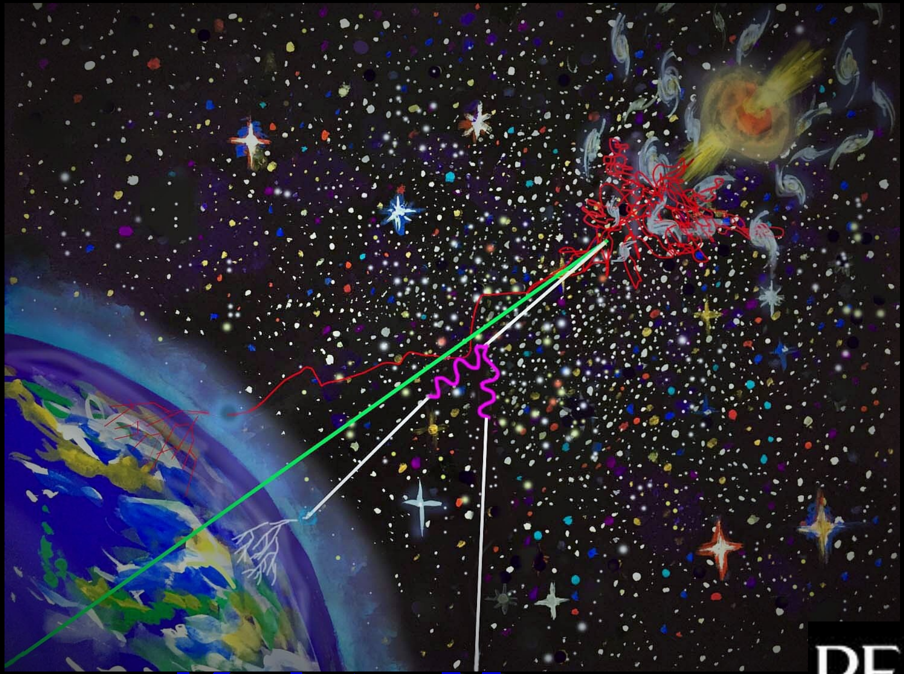
UHECR Sources and Acceleration



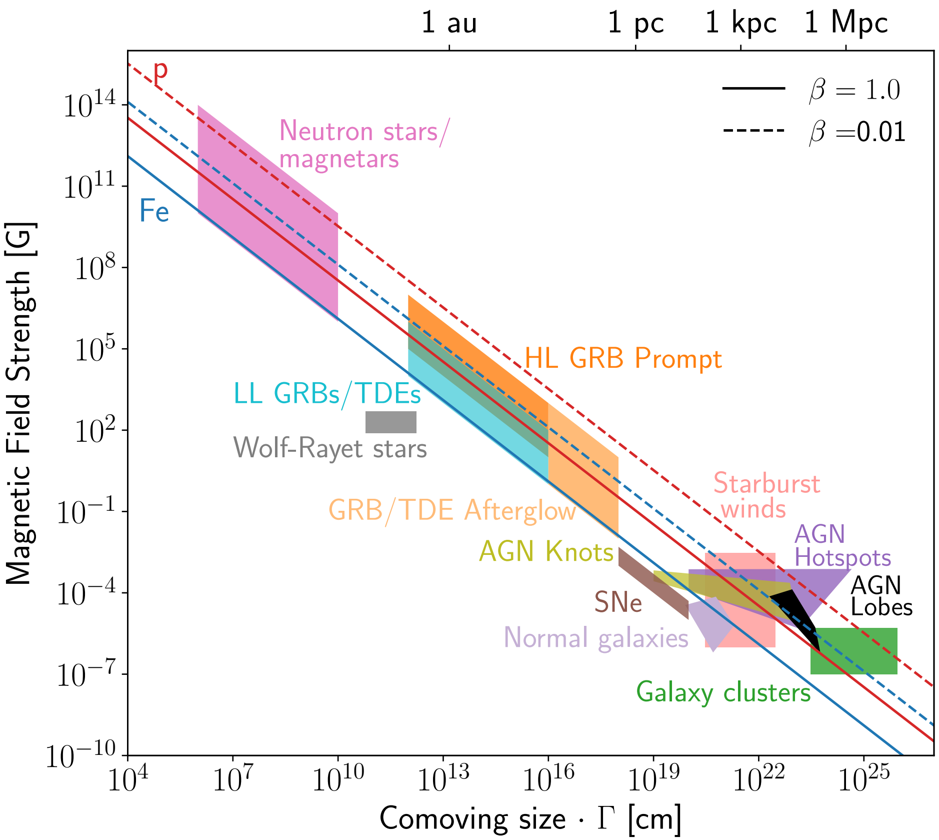
Kohta Murase

Penn State University

GCOS 2021

UHECR Source Candidates? (Classical)

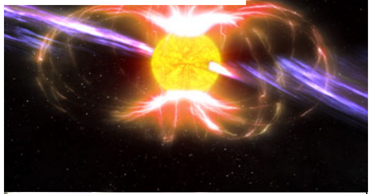
Alves Batista+ KM 19 Frontiers



Hillas condition

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

Magnetar



The **strongest** mag. fields

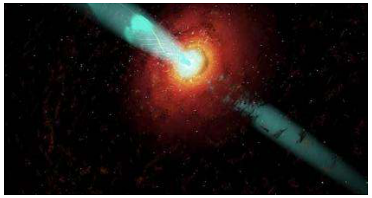
$B \sim 10^{15}$ G

γ-ray burst (GRB)

The **brightest** explosions

$L_\gamma \sim 10^{52}$ erg/s

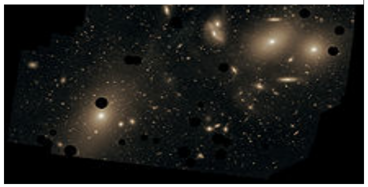
Active galaxy (AGN)



The **most massive** black holes

$M_{BH} \sim 10^{8\text{-}9} M_{sun}$

Galaxy cluster



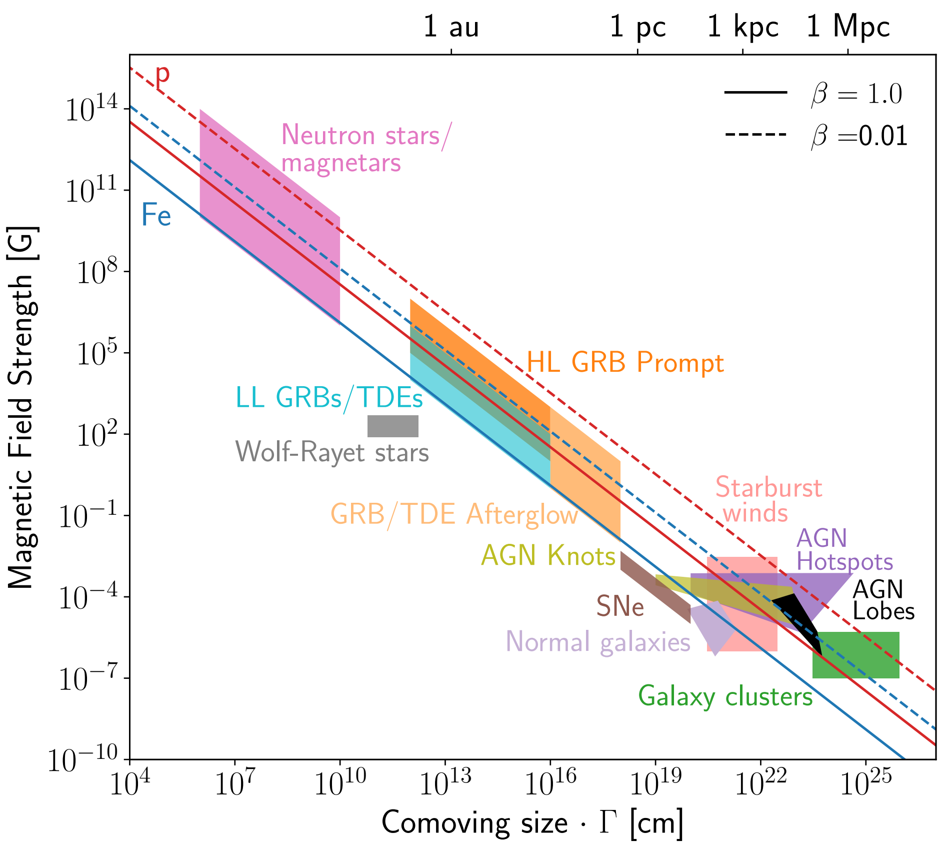
The **largest** gravitational object

$R_{vir} \sim$ a few Mpc

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

UHECR Source Candidates = Cosmic Monsters

Alves Batista+ KM 19 Frontiers



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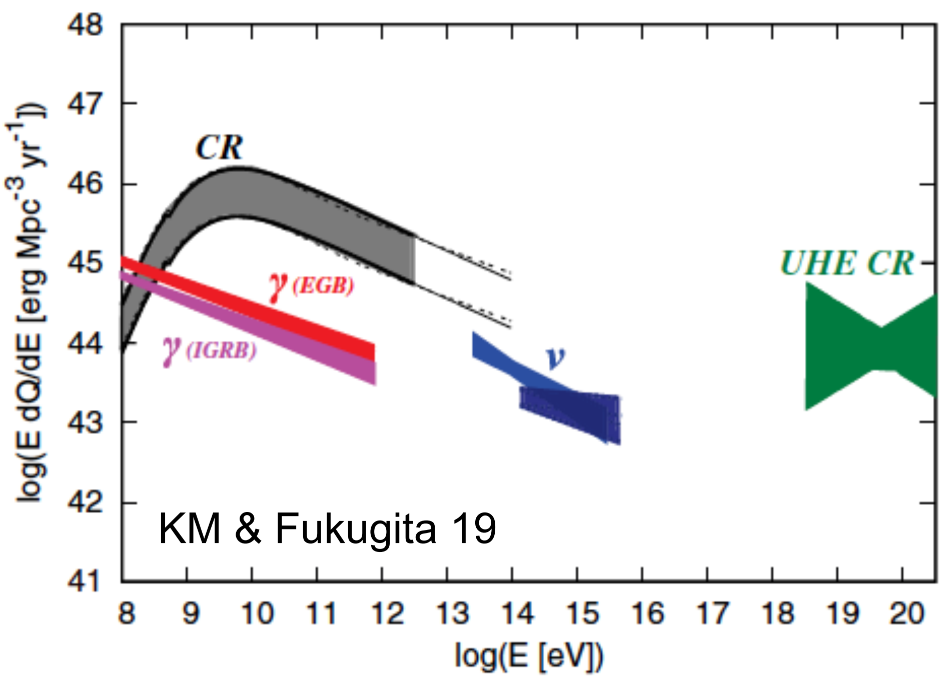
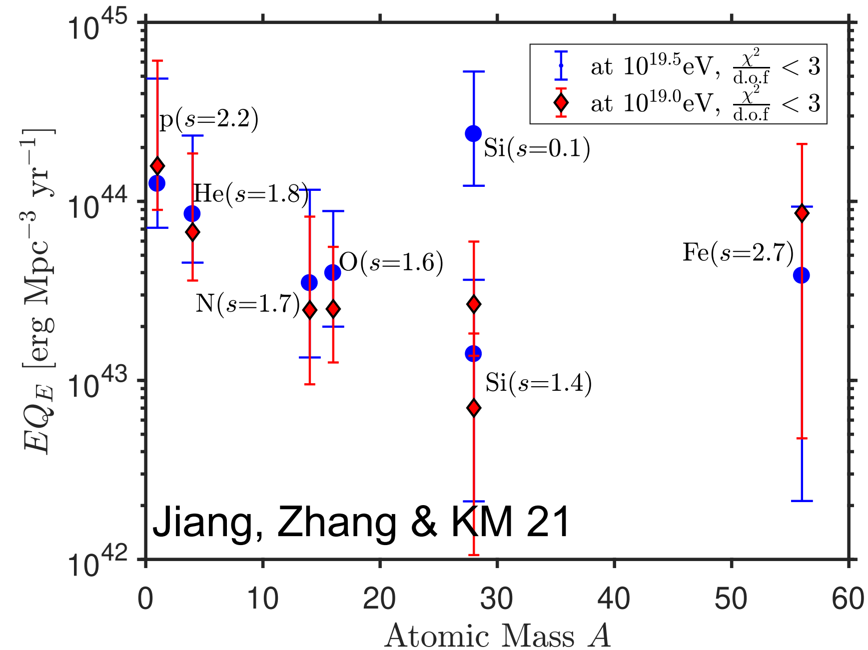
Energetics

UHECR energetics: (0.2-2)x10^{44} erg/Mpc^3/yr @ $10^{19.5}$ eV

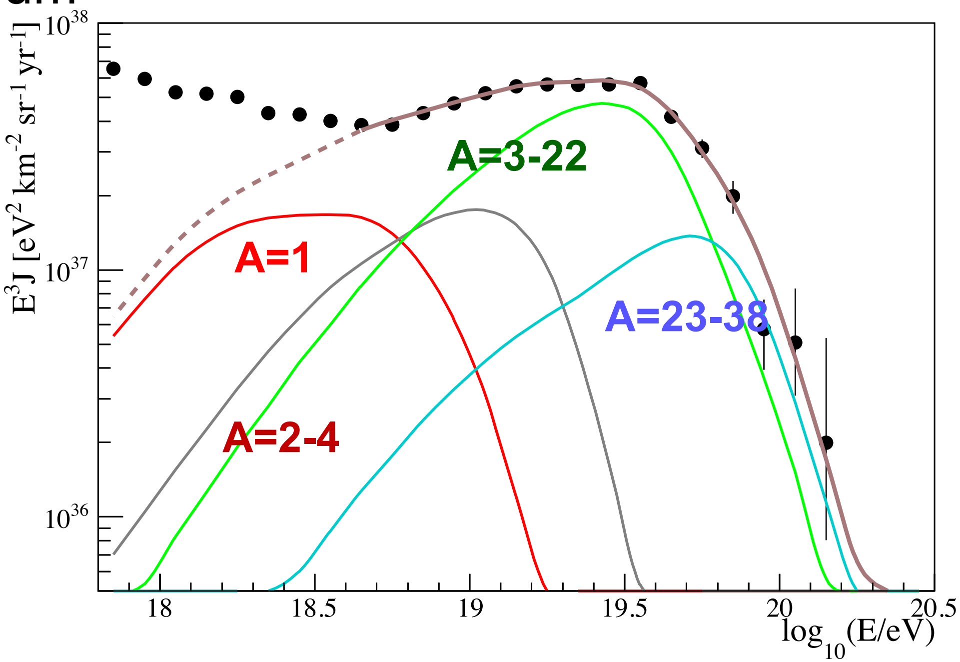




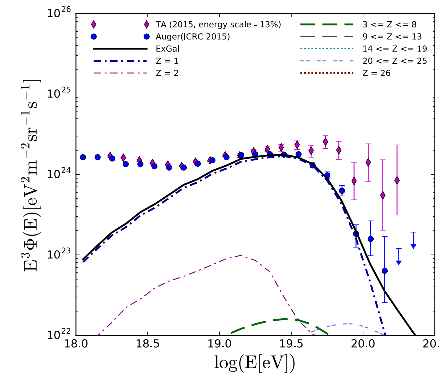
	ccSN (CR)	HN (CR)	DNS (CR)	GRB (γ)	LL GRB (γ)	TDE (γ)
Q [erg Mpc^{-3} yr^{-1}]	$10^{46.6}$	$10^{45.5}$	$10^{44.5}$	$10^{43.6}$	$10^{43.5}$	$10^{43.5}$
ρ [Mpc^{-3} yr^{-1}]	10^{-4}	$10^{-5.5}$	$10^{-5.8}$	10^{-9}	$10^{-6.5}$	$10^{-10.5}$
	SBG (γ)	AGN (X)	BL Lac (γ)	FSRQ (γ)	RG (γ)	Accr/Mger (CR)
Q [erg Mpc^{-3} yr^{-1}]	$10^{44.5}$	$10^{46.3}$	$10^{45.4}$	$10^{44.3}$	$10^{44.6}$	$10^{46.5}$
n [Mpc^{-3}]	10^{-4}	$10^{-4}-10^{-3}$	$10^{-7}-10^{-6.5}$	$10^{-9}-10^{-8}$	$10^{-5}-10^{-4}$	$10^{-6}-10^{-5}$

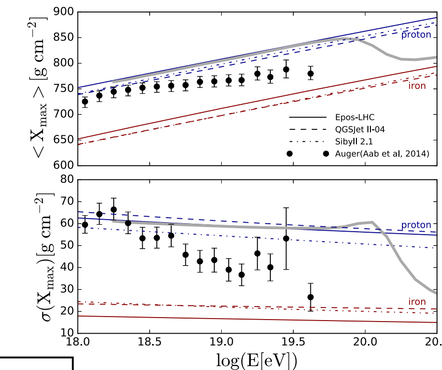
Nuclear-Rich Composition at the Sources?

- hard spectrum (s=0.96)
- Intrinsic abundance
  $f_H=f_{Fe}=0$
  $f_{He}=0.67$
  $f_N=0.28$
  $f_{Si}=0.05$

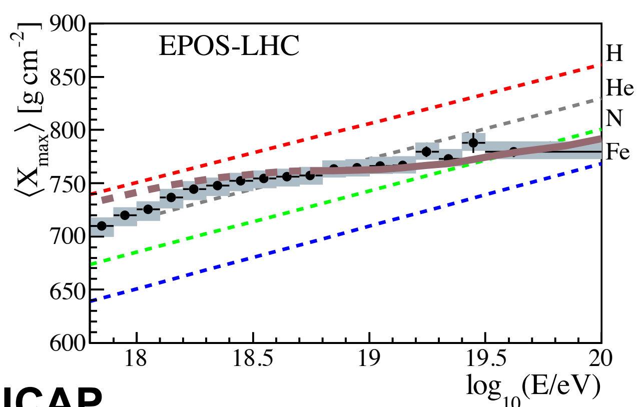


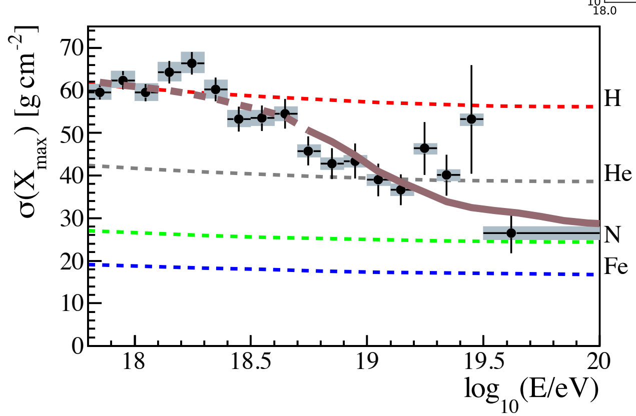
ex. solar abundance





from Zhang, KM+17 PRD





Auger 17 JCAP

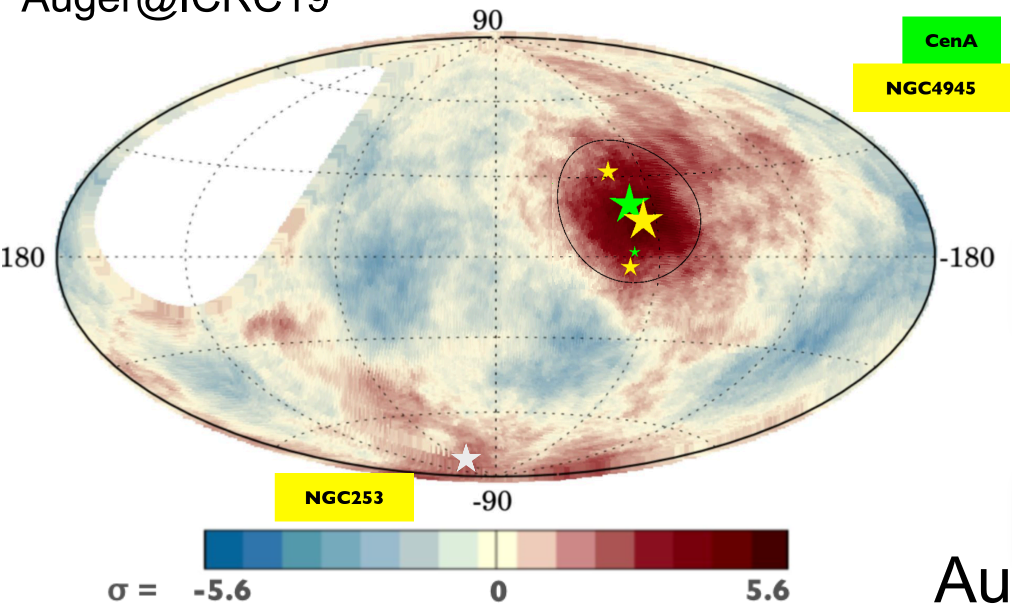
Requirements for Sources of Nuclei

- Hillas condition (luminosity requirement) & energetics
- Anisotropy (including limits on the source density)

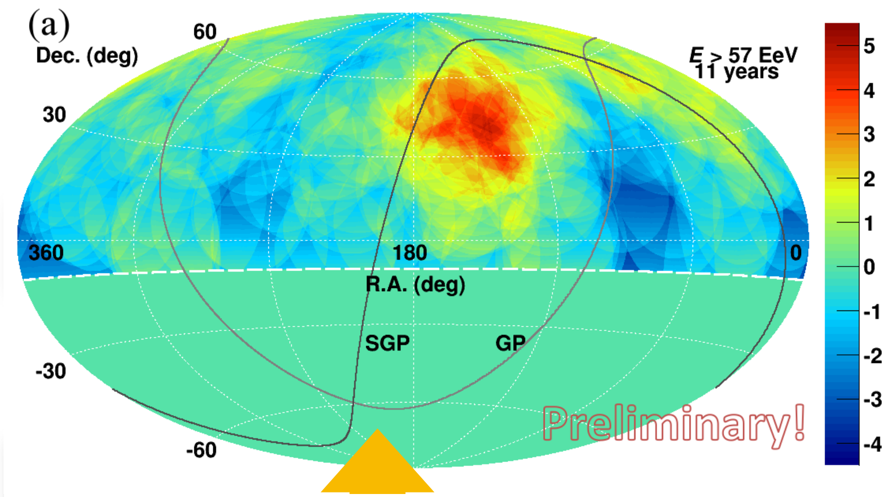
1. Nucleus-survival
   luminosity requirement → powerful sources
   powerful in radiation → efficient disintegration
2. ”Heavy-rich” composition
   a. intrinsic abundance/injection mechanism
   b. reacceleration
3. “Hard” spectrum of nuclei
   a. hard “escape” spectrum (≠acceleration spectrum)
   b. hardening due to “energy losses” in environments

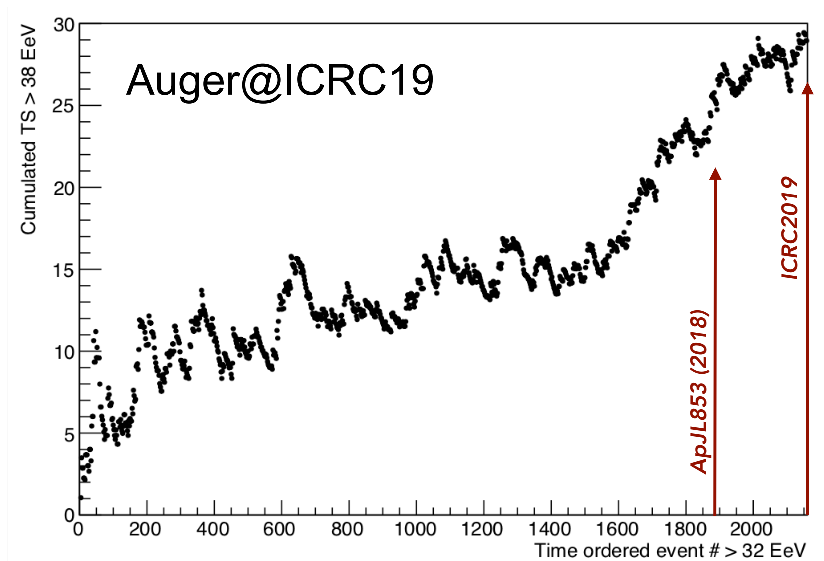
New Hint: Intermediate Anisotropy

Auger@ICRC19



TA@ICRC19





Auger hot spot:

~3.9σ around Cen A (w. 28 deg)

TA hot spot:

~2.9σ (w. 25 deg)

Auger cross correlation:

starburst galaxies

(**stellar deaths**) ~4.5σ

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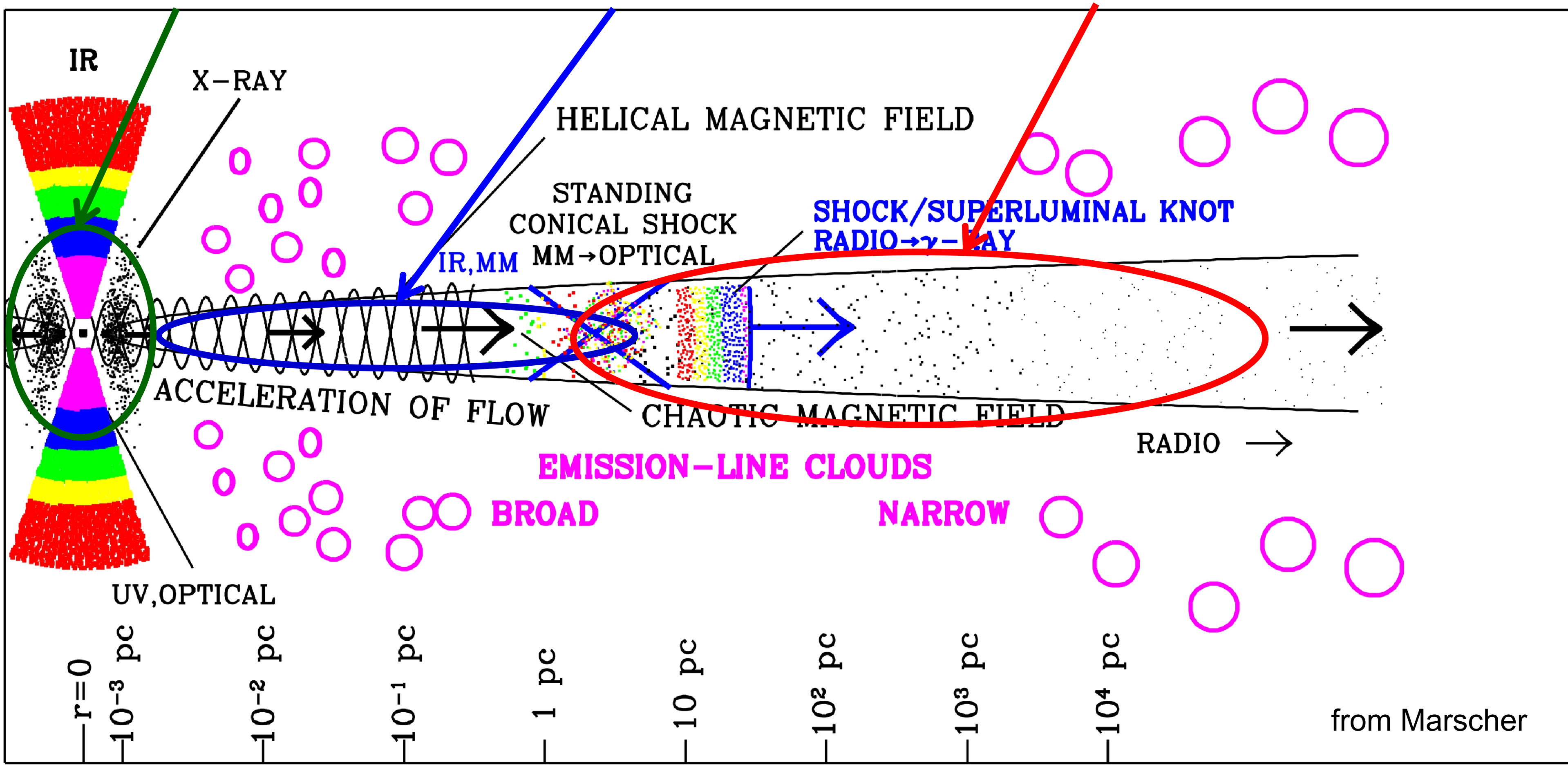
Particle Acceleration in AGN?

Black hole vicinity
$r \sim$ 1-100 Rs,
$B \sim 10\text{-}10^4$ G, $\Gamma \sim 1$

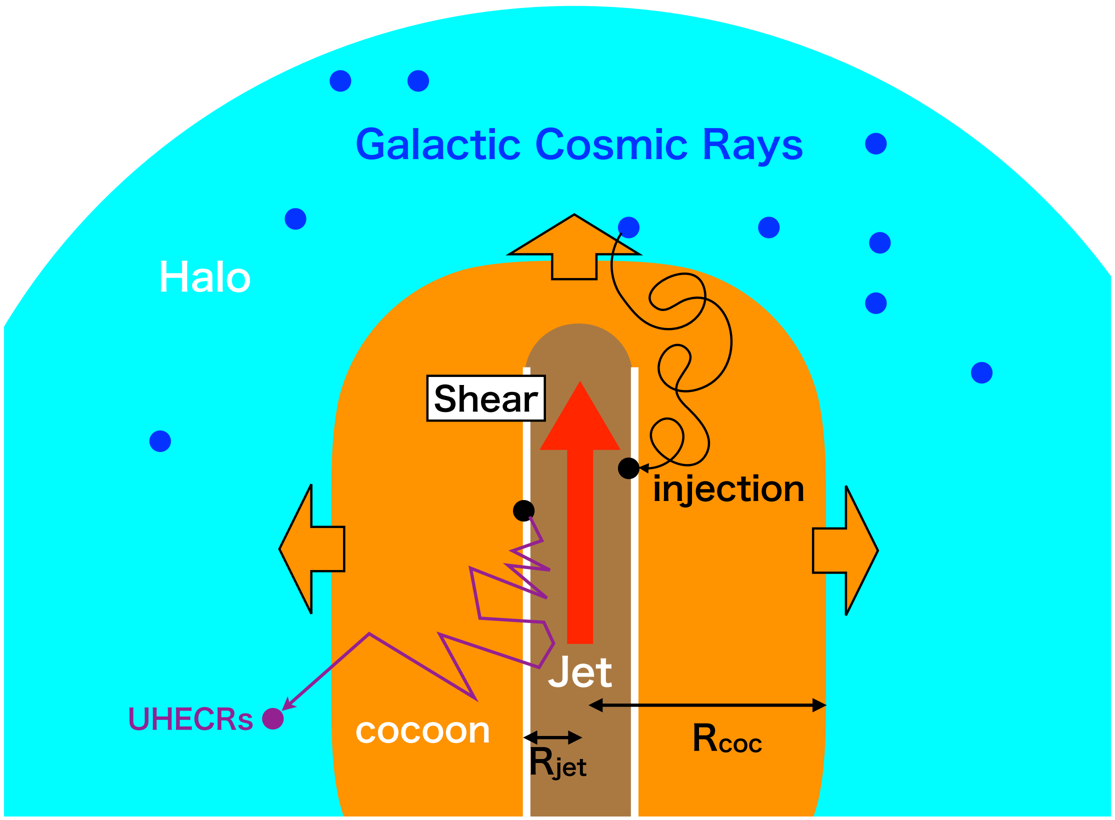
Inner jet (blazar zone)
$r \sim 10^{16}\text{-}10^{18}$ cm,
$B \sim 0.1\text{-}100$ G, $\Gamma \sim 10$

Large-scale jet, hot spot, cocoon
$r \sim 10^{20}\text{-}10^{21}$ cm,
$B \sim 1\mu$G -1 mG, $\Gamma \sim 1$

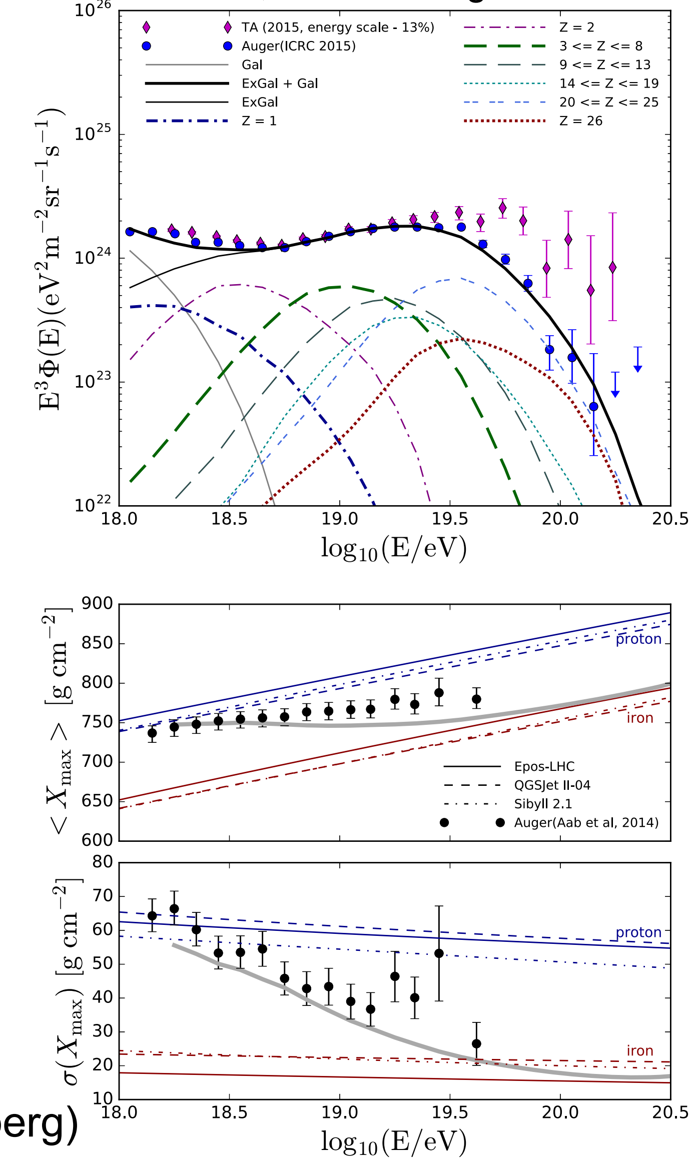


Hillas condition: $E_{max} \sim ZeBr\Gamma \sim 3\text{x}10^{19}$ eV Z (Γ/10) (B/0.1 G) (r/10^{17} cm)

One-Shot/Shear Acceleration at Kpc Scale Jets



Kimura, KM & Zhang 18 PRD



- Super-solar abundance of nuclei in AGN?

→ Reacceleration of “galactic” CRs by AGN jets

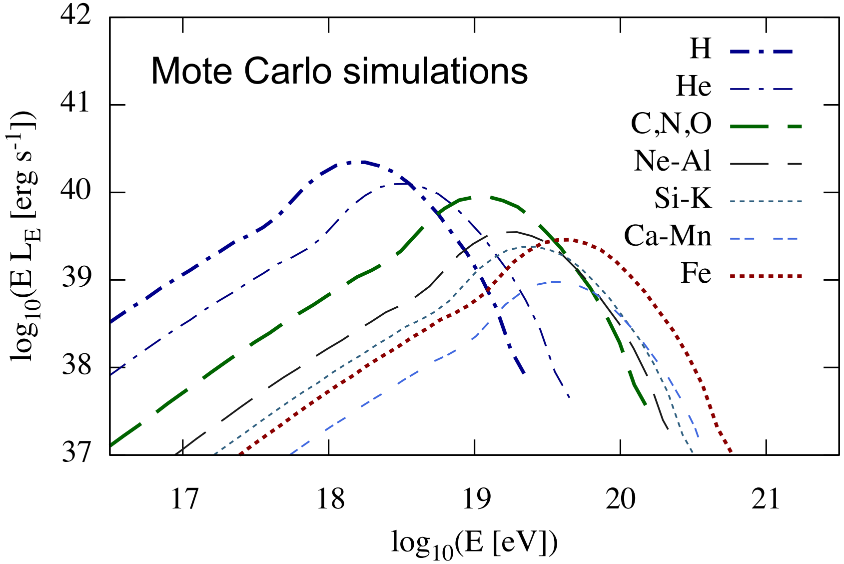
Caprioli 15, Kimura, KM & Zhang 18

Shear acceleration (Γ~1) (ex. Berezhko & Krymskii, Ostrowski)

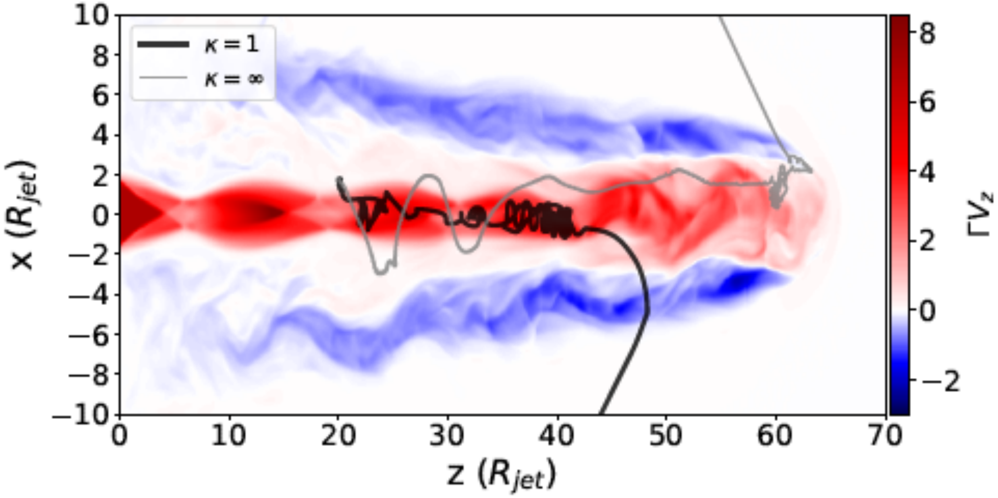
One-shot (espresso) acceleration (Γ>>1) (ex. Gallant & Achterberg)

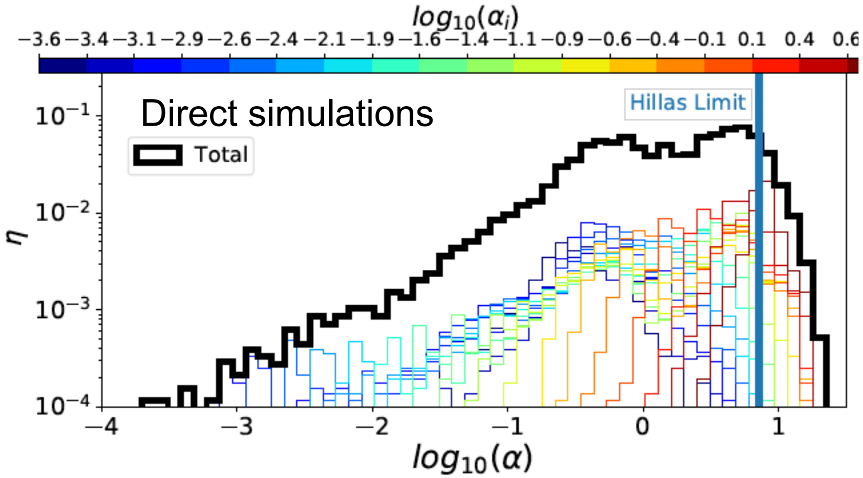
Contd.

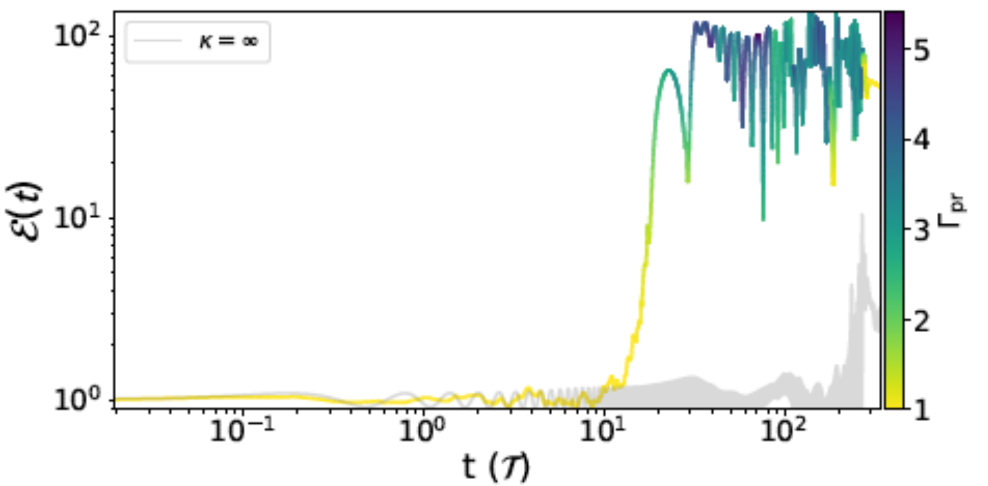
Kimura, KM & Meszaros 18



Mbarek & Caprioli 21



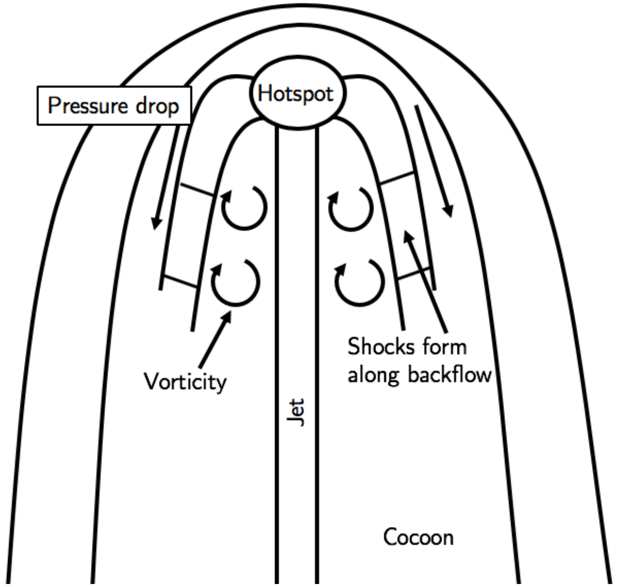




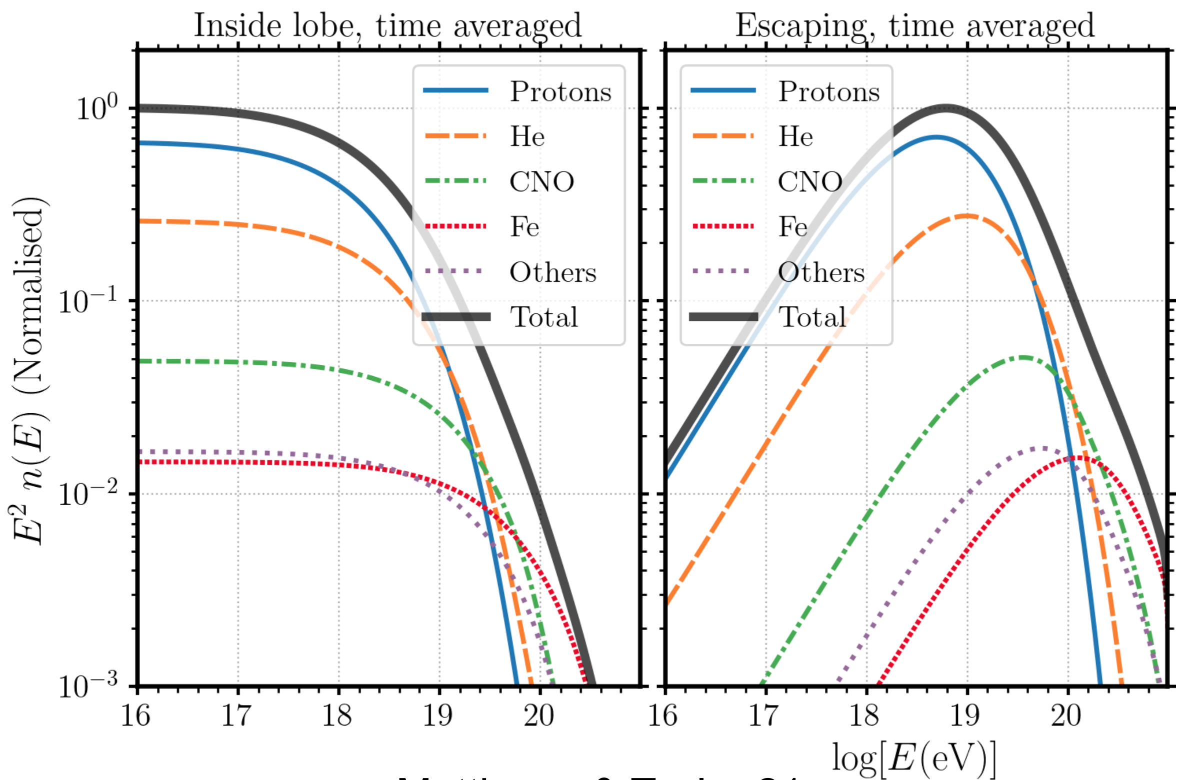
One-shot/shear acceleration has been demonstrated by numerical simulations

Shock Acceleration in Jet Backflows

- Jet-cocoon interactions lead to shocks in backflows forming a cocoon (demonstrated by hydrodynamic jet simulations)
- FR-II galaxies: promising for UHECR acceleration & delayed escape
- "Escape" spectrum is different from "acceleration" spectrum
  ex. cocoon shock: $s_{esc} = s_{acc}+1/2$ (Ohira, KM & Yamazaki 10)



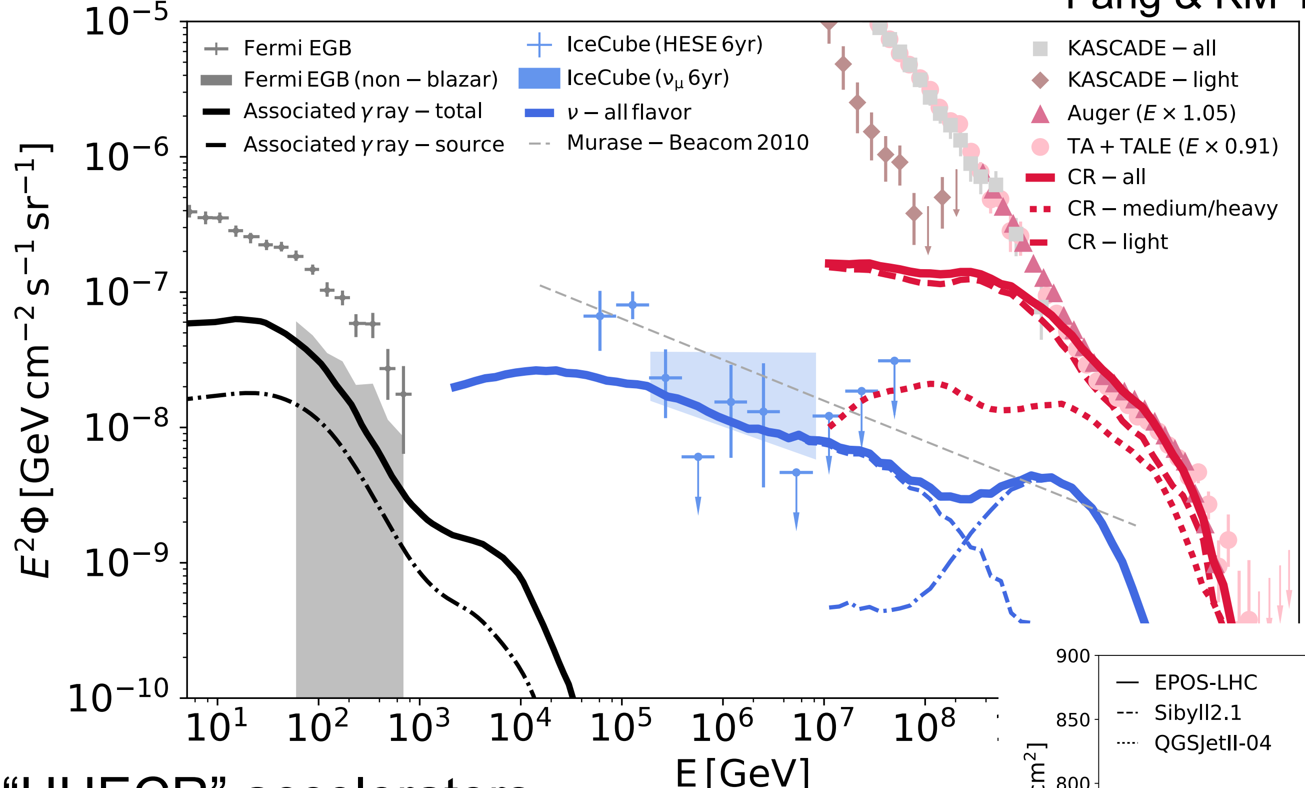
Matthews+ 19

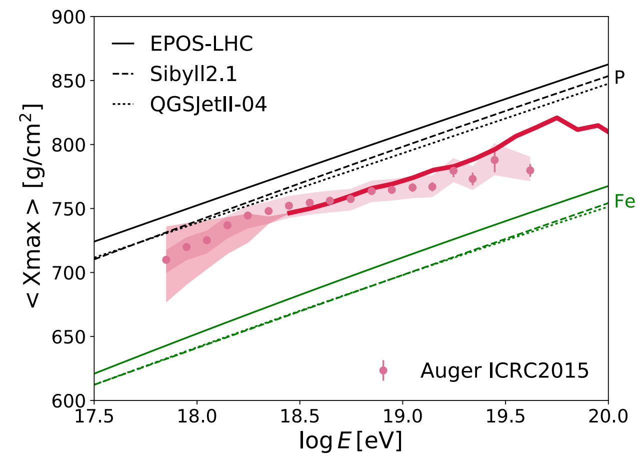


Matthews & Taylor 21

Multi-Messenger Signatures?

Fang & KM 18 Nature Physics





- AGN="UHECR" accelerators
  Galaxy clusters/groups="CR" reservoirs
- LE CRs: confinement in cocoons
  VHE CRs: confinement in clusters
  UHE CRs: escape into intergalactic space
- CR nuclei: photodisintegration -> harder spectra

(Unger, Farrar & Anchordoqui 15)

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$r \sim$ 1-100 Rs,
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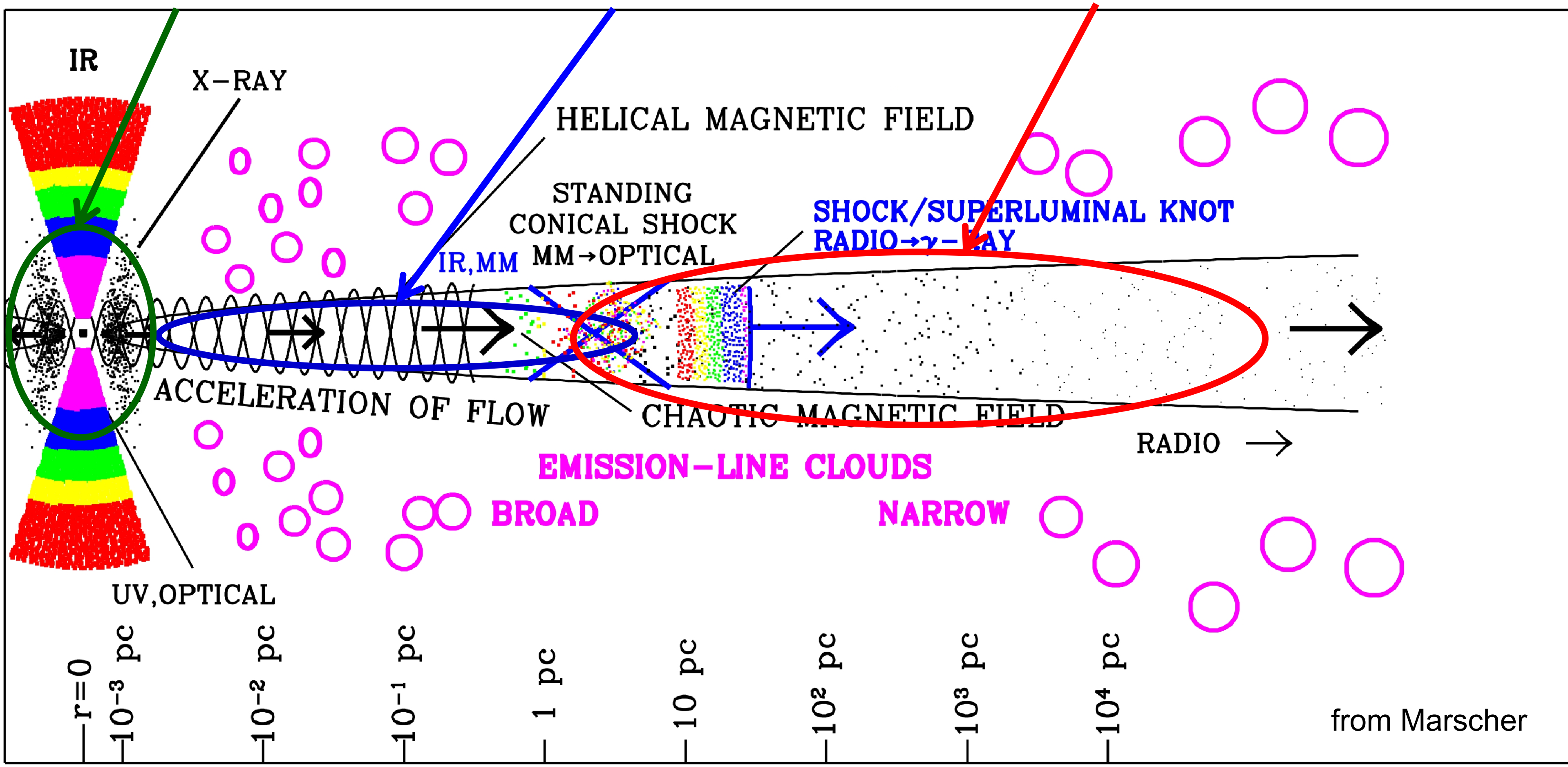

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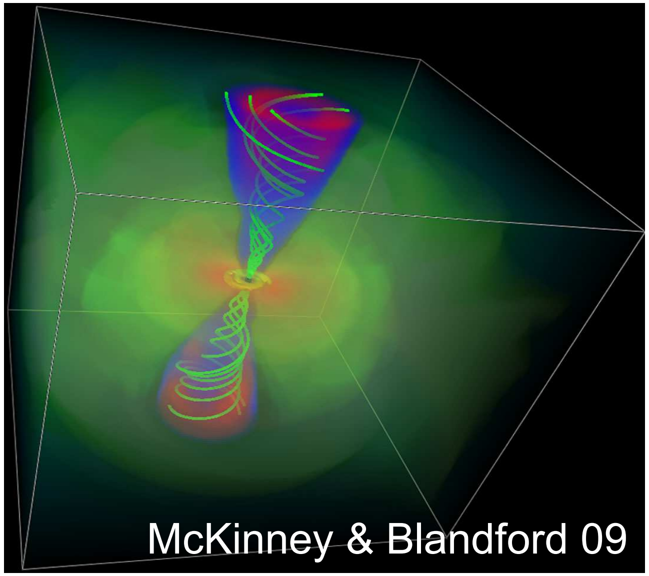
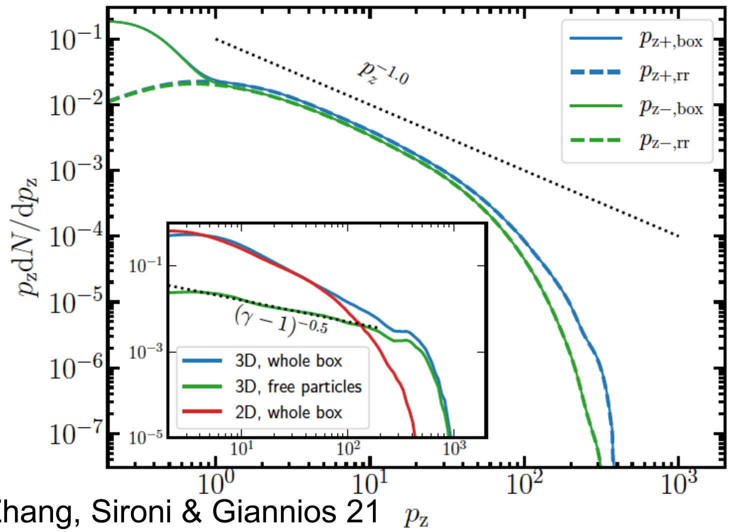
Particle Acceleration in Inner Jets?

Origin of relativistic particles in blazars is under debate





Zhang, Sironi & Giannios 21

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

→ magnetic reconnections?

but $\varepsilon_p/\varepsilon_e$ may not be large

more studies are necessary

Ions? Maximum CR Energy

~10% of AGN have powerful jets: "radio-loud AGN"
~0.1-1% of them are FR II galaxies and FSRQs (on-axis)

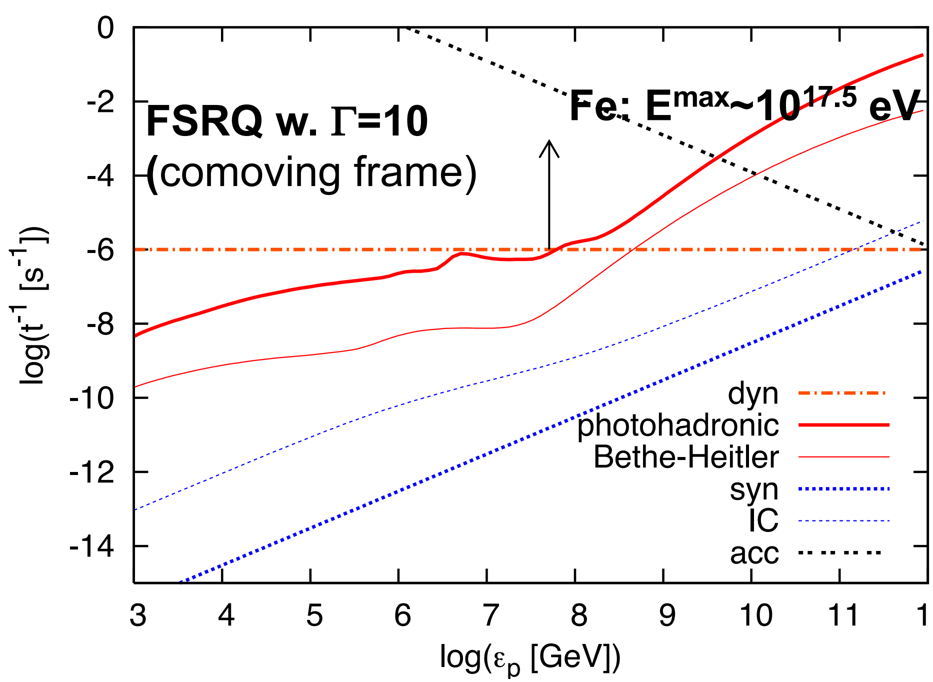
Hillas condition: $E_A^{max}=ZeB'\Gamma R'$
nearby FR I & blazars seen by Fermi

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

$E^{max} < Z10^{19}$ eV for FSRQs
$p\gamma/A\gamma$ losses are very important

FSRQs cannot be 10^{20} eV nuclei sources



Ions? Maximum CR Energy

~10% of AGN have powerful jets: "radio-loud AGN"
Most of them are FR I galaxies and BL Lacs (on-axis)

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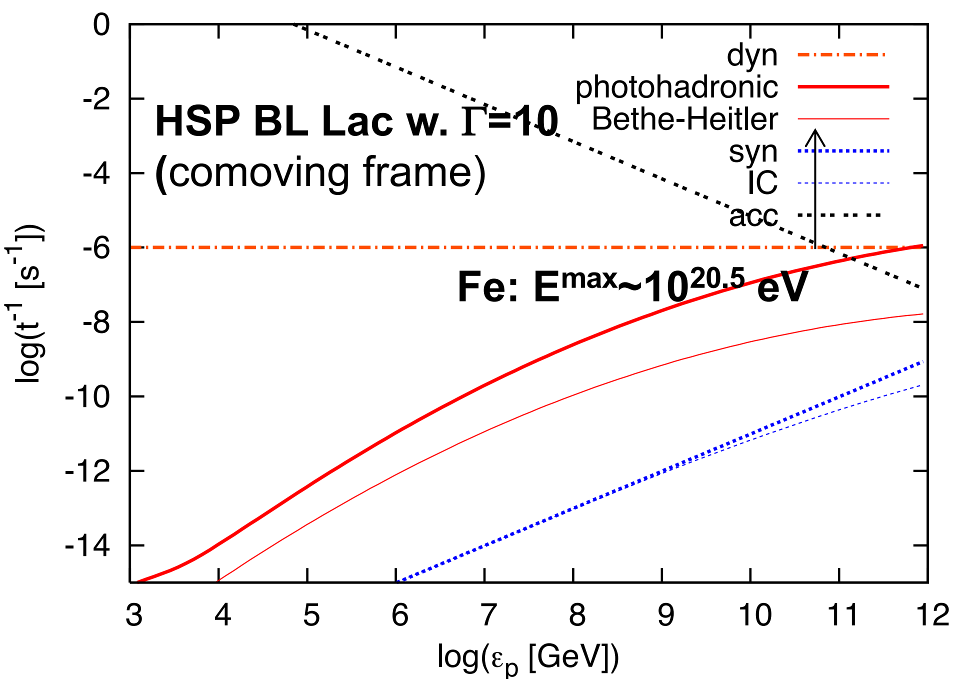
KM, Dermer, Takami, & Migliori 2012 ApJ

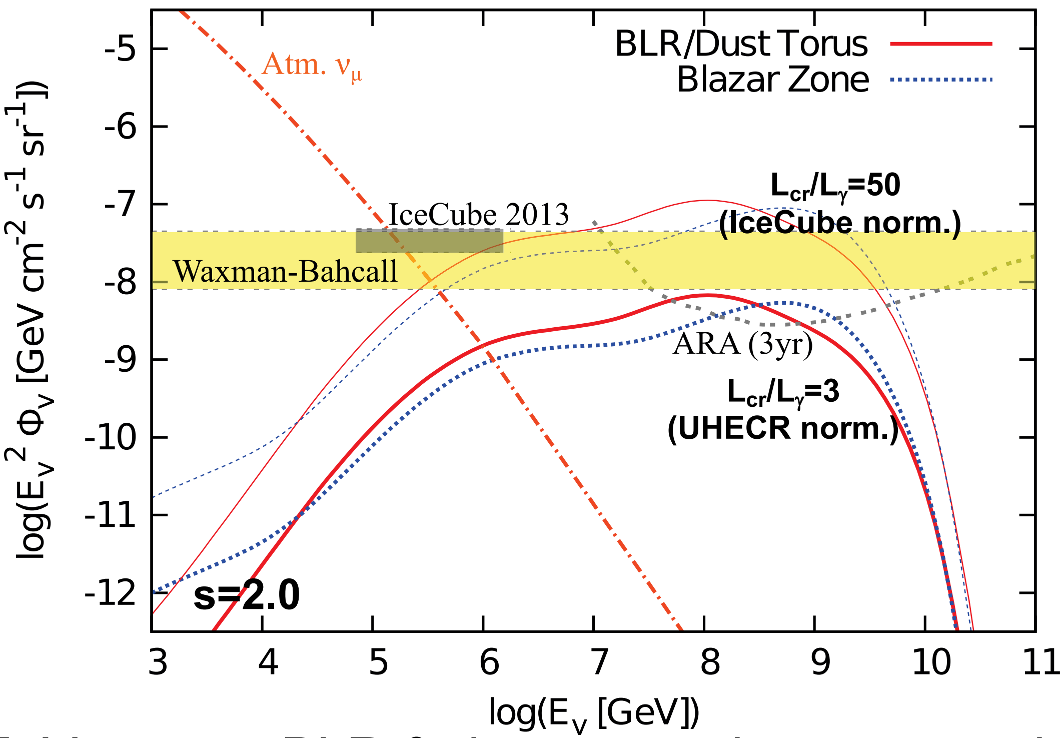
E^{max} ~ $Zx(10^{18}\text{-}10^{19})$ eV for BL Lacs
$p\gamma/A\gamma$ losses are irrelevant

BL Lacs could be 10^{20} eV nuclei sources



Blazars as UHECR Sources?

- FSRQs: efficient ν production, UHECRs largely destroyed
- BL Lac objects: less efficient ν production, UHE nuclei survive

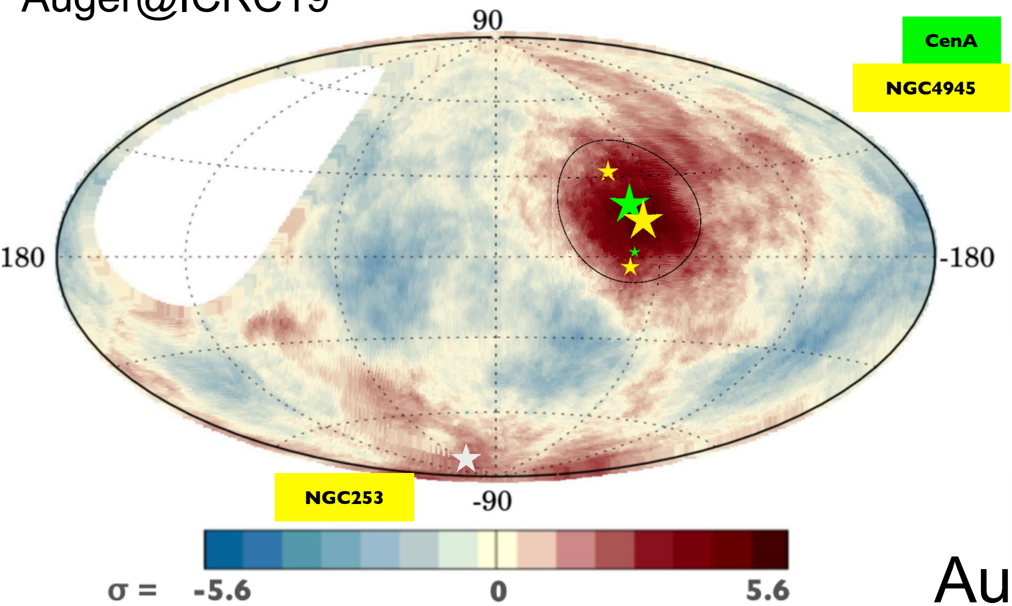


KM, Inoue & Dermer 14 PRD

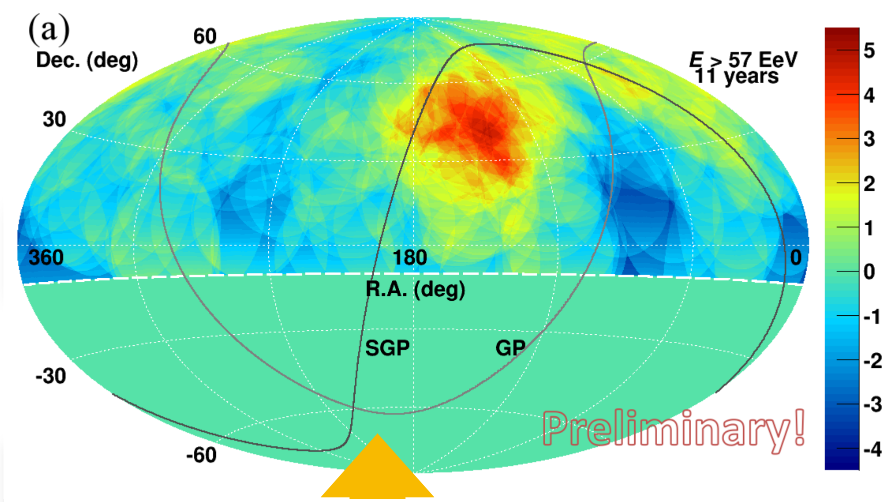
- PeV-EeV ν: pγ w. BLR & dust-torus photons → unique prediction
- UHECR-blazar model → EeV ν detectable by next-generation ν detectors (being tested by IceCube & Auger)
- UHECRs should be isotropized in lobes/clusters/filaments (KM, Dermer+ 12)

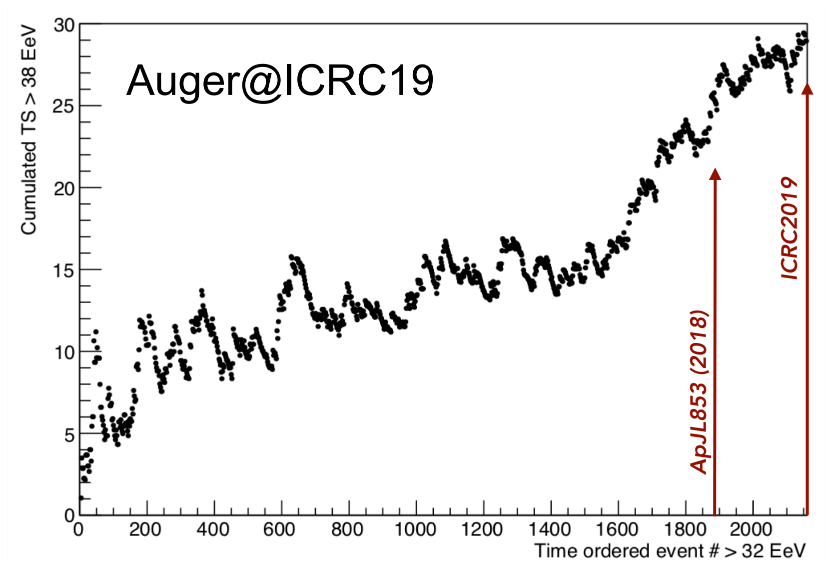
New Hint: Intermediate Anisotropy

Auger@ICRC19



TA@ICRC19





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starburst galaxies

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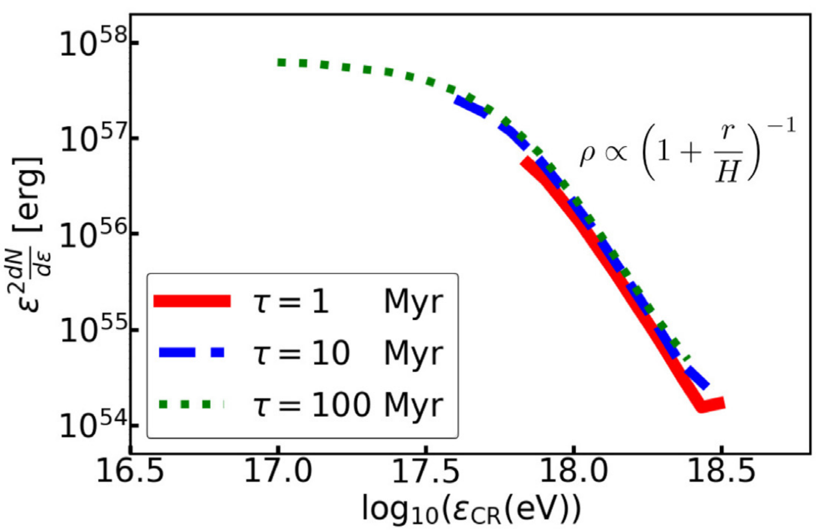
γ-ray emitting **AGN** ~3.1σ

(Re)acceleration by AGN winds/Superbubbles

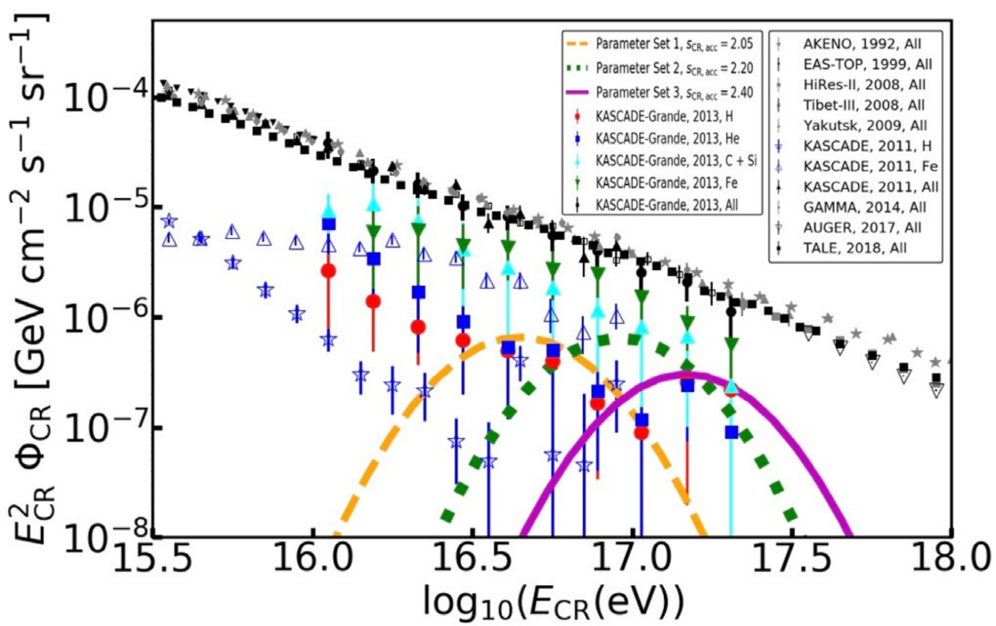
AGN winds $\varepsilon_p^{\max} \approx (3/20)(V_w/c)eB_wR \simeq 21~\mathrm{PeV}~\epsilon_{B,-2}^{1/2}L_{w,44}^{1/2}(V_w/1000~\mathrm{km~s^{-1}})^{1/2}$

superbubble
(e.g., Bykov)

$$\varepsilon_{\max}(t) \simeq \frac{3}{20}\cdot Z\cdot e\cdot B\cdot R_{\rm s}\cdot\frac{V_{\rm s}}{c}$$
$$\simeq 1.6\times10^{17}\,Z\,\epsilon_{\rm B,-2}\,({\rm SFR}_4\cdot E_{\rm ej,51})^{3/5}\rho_{0,-21}^{-1/10}\,t_{\rm Myr}^{-1/5}\,{\rm eV}$$



from Zhang, KM & Meszaros 20



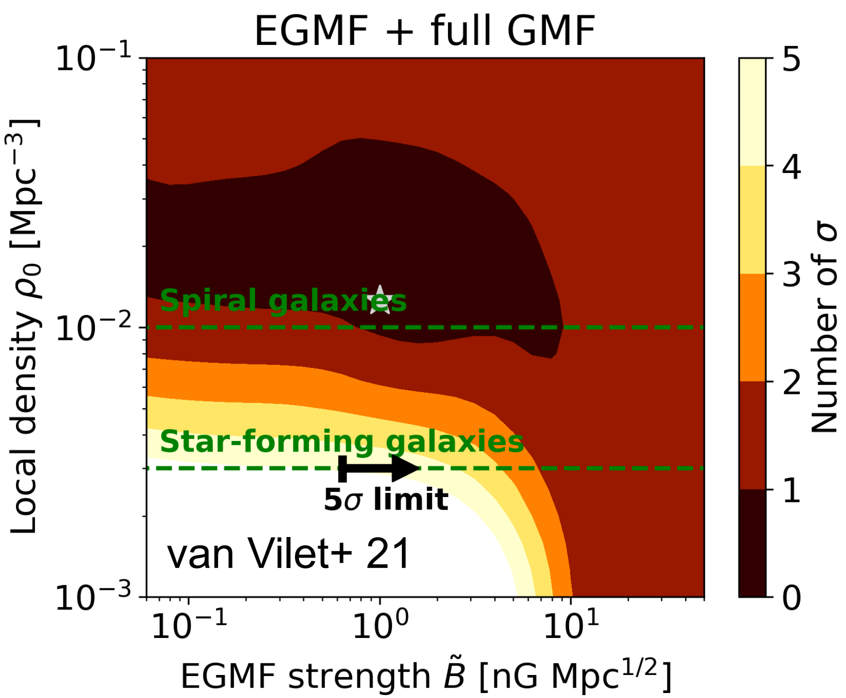
Possibly ~10^{20} eV by scaling up Milky-Way-like galaxies? – under debate
(ex. Anchordoqui 18, KM & Fukugita 19, Peretti+ 21)

Transients?

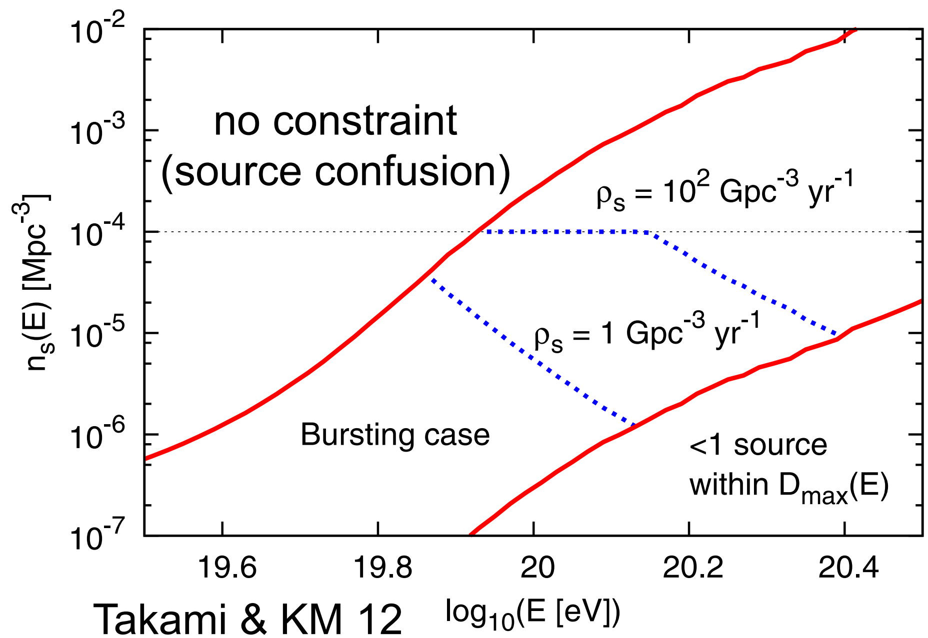
absence of small-scale anisotropy (for protons)

$n_s > 10^{-5}$-10^{-4} Mpc^{-3}

Kashti & Waxman 08 JCAP
Takami & Sato 09 Aph
Auger 13 JCAP
Takami, KM & Dermer 16 ApJ



$n(E) \propto \tau_d \propto E^{-2}$ in burst case



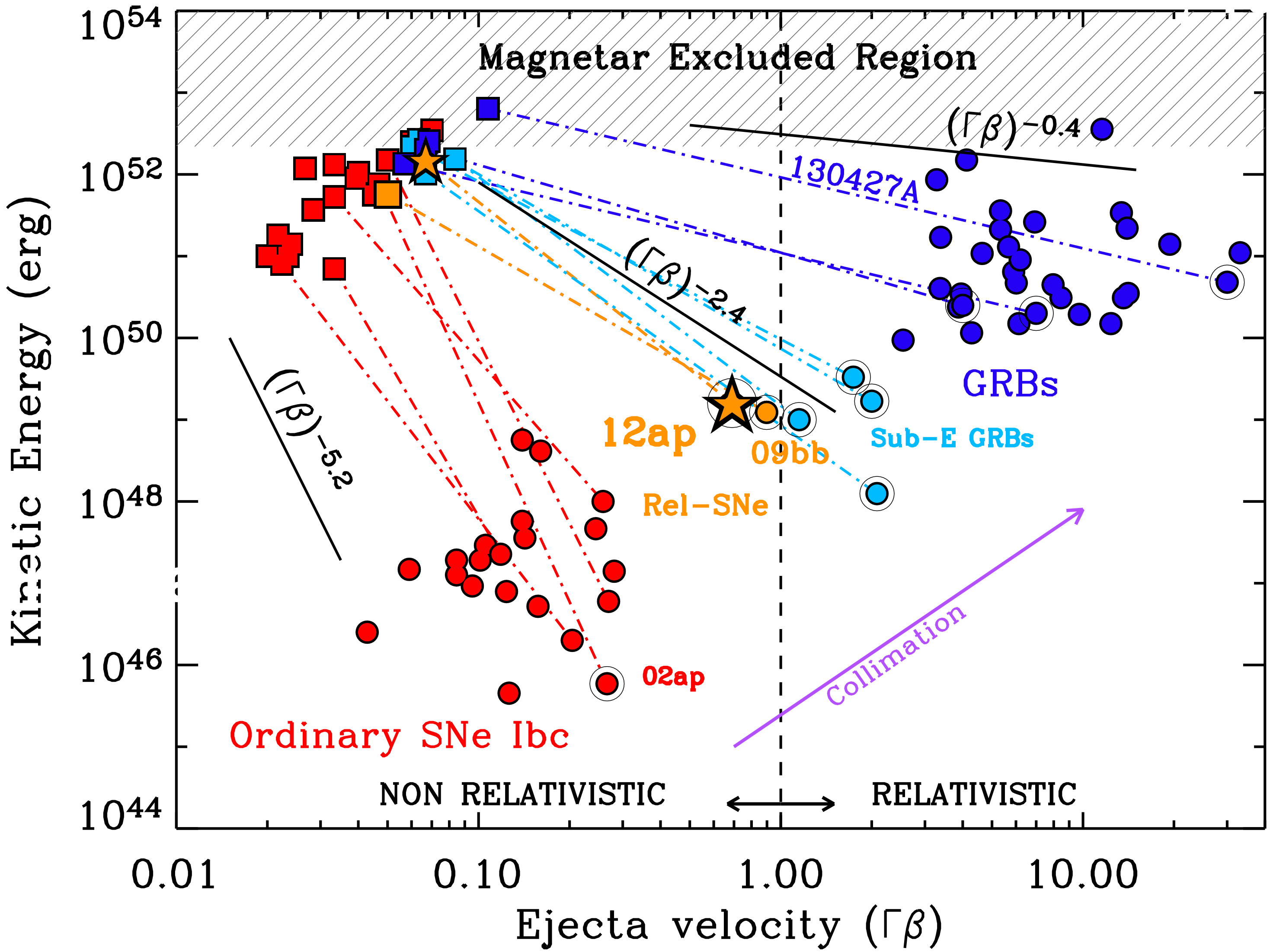
Takami & KM 12

Source density is high if the effective EGMF strength is not strong

Transients: source density can be high & energy dependent

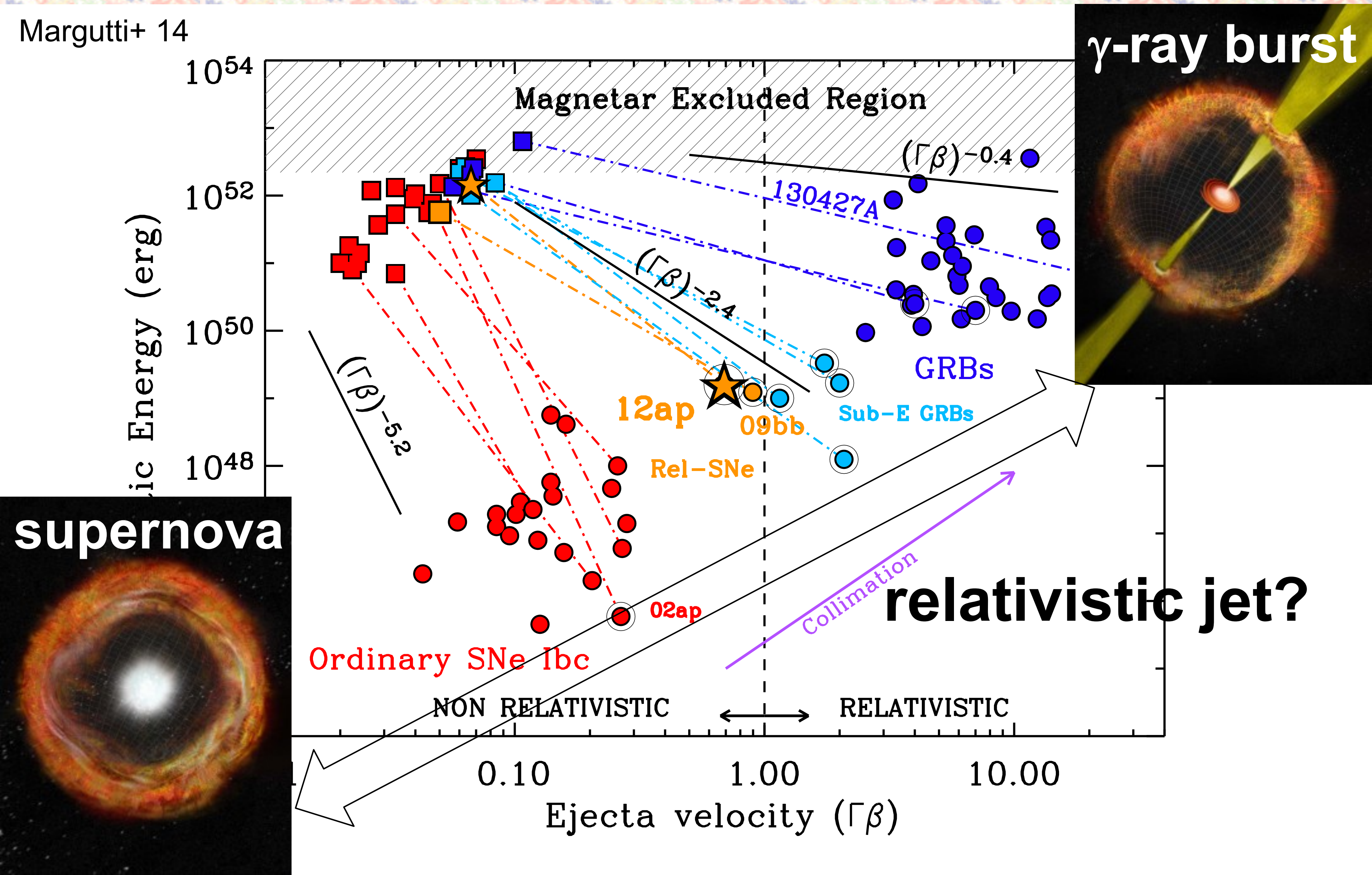
GRB-SN Connection & Tranrelativistic SNe

Margutti+ 14



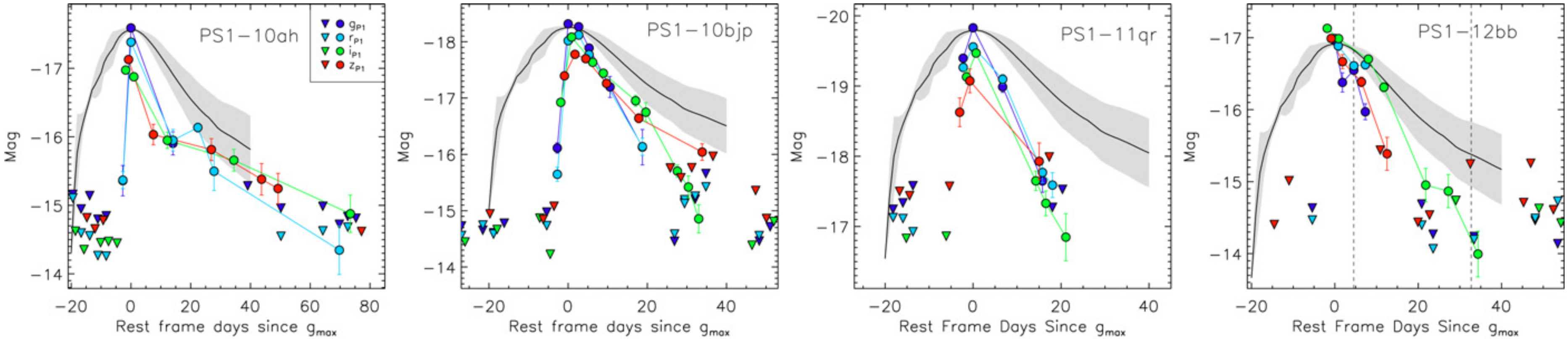
GRB-SN Connection & Tranrelativistic SNe

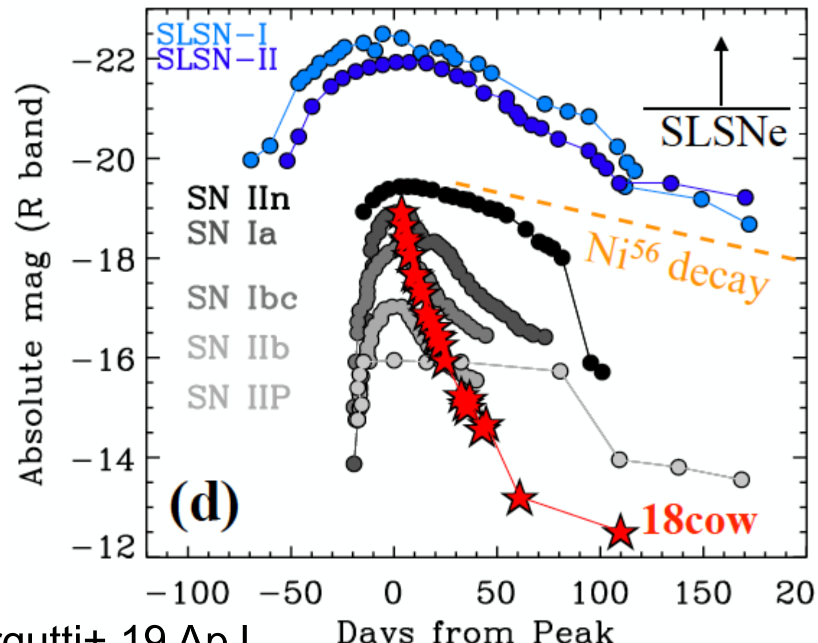
Margutti+ 14



Fast Blue Optical Transients

Drout+ 14 (see also Arcavi+ 13 etc)

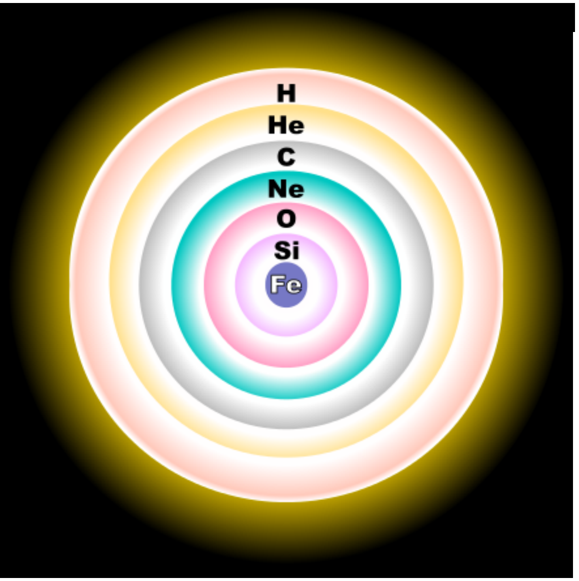


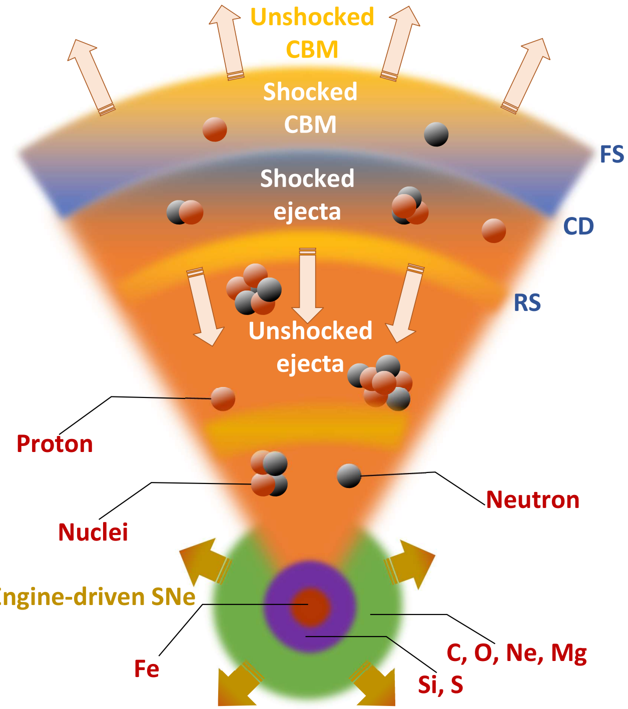


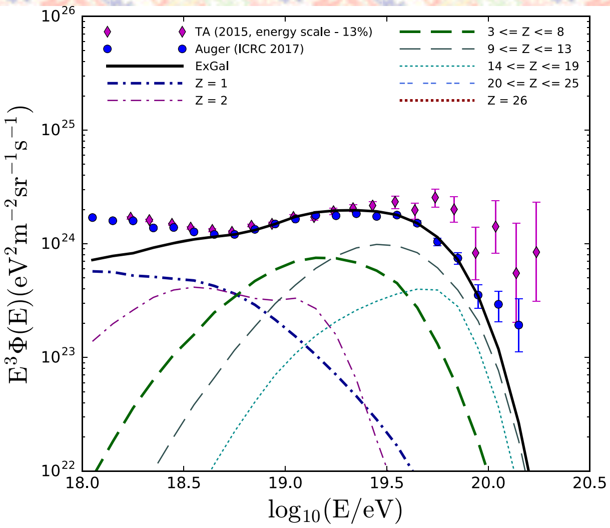
Margutti+ 19 ApJ

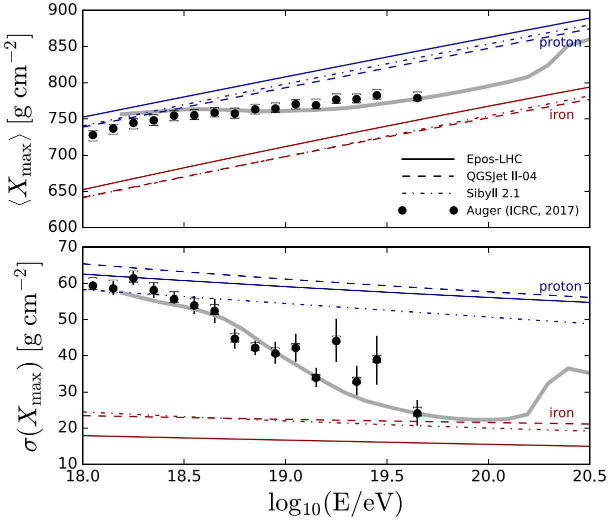
- Rapidly evolving (<10 day)
- Luminous & bright
- T ~ a fewx10^4 K (blue)
- Unlikely to be Ni-powered
- Star-forming region
- ~4-7% of core-collapse SNe
- Transrelativistic shocks

(Low-Luminosity) GRBs/Engine-Driven Supernovae







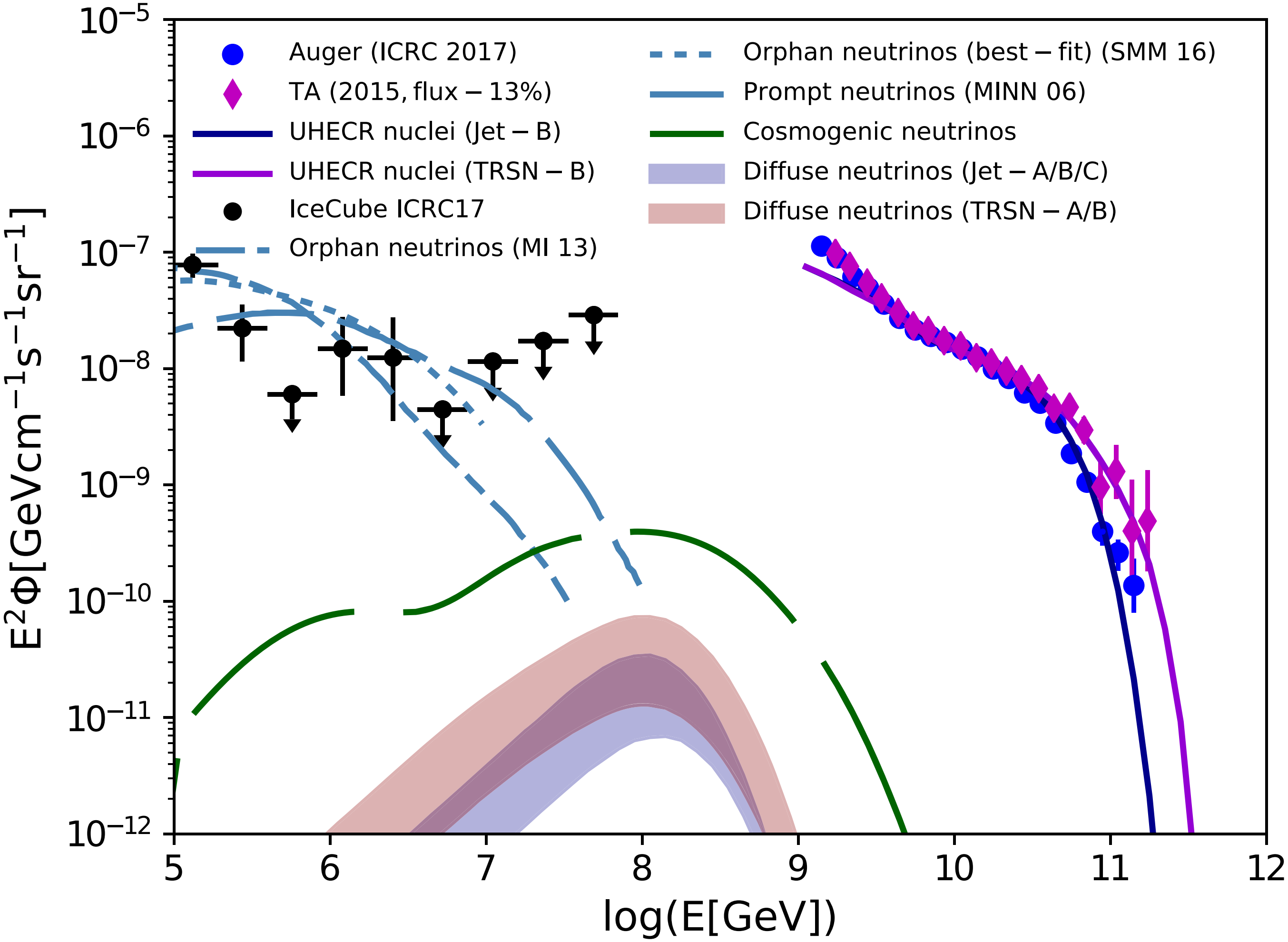


#classical GRBs
Waxman 95, Vierti 95
KM+ 08, Globus+ 15

1. Dominantly “intermediate” mass nuclei:
   "prediction” of progenitor models (not free!)
2. Transrelativistic shocks (promising for DSA)
3. Instantaneous escaping spectrum: can be hard
3. Nuclei can survive
4. Correlation w. starburst galaxies

Zhang, KM+ 18, Zhang & KM 19
(see also KM+ 06, Wang+ 07)

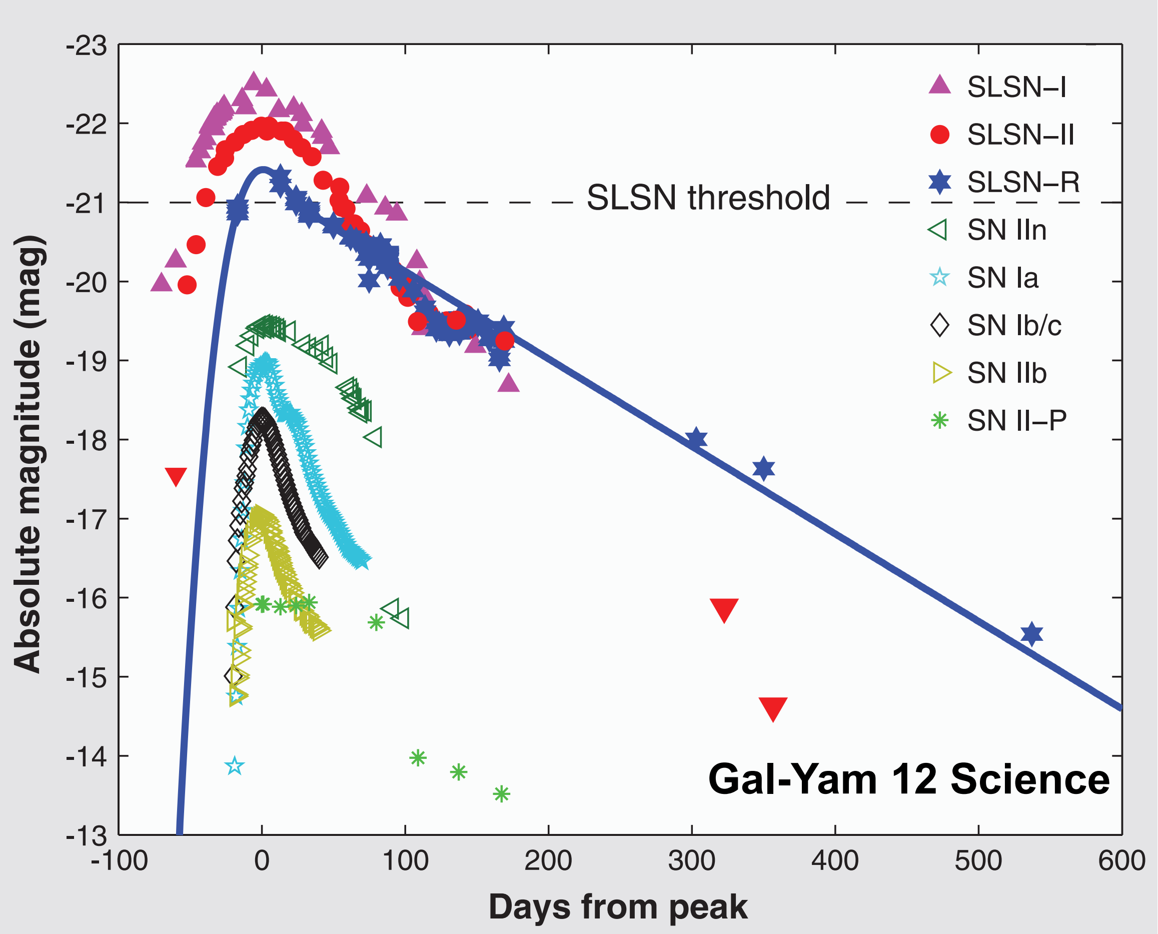
Neutrinos from Engine-Driven SNe



Zhang & KM 19 PRD

- EeV: cosmogenic neutrinos overwhelm source neutrinos
- But PeV νs may come from inner jets (KM+ 06, Senno, KM & Meszaros 16)

Luminous Supernovae as Long-Duration Transients

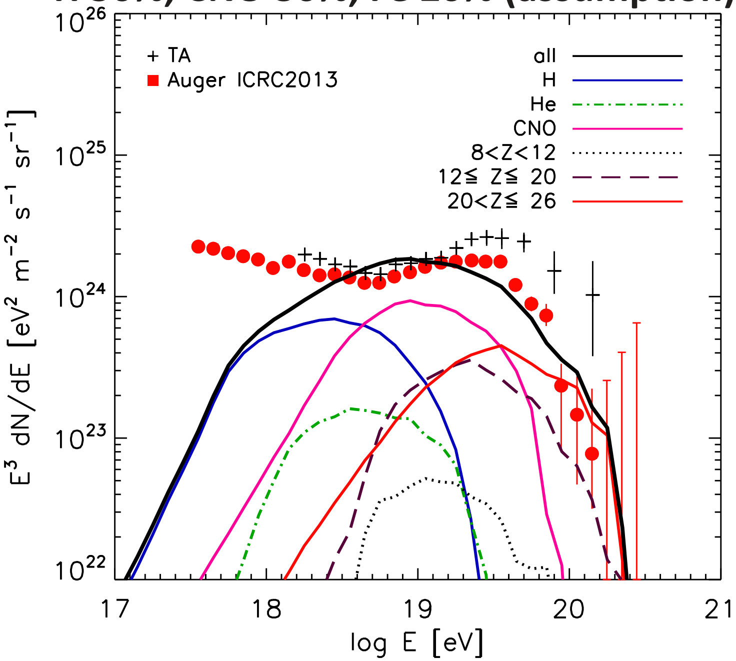


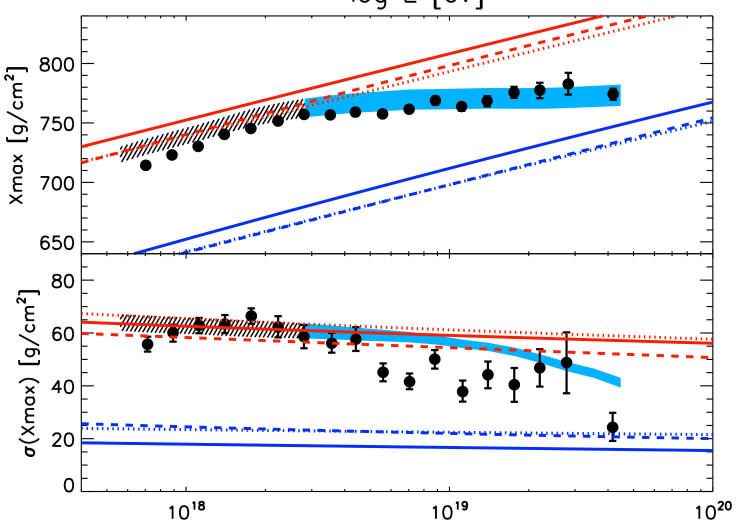
Luminous SNe explanations w. radioactivity for I and II often have difficulty

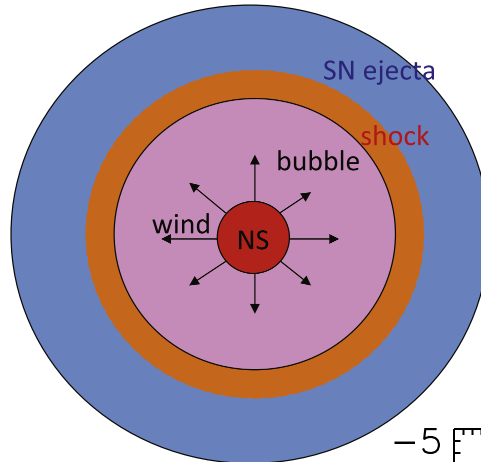
- SLSN-I (hydrogen poor) – energy injection by engine?
- SLSN-II (hydrogen) – circumstellar material interaction

Fast-Rotating Pulsars/Magnetars

H 50%, CNO 30%, Fe 20% (assumption)

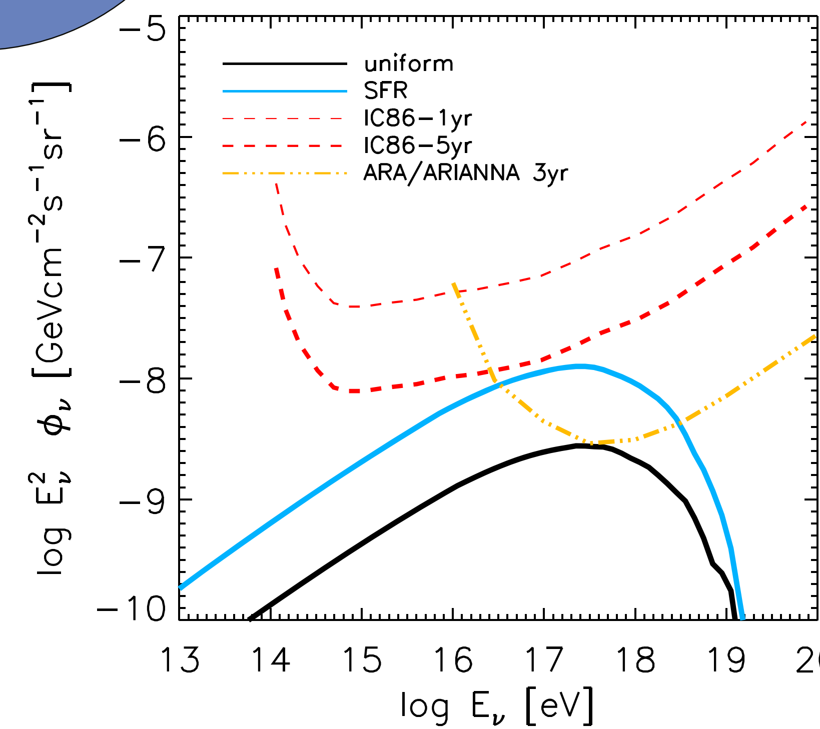






Fang, Kotera & Olinto 12 ApJ
Fang, Kotera, KM & Olinto 14 PRD
see also Blasi, Epstein & Olinto 00 ApJ
Arons 03 ApJ
KM, Meszaros & Zhang 09 PRD

- Nuclei can be supplied from the neutron star surface
- Ion acceleration mechanism?



Summary

New clues from UHECR **composition** & anisotropy data

AGN

- UHECR reacceleration by large-scale jets is promising
  one-shot/shear and/or multiple-shock acceleration
  -> predicted heavy-rich abundance with hard escape spectra, turbulence?
- UHECR acceleration in inner jets (blazars) – acceleration & escape?
  -> EeV neutrinos provide a unique test

Stellar deaths

- Diversity of transients (nuclei → GRBs are not only candidates!)
  - Engine-driven SNe
    transrelativistic shocks (promising sites for Fermi mechanism)
    predicted composition of intermediate nuclei from progenitors, escape?
  - Fast-rotating pulsars/magnetars
    natural loading of iron-like nuclei from NS, acceleration & escape?
  -> PeV-EeV neutrinos provide a unique test
- Acceleration by AGN/starburst-driven winds

Multimessenger tests & modeling of acceleration, escape and abundance