# Inferring the presence of nearby sources of cosmic rays by method of galactic propagation modelling

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# Goal of this Study

- Search for signatures of local sources of cosmic rays (CRs)
- Numerical modelling of CR propagation through the galaxy
- Separate comparison of primary and secondary CRs to observational data

# Motivation

- CRs are accelerated at point-like sources (SN + SNR)
- Primary CRs - depend on local sources
- Secondary CRs - don’t depend on local sources
- 2D CR propagation models can’t include the local source history but should describe secondary CRs well

# Cosmic Rays in the Galaxy

**Cosmic rays**:

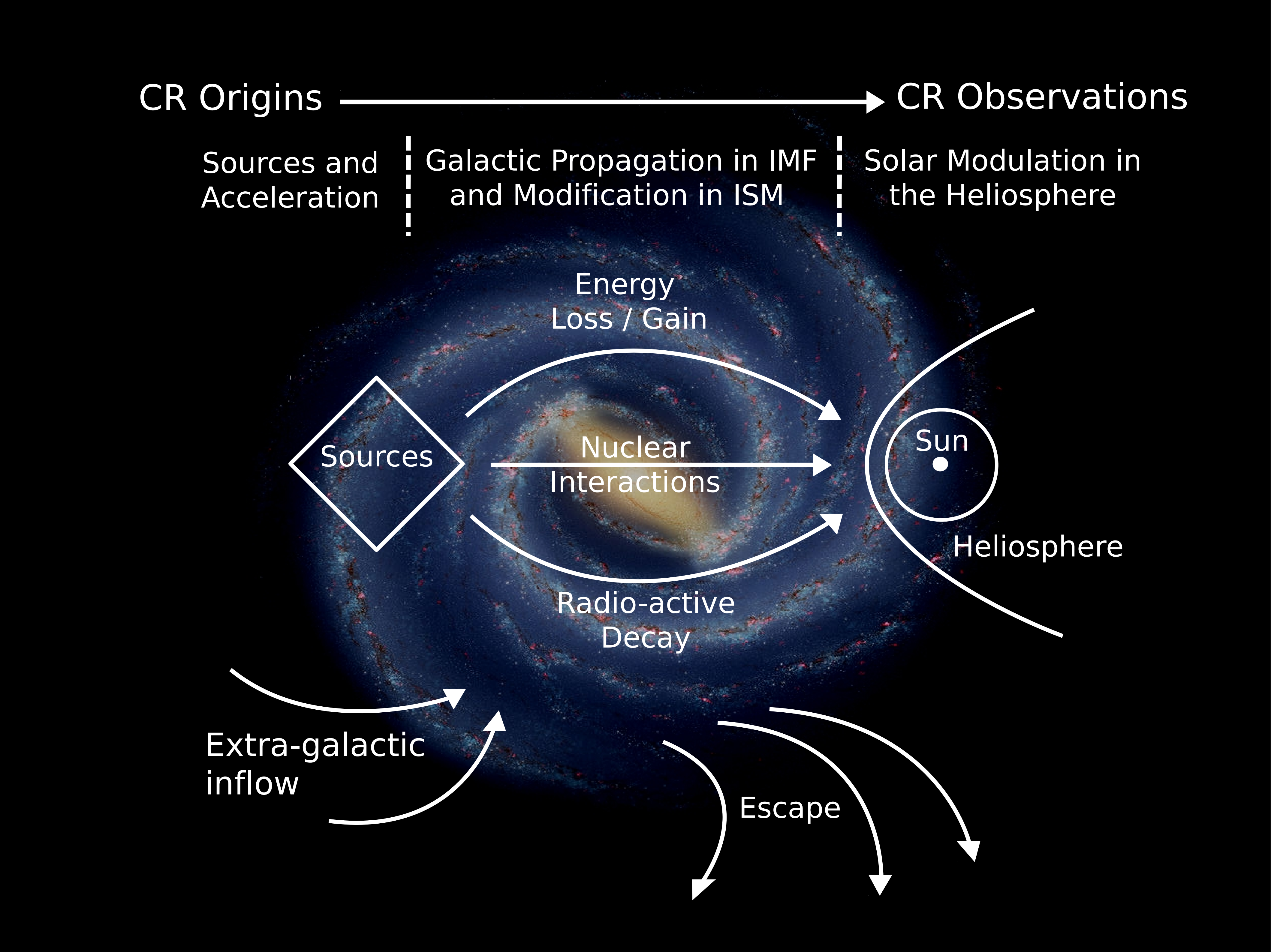
- Fully charged energetic particles
- Originate in discrete sources in the Galaxy
- Propagate through the galactic interstellar medium (ISM)

**Primary CRs**:

- CRs accelerated in sources of high energy particles, such as SNR in the Galaxy, are referred to as Primary CRs

**Secondary CRs**:

- CRs resulting from the fragmentation of the Primary CRs during propagation through the ISM are referred to as Secondary CRs



CR Origins
CR Observations
Sources and Acceleration
Galactic Propagation in IMF and Modification in ISM
Solar Modulation in the Heliosphere
Energy Loss / Gain
Sources
Nuclear Interactions
Sun
Heliosphere
Radio-active Decay
Extra-galactic inflow
Escape

# Galactic CR Propagation Equation

$$\frac{\partial N}{\partial t} = S + \nabla \cdot (K_x \nabla N - \boldsymbol{V} N) + \frac{\partial}{\partial p}\left(p^2 K_p \frac{\partial}{\partial p}\left(\frac{N}{p^2}\right) + \frac{p}{3}(\nabla \cdot \boldsymbol{V}) N - \dot{p} N\right) - \frac{N}{\tau}$$

CR Sources:

$$S(\boldsymbol{r}, p, t)$$

Particle loss:

$$N/\tau$$

Spatial diffusion:

$$\nabla \cdot (K_x \nabla N)$$

Convection:

$$\nabla \cdot (\boldsymbol{V} N)$$

Momentum diffusion:

$$\frac{\partial}{\partial p}\left(p^2 K_p \frac{\partial}{\partial p}\left(\frac{N}{p^2}\right)\right)$$

Adiabatic cooling:

$$\frac{\partial}{\partial p}\left(\frac{p}{3}(\nabla \cdot \boldsymbol{V}) N\right)$$

Momentum loss:

$$\frac{\partial}{\partial p}(\dot{p} N)$$

# The GALPROP Numerical Model

- GALactic PROPagation code
- Developed by A. Strong & I.V. Moskalenko
  - http://galprop.stanford.edu/

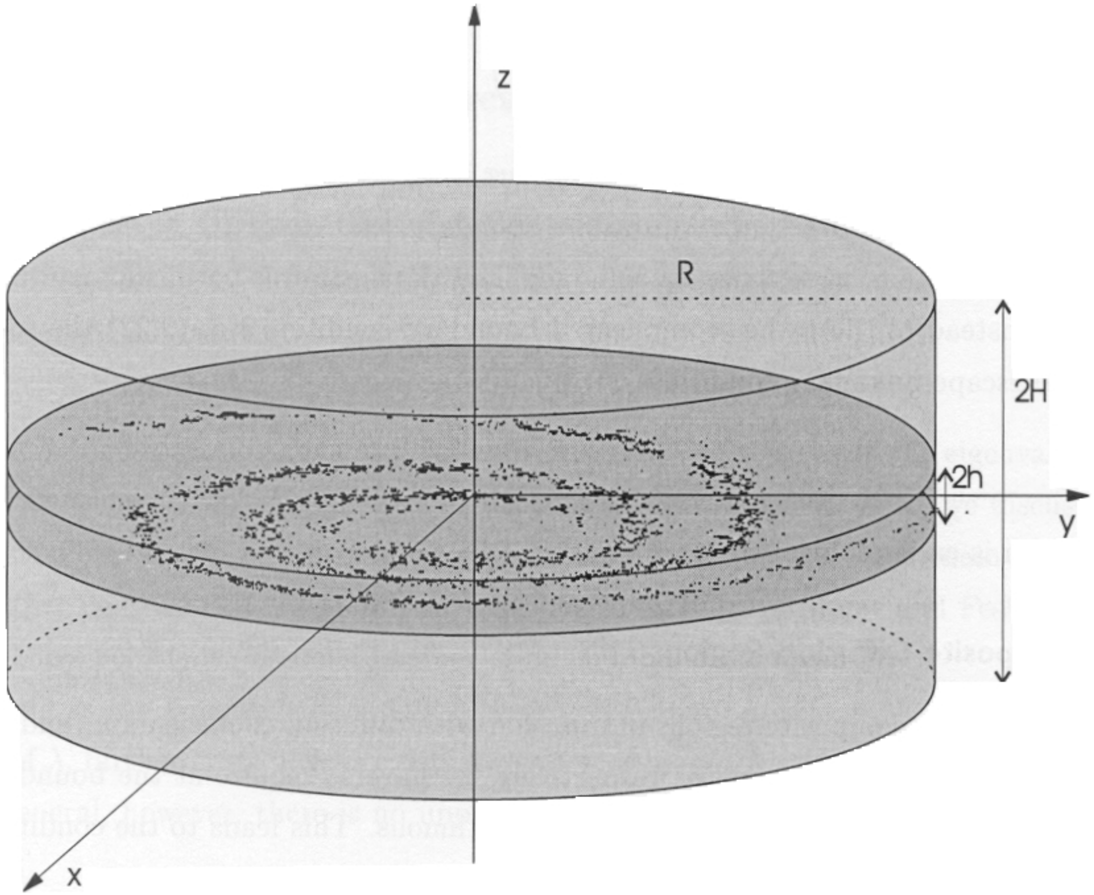
- Calculates propagation of CRs through the Galaxy
- Capable of using realistic astrophysical input
- Latest theoretical developments

- 2D and 3D implementations

$$2H = 8\ \text{kpc}$$

$$2h = 0.3\ \text{kpc}$$

$$R = 20\ \text{kpc}$$




- 2D space + momentum
- Grid spacing:

$$dz = 0.1\ \text{kpc}$$

$$dr = 1\ \text{kpc}$$

- Solar system at 8.5 kpc
- Sources in Galactic plane

# Parameter Study

- The source spectral index: $\alpha$

$$Q(p) \propto p^{\alpha}$$

- The spectral index of the diffusion coefficient: $\delta$
- The magnitude of the diffusion coefficient at a particle rigidity of 4 GV: $k_0$

$$k_x = \delta k_0 \left( \frac{\rho}{\rho_0} \right)^{\delta}$$

# Parameter Study

| Parameter | Min | Max | Units |
|---|---|---|---|
| $k_0$ | 0.5 | 5.0 | $10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1}$ |
| $\delta$ | 0.1 | 1.0 | |
| $\alpha$ | 1.50 | 3.50 | |

- Parameter space: $k_0, \delta, \alpha$
- Plain diffusion model
- Model runs in parallel using MPI on cluster computer
- $\chi^2$ test comparing spectra to data above 4 GeV
- Database maintained by Strong & Moskalenko

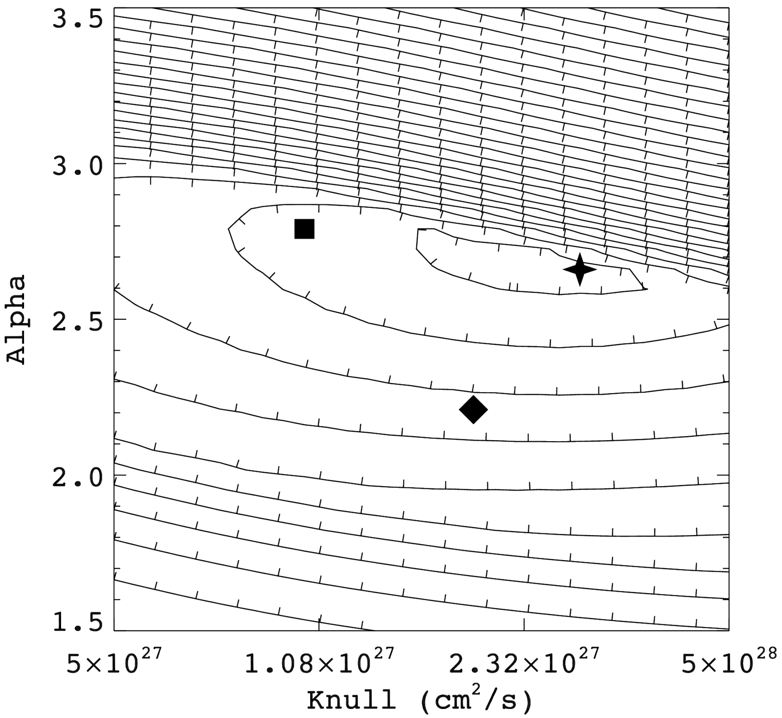
  http://www.mpe.mpg.de/~aws/propagate.html

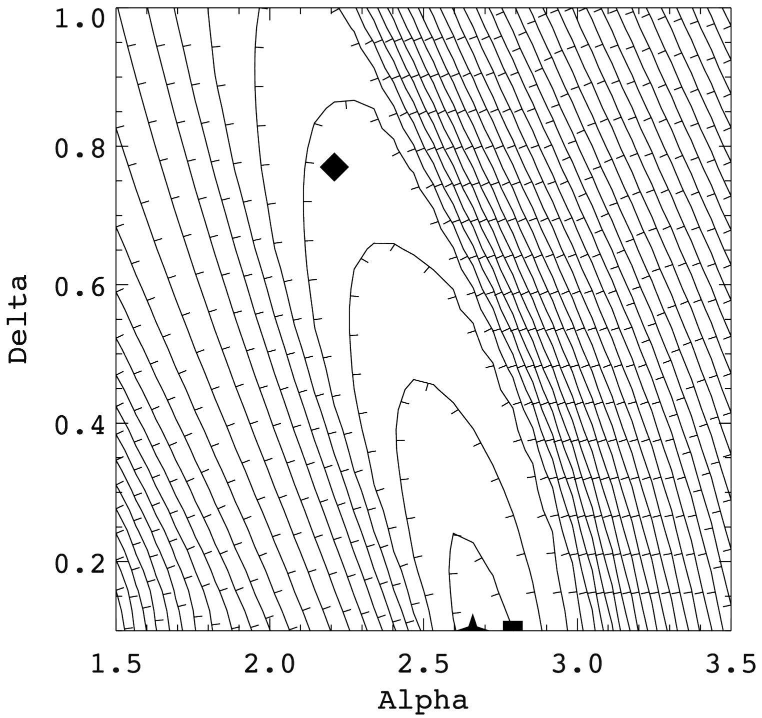
# Primary CRs vs Secondary CRs

- Restricted by experimental data
- Split data between Primary and Secondary
- Giving 3 CR component groups: Primary, Mixed and Secondary

| Primary | Mixed | Secondary |
|---|---|---|
| H | N | Be |
| He | C+N+O | B |
| C | Ne | F |
| O | Na | P |
| Mg | Al | Sc |
| Si | S | Ti |
| Ne+Mg+Si | Cl | V |
| Ca | K | Mn |
| Fe | Cr | |
| | Co | |

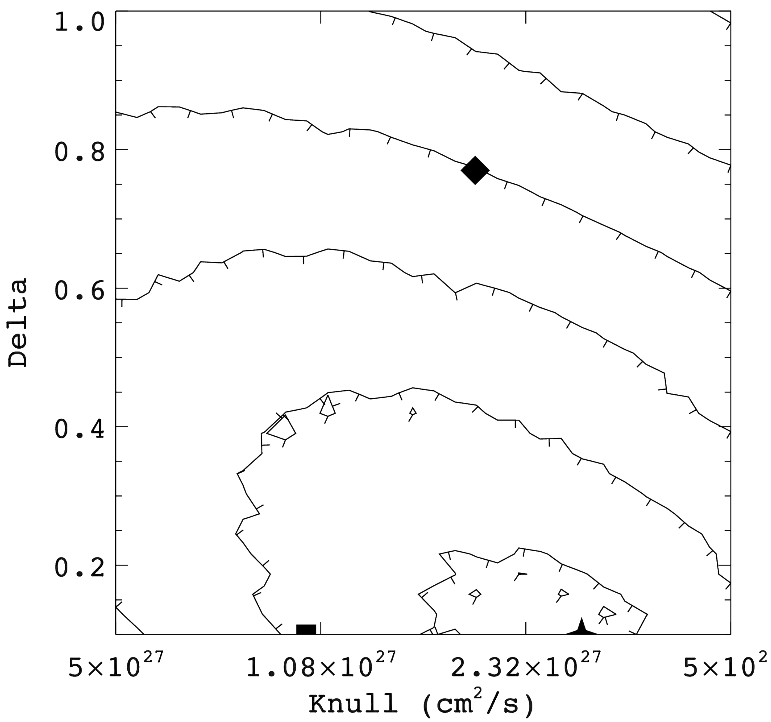
| Component | % of Secondary CR fraction |
|---|---|
| Primary | < 30 % |
| Mixed | > 30 %, < 70 % |
| Secondary | > 70 % |




Minimum $\chi^2$ values for

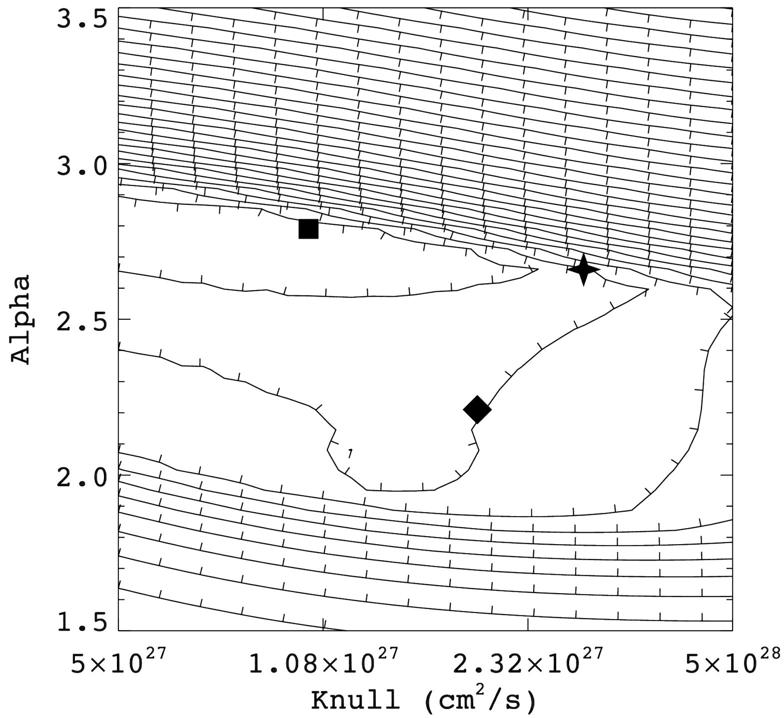
Primary CRs

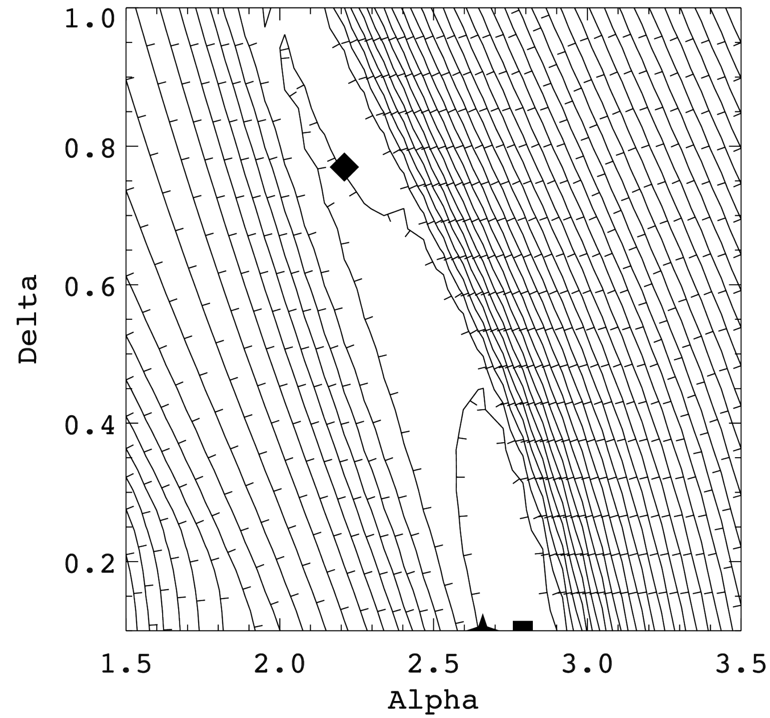



✦ :Primaries best fit model

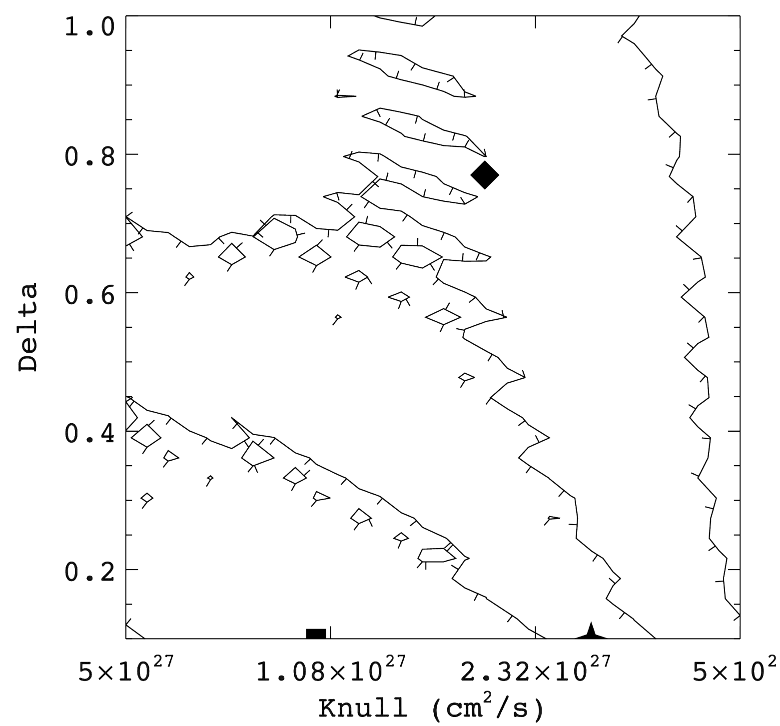
■ :Mixed best fit model

◆ :Secondaries best fit model



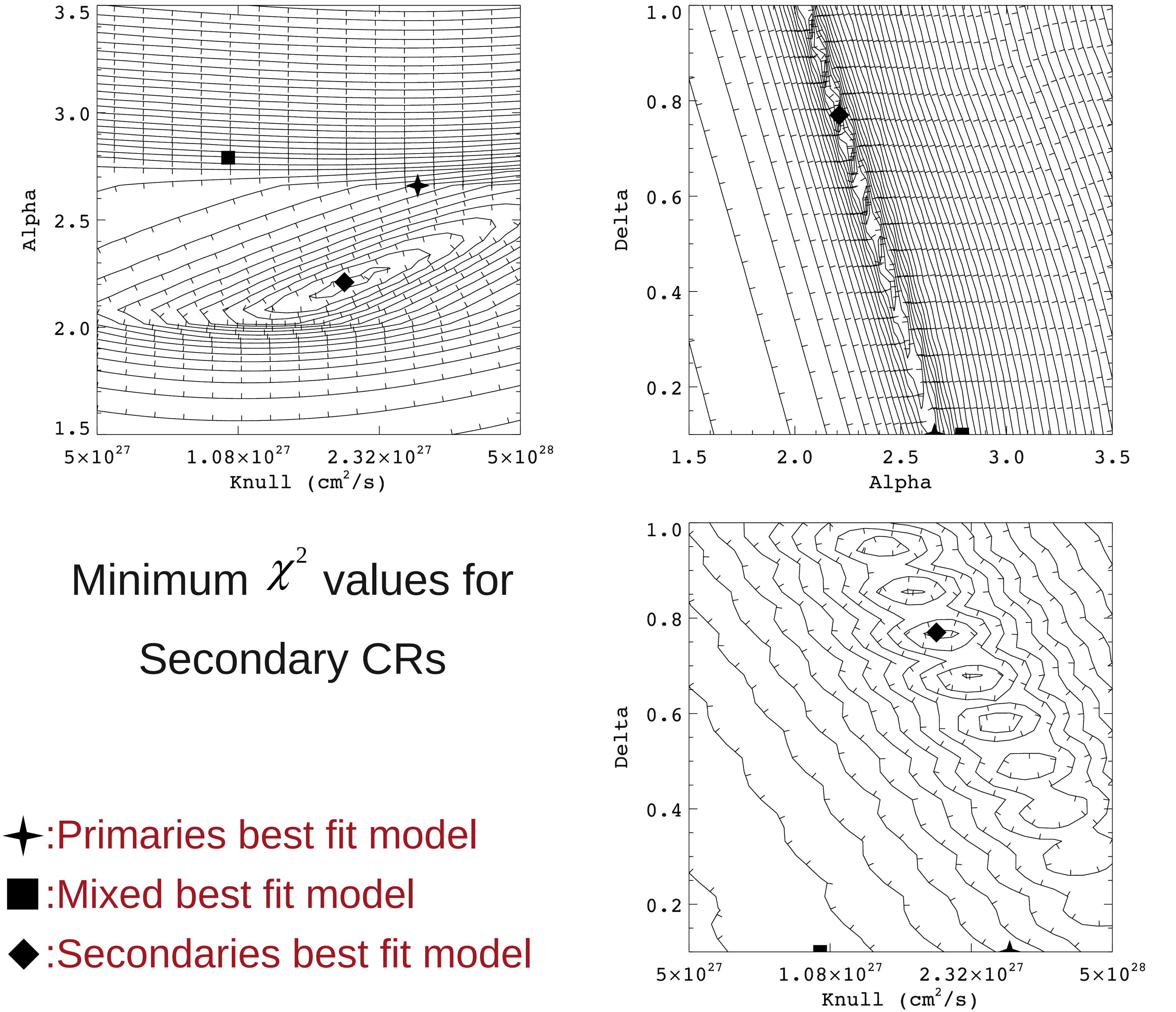

Minimum $\chi^2$ values for Mixed CRs




✦:Primaries best fit model

■:Mixed best fit model

◆:Secondaries best fit model




# Minimum $\chi^2$ values for Secondary CRs

✦:Primaries best fit model

■:Mixed best fit model

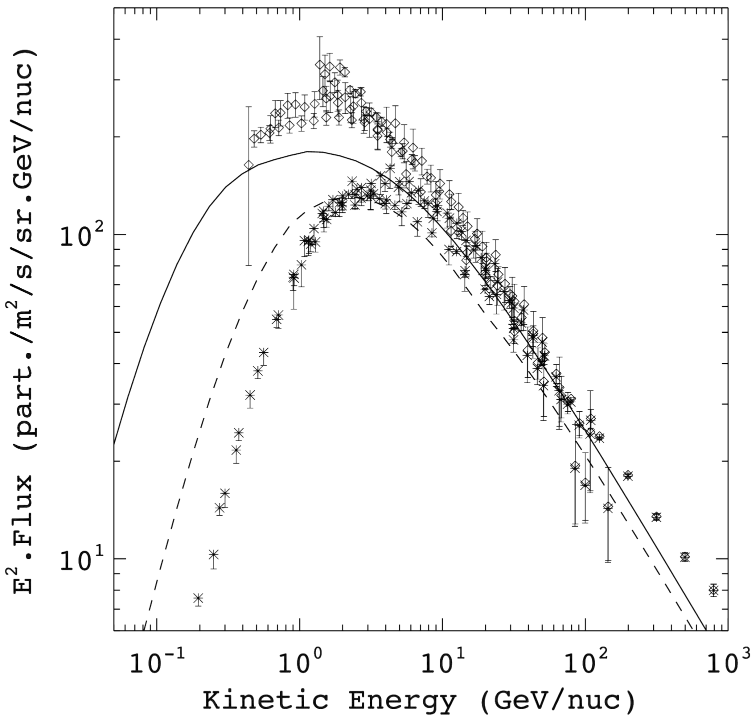
◆:Secondaries best fit model

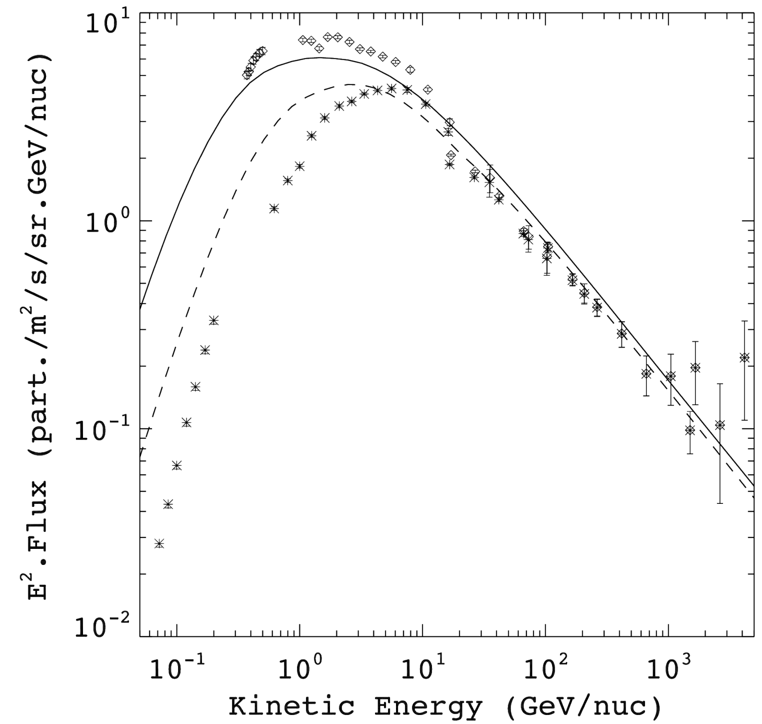
# Results

- Best fit models and parameter values found:

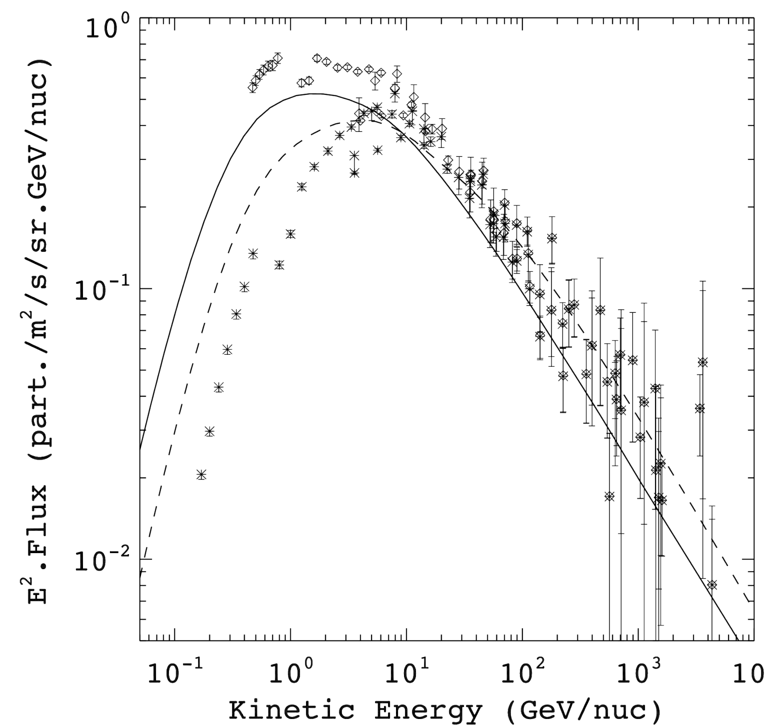
| Parameter | Primary | Mixed | Secondary | Units |
|---|---|---|---|---|
| $k_0$ | 2.868 | 1.022 | 1.928 | $10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1}$ |
| $\delta$ | 0.100 | 0.100 | 0.767 | |
| $\alpha$ | 2.661 | 2.661 | 2.210 | |

- Contours of minimum $\chi^2$ also differ between Primaries and Secondaries




# Spectra for CR Primaries: Helium, Carbon and Iron

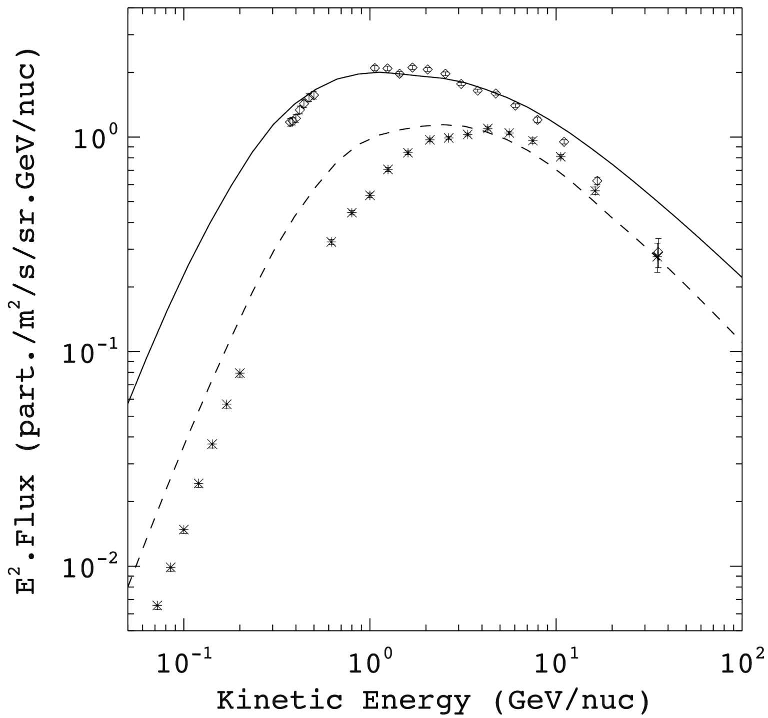


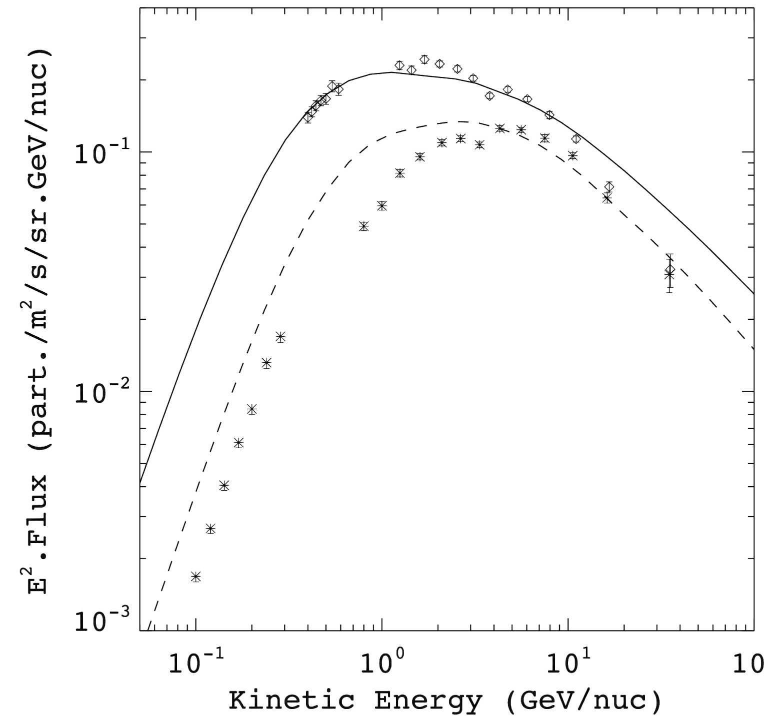

—— :Calculated spectra

- - - - :Moskalenko LIS

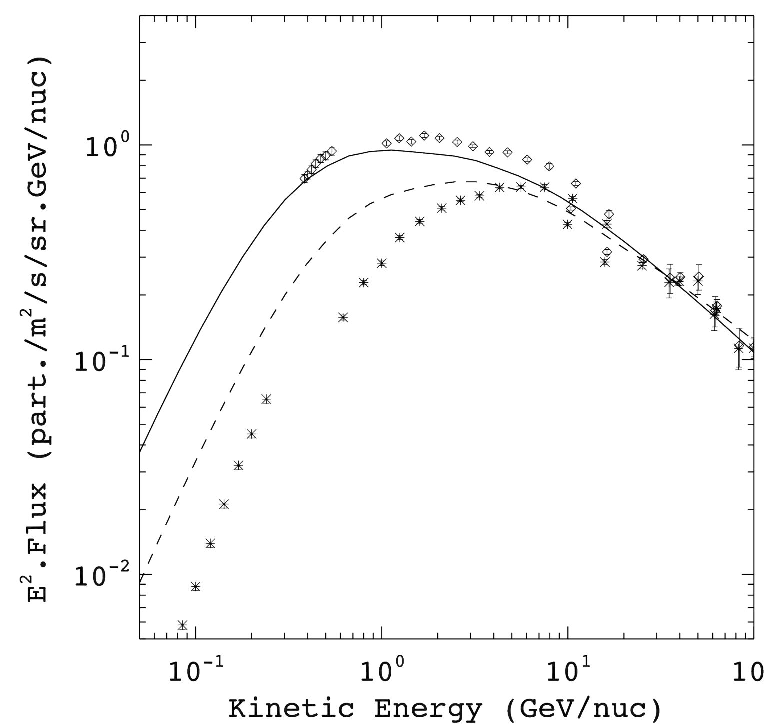
◇ :Data points at Earth

✳ :Data points without modulation




# Spectra for Mixed CRs: Nitrogen, Sodium And Neon

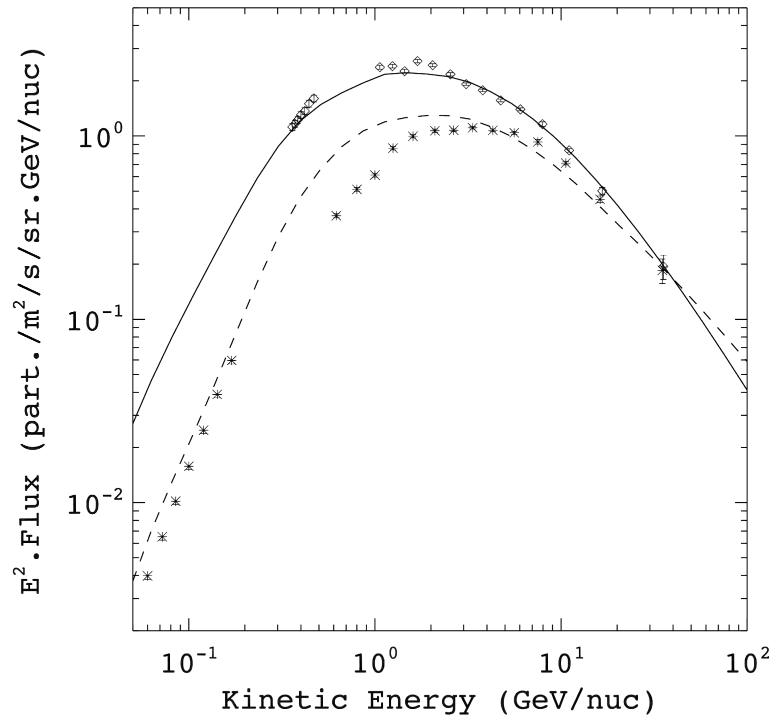


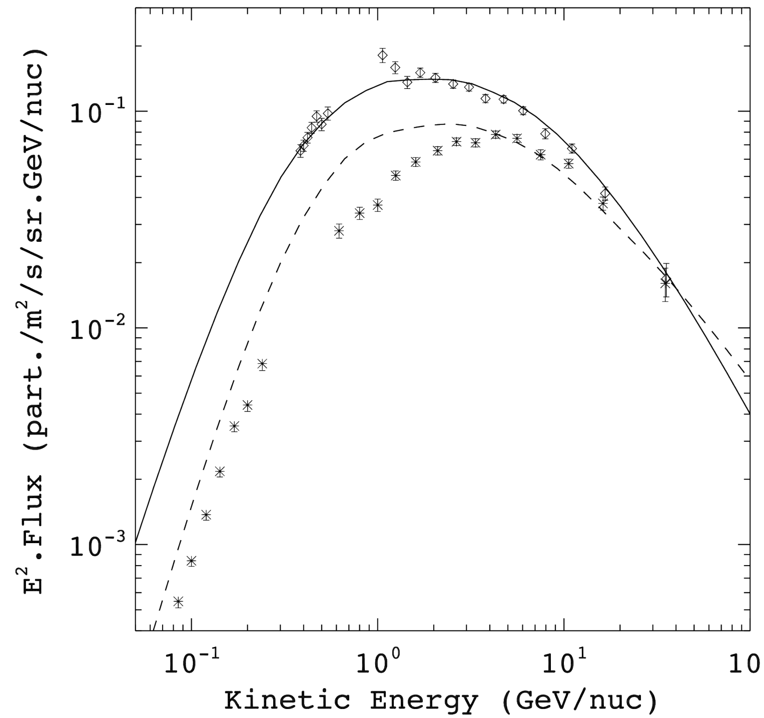

—— :Calculated spectra

- - - - :Moskalenko LIS

◇ :Data points at Earth

✳ :Data points without modulation




# Spectra for CR Secondaries:

# Boron, Fluorine

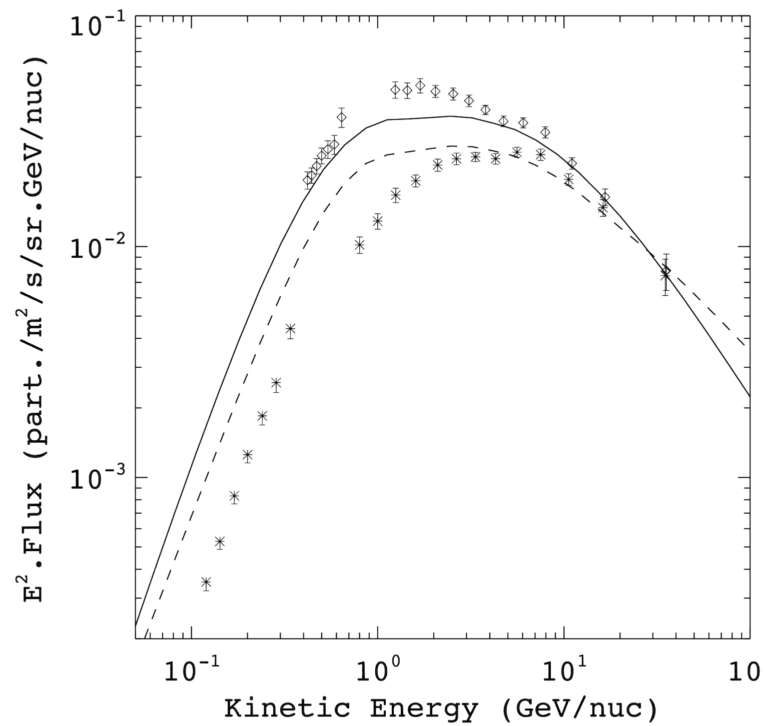
# and Iron

—— :Calculated spectra

- - - - :Moskalenko LIS

◇ :Data points at Earth

✳ :Data points without modulation



# Conclusions

- Separately modelling Primaries and Secondaries
- Components favour different best fit values
- Different sensitivities to model parameters
- Secondaries show in total better fits to the data

This suggests that the Primary CR distribution does indeed vary in time and space depending on the local source history