Nuclear interactions of low-energy cosmic-rays with the interstellar medium

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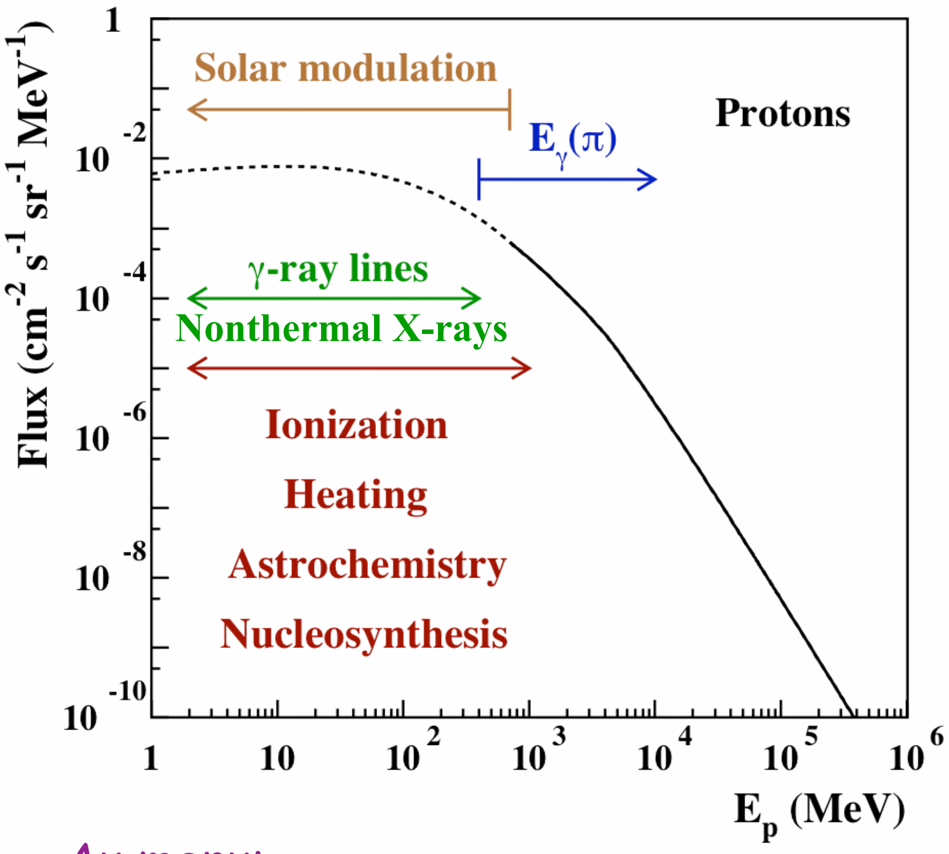
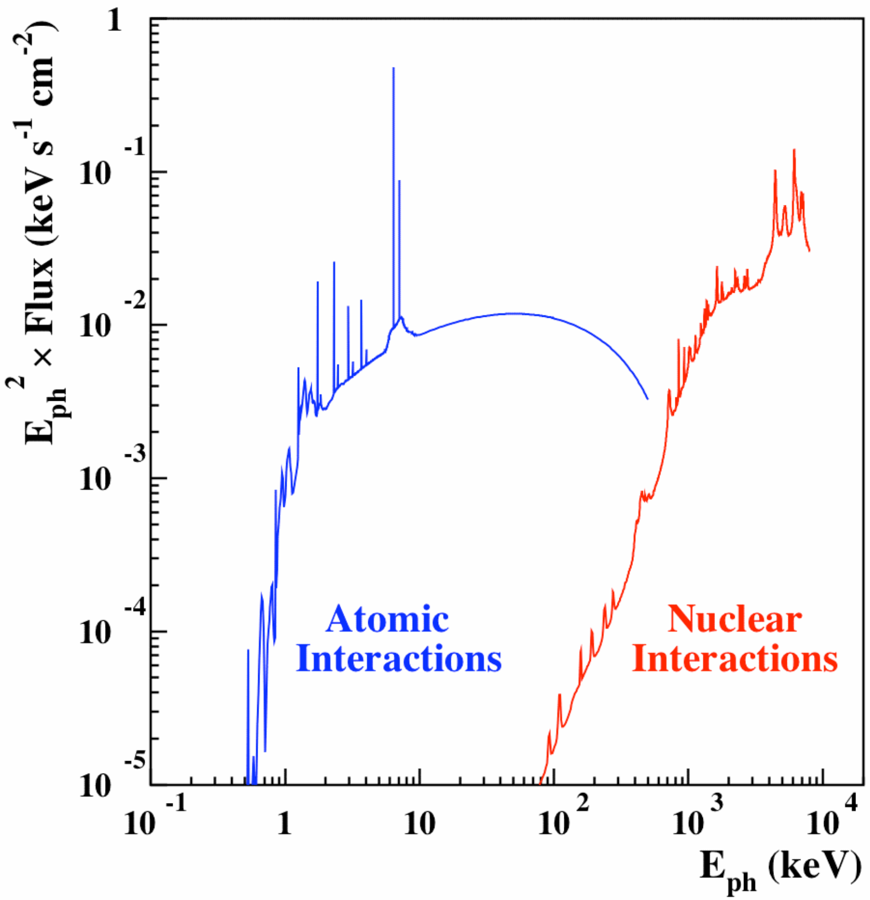


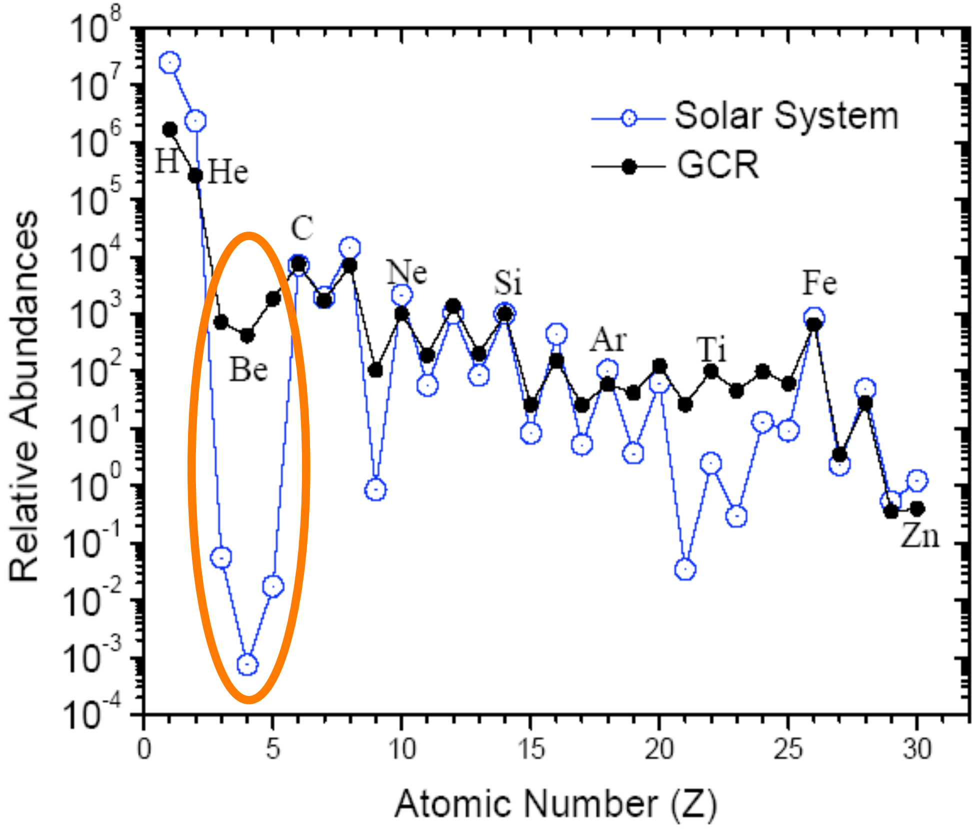


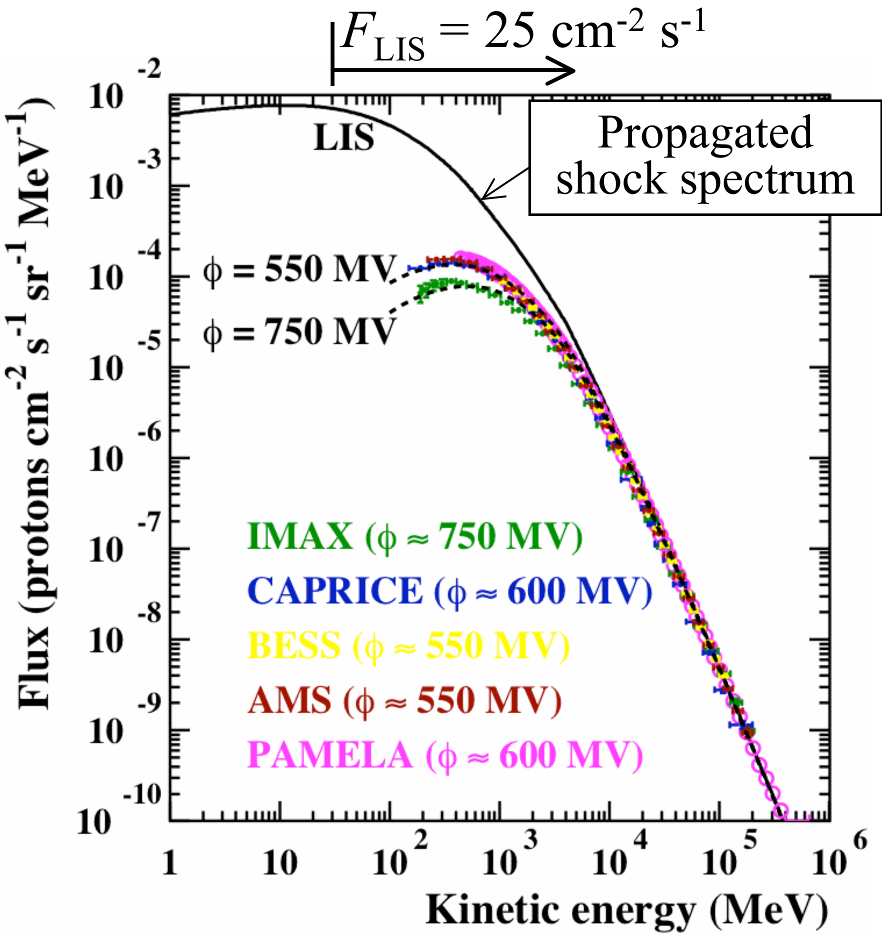
Au menu:

❶ LiBeB nucleosynthesis ❷ Nuclear γ-ray line emission

CRISM-2011, Montpellier, France, 26 June – 01 July 2011

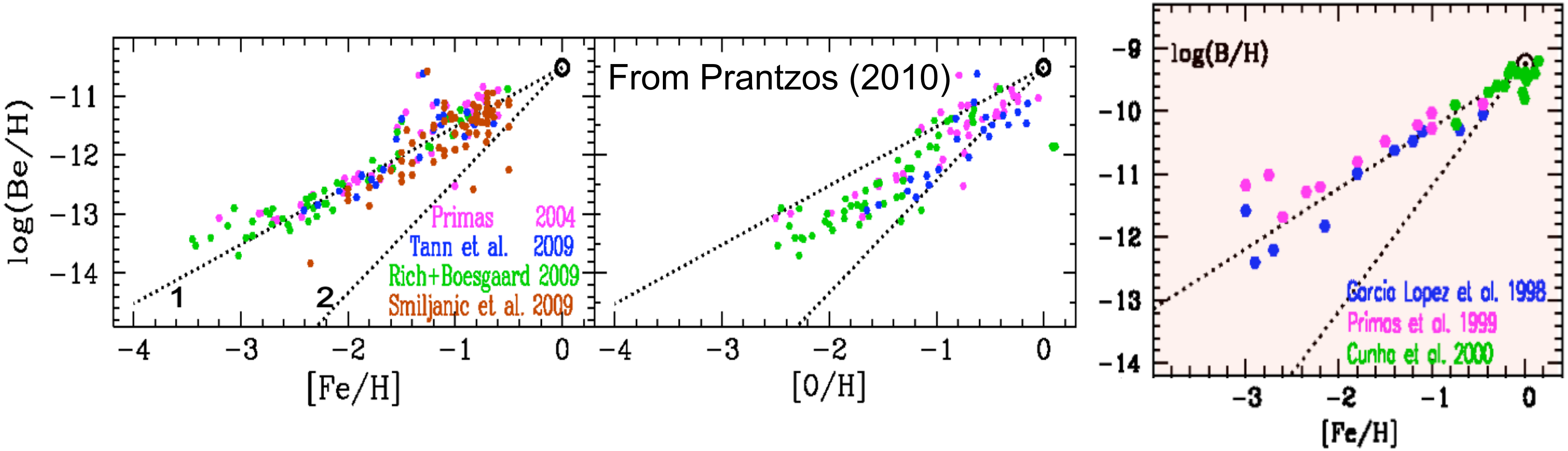
Galactic Cosmic Ray Origin of Li, Be and B





- LiBeB/Si is $10^4 - 10^6$ higher in the GCRs than in the solar system
- Reeves, Fowler & Hoyle (1970): assuming cst CR spectrum and CNO abundances throughout the history of the Galaxy, solar Li (!), Be and B could originate from GCR interactions, provided that the GCR flux $F_{\mathrm{GCR}}(E>30\ \mathrm{MeV/n}) \sim 17\ \mathrm{cm^{-2}\ s^{-1}}$

Be and B are primary elements



- Within the standard model for the origin of Galactic cosmic rays, in which GCRs are accelerated out of the ISM:

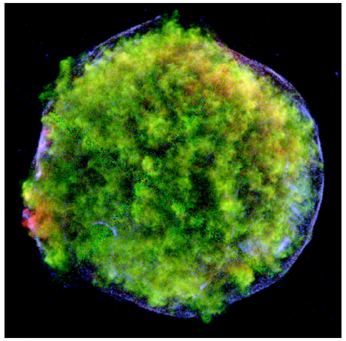
$$\frac{dN_{\mathrm{Be}}}{dt}(t) \propto \Phi^{\mathrm{GCR}}_{p\alpha}(t)N^{\mathrm{ISM}}_{\mathrm{CNO}}(t) + \Phi^{\mathrm{GCR}}_{\mathrm{CNO}}(t)N^{\mathrm{ISM}}_{p\alpha}(t) \propto \frac{dN_{\mathrm{SN}}}{dt}(t)N_{\mathrm{SN}}(0 \to t)$$

$$\Rightarrow N_{\mathrm{Be}}(t) \propto \left[N_{\mathrm{SN}}(0 \to t)\right]^{2} \propto [\mathrm{Fe/H}]^{\textcircled{2}}$$

but observations (from the 90's) show that Be and B vary linearly with [Fe/H]

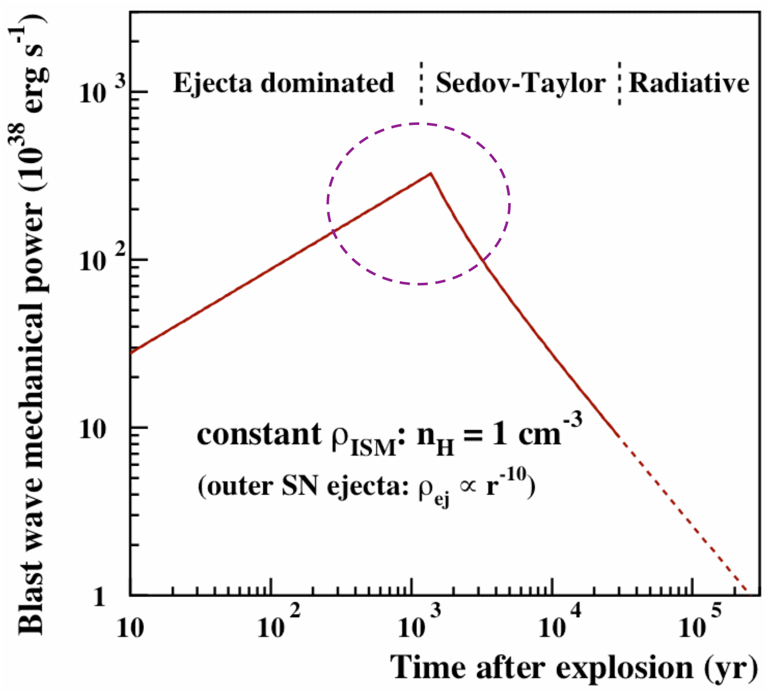
- ^{11}B (^{11}B/^{10}B=4) production by ν spallation of ^{12}C in CC SNe (Woosley et al. 1990)

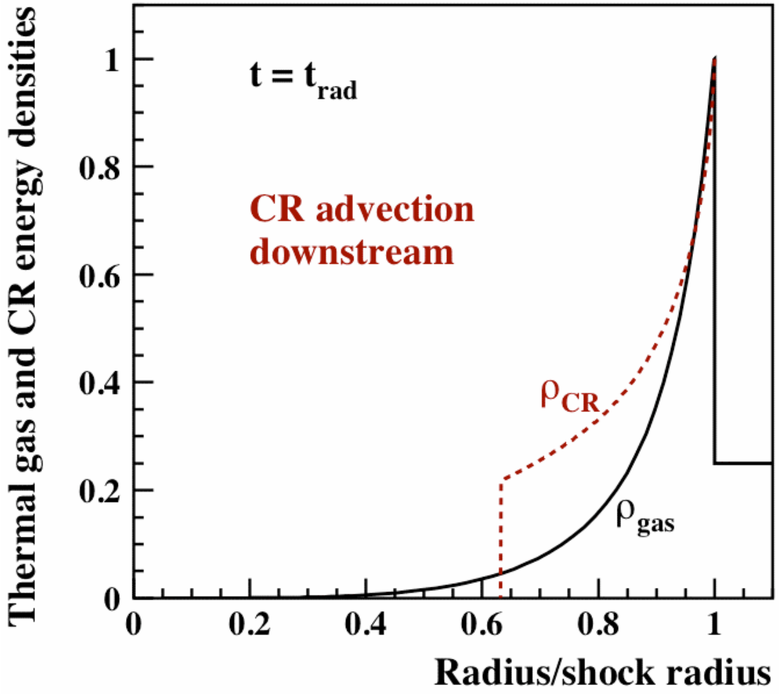
Nucleosynthesis of primary Be in SNRs



- CRs accelerated in a SN blast wave interact with SN ejecta before being released in the ISM
- Parizot & Dury (1999) calculated that this process would produce ~10 times less Be/O in the early Galaxy than required, BUT
  - the CR injection rate was possibly underestimated in this study
  - the assumption of a homogeneous SNR likely underestimates the Be production

⇒ Can GCRs produce enough primary Be before being released in the ISM?



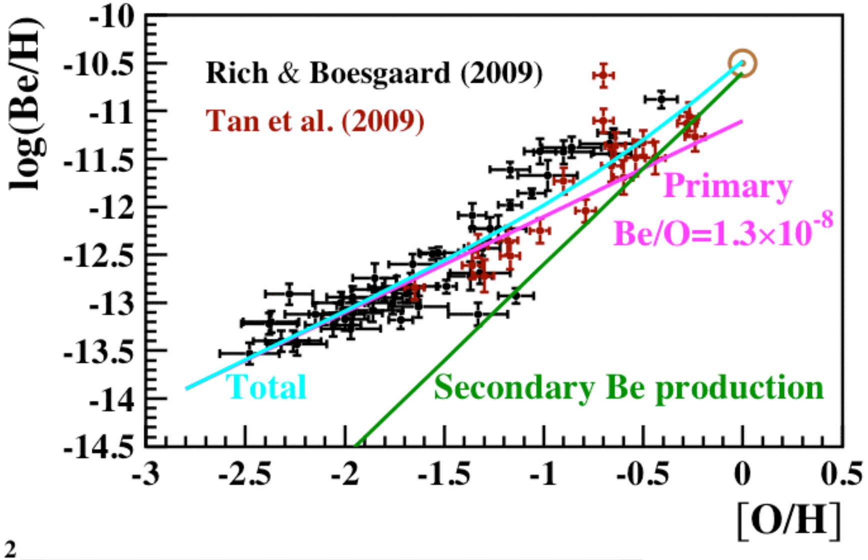


Nucleosynthesis of primary Be in SNRs

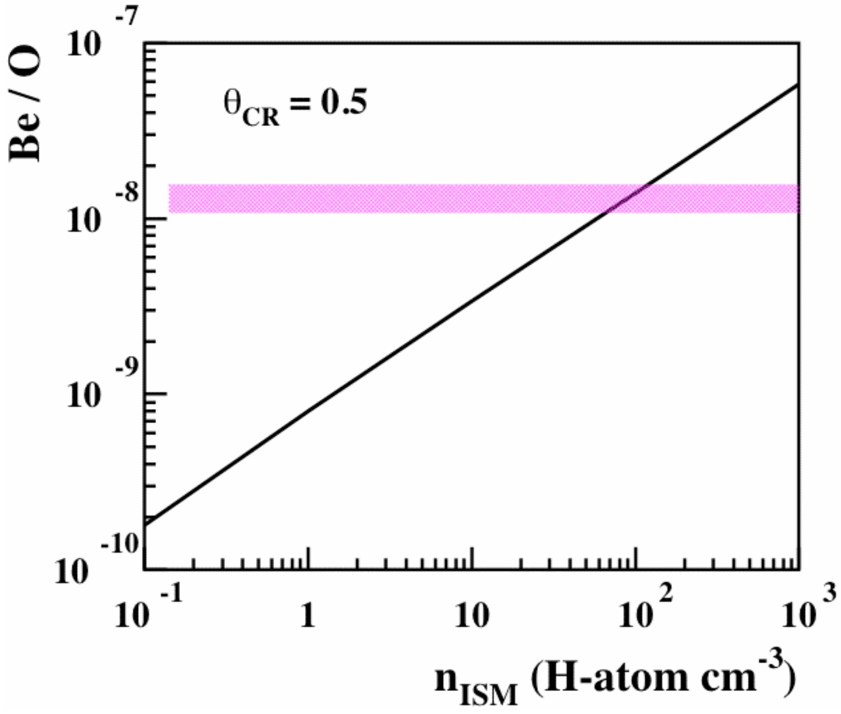
- Required primary Be/0 $\approx 1.3\times10^{-8}$
- Be production rate: $\frac{1}{\mathrm{O}}\frac{d\mathrm{Be}}{dt} = q_{\mathrm{Be}}\varepsilon_{\mathrm{CR}}$

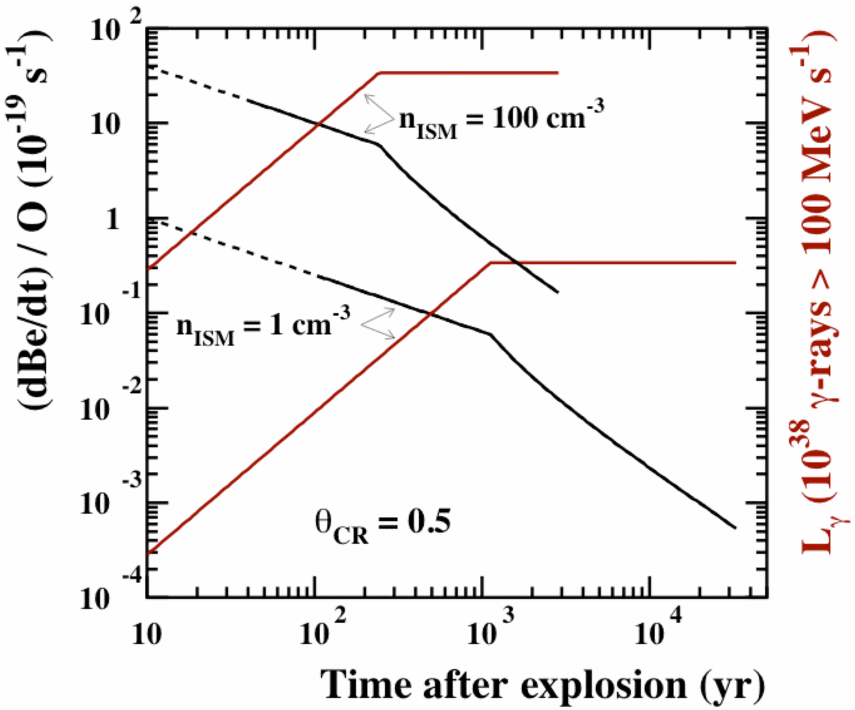
with $q_{\mathrm{Be}} \approx 10^{-13}\ \mathrm{s}^{-1}\ (\mathrm{O\text{-}atom})^{-1}\ (\mathrm{erg\ cm}^{-3})^{-1}$

and the CR E density $\varepsilon_{\mathrm{CR}} = \frac{2}{3}\vartheta_{\mathrm{CR}}\rho_{\mathrm{ISM}}V_s^2$

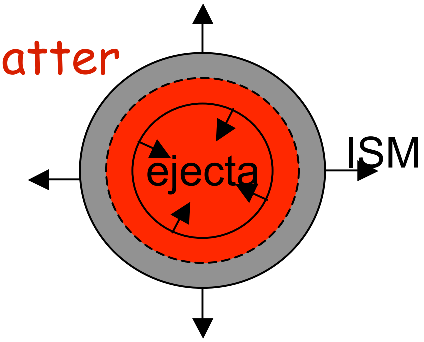


⇒ would require a too high n_{ISM}



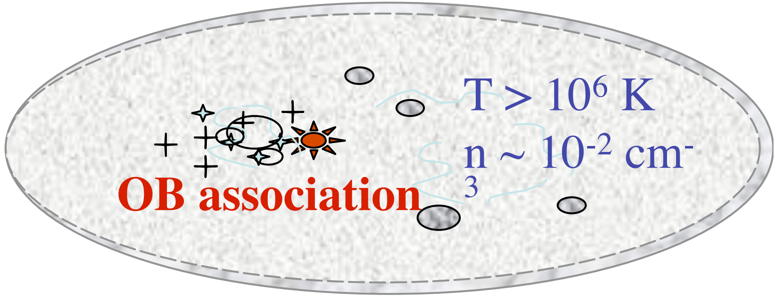


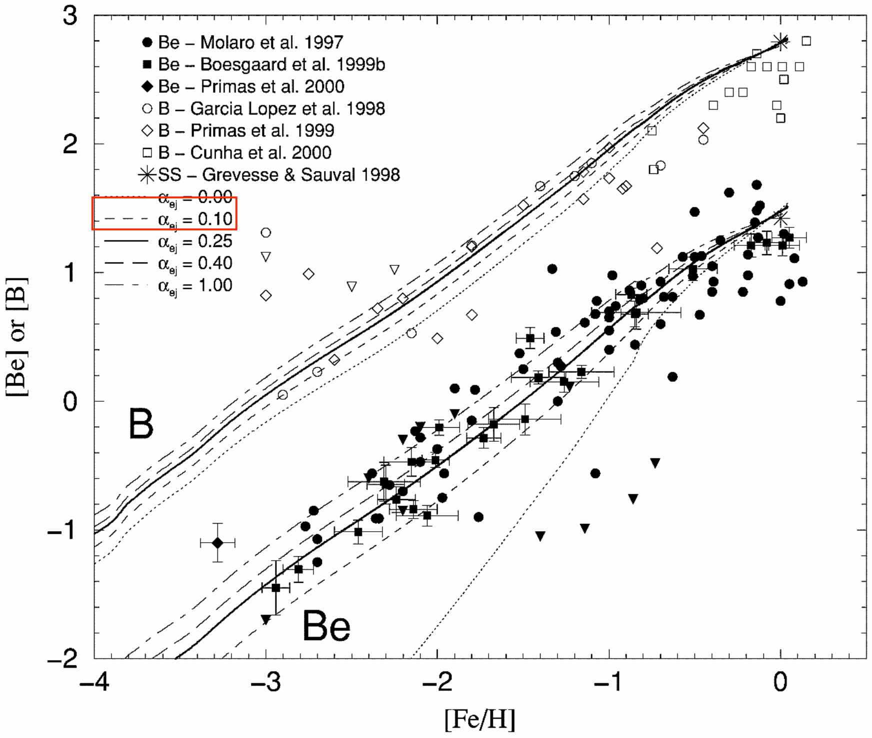
On the origin of Galactic cosmic rays



- CNO GCRs were/are accelerated out of freshly synthesized matter
- Acceleration of SN ejecta at the reverse shock ?
  (e.g. Ramaty et al. 1997)

  No because of the absence of ^{59}Ni ($\tau \sim 10^5$ yr) in the GCR
  $\Rightarrow$ delay $>10^5$ yr between nucleosynthesis and acceleration
- Acceleration in superbubbles ?
  (Higdon et al. 1998; Parizot & Drury 1999)





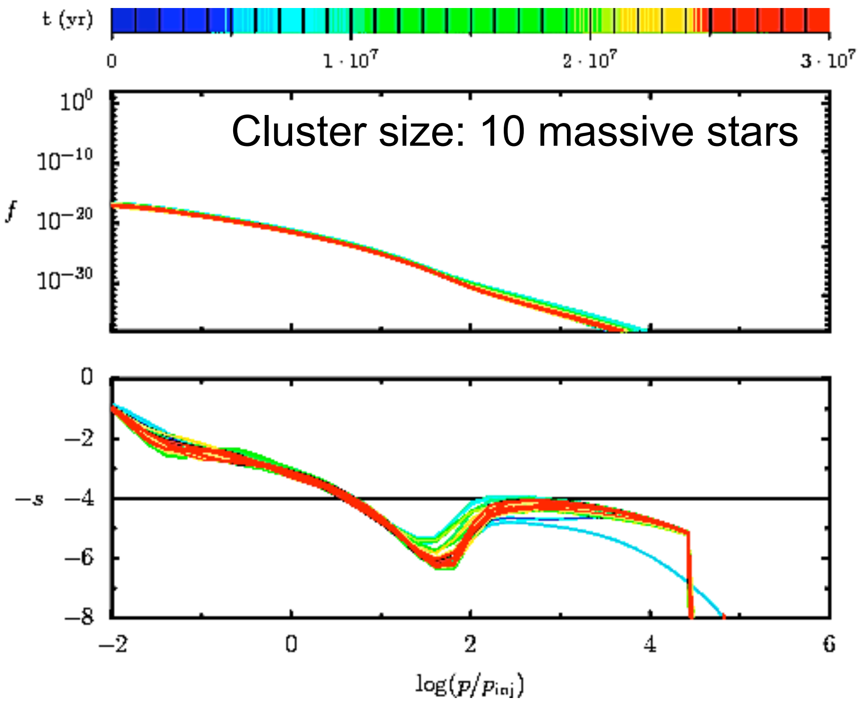
- SNe are strongly associated in time and space and most explode in superbubbles
- From BeB evolution, GCRs may come from ~25% SN/WR material and ~75% ISM (e.g. Alibés et al. 2002)
- Consistent with ^{12}C/^{16}O, ^{22}Ne/^{20}Ne and ^{58}Fe/^{56}Fe in GCRs (Higdon & Lingenfelter 2003) or not (Prantzos 2011)
- Probably no problem with ^{59}Ni

The spectrum of CRs accelerated in superbubbles

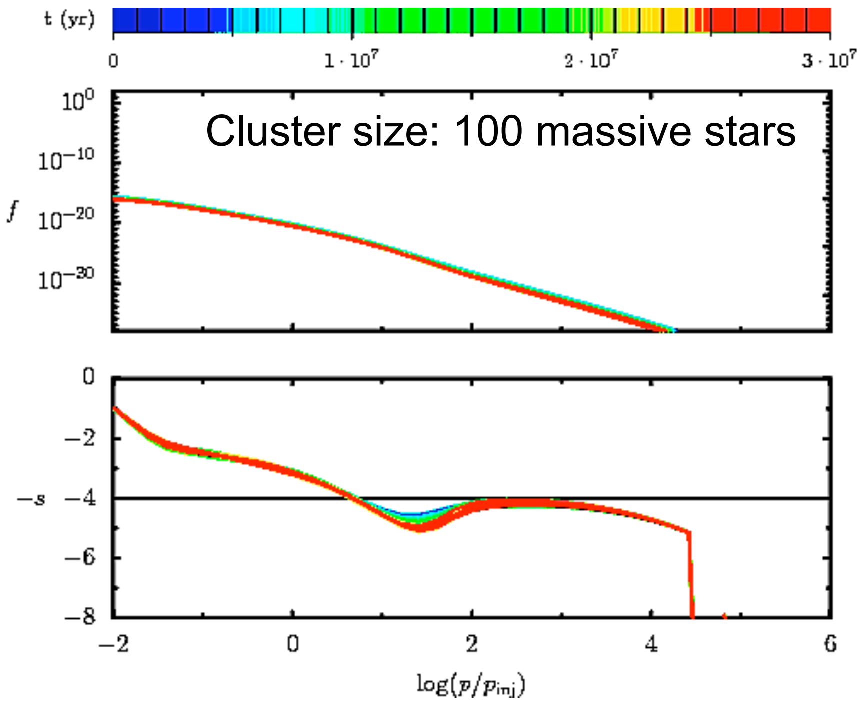
- Collective effects in the acceleration process: multiple shocks (Fermi 1) and stochastic acceleration by turbulence (Fermi 2) between shocks (e.g. Bykov & Fleishman 1992, Parizot et al. 2004, Ferrand & Marcowith 2010)

⇒ CR spectra are harder (resp. softer) than p^{-4} below (resp. above) a critical energy, that depends on the superbubble parameters (no universal spectrum)

⇒ may be inconsistent with the spectral uniformity, consistent with the local CR spectrum, deduced from Fermi γ-ray observations (Ackermann et al. 2011)



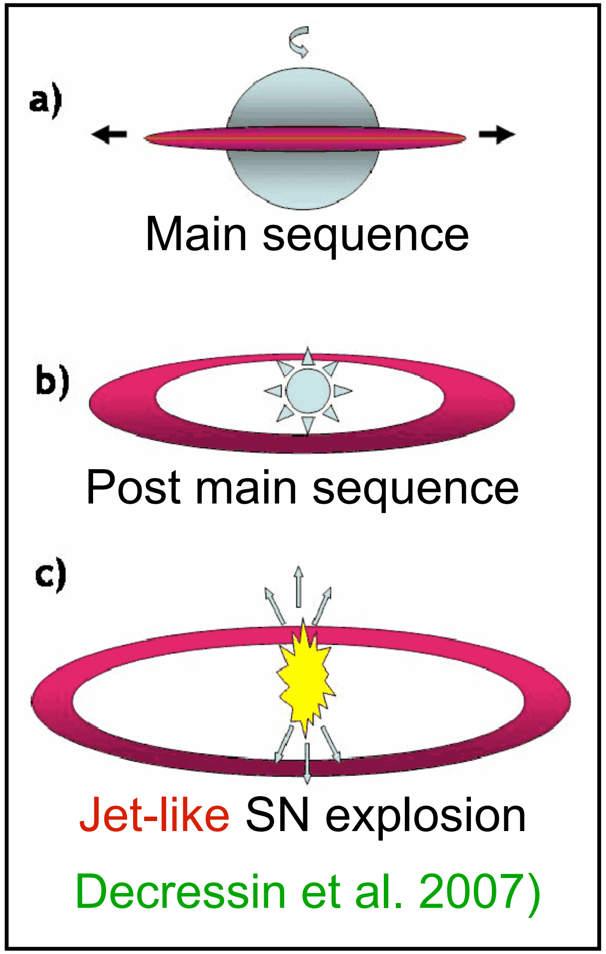
Cluster size: 10 massive stars



Cluster size: 100 massive stars

GCRs from fast rotating massive stars

- Fast rotating massive stars exploding into their former stellar winds could produce cosmic rays of ~constant metallicity (Prantzos 2010)
- Ejection of CNO-rich winds even at low metallicity:
  - H-burning products in the equatorial plane during the main sequence ($v_{\rm surf}$ ~ the critical limit)
  - For $M_{\rm ini} > 40\ M_\odot$, radiatively-driven wind enriched in He-burning products after the main sequence
- But only ~15% of $M_* > 40\ M_\odot$ for a Salpeter IMF
- Jet-like SN explosion (?)

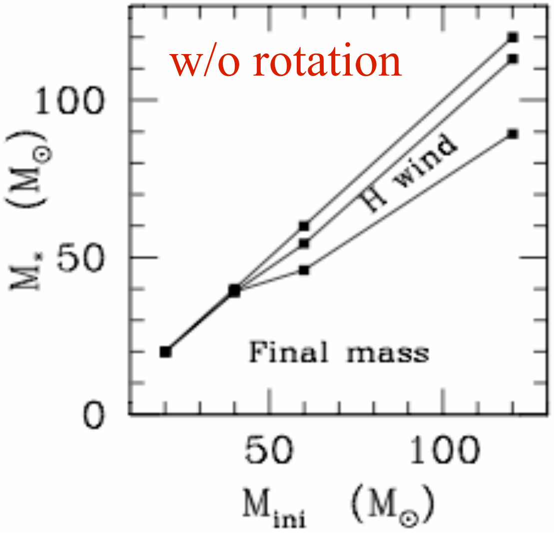


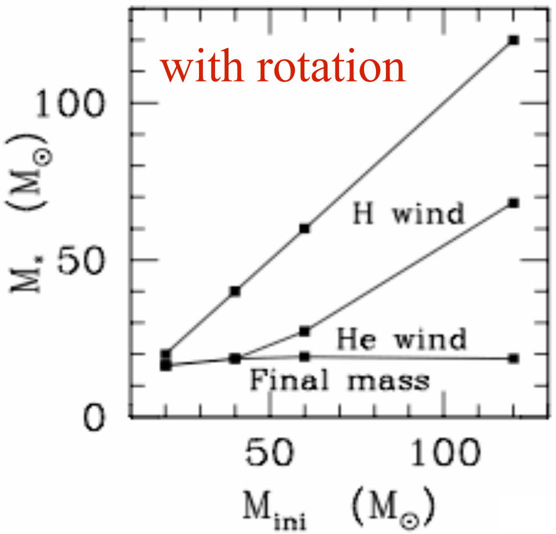
Main sequence

Post main sequence

Jet-like SN explosion

Decressin et al. 2007)





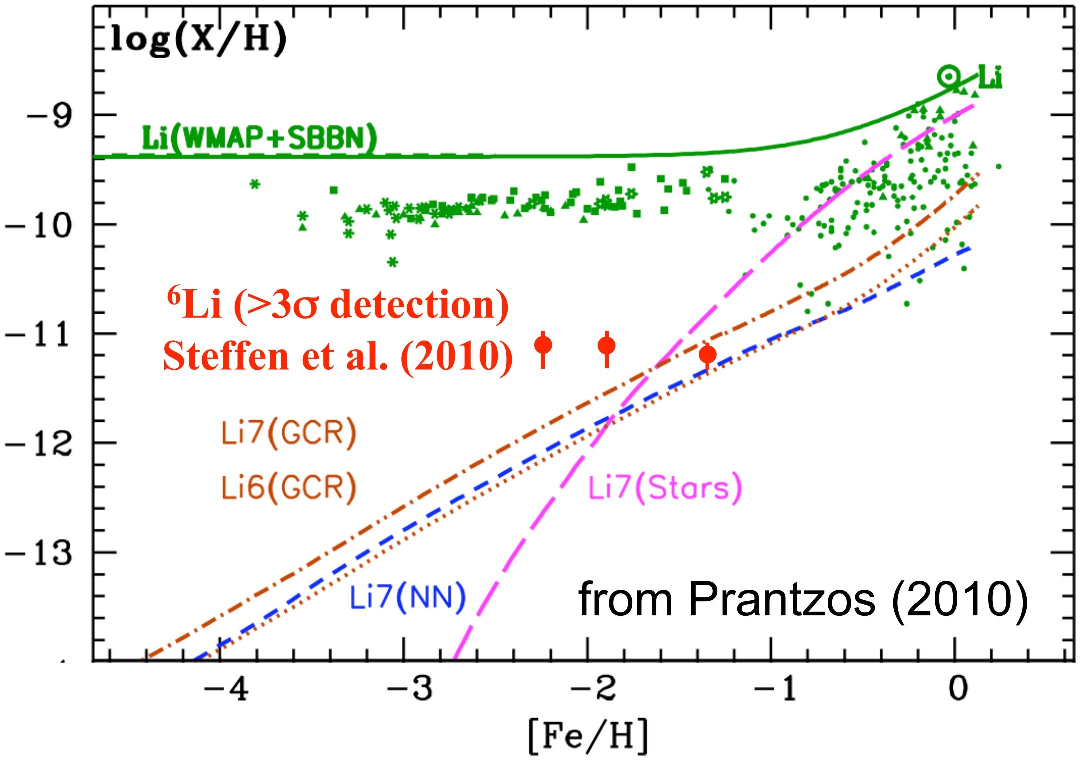
- Is this process really able to account for ~25% of WR wind material in the GCR

On Li nucleosynthesis

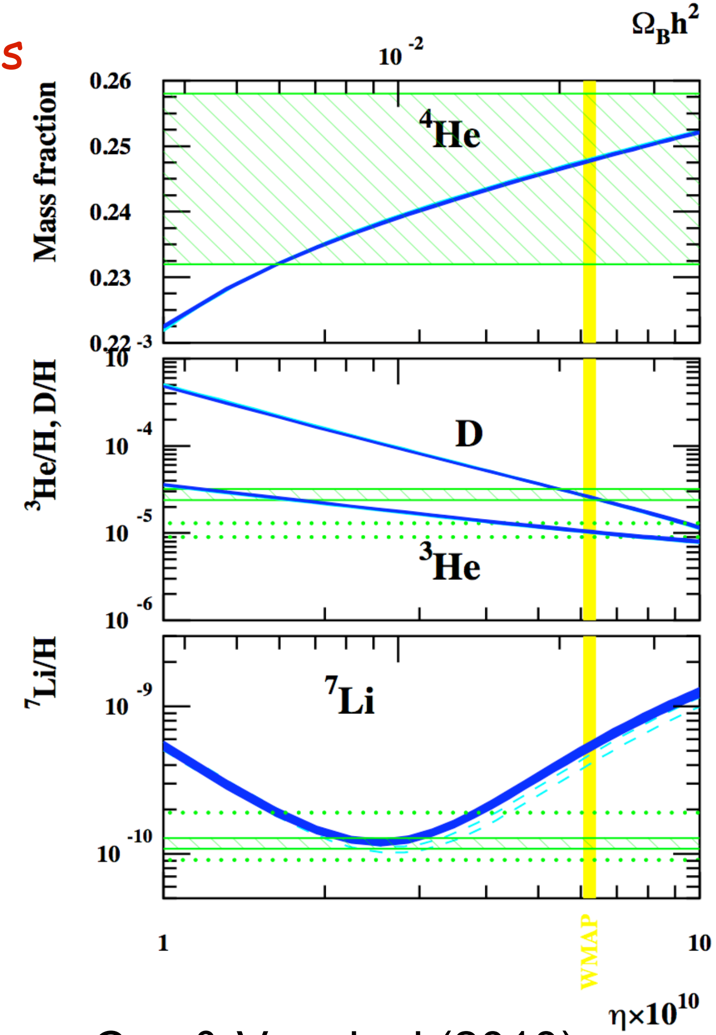
- ^{7}Li is also significantly synthesized in the Big Bang and in stars: AGB stars, novae and type II supernovae
- Standard BBN (with WMAP) produces ~3–5 times more ^{7}Li than observed in metal-poor halo stars

⇒ stellar depletion or new physics ?

- ^{6}Li in 3 metal-poor halo stars (?): stellar flare nucleosynthesis (VT & Thibaud 2007) ?

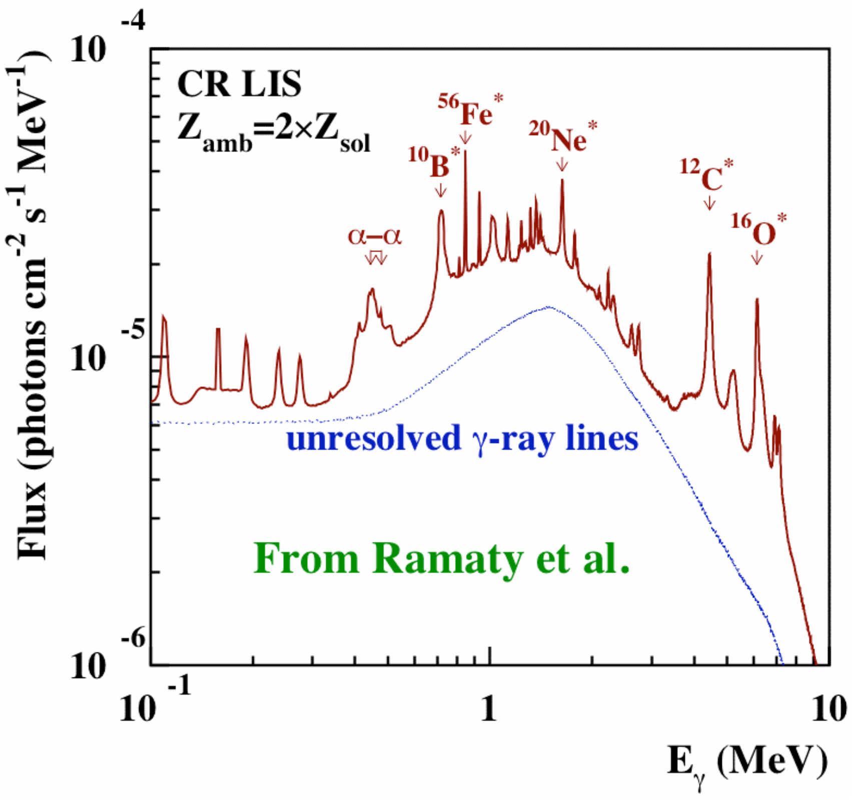


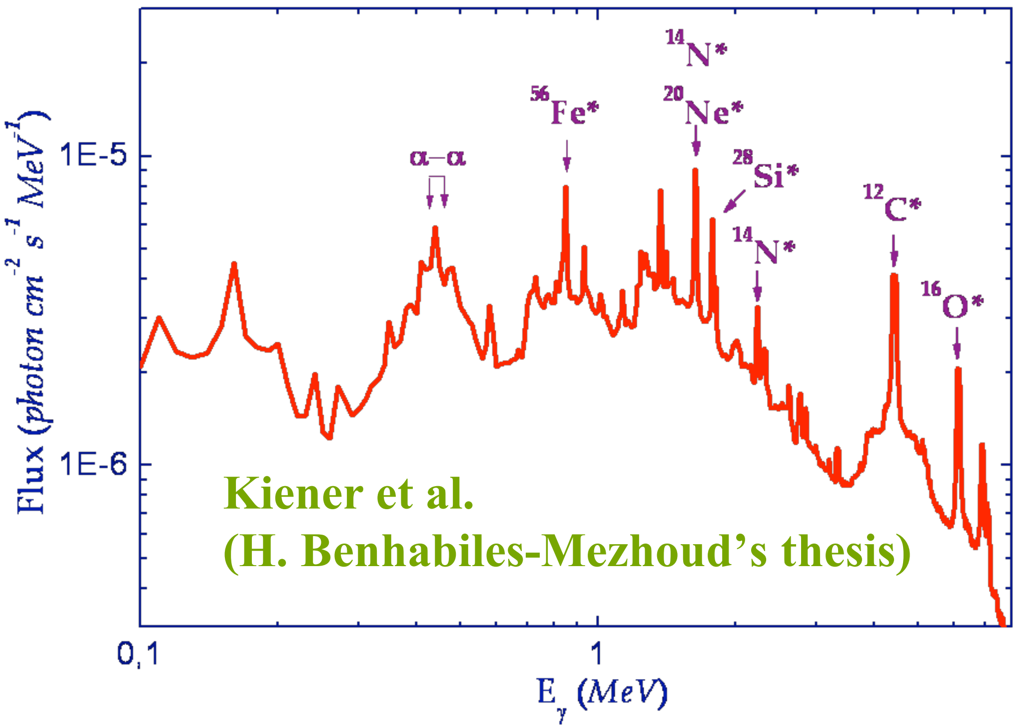
from Prantzos (2010)



Coc & Vangioni (2010)

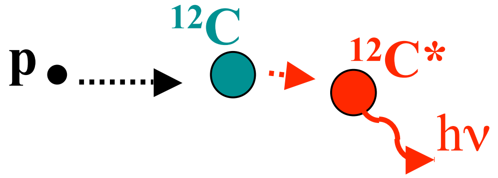
Nuclear γ-ray lines from the ISM

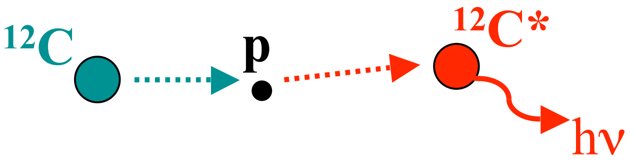




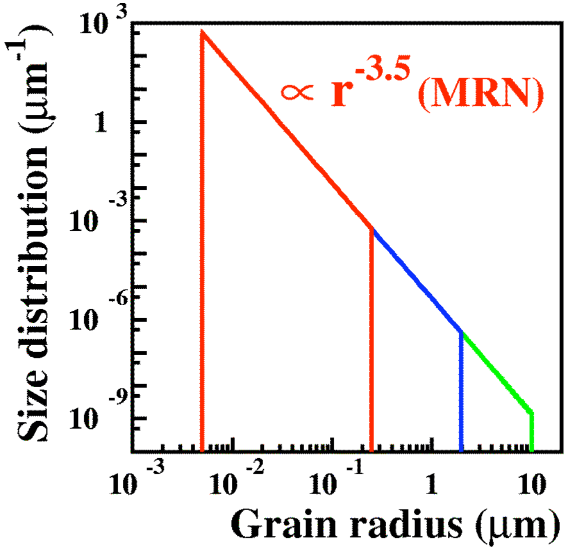
- **Narrow lines**: e.g. $^{12}C(p,p')^{12}C^*_{4,439}$, $^{12}C(p,2pn)^{10}B^*_{0,718}$
- **Broad lines**: e.g. $^{1}H(^{12}C,^{12}C^*_{4.439})^{1}H$
- **α–α line**: $^{4}He(\alpha,n)^{7}Be^*_{0,429}$ and $^{4}He(\alpha,p)^{7}Li^*_{0,478}$

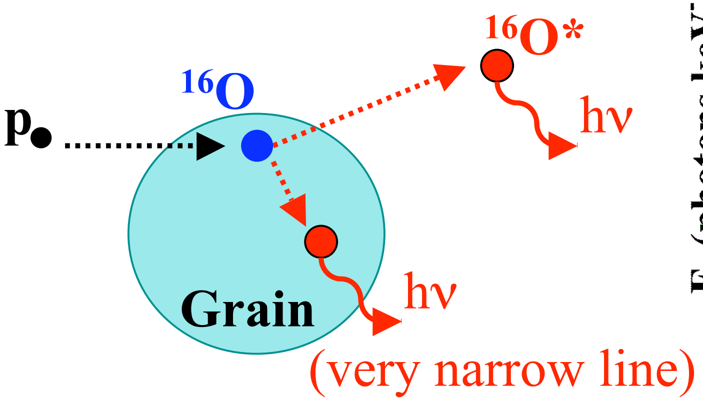
\+ the 511 keV line (not shown)

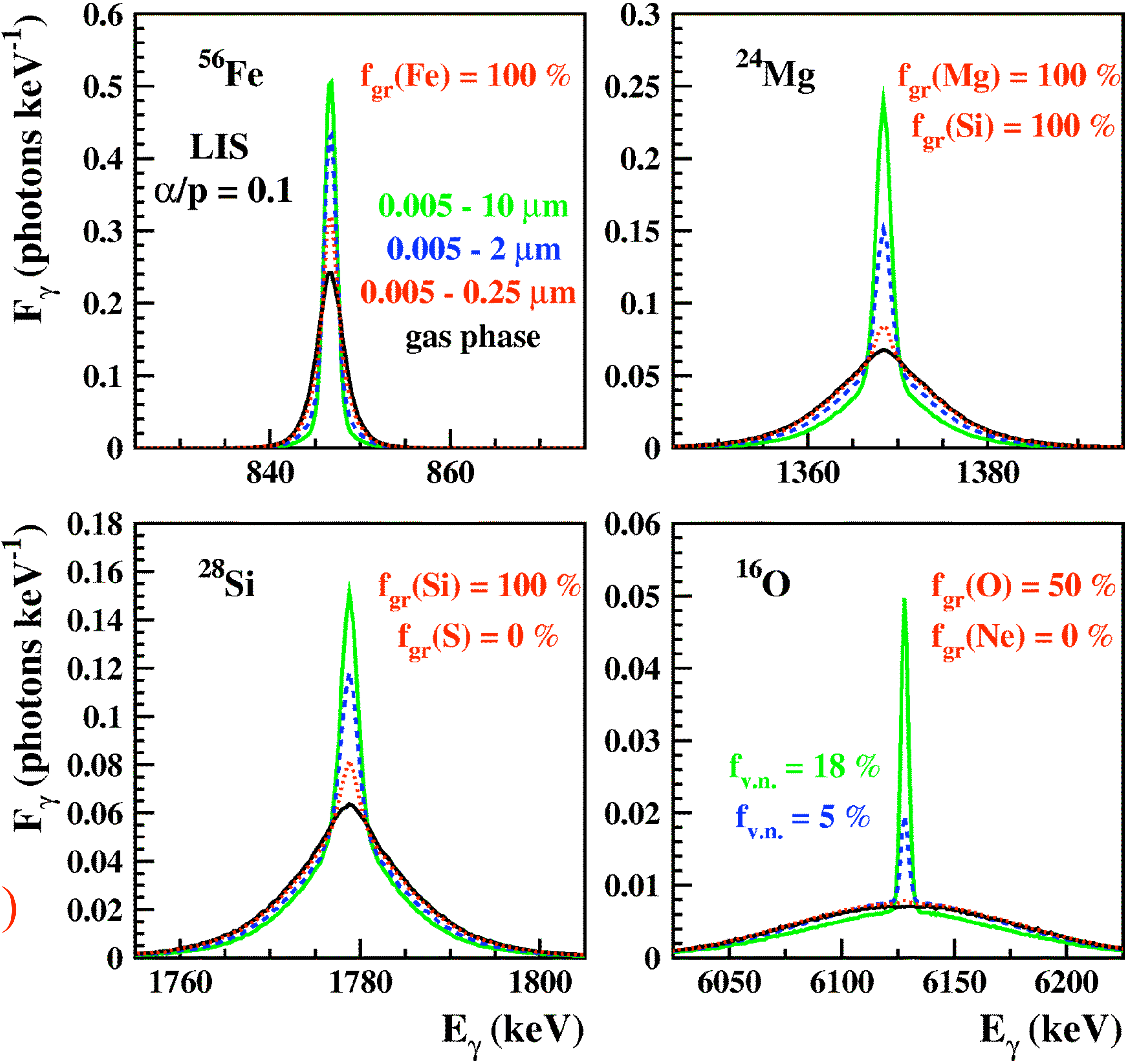




Nuclear γ-ray lines from interstellar dust



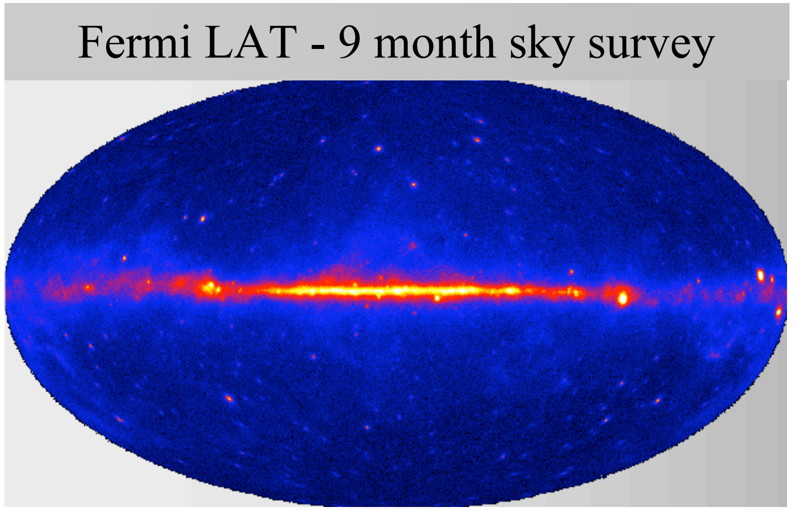


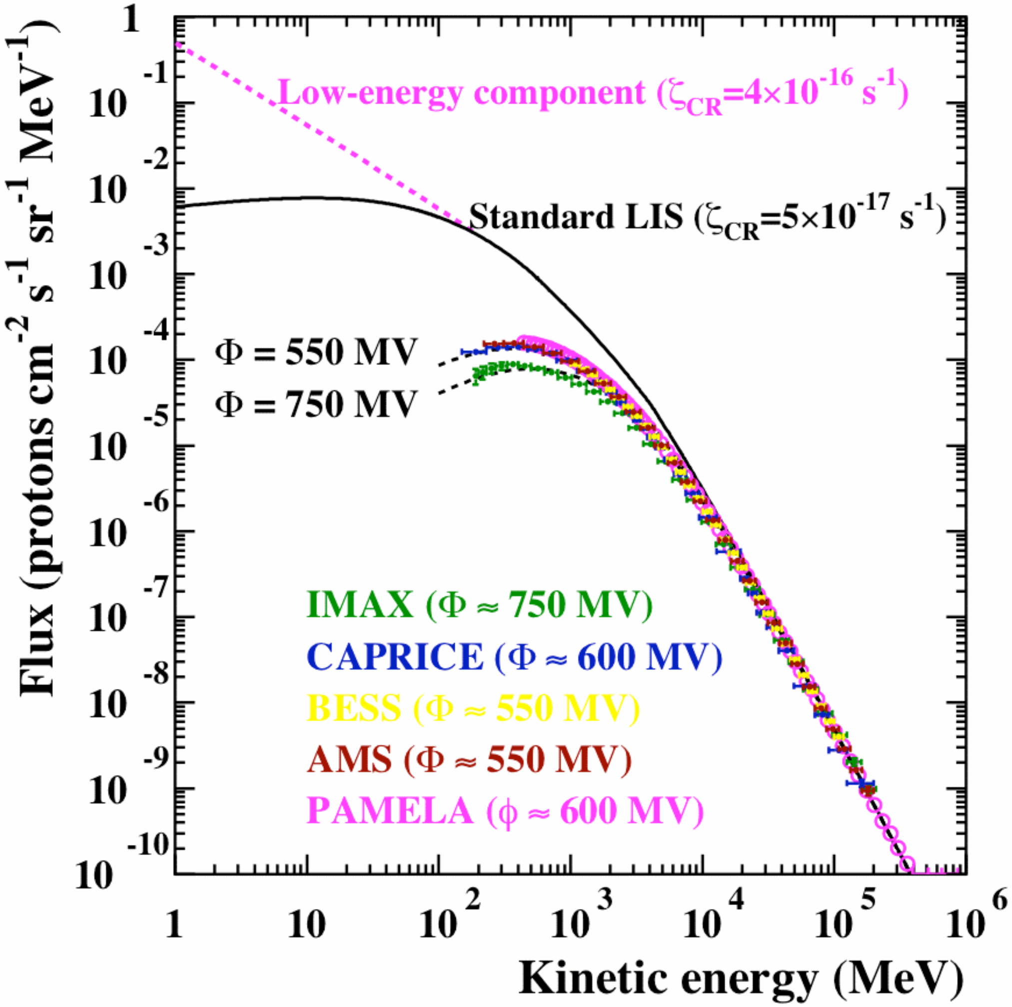


- *A unique way of tracing micrometer-sized dust grains (VT & Kiener 2004)*

Galactic diffuse emission in γ-ray lines – model

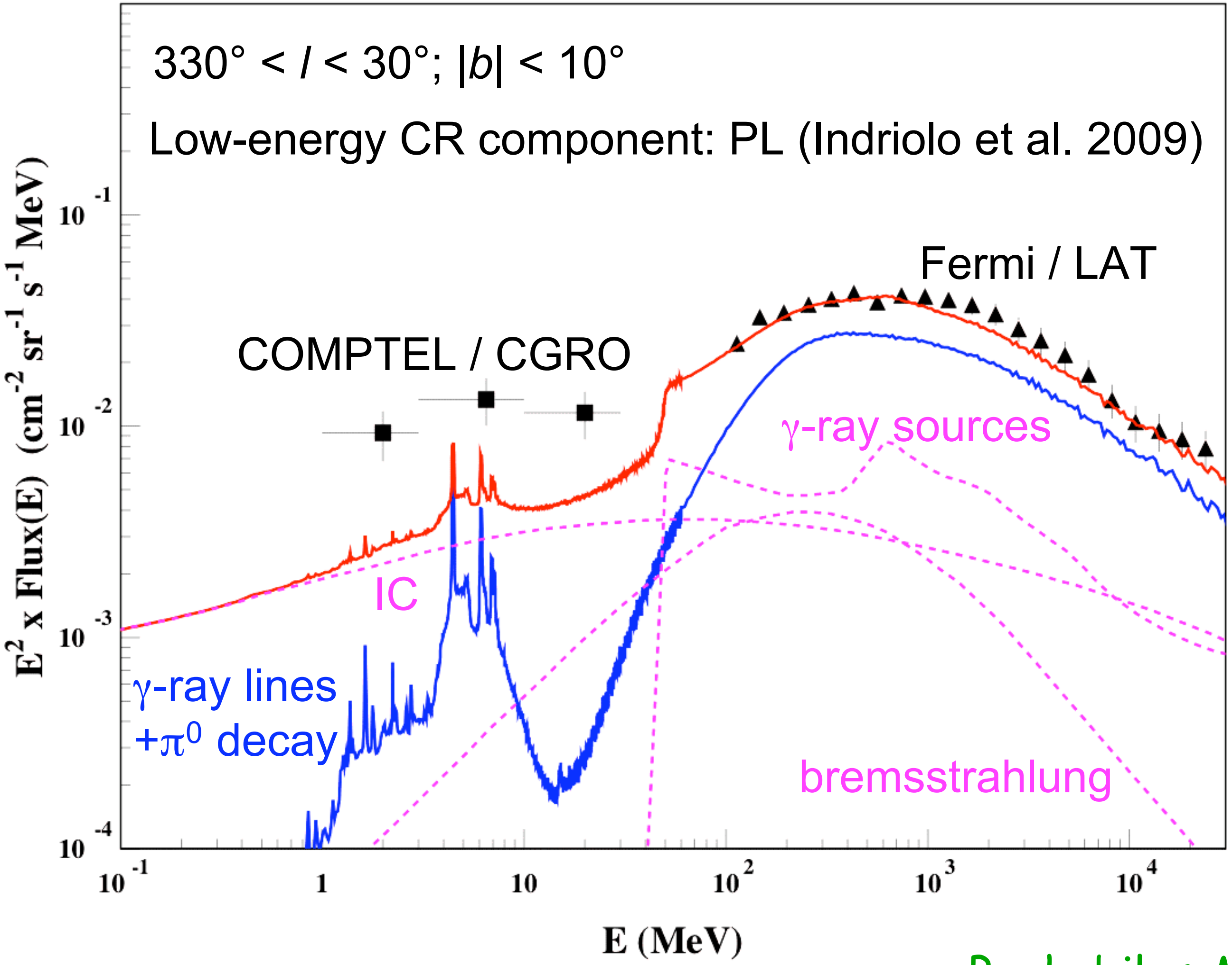
- "Standard" CR spectrum: disk-halo diffusion model (Jones et al. 2001) fitted to local CR proton data
- Additional low-energy component to account for the CR ionization rate $\zeta_{CR}=4\times10^{-16}\ s^{-1}$ deduced from H_3^+ measurements in diffuse H_2 clouds (Indriolo et al. 2009)
- CR composition: measured
  Ambient: two-times solar
- Normalization to π^0 production


Fermi LAT - 9 month sky survey



Galactic diffuse emission in γ-ray lines – results

Fermi data, γ-ray sources and CR electron contributions: Strong et al. (2011)



γ-ray line fluxes
($cm^{-2}\ s^{-1}\ sr^{-1}$)

4.4 MeV: 2.7×10^{-5}
(FWHM ~ 100 keV)

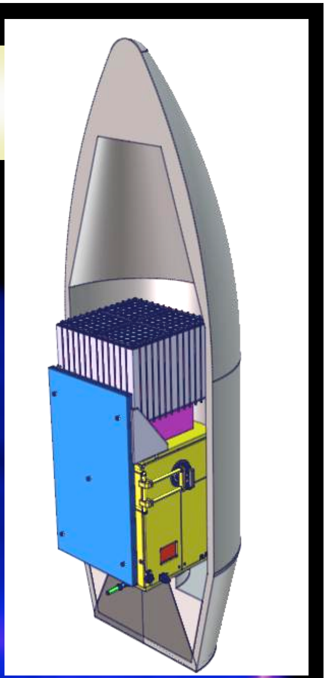
6.1 MeV: 1.2×10^{-5}
(FWHM ~ 100 keV)

1.63 MeV: 5.6×10^{-6}
(FWHM ~ 20 keV)

3-10 MeV: 2.8×10^{-4}

Benhabiles-Mezhoud et al., in prep.

Detectability (in the next 20 years)



- Gamma-ray telescope proposals in response to the recent ESA call (2010) for the third Medium size mission (M3): DUAL (CESR Toulouse), GRIPS (MPE Garching) and CAPSiTT (APC Paris)
- None selected by ESA for an assessment phase…

Estimated 4.4 MeV line flux in $b = \pm 1.5°$, $l = \pm 60°$: 5.9×10^{-6} cm^{-2} s^{-1}

4.4 MeV (ΔE = 100 keV) CAPSiTT 3σ sensitivity for $T_{obs} = 10^6$ s:

2.5×10^{-6} cm^{-2} s^{-1} for a point source

~3.4×10^{-5} cm^{-2} s^{-1} for an extended emission in $b = \pm 1.5°$, $l = \pm 60°$

$\Rightarrow$ a detection would need a minimum of $T_{obs} \sim 3 \times 10^7$ s

Estimated 3 – 10 MeV line flux in $b = \pm 1.5°$, $l = \pm 60°$: 6.0×10^{-5} cm^{-2} s^{-1}

5 MeV CAPSiTT 3σ broad-band sensitivity for 5 years in survey mode:

4.8×10^{-7} cm^{-2} s^{-1} for a point source

~6.7×10^{-6} cm^{-2} s^{-1} for an extended emission in $b = \pm 1.5°$, $l = \pm 60°$

Short summary

❶ The observed primary evolution of Be versus [Fe/H] shows that CNO GCRs were/are partly accelerated out of freshly synthesized matter

❷ CR acceleration in SNRs within superbubbles may be the best explanation; there is no evidence for collective effects in the acceleration process

❸ The detection of nuclear interaction γ-ray lines would provide the best way of studying the various effects of sub-GeV CRs in the ISM ⇒ a major objective for the next-generation of MeV γ-ray telescopes

Ionization of the ISM by low-energy cosmic rays

- Low-energy cosmic rays are the primary source of ionization in shielded H_2 regions ($A_V > \sim 4$ mag; where stars form)
- Ionization fraction in dense clouds ⇒ dynamics of star formation (ambipolar diffusion) + synthesis of polyatomic molecules
- From H_3^+ in diffuse clouds, $\zeta_{CR} \approx 10^{-16}–10^{-15}\ s^{-1}$ (e.g. McCall et al. 1998; Indriolo et al. 2007) 10–100 larger than the "standard" (Spitzer) value

⇒ Higher flux of low-energy cosmic-ray electrons or ions (Indriolo et al. 2009; Padovani et al. 2009)