Massive star clusters as cosmic and gamma-ray sources

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Outlines

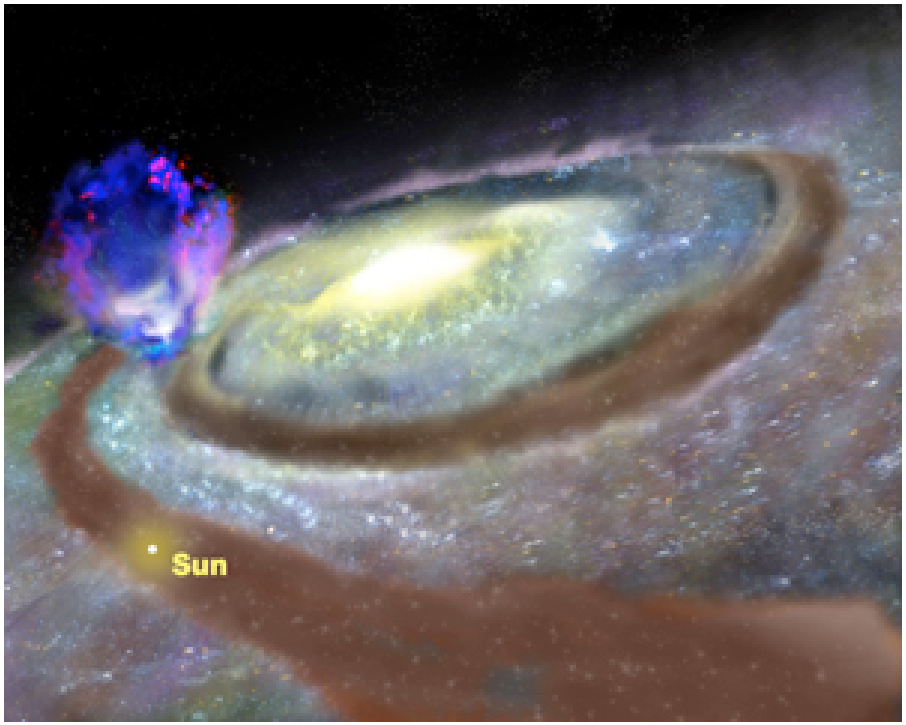
- Introduction:

  Massive star clusters (MSC) and associated superbubbles properties.

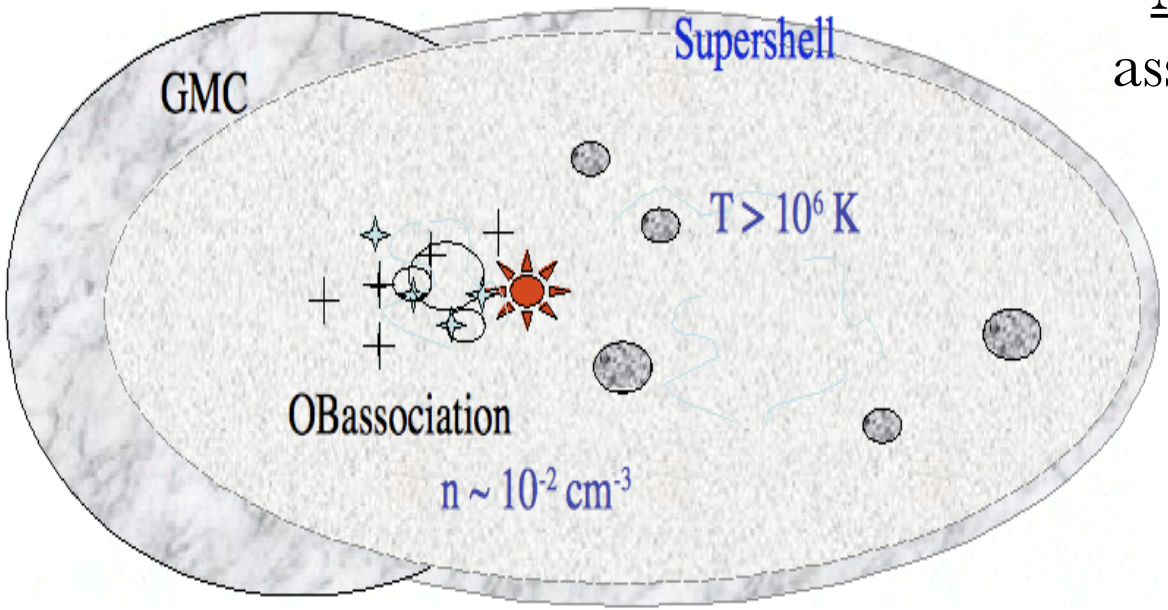
- Particle acceleration mechanisms & Multi-wavelength radiation.
- Conclusions

Massive Star clusters & associated superbubbles

- Physical properties
- Supernova remnants
- High energy radiation



Physical properties



• Massive star clusters (OB association)

D = 1-30 pc

N(OB stars) = 10-1000

$n \sim 0.1\text{-}10\ cm^{-2}$

$T \sim 10^6$ K

• Supershell: swept ambient ISM

$\Delta D \sim 10$ pc

$n \sim 1\text{-}10\ cm^{-3}$

$T \sim 100$ K

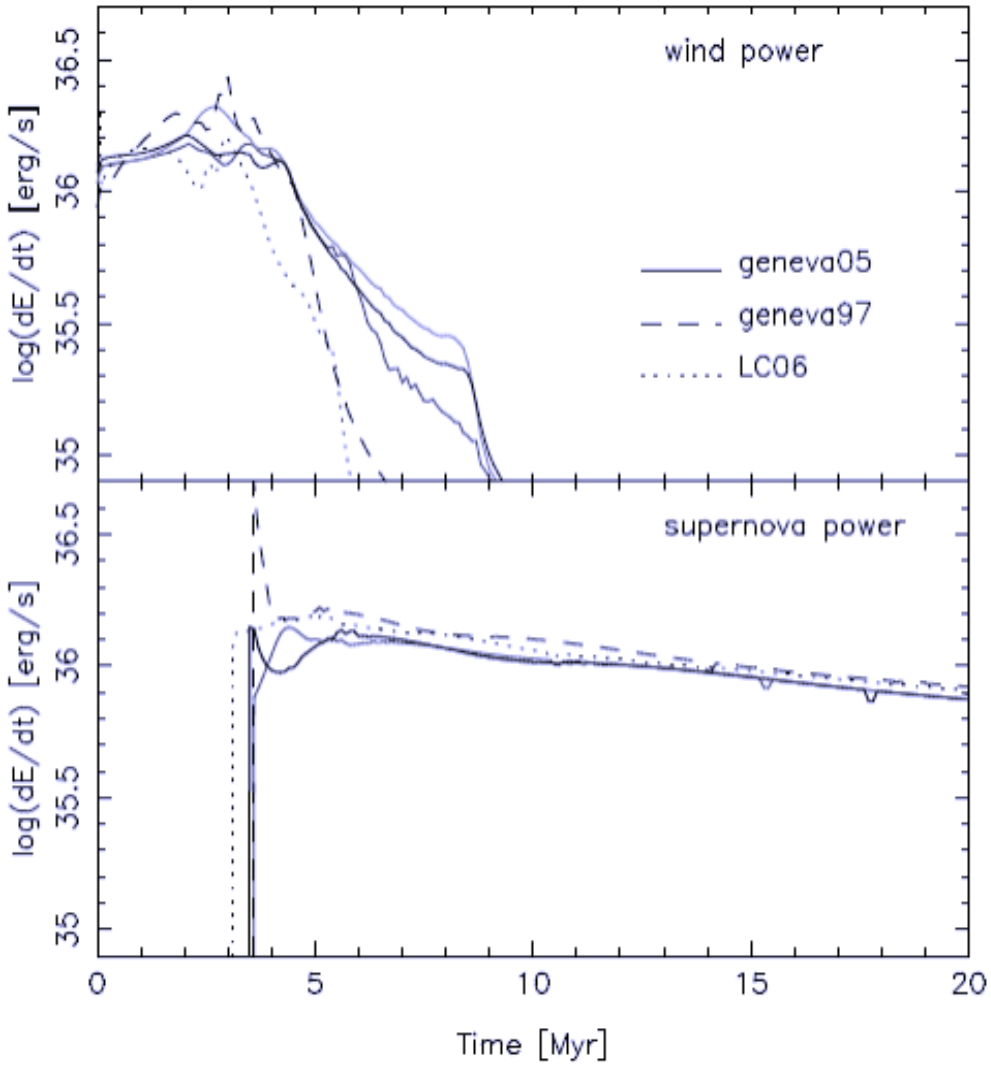
• Superbubbles:

D => 300 pc

$n \sim 10^{-2/-3}\ cm^{-3}$

$T \sim 10^6$ K

Coeval star formation 8-120 solar masses



Voss et al'09

• Before 3 Myrs: Energy input by stellar winds.

* Energy input by a massive star during its lifetime <=> Energy input by a SN.

• Beyond 3 Myrs: the most massive stars explode as SN (Limongi et al'06) and blow the ISM off

* Late SN explosion after 20 Myrs, by 8 solar masses stars.

Supernova remnants in MSCs

- A majority (60 %-90 %) of core collapsed SN explode in MSCs (Garmany'96, Higdon et al'05)
- Strong impact of the pre-SN stellar wind over the shock propagation (and on particle acceleration).
- In a dense and rich MSCs (R136 in LMC, Westerlund 1, 2, Cygnus OB2)
  - Mean half distance between two stars < radius of massive star termination shock.
  - Shock propagation in low density and high temperature medium (stellar wind bubble).
- SN in interaction with molecular clouds (W28, IC443).

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Diffuse X-rays

- Observed in several galactic and LMC OBa and SBs:
  - Thermal X-rays produced by massive star winds.

TABLE 4

DIFFUSE X-RAYS FROM HIGH-MASS STAR FORMING REGIONS

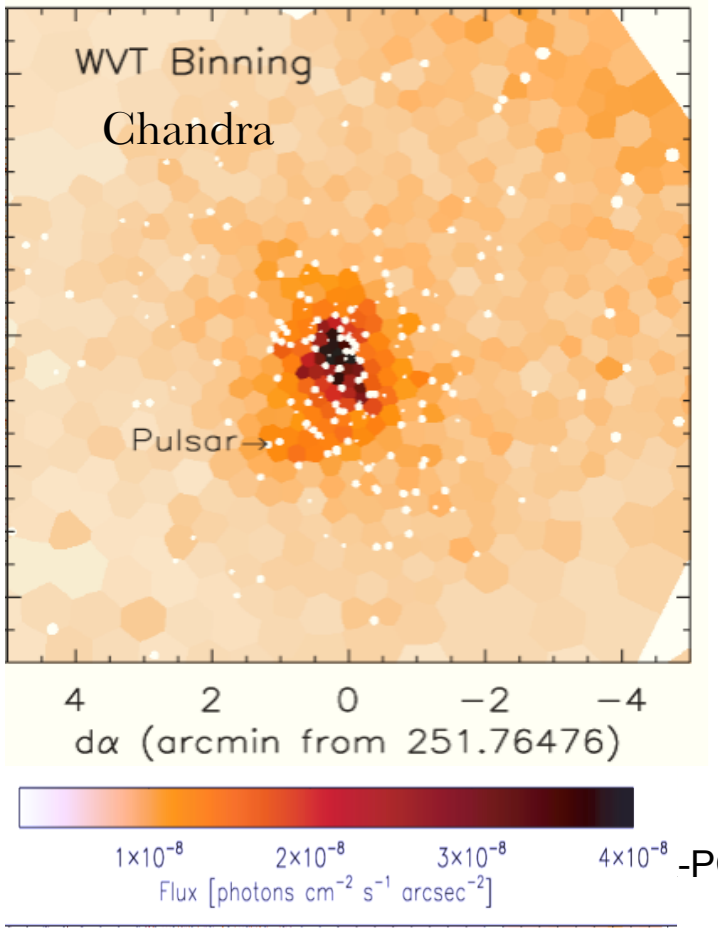
Region	Distance (pc)	Earliest Star[a]	Number O6 or Earlier	Diffuse X-Rays?	Diffuse Area (pc^2)	N_H (10^{21} cm^{-2})	kT (keV)	L_X[b] (10^{33} ergs s^{-1})
LMSFRs[c]	150–350	Late B	0	No	...	...	...	$\leq 10^{-5}$
Orion Nebula	450	O6	1	No	...	...	...	$<10^{-3}$
Eagle Nebula	2000	O5	2:	...	...	...	...	$<10^{-3}$
Lagoon, NGC 6530	1800	O4	3:	No	...	...	...	$<10^{-2}$
Lagoon, Hourglass	1800	O7	0	Probably	0.04	11.1	0.63	≤ 0.7[d]
Rosette Nebula	1400	O4	2	Yes	47	2	0.06, 0.8	≤ 0.6[d]
RCW 38	1700	O5	1:	Yes	2	11.5[e]	2.2[e]	1.6[e]
Omega Nebula[f]	1600	O4	7	Yes	42	4	0.13, 0.6	3.4
Arches cluster	8500	O3/W-R	>30	Yes	14	100	5.7	16
NGC 3603	7000	O3/W-R	>20	Yes	50	7	3.1	20
Carina Nebula	2300	O3/W-R	>30	Yes	1270	3–40	0.8:	200:

Townsley et al'03

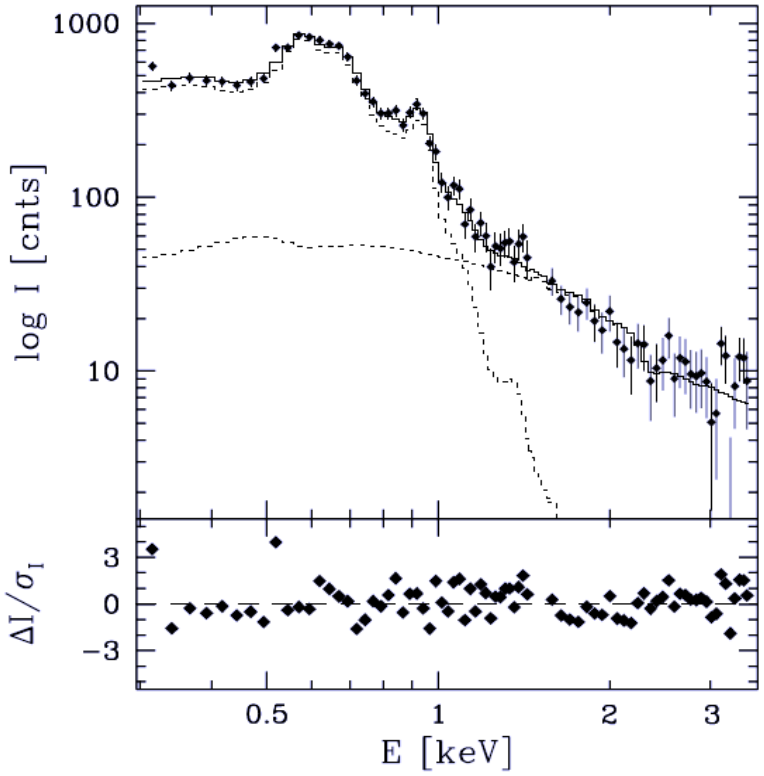
Diffuse X-rays

- Non-thermal X-rays (synchrotron/Bremsstralung)
  - Origin unclear: wind-wind interaction, SN remnants ?

Muno et al'06: Westerlund 1



Cooper et al'04: DEML192



XMM-Newton

Energy Crisis

- Input:
  - Stellar wind: E_{SW}
  - Supernovae: E_{SN}
- Output:
  - Thermal energy of the SB interior: E_{th} ($> E_{NT}$)
  - Kinetic energy of the ionized/neutral supershell: E_{kinH} , E_{kinHI}

TABLE 2

ENERGY BUDGET OF THE SUPERBUBBLE DEM L192

Energies	Amount ($\times 10^{51}$ ergs)
E_{th} of the hot gas in superbubble interior	1.1 ± 0.5
E_{kin} of the ionized (H II) superbubble shell	1.5 ± 0.5
E_{kin} of the neutral (H I) superbubble shell	3.2 ± 0.5
Total energy observed in the superbubble	6 ± 2
Stellar wind energy input in 3 Myr	5 ± 1
Supernova energy input	13 ± 4
Total stellar energy input	18 ± 5

2/3 of the injected energy is missing

Cooper et al'04

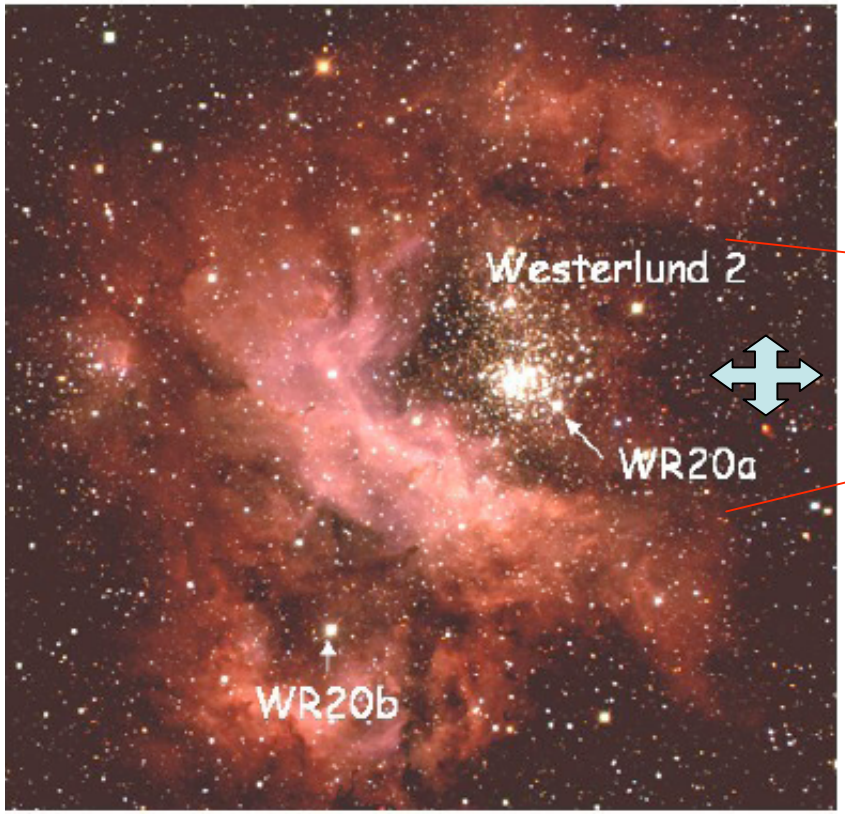
Not the only case

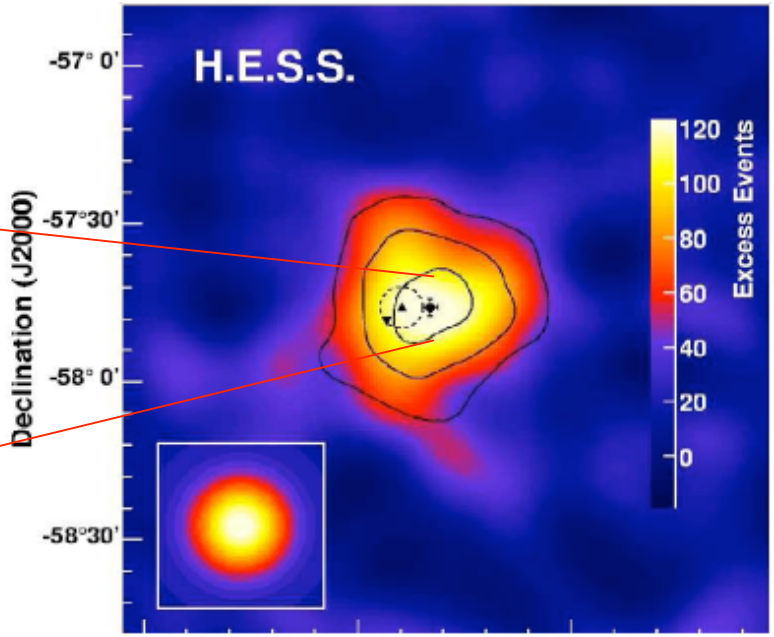
-Thermal conduction ?

- Energetic particles ?

Gamma-Rays

- Gamma-rays detected from (Bremsstrahlung, Inverse Compton or neutral pion decay)
  - Cygnus OB2 (Hegra), Cygnus region (Milagro), Westerlund 1 & 2 (HESS)

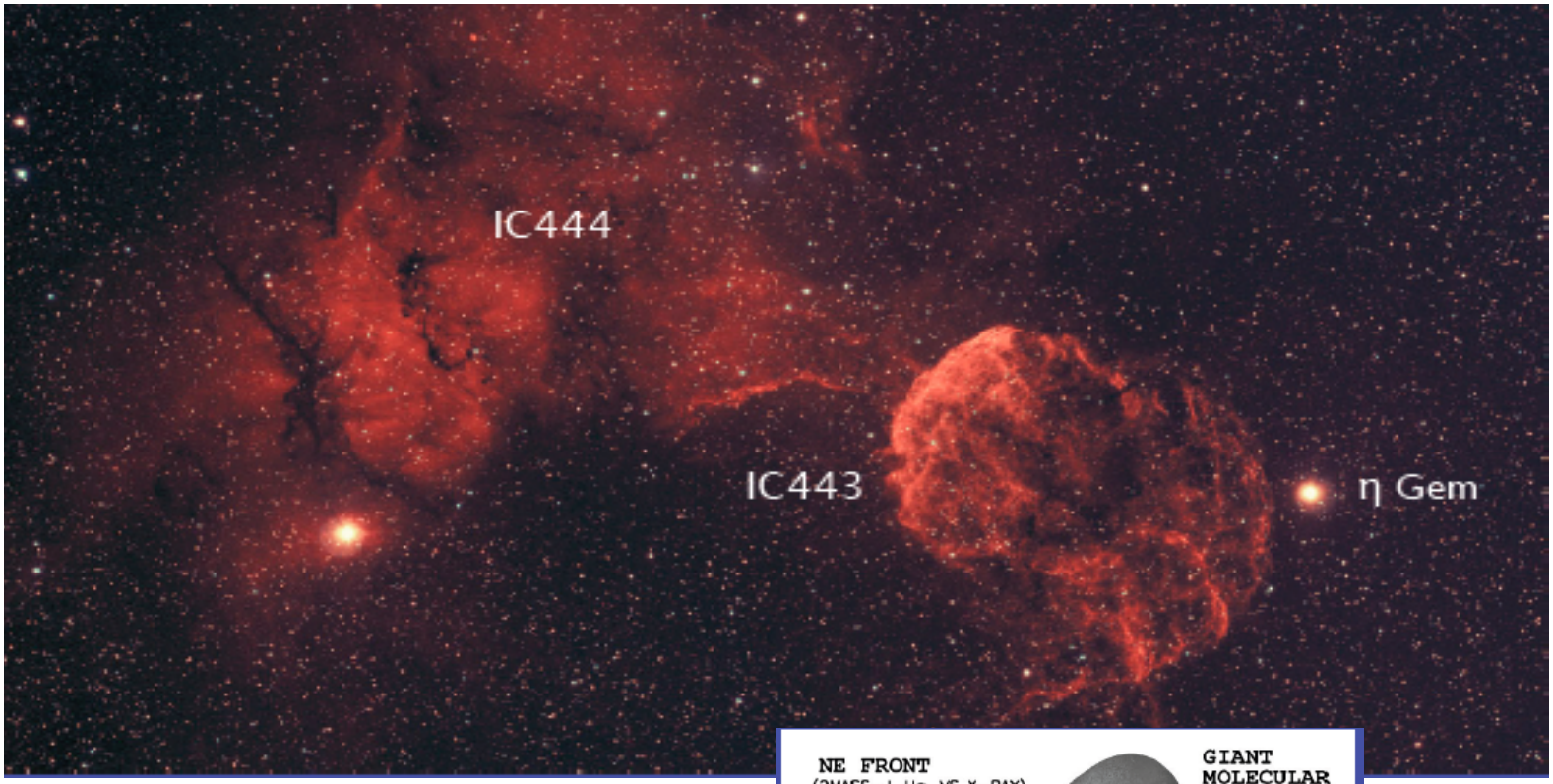




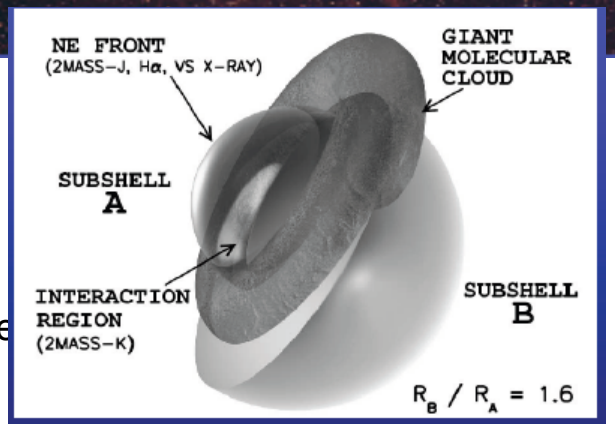
Westerlund 2 by HESS
Aharonian et al'07

Age ~2 M years
Distance ~8 kpc

IC443 SNR



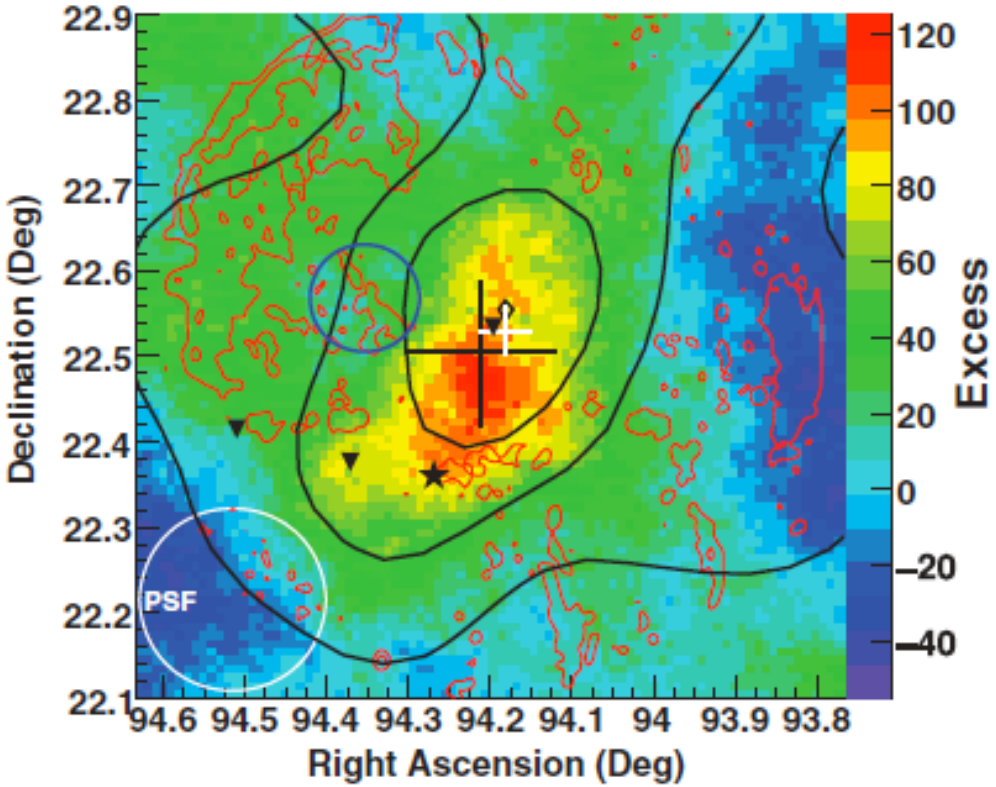
H_α Troja et al'06

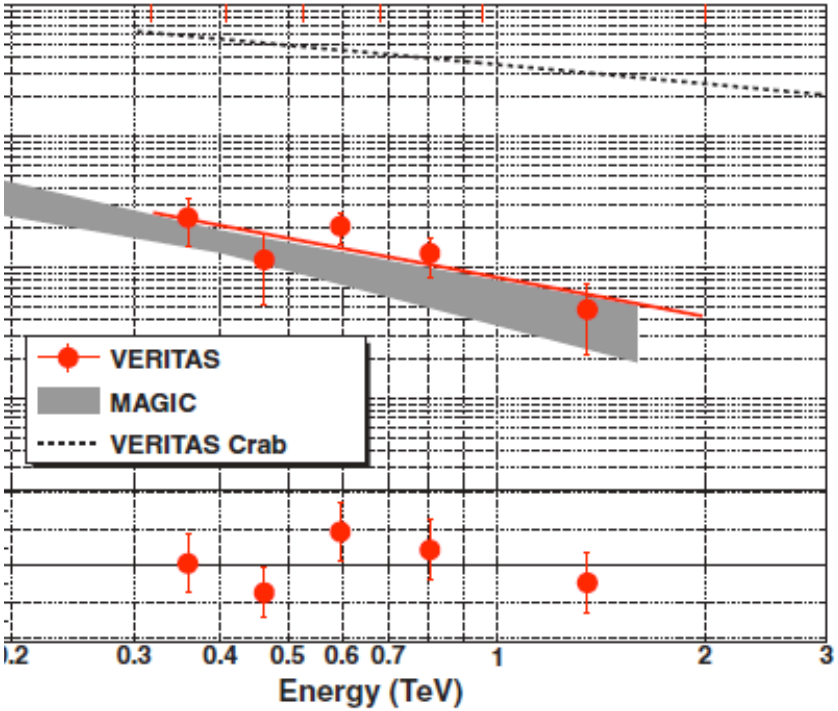


Age ~30 000 years
Distance ~1.5 kpc

IC 443 in gamma-rays

Veritas excess map

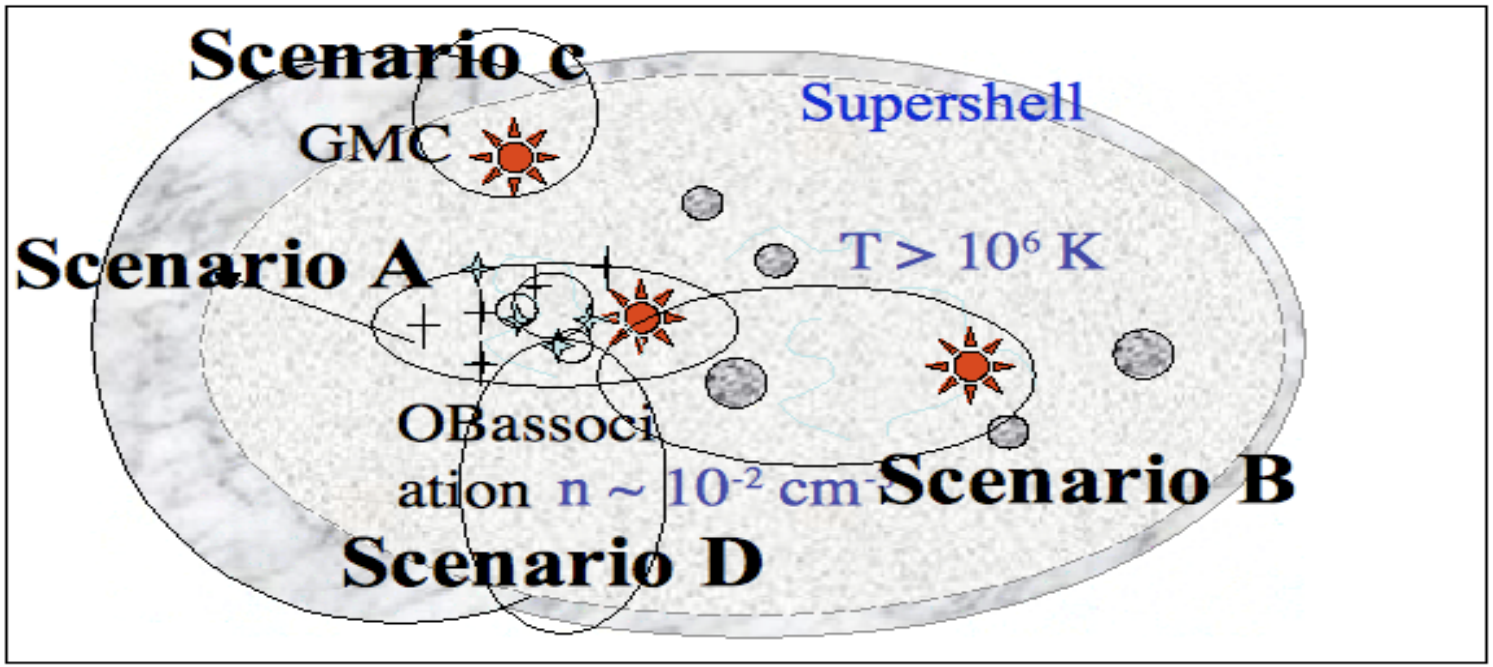




White cross: Magic
Black cross: Veritas + PSF in white
Open blue circle: 95% confidence contour Fermi (Abdo et al'09)
Triangles OH masers
Black contours CO data
Red: optical
Black star: PWN

MAGIC: Albert et al'07
VERITAS: Acciari et al'09

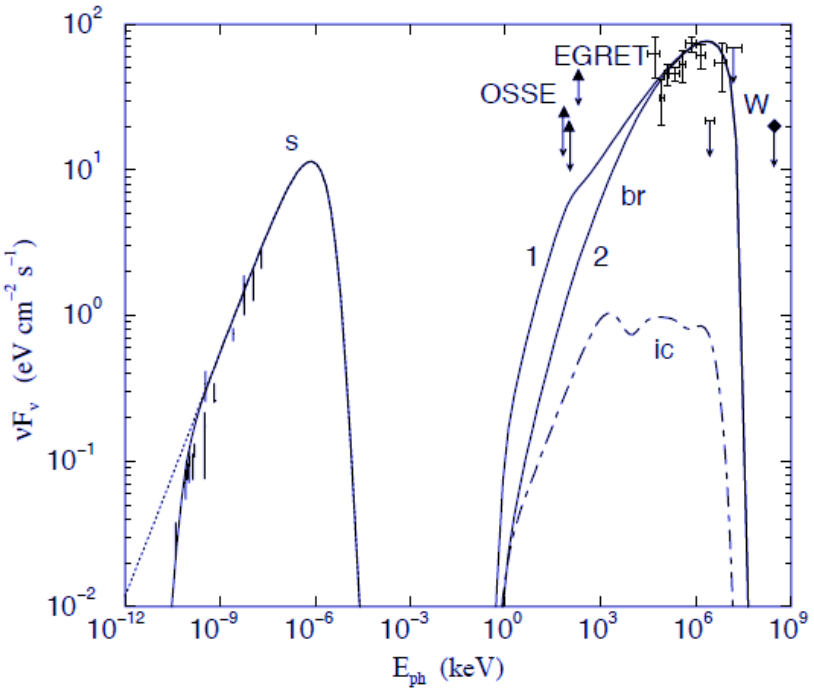
Acceleration/Radiation scenarii



- Scenario A/B: collective winds with internal/external accelerator (Klepach et al'00, Domingo-Santamaria & Torres'06)
- Scenario C: SNr/molecular cloud interaction (Bykov et al'00)
- Scenario D: EP interaction with shells (Bykov & Fleishmann '92)

GeV-TeV: Some predictions

- <u>SNR/MC interaction</u>



IC 443

* Injection from thermal pool at the shock front (Bykov et al'00)

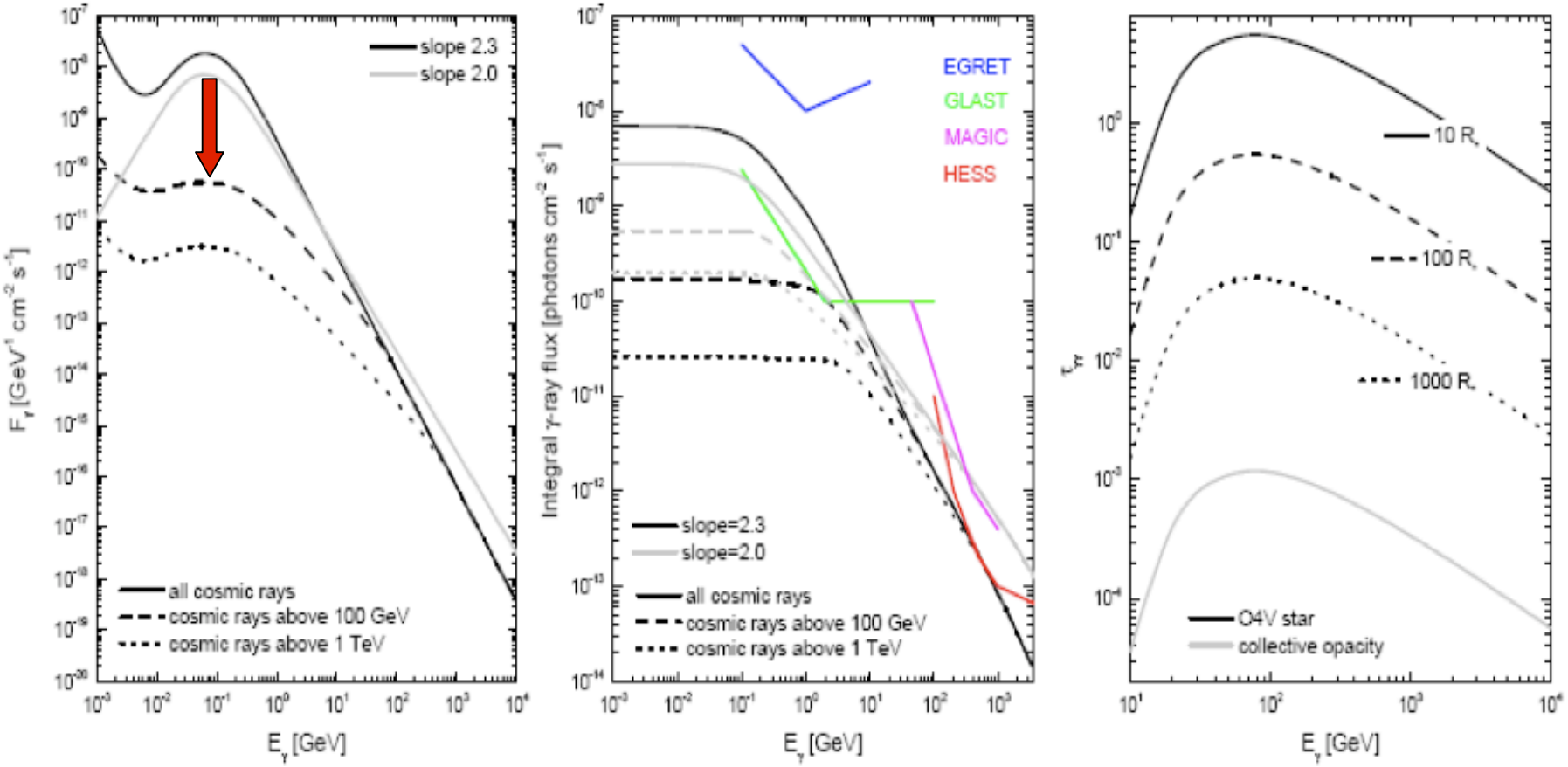
* Min energy electron reacceleration (stochastic)
1/ E=120 keV 2/ E=2 GeV

• No strong TeV radiation expected
  - Low velocity (~100 km/s) shocks
  - Wave absorption by ion-neutral damping.

* TeV radiation from illumated clouds ? (Gabici et al'07)

=> Different slopes expected in GeV and TeV (harder) even v shape-like

Collective massive star winds

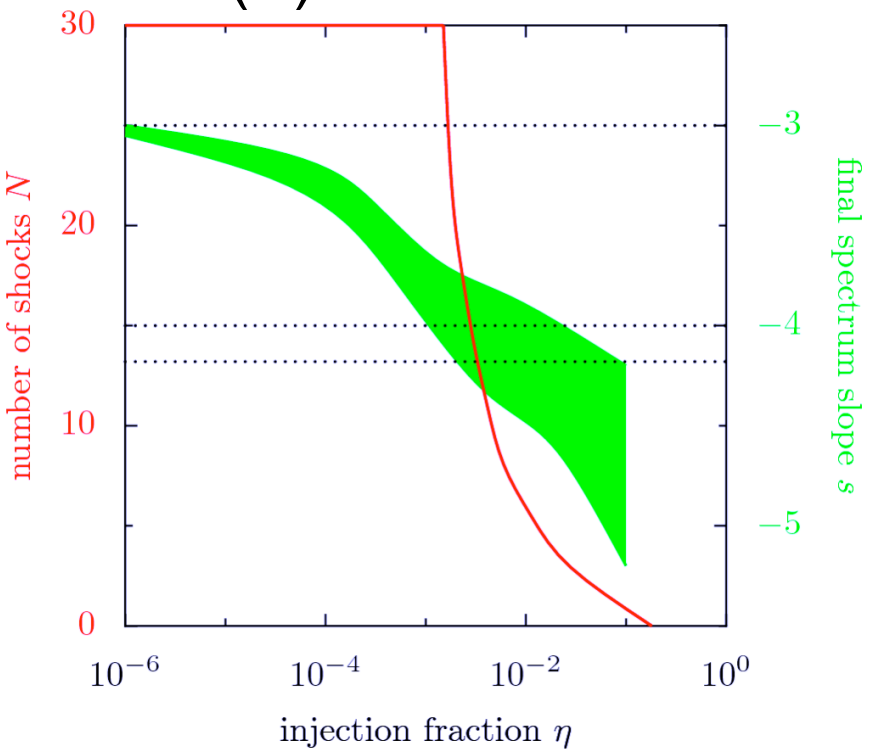


- Lower energy (100 GeV/1 TeV) particles are excluded by the wind modulation effect
- 10-100 GeV radiation may be absorbed by pair production close to the stars.

Domingo-Santamaria & Torres'06

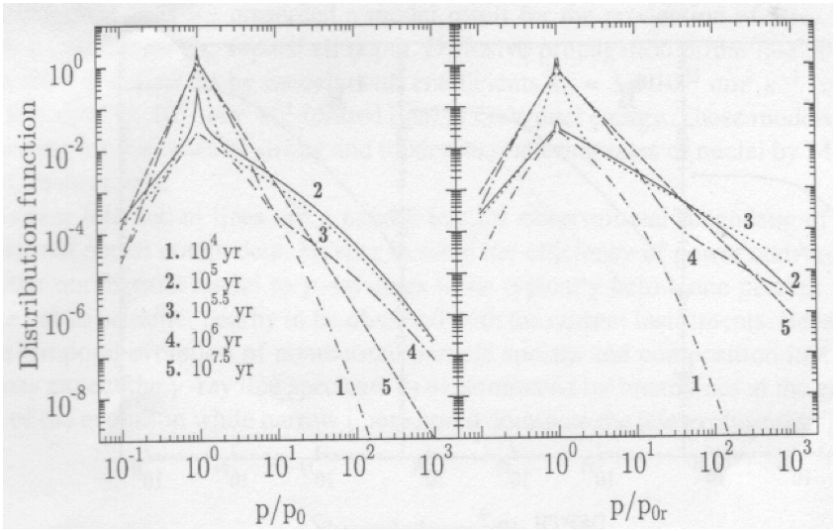
Multiple shock acceleration: non-linear calculations

$N(E) \propto E^{-s}$



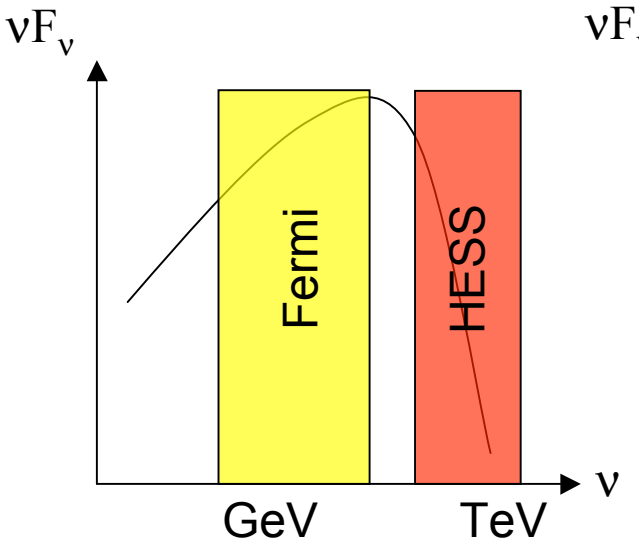
- Reacceleration by strong SN shocks:
  - hard spectra ($s < 2$) possible mostly at low energies (GeV)
  Ferrand et al'08, Ferrand & A.M.'09

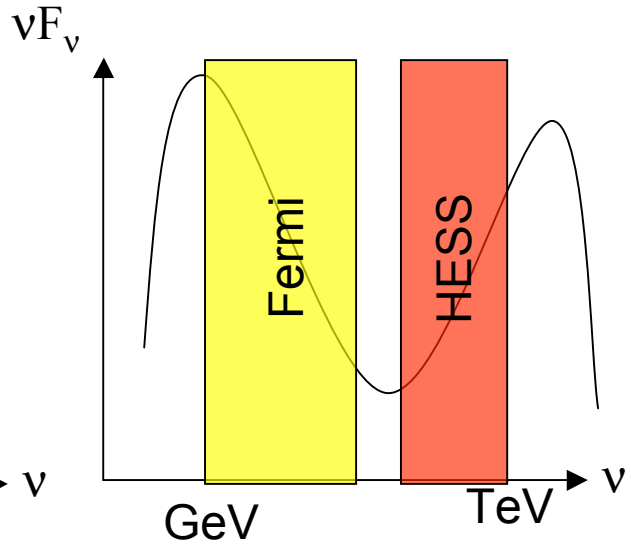
$N(E) \propto E^{-s}$



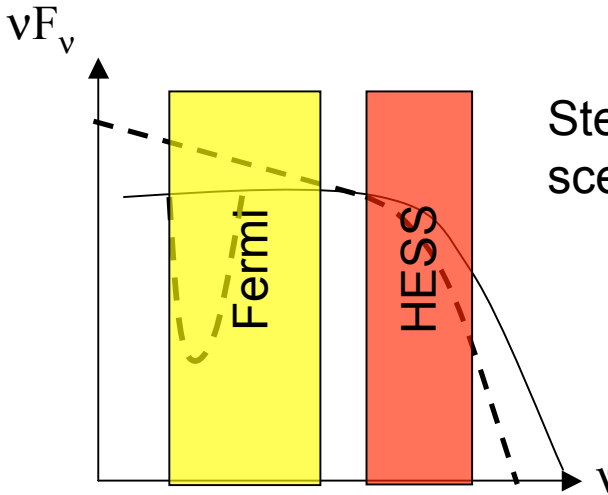
- Reacceleration by MHD turbulence including weak shocks:
  - Intermittent spectra ($2 < s < 3$) Bykov'01
  - Interaction with thick targets (supershell, MCs)

Spectral signatures



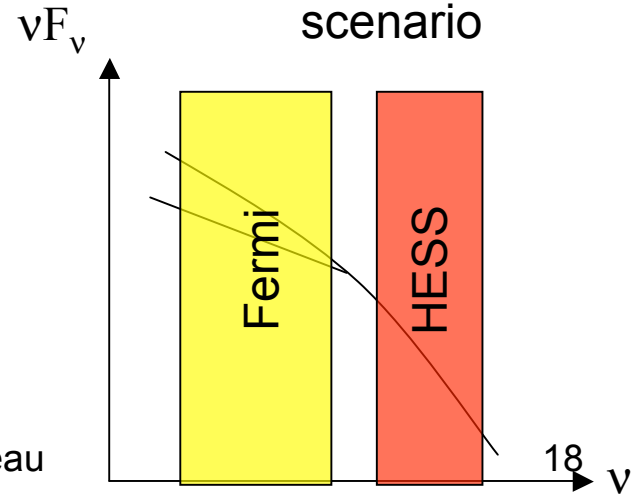


SNR/MC scenario



Stellar wind scenario

SB/supershell scenario



Conclusions

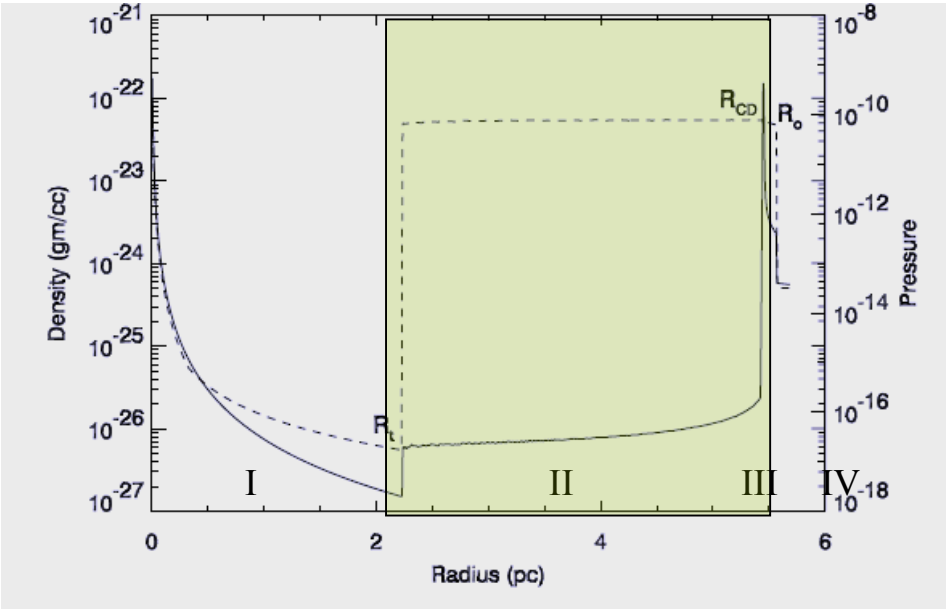
- Very energetic processes inside massive star clusters: stellar winds, binaries, collective interaction, SN explosion.
- A majority of core collapsed SN explode inside MSC/SB.
- Diffuse non-thermal X-rays and gamma-rays observed in several clusters
- Possible indirect hint of particle acceleration: “the missing energy problem”.
- Individual events: SN/MCs interactions like IC443, W28 …
- Great variety of GeV-TeV emission signatures.
- Need more spectral and high angular spatial resolution observations:
  - High energy from stellar winds <=> size of the cluster, modulation/absorption effects in the GeV bands.
  - High energy from SNR/MCs <=> CO measurements, OH masers, different spectral shapes at GeV and TeV.
  - High energy from CRs interacting with dense targets: possibly hard spectra (wrt to s=2), larger scales.

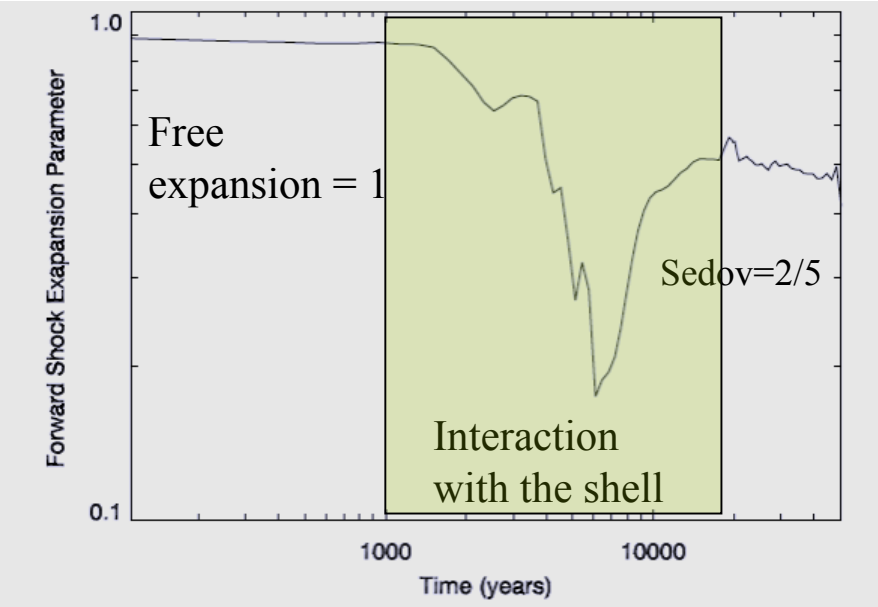
Supplementary material

SNR dynamics in a stellar wind

- Highly dependent on the main sequence star and post-main sequence phase (RSG, LBV) or further phases (Wolf-Rayet): SNII or SNIc/b (Dwarkadas'05)

Case: $M_{shell}/M_{ej} = 3.7$

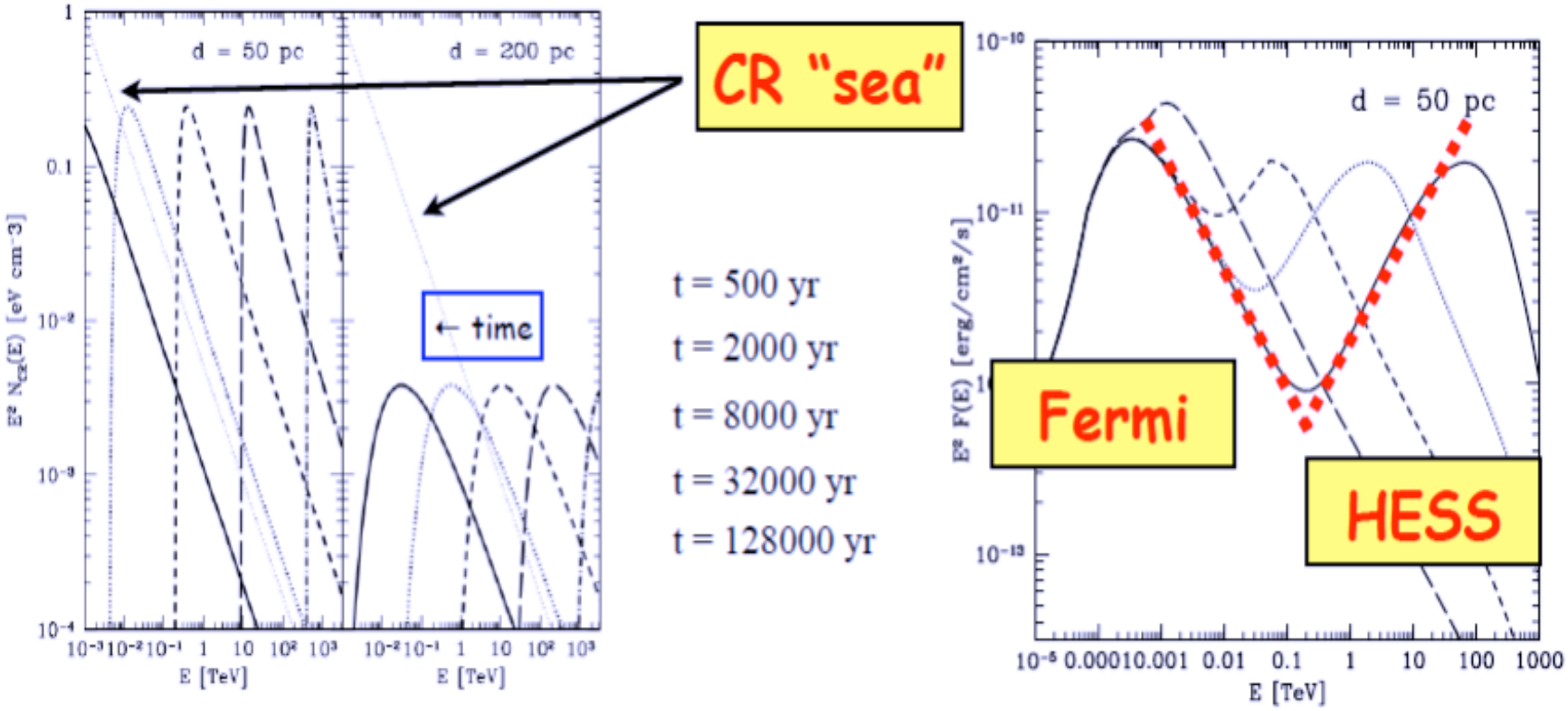




I: free stellar wind
II: shocked stellar wind
III: shocked ambient medium
IV: unshocked ambient medium

$R_{RSN} \propto t^{\alpha}$ Expansion parameter=α

“Passive” cloud radiation



Gabici et al’09