Hunting DM from galactic to extra-galactic scales

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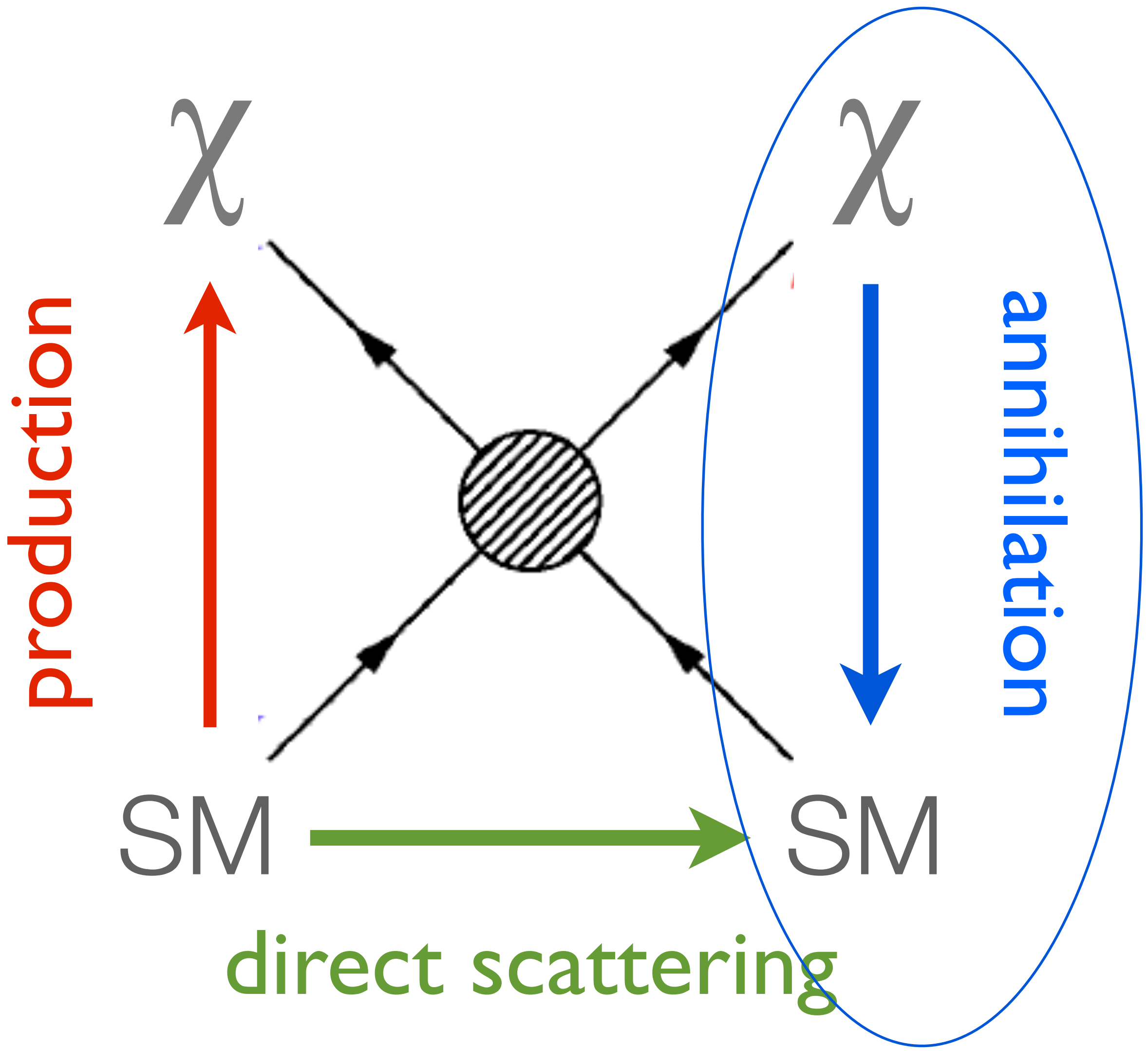
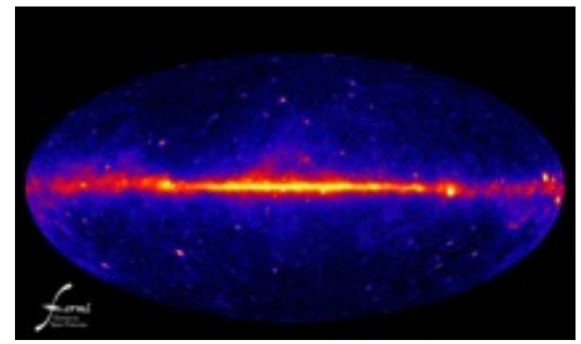
Alliance for Astroparticle Physics

darkattack2012 | Ascona | 19th of July 2012

WIMPs detection strategies

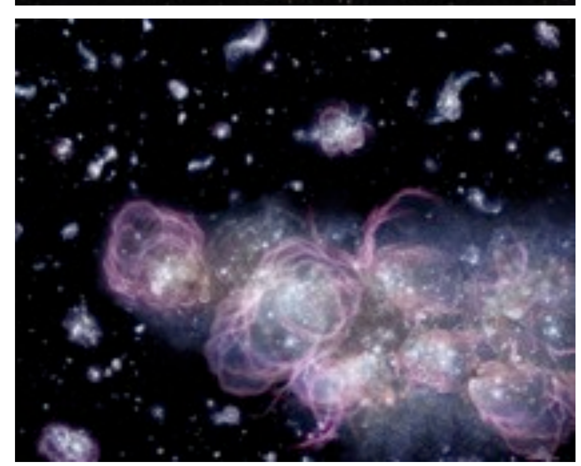


$$\Gamma_{ann} \propto n_\chi^2 \sigma v$$



Galactic Center

Dwarf galaxies



Early Universe

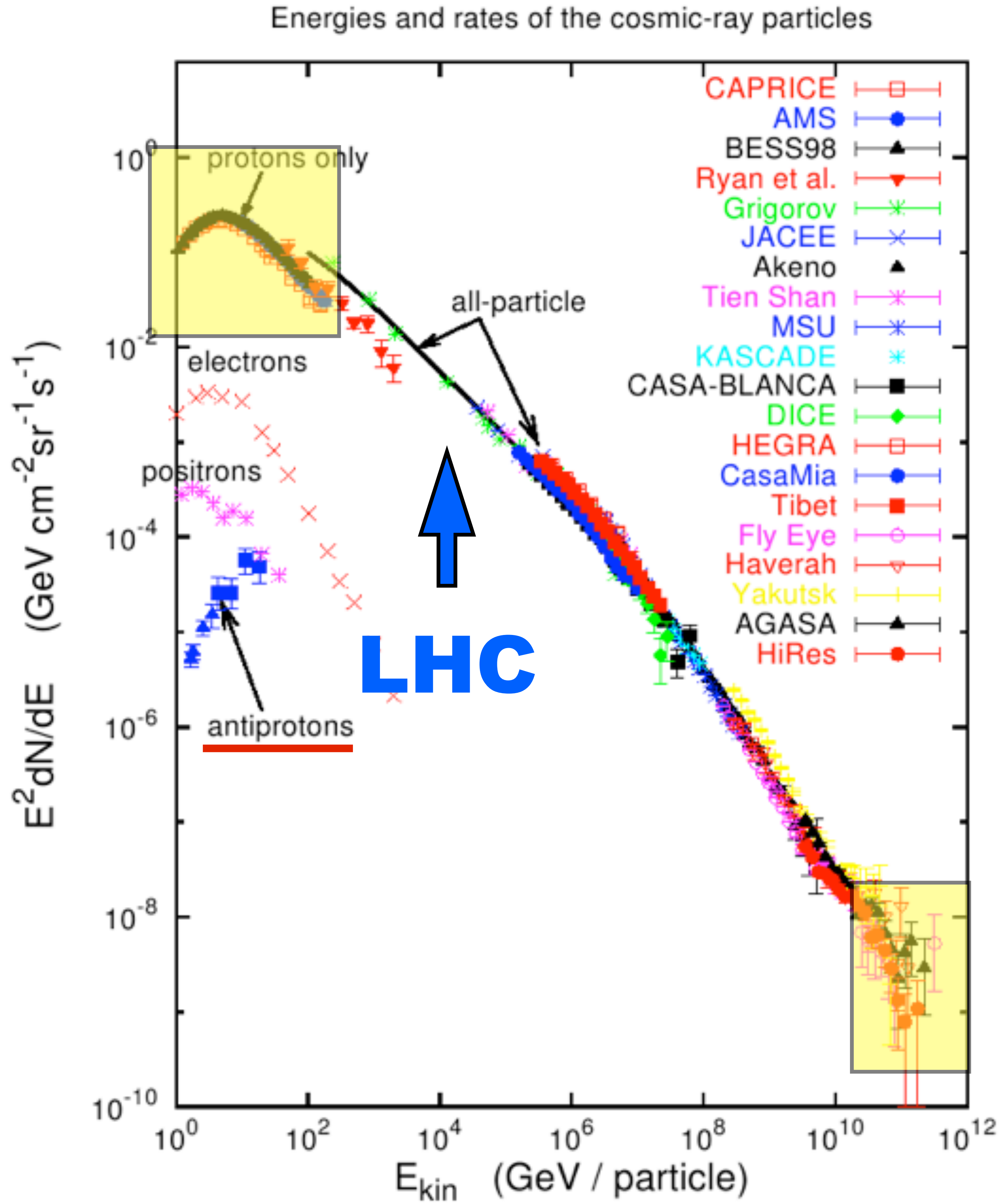
All these approaches are complementary!

Part I - Galactic Cosmic Rays

In collaboration with

- **Giuseppe Di Bernardo**
- **Daniele Gaggero**
- **Dario Grasso**
- **Luca Maccione**
- **Maryam Tavakoli**
- **Ilias Cholis**
- **Piero Ullio**

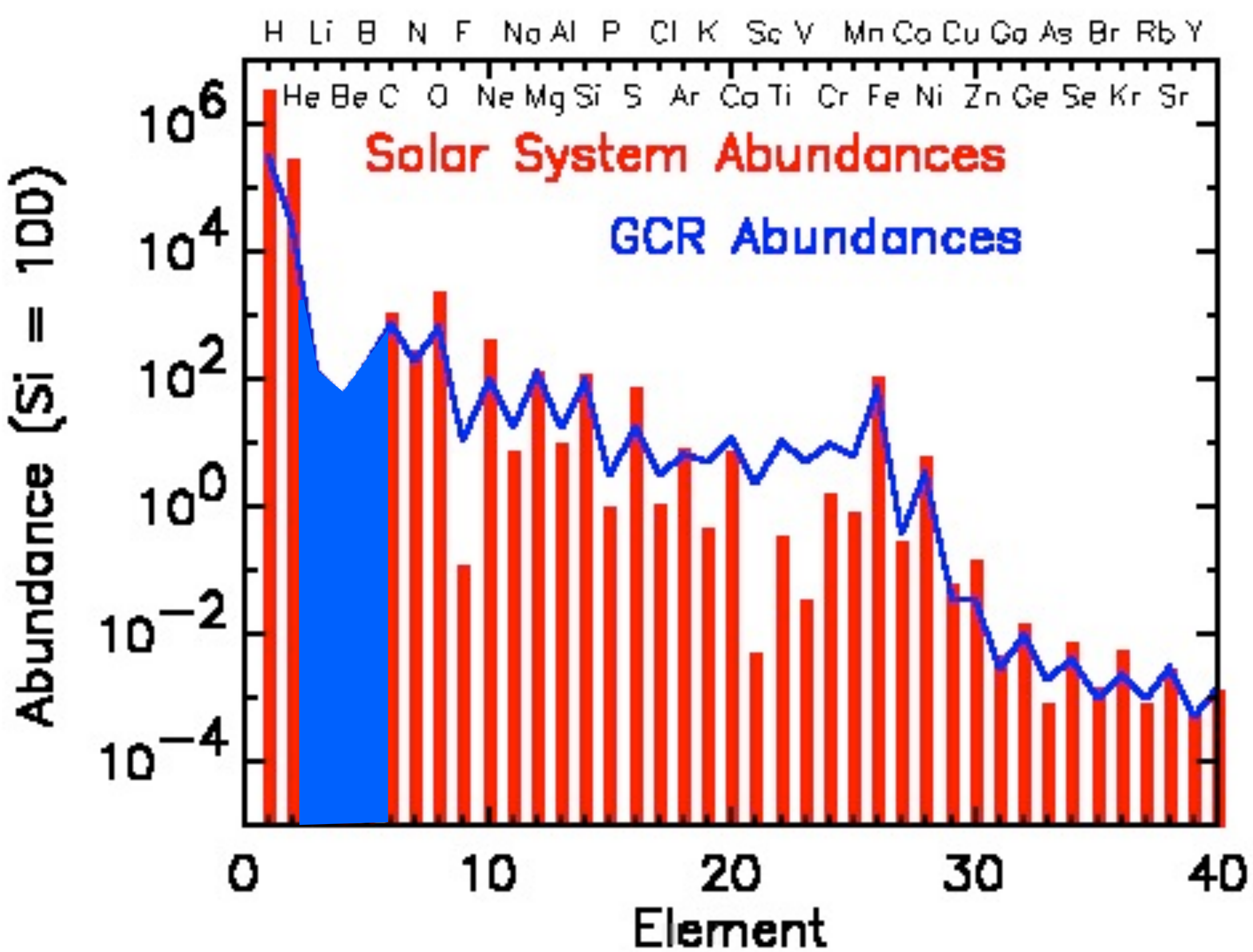
1/cm^2/s



Ivo Karlović
2011 Davis Cup
~10^{12} GeV

1/km^2/century

Secondary / Primary



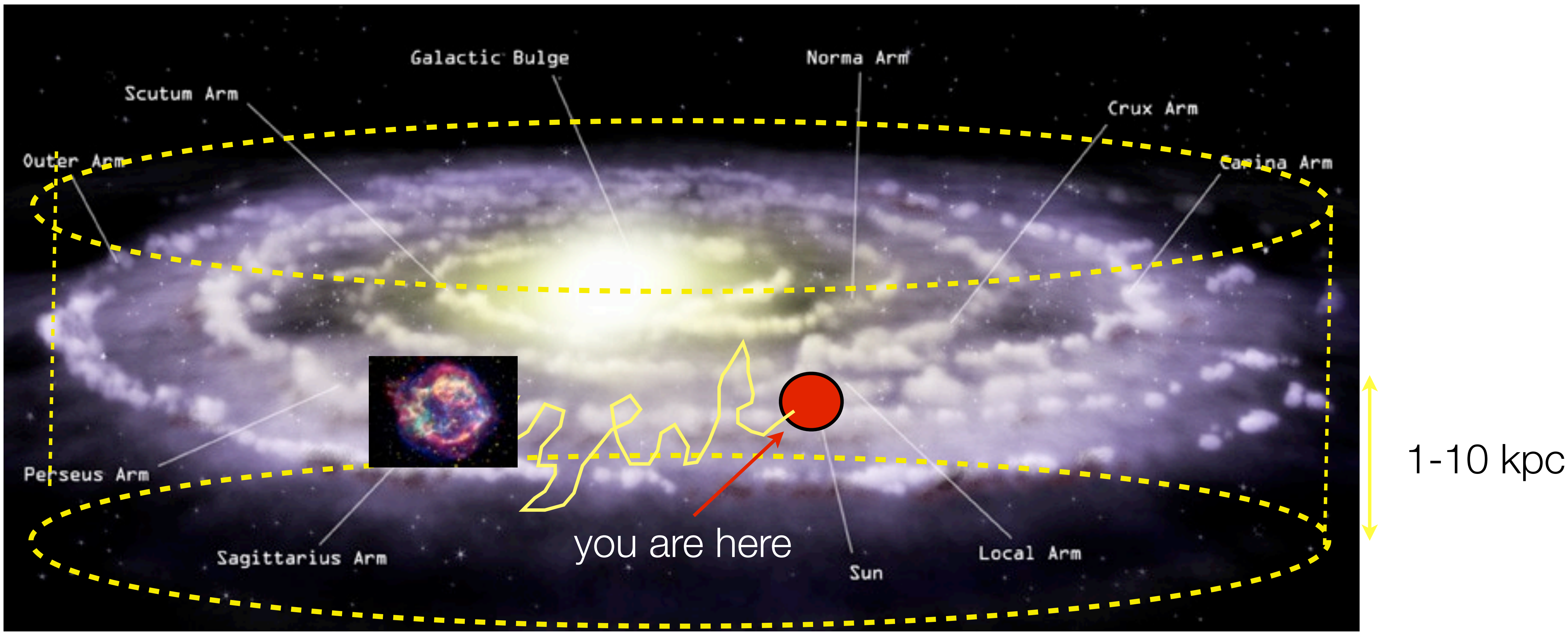
In order to reproduce the measured abundances of stable nuclei, CRs should have traversed: ~10 g/cm^2 material:

$$L = \frac{\text{grammage}}{n_{\text{ISM}} m_p} \sim 10^4\,\text{kpc}$$

>> Galaxy size!

- **Primary** species are present in sources (CNO, Fe). Produced by stellar nucleosynthesis. Acceleration in SN shocks (≥10^4 yr).
- **Secondary** species are absent of sources (LiBeB, SubFe). Produced during propagation of primaries.

Galactic Propagation



CRs propagate into the **turbulent** Galactic magnetic field!
The Larmor radius of a CR is:

$$r_L(E) = \frac{E}{ZeB} \sim 1\,\mathrm{pc}\left(\frac{E}{10^{15}\,\mathrm{eV}}\right)\left(\frac{B}{1\,\mu\mathrm{G}}\right)^{-1}$$

for a MF coherence length ~100 pc $\Rightarrow$ propagation is diffusive up to ~ 10^{16}-10^{17} eV.

CR Diffusion in the MW

The diffusion equation:

$$\frac{\partial N^i}{\partial t} - \nabla\cdot(D\nabla - v_c)N^i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\nabla\cdot v_c\right)N^i - \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{N^i}{p^2} =$$

$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Diffusion tensor:

- $D(E) = D_0(\rho/\rho_0)^{\delta}\exp(z/z_t)$

Ginzburg & Syrovatsky, 1964

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$$Q^i(p,r,z) + \sum_{j>i} c\beta n_{gas}(r,z)\sigma_{ij}N^j - c\beta n_{gas}\sigma_{in}(E_k)N^i$$

Reacceleration:

- $D_{pp} \propto \frac{p^2 v_A^2}{D}$

Ginzburg & Syrovatsky, 1964

DRAGON

- solve the diffusion equation on a 3D (r,z,E) grid
- realistic distributions for sources and ISM
- different models for fragmentation cross sections
- position dependent, anisotropic diffusion
- independent injection spectra for each nuclear species
- speed and memory high-performances
- coupled with DarkSUSY
- public: https://svnsrv.desy.de/public/DRAGON/tags/v2.01

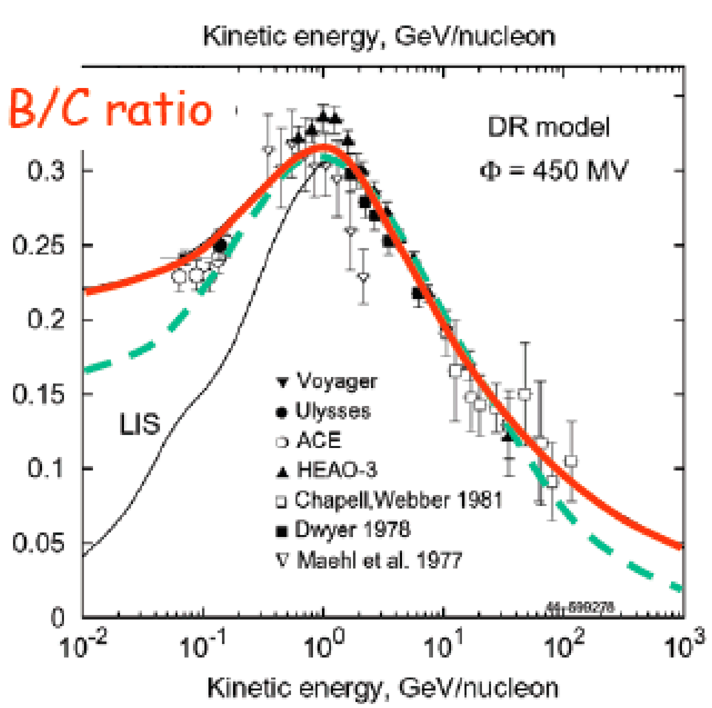
CE, D.Gaggero, D.Grasso & L.Maccione, JCAP, 2008

Secondary Antiprotons

- CR proton/He spallation onto the Galactic gas is an avoidable antiproton source kinematical threshold 7 GeV:

$$p + p_{\rm gas} \rightarrow p + p + p + \bar{p}$$

- In principle, antiprotons data may then be used to constraint a primary component which may produced by astrophysical sources or by dark matter annihilation/decay.



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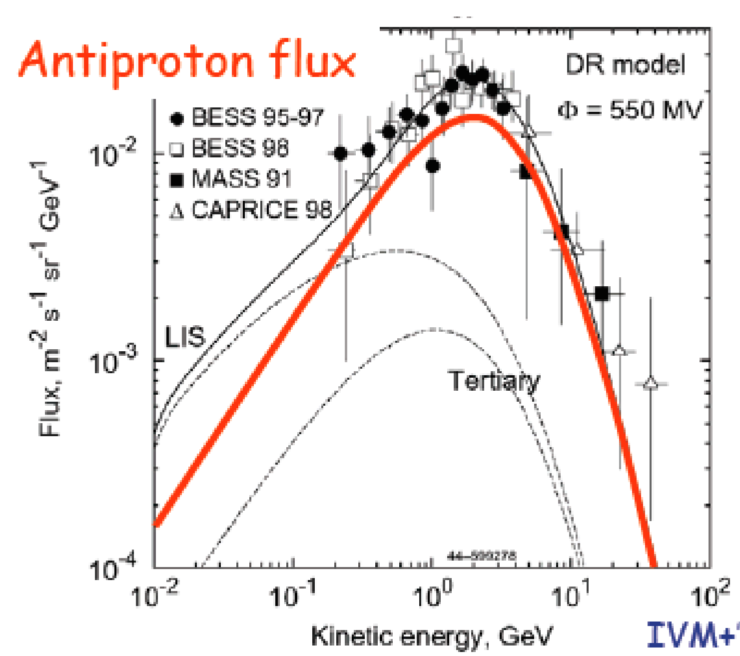
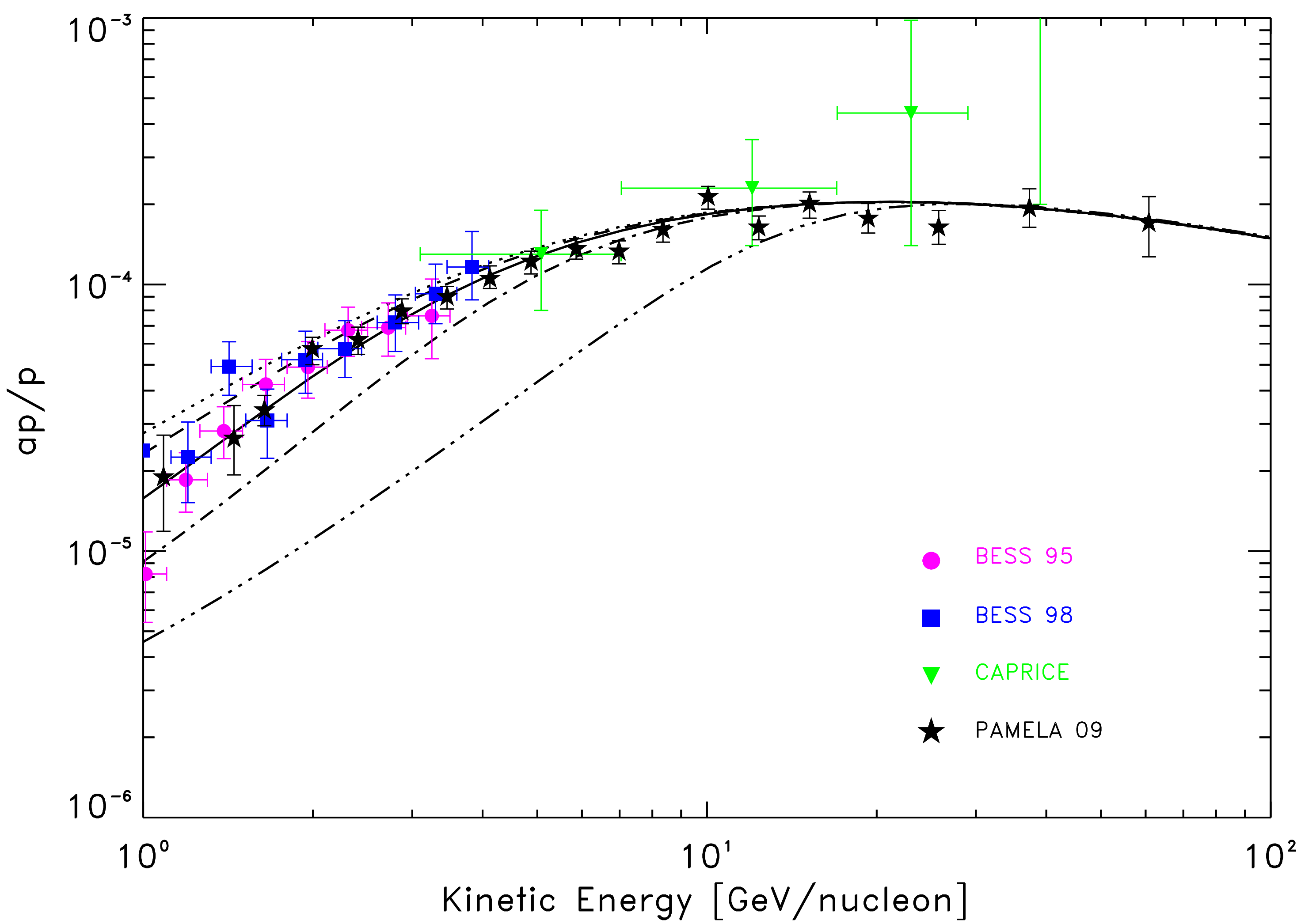


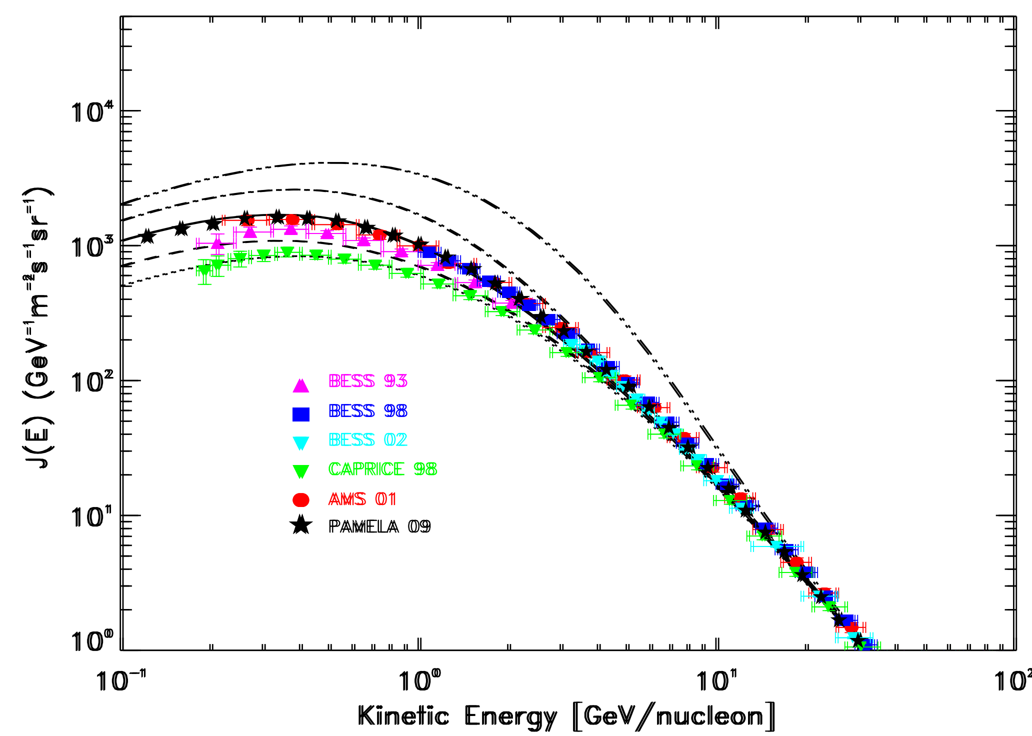
See GALPROP website: http://galprop.stanford.edu/

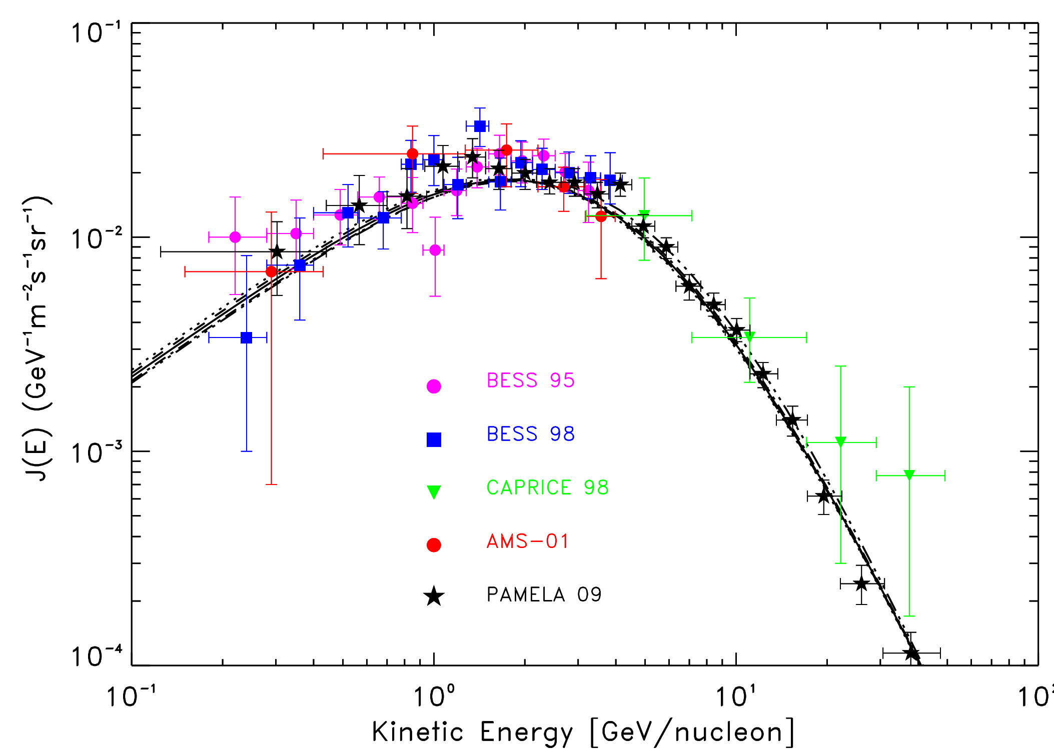
Secondary Antiprotons

- in a "**democratic**" WIMP model the ratio between DM signal and background from standard astrophysical sources is usually much larger in the antiproton channel with respect to all other indirect detection methods!

Antiproton/Protons



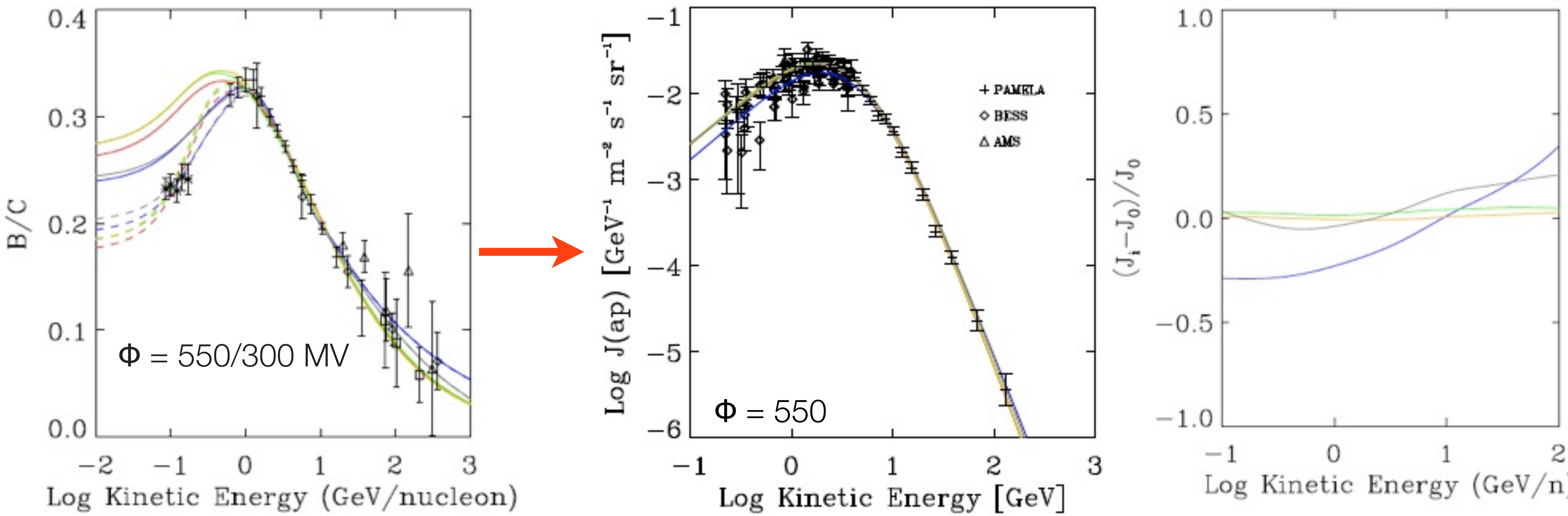




Large effects of reacceleration on the proton spectrum: can it constrain v_A?
Interesting feature: the antiproton flux is less affected by reacceleration!

Uncertainties on the secondary antiproton flux (let's call it *background* for DM indirect search)

This is mainly due to the residual uncertainty on the CR propagation parameters once secondary nuclei data are matched

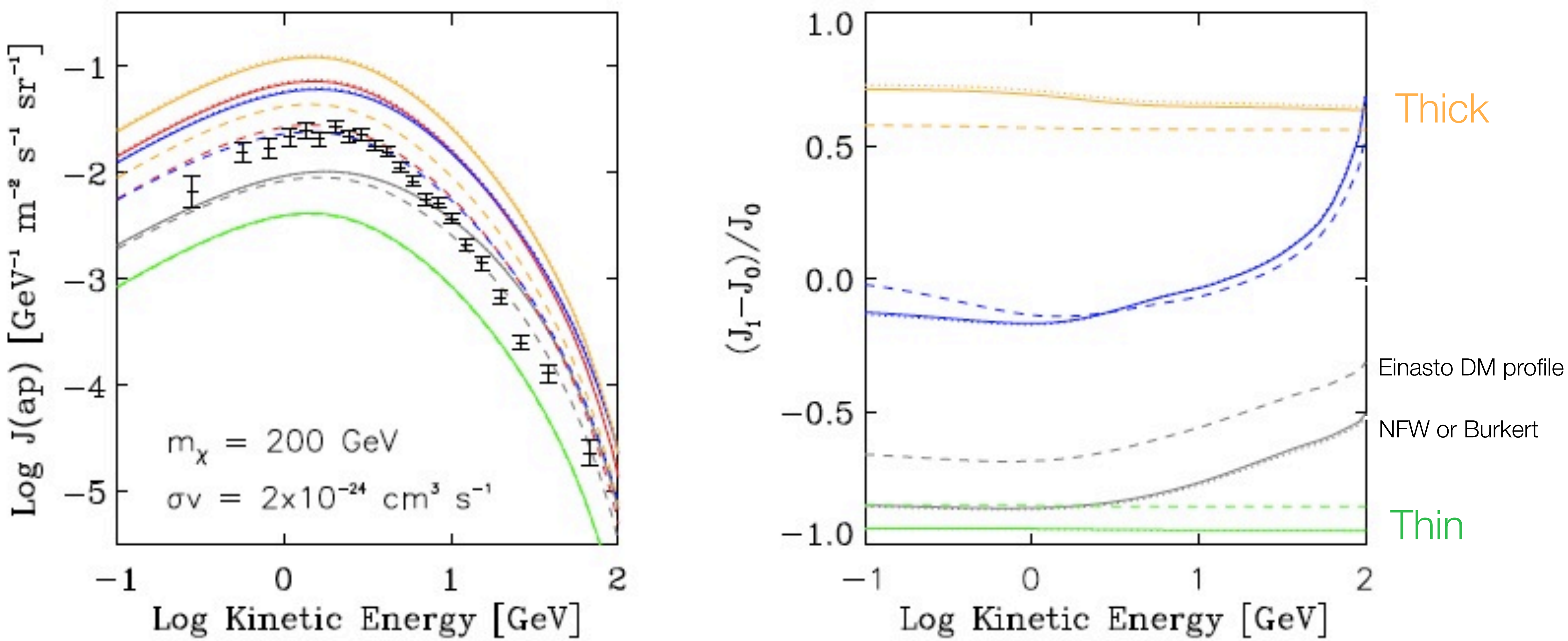


Model	z_t(kpc)	δ	$D_0(10^{28}\mathrm{cm}^2/\mathrm{s})$	η	v_A(km/s)	γ	dv_c/dz(km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (GV)	$\chi^2_{\bar{p}}$	Color in Fig.s
KRA	4	0.50	2.64	−0.39	14.2	2.35	0	0.6	0.47	0.67	0.59	Red
KOL	4	0.33	4.46	1.	36.	1.78/2.45	0	0.4	0.3	0.36	1.84	Blue
THN	0.5	0.50	0.31	−0.27	11.6	2.35	0	0.7	0.46	0.70	0.73	Green
THK	10	0.50	4.75	−0.15	14.1	2.35	0	0.7	0.55	0.69	0.62	Orange
CON	4	0.6	0.97	1.	38.1	1.62/2.35	50	0.4	0.53	0.21	1.32	Gray

The max uncertainty is ~ 30%

Uncertainties on the $\bar{p}$ flux from DM annihilation

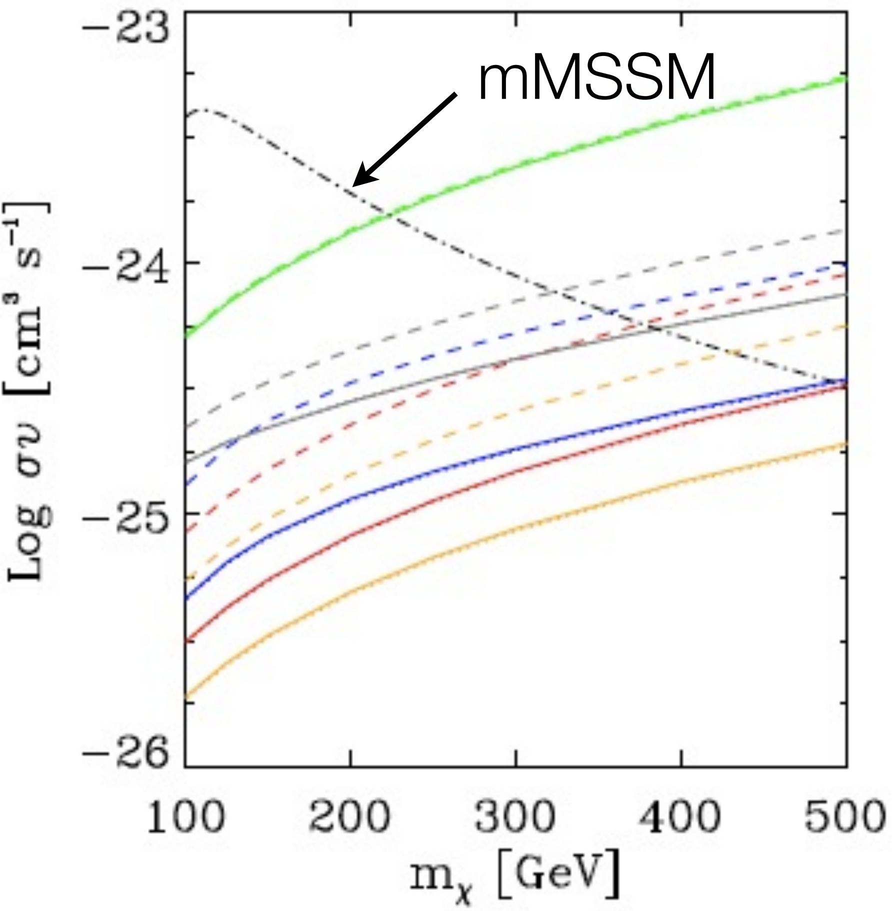
For a given DM model, the main uncertainties are those on the propagation parameters and the DM density profile:

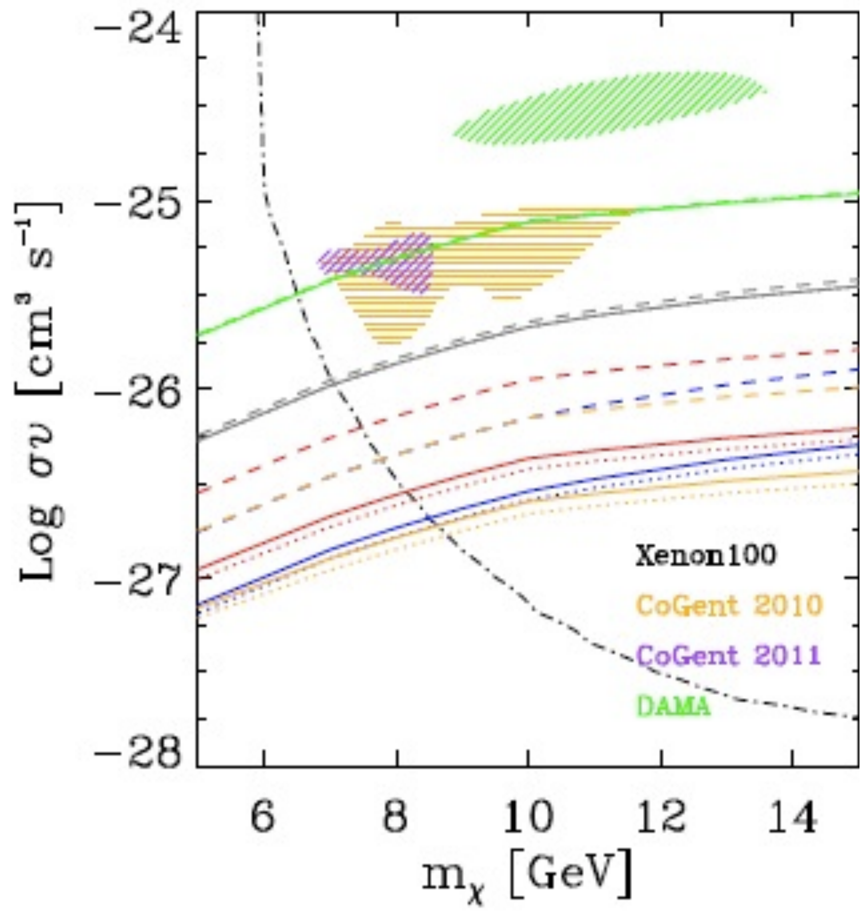


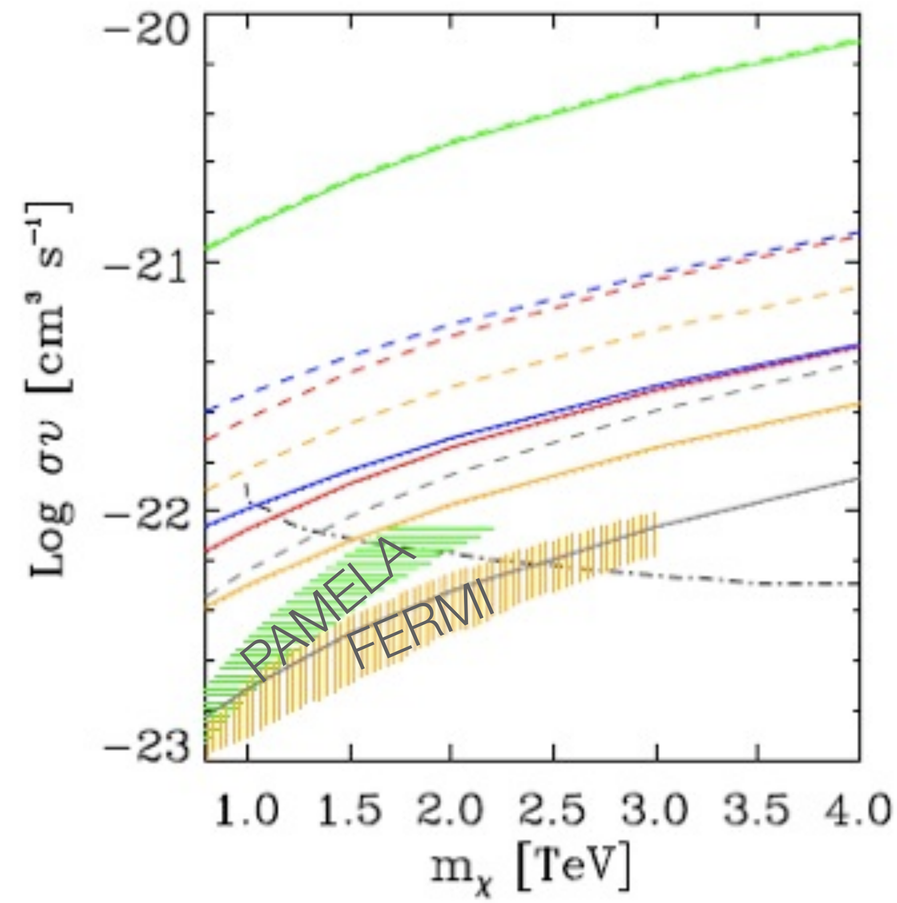
Very large scatter mainly due to the uncertainty on the propagation setup !

The dominant uncertainty source is that on the diffusive halo height

Constraints on DM models







$$\tilde{W}^0\tilde{W}^0 \to W^+W^-$$

Wino model

(motivated by SUSY and PAMELA e+ anomaly)

$$\chi\chi \to \bar{b}b$$

Light WIMPs

with sizable quark coupling (motivated by direct detection recent results)

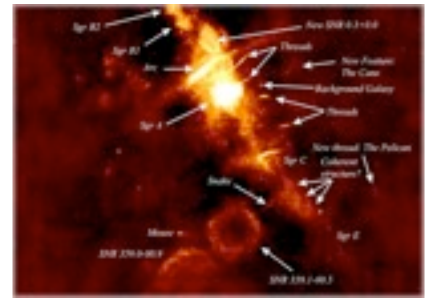
$$\chi\chi \to \mu^+\mu^-$$

Heavy “leptophilic” WIMPs

(motivated by PAMELA, Fermi, HESS) + radiative corrections

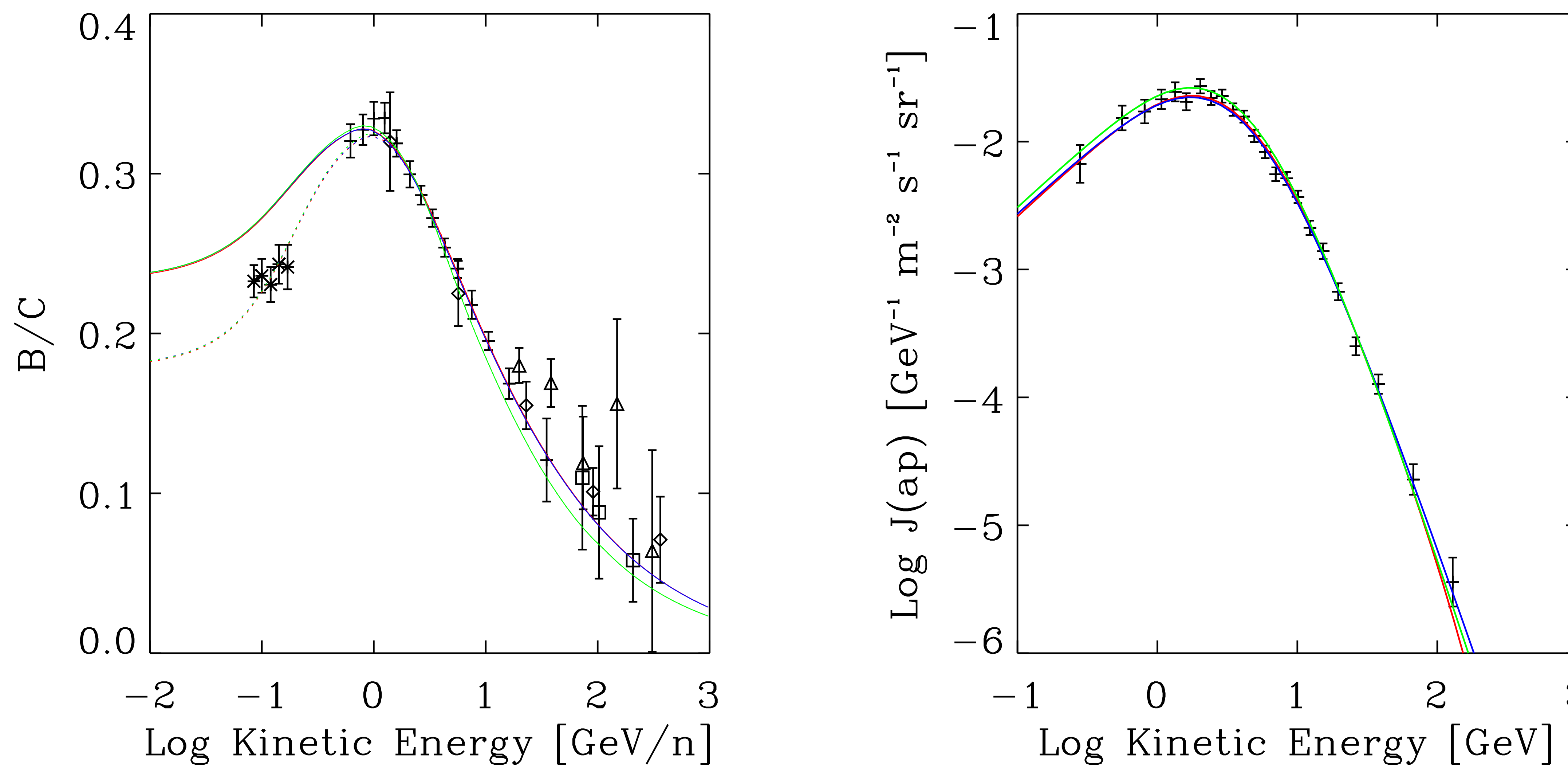
CE, I. Cholis, D. Grasso, L. Maccione & P. Ullio, PRD, 2012, arXiv:1110.5922

Not-local effects?



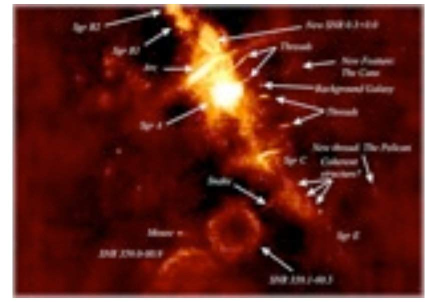
Inefficiency of GC diffusion

Convection wind



Astrophysical anti-protons: negligible effects!

Not-local effects?



Inefficiency of GC diffusion

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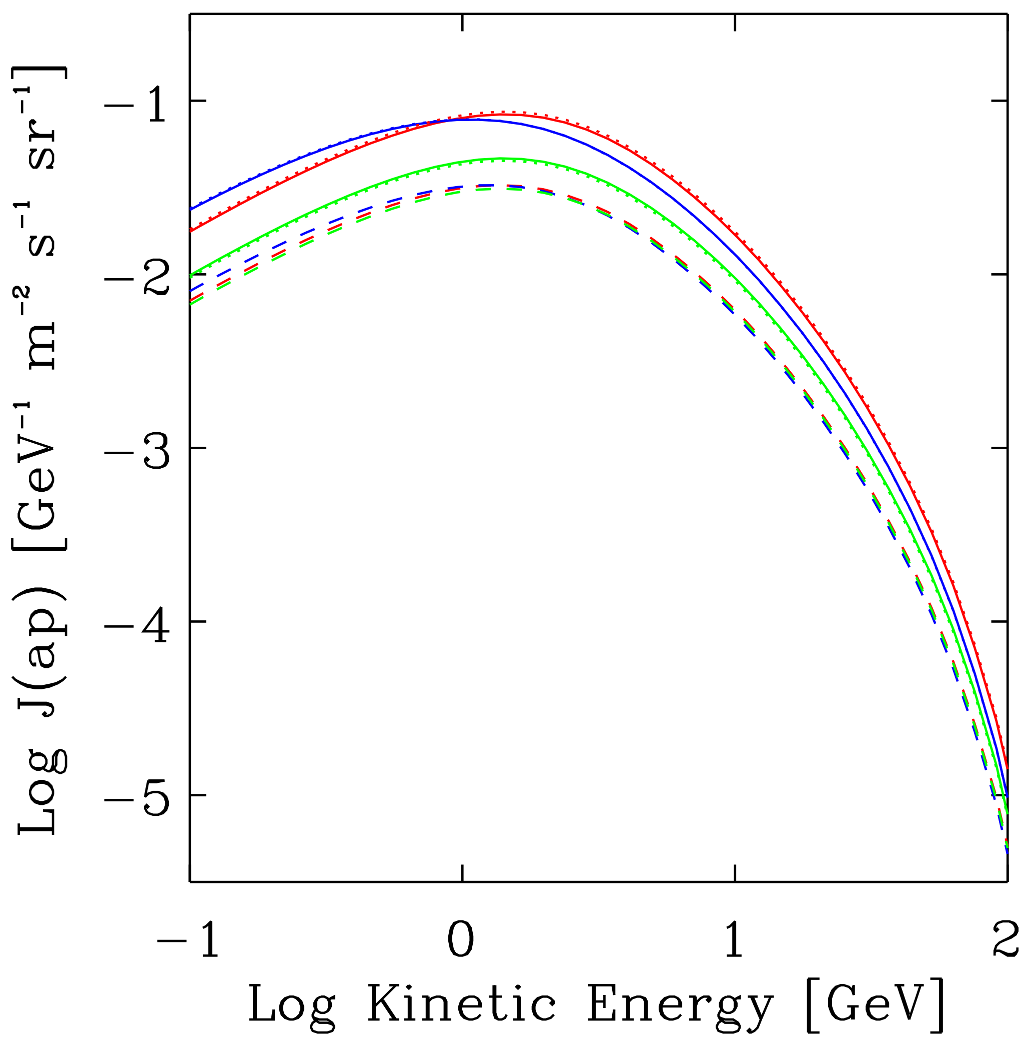
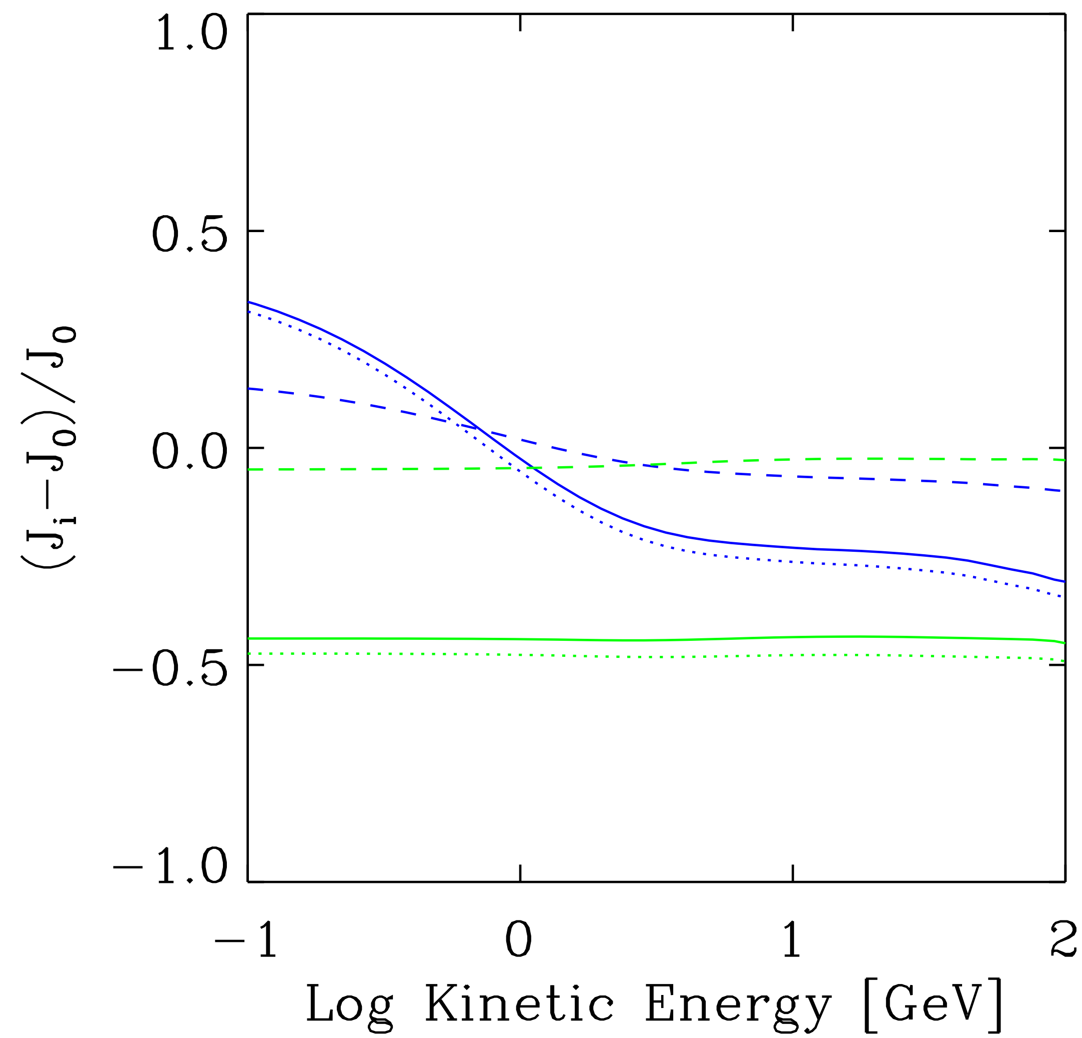




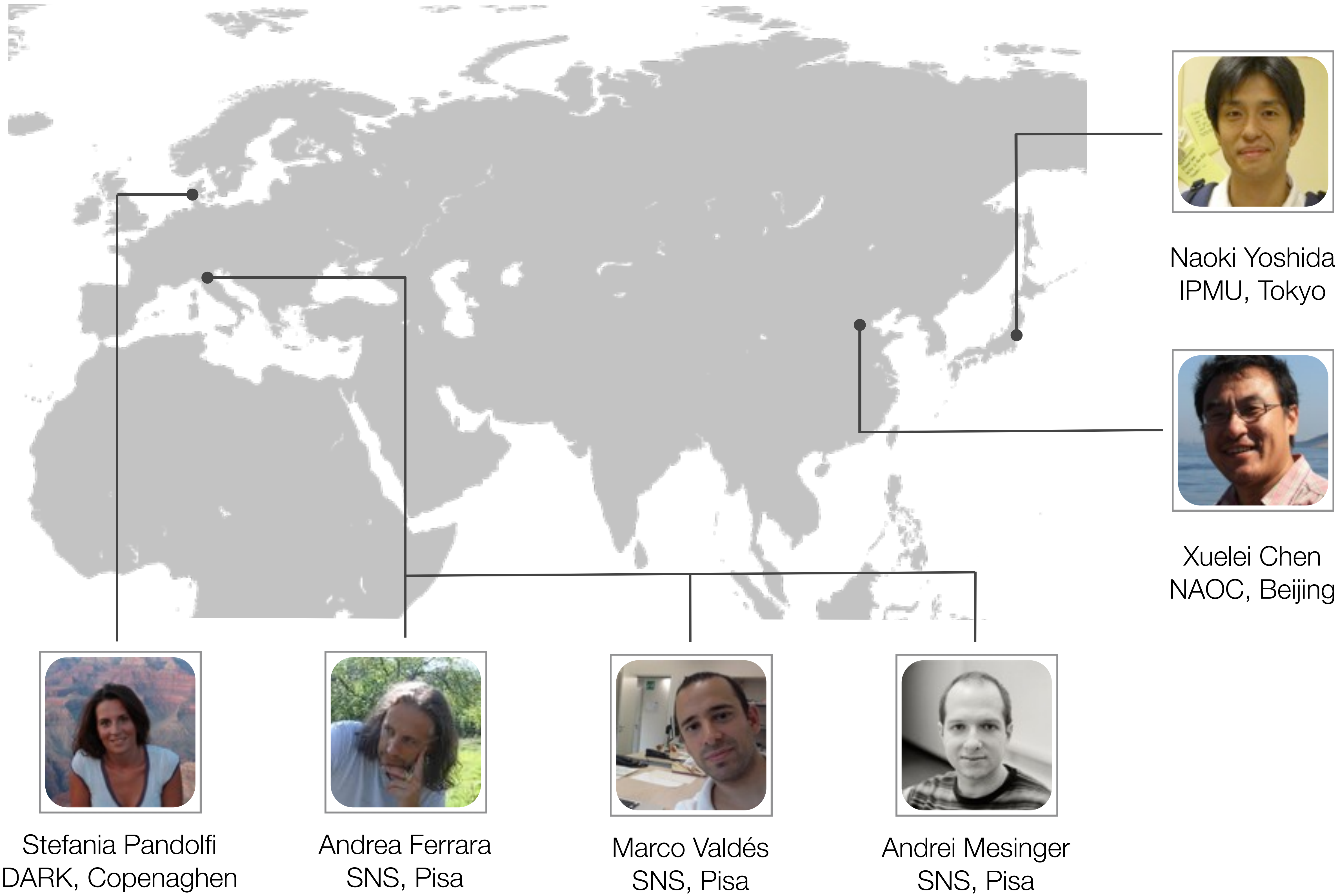
Exotic anti-protons: up to 50%!

Conclusions - Part I

- Galactic ap are an useful tool to constraints DM in our galaxy.
- However, current knowledge of CR propagation in our Galaxy leaves huge uncertainties on their effective role.
- AMS-02 upcoming data will likely reduce dramatically the uncertainties on propagation parameters, but don’t forget **not-local** effects!

Part II - High-redshift Universe

In collaboration with



DM annihilation effects during Dark Ages

- WIMP annihilation produce gamma-ray, cosmic ray, anti-matter: release energy which, in principle, ionize/heat up baryonic gas.

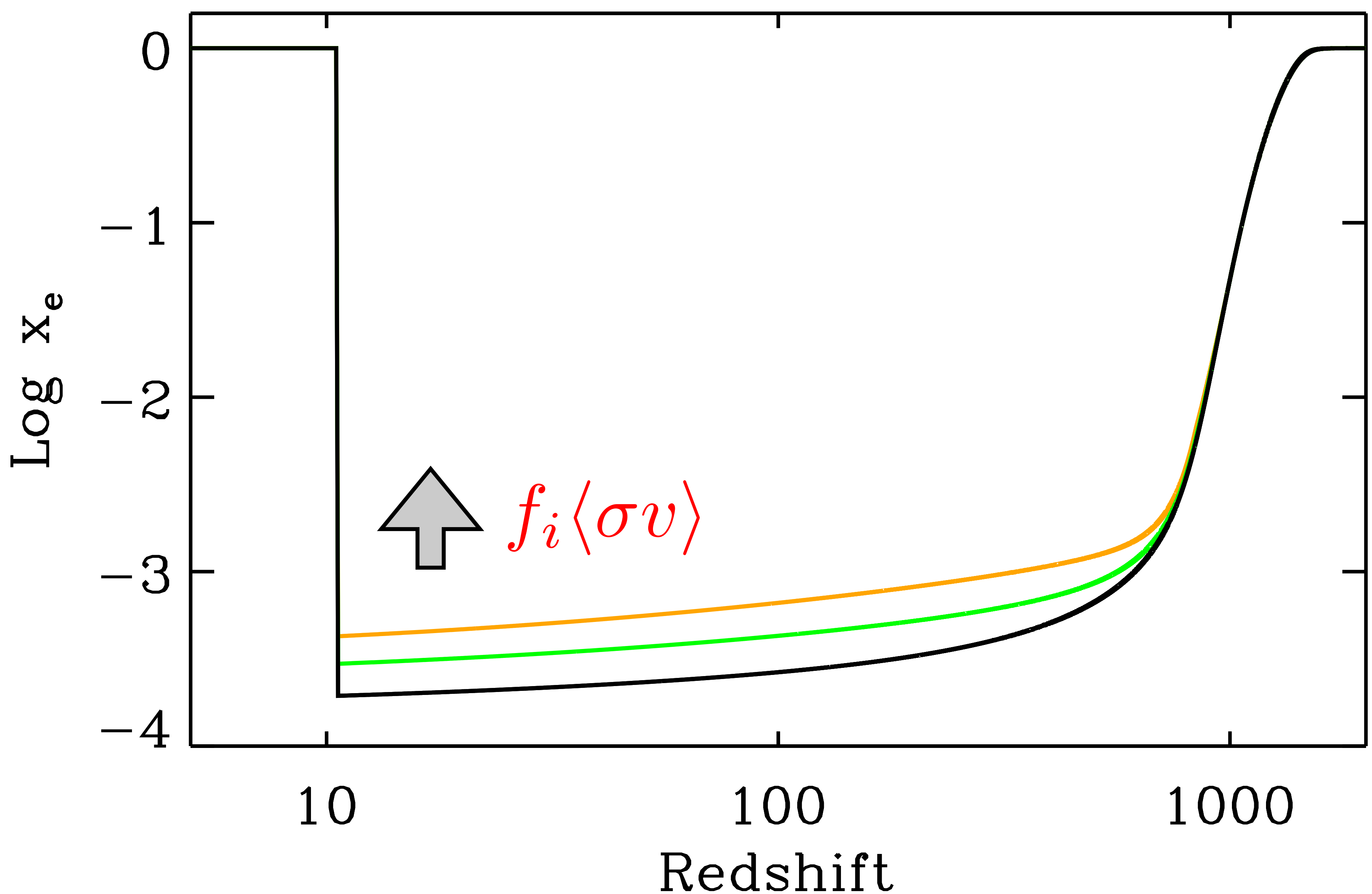
- Energy released enormous: 1 GeV energy is sufficient to ionize ~10^8 hydrogen atoms, only a tiny fraction of DM decay/annihilate is enough to affect ionization history.

- By looking for departures from the “standard recombination” scenario, we can place limits on energy injection at z=100-1000 and translate these limits to exclusions in WIMP parameter space (e.g. the cross-section / mass plane, etc.).

- Note that these results are quite robust since we understand recombination and the CMB quite well and astrophysical backgrounds are less relevant with respect to constraints based on e.g. annihilation in late-time halos.

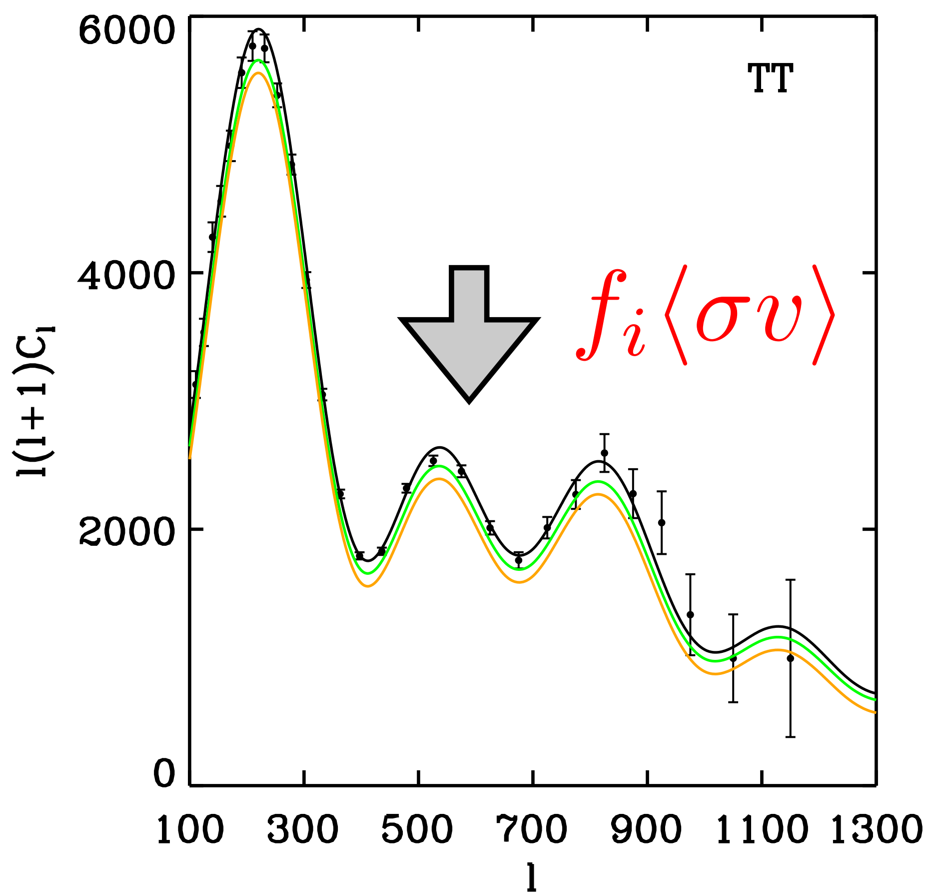
Baryon history in the Universe

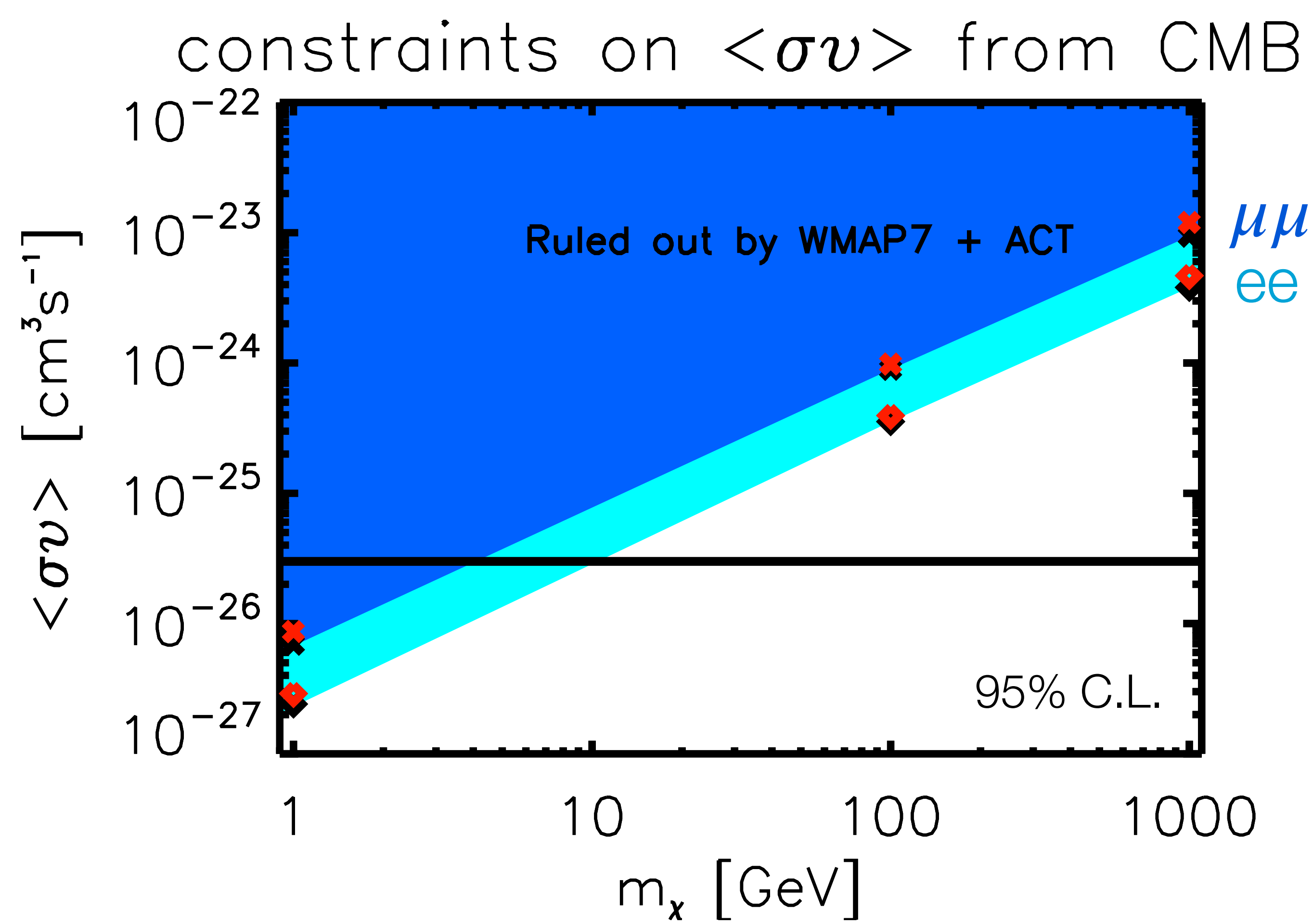
$$\frac{dE_\chi}{dt} = 2M_\chi f_i \langle \sigma v \rangle n_\chi^2$$



CMB constraints

S.Galli, F.Iocco, G.Bertone & A.Melchiorri, PRD, 2011

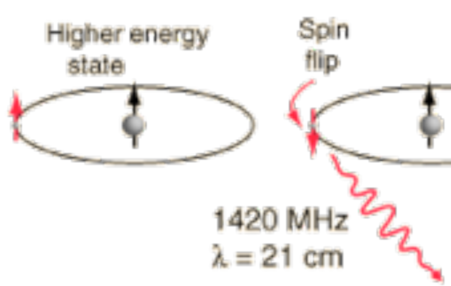




- The amount of **free electrons** that survive at low redshift after recombination is larger compared to the standard case.
- Increase the width of the last scattering surface, and consequently the width of the visibility function. This results in a suppression of the amplitude of the oscillation peaks.

21cm physics

J.Pritchard & A.Loeb, arXiv:1109.6012

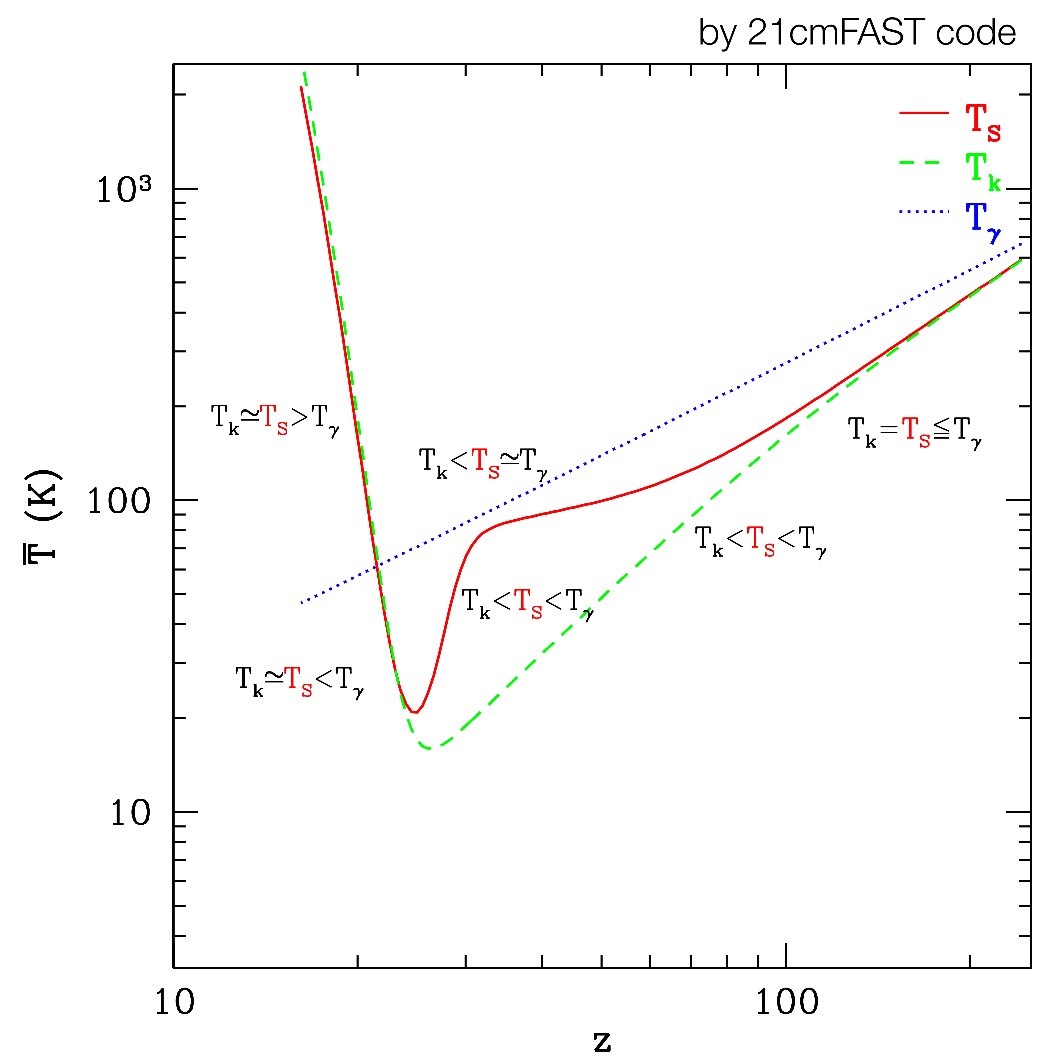
- 

$\rightarrow \dfrac{n_1}{n_0} = 3\exp\left(-T_*/T_S\right)$

- $T_b \approx 8\, mK\, x_{\rm HI}(1+\delta)(1+z)^{1/2}\left[\dfrac{T_S - T_{\rm CMB}}{T_S}\right]$

- Emission if $T_S > T_{CMB}$; absorption if $T_S < T_{CMB}$

- In the absence of coupling mechanisms: T_S=T_{CMB}. But! Two mechanisms couple T_S to T_K: **collisions** and **Lyα pumping** (Wouthuysen-Field Effect).



DM annihilation effects on 21 cm

S.R.Furlanetto, S.P.Oh & E.Pierpaoli, PRD, 2006 ; A.Natarajan & D.J.Schwarz, PRD, 2009

- The evolution of the spin-temperature:

$$T_S = \frac{T_{CMB} + y_\alpha T_k + y_c T_k}{1 + y_\alpha + y_c},$$

$$(1+z)\frac{dT_k}{dz} = 2T_k + \frac{l_\gamma x_e}{H(z)(1+f_{He}+x_e)}(T_k - T_{CMB}) - \frac{2\chi_h \dot{E}_x}{3k_b H(z)(1+f_{He}+x_e)},$$

$$J_\alpha(z) = \frac{\mathcal{N}_H^2 hc}{4\pi H(z)}\left[x_e x_p \alpha_{2^2P}^{\rm eff} + x_e x_{H\,I}\gamma_{eH} + \frac{\chi_\alpha \dot{E}_x(z)}{\mathcal{N}_H h\nu_\alpha}\right],$$

heating fraction

Lya fraction

M.E.DE.A. code

M.Valdés, **CE**, A.Ferrara, MNRAS, 2011

- Several astrophysical and cosmological sources produce high energy particles through different acceleration processes:
  how is this energy transferred to the surrounding environment?

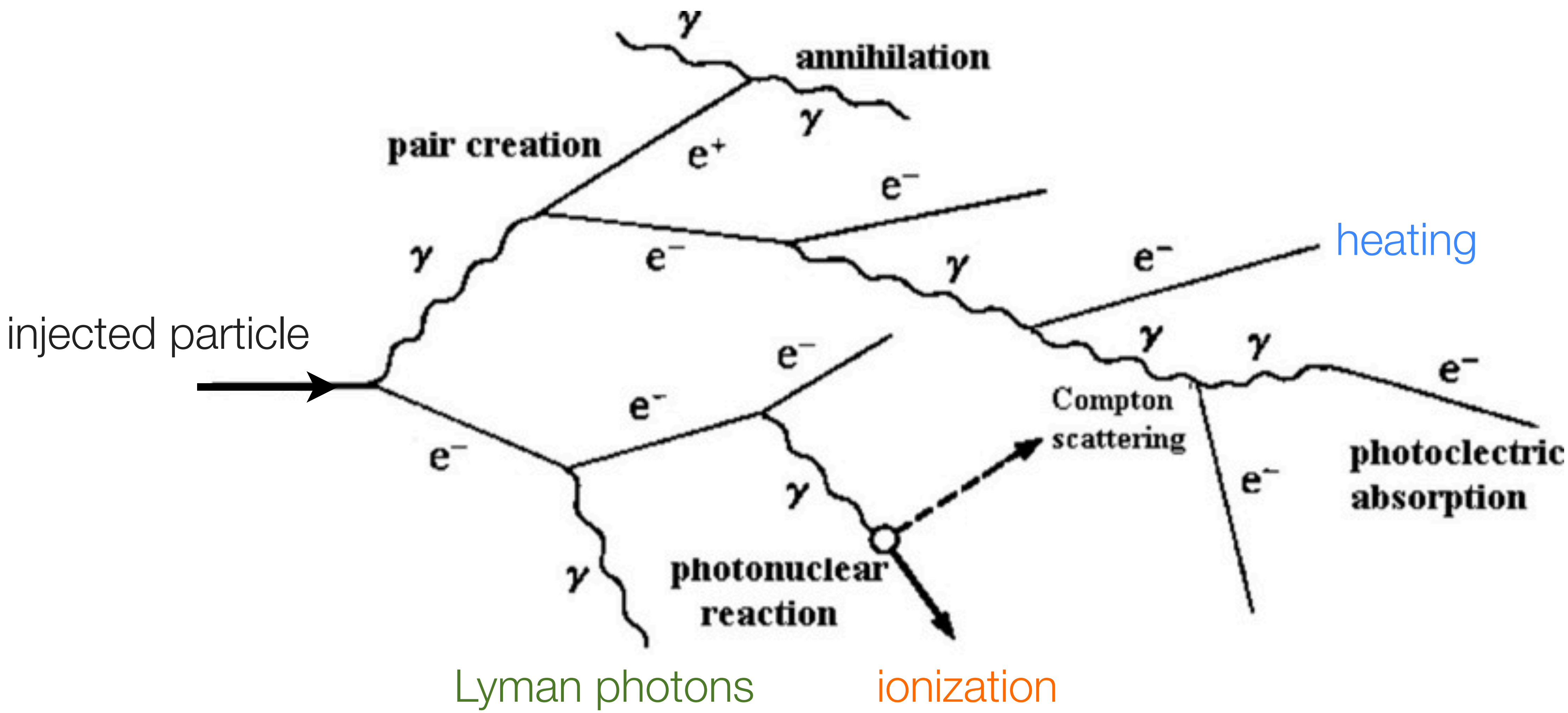
- **Monte Carlo method**: repeated random sampling of the relevant physical quantities and processes (i.e. cross-sections and interaction probabilities) to follow the evolution of a relativistic electron.

- An high energy electron in the IGM produces a chain of reactions: start with one particle, end up with many → the code calculates for every particle the probability of the main interaction channels and then selects one by a random number generator, until the energy is deposited into the IGM.

- **M**ontecarlo **E**nergy **DE**position **A**nalysis.

M.E.DE.A. code

M.Valdés, **CE**, A.Ferrara, MNRAS, 2011

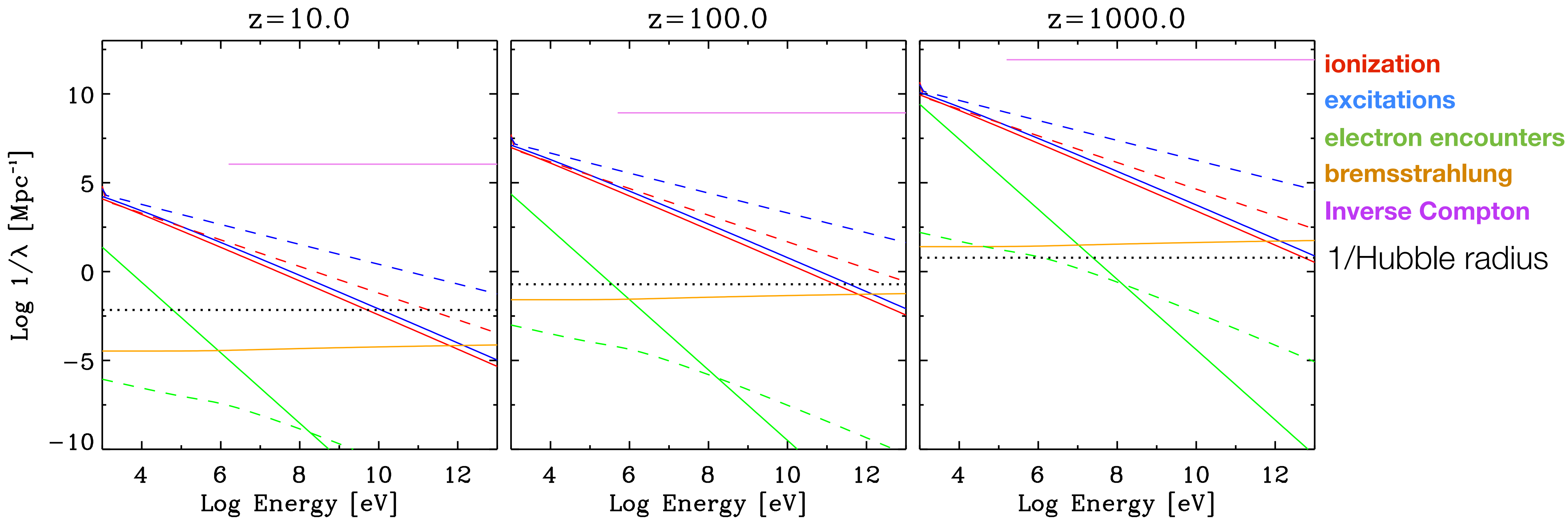


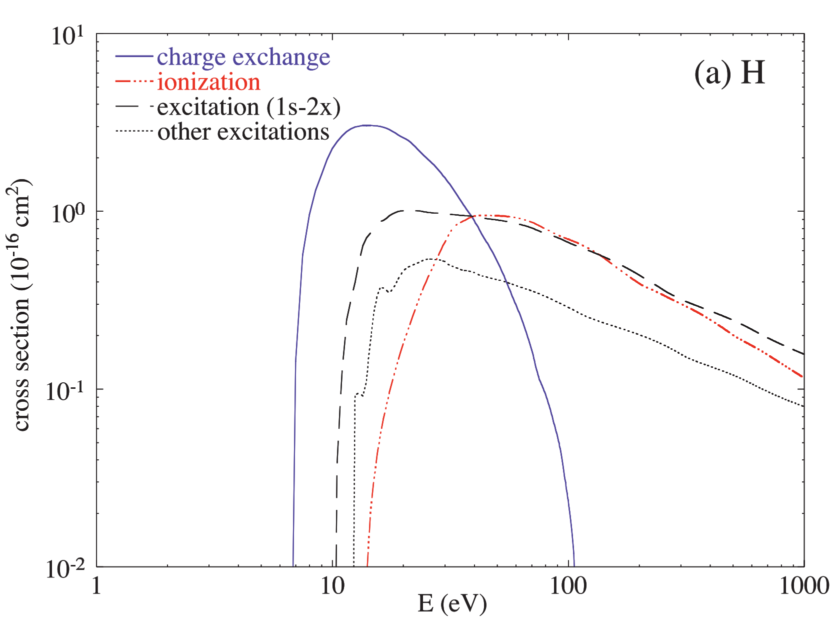
- MEDEA follows every particle from TeV down to eV energies in a continuous way.

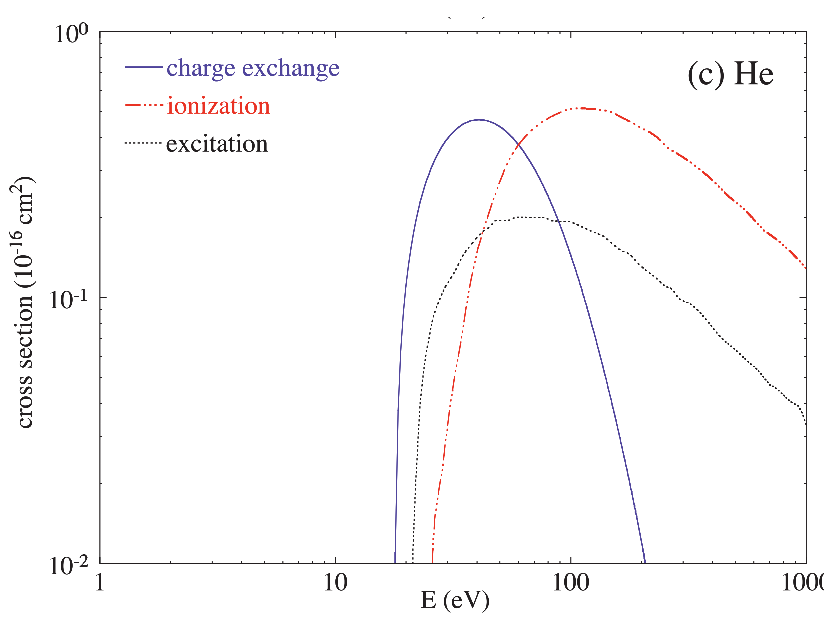
- Previous works have considered electrons up to keV only
(e.g. J.M.Shull & M.E. van Steenberg, APJ, 1985; S.Furlanetto & S.J.Stoever, MNRAS, 2010).

Lepton interactions

N.Guessoum et al., A&A, 2005 ; **CE**, M.Valdés, A.Ferrara & N.Yoshida, MNRAS, 2012







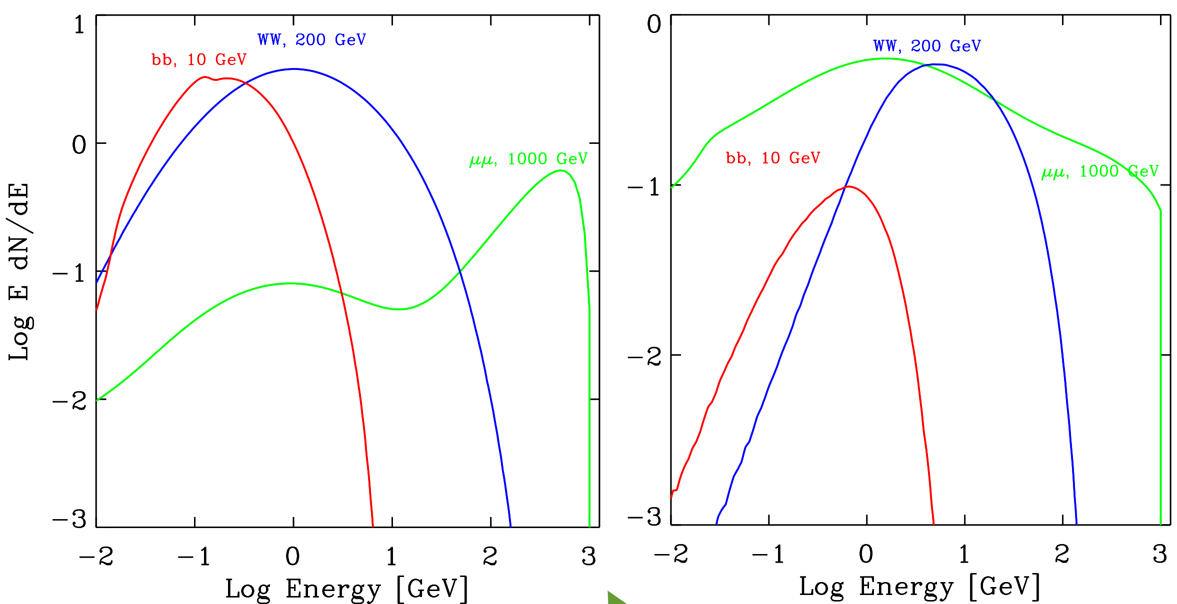
- IC dominant down to a O(MeV) energy
- Positronium formation in positron collision with H and He.

DM candidates

CE, M.Valdés, A.Ferrara & N.Yoshida, MNRAS, 2012

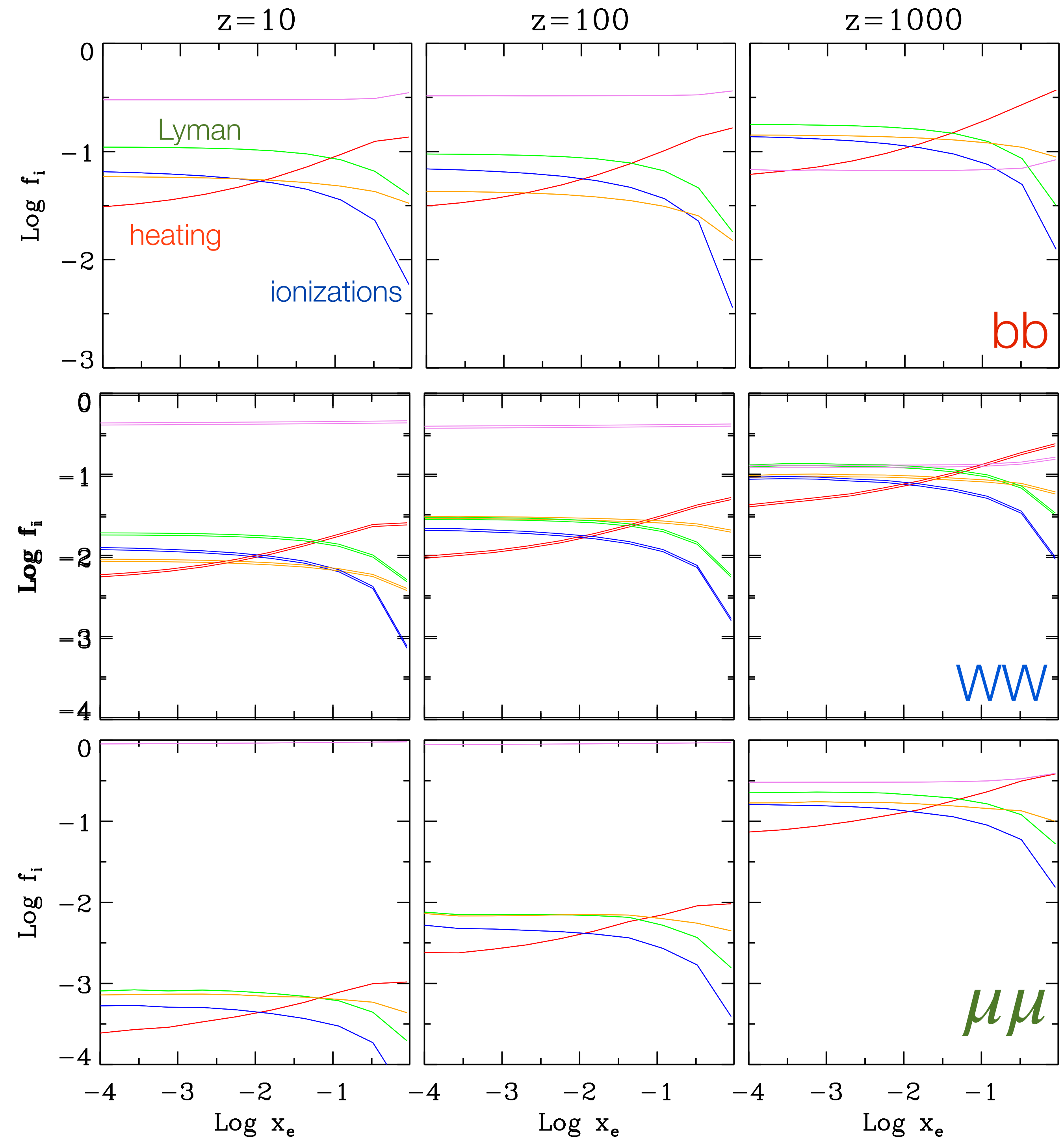
lepton spectra

photon spectra



DarkSUSY v.5.0.5

Ciafaloni et al., JCAP, 2011



$$f_{\rm h}(x_{\rm e}, z) = 10^{A(z)}\left[1 - C(z)(1 - x_{\rm e}^{B(z)})\right],$$

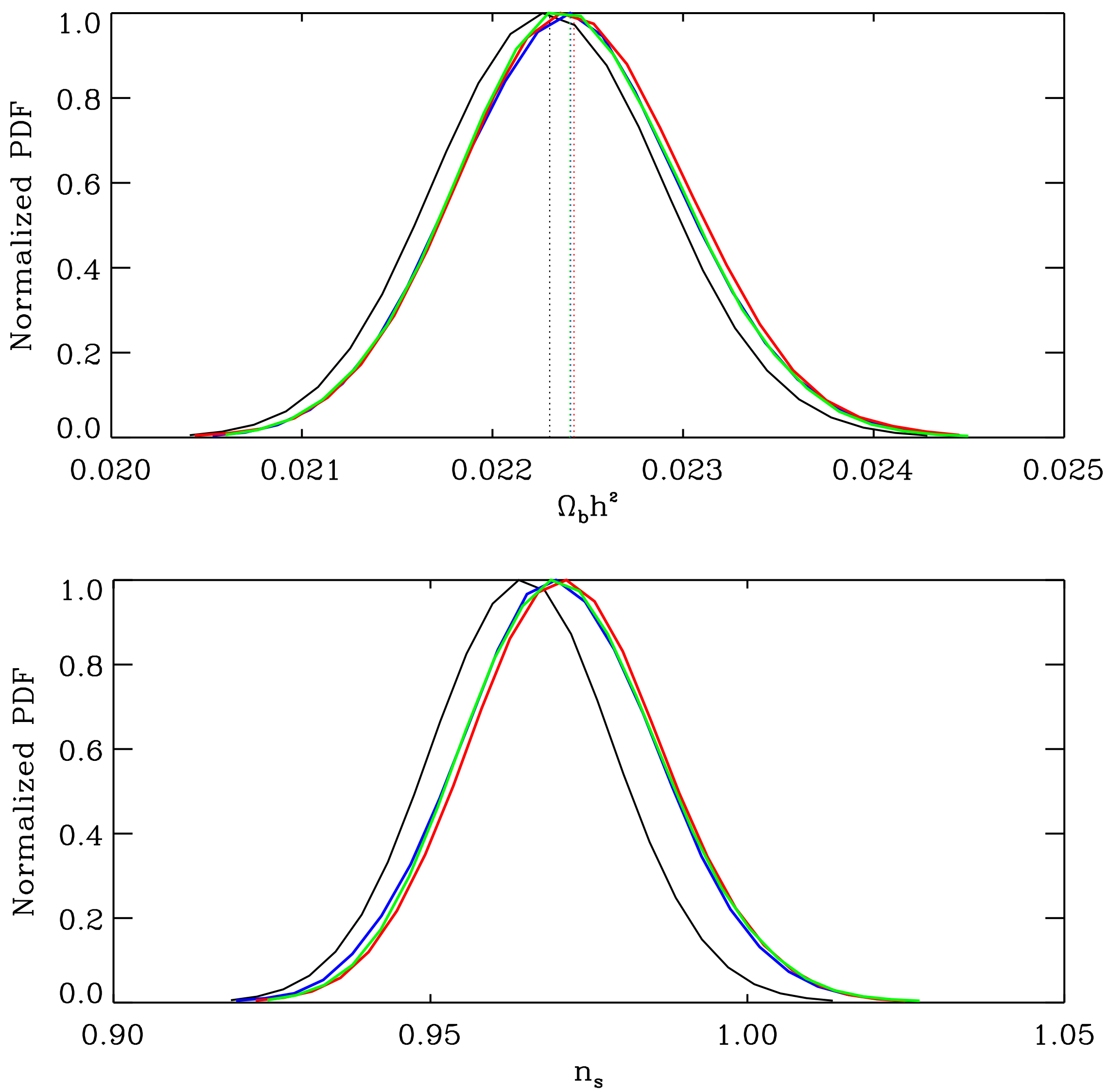
$$f_{\rm a}(x_{\rm e}, z) = 10^{A(z)}(1 - x^{B(z)})^{C(z)},$$

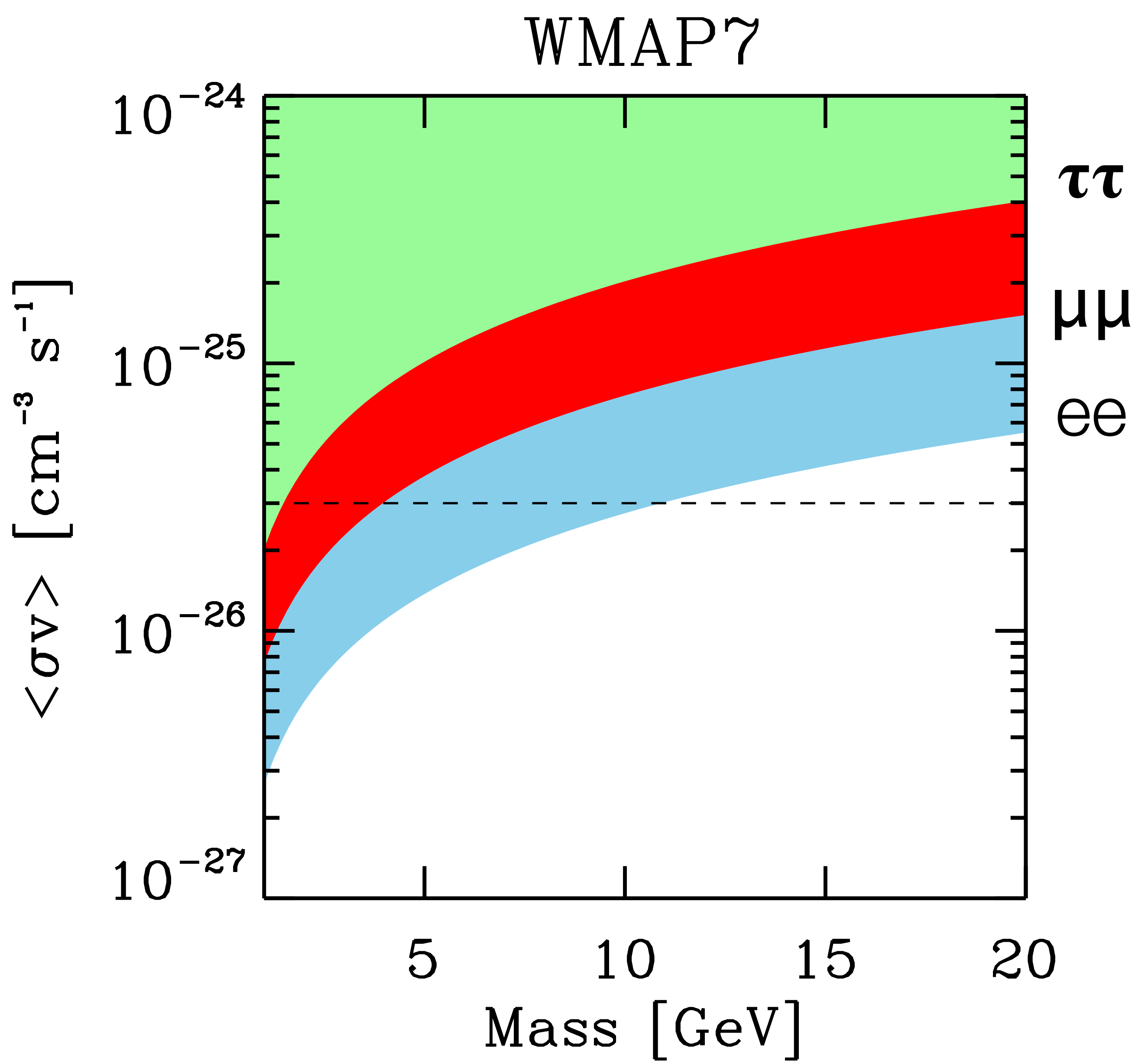
$$f_{\rm ion,H}(x_{\rm e}, z) = 10^{A(z)}(1 - x^{B(z)})^{C(z)},$$

$$f_{\rm ion,He}(x_{\rm e}, z) = 10^{A(z)}(1 - x^{B(z)})^{C(z)},$$

Update CMB constraints

CE & S.Pandolfi, in preparation





- Marginalized likelihood obtained with the public code **CosmoMC** by considering DM energy input from leptonic light DM candidate.

- Differences wrt to previous analysis up to 50%

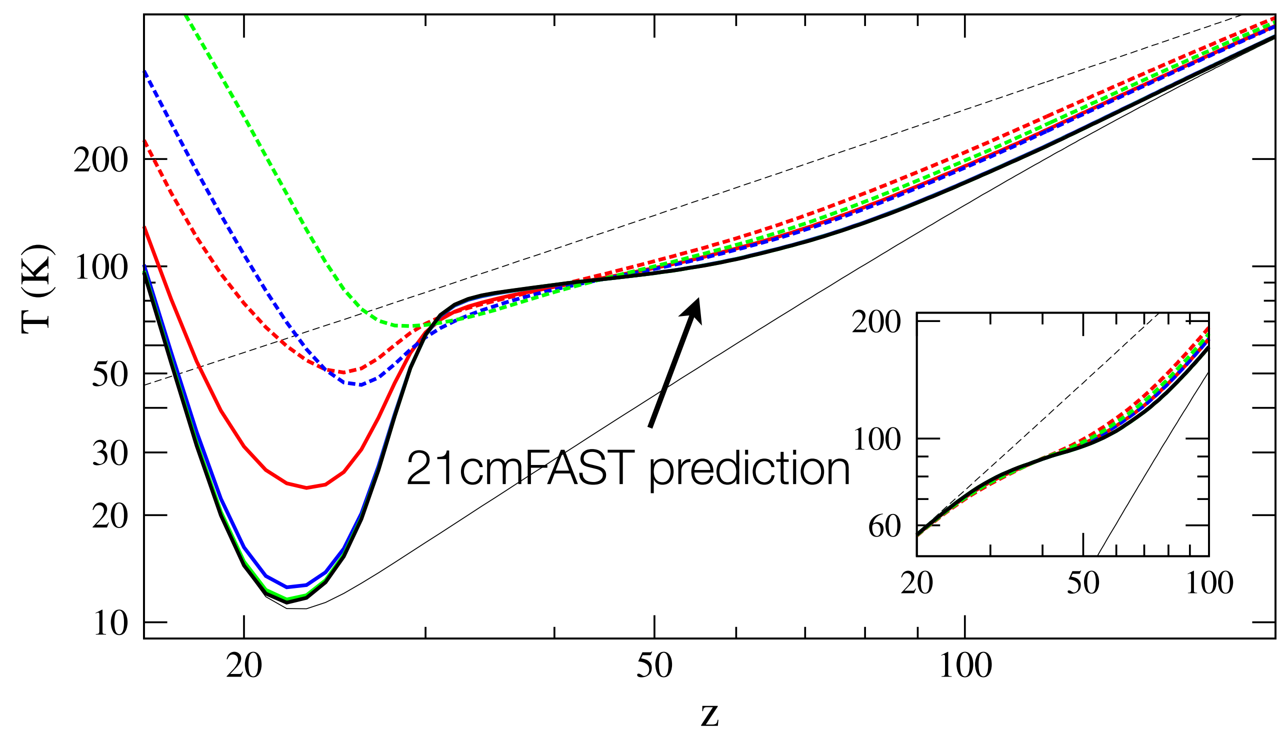
Our predictions for 21 cm global signal

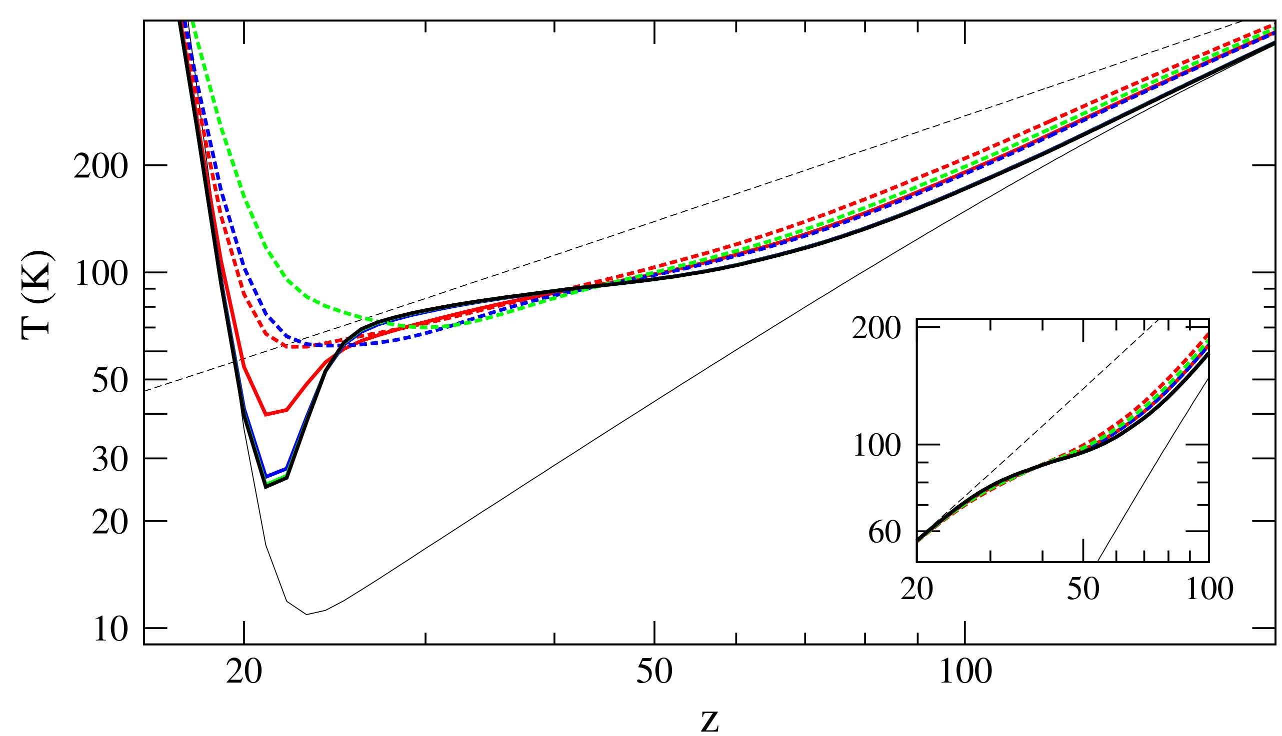
M.Valdés, **CE**, A.Mesinger, A.Ferrara & N.Yoshida, *submitted*

DM model	mass [GeV]	$\langle\sigma v\rangle$ [cm3/s]
W^+W^-	200	$\langle\sigma v\rangle_{th} = 3.0 \times 10^{-26}$
W^+W^-	200	$\langle\sigma v\rangle_{max} = 1.0 \times 10^{-25}$
$b\bar{b}$	10	$\langle\sigma v\rangle_{th} = 3.0 \times 10^{-26}$
$b\bar{b}$	10	$\langle\sigma v\rangle_{max} = 1.2 \times 10^{-24}$
$\mu^+\mu^-$	1000	$\langle\sigma v\rangle_{th} = 3.0 \times 10^{-26}$
$\mu^+\mu^-$	1000	$\langle\sigma v\rangle_{max} = 1.4 \times 10^{-23}$

*complete reionization models

- Deviations on the T_S up to 100mK in the “salable” redshift window.
- Extreme model in which reionization is dominated by X-rays.
- Stronger constraints could come from the power-spectrum ()





Conclusions - part II

- Energy injection by DM annihilation at z ~ 100-1000 can be properly constrained after accounting for degeneracies with cosmological parameters. However, such analysis are frequently based on simple approximations about how the input energy of the cascading particles gets partitioned between ionizations and heating of the environment.

- We have developed a new code, M.E.DE.A., which includes lepton and photon interactions with the IGM, allowing us to compute the energy partition into heating, excitations and ionizations as a function of the **electron initial energy**, the **ionization fraction** and the **redshift**.

- Our results can be applied to calculate DM contribution to the 21 cm cosmological evolution. Observations of the 21 cm signal from the Dark Ages could eventually detect a **clear** signal of exotic processes like DM decays or annihilations.