CRIME, a public tool for Cosmic Ray Interactions in Molecular Environments

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Outline

1. Theory
   - Cross sections
     - Electrons
     - Protons
   - Ionizations by secondary electrons
2. Cosmic ray spectra
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   - Cosmic ray spectra inside a cloud
3. Results
   - Ionizationrate as a function of Column density
   - E($d\zeta_{max}/dE$) vs. N
   - Differential Ionization rate
   - Hard CR proton spectra
4. Conclusions & Outlook

The starting point

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Astronomy & Astrophysics

Cosmic-ray ionization of molecular clouds

M. Padovani[1,2], D. Galli[2], and A.E. Glassgold[3]

The Ionizationrate ζ

$$\zeta = \int_I^\infty j(E)\,\sigma(E) \times (1 + \Phi(E))\,dE$$

- $j(E)$: Flux of particles
- $\sigma(E)$: Ionization cross section
- $\Phi(E)$: Ionizations by secondary electrons per primary ionization

Cross sections

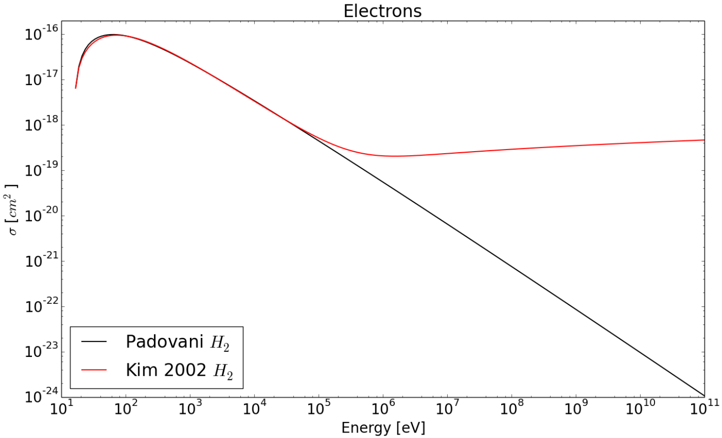
Padovani 2009 (for H_2 and He)

- σ_i Ionisation (electrons + protons)
- $d\sigma_i/dE$ (electrons)
- σ_i^{ec} electron capture (protons)
- Φ based on Glassgold & Langer 1973 (calculation for non relativistic electron impact)

New in this work (for H_2 and He)

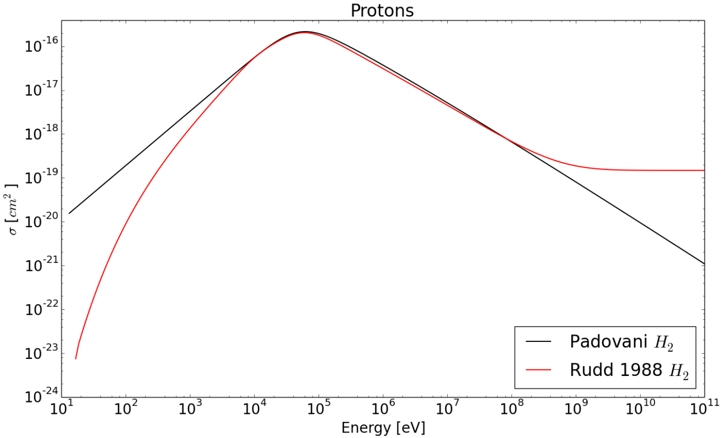
- Electrons: fully relativistic treatment (Kim et al. 2002)
- Protons:
  - $d\sigma_i/dE$ (Rudd et al. 1988)
  - relativistic extension to $d\sigma_i/dE$
- Φ: selfconsistent calculation

Ionization cross section for electron impact



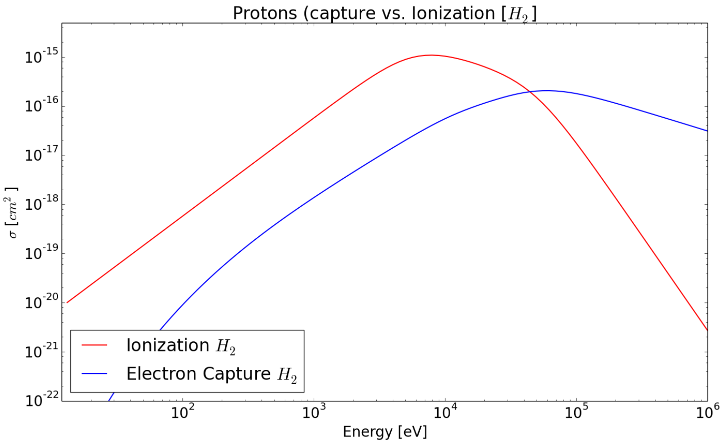
- good agreement at non relativistic energies
- σ_{Kim} ≈const. for $E > mc^2$ ($\sigma_{classical} \propto E^{-1}$)

Ionization cross section for proton impact



- $\sigma_{Rudd} \ll \sigma_{padovani}$ for $E < 10^4$ eV
- agreement within $\sim 20\%$ for $10^4 < E < 10^8$ eV
- $\sigma_{Rudd} \approx$const. for $E > mc^2$ ($\sigma_{classical} \propto E^{-1}$)

The role of electron capture



- for $E < 10^4$ eV $\sigma_{ec} \gg \sigma_i$ and for for $E > 10^5$ eV $\sigma_i \gg \sigma_{ec}$
  $\Rightarrow$ σ_i has no influence on the ionization rate for $E < 10^4$ eV
  $\Rightarrow$ σ_{ec} has no influence on the ionization rate for $E > 10^5$ eV

Secondary electrons

Production rate

$$\frac{dN_s}{dEdV dt} = 4\pi \int_I^\infty n\, j'(E') \frac{d\sigma'(E,E')}{dE} dE'$$

- n: gas density
- $j'(E')$: flux of primary particles
- $\frac{d\sigma'(E,E')}{dE}$: cross section to produce an electron of energy E

Local spectrum

$$\frac{dN_s}{dEdV} = \frac{dN_s}{dEdV dt} \times \tau$$

- τ: residence time of secondary particles

Secondary electrons

Assumption: Secondaries loose all energy inside the molecular cloud

$$\tau = \tau_{loss} = \frac{E}{dE/dt} = \frac{E}{L(E)nv}$$

- $L(E) \equiv dE/dN$ with N Column density
- v: velocity

Flux of secondaries

$$j_s(E) = \frac{dN_s}{dAdEdtd\Omega} = \frac{v}{4\pi}\frac{dN_s}{dEdV}$$
$$= \frac{E}{L(E)}\int_I^\infty j'(E')\frac{d\sigma'(E,E')}{dE}dE'$$

Secondary ionizations

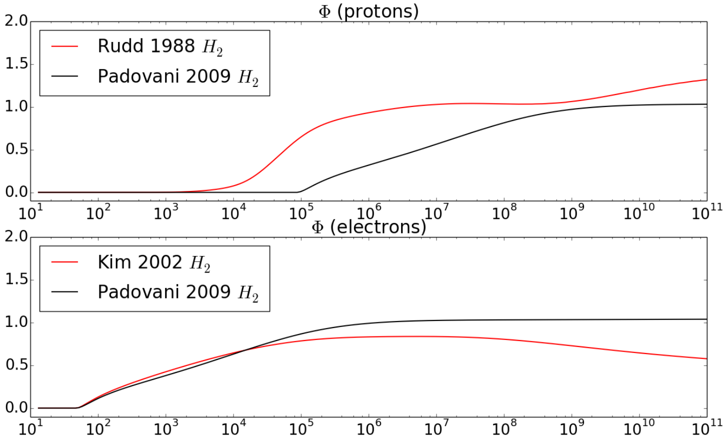
Secondary ionizations per primary ionization Φ

$$\Phi(E') \equiv \frac{\int_I^{E_{max}} \frac{j_s(E)}{dE'} \sigma_s(E) dE}{j'(E')\,\sigma'(E')}$$

$$= \frac{1}{\sigma'(E')} \int_I^{E_{max}} \frac{d\sigma'(E', E)}{dE} \frac{E\,\sigma_s(E)}{L(E)}\, dE$$

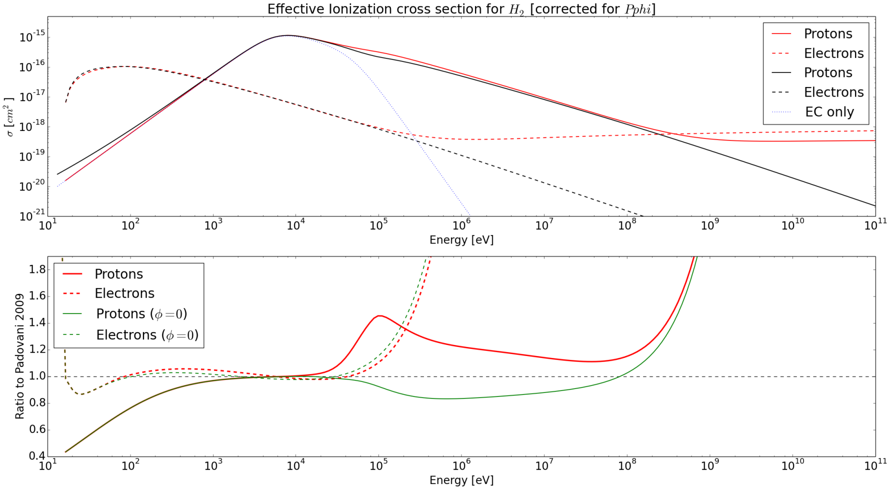
- $\Phi(E')$ is independent of $j'(E')$
- $\Phi(E')$ depends on:
  - interaction of primaries (σ', $d\sigma'/dE$)
  - interaction of secondaries (L_s, σ_s)
- Usually primaries ionizing X will produce secondaries which will mainly ionize H_2!

$\Phi\ (H_2)$



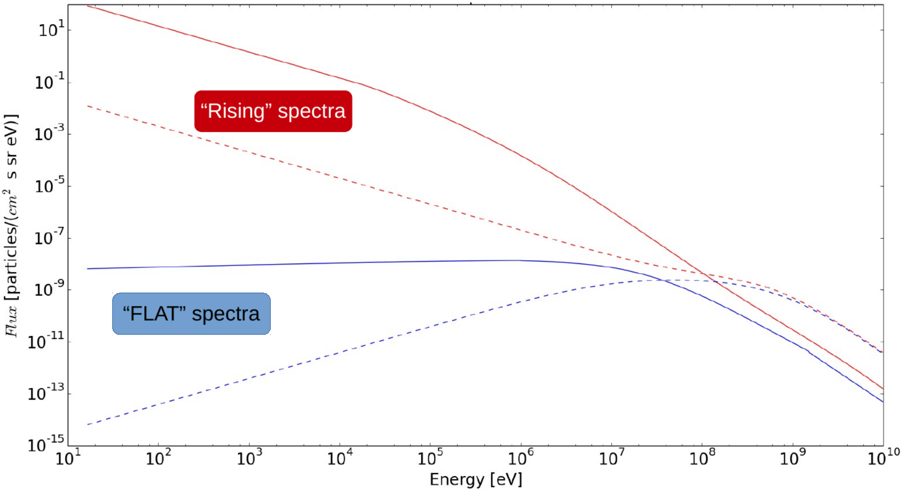
- $O(\Phi) \sim 1$
- Φ in Padovani 2009
  - Φ_e agreement at sub-relativistic energies
  - $\Phi_p(E) = \Phi_e(E \times m_e/m_p)$: no valid assumption

Ionization in **Padovani 2009** vs. this work



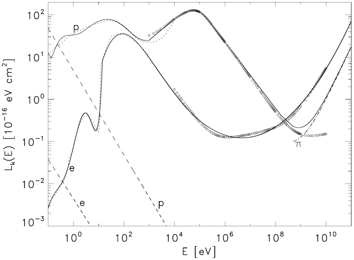
- Electrons: excellent agreement excpet for rel. energies
- Protons: 20–40% due to Φ (0.1MeV to 0.1GeV) + rel. changes

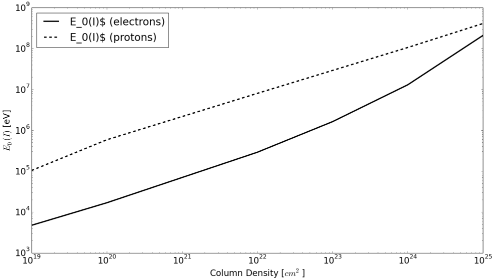
(Interstellar) Cosmic ray spectra $j_0(E)$



Cosmic Ray propagationn into a cloud

Energy losses



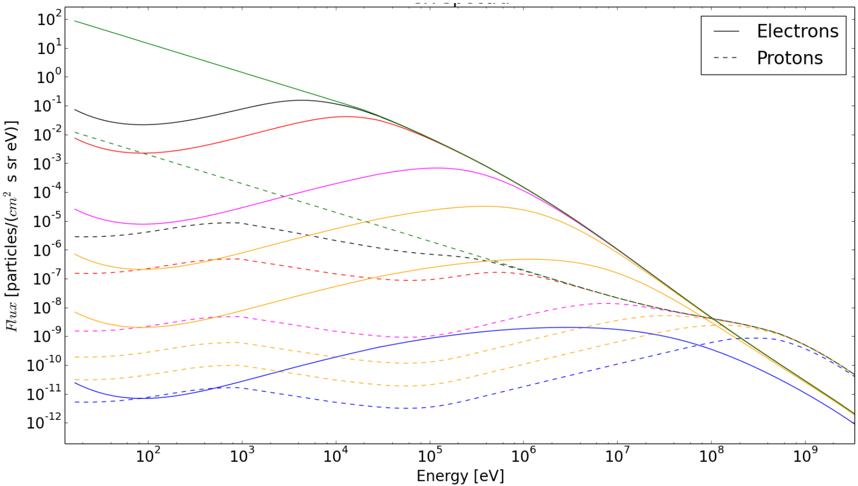


- Ionization losses
- Bremsstrahlung (electrons > 10 MeV)
- Pion production (protons > 300 MeV)

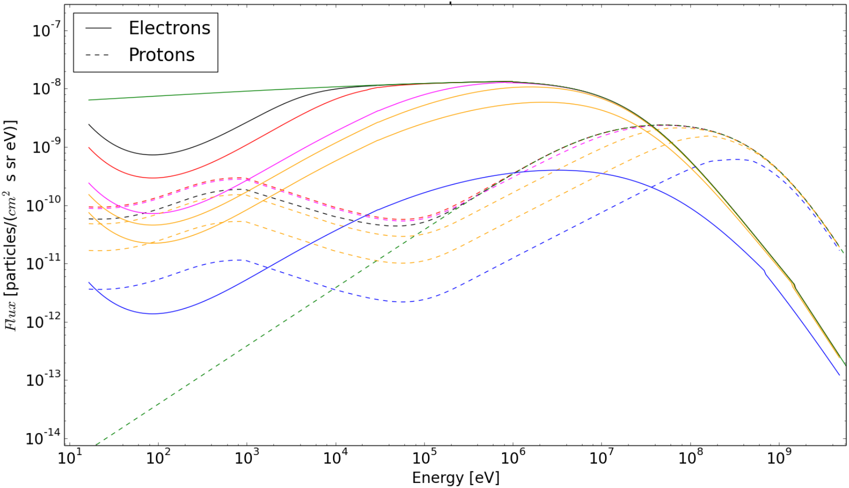
free streaming
(Padovani 2009)

- at N $j_0(E < E_0)) = 0$
- but at N $j_{cl}(E < E_0) \neq 0$
- $j_{cl}(E, N) = j_0(E') \frac{L(E')}{L(E)}$
- E' *cools* to E over N

$j_{cl}(E)$ from rising cosmic ray spectra



$j_{cl}(E)$ from flat cosmic ray spectra



Results

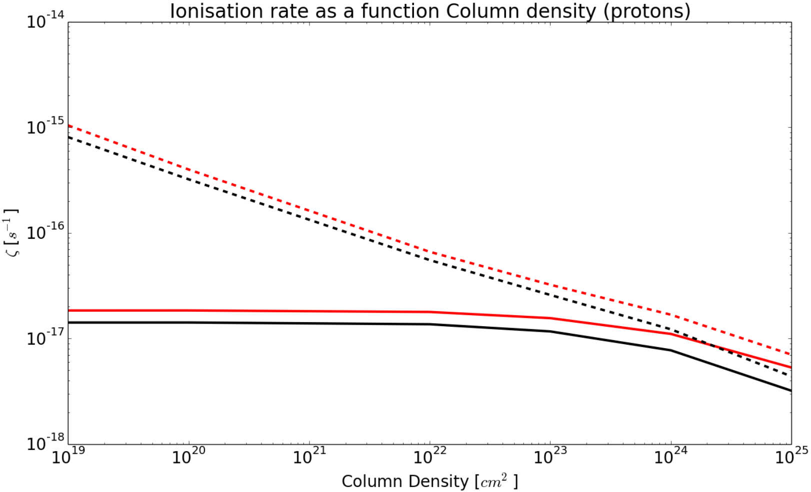
Characterisation of introduced changes

- Consistency checks
- Effect on ζ
- maximum Ionizing energy
- Effect on $d\zeta/dE$
- Role of the low energy tail $j_{cl}(E < E_0)$

Needs to be checked for:

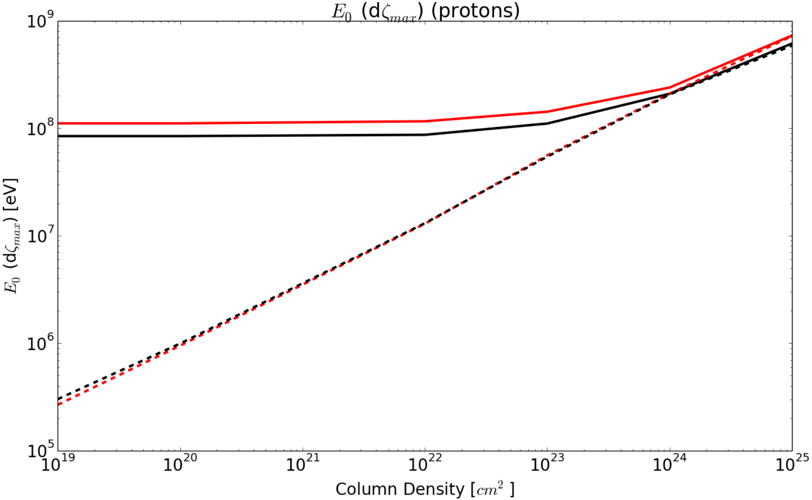
- electrons
- protons
- different Column density N
- different initial spectra j_0

Ionizationrate vs. N (**Padovani** vs. this work)



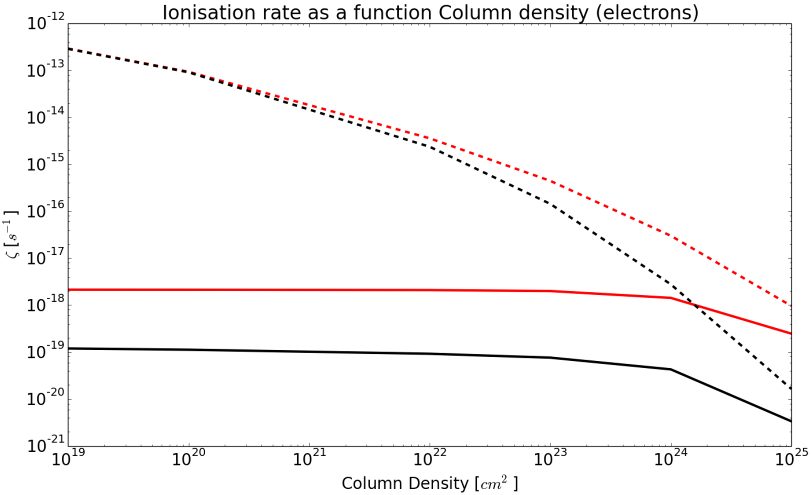
- $\sim 20\%$ increase due to Φ

E($d\zeta_{max}/dE$) vs. N (**Padovani** vs. this work)



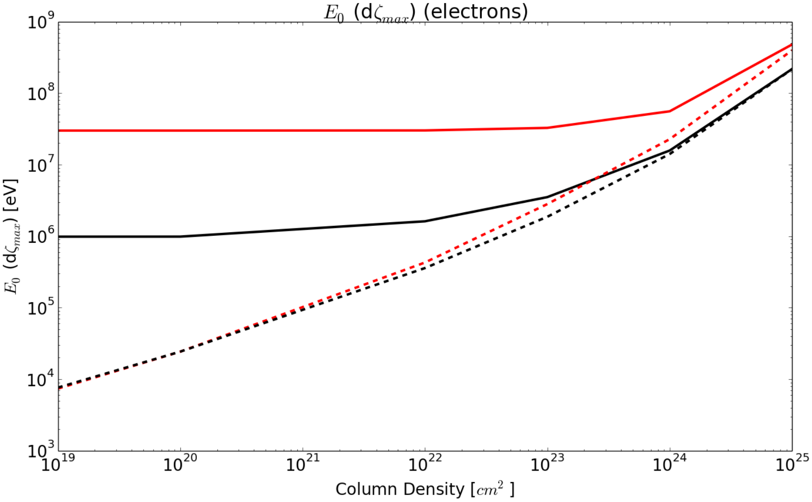
- E mainly responsible for ζ is sub-relativistic

Ionizationrate vs. N (**Padovani** vs. this work)



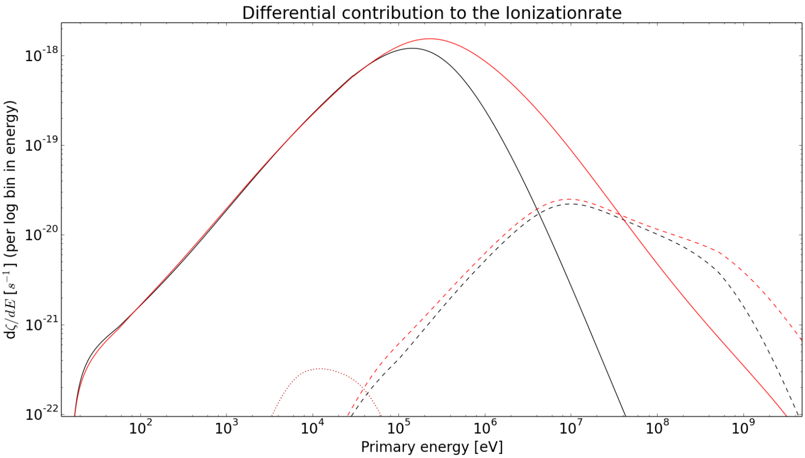
- $10\times$ higher Ionization for flat spectra (rel. effect)
- Significant differences for $N > 10^{22}$ (rel. effect)

E($d\zeta_{max}/dE$) vs. N (**Padovani** vs. this work)



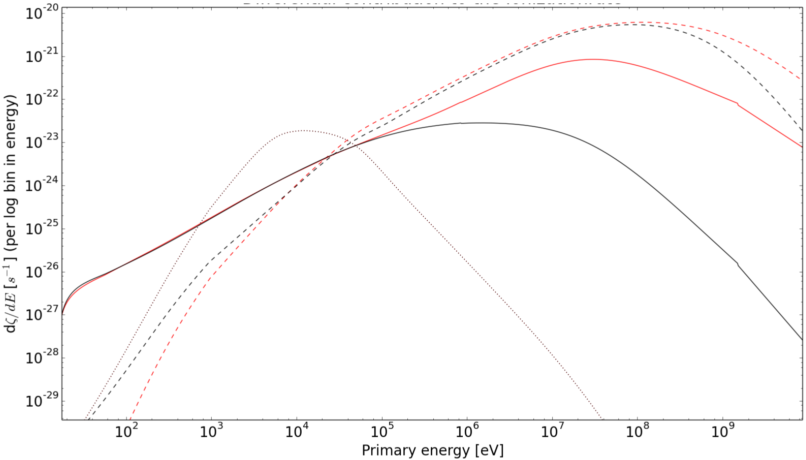
- E mainly responsible for ζ is sub-relativistic (flat spectra and $N > 10^{22}$)

$d\zeta/dE$ ($N = 10^{22}$, $E_0(e) = 3 \times 10^5$, $E_0(p) = 8 \times 10^6$, rise)



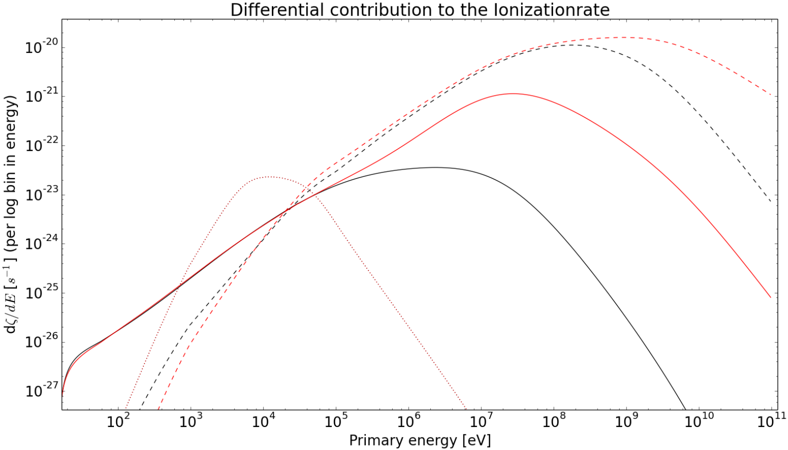
- Energies $\sim E_0$ dominate the ionisation
- minor relativistic corrections

$d\zeta/dE$ ($N = 10^{22}$, $E_0(e) = 3 \times 10^5$, $E_0(p) = 8 \times 10^6$, flat)

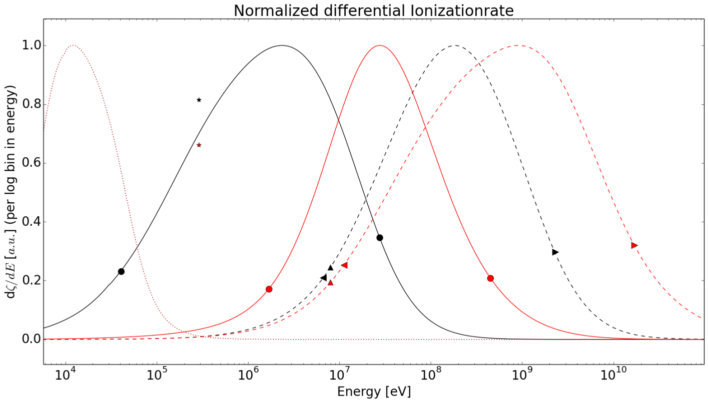


- Energies $> E_0$ dominate the ionisation
- significant relativistic corrections for electrons

Hard($E^{-2} > GeV$) proton spectra



Ionisation by GeV protons



Importance of relativistic proton cross section

- Maximum Ionising energy can reach $\sim GeV$
  $\Rightarrow$ correlation with Fermi/LAT possible
- significant Ionisation up to ~ 10 GeV
- $\zeta \sim 2 \times \zeta$(Padovani)

Summary

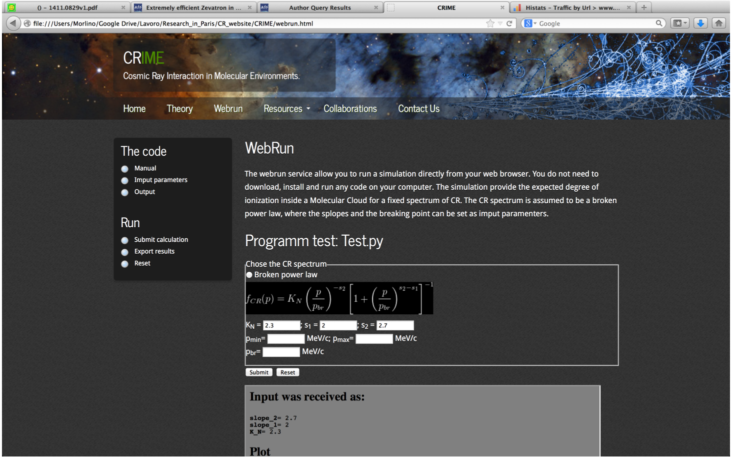
This work

- Relativistic treatment of Ionization
- Selfconsitent calculation of Φ
- Development of a tool to calculate ζ

Comparison to Padovani 2009

- $\sim 20\%$ increase in the Ionization rate for protons
- $10\times$ electron Ionization for flat spectra
- relativistic electrons are important for $N > 10^{22}$
- most ionizing energies (can) shift to higher energies

CRIME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CRIME
Cosmic Ray Interaction in Molecular Environments.
Home
Theory
Webrun
Resources
Collaborations
Contact Us
The code
Manual
Imput parameters
Output
Run
Submit calculation
Export results
Reset
WebRun
The webrun service allow you to run a simulation directly from your web browser. You do not need to download, install and run any code on your computer. The simulation provide the expected degree of ionization inside a Molecular Cloud for a fixed spectrum of CR. The CR spectrum is assumed to be a broken power law, where the splopes and the breaking point can be set as imput paramenters.
Programm test: Test.py
Chose the CR spectrum
Broken power law
$f_{CR}(p) = K_N \left(\frac{p}{p_{br}}\right)^{-s_2} \left[1 + \left(\frac{p}{p_{br}}\right)^{s_2 - s_1}\right]^{-1}$
K_N = 2.3 ; s_1 = 2 ; s_2 = 2.7
p_{min}= MeV/c; p_{max}= MeV/c
p_{br}= MeV/c
Submit
Reset
Input was received as:
slope_2= 2.7
slope_1= 2
K_N= 2.3
Plot

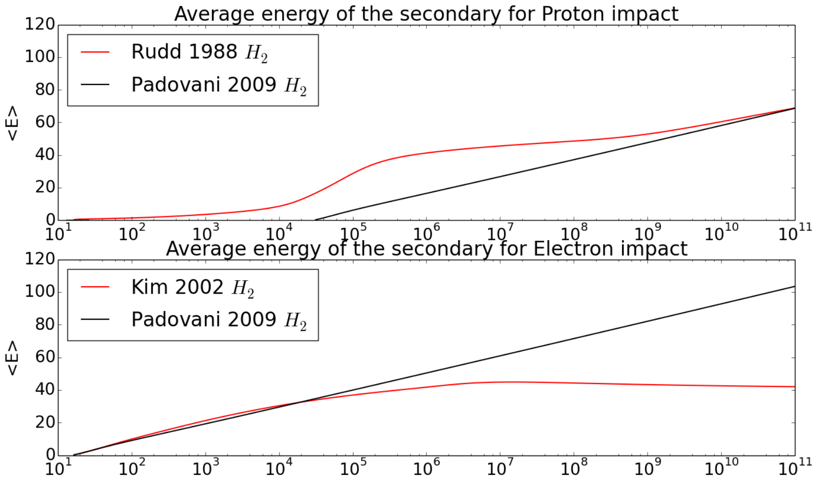
CRIME as a tool

- Fully relativistic Ionization cross sections (H_2+He)
- Electron capture cross section (H_2+He)
- Consistent calculation of Φ
- Strait line propagation
- Calculation of ζ
- CPU time $\sim$ 1 to 20 seconds
- python based

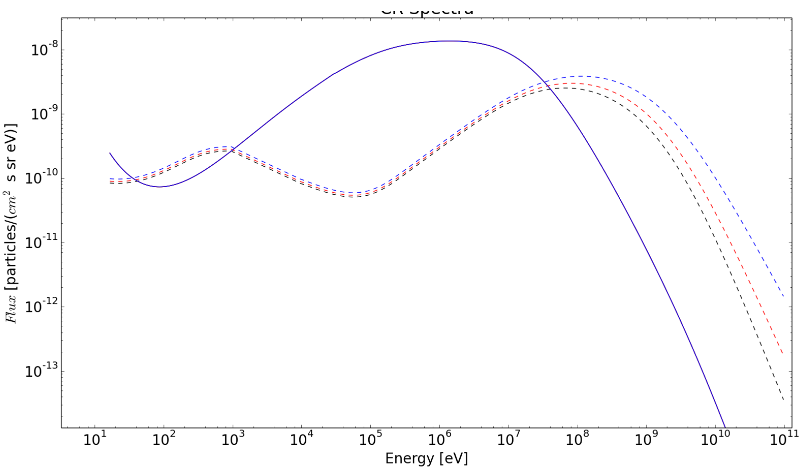
Future CRIMEs

- Gamma ray emission (Ervin Kafexhiu et. al 2014)
- Effect of heavy CRs ?
- Additional target materials?
- CR Heating ?

Average Energy of secondary electrons



FLat Spectra with slopes: $E^{-2.7}$, $E^{-2.4}$, $E^{-2.}$



Differential contribution (slopes: $E^{-2.7}$, $E^{-2.4}$, $E^{-2.}$)