LWS Team meeting

Using Direct Monte-Carlo to study transport

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Motivation

- In using the focused transport equation to model specific event, one often assume that λr or $\lambda_{||}$ are r-independent => no radial dependence for Duu.

- No physical reason, probably for simplicity (easier coding for finite difference method).

- Direct Monte-Carlo is more intuitive, but computationally more demanding in the past. Not a problem any more.

- Want to explore the effect of an r-dependent Duu on particle transport --- time intensity profile, spectra, etc.

- Initially, has electrons in mind (injection delay between ions and electrons).

Origin of pitch angle scattering

In quasi-linear theory, pitch angle scattering is caused by charged partic
l
e interacting with turbulent magnetic field. (Jokipii, 1966)

The change of pitch angle is diffusive, often described by a random walk process, *and the rate of change is proportional to the power of δB*.

$$\frac{\partial f}{\partial t} + (u\cos\psi + \mu v)\bullet\frac{\partial f}{\partial z} - \frac{v(1-\mu^2)}{2B}\frac{\partial B}{\partial z}\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}(D_{\mu\mu}\frac{\partial f}{\partial \mu}) = Q$$

deterministic

characteristic

stochastic

"scattering"–random walk

Solving the transport equation

$$\frac{\partial f}{\partial t} + (u\cos\psi + \mu v)\bullet\frac{\partial f}{\partial z} - \frac{v(1-\mu^2)}{2B}\frac{\partial B}{\partial z}\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}(D_{\mu\mu}\frac{\partial f}{\partial \mu}) = Q$$

1a) Finite difference method (eg. Ruffolo et al 1995)

1b) Finite
differenc
e
method, add a twist of Monte-carlo in deciding Δμ. (Earl 1976, 1994)

2) Using a stochastic approach, f => f/B. Still solving f.

(e.g. Qin et al. 2005)

3) Direct Monte-Carlo
si

Fokker Planck's coefficient Dμμ

QLT

QLT limitation: slab geometry, magnetostatic.

Dynamical Turbulence — Bieber et al. (1994)

$$P_{xx}(k_z, t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} R_{xx}(z, t) e^{-ik_z z} dz = P_{xx}(k_z, 0)\Gamma(k_z, t)$$

$$\Gamma(k_z, t) = \exp(-\alpha |k_z| V_A |t|)$$ Damping model

$$\Gamma(k_z, t) = \exp(-\alpha^2 k_z^2 V_A^2 t^2)$$ Random sweeping model

Fokker Planck's coefficient Dμμ (cont.)

$$\Phi(\mu) = \frac{\Omega^2}{B_0^2}(1-\mu^2)\int_{-\infty}^{+\infty} P_{xx}(k_z, 0) D(k_z) dk_z,$$

Bieber et al. (1994)

$$D(k_z) = \int_{-\infty}^{+\infty} \exp\,[i(k_z \mu V - \Omega)t]\Gamma(k_z, t)dt$$

$\delta(kz - \Omega/\mu v)$

Damping model:

$$D(k_z) = \frac{2}{|\mu| V} \frac{(\alpha |k_z| V_A)/(|\mu| V)}{[(\alpha k_z V_A)/(|\mu| V)]^2 + [k_z - \Omega/(\mu V)]^2}$$

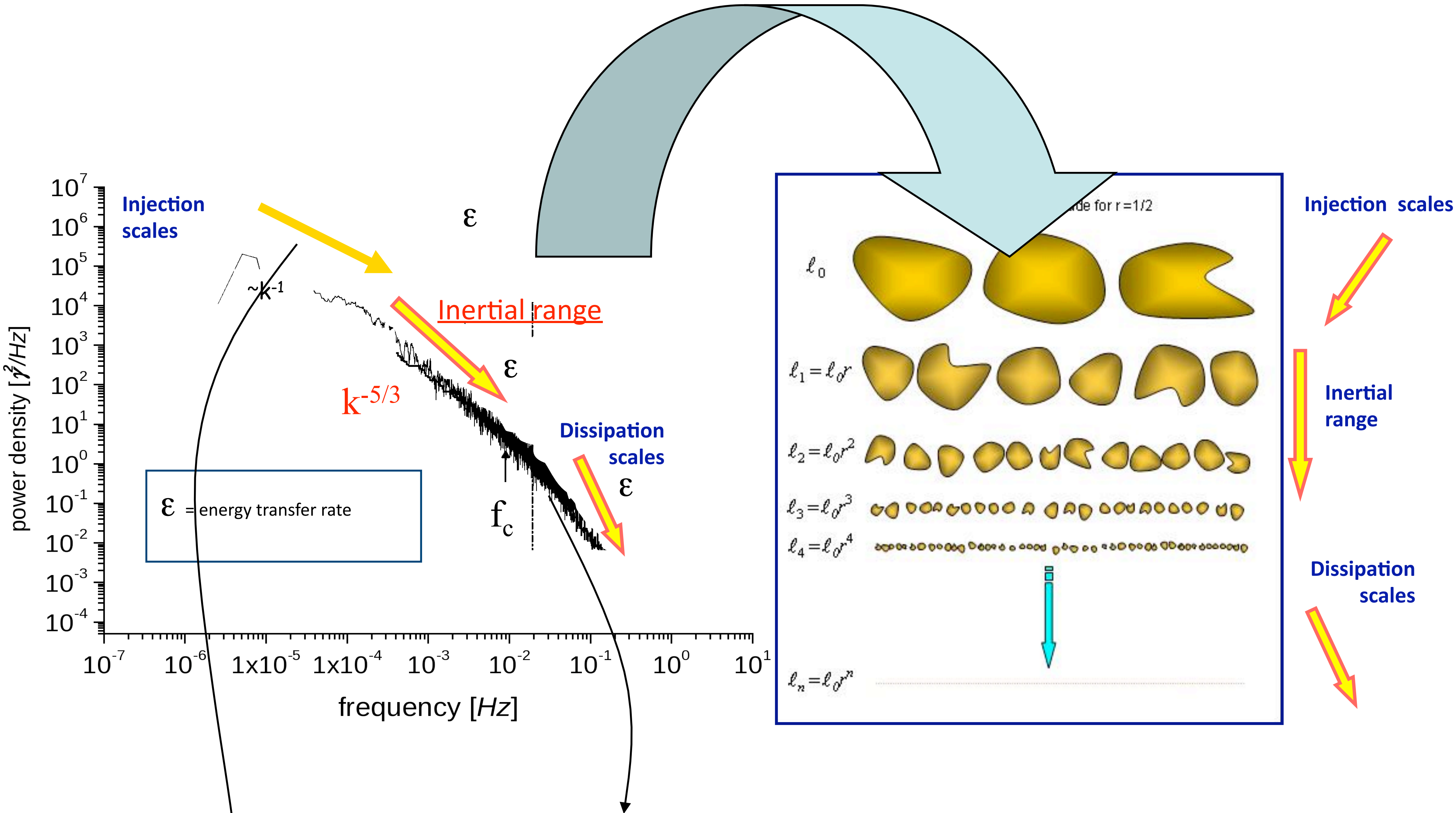
(Cauchy form)

Random sweeping model:

$$D(k_z) = \frac{\pi^{1/2}}{\alpha |k_z| V_A} \exp\left\{-\frac{[k_z - \Omega/(\mu V)]^2}{4\alpha^2 k_z^2 V_A^2/(\mu^2 V^2)}\right\}.$$

(Gaussian form)

Turbulence in the solar wind



Bruno et al., 1985,

q ~ -1

Leamon et al, 1999]

Vasquez et al. 2007

q~ -2.1 - -2.5

Turbulence in the solar wind (2)

Komogorov has -5/3, which is hard to distinguish from -1.5.

In different ranges, energy containing, inertial and dissipation range, q can vary a lot.

consider different cases, q = 1.5, 1.666, 2.5 and vary four cases.

Input:

- 1 AU observations of the power spectrum (dB^2) and correlation length and some r dependence of interplanetary turbulence.

Output:

- time intensity profiles at 3 rs r = 0.5, 1.0, and 1.5 AU.
- spectrum.
- anisotropy analysis [not accomplished yet.]

$$D_{\mu\mu}(p) = \frac{2\pi v(1-\mu^2)}{(R_L * B_0)^2|\mu|} P(k = \frac{1}{R_L|\mu|}),$$

if only examine u dependence, we obtain.

$$D_{\mu\mu} \approx (1-\mu^2)|\mu|^{q-1},$$

This, however, ignores r-dependence completely.

The form of P (power spectrum), including dissipation range is:

$$P_{xx}(k_z, 0) = \begin{cases} 2\pi C\lambda_c(1 + k_z^2\lambda_c^2)^{-q_i/2}, & \text{when}|k_z| \leq k_d \\ 2\pi C\lambda_c(1 + k_d^2\lambda_c^2)^{-q_i/2}(|k_z/k_d|)^{-q_d} & \text{when}|k_z| > k_d \end{cases}$$

C and lambda_c in the above are the two parameters decide the power. Relate them to observed quantity through,

$$\int_0^\infty P(k_z)dk_z = 2\pi C \frac{\sqrt{\pi}\Gamma(\frac{q_i-1}{2})}{2\Gamma(\frac{q_i}{2})} = \frac{<\delta B^2>}{2},$$

$$l_c = \frac{\int_0^\infty <\delta B_x(z)\delta B_x(z+l)> dl}{<\delta B_x^2>} = \frac{\pi P_{xx}(k_z = 0)}{\int_{-\infty}^\infty P_{xx}(k_z)dk_z} = \lambda_c \frac{\sqrt{\pi}\Gamma(\frac{q_i}{2})}{\Gamma(\frac{q_i-1}{2})}$$

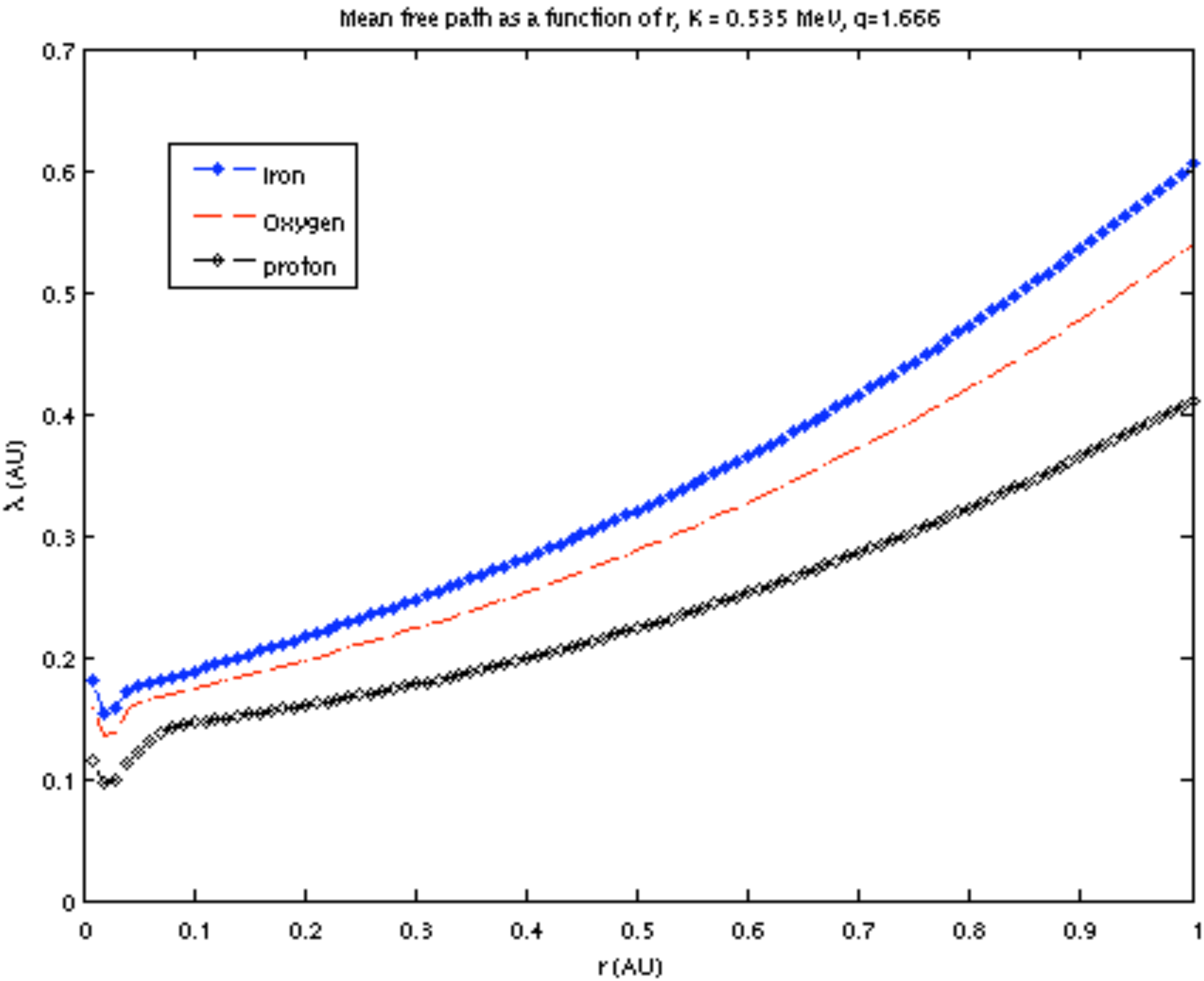
Use the same observed quantities, but different q value (since it is hard to tell the difference between 1.5 and 1.666) to drive the simulation.

Two energies: K = 10 MeV/nucleon and 0.5 MeV/nucleon, for four species: proton, Q/A = 1; Helium Q/A = 2/4, Oxygen Q/A =6/16; Iron Q/A =14/56.

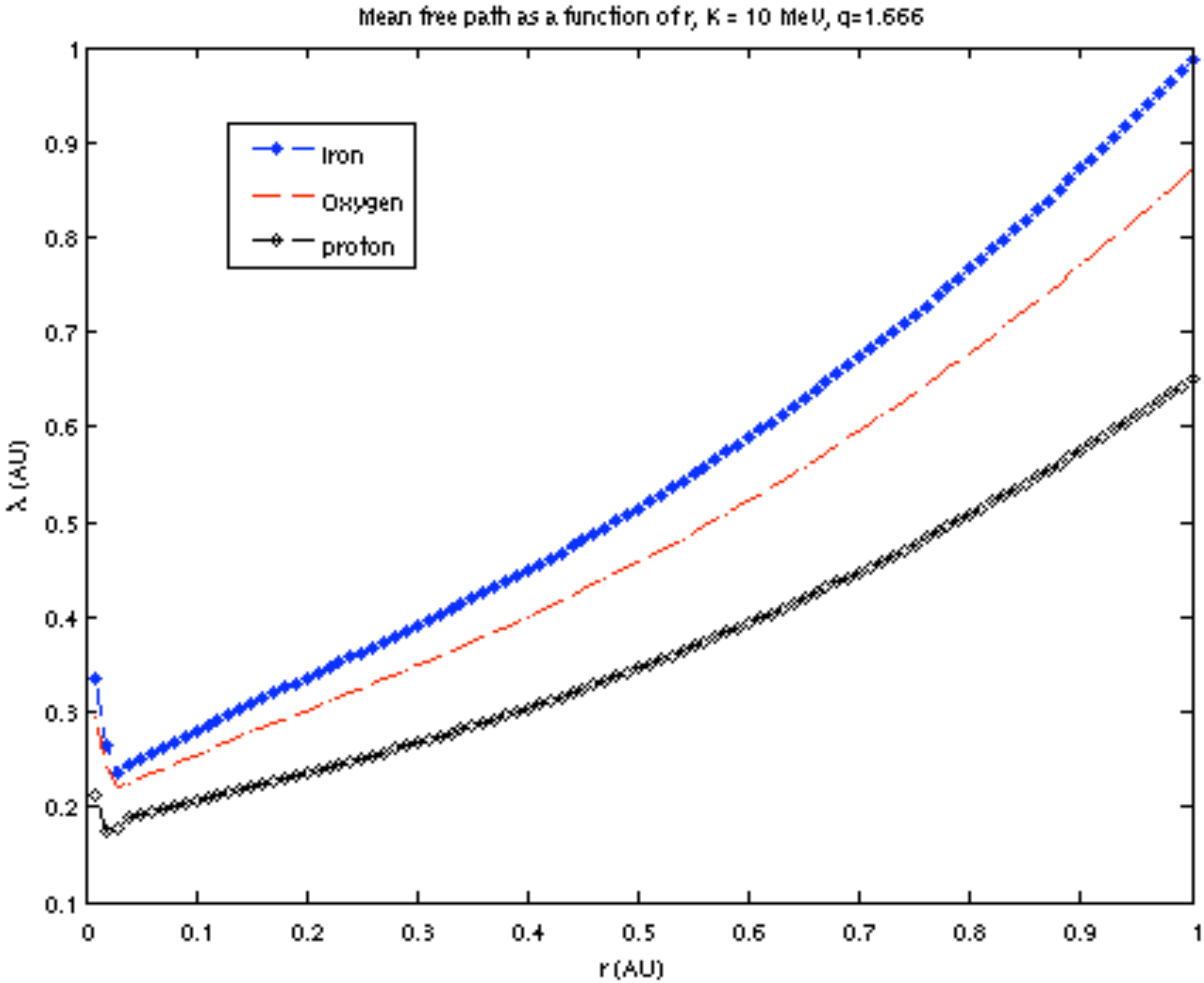
Simulation assumes a delta-injection in time.

- Plot derived quantity lambda.
- Plot time-intensity profiles.

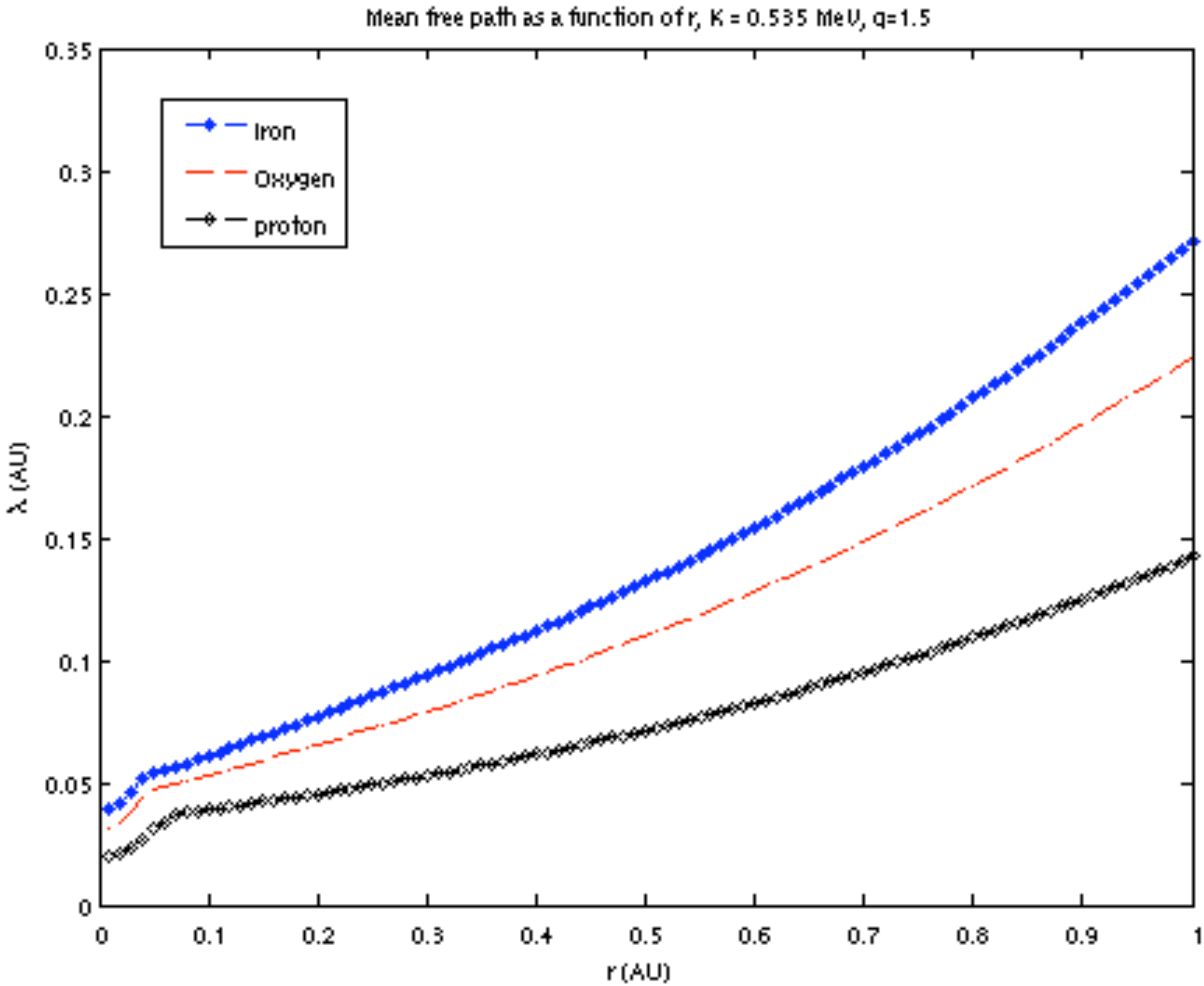
goal is to
1) understanding different pieces in the transort equation.
2) find similarities (resemblance) between simulation and observations
==> guidance for future work. [more realistic injection profiles, etc.]

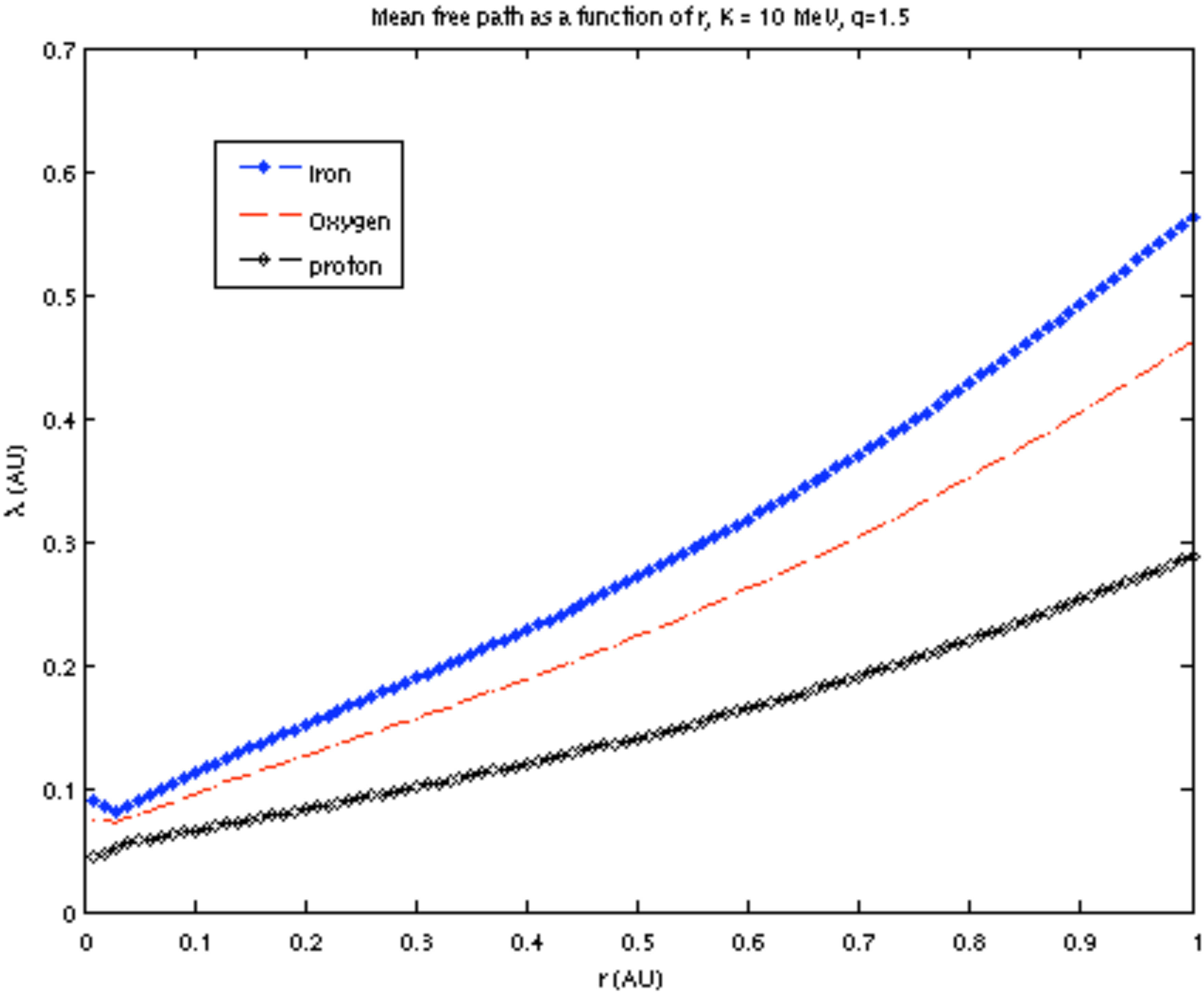


Mean free path as a function of r, K = 0.535 MeV, q=1.666
Iron
Oxygen
proton
λ (AU)
r (AU)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



Mean free path as a function of r, K = 10 MeV, q=1.666
Iron
Oxygen
proton
λ (AU)
r (AU)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

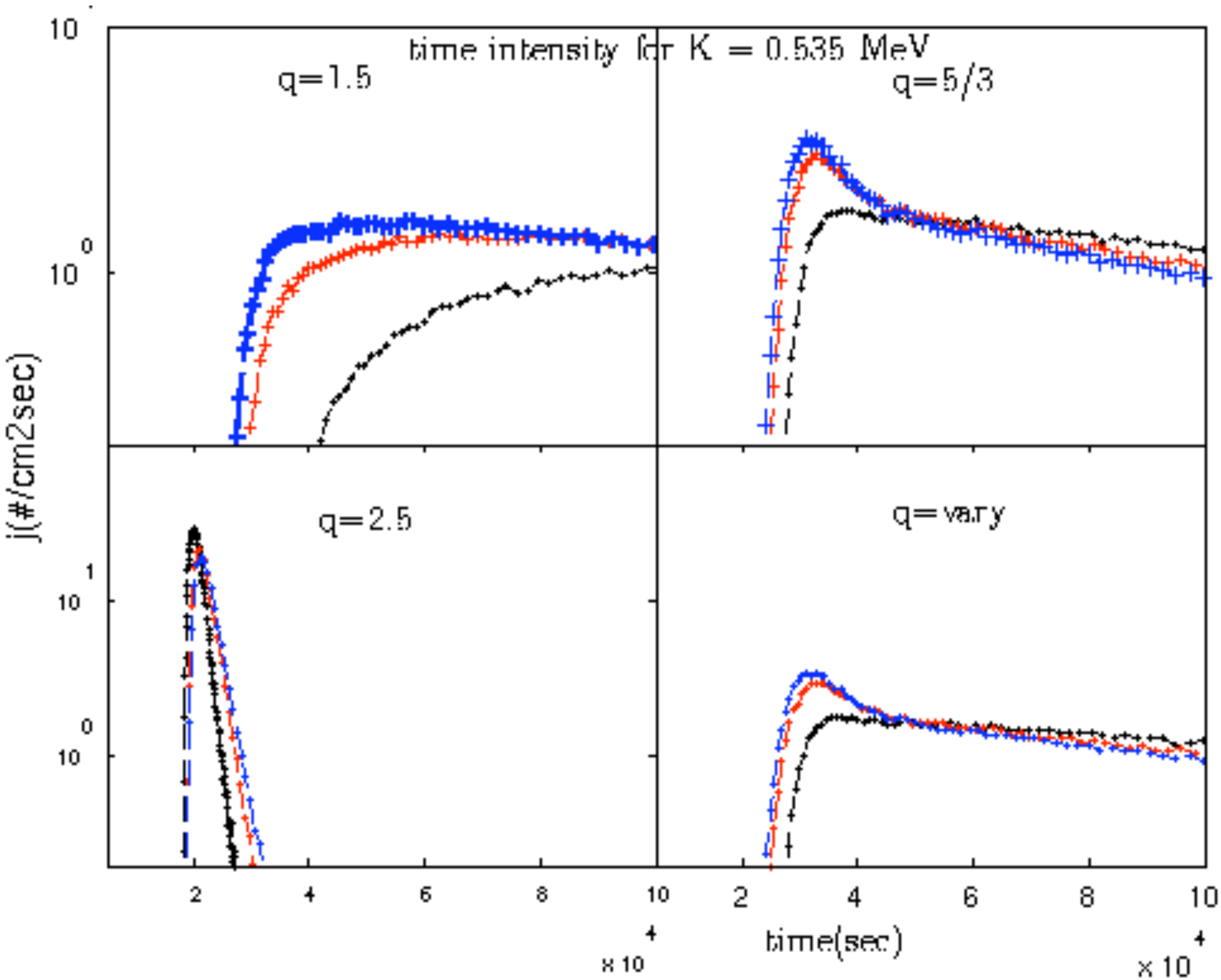

Mean free path as a function of r, K = 0.535 MeV, q=1.5
λ (AU)
r (AU)
Iron
Oxygen
proton
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1



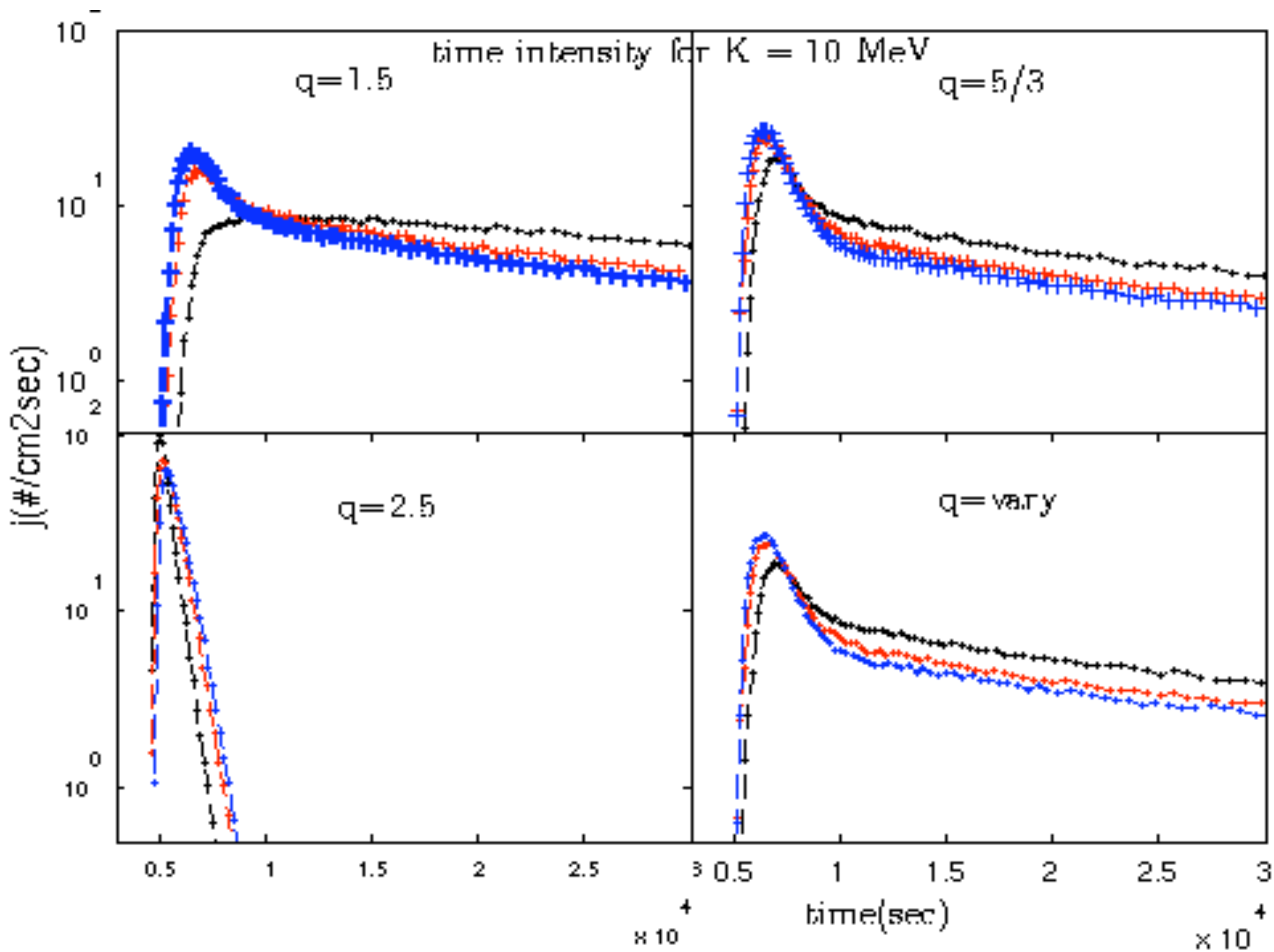
Mean free path as a function of r, K = 10 MeV, q=1.5
Iron
Oxygen
proton
λ (AU)
r (AU)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

In this work, we keep Duu (mfp) unchanged, i.e. we use Duu with its value at (r=1AU) throughout the simulation although previous figures show how Duu change with r in a WKB approximation.

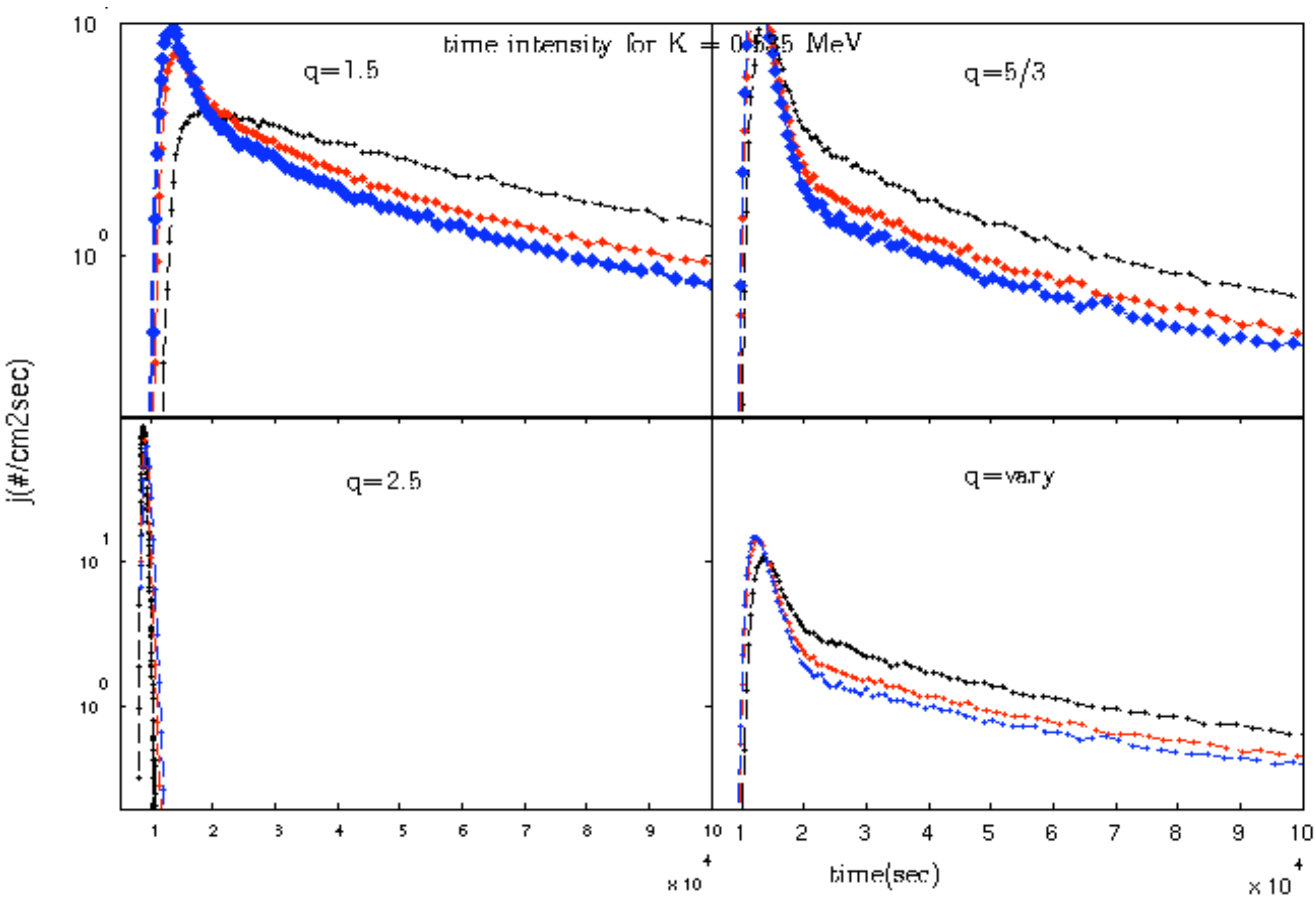
Time intensity profile at r = 1AU



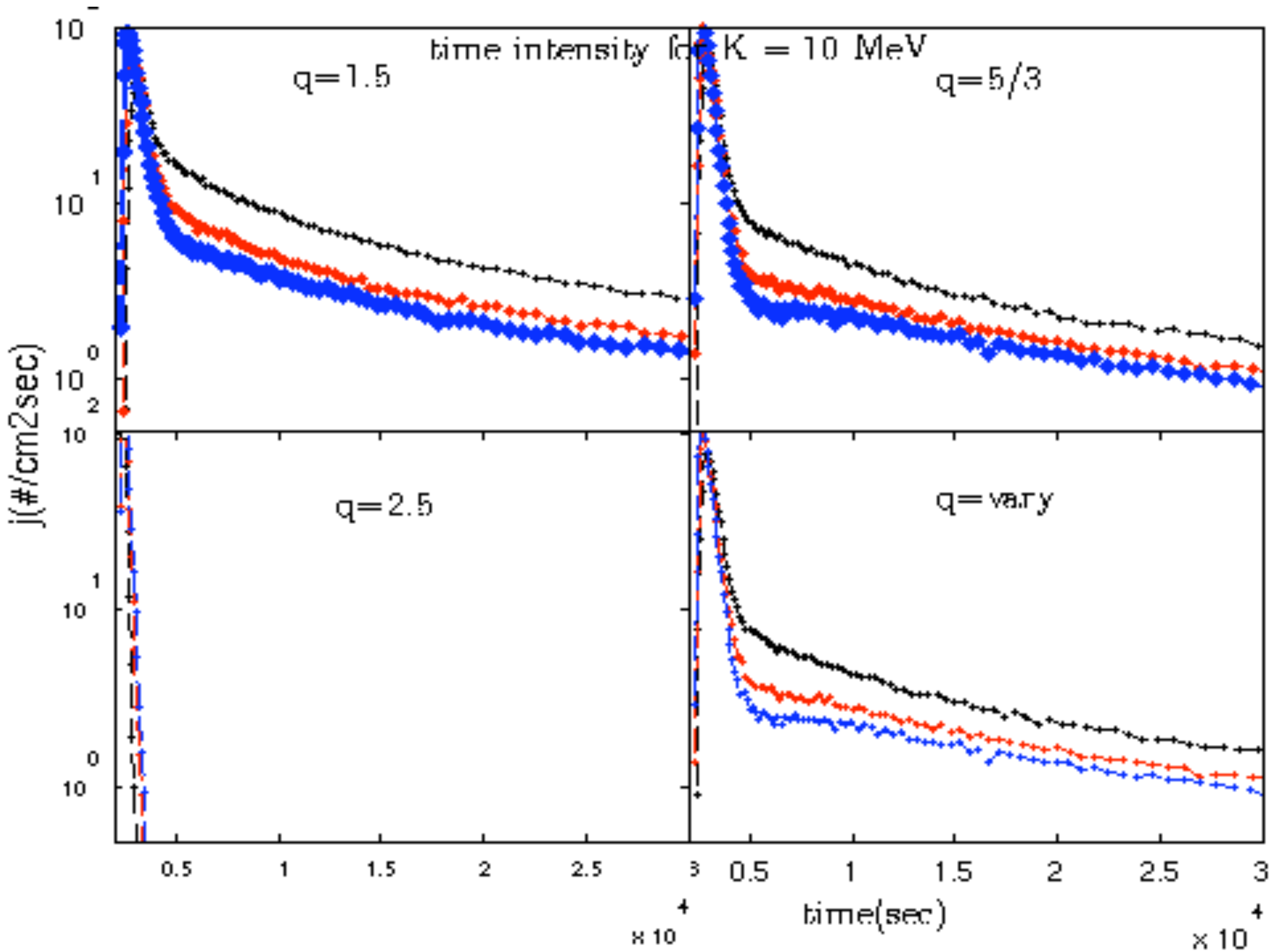
Time intensity profile at r = 1AU



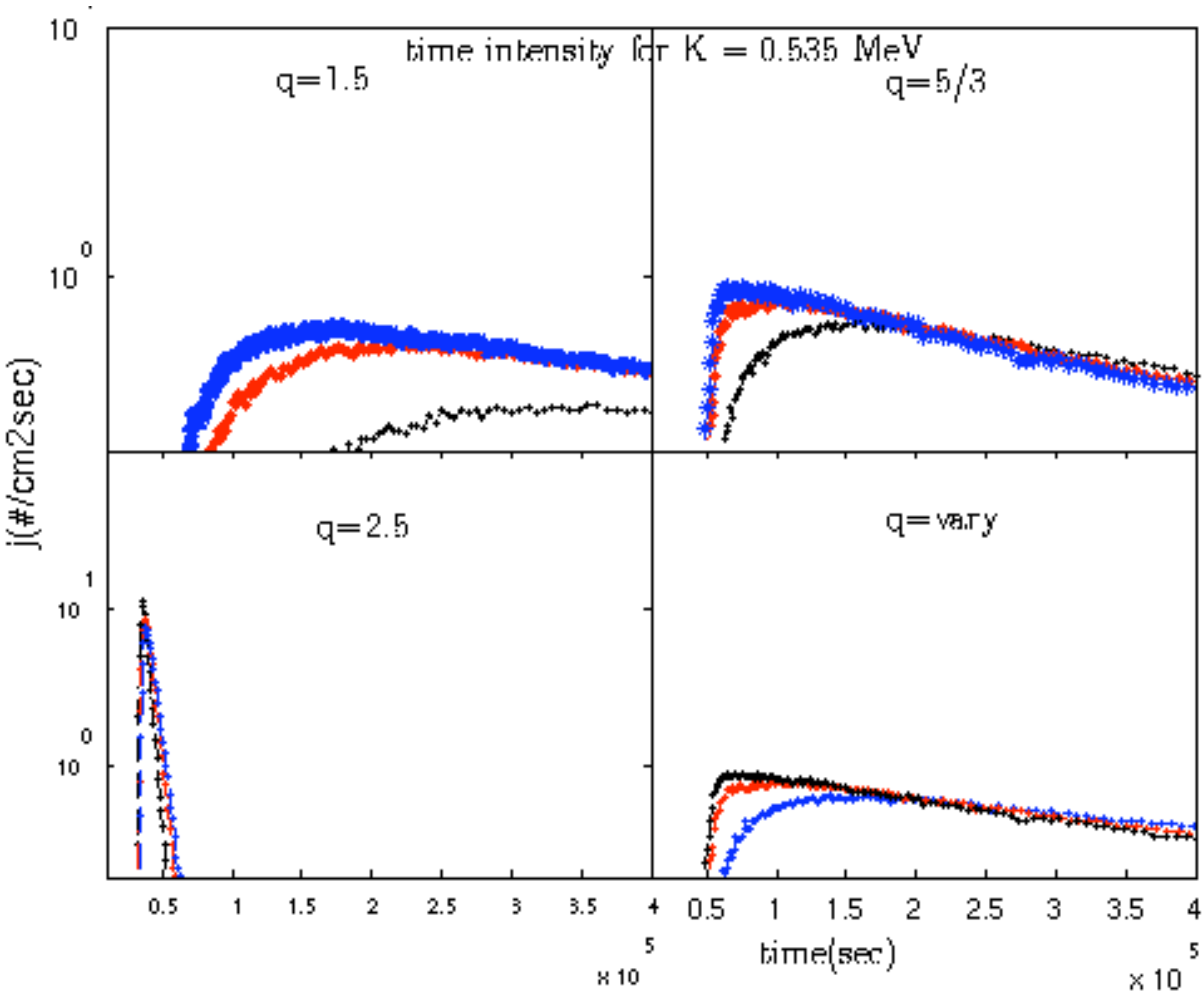
Time intensities at r = 0.5 AU



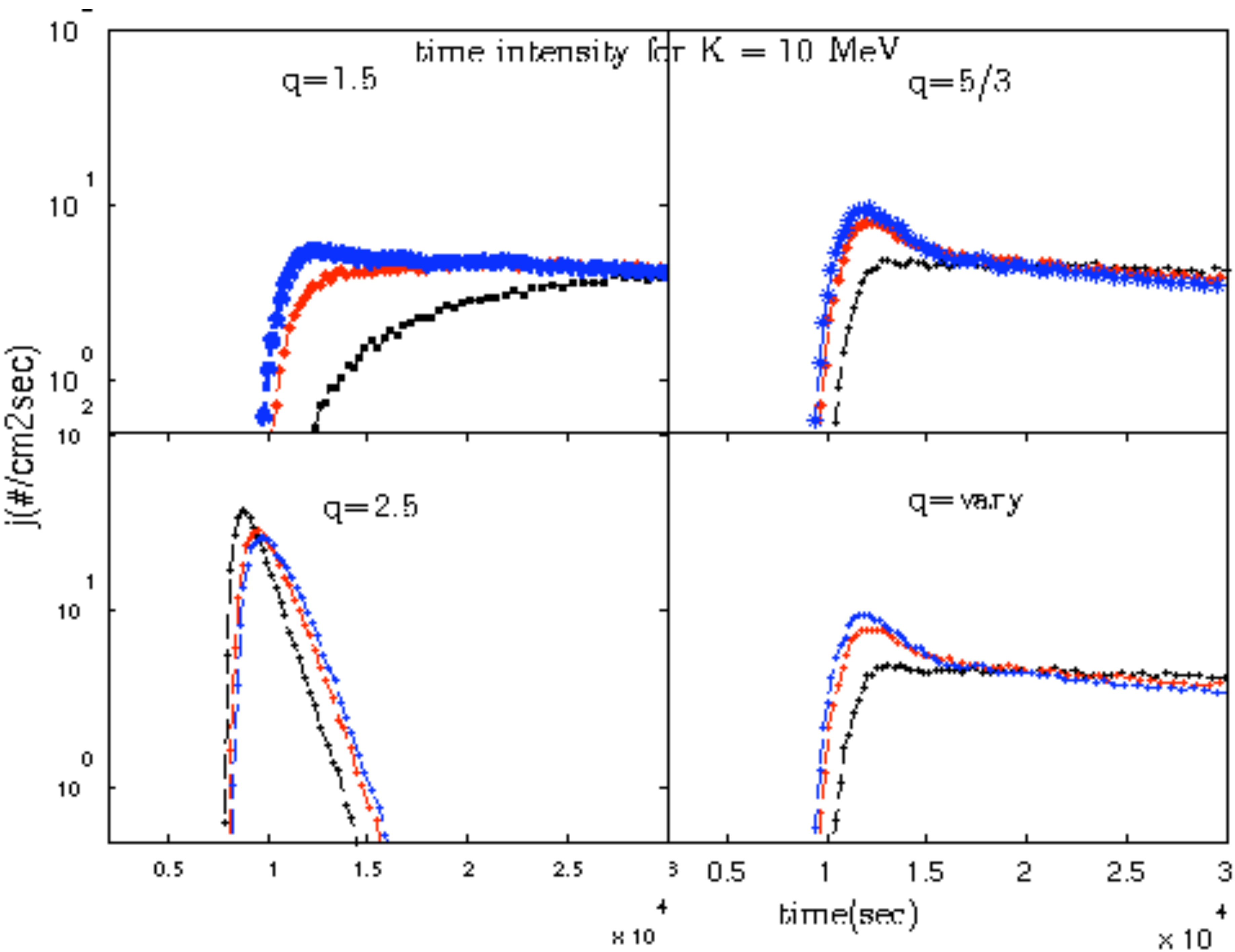
Time intensities at r = 0.5 AU



Time intensities at r = 1.5 AU

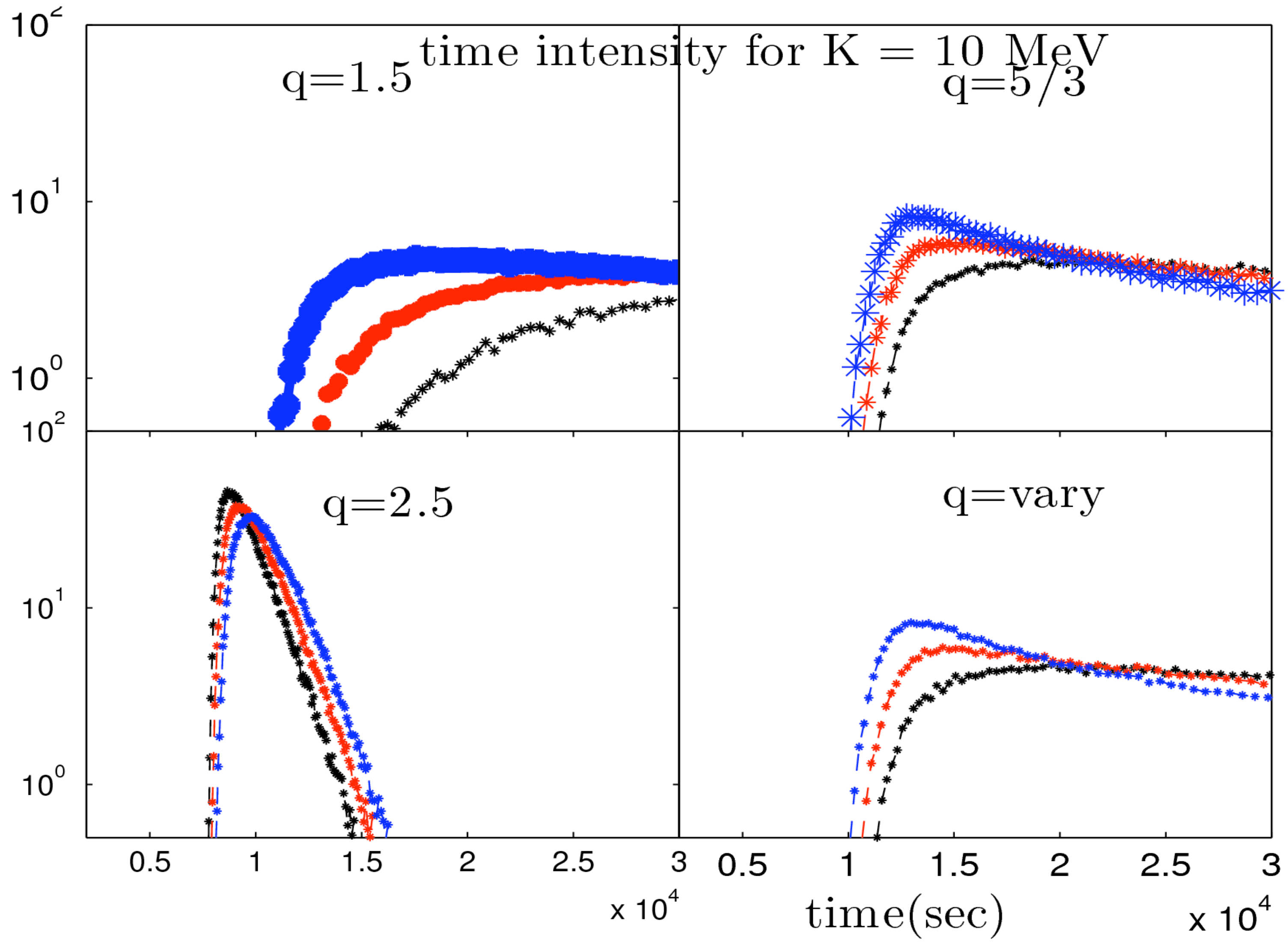


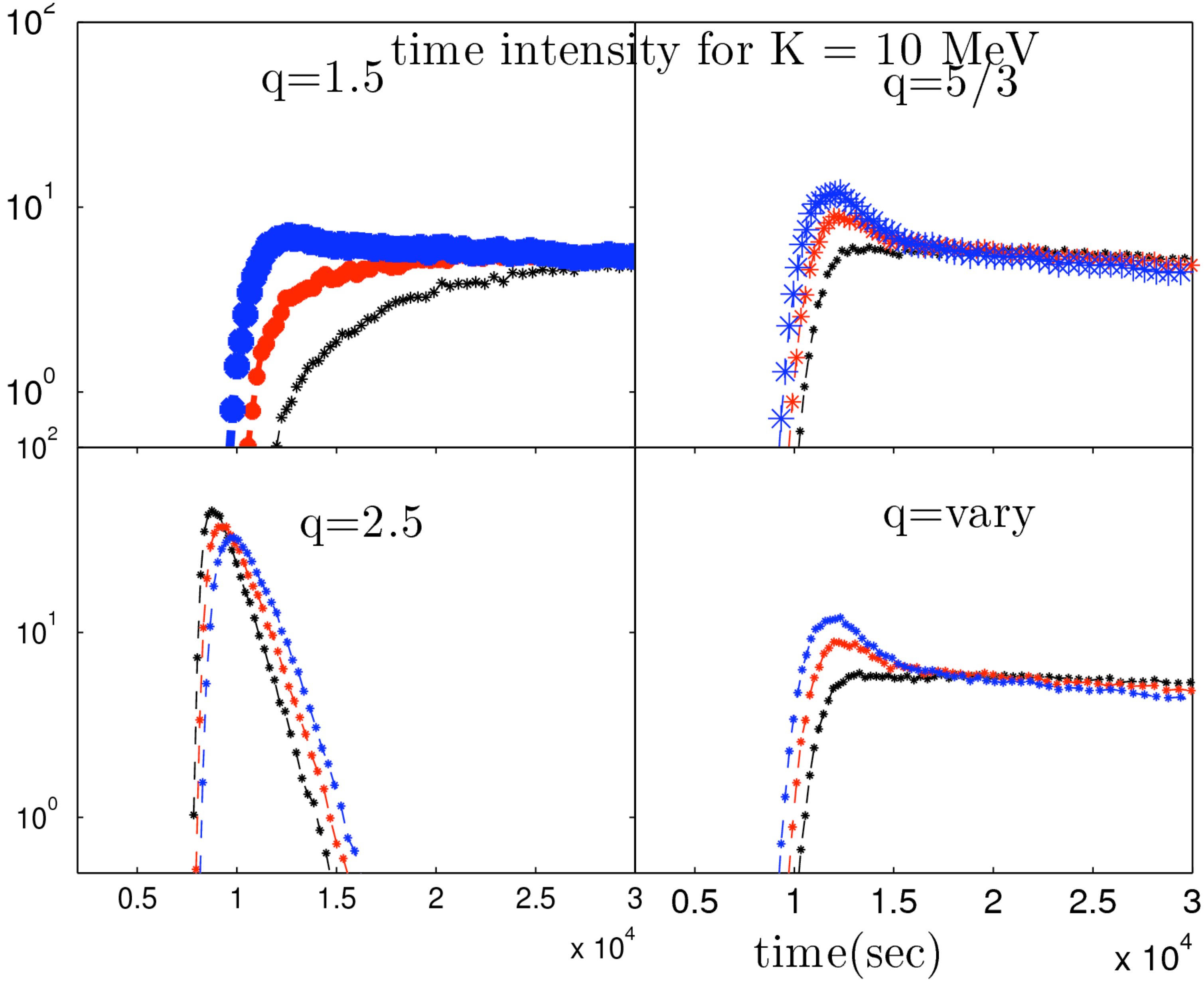
Time intensities at r = 1.5 AU



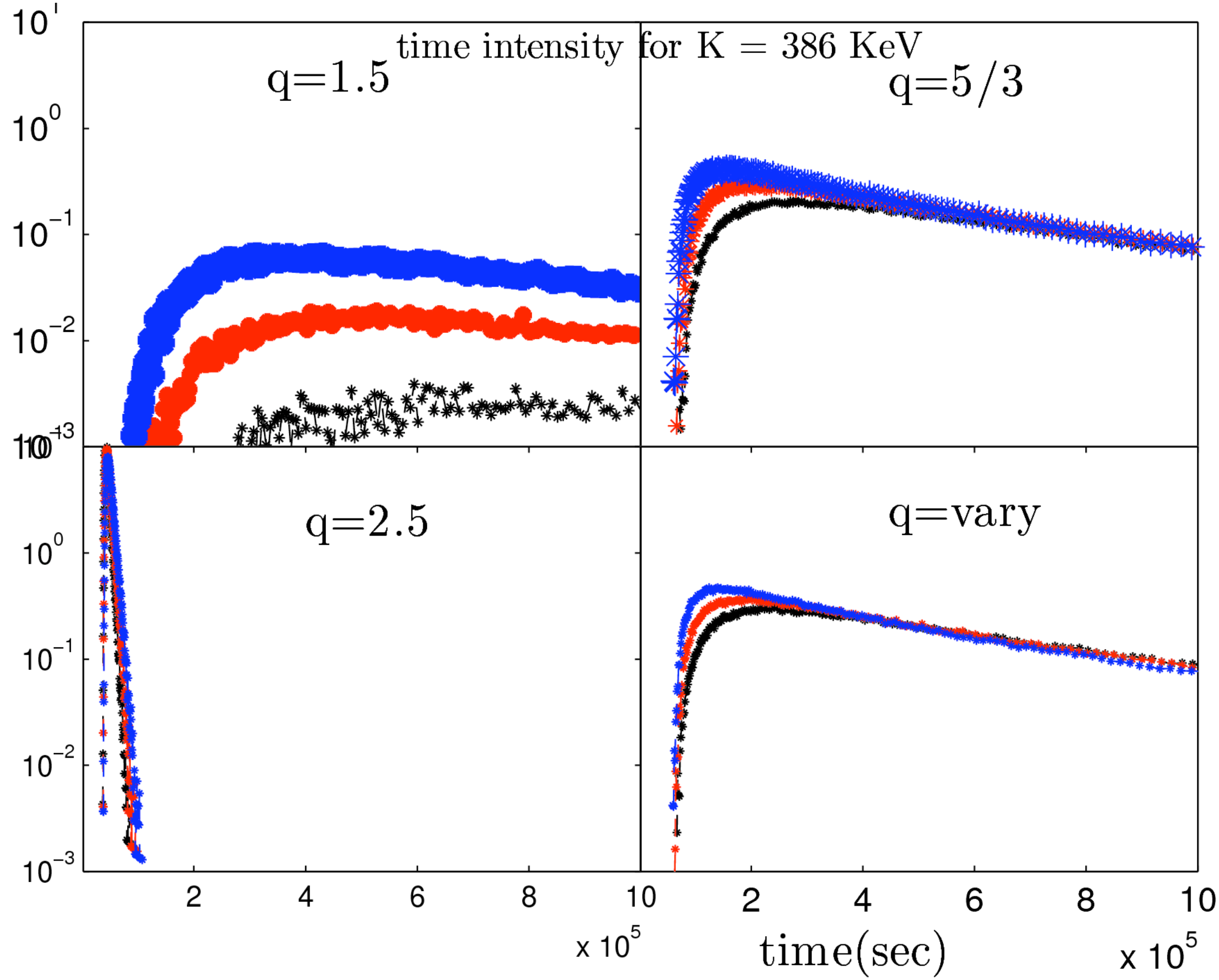
R-dependent Duu

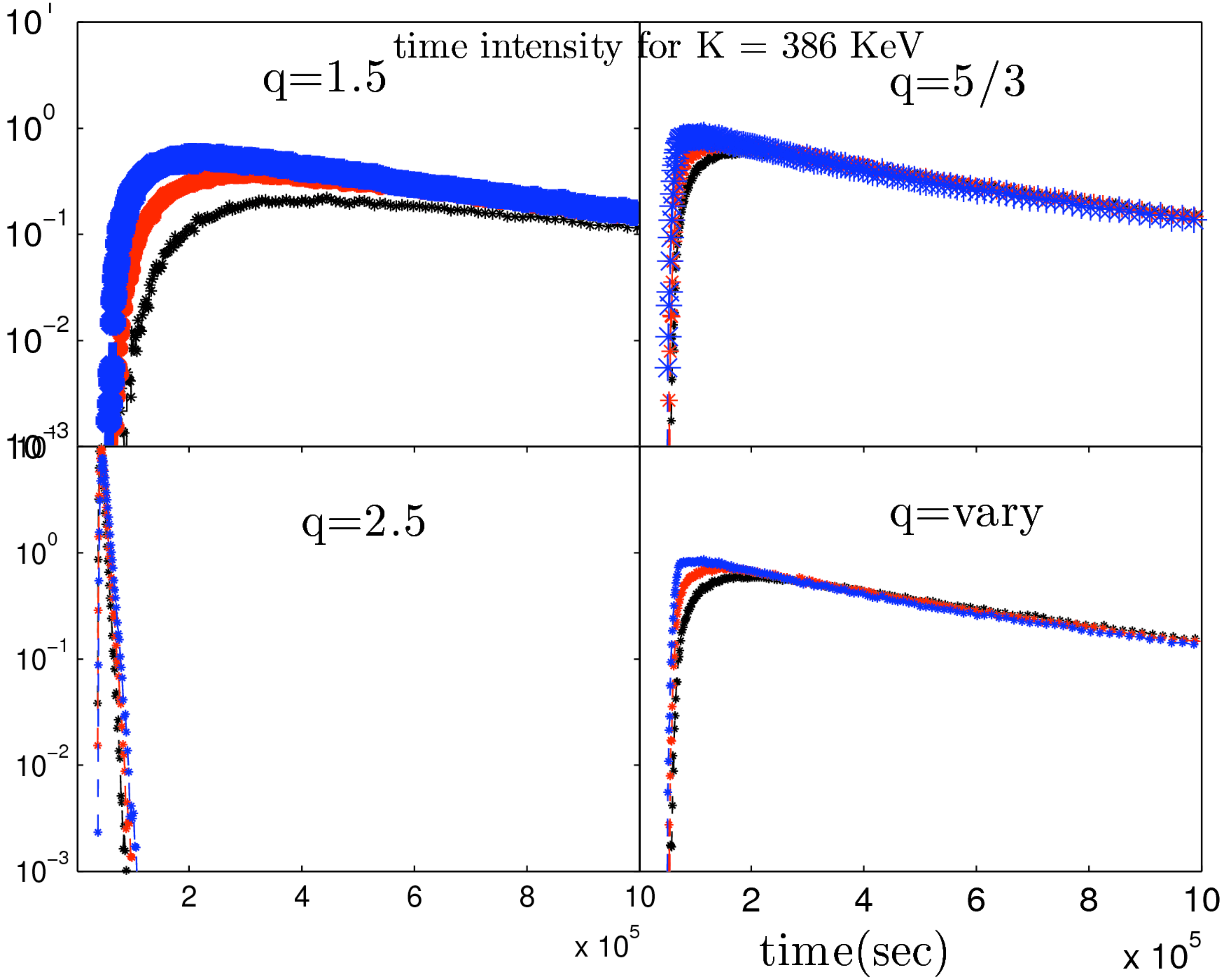
Blue -> proton
red -> Helium
blk -> iron





time intensity for K = 10 MeV
q=1.5
q=5/3
q=2.5
q=vary
10^2
10^1
10^0
0.5
1
1.5
2
2.5
3
x 10^4
time(sec)


time intensity for K = 386 KeV
q=1.5
q=5/3
q=2.5
q=vary
10^1
10^0
10^-1
10^-2
10^-3
2
4
6
8
10
x 10^5
time(sec)



time intensity for K = 386 KeV
q=1.5
q=5/3
q=2.5
q=vary
time(sec)
x 10^5

- confident with the code.

- Time intensity is very sensitive to r. Helios, Solar Orbiter, Solar Probe.

- If Duu has no r dependence --- time intensity scales well.

- R-dependent Duu resembles an extended injection.