Cosmic Rays from Colliding Shock Flows in Massive, Compact Star Clusters

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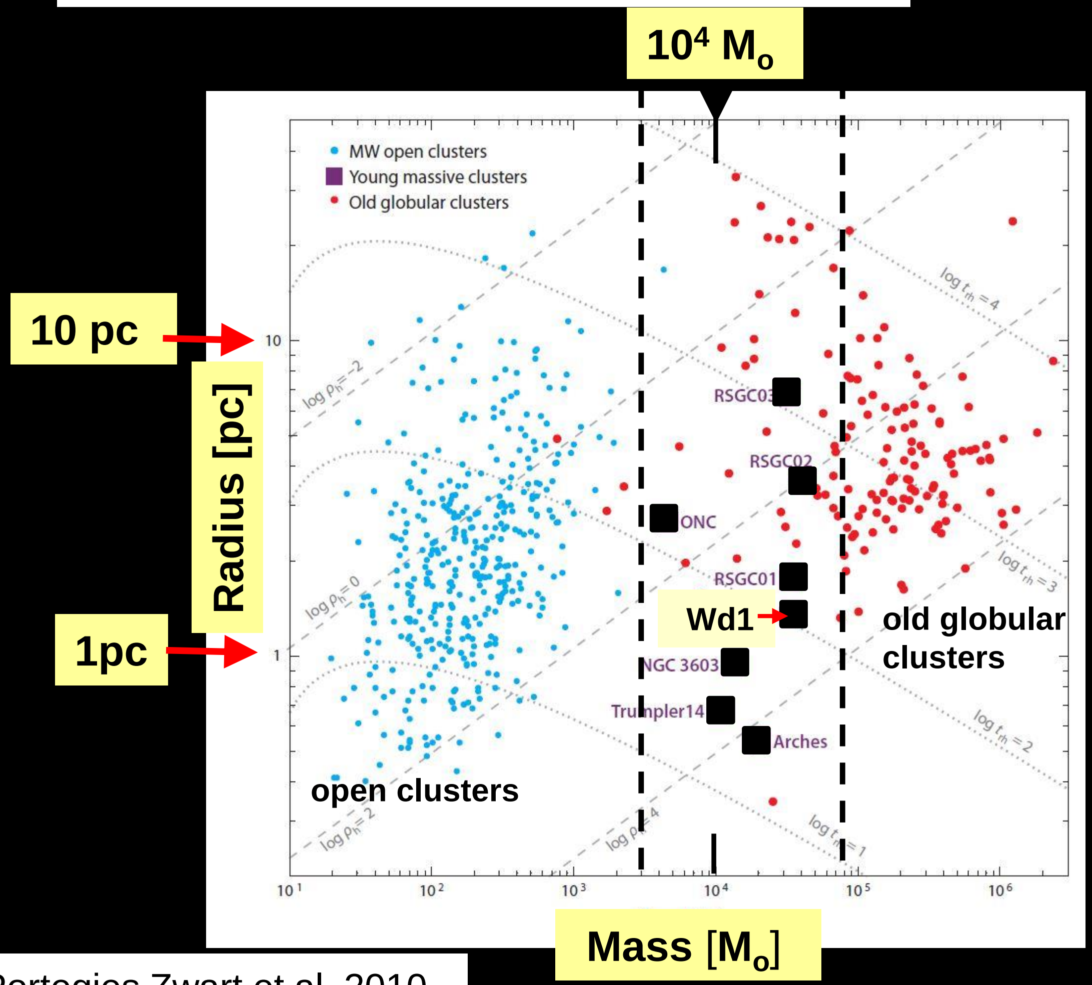
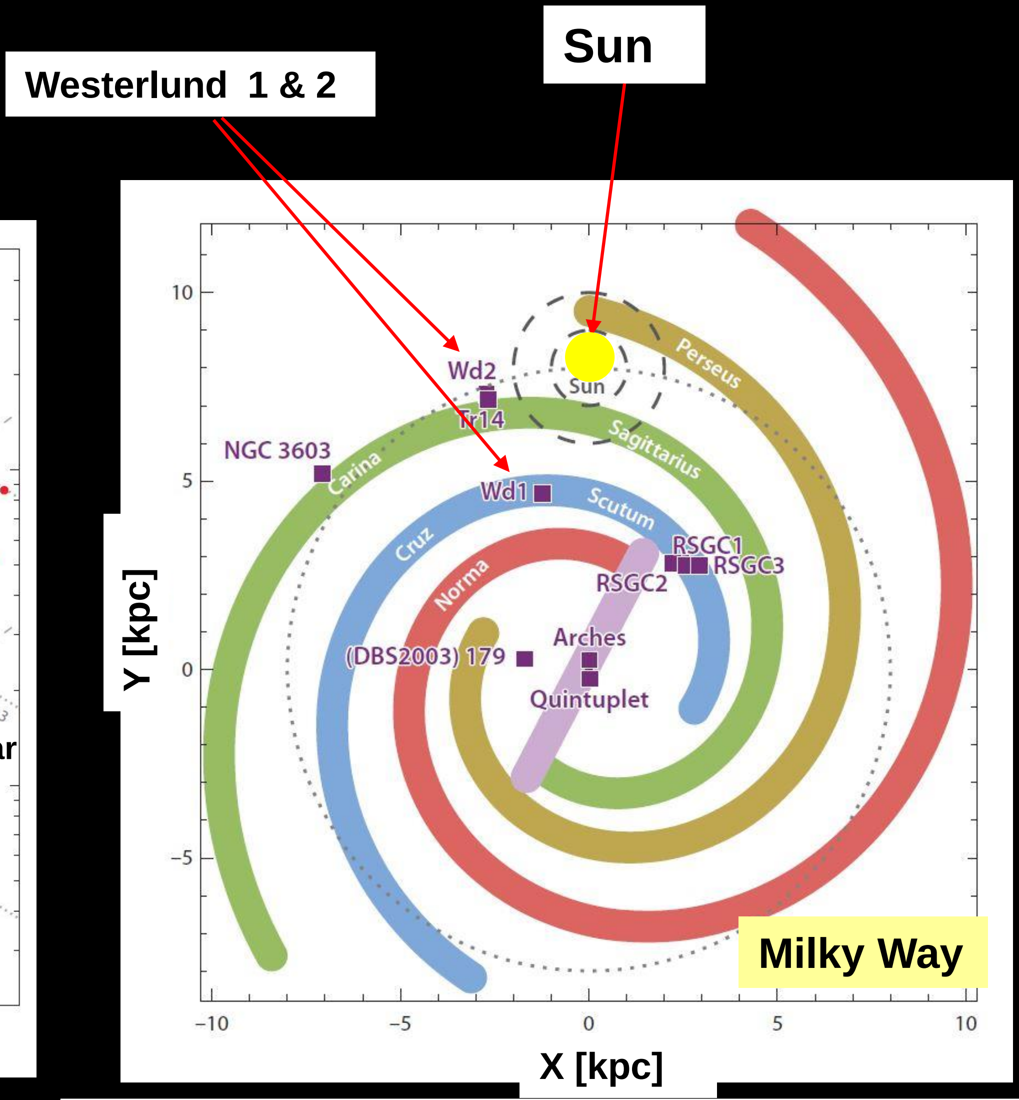
Aim: Provide rational for massive, compact, galactic star clusters as a significant source of cosmic rays in 100 PeV range.

Details of Colliding-shock-flows (CSFs) model in Bykov, Gladilin & Osipov 2013; Bykov et al. 2015

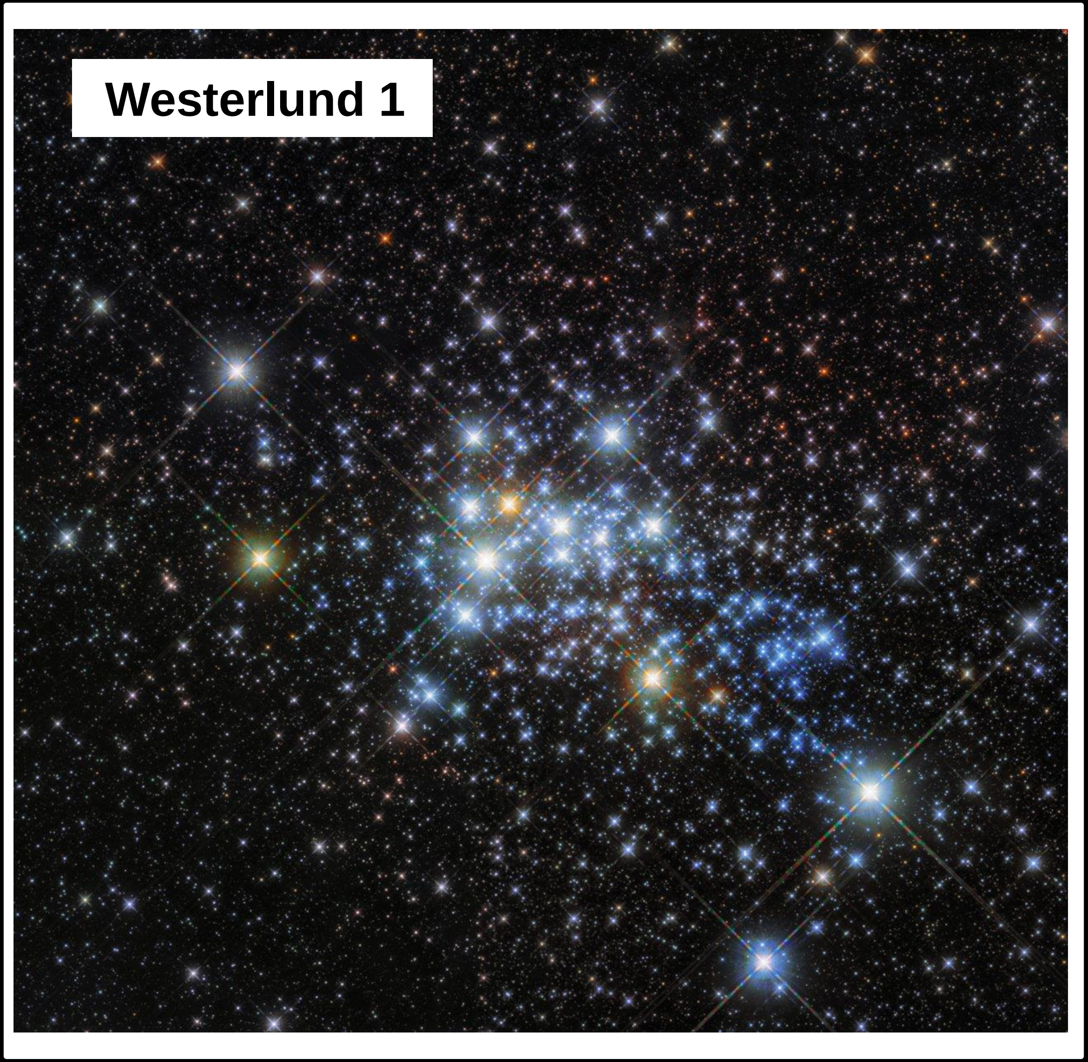
Young Massive star clusters in the Milky Way



Portegies Zwart et al. 2010



These galactic star clusters are compact and contain bright, young stars ➔ SNe

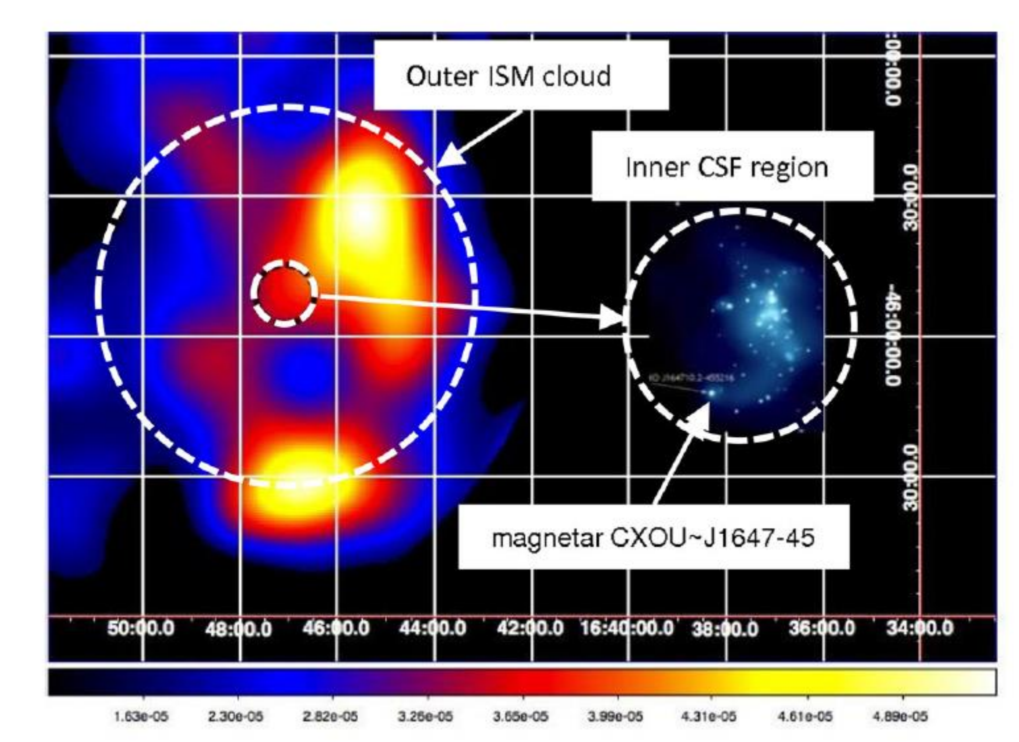


Credit: ESA/Hubble & NASA

Compact cluster Westerlund 1

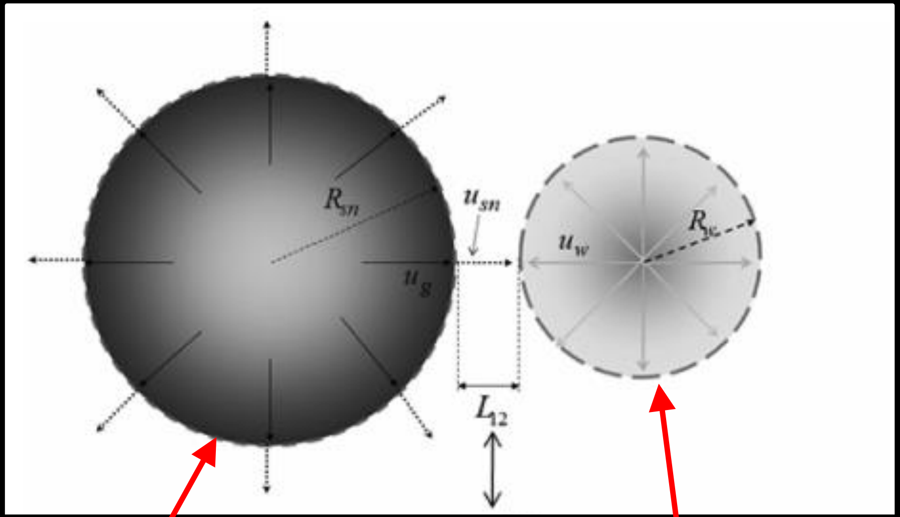
- ➔ **Estimated age 3-5 Myr**
- ➔ **Contains ~50 post-MS stars, including at least 24 Wolf-Rayet stars**
- ➔ **1 parsec-scale core**

(e.g., Clark et al. 2005, Crowther et al. 2006)



Colliding-Shock-Flows (CSFs) In compact star clusters:

- ➔ Expect massive stars with strong winds to be near supernova explosions
- ➔ Fermi shock acceleration will occur in isolated SNRs
- ➔ Interaction between SNR shock and massive star wind, or bow shock, may produce enhanced CR production
- ➔ Intermediate CR sources



SNR blast wave

Wind bow / termination shock from young star.

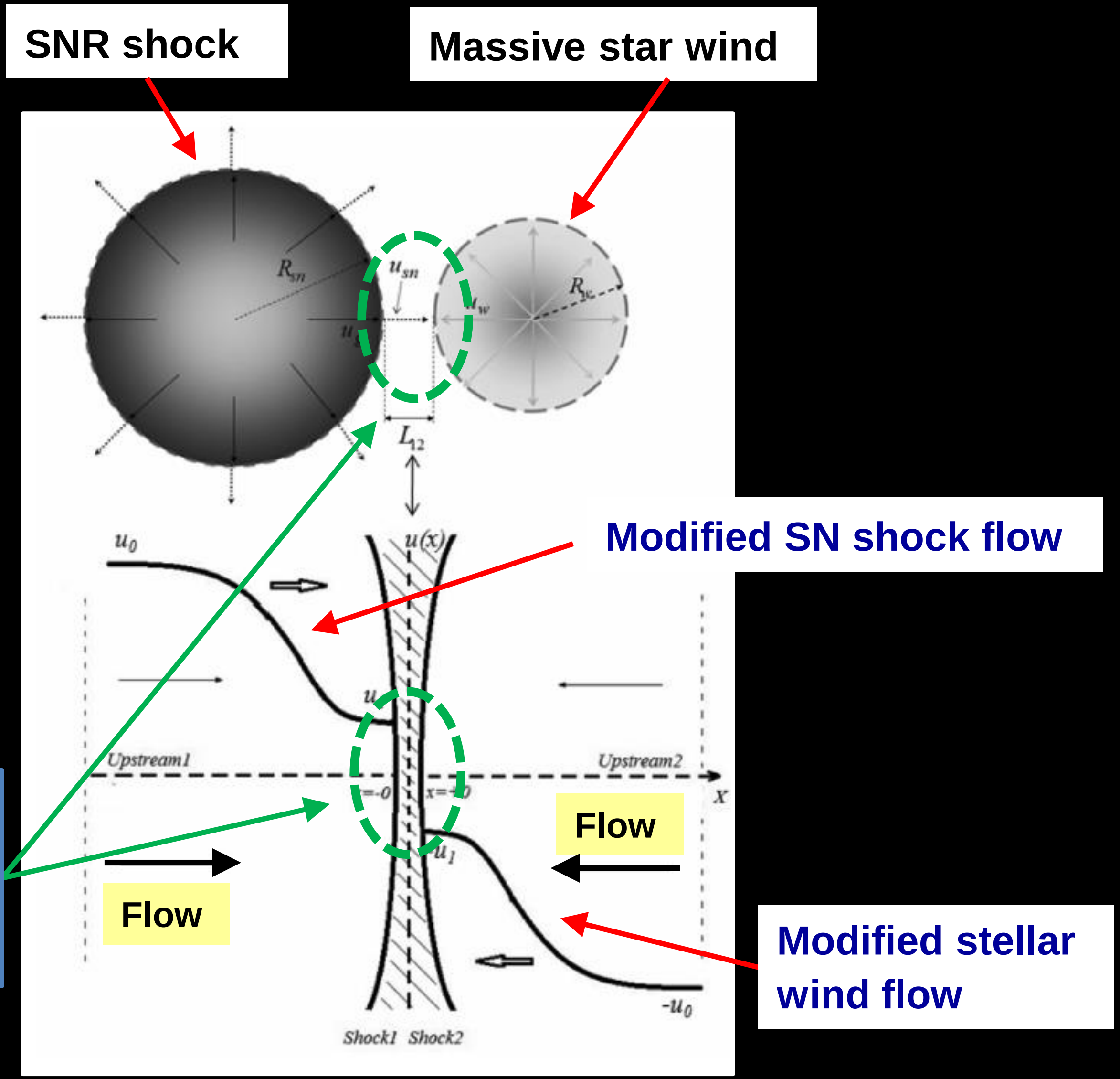
In dense core, winds may combine to drive cluster-scale wind.

Bykov, Gladilin & Osipov (2013)

Generalize semi-analytic method of Blasi, Amato & Caprioli (2004-2010) to model nonlinear Diffusive Shock Acceleration in interaction region

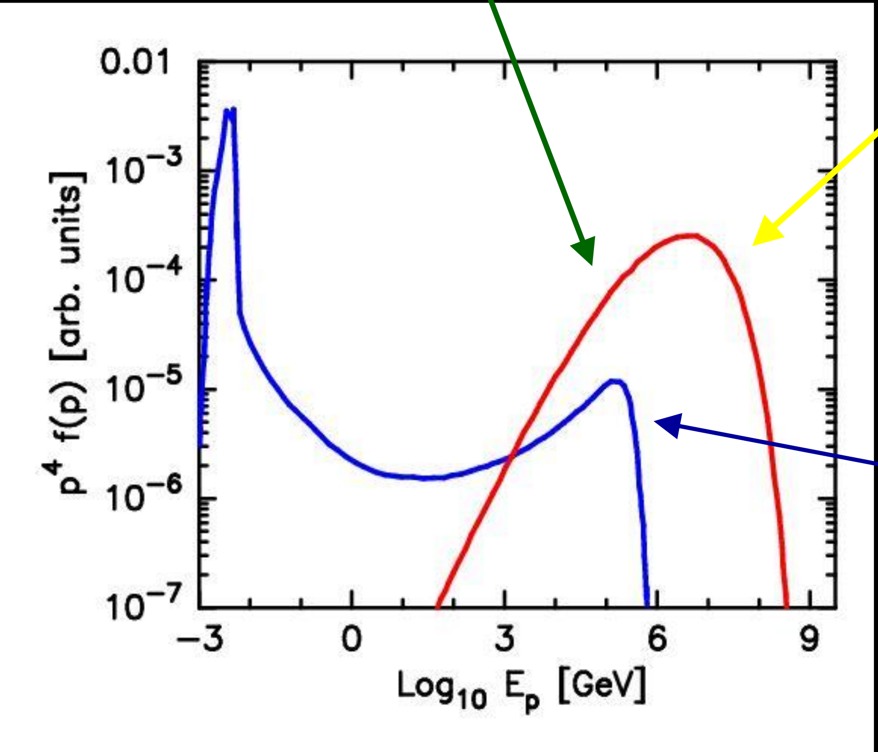
Important features:

- ➔ Include shock modification from efficient CR production
- ➔ Magnetic field amplification in parallel shock approximation
- ➔ Time-dependence as shocks converge
- ➔ Simplified geometry



Enhanced acceleration as CRs bounce between shock and wind

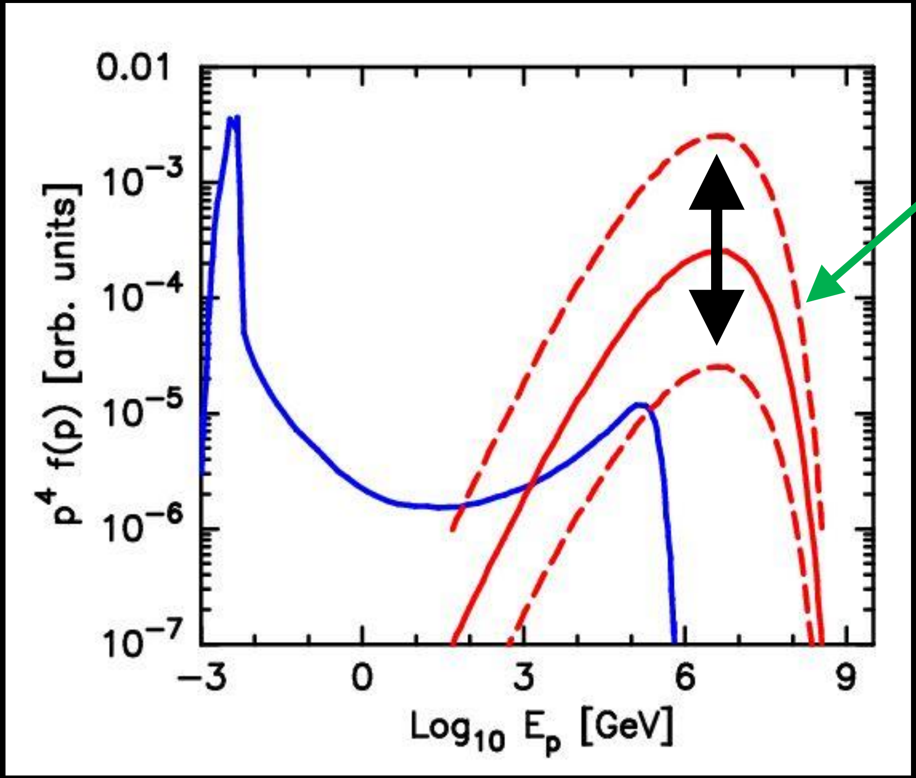
Strongly peaked because only high energy CRs can efficiently "bounce" between SNR shock and wind shock for further acceleration



Efficient Fermi acceleration in isolated SNR shock:

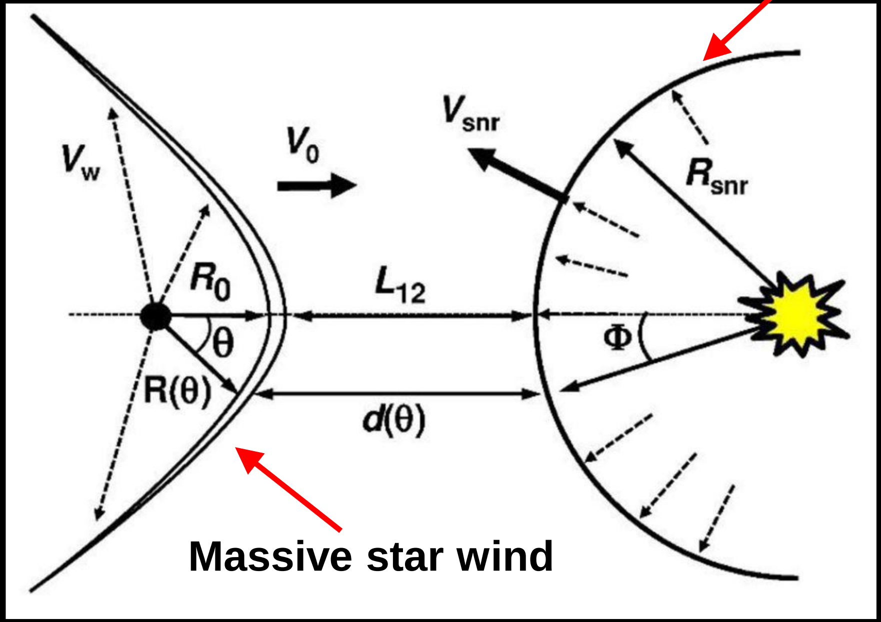
- ➔ **Can produce hard, concave spectrum**
- ➔ **BUT low maximum energy**
  (Lagage & Cesarsky 1983)

References for CFSs:
Bykov et al. 2015, 2017: PeV neutrinos from CFSs
Bykov et al. 2018, 2019: High-energy CRs, electrons, γ-rays
Kalyashova et al. 2019: CFSs as source of $^{22}Ne/^{20}Ne$ excess



Normalization of peak depends on geometry of CSFs !?
Large uncertainty in geometry and strength of peak

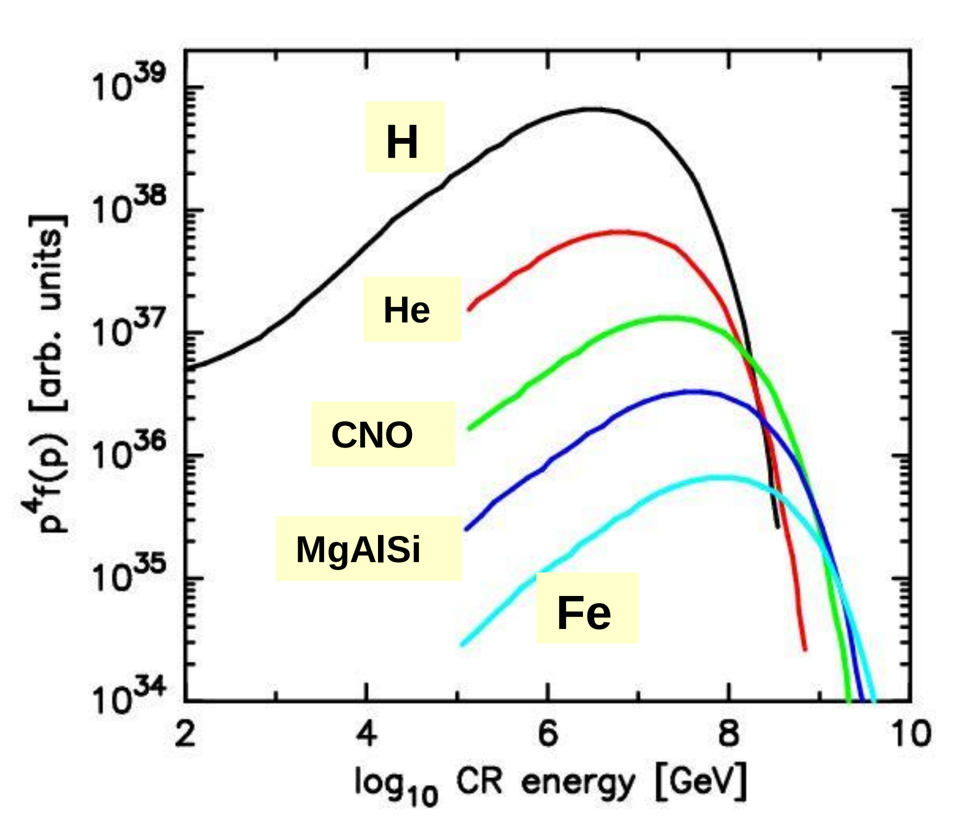
SNR shock



Additional uncertainties for CRs observed at Earth from model of galaxy (Halo/disk) & interstellar CR diffusion

Asymmetric wind / SNR shock

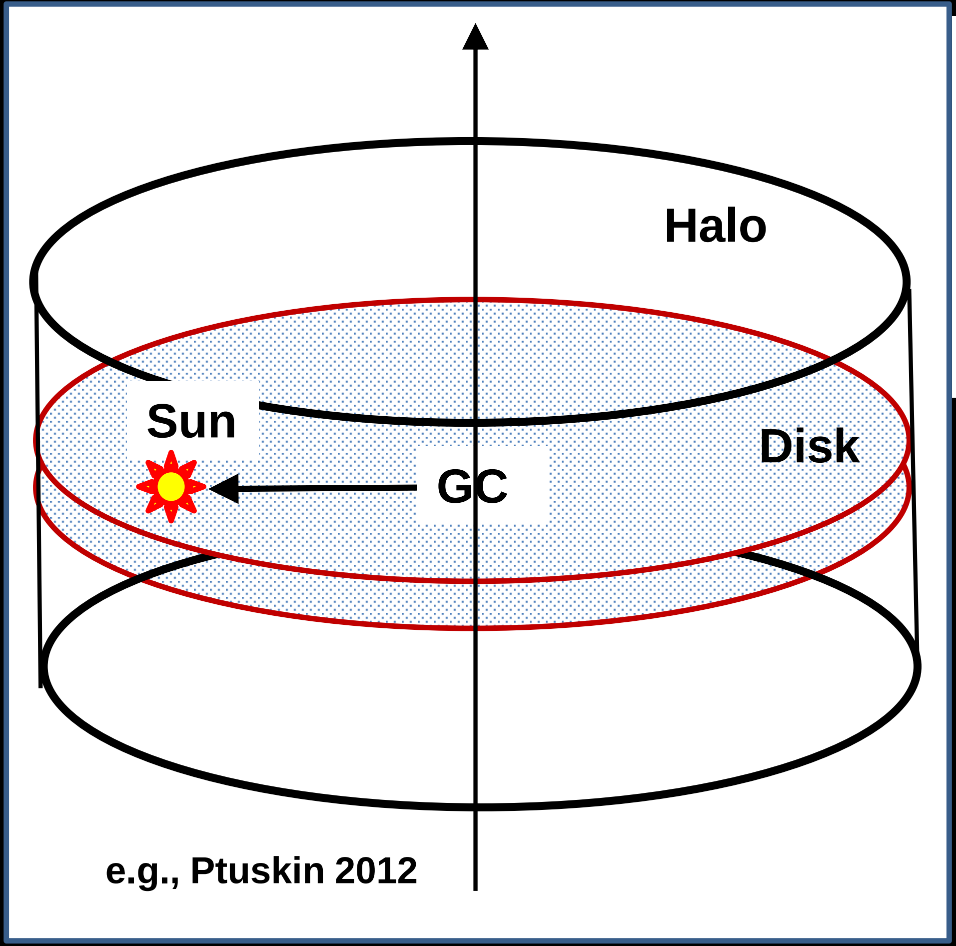
Expect shocks to produce CRs with Emax $\propto$ Charge, Z
Scale proton peak $\propto$ Z for heavy ions



Normalization uncertainty for CRs:

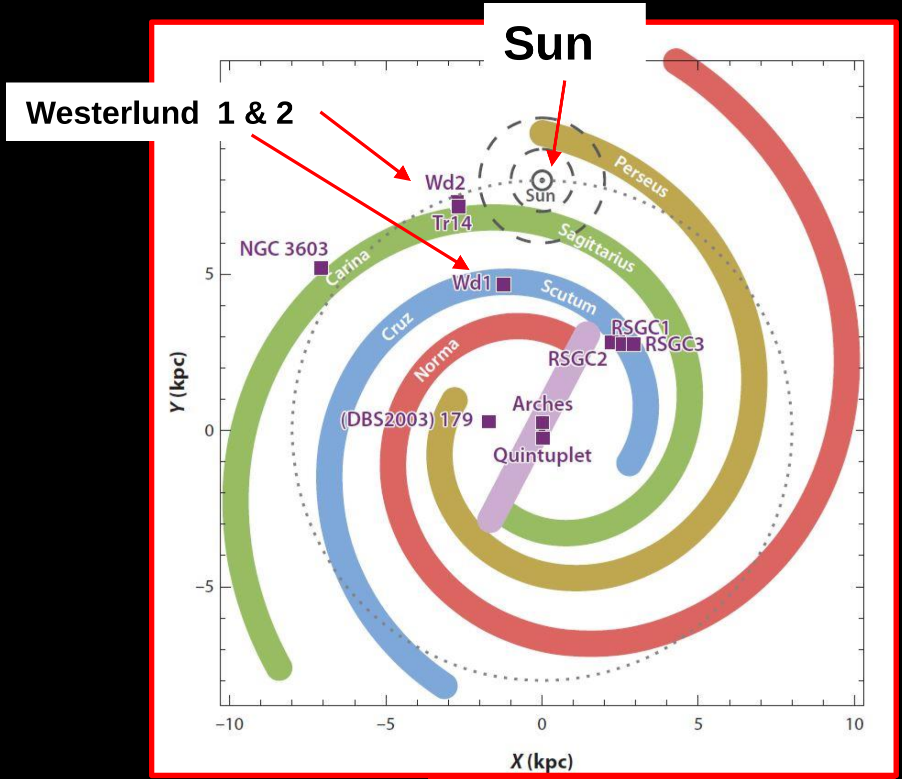
- ➔ Large overall uncertainty, but considerably less uncertainty for heavy ions compared to protons
- ➔ Shock acceleration process (at fully relativistic energies) depends only on CR rigidity
- ➔ Estimate heavy ion injection from observations (Meyer et al. 1997)

See also Caprioli, Blasi & Amato 2011 for heavy ion normalization

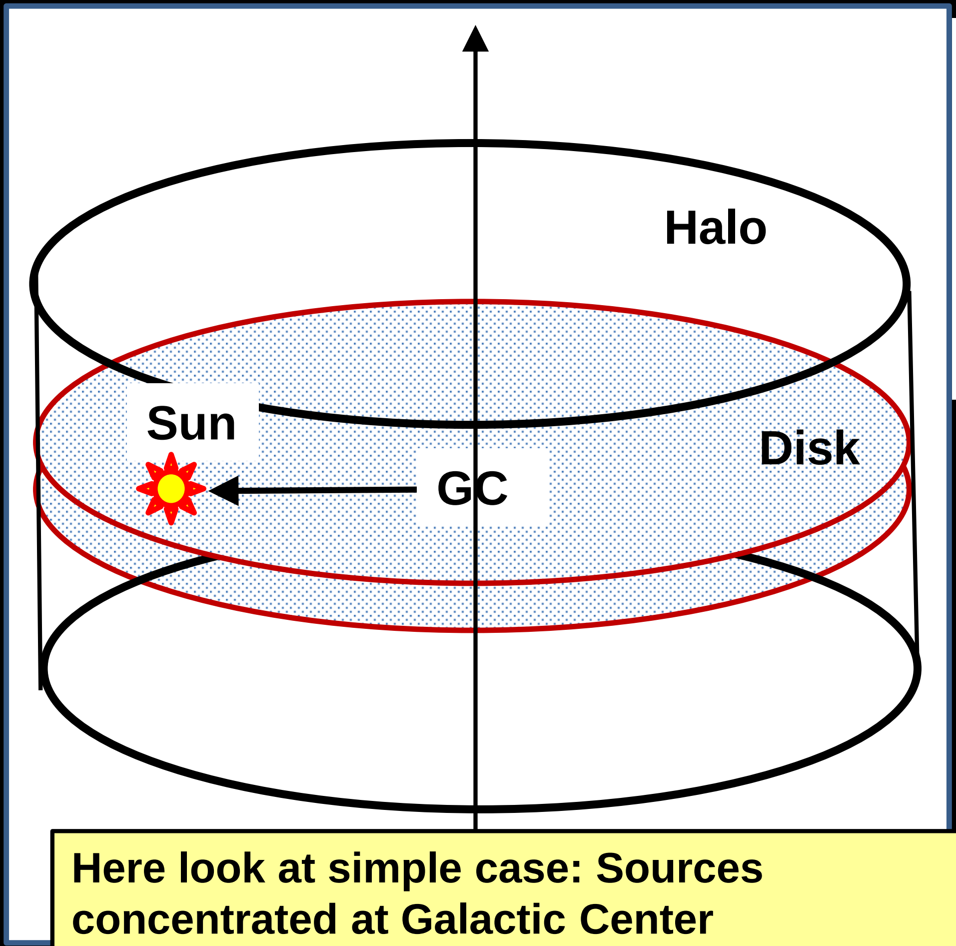


➔ Simple cylindrical model for Milky Way
➔ Compact clusters distributed in thin disk
➔ CRs diffuse in disk & halo

➔ Strong time variability at Sun for CSFs
➔ Flux and anisotropy depend on recent, nearby events



Portegies Zwart et al. 2010



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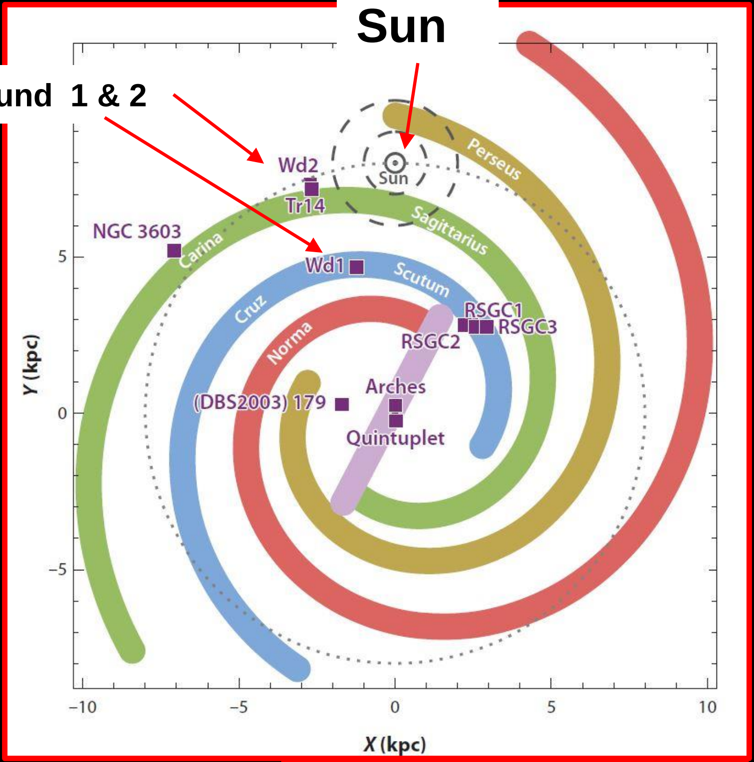
Here look at simple case: Sources concentrated at Galactic Center

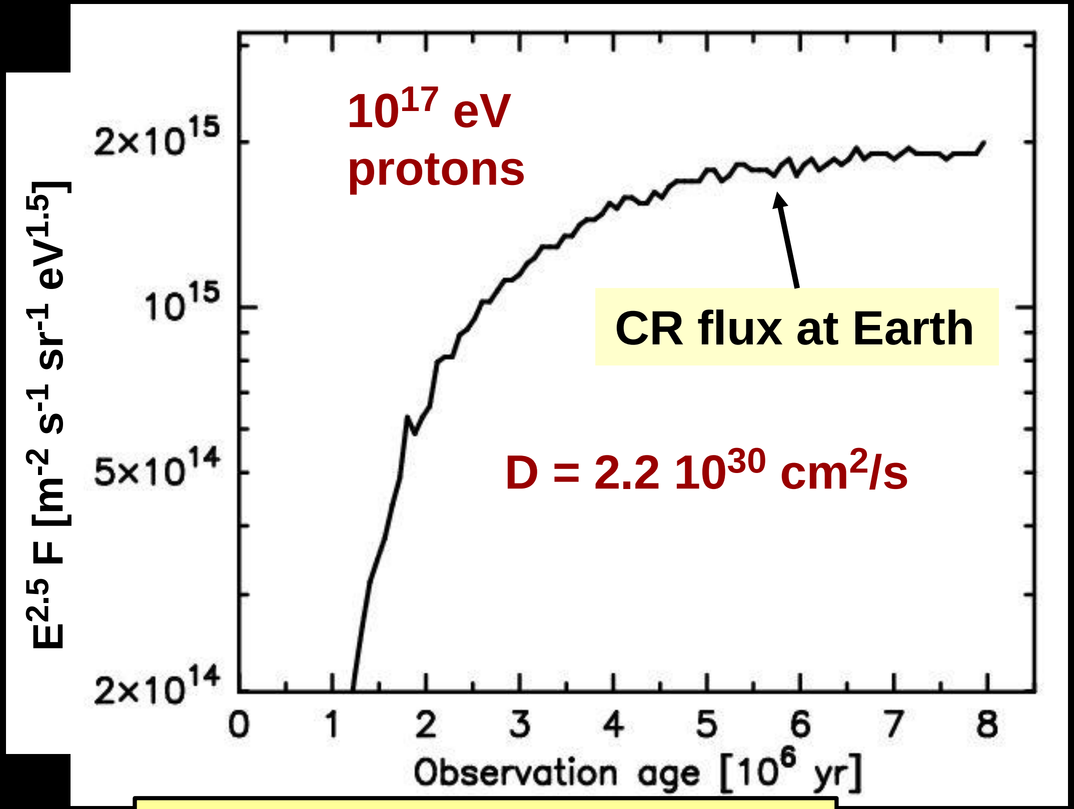
- ➔ Good estimate of average flux and average anisotropy at Earth

- ➔ More complete modeling with time & space variation, and Milky Way B-field structure, done in Bykov, Kalyashova, Ellison & Osipov 2019



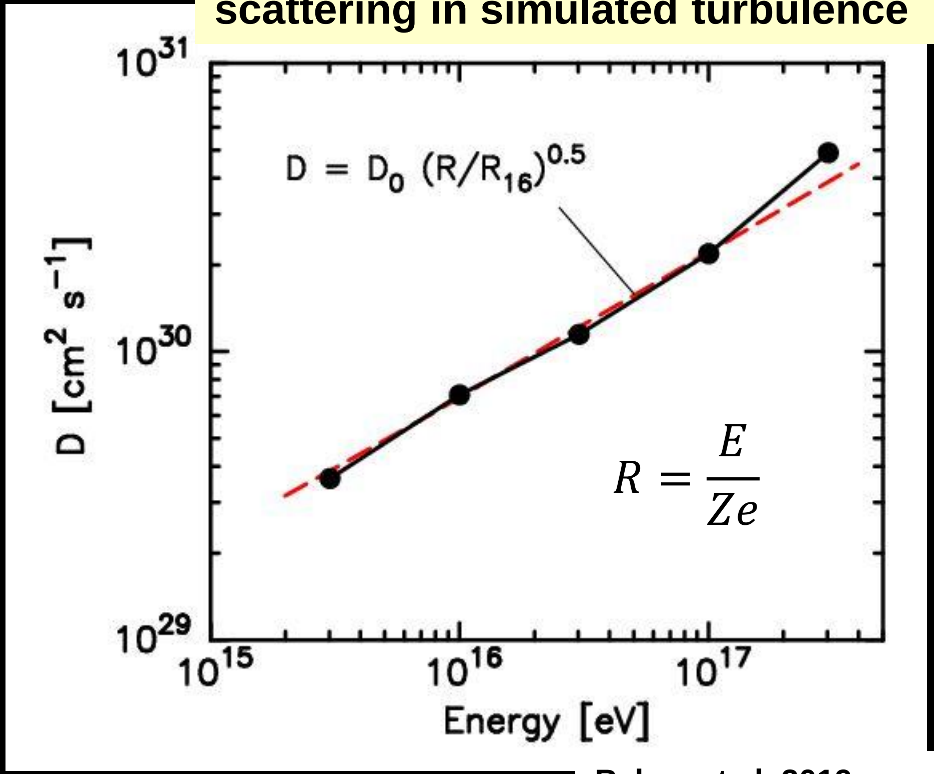
Portegies Zwart et al. 2010

Sources concentrated at Galactic Center



Time from start of simulation

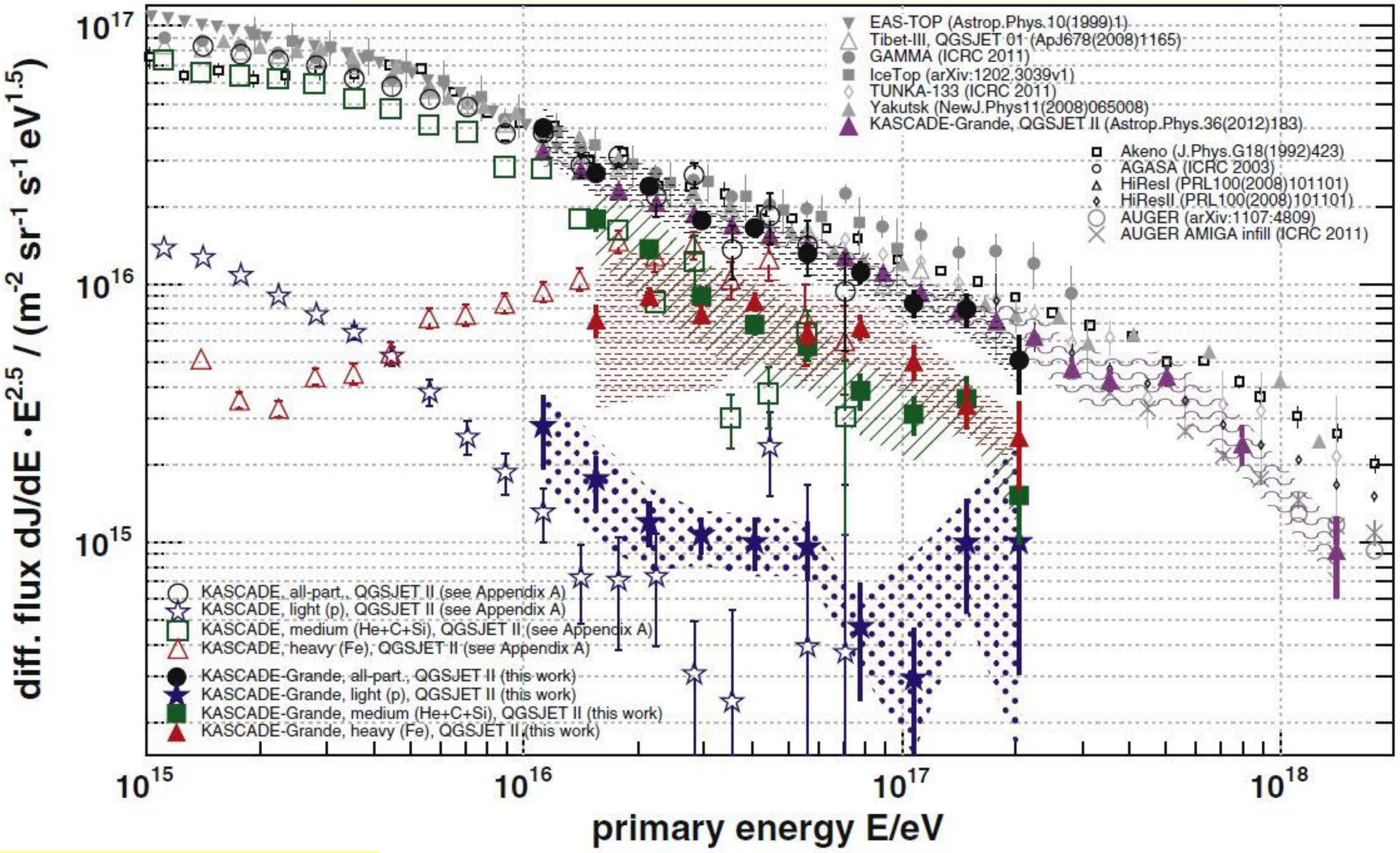
ISM diffusion coefficient from scattering in simulated turbulence



Bykov et al. 2019
using data from Han 2017

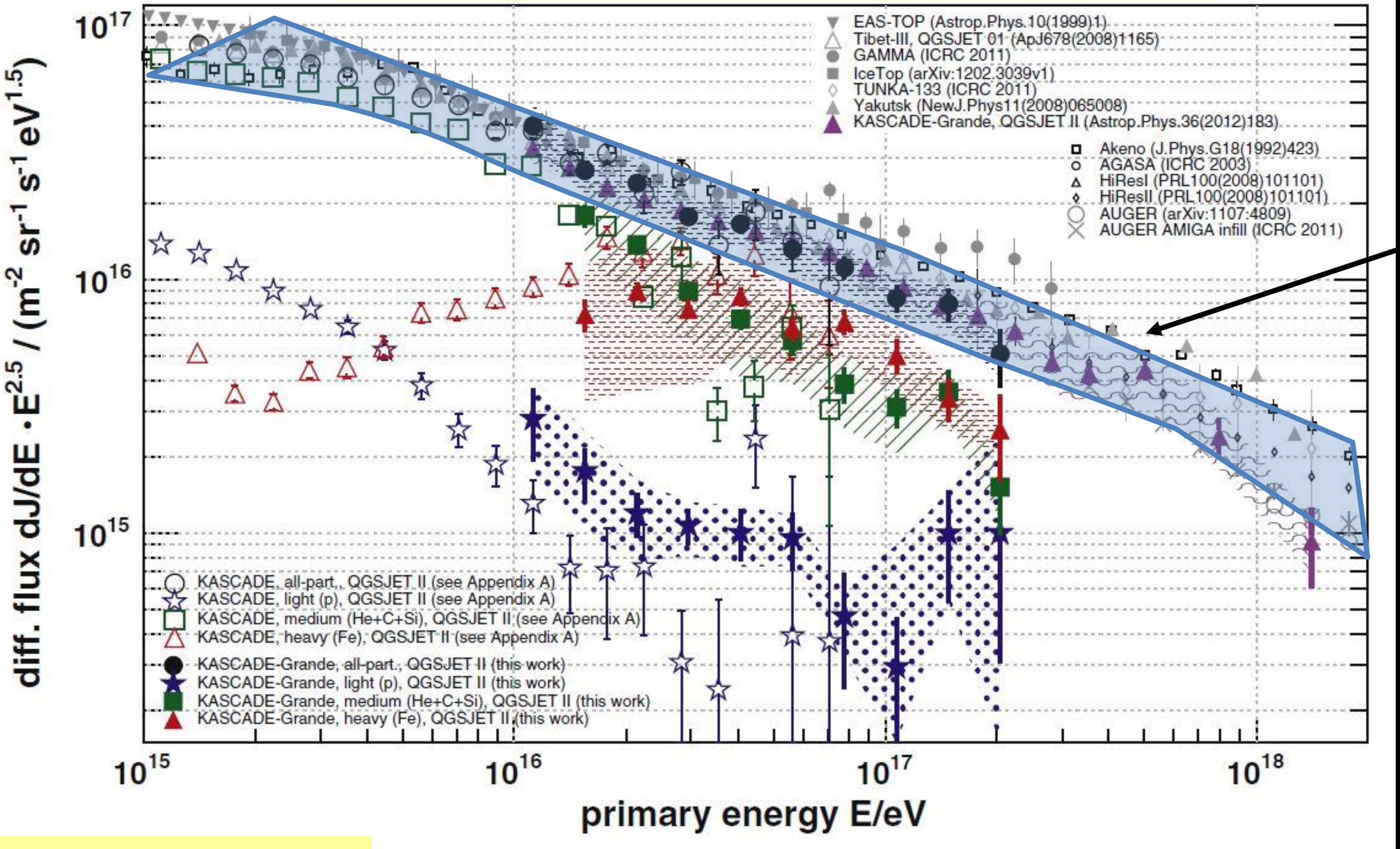
- ➔ 1 Colliding-shock-flow event / 4000 yr
- ➔ 10^{51} erg released in each CSF event
- ➔ Total shock acceleration efficiency = 10%

High-energy CRs observed at Earth



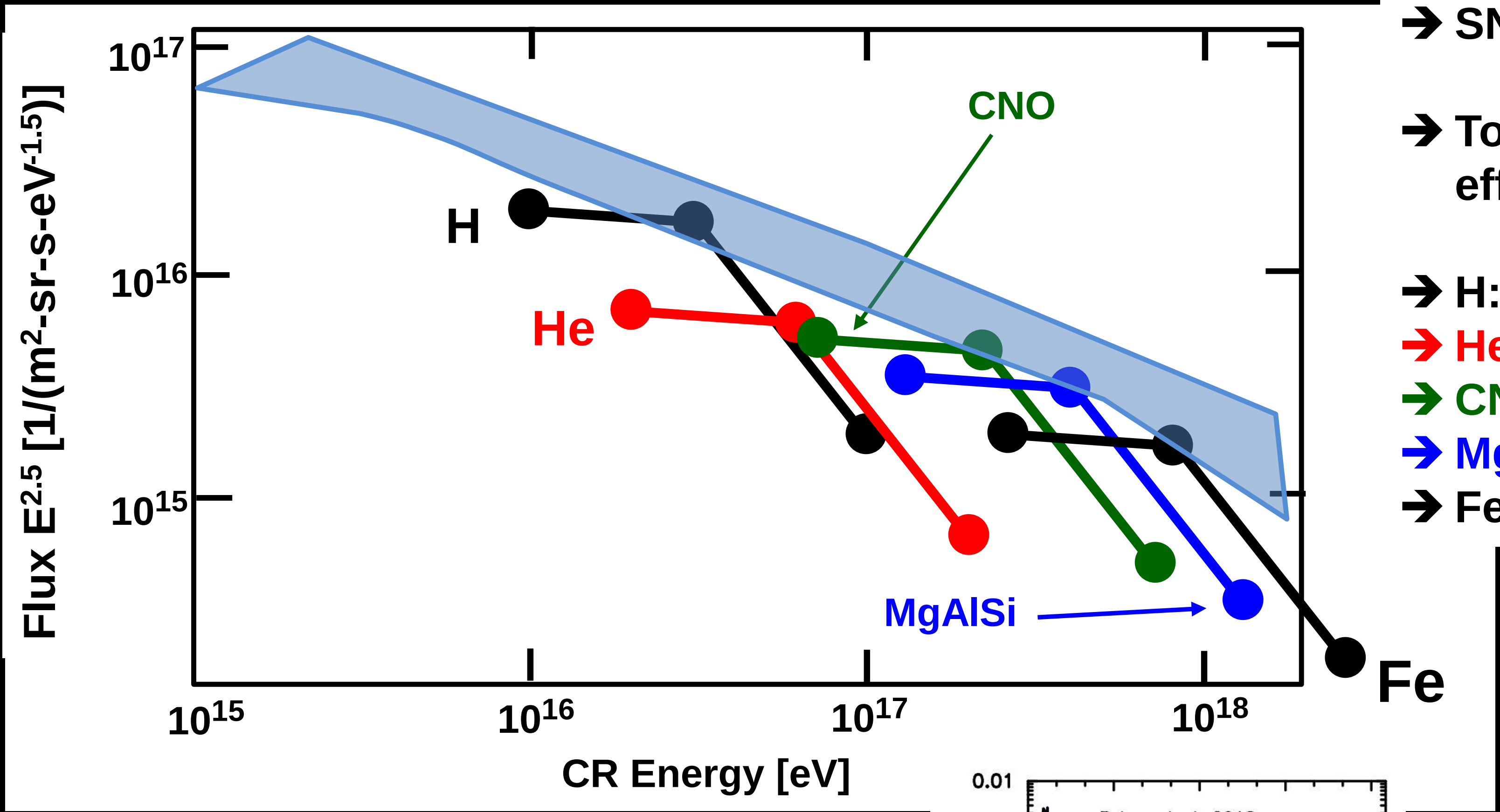
Apel et al. 2013

High-energy CRs observed at Earth



Approximate all-particle spectrum

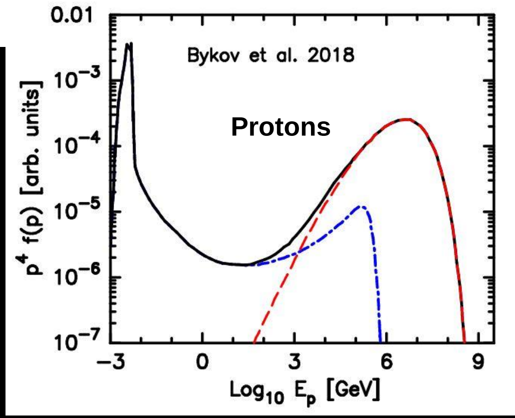
Apel et al. 2013



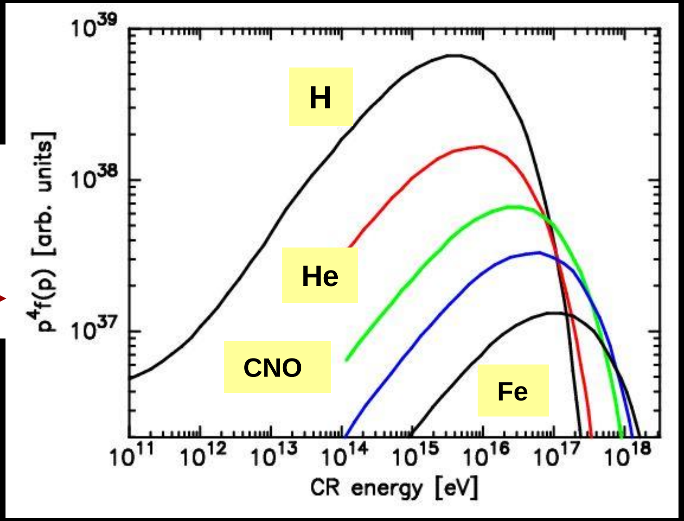
→ SN/wind energy = 10^{51} erg

→ Total shock acceleration efficiency = 10%

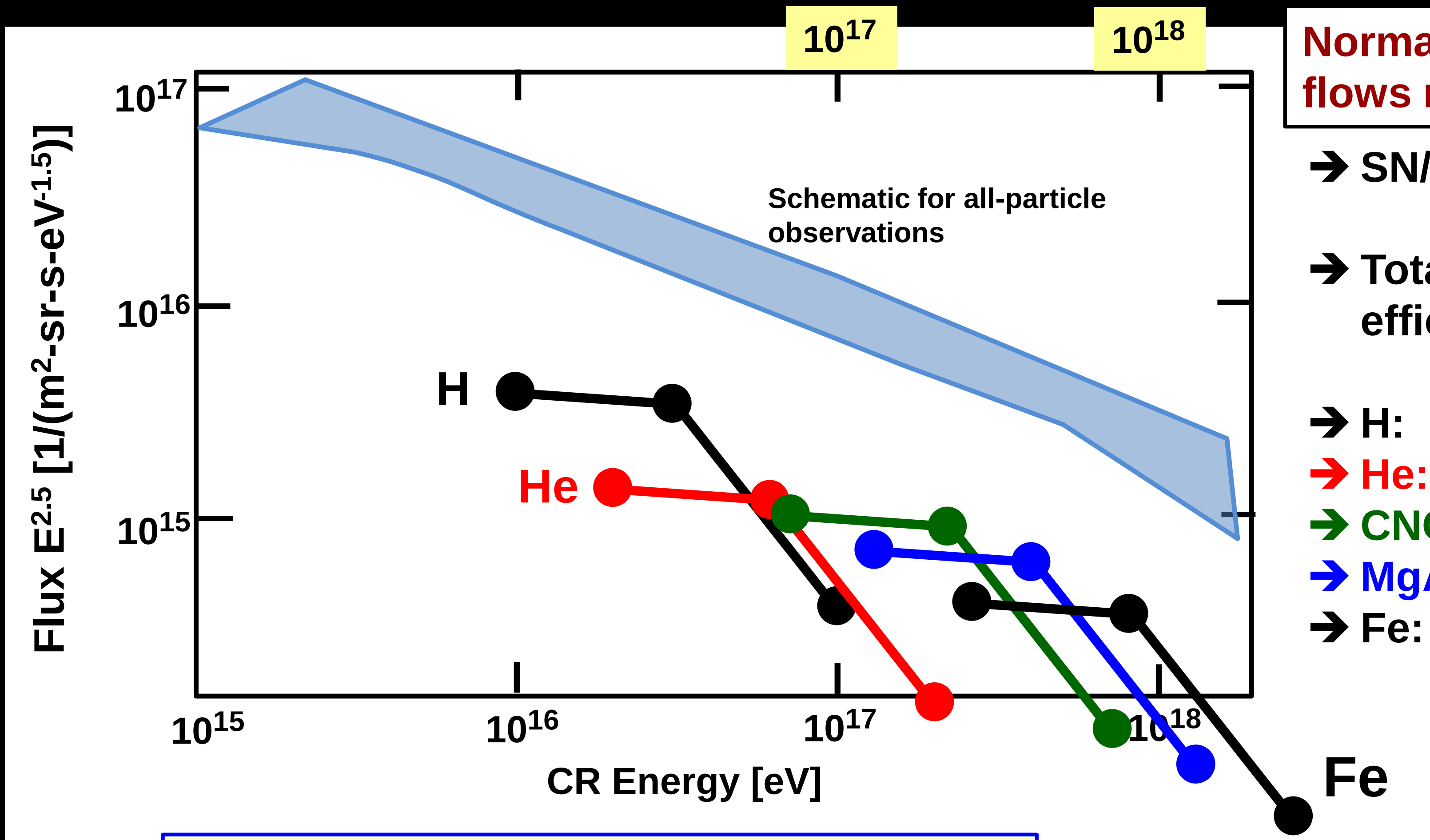
→ H: 7%
→ He: 1.8%
→ CNO: 0.7%
→ MgAlSi: 0.35%
→ Fe: 0.14%



Add ions



Normalization of Colliding-shock-flows model



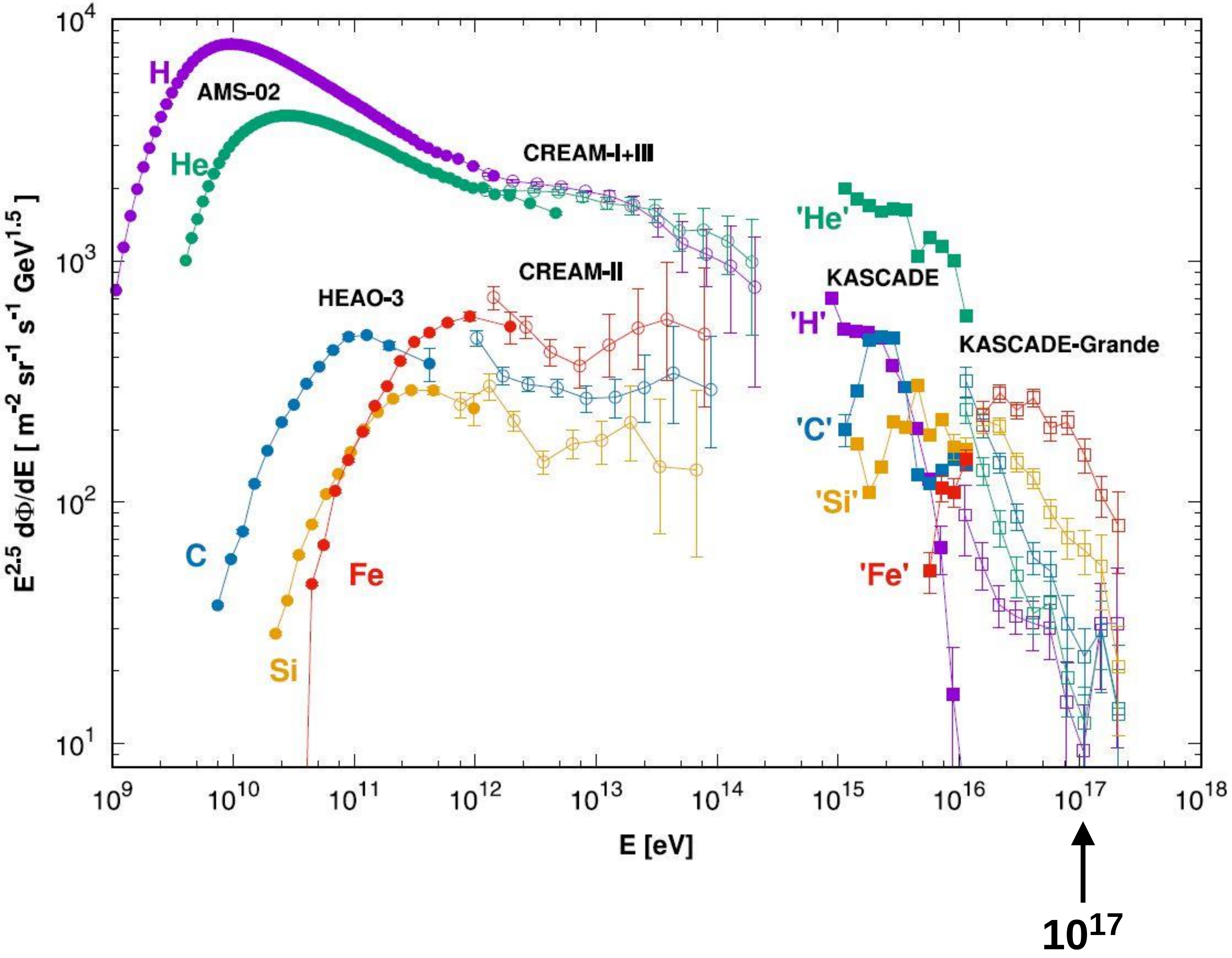
- ➔ SN/wind energy = 10^{51} erg
- ➔ Total shock acceleration efficiency = ~~10%~~ ➔ 2%
- ➔ H: ~~7%~~ 1.4%
- ➔ He: ~~1.8%~~ 0.36%
- ➔ CNO: ~~0.7%~~ 0.14%
- ➔ MgAlSi: ~~0.35%~~ 0.07%
- ➔ Fe: ~~0.14%~~ 0.028%

Drop normalization by factor of 5
➔ 2% of CSF event energy goes into CRs of all energies.

~ 0.0025 % goes into 10^{17} eV protons

~ 0.0005 % goes into ~3×10^{18} eV Fe

Mollerach & Roulet (2018)



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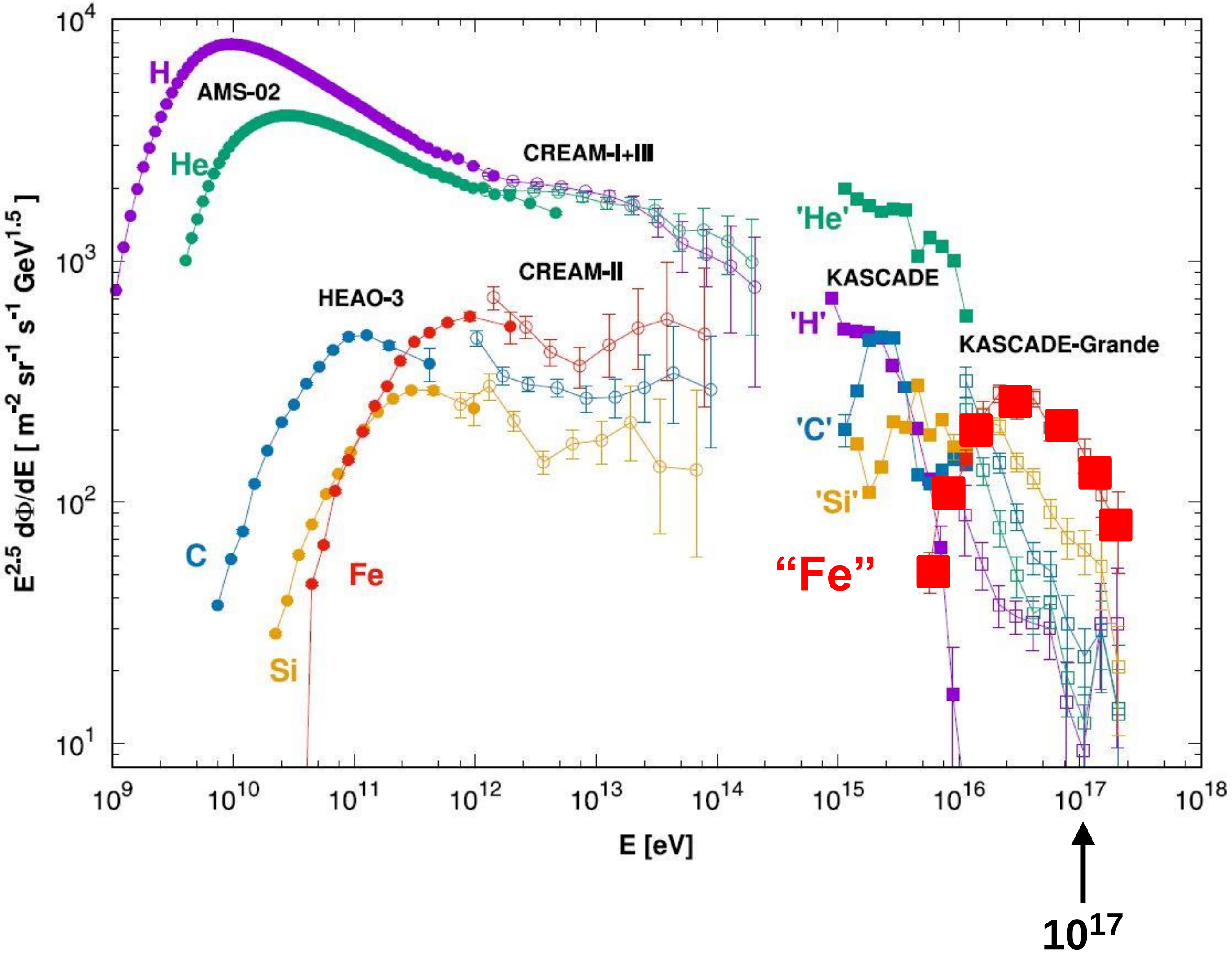

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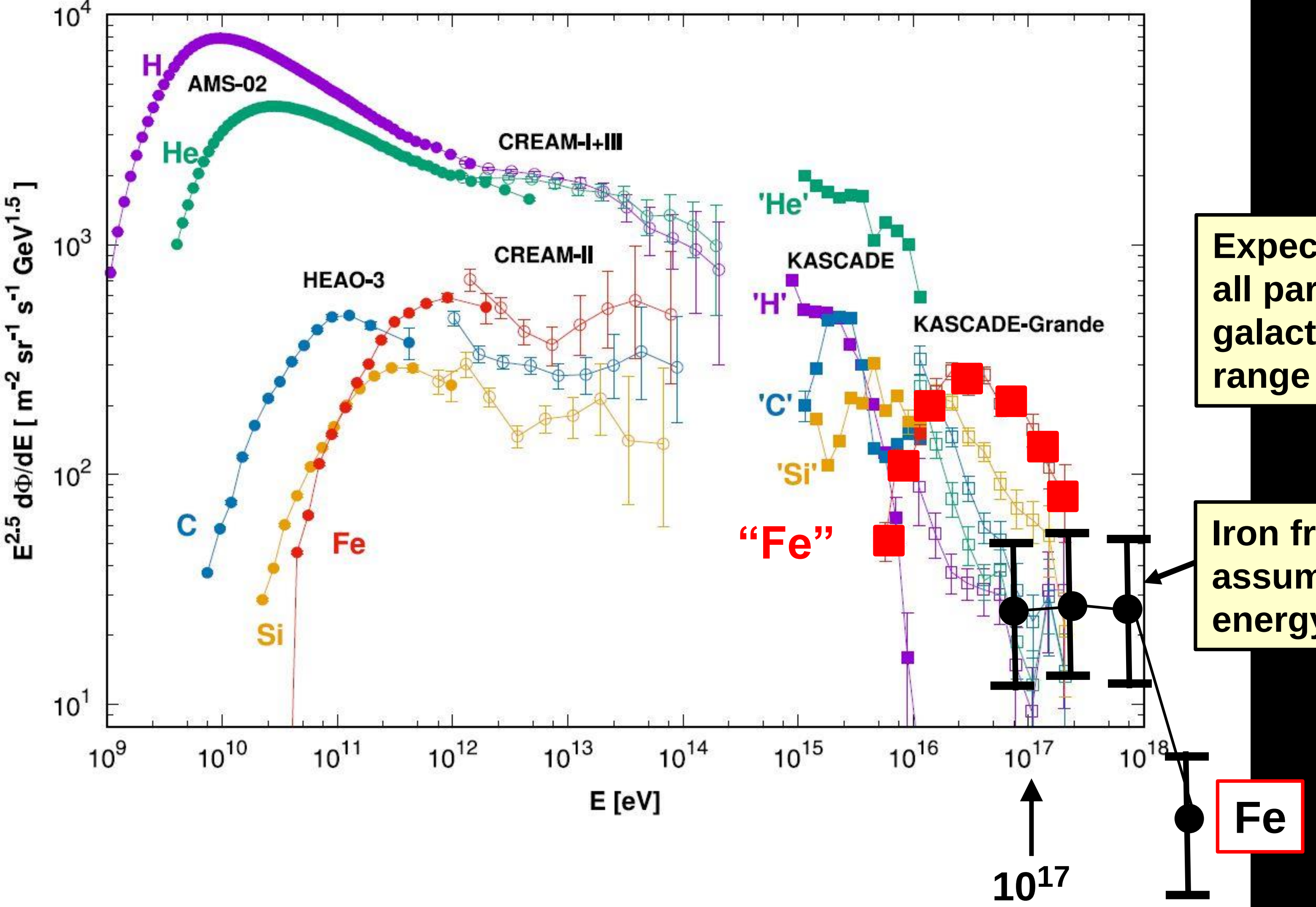
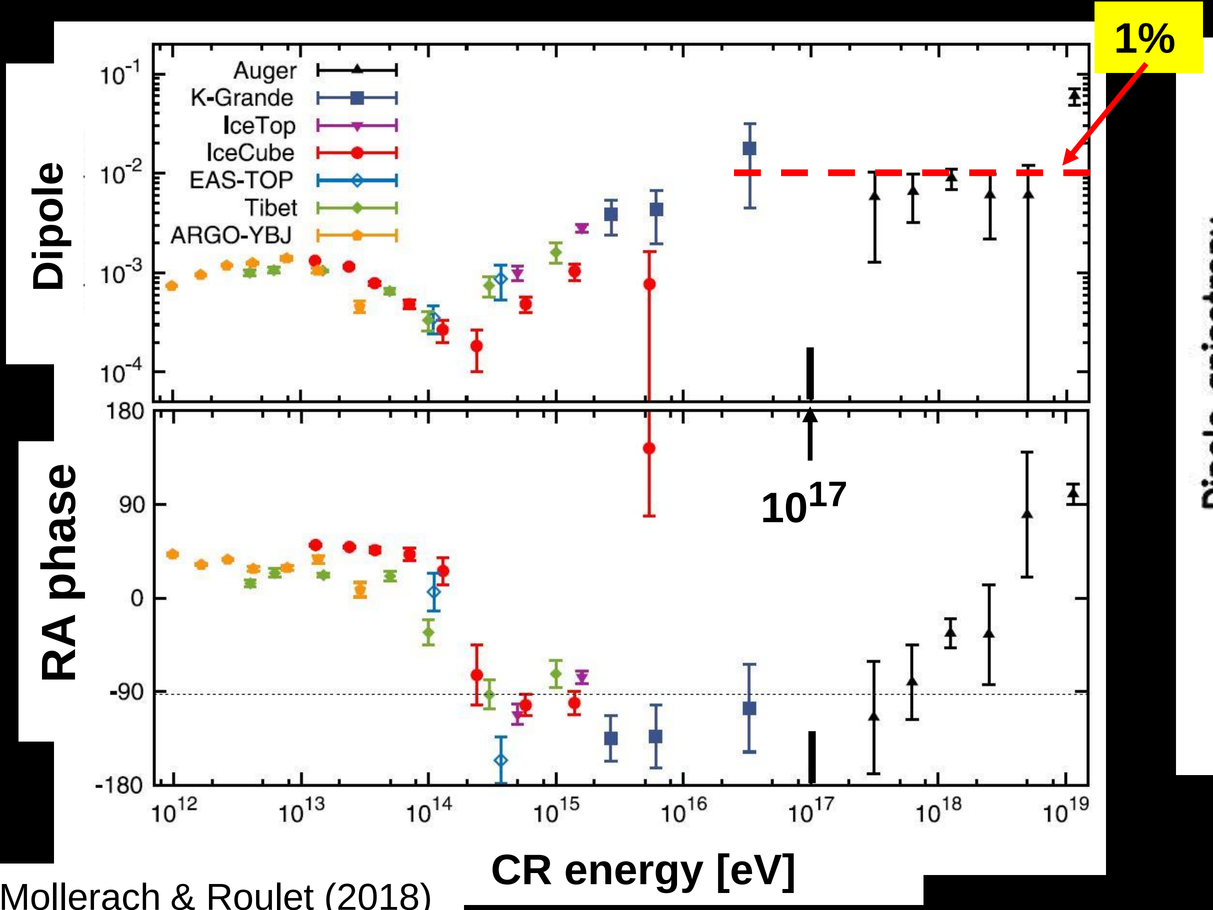


Expect a significant contribution to all particle CR spectrum from galactic sources in 10^{17} – 10^{18} eV range

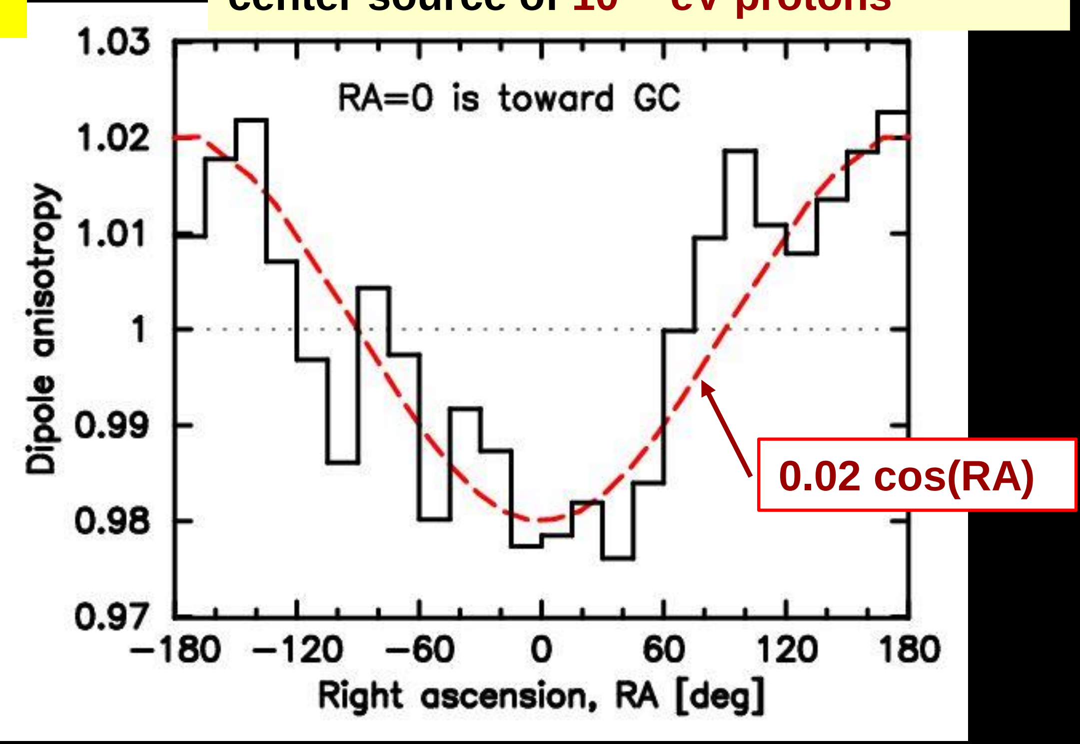
Iron from Colliding-Shock-Flows assuming a few % of CSF event energy goes into CRs of all energies

Important constraint for galactic sources is the low observed anisotropy



Mollerach & Roulet (2018)

Dipole anisotropy, A_{CSF}, for galactic center source of 10^{17} eV protons

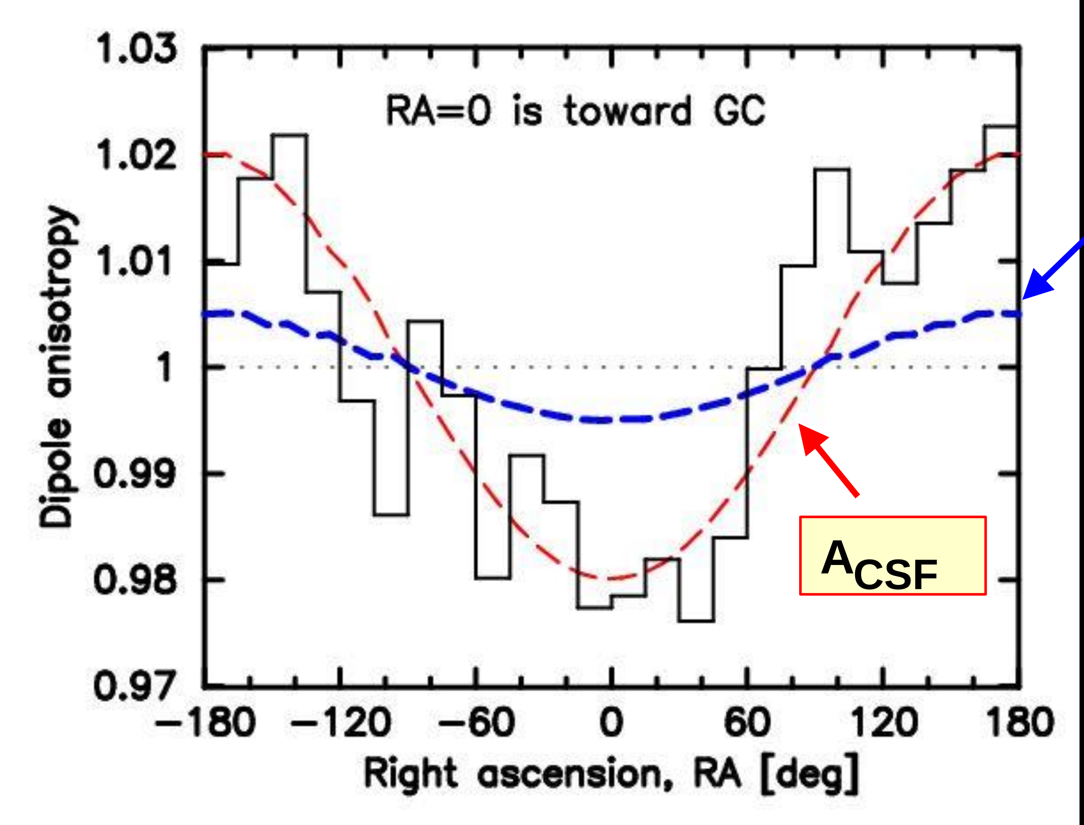


Dipole anisotropy for galactic center model at least a factor of 2 above observations (for our parameters)

Add isotropic extra-galactic source:

Assume isotropic extra-galactic flux is $F_{\mathrm{ex}} = f_{\mathrm{ex}} F_{\mathrm{CSF}}$

Then total anisotropy is $A_{\mathrm{tot}} = \dfrac{A_{\mathrm{CSF}} + f_{\mathrm{ex}}}{1 + f_{\mathrm{ex}}}$



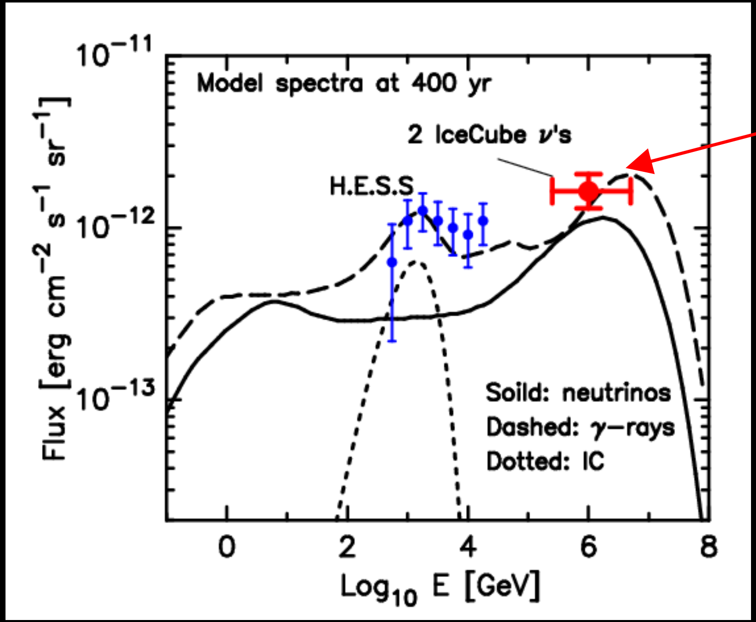
For $\dfrac{F_{\mathrm{CSF}}}{F_{\mathrm{ex}}} = 1/3$

Find ~30% of all 10^{17} eV CRs can be from a galactic source without violating isotropy constraints

Conclusions

1) Massive, young, compact star clusters provide environment for accelerating strongly peaked CRs in PeV-EeV range ➔ may provide substantial fraction of CRs in galactic—extra-galactic transition region.

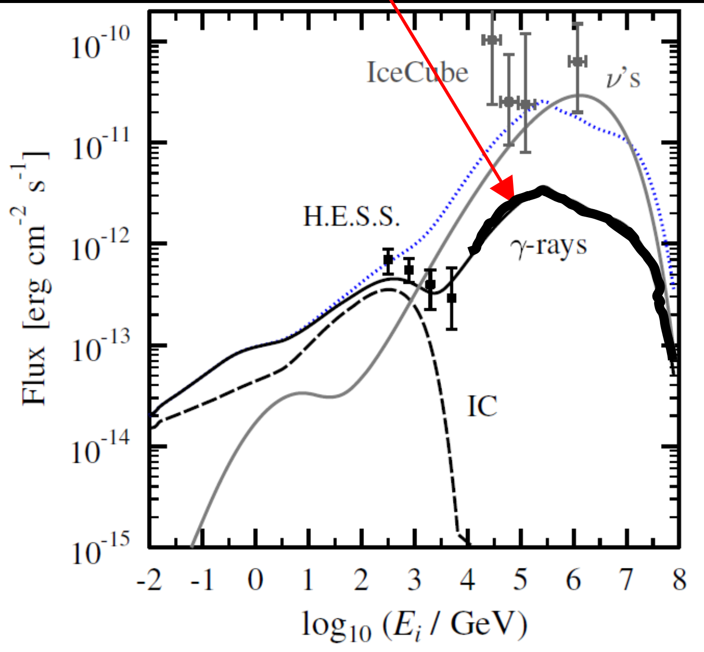
2) Peaked spectrum produced by CSFs may be important factor for neutrino & γ-ray production. Some IceCube neutrinos may come from CSFs (Bykov et al. 2015).



2 IceCube ν's from Westerlund 1

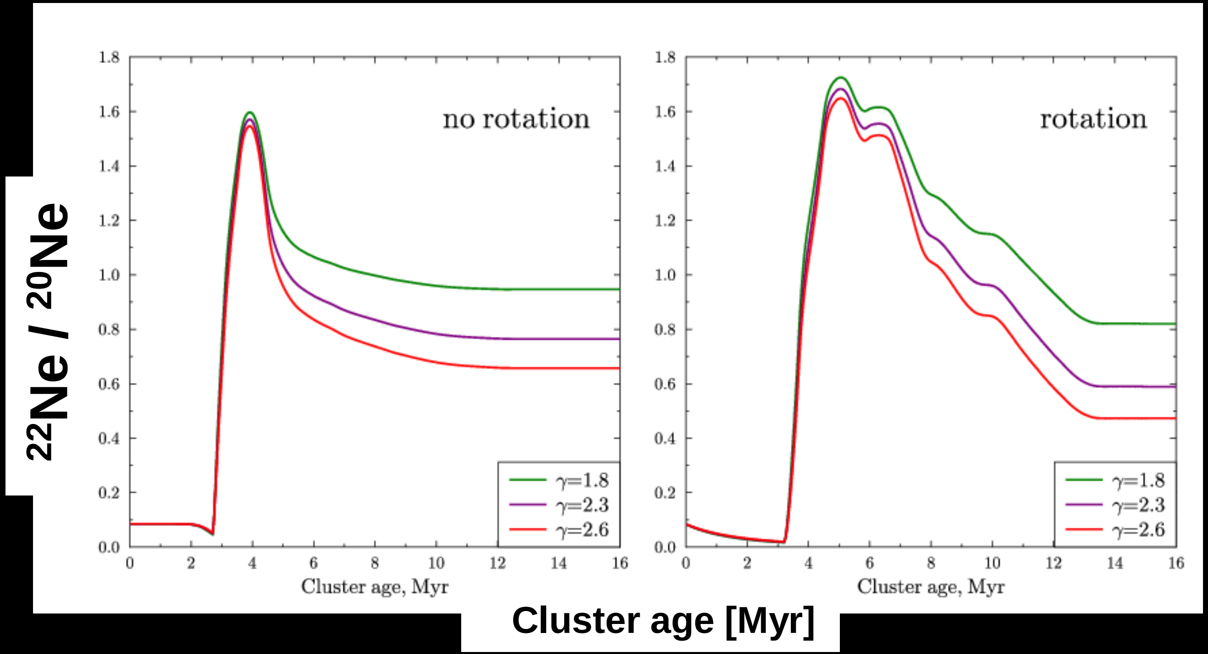
Bykov et al, MNRAS 2015

Peak in γ-ray emission in CTA range



Model of cluster CL* 1806-20 (Bykov et al, NPPP 2018)

3) Wolf-Rayet stars in nearby massive star clusters may have produced $^{22}Ne/^{20}Ne$ excess in CRs



Kalyashova et al. 2019 :

- ➔ Use stellar evolution models from "Geneva" group (Ekstrom et al. 2012) to obtain $^{22}Ne/^{20}Ne$ yield.
- ➔ Assume CR acceleration occurs in shocks from multiple colliding winds (e.g., Seo etal. 2018; Aharonian et al 2019)