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Galactic source modelling

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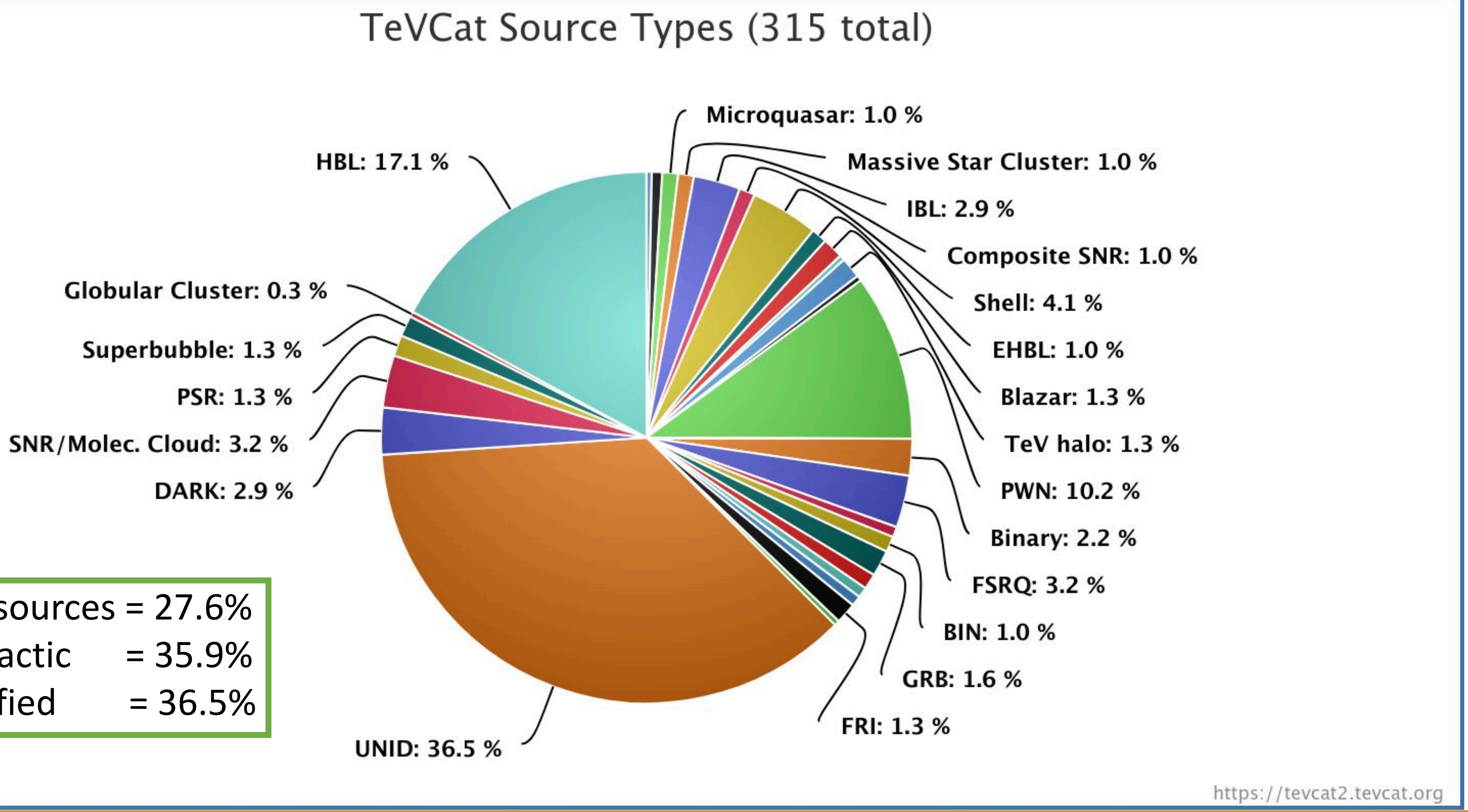
Progetto PNRR CTA+
Proposta IR0000012
CUP: C53C22000430006

Missione 4 Istruzione e Ricerca
Componente 2 Dalla ricerca all'impresa
Linea di investimento 3.1



Galactic sources = 27.6%
Extra-galactic = 35.9%
Unidentified = 36.5%

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The Galactic gamma-ray Zoo

Supernova remnants

Pulsars
Pulsar wind nebulae
TeV halos

Composite SNR

Binaries:
Gamma-ray binaries
Microquasars
Colliding wind binaries
Novae

Young stellar clusters
Super-bubbles

Galactic center

Expected but not observed (yet)

Young massive stellar objects
Isolated stellar mass black holes
…

Diffuse emission

Unidentified

The Galactic gamma-ray Zoo

Supernova remnants

Young stellar clusters
Super-bubbles

I will focus on these two categories

Modeling gamma-ray sources: ingredients

Physics

Geometry

Matter

Interaction

Modeling gamma-ray sources: ingredients

Physics | Geometry | Matter | Interaction

Acceleration mechanisms

- Direct acceleration
  (requires stable electric field)
  - PWN
- Stochastic acceleration
  (due to fluctuations of magnetic field)
  - Fermi II mechanism
  - Diffusive Shock Acceleration
    (Fermi I mechanism)
  - Shear acceleration

Magnetic reconnection

Direct acceleration + Stochastic

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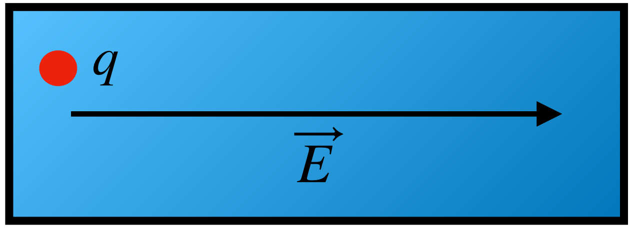
Acceleration mechanisms: the Hillas' criterion

The best possible accelerator



- Absolute maximum energy. $E_{\rm max} = q\,|\vec{E}\,|\,L$
- Current: $\vec{j} = \sigma \vec{E}_{\rm lab} = \sigma \left(\vec{E} + \frac{1}{c} \vec{v} \times \vec{B} \right)_{\rm rest\ frame}$
- Astrophysical plasmas has a very large conductivity (electrons can move almost freely) $\sigma \simeq 7 \times 10^7 \frac{T^{3/2}}{\ln \Lambda}\, {\rm s}^{-1}$

$$\Rightarrow \vec{E}_{\rm lab} \simeq 0; \quad \vec{E}_{\rm RF} \simeq -\frac{1}{c} \vec{v} \times \vec{B}$$

Where does the electric field come from?

Faraday's law: $\nabla \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t}$

$\nabla \times \longrightarrow \frac{1}{L}$ characteristic length

$\frac{\partial}{\partial t} \longrightarrow \frac{1}{T}$ characteristic time

$$\Rightarrow E \approx \frac{L}{T} \frac{B}{c} \approx \frac{U}{c} B$$

$$\boxed{E_{\rm max} \approx \frac{U}{c}\, q\, B\, L}$$

velocity — Charge — Size — B-field

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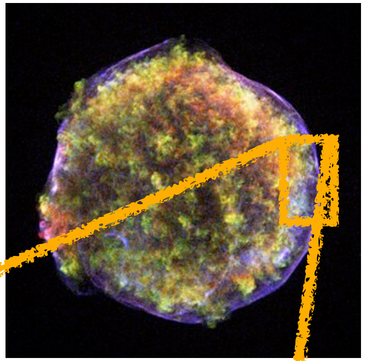
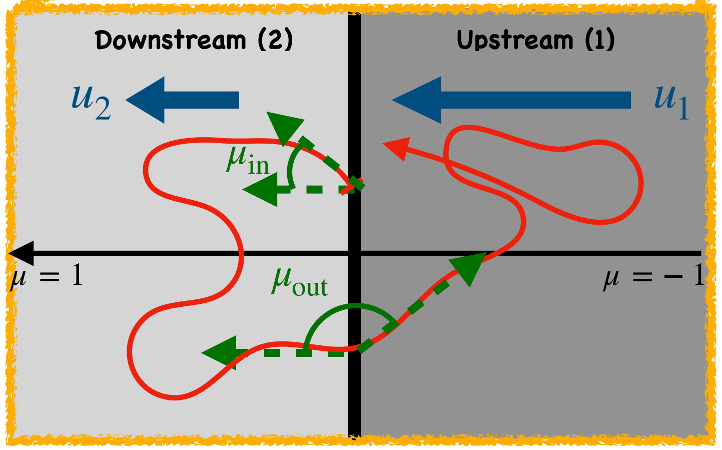
Acceleration mechanisms: diffusive shock acceleration (Fermi I)

Main results of linear DSA

- Energy gain per cycle $\xi \equiv \dfrac{\Delta E}{E} = \dfrac{4(u_1 - u_2)}{3c}$
- Escaping probability per cycle $P_{\rm esc} = 4\dfrac{u_2}{c}$
- Particle spectrum $\boxed{f(E) \propto E^{-\alpha}}$ $\alpha = 1 + \dfrac{P_{\rm esc}}{\xi} = \dfrac{r+2}{r-1} \longrightarrow 2$ Strong Shocks
- Acceleration time. $\boxed{t_{\rm acc} = \dfrac{t_{\rm cycle}}{\Delta E/E} \simeq 8\,\dfrac{D_1}{u_1^2}}$





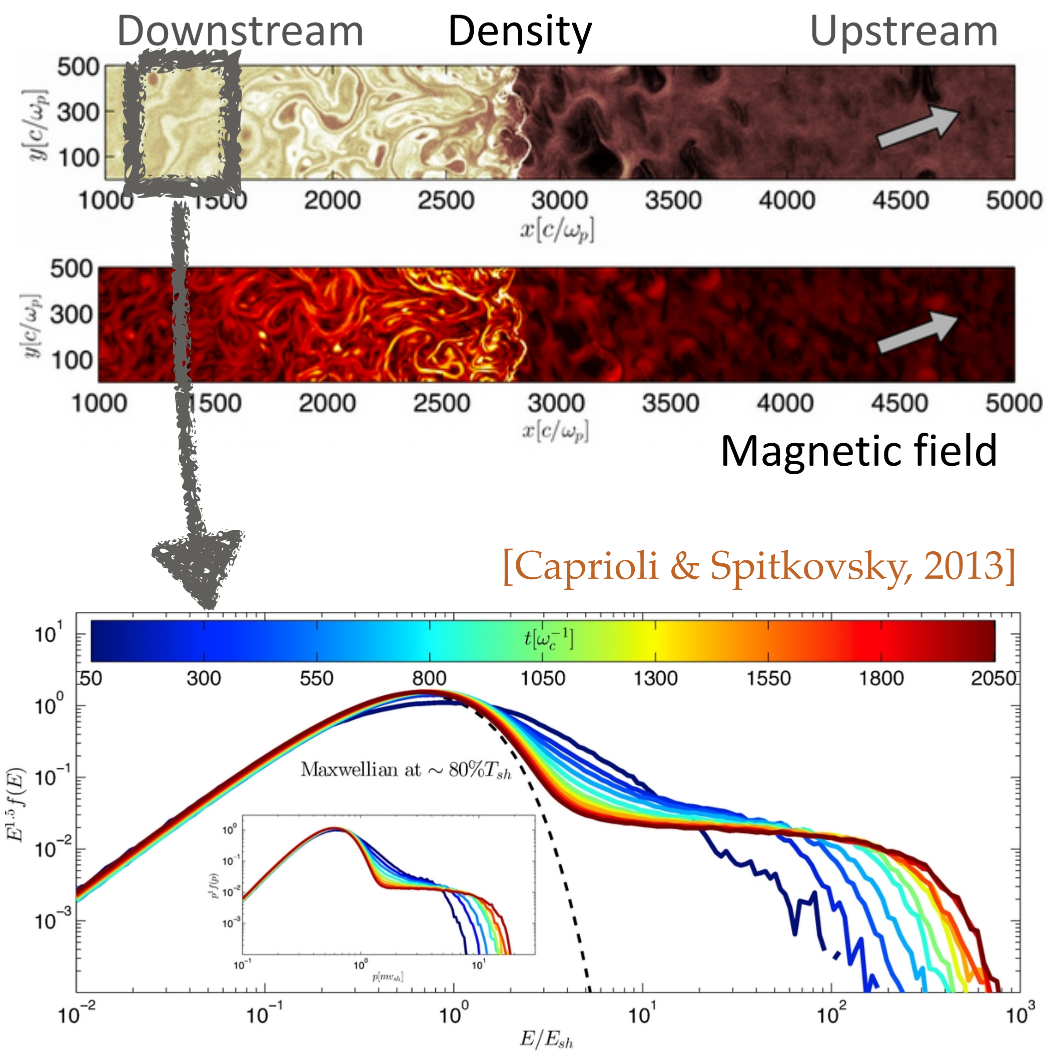
PIC simulation of Fermi I

A nice confirmation of DSA predictions comes from particle in cell (PIC) simulations:

- Large efficiency ~ 10-20%
- Spectrum ~p^{-4} (~$E^{-1.5}$ at non-relativistic energies)
- self-generated magnetic turbulence

However, PICs can only simulate the beginning of the acceleration process (small dynamical range: E_{max} << 1 GeV)

⇒ No conclusion on E_{max}



[Caprioli & Spitkovsky, 2013]

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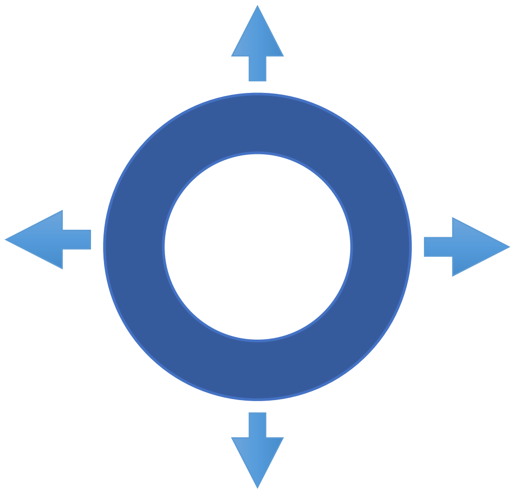
Modeling gamma-ray sources: ingredients

Physics | **Geometry** | Matter | Interaction

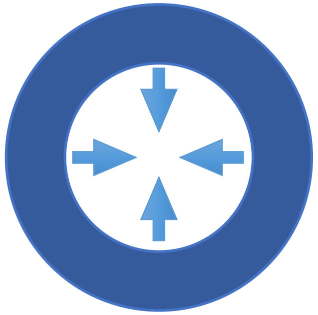
Geometry sets:

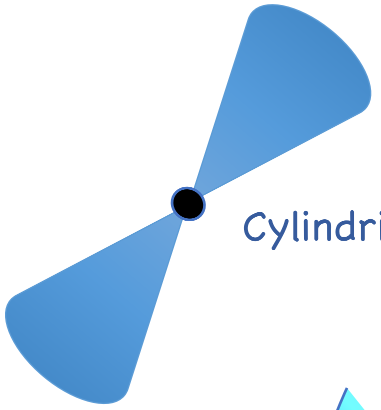
- boundary conditions for the acceleration mechanisms
- Particle escape
- Maximum achievable energy

Expanding spherical shock

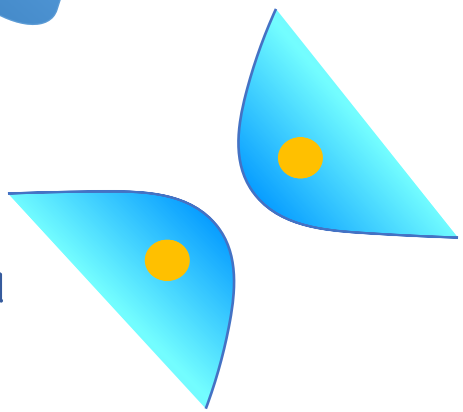


Contracting/standing spherical shock





Cylindrical jets



Colliding wind binaries

Modeling gamma-ray sources: ingredients

Physics | Geometry | **Matter** | Interaction

- Leptons
- Hadrons

- Acceleration mechanisms work in the same way, dependence only on the rigidity **$R = p/Z$**
- Difference: injection mechanism ← depends on the shock microphysics

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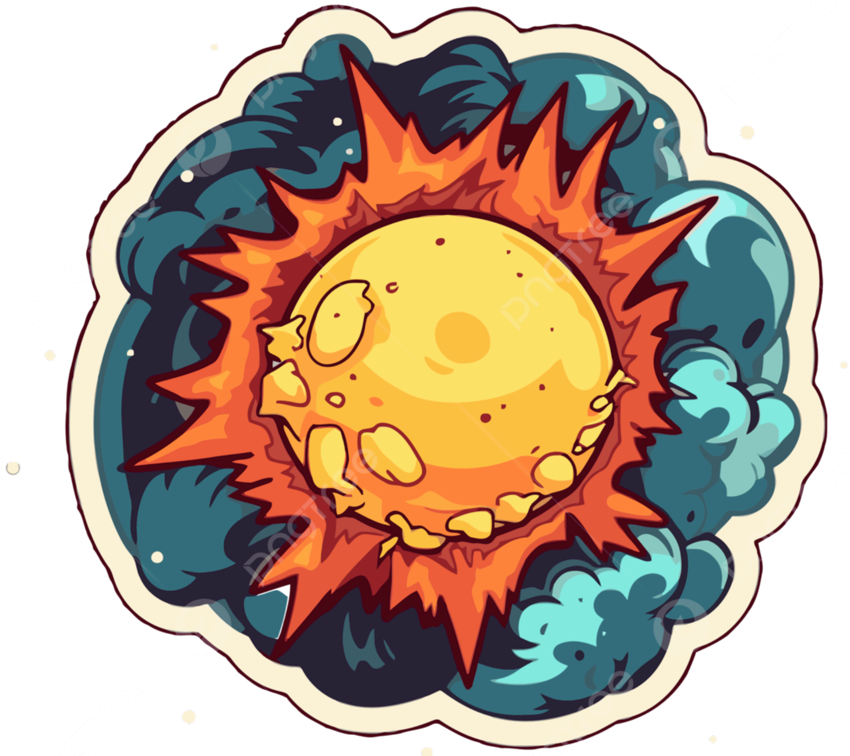
Modeling gamma-ray sources: ingredients

Physics | Geometry | Matter | **Interaction**

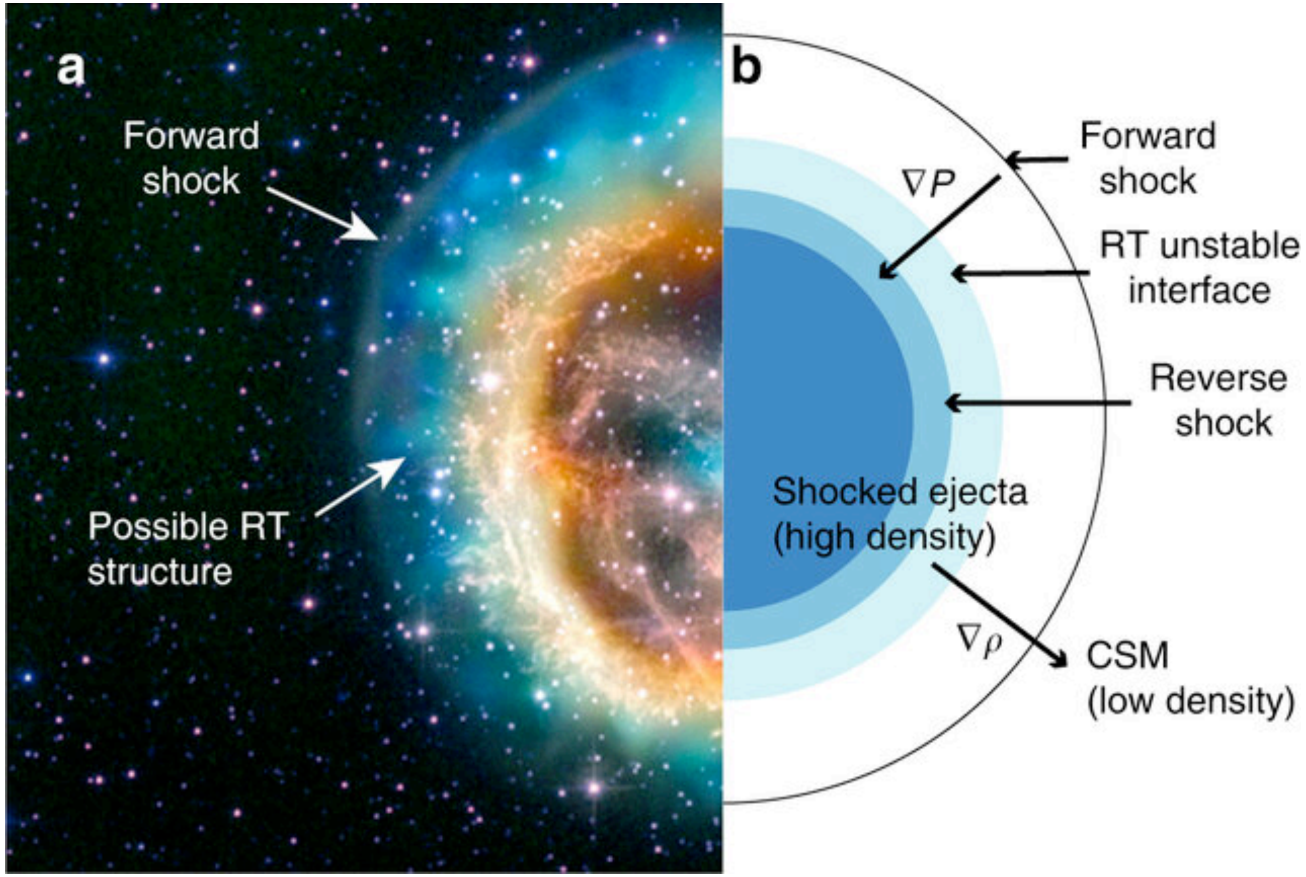
Radiative processes relevant for CR physics

- Leptons
  - Synchrotron emission $e^\pm + B \longrightarrow e^\pm + \gamma$
  - Bremsstrahlung $e^\pm + \text{Nucl.} \longrightarrow e^\pm + \gamma$
  - Inverse Compton $e^\pm + \gamma_{\rm bk} \longrightarrow e^\pm + \gamma$
- Hadrons
  - Pion production: $p_{\rm CR} + p_{\rm gas} \longrightarrow p_{\rm CR} + p_{\rm gas} + \begin{cases} \pi^0 \to \gamma\gamma \\ \pi^\pm \to \mu^\pm \nu_\mu(\bar{\nu}_\mu) \end{cases}$
    - $\mu^\pm \longrightarrow e^\pm \nu_e(\bar{\nu}_e)$
  - Synchrotron emission (?)

Supernova remnants



The structure of a SNR



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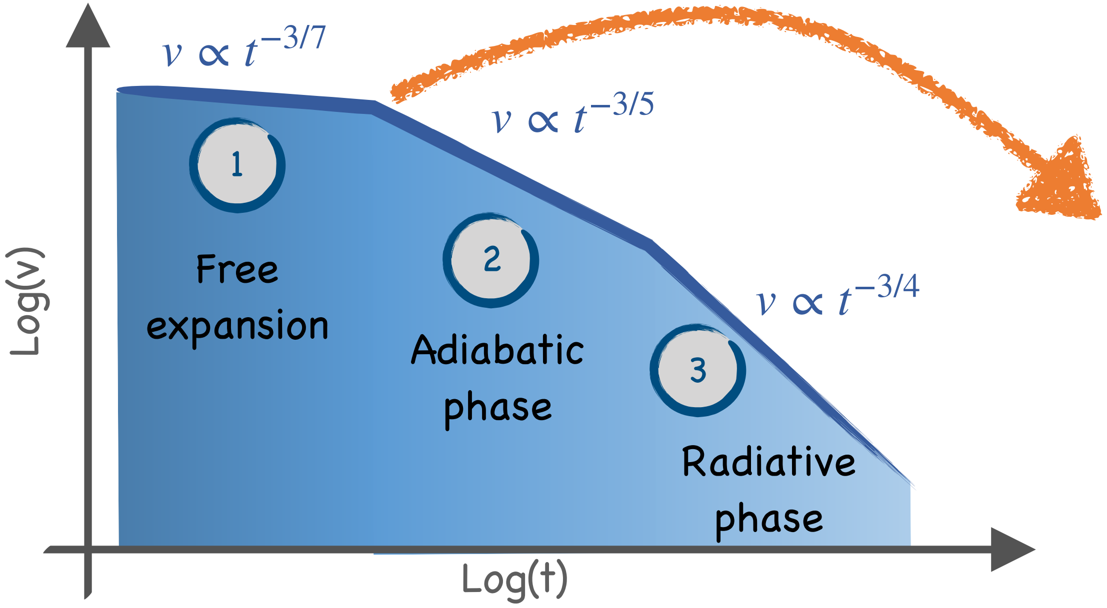
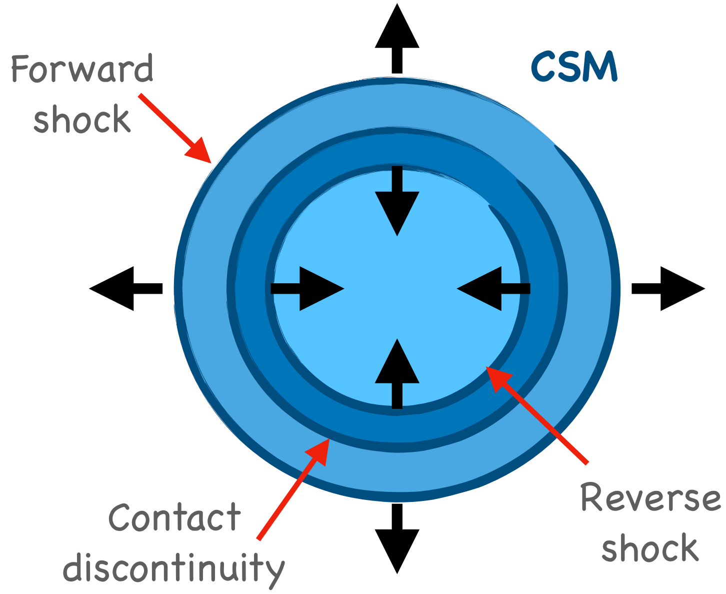
SNR dynamics

We can distinguish 3 different phases:

1. "Ejecta dominated": $M_{ejecta} > M_{swept\text{-}up}$ -> almost stationary motion
2. Adiabatic expansion: $M_{ejecta} < M_{swept\text{-}up}$ -> Energy conservation
3. "Snow-plough" phase: age >> $t_{radiation}$ -> Momentum conservation





Beginning of the ST phase:

$$\boxed{M_{sw} = M_{ej}}$$

$$\begin{cases} M_{sw} = \frac{4\pi}{3} R_{ST}^3 \rho_{CSM} \\ E_{SN} = \frac{1}{2} M_{ej} v_{sh}^2 \\ t_{ST} = \frac{R_{ST}}{v_{sh}} \end{cases}$$

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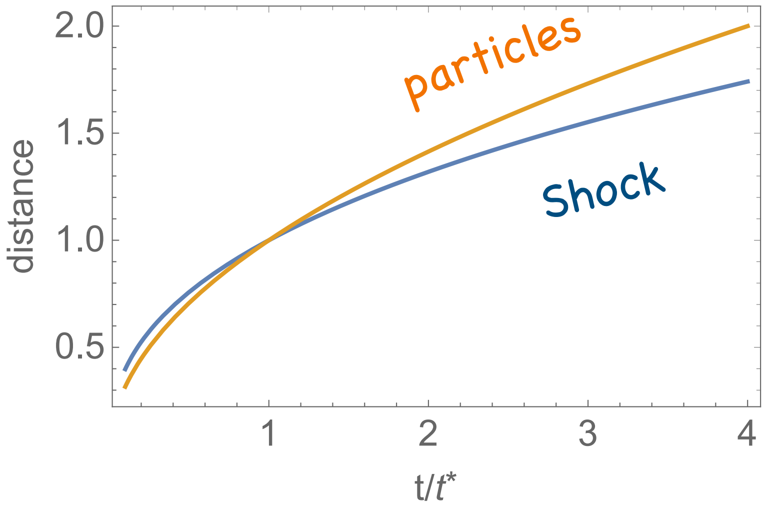
Maximum energy

- E_{max} is obtained from $t_{acc} = \min[t_{age}, t_{loss}]$
- Acceleration time $t_{acc} = \frac{t_{cycle}}{\Delta E/E} \simeq 8\frac{D}{u_{sh}^2}$; what about $t_{age} = ?$
- Maximum energy can only increase during the ejecta dominated phase

Radius: $\begin{cases} R_{sh} \propto t^{4/7} & \text{Ejecta-dominated} \\ R_{sh} \propto t^{2/5} & \text{Sedov-Taylor} \end{cases}$



However, particles ahead of the shock diffuse: $\langle d \rangle \propto \sqrt{Dt}$

$\Rightarrow$ during the ST phase the highest energy particles escape upstream of the shock

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Maximum energy

Equating t_{ST} with the acceleration time

$$t_{acc} \approx 8\frac{D}{u_{sh}} = t_{ST} \approx 50 \left(\frac{M_{ej}}{M_\odot}\right)^{5/6} \left(\frac{E_{SN}}{10^{51}\,\mathrm{erg}}\right)^{-1/2} \left(\frac{n_{ISM}}{cm^{-3}}\right)^{-1/3} \mathrm{yr}$$

Using the diffusion coefficient from linear theory: $D = \frac{1}{3}\frac{r_L(p)c}{k_{res}P(k_{res})}$

$$P(k) = \frac{\delta B(k)^2}{B_0^2}$$

is the power in magnetic turbulence at the resonant scale

$$\Rightarrow \boxed{E_{max} = 50\, k_{res}P(k_{res}) \left(\frac{B}{\mu G}\right) \left(\frac{M_{ej}}{M_\odot}\right)^{-1/6} \left(\frac{E_{SN}}{10^{51}\,\mathrm{erg}}\right)^{1/2} \left(\frac{n_{ism}}{\mathrm{cm}^{-3}}\right)^{-1/3} \mathrm{TeV}}$$

High energies can be achieved only for large B and large turbulence

E_{max} is weakly dependent on ambient parameters

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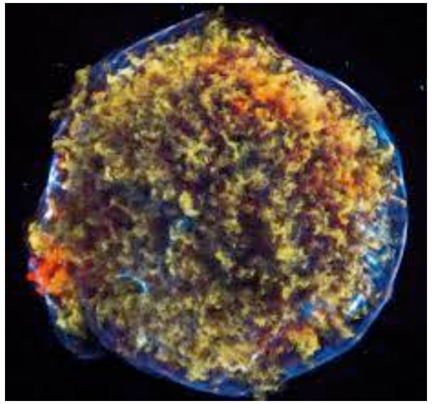
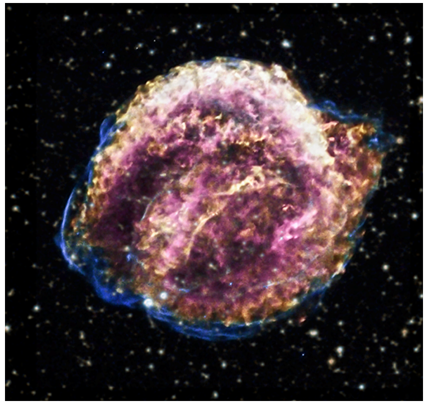
Evidence for magnetic field amplification

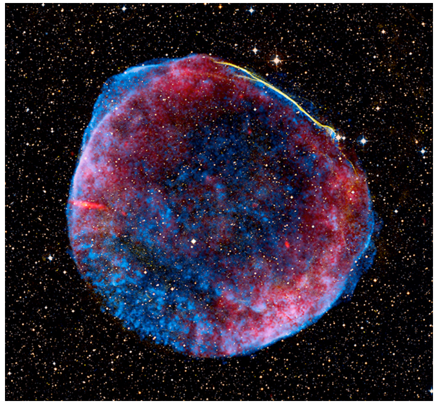

Tycho


G299.-2.92


G292.0+1.8

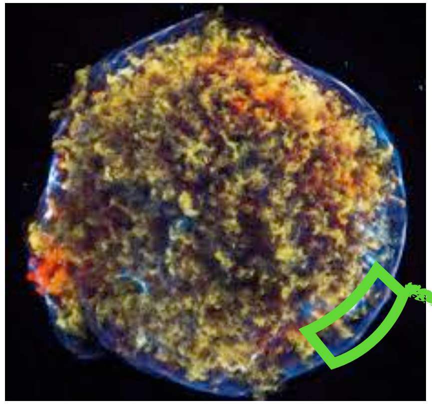

Kepler


Cassiopea A

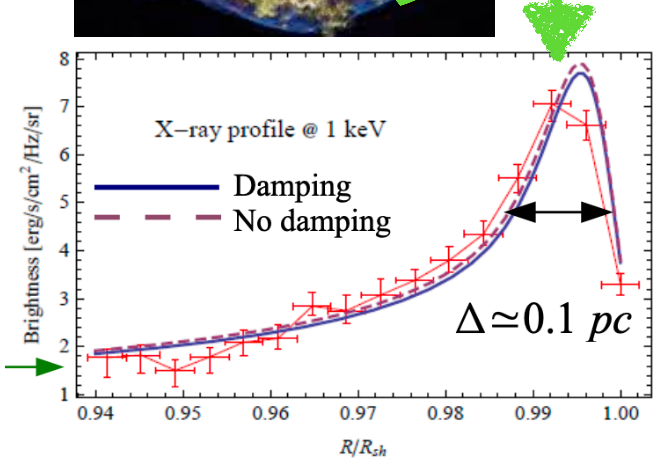

SN 1006

Evidence for magnetic field amplification

Filaments' thickness could be determined by synchrotron losses



Tycho



Bohm diffusion

$$D = \frac{1}{3} r_L c \propto \frac{E}{B}$$

Synchrotron losses

$$\tau_{\rm syn} = \frac{3 m_e c^2}{4 \sigma c \gamma \beta^2 U_B} \propto \frac{E}{B^2}$$

$$\Delta = \sqrt{D \tau_{\rm loss}} \propto B^{-3/2}$$

$$\boxed{\Delta \simeq 0.1\,{\rm pc} \;\Rightarrow\; B \approx 100 - 300\,\mu{\rm G}}$$

Magnetic field amplification: theory

Possible CR-driven instabilities:

- **Resonant streaming instability**
  Skilling 1975; Bell & Lucek 2001; Amato & Blasi 2006; Blasi 2014
- **Non-resonant (Bell) instability**
  Bell 2004; Bell et al. 2013, 2014; Amato & Blasi 2009
- **Turbulent amplification**
  Drury & Downes 2012; Xu & Lazarian 2017

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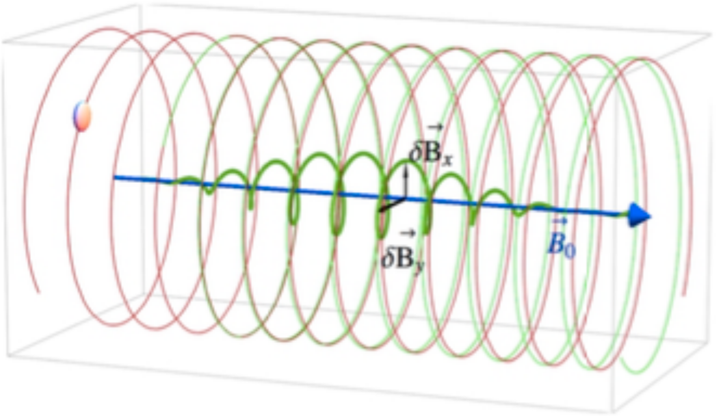
Magnetic field amplification: Resonant streaming instability

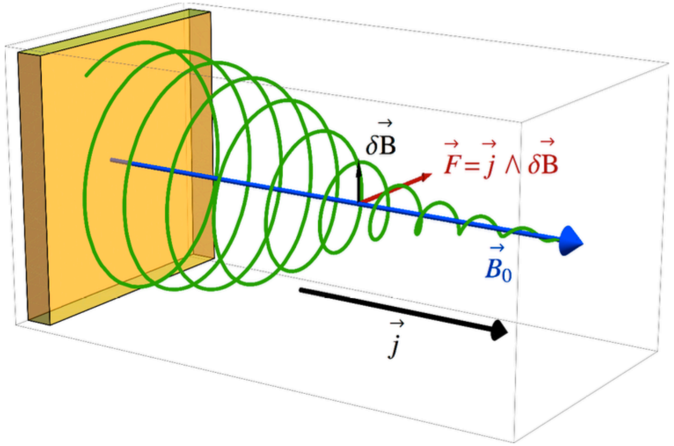


- Amplification is due to resonant interaction between CR with Larmor radius r_L and waves with wave-number $k=1/r_L$.
- Fast growth rate (~10 yr for typical SNR shocks)
- But saturation level at $\boxed{\delta B/B_0 \lesssim 1}$ → $\boxed{E_{max} \approx 50 \text{ TeV}}$

A factor ~50 below the *knee*

Magnetic field amplification: Non-Resonant streaming instability

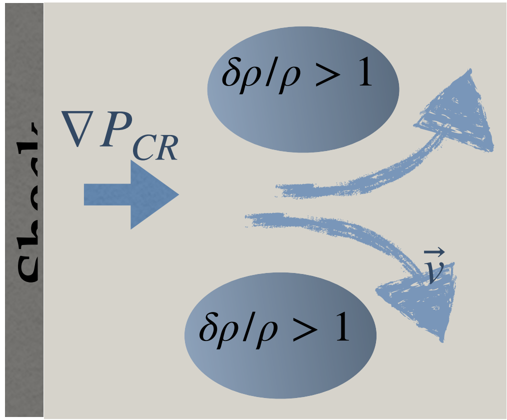
- Amplification due to force of escaping CR current with magnetic field perturbations
- Fast growth rate but excites small wavelength waves
  -> need of inverse cascade?
- high level of amplification only in dense environments (Type II SNe exploding into dense progenitor stellar winds)



$$E_{\max} \simeq \frac{e\,\xi_{cr}}{10\,c} \frac{\sqrt{4\pi\rho}}{\Lambda} v_{sh}^2 R_{sh} \simeq 30\,\mathrm{TeV} \left(\frac{\xi_{cr}}{0.1}\right) \left(\frac{\rho/m_p}{\mathrm{cm}^{-3}}\right)^{1/2} \left(\frac{v_{sh}}{5000\,\mathrm{km/s}}\right)^2 \left(\frac{R_{sh}}{\mathrm{pc}}\right)$$

PeV can be achieves by strong shocks in dense environments

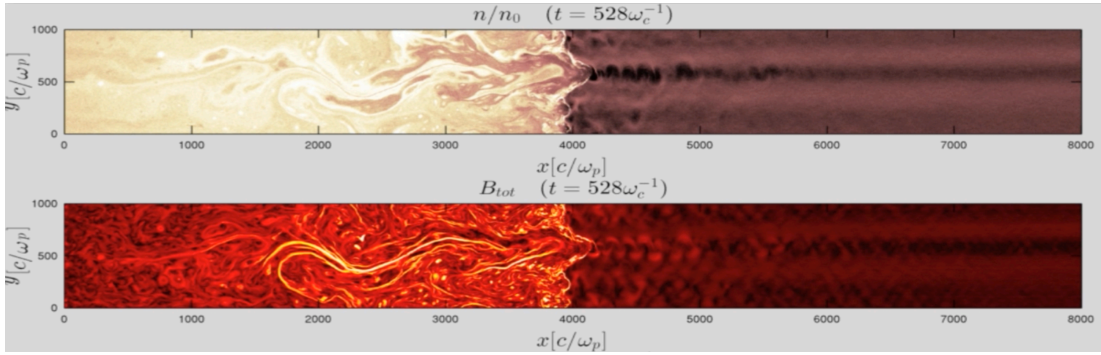
Magnetic field amplification: Turbulent amplification



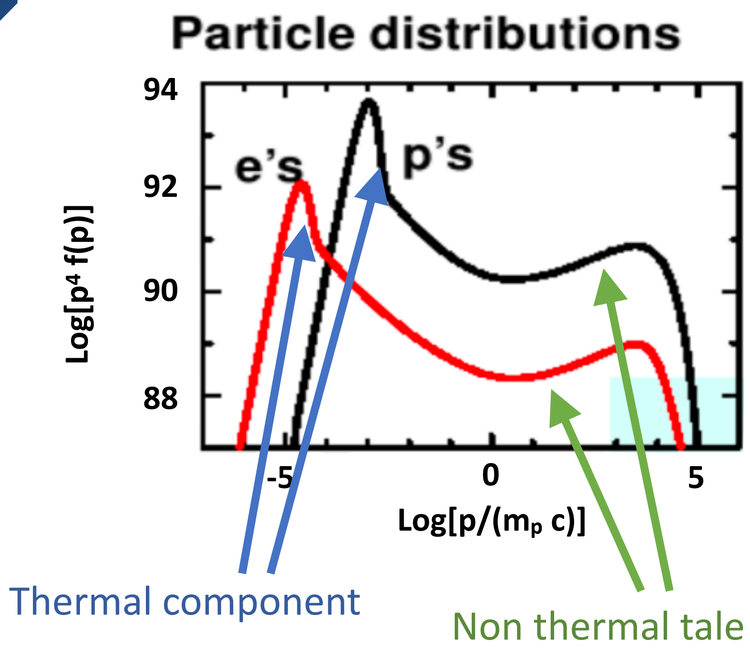
- In presence of density inhomogeneities, the different CR force acting onto plasma can generate vorticity
- This mechanism is effective only in large precursors (hence E_{max} already large enough and flat spectrum ~E^{-2})
- The density discontinuities can be generated even through the non-resonant instability

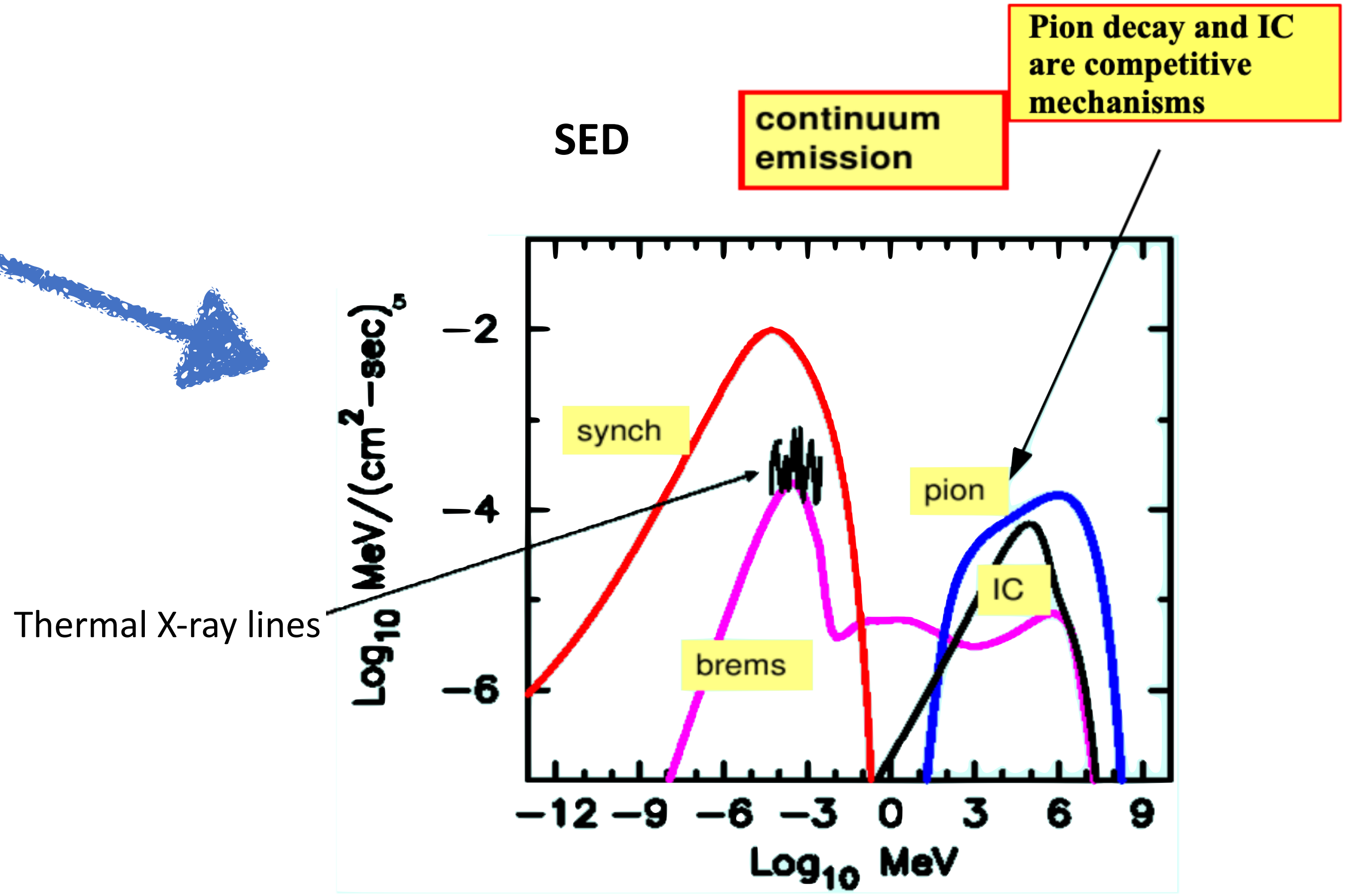
➡ filamentation

Filamentation instability observed in 2D hybrid simulations [Caprioli & Spitkovsky, 2013]

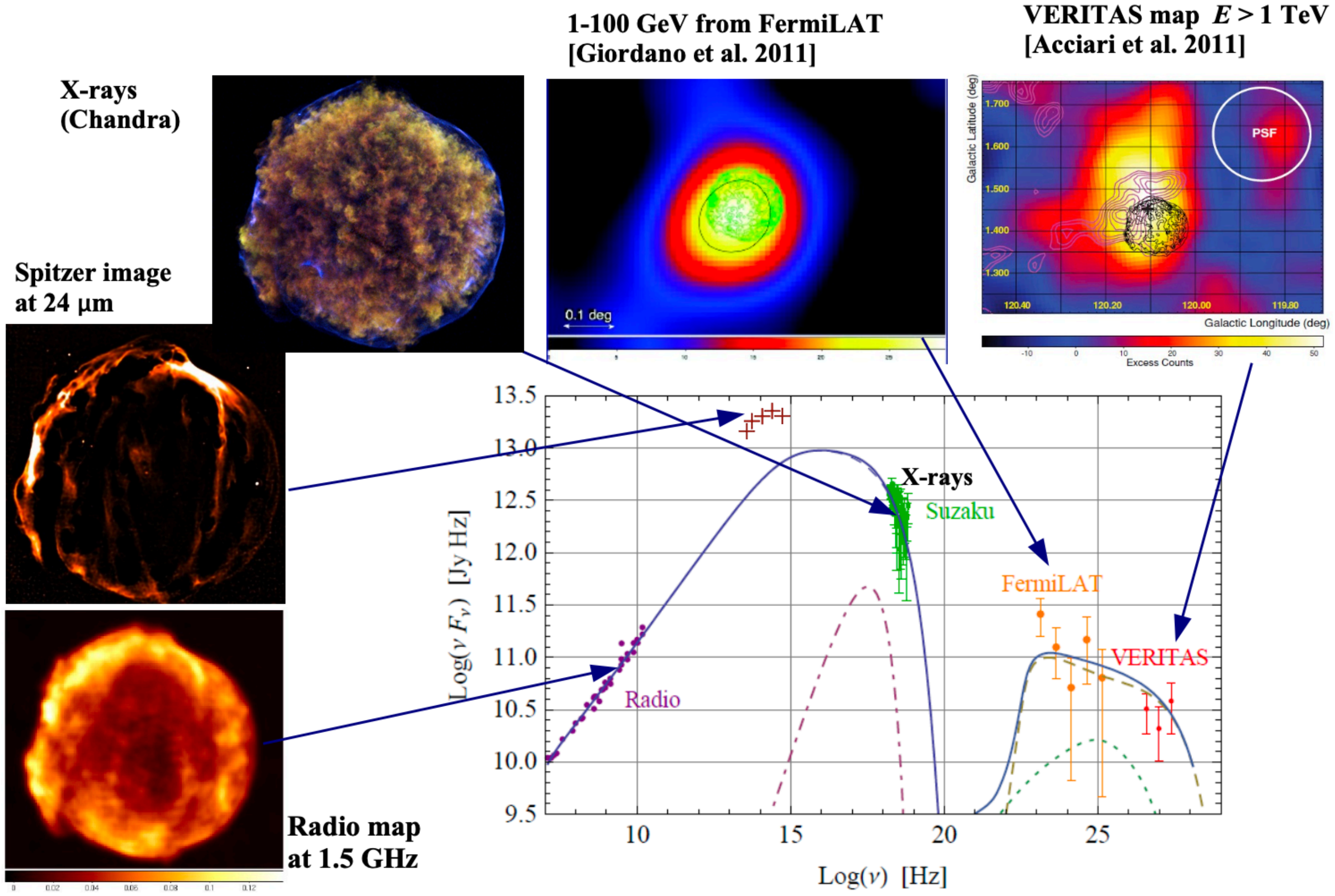


EM radiation from accelerated particles





The case of Tycho



Gamma-ray spectra from SNRs

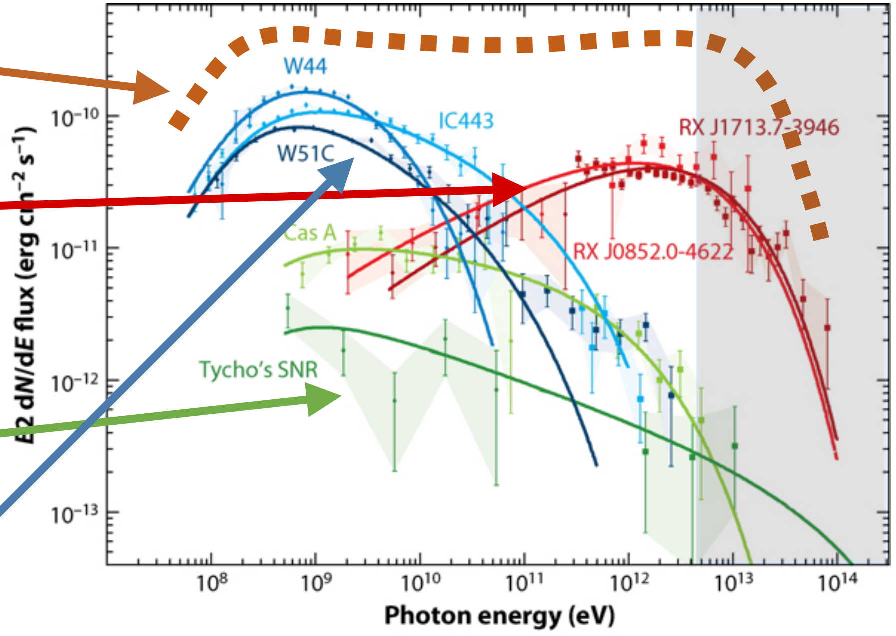
1) Maximum energy is always < 100 TeV

2) The gamma-ray spectrum does not agree with the basic prediction of Fermi acceleration ~E^{-2} from hadronic emission.

Possible explanations:

- Spectra harder than E^{-2}:
  - Leptonic origin
  - Hadronic origin for shock expanding in clumpy media
- Spectra steeper than E^{-2}:
  - Modified velocity of scattering centres
  - Energy losses during acceleration
  - Break of isotropy (only for $v_{sh} > 10^4$ km/s)
  - Shock structure modified by neutral Hydrogen (only for $v_{sh} < 3000$ km/s)
  - Particle escaping (only for middle-aged SNRs)

Gamma-ray emission from shell-type SNRs



Funk S. 2015.
Annu. Rev. Nucl. Part. Sci. 65:245–77

Young stellar clusters

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Young stellar clusters

- Young stellar clusters (age $\lesssim$ few Myr) can reach mass up to $\sim 6 \times 10^4 M_\odot$
- May contains thousand of stars and several tens of OB stars
- They strongly affect the circumstellar environment due to powerful stellar winds
- They can host an high density of supernovae SNe
- **Recently several massive star clusters have been associated with gamma-ray sources**

30 Doradus

Cygnus OB2

Westerlund 1

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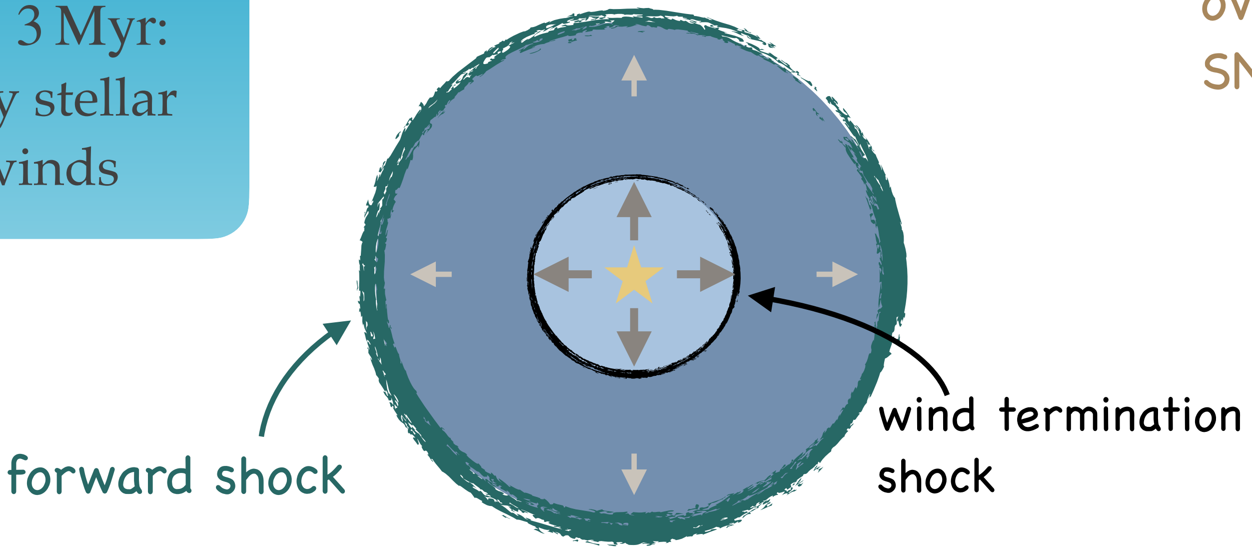
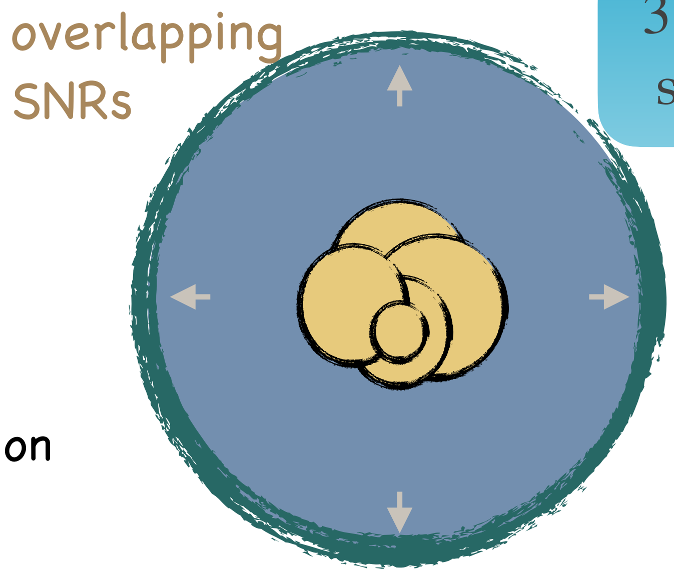
What power stellar clusters?

Phase	Source	Duration
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim\ \mathrm{Myr}$
$3\,\mathrm{Myr} \lesssim t \lesssim 7\,\mathrm{Myr}$	WR stellar winds	$t \sim 10^5\,\mathrm{yr}$
$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$	SNe	$t \sim 10^3 - 10^4\,\mathrm{yr}$

$t \lesssim 3\,\mathrm{Myr}$: only stellar winds



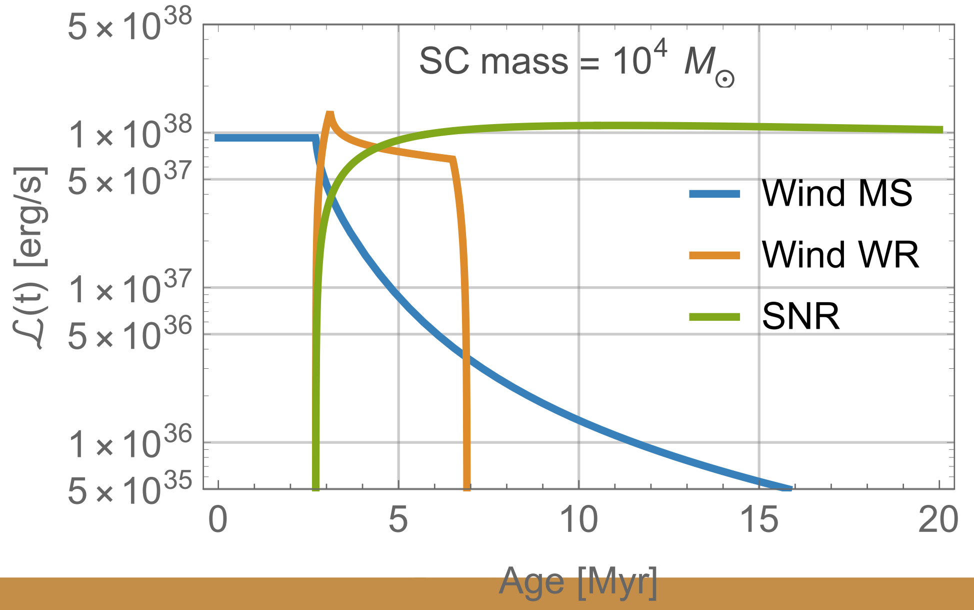


$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$: stellar winds + SNe

What power stellar clusters?

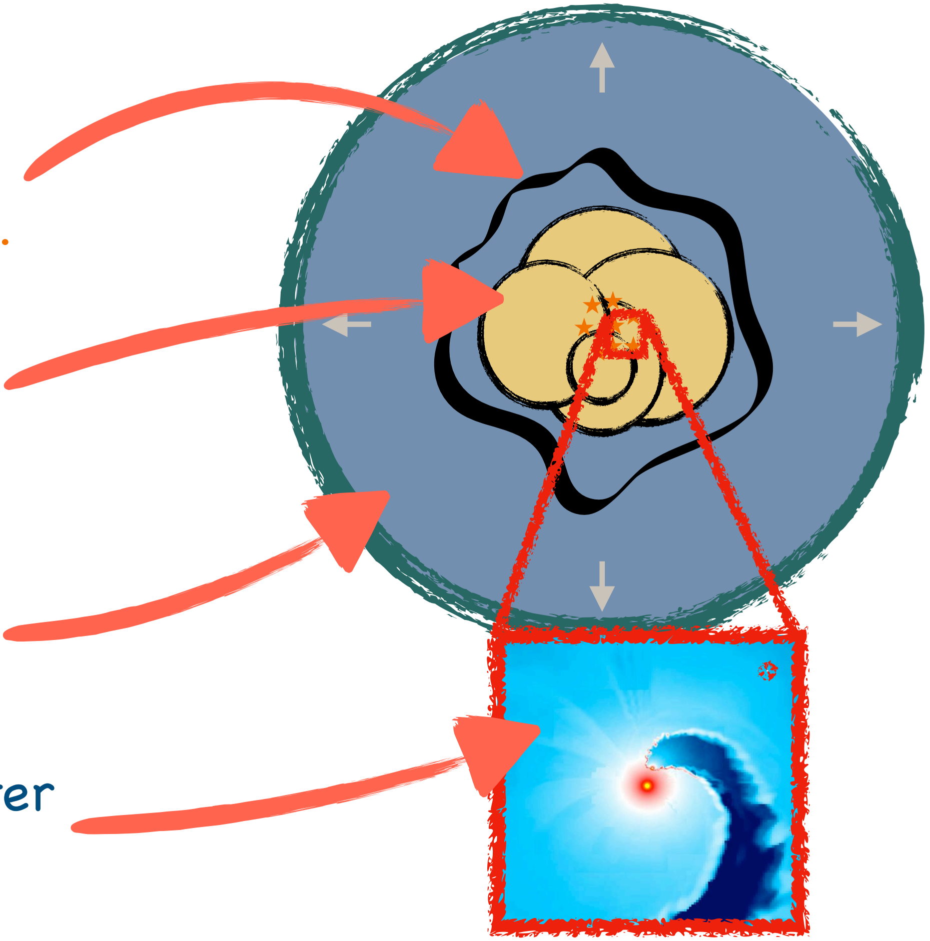
Phase	Source	Duration
$t \lesssim 3\,\mathrm{Myr}$	MS stellar winds	$t \gtrsim\ \mathrm{Myr}$
$3\,\mathrm{Myr} \lesssim t \lesssim 7\,\mathrm{Myr}$	WR stellar winds	$t \sim 10^5\,\mathrm{yr}$
$3\,\mathrm{Myr} \lesssim t \lesssim 30\,\mathrm{Myr}$	SNe	$t \sim 10^3 - 10^4\,\mathrm{yr}$

Stellar cluster luminosity



Possible acceleration mechanisms

- Shock acceleration at the wind termination shock [GM et al. (2021)]
- Shock acceleration at the SNR forward shock propagating inside the bubble. [Vieu et al. (2022); Vieu & Reville (2023); A. Mitchell, GM et al. (2024)]
- II order Fermi acceleration by strong magnetic turbulence [Vieu & Gabici (2023); J. Vink (2024)]
- Wind-wind collisions from massive stars in the cluster center [Bylkov, Gadilin, Osipov (2013)]



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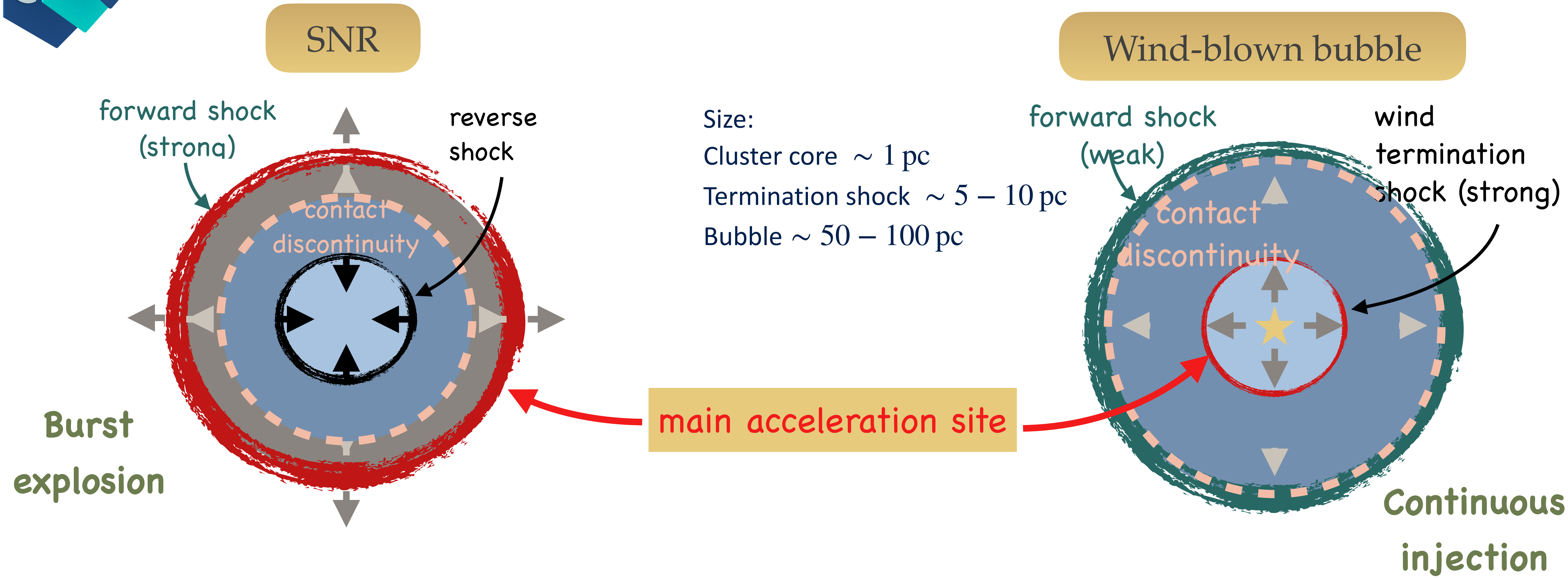
Stellar wind bubble vs. SNR



Size:

Cluster core $\sim 1\,\mathrm{pc}$

Termination shock $\sim 5 - 10\,\mathrm{pc}$

Bubble $\sim 50 - 100\,\mathrm{pc}$

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Stellar wind bubble vs. SNR

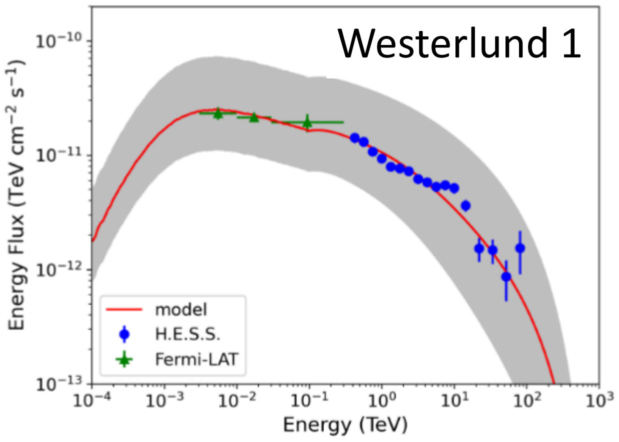
	age	V_{FS} [km/s]	R_{FS} [pc]	V_{RS} [km/s]	R_{RS} [pc]
SNR	kyr	> 5000	< 1	< 3000	< 1
Wind bubble	Myr	10 - 20	50-100	< 3000	1-10

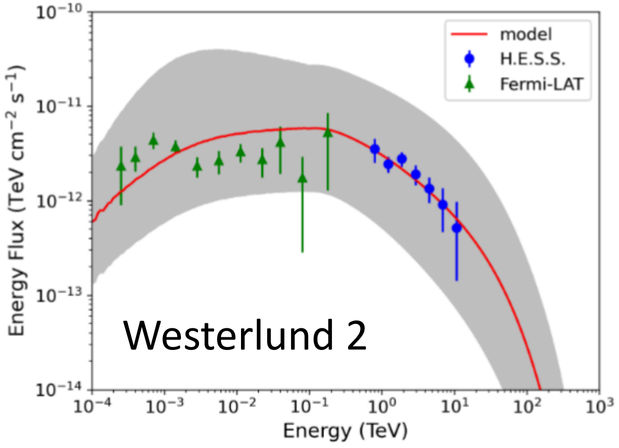
SCs have slower shock but last longer and have larger size than SNRs

Applying DSA to Stellar clusters

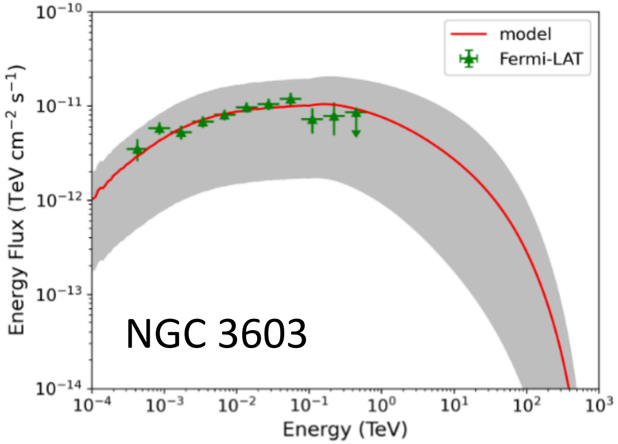
- Model:
  - acceleration at WTS + SNRs
  - SED dominated by hadronic emission

- Main uncertainties due to:
  - Stellar cluster mass
  - Estimated number of SNRs
  - Diffusion coefficient in the bubble
  - Density of the circumstellar medium





Mitchell, GM, Celli, Menchiari, Specovious (arXiv:2403.16650)



Summary

- Diffusive shock acceleration plays a major role in acceleration at Galactic sources (but is not the only possible acceleration mechanism)
- SNRs are among the best studied sources thanks to multi-wavelength studies (if your focus is gamma-rays, do not forget other wavelength!)
- Stellar clusters also important:
  - Host a large fraction of SNR
  - Host powerful stellar winds
  - Host several binary systems

→ I and II order Fermi acceleration