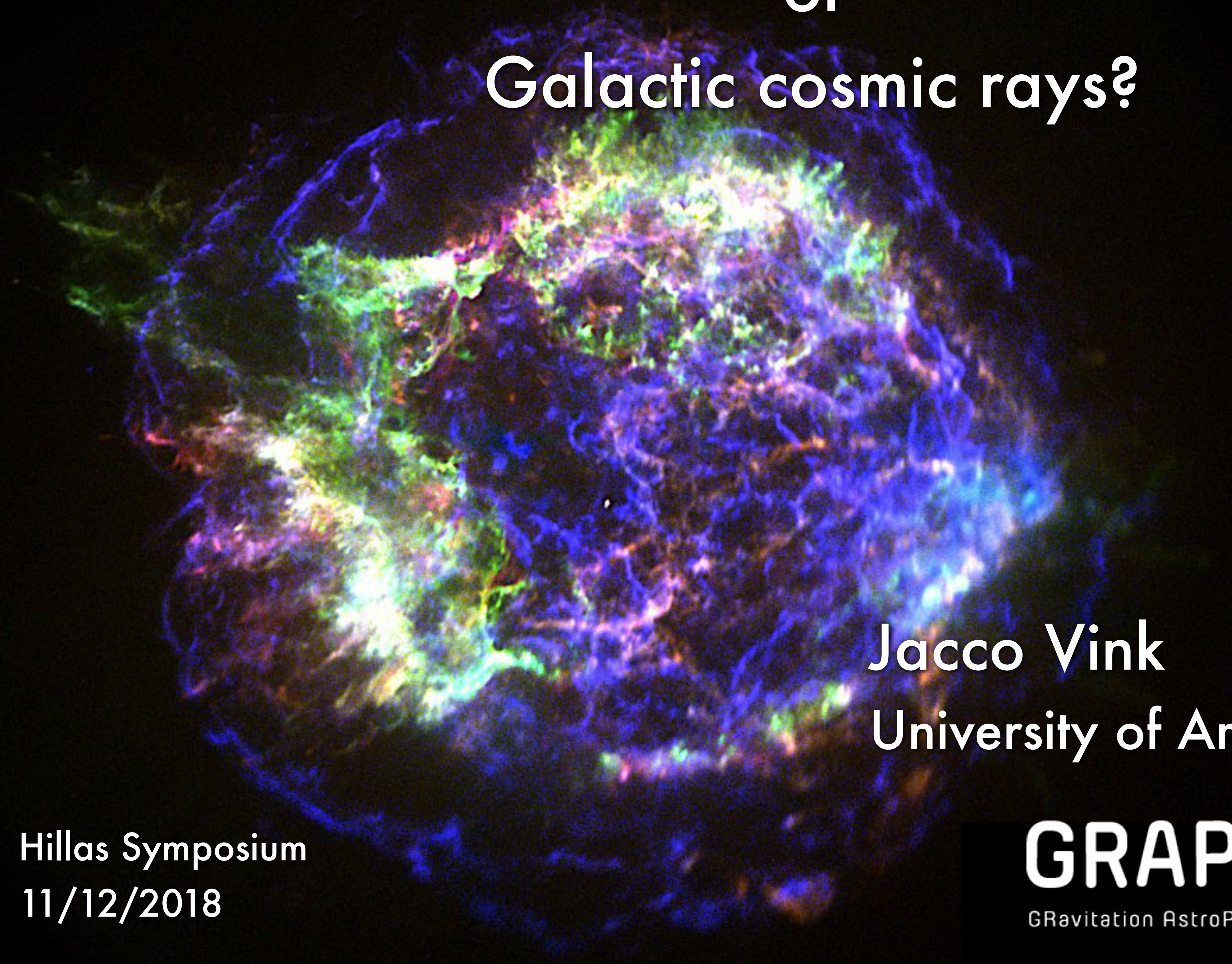
Are supernova remnants the dominant sources of Galactic cosmic rays?

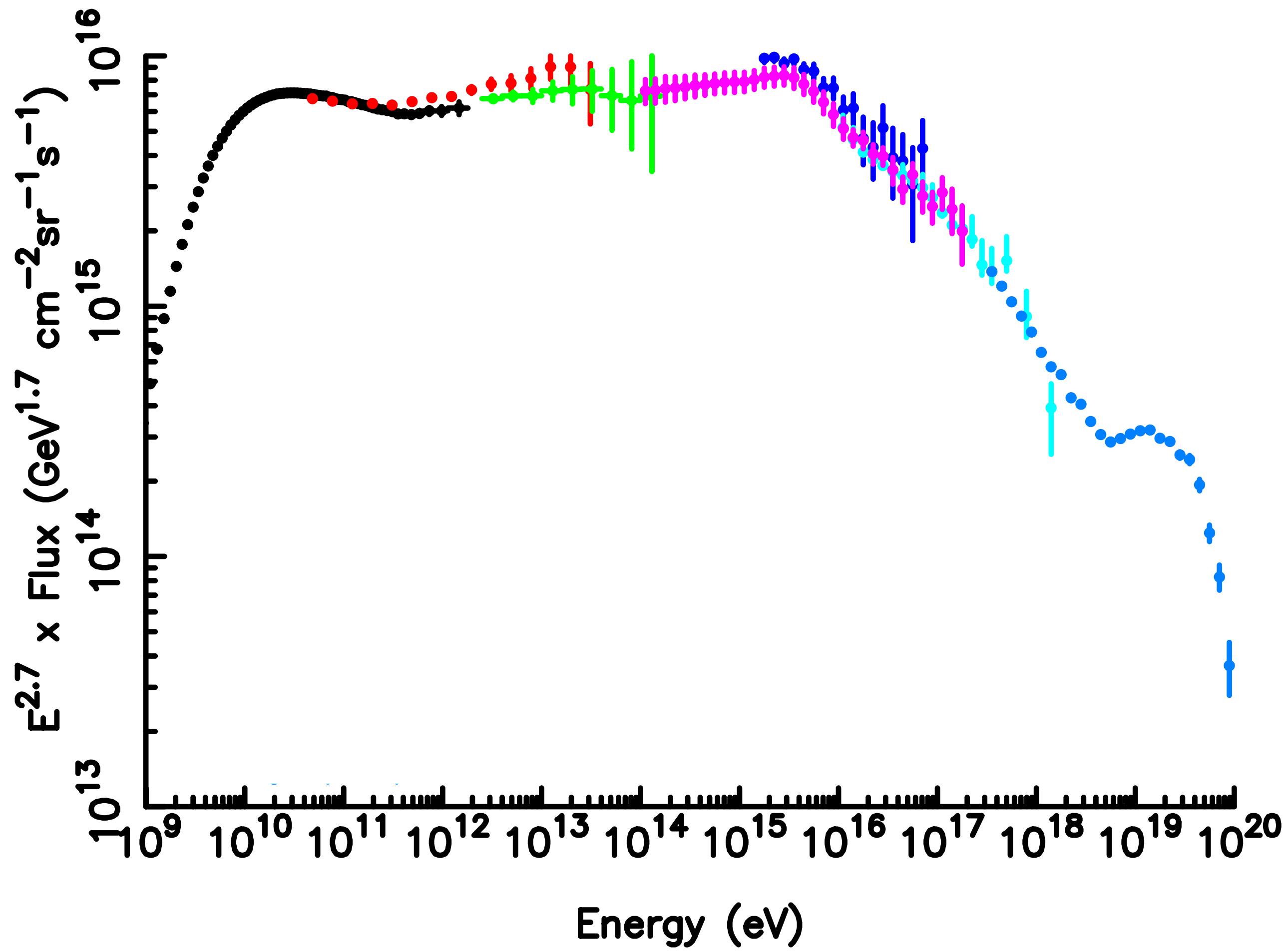


Jacco Vink
University of Amsterdam

Hillas Symposium
11/12/2018

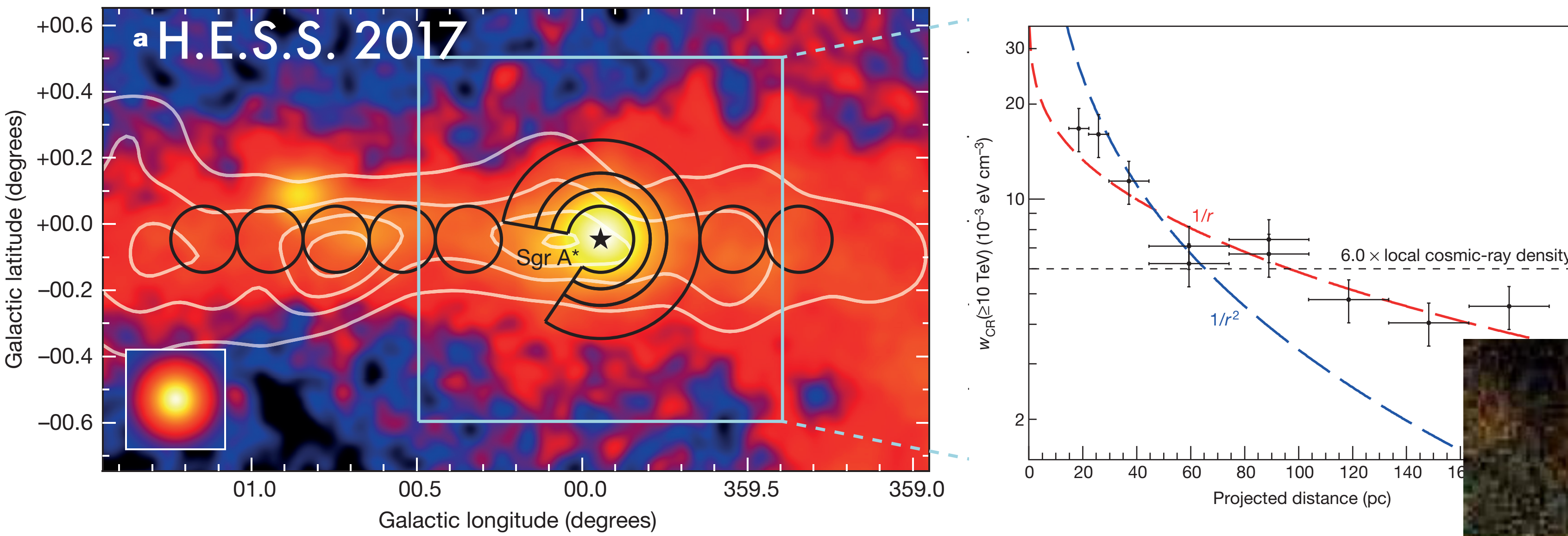
GRAPPA
GRavitation AstroParticle Physics Amsterdam

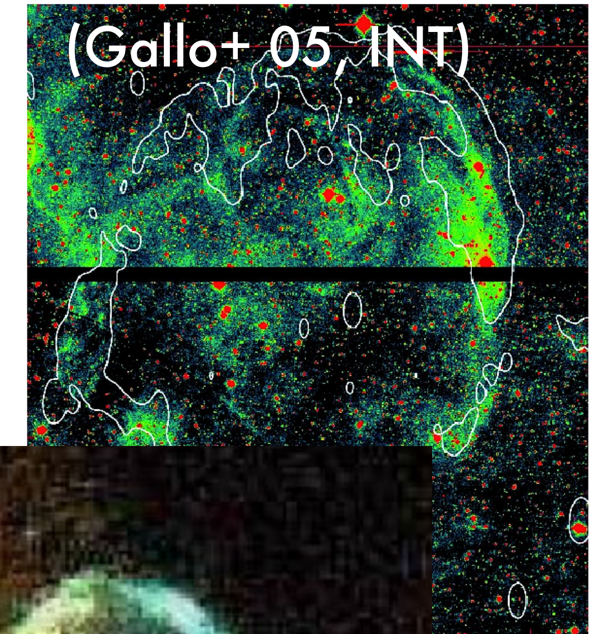
Cosmic-ray spectrum and energy density

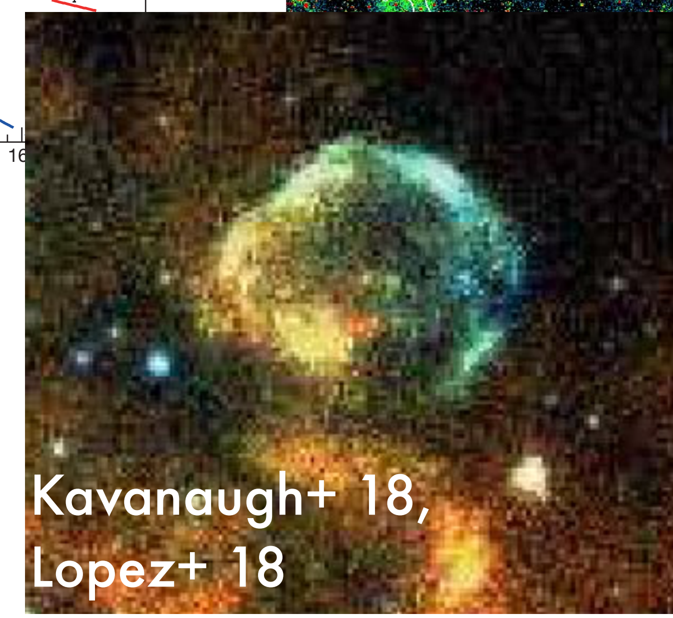


- Galactic CRs: 3×10^{15} eV (protons)
- Composition around "knee"
  - Change proton → Z>2
- Energy density (@ GeV):
  - 1 eV/cm^3
- Energy production (Ginzburg+ 1950s):
  - Q=Energy density x Volume/τ_{esc}
  - Volume =$\pi R^2 2H$
  - From radio-active elements in cosmic rays @ GeV: $\tau_{esc} \approx 1.5\times10^7$ yr
  - $\Rightarrow Q_{cr} \approx 10^{41}$ erg/s
  - SNe: 2-3/century, 10^{51}erg/SN $\Rightarrow Q_{sn} \approx 10^{42}$erg/s
  - ⇒10% CR acceleration efficiency needed ⇒ *SNe can do it*

What are the other potential sources?







Source type	Primary energy source (erg)	Frequency (yr^{-1})	Total Galactic Power (erg s^{-1})
supernova remnants	10^{51}	$\approx 1/30$	$\approx 10^{42}$
pulsars	$E_{rot} = 5 \times 10^{48} (P/100\ \mathrm{ms})^{-2}$ erg	$< 1/30$	$\lesssim 2 \times 10^{40}$
stellar winds	$\approx 2 \times 10^{49}$	$< 1/30$	$\lesssim 5 \times 10^{40}$
superbubbles	10^{51}	$< 1/30$	$\lesssim 10^{42}$
Novae	$\approx 10^{46}$	≈ 50	$\approx 2 \times 0^{40}$
X-ray binaries/micro-quasars	$< 10^{49}$	$50 - 200$ sources	$\lesssim 2 \times 0^{40}$
Central Black Hole		?	$10^{36} - 10^{40}$?

Supernovae and the origin of cosmic rays

Walther Baade (1893 - 1960)

Frits Zwicky (1898-1974)

In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons
can be packed much more closely tha
"gravitational packing" energy in a
large, and, under certain circumstan
nuclear packing fractions. A neutron
most stable configuration of matter
hypothesis will be developed in anothe
some observations that tend to suppor
mainly of neutrons.

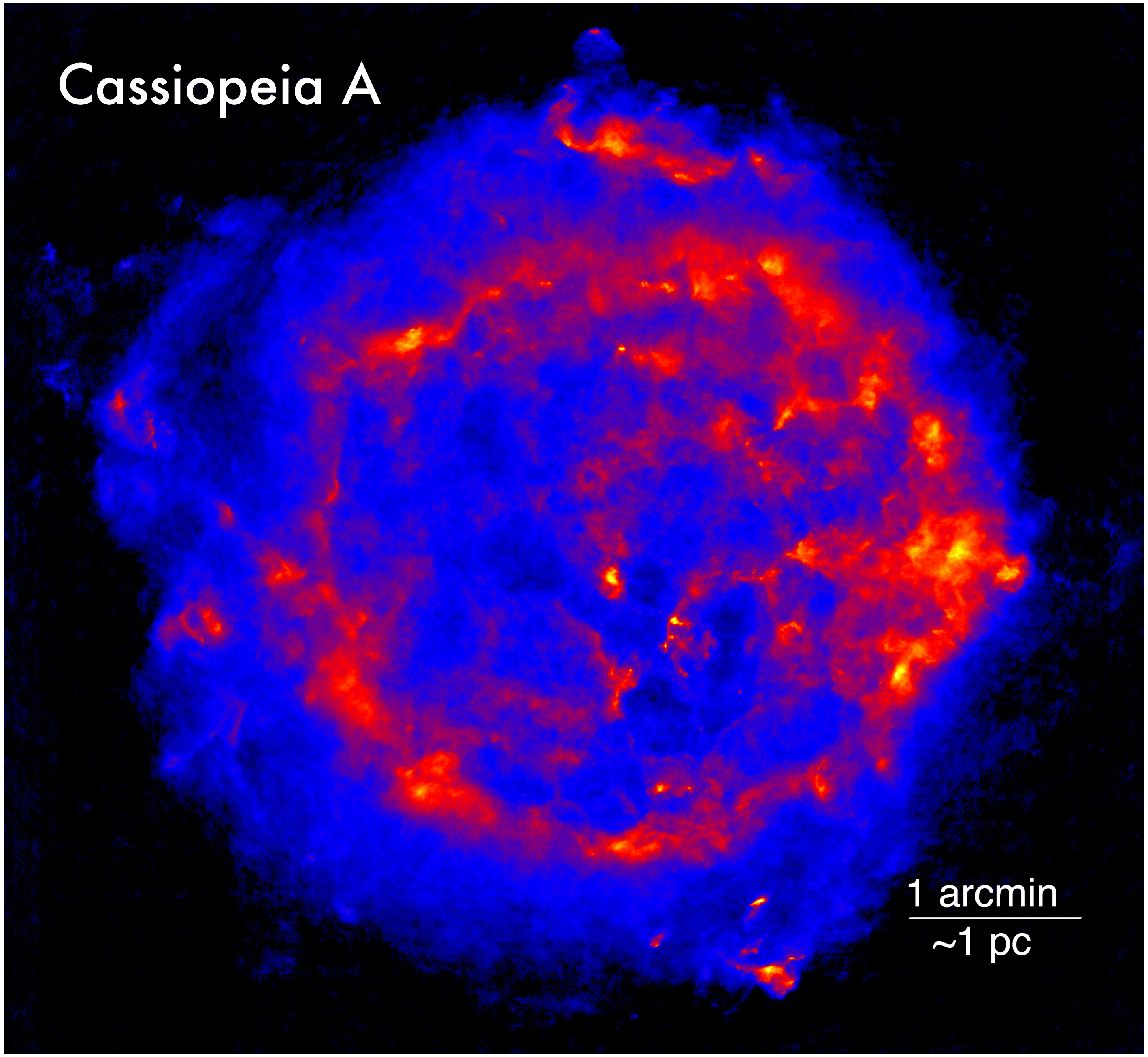
COSMIC RAYS FROM SUPER-NOVAE

BY W. BAADE AND F. ZWICKY

MOUNT WILSON OBSERVATORY, CARNEGIE INSTITUTION OF WASHINGTON AND CALIFORNIA INSTITUTE OF TECHNOLOGY, PASADENA

Communicated March 19, 1934

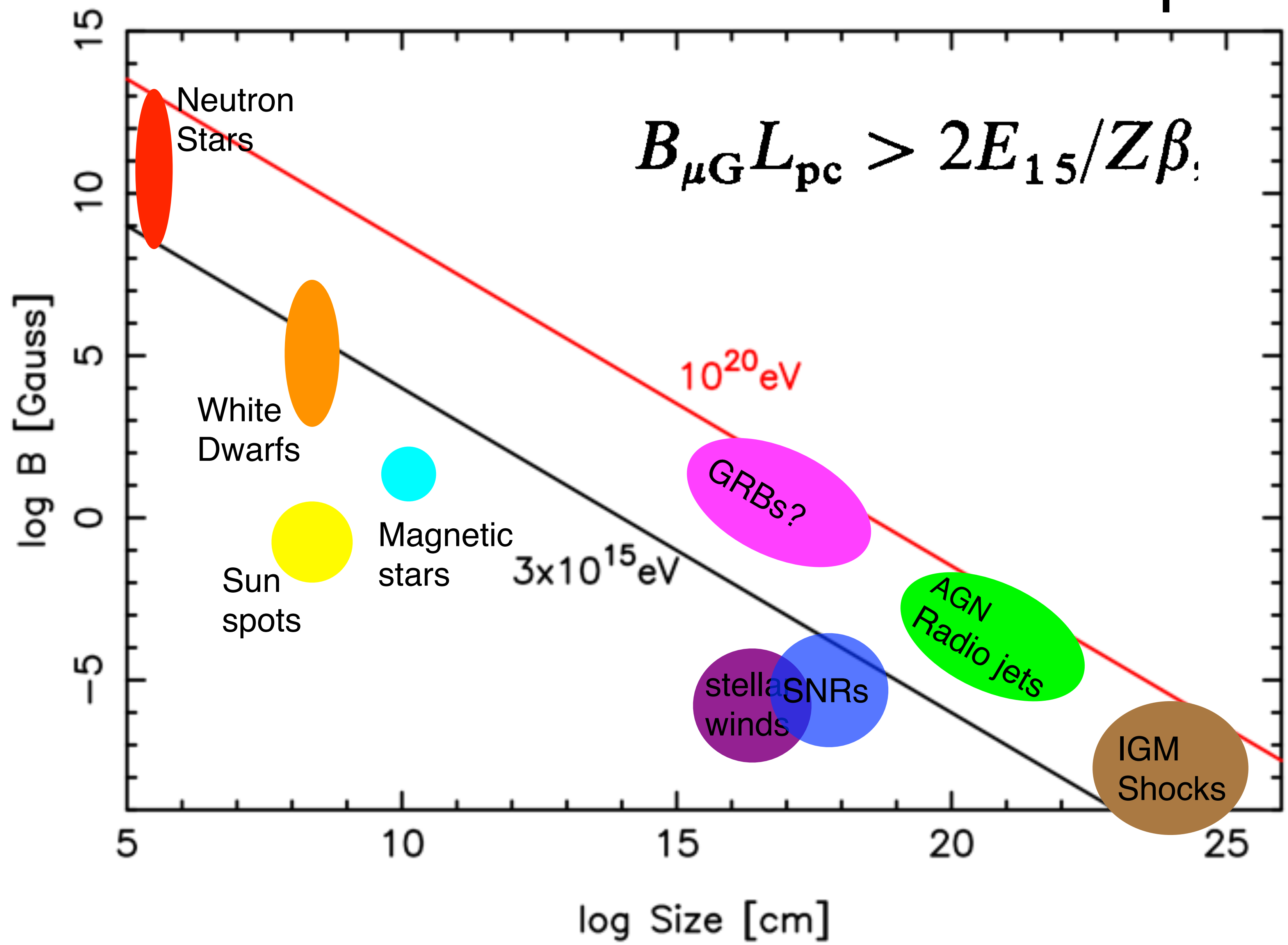
From supernovae to supernova remnants



- 1950s: SNRs discovered as synchrotron radio sources (Skhlovsky)
  - Particles (electrons) are accelerated to relativistic energies
- The “supernova paradigm” shifts (slowly) to the “supernova remnant paradigm”

Efficiency is one thing, but what about maximum energy?

The Hillas plot!



- Acceleration to higher energies: larger magnetic fields (or bigger size needed)
- SNRs: B≈10 μG (?), L≈5 pc ⇒ E_{15}≈0.25

⇒ SNRs cannot so easily do it!!

SNRs cannot so easily accelerate to the knee!

1983:
Thus supernova shock acceleration cannot account for the observed spectrum of galactic cosmic rays in the whole energy range 10^9-10^{13} eV/n.

Assumptions: Galactic magnetic fields of 5μG
Upper limit: high turbulence

Michael Hillas 2005

TOPICAL REVIEW

Can diffusive shock acceleration in supernova remnants account for high-energy galactic cosmic rays?

A M Hillas

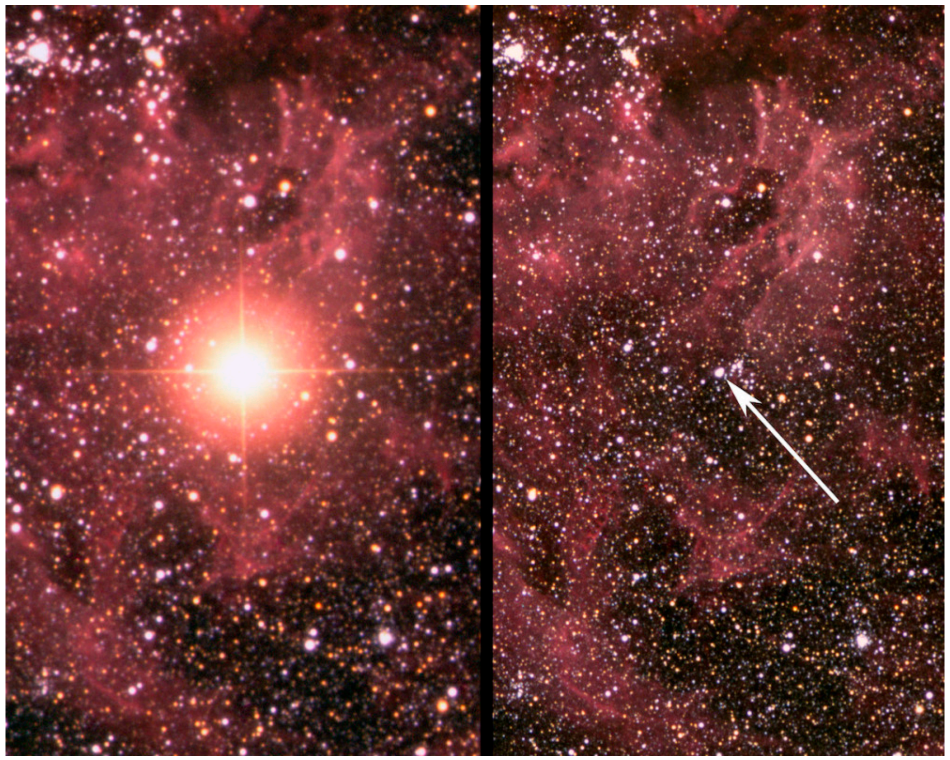
Published 1 April 2005 • 2005 IOP Publishing Ltd
Journal of Physics G: Nuclear and Particle Physics, Volume 31, Number 5

+ Article information

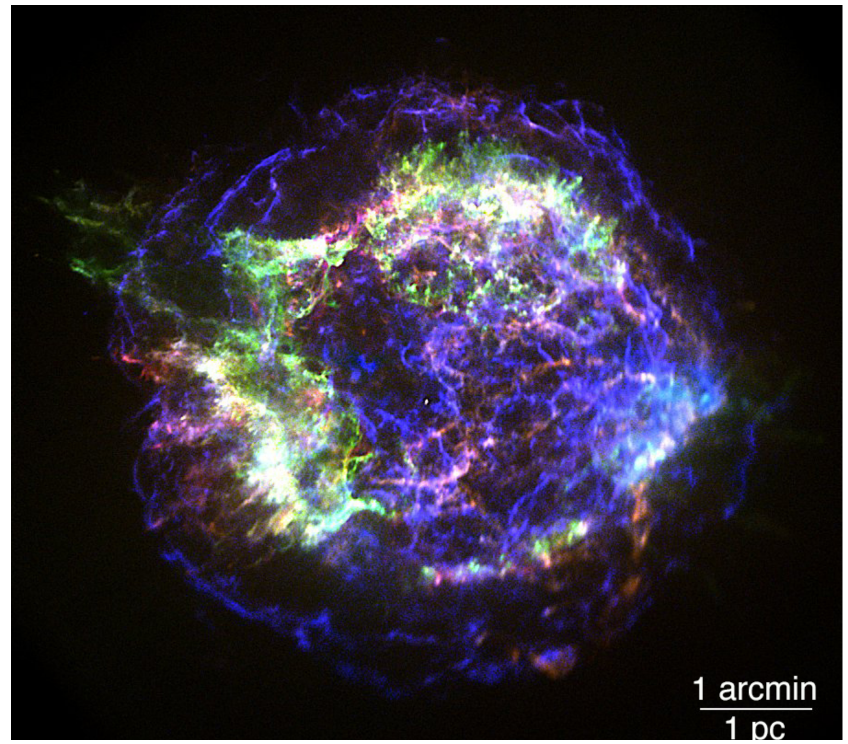
Abstract

Diffusive shock acceleration at the outer front of expanding supernova remnants has provided by far the most popular model for the origin of galactic cosmic rays, and has been the subject of intensive theoretical investigation. But several problems loomed at high energies—how to explain the smooth continuation of the cosmic-ray spectrum far beyond 10^{14} eV, the very low level of TeV gamma-ray emission from several supernova remnants, and the very low anisotropy of cosmic rays (seeming to conflict with the short trapping times needed to convert a E^{-2} source spectrum into the observed $E^{-2.7}$ spectrum of cosmic rays). However, recent work on the cosmic ray spectrum (especially at KASCADE) strongly indicates that about half of the flux does turn down rather sharply near 3×10^{15} V rigidity, with a distinct tail extending to just beyond 10^{17} V rigidity; whilst a plausible description (Bell and Lucek) of the level of self-generated magnetic fields at the shock fronts of young supernova remnants implies that many SNRs in varying environments might very well generate spectra extending smoothly to just this 'knee' position, and a portion of the exploding red supergiants could extend the spectrum approximately as needed. At low energies, recent progress in relating cosmic ray compositional details to modified shock structure also adds weight to the belief that the model is working on the right lines, converting energy into cosmic rays very efficiently where injection can occur. The low level of TeV gamma-ray flux from many young SNRs is a serious challenge, though it may relate to variations in particle injection efficiency with time. The clear detection of TeV gamma rays from SNRs has now just begun, and predictions of a characteristic curved particle spectrum give a target for new tests by TeV observations. However, the isotropy seriously challenges the assumed cosmic-ray trapping time and hence the shape of the spectrum of particles released from SNRs. There is otherwise enough convergence of model and observation to encourage belief that the outline of the model is right, but there remains the possibility that the spectral shape of particles actually released is not as previously predicted.

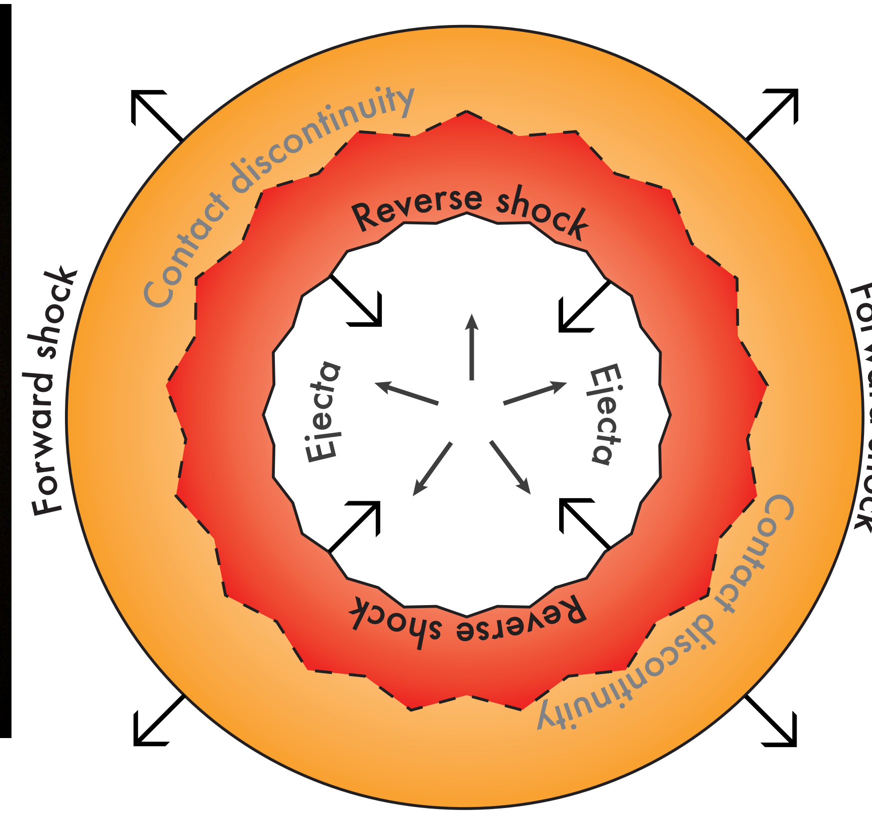
Supernova remants (as a/in a nut) shell!



t=0

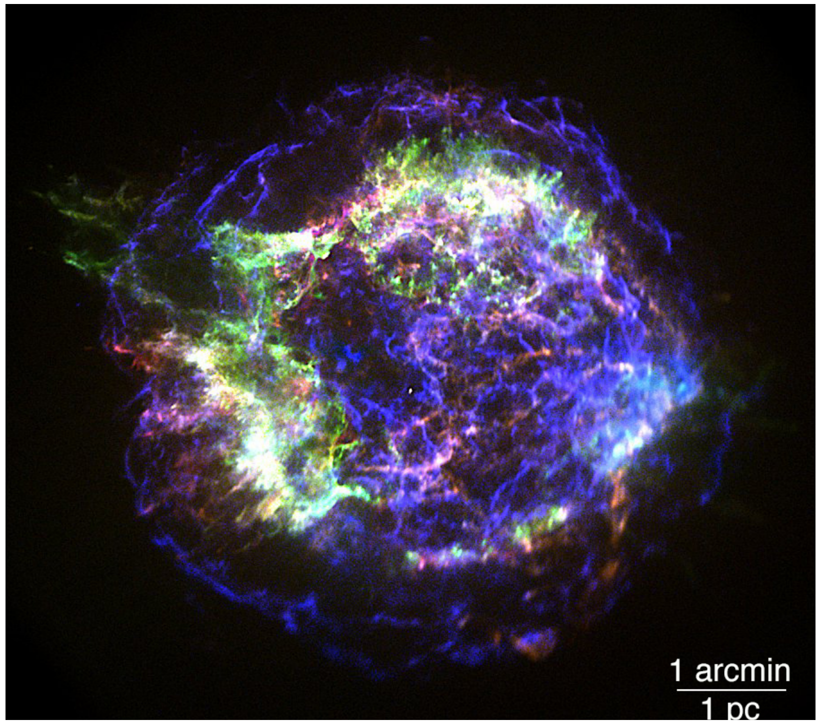


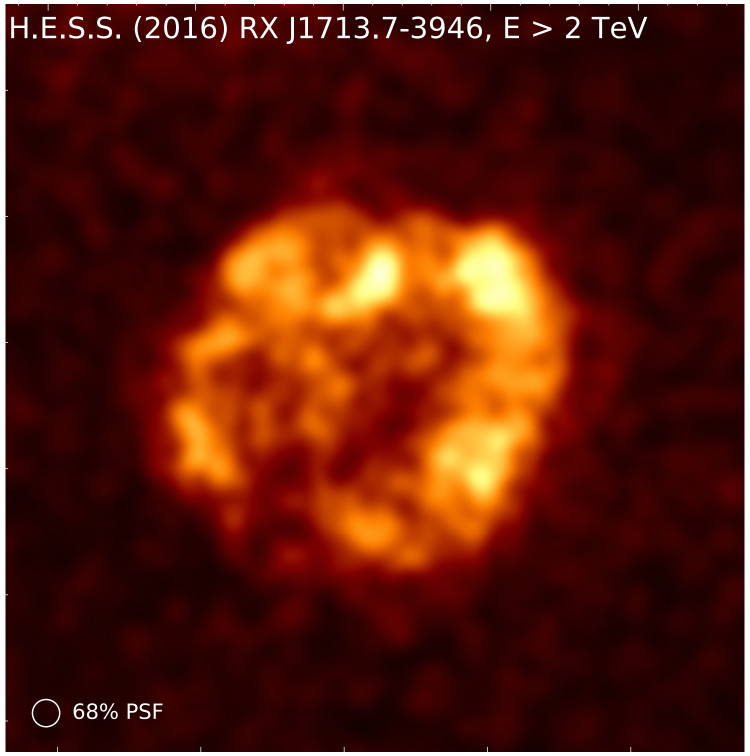
t=340 yr



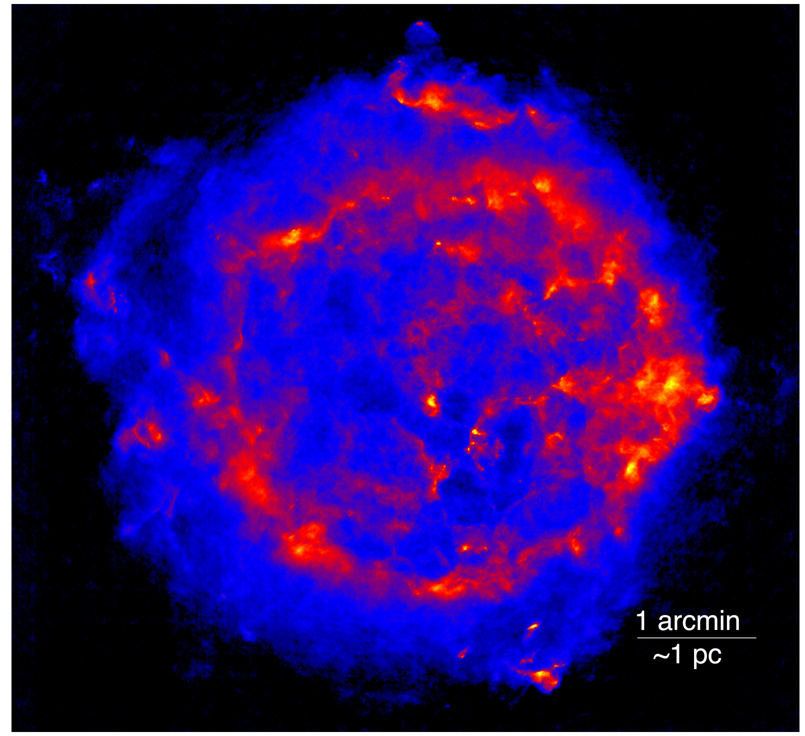
- A supernova explosion generates 10^{51} erg of explosion energy (10^{53} erg in neutrinos)
- Energy contained in fast “cold” ejecta, colliding with circumstellar/interstellar matter
- A forward shock develops and a reverse shock into supernova material
    - A supernova remnant shell forms
    - Unshocked ejecta inside
- Shock velocity starts at 20,000 km/s, after few 100 yr it is ~5000 km/s
- Shock velocity <200 km/s: soft X-ray/UV line emission ⇒ radiative losses
- Supernova remnant dissappears when $v_{sh} \lesssim 30$ km/s (2×10^4 - 10^5 yr?)

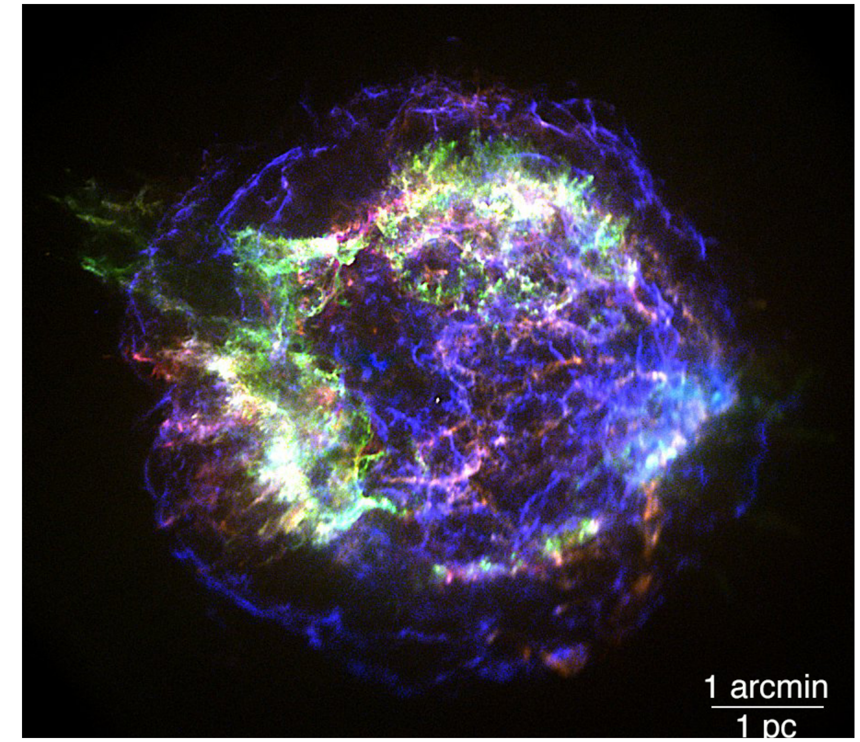
The remainder of this talk:
Something old, something new, something borrowed,...





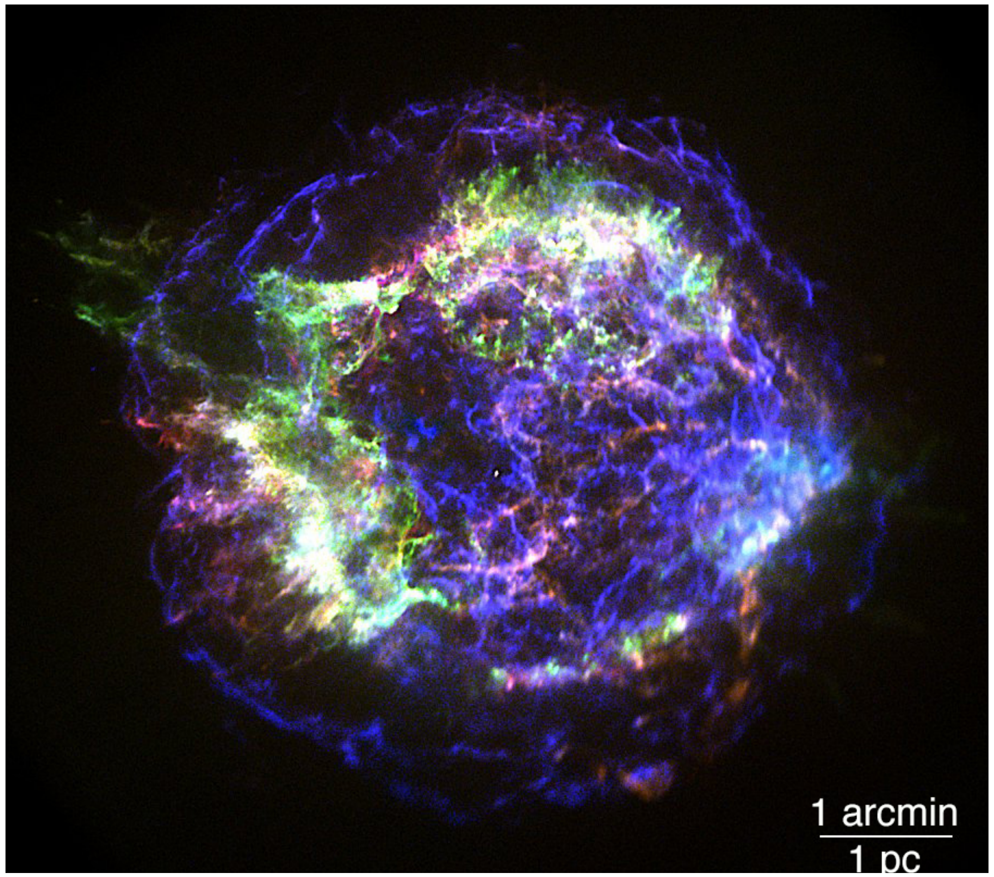
Cassiopeia A



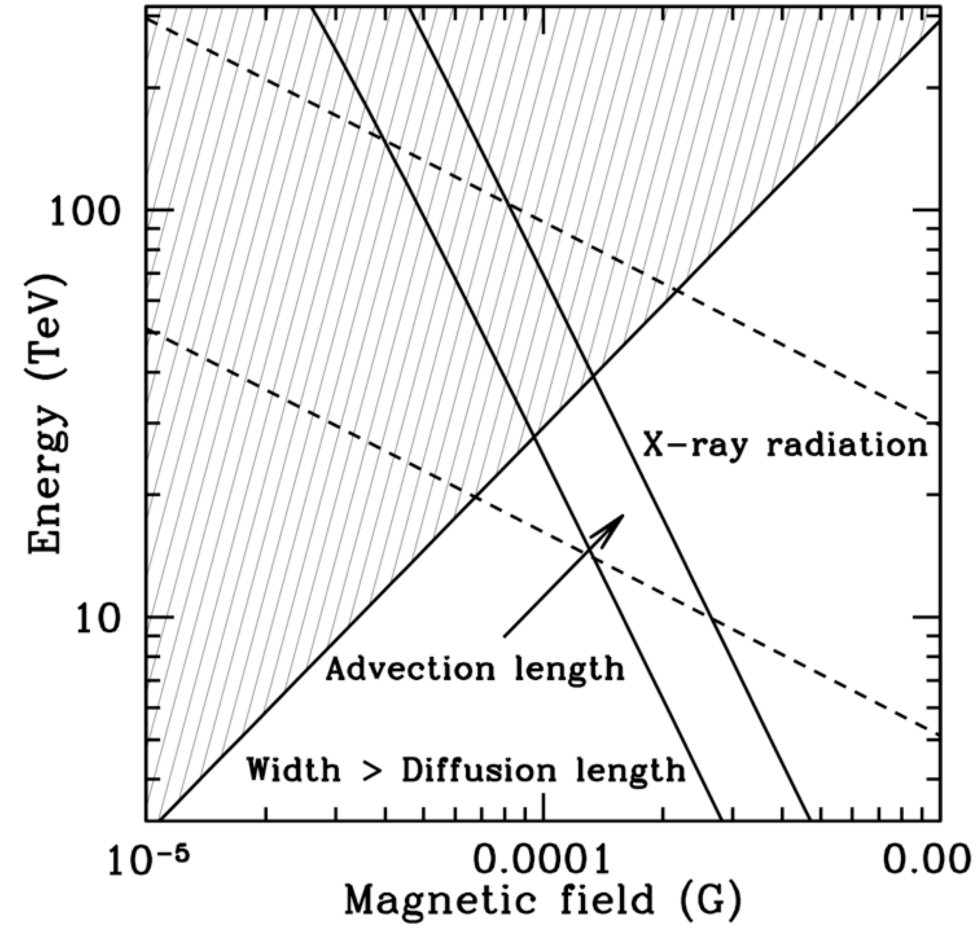


- 340 yr old, r=2.6 pc
- Light echo: SN IIb similor to SN 1993J
- Evolving in dense He/N-rich material: RSG wind?
- Brightest radio source: 2300 Jy @ 1 GHz: electron- rich/high B-field?
- V_{sh}=5000 km/s
- Exp. Par m=0.66

X-ray synchrotron emission



Vink&Laming '03



- Implies highly turbulent B-field:
  η=1: Bohm diffusion (Aharonian&Atoyan 99)

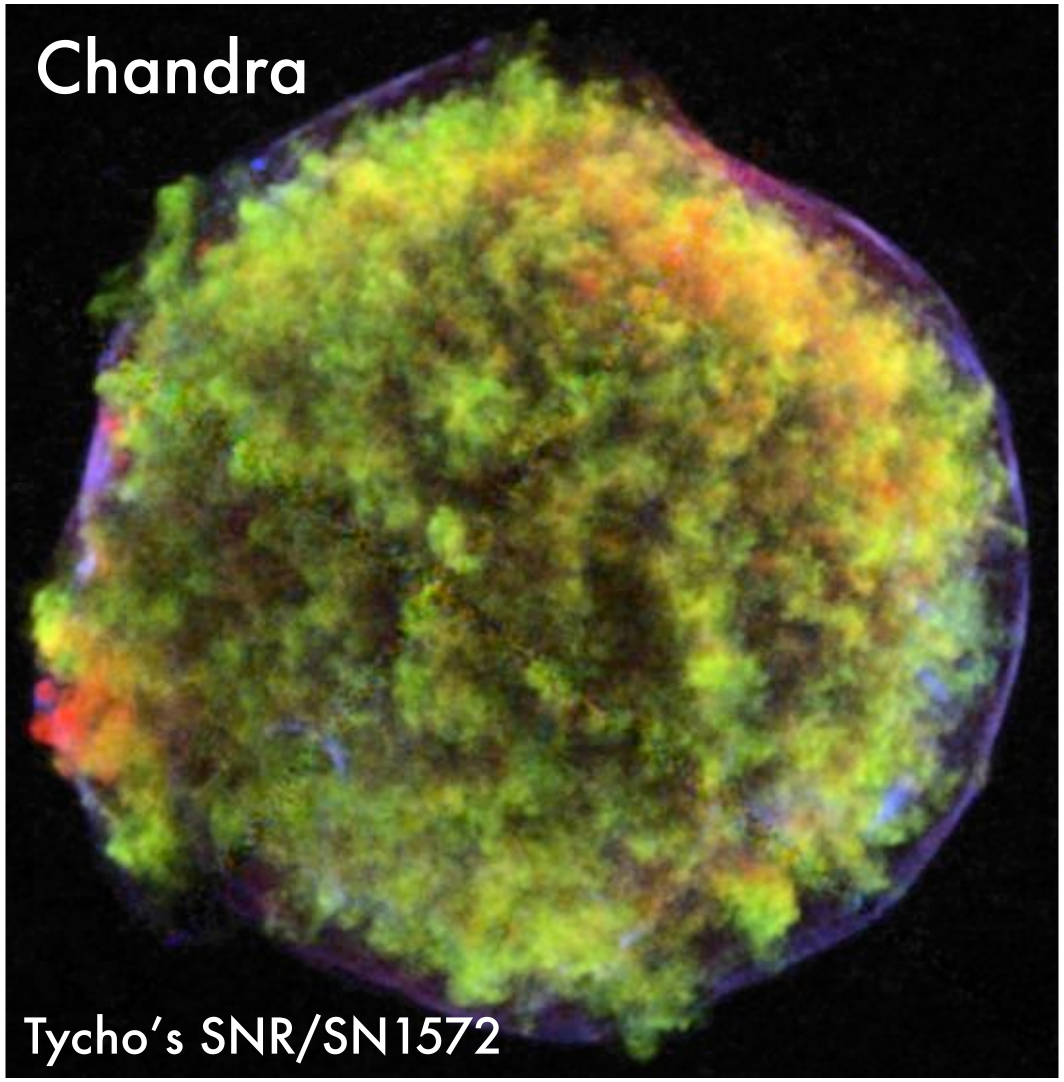
$$h\nu_{\max} \approx 3\eta^{-1}\left(\frac{V_{\rm sh}}{5000\ {\rm kms}^{-1}}\right)^2\left(\frac{\frac{\chi-1}{(1+\chi\chi_B)}}{3/17}\right)\ {\rm keV}$$

- Very thin filaments ("/1E17cm): high B-field B≈200 μG

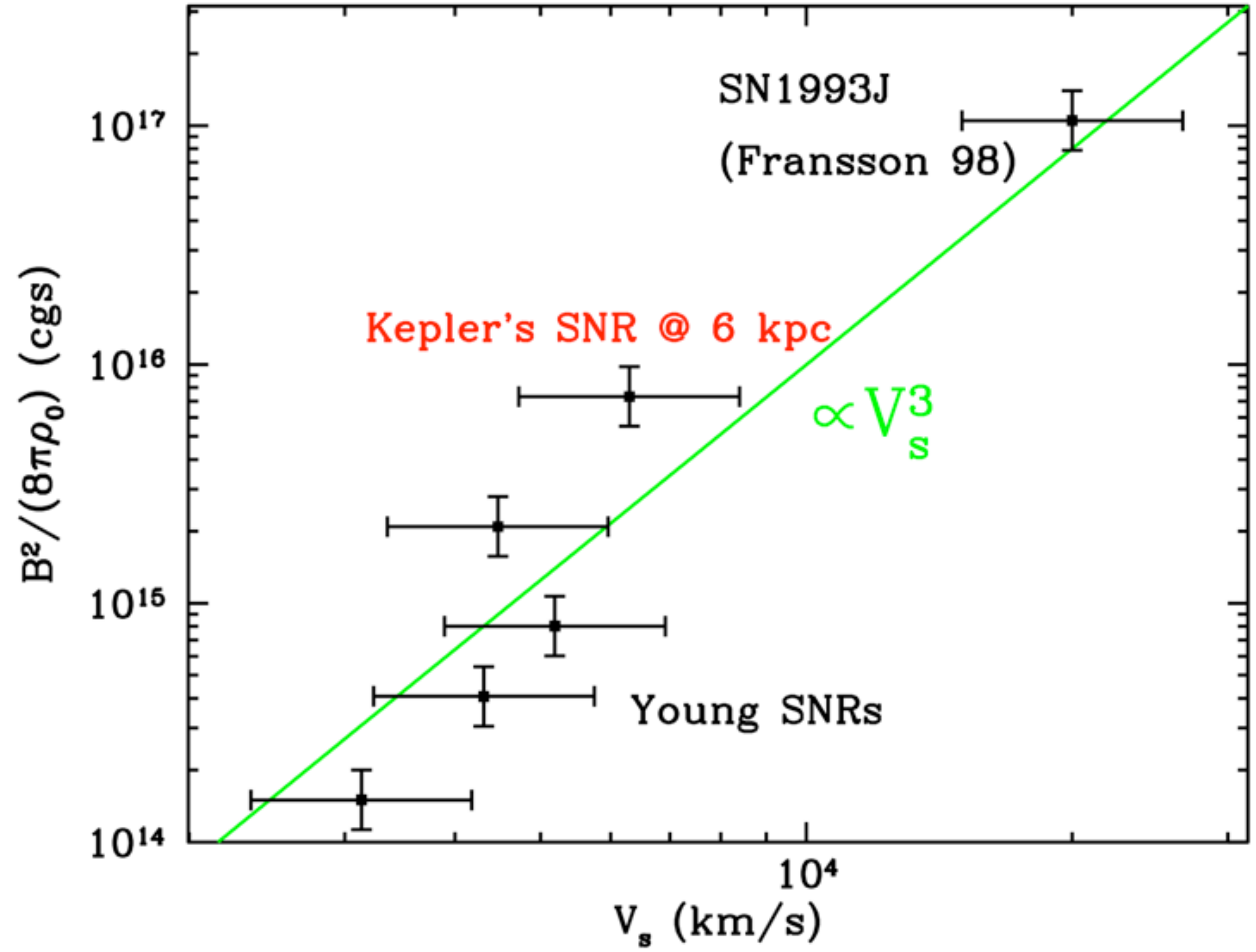
$$B_2 \approx 26\left(\frac{l_{\rm adv}}{1.0\times10^{18}{\rm cm}}\right)^{-2/3}\eta^{1/3}\left(\chi_4-\frac{1}{4}\right)^{-1/3}\ \mu{\rm G}$$

  - Higher B: knee within reach?
  - Hillas criterion: $E=4\text{x}10^{15}$ eV!

Evidence for magnetic field amplification



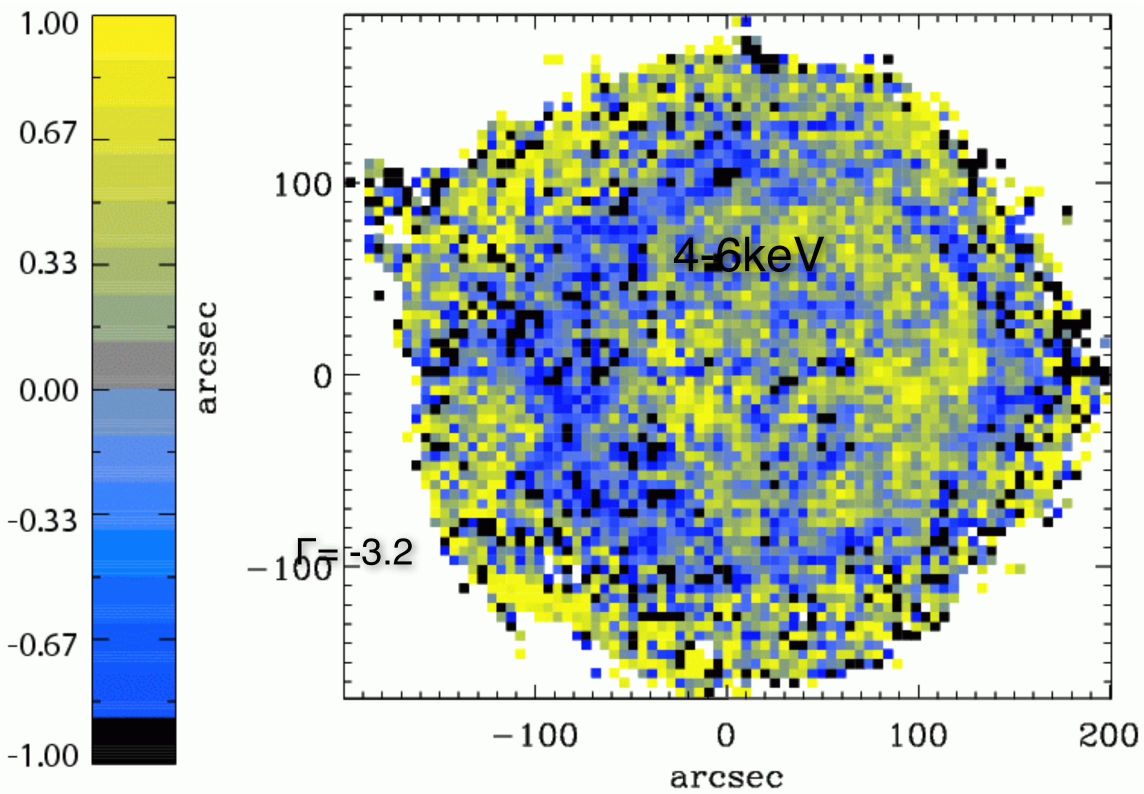
Vink 2008



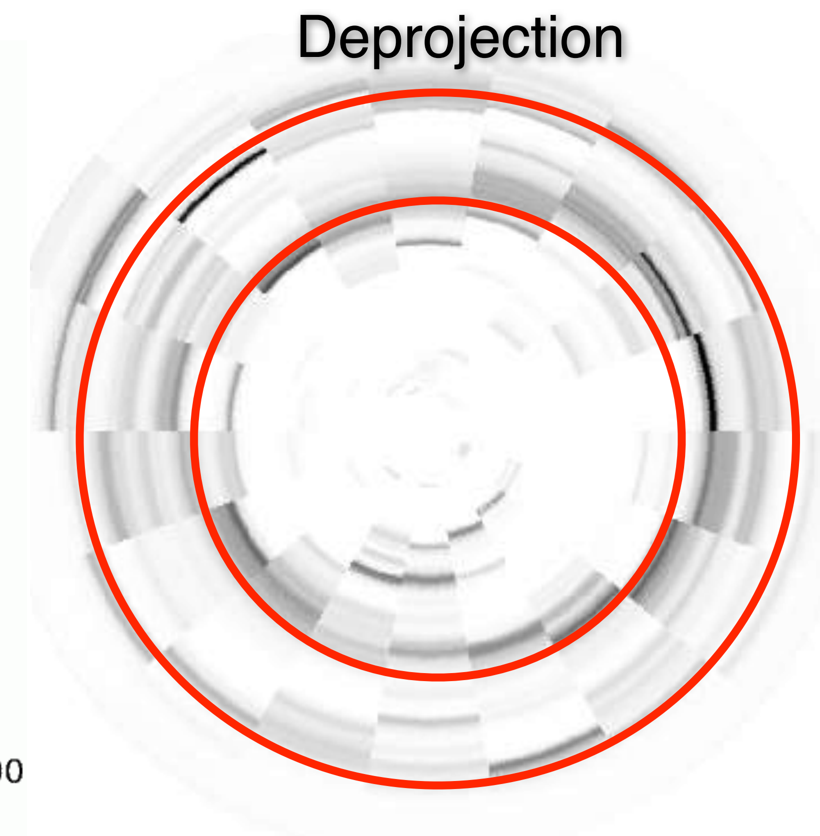
- X-ray synchrotron from all young SNRs
- B-fields above compressed ISM
- Higher B-field for higher densities: have smaller radii
    - *Evidence that $B^2 \propto \rho V_s^3$ (or ρV_s^2): agrees with Bell 2004!*

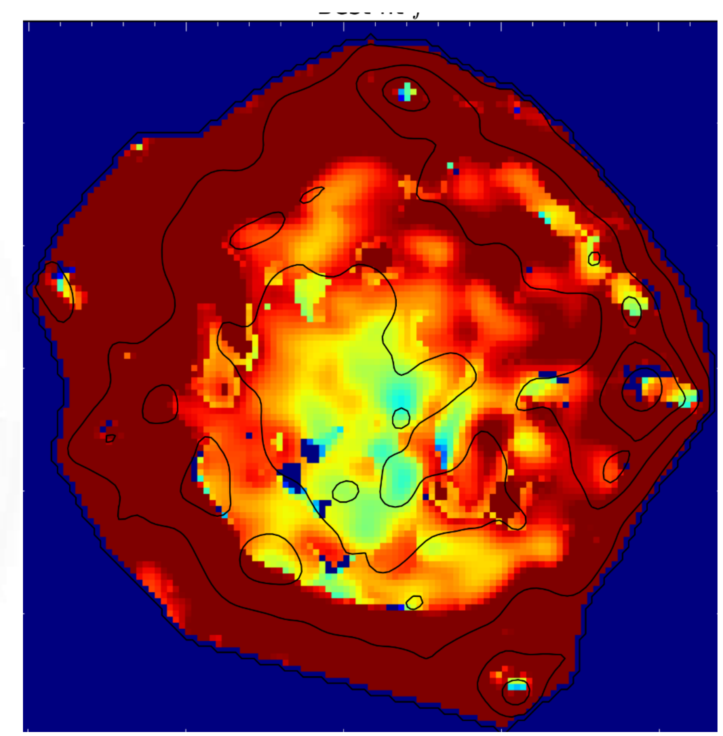
See also Berezhko, Völk, Bamba, Ballet, Helder etc

Acceleration @ Cas A reverse shock



Helder&Vink '08



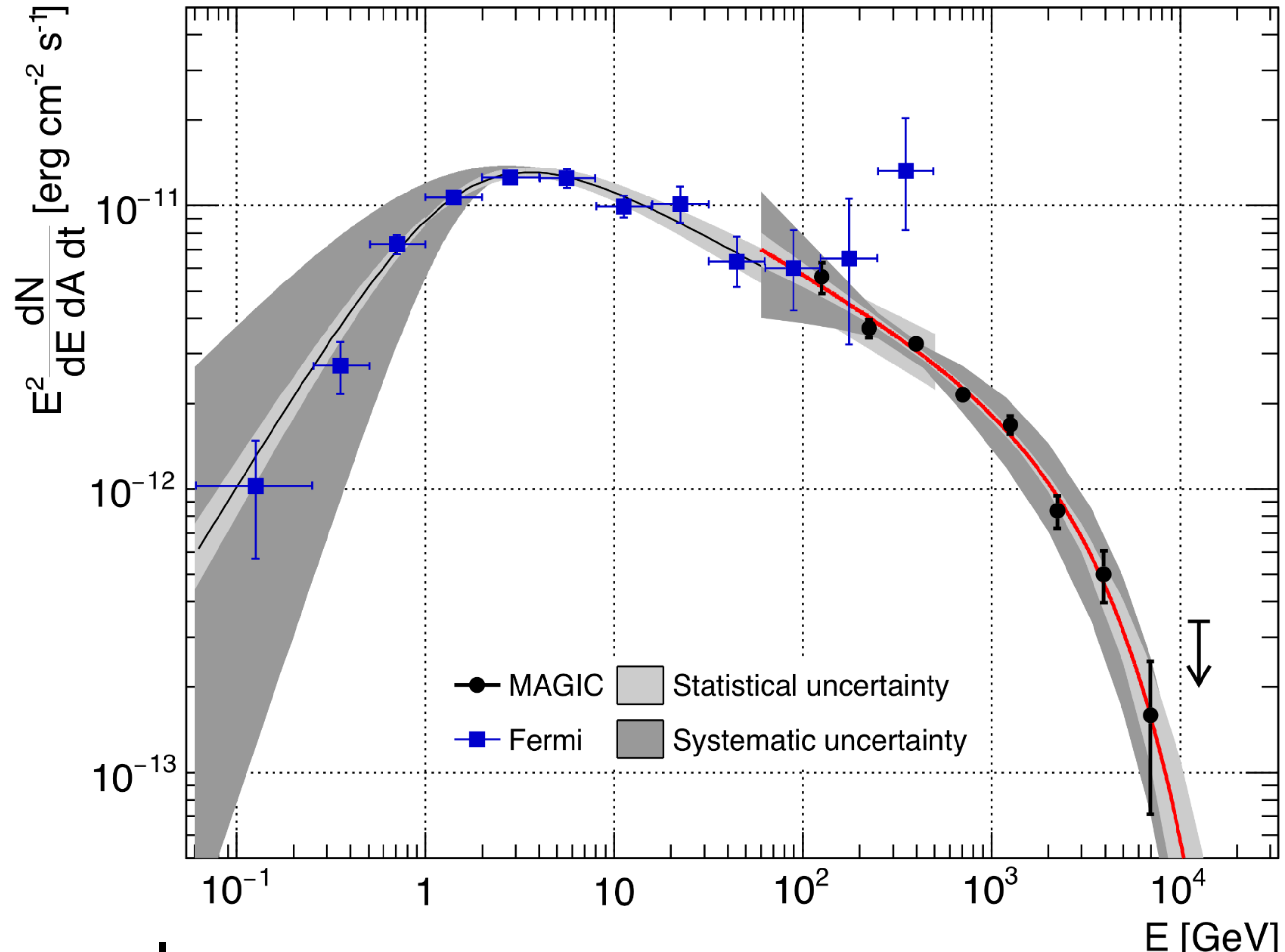


Arias, Vink '18 (LOFAR)

- Spectral index: 2 regions of hard emission: X-ray synchrotron emission
- Deprojection: Most X-ray synchrotron from reverse shock!
- Does not trace total rev shock: only Western part (Arias, Vink+ '18)
- Rev. Shock west at standstill: ejecta plunge into it with >6000 km/s
- Reverse shock: metal-rich → more electrons → bright radio

B-field amplification is not very sensitive to initial B-field!

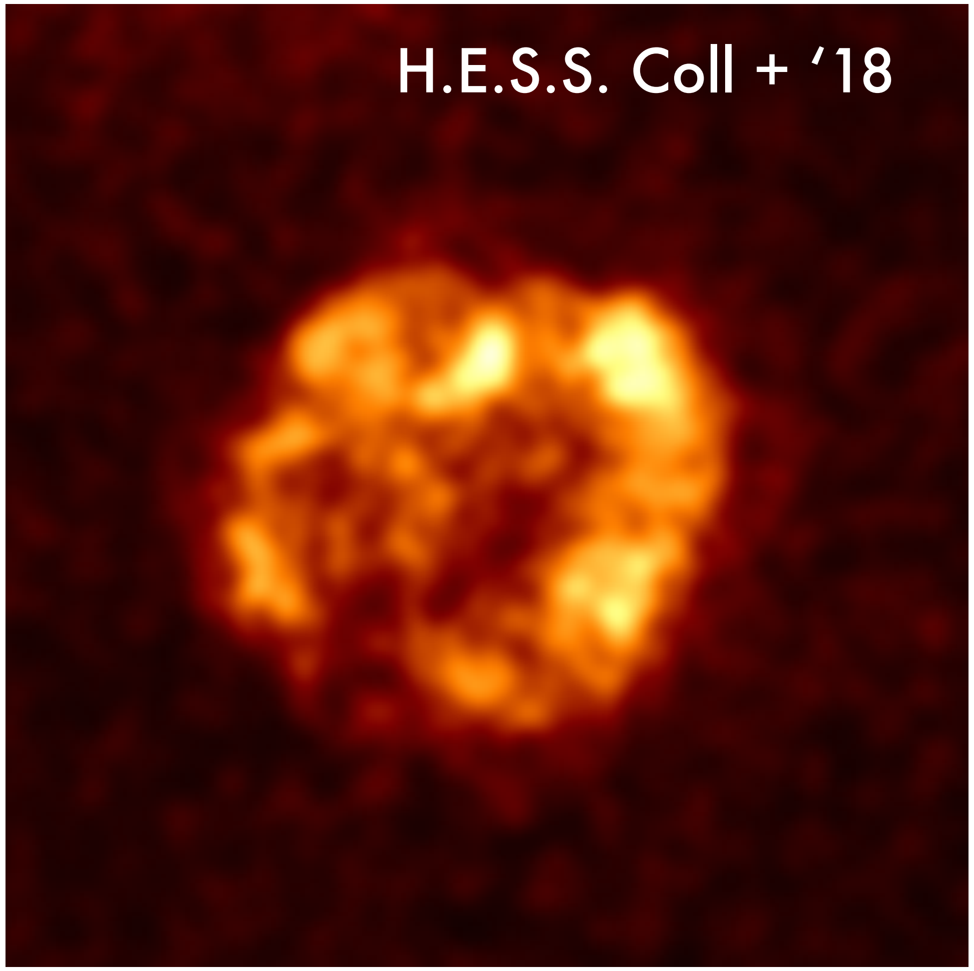
Recent MAGIC results

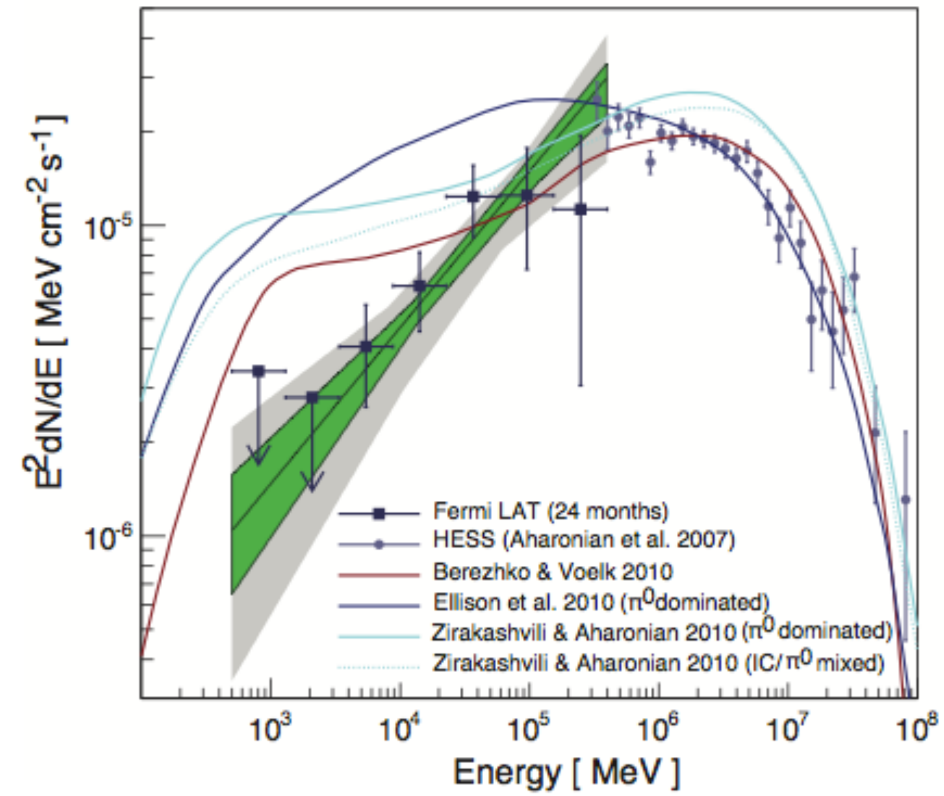


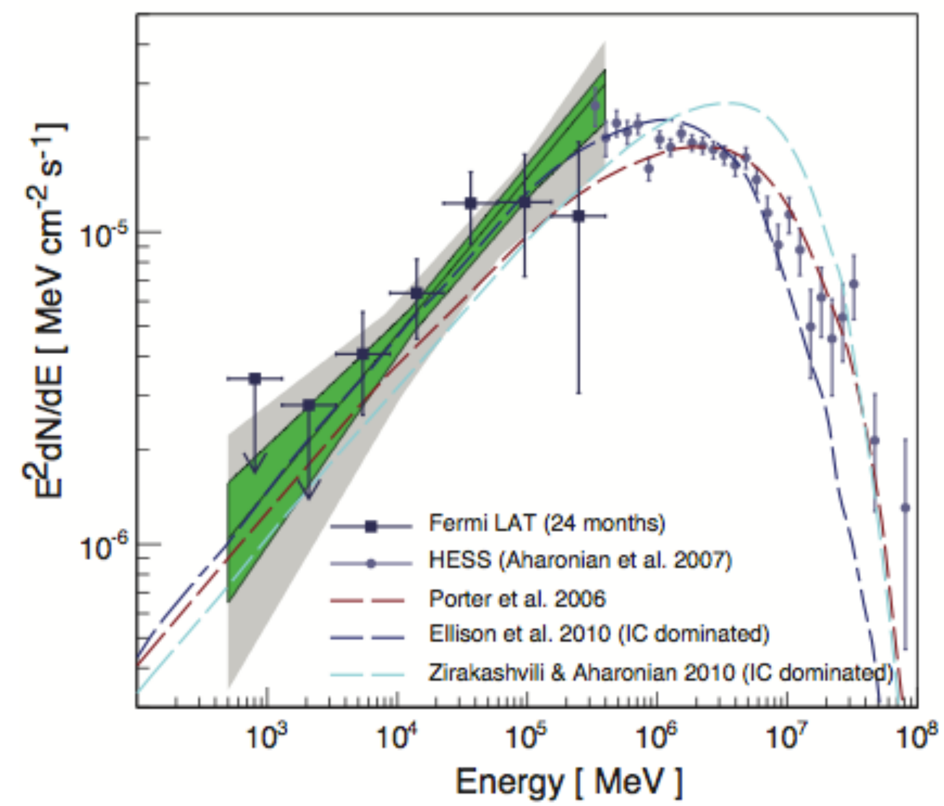
- Cas A checks right boxes for efficient accelerator:
  - Steep spectrum -> non linear acceleration
  - High B-field: substantial cosmic ray streaming, proton acc. to high E
  - Pion bump
- But MAGIC finds: E_{cut}=10 TeV, 0.3% lower than the knee!
- Fermi finds efficiency <5%
  - WTF!
  - Causes?
    - composition: can reduce gamma efficiency by factor 20!
    - spectrum dominated by plateau, shell higher cut off?

The bright mysterious RX J1713

Abdo+ '11

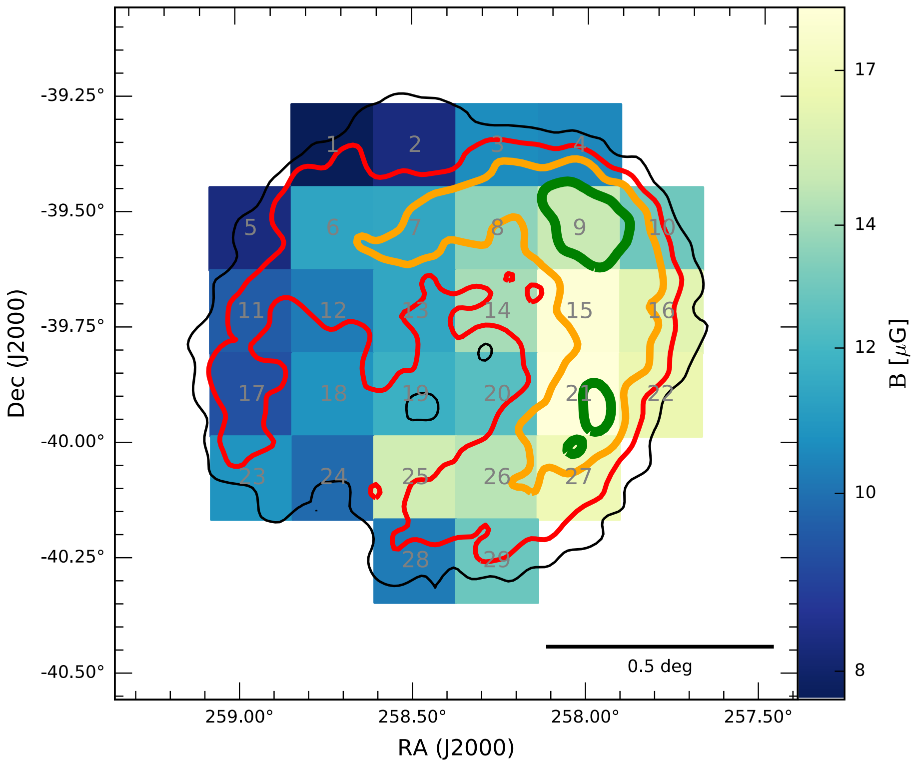


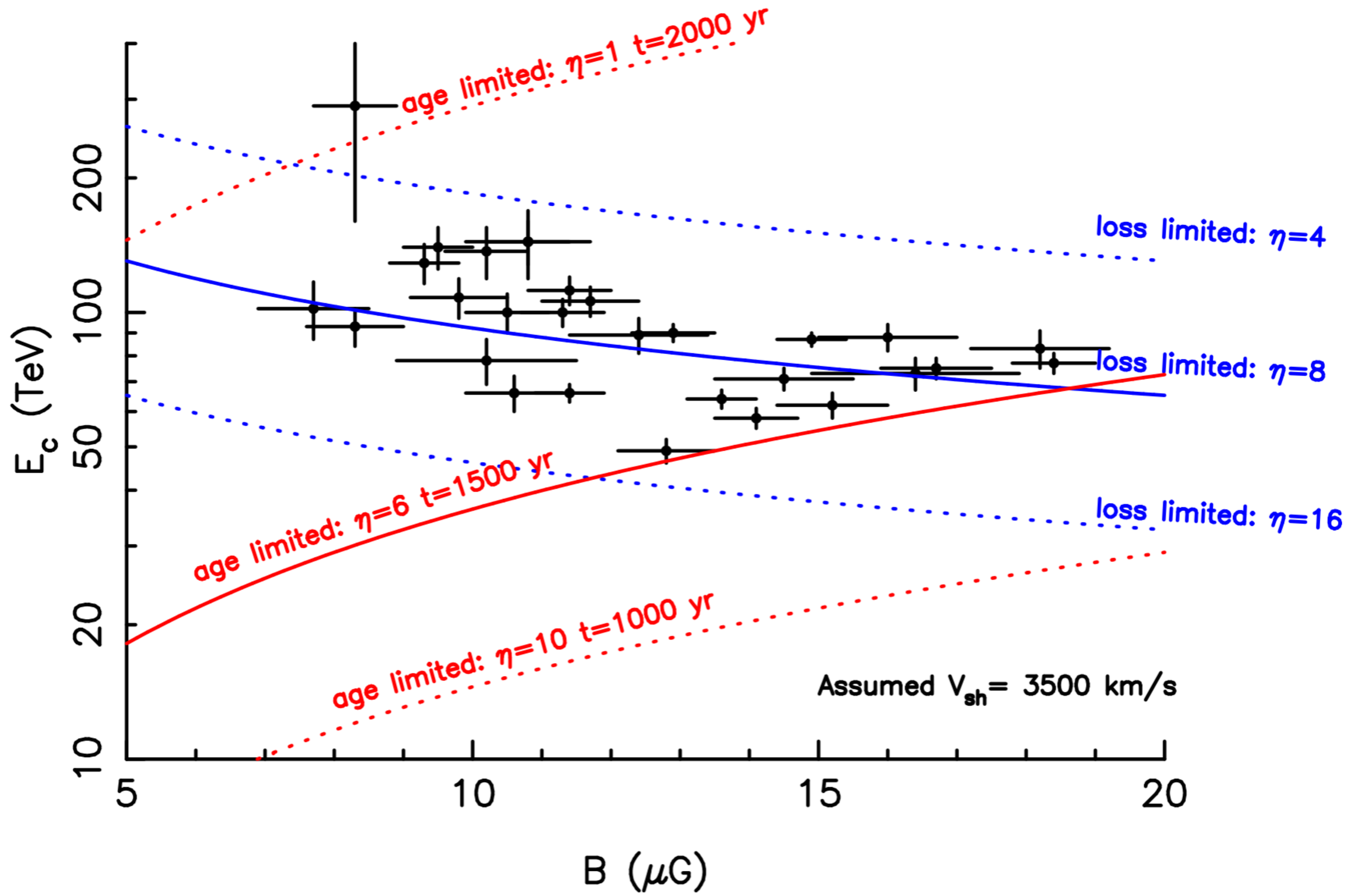




- H.E.S.S. archetypal SNR
- Brightest TeV SNR
- Fermi+H.E.S.S.: hard IC-like spectrum
- New obsevations + new analysis:
  - Better PSF
  - 164 hr of observation time

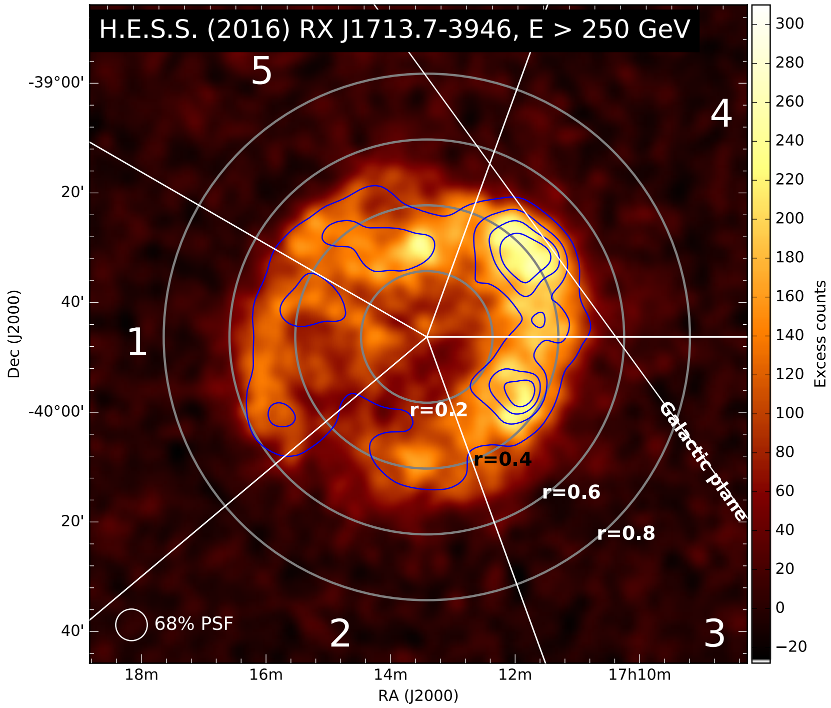
Under assumption of leptonic emission: B map

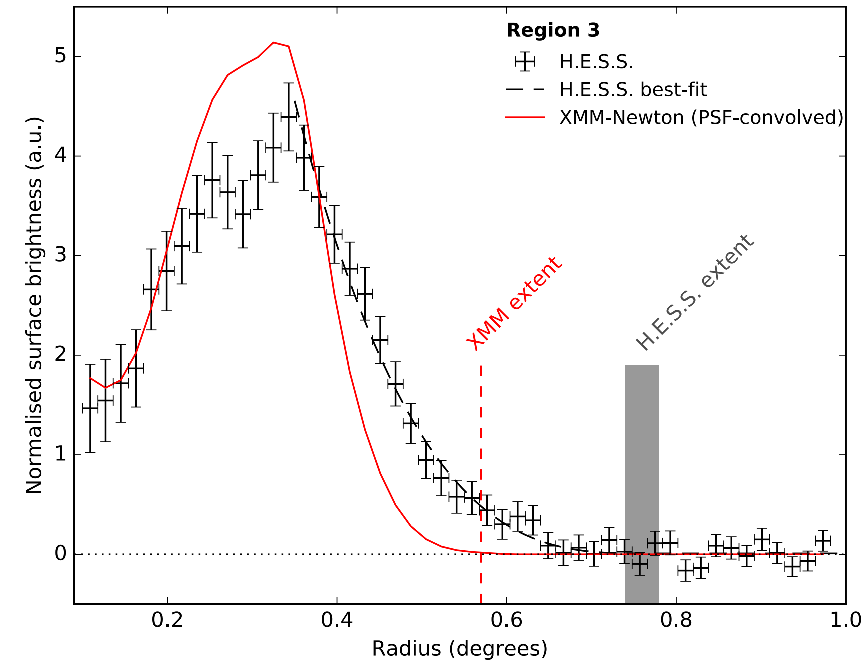




- 5-20 μG fields
- Largely consistent with loss limited Ec
- Needs Bohm factors < 10

A deep H.E.S.S. observation of RX J1713 with improved angular resolution (HESS Coll. A&A 2018)



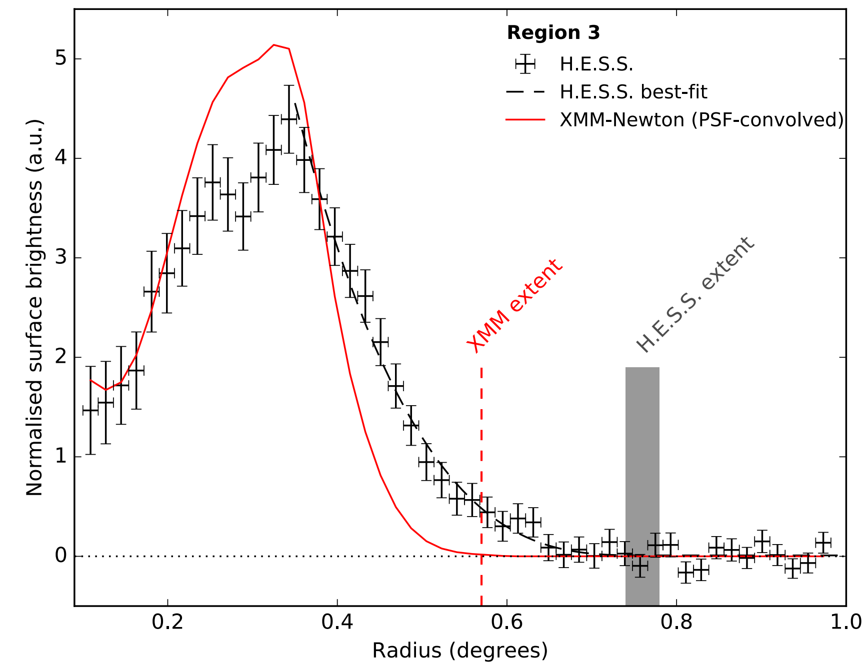


- Assuming inverse Compton radiation: B=2-27 μG
- Suprise: gamma-ray emission in front of X-ray defined shock!!
  - Diffusion length scale ($l_{diff} \approx D/v$)
  - Work out expression:

$$\frac{B}{\eta} \approx 0.36 \left(\frac{E}{10\,\mathrm{TeV}}\right)\left(\frac{u_{\rm shock}}{3000\,\mathrm{km\,s^{-1}}}\right)^{-1}\left(\frac{\Delta r}{\mathrm{pc}}\right)^{-1} \mu\mathrm{G}$$

  - Consistent with low B, or high η!

Escape or precursor?



- Escape: low chance of returning to shock
- Clue: l_{diff}/R_{sh} order 13%
- Use self similor evolution:
  (m=0.4: Sedov)

$$R_{\rm sh} = Kt^m, \;\; V_{\rm sh} = m\frac{R_{\rm sh}}{t}$$

- Using expressions acc. time/diff length

$$\tau_{\rm acc} \approx \frac{8D_1}{V_{\rm sh}^2} = \frac{8l_{\rm diff}}{V_{\rm sh}} < t_{\rm SNR}$$

$$l_{\rm diff} < \frac{m}{8}R_{\rm sh} \approx 0.09R_{\rm sh}$$

- Consistent with escape
- But: systematic uncertainties, so no firm conclusion
- What could cause escape?
  - Sudden drop in velocity due to density gradient
  - Loss of B-field turbulence

When do particles escape?

- Assume: particles escape when diffusion length becomes too large:

$$l_{\rm diff} = \frac{D}{V_{\rm sh}} \gtrsim 0.1 R_{\rm sh}$$

- Combine with:

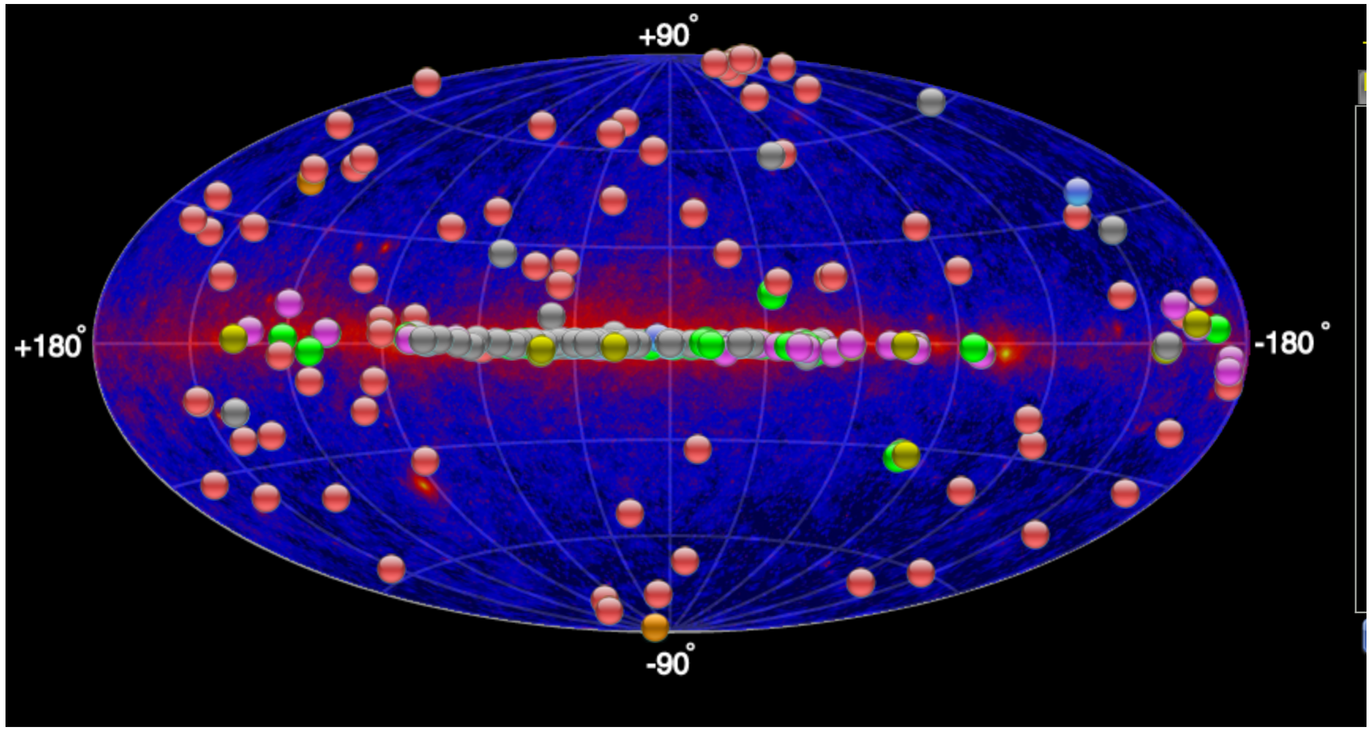
$$R_{\rm sh} = K t^m,\ V_{\rm sh} = m\frac{R_{\rm sh}}{t} \qquad D = \frac{1}{3}\eta\frac{cE}{eB}$$

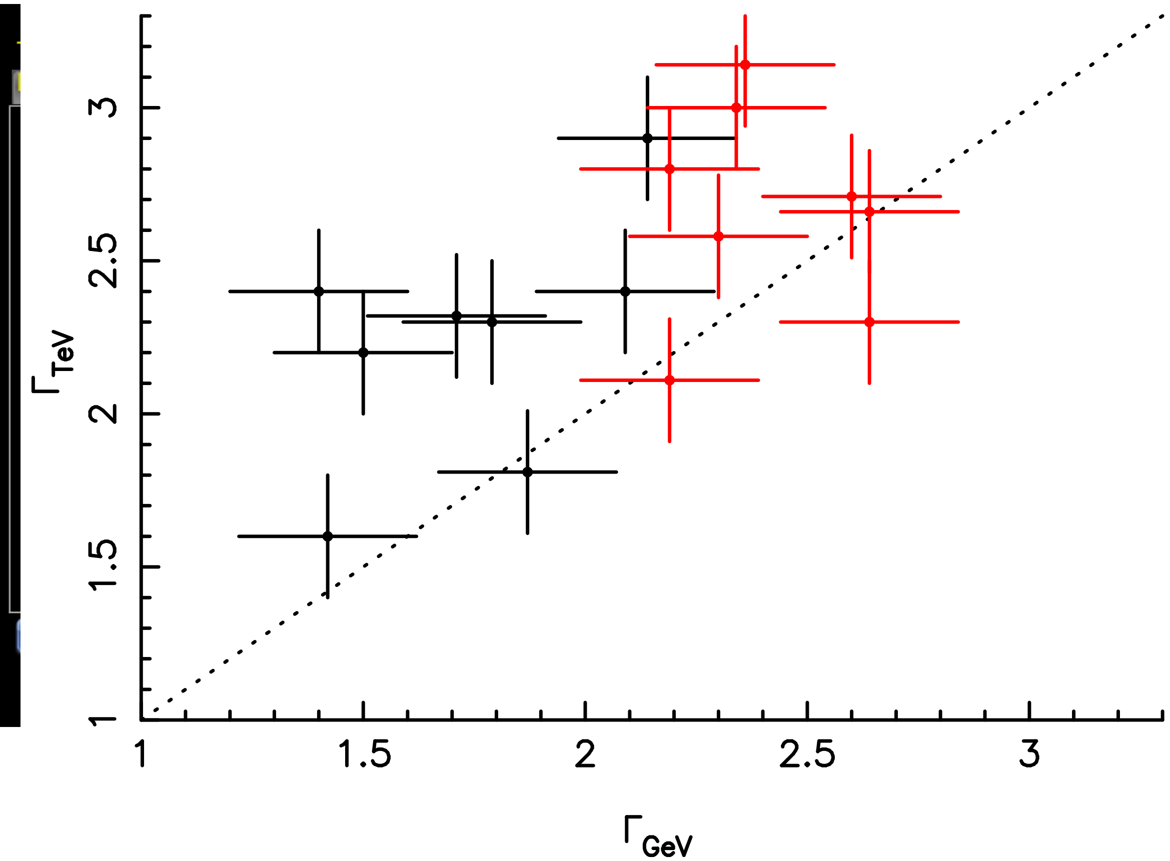
- Result:

$$E \gtrsim 0.3\eta^{-1}\frac{e}{c} B V_{\rm sh} R_{\rm sh} \propto \eta^{-1} B t^{2m-1}$$

- Consequences:
  - Young age, m>0.5: E rises as function of age!
  - Sedov, m<0.5: SNR cannot hold on to high E particles!
  - B decreases with time: escape also for young SNRs!

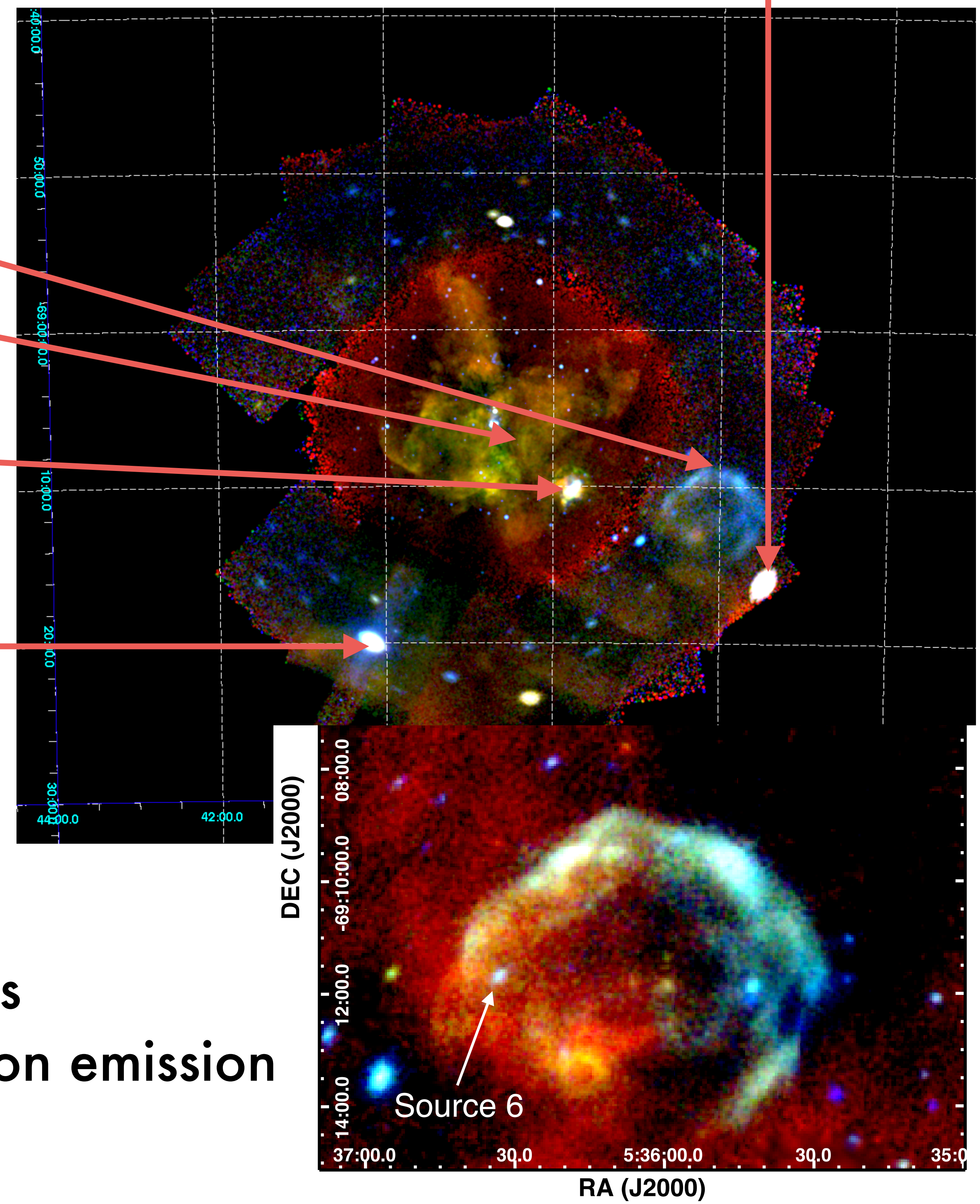
Shells versus SNR/molecular clouds





- Clear distinction in slopes "shells" vs "SNR/mol. cloud"
- Most cases steepening GeV to TeV: losses and cuts
- Exceptions: e.g. W28 (escape?)

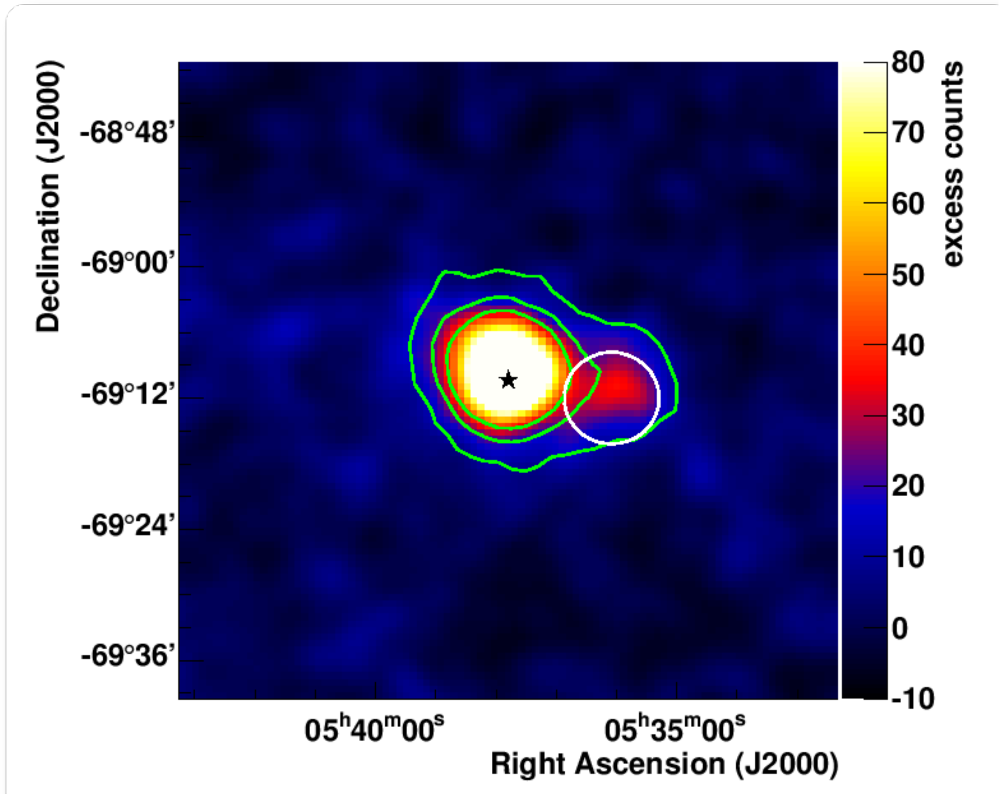
The superbubble 30 Dor C in X-rays



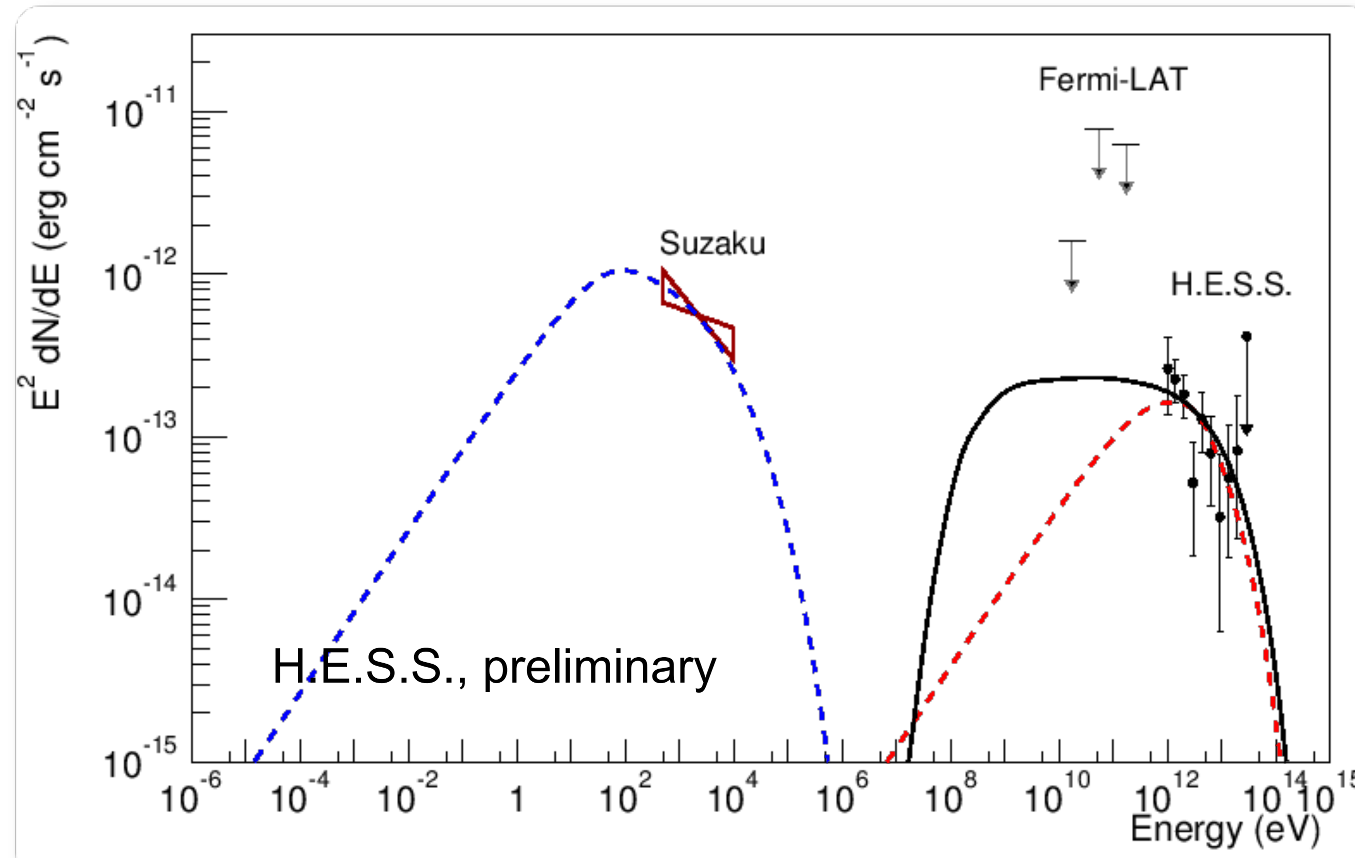
- Doradus region: starburst conditions
- 30 Dor C: partially X-ray synchrotron emission

Bamba+ '04, Kavanagh+ '15

TeV Detection 30DorC by H.E.S.S.



HESS col., Science, '15

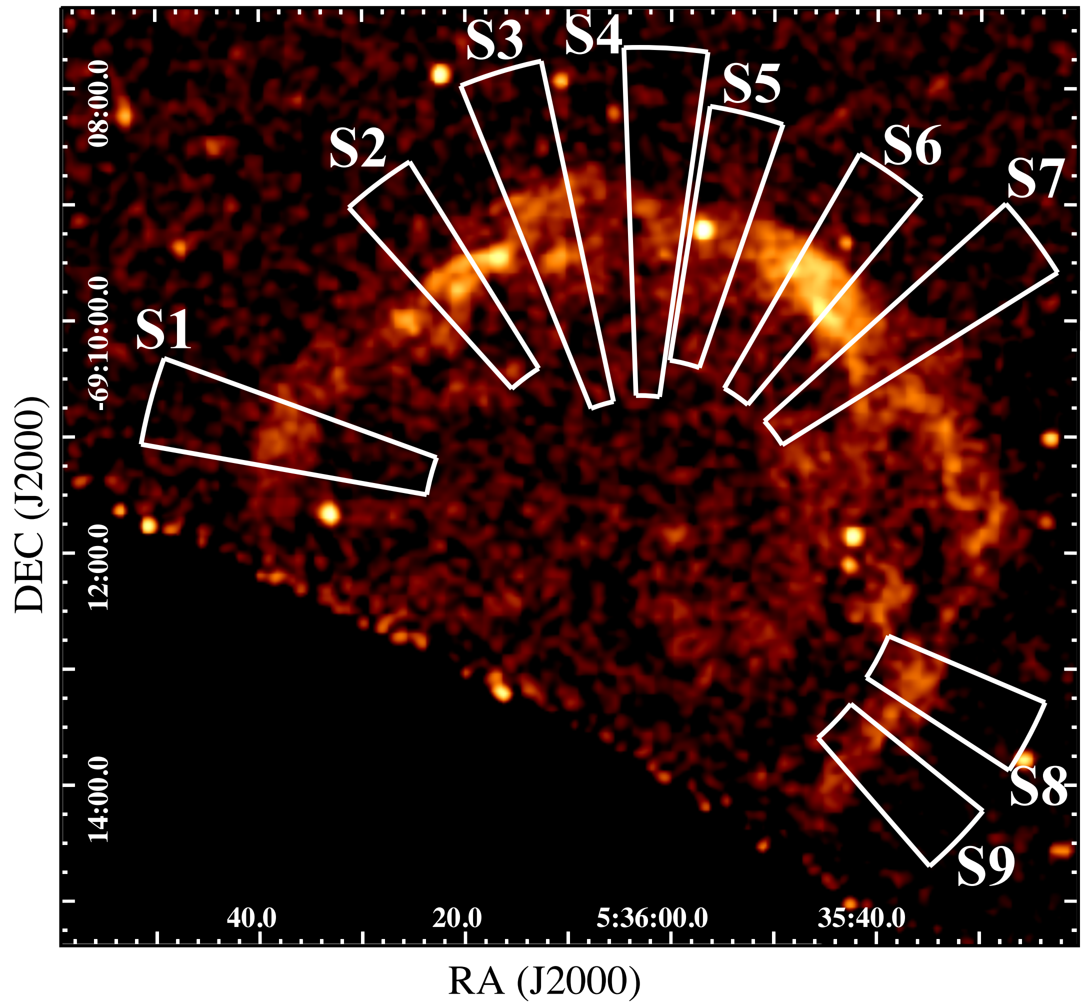


- **hadronic scenario**
  - energy in protons
  - $W_{pp} = (0.7 - 25) \times 10^{52} \, (n_H / cm^{-3})^{-1}$ erg
  - even for 5 supernova explosions high density needed: $n_H > 20$ cm^{-3}
  - thermal X-rays indicate low density: $n_H \sim 0.4$ cm^{-3}

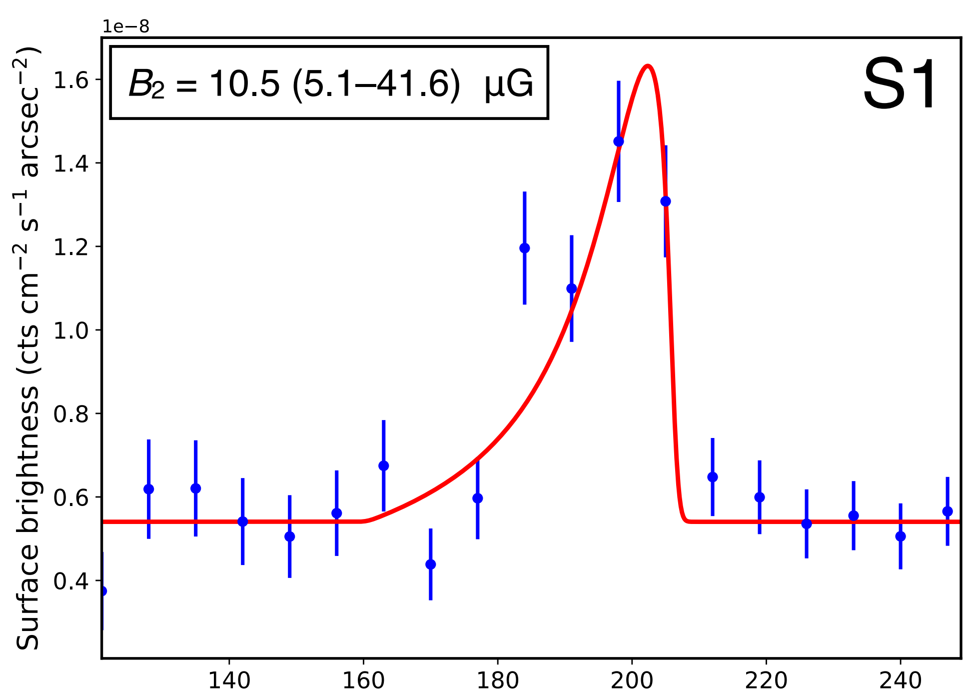
  Bamba+ 04, Kavanagh+ '14
- **leptonic scenario**
  - magnetic field: ~15 μG
  - 4×10^{48} erg in electrons
  - + X-ray synchrotron: high shock velocity ⇒ low interior density 10^{-4}-10^{-3}cm^{-3}
  - X-ray synchrotron from last SNR expanding in rarified medium

New: X-ray B-field determination 30 Dor C with Chandra (Kavanagh, JV+ 2018)

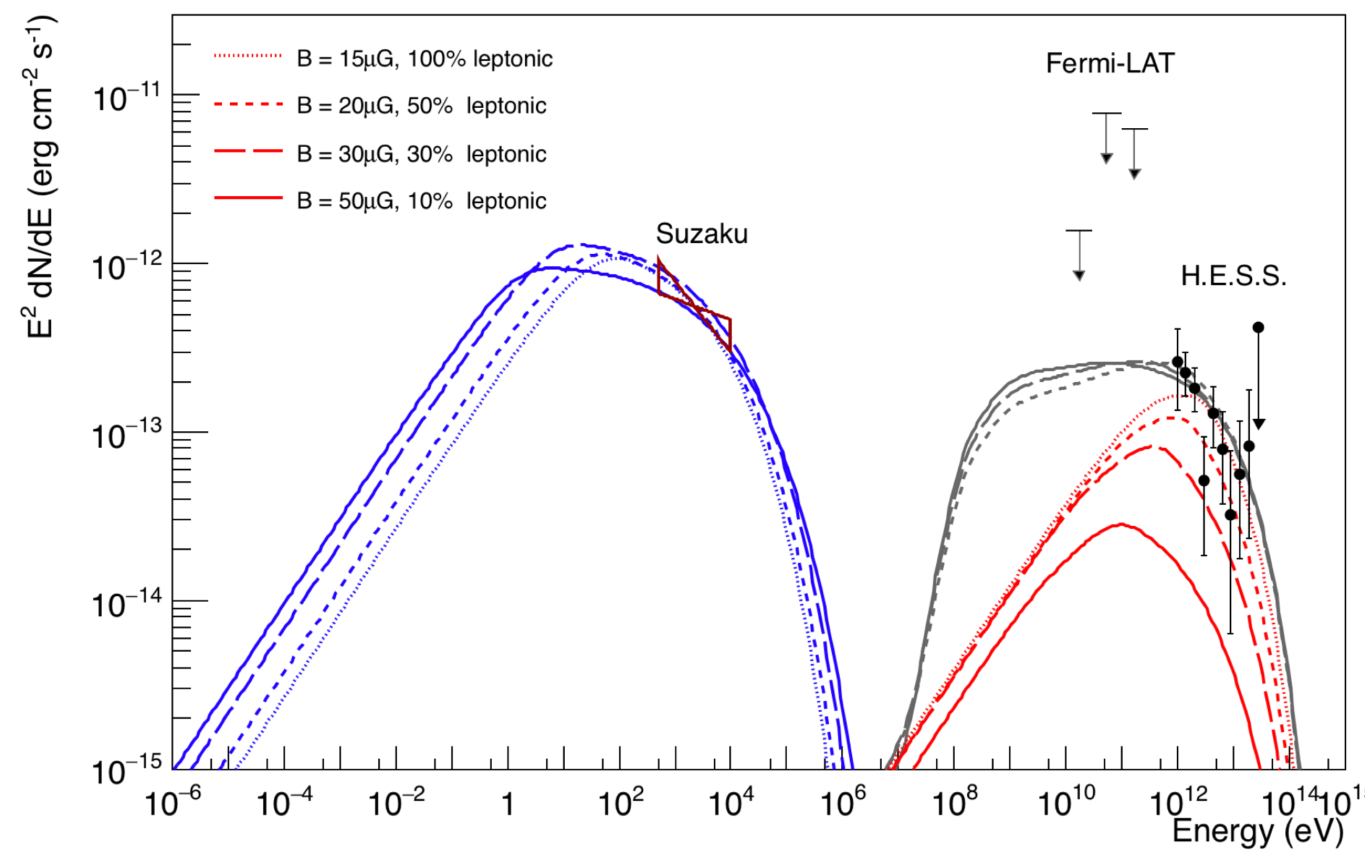
Sector	binning (arcsec)	R (arcsec)	l_{obs} (arcsec)	l_{obs}/R (%)	χ^2_ν	B_2 (μG)
S1	7	206.5 (204.5–212.7)	4.7 (1.2–9.6)	2.3 (0.6–4.7)	1.20_{17}	10.5 (5.1–41.6)
S2	9	172.6 (172.6–178.5)	2.6 (1.9–7.0)	1.5 (1.1–4.1)	1.36_{11}	19.3 (7.0–25.4)
S3	10	191.5 (190.6–198.0)	6.3 (3.3–13.3)	3.3 (1.7–7.0)	0.59_{15}	7.9 (3.7–14.7)
S4	10	180.8 (180.0–182.6)	10.1 (7.9–18.5)	5.6 (4.3–10.2)	1.51_{15}	4.9 (2.7–6.2)
S5	7	182.8 (175.9–183.7)	19.3 (9.0–20.1)	10.6 (4.9–11.4)	0.69_{16}	2.6 (2.5–5.5)
S6	5	195.8	3.8	1.9	3.81_{25}	13.0
S7	6	197.6	11.9	6.0	2.07_{25}	4.1
S8	8	181.2 (180.3–188.3)	3.9 (1.7–10.9)	2.2 (0.9–6.0)	1.14_{9}	12.7 (4.5–28.6)
S9	8	180.3 (172.3–181.2)	6.1 (1.2–10.9)	3.4 (0.7–6.3)	1.51_{9}	8.1 (4.5–41.6)



- Using X-ray synchrotron widths:
  - B= 5 to 20 μG
- Agrees with the leptonic scenario



Spectral Energy Distribution

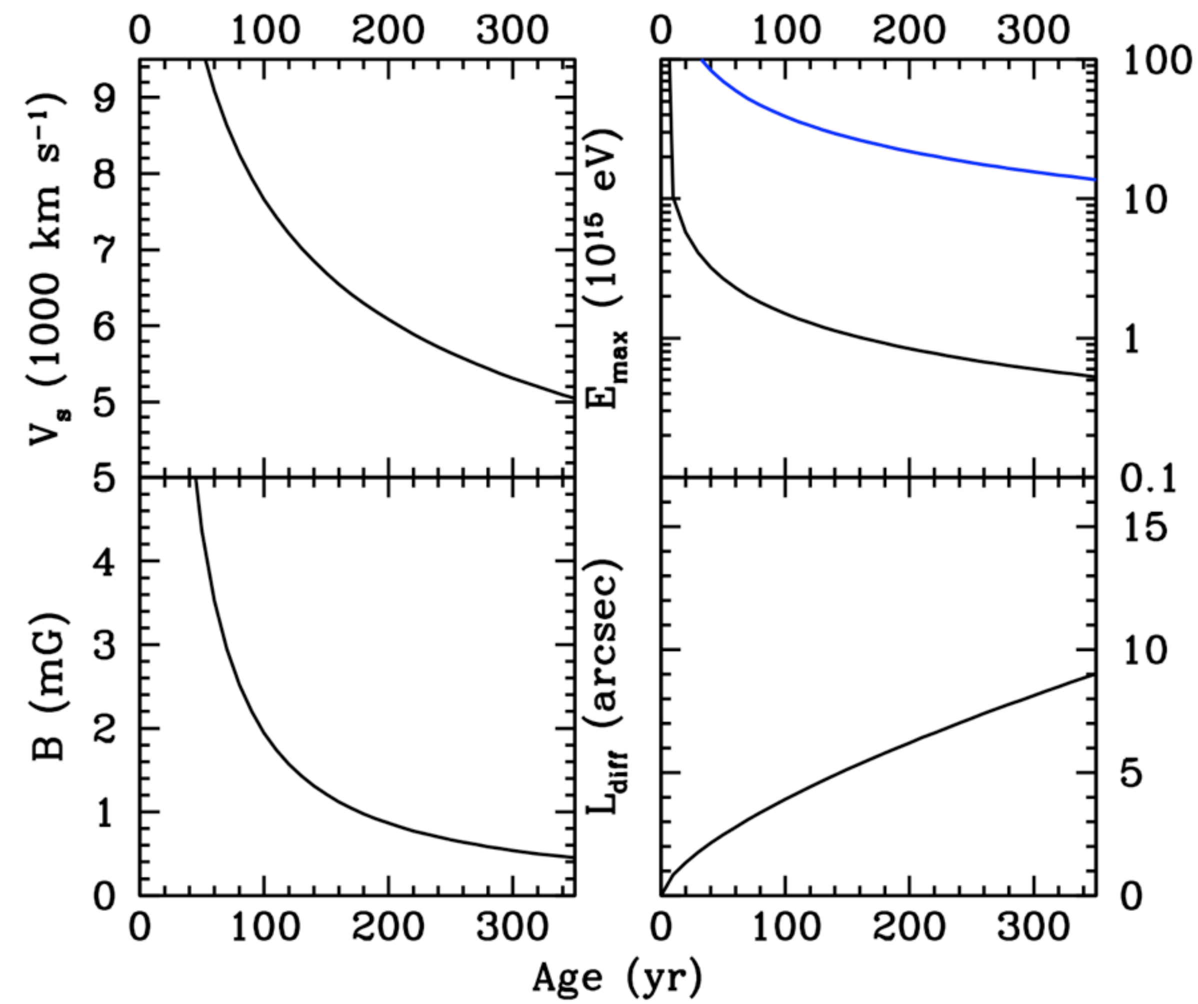


- Leptonic emission: does not preclude presence hadrons
- Hillas criterion with V=3000km/s, B=15 μG, L=25 pc: $B_{\mu G} L_{pc} > 2E_{15}/Z\beta_s$
- E=2x10^{15} eV!
- If true: super bubbles good at accelerating by shaping right SNR conditions, but don't be too optimistic!

(Hillas plot severe filter not green light)

Finally: could supernovae accelerate to the knee?

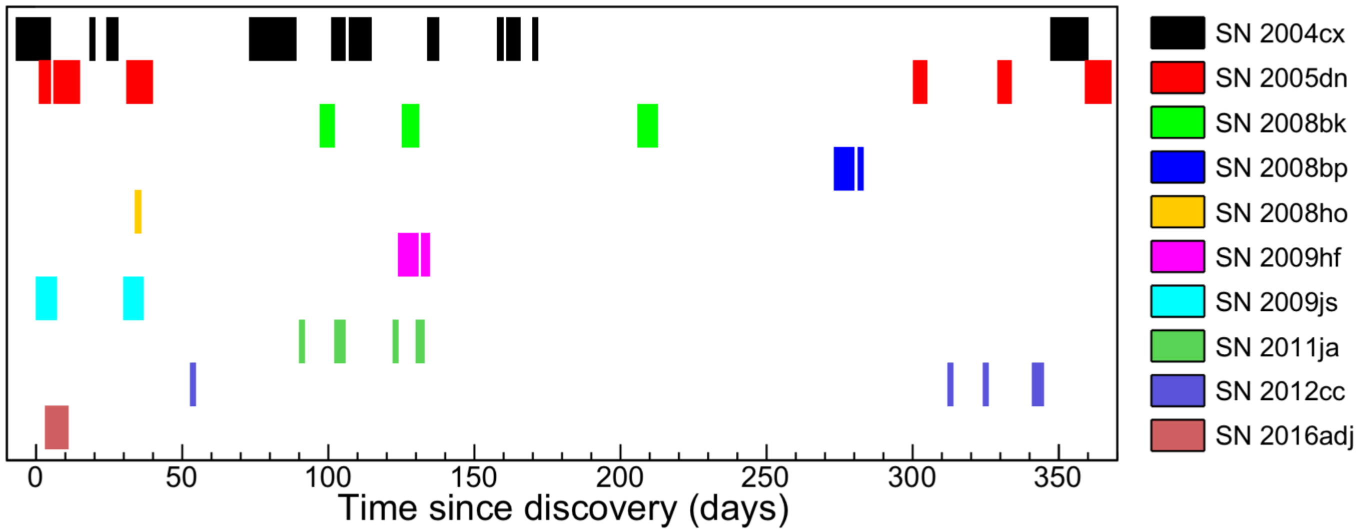
Extrapolate Cas A back in time:

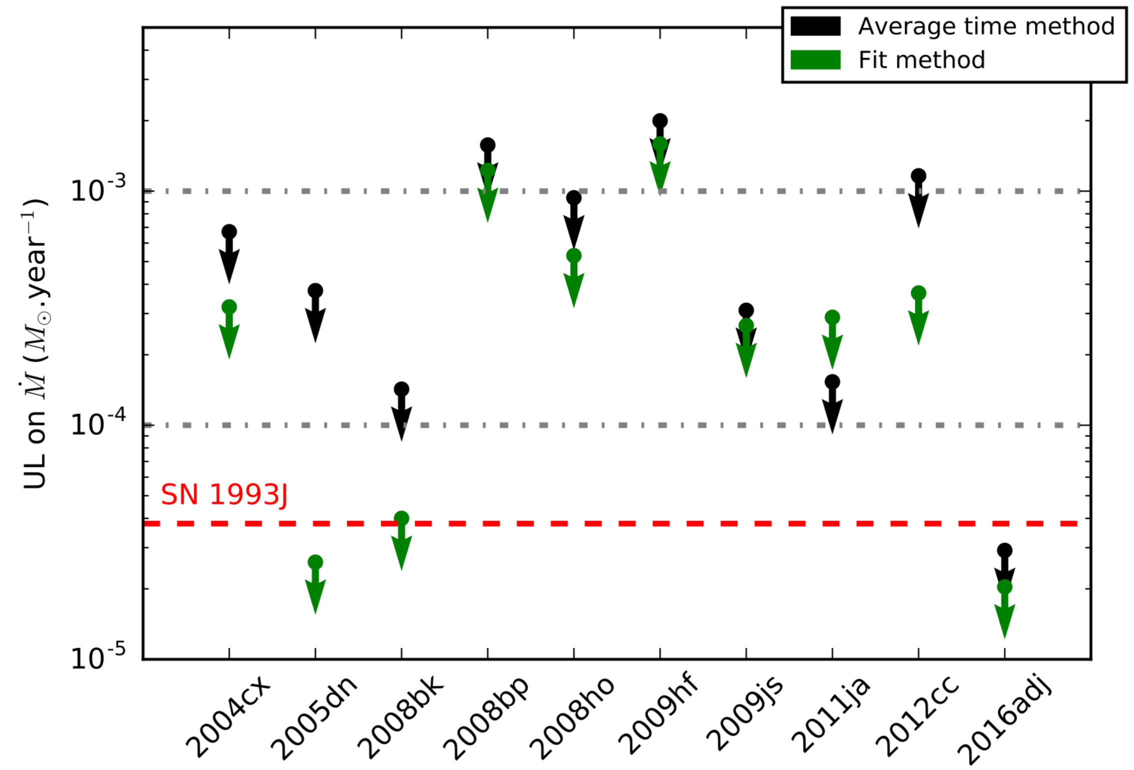


- Shown:
    - Cas A B=200-500 μG, in RSG wind
    - $B^2 \propto \rho V_s^3$
    - Still in RSG wind: $$\rho = \frac{\dot{M}}{4\pi r^2 v_w}$$
    - dM/dt = 10^{-4} M_{sun}/yr

- Consequence: going back in time acceleration faster and higher E!
- Need dense winds: high dM/dt, low vw, i.e. RSG winds not Wolf-Rayet stars
- Problem: large variety in mass loss: only subset can go beyond the knee
- These supernovae are known as radio supernovae, example SN1993J

H.E.S.S. Upper limits on supernovae (preliminary)





- 9 serendipitous target SNe, 1 TOO (sn2016adj)
- Due to fall of in density, expect

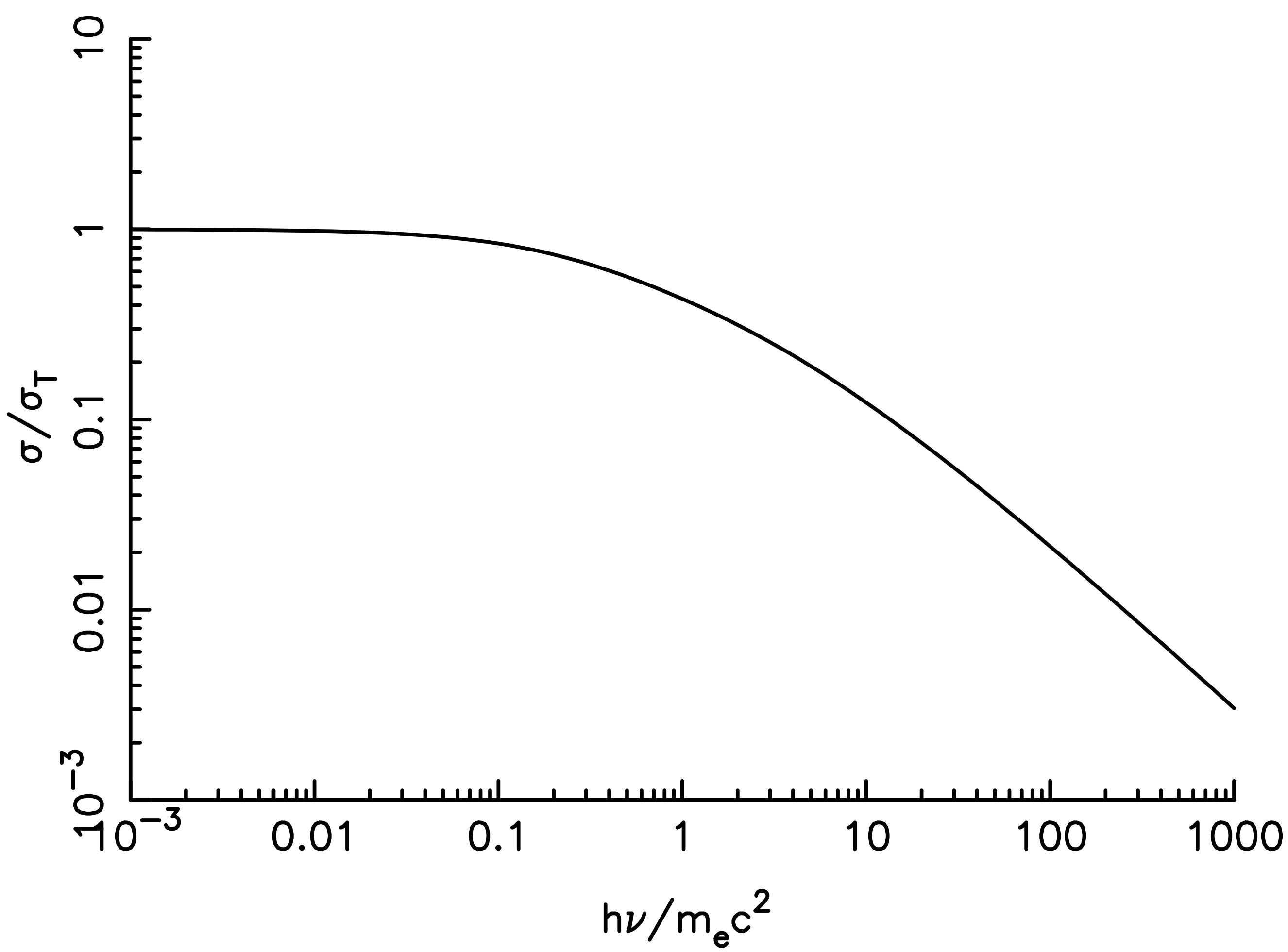
$$F_\gamma(>E_0, \mathrm{t}) = \frac{3 q_\alpha \xi (\kappa C_1) m^3}{32\pi^2(3m-2)\beta\mu m_\mathrm{p} d^2}\left[\frac{\dot{M}}{u_\mathrm{w}}\right]^2 t^{m-2}.$$

- Only upper limits so far :(
- But constraints on dM/dt realistic
- We just need some luck!

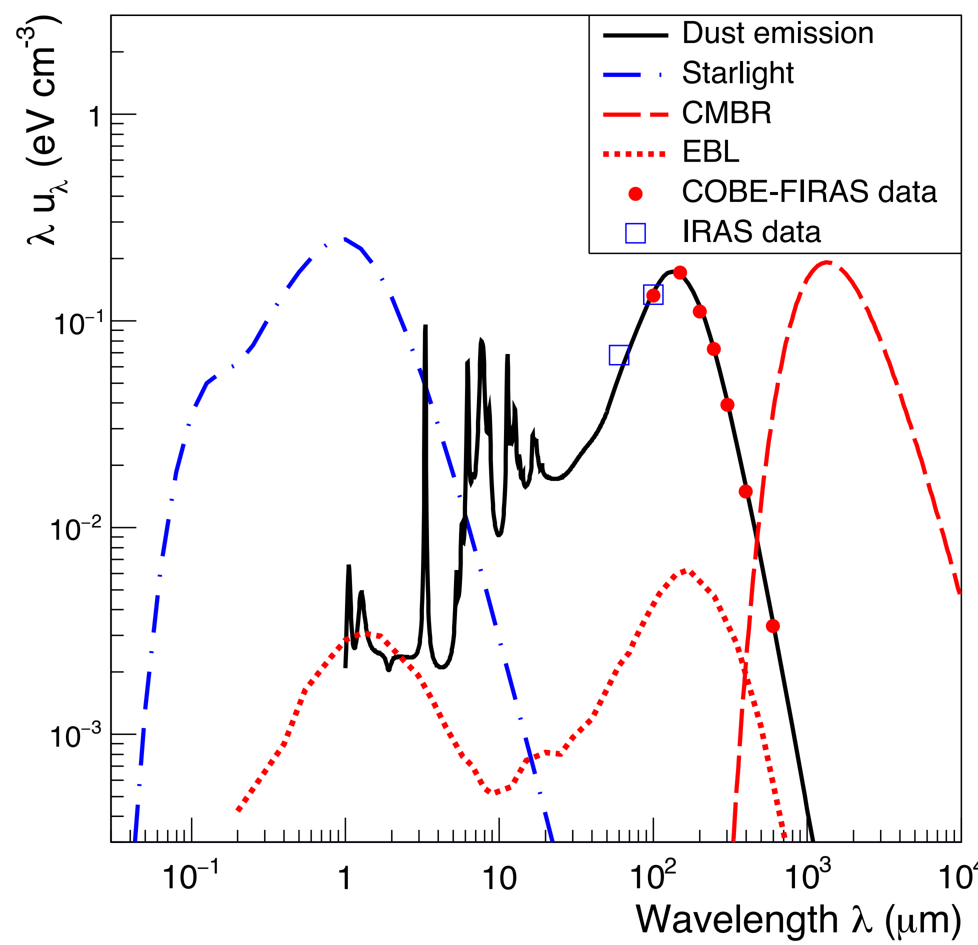
Conclusions

- Supernovae long suspect to power Galactic cosmic rays
- In 1950s: focus on shells
- 1970s/1980s: diffusive shock acceleration theory: knee problematic
- 1990s-2000s:
  - X-ray synchrotron: high B turbulence/high B fields
  - B amplification
  - SNRs are common gamma-ray sources:
  - But cut-off weel below knee, hadronic vs leptonic nog always clear
- Alternatives
  - Super bubbles: one example in gamma-rays and likely leptonic
  - Radio supernovae: promising but still need to be detected

What about the Klein Nishina limit?

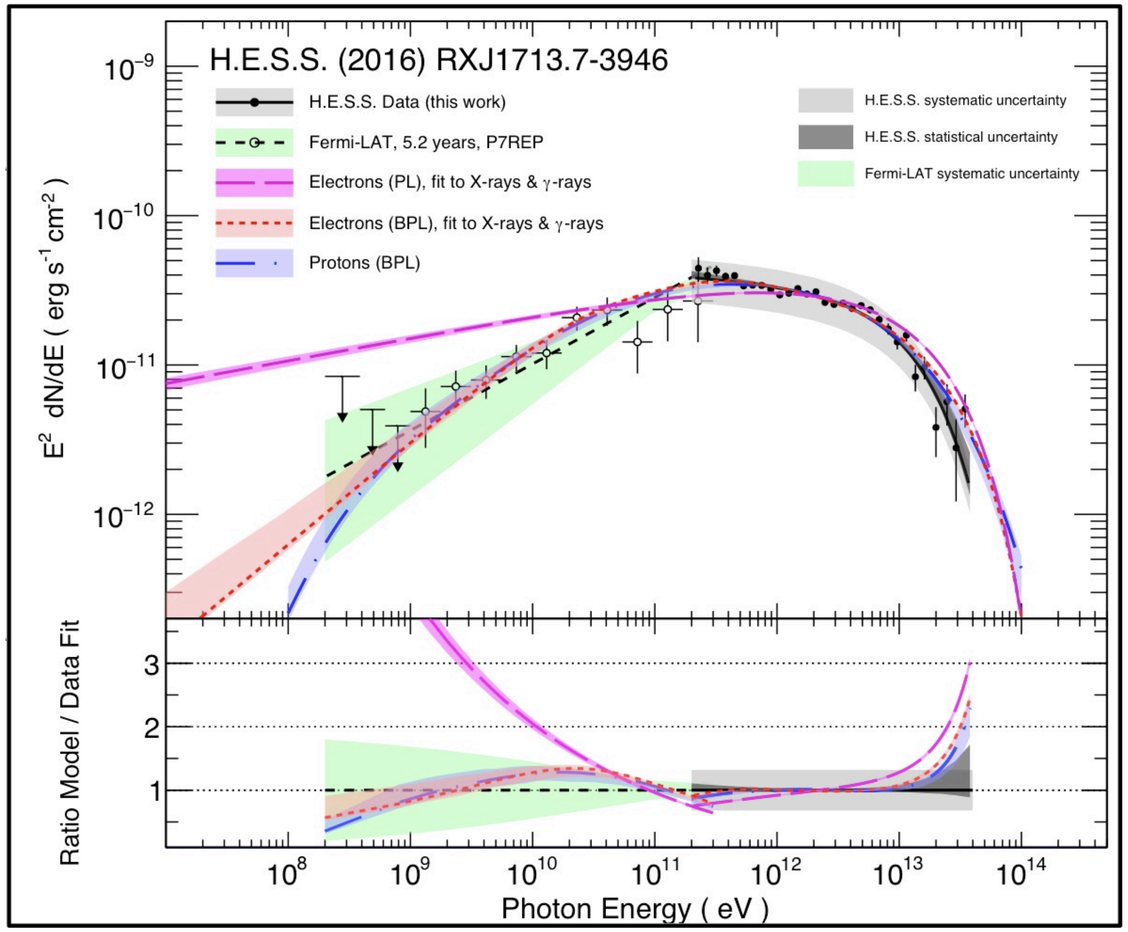


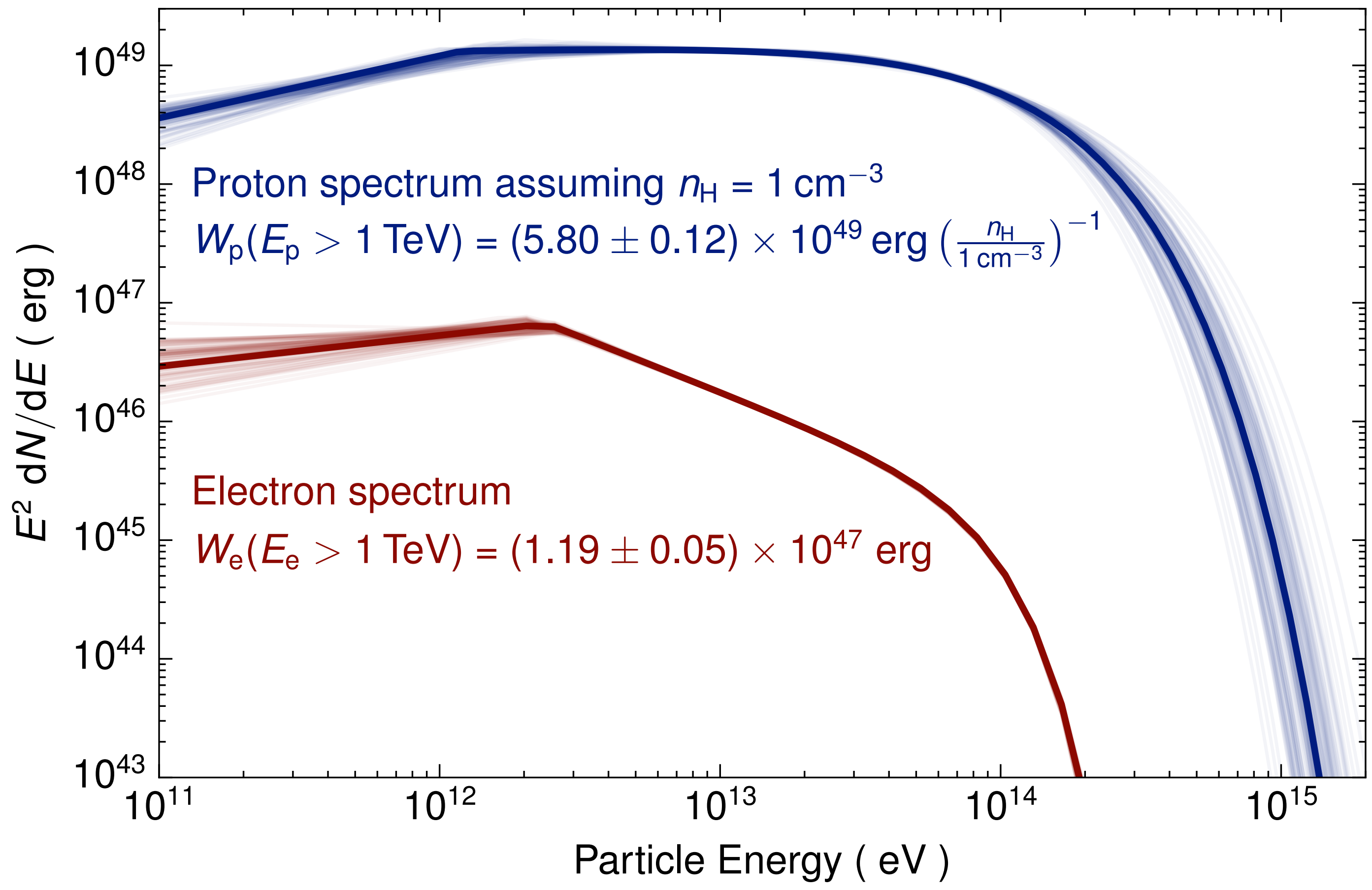
Vernetto & Lipari 16



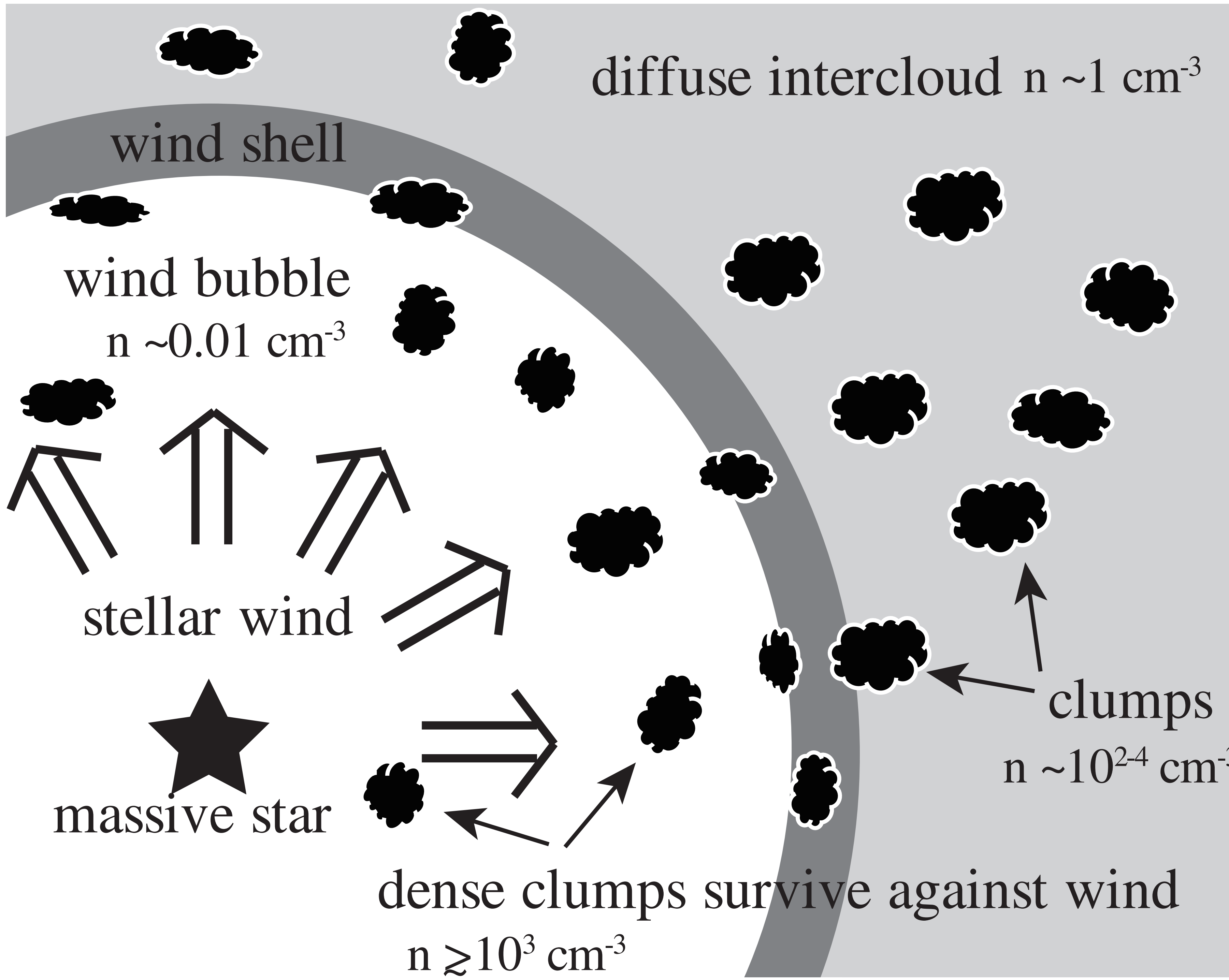
- KN problem for $\dfrac{\gamma_e h\nu}{m_e c^2} \gtrsim 1$
- RX J1713 electron cut-off: $E_e \approx 100$ TeV , $\gamma \approx 2\times10^8$
  - CMB KN problems: $E_e \approx$ 260 TeV
  - IR dust: $E_e \approx$ 26 TeV
  - Optical star light: $E_e \approx$ 0.26 TeV
  - NB: radiation density in optical light high, but few photons (200 vs 0.1 ph cm^{-3})
  - For KN $h\nu' \approx (m_ec^2)^2/h\nu$

A strange break



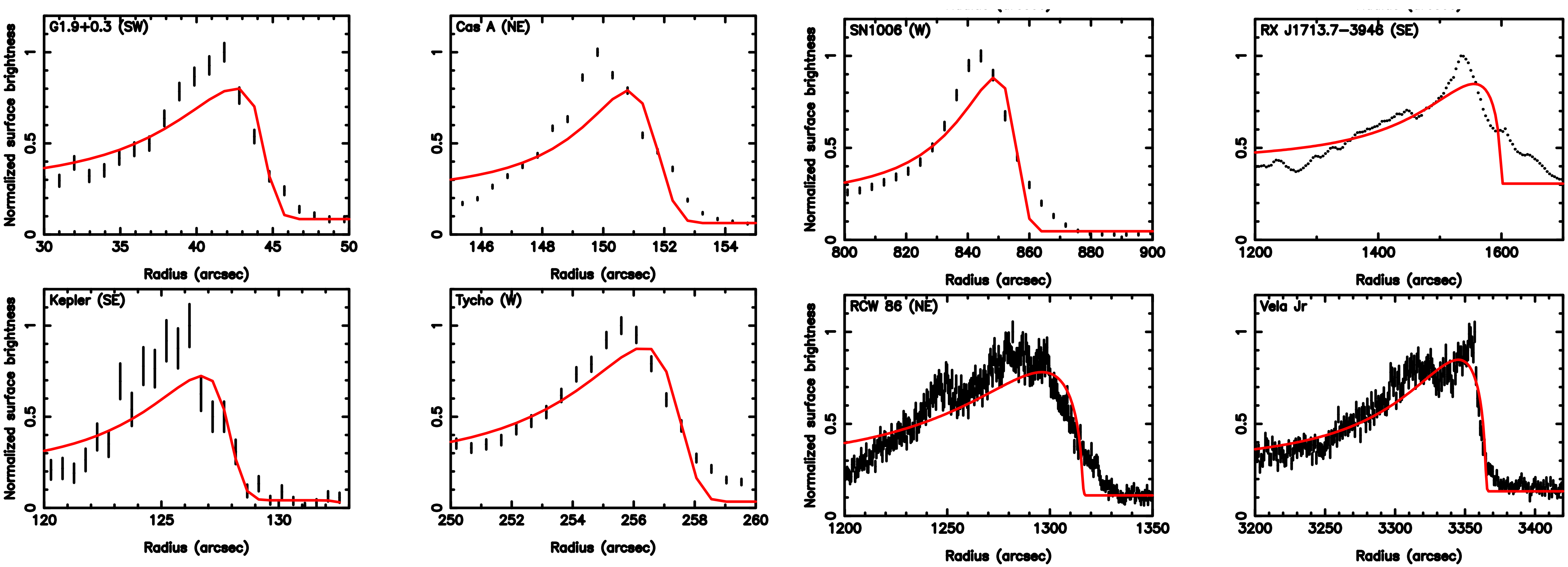


Saving the hadronic scenario: Clumpy medium



Inoue+ 2013, Gabici&Aharonian '14

X-ray synchrotron profiles

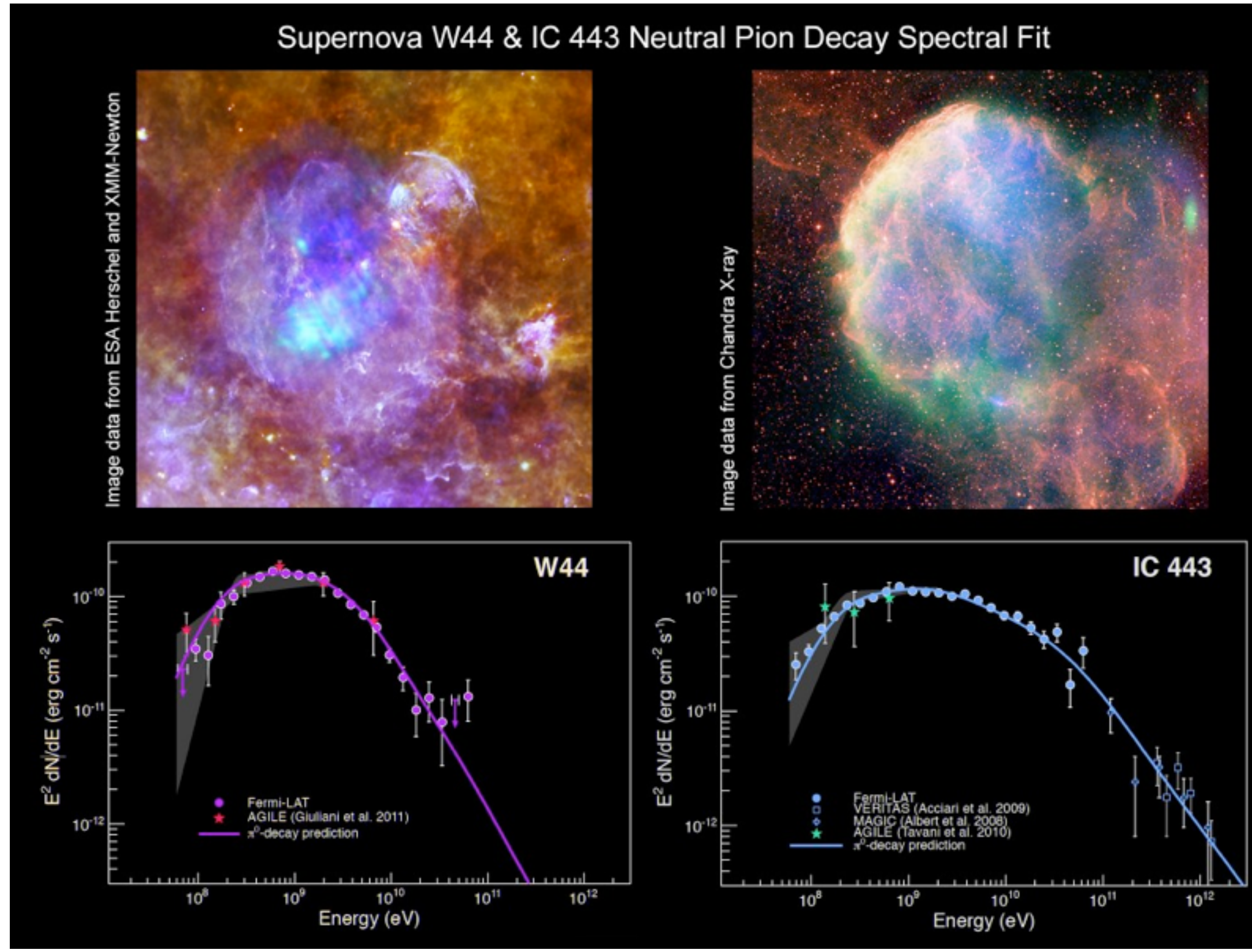


Helder, JV, et al. 2012

- Model: sudden increase at shock + exponential fall off (projected)
- Models do generally not fit very well (exception Vela jr)
- Some filaments (e.g. Cas A & SN1572) very narrow: <1″ or 10^{17}cm

Hadronic CRs confirmed: Fermi detection of pion bumps

Ackermann+ 2013



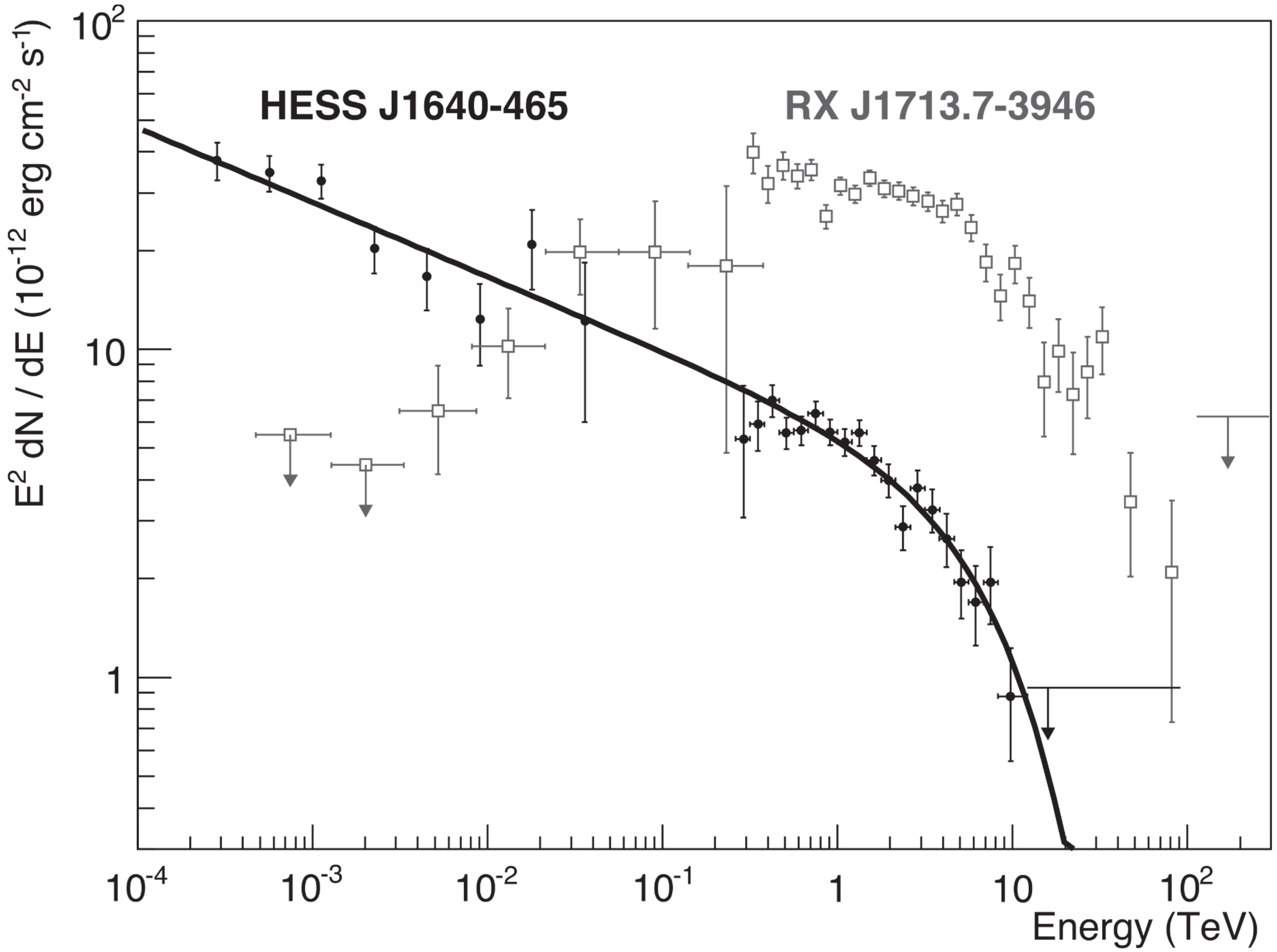
- Mature SNRs do contain cosmic-ray protons!
- *But: SNRs are mature, and E_{max} < 0.1 TeV*
- *What happened to high energy protons? Escape?*

On the leptonic scenario for ϒ-rays from 30Dor C

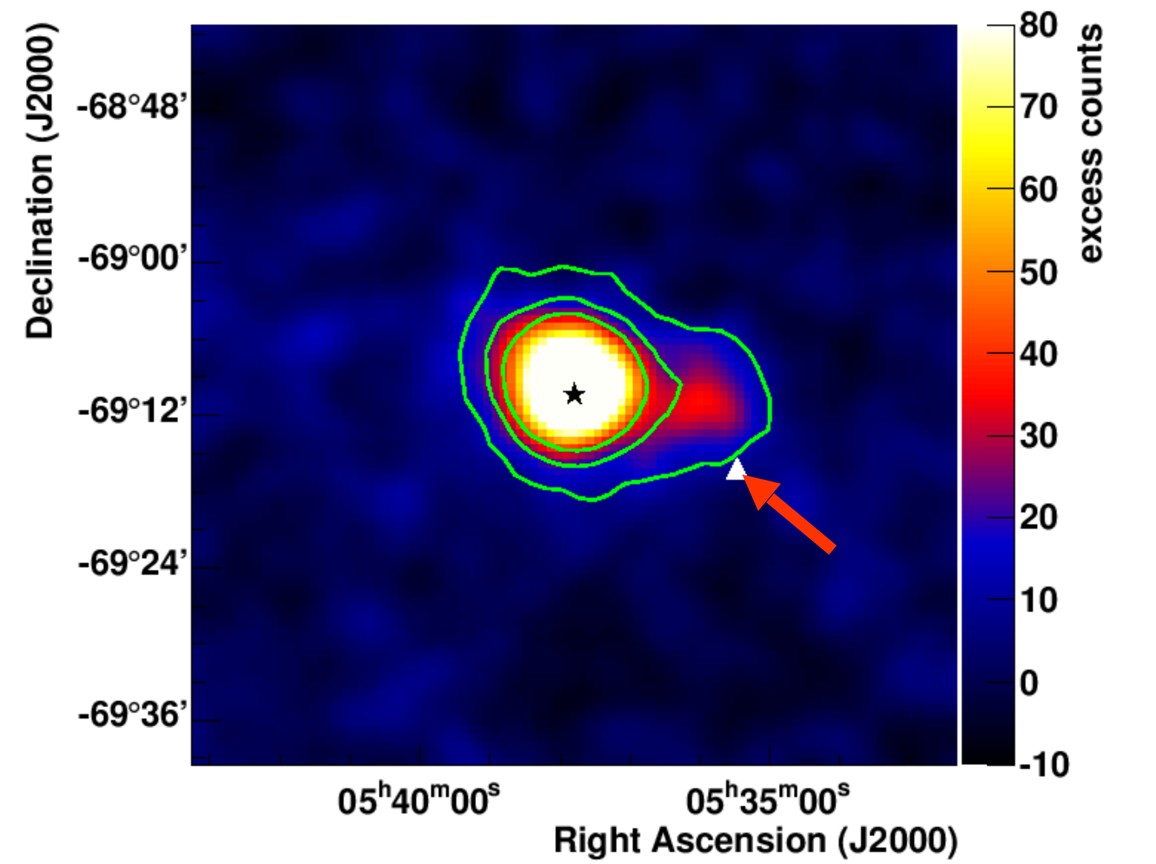
- The leptonic scenarios makes use of X-ray synchrotron detection: $V_s \gtrsim 3000$ km/s
- Assuming Sedov type of evolution:
  - $t = 0.4\, R/V_s \approx 6000$ yr
  - Model 30Dor C: ≃5 SNe went off,
  - But in 6000 yr? → may be one or two?
  - Sedov model density estimate:
    $R = 2.8 \times 10^8 (Et^2/n_H)^{1/5}$ cm → $n_H \approx 5\times10^{-4}\, E_{51}^{1/5}\mathrm{cm}^{-3}$
  - density much lower than inferred from thermal emission SE ($0.4\mathrm{cm}^{-3}$)

- X-ray synchrotron/leptonic scenario:
  - Need extremely low density
  - Adding more energy does not help much ($R \sim E^{1/5} t^{2/5}$)
- *Likely scenario:*
  - *Superbubble creates very low densities (multiple SNe/winds)*
  - *Last supernova remnant moves very fast through tenuous medium*
  - *X-ray synchrotron/ϒ-rays only intermittent periods of 5000-10000 yr*

A true hadronic source?



Non-detection of SN1987A

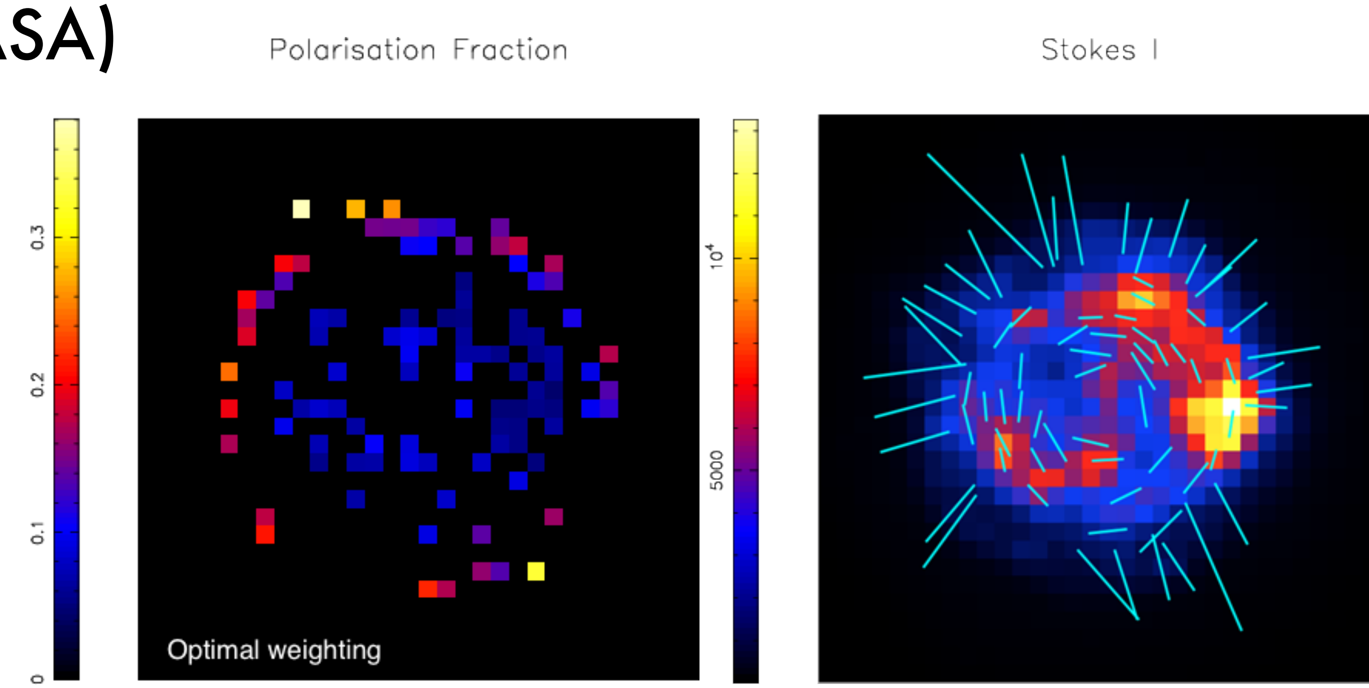


- Gamma-ray flux
  $F\ (>1\ \text{TeV}) < 5 \times 10^{-14}\ \text{cm}^{-2}\text{s}^{-1}$
  - 99% confidence level
- Gamma-ray luminosity
  $L\ (>1\ \text{TeV}) < 2.2\ 10^{34}$ erg/s
- **Hadronic (proton) scenario**
  - **gamma-ray emission** predicted (e.g. Berezhko+ 11)
  - shock front has reached equatorial ring with $n_H = 10^3 \ldots 3\text{x}10^4\ \text{cm}^{-3}$
- Energy in protons: $W_{pp} < 1.4\ f \times 10^{48}$ erg
  - f is fraction of particles interacting with the ring: $f \sim 0.2$

→ SN 1987A is not an efficient accelerator

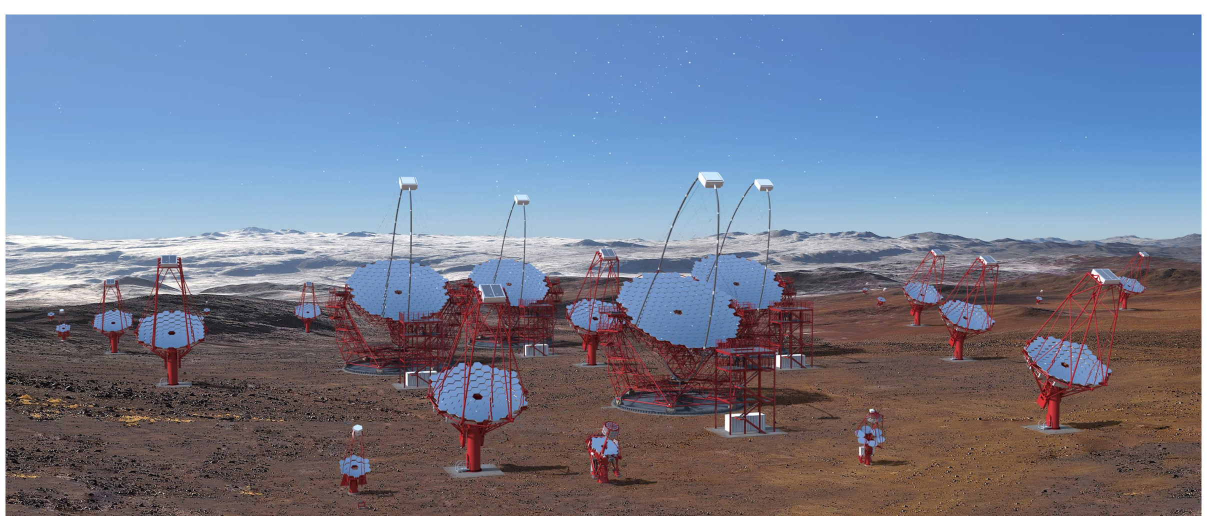
The future in X-ray and gamma-rays

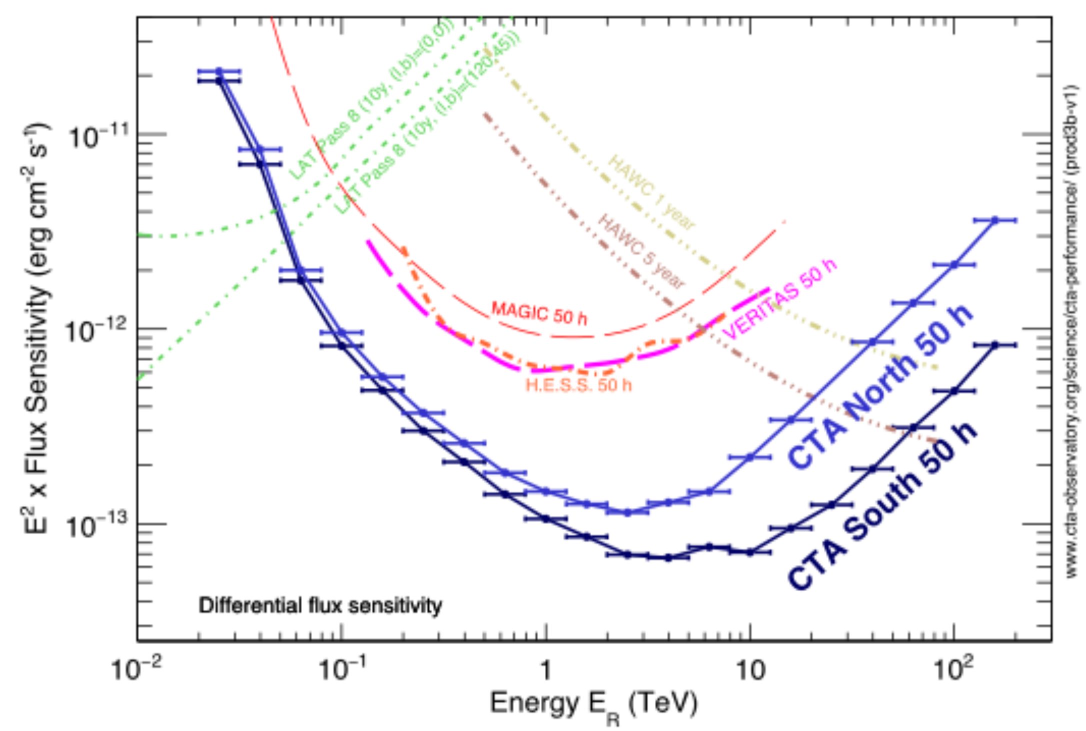
- Imaging X-ray polarisation with IXPE (NASA)
  - PI M Weisskopf
  - Gas Pixel Detector
  - To be launched in 2022
  - Measure magnetic field turbulence (η)!



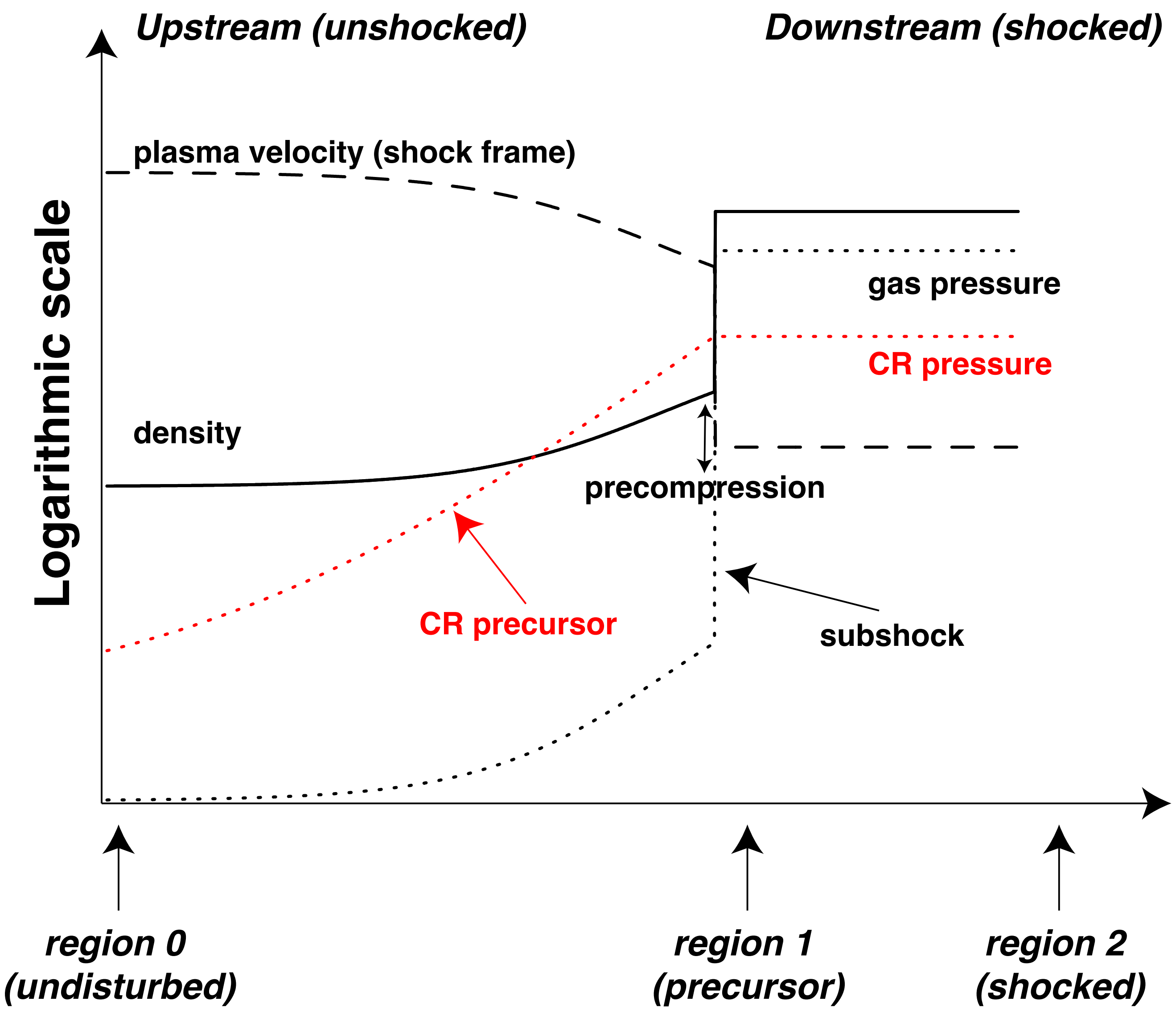
Simulations Cas A (Vink&Zhou 2018)

- Cherenkov Telescope Array (CTA)
  - >100 telescopes, two locations (La Palma, Chile)
  - Operational > 2023





Accelerating shock



- Simple shock: sudden jump in density, velocity and pressure
- Accelerating shock:
  - accelerated particles in front of shock
  - accelerated particles may alter flow into shock
  - may pre-heat the medium ahead of the shock
  - may lower Mach number of the shock → non-linearity
- Cosmic-ray precursor length scale: <10% of shock radius
  - Otherwise particles no longer make it back to the shock!

Maximum photon energy synchrotron radiation

- Electron protons accelerated similarly
  - Electrons 1% of CR composition
- But very-high energy electrons lose energy fast:

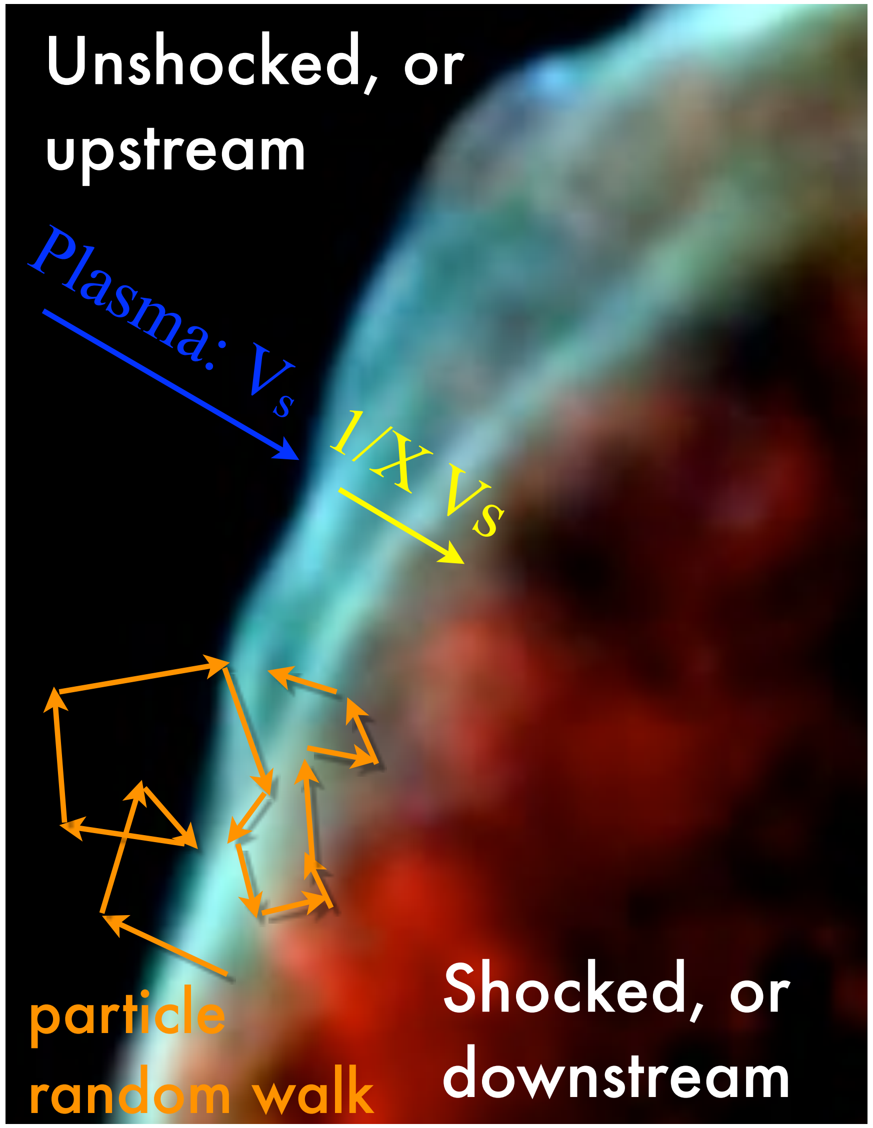
$$\left(\frac{dE}{dt}\right)_{\rm syn} \approx -\frac{B^2E^2}{634}\ {\rm erg\ s^{-1}}.$$

- Maximum energy: acceleration balances losses

$$\frac{dE}{dt} \approx \frac{\Delta E}{\Delta t} = \frac{\frac{4}{3}\frac{\Delta v}{c}E}{\frac{4}{\beta c}\left(\frac{D_1}{v_1}+\frac{D_2}{v_2}\right)} \approx \frac{(v_1-v_2)}{3}\frac{E}{\frac{D_1}{v_1}+\frac{D_2}{v_2}}$$

$$D_1 = \frac{1}{3}\eta_{\rm max}\left(\frac{E}{E_{\rm max}}\right)^{\delta-1}\frac{cE}{eZB_1}$$

$$E_{\rm e,max} \approx 42\eta^{-1}\left(\frac{B_2}{100\ \mu{\rm G}}\right)^{-1/2}\left(\frac{V_{\rm sh}}{5000\ {\rm kms^{-1}}}\right)\left(\frac{\frac{\chi-1}{(1+\chi\chi_B)}}{3/17}\right)^{1/2}\ {\rm TeV}$$

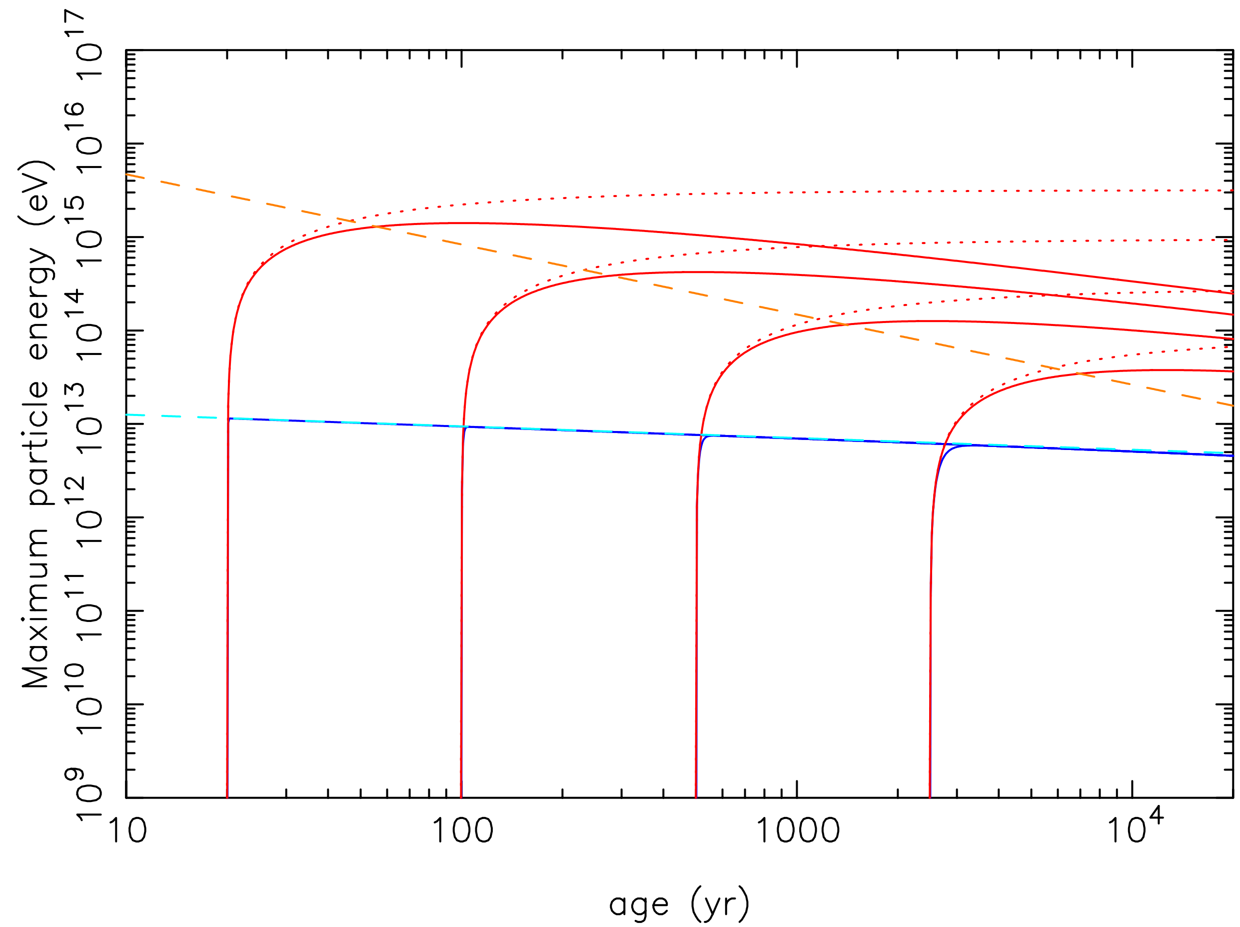


Aharonian &Atoyan 99

- Combining with photon energy hν≈7.4E²B keV:

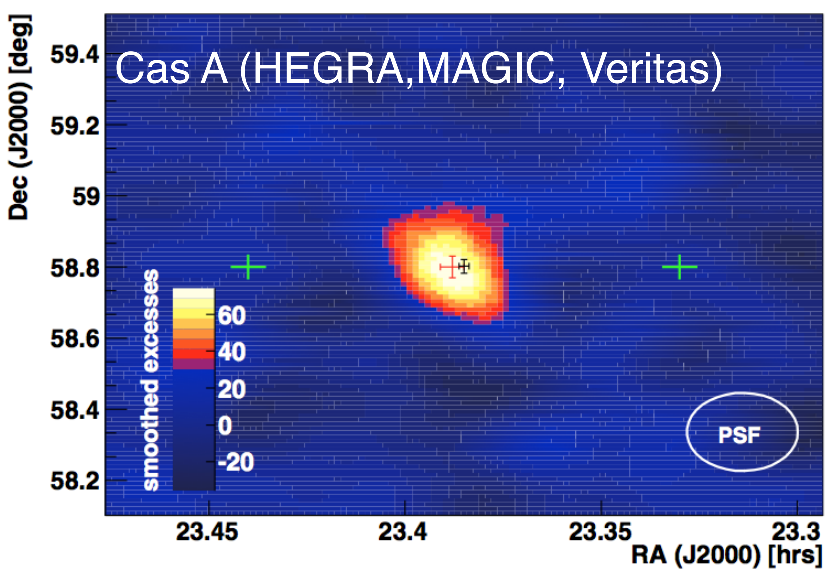
$$h\nu_{\rm max} \approx 3\eta^{-1}\left(\frac{V_{\rm sh}}{5000\ {\rm kms^{-1}}}\right)^2\left(\frac{\frac{\chi-1}{(1+\chi\chi_B)}}{3/17}\right)\ {\rm keV}$$

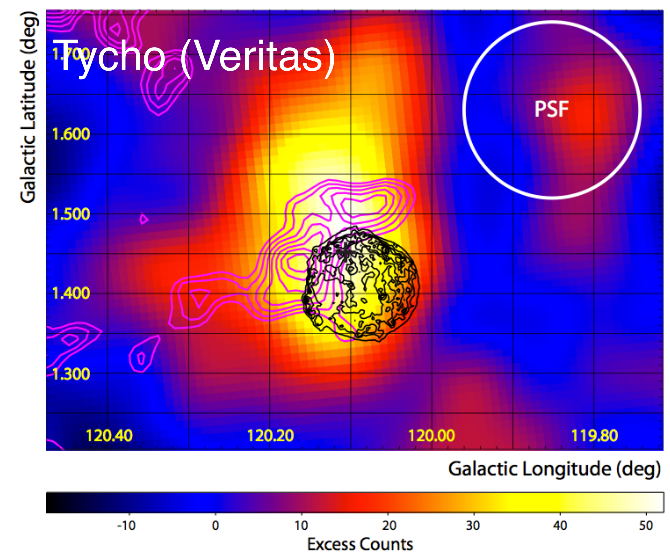
Are the highest energy Galactic cosmic rays accelerated by very young SNRs (radio supernovae)?

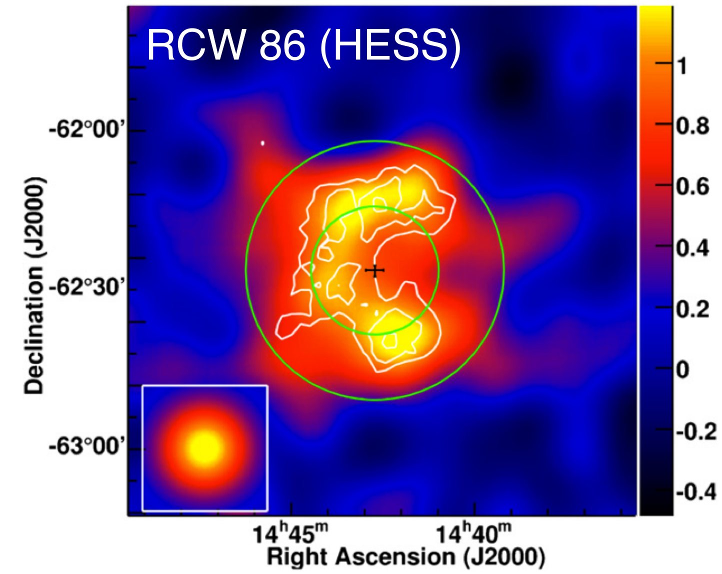


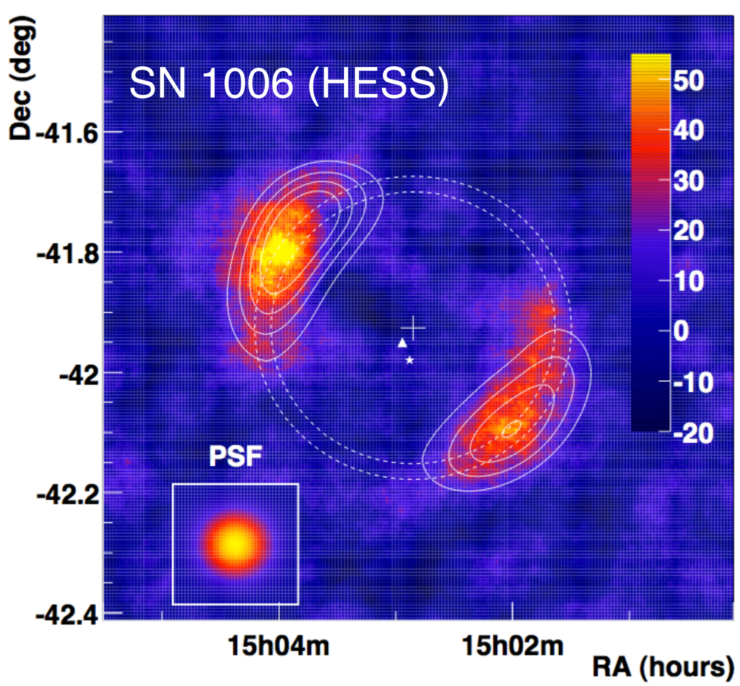
- SNRs in supergiant winds:
  - Very young → very high shock velocity (V_s≈10,000-20,0000 km/s)
  - Late phase winds (RSG) are dense and $\rho \propto 1/r^2$ → highest density in first 50 yr
  - $B^2 \propto \rho V_s^{2\text{-}3}$ → expect fastest acceleration at very young age!
  - Since $\rho \propto 1/r^2$ also many particles enter shock early on
    (Ptuskin& Zirakashvili 05, Schure, Bell, 2013, Cardillo + 2015,...)
- Example of potential accelerators
  - SN1993J in M81 (e.g. Marcowidth+ 2015)

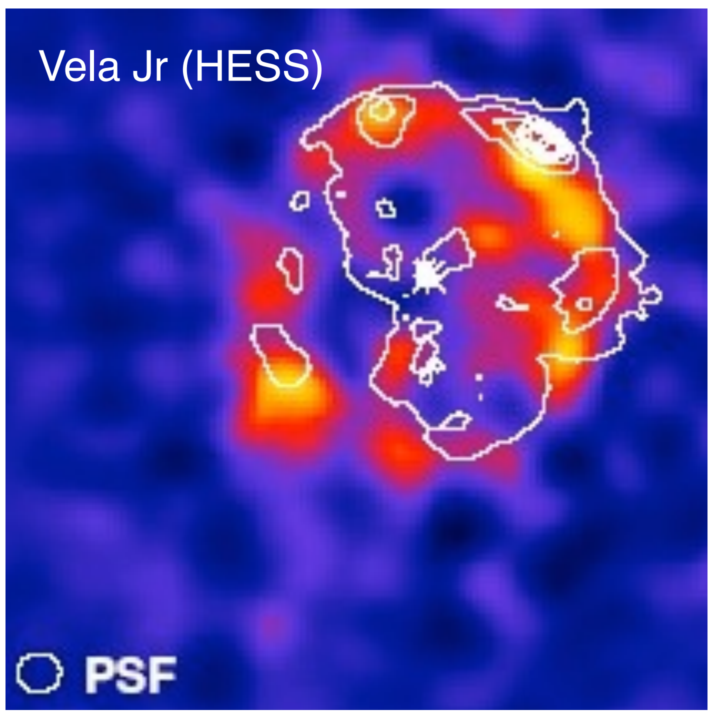
Some young SNRs in TeV gamma-rays

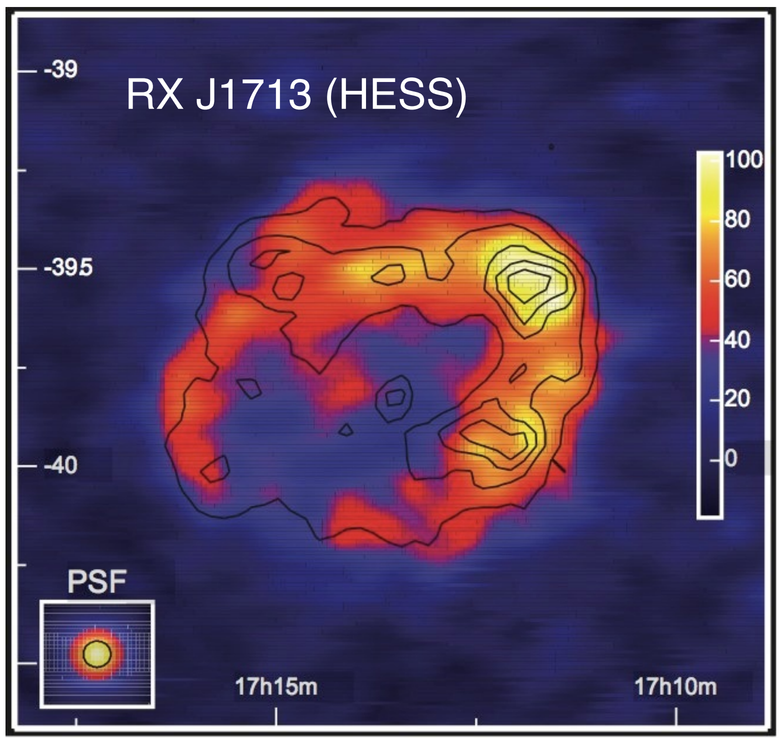




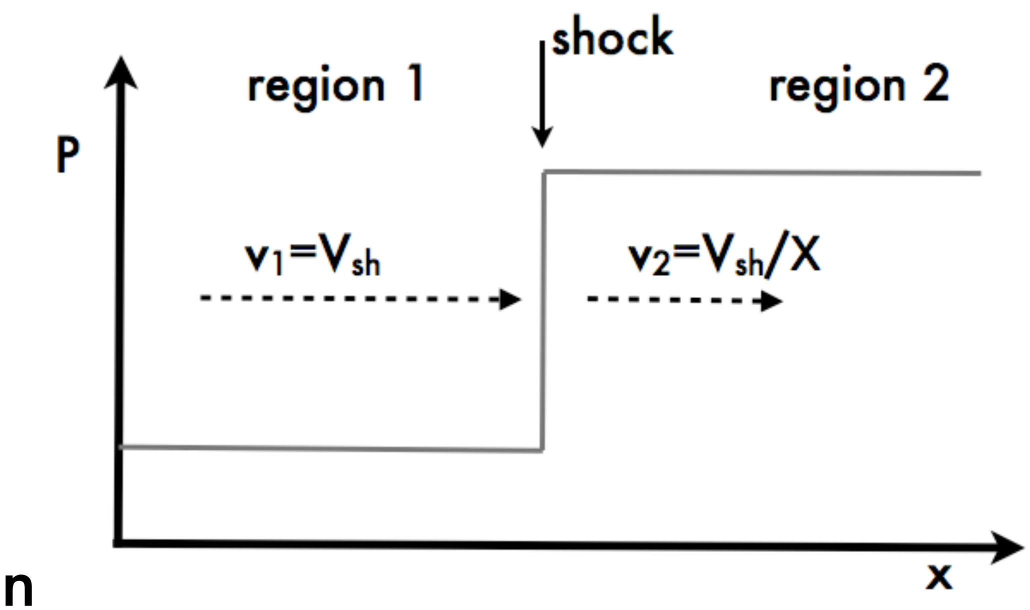








Without particle acceleration shocks are described by Rankine-Hugionot relations



- Rankine-Hugoniot relations:
  mass-, momentum- & enthalpy-flux conservation

$$\rho_1 v_1 = \rho_2 v_2 \qquad \rightarrow \chi \equiv \frac{\rho_2}{\rho_1} = \frac{v_1}{v_2}$$

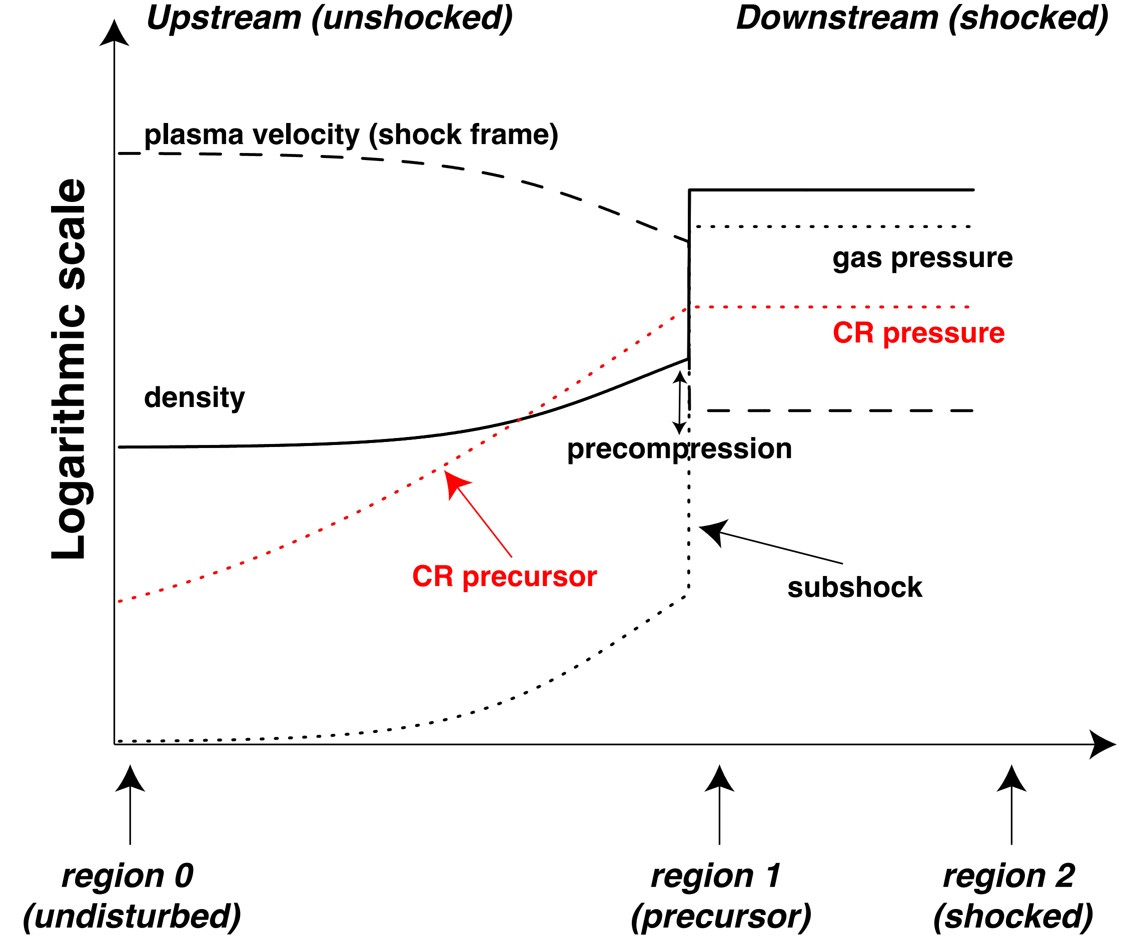
$$P_1 + \rho_1 v_1 = P_2 + \rho_2 v_2$$

$$(P_1 + u_1 + \frac{1}{2}\rho_1 v_1^2) v_1 = (P_2 + u_2 + \frac{1}{2}\rho_2 v_2^2) v_2$$

- Solutions for strong shocks:

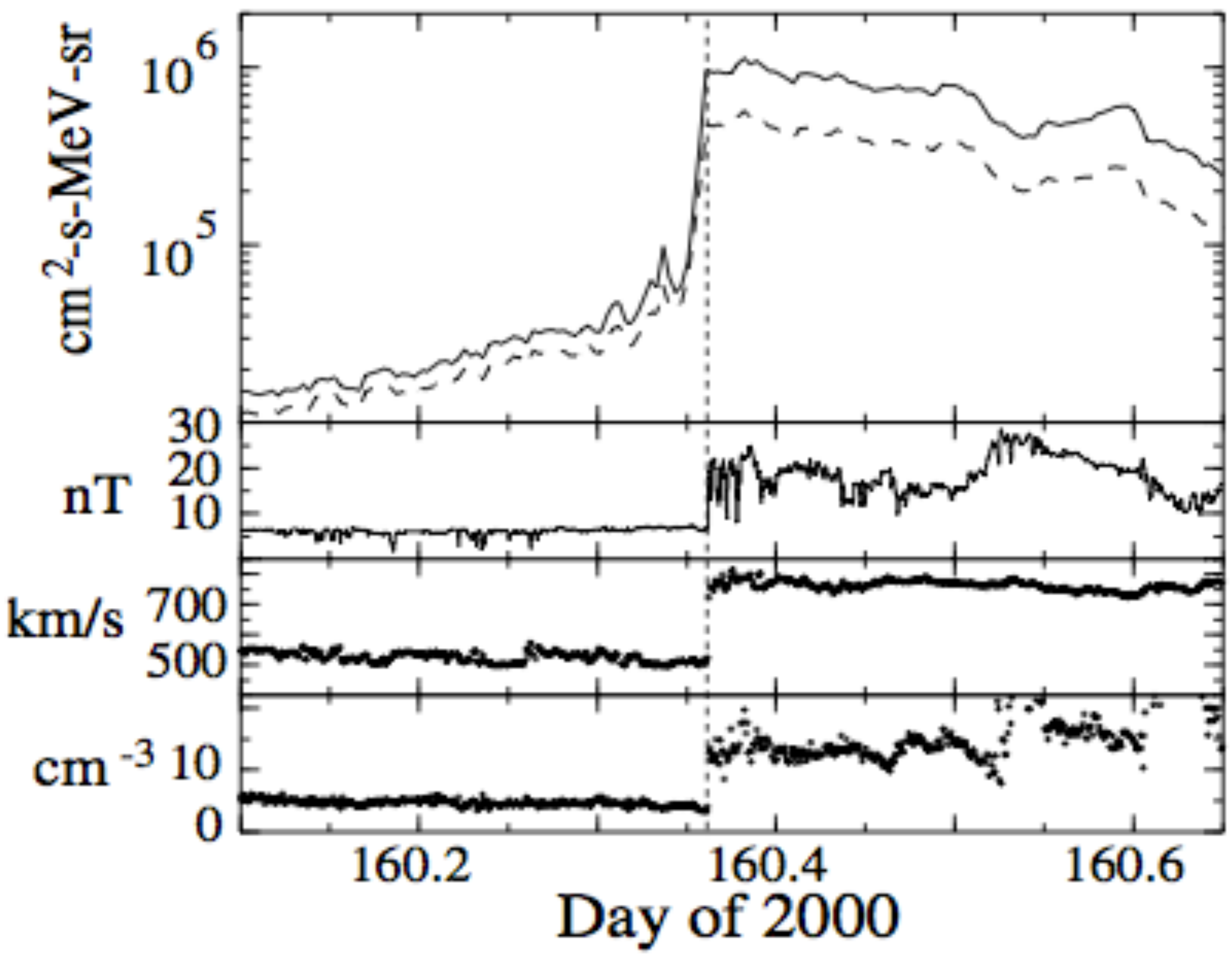
$$\chi = \frac{(\gamma_{\rm g}+1)M_1^2}{(\gamma_{\rm g}-1)M_1^2+2} \qquad \rightarrow 4 \text{ for } \; M_1^2 \equiv \frac{1}{\gamma_{\rm g}}\frac{\rho_1 v_1^2}{P_1} \rightarrow \infty$$

Shock modification due to acceleration (non-linear acceleration)

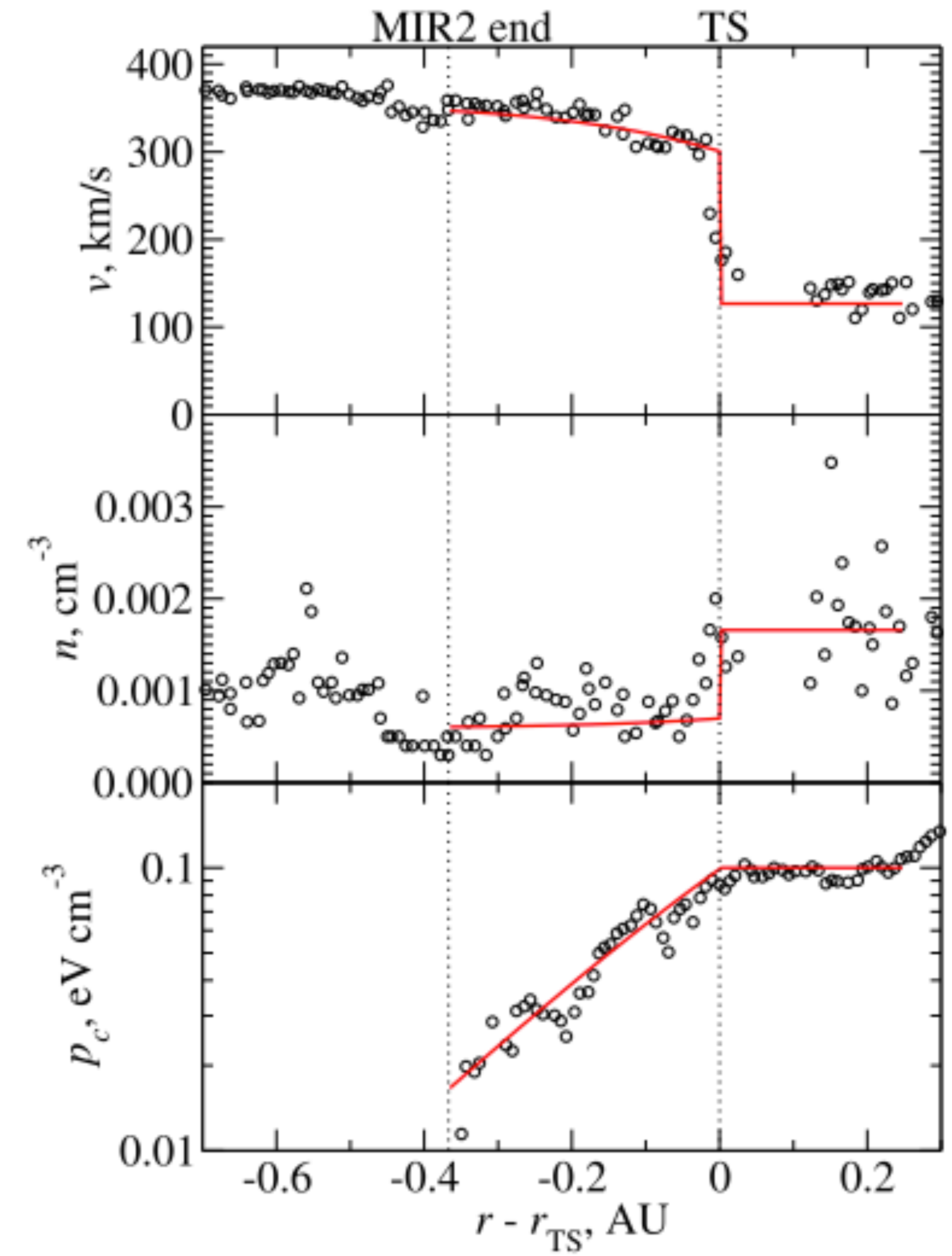


- Particles diffusing in front of shock: modification of shock structure (e.g. Eichler 1979)
- Efficient acceleration results in non-linear shock structures:
  - Precursor region + heating
  - *Lower* post-shock plasma temperatures
  - Higher *overall* shock compression ratios
  - Lower shock compression at the gas shock (=sub shock)

Close-ups of accelerating shocks

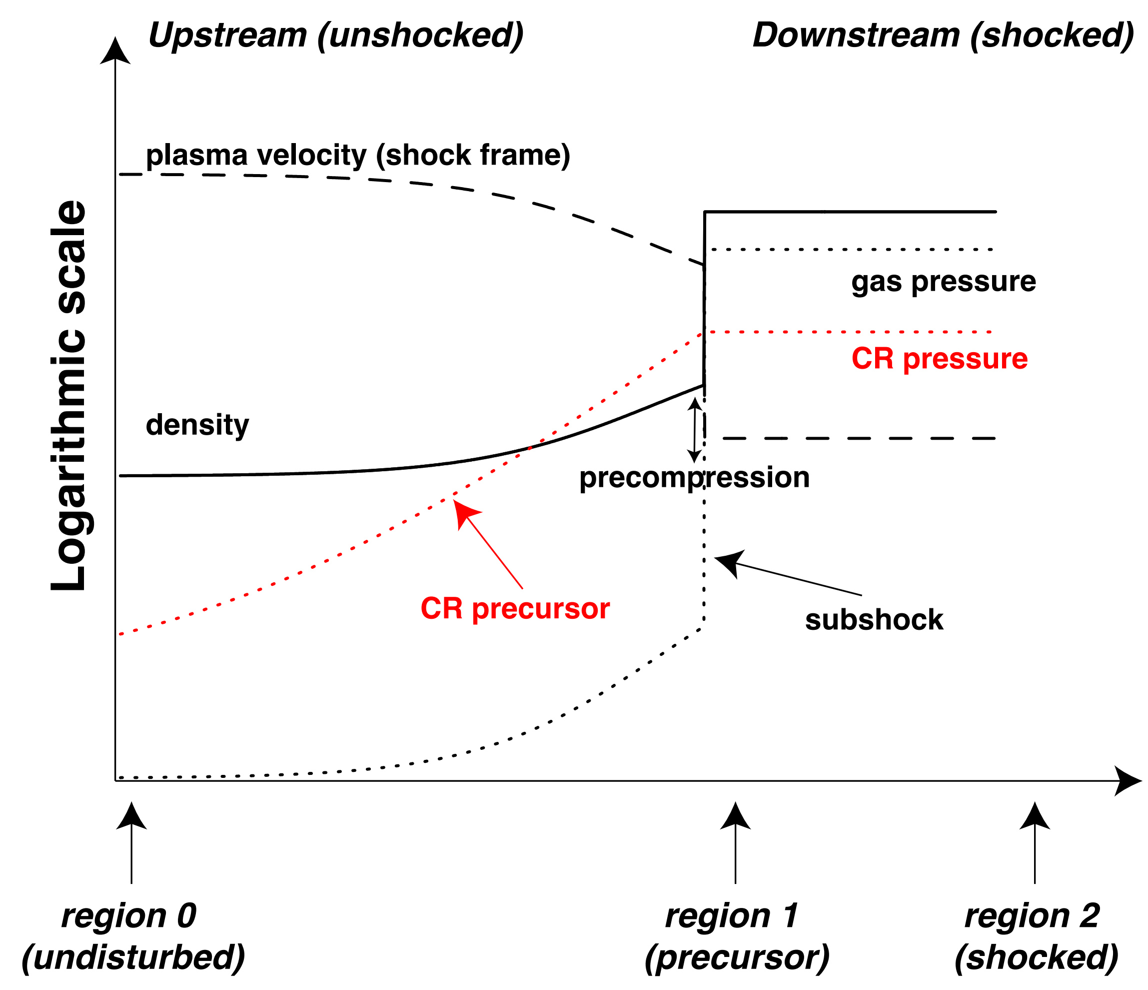


CME induced shock (ACE, Giaccalone '12)



Solar system termination shock (Voyager 2, Florinski+ 09)

Non-linear acceleration: simplify the problem by extending the Rankine-Hugoniot relations



- Assume two "fluids":
    1. plasma with γ_g=5/3,
    2. cosmic rays with $4/3<\gamma_{cr}<5/3$
- Allow for energy to escape (cosmic rays leaving system): $\epsilon \equiv F_{cr,esc}/(\frac{1}{2}\rho_0 v_0^3)$
- Close equations by evaluating conditions in three regions:
    1. undisturbed medium
    2. in cosmic-ray precursor, just ahead of shock
    3. shocked medium
- Closing relation: cosmic-ray pressure continuous across shock (boundary 1 & 2)

The *extended* Rankine-Hugoniot relations

Vink+ '10,Vink&Yamazaki '14

- One *running parameter*: precursor compression X_{prec}
- Assume value of $\gamma_{cr} \in [4/3 - 5/3]$
- Total compression ratio:

$$M_{g,1} = M_{g,0}\chi_{prec}^{-(\gamma_g+1)/2}$$

$$\chi_{tot} = \chi_{prec}\chi_{sub} = \frac{(\gamma_g+1)M_{g,0}^2\chi_{prec}^{-\gamma_g}}{(\gamma_g-1)M_{g,0}^2\chi_{prec}^{-(\gamma_g+1)}+2}$$

- Expression for fractional cosmic-ray pressure:

$$w_2 \equiv \frac{P_{cr,2}}{P_{tot,2}} = \frac{(1-\chi_{prec}^{\gamma_g}) + \gamma_g M_{g,0}^2\left(1-\frac{1}{\chi_{prec}}\right)}{1+\gamma_g M_{g,0}^2\left(1-\frac{1}{\chi_{tot}}\right)}$$

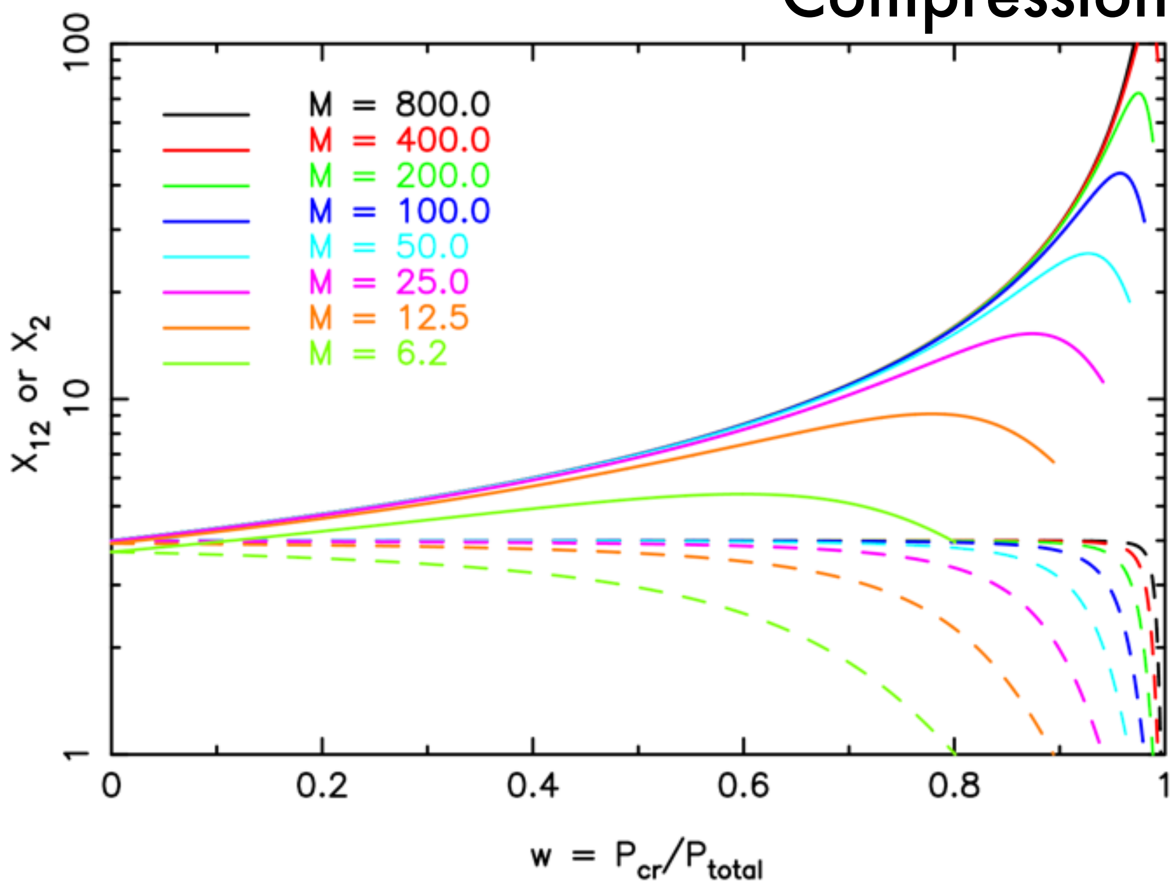
- Expression for energy escape:

$$\epsilon = 1 + \frac{2}{\gamma_g M_{g,0}^2}\left[G_0 - \frac{G_2}{\chi_{tot}}\right] - \frac{2G_2}{\chi_{tot}} + \frac{1}{\chi_{tot}^2}(2G_2-1)$$

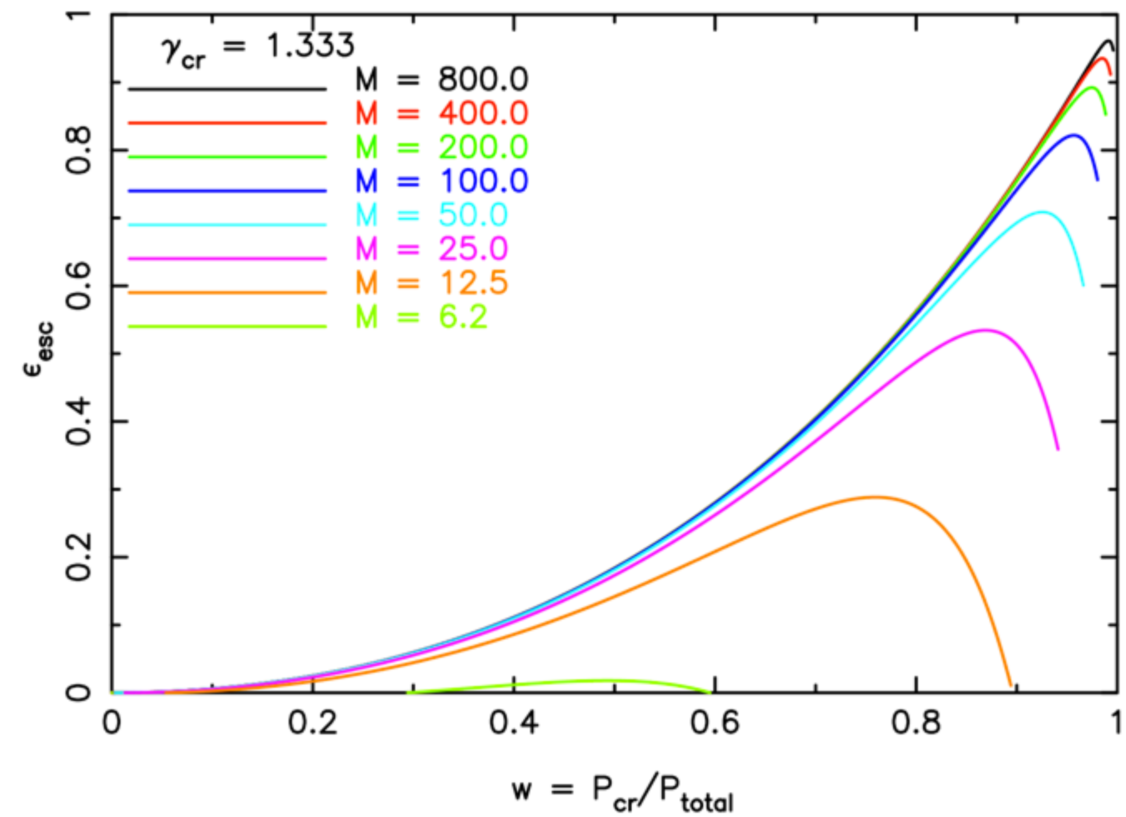
$$G_2 \equiv w_2\frac{\gamma_{cr}}{\gamma_{cr}-1} + (1-w_2)\frac{\gamma_g}{\gamma_g-1}$$

Results of simple Rankine-Hugoniot extensions

Compression



Escape

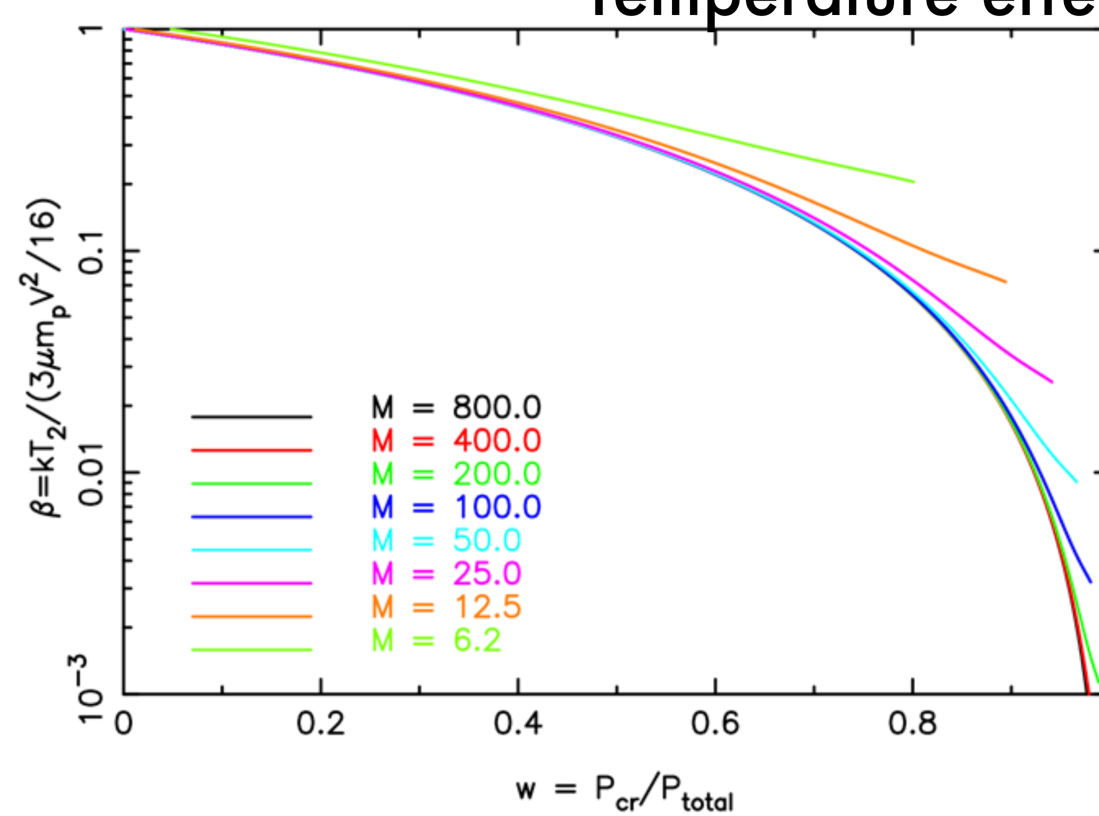


Higher acc. efficiencies

→

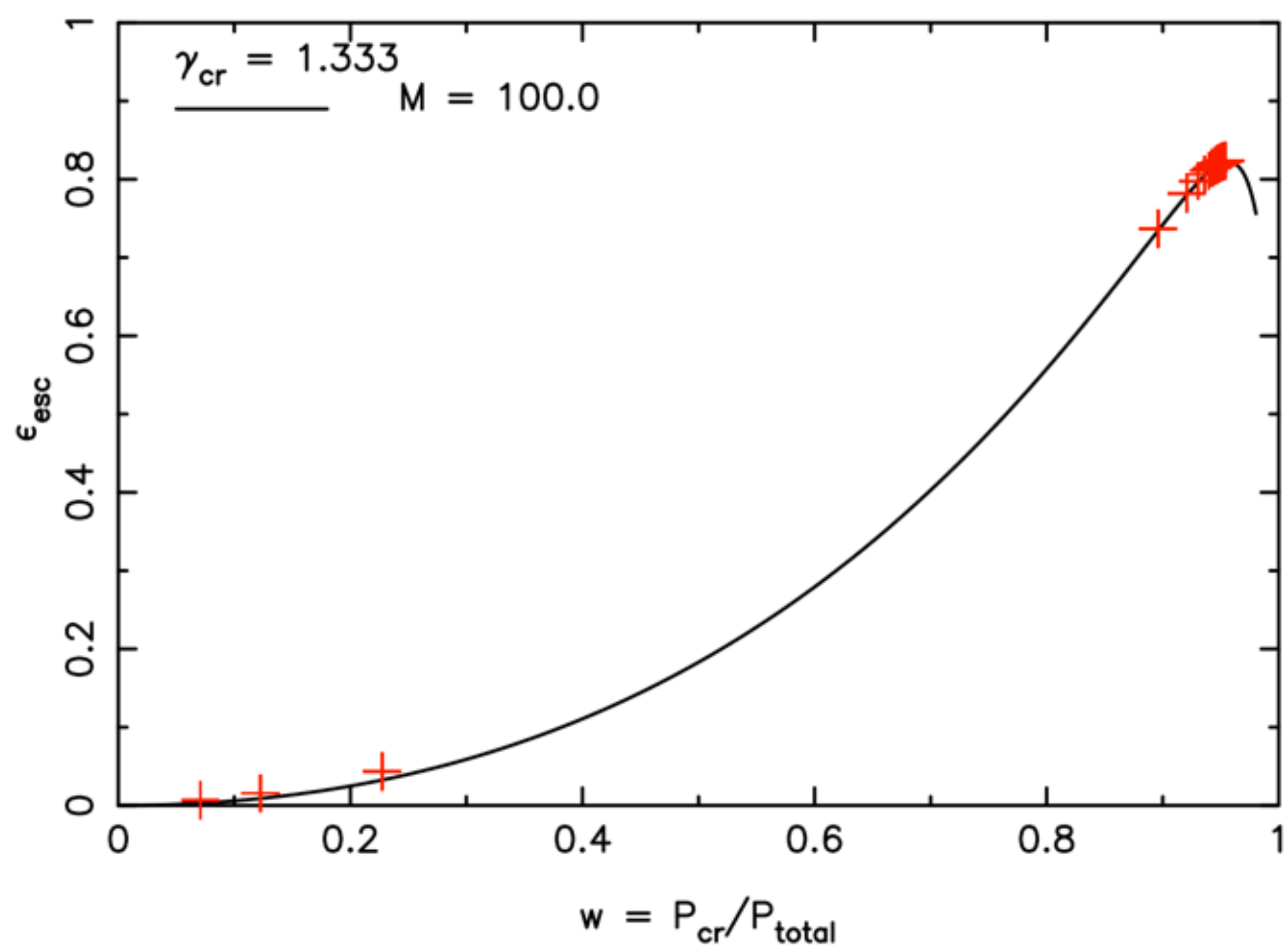
$w = P_{cr}/P_{tot}$

Temperature effects



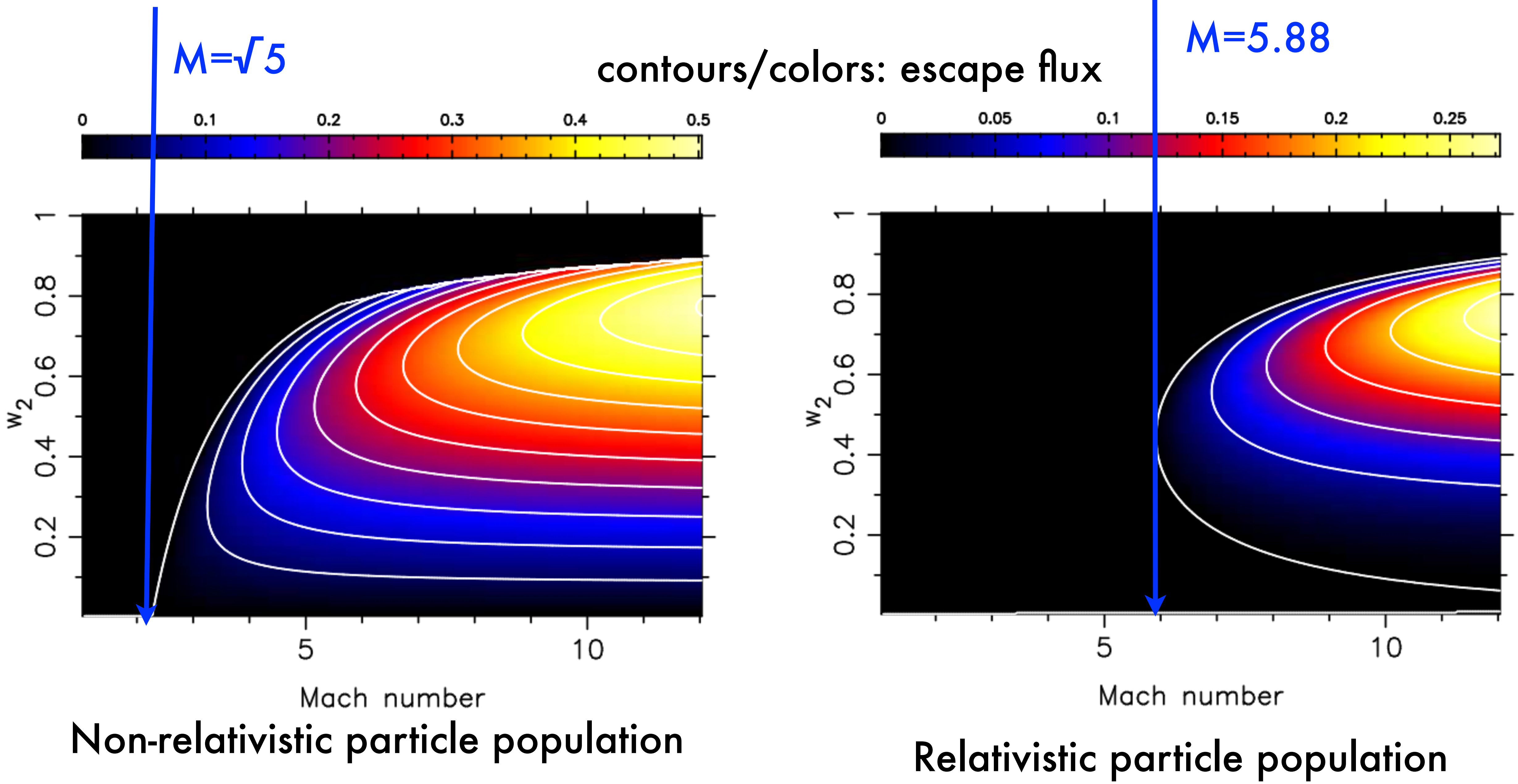
Vink+ '10,Vink&Yamazaki '14

The models agrees with the kinetic non-linear acceleration model of Blasi et al. (2005)



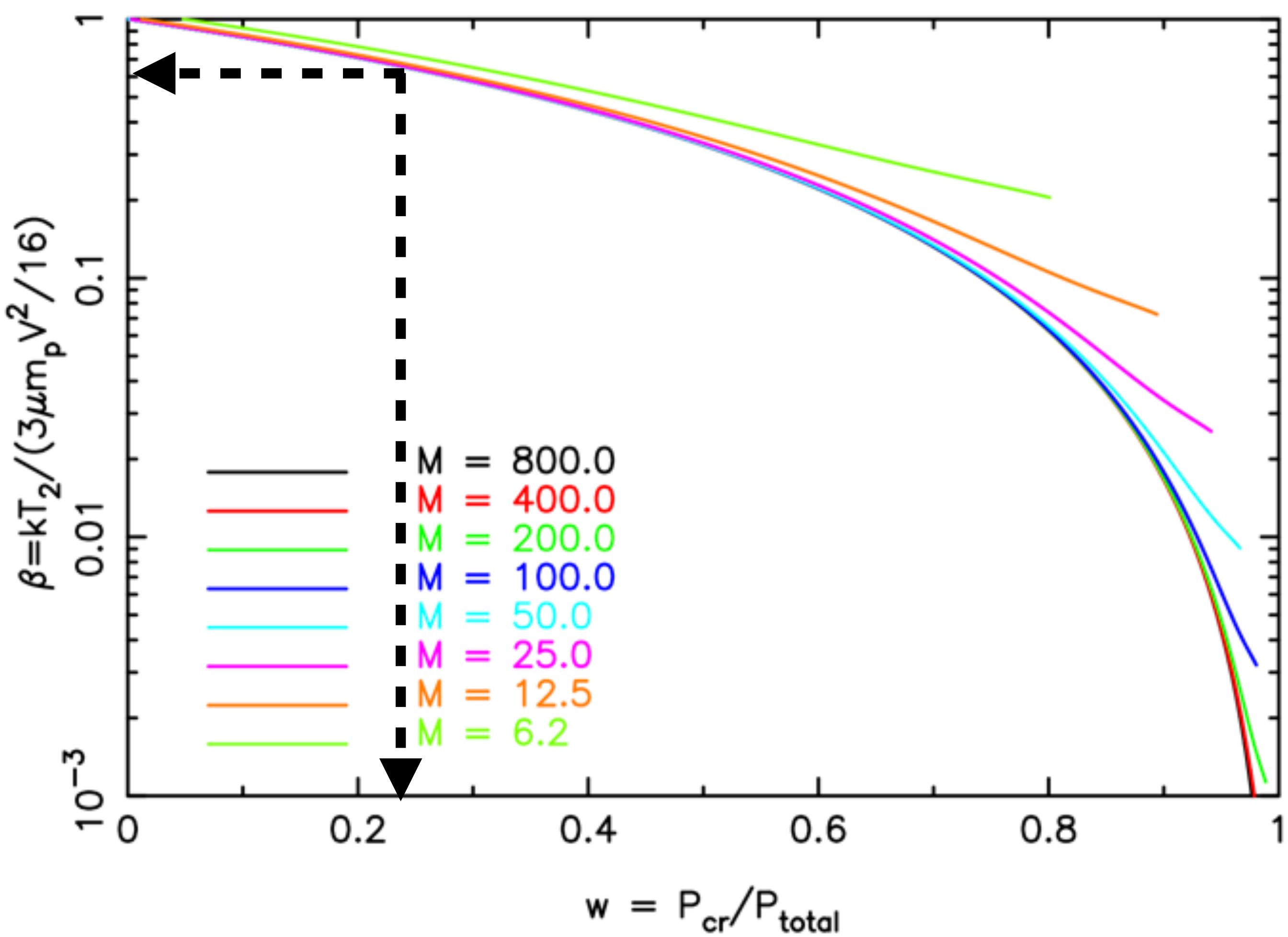
- Crosses: Blasi model for different E_{max}
- Blasi model: one solution (depends on acceleration details)
- Extended Rankine-Hugoniot: allowed possibilities

There are always solutions with conserved energy-flux: correspond to Drury&Völk model

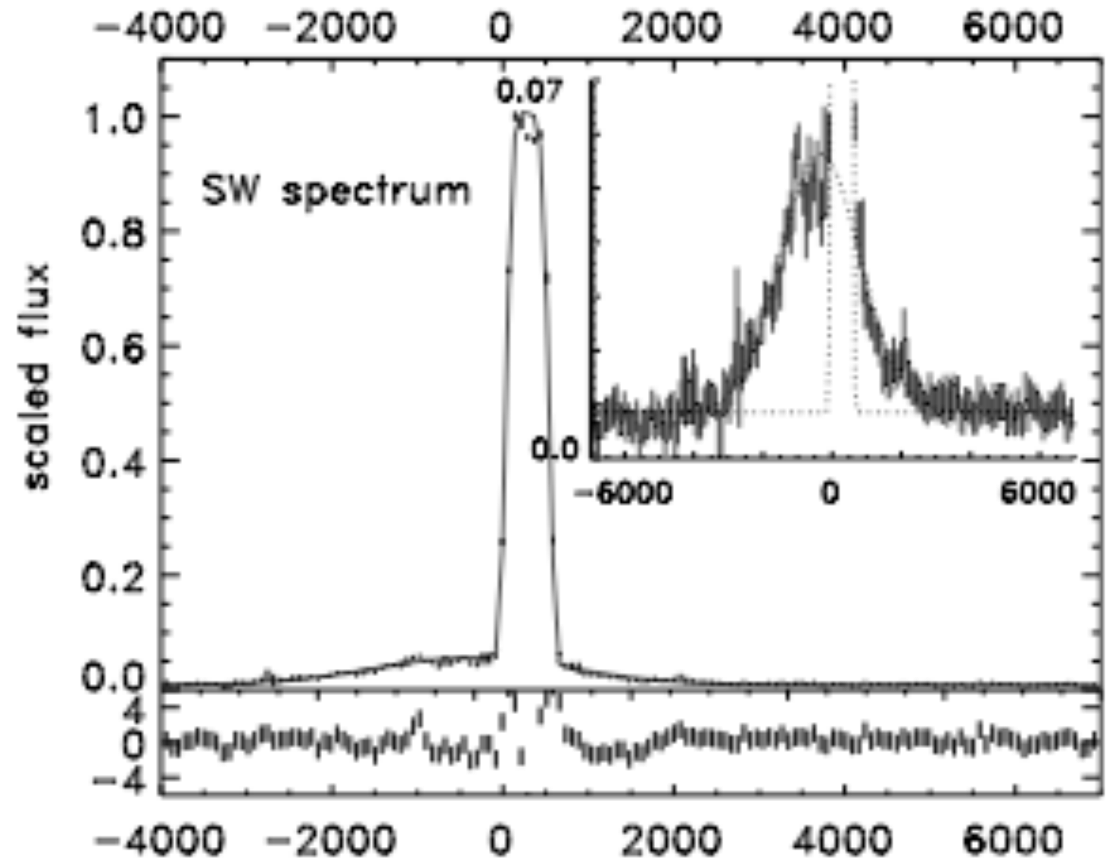


- For non-relativistic cosmic rays for given M: one CR solution with ϵ=0
- For relativistic dominated particles: two CR solutions with ϵ=0
- A lower limit of M=√5 can have implications for shocks in the solar system and clusters of galaxies (relics)

A measurement of the cosmic-ray efficiency in a fast supernova remnant shock 0509-675



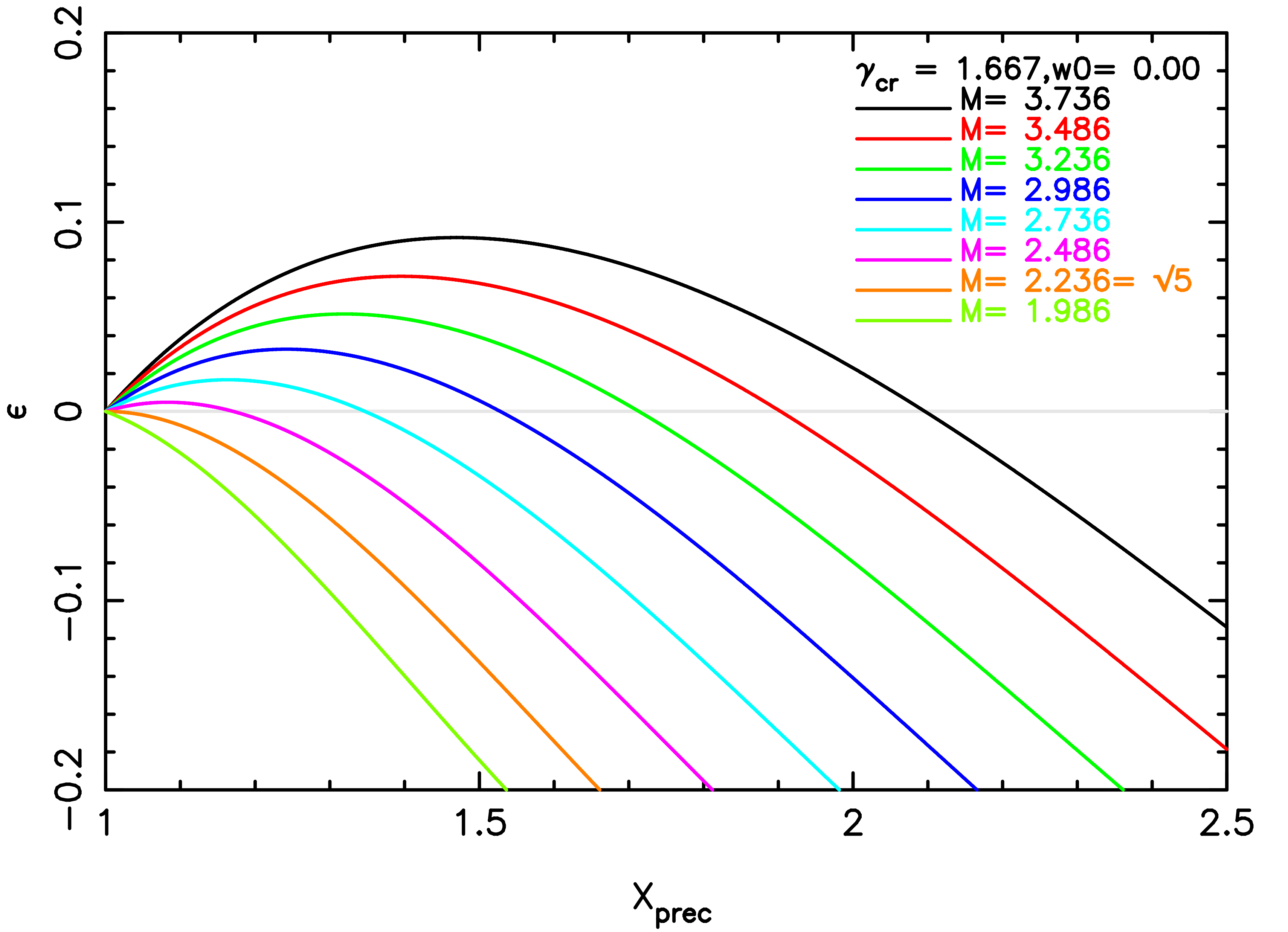
Helder, Kosenko, Vink '10



- Distance known (LMC, 50 kpc)
- Shock velocity: X-ray line broadening + Chandra expansion: Vs> 5000 km/s
  - One of the fastest shocks in a known SNR!
- Hα broad line widths: 2680 ± 70 km/s (SW), 3900 ± 800 km/s
- Discrepancy in kT: $kT_{measured}/kT_{exp} \leq 0.7$
- Hence: cosmic-ray efficiency w≥25%?

Escape energy as a function of pre-cursor compression

Vink&Yamazaki 2014



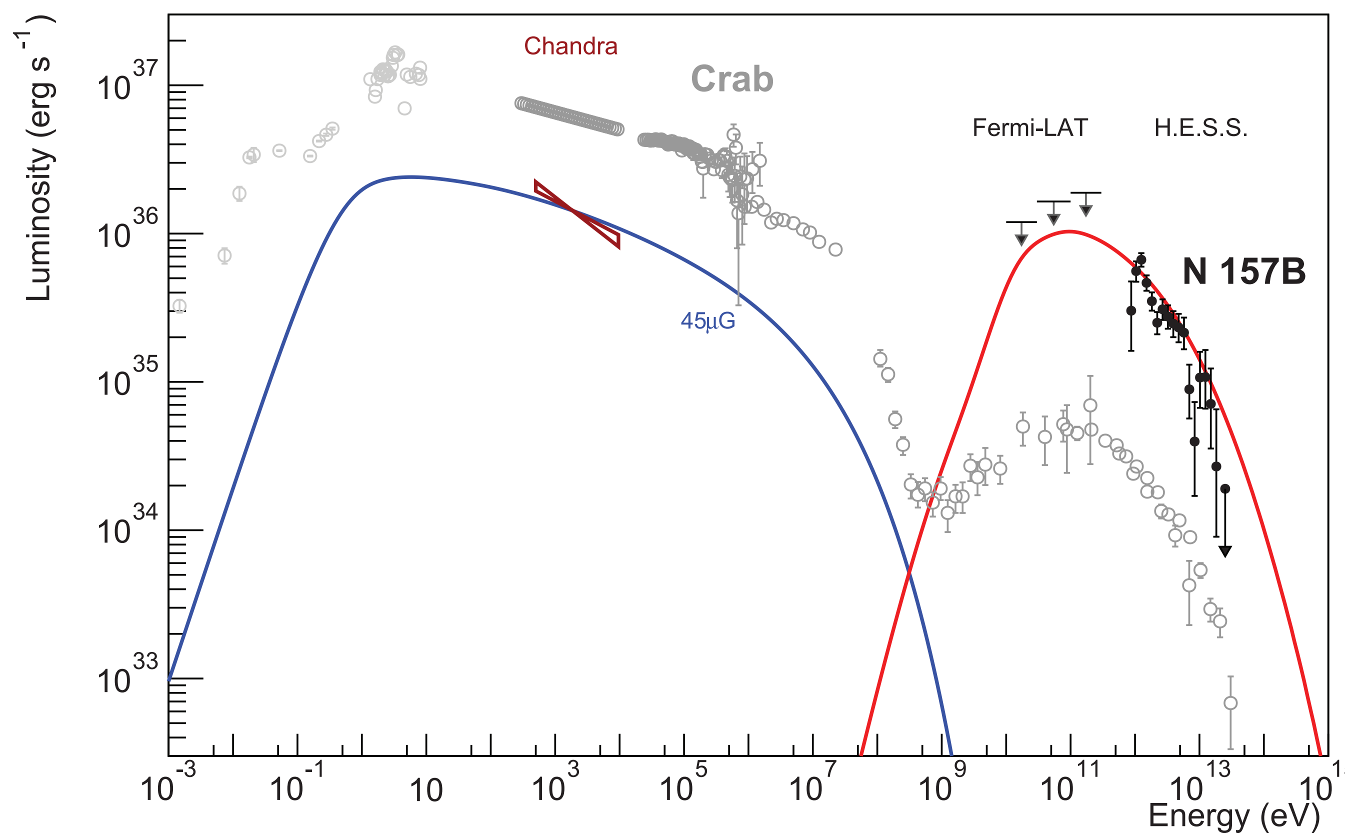
Implications and concerns

- The extended Rankine-Hugoniot relations
  - are simple
  - give acceleration efficiency for a measured shock velocity/post-shock kT
  - should be consistent, but do not replace full kinetic descriptions
    (provide a constraint on efficiency, but do not predict efficiency)
  - are not fully self-consistent: adiabatic index is a parameter, not calculated

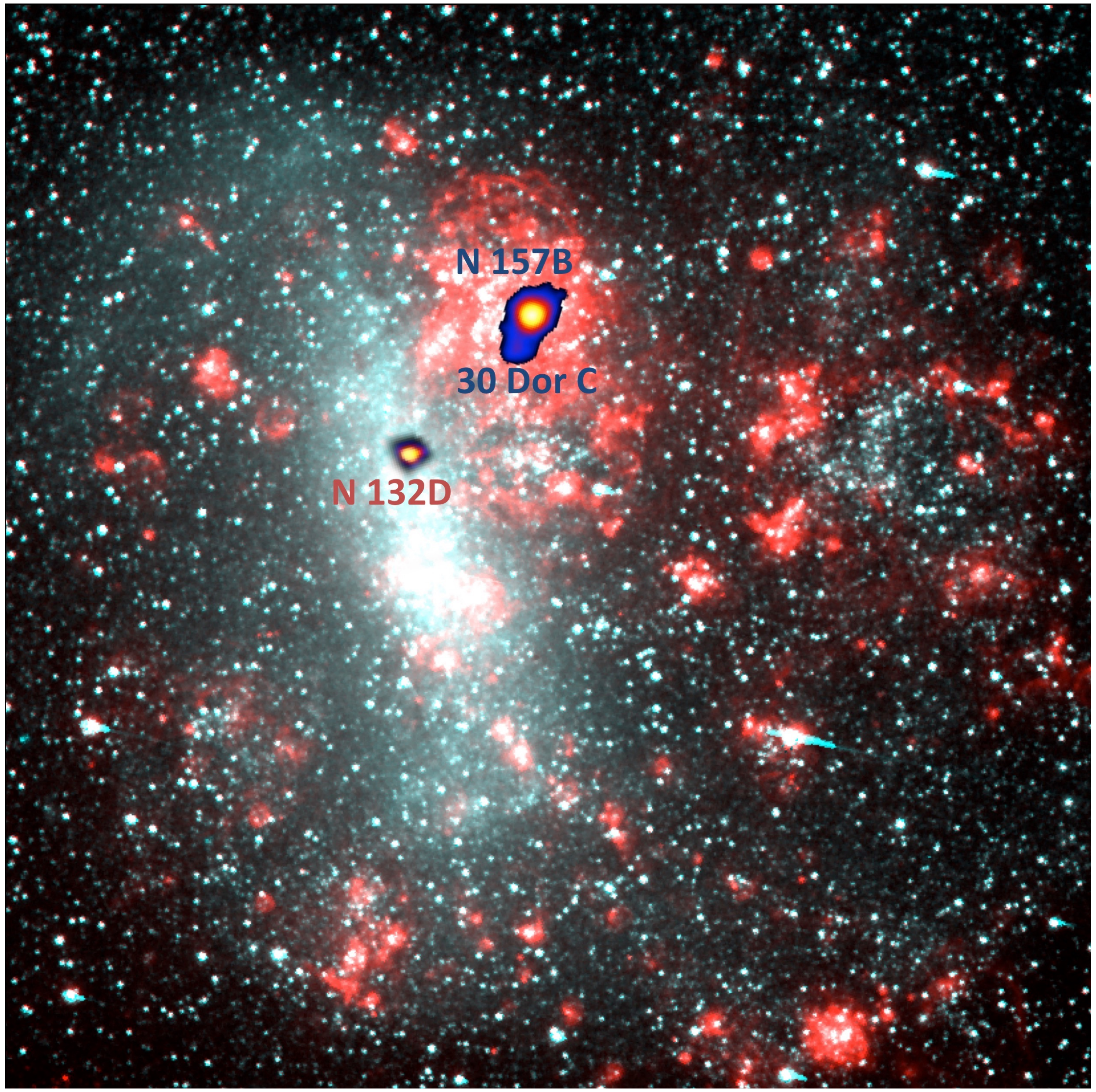
- Two-fluid approach has in general limitations:
  - What about slightly non-thermal particles, non-Maxwellian distributions?
  - What about non-steady state effects?

- A clear prediction: no efficient particle acceleration for $M \leqq \sqrt{5}$
  - Seems consistent with solar system shocks (Giacalone, 2012)
  - May have implications for primary shock acceleration in clusters of galaxies
    -some cluster of galaxies shocks have radio emission others not!

N157B: A very bright gamma-ray PWN



- Associated with fastest rotating pulsar known: PSR J0537-6910 (P=16ms)
- Rotational energy loss comparable to Crab pulsar (5×10^{38} erg/s)
- Much more dominated by inverse Compton:
  - radiation field in Doradus region?
  - lower B-field than Crab
- Not detected in field: B0540/PSR J0540-6919 ($E_{dot}=1.5 \times 10^{38}$erg/s)
  - B0540 bright in X-rays and Fermi detected



- Presentation based on
  "The exceptionally powerful TeV gamma-ray emitters in the Large Magellanic Cloud"
  by The H.E.S.S. Collaboration, 2015 Science 347, 406

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