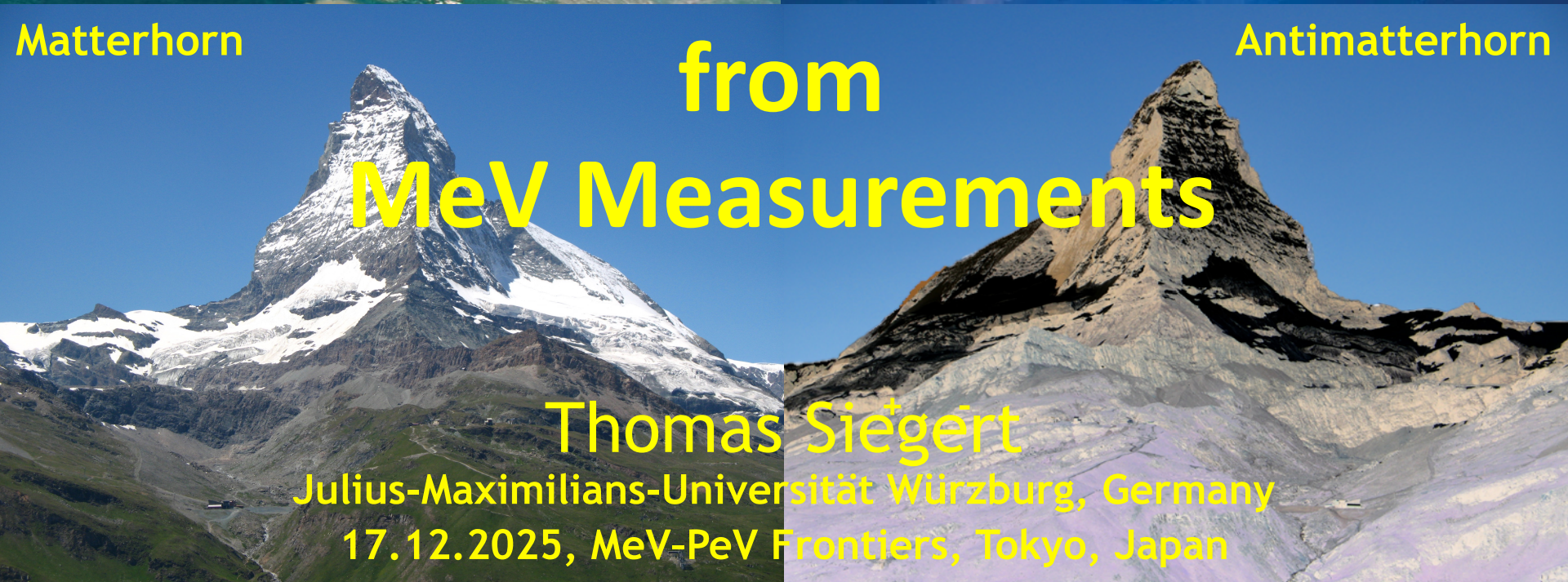
The Onset of Particle Acceleration from MeV Measurements

Matterhorn

Antimatterhorn

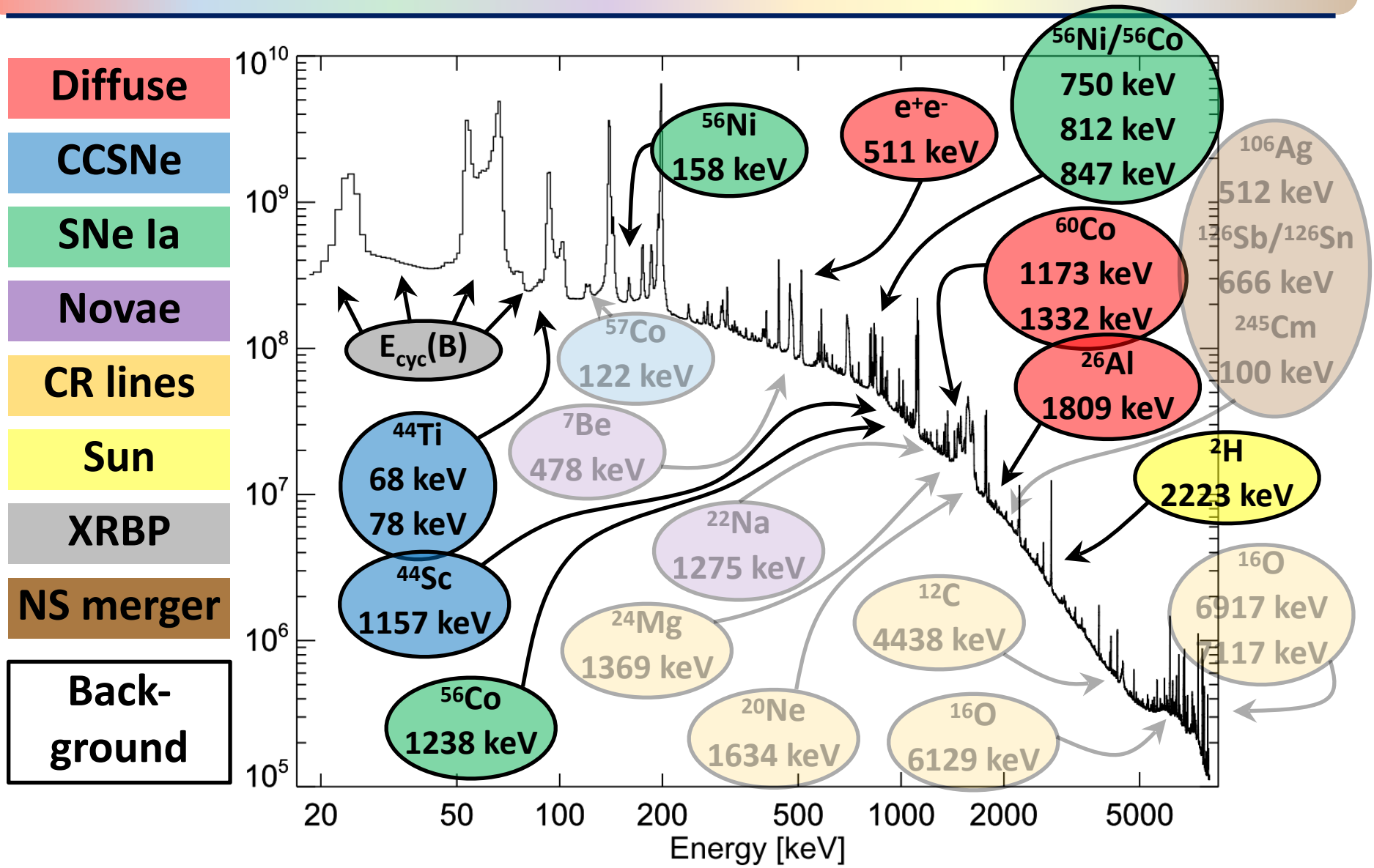


Thomas Siegert

Julius-Maximilians-Universität Würzburg, Germany

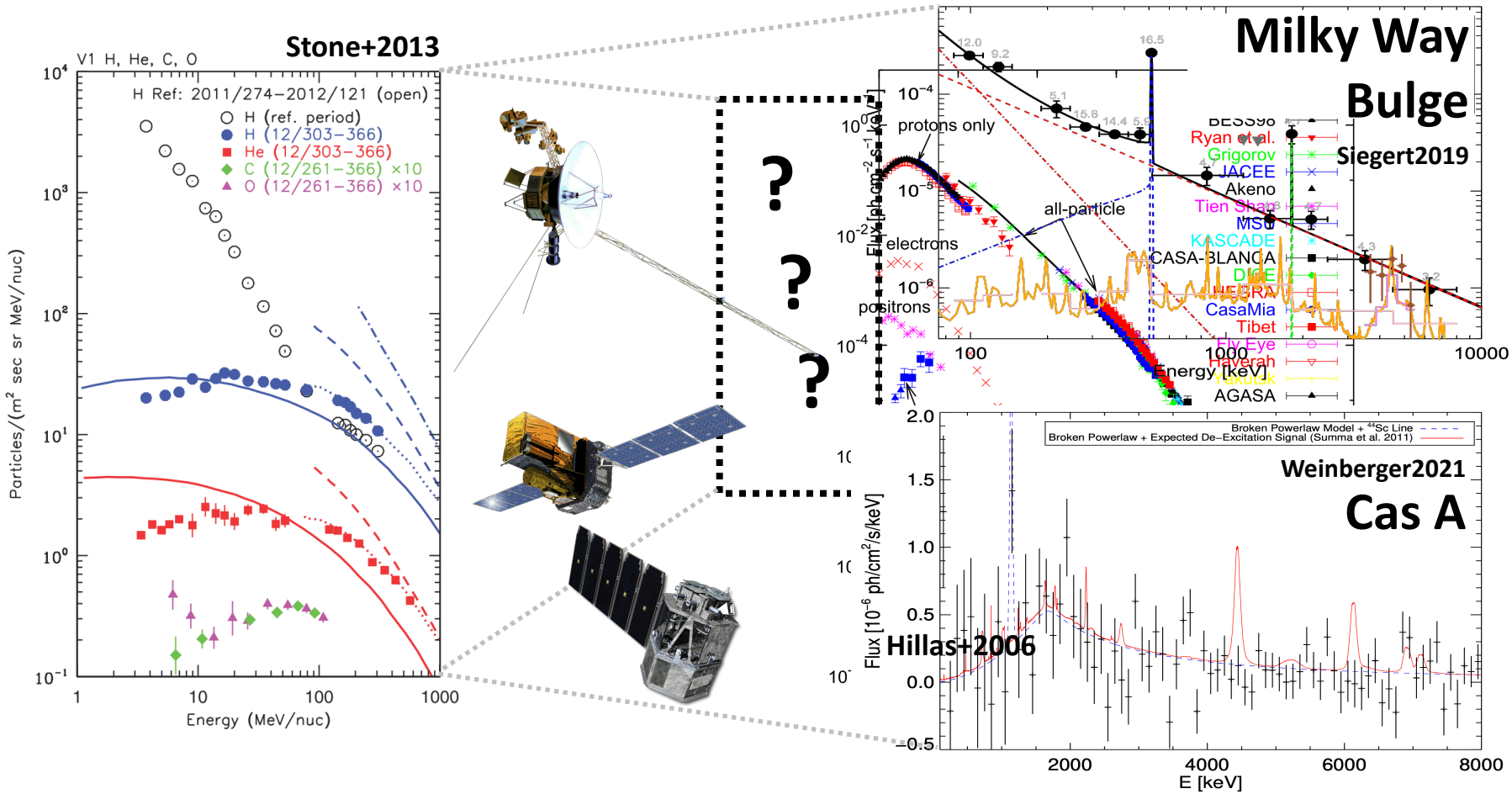
17.12.2025, MeV-PeV Frontiers, Tokyo, Japan

The MeV range - A Messenger for Everything



Cosmic-Ray De-Excitation Lines

Questions: **1) How does particle acceleration work?**
2) What are the abundances in the ISM / SNR / CSM?
3) What is the low-energy cosmic-ray spectrum?

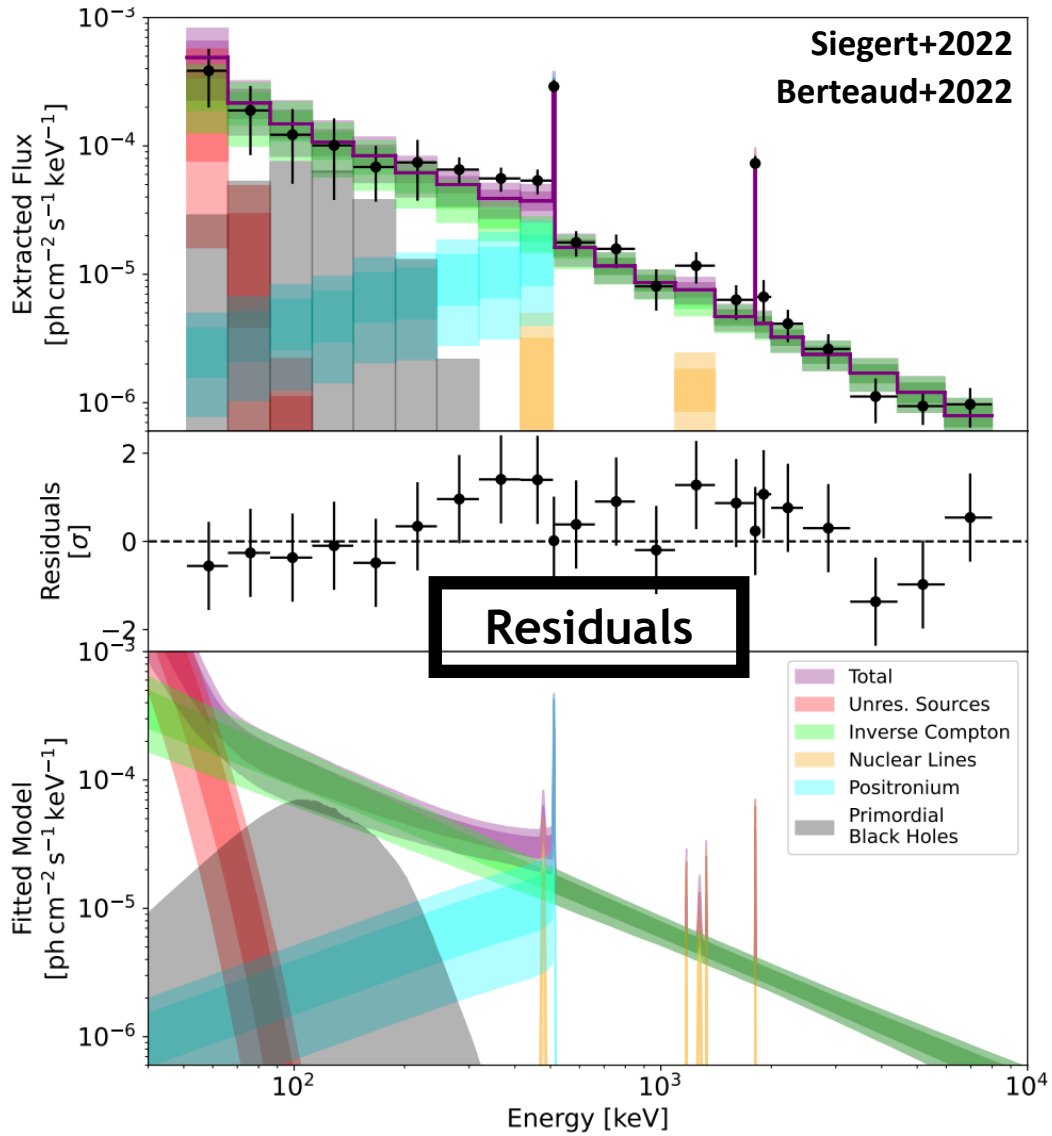


The Milky Way in MeV Gamma-Rays

Positronium 511 keV + ortho-Ps

Unresolved Point Sources

Astrophys. Model Components



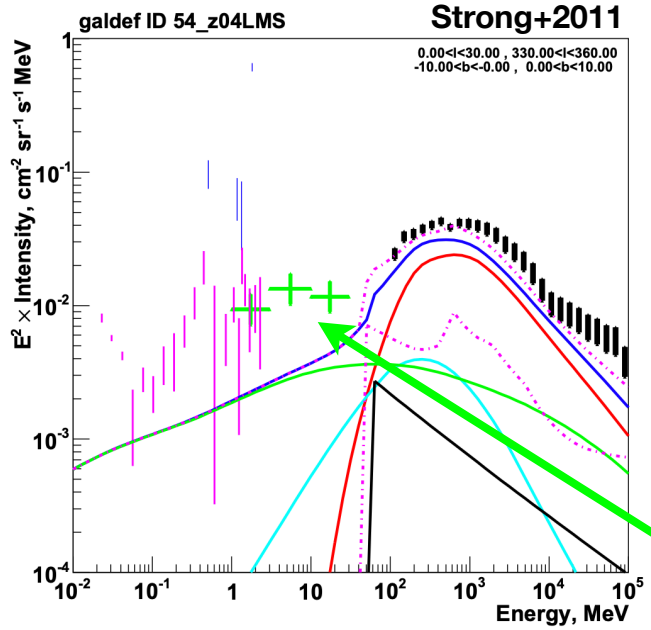
INTEGRAL/ SPI Data Points

Inverse Compton Scattering

Nuclear Decay Lines ^{26}Al, ^{60}Fe, …

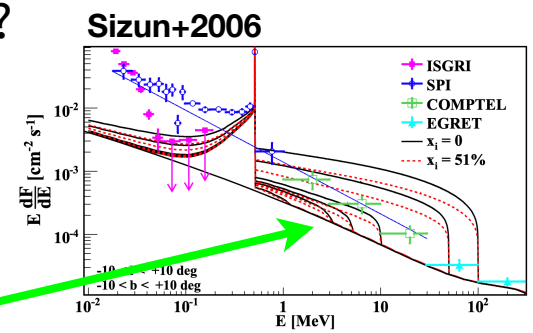
The “COMPTEL Bump”

Until ~2013

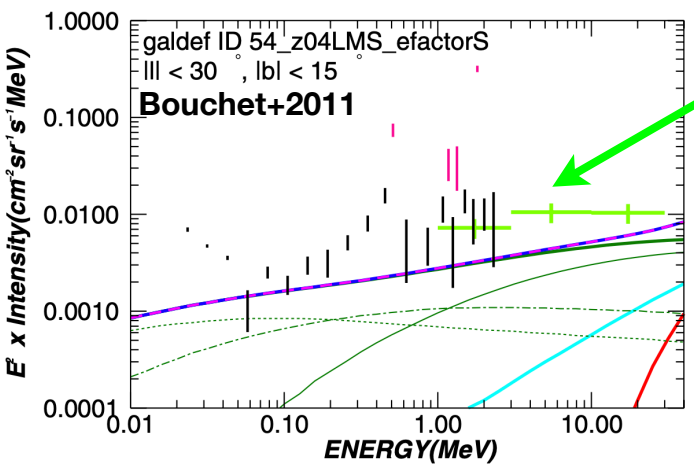


Search for positron annihilation in flight:

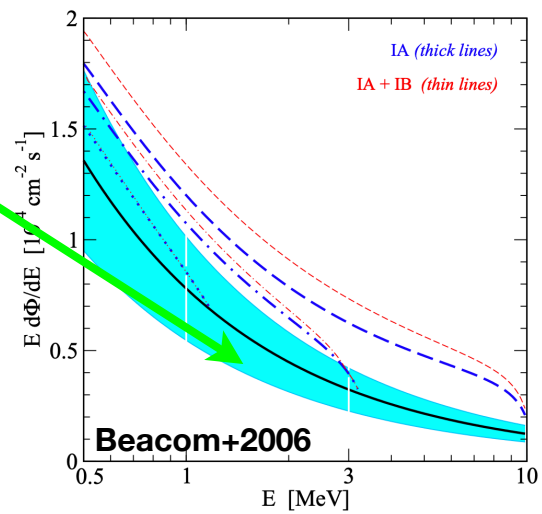
- ➡ Positron sources (injection energy)
- ➡ Dark matter?



“COMPTEL Bump”???



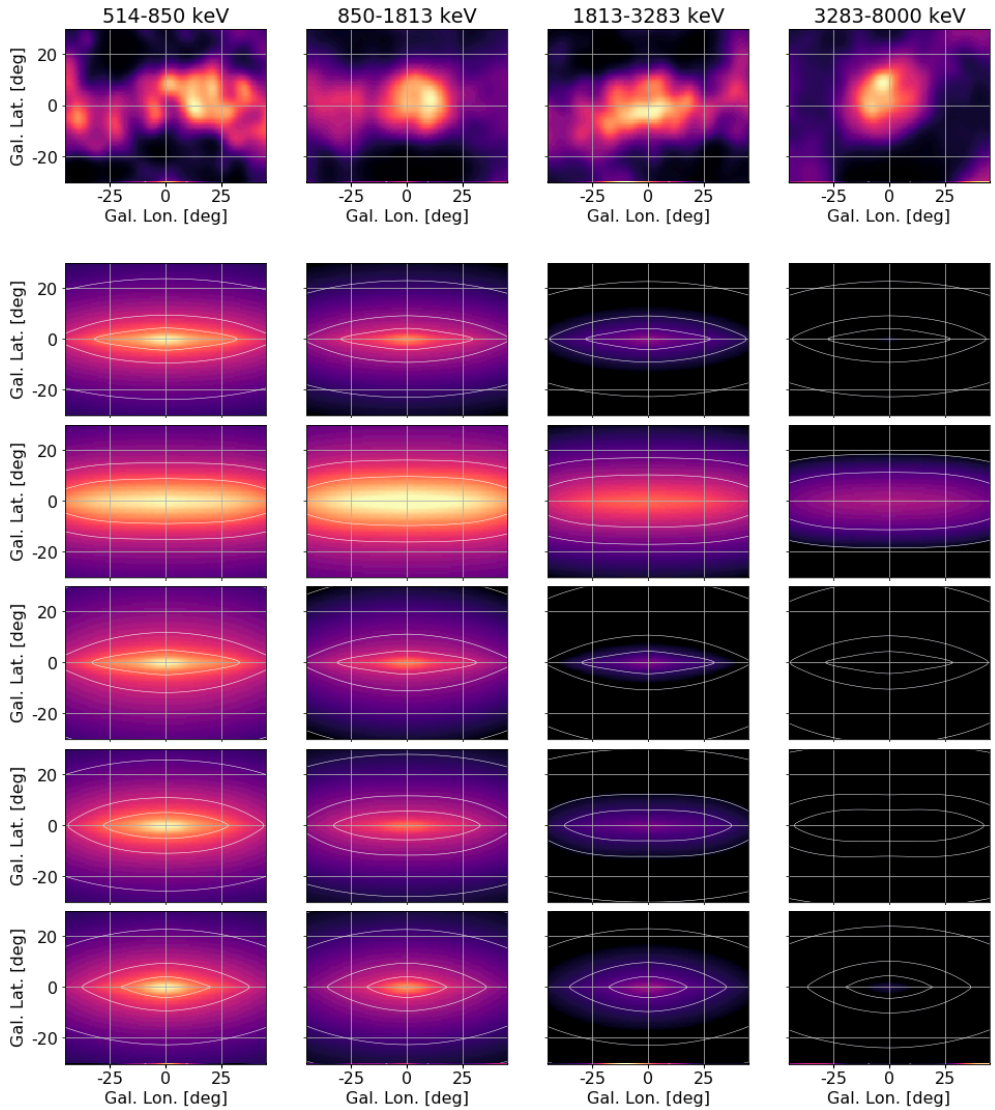
IC (2x e⁻)
IC (optical)
Bremsstrahlung
IC (IR)
IC (CMB)
π⁰ decay



SPI Spatial Fit - Inverse Compton

GALPROP (v56) Spatial Models

Testing systematic flux variations



Background-only residuals

Bisschoff+2019
(Incl. Voyager data)

$\delta_1 = 0$
(low rigidities)

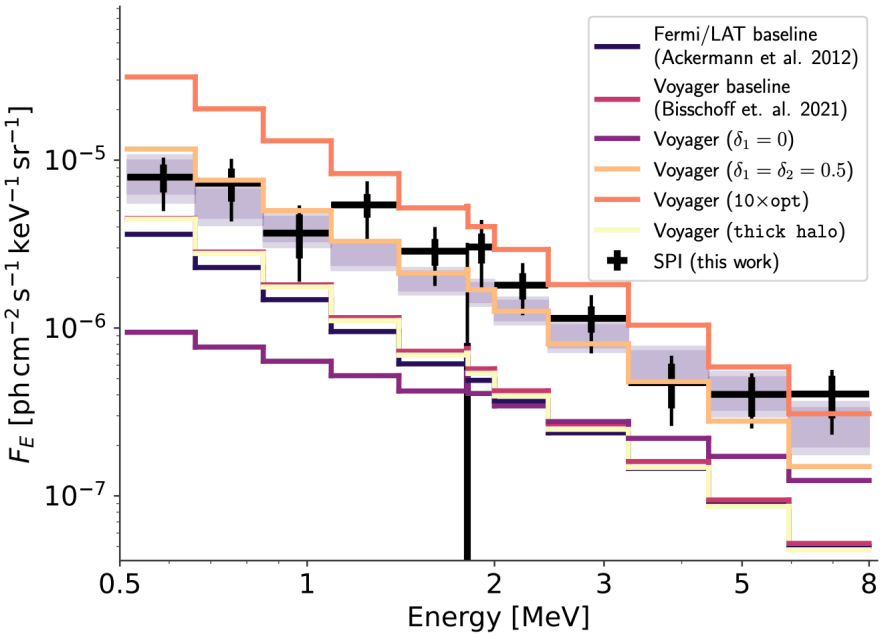
ISRF(opt) x 10
(central star light)

z = 8 kpc
(halo size / diffusion)

$\delta_1 = \delta_2 = 0.5$
(secondary/primary)

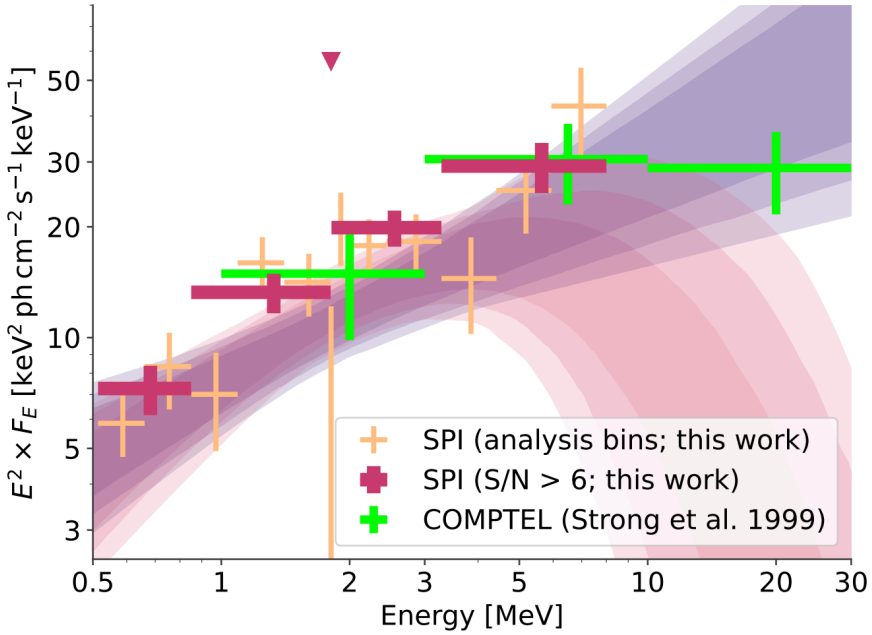
SPI Spectral Modelling

GALPROP (v56) Spectral Models



$\delta_1 = \delta_2 = 0.5$:
secondary/primary important in 0.5–8 MeV
ISRF(opt.) x 10:
Too much, too steep
$\delta_1 = 0$:
Too shallow, no turn-over

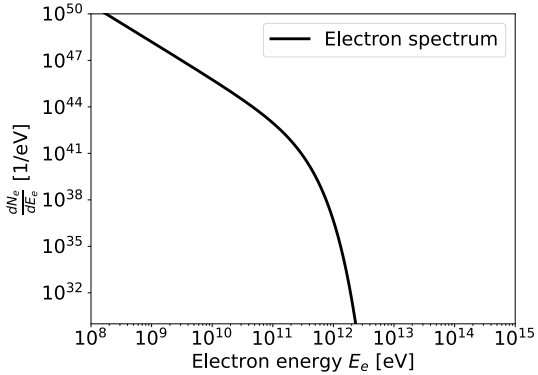
Comparison to COMPTEL

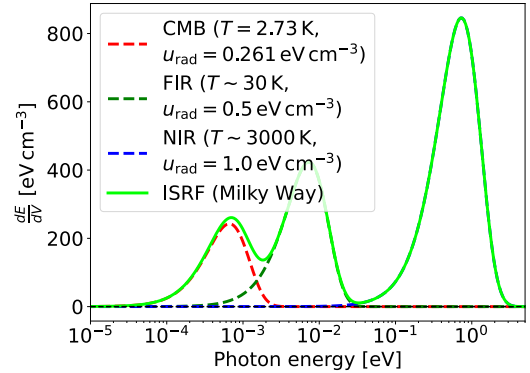


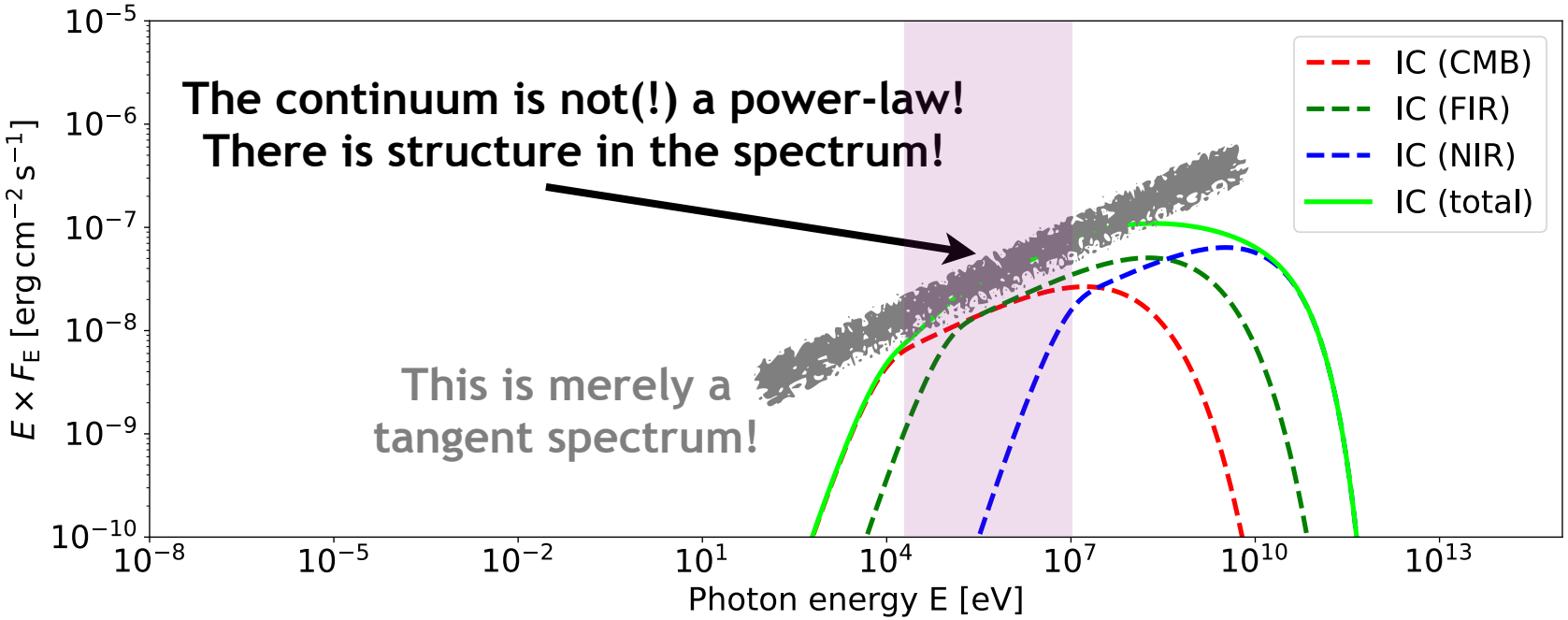
Power-law: $C_0(E/\mathrm{MeV})^\alpha$
$C_0 = (3.1 \pm 0.3) \times 10^{-6}$ ph/cm^2/s/keV/sr
$\alpha = -1.39 \pm 0.09$
Cut-off power-law: $C_0(E/\mathrm{MeV})^\alpha \exp(-E/E_C)$
$\alpha = -0.95 \pm 0.16$
$E_C = 4.9 \pm 1.4$ MeV (Bouchet+2011: 4.0±1.8 MeV)

Modelling the Galaxy

Inverse Compton Scattering

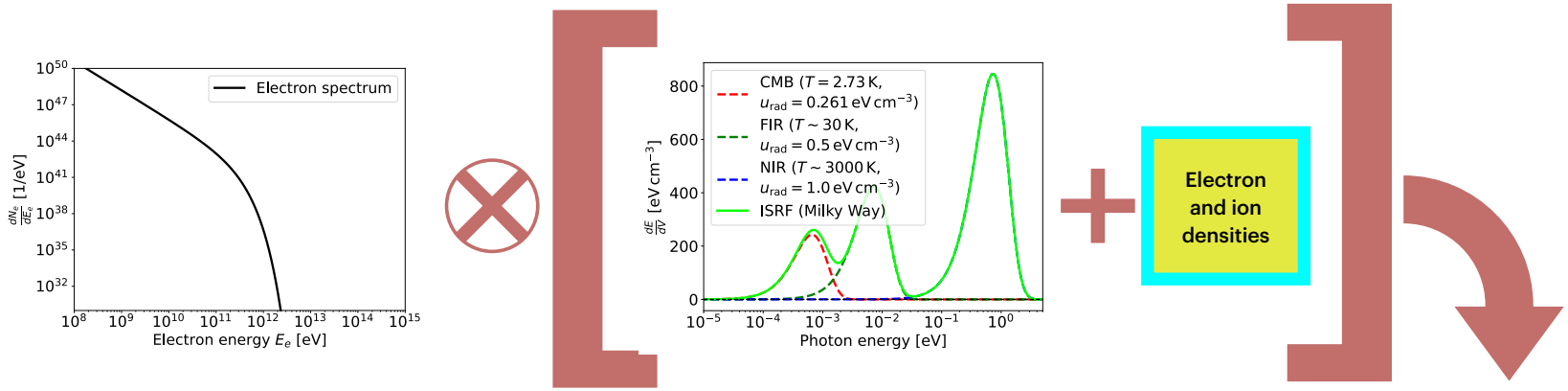


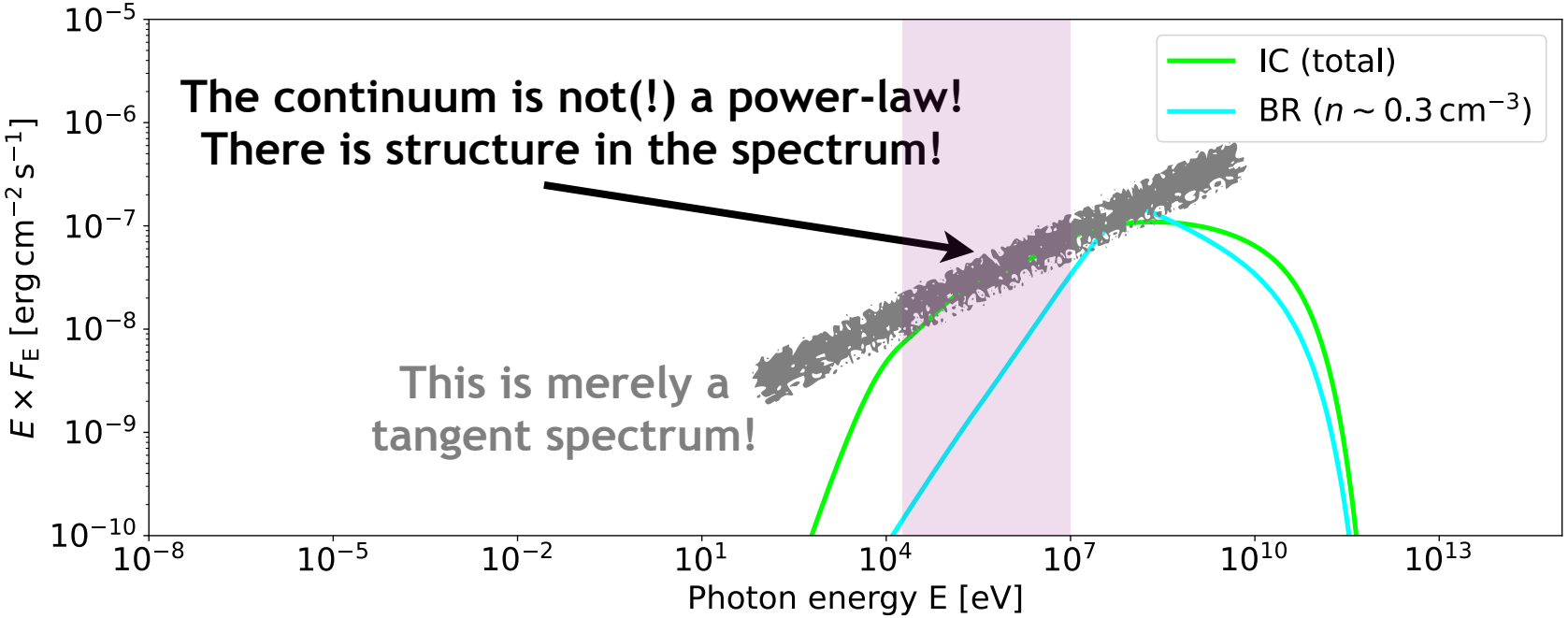




Modelling the Galaxy

Bremsstrahlung



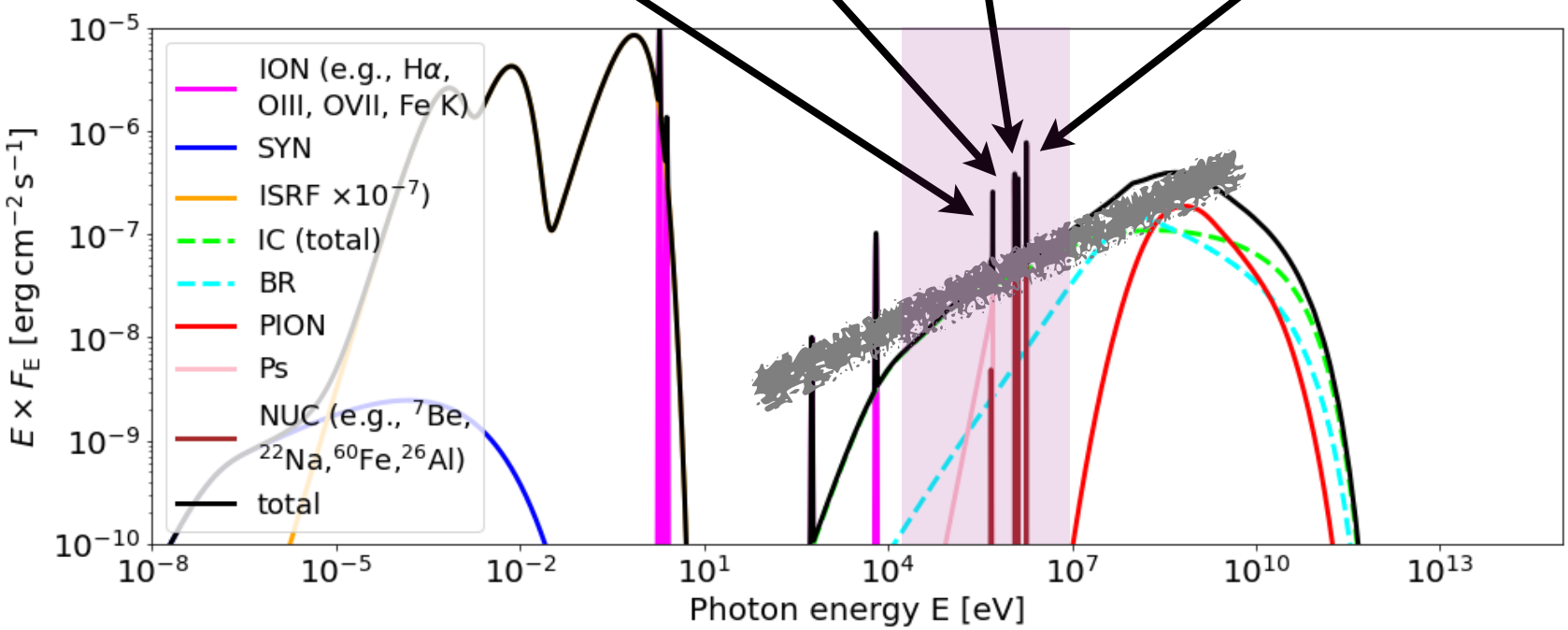


Modelling the Galaxy

Detected High-Energy Components

About ~25 “good” data points between 50 and 8000 keV

Some gamma-ray lines peak out:
511 keV, ^{60}Fe (1173, 1332 keV), ^{26}Al (1809 keV)

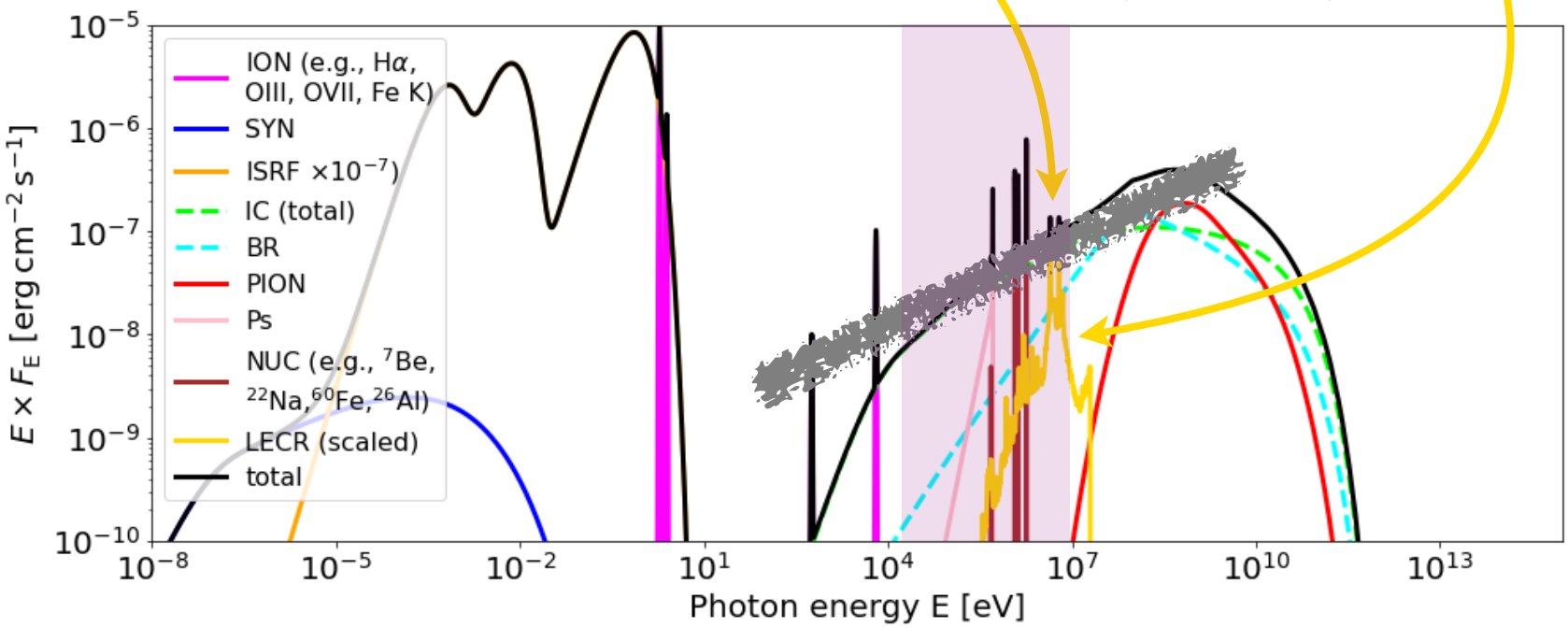


Modelling the Galaxy

Missing Components

Low-Energy Cosmic-Ray De-Excitation Lines

LECR gamma-ray lines:
^{12}C (4439 keV),
^{16}O (6129 keV)



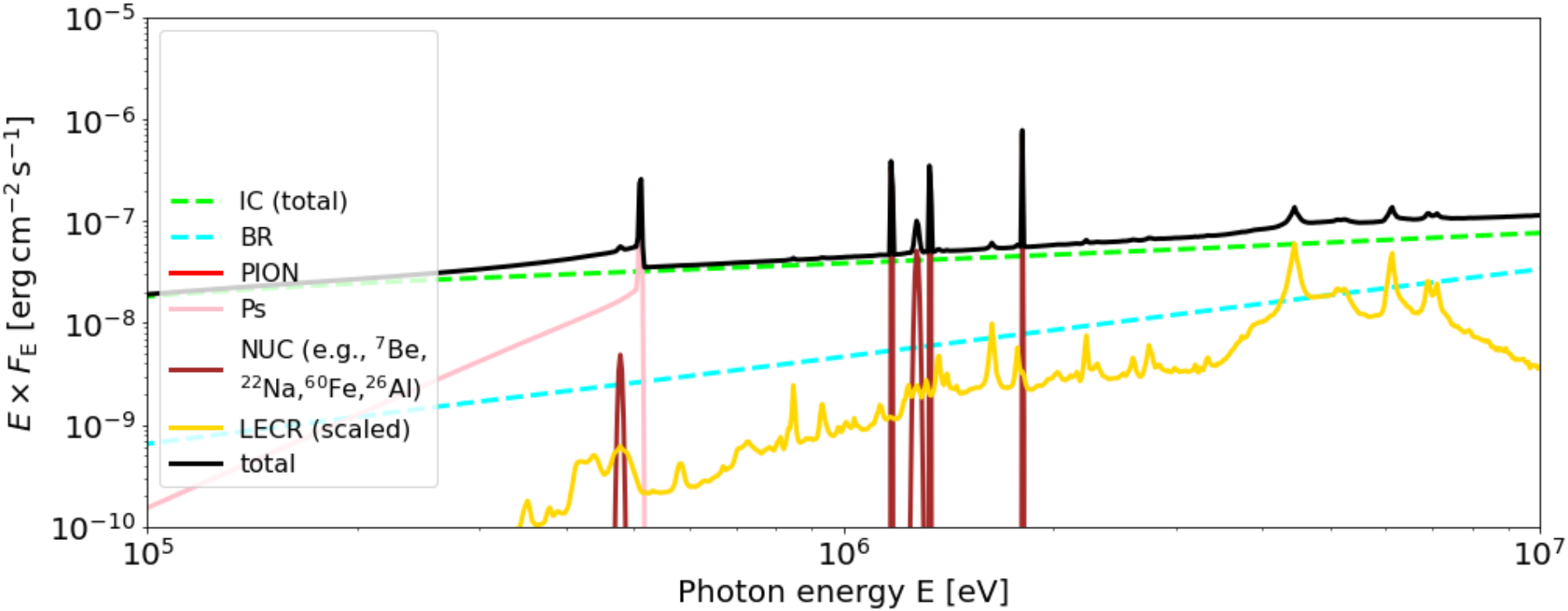
Modelling the MeV Galaxy

Low-Energy Cosmic-Ray De-Excitation Lines

Pros/Cons:

- We have never detected any (only for Solar flares: same mechanism)
- They are at the energy boundaries of typical MeV telescopes (small effective area)

+ There are many of them (look for cumulative effect, not individual lines)
+ They should appear everywhere, plus localised (diffuse ISM, SNRs)



Calculating the LECR Gamma-Rays

Approximations in 2D (projected column densities)

De-excitation line flux (approx.) [ph/cm²/s/sr]

$$I_{\rm exc} = N_{\rm H} \sum_{\rm X} R_{\rm X} \int F_{\rm CR}(E)\, \sigma_{\rm X}(E)\, dE,$$

Cosmic Ray spectrum
Test with Broken PL & "Carrot" models adopted from e.g. Indriolo+2009

Cross section
estimated with TALYS [ver. 2.0; Koning+2023]

Hydrogen column density
$N_H = 2 \times 10^{22}$ cm^{-2}
(Roughly reproducing the diffuse GeV gamma-rays)

Abundances in ISM
Solar abundance [Lodders 2010] & Metallicity x2

Tomohiko Oka (JMU) et al. in prep. (2026)

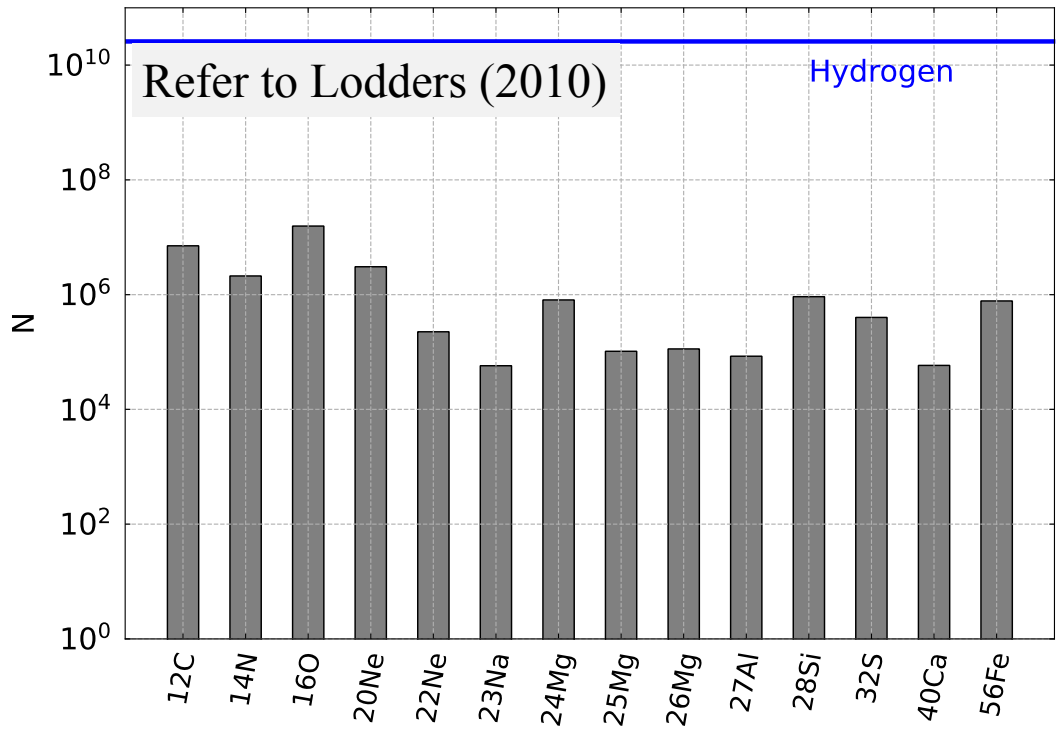
Then complete 3D modelling!

Calculating the LECR Gamma-Rays

Abundances in the ISM (may vary more then 1 oom!)

$$I_{\rm exc} = N_{\rm H} \sum_{\rm X} R_{\rm X} \int F_{\rm CR}(E)\, \sigma_{\rm X}(E)\, dE,$$

Abundances in ISM
Solar abundance [Lodders 2010]
& Metallicity x2



Tomohiko Oka (JMU) et al.
in prep. (2026)

Then complete 3D modelling!

Calculating the LECR Gamma-Rays

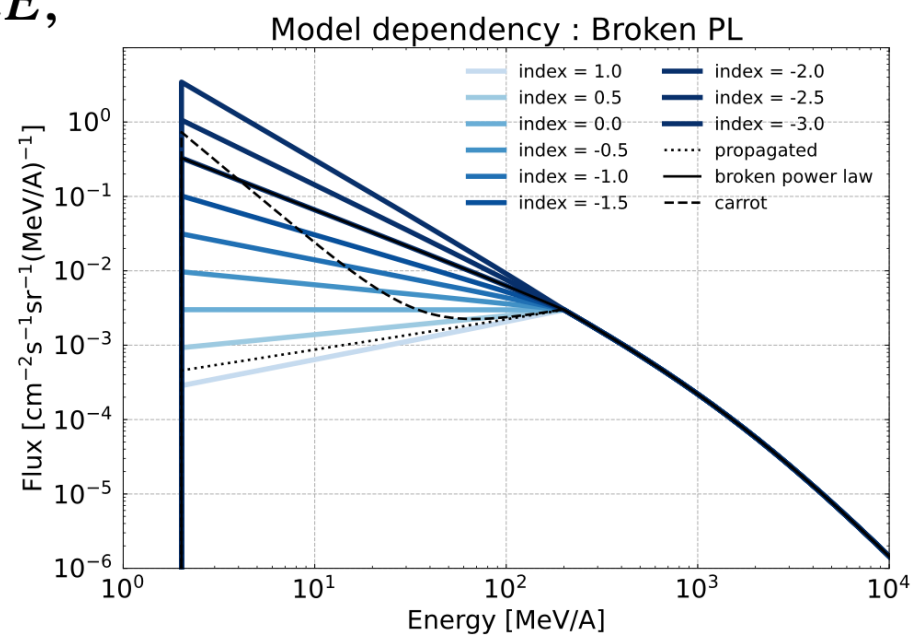
LECR spectrum (the thing we want to know)

$$I_{\rm exc} = N_{\rm H} \sum_{\rm X} R_{\rm X} \int F_{\rm CR}(E)\, \sigma_{\rm X}(E)\, dE,$$

Cosmic Ray spectrum

Test with Broken PL & "Carrot" models adopted from e.g. Indriolo+2009

Broken PL model



Tomohiko Oka (JMU) et al. in prep. (2026)

Then complete 3D modelling!

$$\phi_{\rm p} = \begin{cases} N_0 \left(\frac{p(E)}{p(E_1)}\right)^{s_{\rm high}}, & \text{if } E > E_2 \\ N_0 \left(\frac{p(E_2)}{p(E_1)}\right)^{s_{\rm high}} \left(\frac{p(E)}{p(E_2)}\right)^{s_{\rm low}}, & \text{if } E_{\rm cut} \le E \le E_2 \\ 0, & \text{if } E \le E_{\rm cut} \end{cases}$$

$$s_{\rm low} = +1.0 - -3.0$$

Calculating the LECR Gamma-Rays

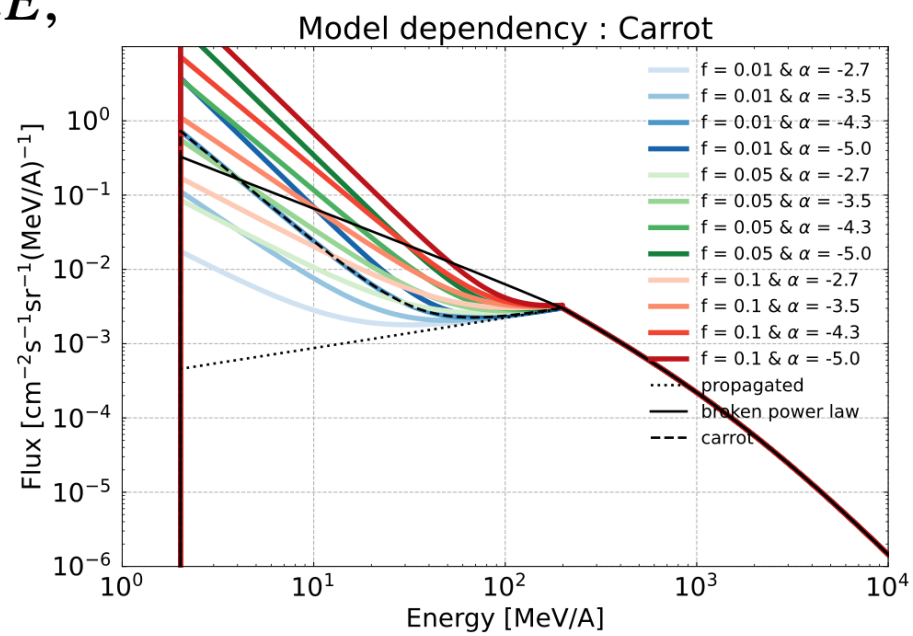
LECR spectrum (the thing we want to know)

$$I_{\rm exc} = N_{\rm H} \sum_{\rm X} R_{\rm X} \int F_{\rm CR}(E)\, \sigma_{\rm X}(E)\, dE,$$

Cosmic Ray spectrum

Test with Broken PL & "Carrot" models adopted from e.g. Indriolo+2009

Carrot model



Tomohiko Oka (JMU) et al. in prep. (2026)

Then complete 3D modelling!

$$\phi'_{\rm p} = \phi_{\rm p} + f \times N_0 \left(\frac{p(E_2)}{p(E_1)}\right)^{s_{\rm high}} \left(\frac{p(E)}{p(E_2)}\right)^{\alpha}$$

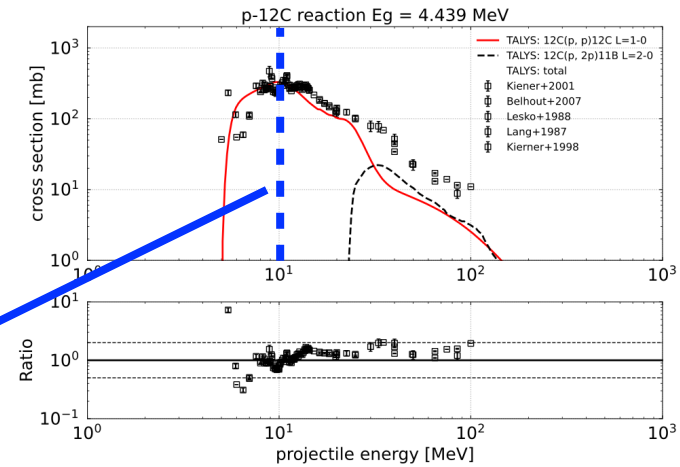
$$\alpha = -2.7 - -5.0$$
$$f = 0.01 - 0.1$$

Calculating the LECR Gamma-Rays

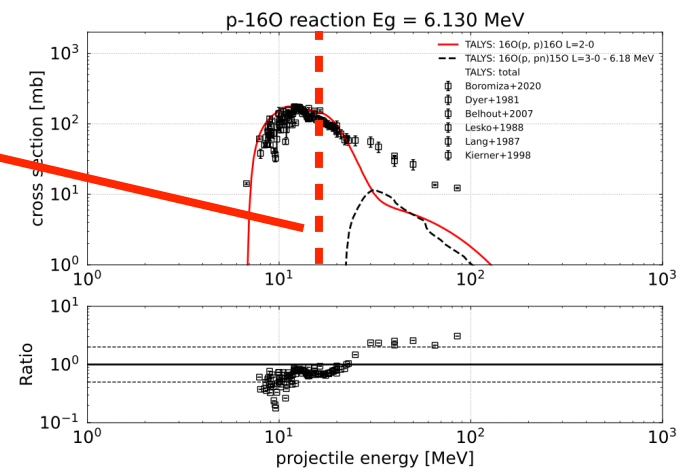
Nuclear Excitation Cross Sections (TALYS code)

$$I_{\rm exc} = N_{\rm H} \sum_{\rm X} R_{\rm X} \int F_{\rm CR}(E)\, \sigma_{\rm X}(E)\, dE,$$

Cross section
estimated with TALYS
[ver. 2.0; Koning+2023]



For simplicity of illustration:
Use max cross section
at mean energy:
^{12}C: 10 MeV
^{16}O: 20 MeV



Tomohiko Oka (JMU) et al.
in prep. (2026)

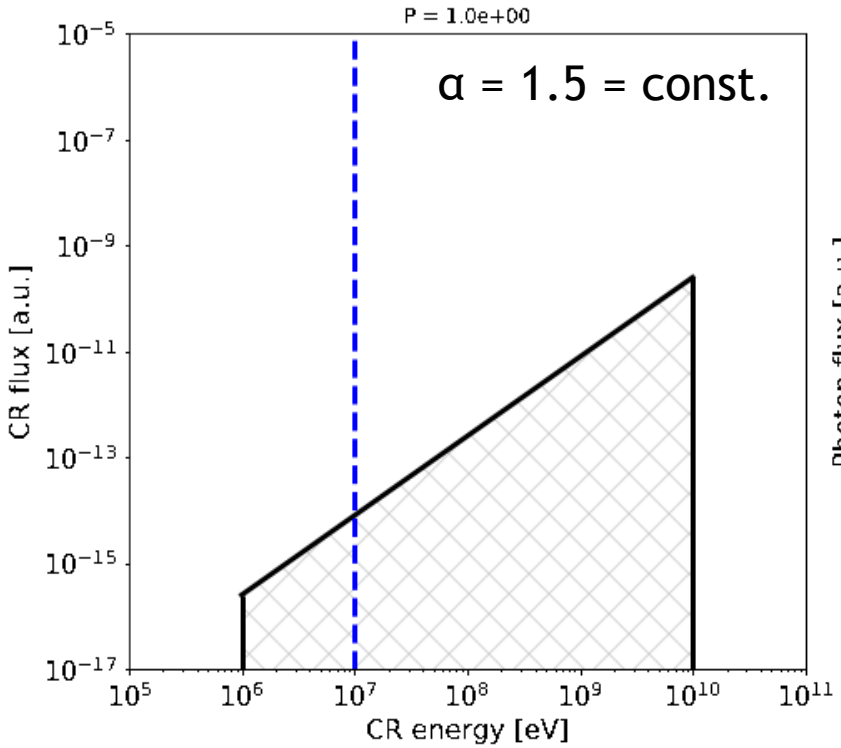
Then complete 3D modelling!

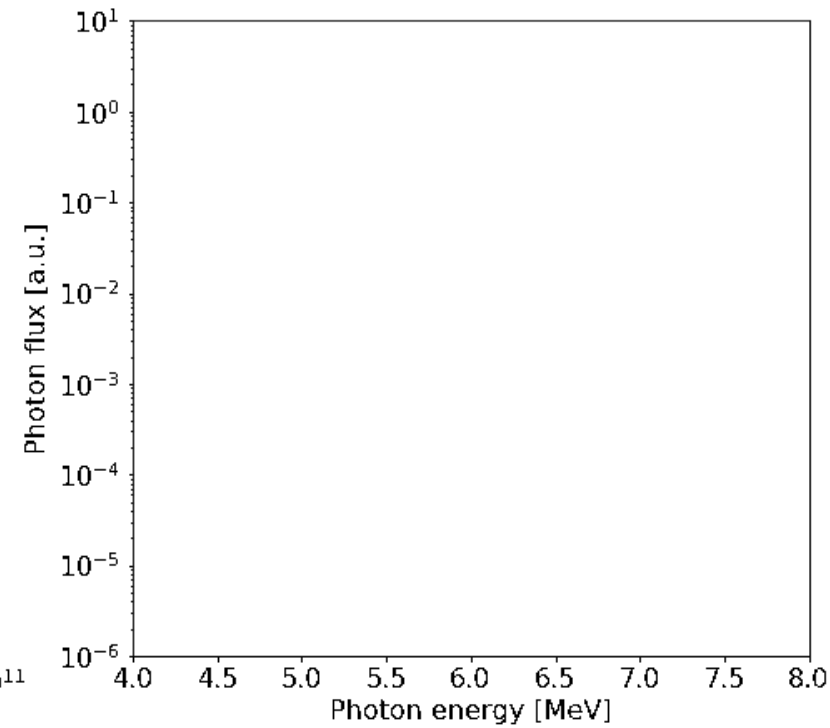
What does it help to measure LECR lines?

LECR lines step-by-step: **Step 1: Varying the total power P**

- CR proton spectrum: $\frac{dN}{dE} = P \cdot \frac{\alpha + 2}{E_{\max}^{\alpha+2} - E_{\min}^{\alpha+2}} E^{\alpha}$ Total Power: $\int_{E_{\min}}^{E_{\max}} \frac{dN}{dE} E\, dE = P$
- Only ^{12}C in the ISM: Strongest line 4.439 MeV

➡ **Get P from one measured line.**



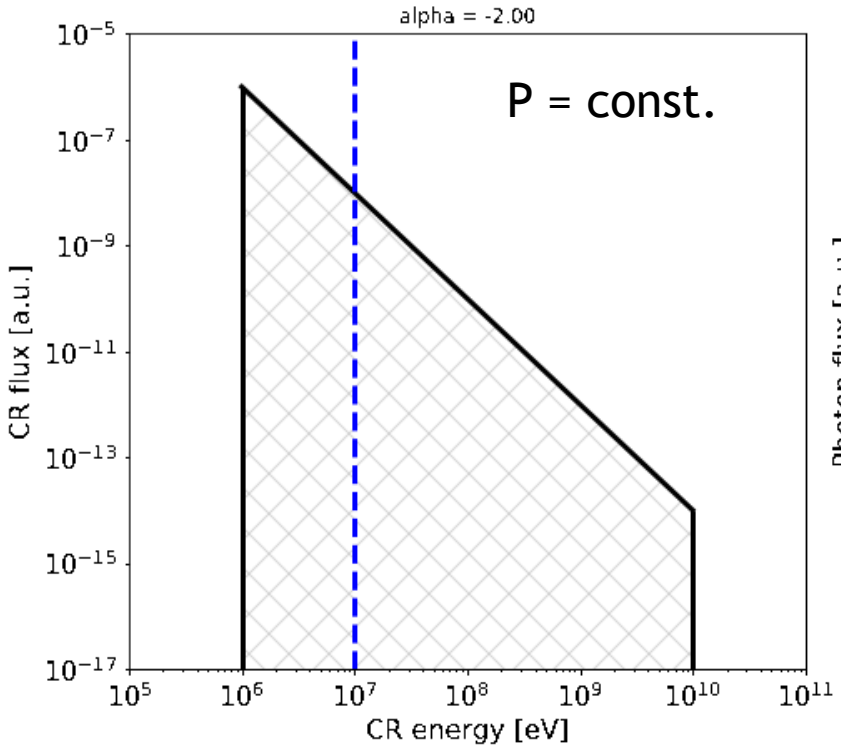


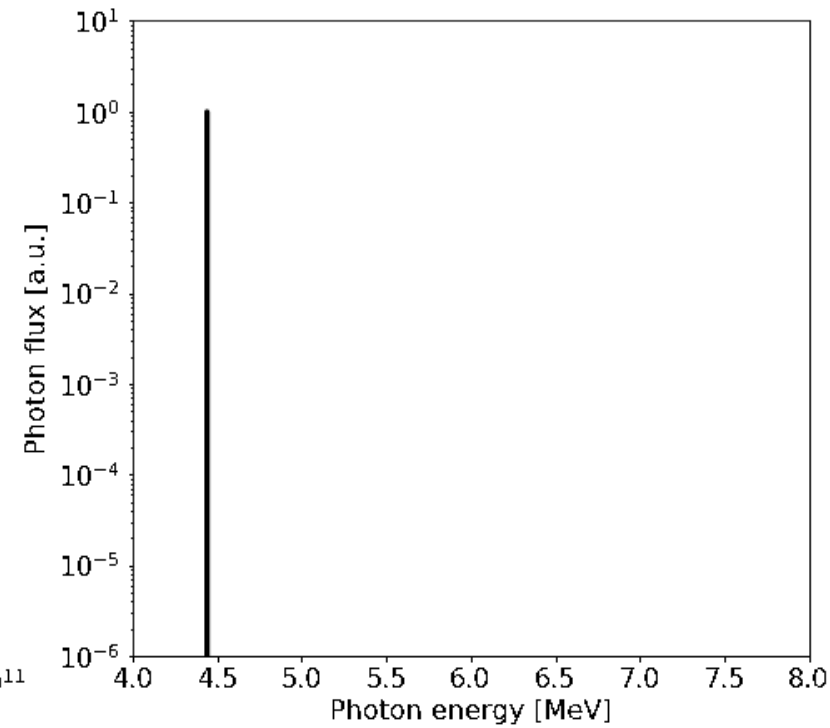
What does it help to measure LECR lines?

LECR lines step-by-step: **Step 2: Varying the index α**

- CR proton spectrum: $\frac{dN}{dE} = P \cdot \frac{\alpha+2}{E_{\max}^{\alpha+2} - E_{\min}^{\alpha+2}} E^{\alpha}$ Total Power: $\int_{E_{\min}}^{E_{\max}} \frac{dN}{dE} E\, dE = P$
- Only ^{12}C in the ISM: Strongest line 4.439 MeV

➡ **But P is degenerate with α.**



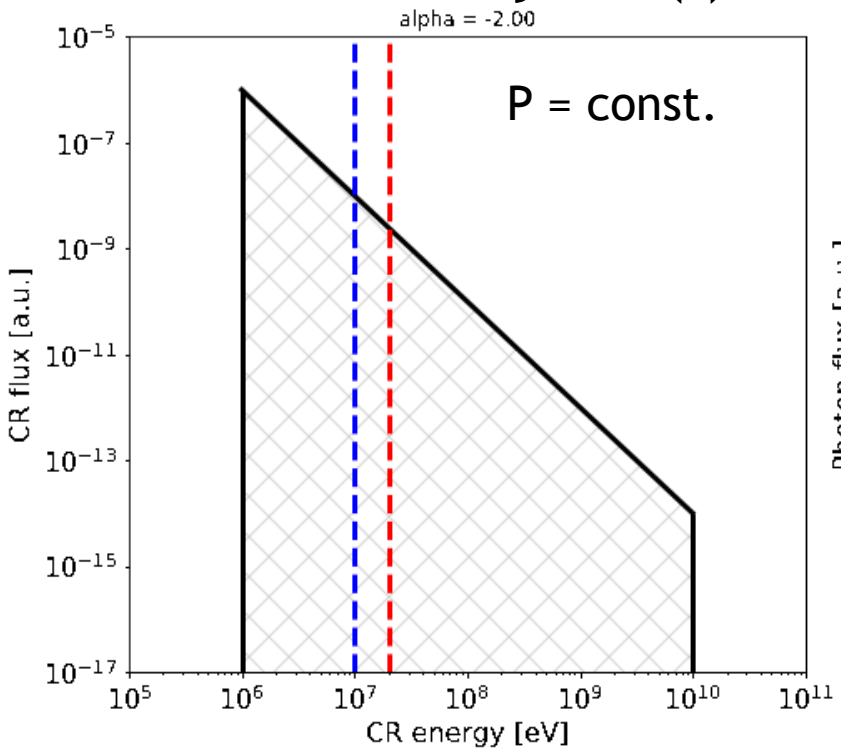


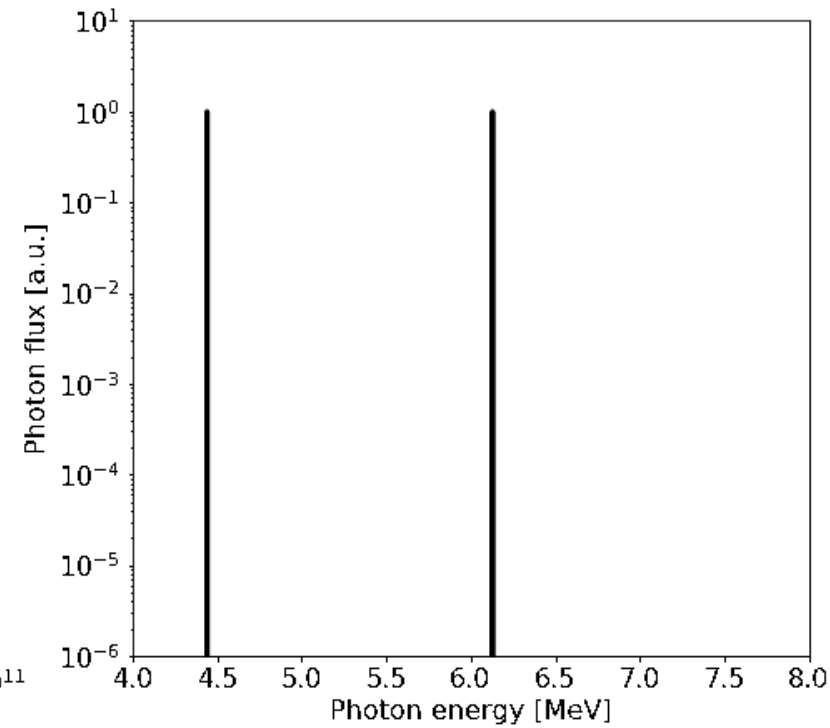
What does it help to measure LECR lines?

LECR lines step-by-step: **Step 3: Adding other elements**

- CR proton spectrum: $\frac{dN}{dE} = P \cdot \frac{\alpha + 2}{E_{\max}^{\alpha+2} - E_{\min}^{\alpha+2}} E^{\alpha}$ Total Power: $\int_{E_{\min}}^{E_{\max}} \frac{dN}{dE} E\, dE = P$
- ^{12}C & ^{16}O in the ISM: Strongest lines 4.439, 6.129 MeV

➡ **Get α/P from only two(!) measured lines!**



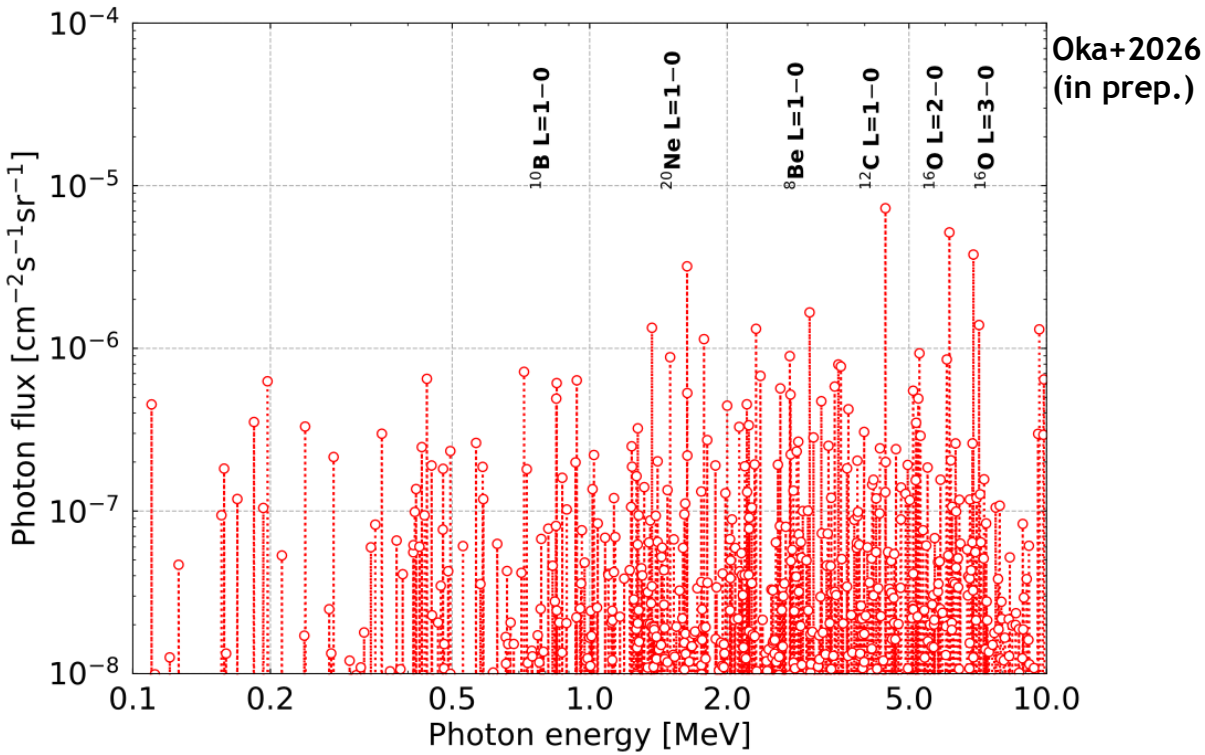


What does it help to measure LECR lines?

LECR lines step-by-step: **Step 5: Add more lines / elements**

- CR proton spectrum: $\frac{dN}{dE} = P \cdot \frac{\alpha+2}{E_{\max}^{\alpha+2} - E_{\min}^{\alpha+2}} E^{\alpha}$ Total Power: $\int_{E_{\min}}^{E_{\max}} \frac{dN}{dE} E\,dE = P$
- All elements in the ISM: many many lines

➡ **Get α and(!) P from three+ measured lines! (+ LECR shape!)**

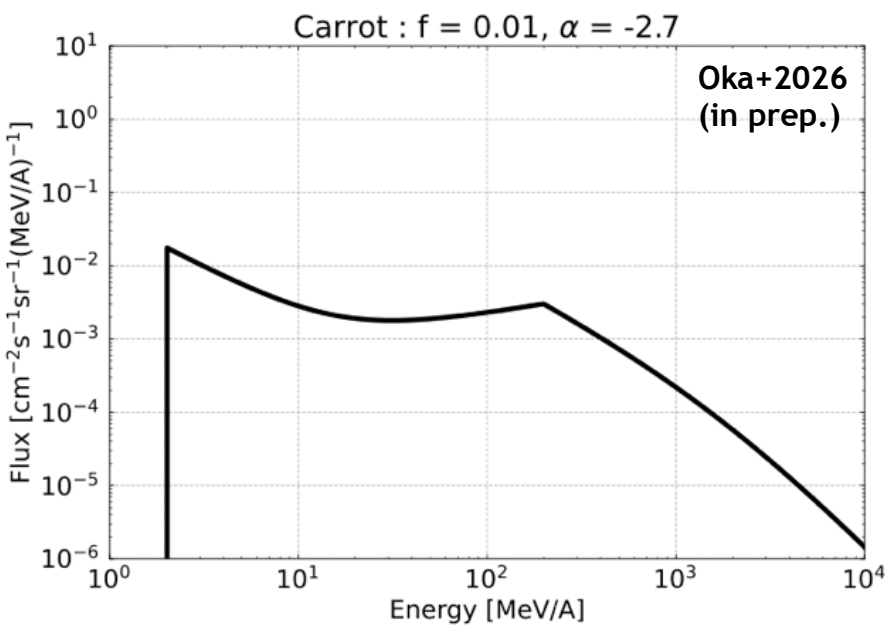


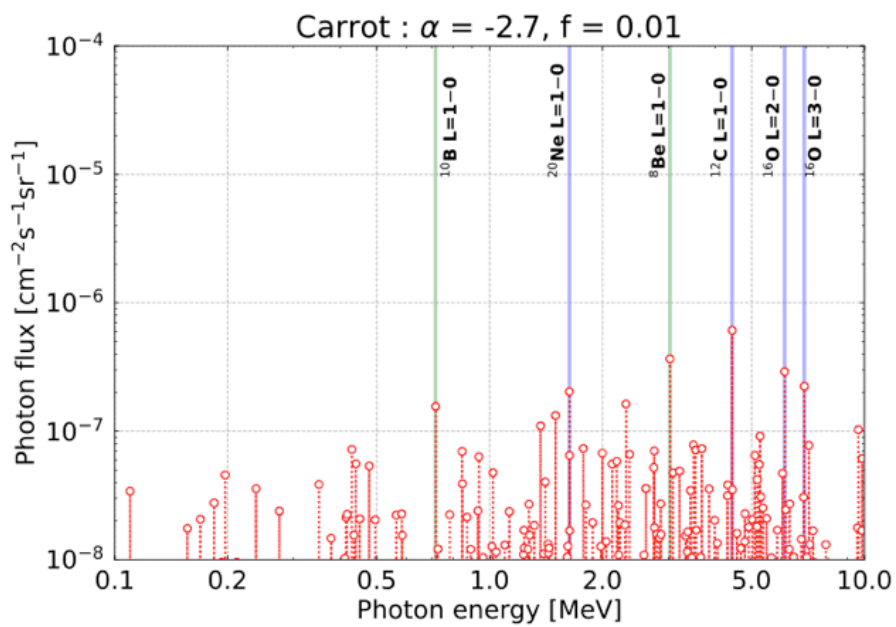
What does it help to measure LECR lines?

LECR lines step-by-step: **Step 5: Add more lines / elements**

- CR proton spectrum: $\frac{dN}{dE} = P \cdot \frac{\alpha+2}{E_{\max}^{\alpha+2} - E_{\min}^{\alpha+2}} E^{\alpha}$ Total Power: $\int_{E_{\min}}^{E_{\max}} \frac{dN}{dE} E\,dE = P$
- All elements in the ISM: many maye lines

➡ **Get α and(!) P from three+ measured lines! (+ LECR shape!)**

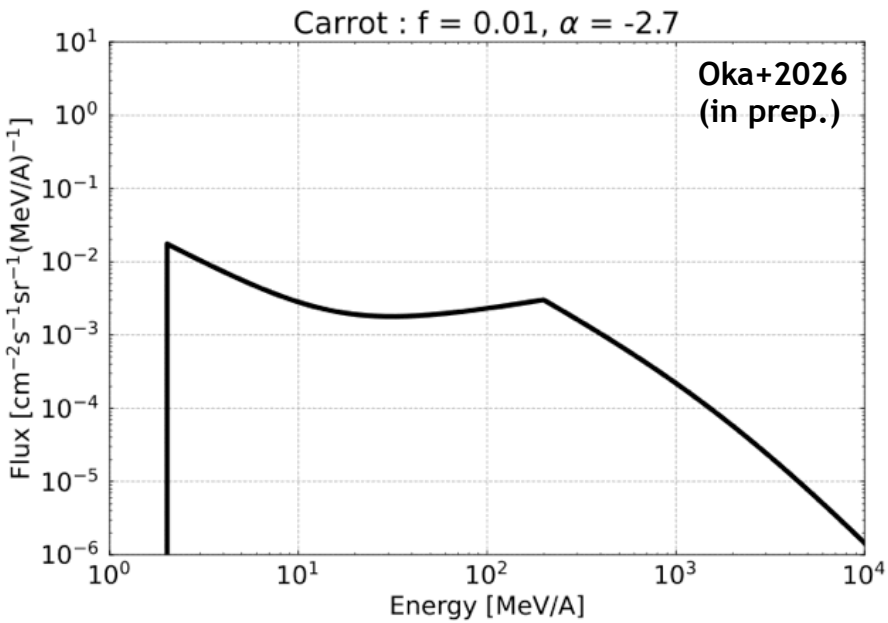


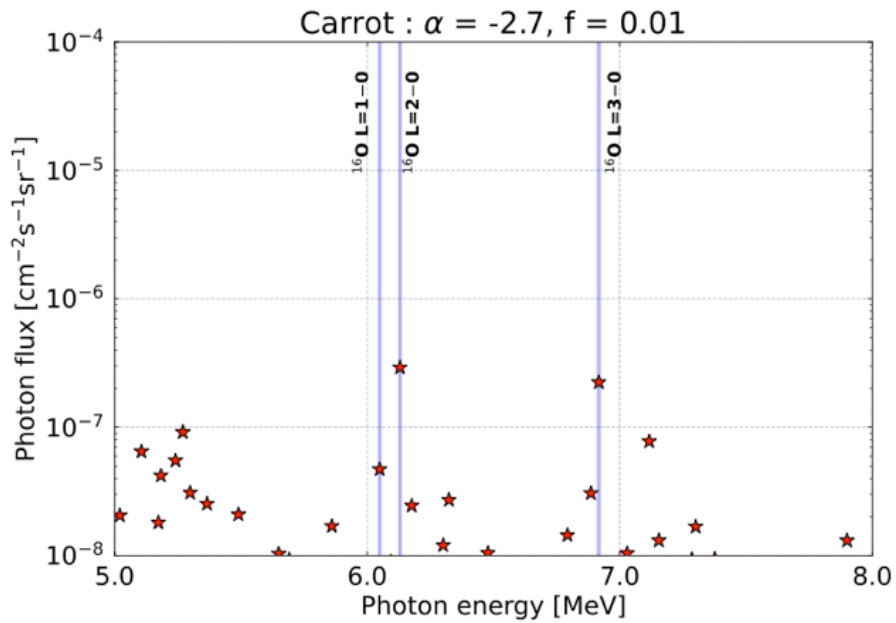


What does it help to measure LECR lines?

LECR lines step-by-step: **Step 6: Carefully check TALYS**

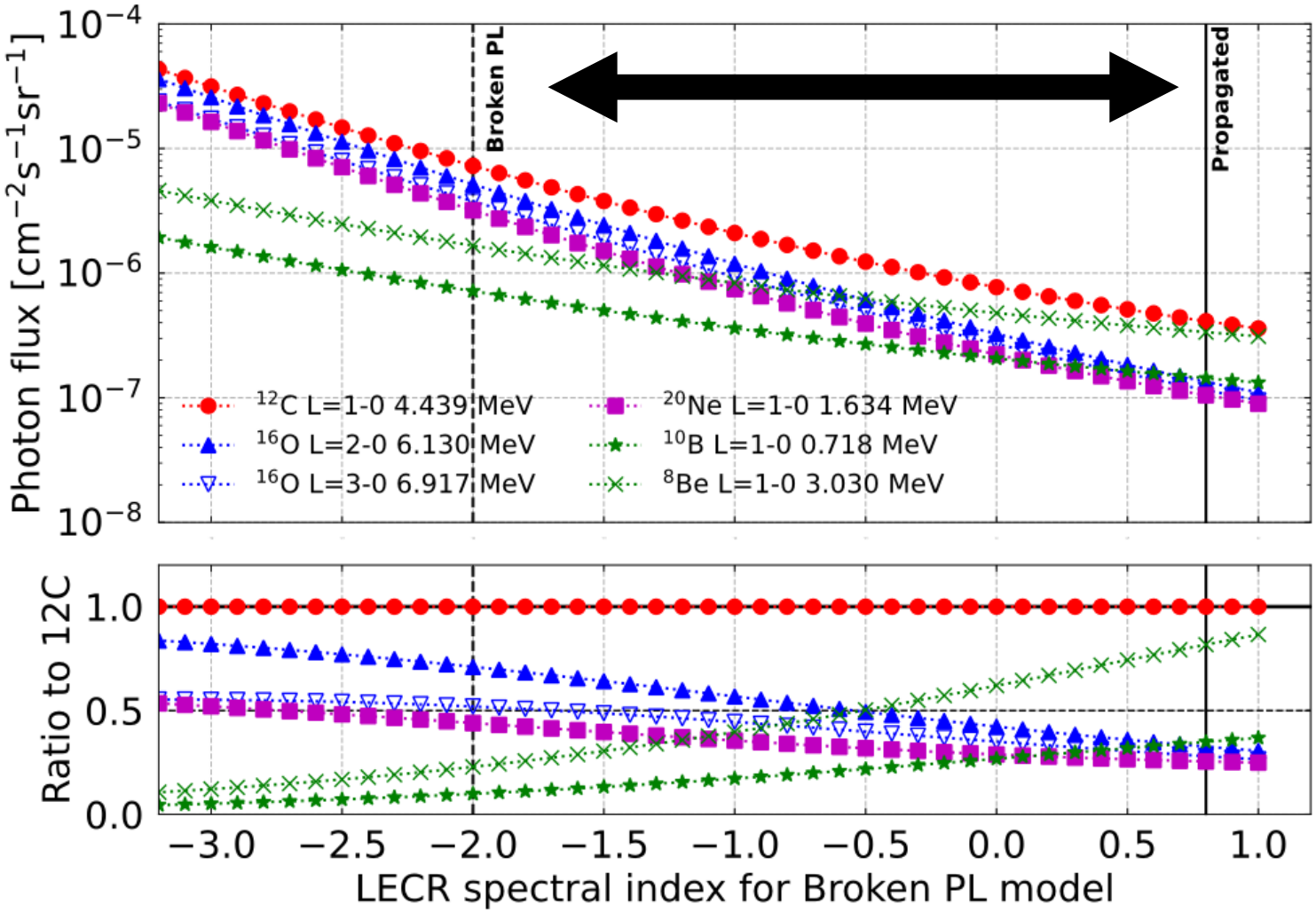
- TALYS does not check if line is forbidden
- ^{16}O L=1–0 is an E0 transition (no gamma-rays!)
- ^{16}O L=1–0 is **internal pair creation** (**IPC:** e^+/e^- pair created!)
- **$^{16}O^*$(6049) is not a real γ-ray, but leads to 2.5 MeV positrons**





What does it help to measure LECR lines?

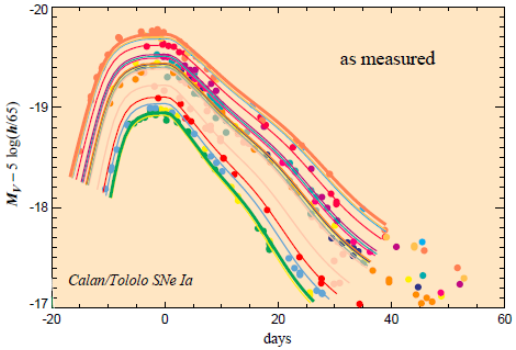
Line flux ratios for strongest lines



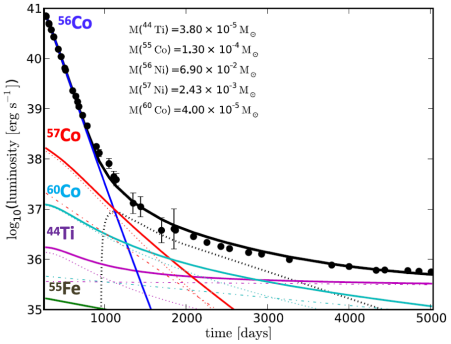
Supernovae: Timescales

Non-gamma-ray observations

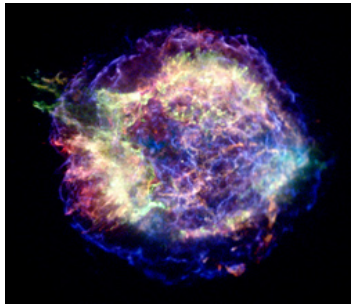
Explosion



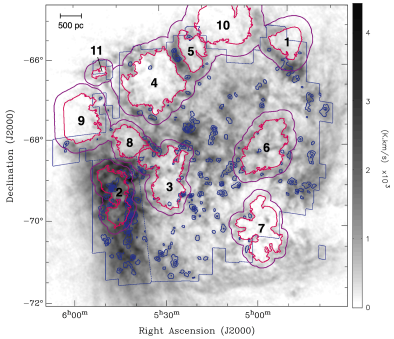
Lightcurve



Remnant



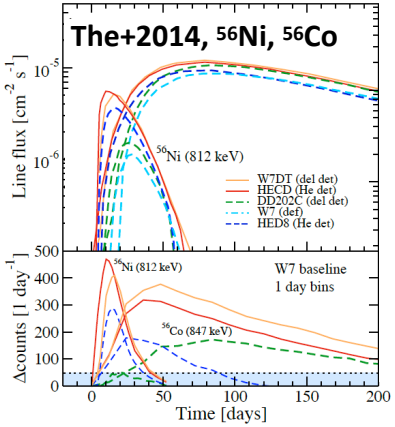
Superbubble

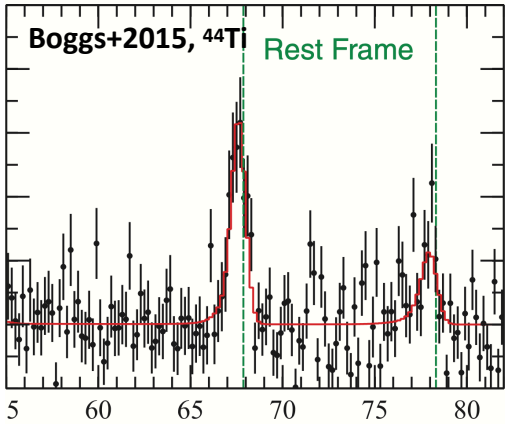


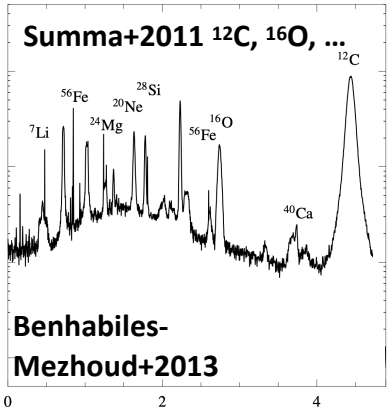
Day -20–50 | Day <5000 | Year <1000 | Year <10^7

$<10^7$ s | $<10^9$ s | $<10^{11}$ s | $<10^{15}$ s

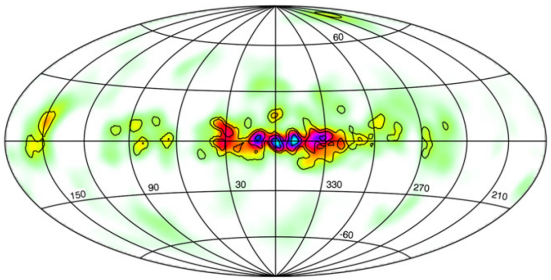
Gamma-ray observations and modelling







Bouchet+2015, ^{26}Al

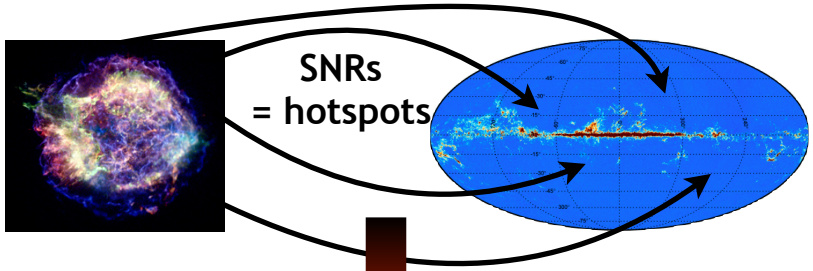


SN Remnants vs. Galactic Diffuse

Pathway to solve the onset of particle acceleration

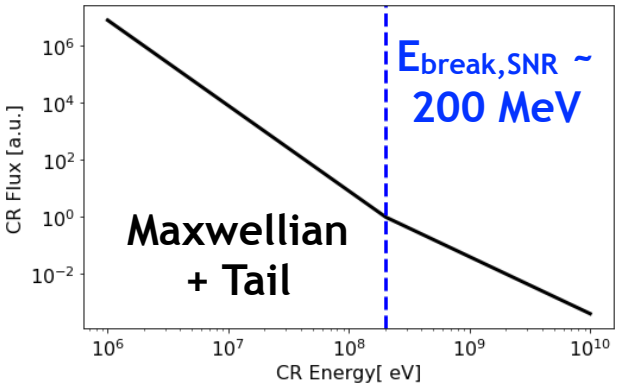
Injection at SNRs

$E_{inj} \sim E_{break,SNR}$

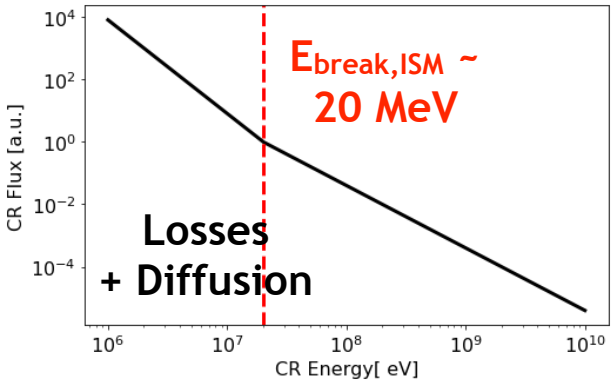


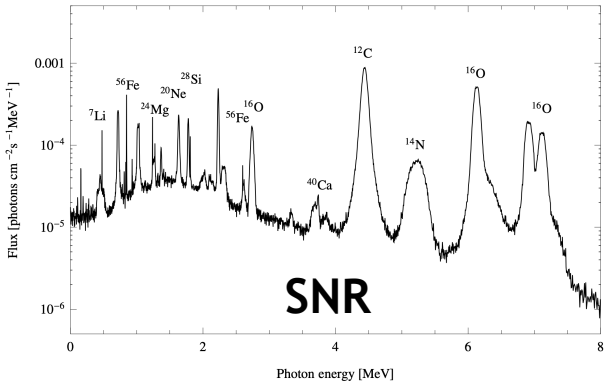
Propagation in ISM

$E_{inj,prop} \sim E_{break,ISM}$

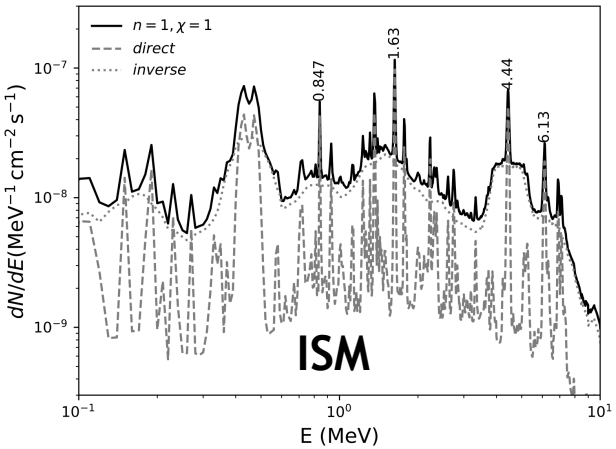


"Inference"





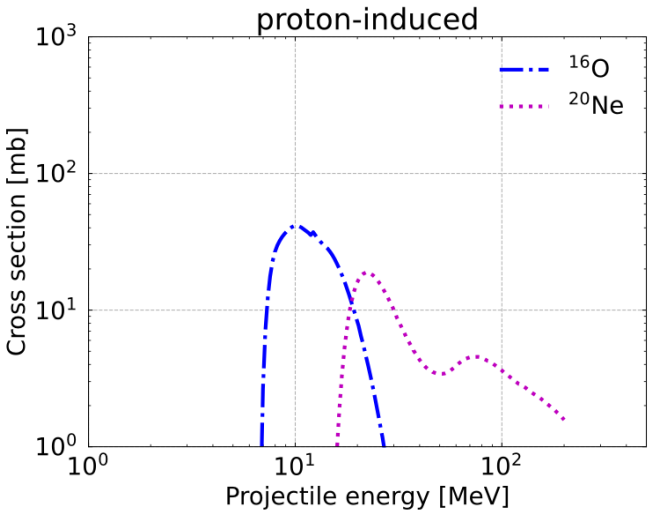
"Measurements"

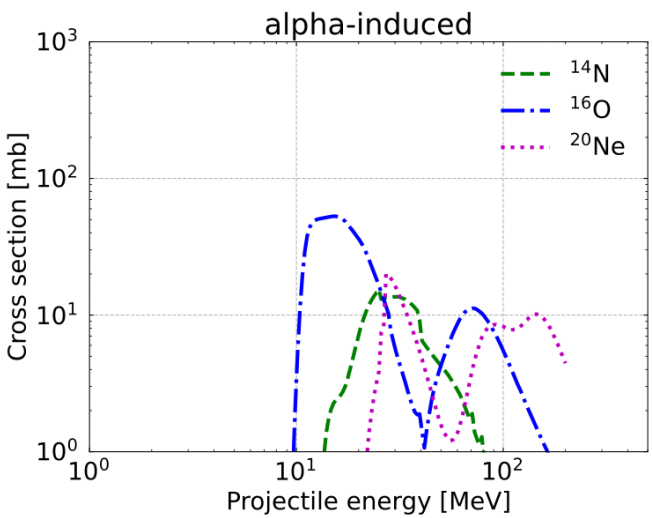


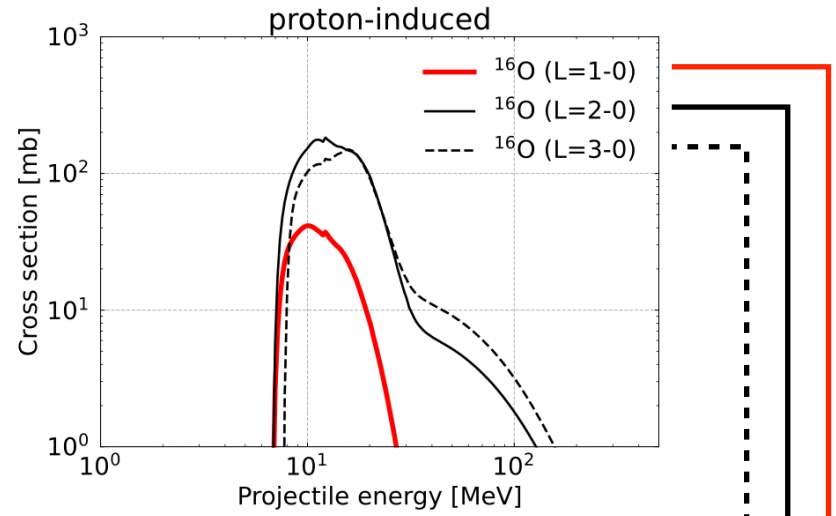
Internal Pair Creation: Link to 511 keV

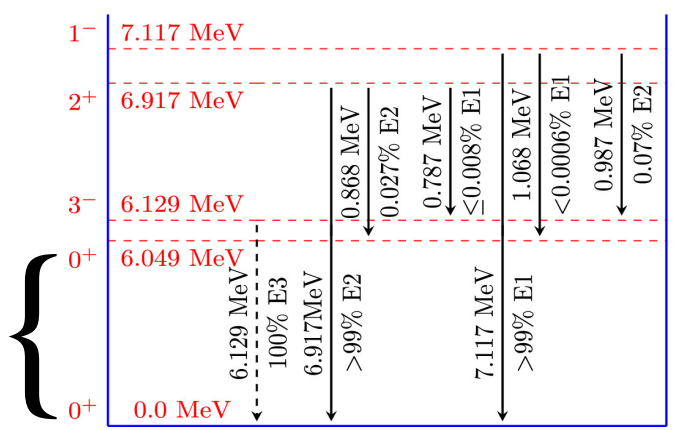
$CR + X \rightarrow 16O^* \rightarrow e^+/e^-(5.027/2\ MeV)$

$CR + X \rightarrow 16O^* \rightarrow anything$





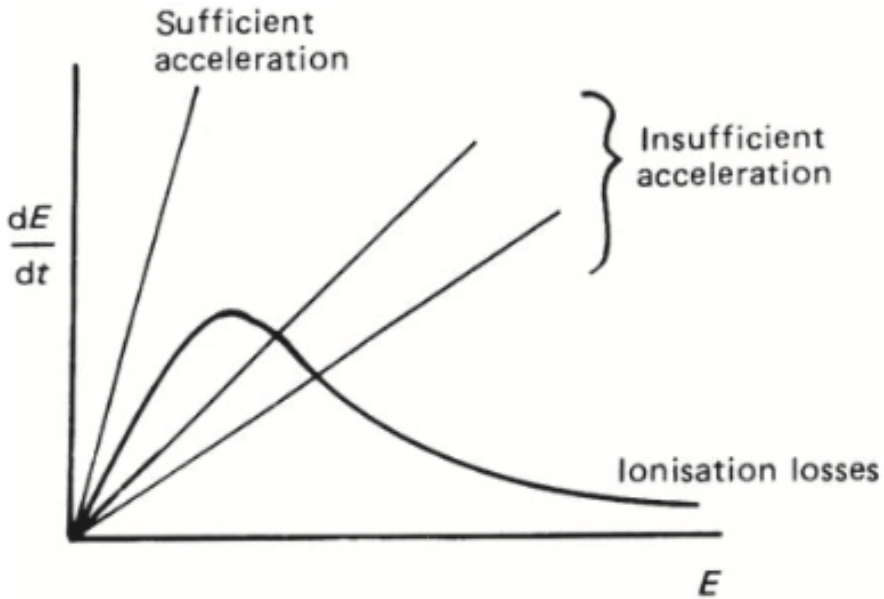


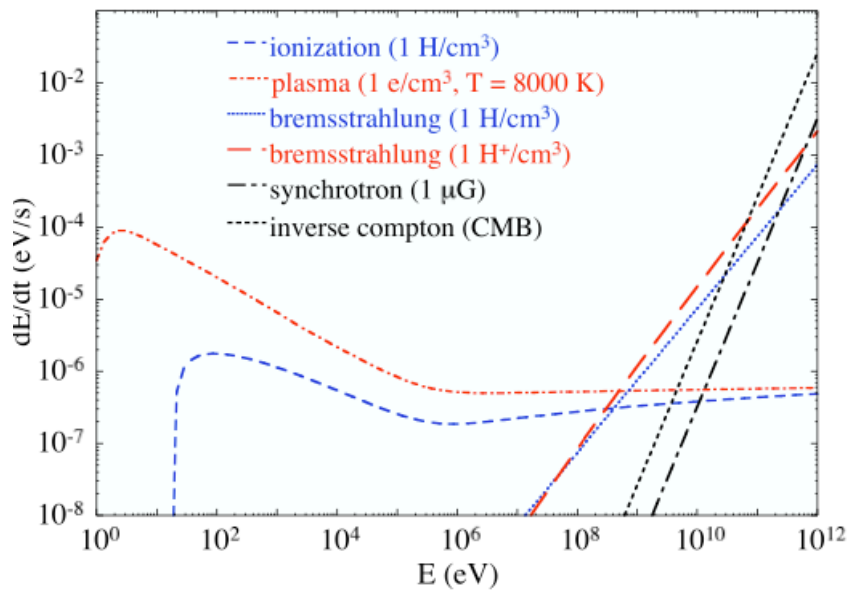


forbidden

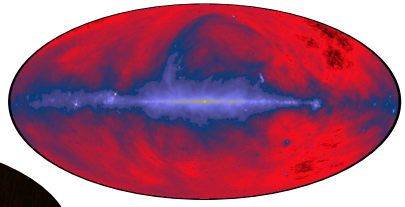
Injection Problem

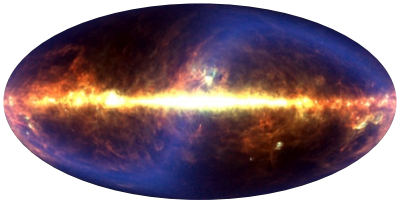
- Use positrons as tracers for acceleration
- Similar idea, plus: Annihilation tells us about efficiency
- Expect an annihilation signal for particles that don't escape



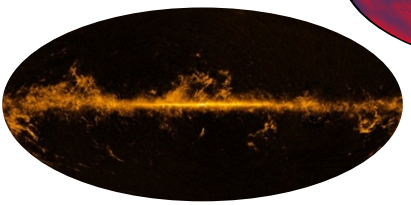


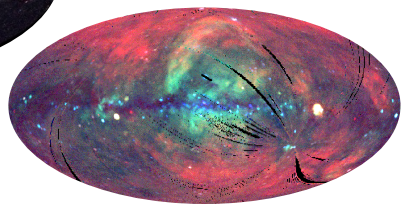
The Milky Way from Radio to Gamma

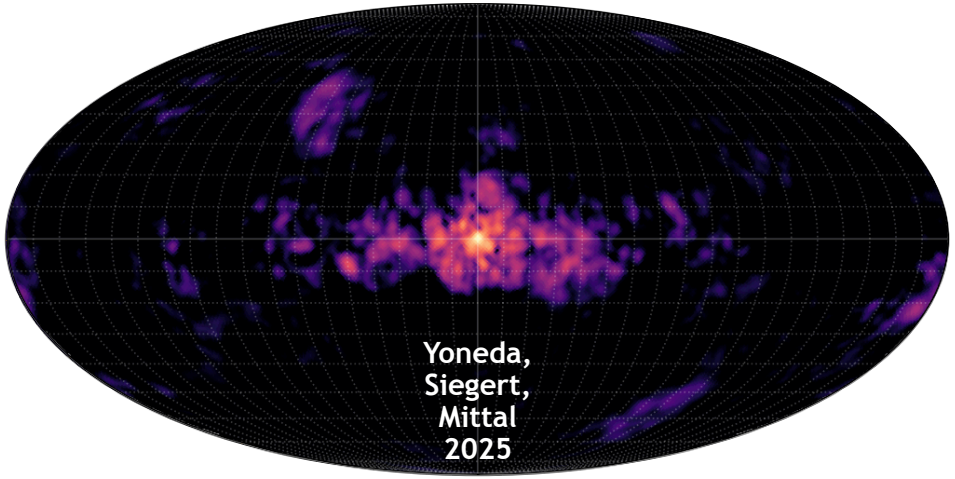

430 MHz


IR

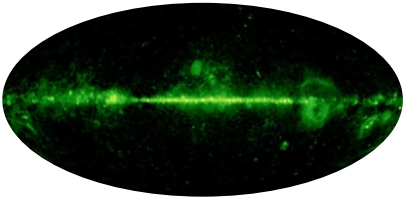

Visible

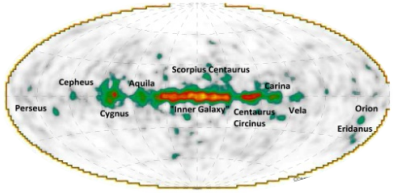

CO


X-ray

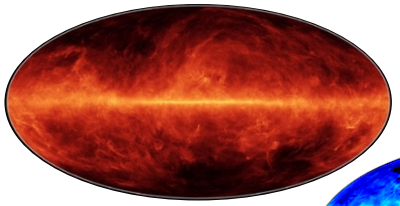


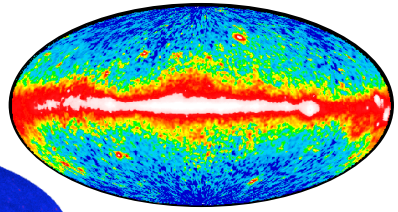
511 keV

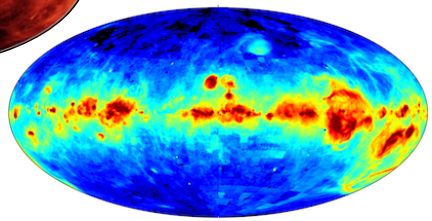

Free-Free

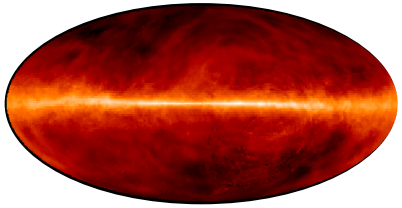


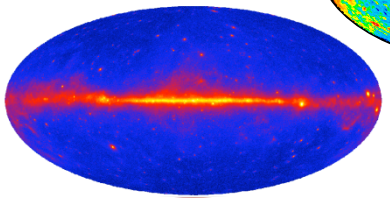
1.809 MeV


Dust

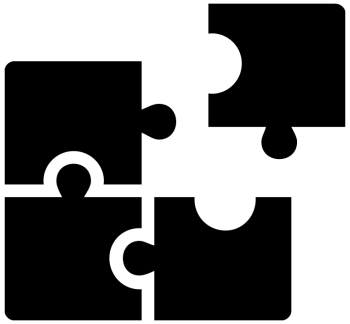

>100 MeV


Hα 656 nm


21 cm

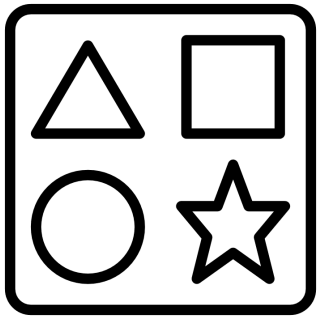

> 1GeV

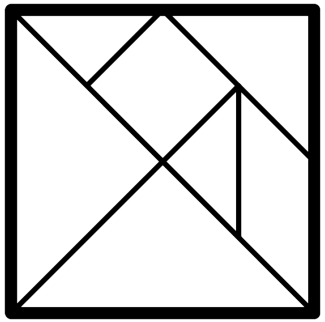
The Positron Puzzle



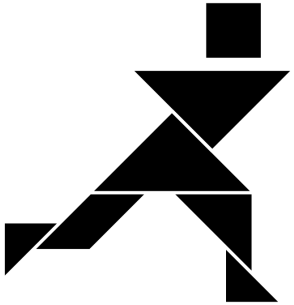
What do we see?

Where do the positrons come from?





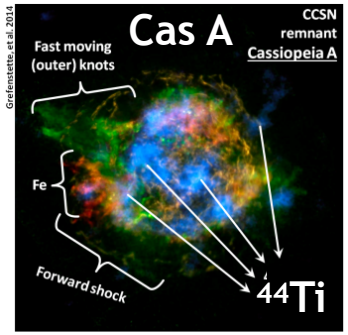
Why does it look like that?



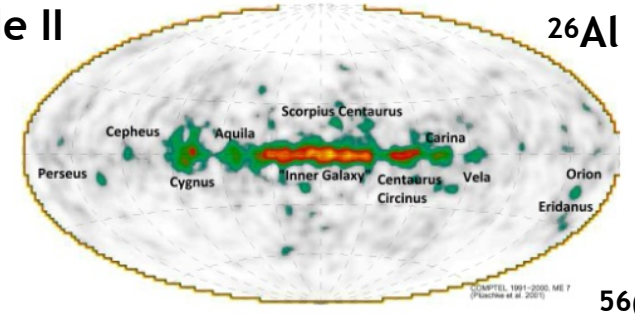
Positron Sources in Space

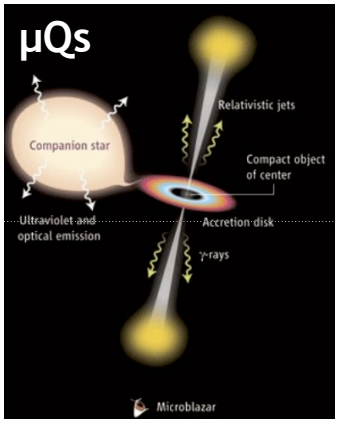
Positron production is ubiquitous!

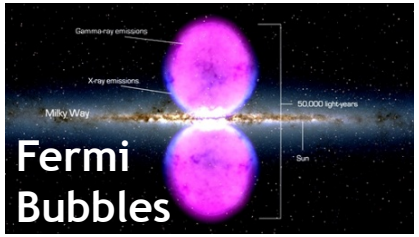
- **Massive stars / Novae / SNe Ia&II**
→ Radioactivity from β^+-decay
- **XRBs / Microquasars**
→ "Compact γ-ray source"; Jets; …
- **Sgr A***
→ Past AGN activity; Accretion disk
- **Cosmic rays**
→ p-p collisions: Secondary positrons
- **Pulsars**
→ Magnetic field interactions
- **Dark Matter**
→ Decay; Annihilation; Excitation
- **Stars**
→ Stellar flares; e^+-capture
- **Your ad here**

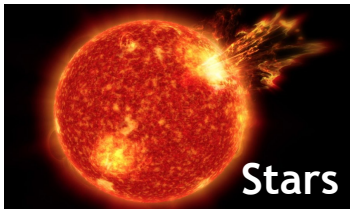


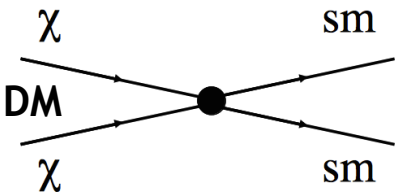
SNe II

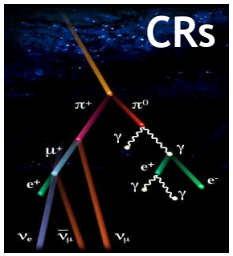




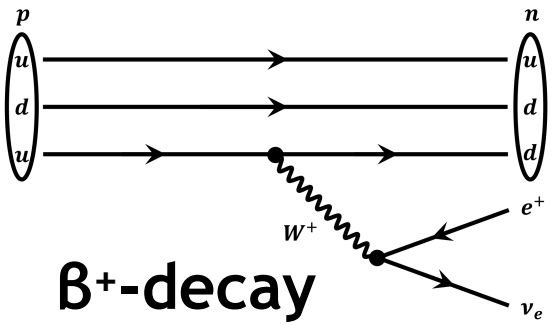








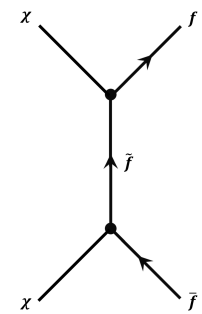
Positron Production Mechanisms



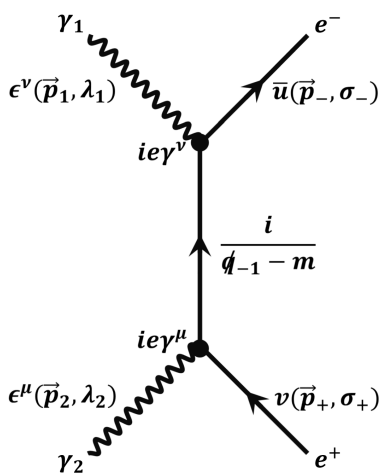
β⁺-decay

High-energy processes!

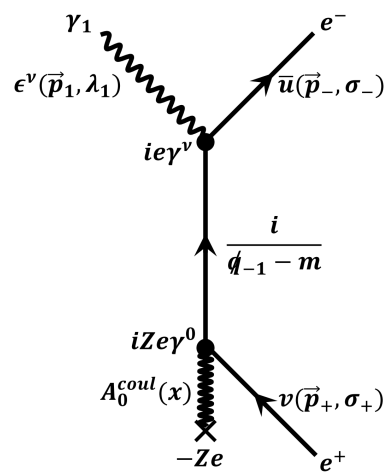
Dark matter …



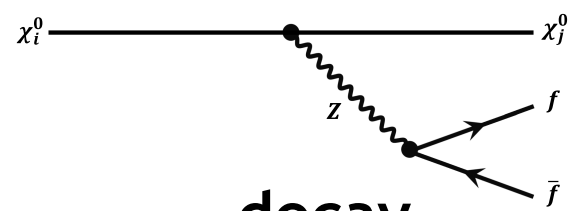
… annihilation



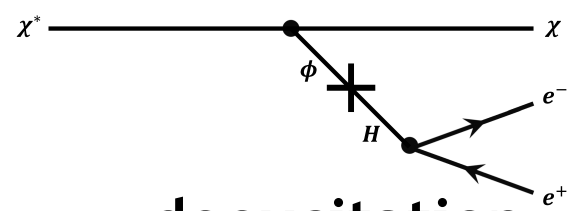
γγ pair production



γ/EM-field pair production



… decay



… deexcitation

SNRs: Injection, Escape, and Annihilation

Time-dependent escape of positrons from SNRs as tracers for acceleration

By measuring the annihilation gamma-rays, we find the escaping spectrum

$$\frac{\partial f}{\partial t} + \mathbf{u}(\mathbf{r},t)\cdot\nabla f - \frac{1}{3}(\nabla\cdot\mathbf{u})\,p\,\frac{\partial f}{\partial p} = \nabla\cdot[D(\mathbf{r},p,t)\,\nabla f] + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D_{pp}(\mathbf{r},p,t)\,\frac{\partial f}{\partial p}\right] + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(\frac{dp}{dt}\right)_{\text{loss}} f\right] + Q(\mathbf{r},p,t) - \Gamma_{\text{ann}}(\mathbf{r},p,t)\,f$$

Phase space density

Advection term

Adiabatic losses: compression/ expansion

Spatial diffusion

Reacceleration term

Energy losses

Source term:
$Q = n(\mathbf{r},t)\lambda F(p)$

Annihilation term:
$\Gamma = n_X(\mathbf{r},t)\sigma_{ann}v$

SNRs: Injection, Escape, and Annihilation

Time-dependent escape of positrons from SNRs as tracers for acceleration

By measuring the annihilation gamma-rays, we find the escaping spectrum

Link to nucleosynthesis

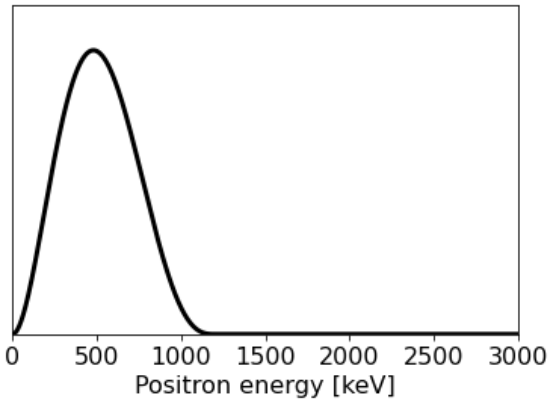
Link to LECR spectrum

Source term:

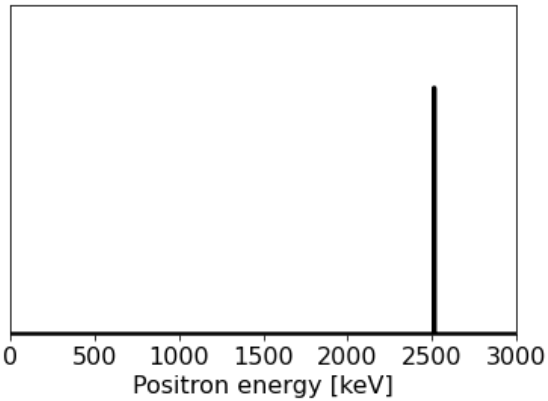
$$Q(\mathbf{r}, p, t)$$

Radioactive decay (β^+)

Internal pair creation ($^{16}O^*$)



Unique annihilation spectrum



Conclusion / Outlook

Measuring the LECR spectrum in SNRs and ISM will:

+ shed light on injection problem
+ estimate the ionisation rate in the Galaxy
+ have links to the 511 keV positron puzzle
+/- be a major target for COSI and successors
- require high sensitivity and spectral resolution

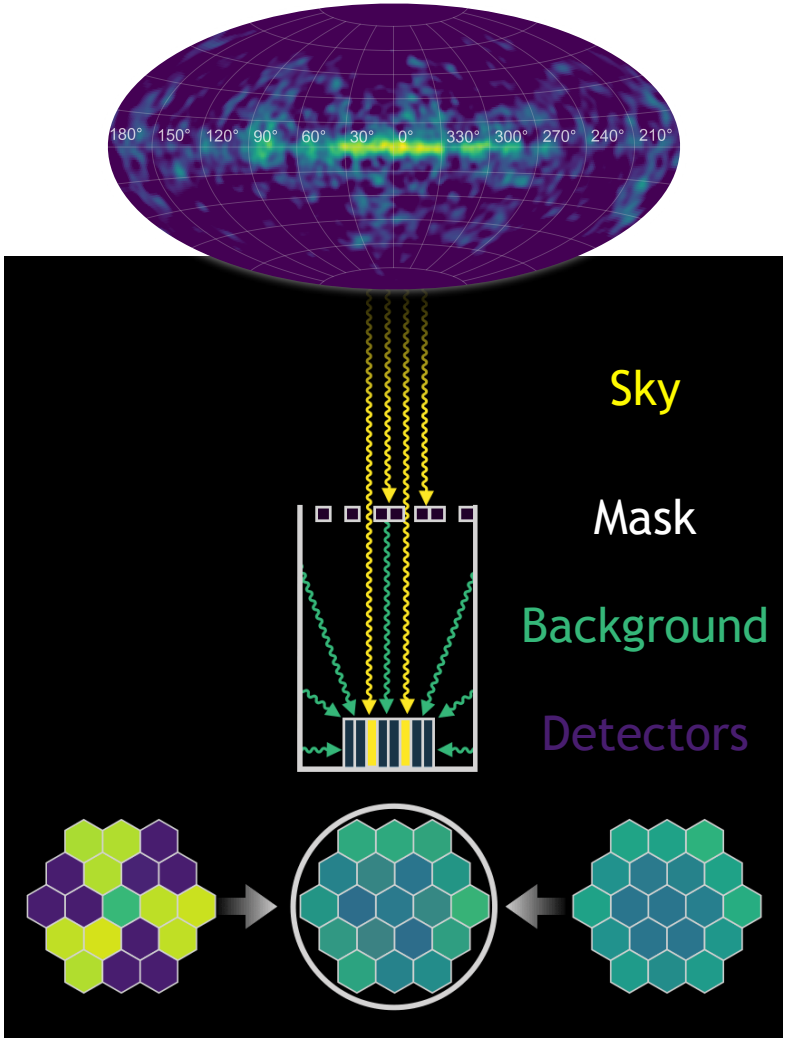
MeV Gamma-Ray Measurements

Coded-Mask Spectrometer Telescope **SPI**

INTEGRAL

INTErnational
Gamma-Ray
Astrophysics
Laboratory

Patterns from the sky



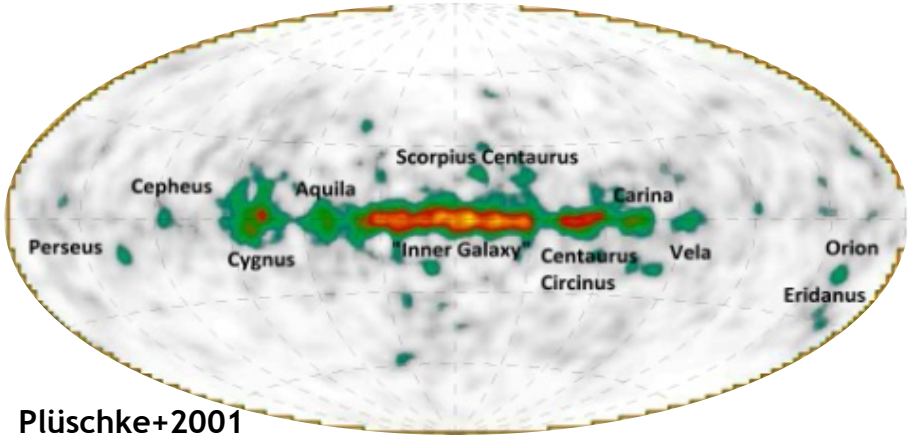
SPI specs:

Energy range:
0.02–8 MeV
FWHM:
2.1 keV @ 511 keV
Angular res.:
2.7° resolution
Line sensitivity (3σ/1Ms):
$3 \cdot 10^{-5}$ ph cm^{-2} s^{-1} @ 1.8 MeV
Conti. sensitivity (3σ/1Ms):
$2 \cdot 10^{-10}$ erg cm^{-2} s^{-1} @ 1 MeV

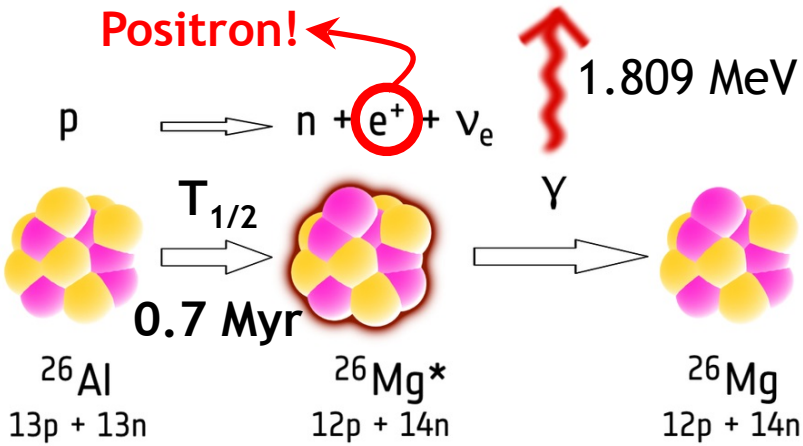
Patterns from the background

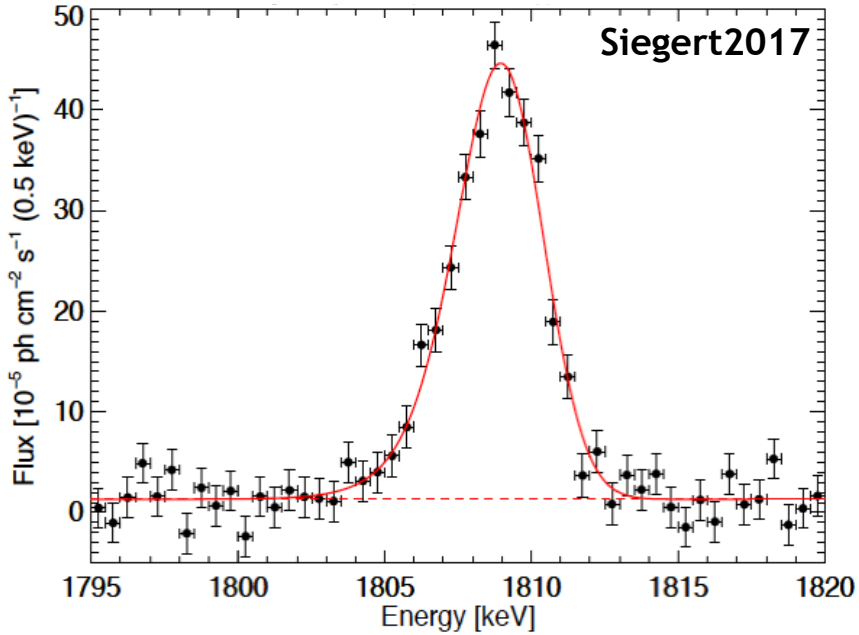
Massive Star Nucleosynthesis

Milky Way in ^{26}Al from massive star ejecta (1.809 MeV)



Plüschke+2001





Siegert+2023

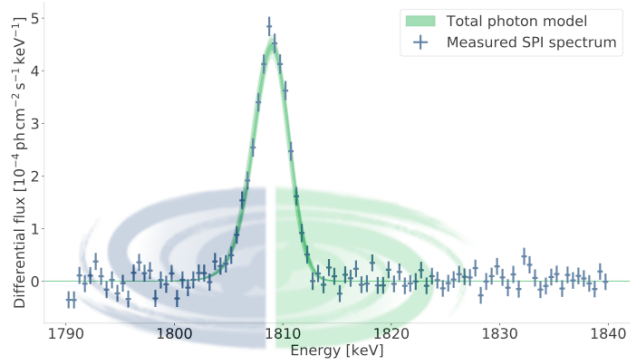
- 1.2–2.4 M_{Sun} of ^{26}Al in the Galaxy
- Star formation rate: 4–8 $M_\odot$ yr^{-1}
- 0.3×10^{43} e^+ s^{-1} along Galactic plane

→ **Constrain star formation and nucleosynthesis at the same time**

Massive Stars: 20 years of SPI

How does nucleosynthesis feedback from massive star groups affect the chemical evolution of the Milky Way and the Solar System?

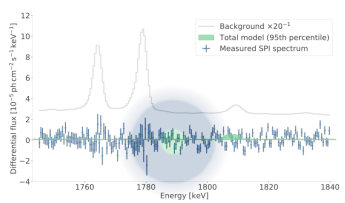
Diehl+2006/2010
Wang+2007/2020
Martin+2009/2012
Kretschmer+2013
Krause+2015/2018
Siegert+2017/2024
Pleintinger+2019/2024



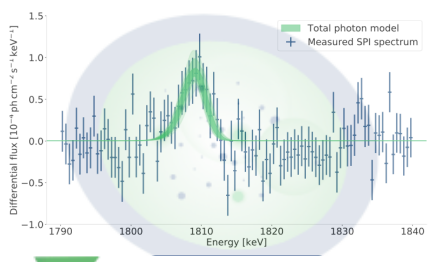
Galaxy
Milky Way

Star Formation

Feedback

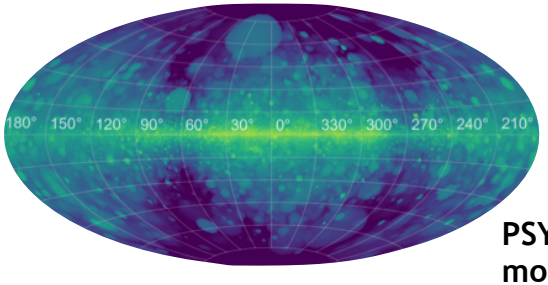


Single Star
γ²-Velorum



Star Group
Perseus OB

Nucleosynthesis



PSYCO model

⇒ Milky Way

- M(^{26}Al) $\approx 2\,M_\odot$
- SFR $\gtrsim 4\,M_\odot\,yr^{-1}$
- CFR $\gtrsim 0.29 \times 10^{-2}\,yr^{-1}$
- SNR $= (1.4 \pm 1.1) \times 10^{-2}\,yr^{-1}$

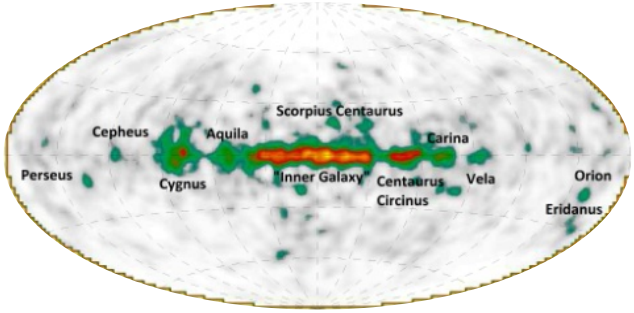
⇒ Single Stars and Star Groups

- Reduced explodability for massive stars
- Clustered star formation
- Frequent superbubble merging

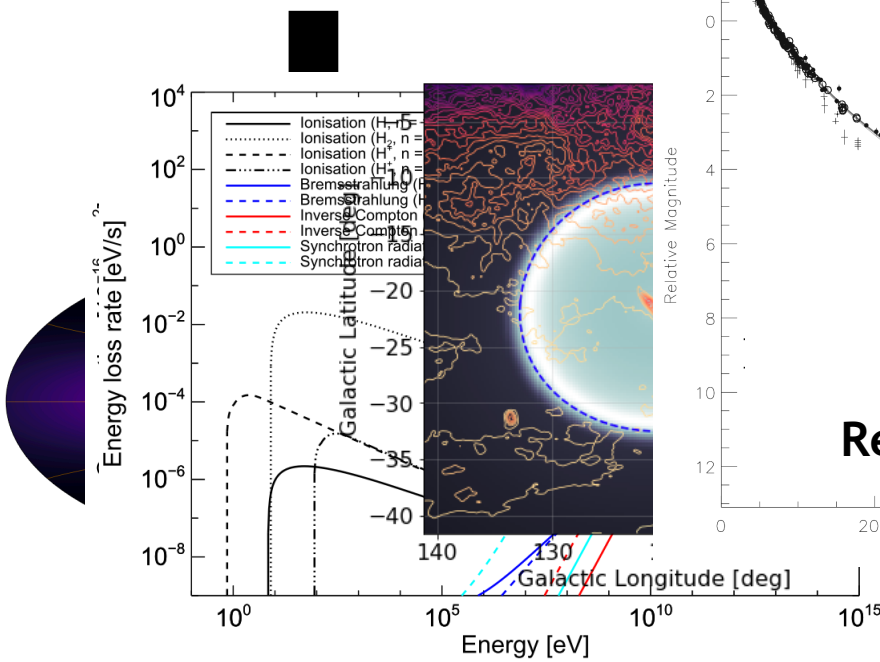
⇒ Solar Vicinity

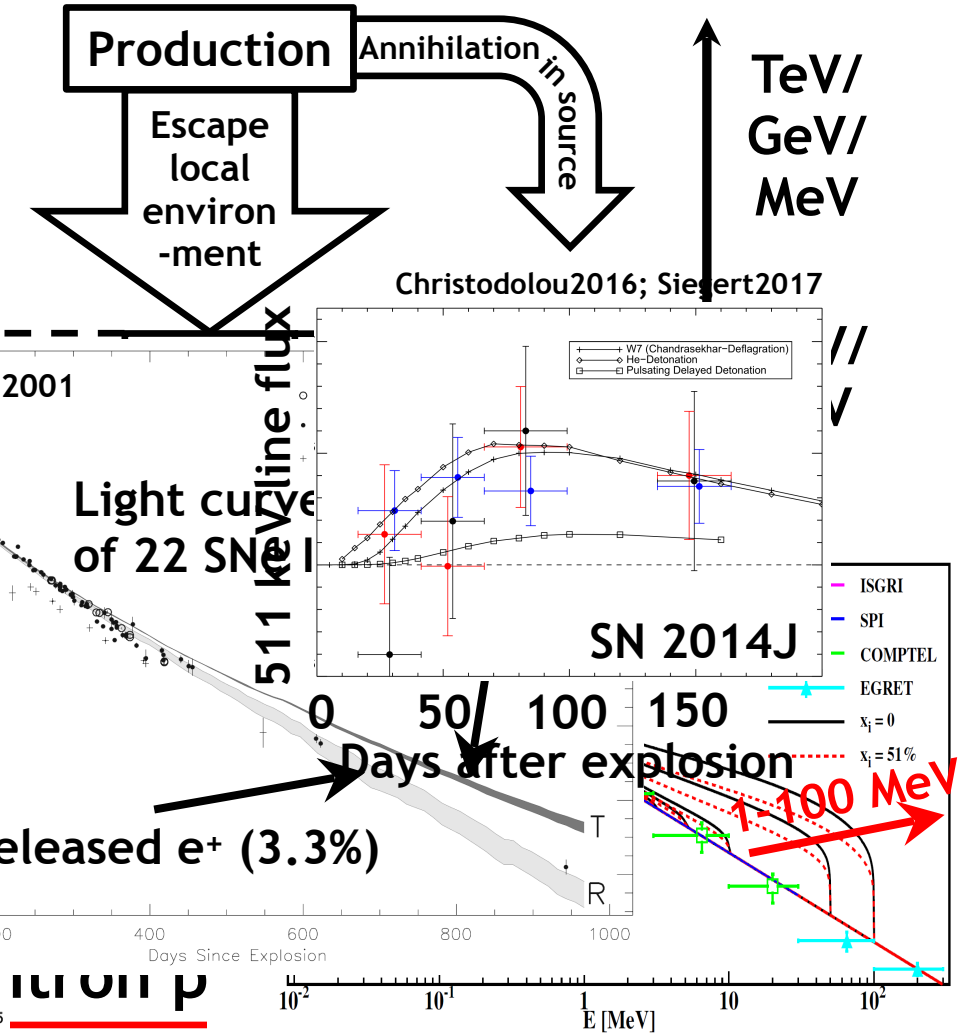
- Large ^{26}Al flux
- Small ^{60}Fe/^{26}Al flux ratio
- High latitude emission
- Prominent nearby emission

Life of a Positron in Space



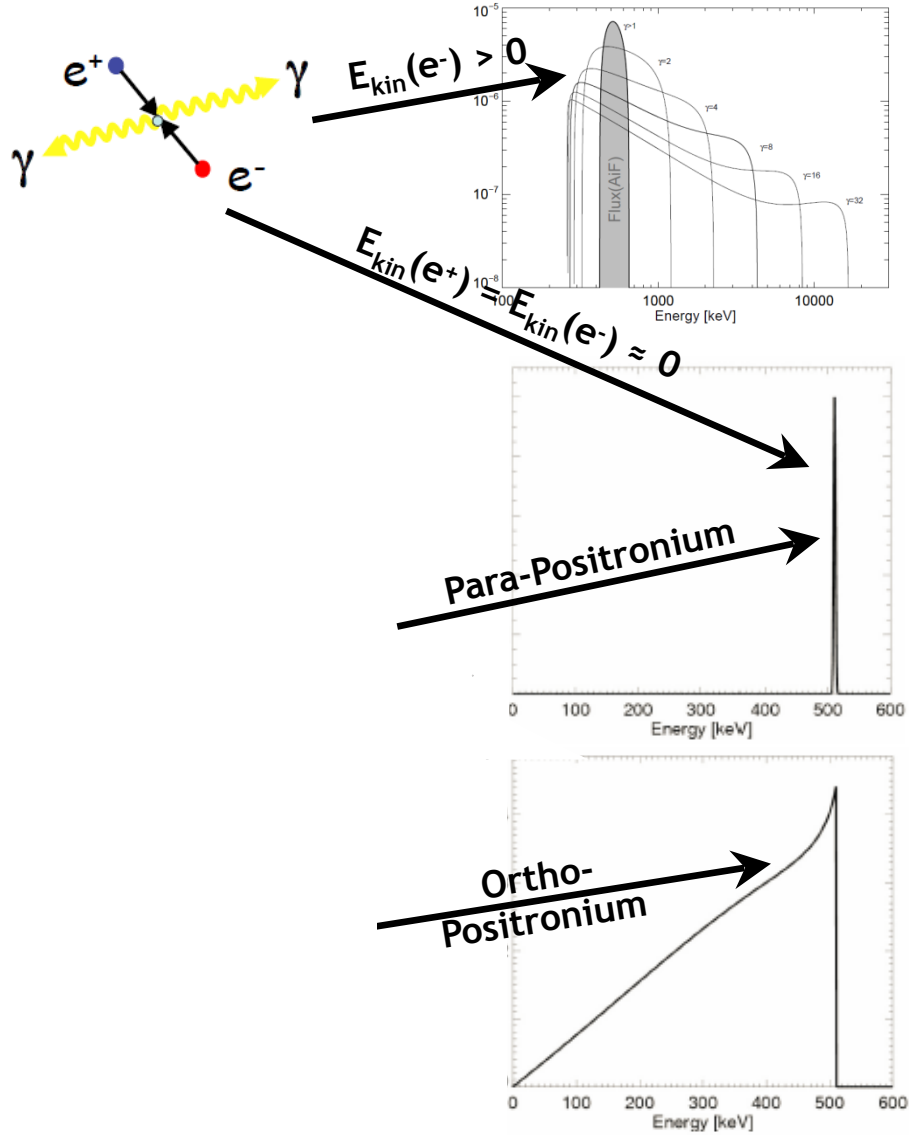
Source distribution





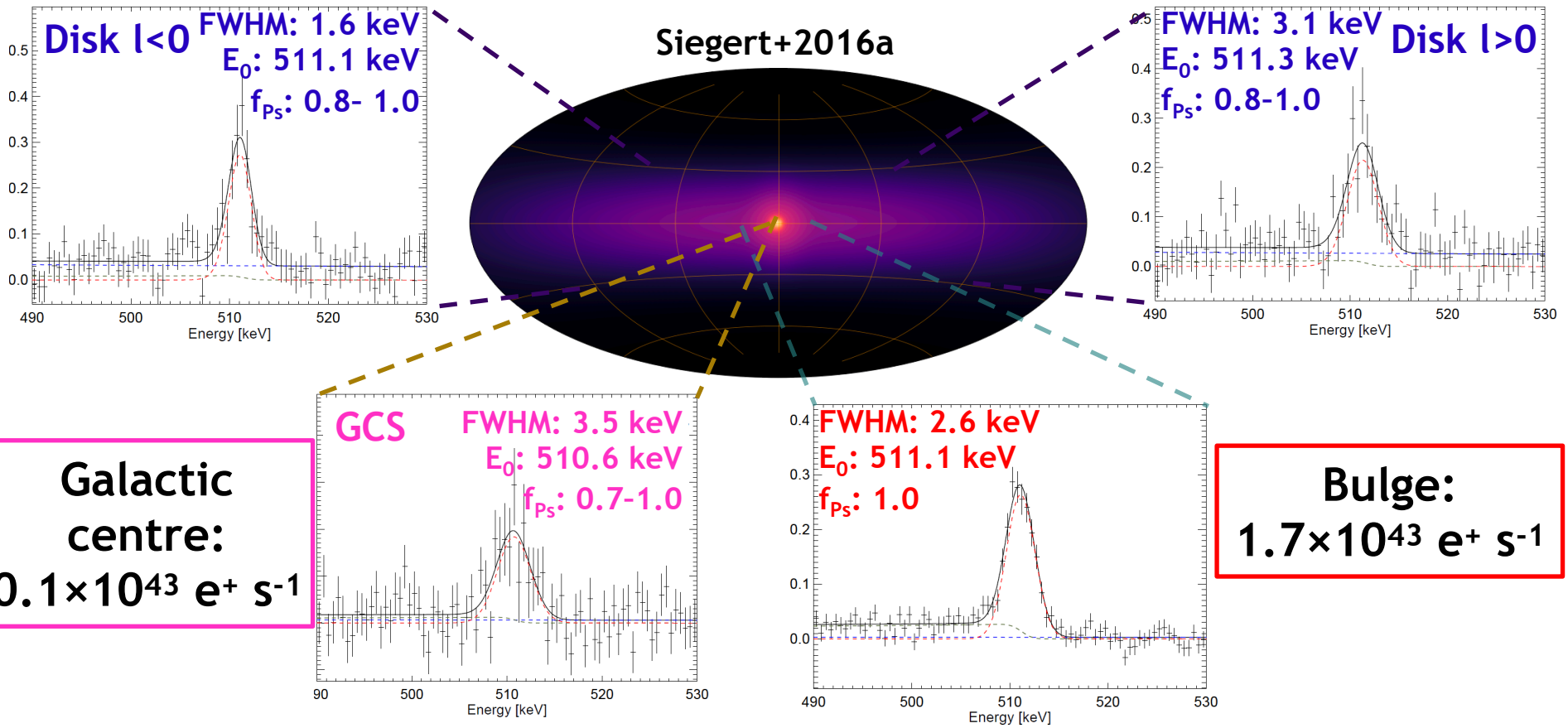
Positron Annihilation: $e^+ + e^- \geq 2\gamma$

- <u>Annihilation in Flight:</u>
  - → Direct annihilation with $E_{kin}(e^{\pm}) \geq 0$
  - → $E_{kin}(e^+) = E_{kin}(e^-) \approx 0$: **511 keV line**



INTEGRAL/SPI 511 keV Portrayal

Disk Annihilation budget: 3.1×10^{43} e^+ s^{-1}



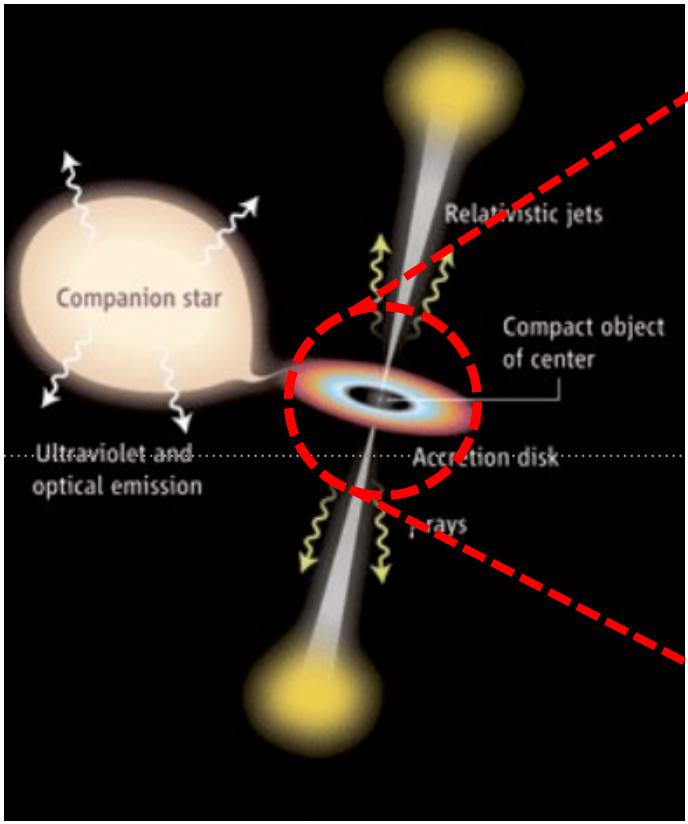
Galactic centre: 0.1×10^{43} e^+ s^{-1}

Bulge: 1.7×10^{43} e^+ s^{-1}

Total Milky Way: $(4.9\pm1.7)\times10^{43}$ e^+ s^{-1}

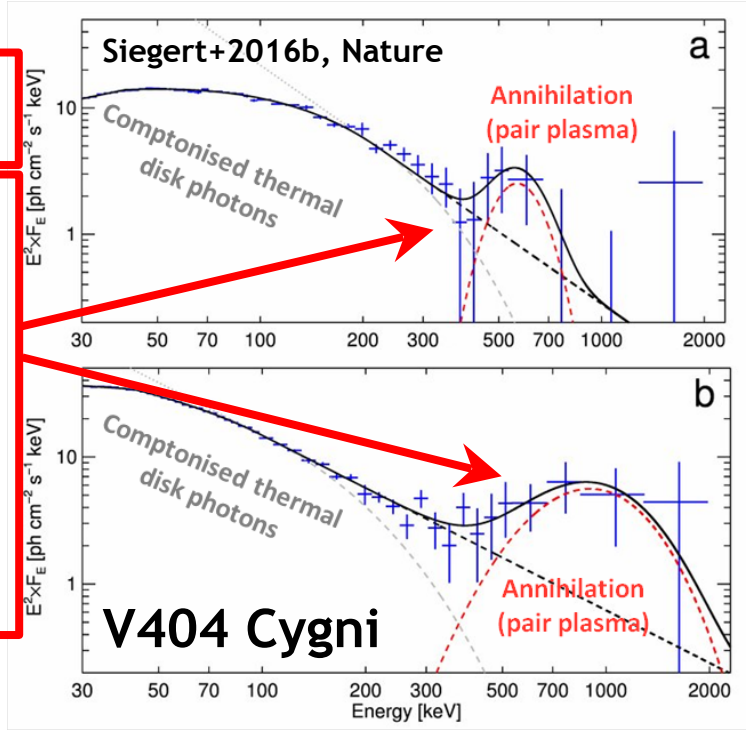
Compact Objects: Microquasars

Microquasars are Galactic positron sources!



$\gamma + \gamma \rightarrow e^+ + e^-$

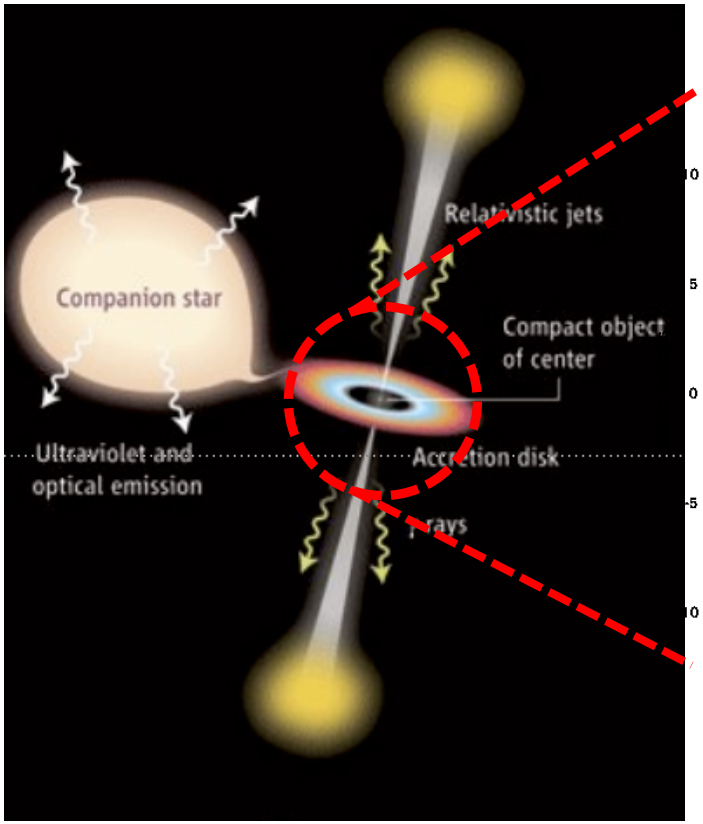
- e^+ annihilated:
  $\approx 10^{42}\ s^{-1}$
- Duty cycle:
  $\approx 10^{-3}$
- Escape fraction:
  $\approx 20\%$

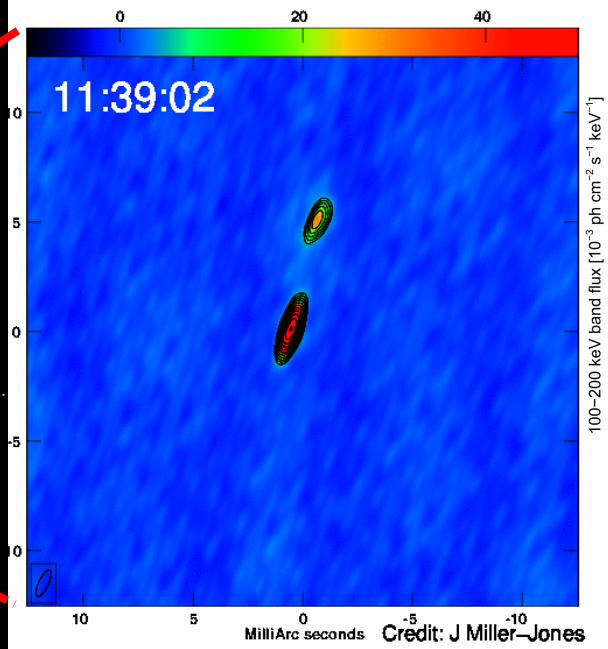


10^3 – 10^8 μQs expected in the Milky Way:
Understanding the "inner engine" of accreting black holes!

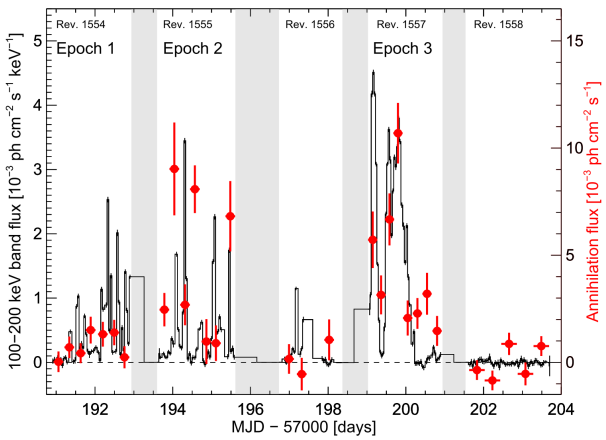
Compact Objects: Microquasars

V404 Cygni flaring





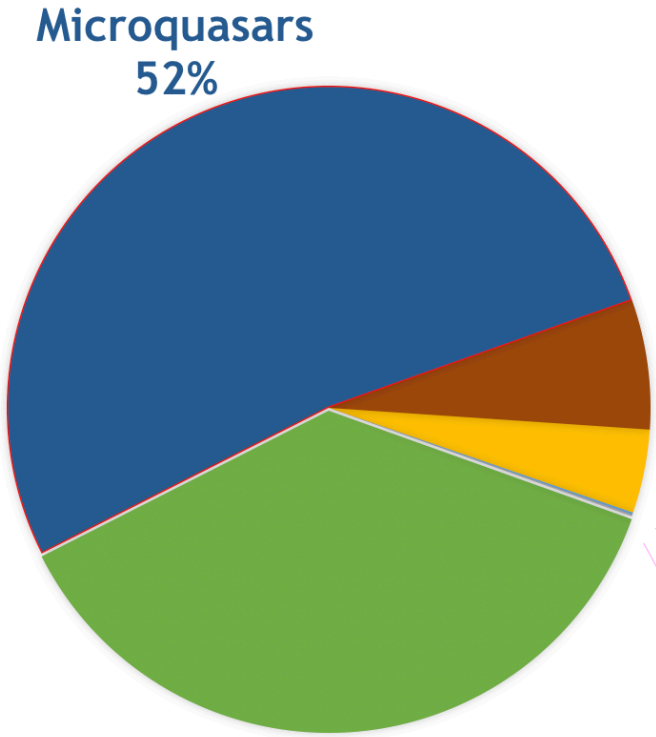
Siegert+2016b, Nature



Pair-plasma annihilation light curve in V404 Cygni

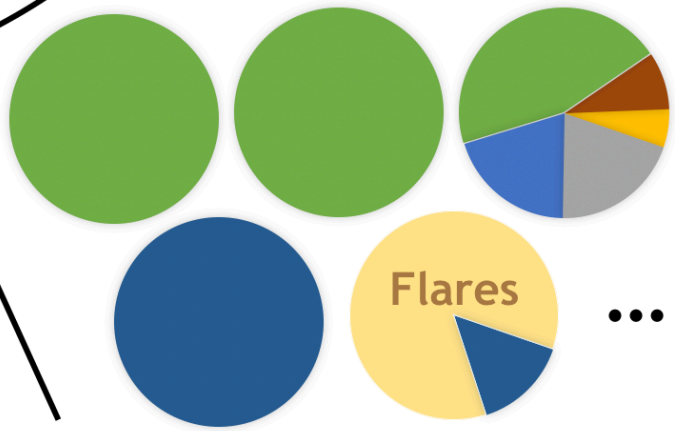
Radio emission associated with pair plasma?

Budgeting Galactic Positrons



In-situ annihilation
Escape from Galaxy
Non-steady state

Upper contribution limit



Lower contribution limit

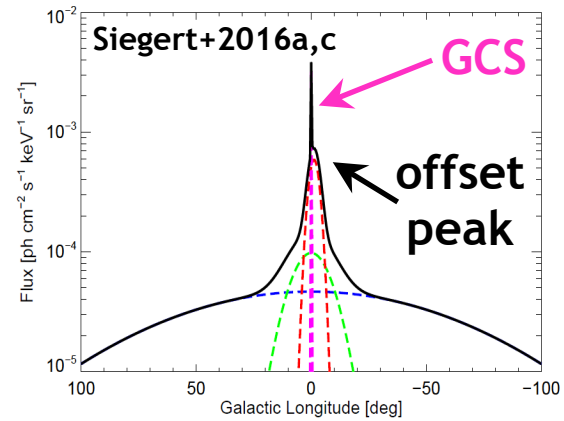
More sources required

Dark Matter in the Light of 511 keV

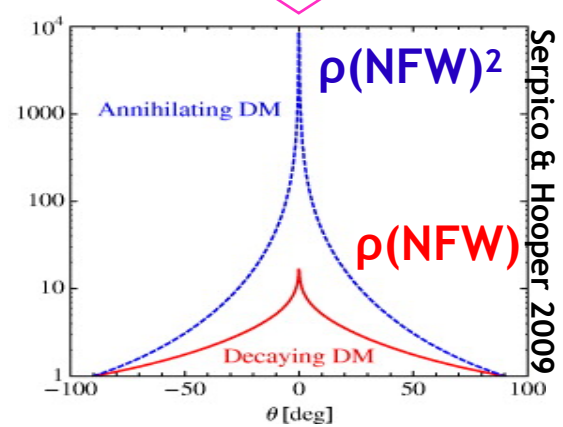
Decay, Annihilation, De-excitation

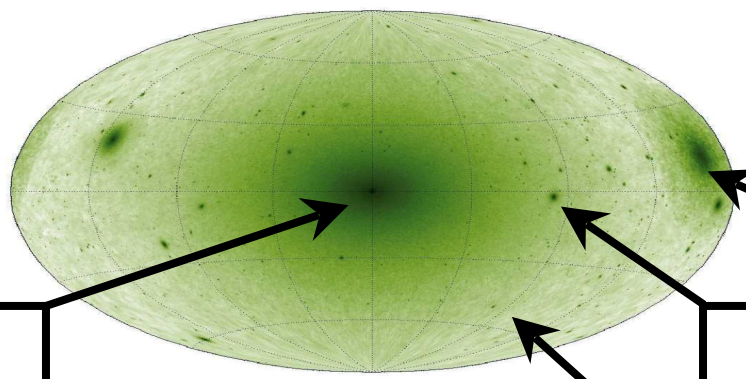
$$F_{511} \propto \left(\rho_{DM}\right)^n \ ?$$

→ DM density very similar to 511 keV profile
→ Predict **coherently** primary (prompt), secondary (Inverse Compton, synchrotron), and tertiary (positron annihilation) emission for galaxies



?





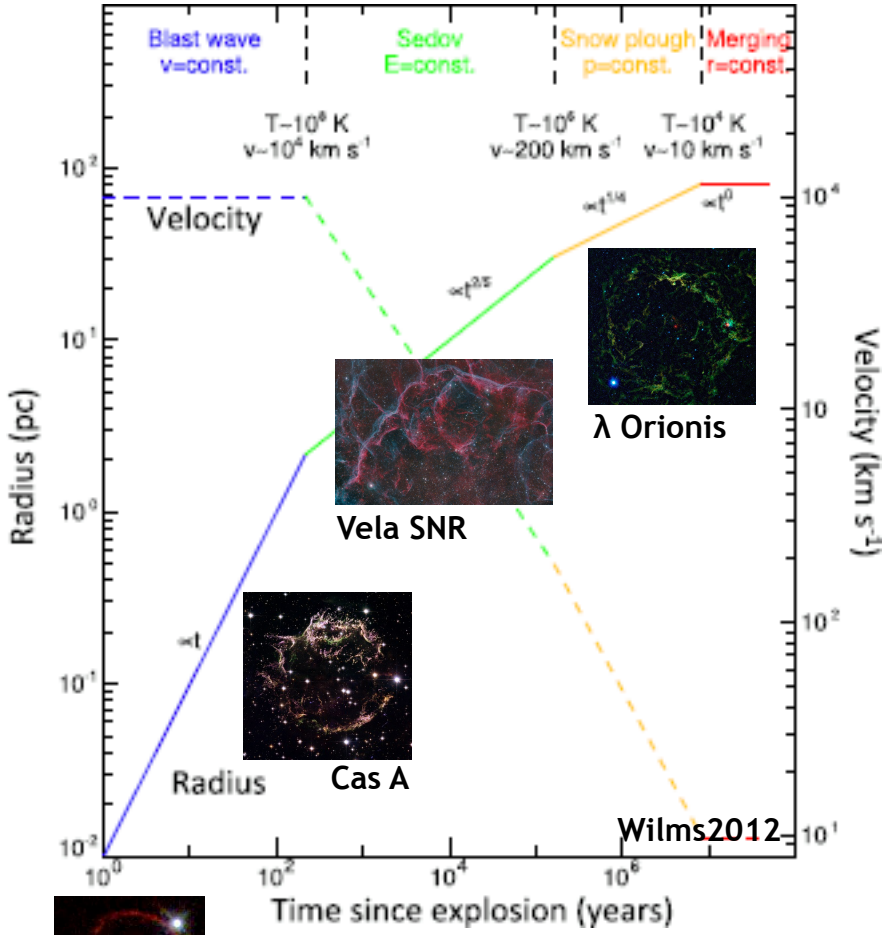
Dark matter simulation
Kuhlen+2008

Galactic centre
⇕
DM main halo

Dwarf galaxies
⇕
DM sub-haloes

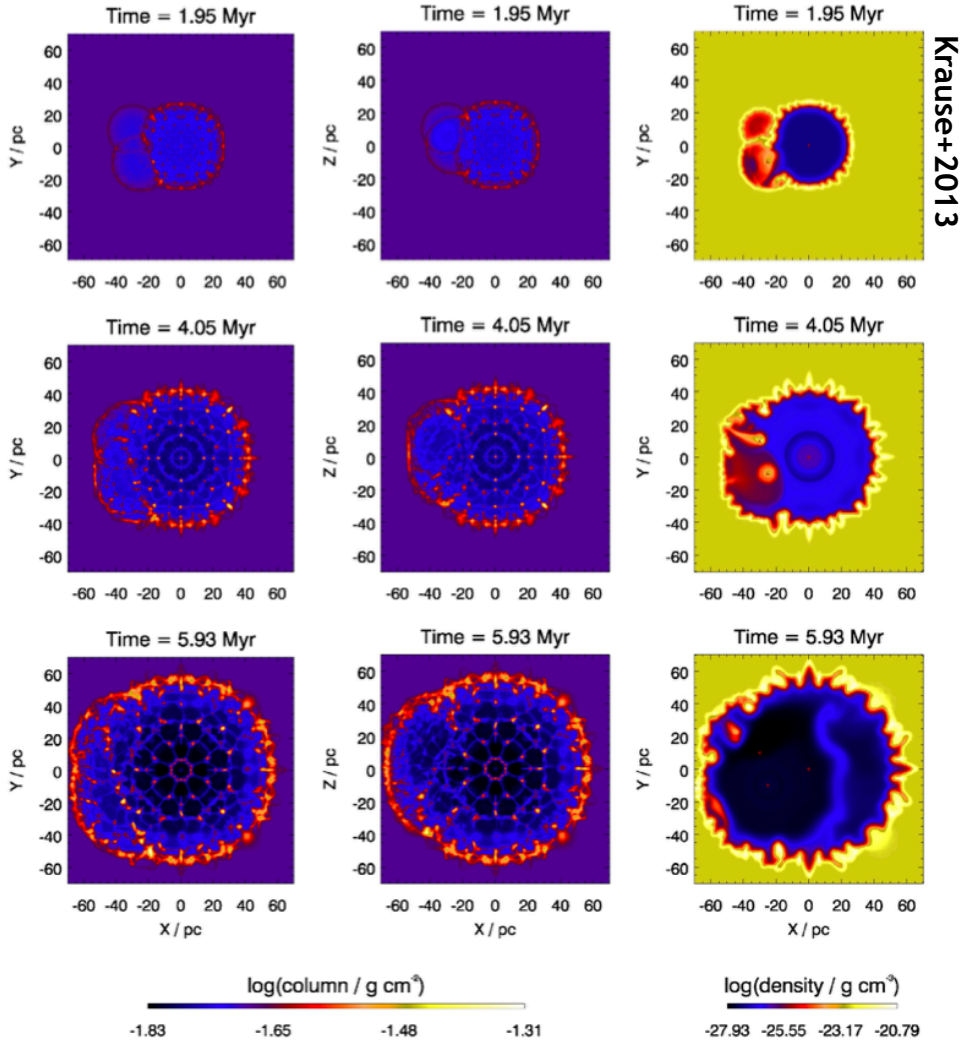
From Remnants to Superbubbles

Evolution of Supernova Remnants



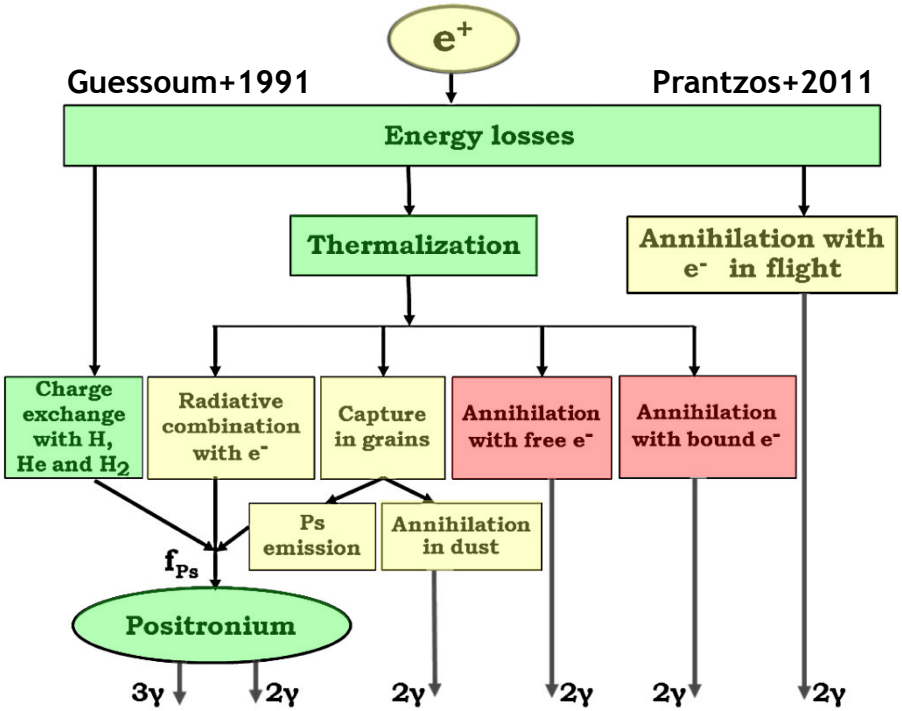
SN1987A

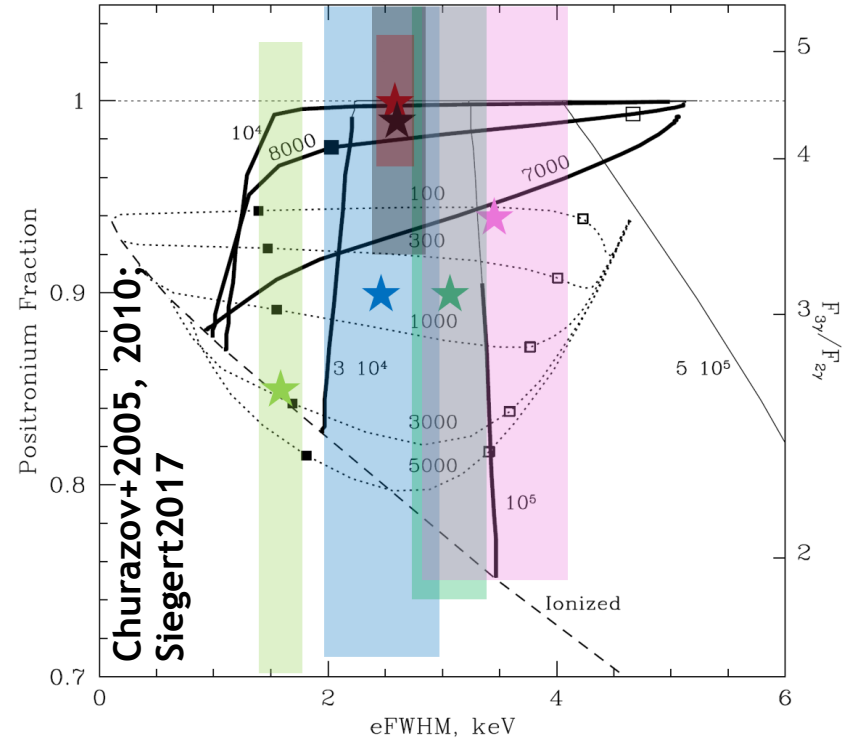
Hydro-Simulations of Superbubble Phase



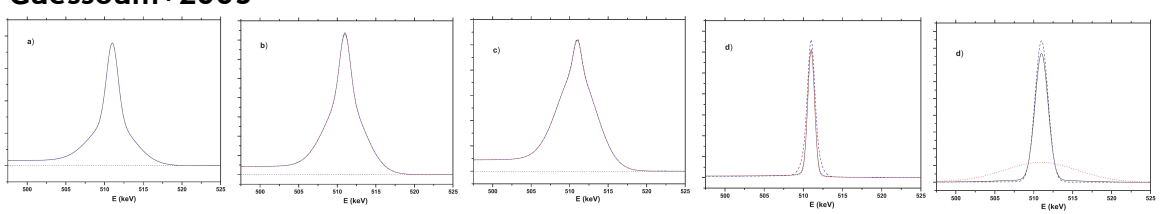
Krause+2013

What do Line Shapes tell us?





Guessoum+2005



Cold H_2 | Cold H | Warm neutral | Warm ionised | Hot plasma

Line shapes trace warm and partly ionised gas:

- T ≈ 7000-40000 K
- x_{ion} ≈ 2-25%

Sources and Sinks