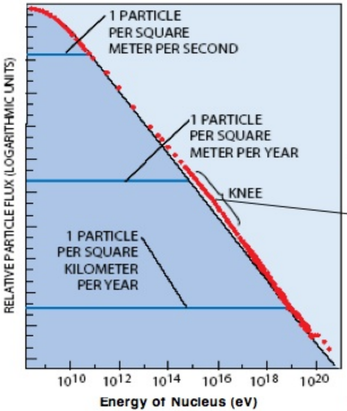
Status of evidence for particle acceleration from high-energy observations of shell-type SNRs (*not* interacting with MCs)

Yves Gallant

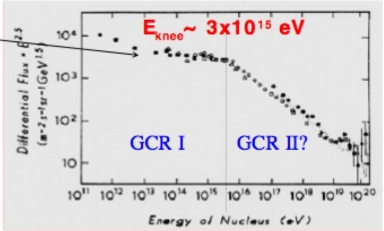
LPTA, Montpellier, France

Molecular clouds as probes of CR acceleration in SNRs
Palavas-les-Flots, September 7, 2009

Galactic Cosmic Rays (GCRs)



- E< a few hundred MeV :Solar cosmic rays
- E> 3 X 10^{18} eV (not confined by *B*) : extragalactic (UHE)CRs
- in between: Galactic CRs



- **Direct measurements only at Earth (satellites and atmosphere)**
- **Known to fill the Galaxy from diffuse gamma- ray emission (*EGRET*)**
- **Known *not* to fill intergalactic space from non- detection of SMC (and lower inferred CR density in LMC)**

High-energy observations of (shell-type) SNRs and the origin of Galactic Cosmic Rays

- Supernova remnants are widely considered likely sources of Galactic cosmic rays up to the "knee", $E \sim 3 \times 10^{15}$ eV :
  - well-studied shock acceleration mechanism;
  - GCR composition compatible with and SNR origin;
  - energetics require $\sim$10% of total SN energy of 10^{51} erg

Part I : X-ray observations of SNRs

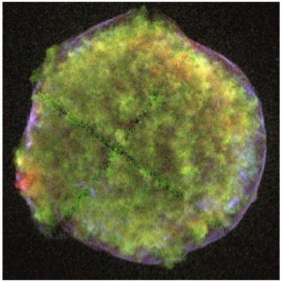
- Observational evidence for accelerated e^- (synchrotron)
- indirect evidence for accelerated protons/ions (magnetic field amplification, modified hydrodynamics)

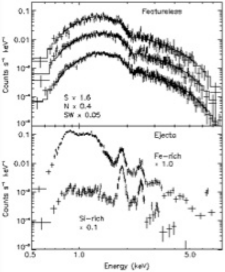
Part II : TeV γ-ray observations

- For accelerated p (and ions), **hadronic** interactions with ambient matter produce π^0, decaying into two γ-rays which we observe
- On of aims of TeV γ-ray astronomy (e.g. Drury et al. 1994)
- But how to discriminate from **leptonic** (IC) emission?

X-ray evidence : the case of Tycho's SNR

(1) Non-thermal spectra (Warren et al. 2005)





X-ray colors: S,Si and Fe line Emission (thermal from ejecta), 4-6 keV continuum

Continuum rim (blast wave) shows featureless power-law spectra (no detectable thermal line emission)

- most young shell SNRs (Cas A, *Kepler*, SN 1006, **G347.3-0.5**, **G266.2-1.2**, RCW 86...) display (dominant) non-thermal spectra
- if synchrotron radiation, $\Rightarrow E_e \sim$ 10-100 TeV (for typical B)

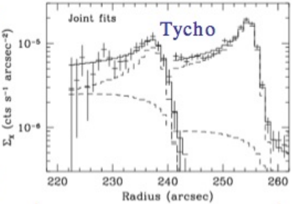
(2) Morphology : Thin non-thermal rims

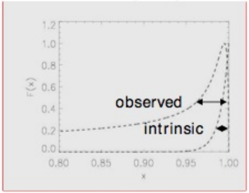
- Thin, non-thermal filaments at SNR edge: not expected morphology for thermal or adiabatic synchrotron emission
  - Most likely due to synchrotron losses of the high-energy emitting electrons (Vink & Laming 2003, Berezhko & Völk 2004...); implies large magnetic fields
  - Magnetic field amplification driven by CRs (Bell & Lucek 2001, Bell 2004) can help accelerate ions towards $E \sim 3 \times 10^{15}$ eV
- Filament geometry: projection effect

Δ For an exponential profile the de-projected width is P/4.6 (Ballet 2005)

Typical filament width = 0.05 - 0.2 pc

- Alternate explanation: sharp rim due to decay of magnetic turbulence (Pohl, Yan & Lazarian 2005); but consistent with radio morphology?





Methodology : Self-consistent magnetic field

- *Isotropic* turbulence + diffusion laws up/downstream
  - Radiatively limited rims:

    $t_{acc}(E_{emax}) = t_{sync}(E_{emax})$
  - Compare $\Delta R_{obs}/P$ with size of the rim:

    $\Delta R_{rim}(D,B) = f(\Delta R_{adv}, \Delta R_{diff})$ Berezhko & Voelk 2004

$\Rightarrow \Delta R_{rim}, E_{emax} \Rightarrow B(\alpha, r, V_{sh}, E_{ph\text{-}cut\text{-}off}, \Delta R_{obs})$

Parizot, Marcowith, Ballet & Gallant 2006

SNR	(r=4)	B(α=1, r=4) μG	B(1,10)	B(1/3,4)
Cas A	3.2	390	280	350
Kepler	4.5	340	250	300
Tycho	10	530	400	400
SN 1006	1	110	95	100
G347.5-0.5	1	96	84	92

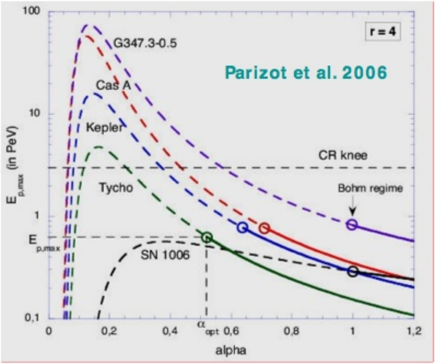
The magnetic field is highly amplified in SNR displaying X-ray filaments

Maximum energy and constraints on turbulence

- $B \Rightarrow E_{pmax}(\alpha)$ for protons
  $t_{acc}(E_{pmax}) = t_{SNR}$

- Constraints on α:
  Dashed lines are the rejected values of α: $D(E_{pmax}) < D_{Bohm}$

  $E_{pmax} < E_{knee}$ (3 PeV)
- "Worse" for r = 10

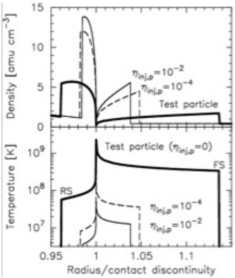


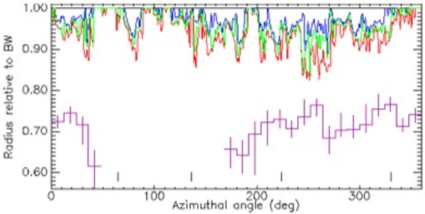
It is difficult to reach/ go beyond the knee even with B-field amplification

Caveat: Turbulence assumed *isotropic*: $\kappa_{perp} = \kappa_{parallel}$

(3) Indirect evidence for accelerated ions : modified hydrodynamics

- Warren et al. (2005) measured ratio between blast wave (BW) and contact discontinuity (CD) radii : mean 0.96
  - ejecta / shocked ambient medium CD subject to Rayleigh-Taylor instability => protruding fingers; correcting for this bias, still get ~ 0.93
  - pure gas dynamics: expect 0.86 or less

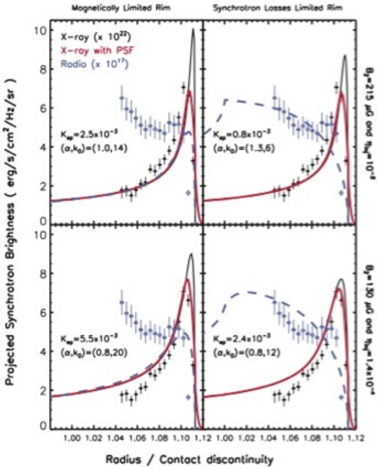




- Decourchelle, Ellison & Ballet (2000) showed this can be explained by significant accelerated ion pressure
  - **Caveat**: turbulent B-field pressure not taken into account

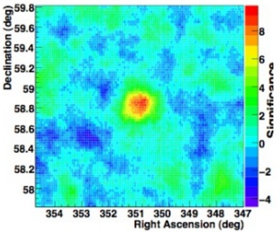
More detailed studies in Tycho
(Cassam-Chenaï et al. 2007)

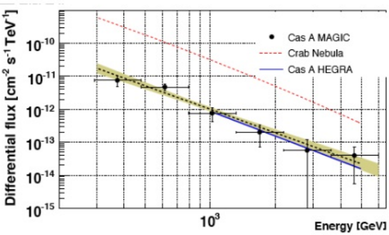
- Observe X-ray spectral steepening behind shock (synchrotron losses)
- Lack of thermal emission from rim: $n_0 < 0.6\ \mathrm{cm}^{-3}$
- Use cosmic-ray-modified hydrodynamics to reproduce distance between blast wave and contact discontinuity
- Consider synchrotron-loss vs magnetic damping-limited rims, radio and X-ray profiles
- Magnetic damping scenario fails to explain radio profile



(Next to) youngest Galactic SNR : Cassiopeia A

- age~330 yr (no clear SN observation)
- VHE emission discovered by *HEGRA* (Aharonian et al. 2001, *A&A* **370**, 112)
- 232 hours (!), significance 5 σ
- unresolved, centroid in Cas A
- Confirmed by *MAGIC* : 5.2 σ in 47 h (Albert et al. 2007) and by *VERITAS*





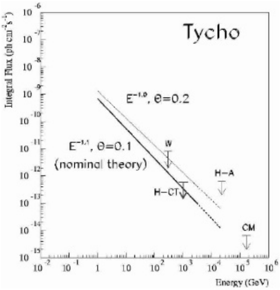
- spectra compatible
- steep spectrum : $\Gamma = 2.4 \pm 0.2$
- $L_{1-10\ \mathrm{TeV}} \sim 3 \times 10^{33}$ erg/s ($D \approx 3.4$ kpc)
- sharp synchrotron X-ray rims, etc. $\Rightarrow$ high $B \sim$ mG
- hadronic emission favoured

Other young (historical) shell-type SNRs

Tycho (SN 1572)

- deepest upper limit: *HEGRA* 2001 (*A&A* **373**, 292) with 65 hours
- $L_{1\text{–}10\ \mathrm{TeV}} < 10^{33}\ \mathrm{erg/s}$

  (assuming $D \approx 2.3$ kpc and $\Gamma = 2$)
- synchrotron X–rays $\Rightarrow B > 22\ \mu\mathrm{G}$



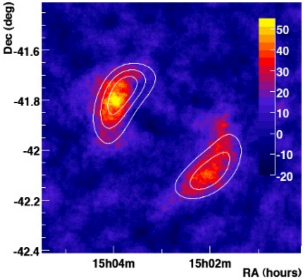
Kepler (SN 1604)

- recent *HESS* upper limit (*A&A* **488**, 219)
- $L_{1\text{–}10\ \mathrm{TeV}} < 2\times10^{33}\ \mathrm{erg/s}$ (assuming $D \approx 4.8$ kpc and $\Gamma = 2$)

  (distance uncertain by ±1.5 kpc $\Rightarrow$ factor ~ 2 in $L_{1\text{–}10\ \mathrm{TeV}}$)

Other historical shell-type SNR : **SN 1006**

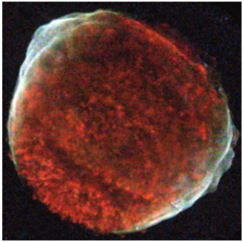
- ~30' diameter shell
- *CANGAROO–I* claimed bright NE hotspot (Tanimori et al. 1998), not confirmed by *HESS* (2005, *A&A* **437**, 135) nor *CANGAROO–III*
- after 130 h, *HESS* detection! (Naumann-Godo et al., ICRC 2009)
- flux ⇒ $L_{1\text{-}10\ \mathrm{TeV}} \sim 6{\times}10^{32}$ erg/s (assuming $D \approx 2.2$ kpc)



- Morphology seems to match X-ray synchrotron (contours: *XMM* map smoothed to match *HESS* PSF)
- Leptonic scenario ⇒ $B \sim 30\ \mu$G (lower than inferred from rims)
- Hadronic scenario : given low ($n \sim 0.05$ cm^{-3}) medium density, requires flat ($p \approx 2$) spectrum for reasonable energetics
- whether protons or electrons, shows distribution of accelerated particles in SN 1006

Bipolar morphology of particle acceleration

- SN 1006 : explosion in nearly uniform, undisturbed medium?
  - Type Ia : no stellar progenitor wind
  - High above the Galactic plane
- Rothenflug et al. (2004) : X–ray image compatible with synchrotron “polar caps”, not with “equatorial band”
- Suggests that **parallel** shocks, and not **perpendicular**, are where particle acceleration is most efficient

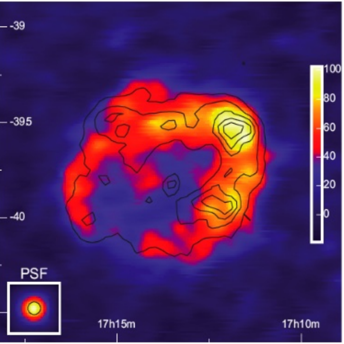


Young SNRs in TeV gamma–rays

- Other historical shell–type SNRs somewhat less luminous in TeV γ-rays than Cas A
- Lower surrounding medium density(?), or less efficient particle acceleration

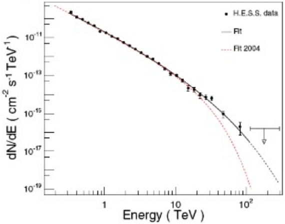
SNRs with shell morphology in TeV γ-rays

RX J1713.7−3947 (or G347.3−0.5)



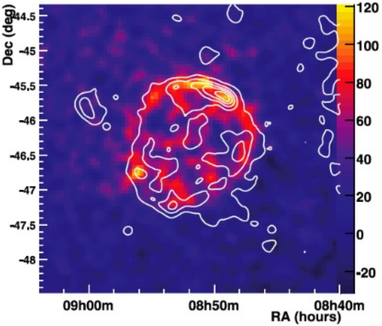
- VHE γ−ray emission discovered by *CANGAROO* (Muraishi et al. 2000)
- first resolved SNR shell in VHE γ−rays (*HESS* 2004, *Nature* **432**, 75)
- very good spatial correlation with (non−thermal) X−rays (ASCA 1−3 keV) (*HESS* 2006, *A&A* **449**, 223)
- large zenith angle observations ⇒ spectrum 0.3−100 TeV (*HESS* 2007, *A&A* **449**, 223)

- power law $\Gamma \approx 2.0$ with cutoff or break at $E_\gamma \sim 10$ TeV (depending on model)
- $L_{1-10\,\mathrm{TeV}} \sim 10^{34}$ erg/s (assuming $D \approx 1.3$ kpc)
- leptonic emission scenario ⇒ $B \sim 9\ \mu$G

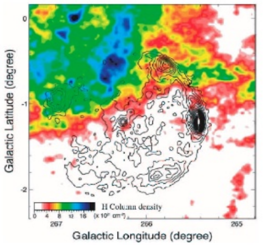


TeV γ-ray shells

RX J0852.0–4622 (or G266.2–1.2, "Vela Junior")



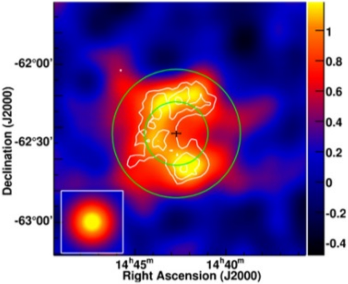
- Detection of a thin, 2° diameter shell (*HESS* 2005, *A&A* **437**, L7)
- *CANGAROO–II* detected NW rim (Katagiri et al. 2005), *–III* confirmed the shell (Enomoto et al. 2006)
- High spatial correlation with X-rays (ROSAT, ASCA); no clear correlation with CO (*HESS* 2007, *ApJ* **661**, 236)



- power law $\Gamma = 2.24 \pm 0.04_{\rm stat} \pm 0.15_{\rm sys}$ (indication of steepening at high energies)
- $L_{1\text{-}10\,\rm TeV} \sim 6 \times 10^{33}$ erg/s at "far" $D \approx 1$ kpc
- leptonic emission scenario $\Rightarrow B \sim 7\ \mu$G

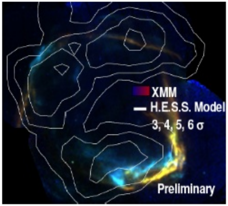
Probable TeV shell : **RCW 86** (or MSH 14–63)

(*HESS* 2009, *ApJ* **692**, 1500)



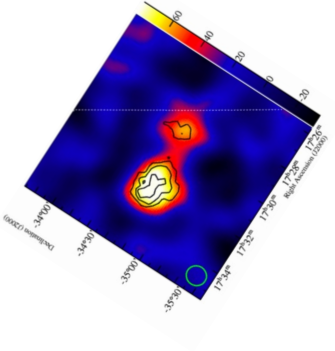
- $\sim 4\sigma$ excess earlier reported by *CANGAROO* (Watanabe et al. 2003)
- 8.5σ in 31h : clear detection
- hint of shell morphology (more data needed), like synchrotron X–ray and radio shell
- no hint of strong enhancement at SW dense interaction region

- fairly steep power law, $\Gamma = 2.54 \pm 0.12_{\rm stat}$
- $L_{1-10\ \rm TeV} \sim 7 \times 10^{33}$ erg/s assuming $D \approx 2.5$ kpc
- leptonic emission scenario $\Rightarrow B \sim 30\ \mu$G (compatible with X–ray rims, Vink et al. 2006)
- hadronic scenario : extrapolated proton spectrum too high, need $\Gamma \approx 2$ and cutoff (also compatible with spectral data)

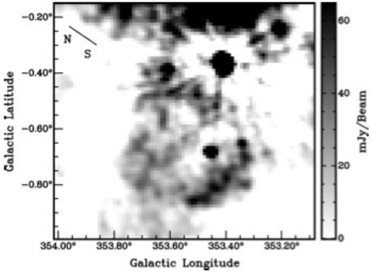


A new non-thermal shell : HESS J1731–347

- discovered in *HESS* Galactic plane survey; $\Gamma = 2.3 \pm 0.1 \pm 0.2$
- coincident radio shell discovered with ATCA data: G 353.6–0.7



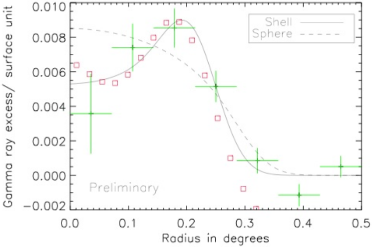
(Tian et al. 2008)



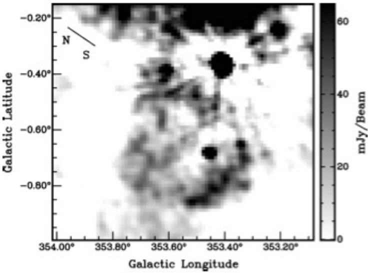
A new non-thermal shell : HESS J1731–347

- discovered in *HESS* Galactic plane survey; $\Gamma = 2.3 \pm 0.1 \pm 0.2$
- coincident radio shell discovered with ATCA data: G 353.6–0.7

(Acero et al., ICRC 2009)



(Tian et al. 2008)

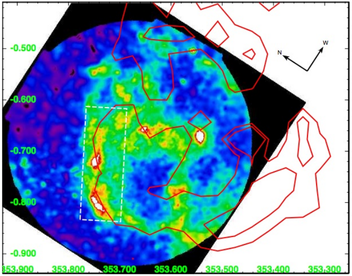


- further *HESS* observations: hint of limb-brightening ($\sim 2\sigma$ level)

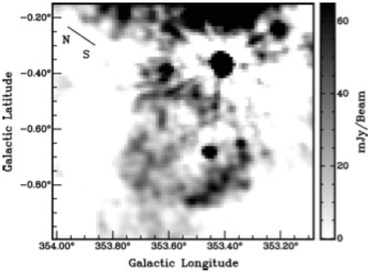
A new non-thermal shell : HESS J1731–347

- discovered in *HESS* Galactic plane survey; $\Gamma = 2.3 \pm 0.1 \pm 0.2$
- coincident radio shell discovered with ATCA data: G 353.6–0.7

(Acero et al., ICRC 2009)



(Tian et al. 2008)



- further *HESS* observations: hint of limb-brightening ($\sim 2\sigma$ level)
- X-ray observations of (part of) shell reveal rims of emission with non-thermal spectra! (no evidence for thermal emission)
- X-ray absorption gradient suggest SNR lies behind a CO cloud
- $D > 3.5\,\text{kpc} \quad \Rightarrow \quad L_{1-10\,\text{TeV}} > 2 \times 10^{34}\,\text{erg/s}, \quad R > 15\,\text{pc}$

TeV γ-ray shells : general properties

- dominantly non-thermal X-ray emission
  (thermal only in RCW 86, SN 1006 and especially Cas A)
- weak radio synchrotron emission (except younger SNRs)
- similar TeV luminosities, $L_{1-10\,\mathrm{TeV}} \sim 10^{34}$ erg/s
  (historical SNRs $\sim 10^{33}$ erg/s)

Leptonic emission scenario

- might explain spatial correlation with synchrotron X-rays
- implies fairly low $B \sim 10\,\mu$G (in one-zone model), in apparent contradiction with evidence for turbulent B-field amplification
- TeV shell widths larger than X-ray filaments (e.g. Renaud 2009): if rapid B-field damping behind the shock, may be compatible with weak *spatially-averaged* B value
- difficult to fit TeV spectral shapes in one-zone model

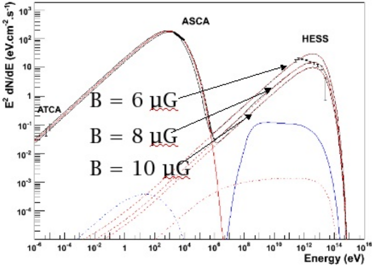
One-zone spectral modeling of **G 347.3–0.5**

Primary population: electrons ?

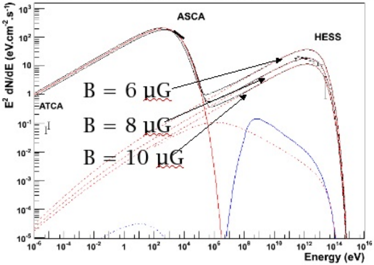
- Need about 8 μG B field to match flux ratios
- Simplest electronic models don't work well

- Simple one-zone model
- Electrons & protons injected with the same spectral shape
- Energy losses + escape of particles out of the shell taken into account

Power-law index = 2.2 at injection



Power-law index = 2.4 at injection

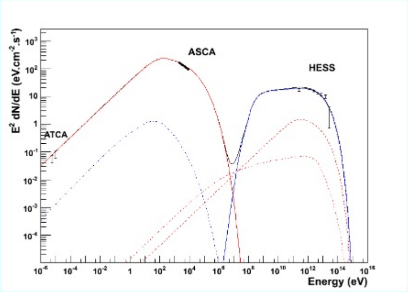


(M. Lemoine-Goumard)

One-zone spectral modeling of **G 347.3–0.5**

Primary population: protons ?

- Spectral shape at injection : power–law w/exponentional cut–off E_{cut} = 120 TeV and index = 2.0
- Energy injected = 10^{50} ergs
- Electron/proton ratio = 5 x 10^{-4}
- Magnetic field = 35 µG & Density = 1.5 cm^{-3}



(M. Lemoine-Goumard)

TeV γ-ray shells : general properties

Hadronic emission scenario

- no obvious explanation for high correlation with X-rays, and poor correlation with surrounding medium density
- **all** TeV-detected SNRs have $\Gamma > 2.0$ or cutoff at $E_\gamma \sim 10\,\mathrm{TeV} \;\Rightarrow\; E_p \sim 10^{14}\,\mathrm{TeV}$ — well short of "knee"
- spectrum must flatten to $\Gamma \sim 2$ at lower energies (as seen in G 347.3 and hinted in others), otherwise CR energetics prohibitive
- relatively high surrounding medium density ($n \sim 1\,\mathrm{cm}^{-3}$) required to explain G 347.3, Vela Jr and HESS J1731
- but upper limits on n from lack of thermal X-ray emission are a few$\times 0.01\,\mathrm{cm}^{-3}$ (assuming $k_B T \sim \mathrm{keV}$)
- **Caveat:** distances to these SNRs uncertain; most precise estimates often rely on unmodified shock jump conditions

Summary and Outlook

Summary on shell-type SNRs

- indirect evidence for **hadron** acceleration from X-ray and other observations (magnetic amplification, shock modification)
- ambiguity between hadronic and **leptonic** interpretation of γ-ray emission : correlation with synchrotron, not clearly with matter
- no clear evidence that $E_{\mathrm{max}} \sim 3 \times 10^{15}$ eV can be attained by p

Outlook on SNRs interacting with MCs

- often clear correlation with dense matter $\Rightarrow$ **hadronic** interpretation natural; "probes of CR acceleration"?
- likely correlated dense photon fields (thermal IR from dust, stellar photons from embedded recently-formed stars…)
  $\Rightarrow$ more detailed study of **leptonic** scenarios necessary
- key observational issue : angular resolution in γ-rays
- important theoretical issue : changes in shock acceleration, evolution and modification due to interaction with dense cloud (spectrum and maximum energy of accelerated particles…)