Welcome to

Siena

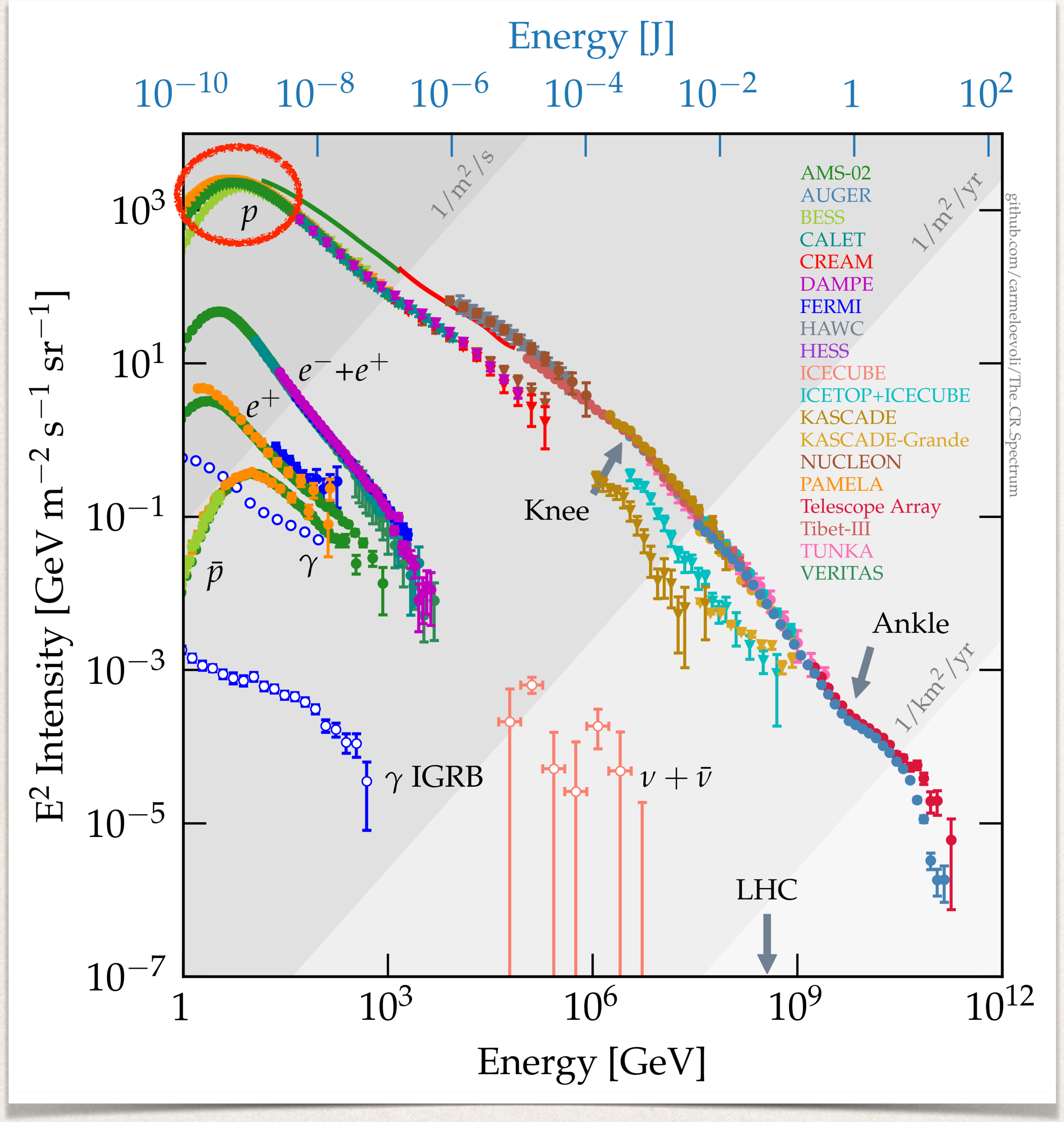
28th-31st October

TOSCA 2024

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

Topical Overview on Star Cluster Astrophysics

How to explain the origin of Galactic CRs



Requirements

- **Luminosity:** $\sim 10^{40}$ erg/s

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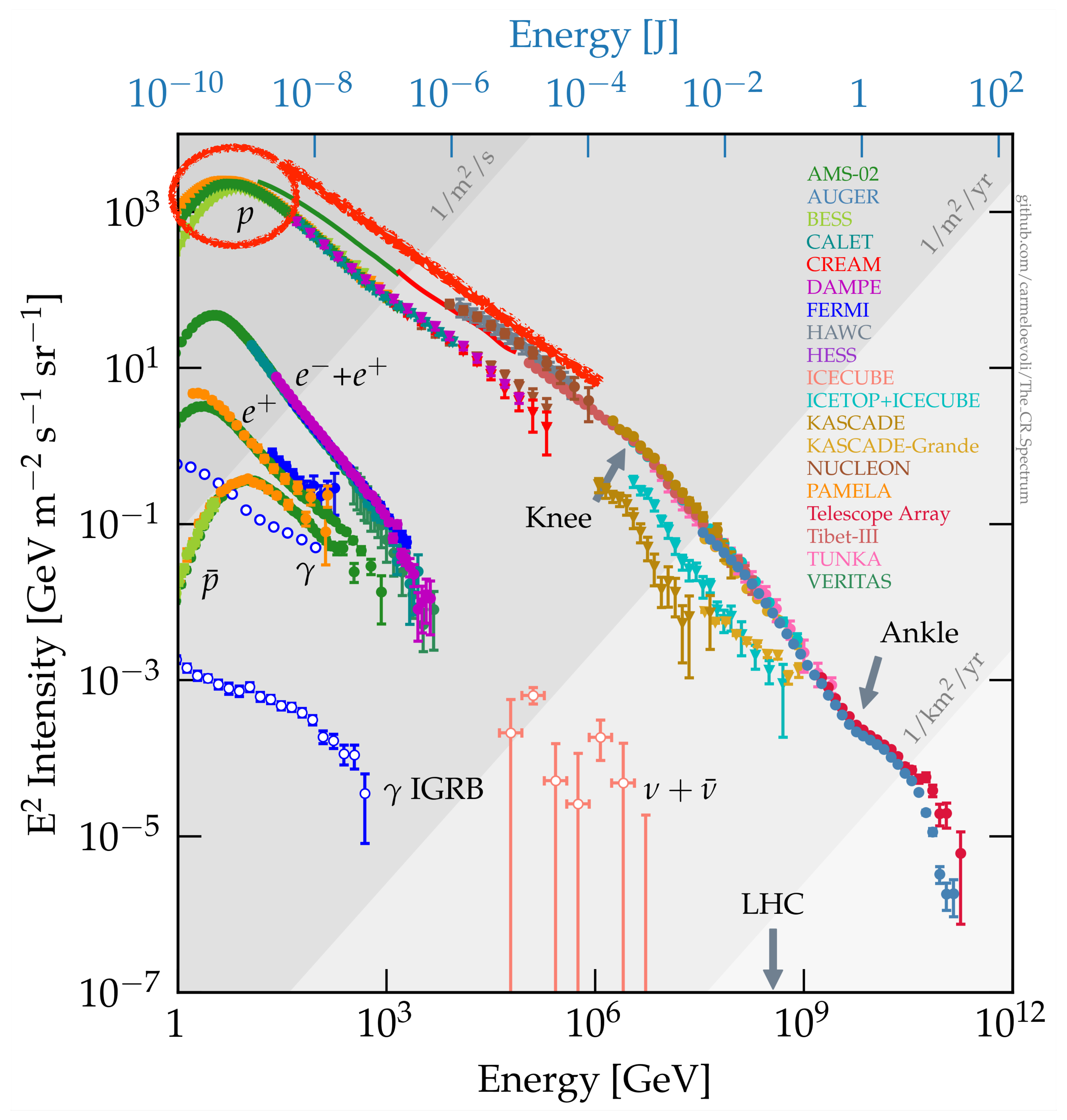

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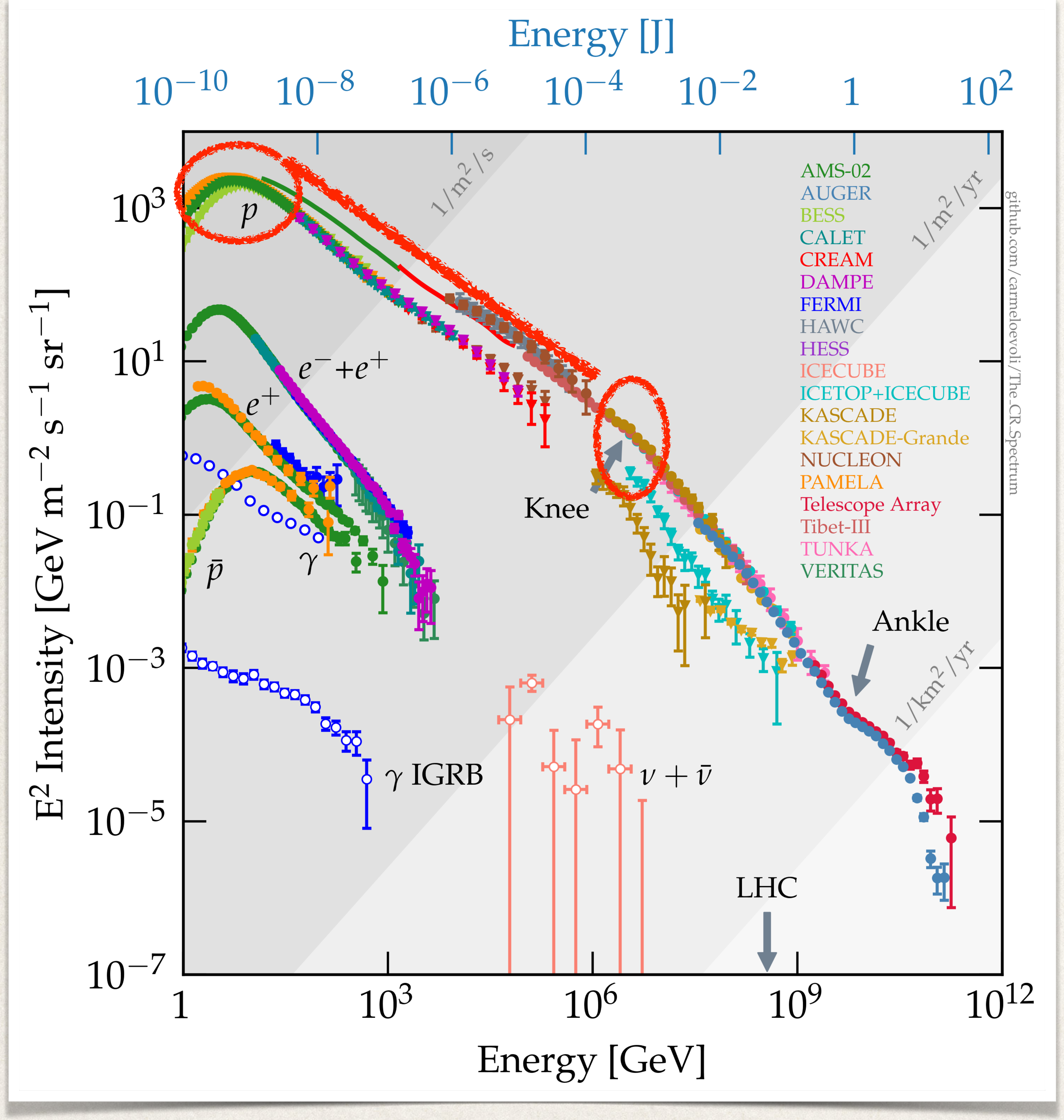

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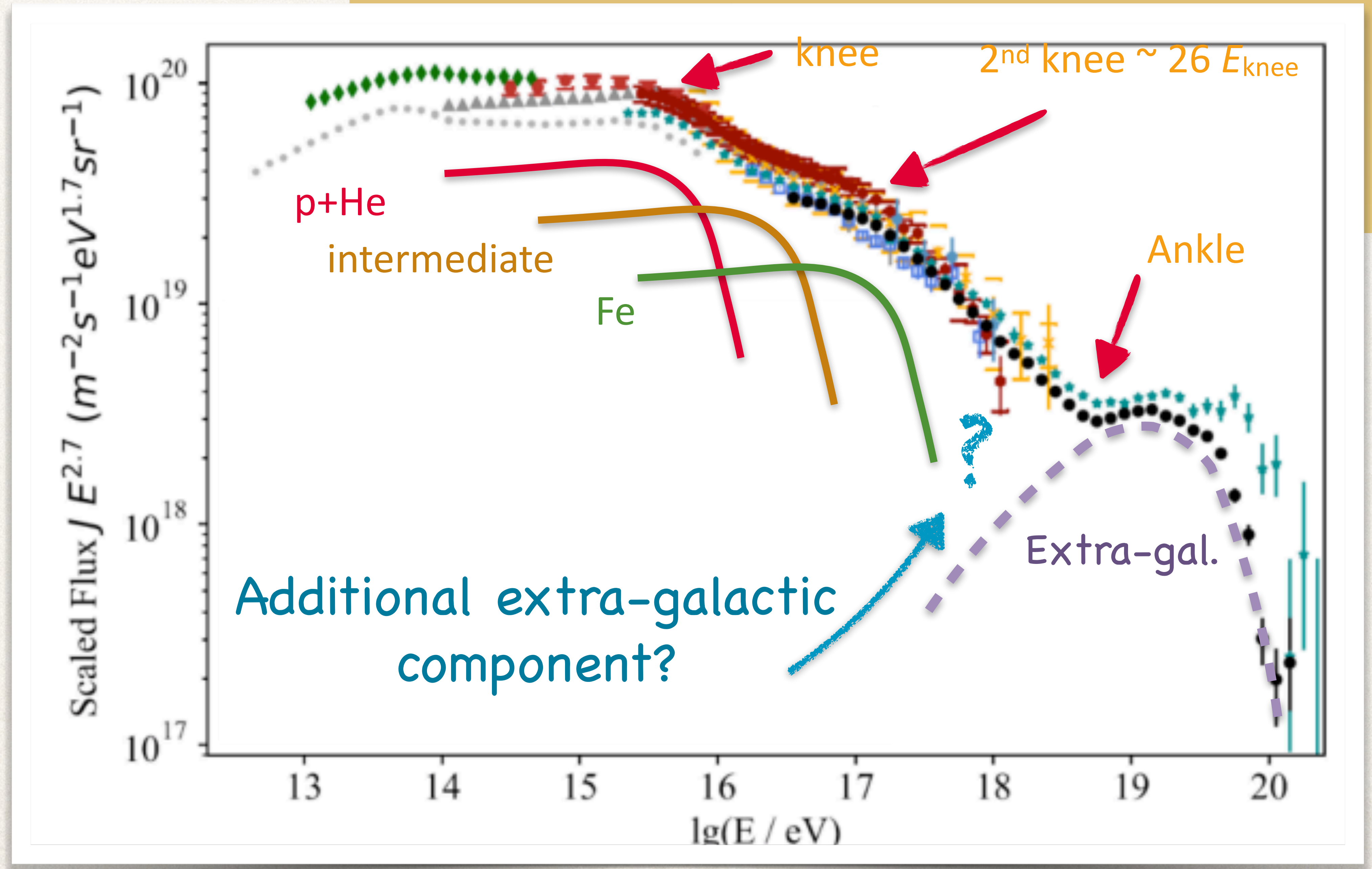

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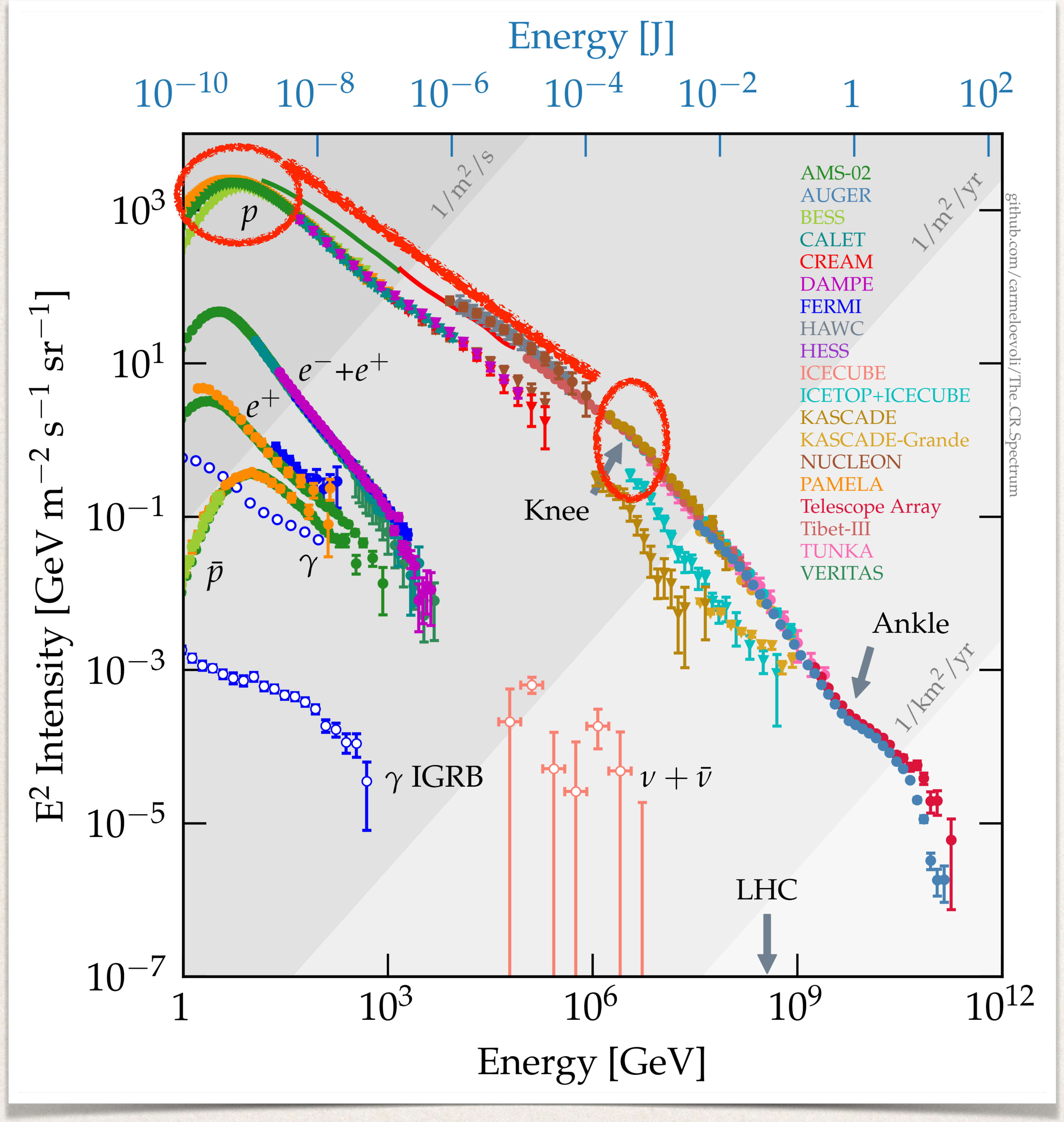

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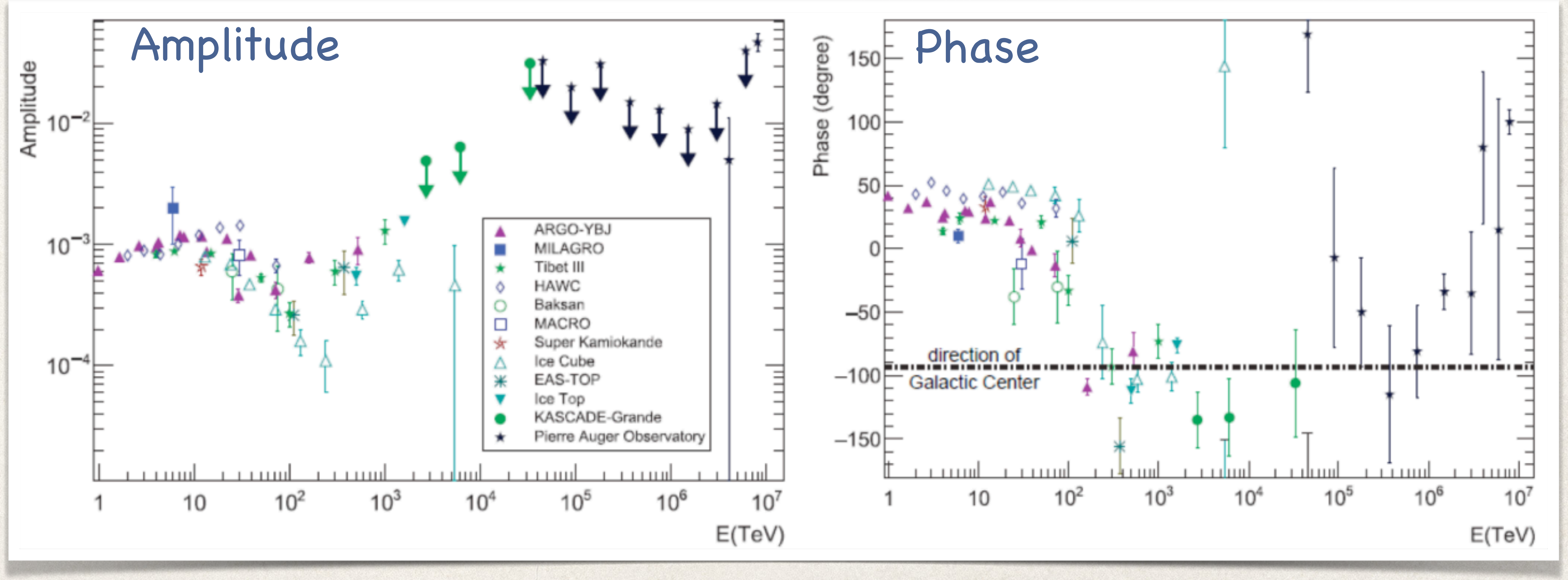

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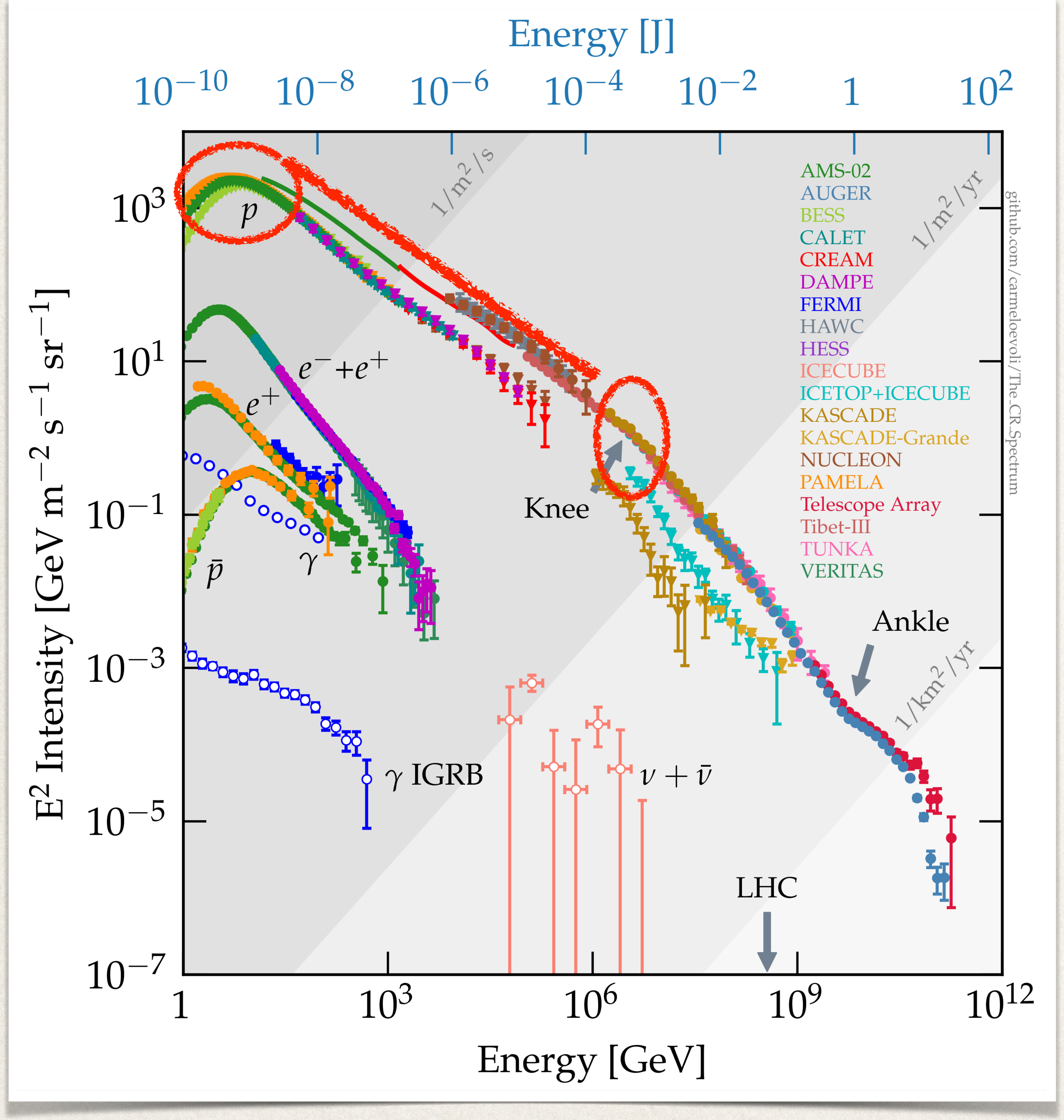

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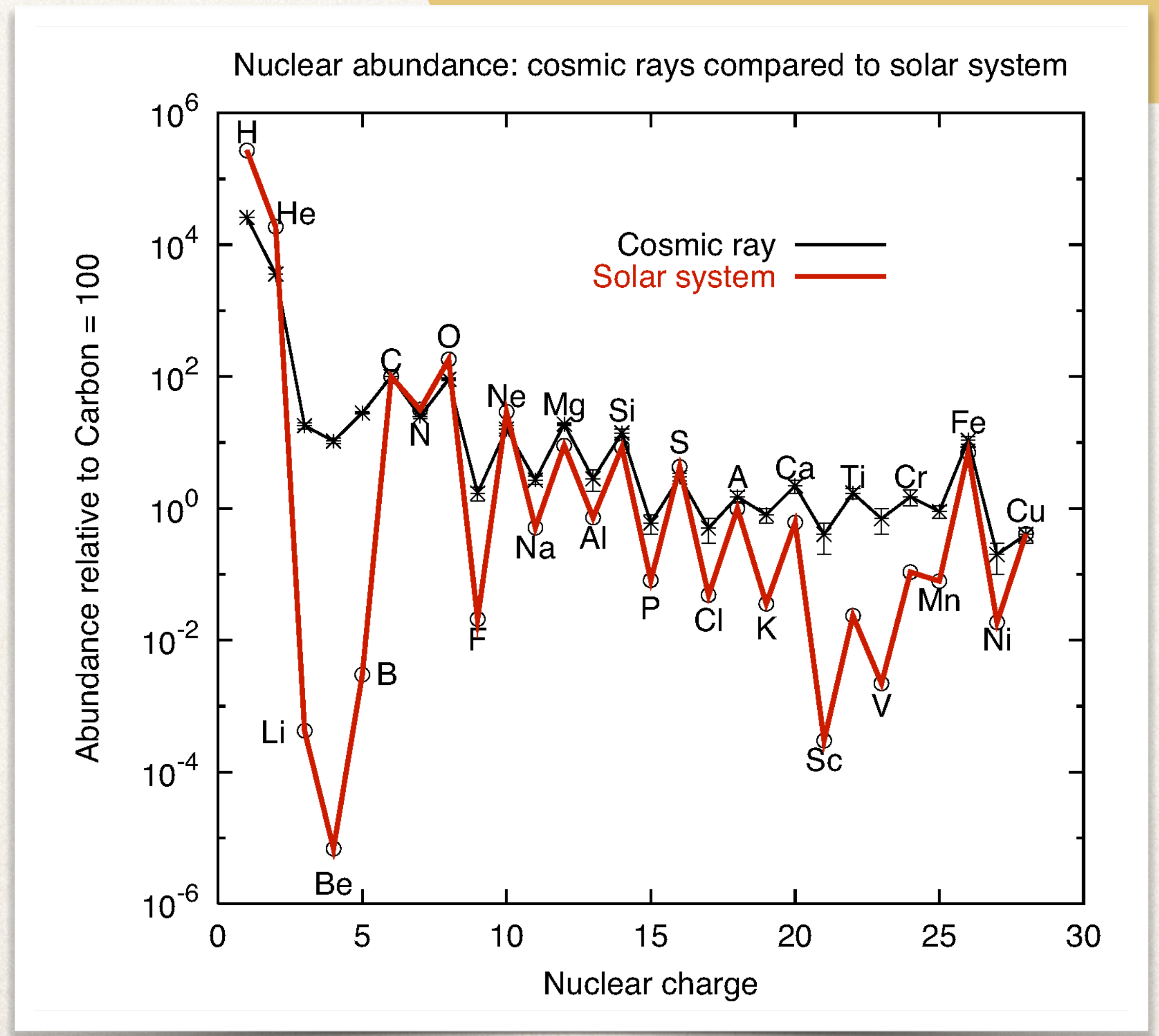
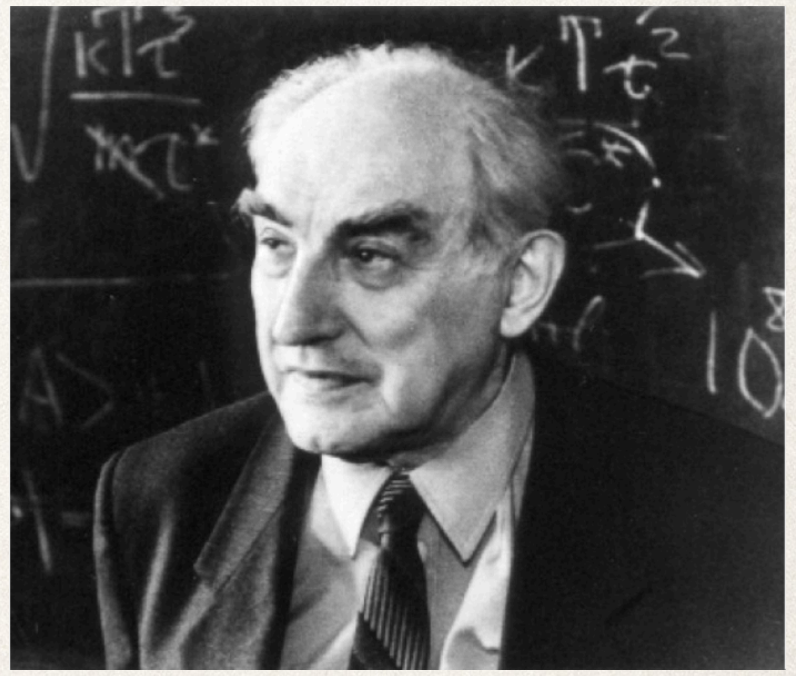
- **Composition:** few anomalies w.r.t. Solar



SNR-CR connection: an historical overview

- **1934** - Baade & Zwicky were the first to mention SNRs as sources of CRs, but arguing against them because CRs where thought to be extragalactic.
- **1942** - Alfvén theorised the existence of MHD waves
- **1949** - E. Fermi proposed stochastic acceleration for CRs (II order acceleration)
- **1964** - Ginzburg & Sirovatskii made the argument for SNRs as sources of Galactic CR in the 60's in a more quantitative form (10% kinetic energy needed to be converted in CRs).
- **'70** - Many authors apply Fermi's idea to SNR shocks (I order acceleration) [Axford et al. 1977; Bell 1978; Blandford & Ostriker 1978; Krymskii 1977; Skilling 1975]
- Observational evidences:
  - **1949**: First radio observation of SNR (~300 sources known today)
  - **1995**: First non-thermal X-ray emission detected from SN1006 by ASCA (Since 2000: Chandra and XMM-Newton)
  - **2001**: first detection of shell type SNR in γ-rays by HEGRA

Baade & Zwicky



V. L. Ginzburg

The SNR paradigm for the origin of CRs

Why SNRs are so popular?

- Enough power to supply CR energy density (~10% of the explosion energy)
- Spatial distribution of SNRs compatible with the CR distribution
- Presence of non-thermal emission in SNRs
- A solid theory applicable to SNR shocks (DSA = *diffusive shock acceleration*)

The SNR paradigm for the origin of CRs

Unsolved issues:

The SNR paradigm for the origin of CRs

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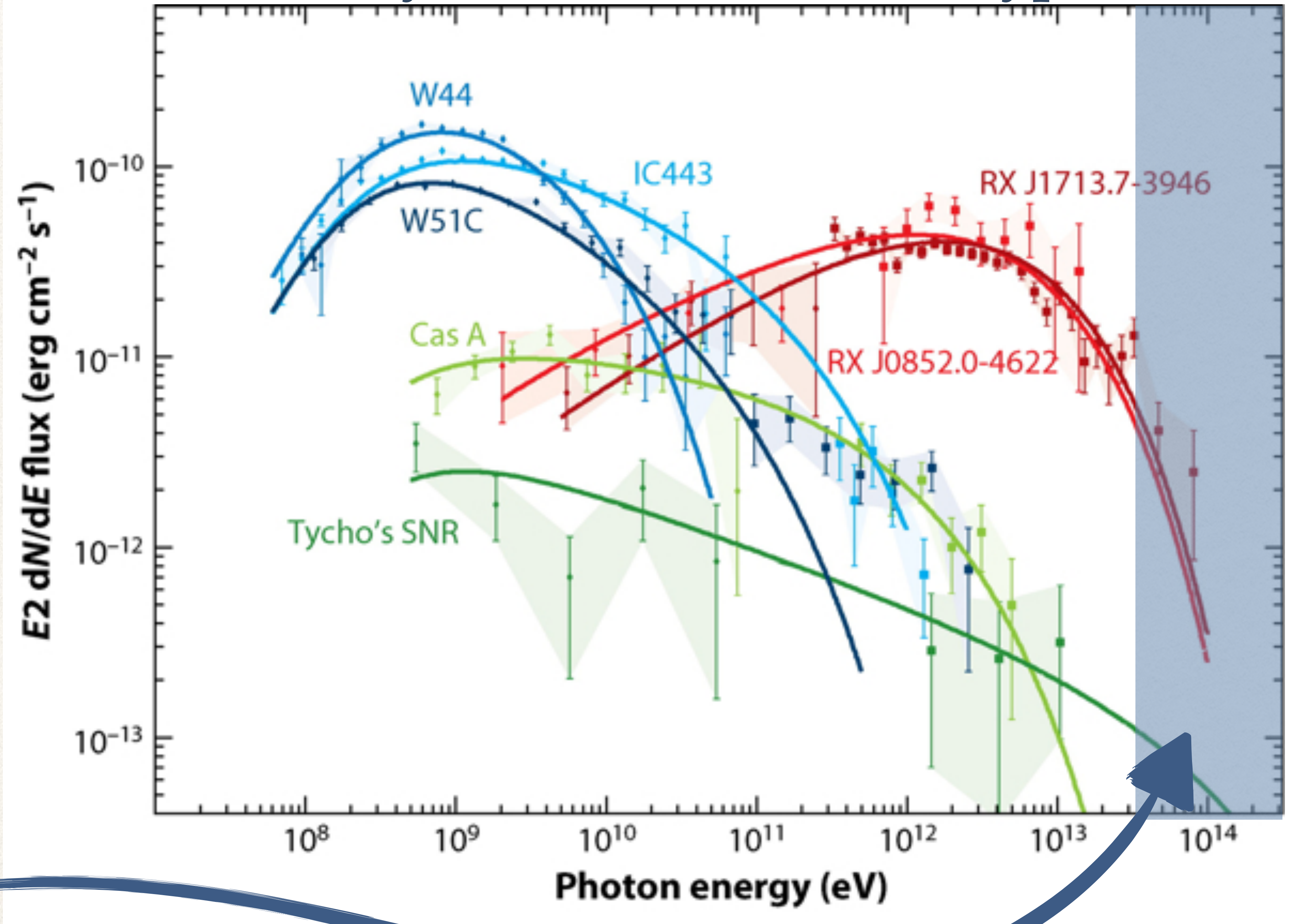
- No evidence of acceleration beyond ~100 TeV even in very young SNRs

Gamma-ray emission from shell-type SNRs



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

Expected region for the cutoff for a pion decay process if $E_{\max,\mathrm{proton}} \simeq 1\,\mathrm{PeV}$

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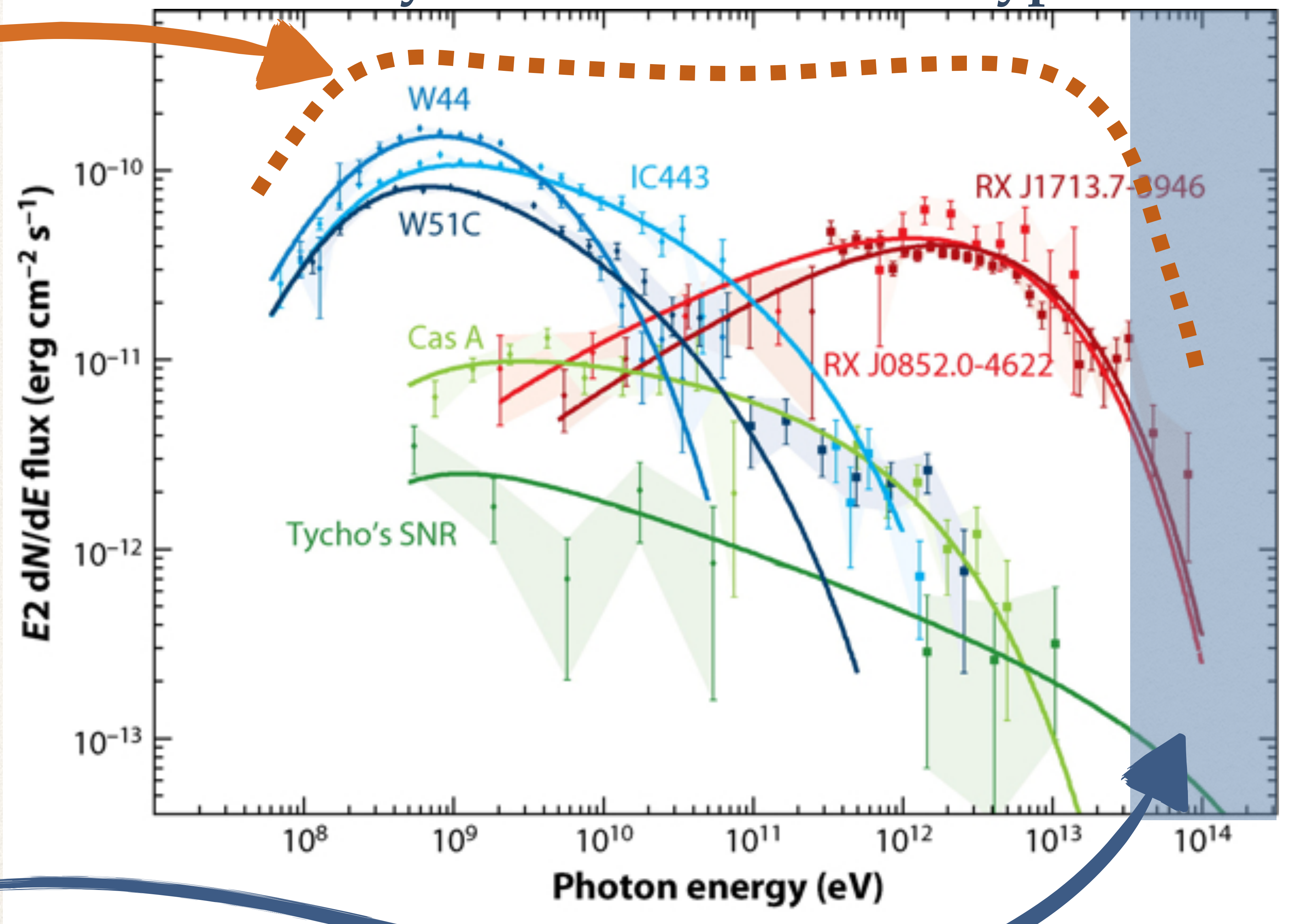

Prediction from test particle theory

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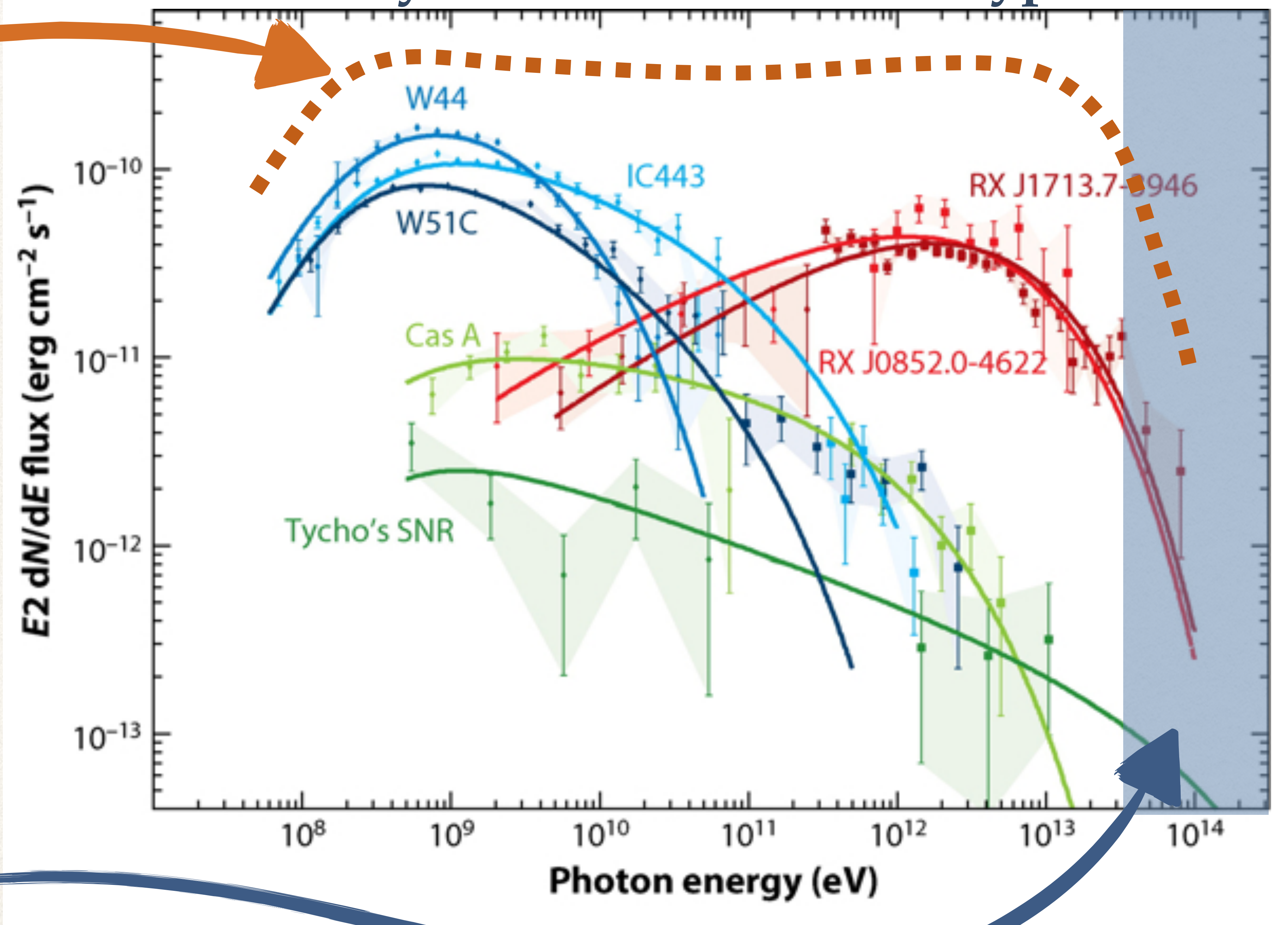

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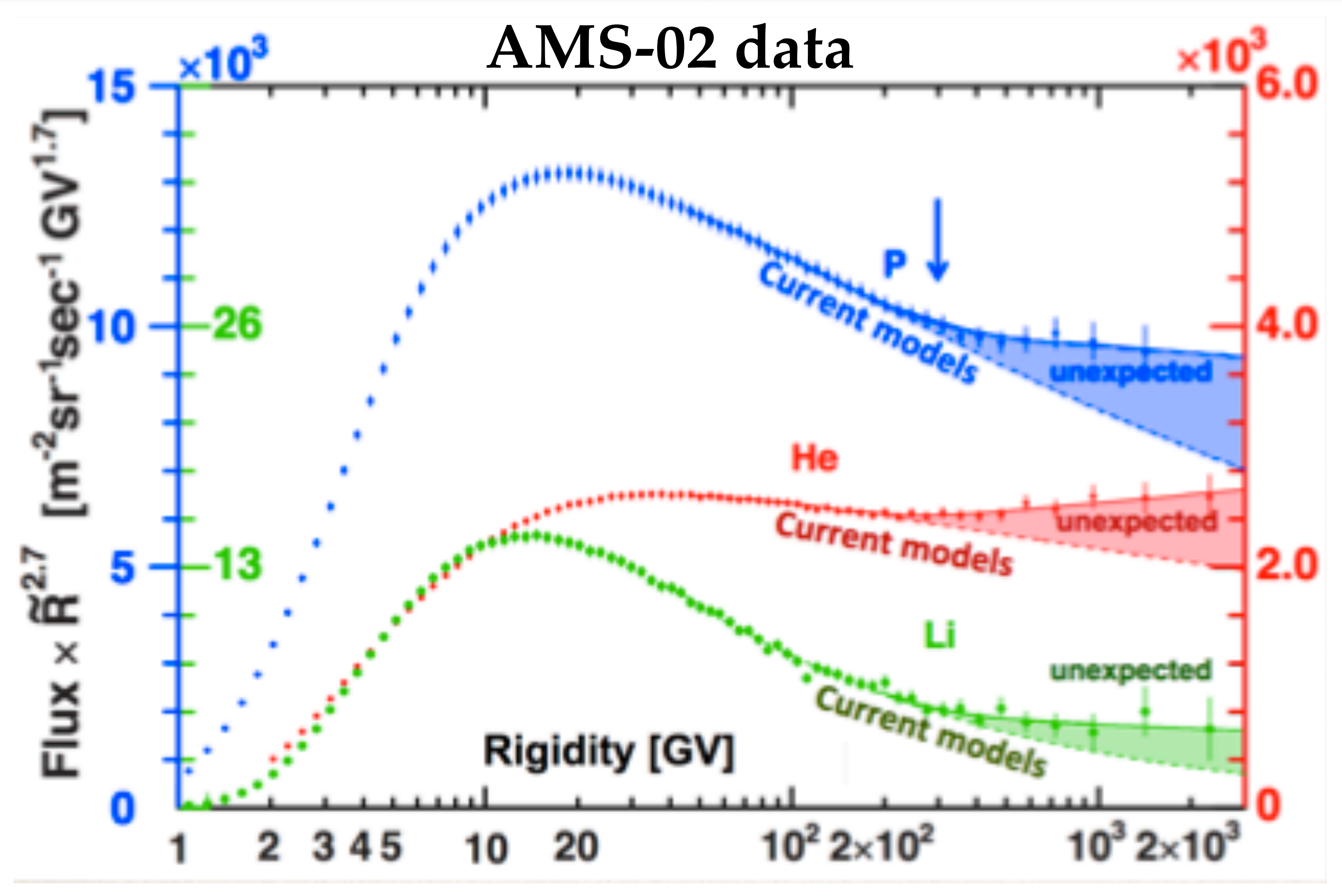
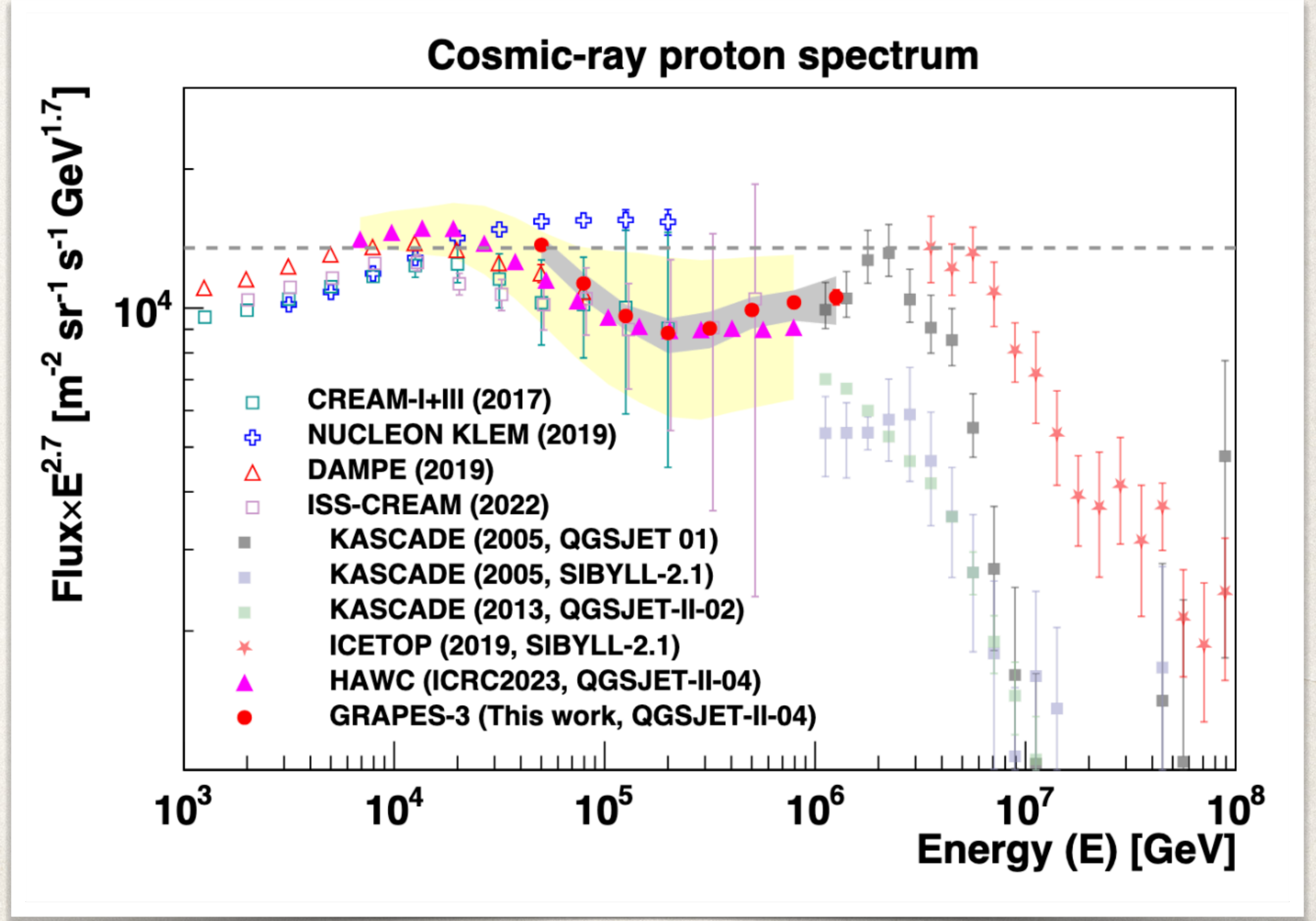


Proton and He spectra requires different injection slope

"Bumps" in the proton spectrum suggests the existence of different source types



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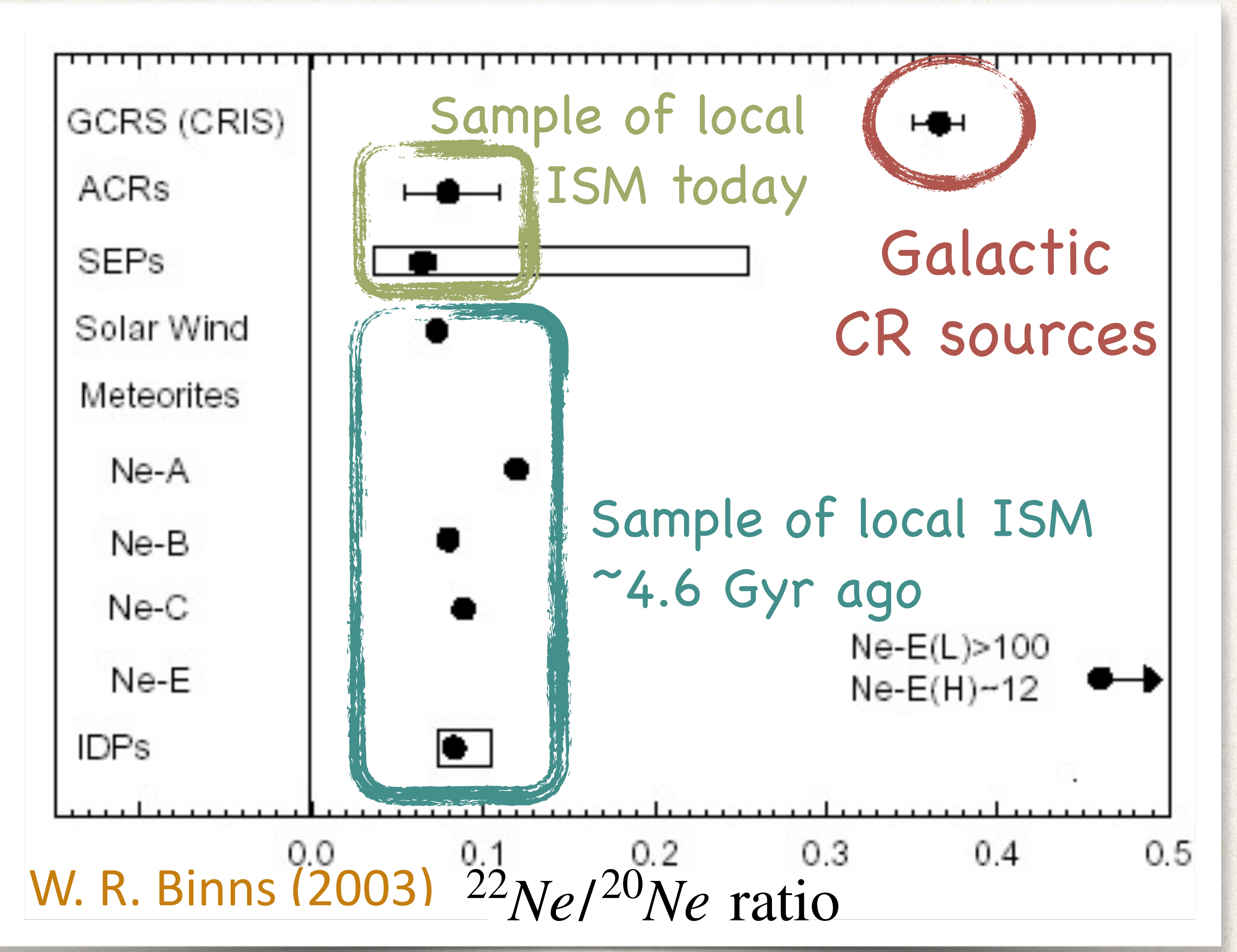

^{22}Ne/^{20}Ne ratio

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Incorrect/incomplete models for SNRs?

Looking for additional sources?

The role of star clusters

Massive stars born in OB associations

SNR types:
- ~20% type Ia
- ~80% core collapse:
  - (60-80)% explode inside the parent star cluster
  - (20-40)% explode outside the cluster (runaway massive stars)

The role of star clusters

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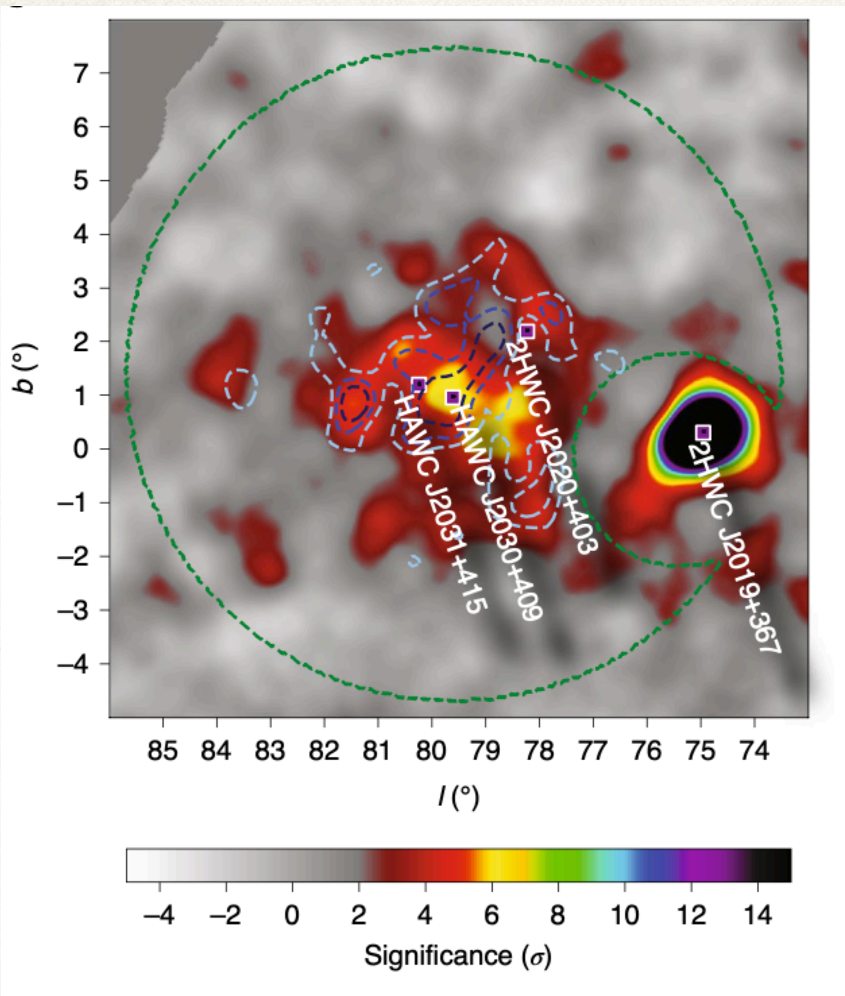
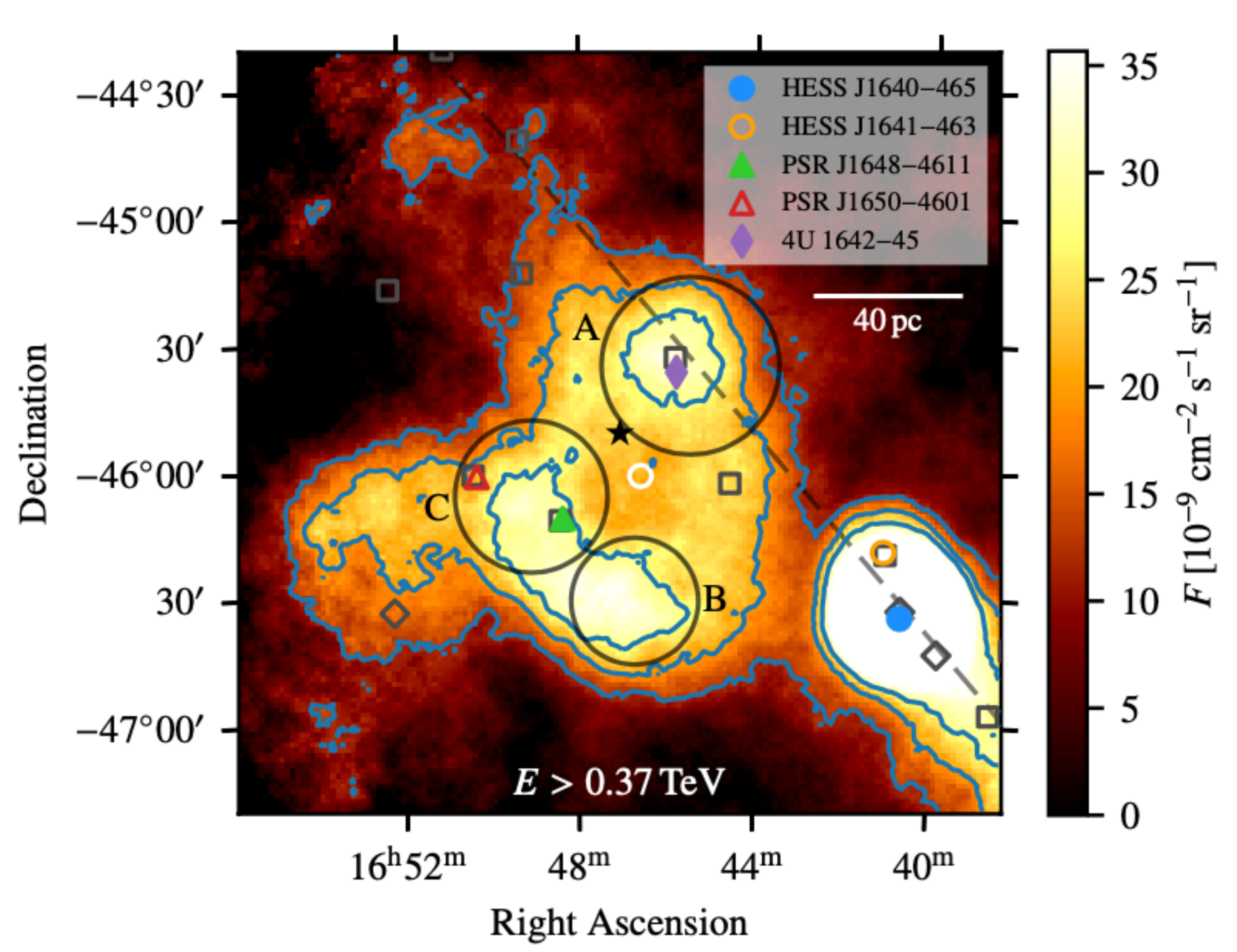
Massive stars born in OB associations

Recently several massive star clusters have been associated with gamma-ray sources

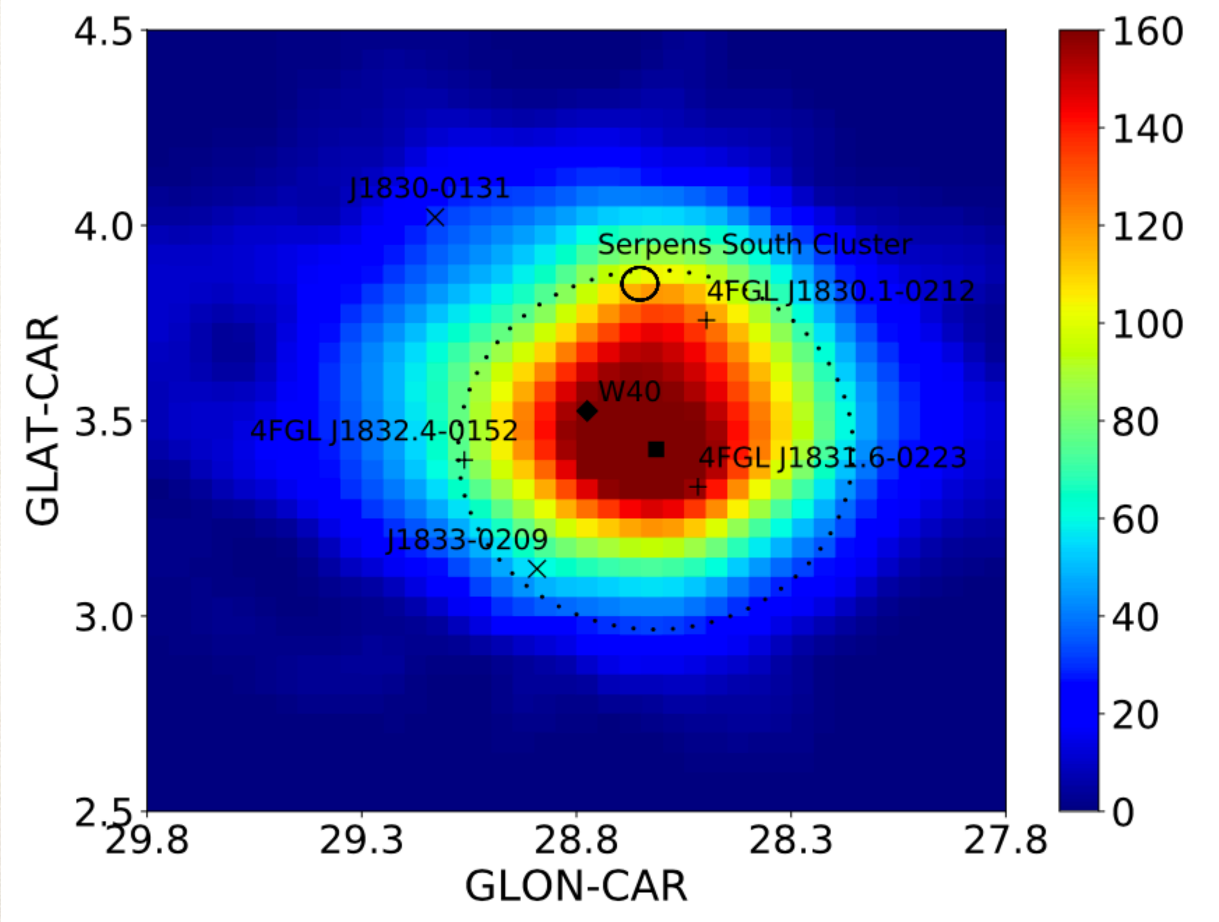
Cygnus Cocoon HAWC coll. Nat. Astr.(2020)



Westerlund 1; HESS coll. A&A (2022)



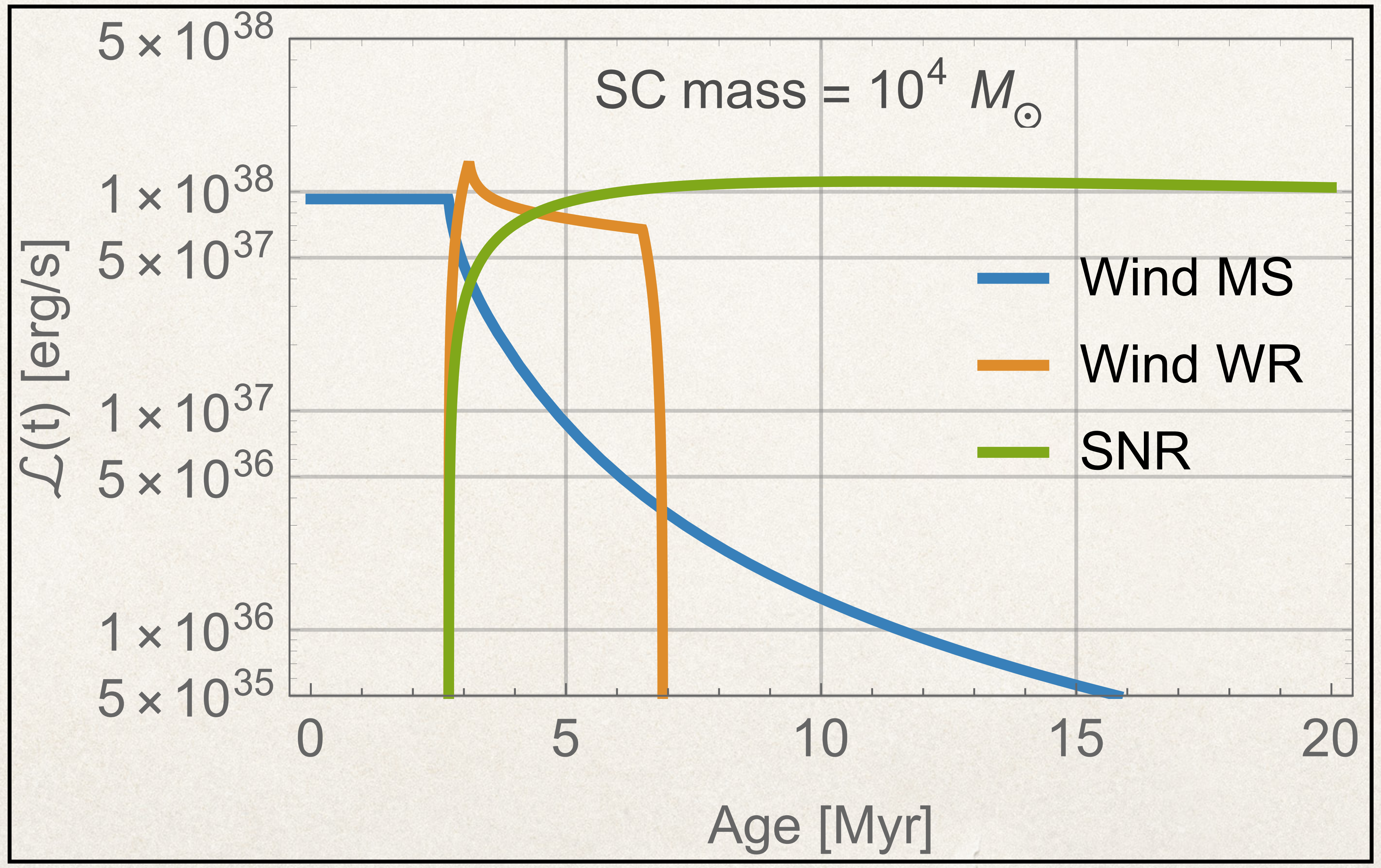
W40 - FermiLAT Sun et al. (2020)



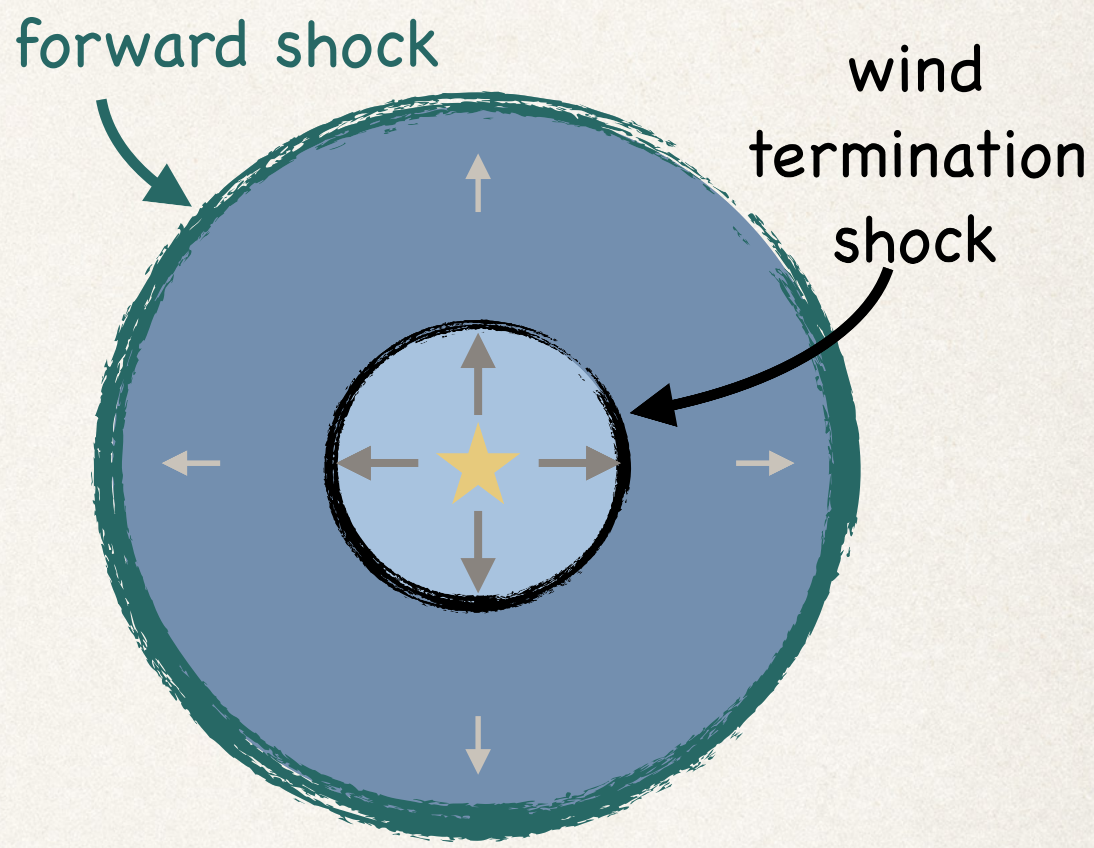
What power Stellar Clusters?

Phase	Source	Time-scale
$t \lesssim 3\,\mathrm{Myr}$	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	$t \sim 10^3 - 10^4\,\mathrm{yr}$

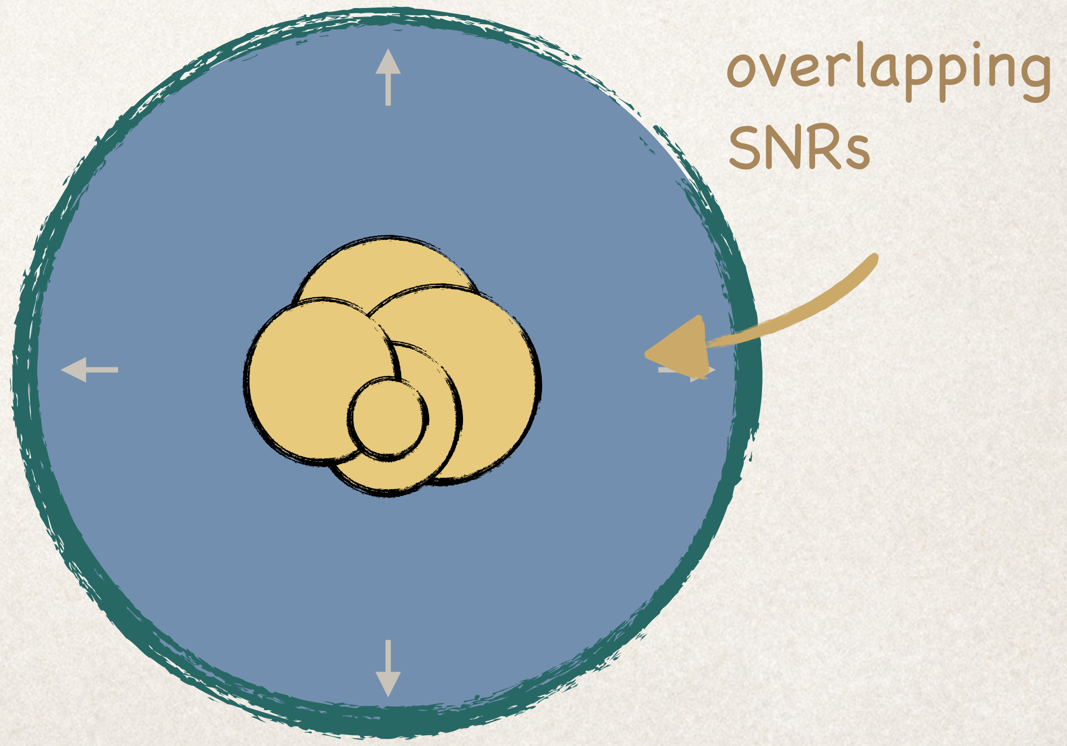
Stellar cluster kinetic luminosity



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



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



Size:

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

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

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

Where does the acceleration occurs?

Possible acceleration mechanisms

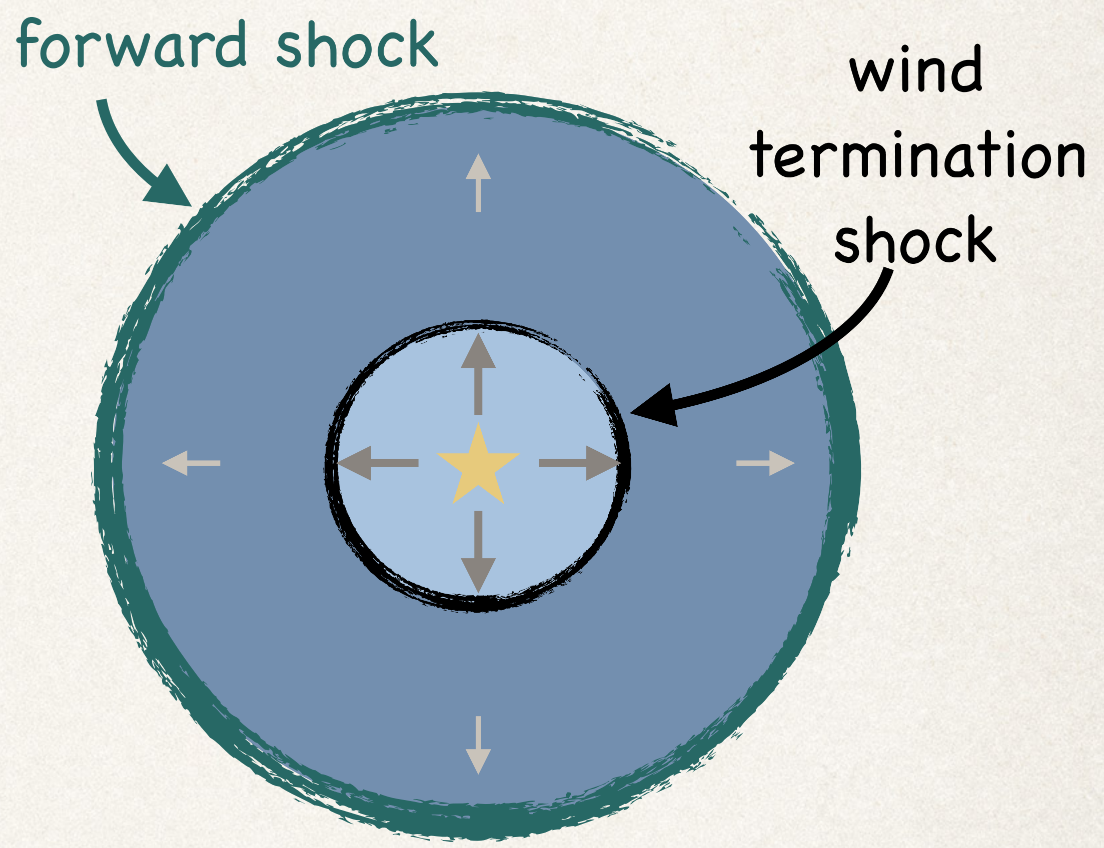
1. Wind termination shock (I order)
2. SNR shocks (I order)
3. Magnetic turbulence (II order)

Propagation

Irrespective of the acceleration mechanism, particles escape from the bubble after being accelerated. A correct description of escape requires the knowledge of:

- Bubble size
- Magnetic turbulence
- Gas and radiation distribution (need for energy losses)

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



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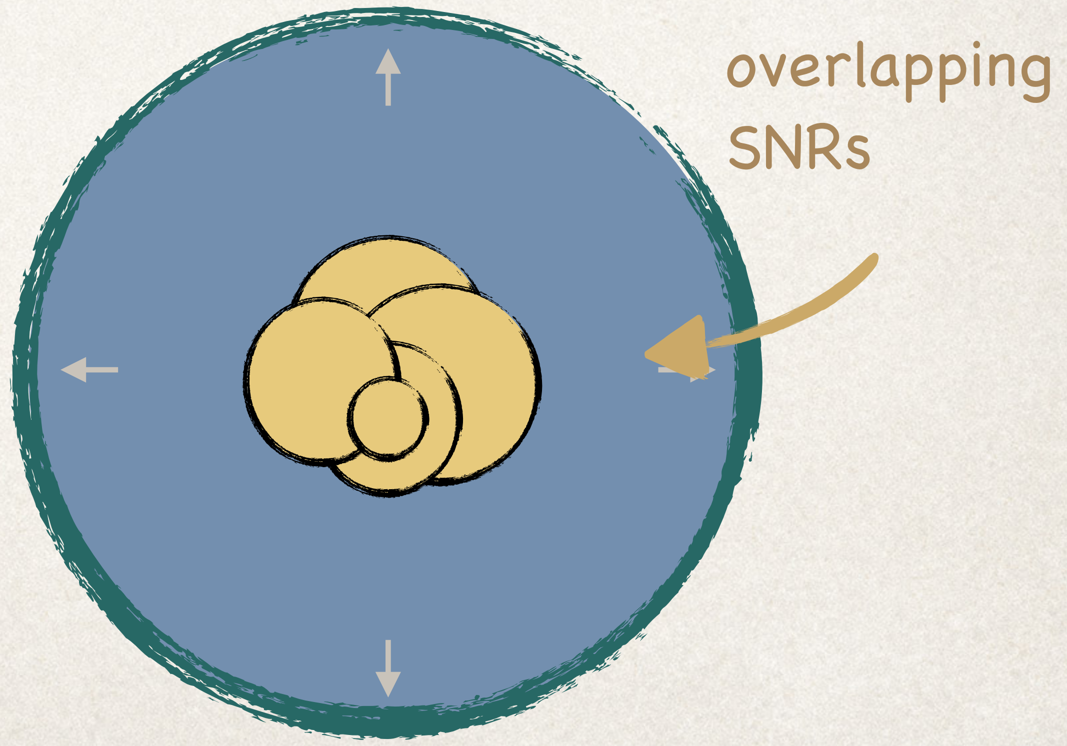
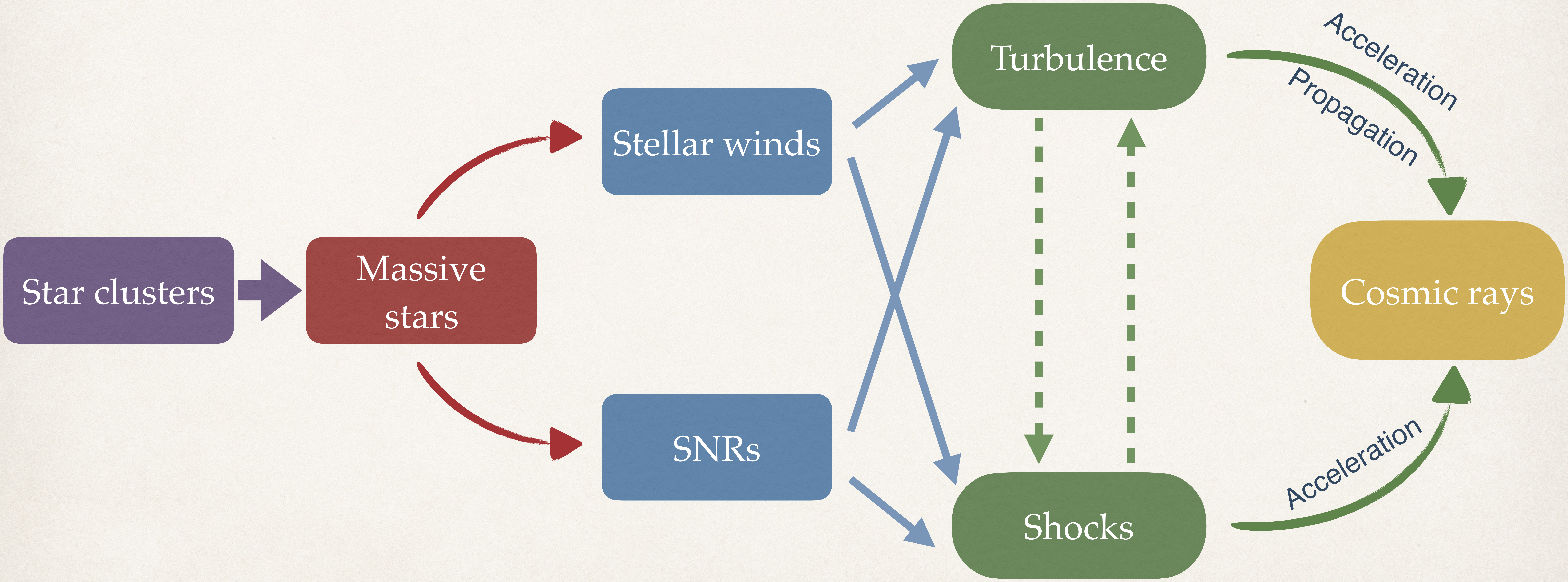


A complex chain



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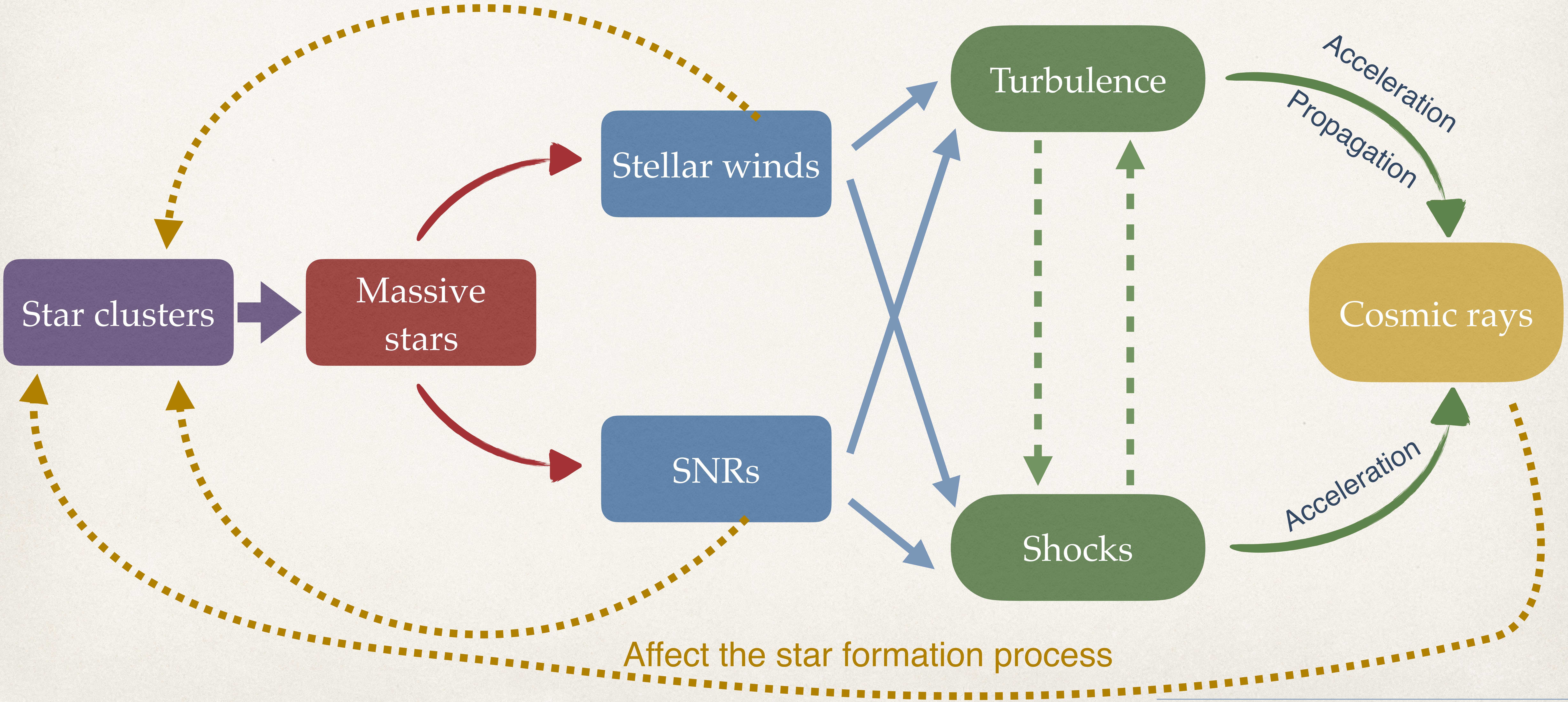

Questions we need to answer

How many SCs there are in the Galaxy? Which is their mass distribution?

Which is the stellar mass distribution for each cluster (especially at higher mass)?

How powerful are stellar winds? How much turbulence they drive?

How does the wind-blown bubble evolve in time?

How do SNRs evolve in the SC environment?

How efficient is the particle acceleration?

Which is the chemical composition inside the bubble?

Plan of the TOSCA workshop

- Gamma-ray observation of star clusters (today)
- Star clusters as cosmic ray factories (Tuesday morning)
- Stellar feedback (Tuesday afternoon)
- Stellar wind physics (Wednesday afternoon)
- Population properties (Thursday morning)

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ENJOY THE MEETING!!!