The Cygnus region seen in gamma-ray lines

Pierrick MARTIN (CESR - Toulouse)

Jürgen KNÖDLSEDER (CESR - Toulouse)

Outline

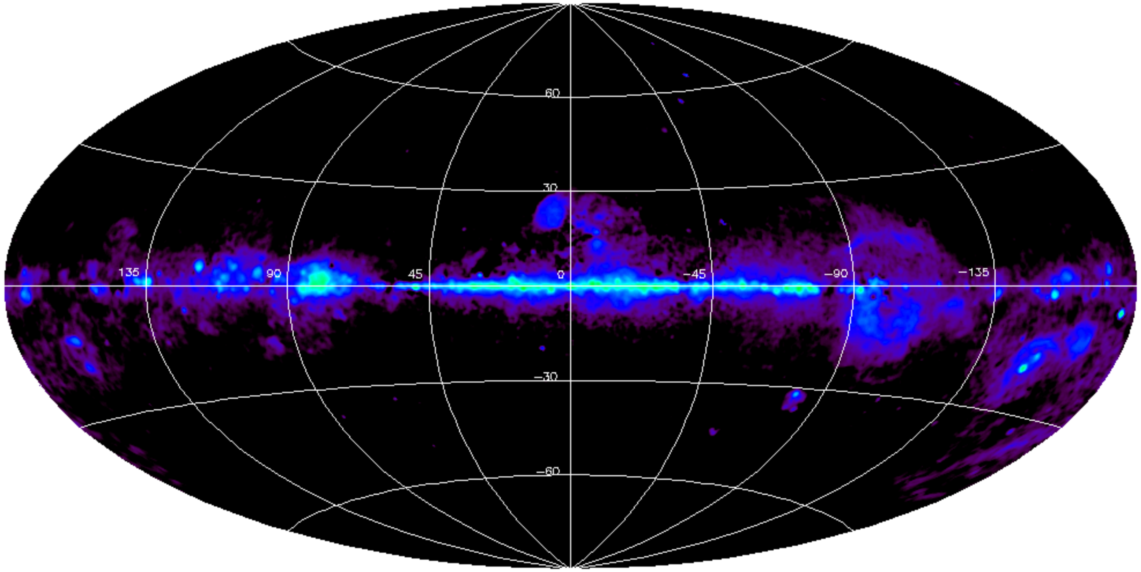
- **Interest of the Cygnus region for nucleosynthesis studies ?**

- **INTEGRAL/SPI observations of ^{26}Al and ^{60}Fe lines…**
  - Data analysis (in short)
  - ^{26}Al emission morphology, photometry and spectroscopy
  - ^{60}Fe emission from the Cygnus region ?

- **… versus theoretical predictions**
  - Stellar evolution and nucleosynthesis models
  - Predicted line fluxes

- **Summary and perspectives**

- **Interest of the Cygnus region for nucleosynthesis studies**
  - High concentration of massive stars: 200 O stars, 10 WR stars (Knödlseder et al. 2002)
  - Proximity: between 1.5 and 2 kpc (Knödlseder et al. 2000)
  - Young: few or no SNR or pulsars (Wendker et al. 1991, ATNF catalogue)



WMAP 3 years allsky free-free map
Gas ionized by massive stars Lyman continuum photons glows in radio through bremsstrahlung

^{26}Al source morphology

- **Characterization of the source morphology by model-fitting**
  - Scanning the Cygnus region with different gaussian sources
    - Emission center moved over $l \in [65°,95°]$ and $b \in [-10°,10°]$
    - Emission extension: point-source and 2D gaussians with σ = 1,2,3,4 and 5°
  - Grid of Maximum Likekihood Ratio values
    - Outcomes of a χ^2 distribution with 3 dof
  - Correcting for the number of trials
    - SPI angular resolution 2.8° $\rightarrow$ N_1 independent pixels in the sky
    - Size of the source $\rightarrow$ N_2 independent tests

$$N = \min(N_1, N_2)$$

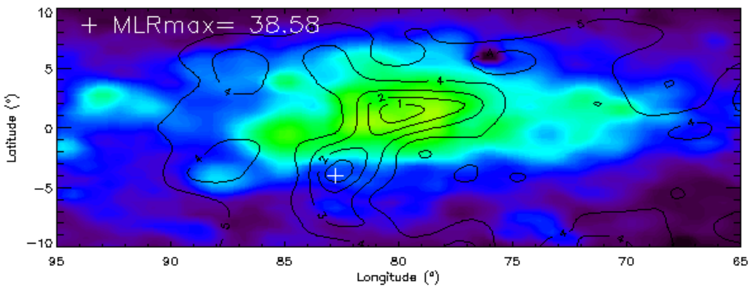
$$MLR_{pre} \rightarrow P = \mathrm{Pr}\,ob(X \leq MLR_{pre}, \chi_3^2)$$

$$P^N = \mathrm{Pr}\,ob(X \leq MLR_{post}, \chi_3^2) \rightarrow MLR_{post}$$

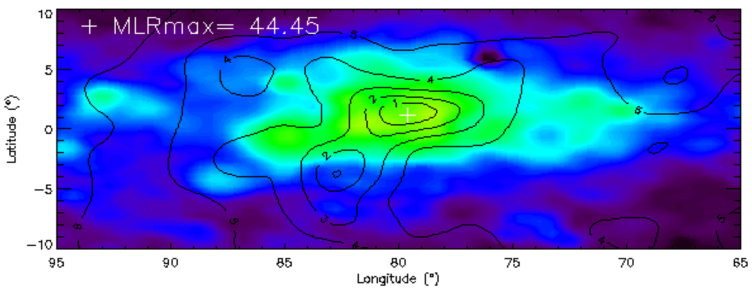
  - Approach successfully tested on simulated observations

- **Post-trial MLR maps**
  - Confidence intervals overlaid on WMAP free-free emission map

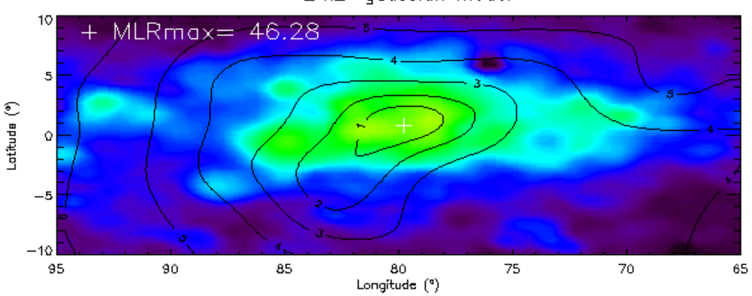
point source model



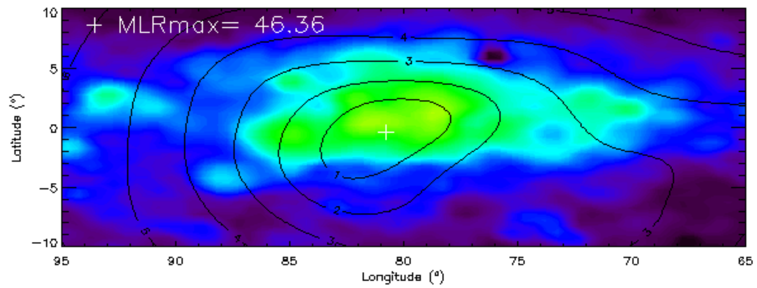
1°x1° gaussian model



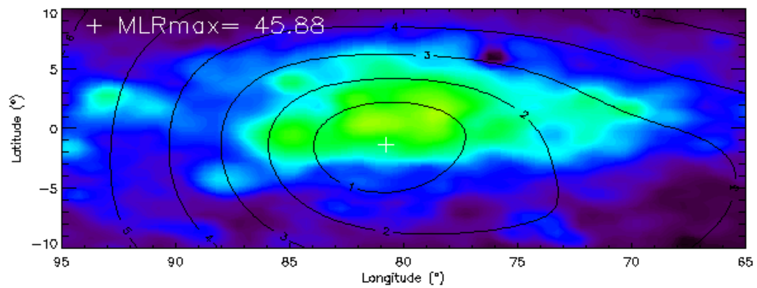
2°x2° gaussian model



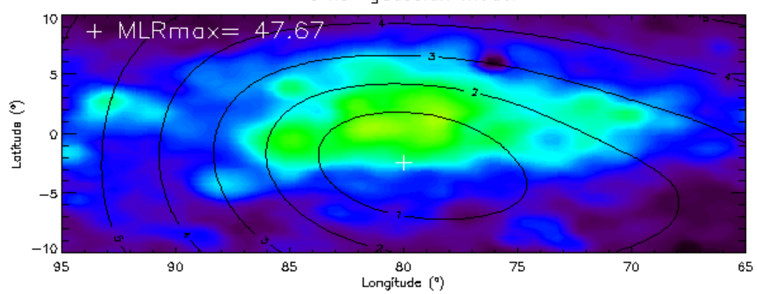
3°x3° gaussian model



4°x4° gaussian model



5°x5° gaussian model



^{26}Al source morphology

- **Main outcomes**
  - Single point-source (ie ≤ 2.8° for SPI) clearly excluded
  - Poor constraints on the maximum extent of the source
    - Coded-mask imaging performance breaks down for very extended sources
    - Effect of the galactic 1809 keV emission, especially towards GC ?
  - Use of a galactic model in addition to the Cygnus model
    - Model 1: exponential disk with R=3.5 kpc and H=90 pc
    - Model 2: exponential disk with R=2.5 kpc and H=180 pc
    - Similar trends but smaller contrast
    - Interplay between models and weighting by exposure

- **Selected model for Cygnus 1809 keV emission**
  - Smallest of the most significant models
  - Shape: 3°x3° gaussian with estimated uncertainty of ±1° on σ
  - Position: l= 80.8° b= -0.4° with estimated uncertainty of about ±3°

^{26}Al source morphology

- **How likely is our model of the Cygnus 1809 keV emission ?**
  - Size of a bubble blown by a constant wind (Castor et al. 1975, Weaver et al. 1977)

$$R(t) = 66 n_0^{-1/5} L_{38}^{1/5} t_6^{3/5}$$
$$v(t) = 39 n_0^{-1/5} L_{38}^{1/5} t_6^{-2/5}$$

n_0 ambient density (cm^{-3})
L_{38} wind power (10^{38} $erg.s^{-1}$)
t_6 age of the bubble (10^6 yrs)

  - Arithmetic for Cyg OB2 (Lozinskaya et al. 2002)

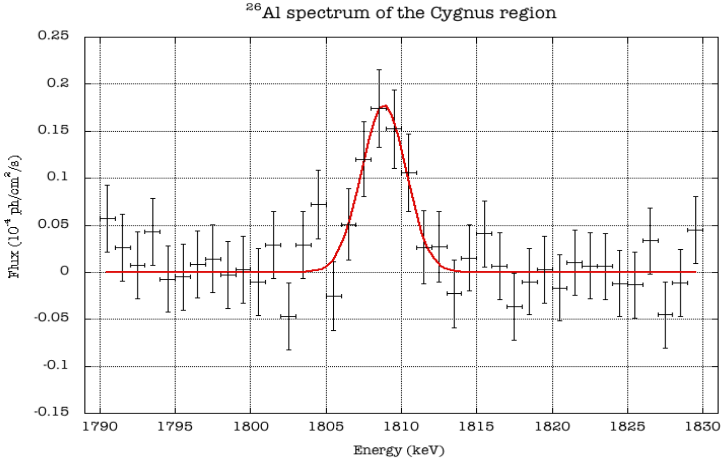
$$R(t) \approx 200\ pc$$
$$v(t) \approx 50\ km/s$$

$n_0 = 1\ cm^{-3}$
$L_{38} = 15$ (Leitherer et al. 1992)
$t_6 = 2.5$ (Knödlseder et al. 2000)

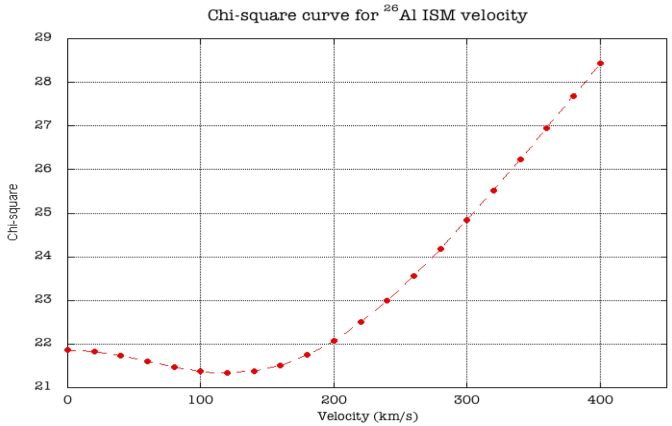
  - Angular size of the Cygnus superbubble for a distance of 1700 pc
    - Theoretical: about 13° diameter,
    - Observed: X-ray bubble (ROSAT), free-free emission (WMAP) … about 10°
    - Selected ^{26}Al model extension: about 9°

Photometry and spectroscopy of ^{26}Al signal

- **Flux in the 1806-1812 keV band for the selected Cygnus model**
  - Cygnus + Galaxy: 6.3 ± 1.0 10^{-5} ph/cm²/s
  - Cygnus - Galaxy: 4.9 ± 1.1 10^{-5} ph/cm²/s
  - COMPTEL: 6.9 ± 1.5 10^{-5} ph/cm²/s

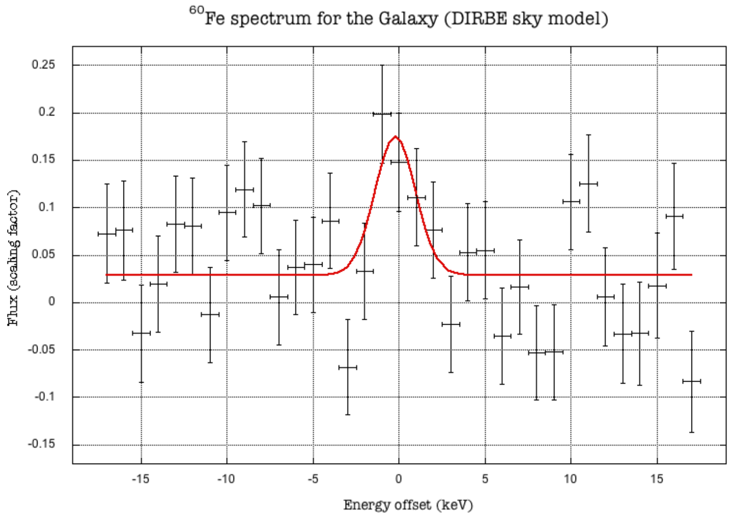


- **Source spectrum**
  - Position of the line
    - 1808.86 ± 0.37 keV
    - Theoretical: 1808.65 keV
    - Galactic motion in Cygnus: -10 to +10 km/s
  - Width of the line (FWHM)
    - Total line width: 3.47 ± 0.67 keV
    - SPI resolution: 3.01 keV
    - Astrophysical line width: 1.73 keV
    - Implied ^{26}Al velocity of about 120 km/s
    - Consistent with ISM turbulence



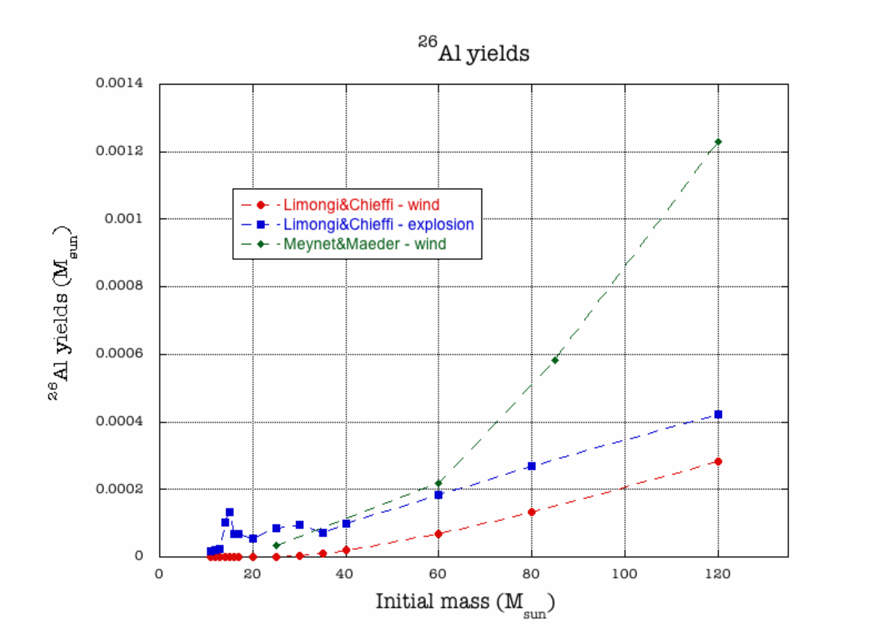
^{60}Fe emission from the Cygnus region

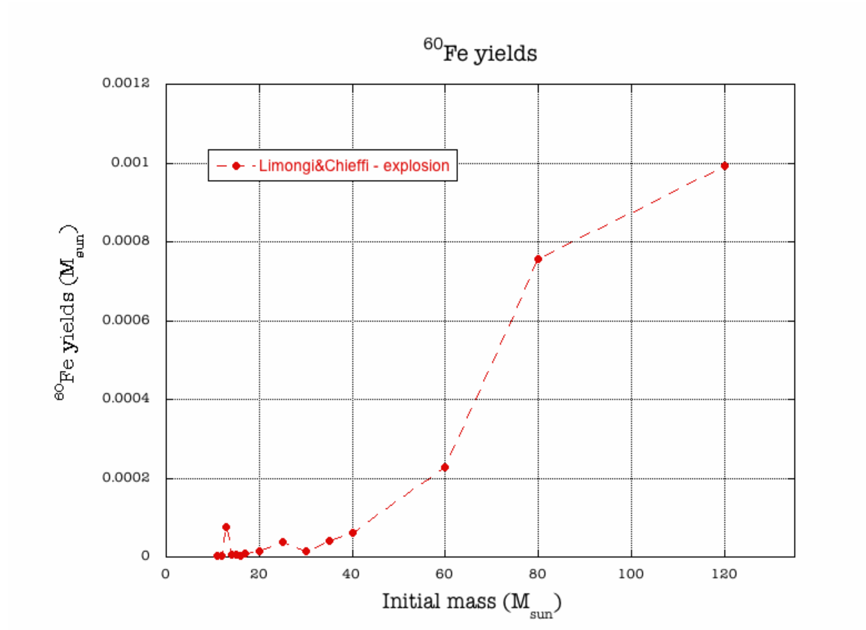
- **Testing the method on the Galaxy…**
  - Revolution 19 to 394
  - SE & ME2 data
  - 1173.2 & 1332.5 keV lines
  - Sky model: DIRBE 240 µm skymap
  - Flux: 4.3 ± 1.1 10^{-5} ph/cm^2/s
  - Comparison with the latest value
    - 4.4 ± 0.9 10^{-5} ph/cm^2/s (Wang et al. 2007)



- **… and then applying it to the Cygnus region**
  - Revolution 19 to 484
  - SE & ME2 data
  - 1173.2 & 1332.5 keV lines
  - Sky model: 3°x3° gaussian from ^{26}Al emission study
  - Upper limit on the flux (2σ): 1.6 10^{-5} ph/cm^2/s

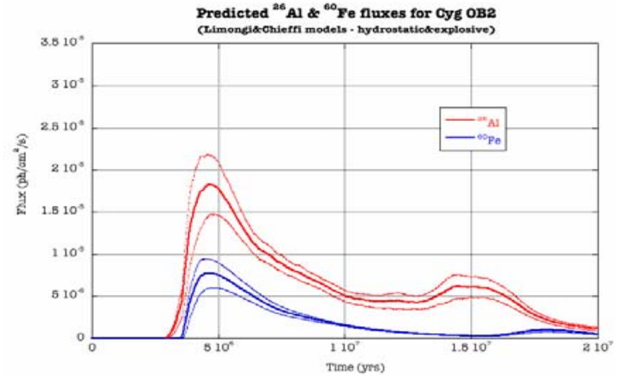
- **Latest stellar models and nucleosynthesis calculations**
  - Limongi&Chieffi 2006 (hereafter L&C)
    - 11 to 120 $M_{\odot}$, no rotation, hydrostatic+supernova, solar metallicity
  - Meynet&Maeder 2003-2005 (hereafter M&M)
    - 20 to 120 $M_{\odot}$, with rotation, hydrostatic only, various metallicities

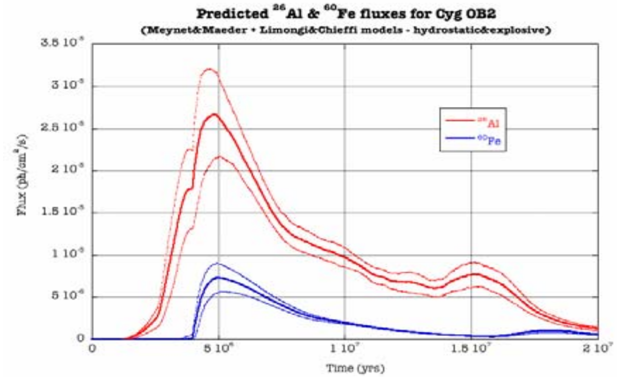


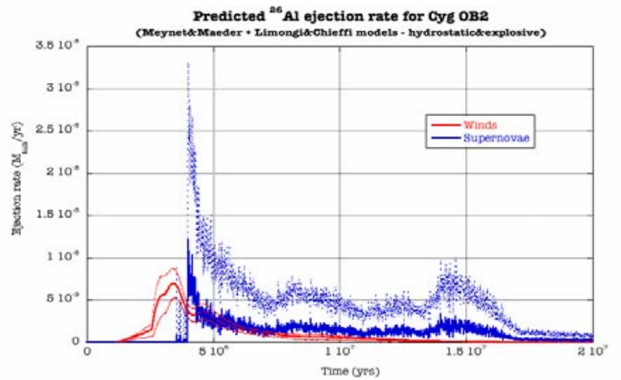


Predicted fluxes: Cyg OB2

- **Simulated ^{26}Al and ^{60}Fe fluxes for Cyg OB2**
  - Salpeter IMF (slope = 2.35)
  - 120 O stars ($M/M_{\odot} \in [20,120]$)
  - Starburst over 5.10^5 yrs
  - Distance 1700 pc
  - Solar metallicity (Z=0.02)
- **Main outcomes**
  - Peak ^{26}Al flux of ≈ 3.10^{-5} ph/cm^2/s at 5 Myr
    - HRD estimated Cyg OB2 age: 2.5 Myr
    - Observed flux: $4\text{-}6.10^{-5}$ ph/cm^2/s
  - Ejected ^{26}Al masses over 20 Myr
    - Winds L&C: 0.0038 $M_{\odot}$
    - Winds M&M: 0.019 $M_{\odot}$
    - Supernovae L&C: 0.023 $M_{\odot}$
  - Peak ^{60}Fe flux shifted of ≈1 Myr by rotation

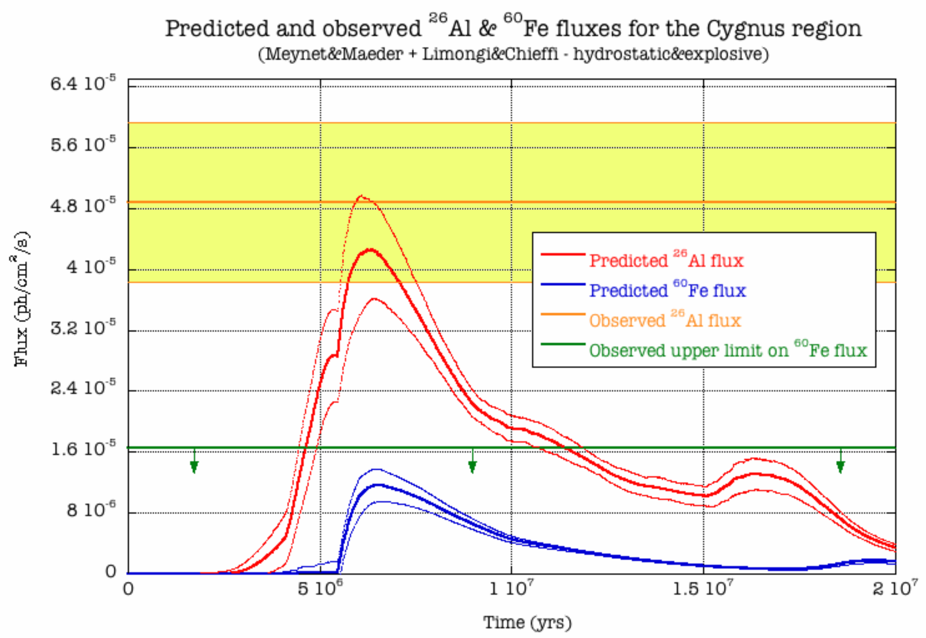






Predicted fluxes: the Cygnus region

- **Simulated ^{26}Al and ^{60}Fe fluxes for the whole Cygnus region**
  - Salpeter IMF
  - 200 O stars
  - Starburst over 2.10^6 yrs
  - Distance 1700 pc
  - Z= 0.02



- **Main conclusions**
  - Consistency with observations
    - Peak ^{26}Al flux at 6 Myr
    - Need supernova contribution
  - Age problem ?
    - HRD ages of most Cygnus OB associations: 2-6 Myr
    - … but large spread and estimated from old isochrones (no rotation included)
  - SN problem ?
    - Need about 10-20 SN to reproduce the flux but few SNR or pulsar observed

Conclusions & perspectives

- **^{26}Al emission from the Cygnus region**
  - Emission extension larger than 6 - 9°, but poor constraints on maximal size
  - Source position about (l,b) = (80°,0°), close to Cyg OB2
  - Source flux of 4 - 6 10^{-5} ph/cm^2/s, uncertain galactic background contribution
  - Broadened signal, likely due to bubble expansion and/or ISM turbulence

- **^{60}Fe emission from the Cygnus region**
  - Upper limit (2σ): 1.6 10^{-5} ph/cm^2/s

- **Nucleosynthesis predictions for the Cygnus region**
  - Observations can be reconciled with predictions (for the first time)
  - Need all Cygnus O stars
  - Need rotation and associated increased ^{26}Al yields
  - Need SN contribution to the ^{26}Al budget

Conclusions & perspectives

- **Points to be addressed…**
  - Is it possible to hide 10-20 SN in a superbubble ?
  - What is the effect of metallicity (Cygnus is subsolar) ?
  - What is effect of binarity (different IMF) ?
  - What if I change nucleosynthesis calculations (especially explosive) ?
  - What is the contribution of the galactic 1809 keV background ?

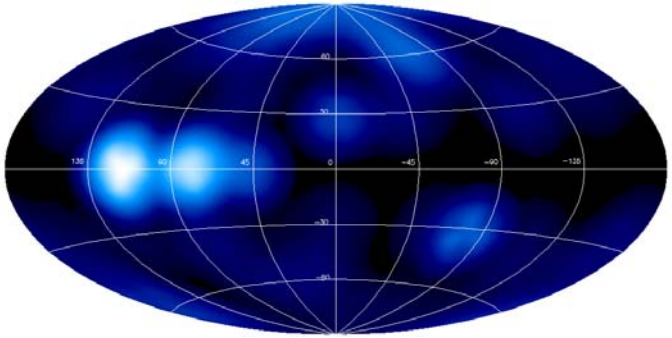
- **Other projects**
  - Simulation of superbubble evolution and isotopes distributions
  - Diffusion of the positrons created by ^{26}Al decay

Thank you for your attention !

Bonus slides

Data analysis

- **Data set**
  - Revolutions 19 to 484
  - ON: pointings to the Cygnus region (10.8 Ms)
  - OFF: High-latitude, empty pointings (11.2 Ms)
  - Single & double events (SE & ME2)
  - Energy bands
    - ^{26}Al: 1770-1850 keV
    - ^{60}Fe: 1130-1200 & 1300-1370 keV



Exposure map

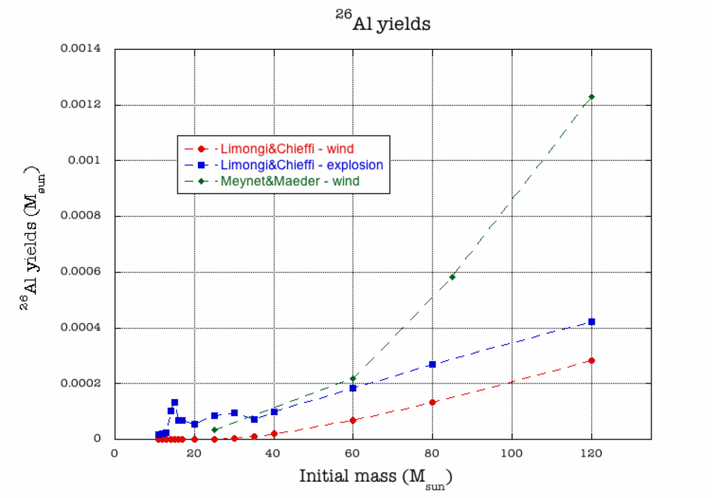
- **Analysis (or how to get rid of more than 99% of the data…)**
  - Background models based on activity tracer (rate of saturating events)
  - Source models (analytical or observational)
  - Maximum likelihood fit of the models to the data (Poissonian statistics)
  - Residuals examination over all data-space dimensions

Stellar evolution

- **Simulation of a stellar population**
  - Inputs: stellar tracks and nucleosynthesis yields
    - Limongi&Chieffi 2006
    - Meynet&Maeder 2003-2005
  - Parameters
    - IMF
    - Number of observed stars in a given mass interval
    - Starburst or constant formation rate
  - Workings
    - Random sampling of the IMF until observed stars are generated
    - Log-log spline interpolation of the durations of the main burning stages
    - Linear interpolation between fractions of burning stages for all ejected quantities
  - Outputs
    - Time-profiles for ejected mass, energy, ^{26}Al, ^{60}Fe,…
    - Number of O stars, WR stars, SN … as a function time
    - Gamma-ray line fluxes for a given distance to the object
    - Variances for all these quantities at each time step (due to IMF sampling only)

Nucleosynthesis yields

- **^{26}Al yields of the latest nucleosynthesis calculations**
  - Sites of ^{25}Mg(p,γ)^{26}Al
    - H central-burning
    - C/Ne shell-burning
    - C/Ne shells explosive burning
  - Some important factors
    - H convective core size and mass-loss
    - Burning shells size and convection
  - Effects of rotation
    - Larger H convective cores, hence larger initial ^{25}Mg reservoir
    - Increased mass-loss & rotational mixing: earlier ejection of ^{26}Al
    - Increased mass-loss: He core size, impact on late evolution
  - Uncertainties - improvements
    - Nuclear cross-sections
    - Initial ^{25}Mg content
    - Effect of rotation/mixing on shell-burnings ?
    - Explosion scenario ?



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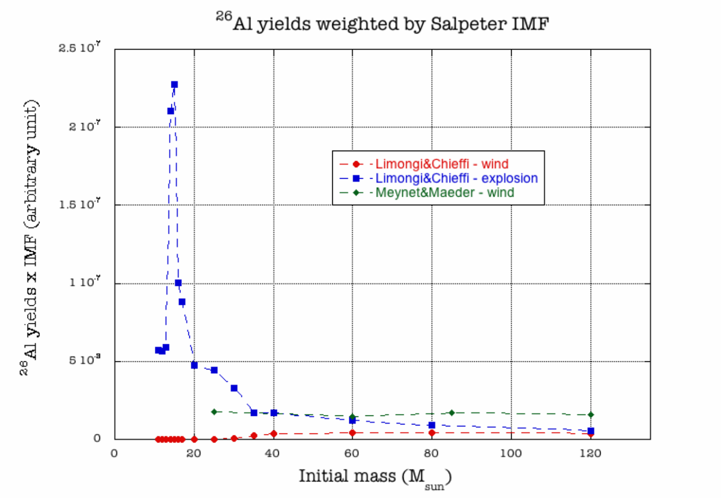

- **Connexion of hydrostatic models to supernova models**
  - Through initial mass (left) or CO core mass (right)
  - Non-rotating models
    - Bigger M&M CO core between 30 and 80 $M_\odot$
    - To be investigated…
  - Effect of rotation
    - Bigger CO core for $M < 60\ M_\odot$ (increased convection)
    - Smaller CO core for $M > 60\ M_\odot$ (increased mass-loss)