MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK
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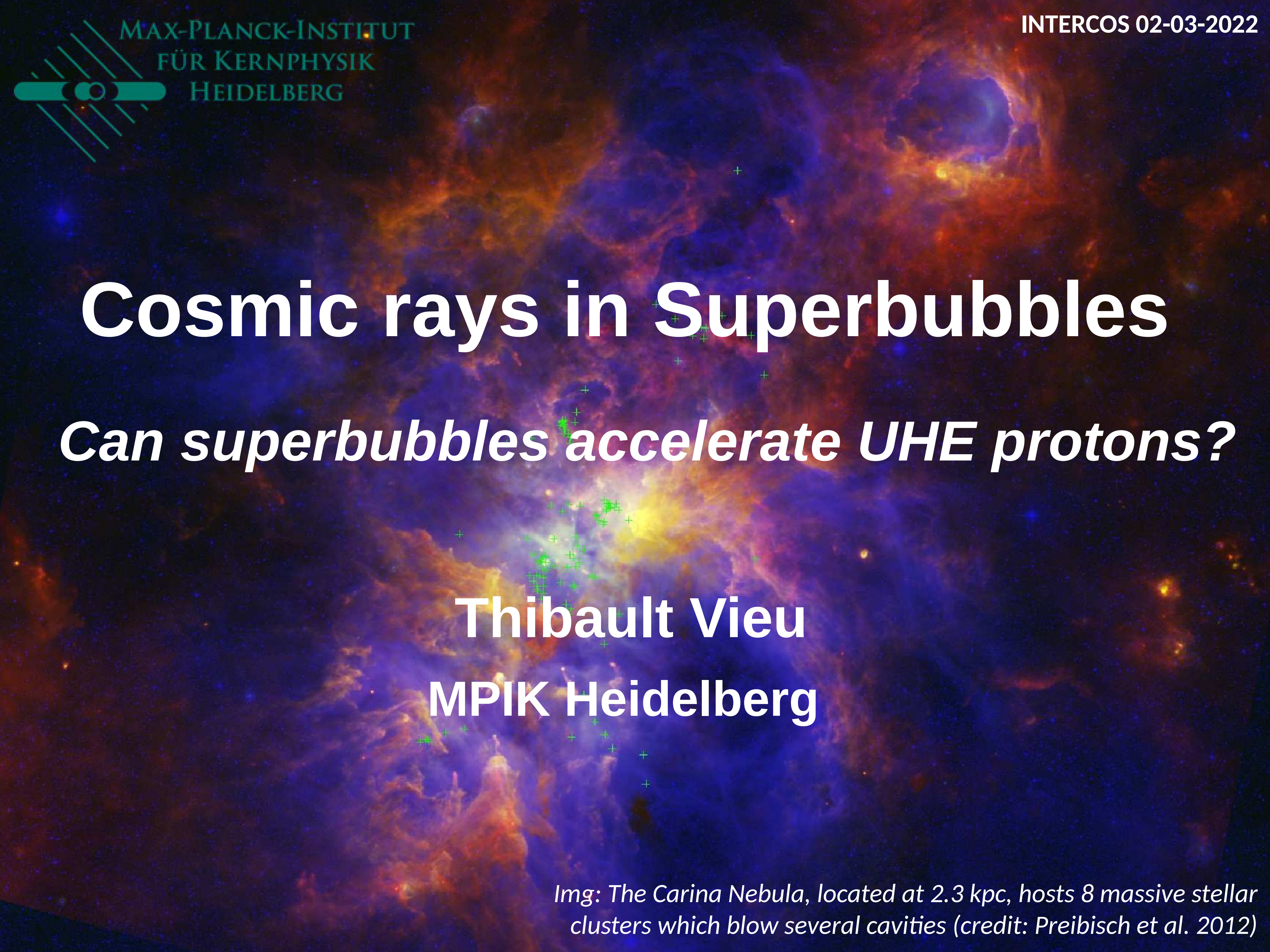
INTERCOS 02-03-2022

Cosmic rays in Superbubbles

Can superbubbles accelerate UHE protons?

Thibault Vieu

MPIK Heidelberg



Img: The Carina Nebula, located at 2.3 kpc, hosts 8 massive stellar clusters which blow several cavities (credit: Preibisch et al. 2012)

Introduction

Why do we need UHE protons?

Cosmic Ray Origin: Lessons from Ultra-High-Energy Cosmic Rays and the Galactic/Extragalactic Transition

Etienne Parizot

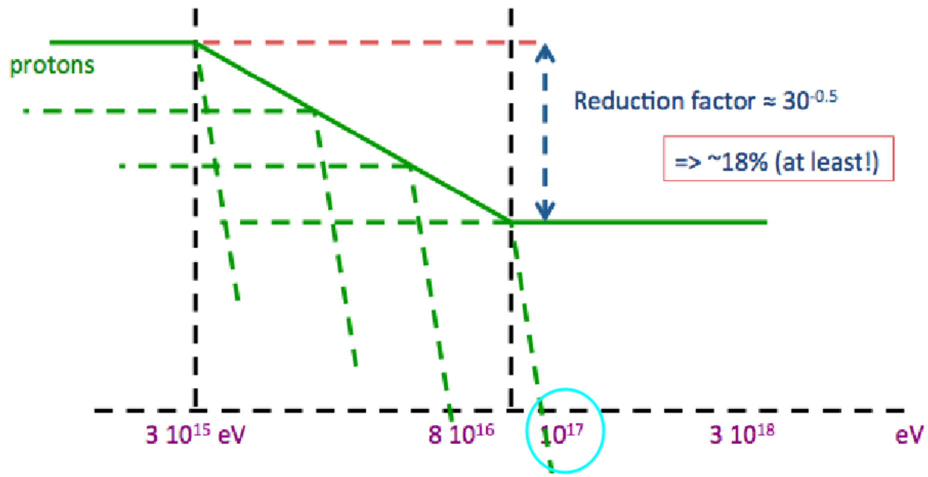
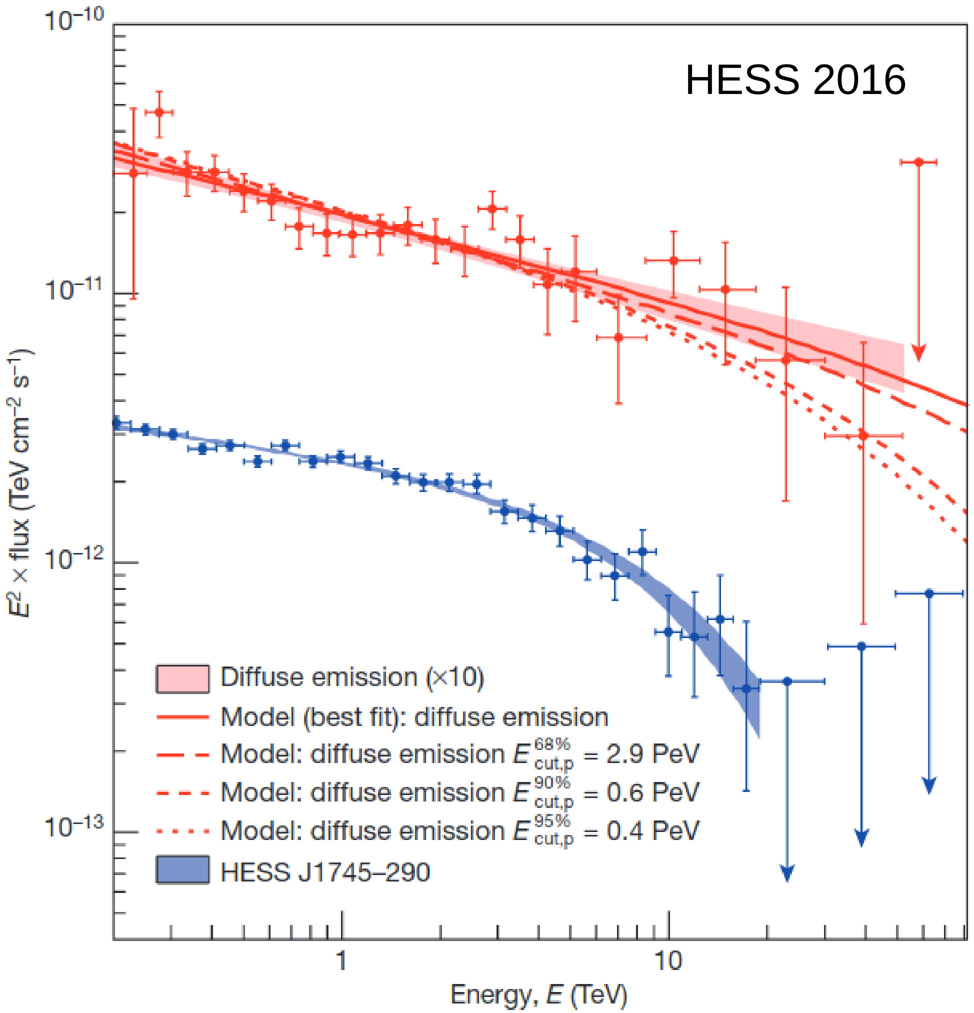


Figure 5: Sketch of the GCR proton flux above the knee, showing the contribution of a smaller and smaller number of sources at higher and higher energy, up to $\sim 10^{17}$ eV, where the EGCR proton component becomes more abundant (compare with the "proton line" of Fig. 4). The various dashed lines show, schematically, the contributions of all the sources which contribute up to a given energy (where the dashed line touches the plain line), with an arbitrary cut-off above that energy.

Protons of tens of PeV:

This is what we need to match KASCADE-Grande and Auger data

Why do we need UHE protons?



Galactic centre

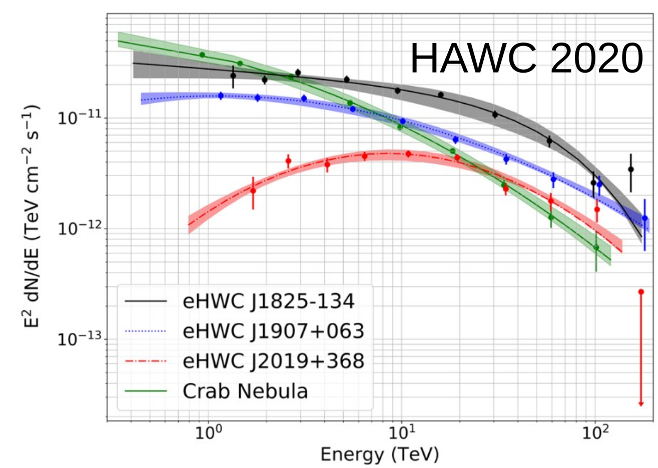


FIG. 3. The spectra of the three sources exhibiting significant $\hat{E} > 100$ TeV emission. For each source, the line is the overall forward-folded best fit. The error bars on the flux points are statistical uncertainties only. The shaded band around the overall best fit line shows the systematic uncertainties related to the HAWC detector model, as discussed in [19]. The Crab Nebula spectrum from [19] is shown for comparison.

Why do we need UHE protons?

Article | Published: 17 May 2021

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, ... X. Zuo + Show authors

Nature **594**, 33–36 (2021) | Cite this article

From Cygnus-X star forming region / OB2 association of massive stars

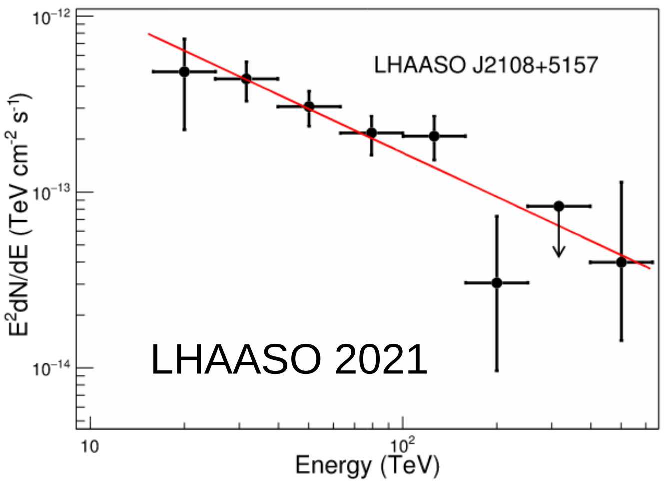


Figure 3. The SED of LHAASO J2108+5157. The solid red line shows the best-fit power-law function.

Unknown source, but correlated with a giant MC

UHE photons: produced by UHE protons?

Candidates:

Pulsar wind nebulae

Massive star clusters/superbubbles

Sagittarius A*

Why do we need UHE protons?

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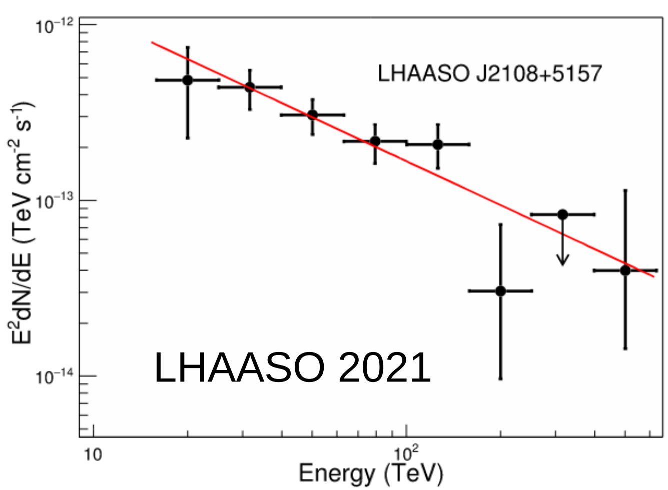

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Unknown source, but correlated with a giant MC

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UHE photons: produced by UHE protons?

Candidates:
Pulsar wind nebulae
Massive star clusters/superbubbles
Sagittarius A*

Can superbubbles accelerate UHE protons?

Can superbubbles accelerate UHE protons?

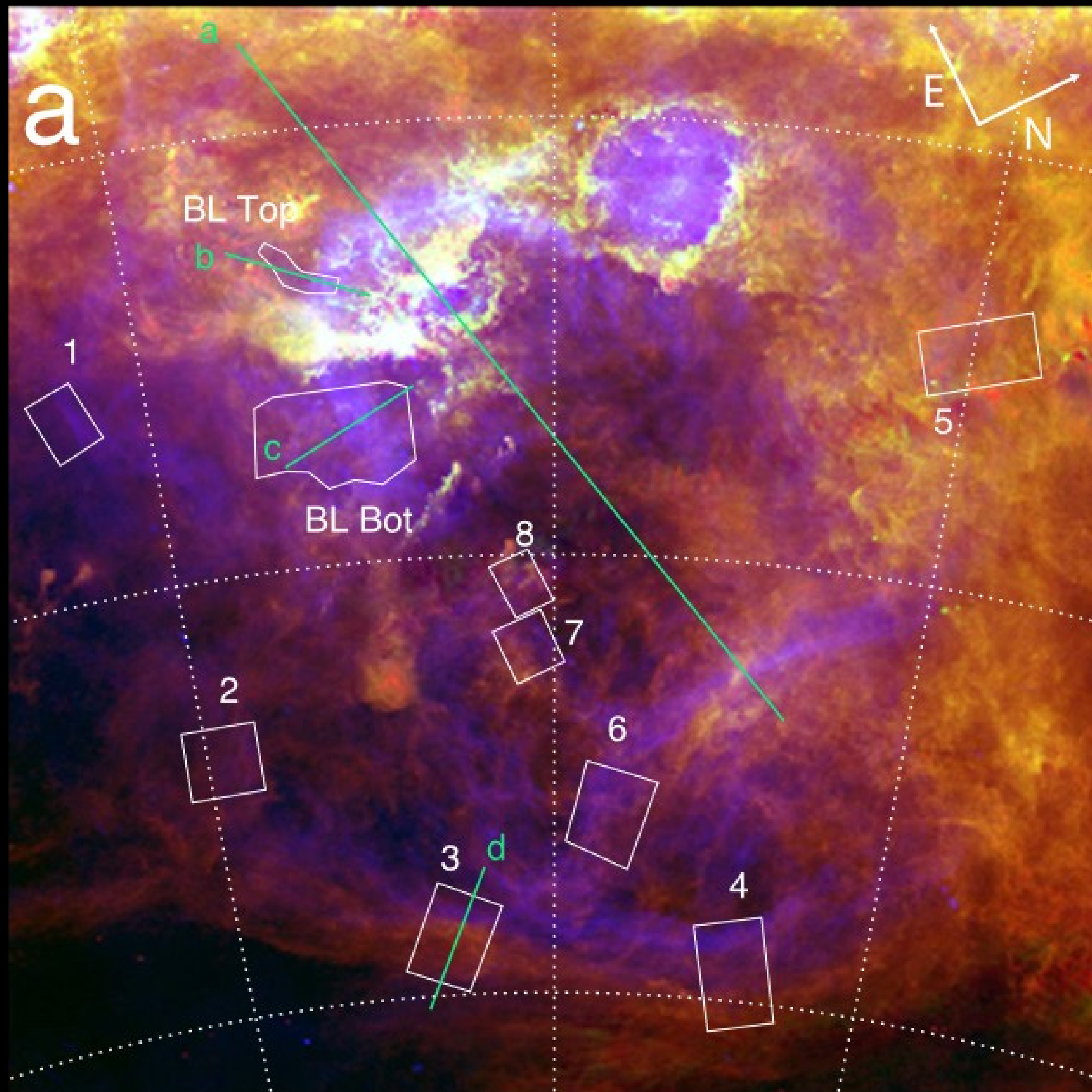
What are “superbubbles”? Formation? Properties?

What is the difference between superbubbles, massive star clusters, star-forming regions, interstellar bubbles…?

How particle acceleration works in superbubbles?

What is the maximum energy?

Superbubbles



Multi-wavelength view of the Orion-Eridani superbubble

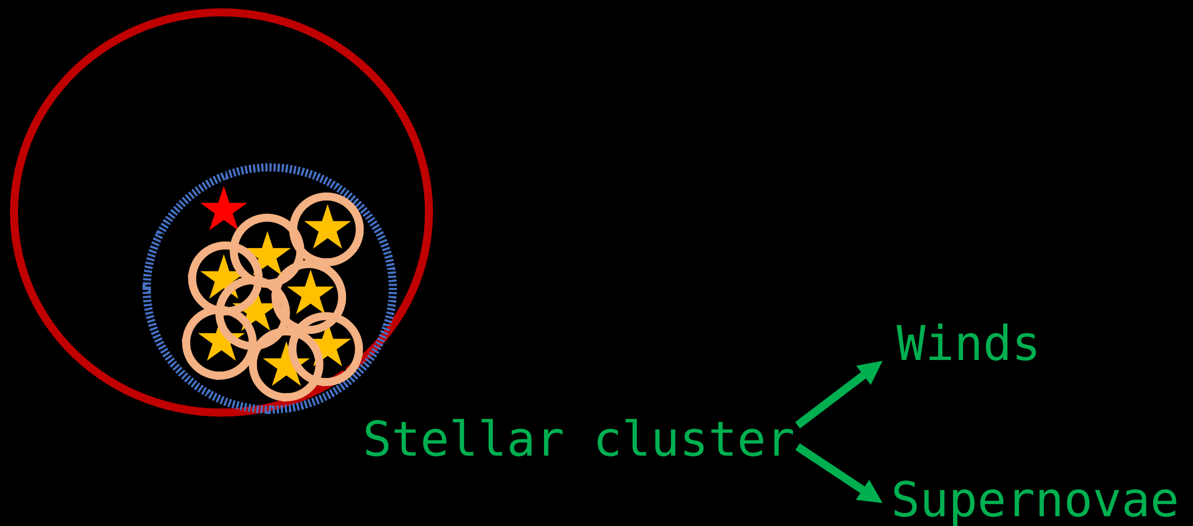
From Ochsendorf et al. 2015

Superbubble formation

Stellar cluster

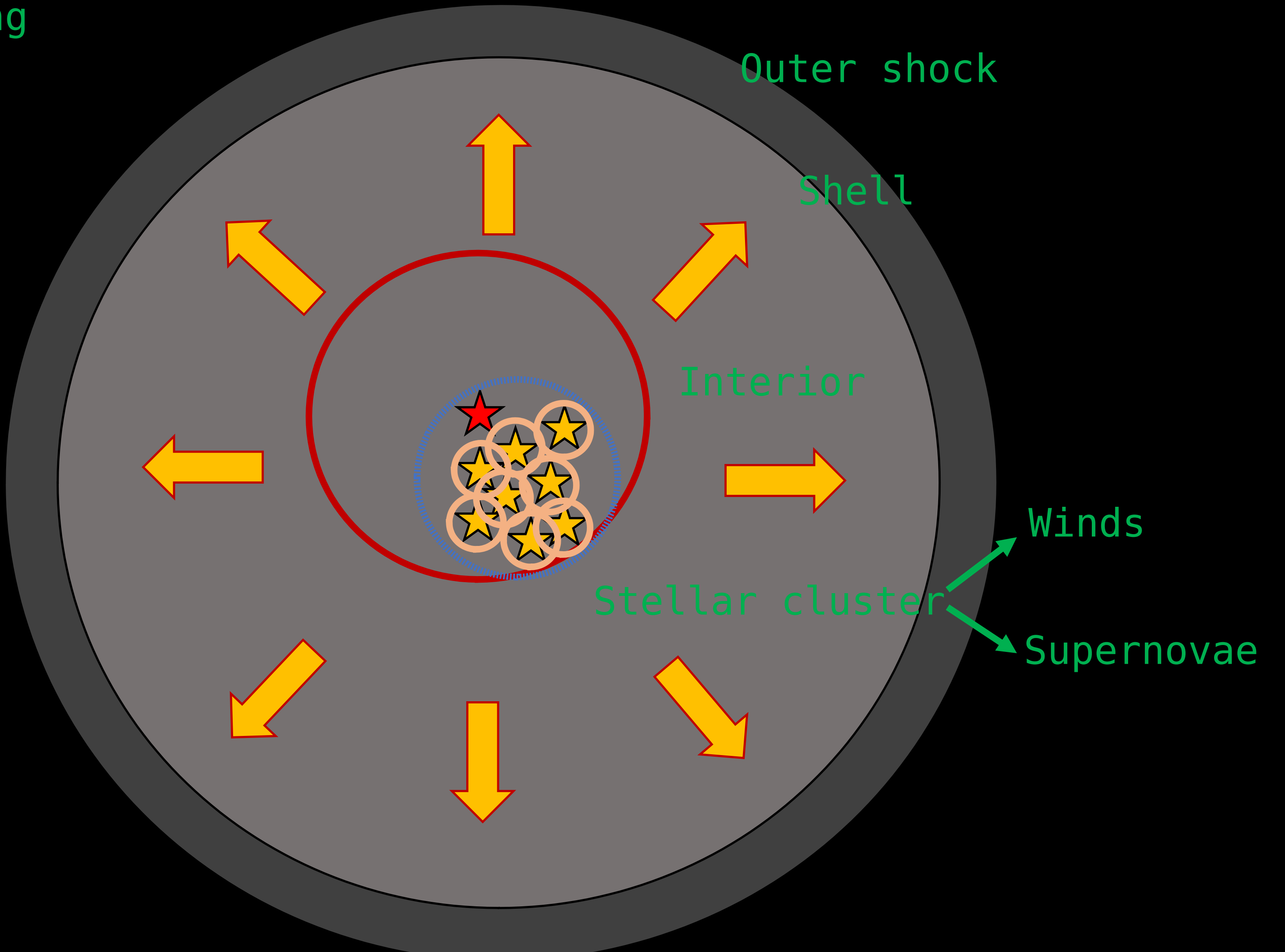
Superbubble formation

Superbubble formation



Superbubble formation

Superbubble
– Low density cavity
– Expanding



Nomenclature of bubbles (everybody uses different definitions...)

Small bubbles (1 pc) = circumstellar bubbles

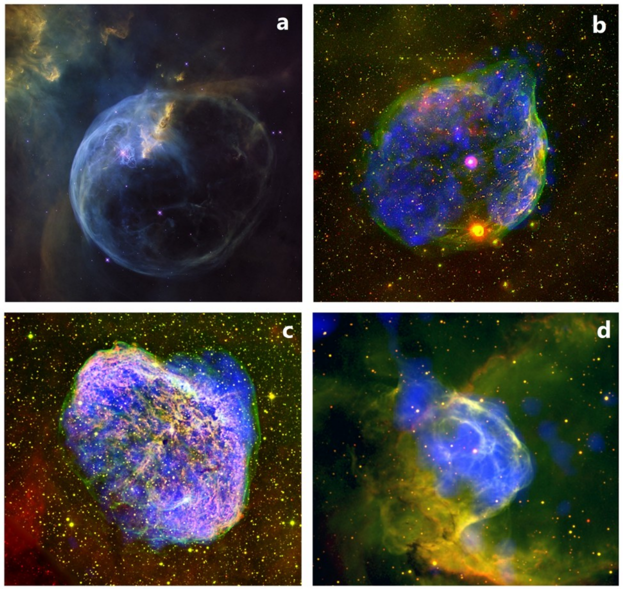


Figure 1.6: Composite images in optical lines and soft X-ray bands of three well-observed galactic circumstellar bubbles: the Bubble nebula (a), S308 (b), the Crescent nebula (NGC6888) (c), the Thor's Helmet nebula (d).

Credits: **Bubble nebula**: NASA, ESA, Hubble Heritage Team. **S308**: J. A. Toala and M. A. Guerrero (IAA-CSIC), Y.-H. Chu and R. A. Gruendl (UIUC), S. J. Arthur (CRyA - UNAM), R. C. Smith (NOAO/CTIO), S. L. Snowden (NASA/GSFC) and G. Ramos-Larios (IAM), ESA/XMM-Newton. **Crescent nebula**: J. A. Toalá, M. A. Guerrero, Y.-H. Chu et al. and ESA. **Thor's Helmet nebula**: J. A. Toala and M. A. Guerrero (IAA-CSIC), Y.-H. Chu (UIUC/ASIAA), R.A. Gruendl (UIUC), S. Mazlin, J. Harvey, D. Verschatse and R. Gilbert (SSRO-South) and ESA/XMM-Newton.

Medium bubbles (10 pc) = interstellar bubbles (young clusters)

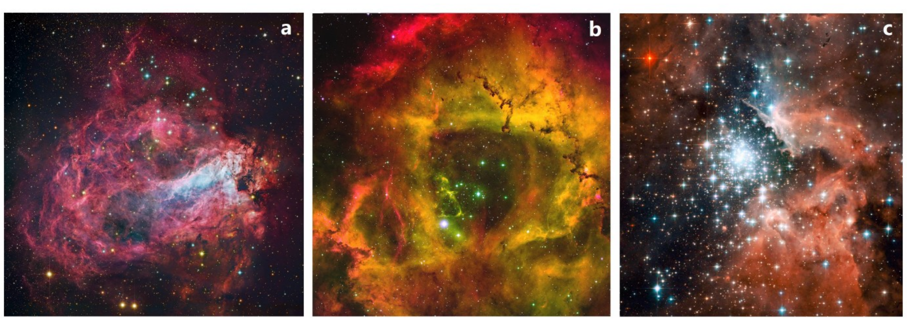


Figure 1.8: Interstellar bubbles. (a) Composite image of the Omega nebula (M17). (b) The Rosette nebula in false colours (SII in blue, [OIII] in green, Hα in red). (c) NGC3603 in three optical wavelengths: 435 nm (blue), 550 nm (green), 850 nm (red).

Credits: **M17**:Copyright 2013 Robert Gendler, Subaru Telescope (NAOJ), HST (composite image). **Rosette**: T. A. Rector/University of Alaska Anchorage, WIYN and NOIRLab/NSF/AURA. **NGC3603**: NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration.

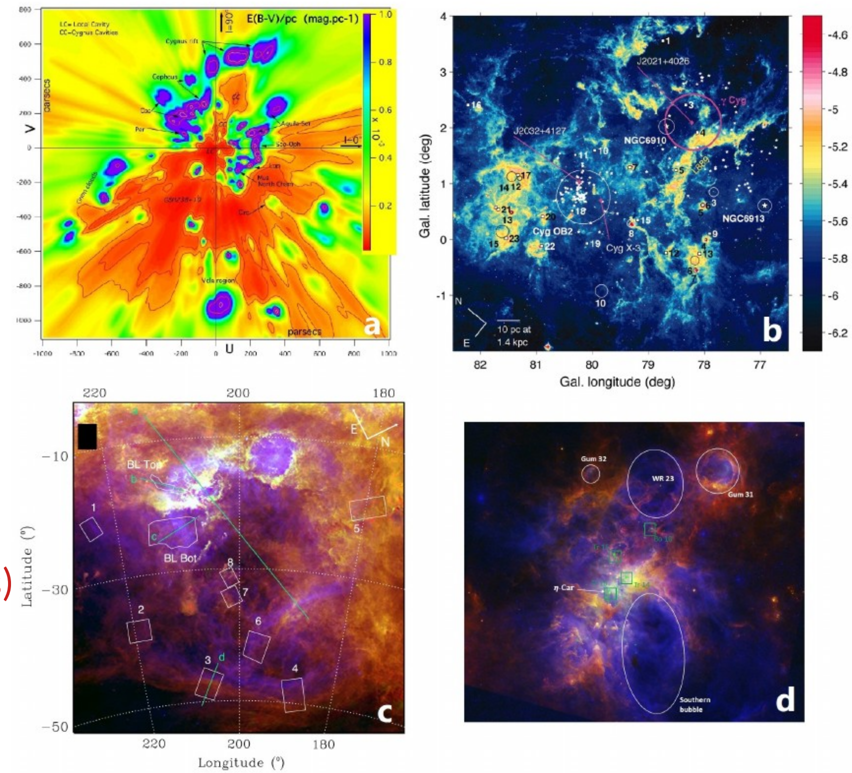


Figure 1.9: Galactic superbubbles. (a) Opacity distribution (increasing from red to violet) in the galactic plane, showing the nearby local cavities, including the local bubble within a radius of about 100 pc at the centre (adopted from Lallement et al. (2014)). (b) 8 μm intensity map of the Cygnus-X complex (adopted from Ackermann et al. (2011)). (c) Multi-wavelength image of the Orion-Eridanus superbubble: Hα in blue (ionised regions), WISE 12 μm band in green and Planck 353 GHz in red (dust) (adopted from Ochsendorf et al. (2015). (d) Composite optical/IR image of the Carina nebula: red optical in blue, Herschel 70 μm in green, Herschel 160 μm in red (adopted from Preibisch et al. (2012), apart from the annotations which I have added).

Large bubbles (100 pc) = superbubbles (old clusters)

Nomencla

Figure 1.6: Composi
galactic circumstellar bu
(c), the Thor's Helmet
Credits: **Bubble nebula:** NASA,
Gruendl (UIUC), S. J. Arthur (CF
ESA/XMM-Newton. **Crescent ne**
A. Guerrero (IAA-CSIC), Y.-H. Ch
and ESA/XMM-Newton.

Medium bub

Figure 1.8: Interste
Rosette nebula in fal
optical wavelengths:
Credits: **M17:**Copyright 2013
of Alaska Anchorage, WIYN a
Collaboration.

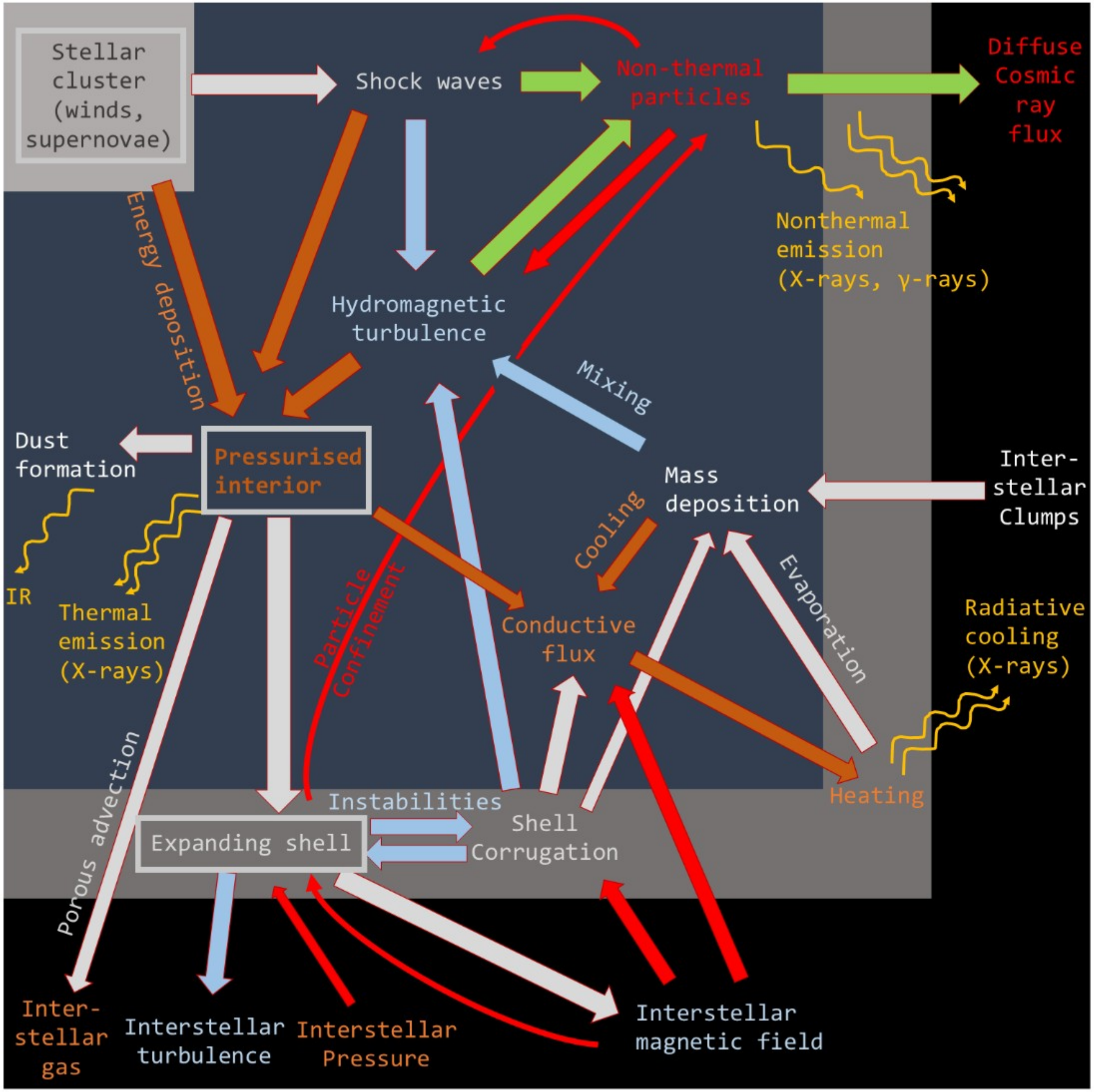
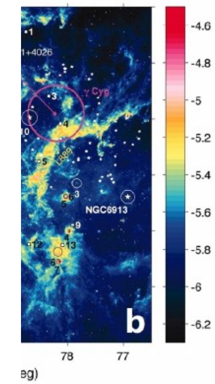


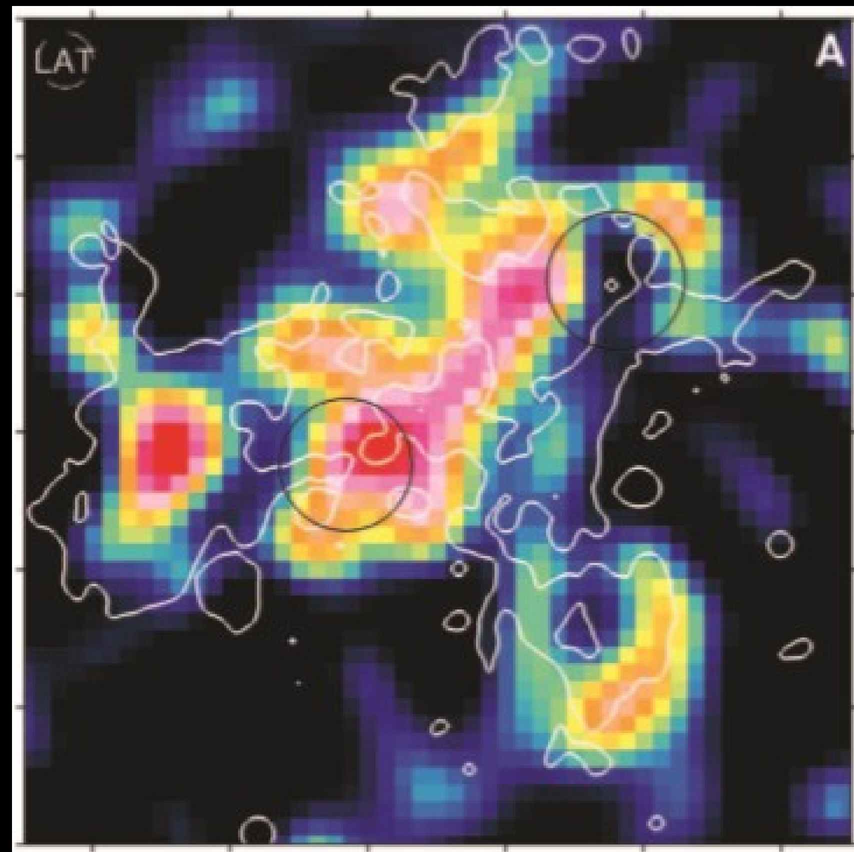
Figure 1.14: The physical processes driving the dynamics of superbubbles and their couplings.



from red to violet) in
bubble within a radius
8 μm intensity map of
ti-wavelength image of
μm band in green and
Composite optical/IR
n, Herschel 160 μm in
ich I have added).

(old clusters)

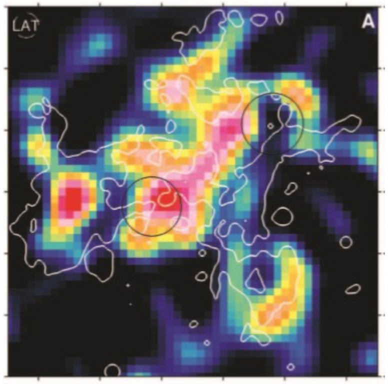
Cosmic rays in superbubbles



The Cygnus-X region in gamma-rays

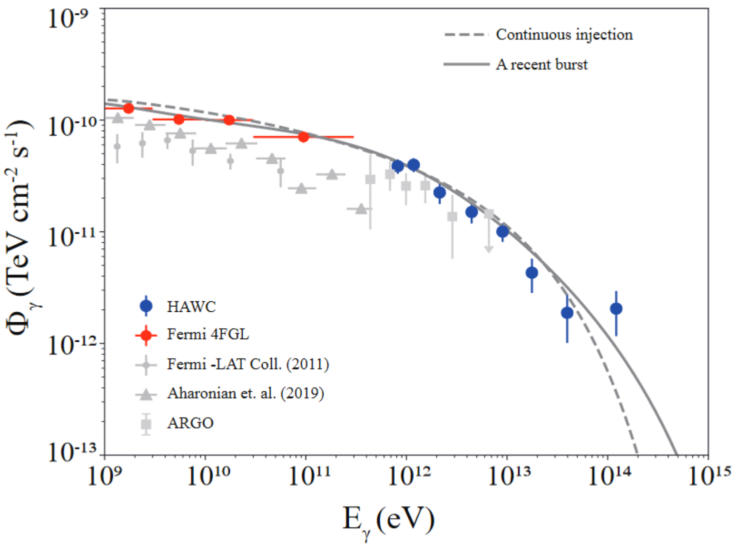
Fermi collab. 2011

Stellar clusters / Superbubbles do accelerate cosmic rays…



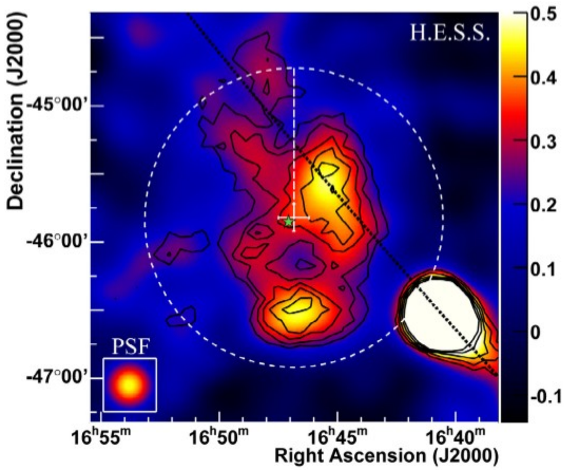
Fermi collab. 2011

HAWC collab. 2021



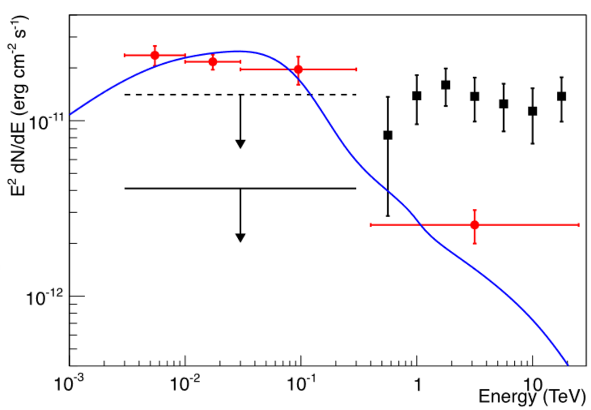
Cygnus OB2

Westerlund I

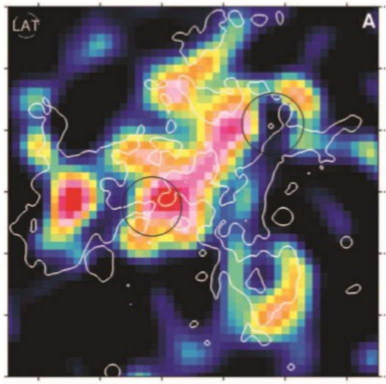


HESS collab. 2012

Ohm et al. 2013



Stellar clusters / Superbubbles do accelerate cosmic rays…



Fermi collab. 2011

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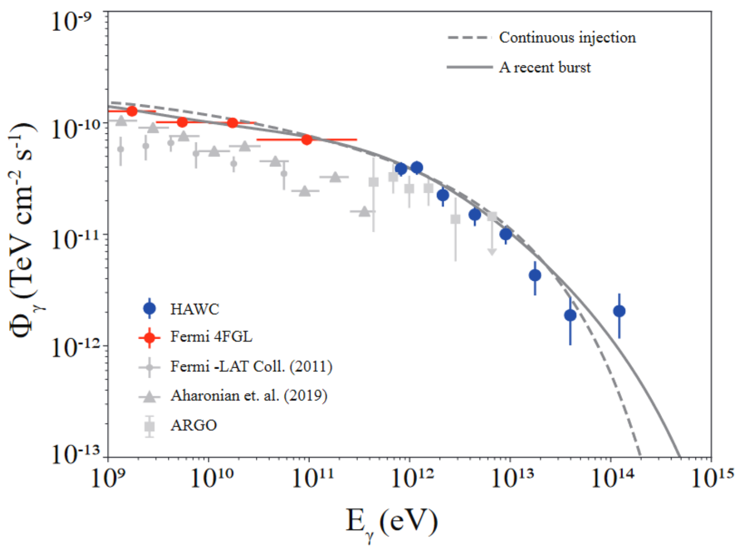
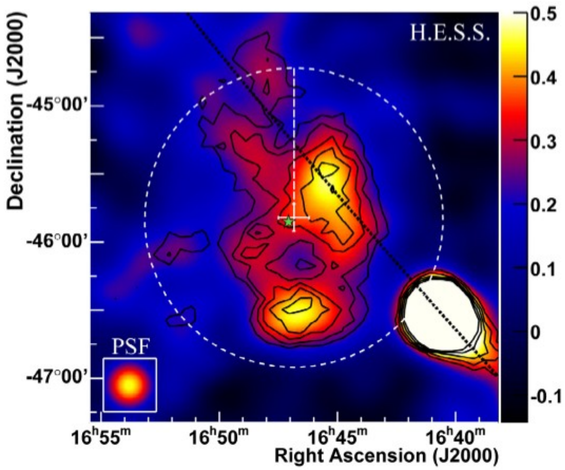


Cygnus OB2



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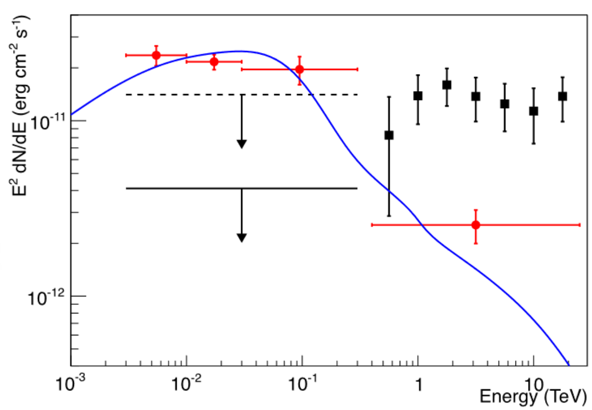


… up to 10s PeV according to common belief

Hillas 1984

Maximum energy = achieved in the electric potential uBR :

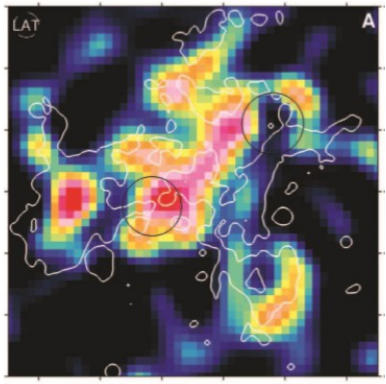
Emax = q uBR

= 100 PeV for B = 100 µG

u = 3000 km/s

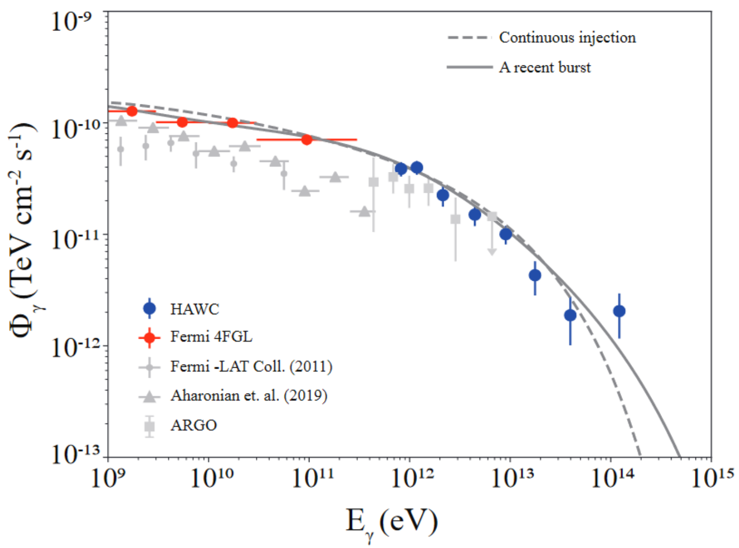
R = 100 pc

Stellar clusters / Superbubbles do accelerate cosmic rays…



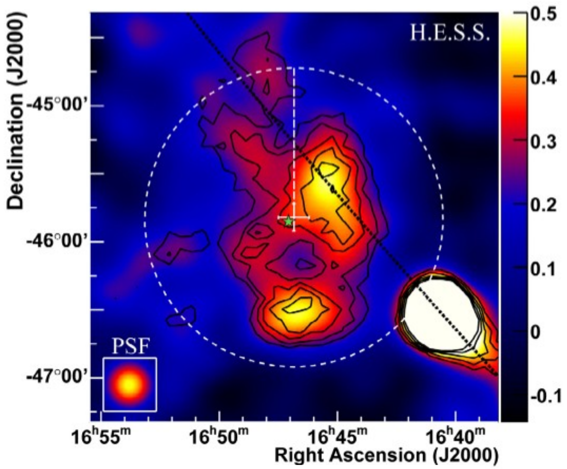
Fermi collab. 2011

HAWC collab. 2021



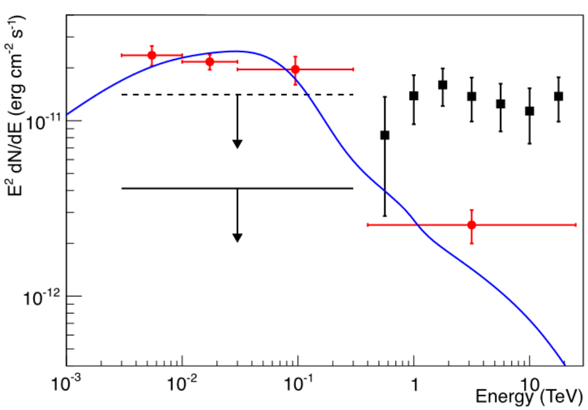
Cygnus OB2

Westerlund I



HESS collab. 2012

Ohm et al. 2013



… up to 10s PeV according to common belief

Hillas 1984

Maximum energy = achieved in the electric potential uBR :

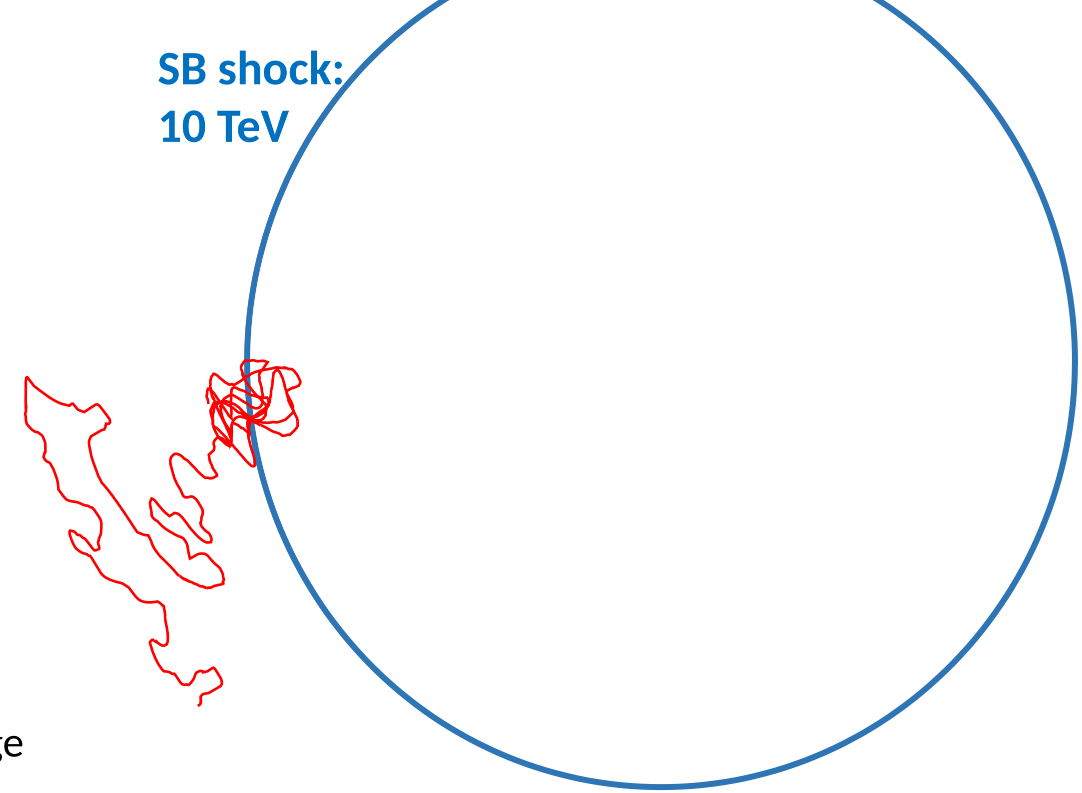
Emax = q uBR

= 100 PeV for B = 100 μG
u = 3000 km/s
R = 100 pc

Very nice but…

What is the acceleration mechanism ?

WITAM What is the acceleration mechanism ?

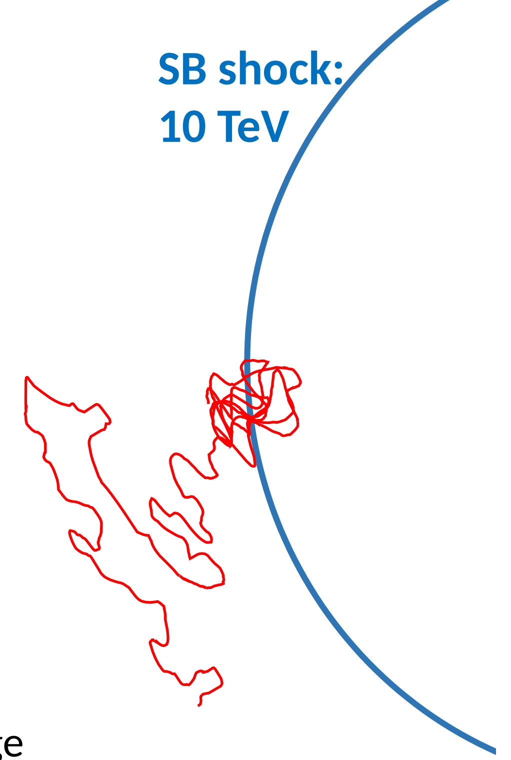


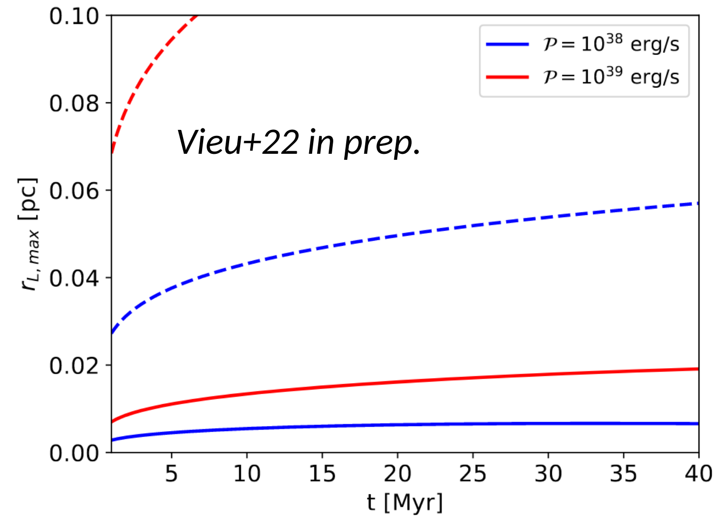
SB forward shock?
Standard DSA mechanism
Emax = acceleration rate VS SB age

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	E_{max}, canonical [PeV]	E_{max}, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1

WITAM What is the acceleration mechanism ?

SB shock: 10 TeV



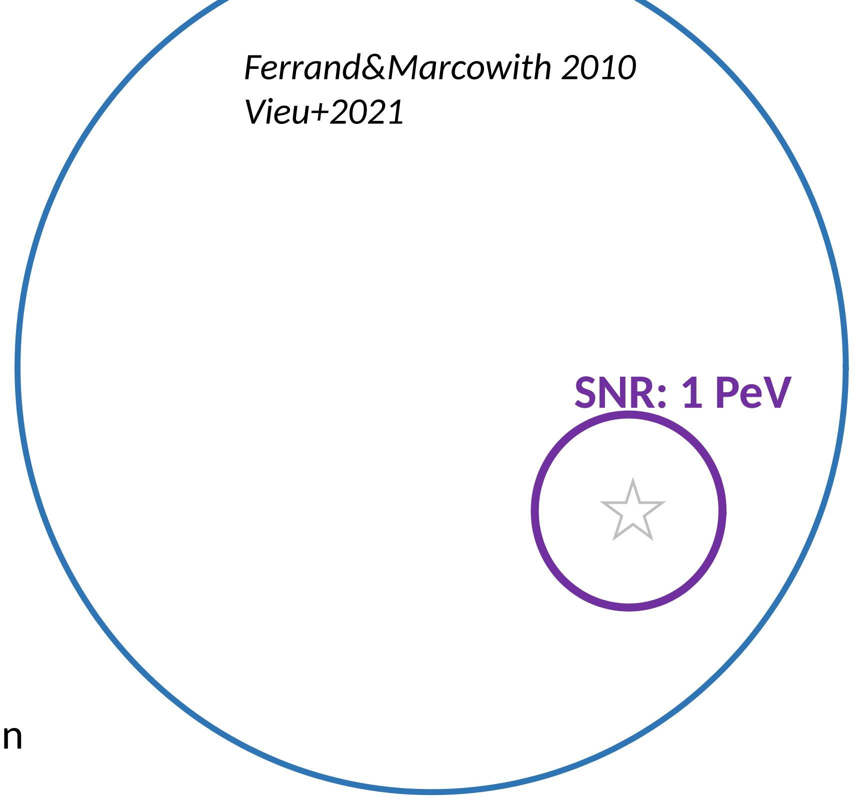


SB forward shock?
Standard DSA mechanism
Emax = acceleration rate VS SB age

Figure 1. Evolution of the maximum Larmor radius achieved in the SB forward shock around a canonical cluster ($\mathcal{P} = 10^{38}$ erg/s, blue curve) and around a very massive cluster ($\mathcal{P} = 10^{39}$ erg/s, red curve). The solid curves show the limitation due to the finite age of the SB while the dotted curves show the limitation due to the finite size of the SB. We assumed optimistic parameters: $\xi_b = 1$, $n_{\rm ISM} = 1$ cm^{-3}, and an ISM temperature of 10^4 K.

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	$E_{\rm max}$, canonical [PeV]	$E_{\rm max}$, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1

WITAM What is the acceleration mechanism ?



Supernova remnants expanding in the SB?
Standard DSA mechanism
Emax = acceleration rate VS SNR age

Low-density => longer expansion
Low-density => less efficient B field amplification

Note: compact cluster => SNR expand in the free-wind
B ~ hundreds of μG in the free-wind for very massive clusters!

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	$E_{\max}$, canonical [PeV]	$E_{\max}$, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1
SNR inside SB	3000	10 – 50	10 – 30	1	1 – 3

WITAM What is the acceleration mechanism ?

Supernova remnants expanding in the SB?
Standard DSA mechanism
Emax = acceleration rate VS SNR age

Low-density => longer expansion
Low-density => less efficient B field amplification

Note: compact cluster => SNR expand in the free-wind
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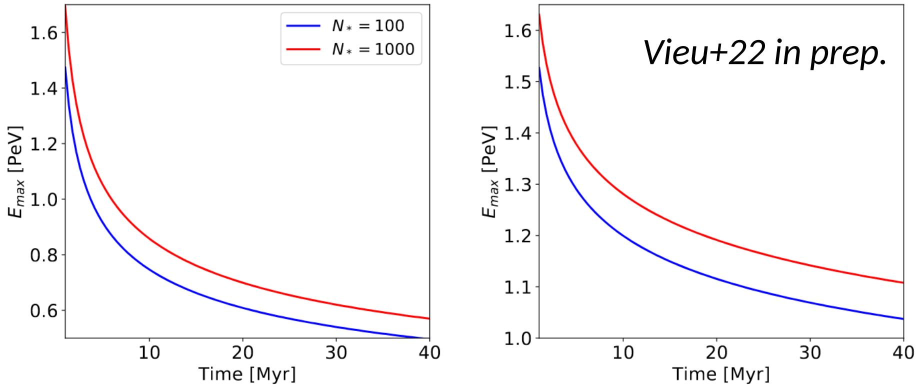
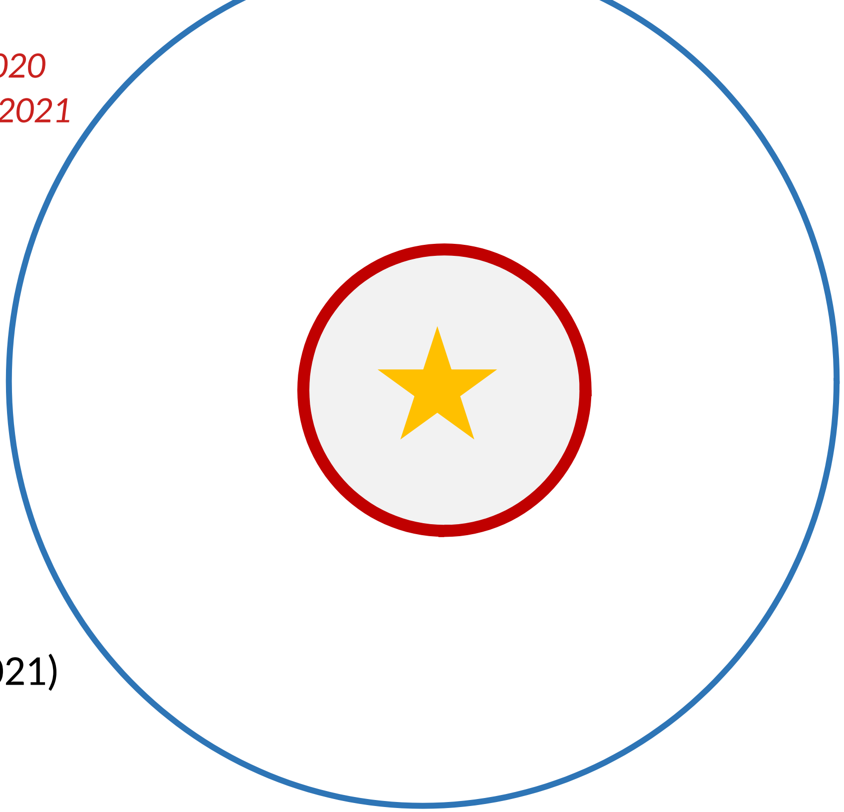


Figure 2. Evolution of the maximum momentum achieved in a SNR. The left panel shows the case where the magnetic field is generated by the stars assuming rather optimistic parameters: $n_{\rm ISM} = 1$ cm^{-3}, $\eta_T = 50\%$, $L = 10$ pc. The right panel shows the case where the magnetic field is generated by CR streaming instability assuming rather optimistic parameters: $n_{\rm ISM} = 100$ cm^{-3}, $\eta_{CR} = 10\%$, $L = 10$ pc.

Acceleration mechanism	U [km/s]	B [µG]	R [pc]	$E_{\rm max}$, canonical [PeV]	$E_{\rm max}$, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1
SNR inside SB	3000	10 – 50	10 – 30	1	1 – 3

WITAM What is the acceleration mechanism ?

Gupta+2020
Morlino+2021

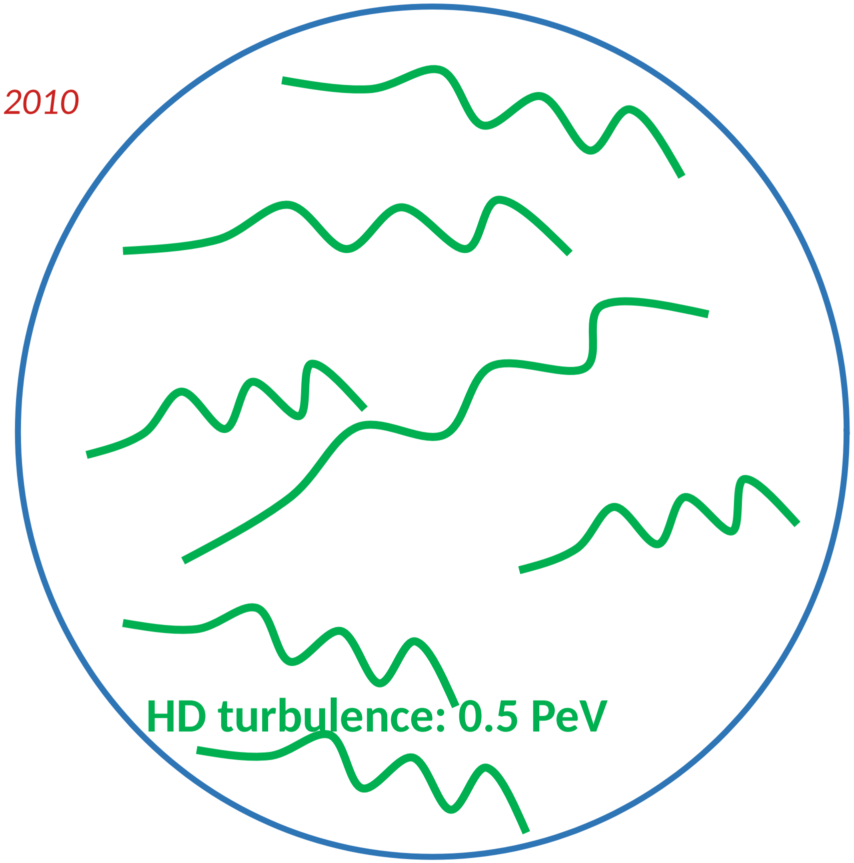


Collective wind termination shock?
Requires a compact cluster (e.g. Westerlund 1)
Standard DSA
Emax = geometry limitations (e.g. Morlino et al. 2021)

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	E_{max}, canonical [PeV]	E_{max}, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1
SNR inside SB	3000	10 – 50	10 – 30	1	1 – 3
WTS around a compact cluster	2000	1 – 20	1 – 30	1	3

WITAM What is the acceleration mechanism ?

Bykov+199x
Ferrand&Marcowith 2010
Vieu+2021



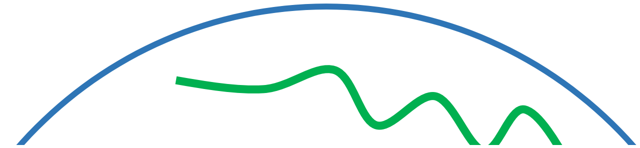
MHD turbulence?
Stochastic (re)acceleration / Fermi II
Emax = acceleration rate VS escape rate

Very inefficient if the diffusion is not Bohm-like.

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	E_{max}, canonical [PeV]	E_{max}, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1
SNR inside SB	3000	10 – 50	10 – 30	1	1 – 3
WTS around a compact cluster	2000	1 – 20	1 – 30	1	3
HD turbulence	100	1 – 10	50 – 100	0.5	1

WITAM

What is the acceleration mechanism ?



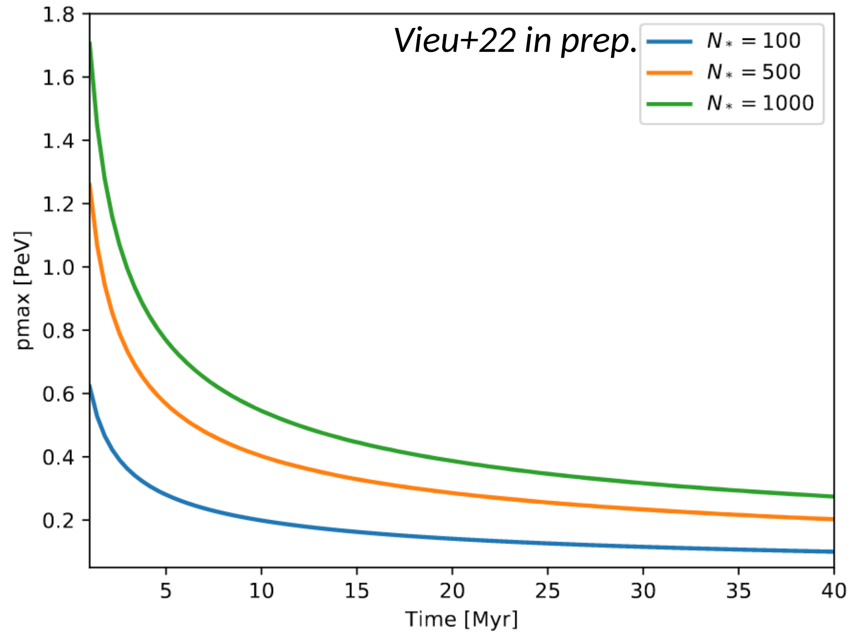


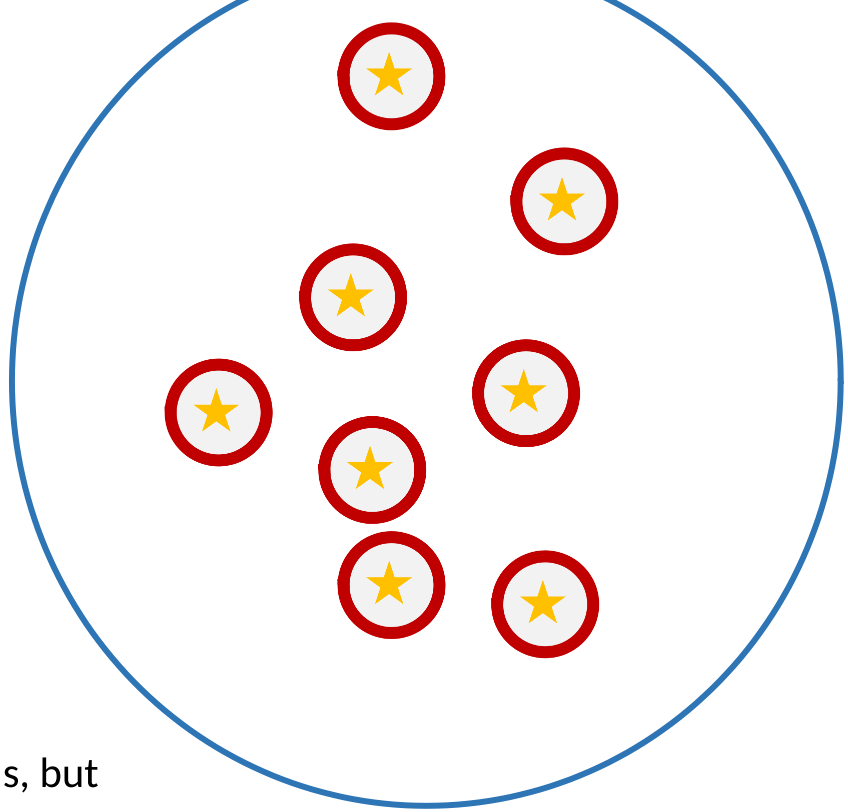
Figure 5. Evolution of the maximum momentum achieved via Fermi II acceleration over diluted turbulence.

MHD turbulence?
Stochastic (re)acceleration / Fermi II
Emax = acceleration rate VS escape rate

Very inefficient if the diffusion is not Bohm-like.

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	E_{max}, canonical [PeV]	E_{max}, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1
SNR inside SB	3000	10 – 50	10 – 30	1	1 – 3
WTS around a compact cluster	2000	1 – 20	1 – 30	1	3
HD turbulence	100	1 – 10	50 – 100	0.5	1

WITAM What is the acceleration mechanism ?



Individual wind termination shock?
Requires a loose cluster (e.g. Cygnus OB2)
Nonlinear stochastic acceleration (Bykov+ 199x)
Emax = acceleration rate VS escape rate

Issue: the relevant velocity is NOT that of the winds, but
The mean velocity in the SB
=> needs to introduce a CR-wind « scattering cross-section »
=> this cross-section is very low

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	E_{max}, canonical [PeV]	E_{max}, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1
SNR inside SB	3000	10 – 50	10 – 30	1	1 – 3
WTS around a compact cluster	2000	1 – 20	1 – 30	1	3
HD turbulence	100	1 – 10	50 – 100	0.5	1
Collection of individual winds (loose cluster)	10 – 100	10 – 30	1 – 10	0.05	0.2

WITAM What is the acceleration mechanism?

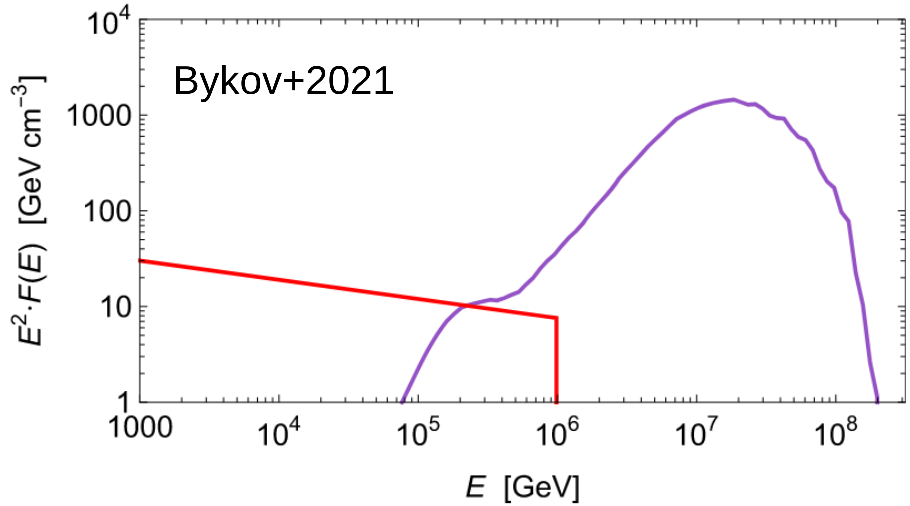


Figure 2. (Red) The energy distribution function of particles injected into the colliding wind flows (extends down to 1 GeV). (Purple) The result of the Monte Carlo simulation of the spectrum of particles accelerated in the colliding wind flows in the collision zone of the pulsar and stellar winds.

Pulsar-WTS collision? (Bykov+ 201x)
Emax = geometry limitations
Unclear how to inject and confine the CR
But large B => can work in principle
A nice way to use the properties of a pulsar to reaccelerate protons.
Numerical simulations are now needed.

(see also Vieu+2020 for similar results but discussion on the time limitation)

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	E_{max}, canonical [PeV]	E_{max}, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1
SNR inside SB	3000	10 – 50	10 – 30	1	1 – 3
WTS around a compact cluster	2000	1 – 20	1 – 30	1	3
HD turbulence	100	1 – 10	50 – 100	0.5	1
Collection of individual winds (loose cluster)	10 – 100	10 – 30	1 – 10	0.05	0.2
Colliding winds with pulsar companion	2000	100	10	3	10

Exemple from proper computations (detailed self-consistent model)

Cosmic ray production in superbubbles

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Provides useful estimates of the SB properties

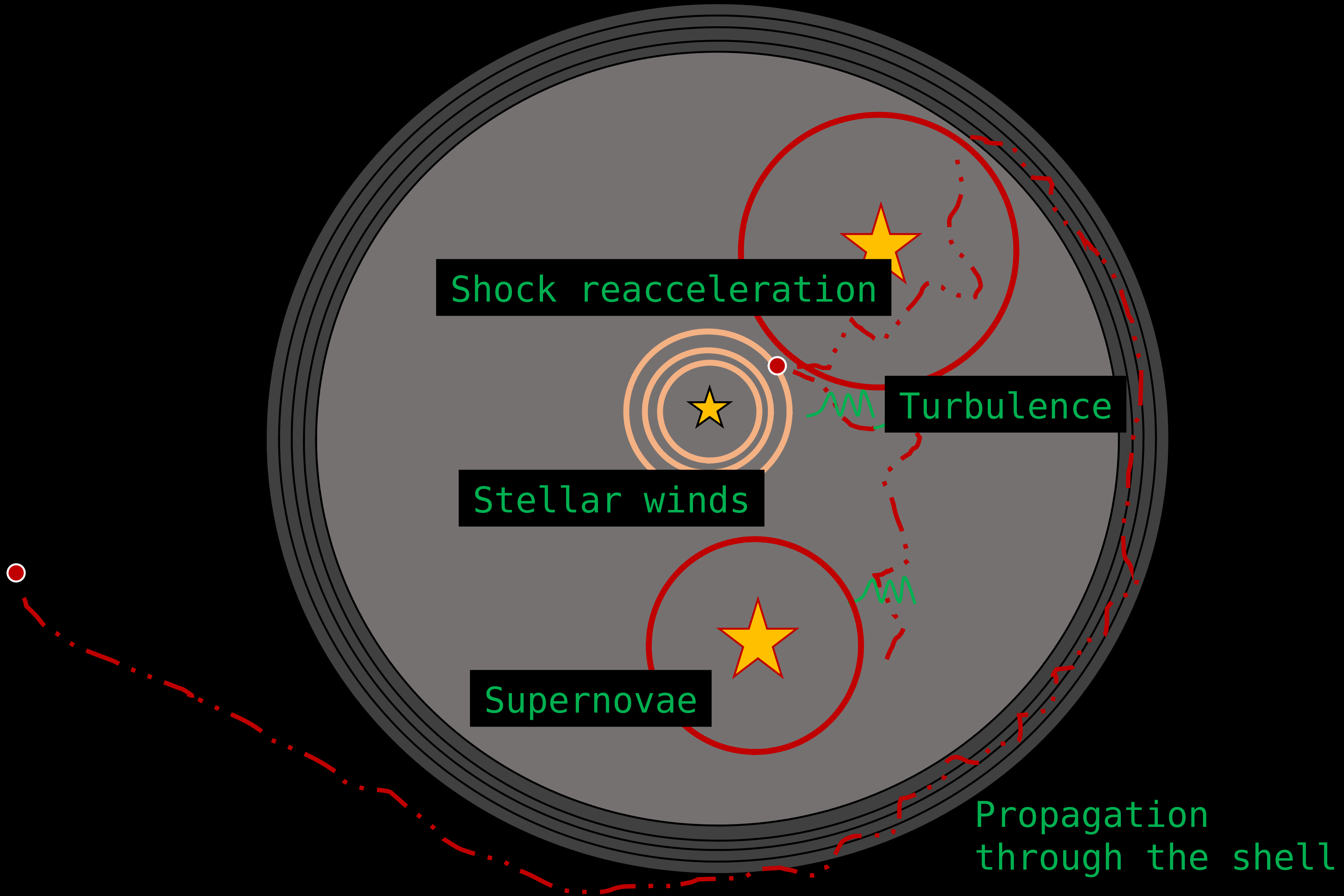
Geometry, magnetic fields, turbulence level, diffusion coefficient, shock sizes, density, temperature…

Qualitative results on the typical shapes of CR and gamma-ray spectra produced in SBs, in various configurations (e.g. loose/compact, effect of the shell...)

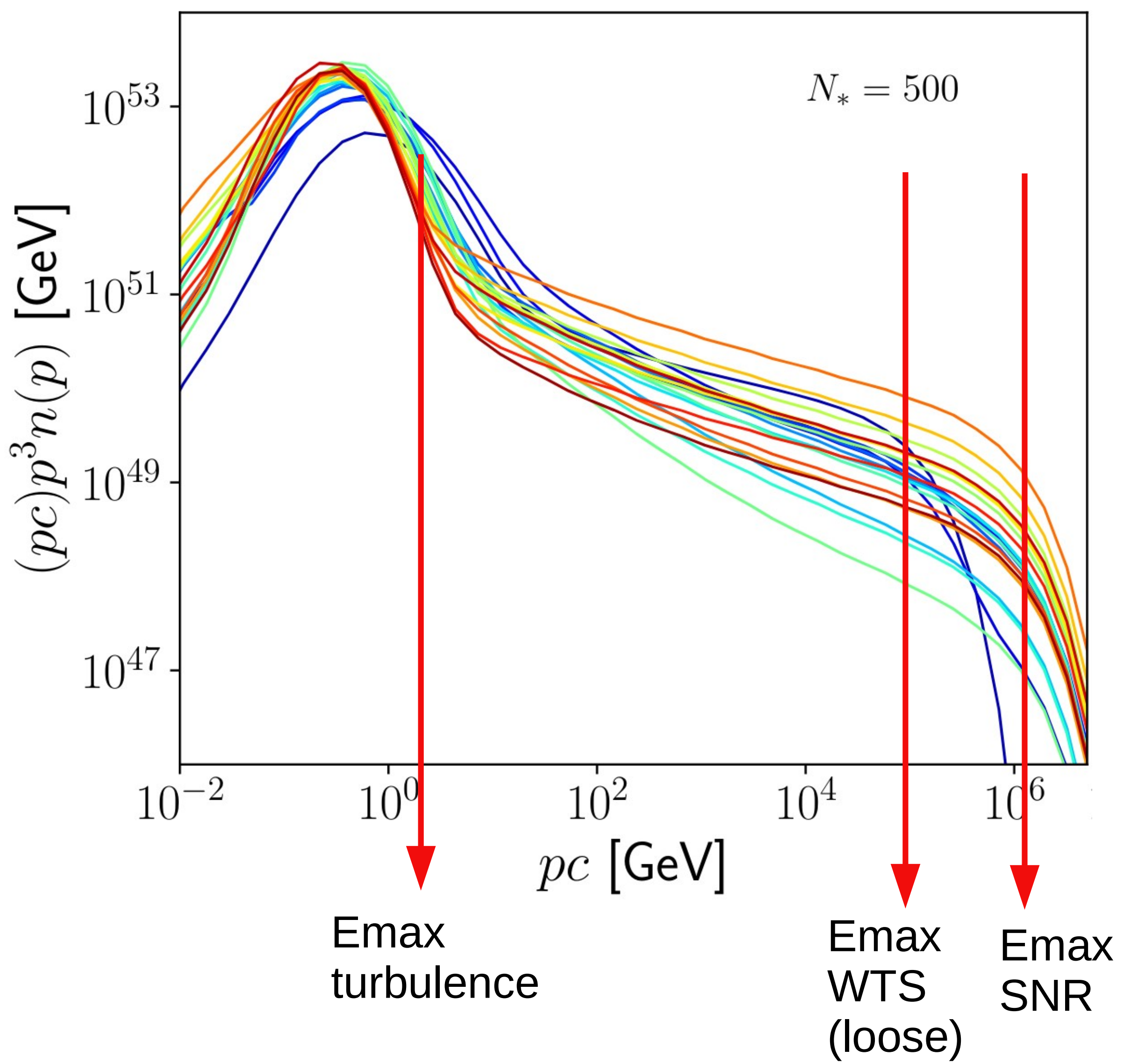
First quantitative comparison with gamma-ray data and the local CR spectrum

If you're looking for a pedagogical approach to the subject and have some time to lose, have a look at my PhD thesis (available on TEL)

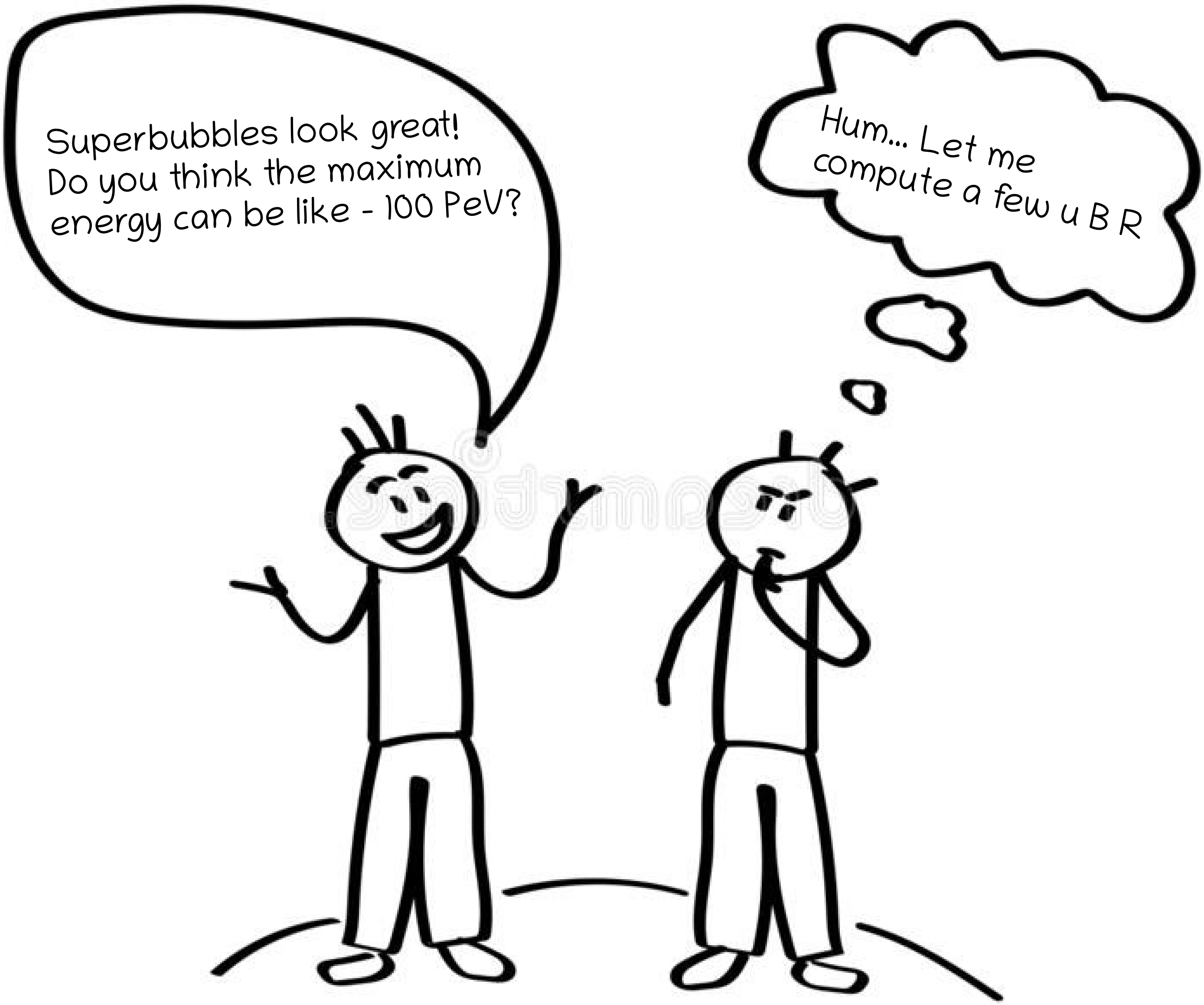
Exemple from proper computations (self-consistent model)



Exemple from proper computations (detailed self-consistent model)



Conclusions



Can superbubbles accelerate UHE protons?

Acceleration mechanism	U [km/s]	B [μG]	R [pc]	E_{max}, canonical [PeV]	E_{max}, optimistic [PeV]
SB forward shock	30	1 – 10	50 – 100	0.01	0.1
SNR inside SB	3000	10 – 50	10 – 30	1	1 – 3
WTS around a compact cluster	2000	1 – 20	1 – 30	1	3
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Colliding winds with pulsar companion	2000	100	10	3	10

Loose associations => Emax ~ few PeV

Compact and very massive clusters => Emax ~ up to 5 PeV

Colliding pulsar-WTS => Emax ~ 10 PeV

Is this enough to account for the proton flux near Earth and recent gamma-ray observations?

Loose associations => Emax ~ few PeV

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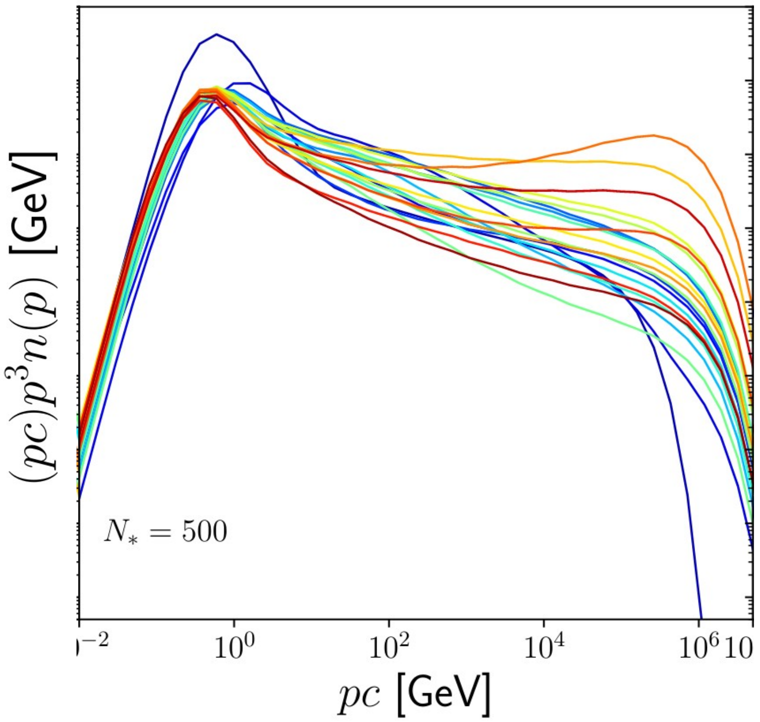
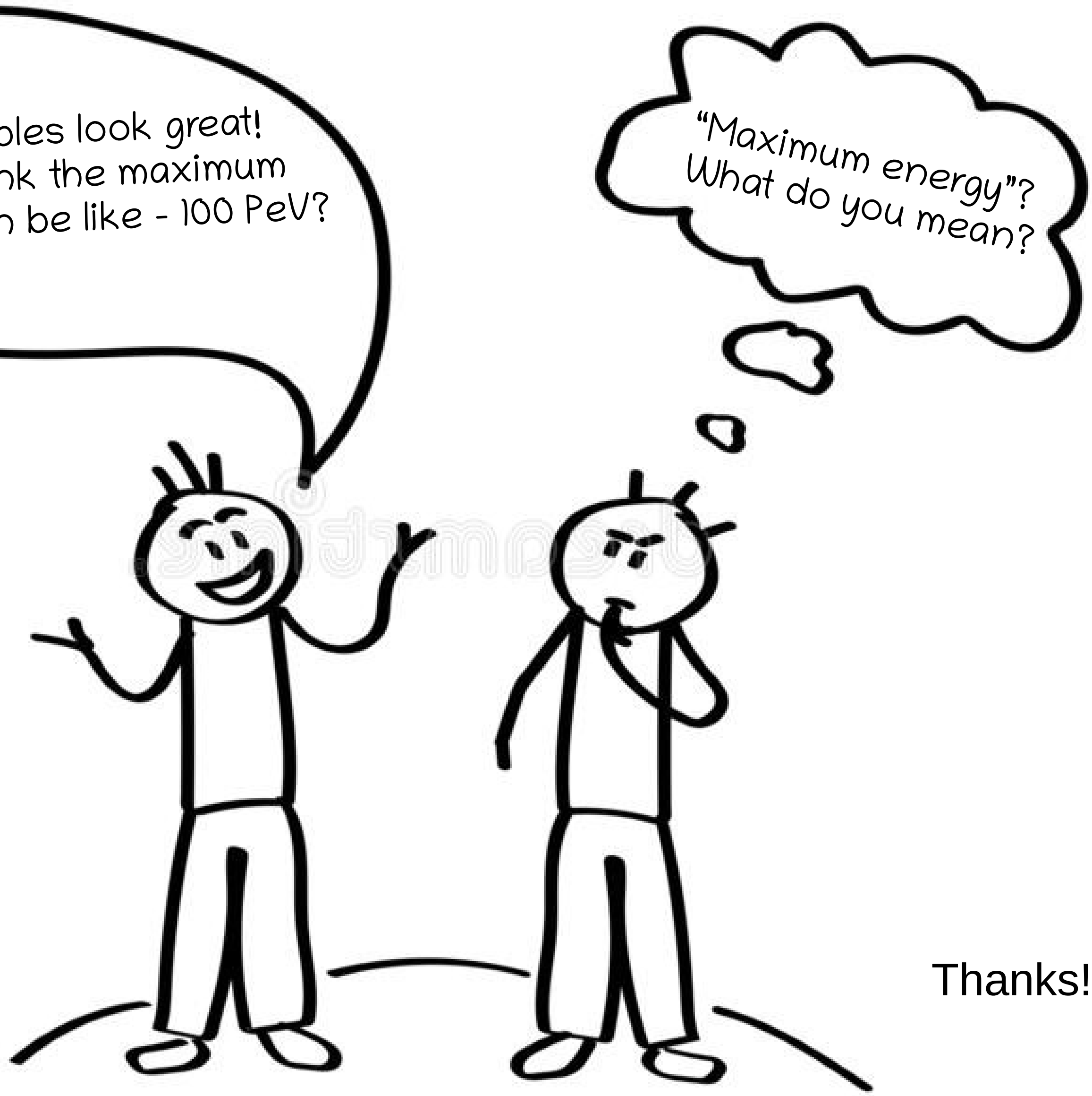
Is this enough to account for the proton flux near Earth and recent gamma-ray observations?



In fact… how do we define Emax, observationally speaking?

f(p) = p^-s exp(-E/Emax)


Superbubbles look great! Do you think the maximum energy can be like - 100 PeV?
“Maximum energy”? What do you mean?

Thanks!