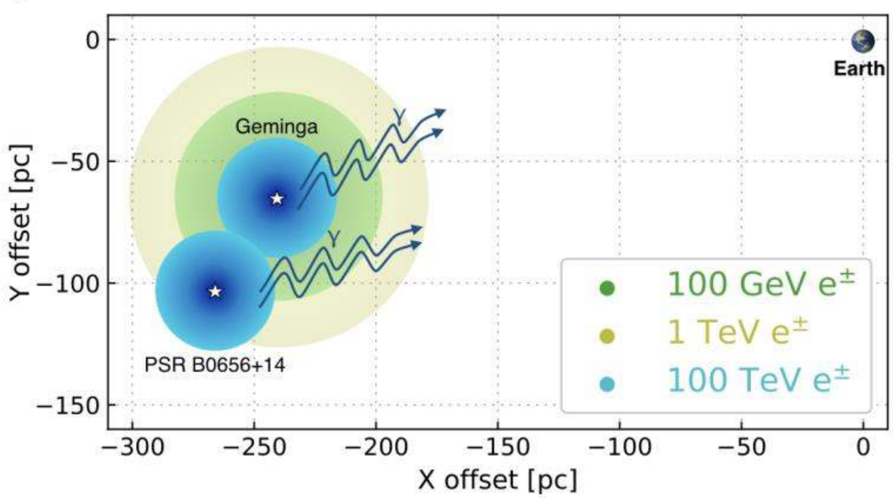
W44

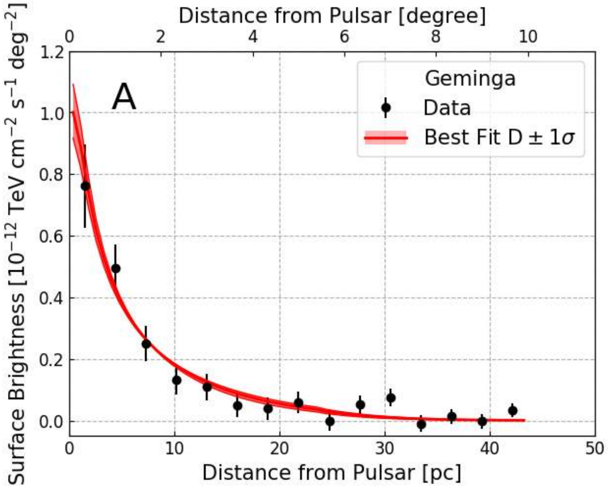


Uchiyama+ 12 ApJ

Cf. TeV Gamma-Ray Halo

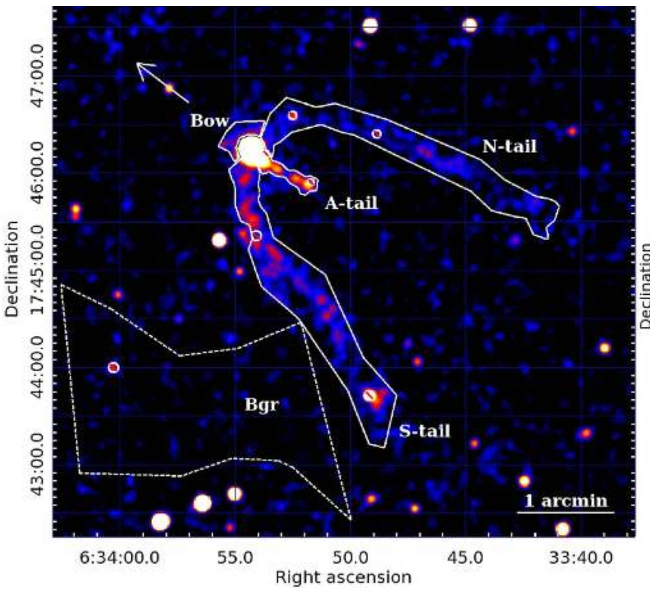
HAWC established PWNe as e^-e^+ emitters

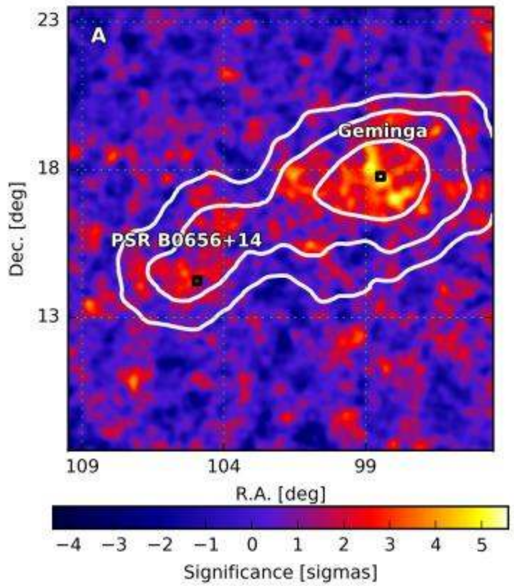




HAWC 17 Science

X ray



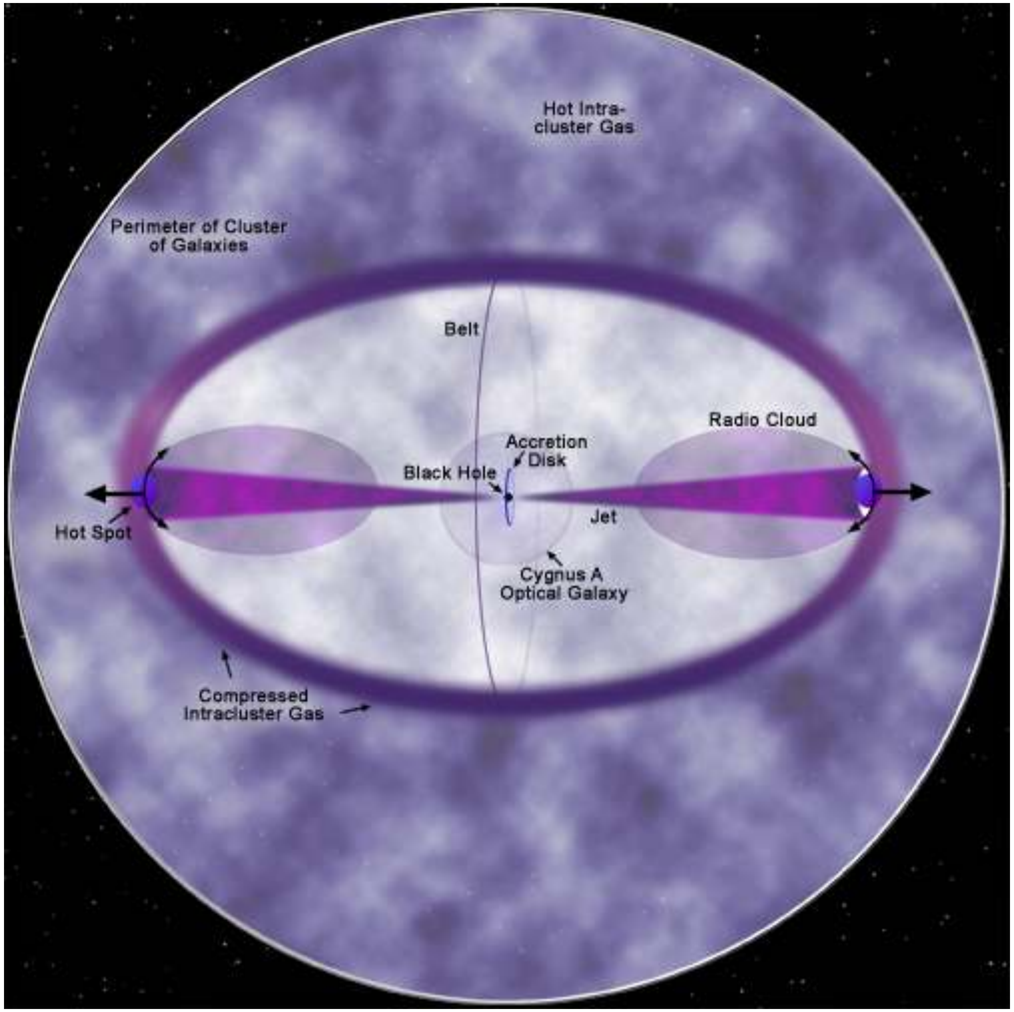


γ ray

Possert + 17 ApJ

Applications to Extragalactic Sources?

CR escape spectrum: source-dependent
(dynamics & acceleration & magnetic field amplification)



Jet-induced cocoon

(Begelman & Cioffi 89)

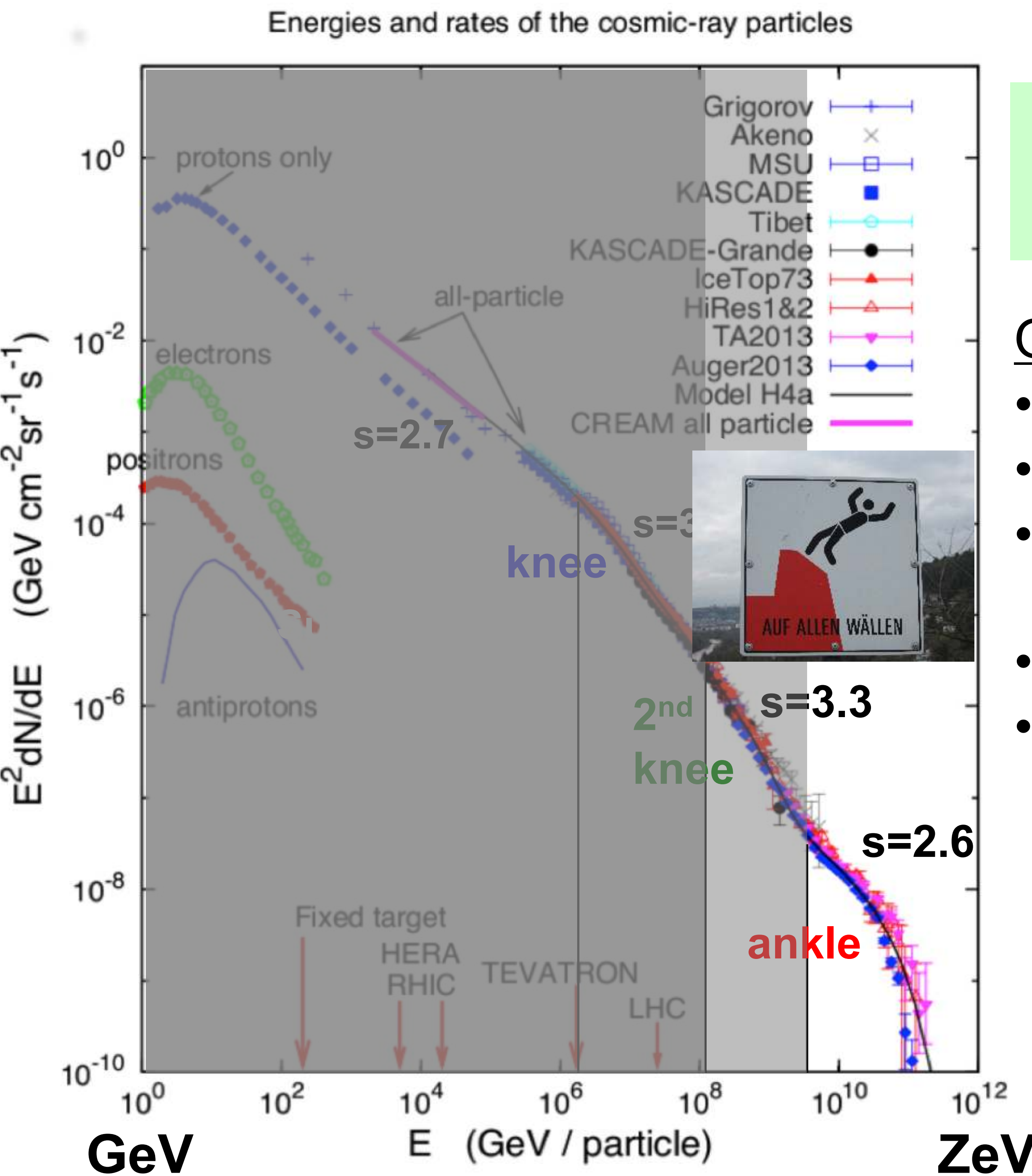
Jet velocity ~ const.
cocoon velocity $V_c \propto t^{-1/2}$

Jet head $R_h \propto t$
cocoon size $R_c \propto t^{1/2}$

Volume $\propto R_h R_c^2 \propto t$
Pressure: $P_{cr} \propto \rho V_c^2 \propto t^{-1}$

$E_{max} \propto R_c V_c B \propto B$
$\mathcal{E}_{inj} \propto R_h R_c^2 P_{cr} \propto t$

$s_{esc} \neq s$



CR spectrum

$$\frac{dN_{\rm CR}}{dE} \propto E^{-s_{\rm CR}}$$

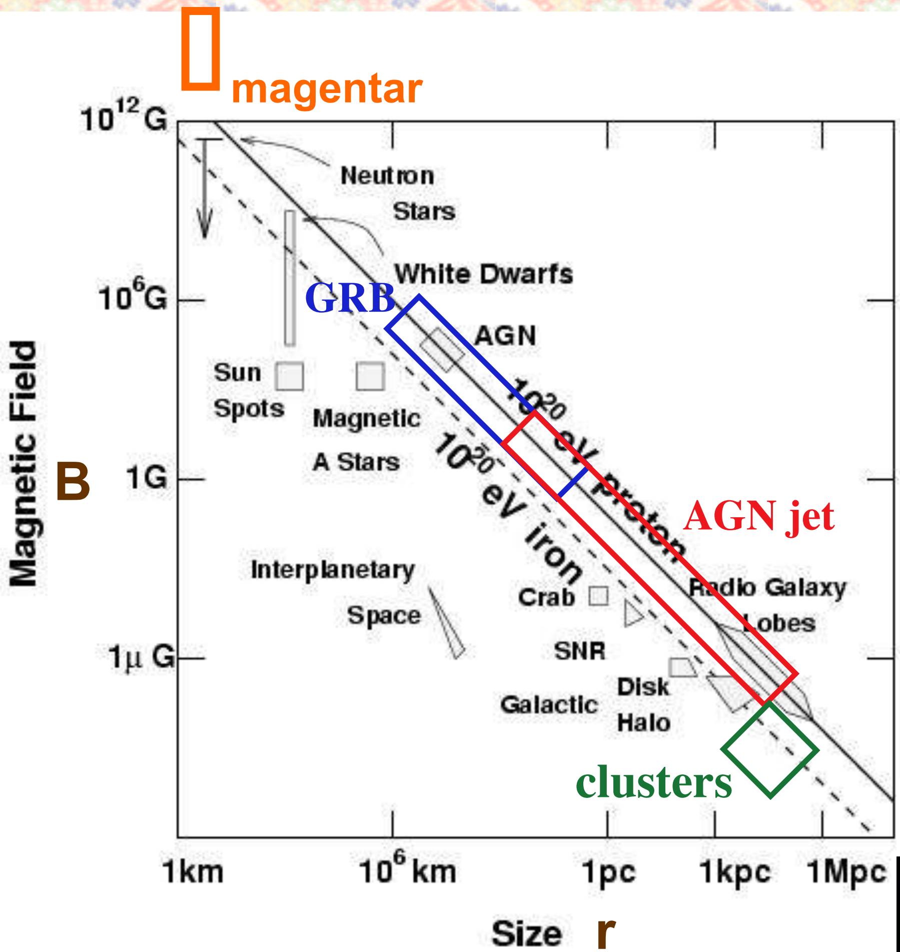
Open problems

- Sources?
- Galactic/extragalactic?
- Composition?

- Acceleration?
- Propagation?

※energy scale
MeV=10^6 eV, GeV=10^9 eV,
TeV=10^{12} eV, PeV=10^{15} eV,
EeV=10^{18} eV, ZeV=10^{21} eV

UHECR Source Candidates: Cosmic Monsters

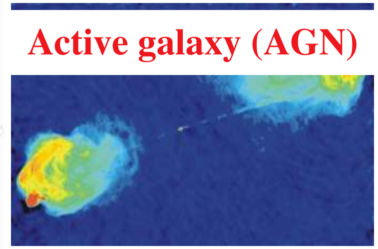


Hillas condition

$E < e\,B\,r\,\beta$

The **strongest** mag. fields
$B \sim 10^{15}$ G

The **brightest** explosions
$L_\gamma \sim 10^{52}$ erg/s



The **most massive** black holes
$M_{BH} \sim 10^{8\text{-}9} M_{sun}$

The **largest** gravitational object
$R_{vir} \sim$ a few Mpc

cf. $B_{sun} \sim 1$ G, $L_{sun} \sim 4\times10^{33}$ erg/s,
$M_{sun} \sim 2\times10^{33}$ g, $R_{sun} \sim 7\times10^{10}$ cm

Luminosity Requirement

Blandford 00

Hillas condition

$$E < ZeB'l'\beta'\Gamma = ZeB'r\beta'$$

magnetic luminosity

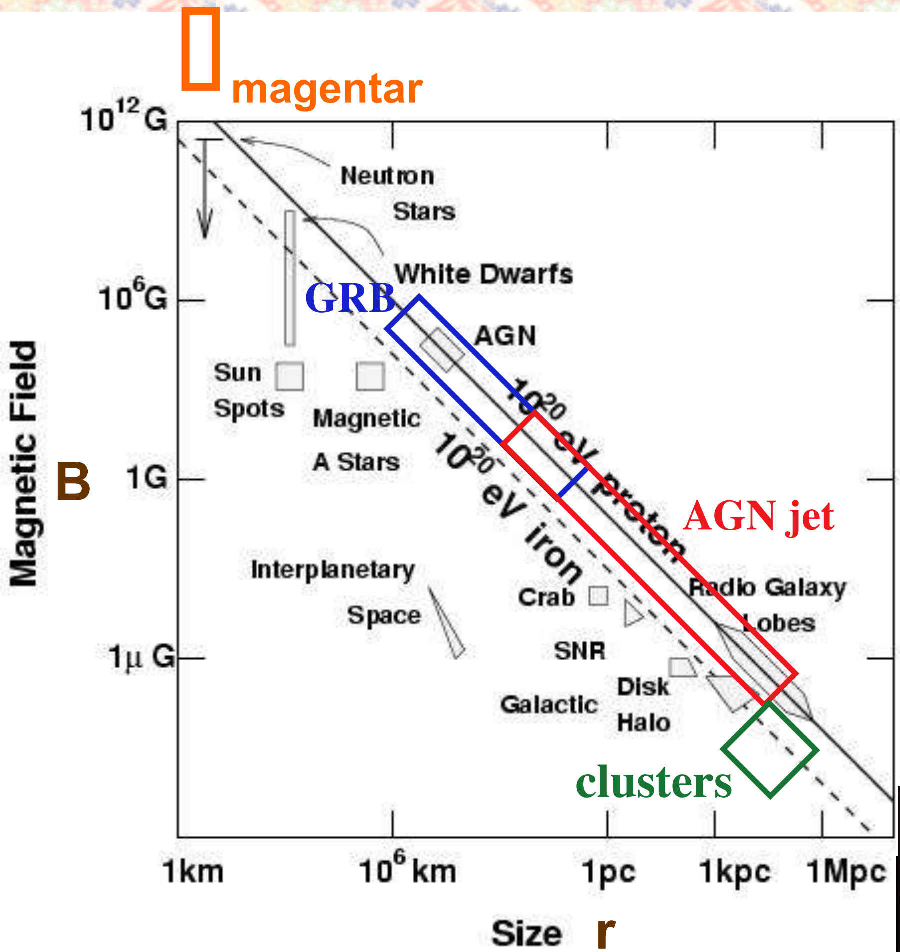
$$L_B = \epsilon_B L = (4\pi r^2 \Gamma^2 c\beta)\frac{B'^2}{8\pi}$$

if β~β'

$$L_B > \frac{1}{2}\Gamma^2 c\beta \left(\frac{E}{Ze\beta'}\right)^2 \sim 2\times 10^{46}\ \mathrm{erg\ s^{-1}}\ \Gamma^2\beta^{-1}\ [E/(Z10^{20.5}\ \mathrm{eV})]^2$$

Transient Sources AND/OR Sources of Nuclei

UHECR Source Candidates: Cosmic Monsters



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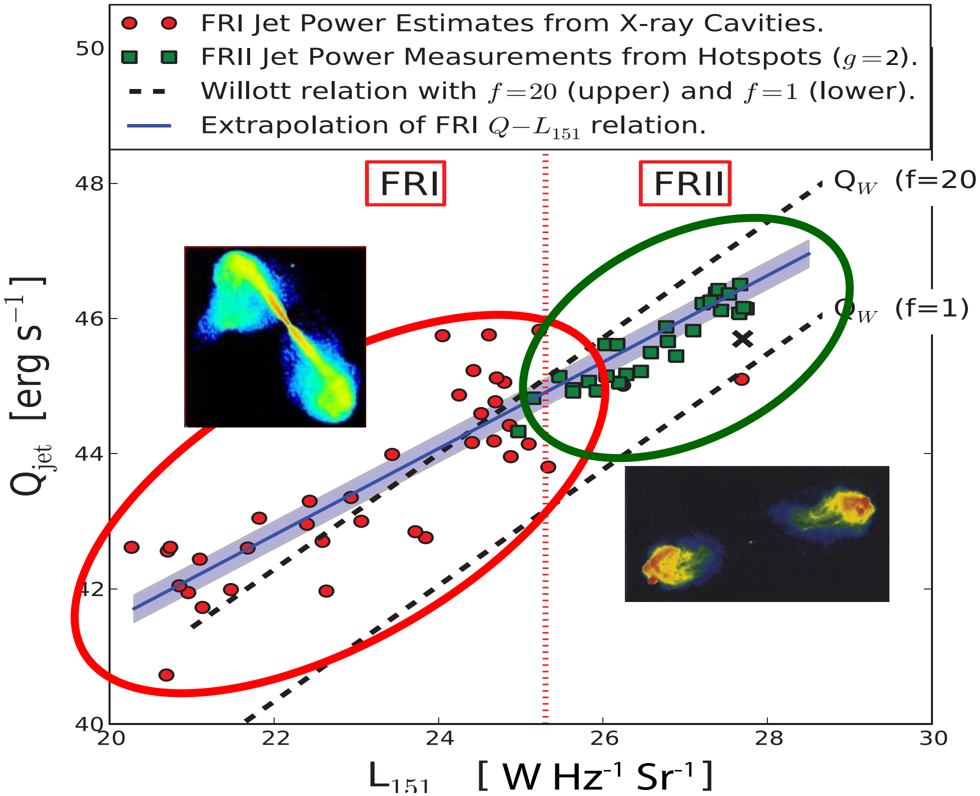
Maximum CR Energy

Nearby FR I & blazars seen by Fermi

ID	Source	d_L [Mpc]	$E_A^{max\,(f)}/Z[10^{19}]$ [eV]
1	CenA(core)	3.7	0.004-3.3
2	M87	16.7	0.040
3	NGC1275	75.3	4.6
4	NGC6251	104	0.27
5	Mrk421	130.0	0.29
6	Mrk501 (h.$^{(g)}$,1997)	146.0	0.17-1.5
7	Mrk501 (l.$^{(g)}$,1997)	146.0	0.28-1.5
8	Mrk501 (l.$^{(g)}$,2007)	146.0	0.2
9	Mrk501 (l.$^{(g)}$,2009)	146.0	0.12-0.6
10	1ES1959+650(h.$^{(g)}$)	206	0.12-2.9
11	1ES1959+650(l.$^{(g)}$)	206	1.3
12	PKS2200+420/BL Lac	307.0	1.1
13	PKS2005-489	316.0	3.1
14	WComae	464.0	0.37-0.57
15	PKS2155-304	533.0	0.23

KM, Dermer, Takami, & Migliori 2012 ApJ

Radio & X-ray data



Godfrey & Shabala 13

$$E < ZeB'l'\beta'\Gamma$$

$$L_B >\sim 2\times 10^{46}\ \mathrm{erg\ s^{-1}}\ \Gamma^2\beta^{-1}\ [E/(Z10^{20.5}\ \mathrm{eV})]^2$$

Energy Losses

acceleration (plasma frame) $t_{acc} = \eta r_L / c = \eta \varepsilon_A / (ZeBc)$

photohadronic/photonuclear energy loss (plasma frame)

$$-\frac{1}{\varepsilon_p}\frac{d\varepsilon_p}{dt} = \frac{c}{2}\int d\cos\theta(1-\beta\cos\theta)\int d\varepsilon \frac{dn}{d\varepsilon}\sigma_{p\gamma}(\bar{\varepsilon})\kappa_{p\gamma}(\bar{\varepsilon})$$

cross section **inelasticity**

$t_{p\gamma} \sim (n_\gamma \kappa_{p\gamma} c \sigma_{p\gamma})^{-1} \propto \varepsilon_p^{1-\beta}$ **(for photon index β>1)**

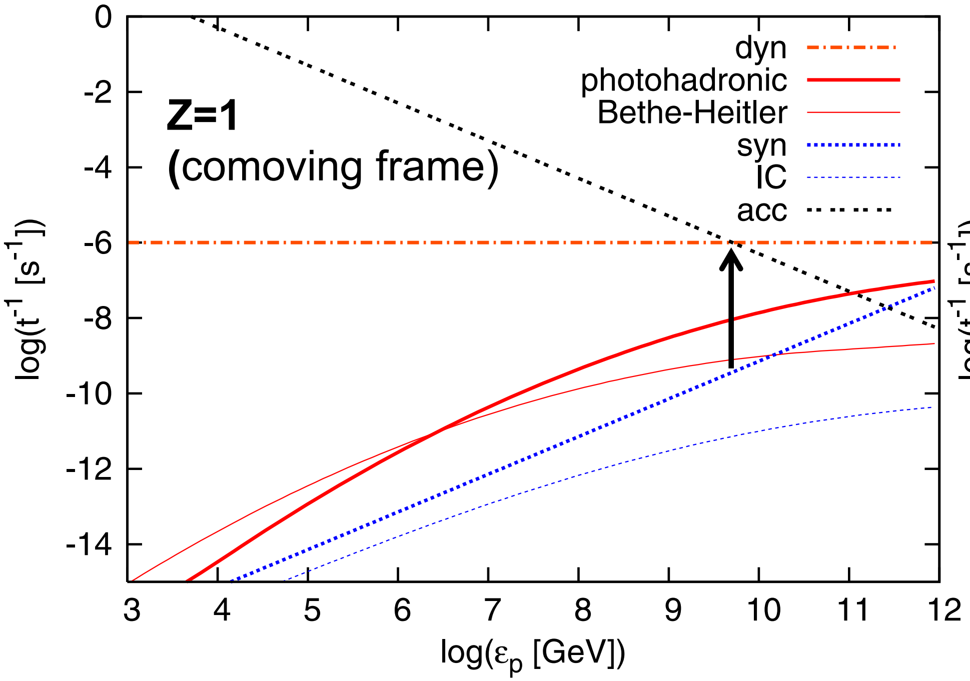
synchrotron energy loss (plasma frame)

$$-\frac{1}{\varepsilon_N}\frac{d\varepsilon_N}{dt} = \frac{1}{\gamma_N m_N c^2}\frac{2}{3}\frac{Z^4 e^4}{m_N^2 c^4} c\beta_N^2 \sin^2\alpha \gamma_N^2 B^2$$

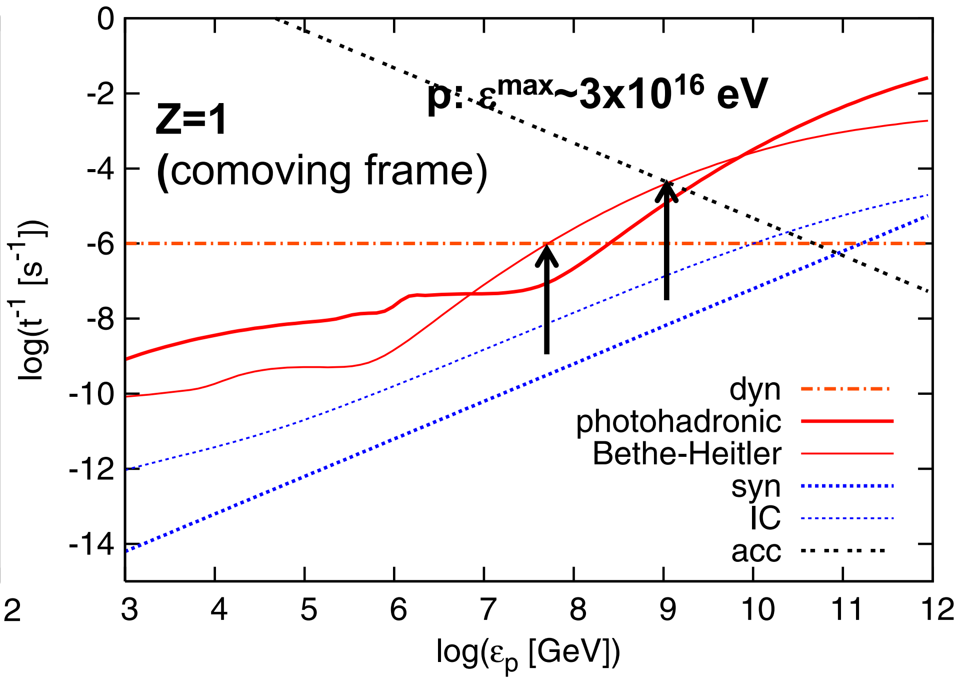
$$t_{syn} \sim \frac{6\pi m_N^4 c^3}{\sigma_T Z^4 B^2 m_e^2 \varepsilon_N} \propto B^{-2}\varepsilon_N^{-1}(A^4/Z^4)$$

Example: Active Galactic Nuclei

BL Lac (low-power blazar)



FSRQ (high-power blazar)

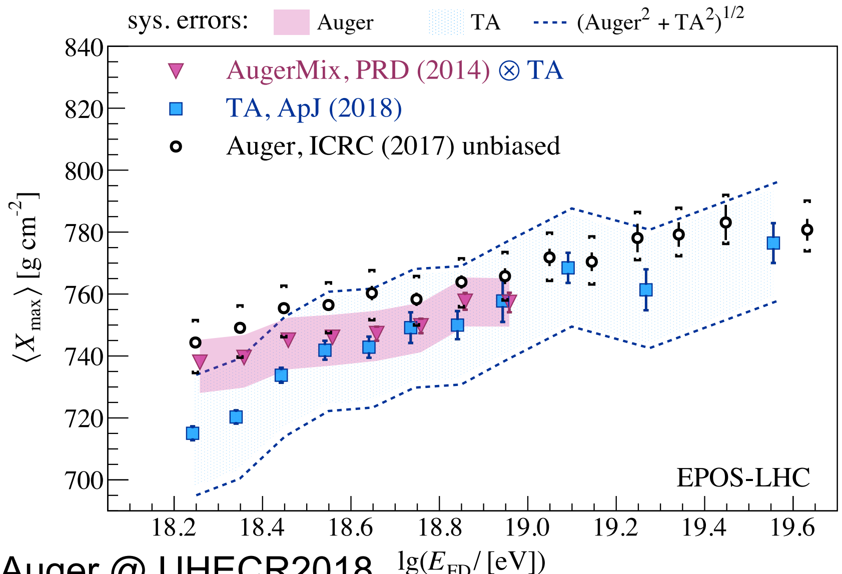


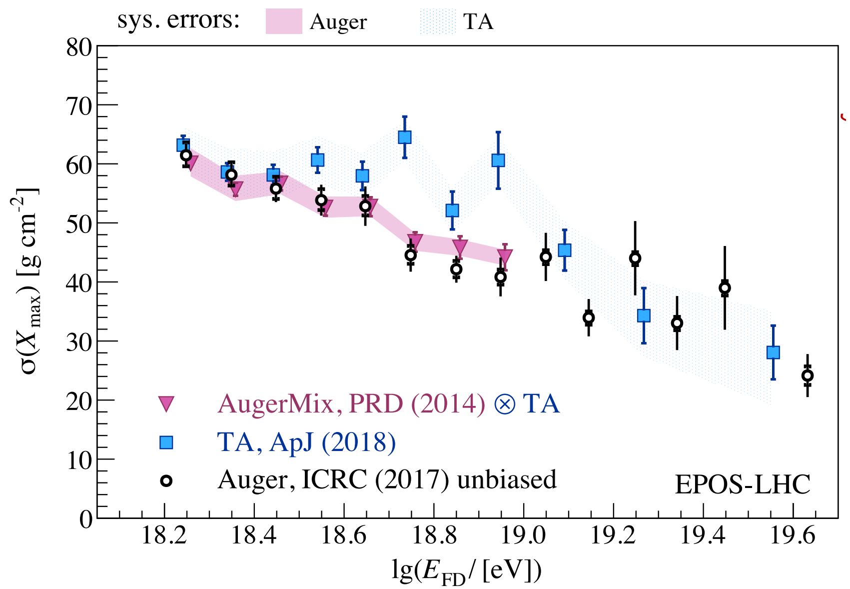
$E \sim \Gamma\varepsilon$

$E^{max} \sim 3 \times 10^{19}$ eV
limited by dynamical time

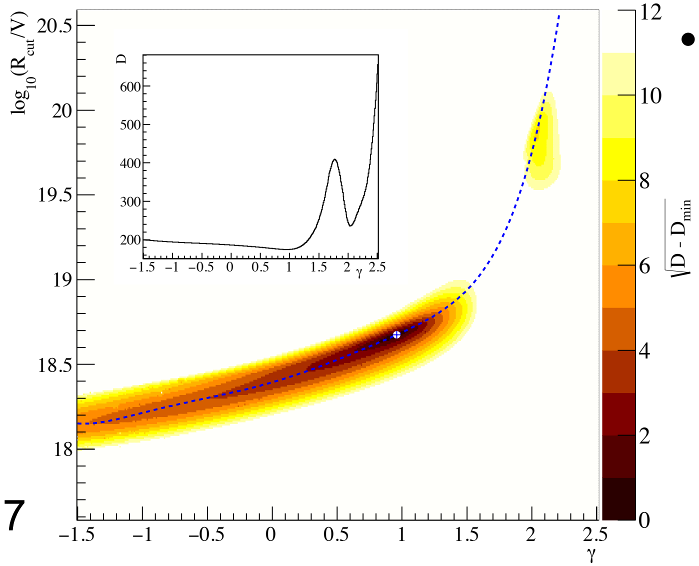
$E^{max} \sim 3 \times 10^{17}$ eV
limited by $p\gamma$ losses

UHECR Composition?





TA-Auger @ UHECR2018



Auger 2017

- Composition **well above** the ankle: ***under debate…***

  TA: compatible w. light (or mixed)

  Auger combined-fit:

  - nucleus-rich abundance (f_H=f_{Fe}=0, f_{He}=0.67, f_N=0.28, f_{Si}=0.05)
  - hard spectra (s~1: best-fit)

  again need TAx4

New Challenges for Source Modeling

1. Nucleus-survival problem
   luminosity requirement → powerful sources
   powerful in radiation → efficient disintegration

2. Heavy-rich composition
   a. intrinsic abundance
   b. reacceleration
   c. injection mechanism

3. Hard spectrum of nuclei
   a. hard “escape” spectrum
   b. hard “accelerated” spectrum
   c. hardening due to “energy losses”

photodisintegration

Giant Dipole Resonance (GDR)

$$A + \gamma \rightarrow (A - 1) + p/n$$

threshold: ~10 MeV

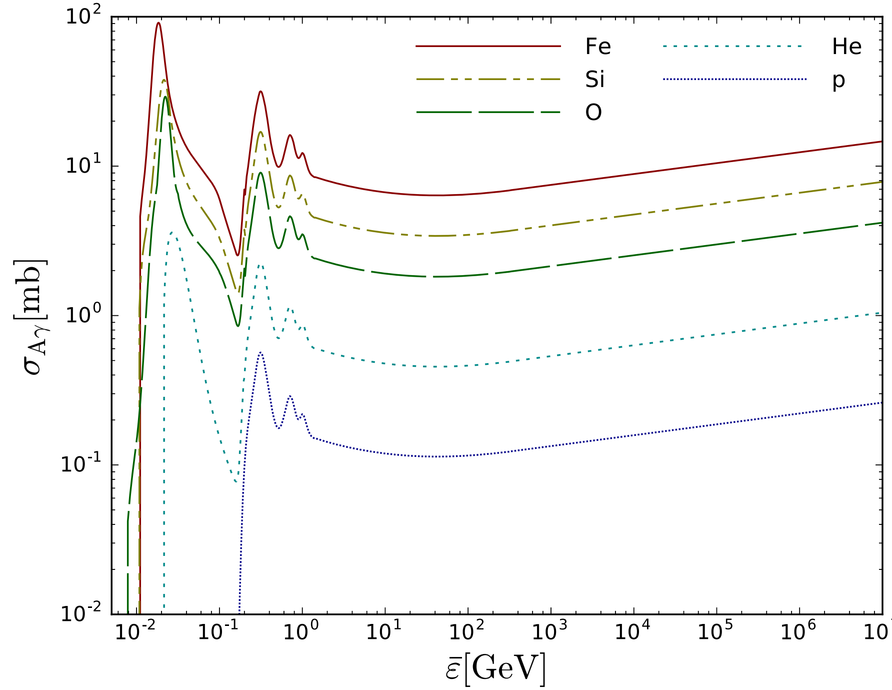
$\sigma_{A\gamma} \sim \alpha\, \pi R_A^2 \sim 30(A/56)^{0.7}$ mb

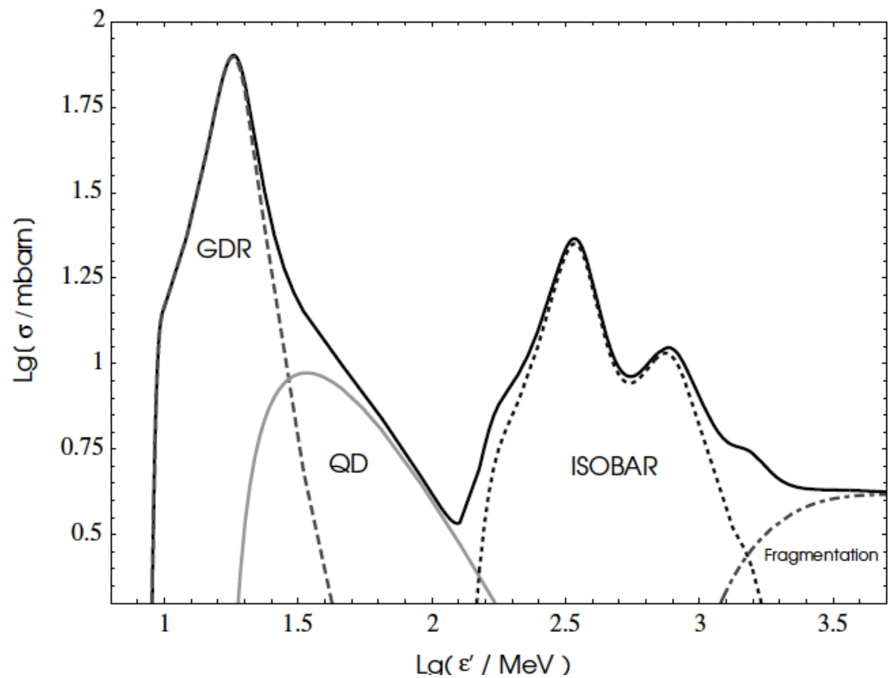
$\varepsilon_A\, \varepsilon_\gamma \sim 10^{-2}\, A\ \mathrm{GeV}^2$

$\varepsilon_{nuc} = \kappa\, \varepsilon_A \sim \varepsilon_A / A$

Neutrinos from n decay

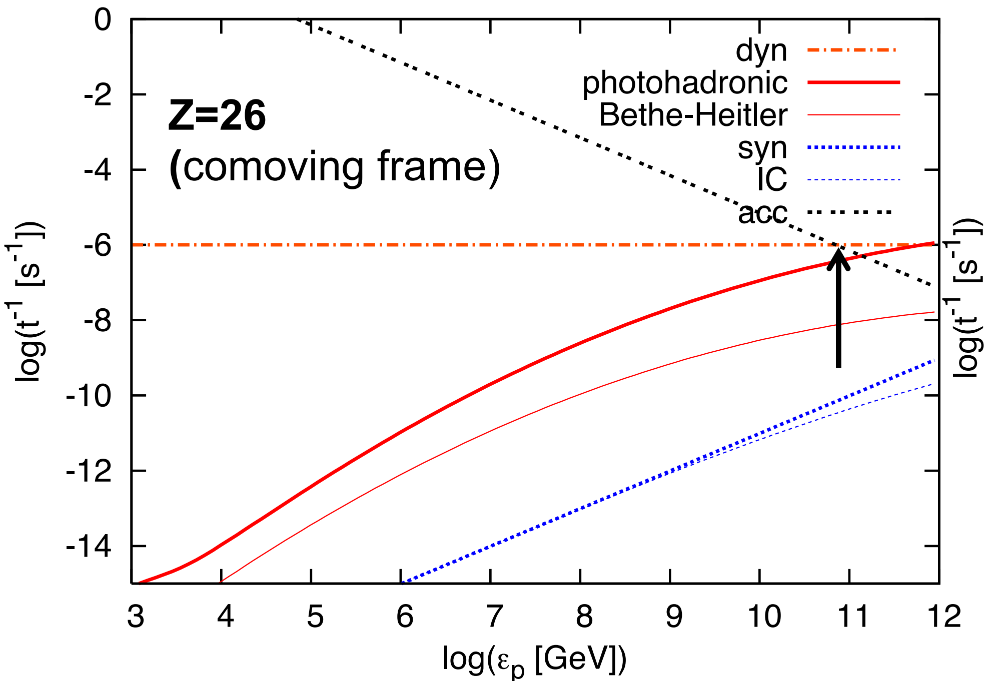
analogy from pγ interactions



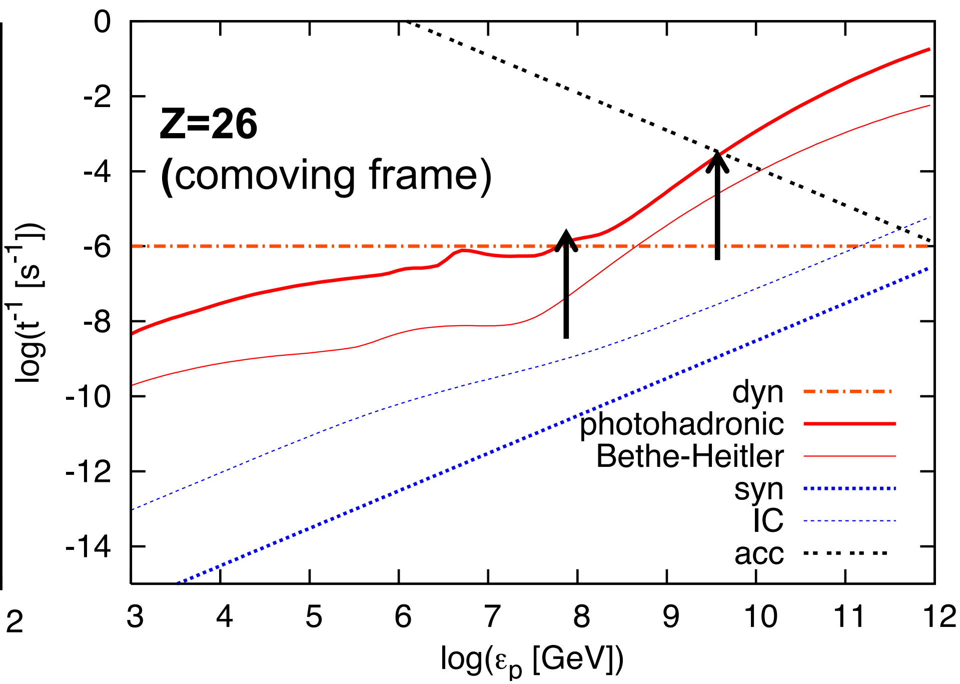


Example: Active Galactic Nuclei

BL Lac (low-power blazar)



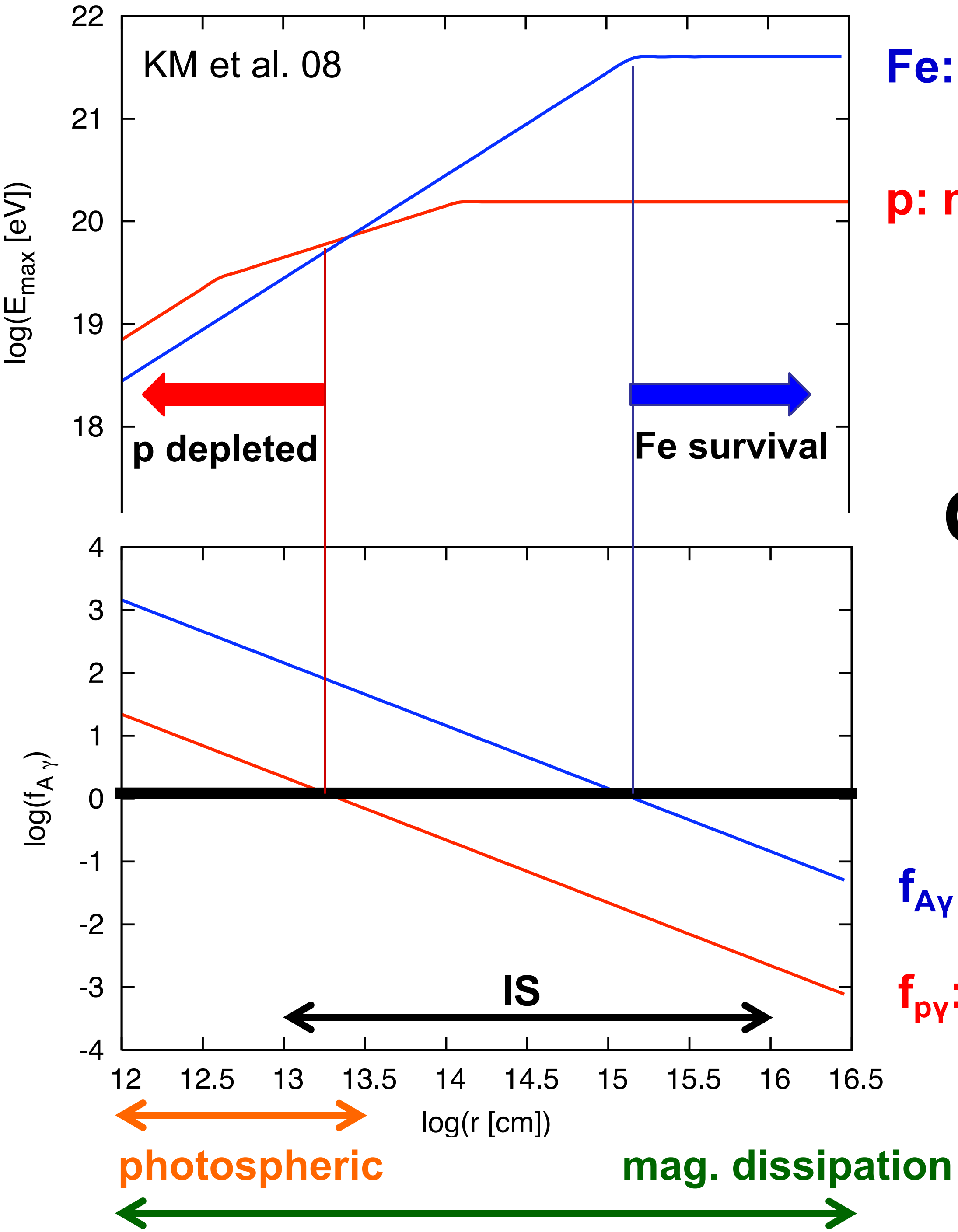
FSRQ (high-power blazar)



$E \sim \Gamma \varepsilon$

$E^{max} \sim 10^{21}$ eV
limited by dynamical time

$E^{max} \sim 5 \times 10^{17}$ eV
limited by $A\gamma$ losses



Fe: maximum energy

p: maximum energy

Gamma-ray burst

$L_\gamma^b = 10^{51.5}$ erg/s
Γ=300, U_e=U_B

$f_{A\gamma}$: disintegration efficiency

$f_{p\gamma}$: meson production efficiency

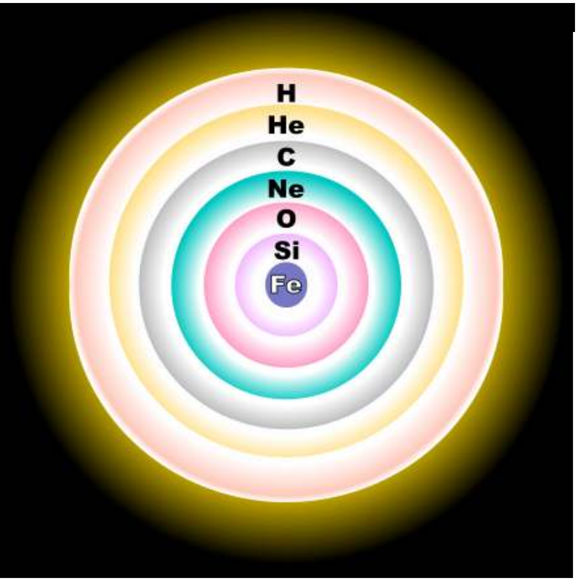
New Challenges for Source Modeling

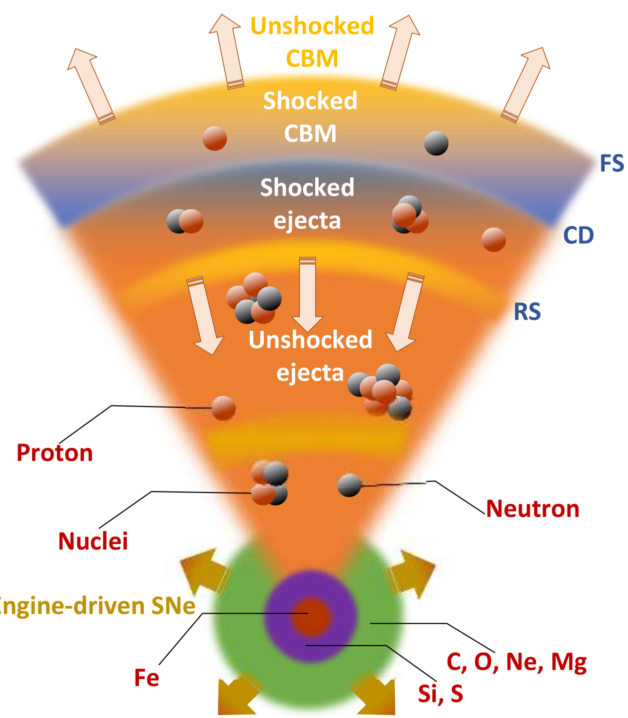
1. Nucleus-survival problem
   luminosity requirement → powerful sources
   powerful in radiation → efficient disintegration

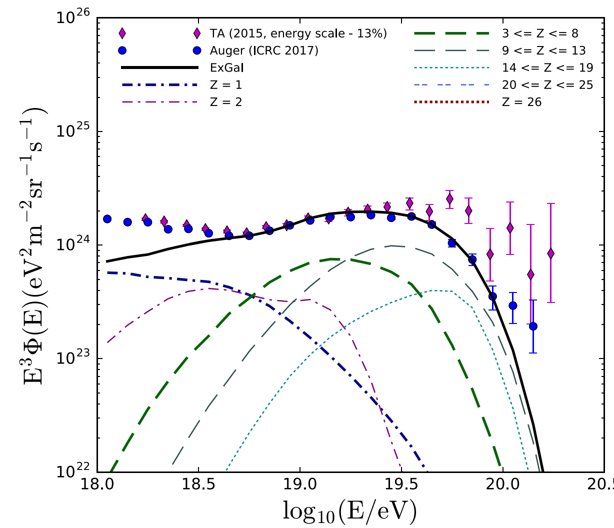
2. Heavy-rich composition
   a. intrinsic abundance
   b. reacceleration
   c. injection mechanism

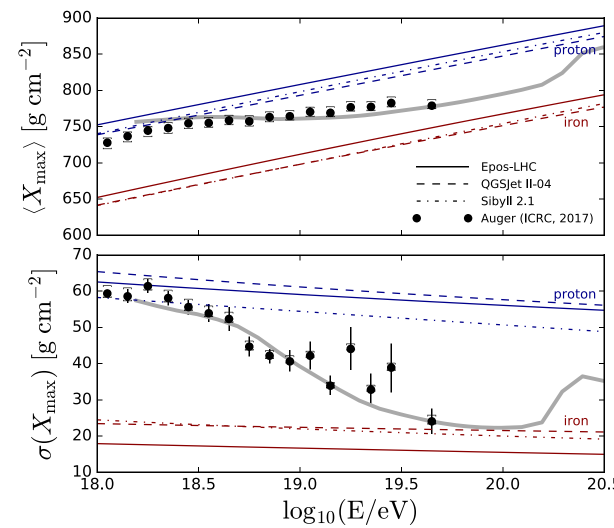
3. Hard spectrum of nuclei
   a. hard “escape” spectrum
   b. hard “accelerated” spectrum
   c. hardening due to “energy losses”

Ex. Low-Luminosity GRBs/Engine-Driven Supernovae





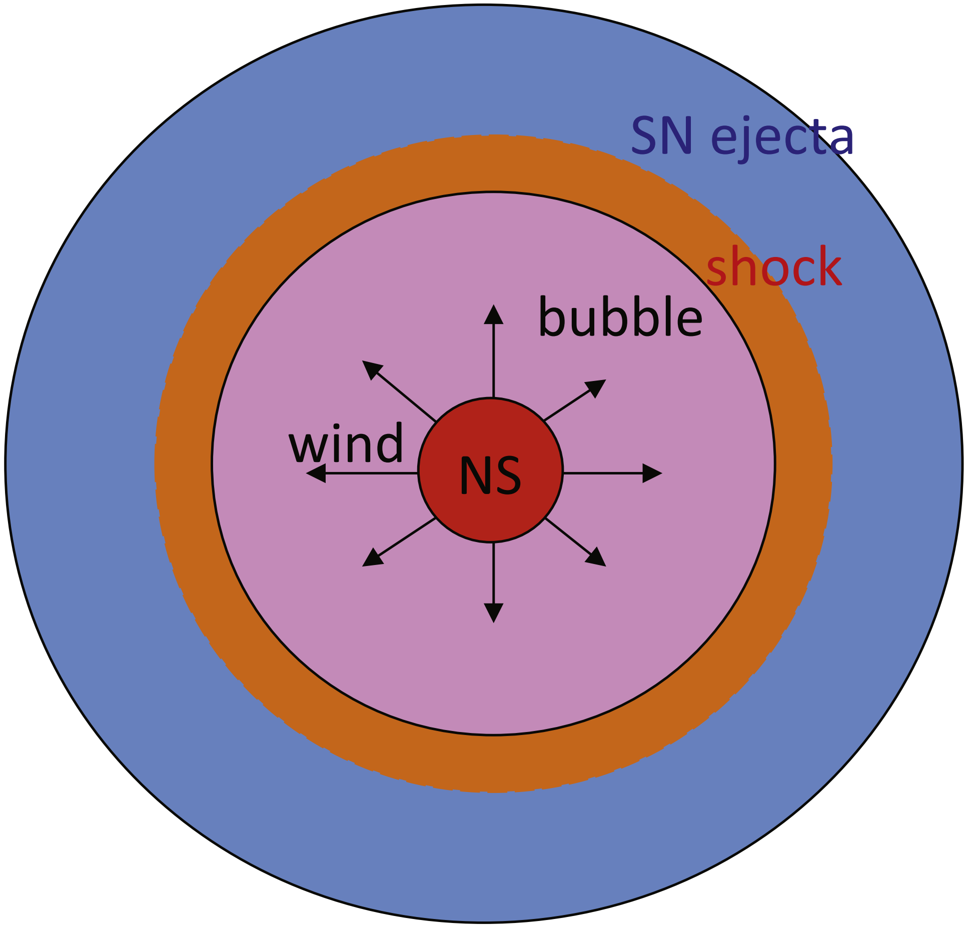


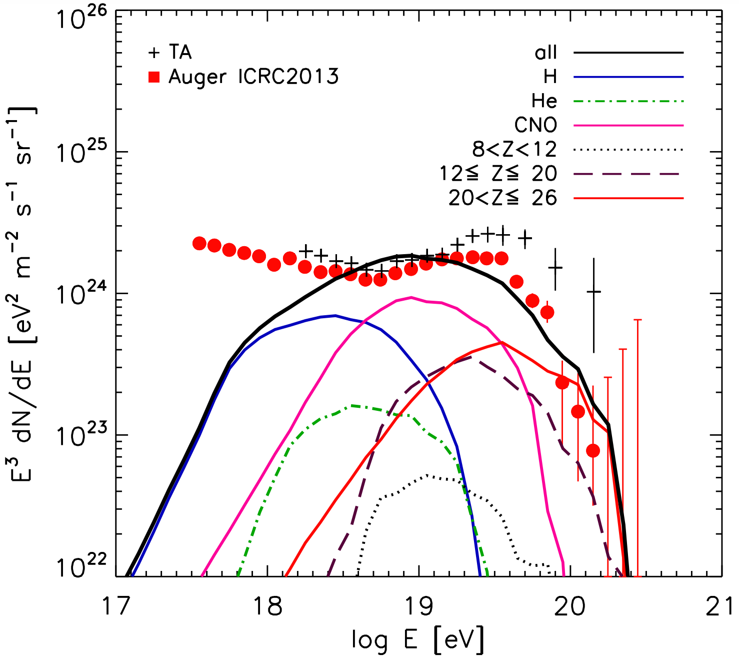


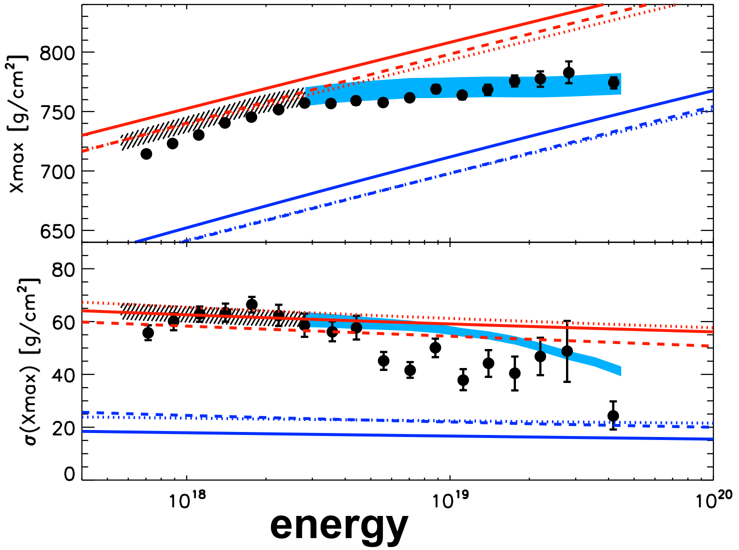
1. Dominantly "intermediate" mass nuclei: consequences of progenitor models
2. Instantaneous escaping spectrum: hard
3. Nuclei can survive (cf. BronIcoli+)
4. Correlation w. starburst galaxies

Zhang, KM+ 18, Zhang & KM 19

Ex. Magnetars & Fast-Rotating Pulsars





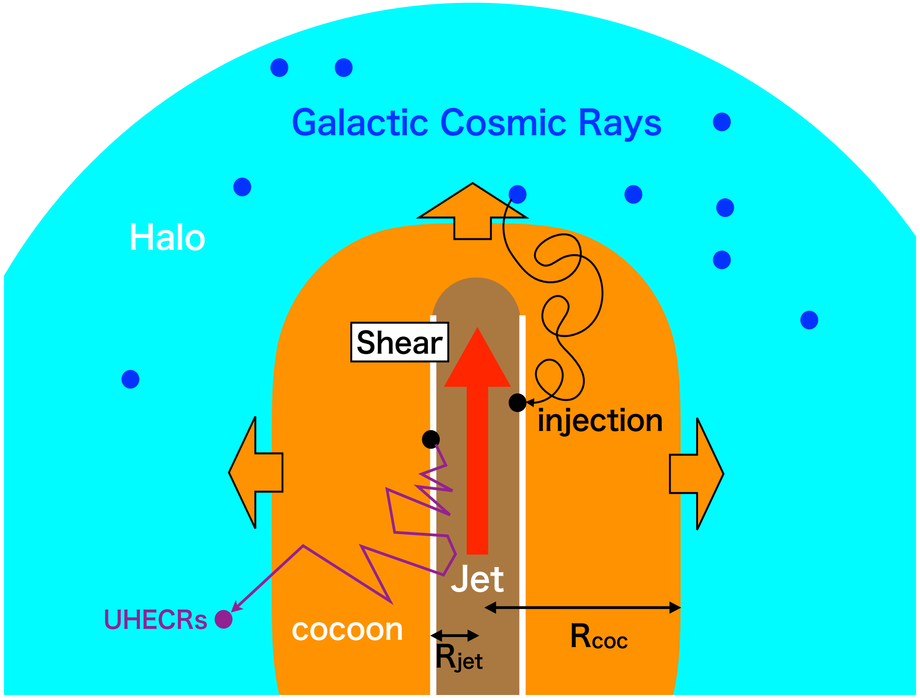


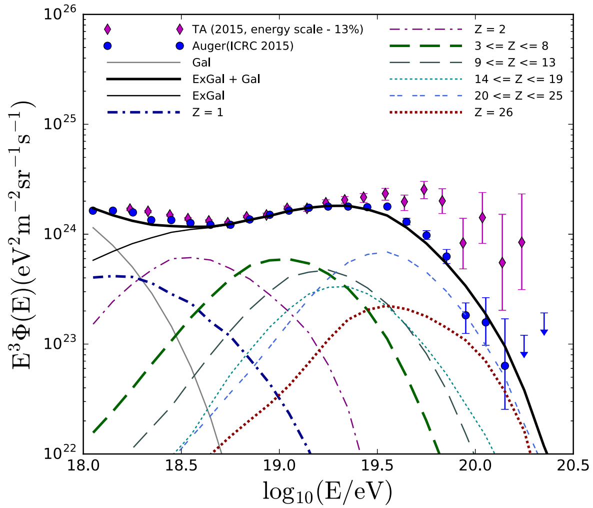
Fang, Kotera, KM & Olinto 12 ApJ
Fang, Kotera, KM & Olinto 14 PRD
see also Arons 03 ApJ
KM, Meszaros & Zhang 09 PRD

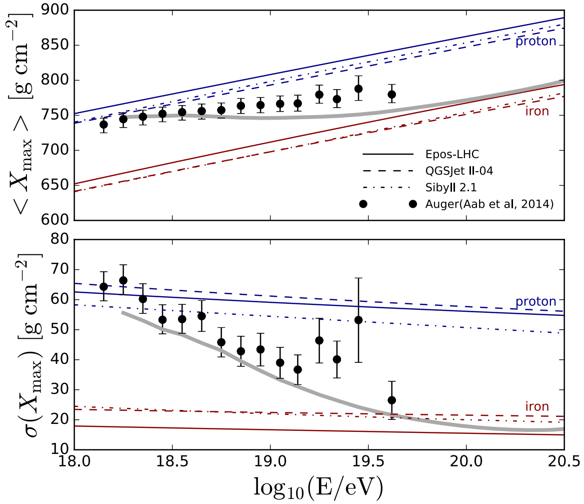
Ex. Active Galactic Nuclei Jet Shear

shear acceleration: Fermi acc. at the jet-cocoon boundary

(Berezhko & Krimskii 81, Earl & Jokipii 88)







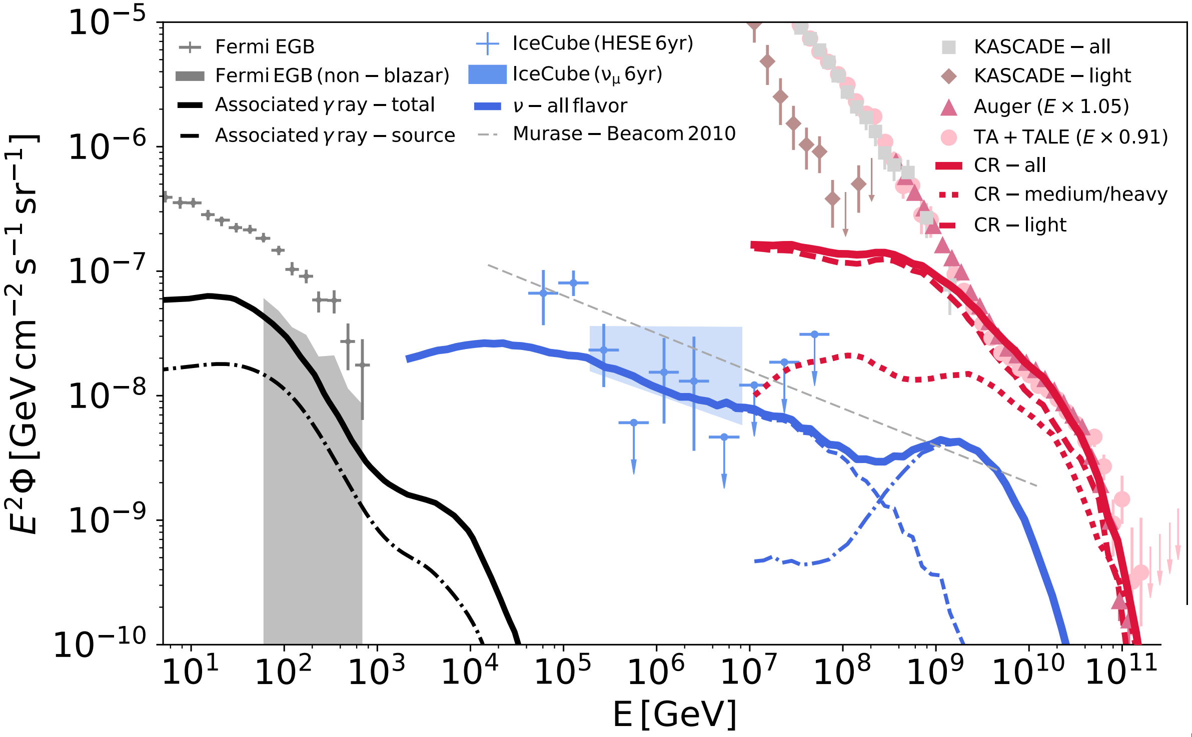
1. Recycling galactic TeV-PeV CRs
2. Hard spectrum predicted
3. Nuclei can survive
4. Correlation w. radio galaxies

cf. O'Sullivan+ 09, Caprilori 15, Matthews+ 18

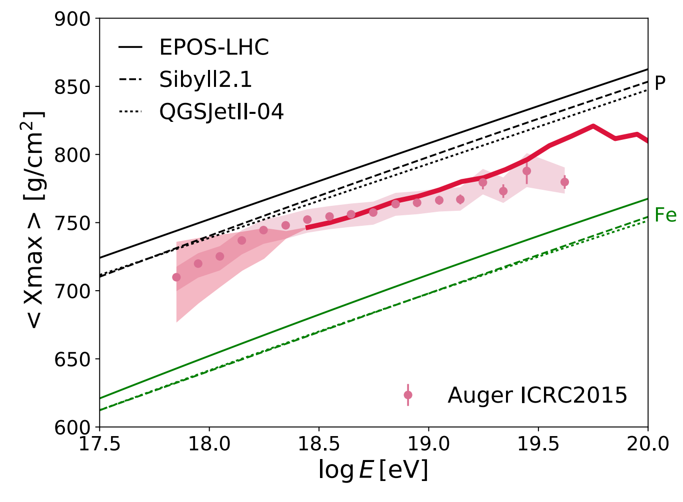
from Kimura KM Zhang 18 PRD

Ex. Active Galactic Nuclei Embedded in Clusters

Hardening due to photodisintegration in environments (ex. Unger+ 15 PRD)



Fang & KM 18 Nature Physics



- Low-energy CRs: confinement in clusters
- CR nuclei: photodisintegration during diffusion consistent w. Fermi acceleration (s~2)
- Correlation w. large-scale structures/AGN

Summary II

Source physics is important
1. dynamics 2. particle acceleration 3. particle interaction

- Supernova: established multi-messenger source
  long GRB: next multi-messenger target
  diversity of transients (SN-GRB-SLSN-FRB etc.)
  "What is the central engine?"

- Cosmic-ray "emission"
  diffusive shock acceleration: standard
  escaping CRs ≠ accelerated CRs
  Auger results: new challenges for source models

Problems for Exercise (Astro)

Kilonova: (brighter than nova and dimmer than supernova)

The discovery of a neutron star merger event, GW170817, which is coincident with GRB 170817A, was followed by the observations of their electromagnetic counterparts. In particular, the optical and infrared counterpart is so-called a kilonova/macronova, which is likely to be powered by r-process elements. Analogous to supernovae, the ejecta with total mass M freely expands with velocity V. Initially, the system is optically thick, i.e. the optical depth for the ejecta, $\tau = \xi K \rho R$, is larger than unity. Here K is the opacity, $\rho \approx \frac{3M}{4\pi R^3}$ is the mass density, R is the ejecta radius, and $\xi = 0.1$ is a correction factor related to the density structure. Most of the photons in the ejecta can break out when the expansion is faster than the photon diffusion time. For the near-infrared component, the observed luminosity at the peak time (about a week after the coalescence) is $L_{\rm NIR} = 10^{41}$ erg s^{-1} and the effective temperature is $T_{\rm NIR} = 3000$ K. For simplicity, the ejecta is assumed to be spherical.

1. Estimate the ejecta radius R at the peak time.
2. By equating the photon diffusion time to the ejecta expansion time, give the condition for the photon breakout using τ and V. You may ignore numerical factors.
3. Using the previous result and assuming $V = 0.1c$ and $K = 10$ cm^2 g^{-1}, estimate the ejecta mass M.
4. If the ejecta is powered by radioactive nuclei, as in the theory of supernova light curves, the luminosity around the peak time is essentially equal to the heating luminosity Q. According to the Fermi theory, the heating luminosity is roughly given by

$$Q(t) = \frac{m_e}{\langle A \rangle m_p} \frac{Mc^2}{t_F} \left(\frac{t}{t_F} \right)^{-1.2}, \qquad (1)$$

where $t_F = 8610$ s, $m_p/m_e \simeq 1836$ is the proton-electron mass ratio, and $\langle A \rangle$ is the average mass number. Assuming that the peak time is 10^6 s, give the order of magnitude estimate on $\langle A \rangle$ and discuss its implications.

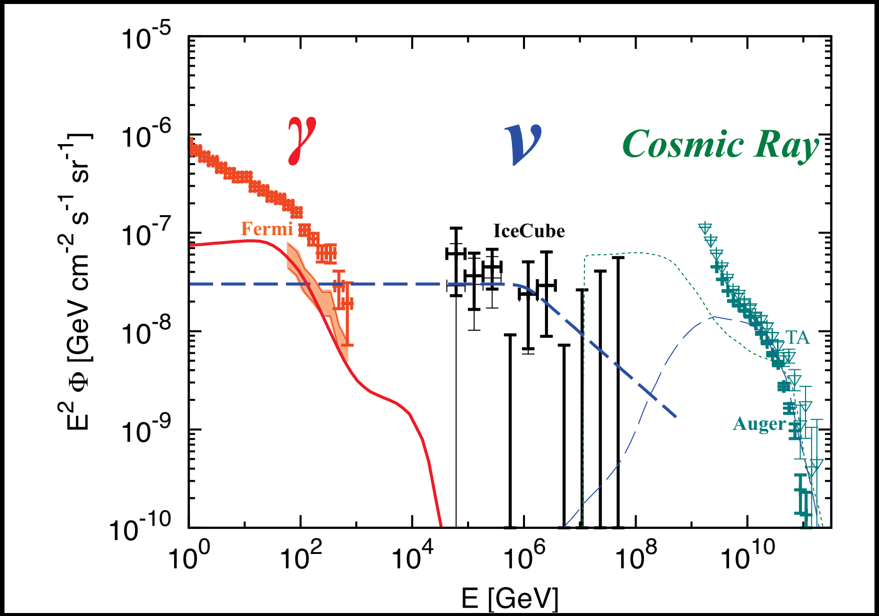
Problems for Exercise (CR)

1. Self-similar solution (w. fixed B)
   a. When does the deceleration happen?
   b. What is the time evolution of radius for the Sedov-Taylor phase?
   c. What is the time evolution of injected particles (assuming that it is proportional to energy carried by a shell)?
   d. What is the time evolution of the maximum energy assuming the Sedov-Taylor expansion?

   optional.
   What is the time evolution of the maximum energy assuming the Blandford-McKee expansion or jet-induced cocoon expansion?

2. Estimate photodisintegration optical depth for TXS 0506+056
   a. Estimate the iron energy that causes a resonance with 4 keV photons
   b. Estimate the photodisintegration optical depth (L_X=3x10^{44} erg/s, r=10^{18} cm, Γ=20)
   c. Can UHECR irons survive? (assume photon index β=2.8~3)

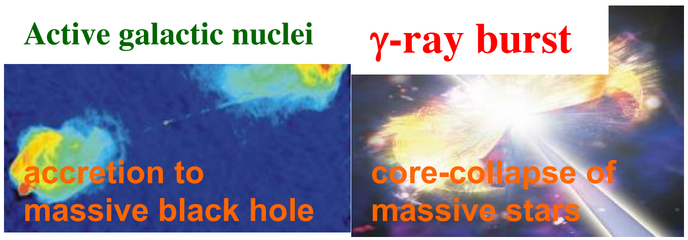
Cosmic-Ray Reservoirs



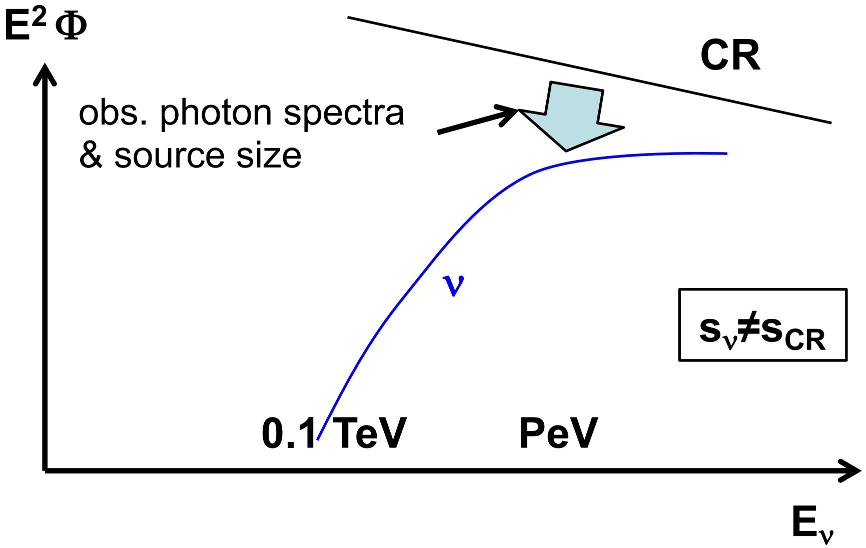
Astrophysical Extragalactic Scenarios

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

Cosmic-ray Accelerators
(ex. UHECR candidate sources)



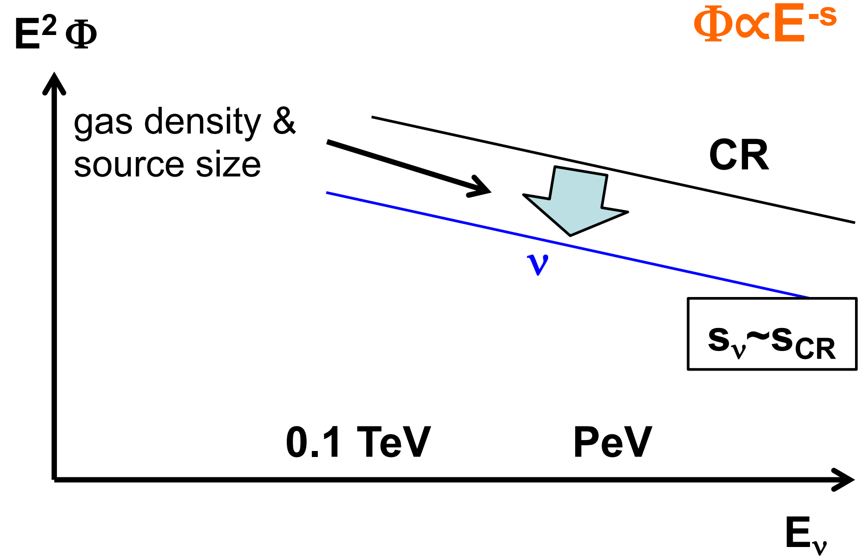
$$p + \gamma \rightarrow N\pi + X$$



Cosmic-ray Reservoirs

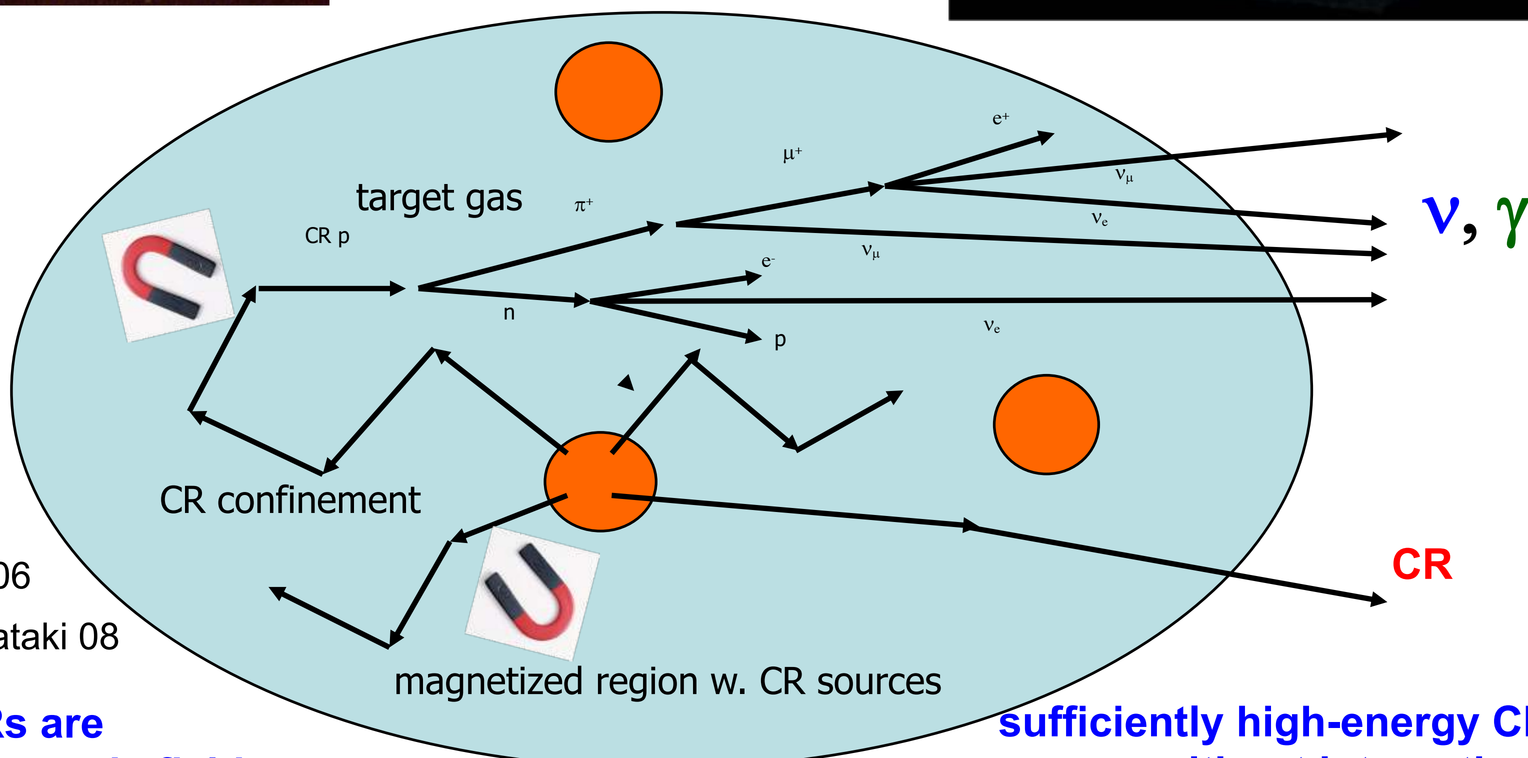
$$p + p \rightarrow N\pi + X$$

$\Phi \propto E^{-s}$



Cosmic-Ray Reservoirs

“cosmic-ray reservoirs”



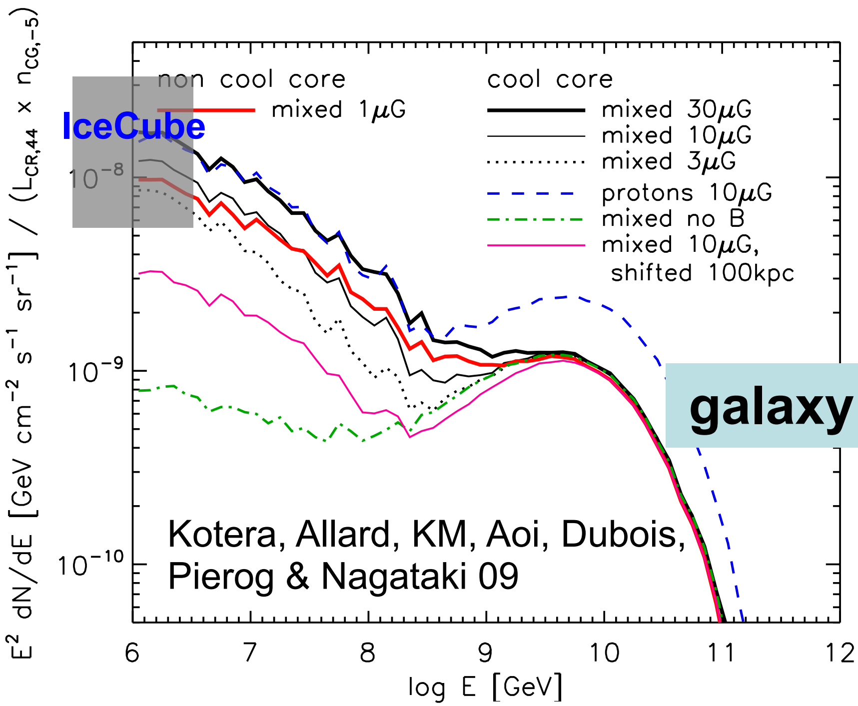
Loeb & Waxman 06

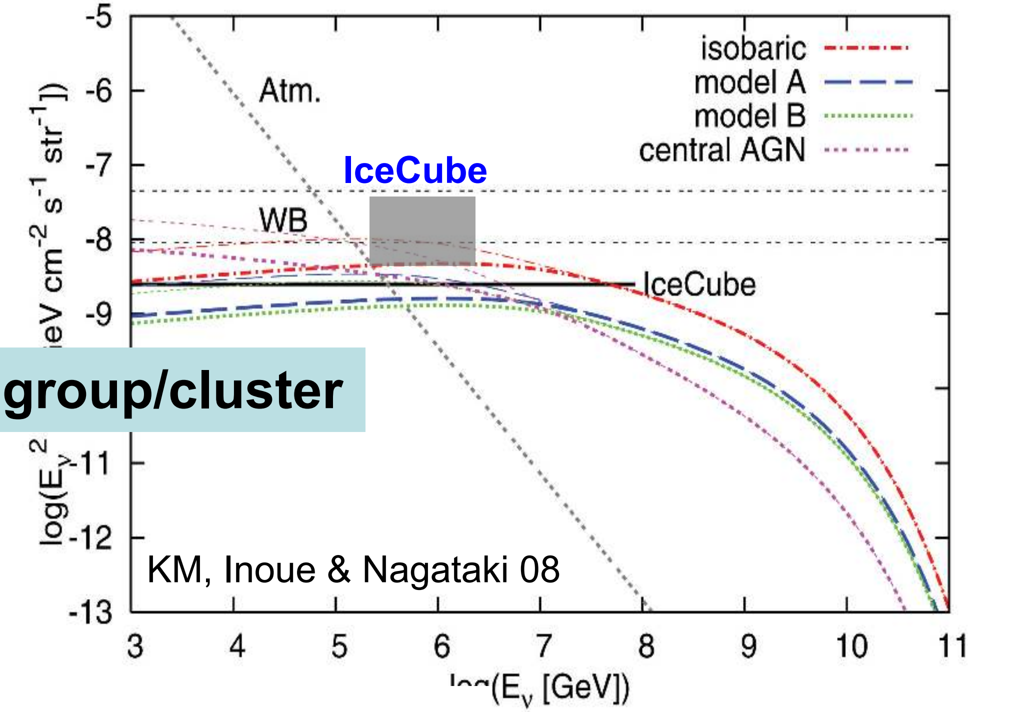
KM, Inoue & Nagataki 08

low-energy CRs are confined by magnetic fields

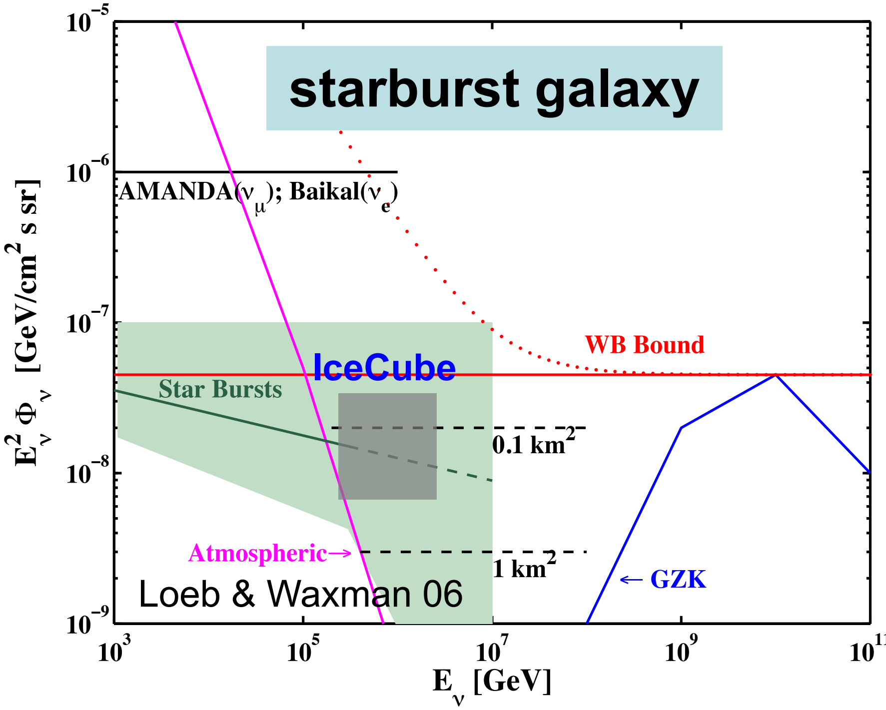
sufficiently high-energy CRs escape without interactions

galaxy group/cluster



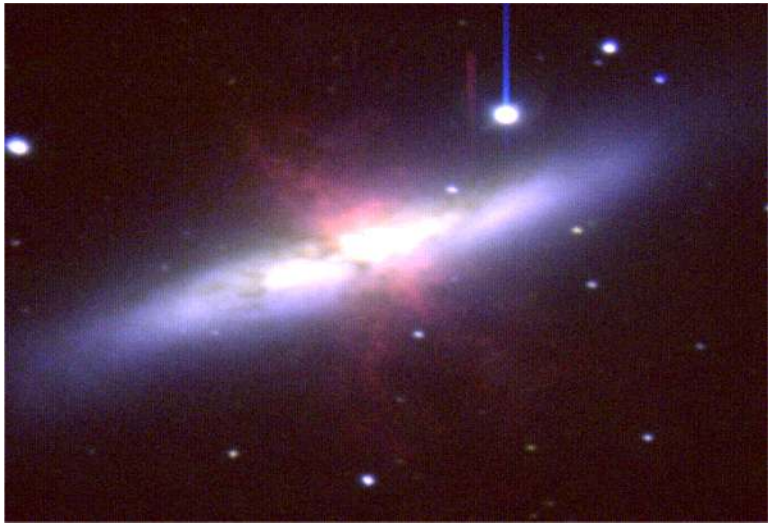


starburst galaxy



consistent w. observations but uncertain

Starburst/Star-Forming Galaxies: Basics



- High-surface density

  M82, NGC253: Σ_g~0.1 gcm^{-3} → n~200 cm^{-3}

  high-z MSG: Σ_g~0.1 g cm^{-3} → n~10 cm^{-3}

  submm gal. Σ_g~1 gcm^{-3} → n~200 cm^{-3}
- CR accelerators

  Supernovae, hypernovae, GRBs,

  Super-bubbles (multiple SNe)

  Galaxy mergers, AGN

SBG CR luminosity density $Q_{\rm cr} \sim 8.5 \times 10^{44} \ {\rm erg \ Mpc^{-3} \ yr^{-1}} \ \epsilon_{{\rm cr},-1} \varrho_{{\rm SFR},-3}$

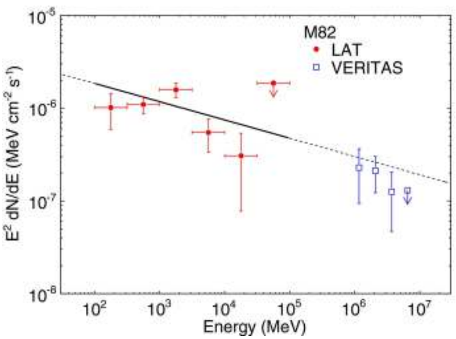
(SFG CR energy budget ~ Milky Way CR budget is ~10 times larger)

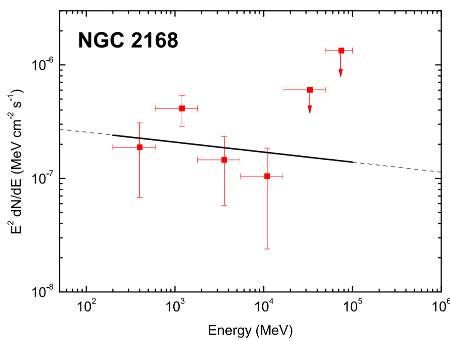
advection time (Gal. wind) $t_{\rm esc} \approx t_{\rm adv} \approx h/V_w \simeq 3.1 \ {\rm Myr} \ (h/{\rm kpc}) V_{w,7.5}^{-1}$

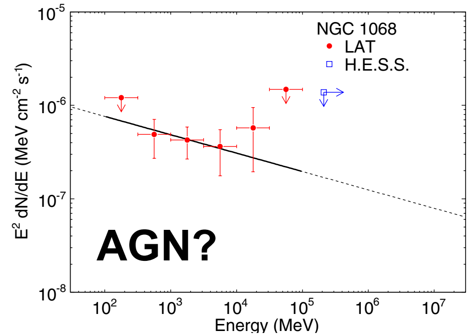
pp efficiency $f_{pp} \approx \kappa_p \sigma_{pp} n c t_{\rm esc} \simeq 1.1 \ \Sigma_{g,-1} V_{w,7.5}^{-1} (t_{\rm esc}/t_{\rm adv})$

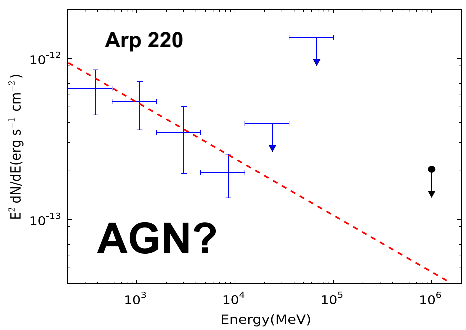
Gamma-Ray Detection from Starbursts

Starbursts have been detected in GeV-TeV gamma rays

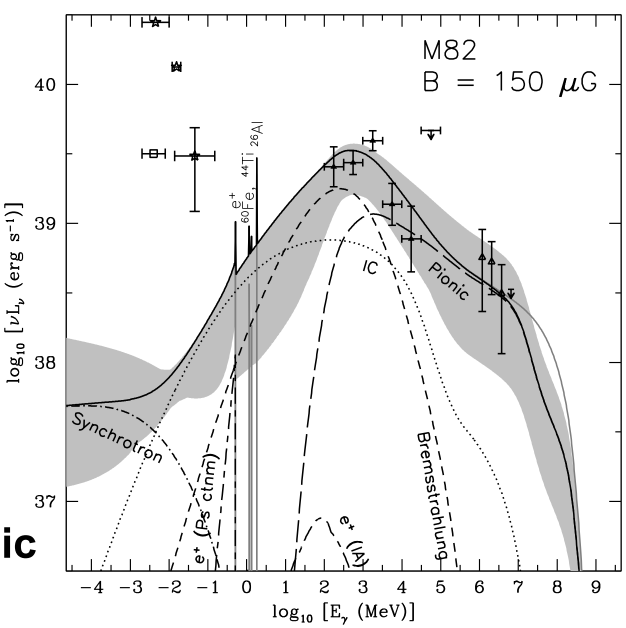




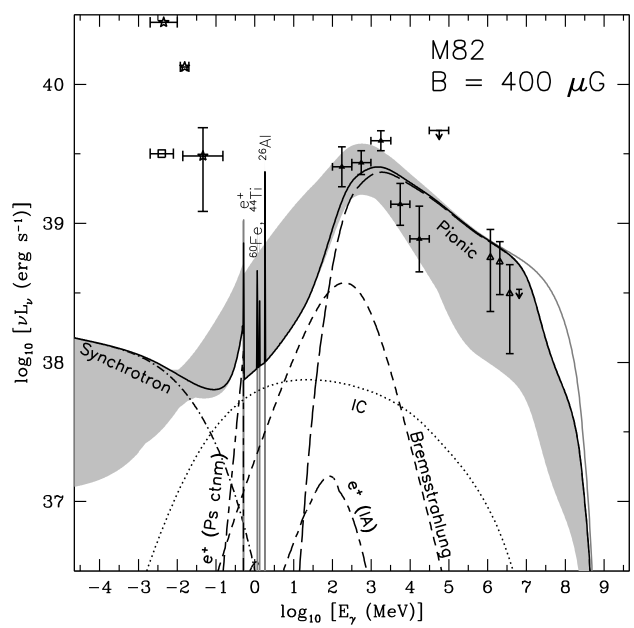




Ackermann+ 12 ApJ, Tang+ 14 ApJL, Peng+ 16 ApJL, Griffin+ 16 ApJL



leptonic+hadronic



hadronic

Lacki, Horiuchi & Beacom 14 ApJ

Luminosity Function & Calorimetry

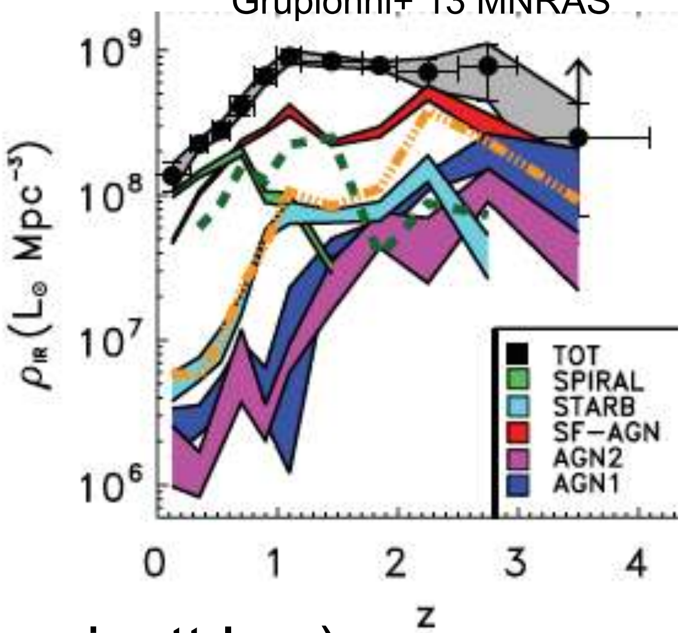
LF is described by the Schechter function

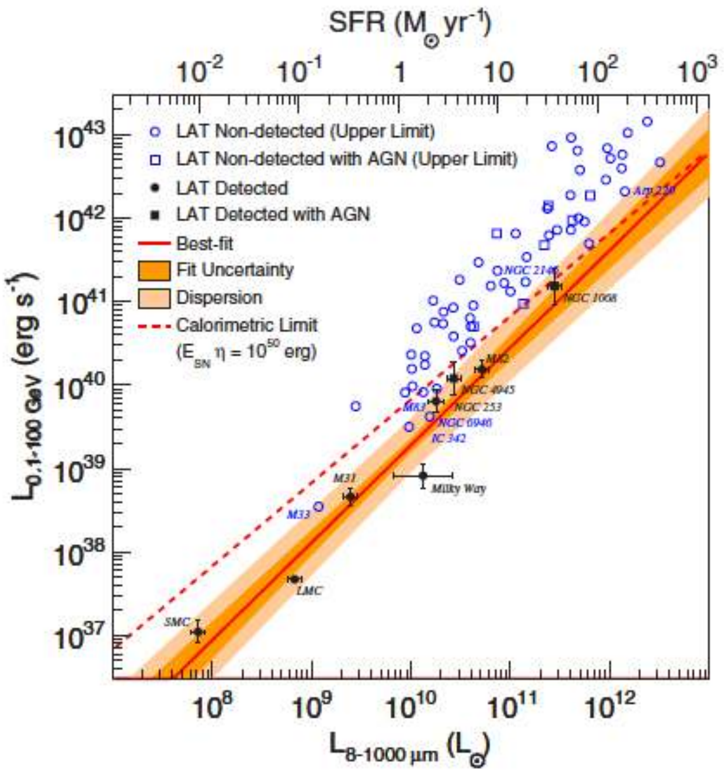
$$\Phi(L)\mathrm{d}\log L = \Phi^* \left(\frac{L}{L^*}\right)^{1-\alpha} \exp\left[-\frac{1}{2\sigma^2}\log_{10}^2\left(1+\frac{L}{L^*}\right)\right] \mathrm{d}\log L$$

$\alpha \sim 1$, $L^* \sim 10^{11}\ L_{sun}$: typical infrared luminosity

Redshift evolution: m~3-4 up to z~1 for $(1+z)^m$

Grupionni+ 13 MNRAS





SFR ∝ L_{IR} (Kennicutt law)

$L_\gamma \propto L_{IR}^{1.17}$ (Fermi collaboration 12 ApJ)

(basic agreement w. calorimetry)

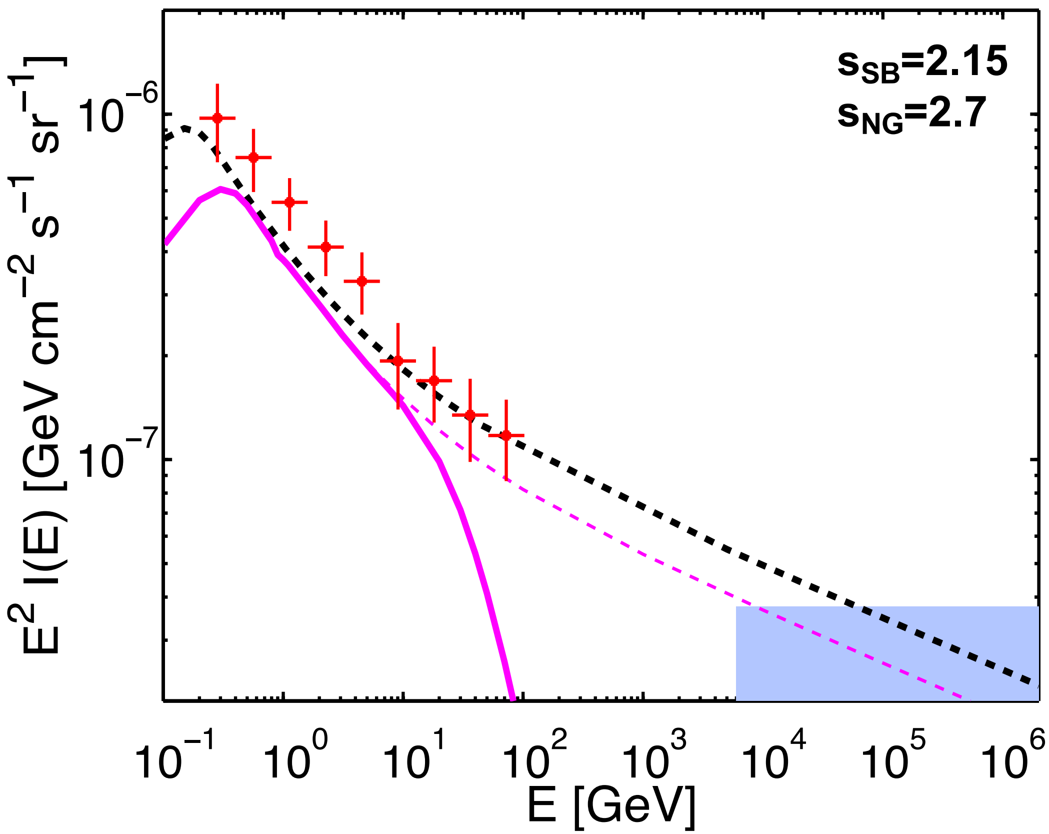
→ "typical" muon neutrino luminosity:

$EL_E \sim 2\times10^{40}$ erg s^{-1}

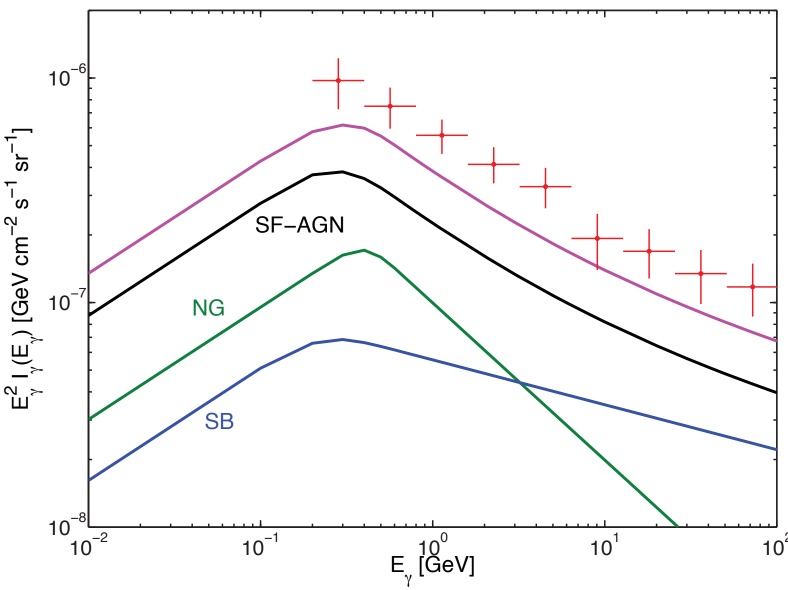
"effective" density: $n_0 \sim 10^{-5}\ Mpc^{-3}$

can be reached by Gen2 (KM & Waxman 16)

Star-Forming/Starburst Galaxies, νs, γs



Tamborra, Ando & KM 14 JCAP



Starbursts can potentially explain ν and γ simultaneously, but keep in mind

- Normalization is uncertain (L_γ-L_{IR}, uncertain AGN contribution)
- Spectral indices are uncertain (could be s_{SB}=2.0 at high energies)

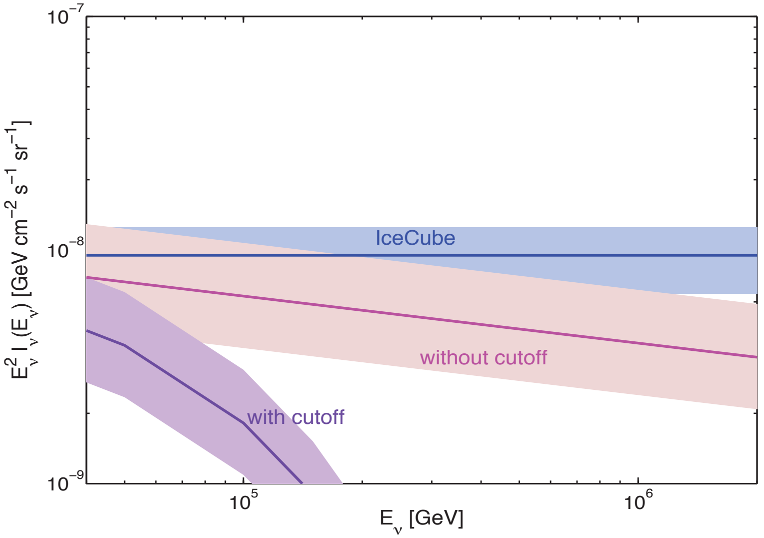
Necessity of Super-Pevatrons

Our Galaxy's CR spectrum

Knee at 3 PeV

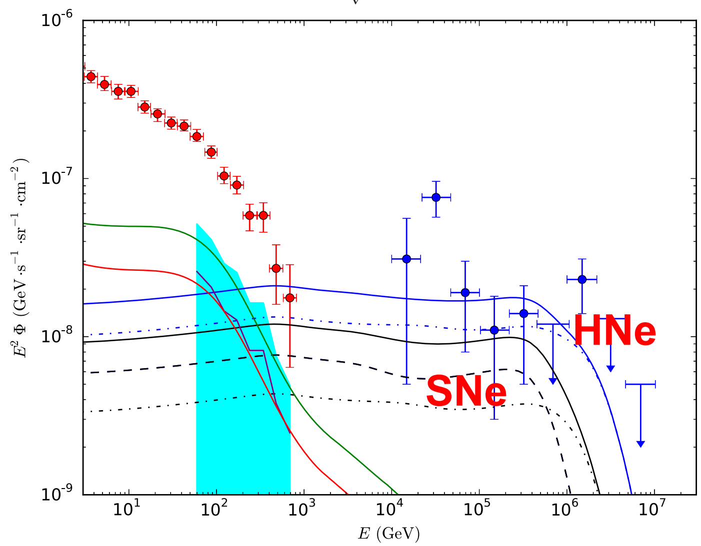
→ neutrino knee at ~100 TeV

Normal supernovae (SNe) are not sufficient to explain >0.1 PeV data



Possible solutions

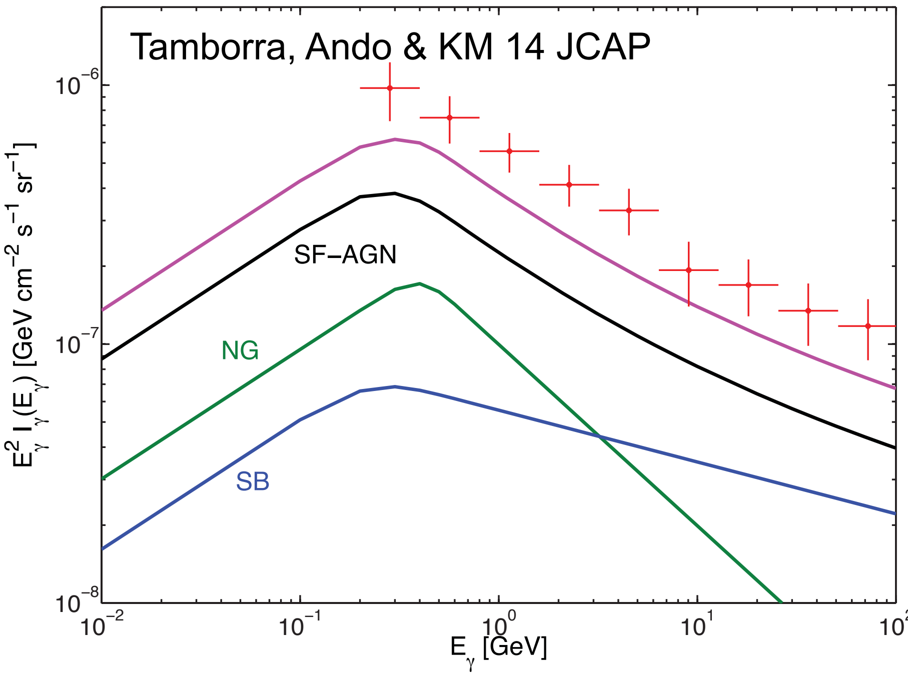
1. B fields amplified to ~ mG KM+ 13
2. Hypernovae (HNe) KM+ 13, Liu+ 14, Senno+ 15
3. Trans-relativistic supernovae gamma-ray bursts Dado & Dar 14, Wang+ 15
4. Type IIn/IIb supernovae Zirakashvilli & Ptuskin 16
5. Super-bubbles
6. AGN disk-driven outflows Tamborra+ 14
7. Galaxy mergers Kashiyama & Meszaros 14



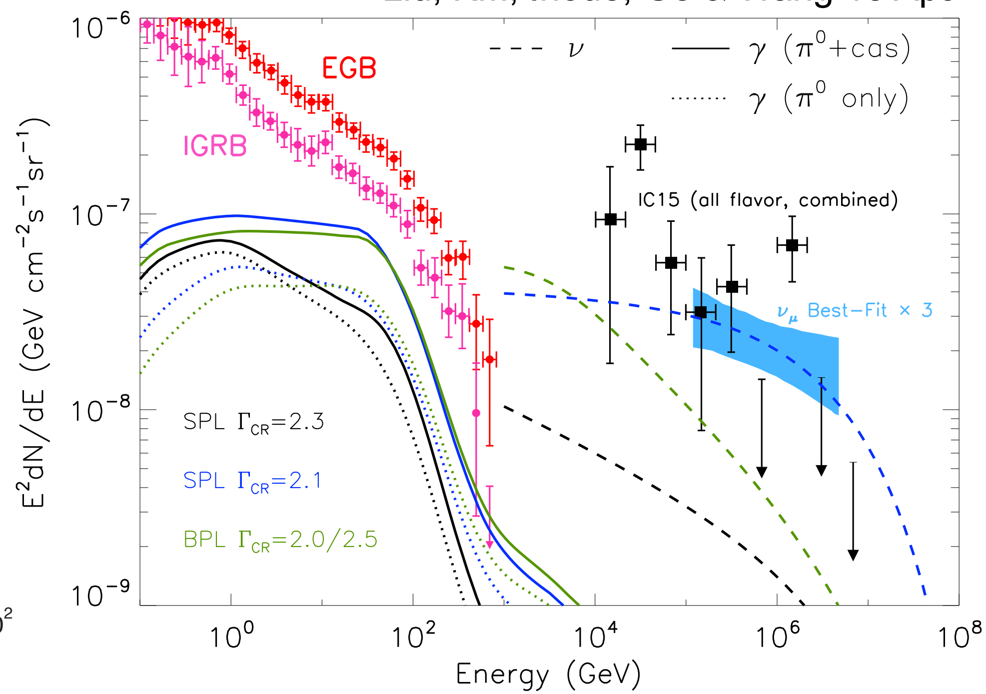
Senno, Meszaros, KM, Baerwald & Rees 15 ApJ
Xiao, Meszaros, KM & Dai 16 ApJ

Ex. Star-Forming Galaxies w. AGN

Starbursts can potentially explain ν and γ simultaneously but...
1. CR accelerators are more powerful than supernovae (beyond the knee)
2. Diffusion should be much slower than expected from that of our Galaxy
3. Tension with Fermi and IACT data (normalization & photon index)

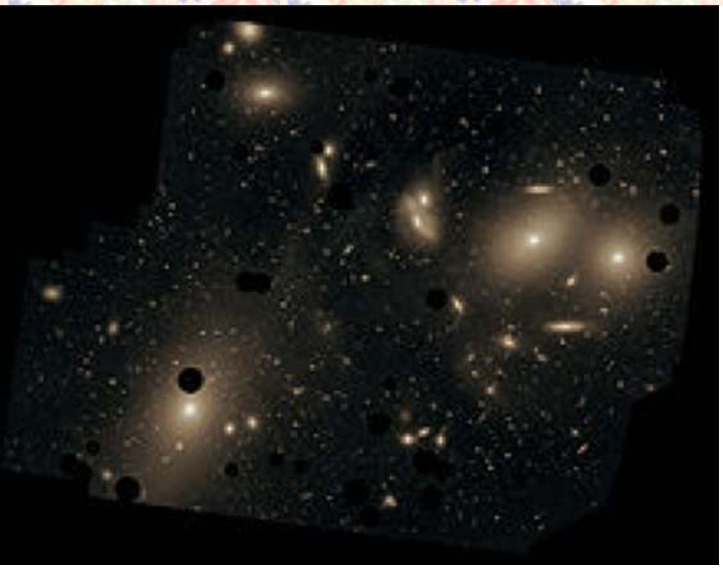


Liu, KM, Inoue, Ge & Wang 18 ApJ



1. Disk-driven winds are likely to accelerate CRs up to ~10-100 PeV
2. Diffusion coefficients can be smaller from those of star-forming galaxies
3. Consistent w. Fermi limits and CR spectra can be harder

Example: Galaxy Groups and Clusters



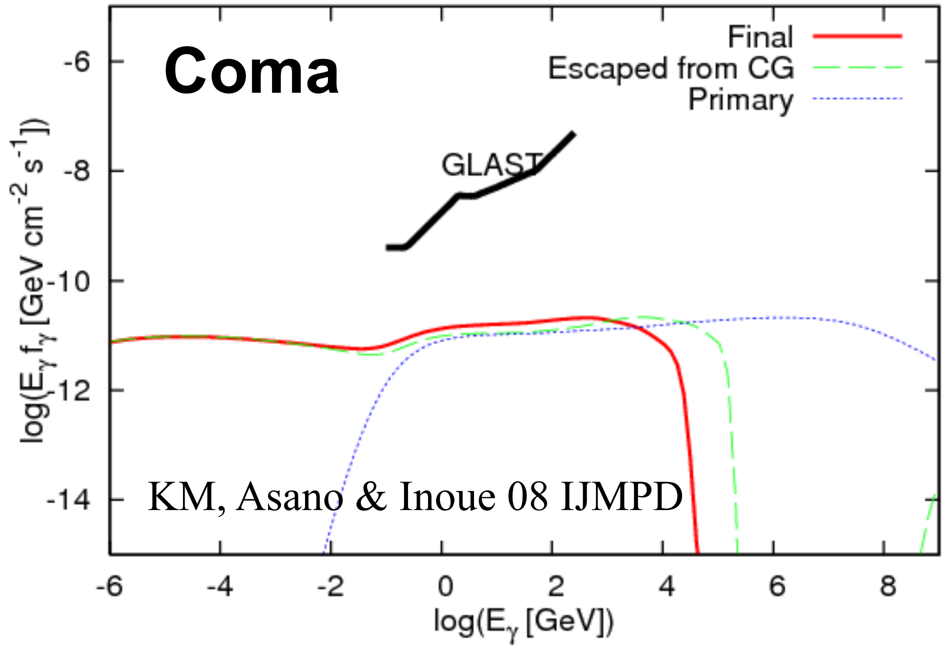
- Intracluster gas density (known)
  $n \sim 10^{-4}\ \mathrm{cm}^{-3}$, a few$\times 10^{-2}\ \mathrm{cm}^{-3}$ (center)
- CR accelerators
  active galactic nuclei
  accretion shocks (massive clusters)
  galaxy/cluster mergers

AGN jet luminosity density $Q_{\rm cr} \sim 3.2 \times 10^{46}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}\ \epsilon_{{\rm cr},-1} L_{j,45} \rho_{{\rm GC},-5}$

cluster luminosity density $Q_{\rm cr} \sim 1.0 \times 10^{47}\ {\rm erg\ Mpc^{-3}\ yr^{-1}}\ \epsilon_{{\rm cr},-1} L_{{\rm ac},45.5} \rho_{{\rm GC},-5}$

pp efficiency $f_{pp} \approx \kappa_p \sigma_{pp} n c t_{\rm int} \simeq 0.76 \times 10^{-2}\ g \bar{n}_{-4} (t_{\rm int}/2\ {\rm Gyr})$

Gamma-Ray Limits?

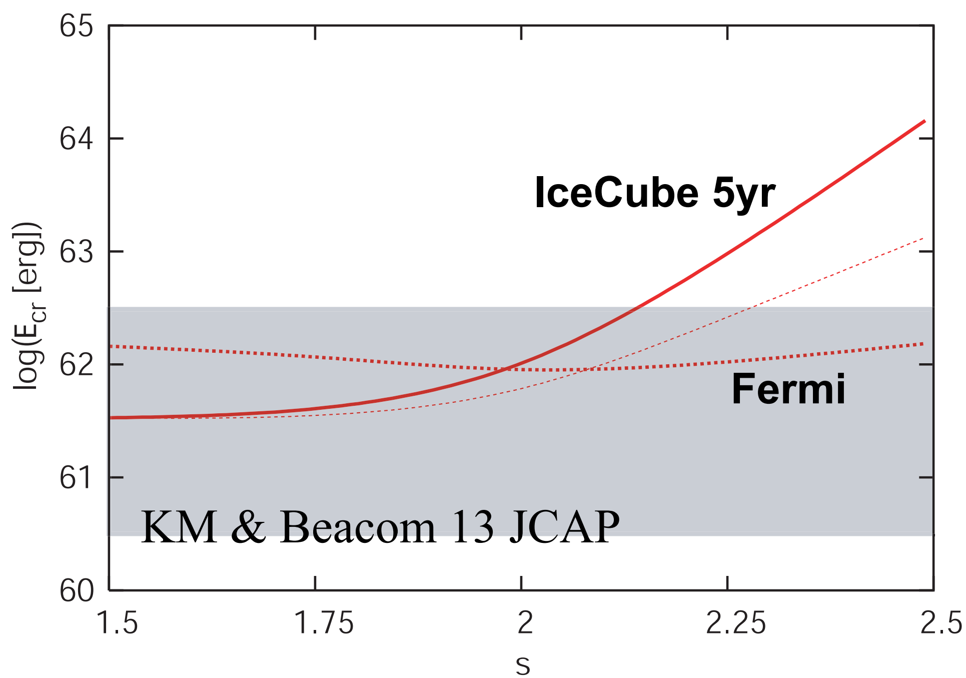


consistent with nondetection of gamma rays

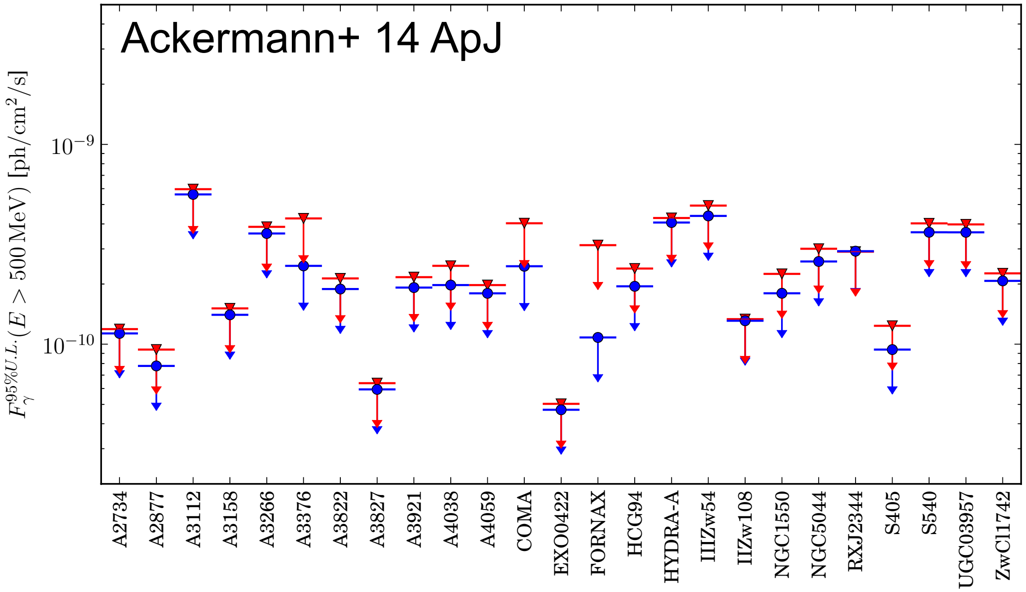
(but connection to the diffuse flux is actually not trivial)

L_{cr}~0.5x10^{45} erg s^{-1} (Virgo)

→ $E_{cr}=L_{cr}t_{inj}$~3x10^{61} erg



Gamma-Ray Limits on Galaxy Clusters



γ rays from virial shocks have been constrained

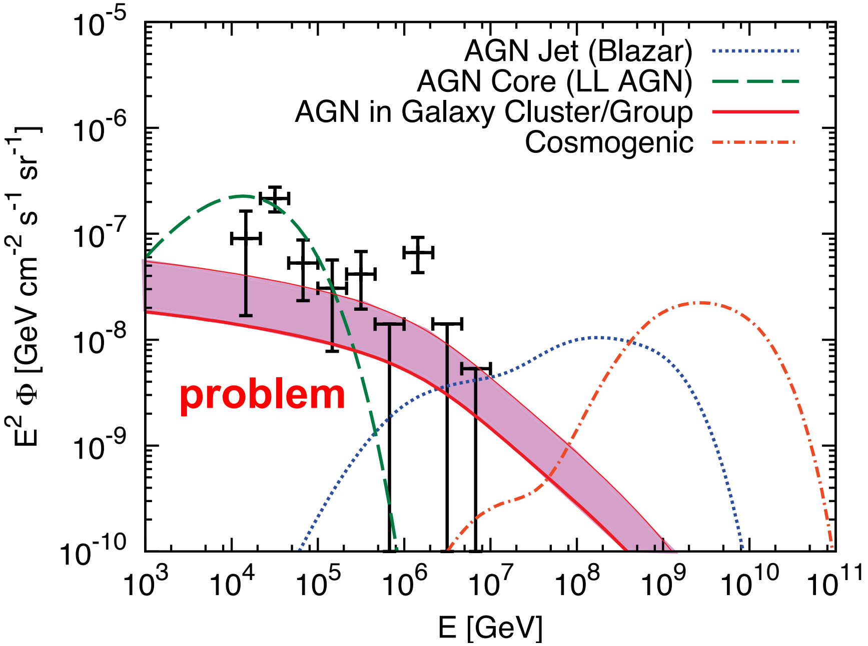
- CR pressure:
  < 1% of thermal pressure
- CR efficiency: < 15%

but see: Ackermann+ 16 ApJ
Reiss+ 17

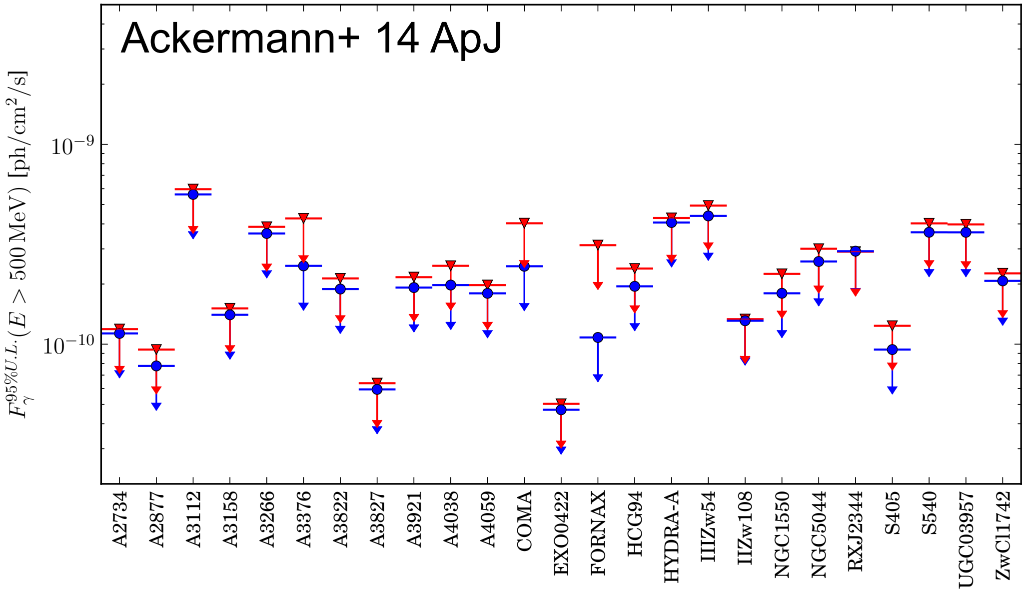
Issues:

- γ-ray limits from nearby clusters
- overshooting diffuse γ-ray bkg.
- radio constraints for massive clusters

-> spectral indices cannot be steep
accretion shock scenario is disfavored



Gamma-Ray Limits on Galaxy Clusters



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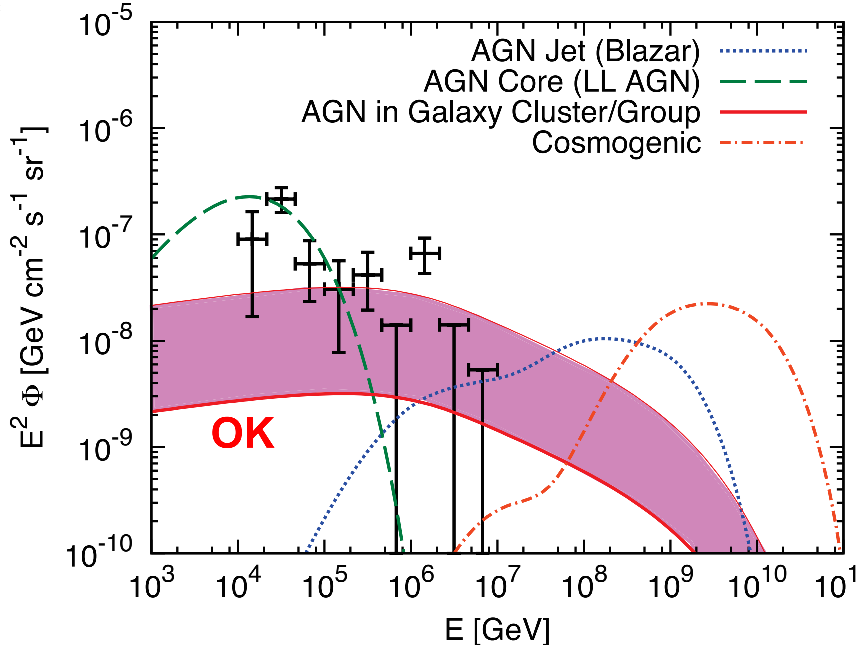


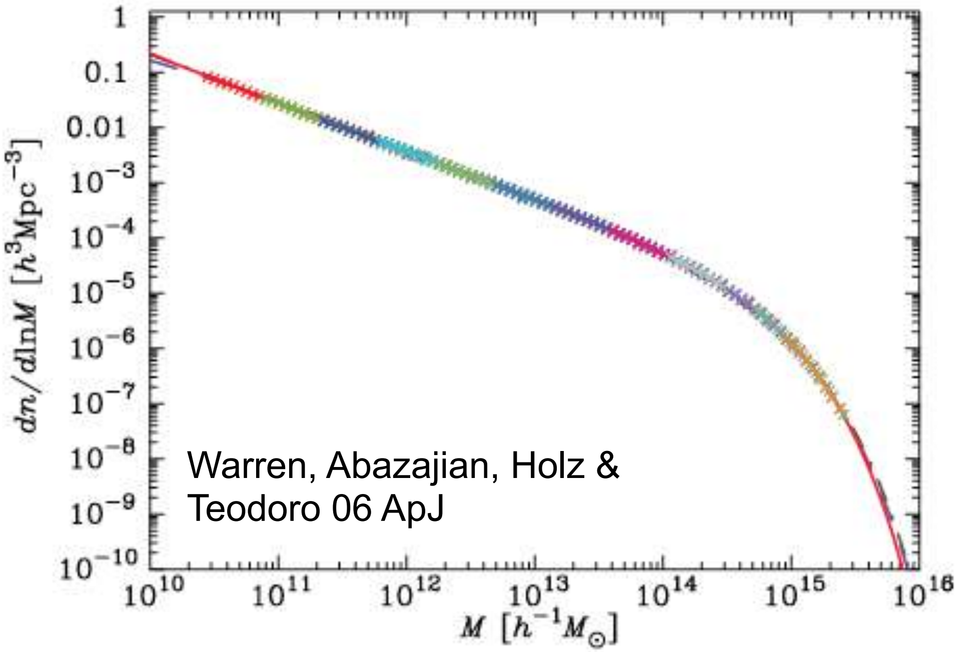
AGN with Galaxy Clusters

- Maximum energy of CRs is expected to be high enough (if AGN are the sources of UHECRs)
- Gigantic! → CR confinement is easy (E < eBR~10^{21} eV)

CR diffusion time $t_{\rm diff} \approx (r_{\rm vir}^2/6D) \simeq 1.6 \, {\rm Gyr} \, \varepsilon_{p,17}^{-1/3} B_{-6.5}^{1/3} (l_{\rm coh}/30 \ {\rm kpc})^{-2/3} M_{15}^{2/3}$

$t_{\rm diff} = t_{\rm inj}$ ⟹ $\varepsilon_\nu^b \approx 0.04 \varepsilon_p^b \simeq 2.0 \, {\rm PeV} \, B_{-6.5} (l_{\rm coh}/30 \ {\rm kpc})^{-2} M_{15}^2 (t_{\rm inj}/2 \ {\rm Gyr})^{-3}$

ν break



- cluster mass function: known (low-mass clusters are important)

- AGN evolution: $(1+z)^{3\text{-}4}$

- gas density: relatively known (β profile)

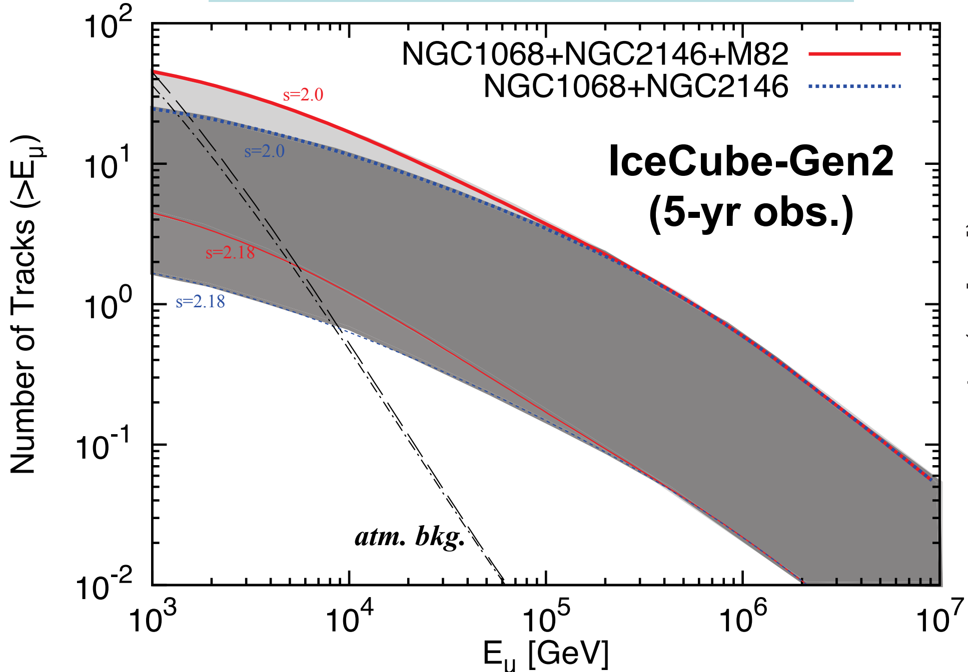
→ reasonable predictions

Testing CR Reservoir Models w. Neutrinos

Starburst galaxies: $n_0 \sim 10^{-5}$ Mpc^{-3} (calorimetric or L_γ-L_{IR} corr.)

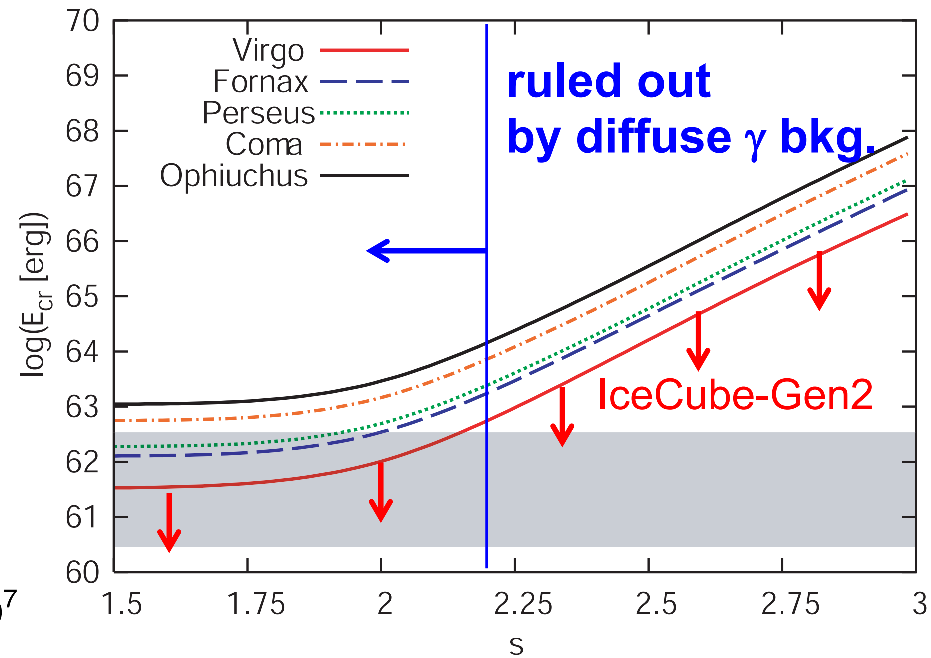
Galaxy clusters: $n_0 \sim 10^{-5}$ Mpc^{-3}, $n_0 \sim 10^{-6}$ Mpc^{-3} (massive clusters)

Muon neutrino event rates from nearby starbursts



KM & Waxman 15

Muon neutrino constraints from nearby galaxy clusters

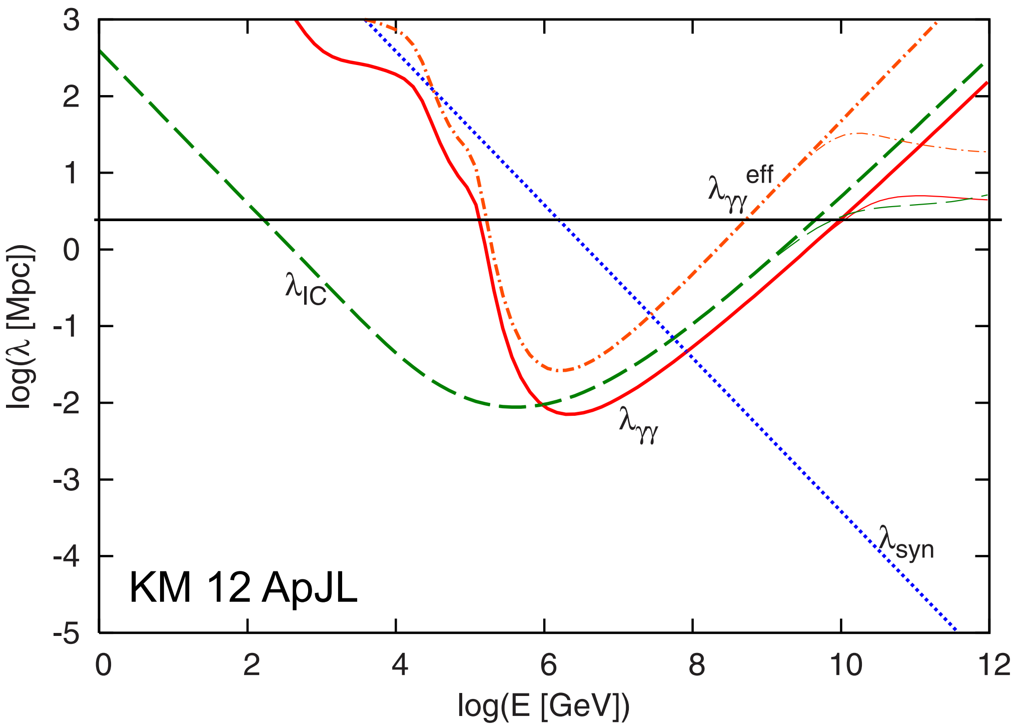


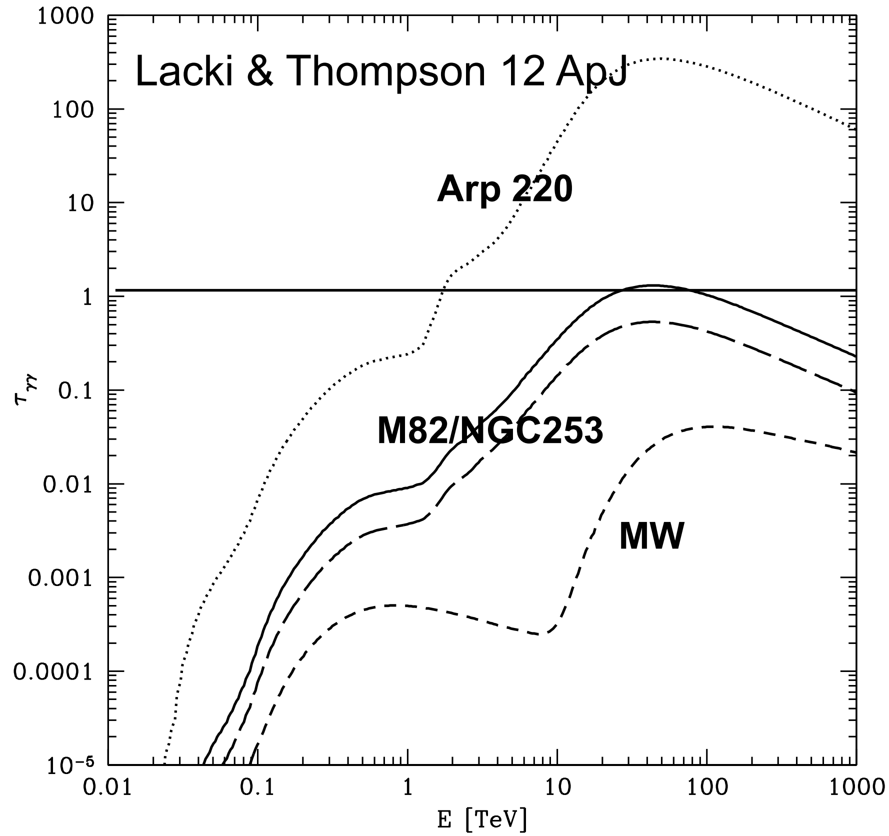
KM & Beacom 13 JCAP

Good chances to see neutrinos if CR reservoir models are correct

Gamma-Ray Transparency

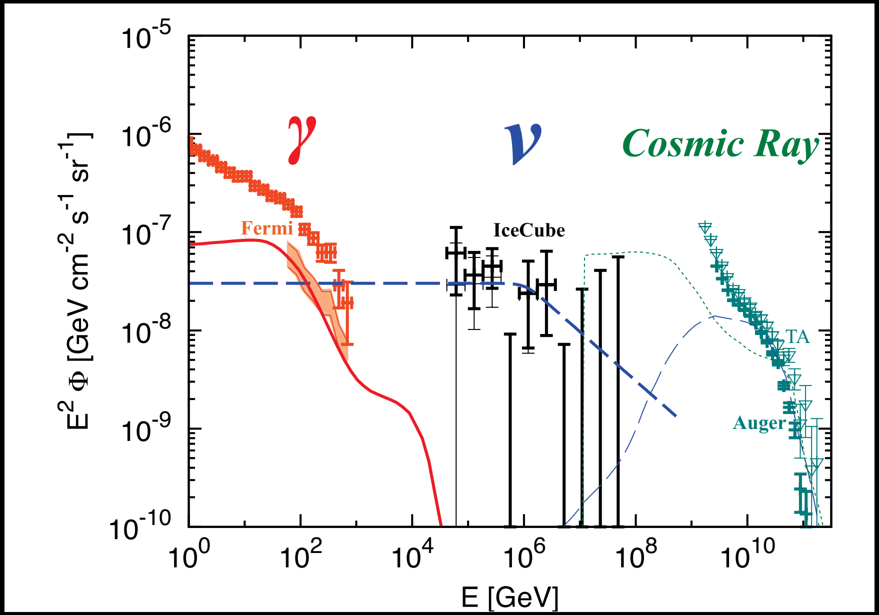
escaping γ = attenuated component + intra-source cascade component



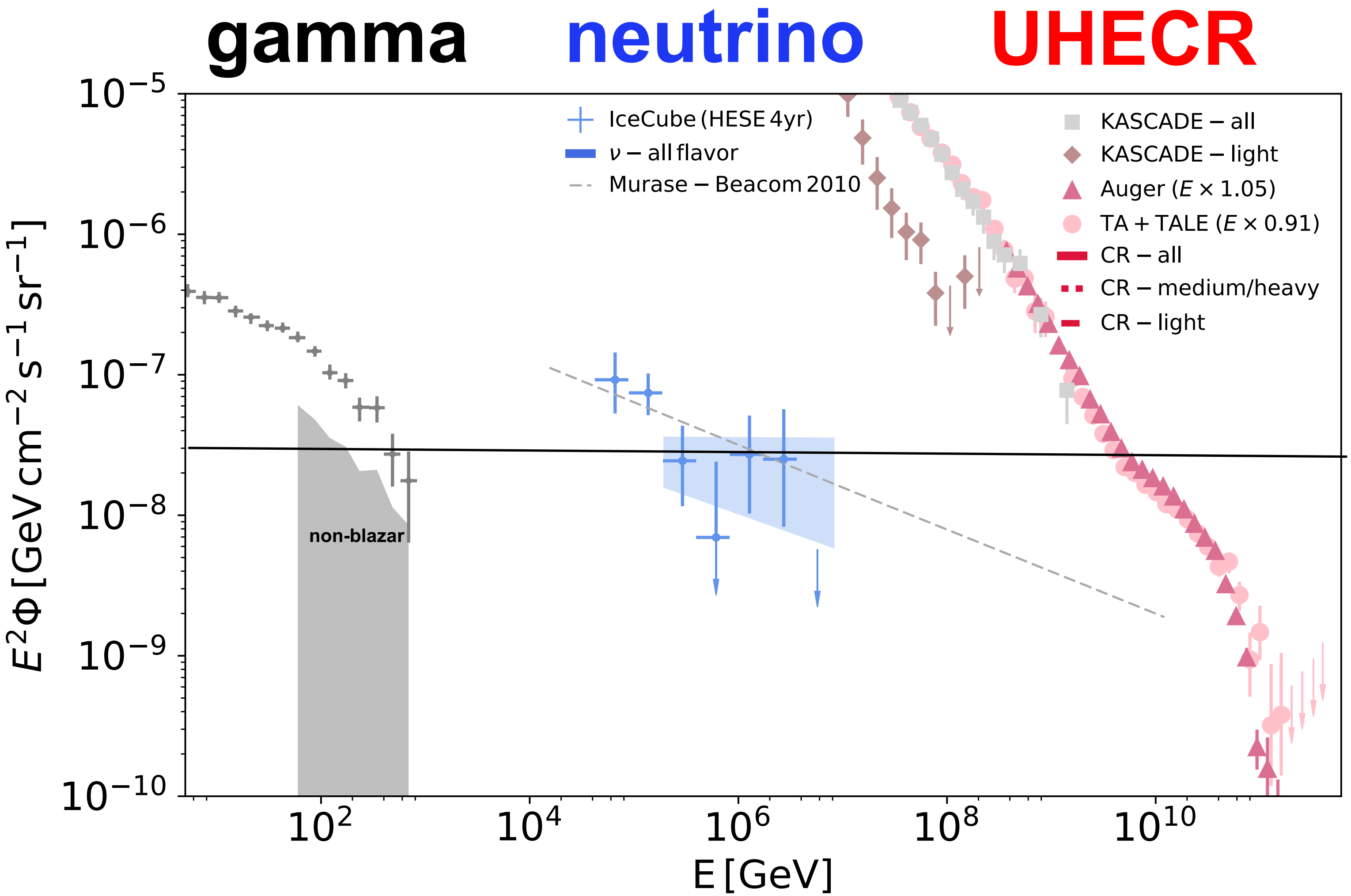


- $E_{\tau=1}$~100 TeV for clusters, $E_{\tau=1}$~10 TeV for starbursts (escape is possible for elliptical galaxies except for cores)
- GeV-TeV gamma rays should escape from the sources

Multi-Messenger Implications

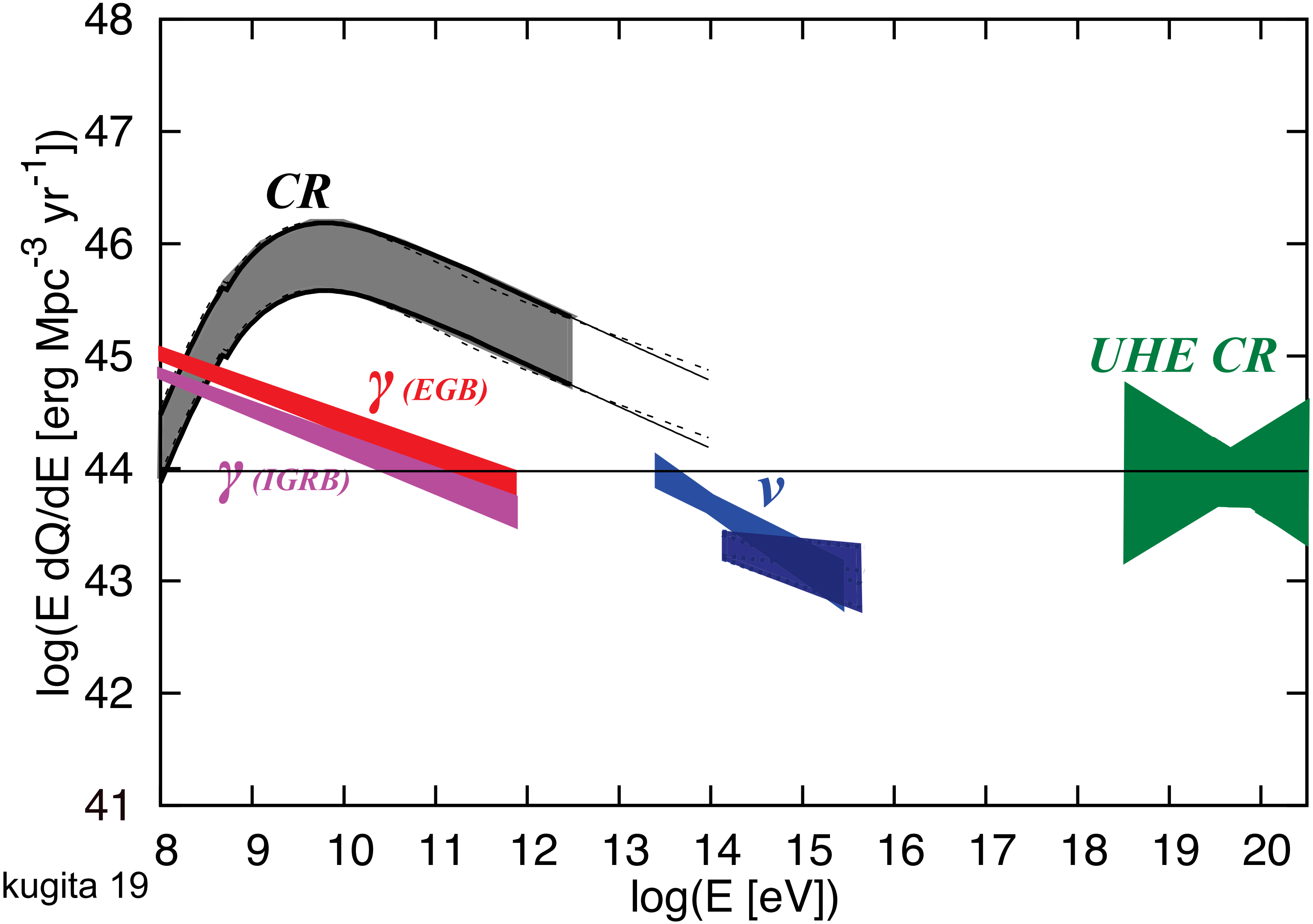


Multi-Messenger Cosmic Particle Backgrounds



Energy budgets are all comparable (a few x 10^{43} erg Mpc^{-3} yr^{-1})

High-Energy Cosmic Particle Energetics



KM & Fukugita 19

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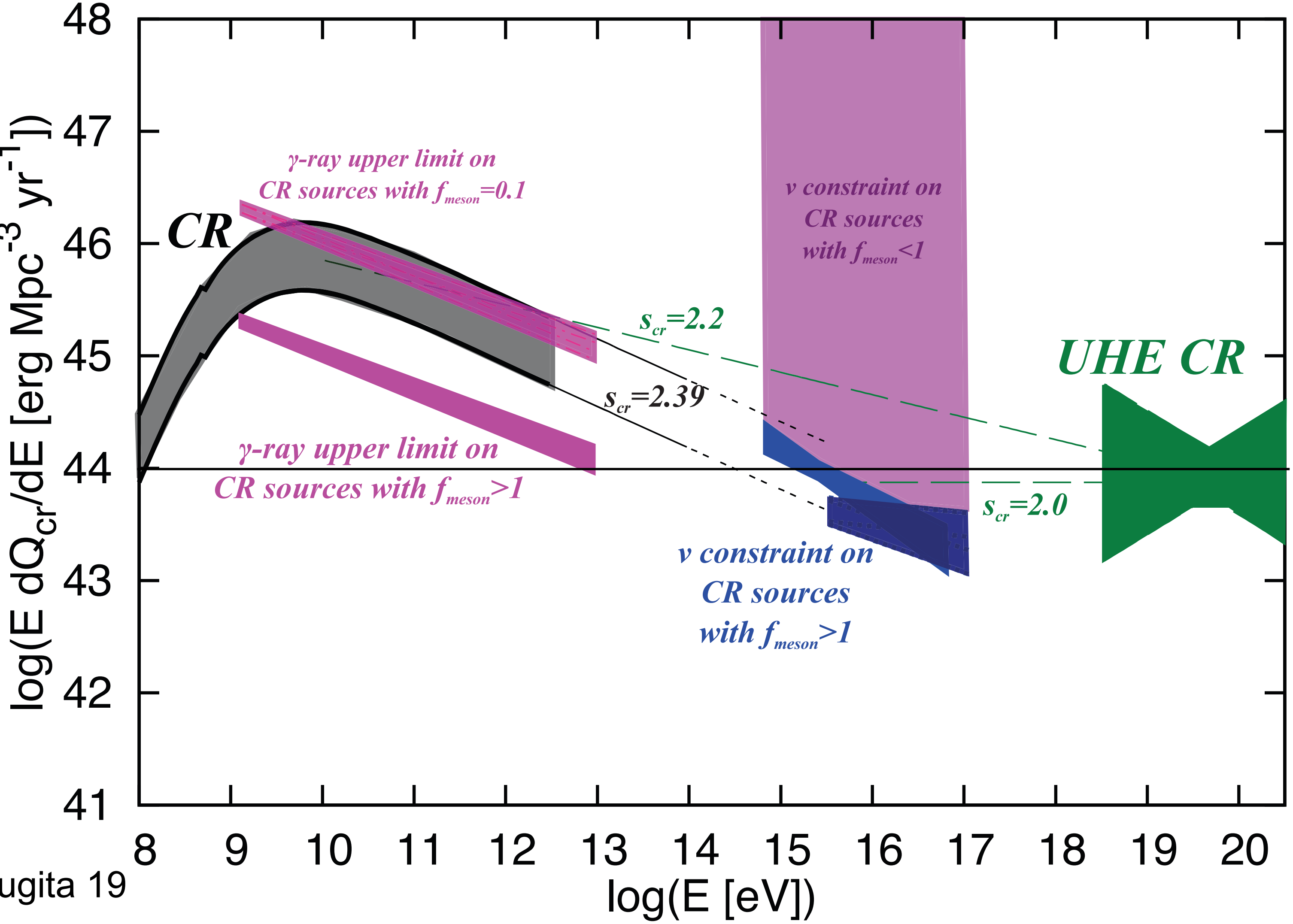
High-Energy Cosmic Particle Energetics



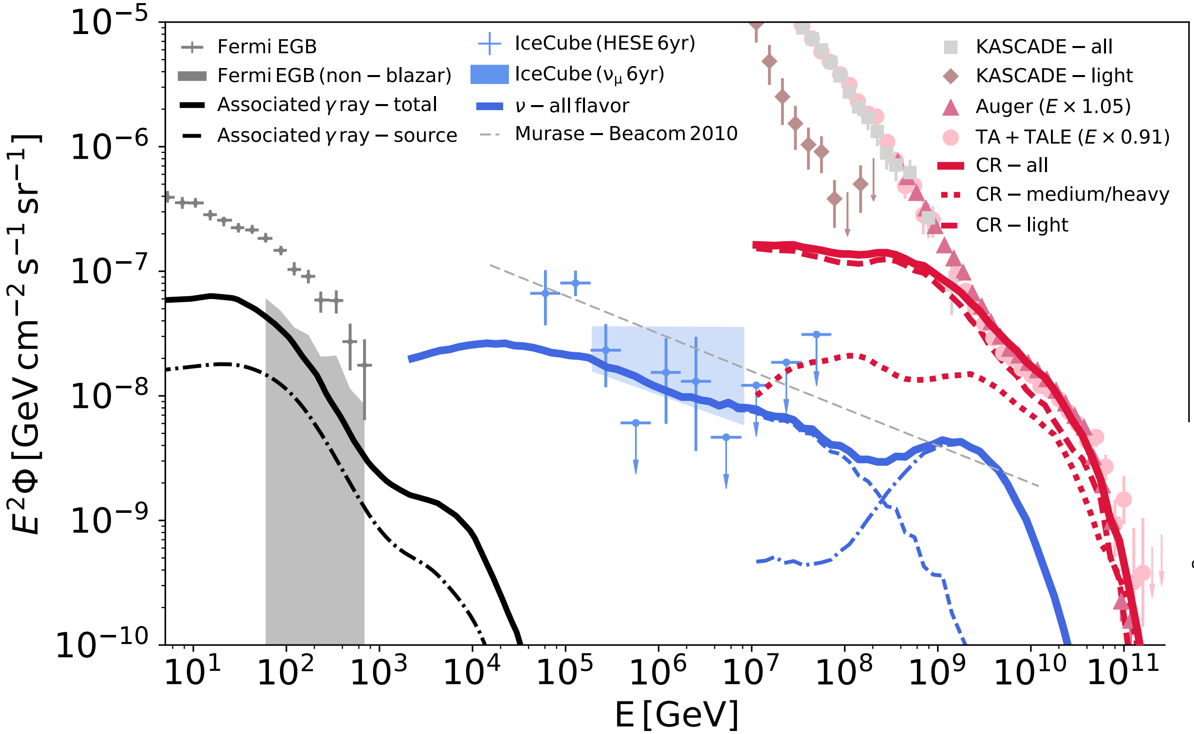
KM & Fukugita 19

Energy budgets are all comparable (a few x 10^{43} erg Mpc^{-3} yr^{-1})

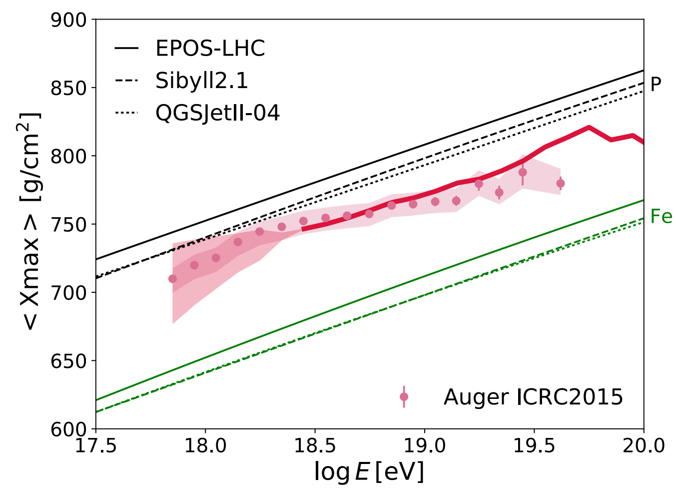
Neutrino-Gamma-UHECR Connection?

Grand-unification of neutrinos, gamma rays & UHECRs

- Explain ν data by confined CRs with energies less than a few PeV
- Escaping CRs may contribute to the observed UHECR flux



Fang & KM 18 Nature Physics

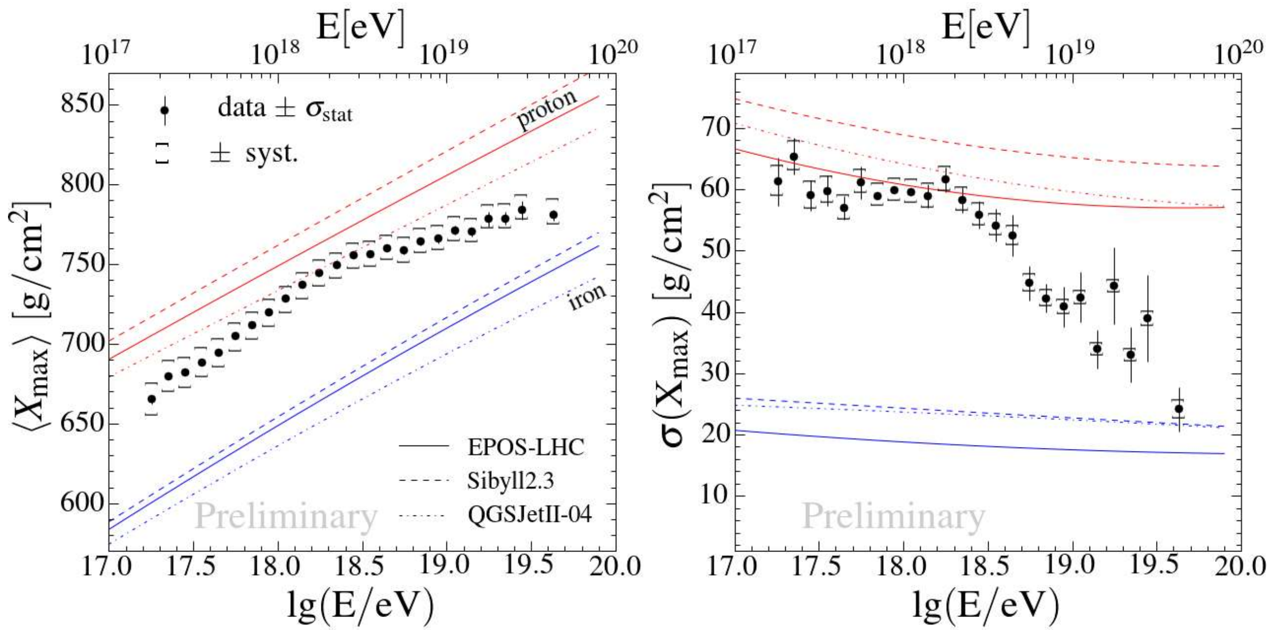


- AGN as "UHECR" accelerators
- CR nuclei: harder than CR protons due to photodisintegration inside clusters

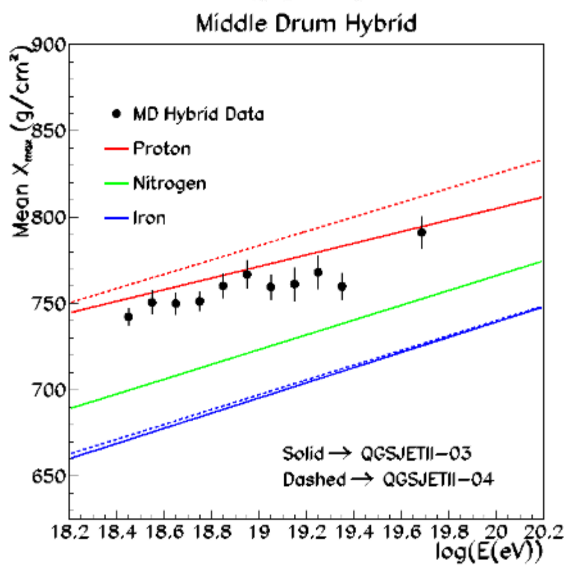
UHECR Data

UHECR Composition

Auger 2017 at ICRC

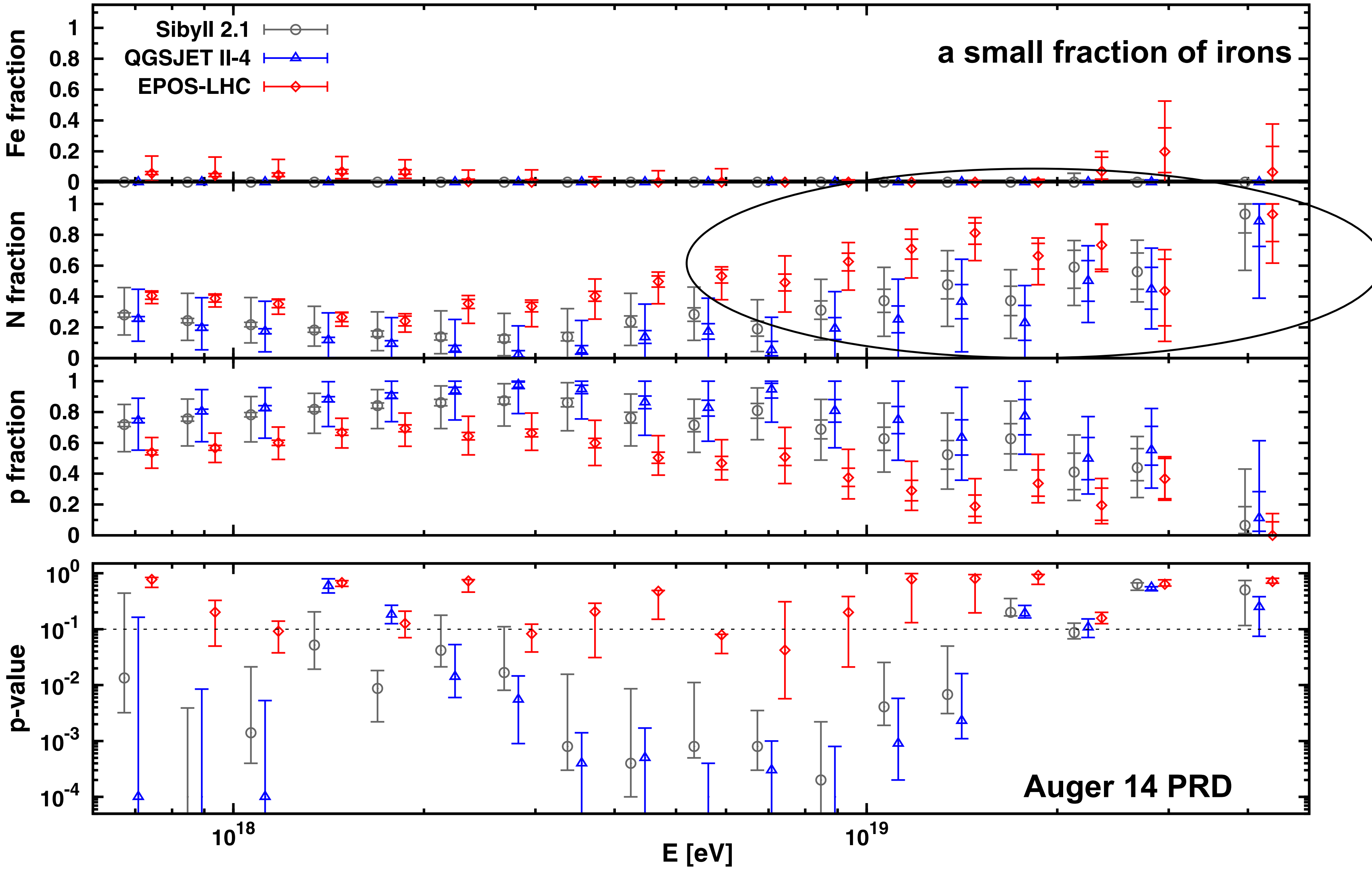


TA 2015 at ICRC

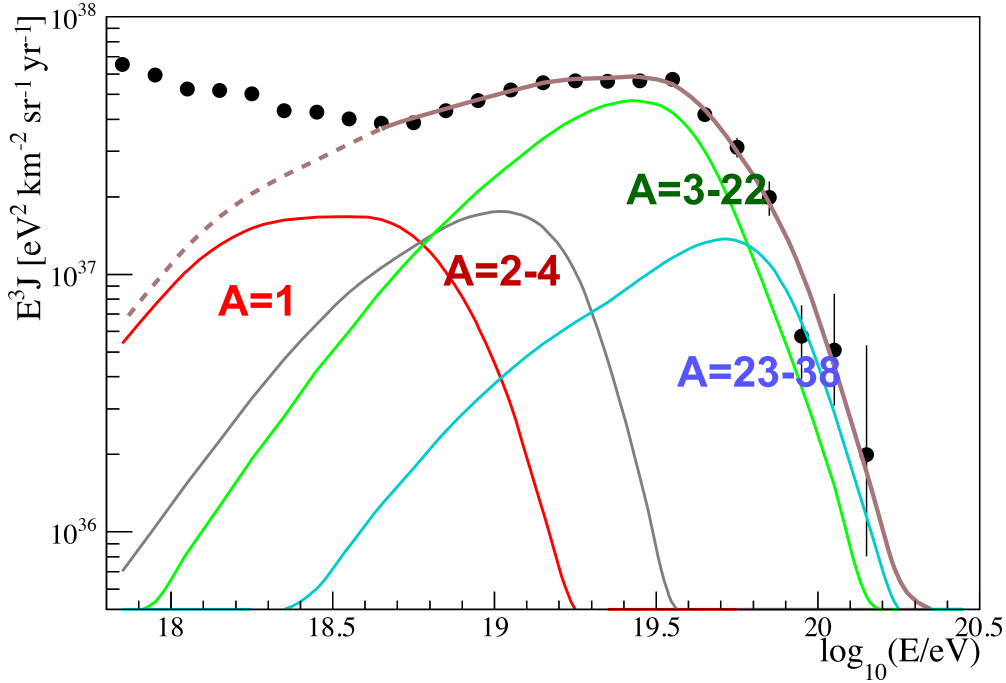


- Break in $<X_{max}>$ & $\sigma(X_{max})$?
- Auger & TA are compatible Interpretation is different
- Uncertainties in hadronic interaction models

Composition at Earth

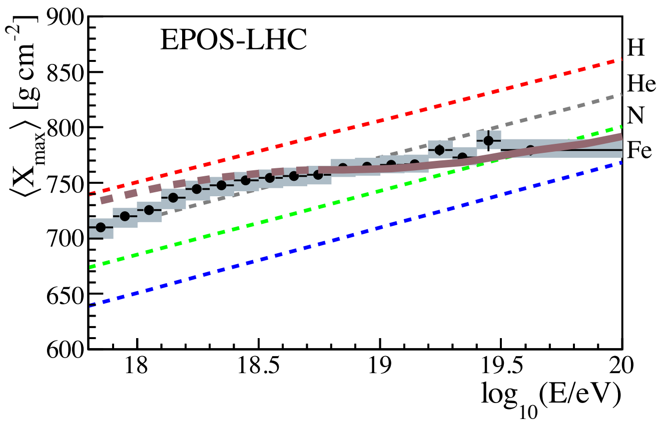


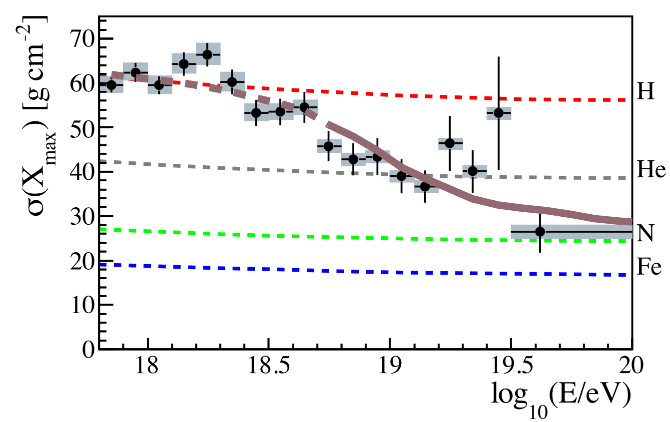
Composition at the Sources?



Auger 17 JCAP

- hard spectrum (s=0.96 <<2)
- intrinsic composiiion
  $f_H=f_{Fe}=0$
  $f_{He}=0.67$
  $f_N=0.28$
  $f_{Si}=0.05$

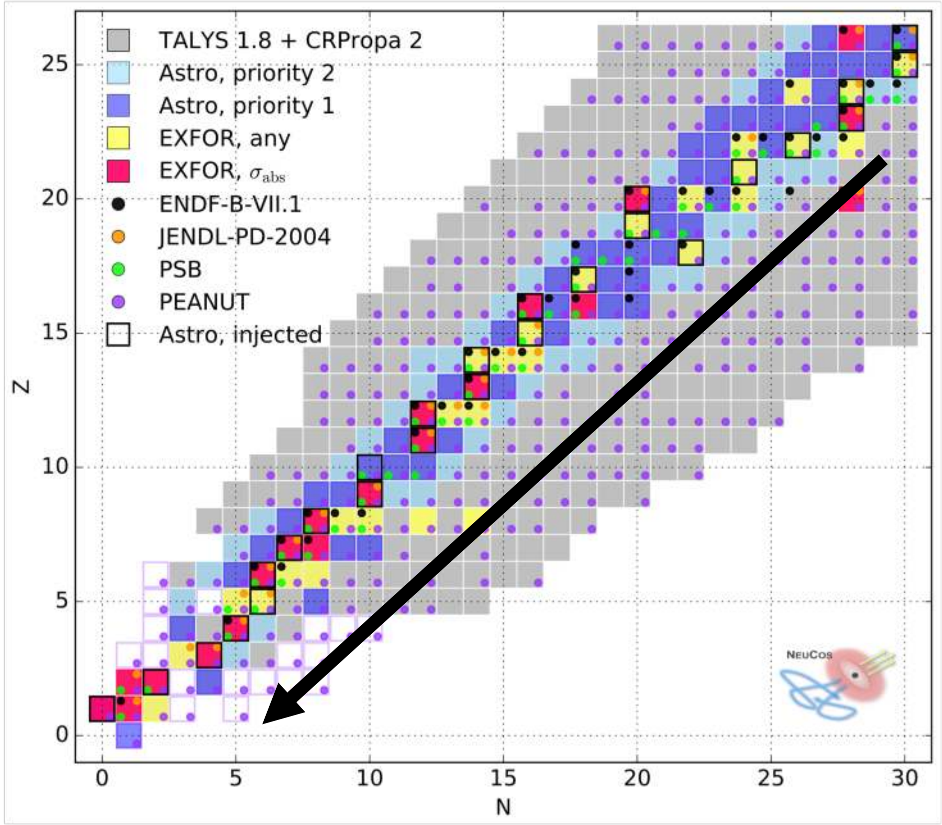


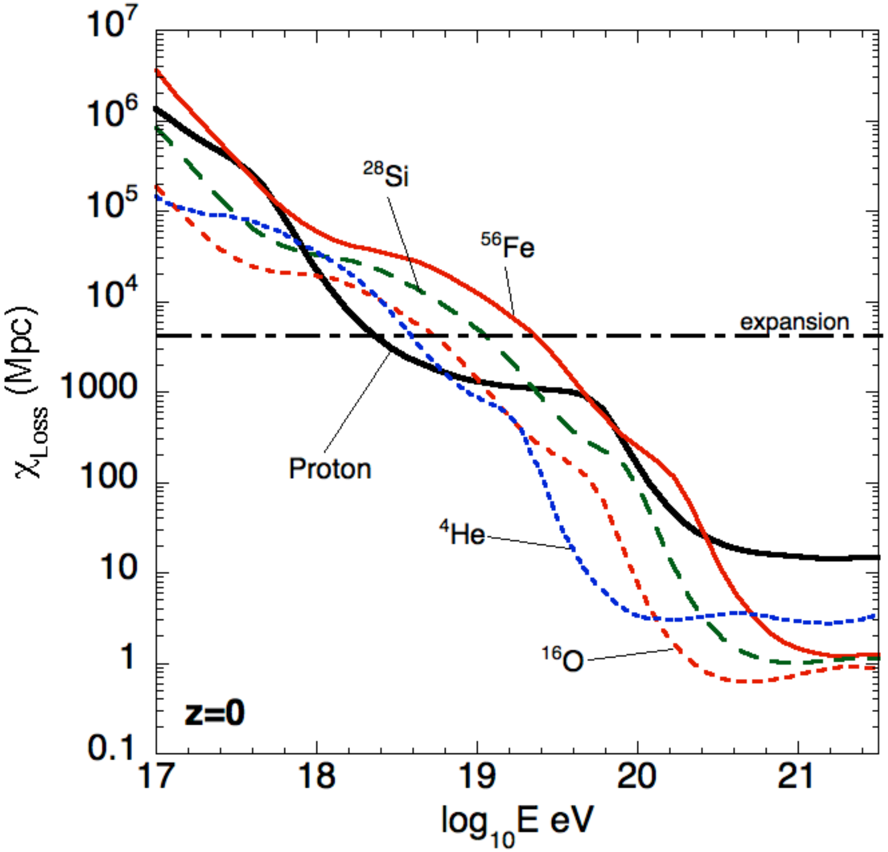


Nuclear Cascade

diffuse CR flux formula (computationally heavy)

$$\Phi_A(E) = \sum_{A'} \frac{c}{4\pi} \int_{z_{\min}}^{z_{\max}} dz \left| \frac{dt}{dz} \right| F_{\mathrm{GRB}}(z) \int_{L_{\min}}^{L_{\max}} \frac{d\rho_0}{dL} \int_{E'_{\min}}^{E'_{\max}} dE' \, \frac{dN_{A'}}{dE'} \frac{d\eta_{AA'}(E, E', z)}{dE}$$





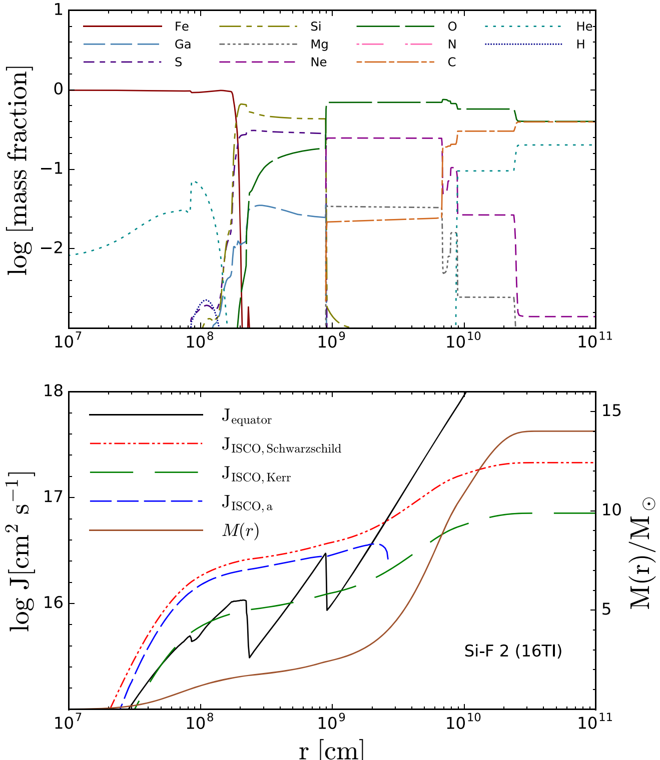
Application to Low-Luminosity Gamma-Ray Bursts

"Top-down" theory model

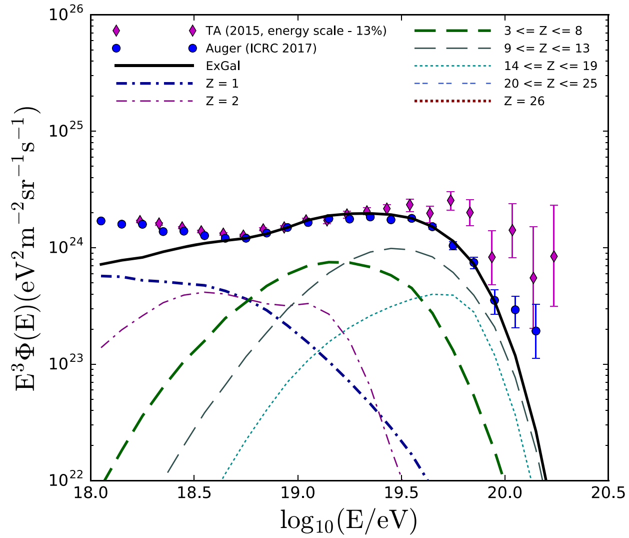
Zhang, KM et al. 2018 PRD

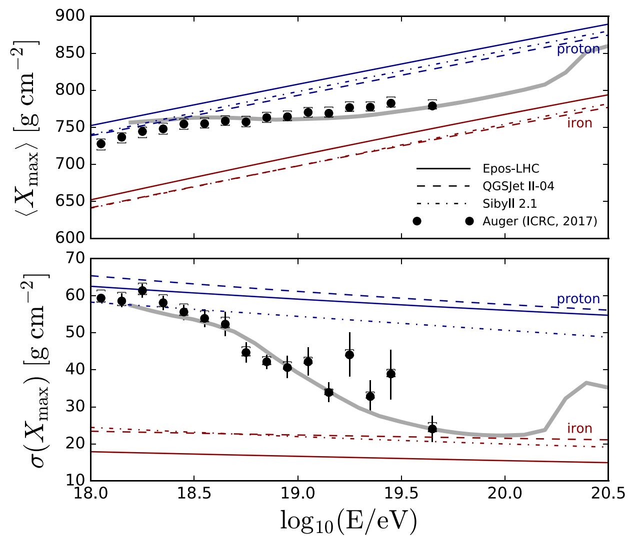
- Abundance: results from stellar evolution
- Acceleration: results from DSA
- Survival: based on LL GRB observations

Spectrum & composition are not free!

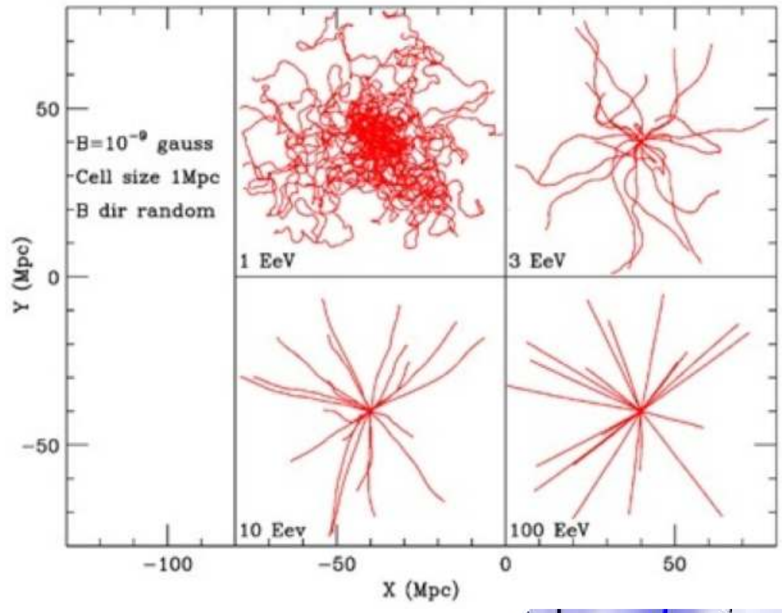


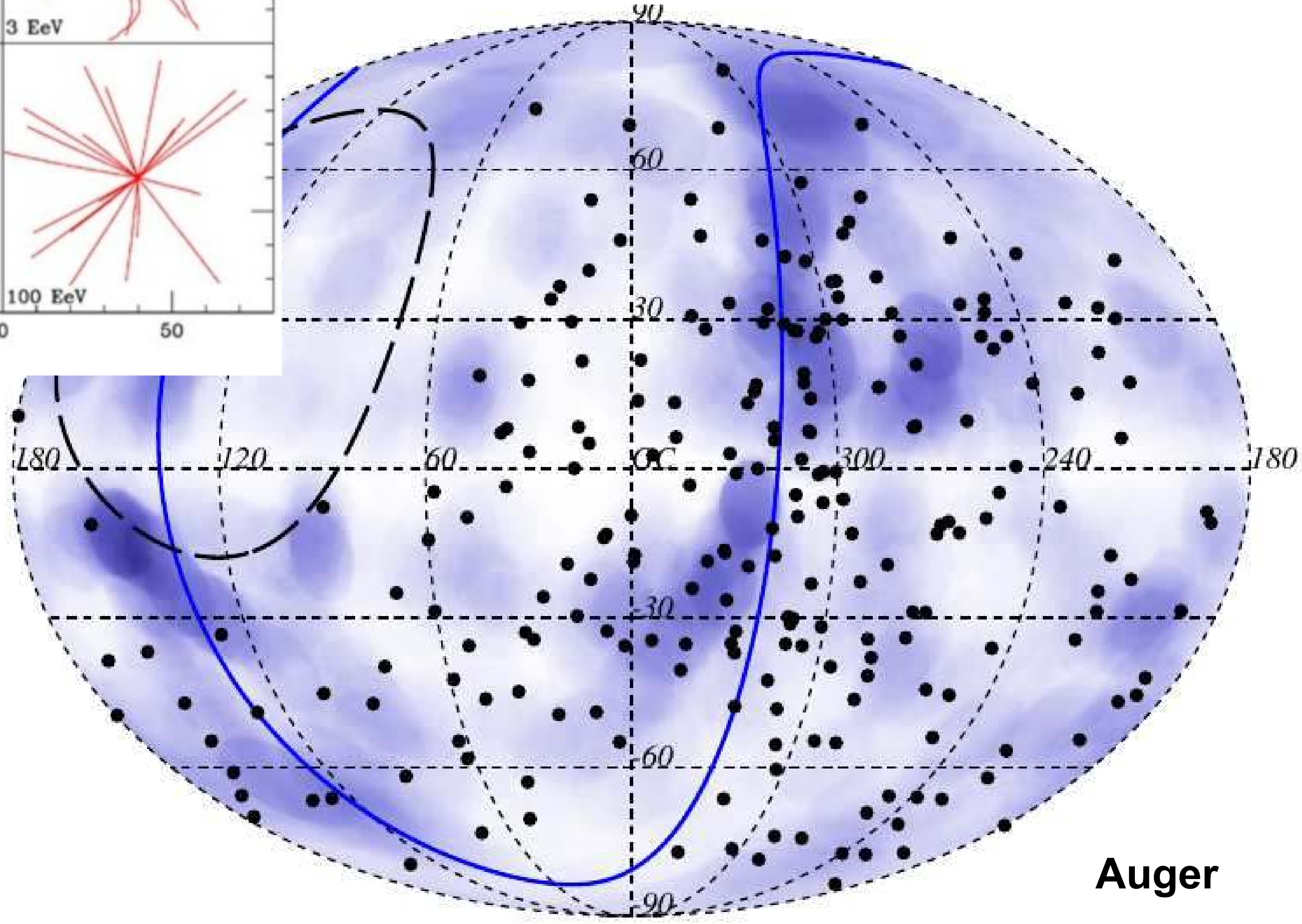
progenitor of gamma-ray bursts (O core)





What Can We Learn from UHECR Sky

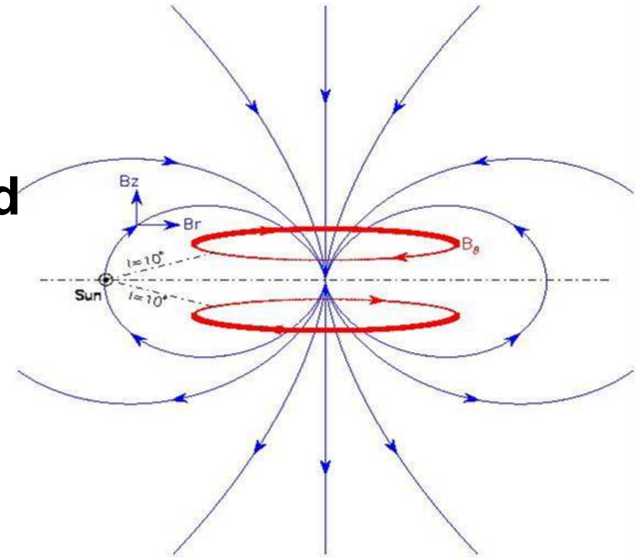




Auger

Deflection & Time Delay

$$\theta_{\rm Gal} = \theta_{\rm Disk}^{\rm regular} + \theta_{\rm Disk}^{\rm turbulent} + \theta_{\rm Halo}^{\rm regular} + \theta_{\rm Halo}^{\rm turbulent}$$



deflection by the ordered Galactic magnetic field

$$\vartheta \simeq \frac{d}{R_L} \simeq 0.52^\circ Z \left(\frac{p_\perp}{10^{20}\,{\rm eV}}\right)^{-1} \left(\frac{d}{1\,{\rm kpc}}\right) \left(\frac{B}{\mu{\rm G}}\right)$$

deflection by the extragalactic magnetic field a coherence length l_c

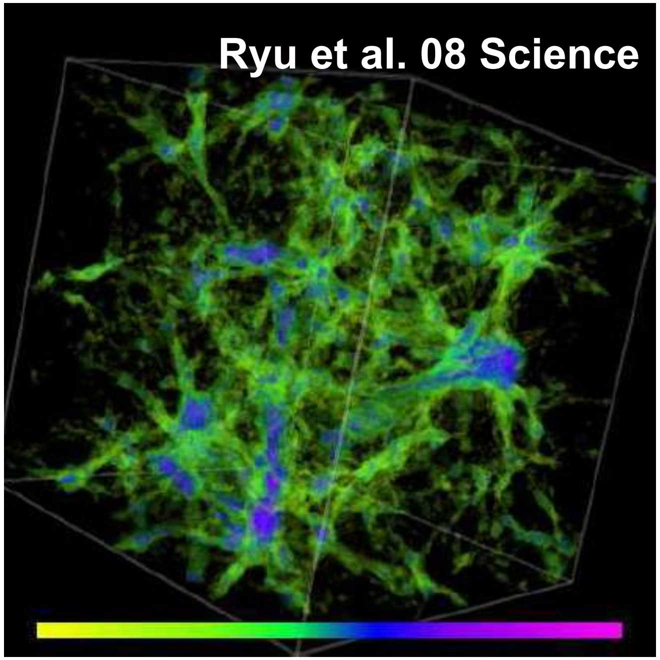
$$\delta_{\rm rms} \simeq \frac{(2dl_c/9)^{1/2}}{R_L} \simeq 0.8^\circ\, Z \left(\frac{E}{10^{20}\,{\rm eV}}\right)^{-1} \left(\frac{d}{10\,{\rm Mpc}}\right)^{1/2} \left(\frac{l_c}{1\,{\rm Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,{\rm G}}\right)$$

time delay & time spread

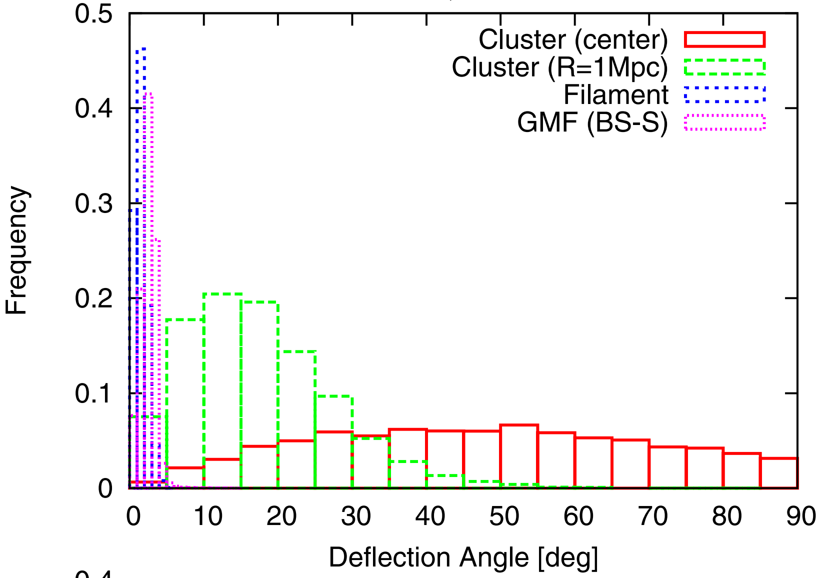
$$\tau \simeq \delta_{\rm rms}^2 d/4 \simeq 1.5 \times 10^3\, Z^2 \left(\frac{E}{10^{20}\,{\rm eV}}\right)^{-2} \left(\frac{d}{10\,{\rm Mpc}}\right)^2 \left(\frac{l_c}{1\,{\rm Mpc}}\right) \left(\frac{B}{10^{-9}\,{\rm G}}\right)^2 {\rm yr}$$

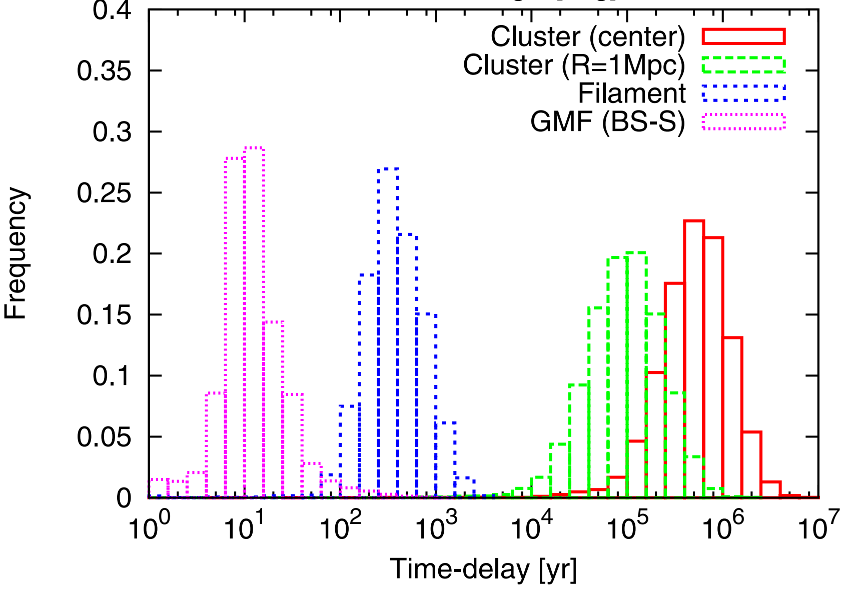
Importance of Structured Magnetic Fields

- B_{EGMF} is an "effective" value
- Earth or sources are embedded in structured magnetic fields
- Structured magnetic fields clusters: ~0.1-10 μG, filament: ~10-100 nG



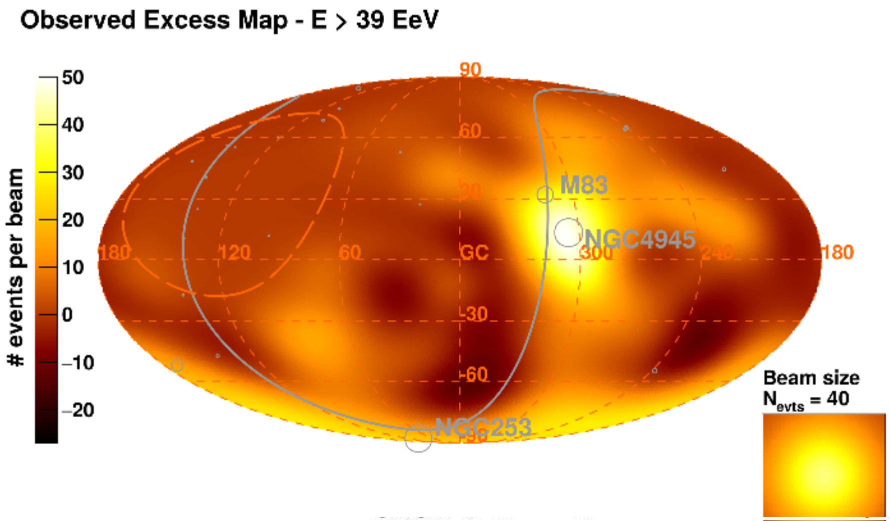
KM & Takami 09, Takami & KM 12

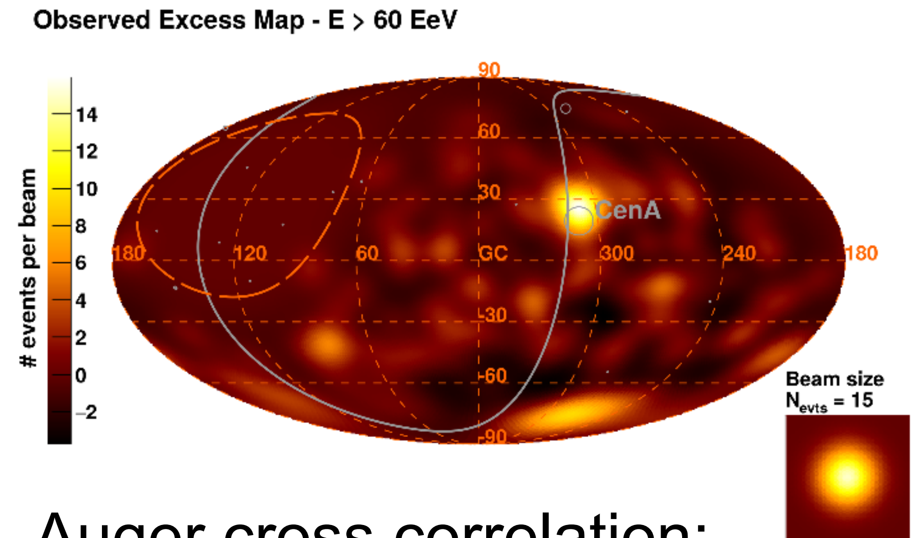


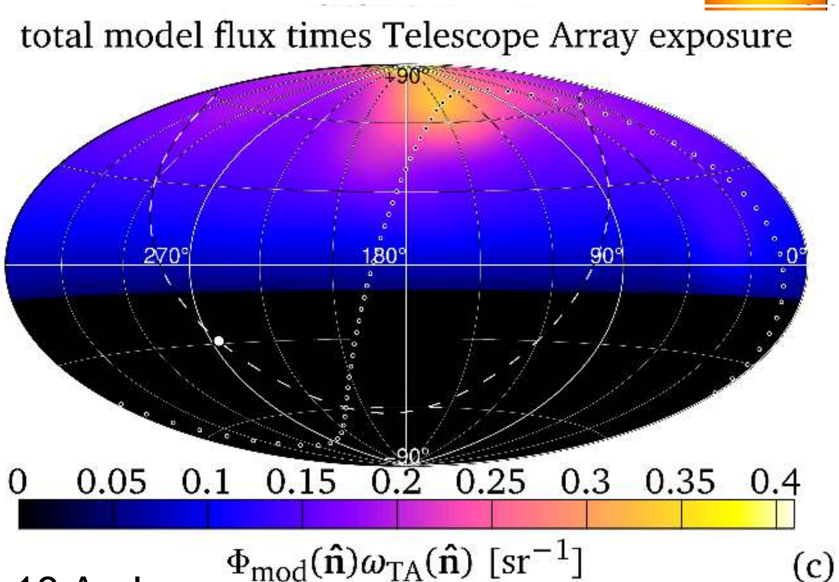


Encouraging News: Cross Correlation

starburst Auger 18 ApJL AGN







TA 18 ApJ

Auger cross correlation:

starburst galaxies ~4σ

AGN ~3σ

TA cross correlation:

not confirmed yet

need TAx4

Predictions for Fermi, CTA, Gen-2, KM3Net (KM& Waxman 16)