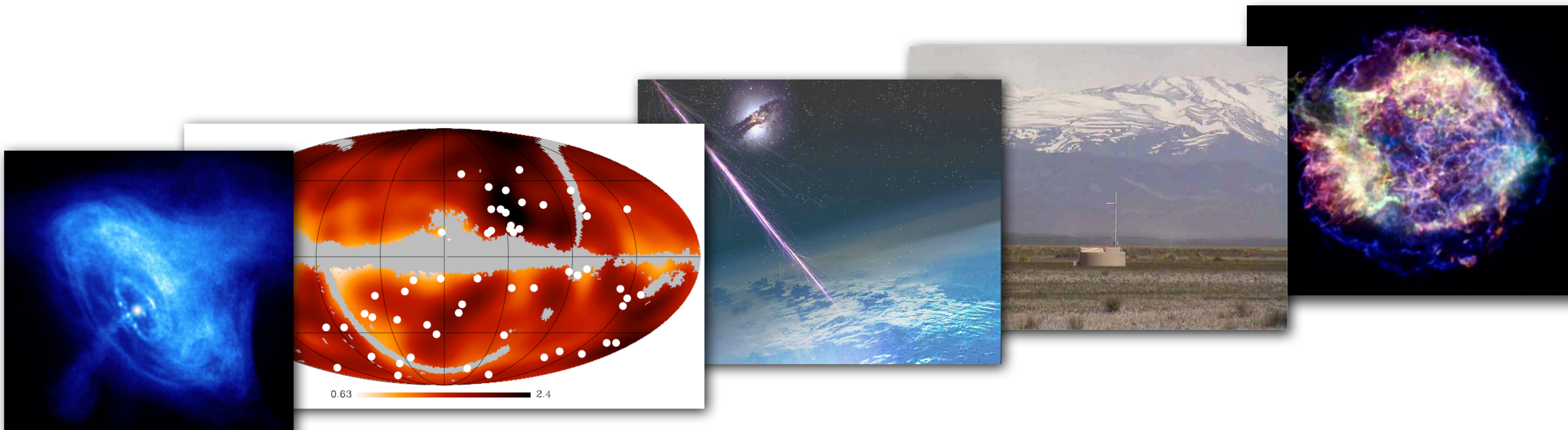
Ultrahigh energy cosmic rays sources? and pulsar winds



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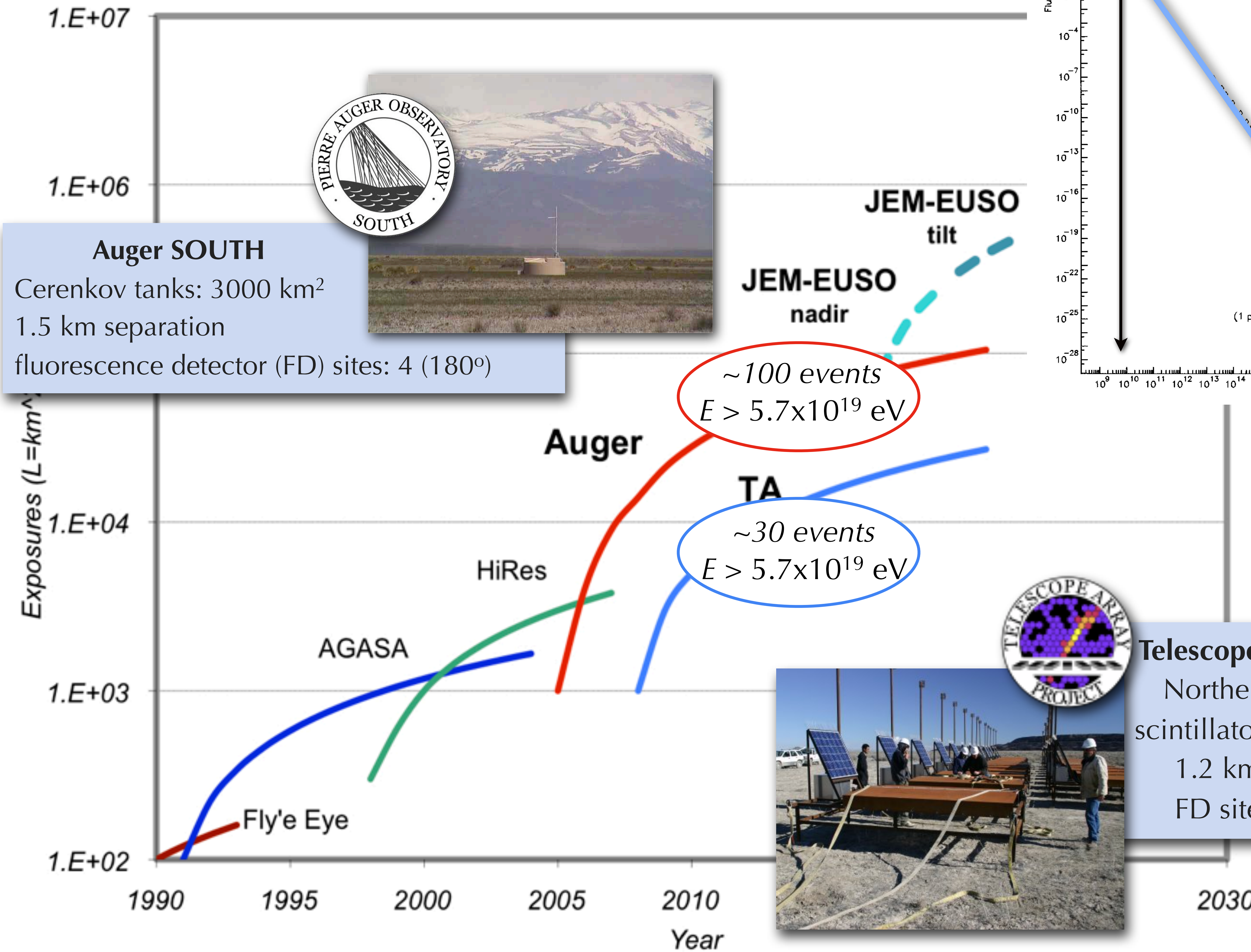
Atelier Accélération - 03/10/12

Since 1990 in ultrahigh energy cosmic rays

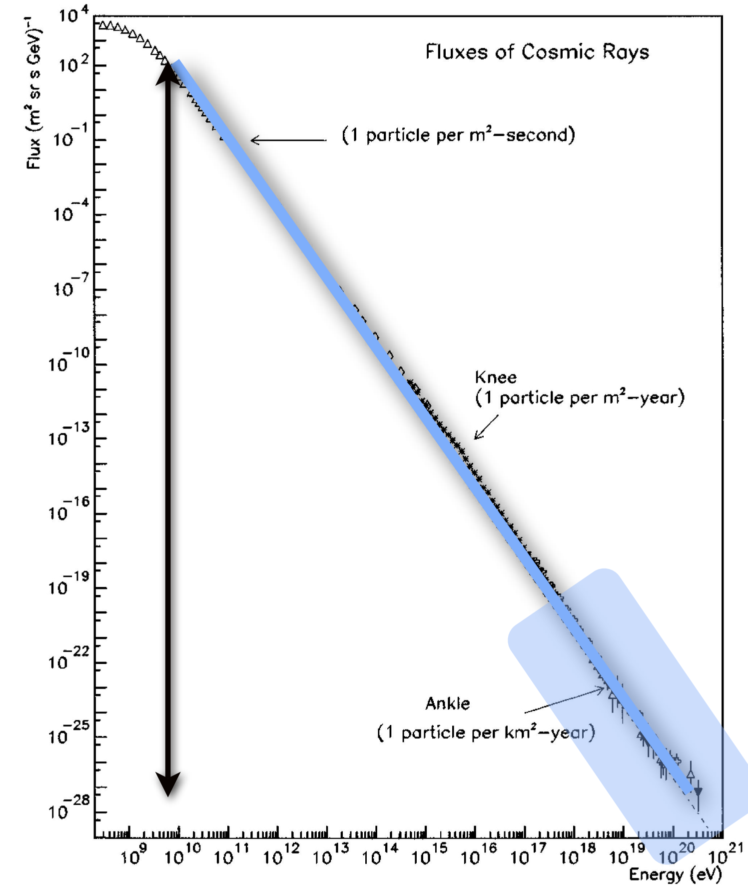


Auger SOUTH

Cerenkov tanks: 3000 km²

1.5 km separation

fluorescence detector (FD) sites: 4 (180°)



Telescope Array (TA)

Northern hemisph.

scintillators: 762 km²

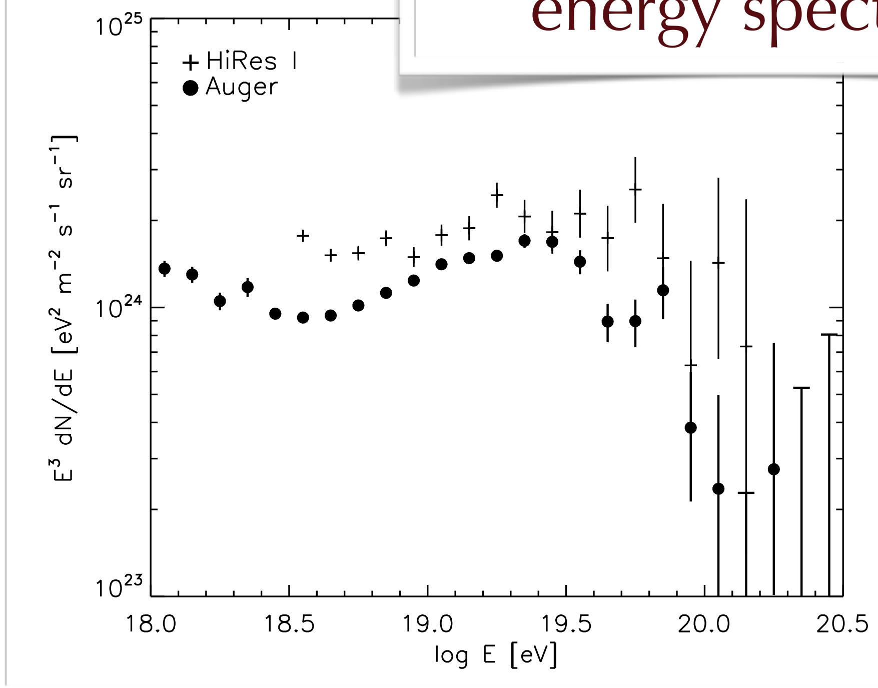
1.2 km separation

FD sites - 3 (180°)

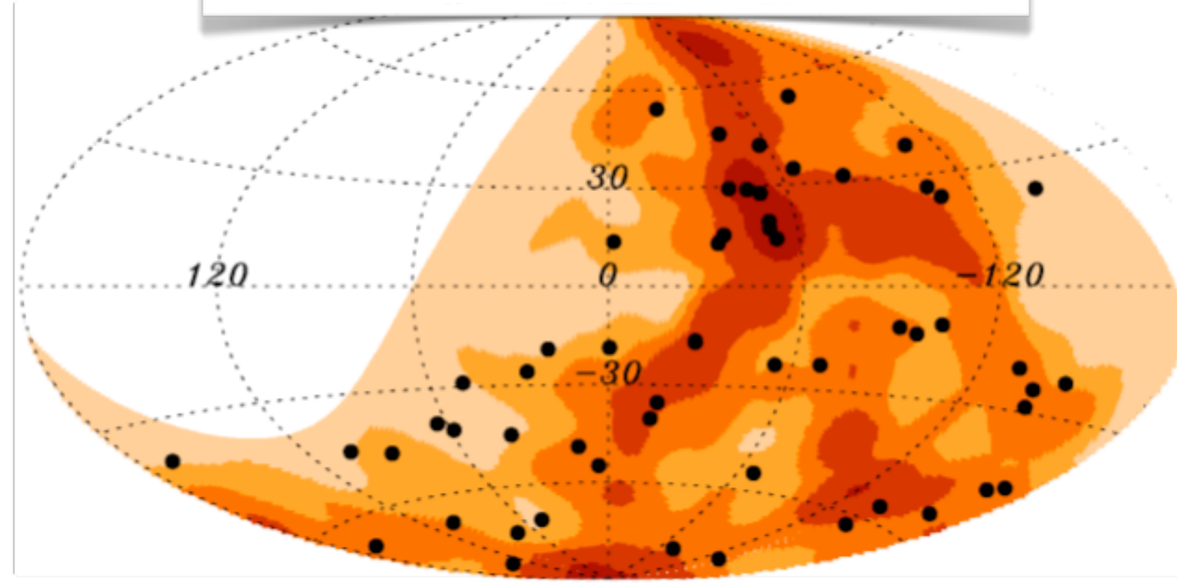
K.K. & Olinto 11

What observational information do we have?

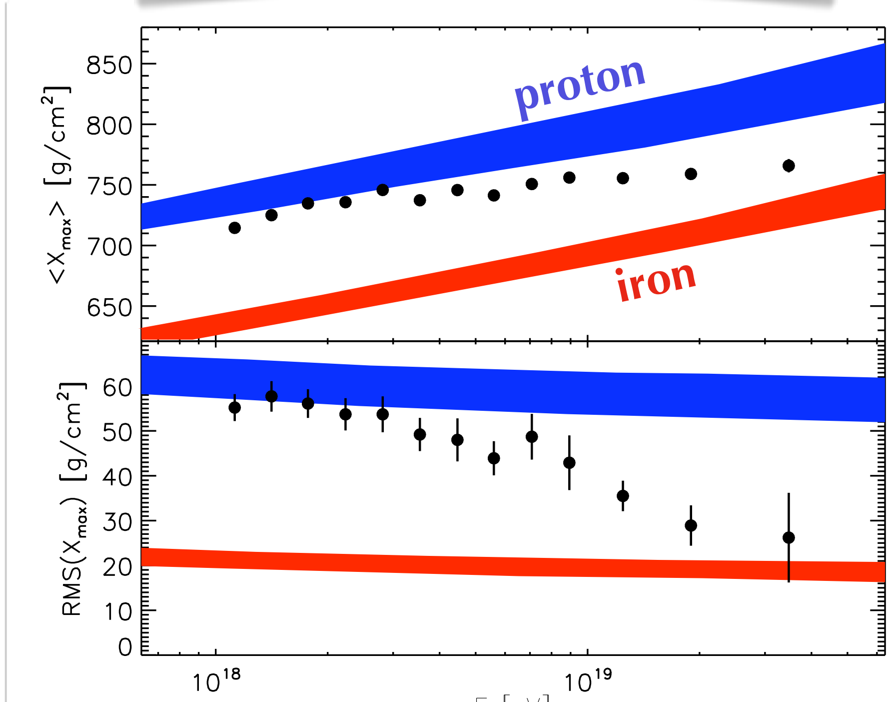
energy spectrum



arrival directions in the sky

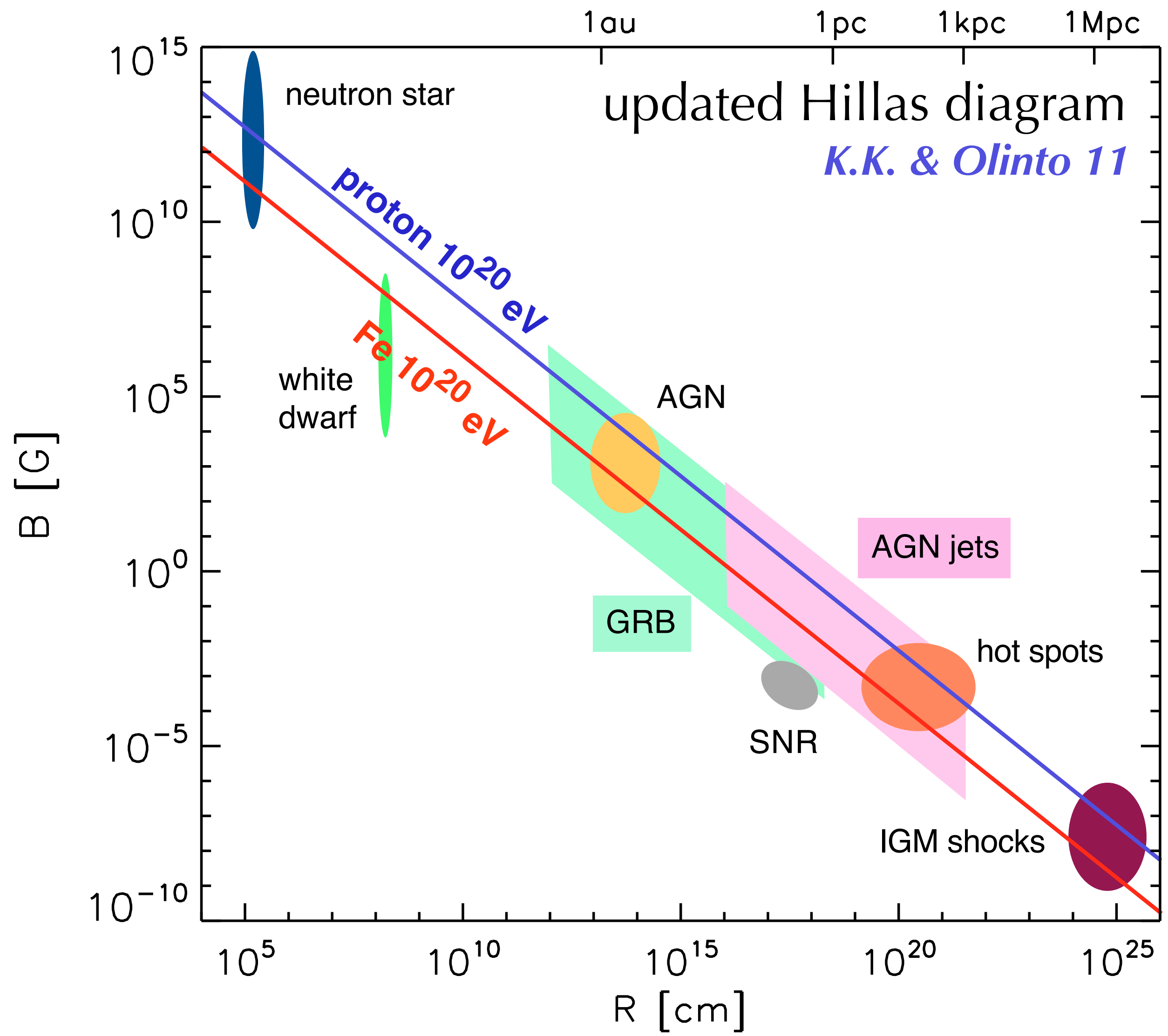


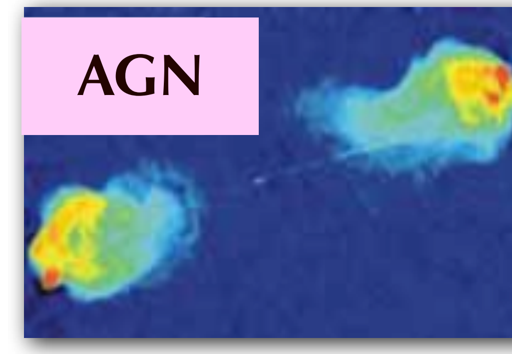
chemical composition



other messengers:
secondary gamma-rays,
neutrinos

EUHECR > 10^{20} eV: first selection of local sources





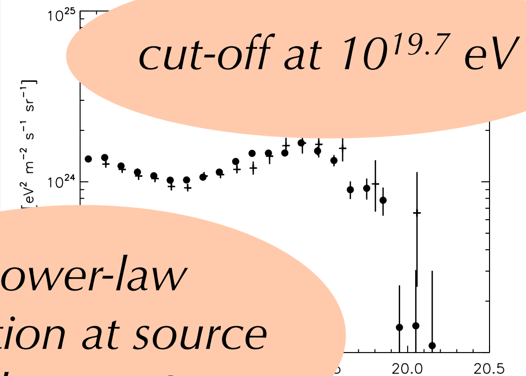
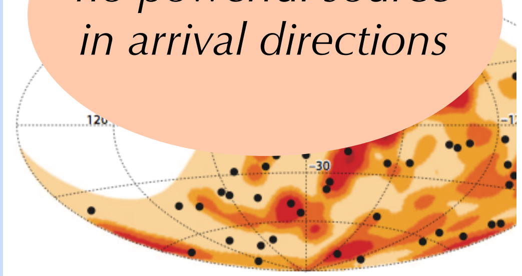
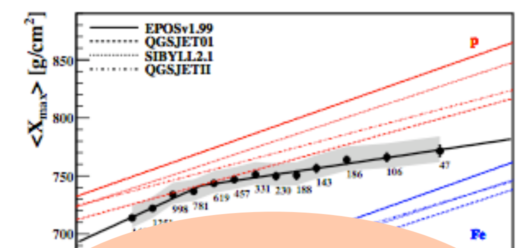
confinement of particle in source:
particle Larmor radius < size of source

$$r_{\rm L} \leq L$$

$$r_{\rm L} = 1.08 \ {\rm Mpc} \, Z^{-1} \left(\frac{E}{10^{18} \ {\rm eV}} \right) \left(\frac{B}{1 \ {\rm nG}} \right)^{-1}$$

! caution when applied to relativistic outflows

Confronting candidates to observables

Hillas diagram (confinement in source)	acceleration $E>10^{20}$ eV energy budget	shape of spectrum	arrival directions	composition heavy nuclei possible?
	$\mathcal{E}_{\rm UHECR}\dot{n}$ ~ 0.5×10^{44} erg Mpc^{-3} yr^{-1}	 cut-off at $10^{19.7}$ eV; power-law injection at source slope ~ -2	 no powerful source in arrival directions	 ?? light --> heavy transition ~10^{19} eV
 **AGN**	FRII: OK ✓? FRI: energetics tight for protons *e.g. Norman et al. 1995, Rachen & Biermann 1995, Henri et al. 1999, Lemoine & Waxman 2009*	✓	FRII: point sources expected ✓? FRI: OK if heavy nuclei	not metal rich, no efficient nucleosynthesis, photodisintegration ✗ *e.g., Lemoine 02, Pruet et al. 02, Wang et al. 08, Murase et al. 08*
 **GRB**	accelation ok, but tight energy budget because rare source ✓? *e.g. Waxman 1995, Vietri 1995, Murase 2008*	*e.g., K.K. & Olinto 2011* ✓	✓	**hope for GRBs:** *Horiuchi et al. 2012* ✓?
 **pulsars**	e.g., unipolar induction *Blasi et al. 2000, Arons 2003* ✓	✗✓ too hard! slope ~-1 but see *K.K. 2011* *Fang, K.K., Olinto 2012*	✓ *Fang, K.K., Olinto 2012*	metal rich, escape of nuclei from source OK ✓ *Fang, K.K., Olinto 2012*

Acceleration of UHECR in newly-born ms pulsars

Gunn & Ostriker 69,
Bednarek & Protheroe 97, 02,
Blasi et al. 00,
Giller & Lipski 02, Arons 03,
Bednarek & Bartosik 04,
Fang, KK, Olinto, in prep.

unipolar induction in the pulsar wind

strong magnetic field $\mathbf{B}$
fast rotation velocity $\boldsymbol{\Omega}$

$$\mathbf{E} = -\boldsymbol{\Omega} \times \mathbf{B}$$

particles accelerated to energy:

$$E(\Omega) \sim 8.6 \times 10^{20}\, Z_{26}\, \eta_1\, \Omega_4^2\, \mu_{31}\ \mathrm{eV}$$

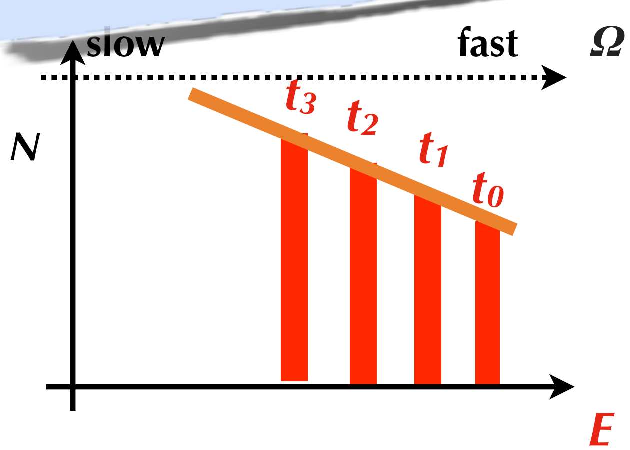
10% fraction of voltage experienced by particle
magnetic moment 10^{31} cgs ($B \sim 10^{13}$ G)
rotation velocity 10^4 s^{-1}

NB: toy model!

in reality: surf-riding acceleration in wind?
magnetic reconnections at termination shock?
--> stochastic processes?

pulsar spins down

energy spectrum for one pulsar:

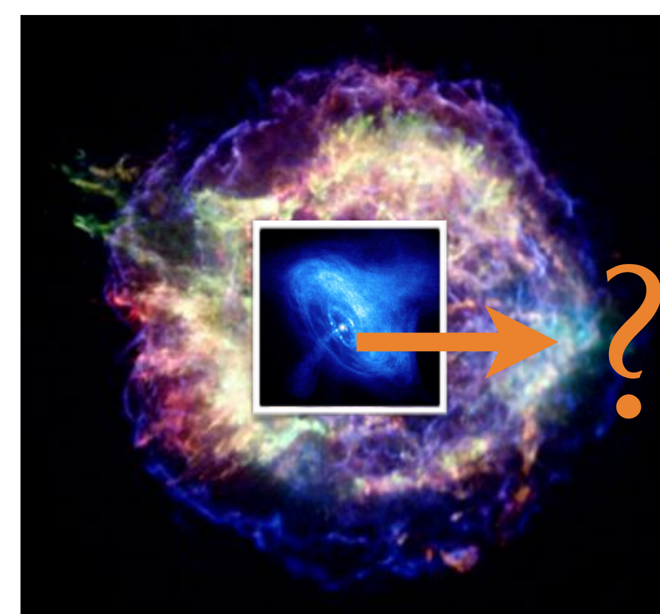


$$\frac{\mathrm{d}N_\mathrm{i}}{\mathrm{d}E} = \frac{9}{2}\frac{c^2 I}{ZeB_* R_*^3 E}\left(1 + \frac{E}{E_\mathrm{g}}\right)^{-1}$$

hard injection spectrum:
-1 slope

supernova envelope: do accelerated particles survive?

SN envelope = dense baryonic background
UHECR experience hadronic interactions

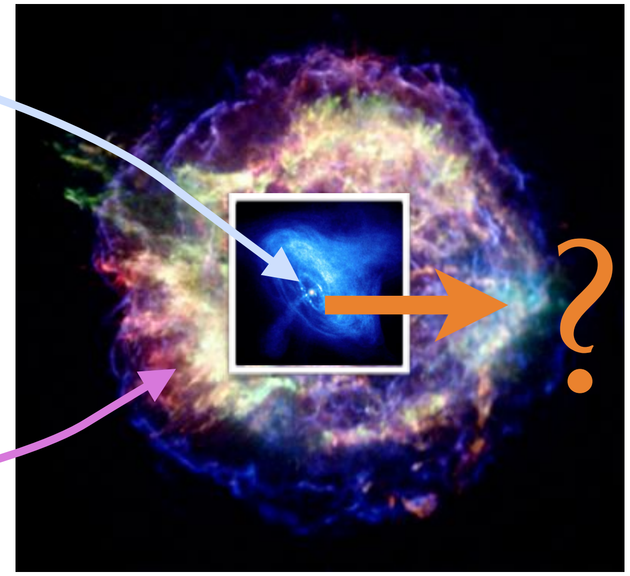


Parameter space for successful acceleration+escape

Fang, KK, Olinto 2012

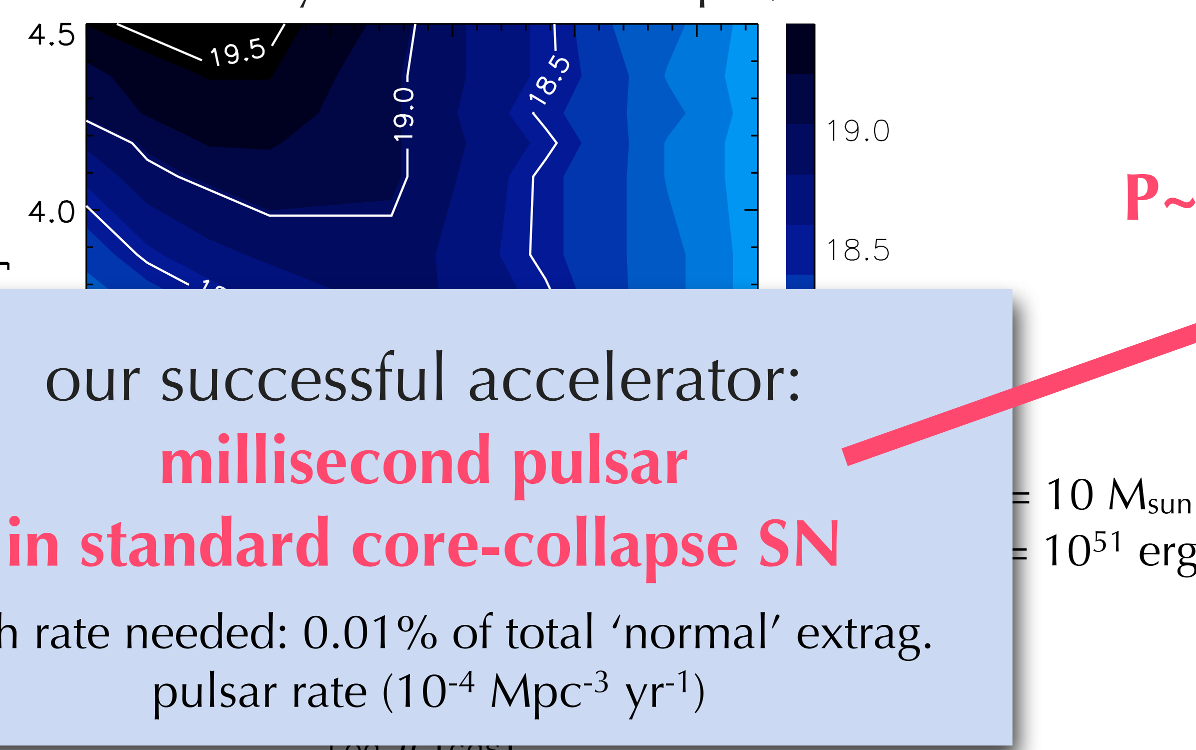
pulsar
magnetic moment μ,
rotation velocity Ω,
particle acceleration rate η

supernova
ejecta energy E_{ej},
ejected mass M_{ej},



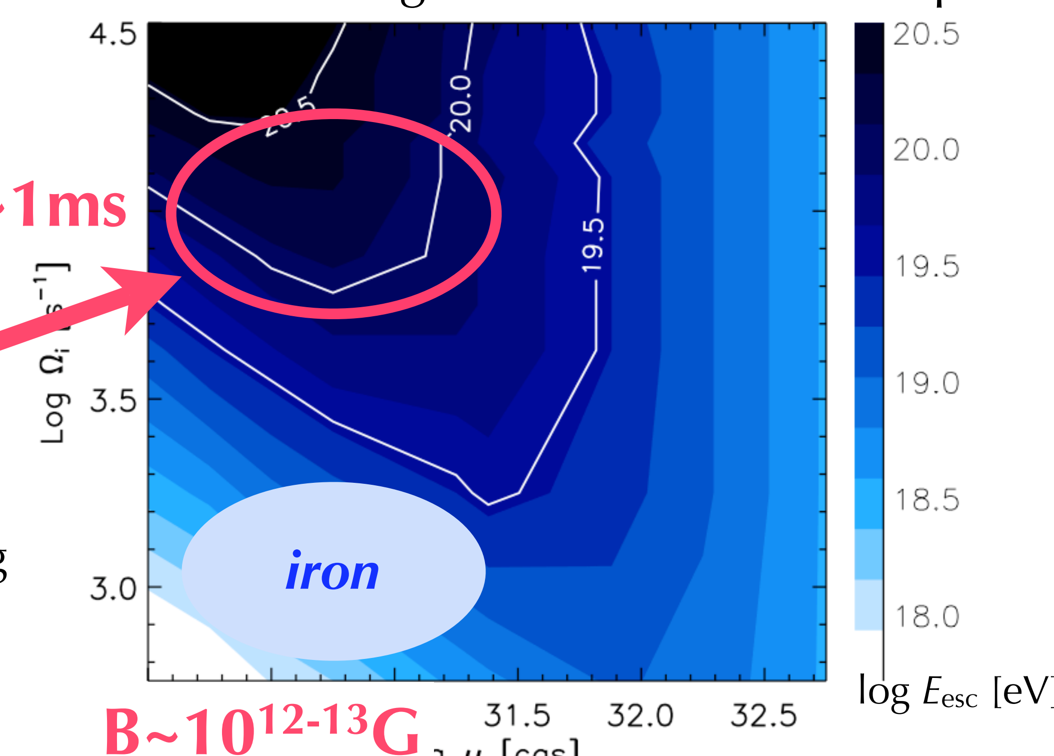
- Analytical estimates
- Monte-Carlo propagation, hadronic interactions with EPOS + CONEX

tight for protons
(would work for very dilute SN envelopes)



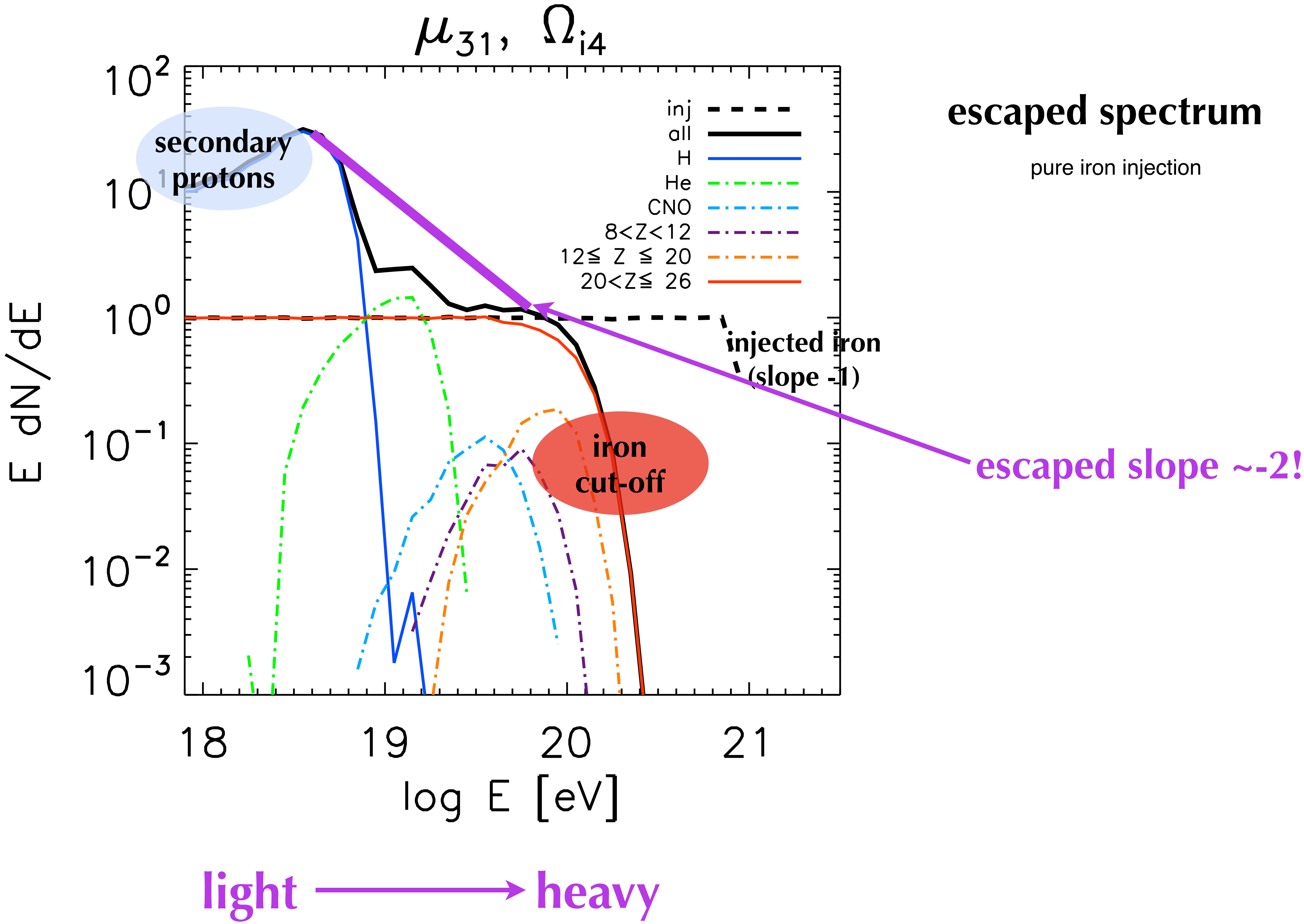
our successful accelerator:
millisecond pulsar
in standard core-collapse SN
birth rate needed: 0.01% of total 'normal' extrag. pulsar rate (10^{-4} Mpc^{-3} yr^{-1})

OK for iron:
accelerated to Z x higher E when SN envelope dilute



Collateral good news: spectrum, composition!

Fang, KK, Olinto 2012

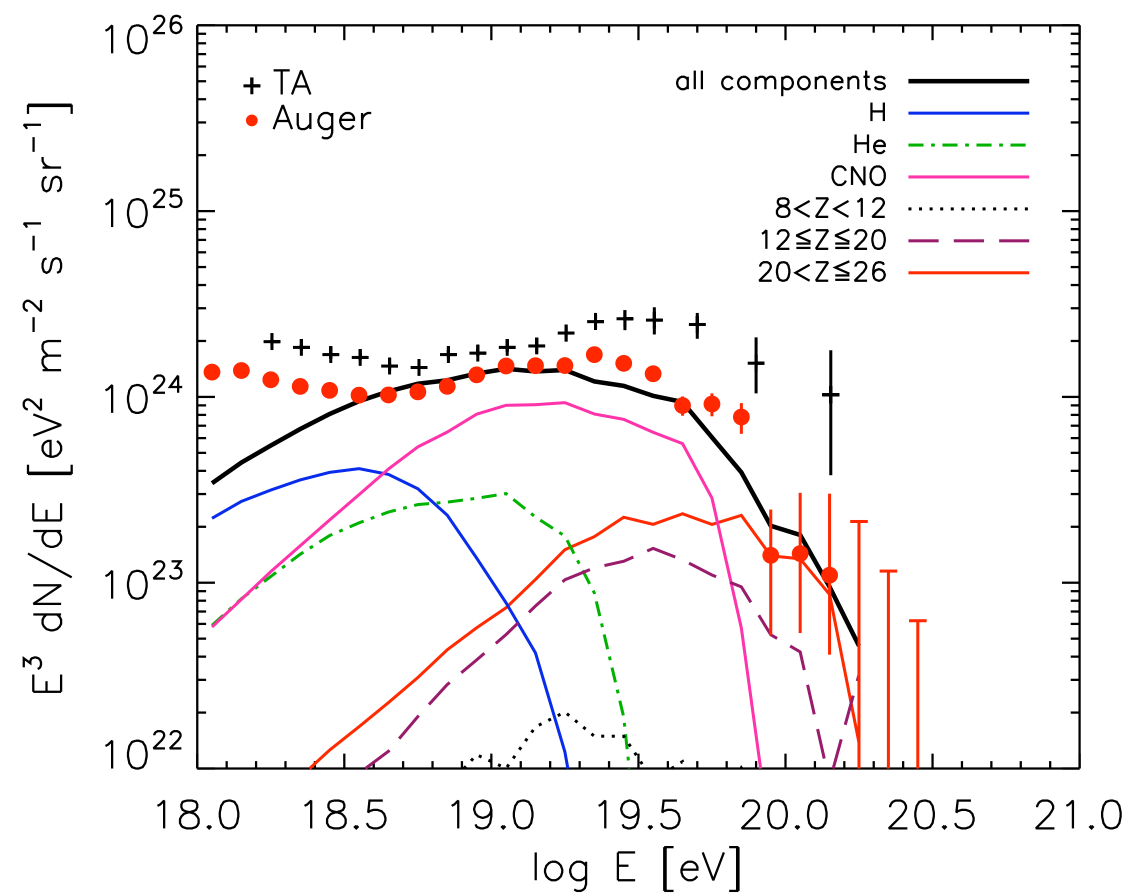


escaped spectrum

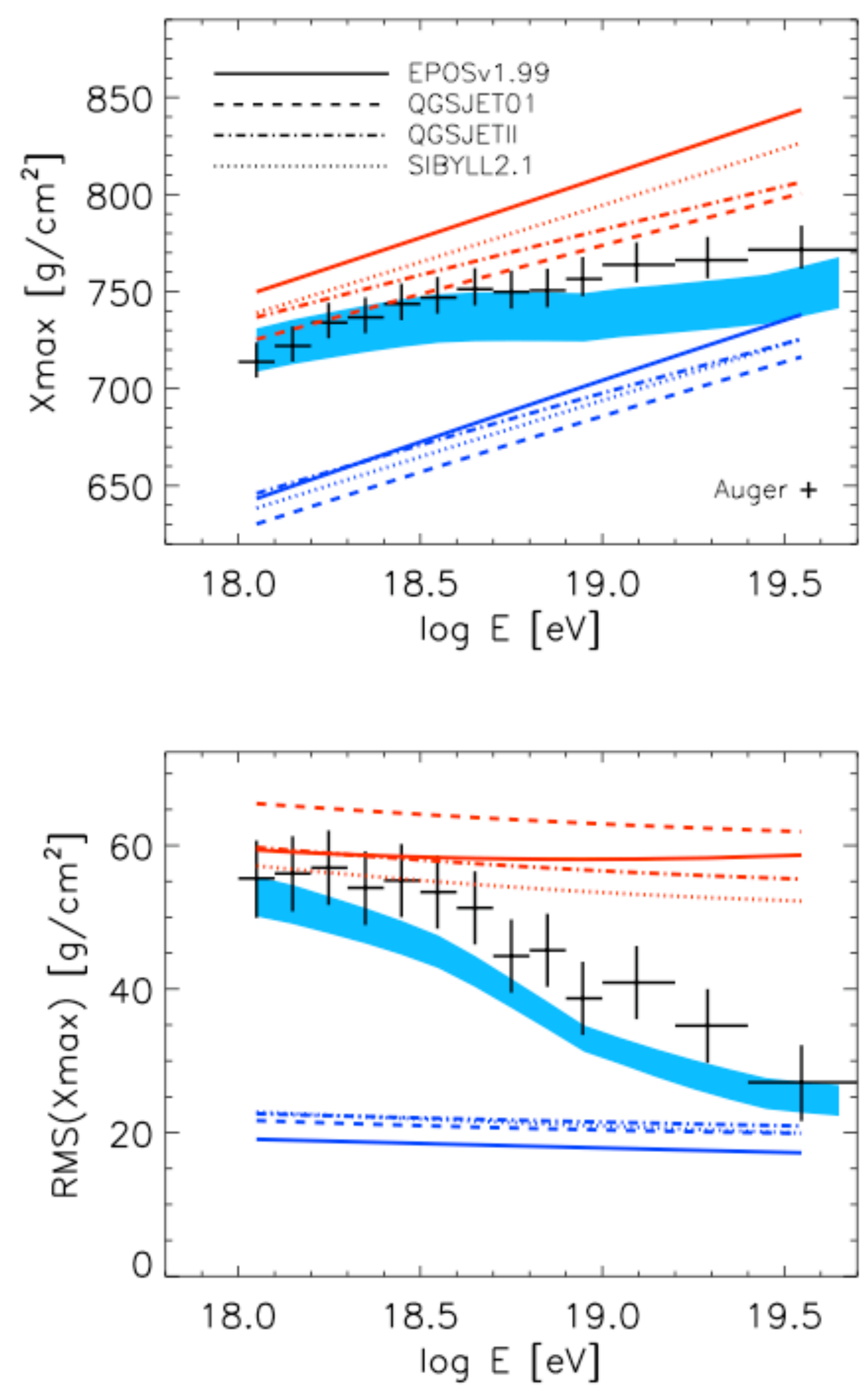
pure iron injection

A scenario that fits UHECR Auger data (rare)

Fang, KK, Olinto 2012
Fang, KK, Olinto, in prep.



spectrum



composition

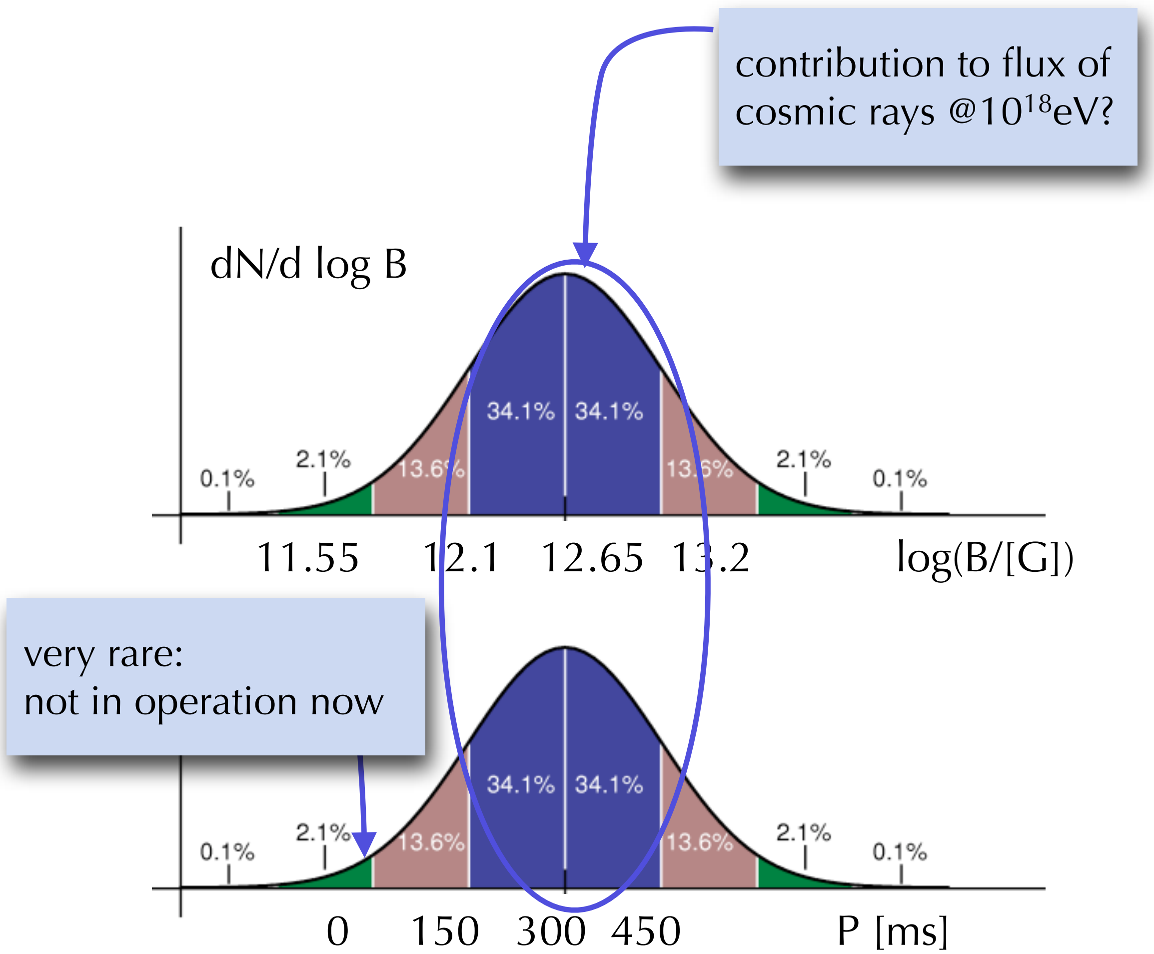
propagated from extragalactic pulsar population

35% Proton, 40% Helium, 22% CNO and 3% Fe

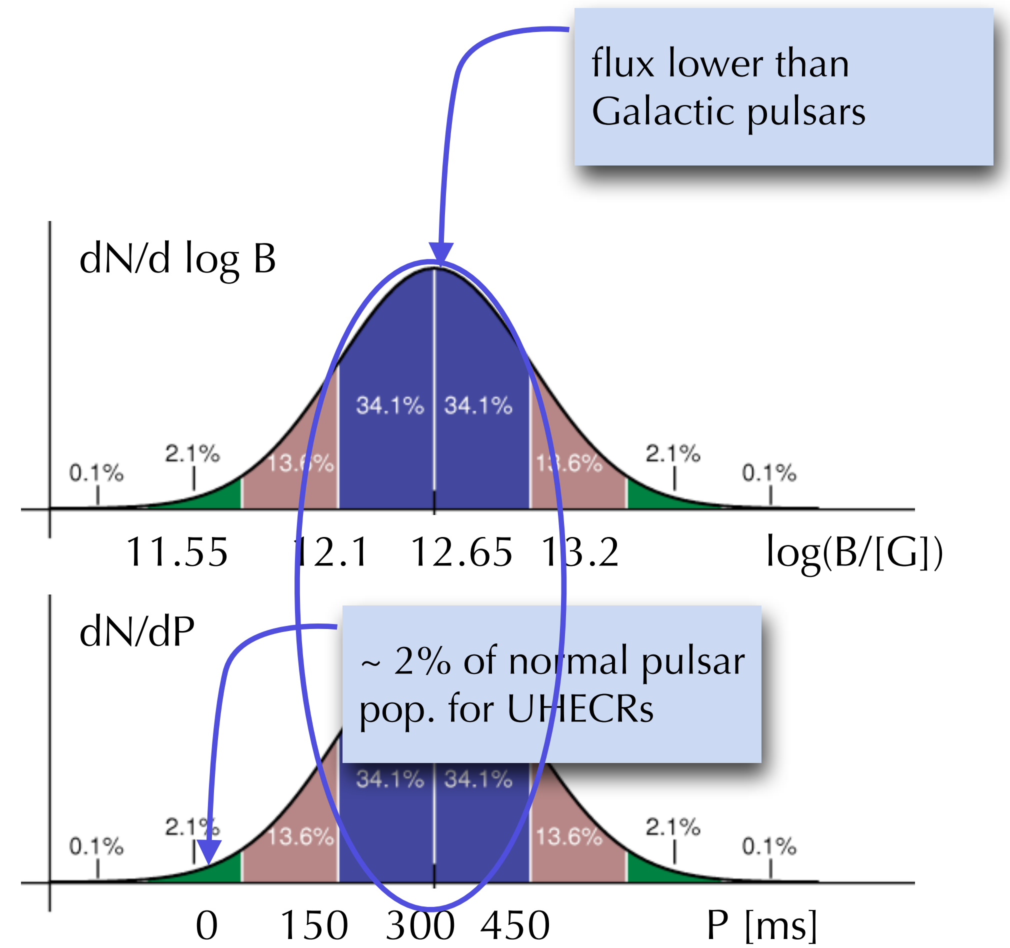
Contribution of all Galactic+extragactic pulsars?

Fang, KK, Olinto, in prep.

whole population of pulsars Galactic + extragalactic,
each distributed: *Faucher-Giguère & Kaspi 06*

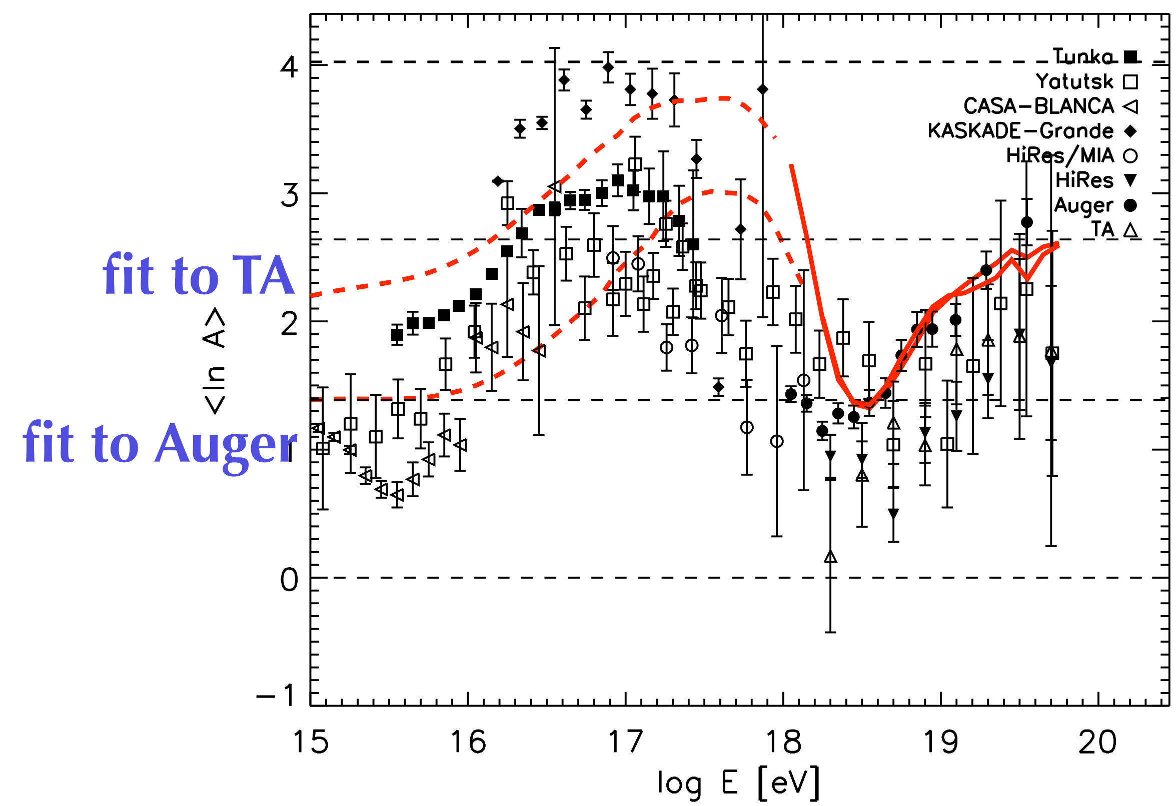


Galactic

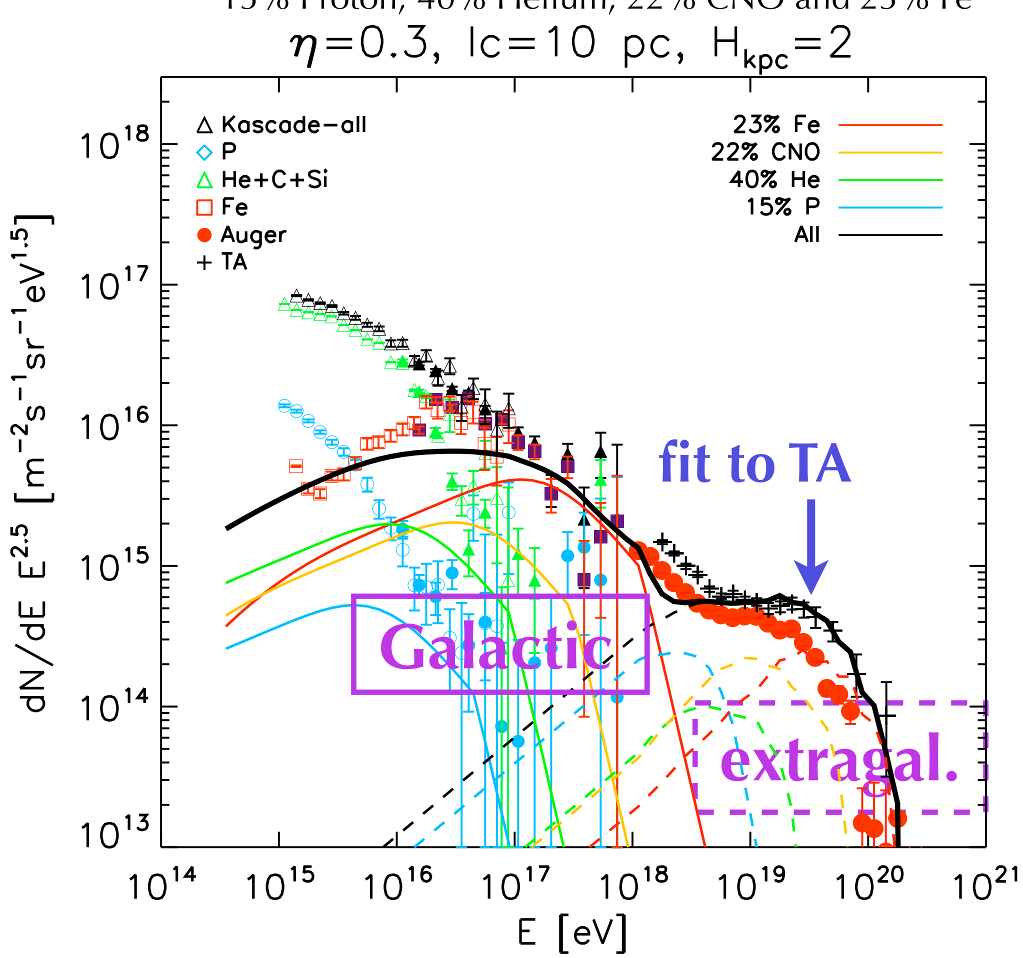


extragal.

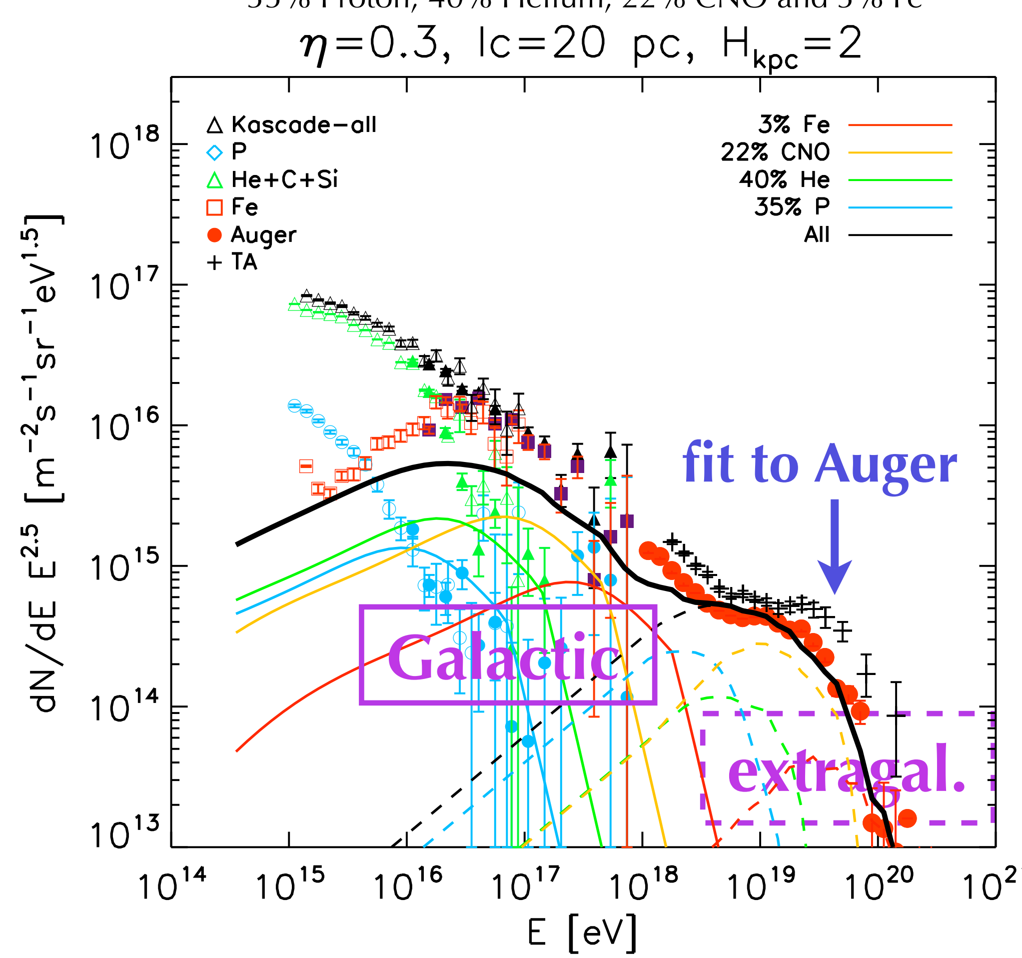
Contribution of all Galactic+extragactic pulsars?



15% Proton, 40% Helium, 22% CNO and 23% Fe



35% Proton, 40% Helium, 22% CNO and 3% Fe

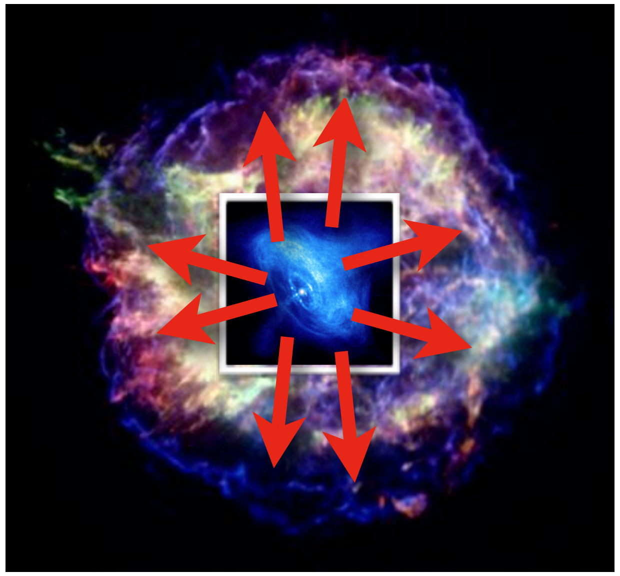


A signature in the supernova lightcurves

KK, Phinney, Olinto in prep.

M_{ej} = 5 M_{sun}
E_{SN} = 10^{51} erg
10% pulsar rotational energy into radiation

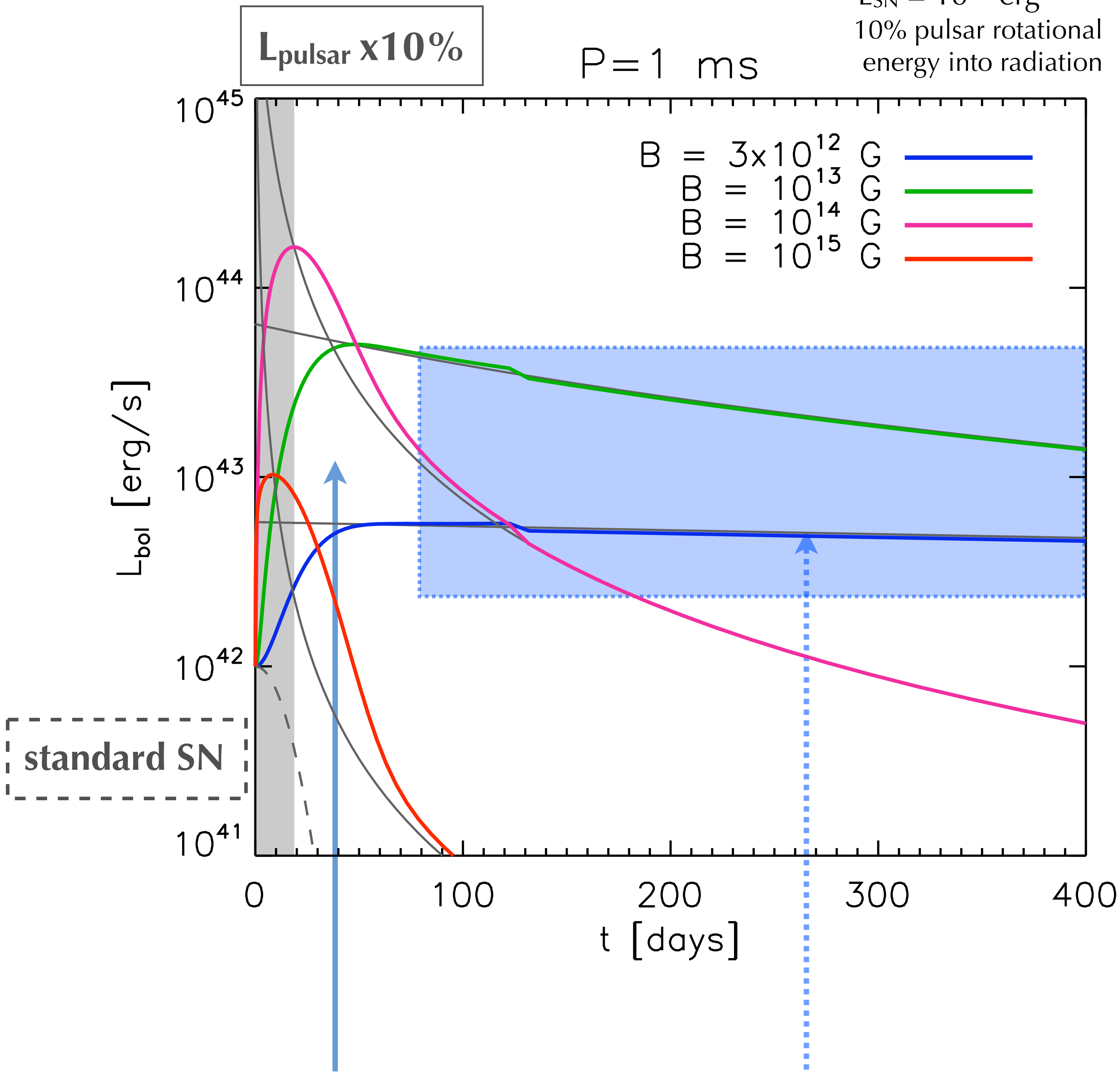
pulsar millisecond with B~10^{13}G



injection of LARGE pulsar rotational energy into SN ejecta E~10^{52} erg

↓

change radiation emission from SN

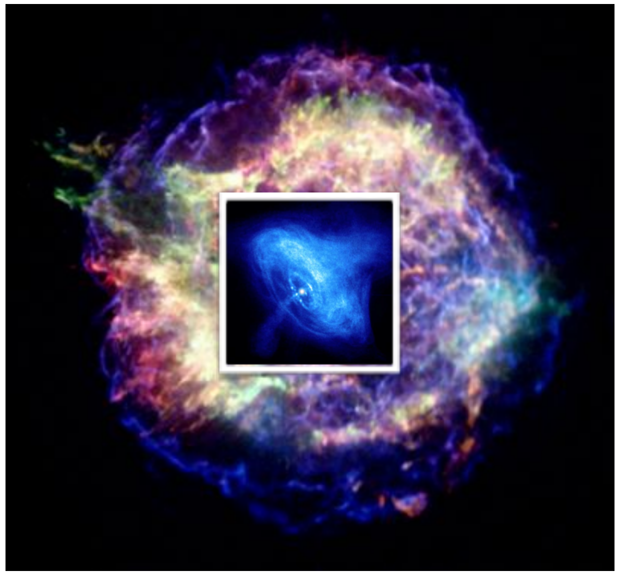


- possibly ultraluminous
- interesting lightcurve @ few years

high plateau (in bol.)

Peculiar supernova lightcurves

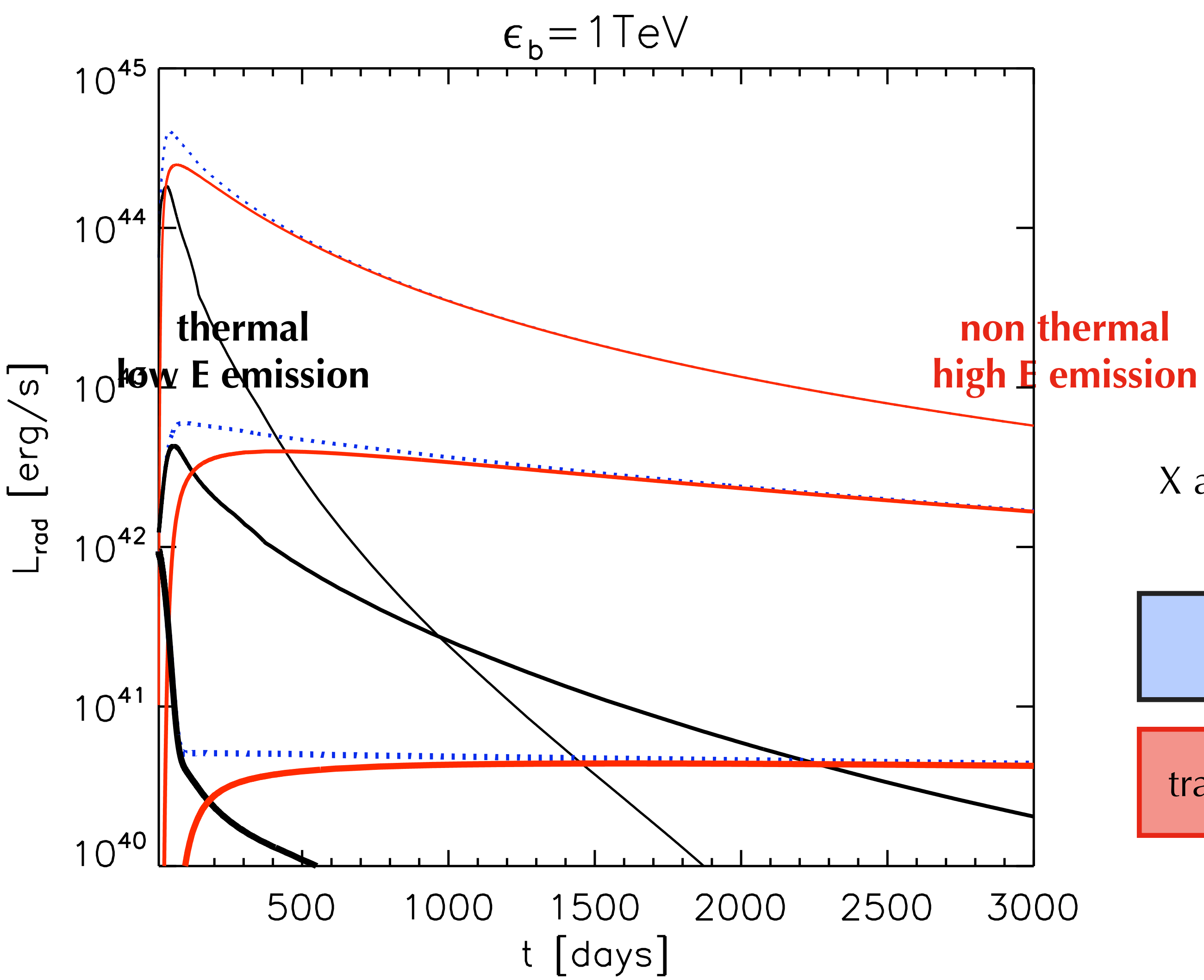
KK, Phinney, Olinto in prep.



$M_{ej} = 5\ M_{sun}$
$E_{SN} = 10^{51}$ erg

10% pulsar rotational energy into radiation

Follow up of SN lightcurves over **a few years** in **all wavelengths** will be crucial



X and gamma ray injection from pulsar wind nebula

SN ejecta opaque to X,gamma rays --> thermalization

transparent : X ray emission

Smoking gun of the millisecond pulsar scenario

Fang, KK, Olinto 2012
Fang, KK, Olinto, submitted
KK, Phinney, Olinto in prep.

energy spectrum at E>10^{20} eV

E_{cut} --> no recovery expected unlike in GZK cut-off

arrival directions

- no coincidence from source out of Local Group expected, as pulsars cannot be observed
- ms pulsar in core-collapse SN in our Local Group:

protons: a burst lasting $\delta t_{\rm Gal} \sim 0.1\, Z^2 \left(\frac{r}{2\,{\rm kpc}}\right)^2 \left(\frac{B_{\rm turb}}{4\,\mu{\rm G}}\right)^2 \left(\frac{\lambda_{\rm turb}}{50\,{\rm pc}}\right) \left(\frac{E}{E_{\rm GZK}}\right)^{-2}$ yr.
delayed of that time after onset of explosion.

iron: will appear as an increase of number of events for ~70 years
if sudden decrease of number of events happens, could be associated with birth of pulsar 70 yrs ago
but some anisotropy would then be apparent

secondaries

- neutrinos produced during escape possibly observable by IceCube
  (***Murase et al. 2009*** --> *high density chosen though*)
- diffuse gravitational wave signatures in some highly optimistic cases (***K.K. 2011***)

SN lightcurves!

look for signatures in SN light curves @ few years after explosion *KK, Phinney, Olinto in prep.*

Major point to investigate in the scenario: acceleration in pulsar wind
unipolar induction?? magnetic reconnection?