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Prospects for gamma-ray detection of Galactic Stellar Clusters

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TOSCA - Topical Overview on Star Cluster Astrophysics

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PeVatrons

Accelerators of Galactic Cosmic Rays to ~10^{15} eV

Suitable PeVatron candidates are those that meet the Hillas criterion:

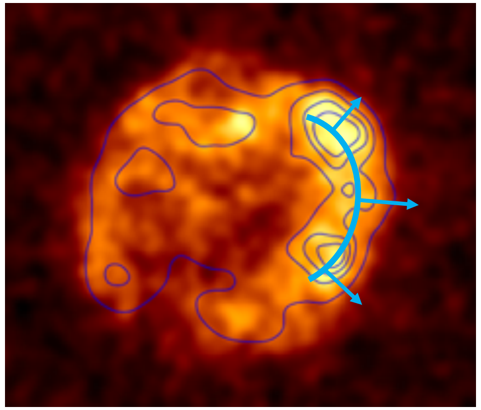
$$E_{\max} = Ze\beta cBL$$

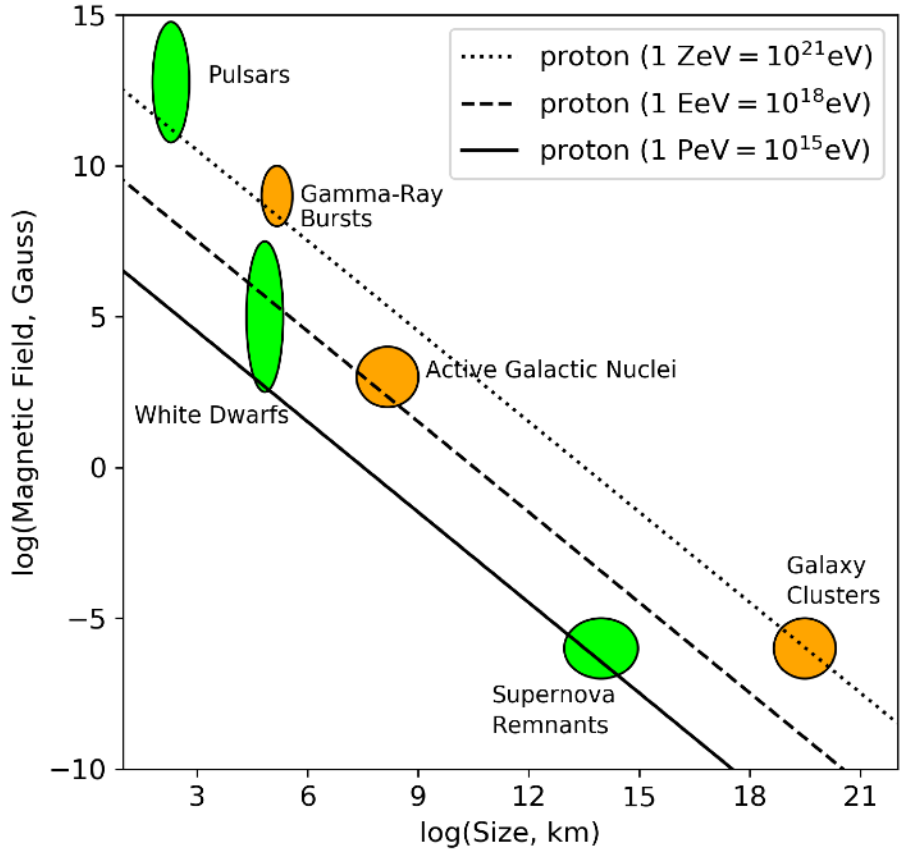
Supernova remnants are prime candidates as a Galactic source

~10^{51} erg per explosion,
~10% into CR acceleration,
~3 per century in the Milky Way
—> would be sufficient to power Cosmic Rays

BUT —> no active PeVatron supernovae seen to date

Only act as accelerators for a short period of time?

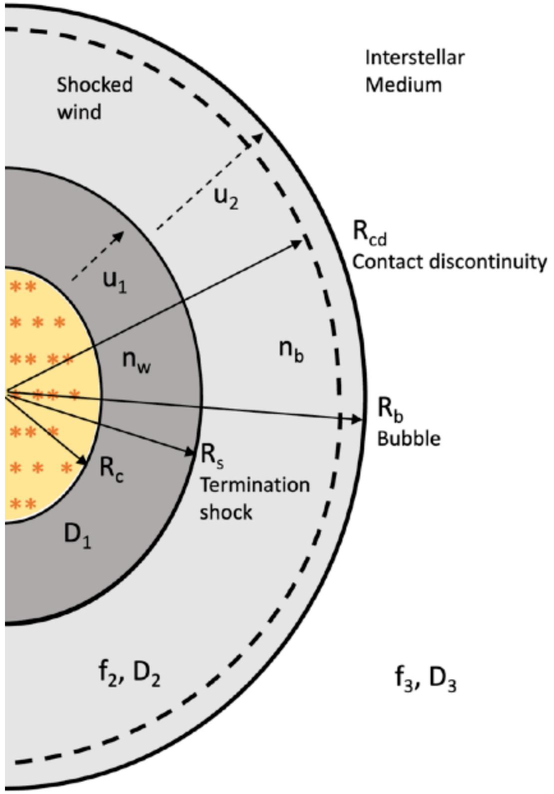




Gamma-ray emission from Stellar Clusters

- Stellar clusters can drive a collective wind into the surrounding medium
- Particle acceleration may occur at the wind termination shock - up to PeV?
- Analytical model for CR acceleration from G. Morlino et al. 2021
  - apply this model to stellar clusters listed in Gaia DR2
  - estimate the expected CR flux and resulting gamma-ray emission

See AM, Morlino, Celli, Menchiari, Specovius https://arxiv.org/abs/2403.16650 (submitted)



Dimensions of the wind-blown bubble?

Relevant sizes can be approximated based on cluster properties:

Bubble radius R_b:

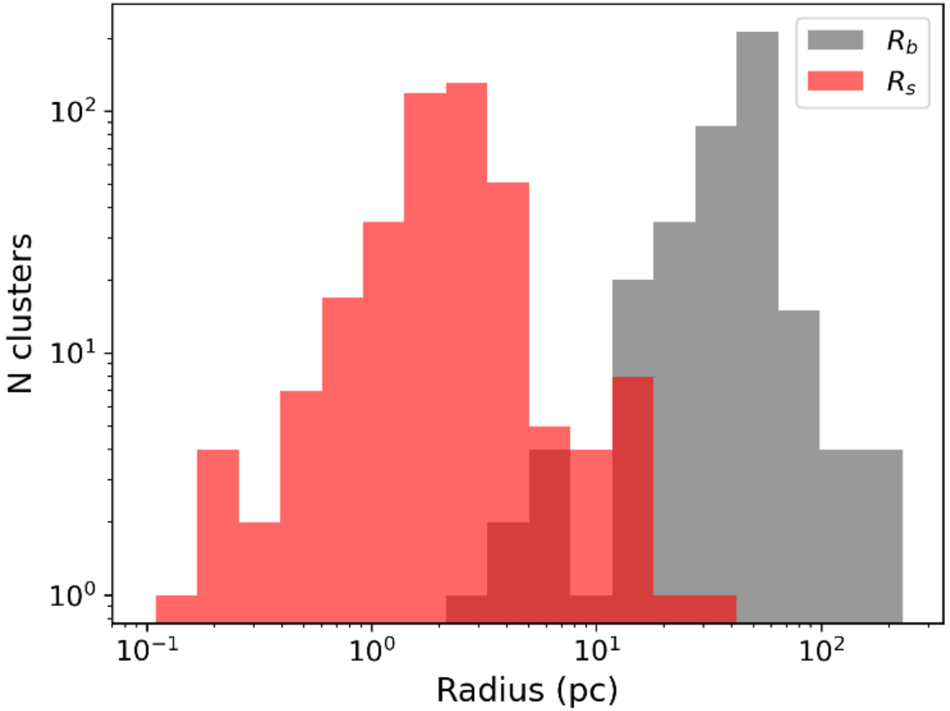
$$R_b(t) = 112 \left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-0.2} \left(\frac{L_{\mathrm{w,c}}}{10^{37}\,\mathrm{erg\,s^{-1}}}\right)^{0.2} \left(\frac{t}{10\,\mathrm{Myr}}\right)^{0.6} \mathrm{pc}$$

$R_{cd} = 0.95 R_b$ (contact discontinuity)

Wind termination shock radius R_s:

$$R_s(t) = 26 \left(\frac{n}{\mathrm{cm}^{-3}}\right)^{-0.3} \left(\frac{\dot{M}_{\mathrm{c}}}{10^{-4}\mathrm{M_\odot yr^{-1}}}\right)^{0.3} \left(\frac{v_{\mathrm{w}}}{2000\,\mathrm{km\,s^{-1}}}\right)^{0.1} \left(\frac{t}{10\,\mathrm{Myr}}\right)^{0.4} \mathrm{pc}$$

Cluster radius R_c :
use the angular radius containing 50% of the member stars as reported in the Gaia DR2 stellar cluster catalogue, converted into a physical size using the most recent distance estimate (i.e. from Gaia DR3 if available).



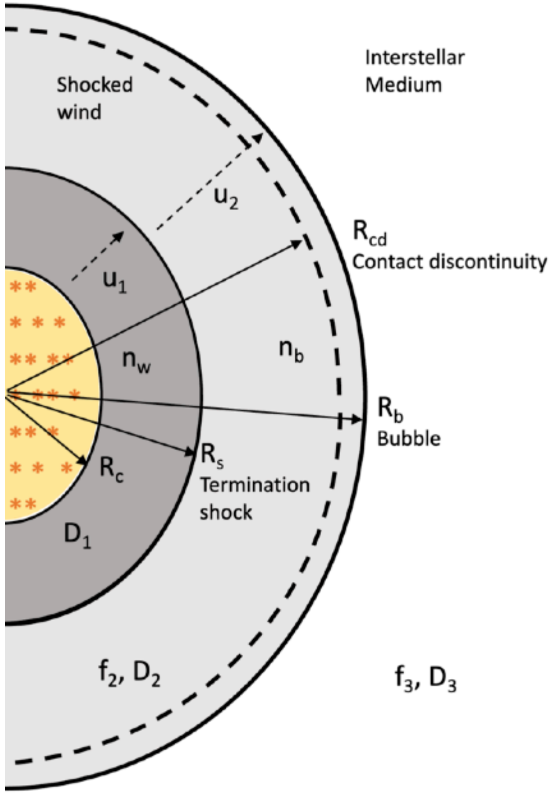
Gamma-ray emission from Stellar Clusters

- Model from Morlino et al. 2021
- Estimate the resulting gamma-ray emission from the wind-blown bubble around stellar clusters as listed in the Gaia DR2
- Particle injection spectrum depends on location within the system:
- In the bubble:

$$f_2(r,p) = f_s(p)e^{\alpha(r)}\frac{1+\beta(e^{\alpha(R_b)}e^{-\alpha(r)}-1)}{1+\beta(e^{\alpha(R_b)}-1)} + f_{\text{Gal}}(p)\frac{\beta\left(e^{\alpha(r)}-1\right)}{1+\beta(e^{\alpha(R_b)}-1)}$$

- In the surrounding ISM:

$$f_3(r,p) = f_b(p)\frac{R_b}{r} + f_{\text{Gal}}(p)\left(1-\frac{R_b}{r}\right)$$



Particle distribution function

Particle injection spectrum from the termination shock:

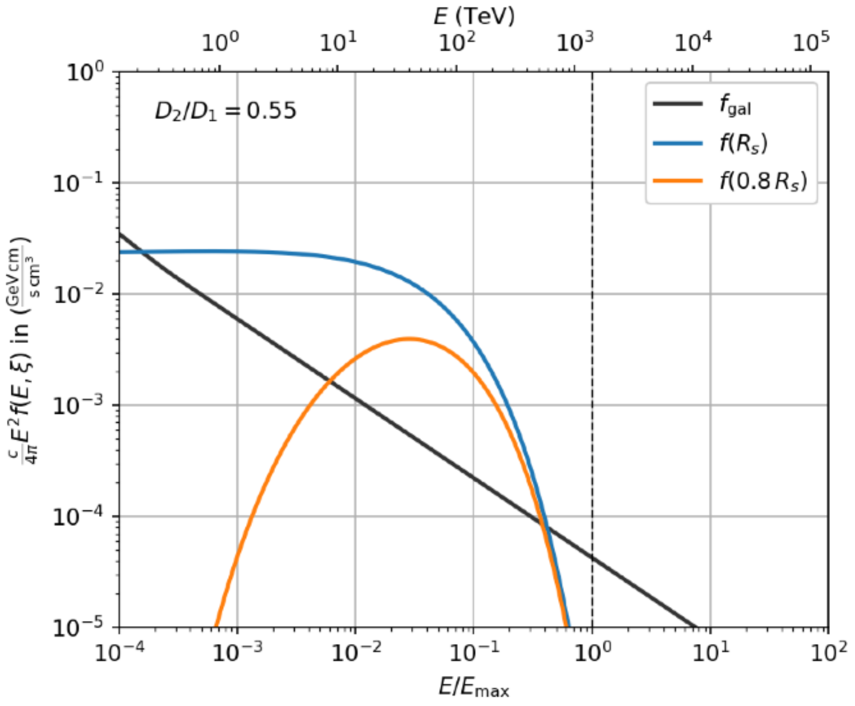
$$f_s(p) = \frac{\chi_{\rm CR}}{2}\frac{\sigma n_1 u_1^2}{4\pi\Lambda_p(m_p c)^3 c^2}\left(\frac{p}{m_p c}\right)^{-s} e^{-\Gamma(p)}$$

and where $e^{-\Gamma(p)} \simeq \left[1 + A_0\left(\frac{p}{p_{\rm max,1}}\right)^{A_2}\right] \exp\left[-A_1\left(\frac{p}{p_{\rm max,1}}\right)^{A_3}\right]$,

is an approximation that depends on the diffusion scenario being considered.

Note that $\alpha(r,p) = \frac{u_2 R_s}{D_2(p)}\left(1 - \frac{R_s}{r}\right)$ and $\beta(p) = \frac{D_3(p)R_b}{u_2 R_s^2}$

also depend on the diffusion properties of the medium.



Wind velocity profile

Again, region 1 within the wind and region 2 within the wind-blown bubble.

The wind velocity takes the following form: $u(r) = \begin{cases} u_1 & r < R_s \\ u_2 \left(\frac{R_s}{r}\right)^2 & R_s < r < R_b \\ 0 & r > R_b \end{cases}$

Where $u_2 = u_1/4$ due to a shock compression ratio of $\sigma = 4$ being assumed.

Density profile in the wind and bubble

The density of the wind depends on the mass-loss rate from the cluster

$$n_\mathrm{w}(r) = \frac{\dot{M}_\mathrm{c}}{4\pi r^2 v_w} \qquad R_\mathrm{c} \le r < R_\mathrm{s}$$

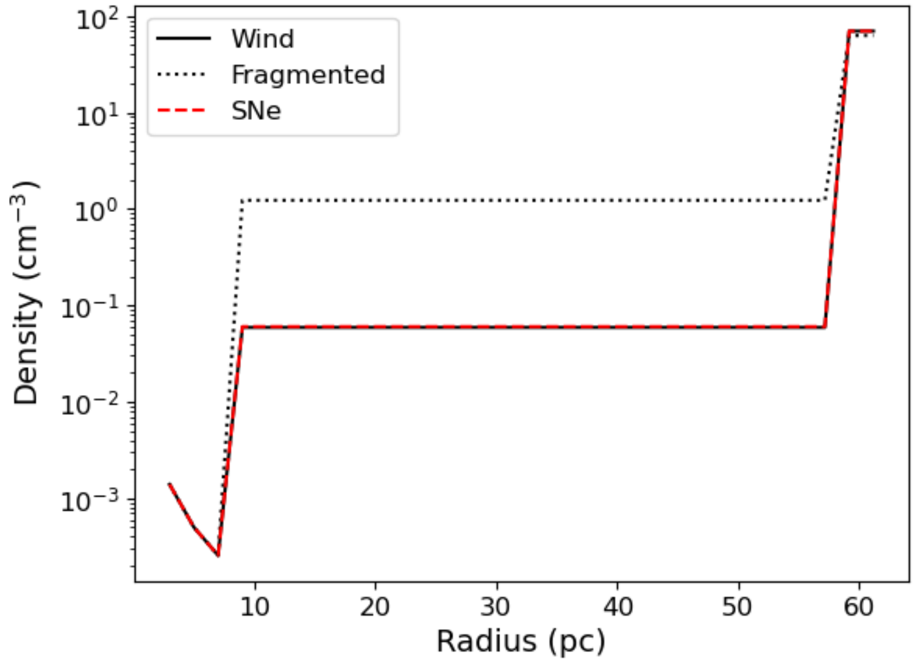
The density of the bubble is: $n_\mathrm{b} = \dfrac{M_\mathrm{b}}{m_\mathrm{p}\frac{4}{3}\pi(R_\mathrm{cd}^3 - R_\mathrm{s}^3)}$

where the mass of the bubble:

$$M_\mathrm{b} = (\dot{M}_\mathrm{sh} + \dot{M}_\mathrm{w})T_\mathrm{age} - \frac{\dot{M}_\mathrm{w}}{v_\mathrm{w}(R_\mathrm{s} - R_\mathrm{c})}$$

And the evaporated mass

$$\dot{M}_\mathrm{sh} = 2 \times 10^{-4} \left(\frac{L_\mathrm{w,c}}{10^{37}\,\mathrm{erg/s}}\right)^{\frac{27}{35}} \left(\frac{n}{10\,\mathrm{cm}^{-3}}\right)^{-\frac{2}{35}} \left(\frac{t}{1\,\mathrm{Myr}}\right)^{\frac{6}{35}} M_\odot\,\mathrm{yr}^{-1}$$



… in the case of a clumpy medium, this mass can be redistributed.
~10% of the shell material may fragment to form uniformly distributed clumps of material.

The bubble density is then modified as: $n_b^* = n_b^0 + 0.117 n_\mathrm{ism}$ and the shell density: $n_\mathrm{sh}^* = 0.9 n_\mathrm{sh}^*$

Conversion to gamma-ray or neutrino flux

Now we have most ingredients of the physical model (skipping some details…)

The particle distribution is converted into a gamma-ray flux using Kelner et al. 2006:

$$\Phi_{\gamma,\nu}(E_{\gamma,\nu}, R', t') = cn \int_{E_{\gamma,\nu}}^{\infty} \sigma_{\mathrm{pp}}(E) f(E, R', t') K_{\gamma,\nu}\left(\frac{E_{\gamma,\nu}}{E}, E\right) \frac{dE}{E}$$

The flux detected at Earth is therefore:

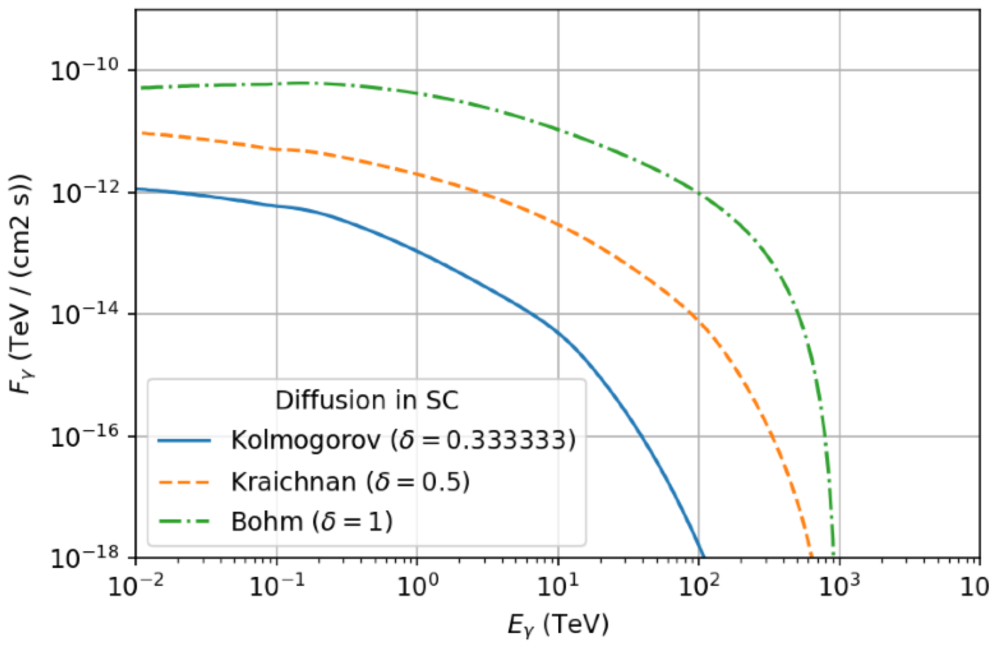
$$F(E_{\gamma,\nu}, t) = \Phi_{\gamma,\nu}(E_{\gamma,\nu}, t)/(4\pi D_c^2)$$

Where D_c is the distance to the cluster.

Consider a representative (hypothetical) stellar cluster to explore how free parameters affect the model.

Parameter	Value
χ_{CR}	10%
χ_{B}	10%
L_{coh}	2 pc
σ	4

Parameter	Value
t	10 Myr
$\dot{M}$	10^{-4} $\mathrm{M}_\odot$ /yr
$v_{w,c}$	3000. km /s
δ	0.5 (Kraichnan)
D_0 (10 GeV)	3.0×10^{28} cm^2 /s
n_{ism}	10 cm^{-3}

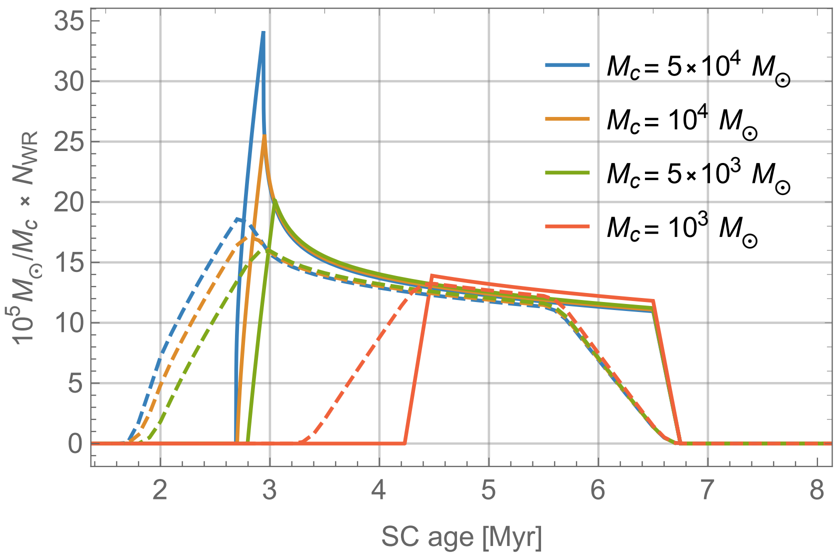


What about supernovae and Wolf-Rayet stars?

Massive Wolf-Rayet stars contribute with their strong stellar winds
—> contribution added explicitly to each cluster based on Gaia DR3 catalogue of Wolf-Rayet stars.

Below an age ~ 3Myr, no supernovae will have occurred.

Above this age, a number of supernovae are expected to have occurred, depending on the stellar cluster mass and age.



For each cluster, we estimate the number of supernovae already occurred.
—> All SNe will contribute material to increase the density of the bubble region
—> Only SNe within 1 advection time will contribute to the cluster wind luminosity
—> We assume the contribution from SNe does not affect the bubble size

The contribution from SNe does, however, enhance the flux.

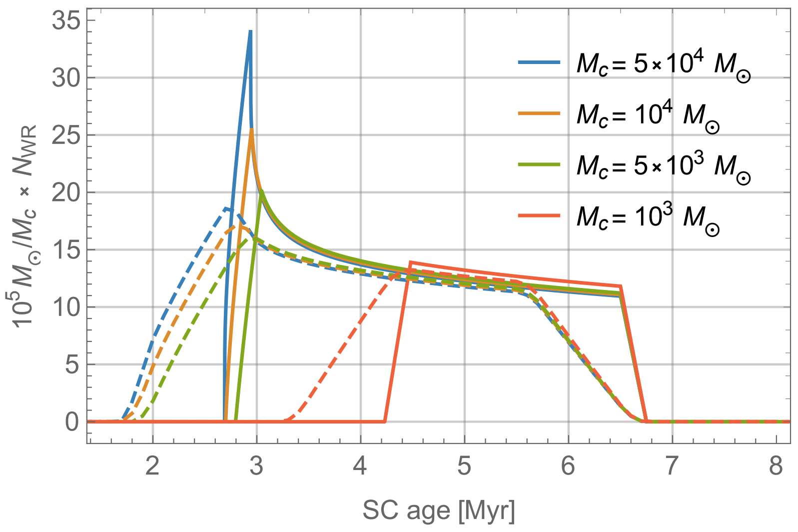
What about supernovae and Wolf-Rayet stars?

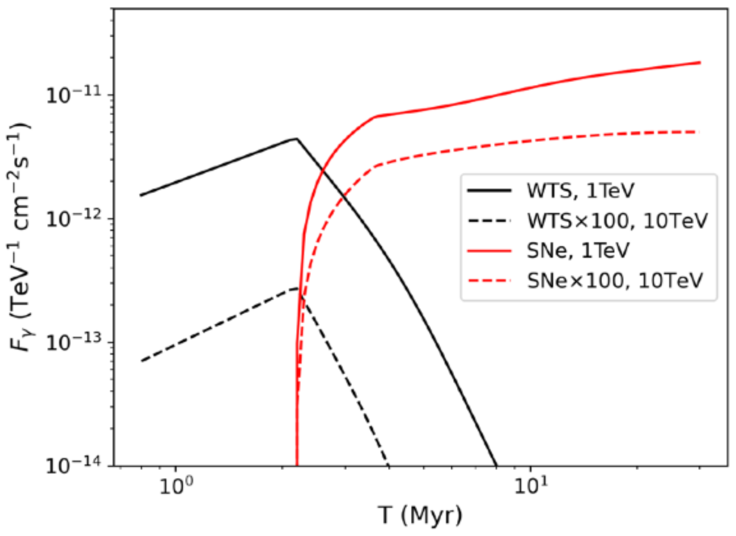
We find that the SNe contribution enhances the flux as

$$\langle f_{\rm SNR}(E)\rangle = 1.74 N_{\rm SN}(t_{\rm esc})\left(\frac{E_{\rm SN}}{10^{51}{\rm erg}}\right)\left(\frac{L_w}{10^{37}{\rm erg/s}}\right)^{-1}\left(\frac{t_{sc}}{3{\rm Myr}}\right)^{-1}\times f_s(10\,{\rm GeV})\left(\frac{E}{10\,{\rm GeV}}\right)^{-2.3}\exp(-E/E_{\rm max})$$

Which contribution dominates the gamma-ray flux depends on the age of the cluster

After ~3Myr, supernovae dominate





But wait - how do we get the mass and luminosity?

The expressions so far have assumed that the cluster mass M_c (mass-loss rate $\dot{M}_c$) and wind luminosity $L_{w,c}$ are available as free parameters of the model and required as input.

How do we determine them for known stellar clusters?

Turned out to not be straight forward.

Developed a multi-step procedure, outlined in:

"On the mass and wind luminosity of young Galactic open clusters in Gaia DR2"
Celli, Specovius, Morlino, AM, Menchiari, A&A **686** (2024) A118
https://doi.org/10.1051/0004-6361/202348541

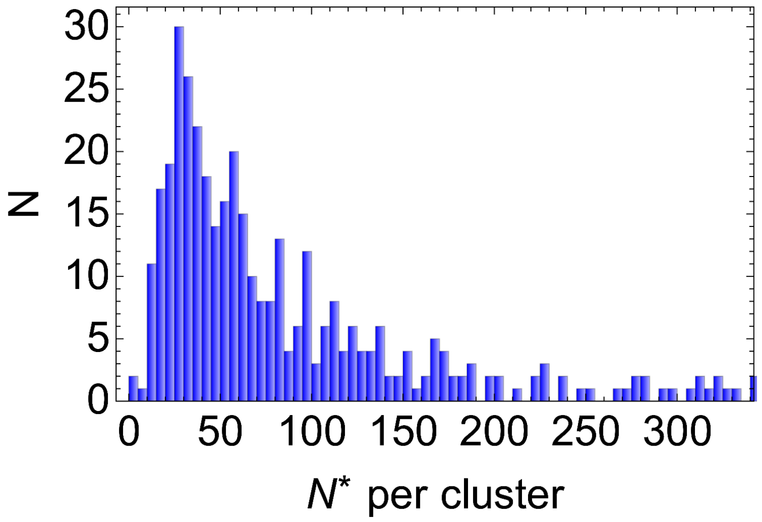
How to estimate the mass of a stellar cluster?

1) Extract the number and magnitude of stars in each cluster in the catalogue

We adopt the initial mass function:

$$\xi(M) = k \times \begin{cases} \left(\frac{M}{M_{\mathrm{min}}}\right)^{-\beta_1} & M_{\mathrm{min}} \leq M < M_0 \\ \left(\frac{M_0}{M_{\mathrm{H}}}\right)^{-\beta_1} \left(\frac{M}{M_0}\right)^{-\beta_2} & M_0 \leq M < M_1 \\ \left(\frac{M_0}{M_{\mathrm{H}}}\right)^{-\beta_1} \left(\frac{M_1}{M_0}\right)^{-\beta_2} \left(\frac{M}{M_1}\right)^{-\beta_3} & M_1 \leq M < M_{\mathrm{max}} \end{cases} \quad (1)$$

with $\beta_1 = 1.30$, $\beta_2 = 2.30$, $\beta_3 = 2.35$, $M_{\mathrm{min}} = 0.08\,M_\odot$, $M_0 = 0.50\,M_\odot$, and $M_1 = 1.00\,M_\odot$, $M_\odot$ being the Sun mass.



2) Perform a kernel density fit to the G-band magnitude distribution of each cluster to obtain Gmin & Gmax
In place of the maximum magnitude, we use the **mode** magnitude —> i.e. completeness limit.

Convert to bolometric magnitude: $\mathscr{M}_{\mathrm{bol}} = \mathscr{M}_G + BC_G$ with Bolometric correction $BC_G(T_{\mathrm{eff}}) = \sum_{i=0}^{4} \alpha_i \left(T_{\mathrm{eff}} - T_{\mathrm{eff},\odot}\right)^i$

How to estimate the mass of a stellar cluster?

3) Convert into intrinsic luminosity accounting for the extinction correction via:

$$L_s = 10^{0.4(\mathscr{M}_{\odot,\mathrm{bol}} - \mathscr{M}_{\mathrm{bol}} + A_G)}\, L_\odot$$

4) Convert from luminosity to stellar mass via the mass-luminosity relation:

$$L_s(M) = \begin{cases} L_{b1}\left(\frac{M}{M_{b1}}\right)^{\gamma_1}\left[\frac{1}{2} + \frac{1}{2}\left(\frac{M}{M_{b1}}\right)^{1/\Delta_1}\right]^{\Delta_1(-\gamma_1+\gamma_2)} & M/M_\odot < 12 \\ \epsilon L_{b2}\left(\frac{M}{M_{b2}}\right)^{\gamma_2}\left[\frac{1}{2} + \frac{1}{2}\left(\frac{M}{M_{b2}}\right)^{1/\Delta_2}\right]^{\Delta_2(-\gamma_2+\gamma_3)} & M/M_\odot \geq 12 \end{cases}$$

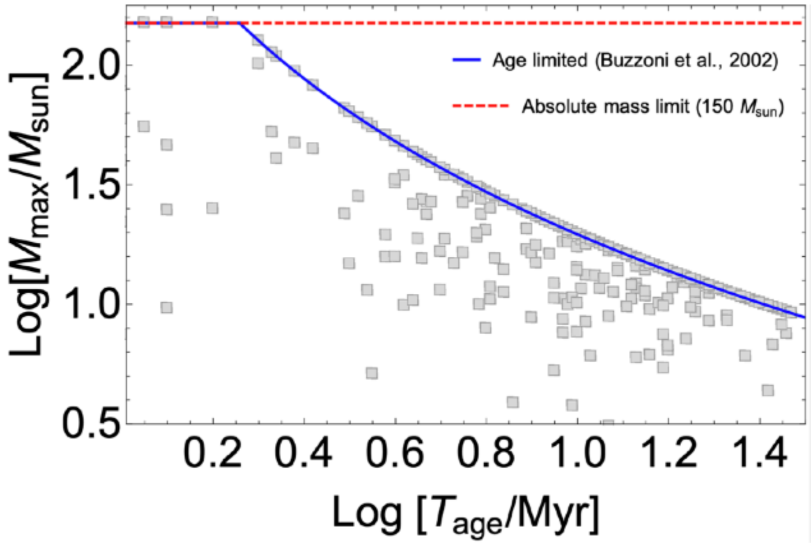
—> Yields the **minimum** M^*_{min} and **maximum** M^*_{max} mass of *observed* member stars

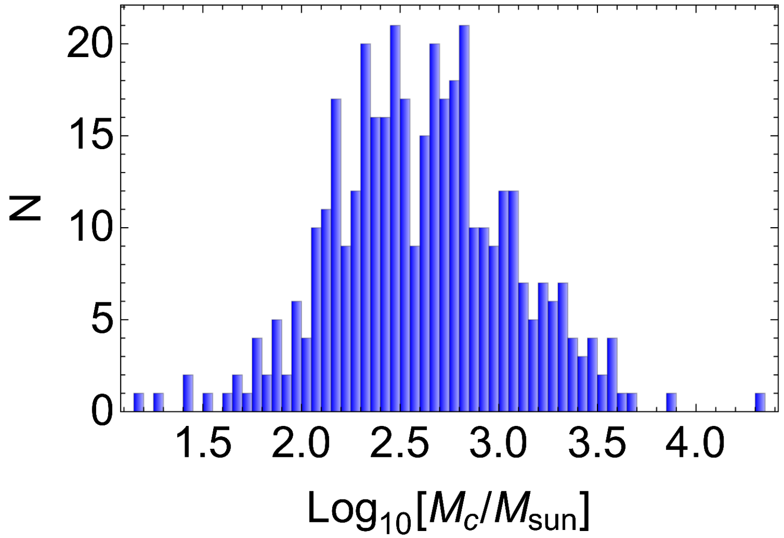
5) Derive the normalisation k of the stellar mass function $\xi(M)$ by inverting the integral: $N^* = \int_{M^*_{\mathrm{min}}}^{M^*_{\mathrm{max}}} \xi(M)\, dM$

How to estimate the mass of a stellar cluster?

6) Then the total cluster mass can be obtained via $M_{\rm c} = \int_{M_{\min}}^{M_{\max}} \xi(M) M \, dM$

— this time the bounds of the integral are given by theoretical considerations:
$M_{\min} = 0.08 M_{\odot}$ and $M_{\max}$ depends on the age of the stellar cluster.





We expect a systematic underestimate of a factor ~2-3, based on clusters where the mass can be determined independently.

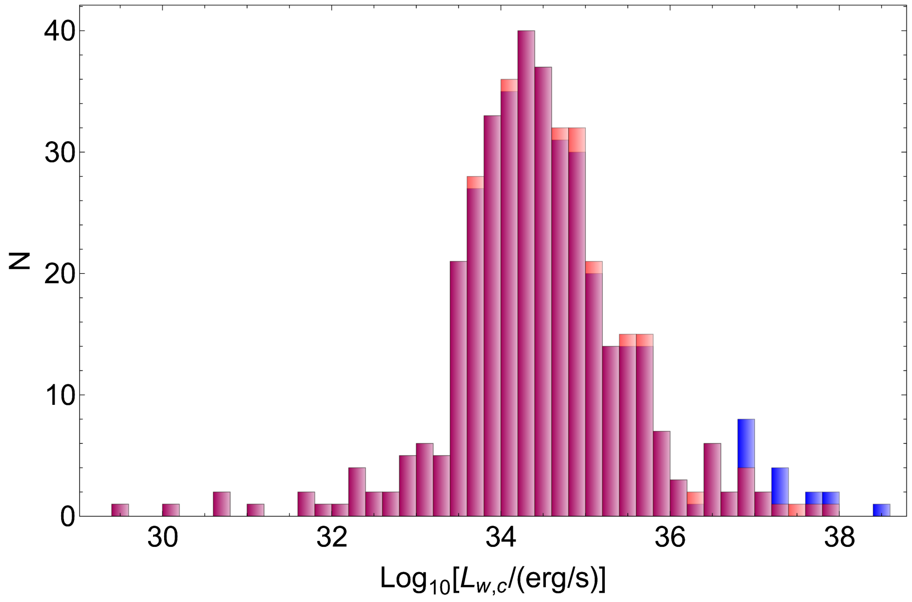
What about the cluster mass-loss rate & luminosity?

The cluster mass-loss rate can be estimated from the mass-loss rates of individual stars $\dot{M}_s$

$$\dot{M}_{\rm c} = \int_{M_{\rm min}}^{M_{\rm max}} \xi(M)\dot{M}_{\rm s}(M)\, dM$$

Similarly, via momentum conservation

$$\dot{M}_{\rm c} v_{\rm w,c} = \int_{M_{\rm min}}^{M_{\rm max}} \xi(M)\dot{M}_{\rm s}(M) v_{\rm w,s}(M)\, dM$$, where $v_{w,s}$ is the stellar wind velocity.



Finally, the cluster wind luminosity can be obtained via:

$$L_{\rm c,w} = \frac{1}{2}\dot{M}_{\rm c} v_{\rm w,c}^2 = \frac{1}{2}\frac{\left(\int_{M_{\rm min}}^{M_{\rm max}} \xi(M)\dot{M}_{\rm s}(M) v_{\rm w,s}(M) dM\right)^2}{\int_{M_{\rm min}}^{M_{\rm max}} \xi(M)\dot{M}_{\rm s}(M) dM}$$

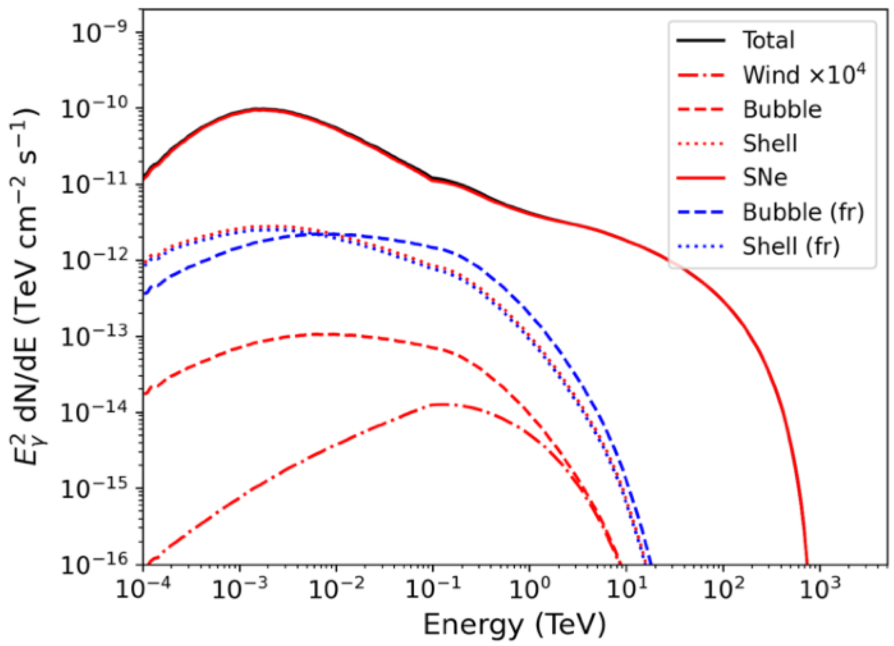
Free parameters of the model

…and their default values

Properties of the cosmic ray efficiency and particle diffusion —> CR

Properties of the stellar cluster (age, mass, wind etc.) —> Cluster

Number of supernovae occurring in the stellar cluster —> SNR



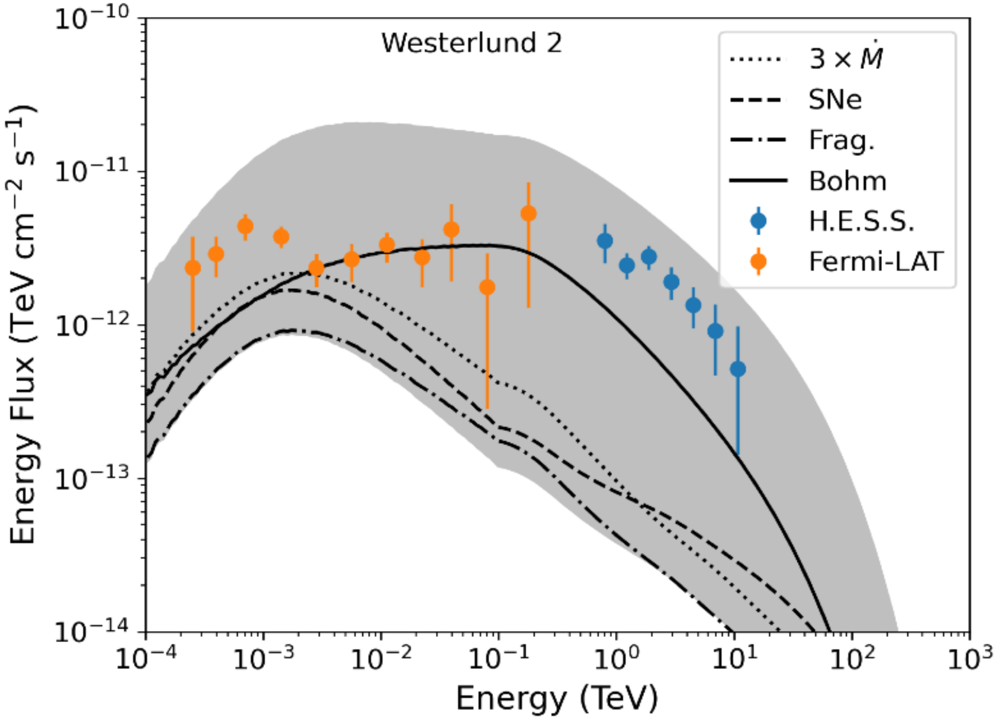
	Parameter	Value
CR	ξ_{CR}	10%
	ξ_{B}	10%
	L_{coh}	2 pc
	σ	4
	s_{wts}	4.0
	δ	0.5 (Kraichnan)
	D_0 (10 GeV)	3.0×10^{28} cm^2 /s
Cluster	t_{age}	3 Myr
	M_{sc}	$10^4\, M_\odot$
	$\dot{M}$	10^{-5} M$_\odot$ /yr
	v_w	2500 km s^{-1}
	n_{ISM}	10 cm^{-3}
	d	1 kpc
	η_{fr}	0.1
SNR	N_{SN}	5
	M_{ej}	$5\, M_\odot$
	E_{sn}	10^{51} erg
	s_{sn}	4.3

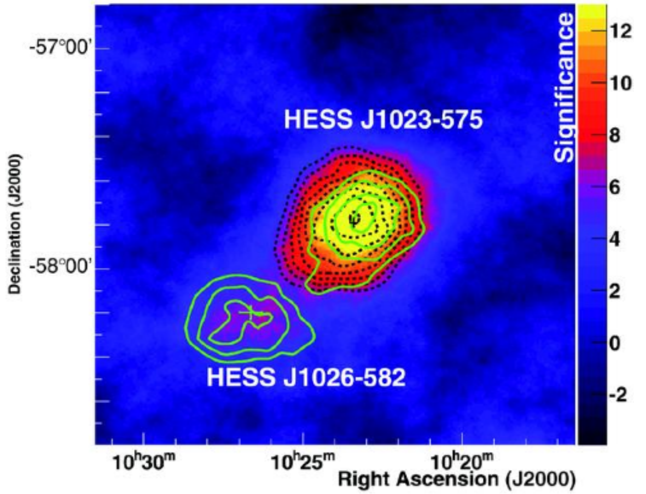
Comparison to data

Gamma-ray detected stellar clusters in Gaia DR2

We apply the model to known stellar clusters with gamma-ray emission

Shaded band - allowed variation via reasonable changes to the model





H.E.S.S. collaboration A&A **525** (2011) A46

Spectral energy distributions adjusted to data by varying (e.g.) the average ambient density in the surrounding ISM and the CR efficiency

Shape of Bohm diffusion curve is more consistent with data than Kraichnan

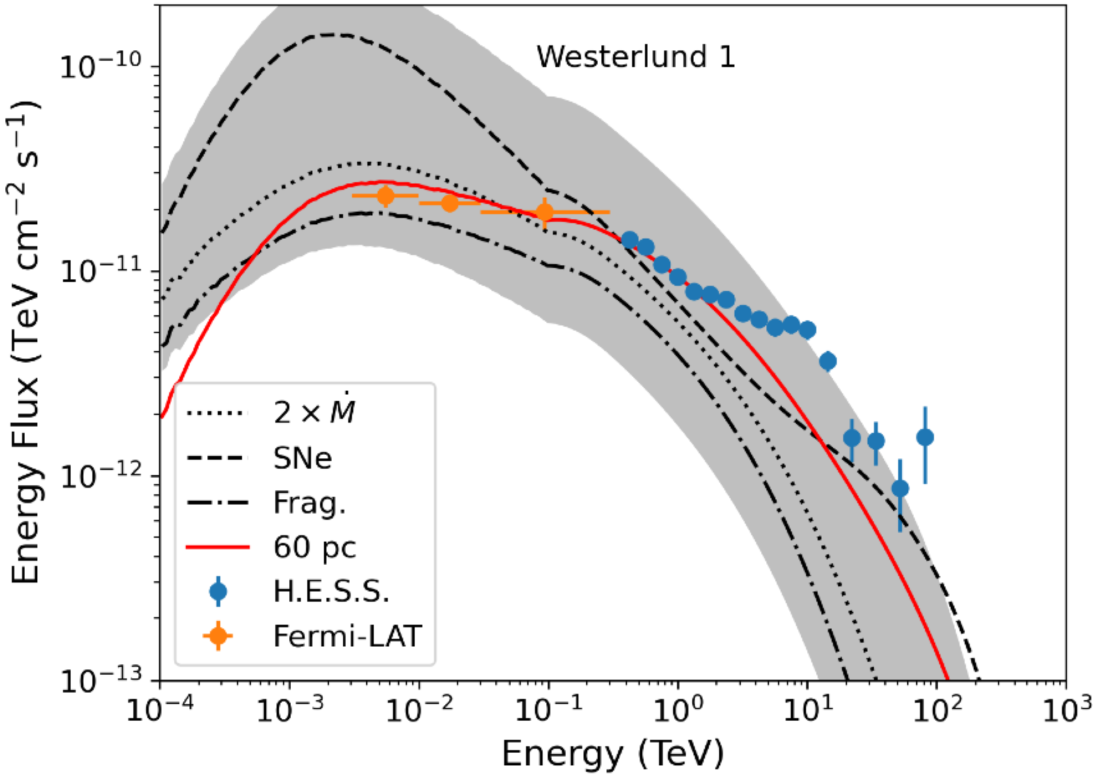
(No fitting —> visual comparison only)

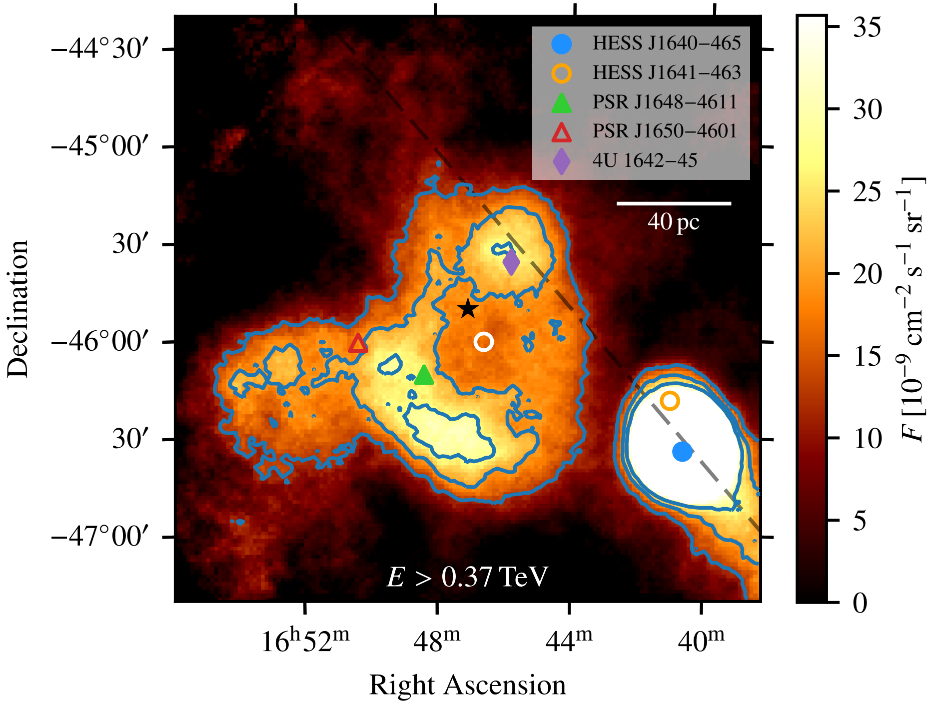
Comparison to data

Gamma-ray detected stellar clusters in Gaia DR2

Westerlund 1 —> Smaller observed bubble size (~60pc) & revised distance estimate are consistent with red line

Provided a higher ISM ambient density is assumed —> also consistent with observations.





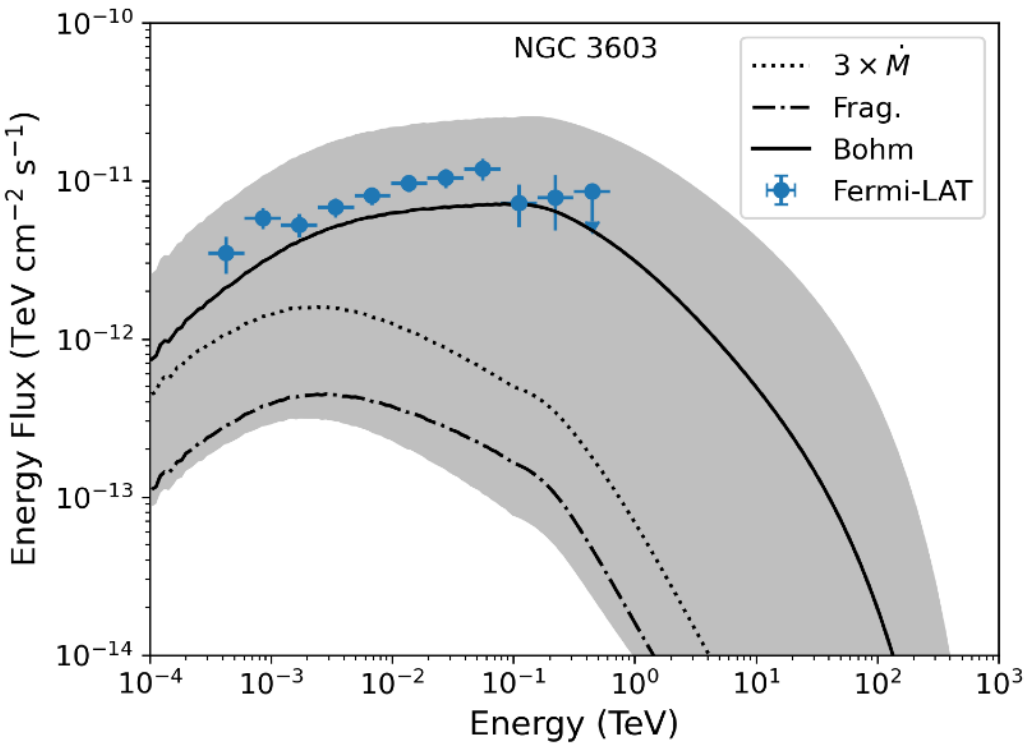
H.E.S.S. collaboration A&A **666** (2022) A124

Comparison to data

Gamma-ray detected stellar clusters in Gaia DR2

NGC 3603 —> based on Fermi-LAT data, the expected emission in the TeV range is well above HESS sensitivity

Detection of Danks 1 & 2 also recently reported based on Fermi-LAT data.



FGES J1109.4–6115e

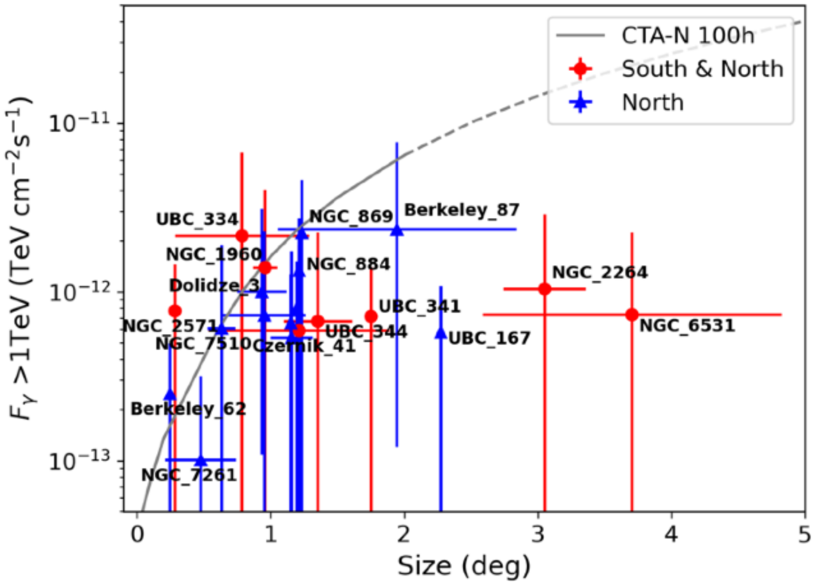
Predictions for stellar clusters in Gaia DR2

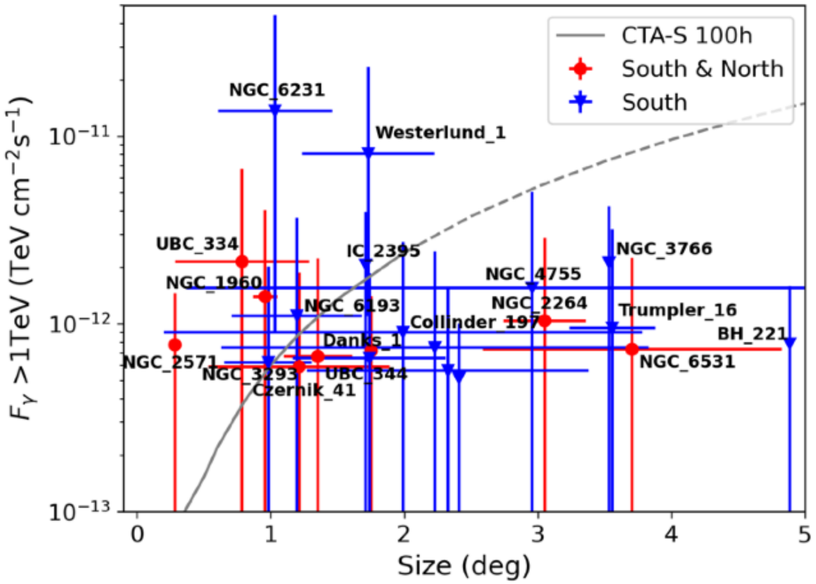
Select young stellar clusters (< 30 Myr) for which necessary information is available

Determine v_w based on the aforementioned estimates for $\dot{M}_c$ and L_w —> coupled via: $L_w = \frac{1}{2}\dot{M}_c v_w^2$

Angular size given by R_b and distance.

Compare predicted gamma-ray / neutrino flux to instrument sensitivity



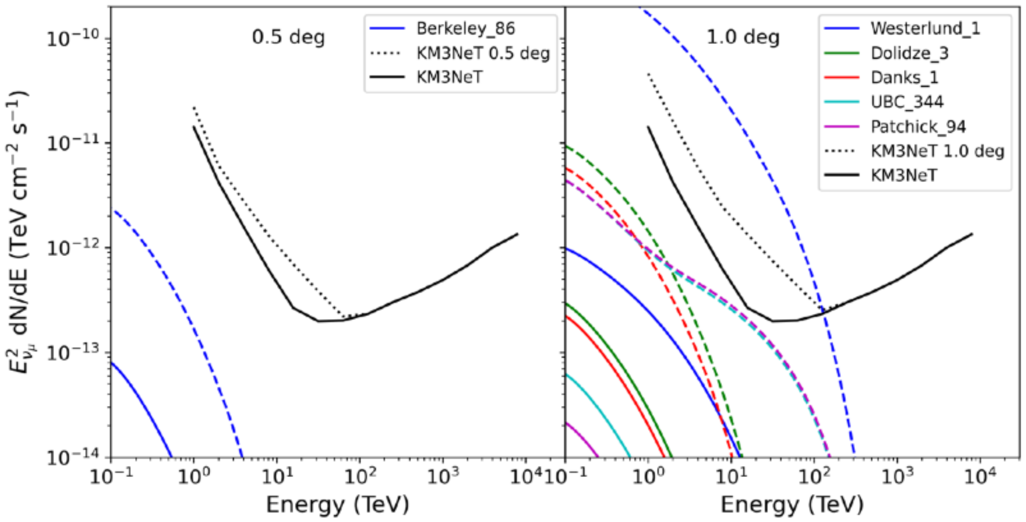


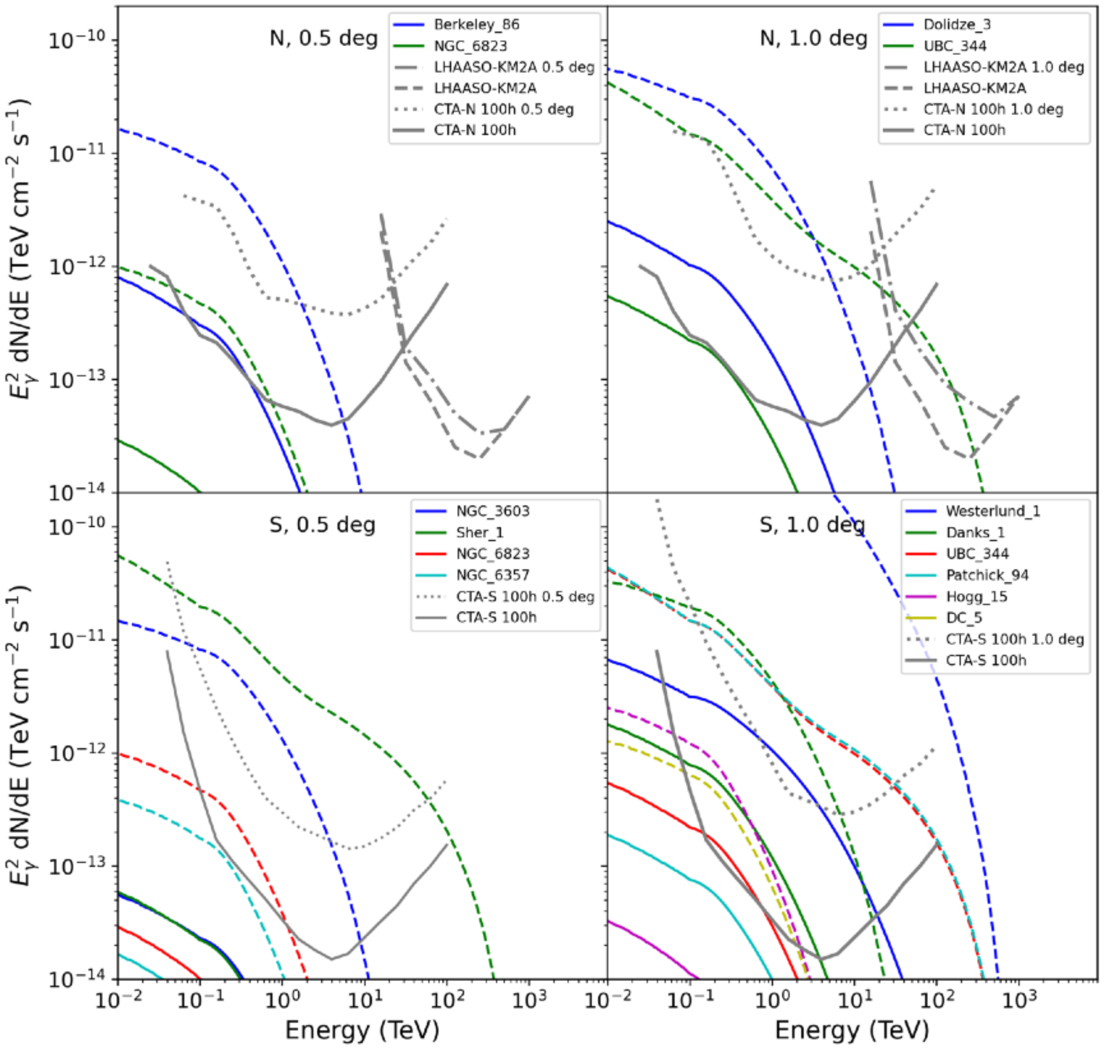
Comparison of gamma / neutrino flux to instrument sensitivity

Many wind-blown bubbles around stellar clusters are simply large, which decreases the surface brightness.

Instrument sensitivity is also reduced at larger angular sizes.

Solid and dashed lines indicate the plausible range for each stellar cluster



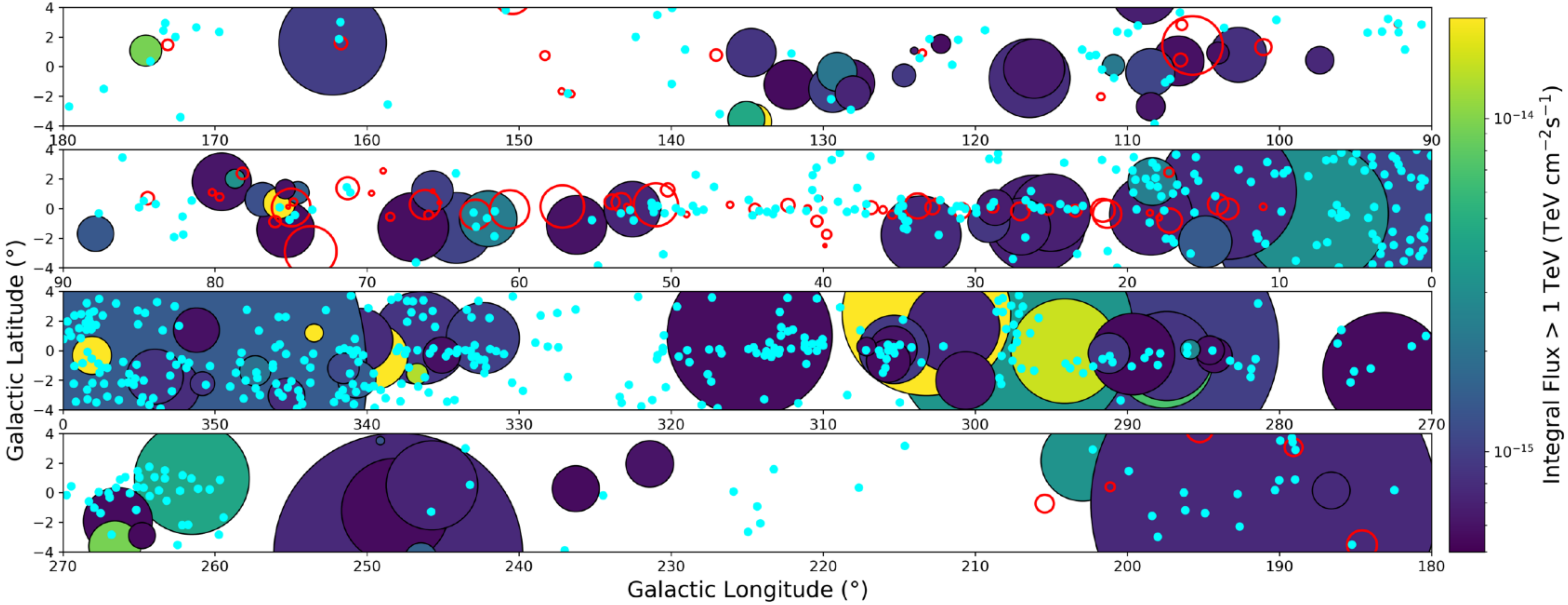


Wind-blown bubbles in the Galactic Plane

Using the most optimistic scenario for the model (upper bound / dashed line curves)

Red circles = LHAASO ultra-high-energy sources & Cyan points = 4FGL unidentified sources

Many bubbles have predicted sizes that are ~multi-degree scale and often multiple overlapping along the line of sight



What is the maximum energy reached?

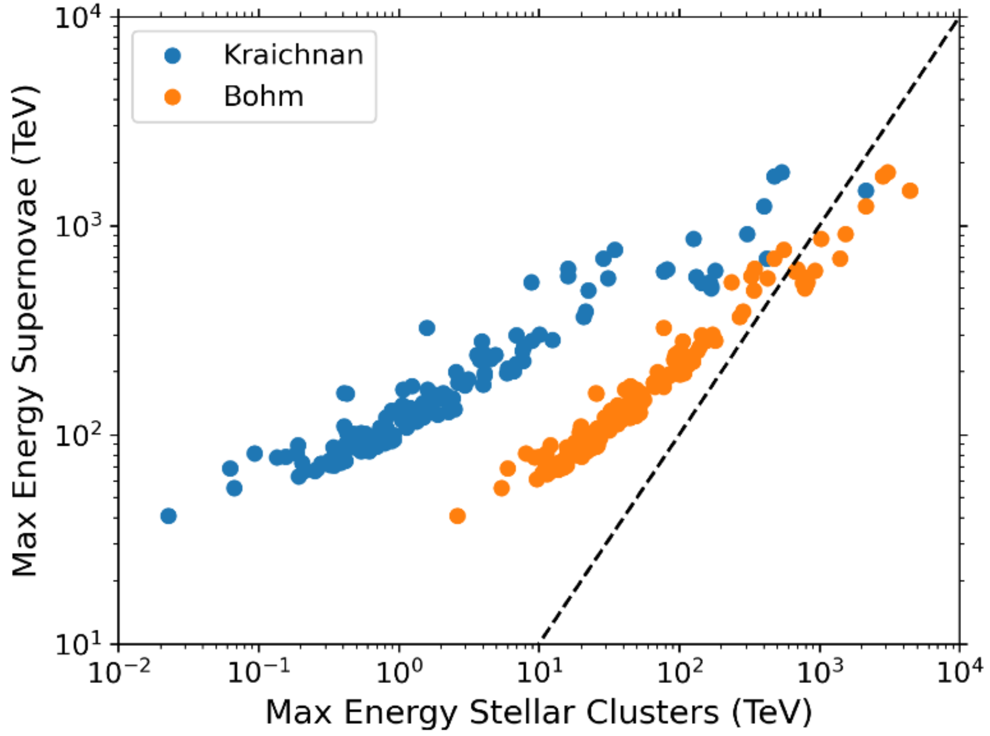
Due to either supernovae or the stellar cluster wind
—> we wish to identify not only those clusters likely to be detectable, but also those for which this indicates PeVatron activity

Usually, supernovae dictate the maximum energy

$$E_{\max} = 48 \left(\frac{B}{10\,\mu\mathrm{G}}\right)\left(\frac{L_{\rm coh}}{2\,\mathrm{pc}}\right)^{-1}\left(\frac{u_{st}}{5000\,\mathrm{km/s}}\right)^{\frac{1}{2}}\left(\frac{R_{st}}{10\,\mathrm{pc}}\right)^{\frac{1}{2}}\ \mathrm{TeV}$$

Whilst the maximum momentum determined via confinement in the wind is:

$$cp_{\rm max,1}^{\rm Bohm} = 3u/c\, eB\, R_s$$
$$cp_{\rm max,1}^{\rm Kra} = (3u/c\, R_s)^2\, eB/L_{\rm coh}$$



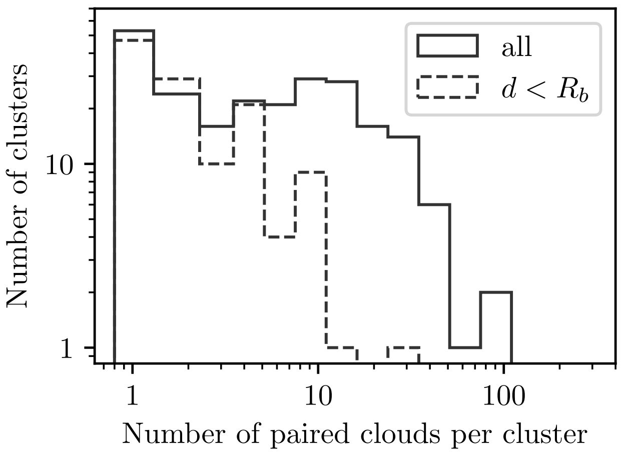
Predicting emission from molecular clouds near stellar clusters?

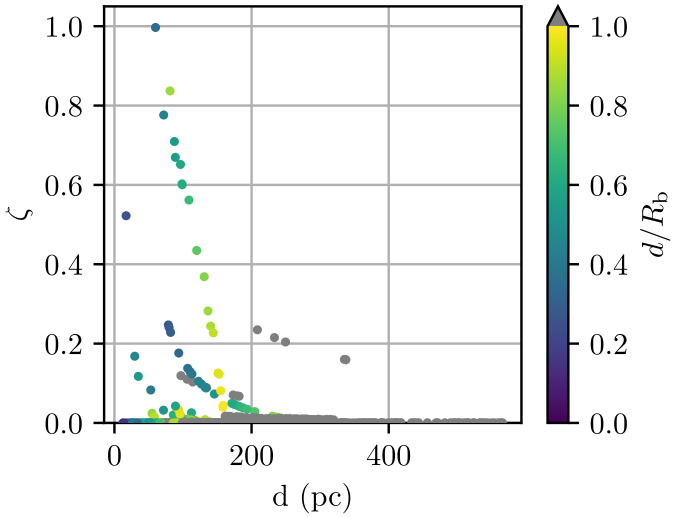
In the vicinity of stellar clusters, molecular clouds may locally enhance the expected gamma-ray / neutrino flux.

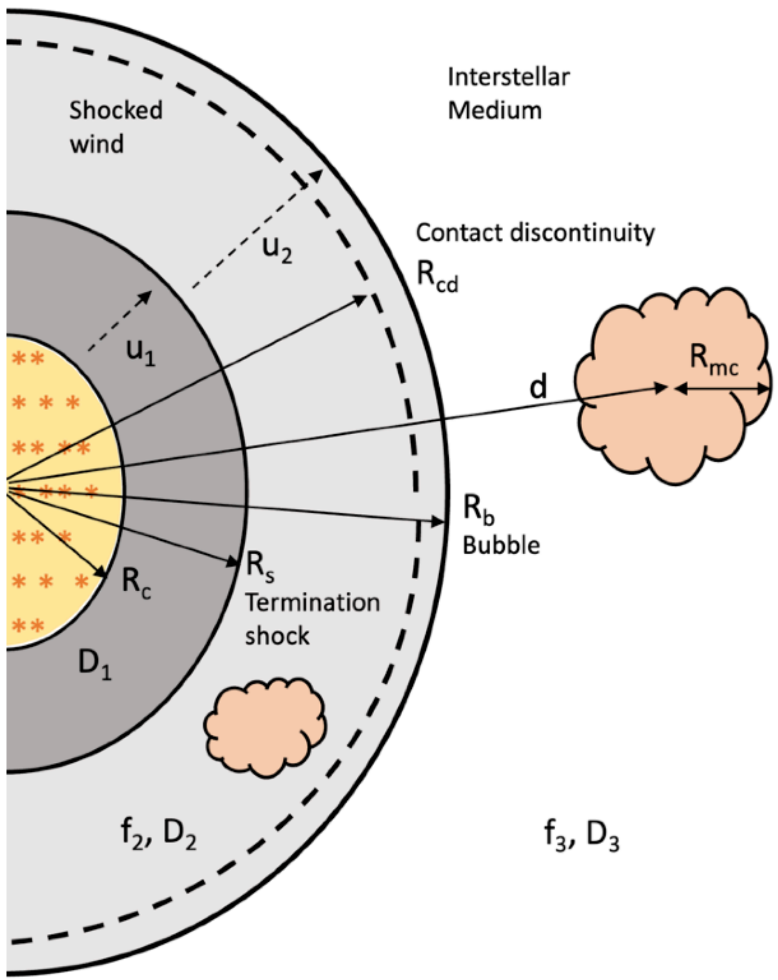
Clouds — from catalogues based on CO data — are paired with clusters out to a distance $2R_b$ from the cluster centre.

An important consideration here is also the fraction of the flux due to the stellar cluster wind vs illumination by the sea of galactic cosmic rays.

Define $\zeta = F_\gamma^{\rm sc}/F_\gamma^{\rm sc+gal}$







Outlook

- Detailed modelling of specific clusters, especially those with detected emission
- Addressing some assumptions of the model (e.g. losses, transport, composition, density & B-field profiles…)
- Follow-up analyses and/or observation proposals for clusters with the brightest predicted fluxes
- Predicting the anticipated enhancement factor for flux from nearby clouds
- Selection of which molecular cloud catalogue / gas distribution maps are most suitable

Thank you for your attention

Any questions?

Influence of free parameters on the model

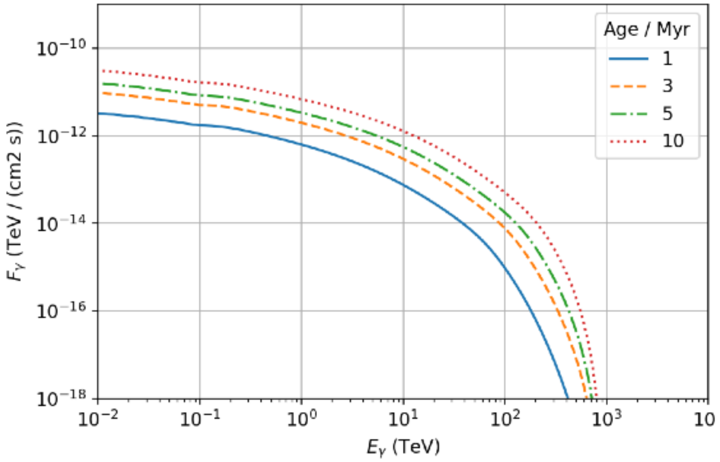
Total flux increases with age, with wind velocity and with the mass loss rate.

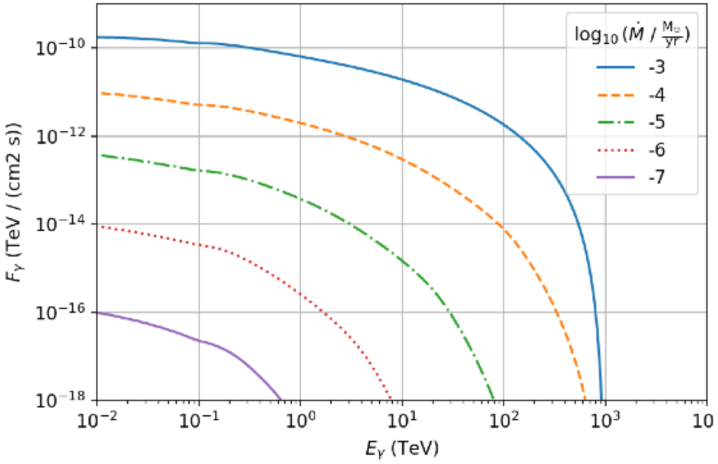
The bubble contributes most to the total flux.

Note: below 100 GeV, we use the expression

$$\frac{dN_\gamma}{dE_\gamma} = 2\int_{E_{\min}}^{\infty} \frac{q_\pi(E_\pi)}{\sqrt{E_\pi^2 - m_\pi^2}} dE_\pi \quad \text{with } E_{\min} = E_\gamma + m_\pi^2/4E_\gamma$$

and $q_\pi(E_\pi) = \tilde{n}\frac{c n_H}{K_\pi}\sigma_{\text{inel}}\left(m_p + \frac{E_\pi}{K_\pi}\right) J_p\left(m_p + \frac{E_\pi}{K_\pi}\right)$.





Neutrino Oscillations

For neutrinos, we assume that the neutrino flux at source is: $\Phi_{\nu}^{*} = \phi_{\nu_e}^{*} + \phi_{\nu_\mu}^{*}$

Such that the flux arrive at Earth is modified due to neutrino oscillations and distributed over three neutrino flavours:

$$\begin{aligned}
\phi_{\nu_e} &= P_{ee}\phi_{\nu_e}^{*} + P_{\mu e}\phi_{\nu_\mu}^{*} \\
\phi_{\nu_\mu} &= P_{e\mu}\phi_{\nu_e}^{*} + P_{\mu\mu}\phi_{\nu_\mu}^{*} \\
\phi_{\nu_\tau} &= P_{e\tau}\phi_{\nu_e}^{*} + P_{\mu\tau}\phi_{\nu_\mu}^{*}
\end{aligned}$$

For comparing to neutrino detector sensitivity, we use the muon neutrino flux only as the most promising channel for detection

Stellar wind and mass-loss rate

Stellar mass-loss rate:

$$\dot{M}_{\mathrm{s}}(M) \simeq 9.55 \times 10^{-15} \left(\frac{L_{\mathrm{s}}(M)}{L_{\odot}}\right)^{1.24} \left(\frac{M}{M_{\odot}}\right)^{0.16} \left(\frac{R_{\mathrm{s}}(M)}{R_{\odot}}\right)^{0.81} \frac{\mathrm{M}_{\odot}}{\mathrm{yr}}$$

The stellar radius depends on mass as:

$$R_{\mathrm{s}}(M) = 0.85\, R_{\odot}\, (M/M_{\odot})^{0.67} \,.$$

The stellar wind velocity is given by:

$$v_{\mathrm{w,s}}(M) = C(T_{\mathrm{eff}}) \sqrt{\frac{2G_{\mathrm{N}}M}{R_{\mathrm{s}}(M)}\left(1 - \frac{L_{\mathrm{s}}(M)}{L_{\mathrm{Edd}}(M)}\right)}$$