New developments in astroparticle physics

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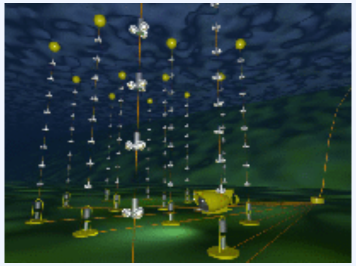
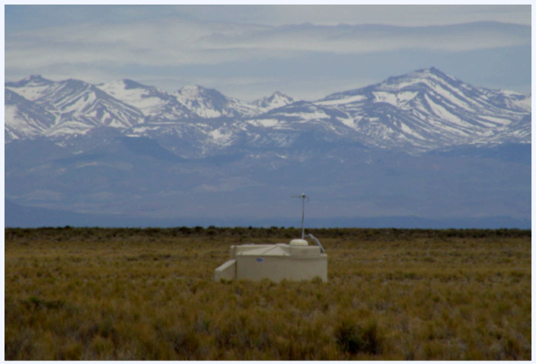
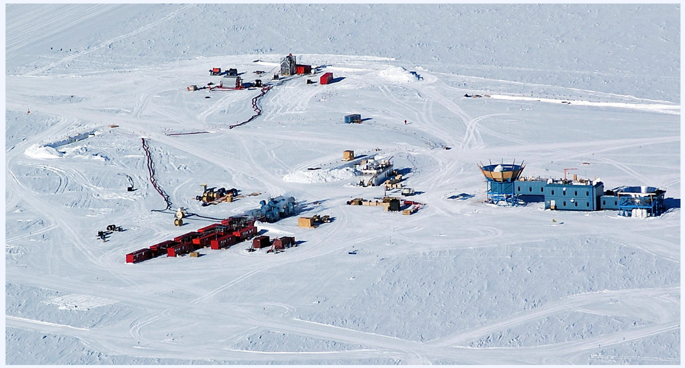
Rudolf Peierls Centre for Theoretical Physics







CHIPP Workshop, EPFL Lausanne, 2-3 June 2009

The (re)birth of astroparticle physics

Many of us particle physicists and astrophysicists have been conducting an illicit cosmological affair for some time now. This meeting seems to constitute an official consecration of that relationship, a sort of marriage ceremony.

John Ellis

('A brilliant past in front of us', First ESO-CERN Symposium, Nov1983. p.435)

"The convening of this symposium by two great European scientific institutes, one for particle physics and the other for astronomy, makes clear how widespread is the realisation that particle physics on the one hand, and astrophysics and cosmology on the other, are inextricably linked

… These developments have highlighted a major problem, namely the culture gap which results from the fact that both modern particle physics and modern astrophysics are highly technical and sophisticated disciplines, and that very few people are conversant with both".

Dennis Sciama

(*Introductory Survey*, op. cit, p.3)

What particle physicists have learnt through experience
(UA1 monojets, NuTeV anomaly, CDF high E_T excess ...)

Yesterday's discovery is today's calibration

Richard Feynman

… and tomorrow's background!

Val Telegdi

… is also a major issue now for astroparticle physics *viz*
how well do we know the 'astrophysical background' for signals of (apparently) new particle physics?

The PAMELA anomaly

PAMELA has measured the positron fraction:

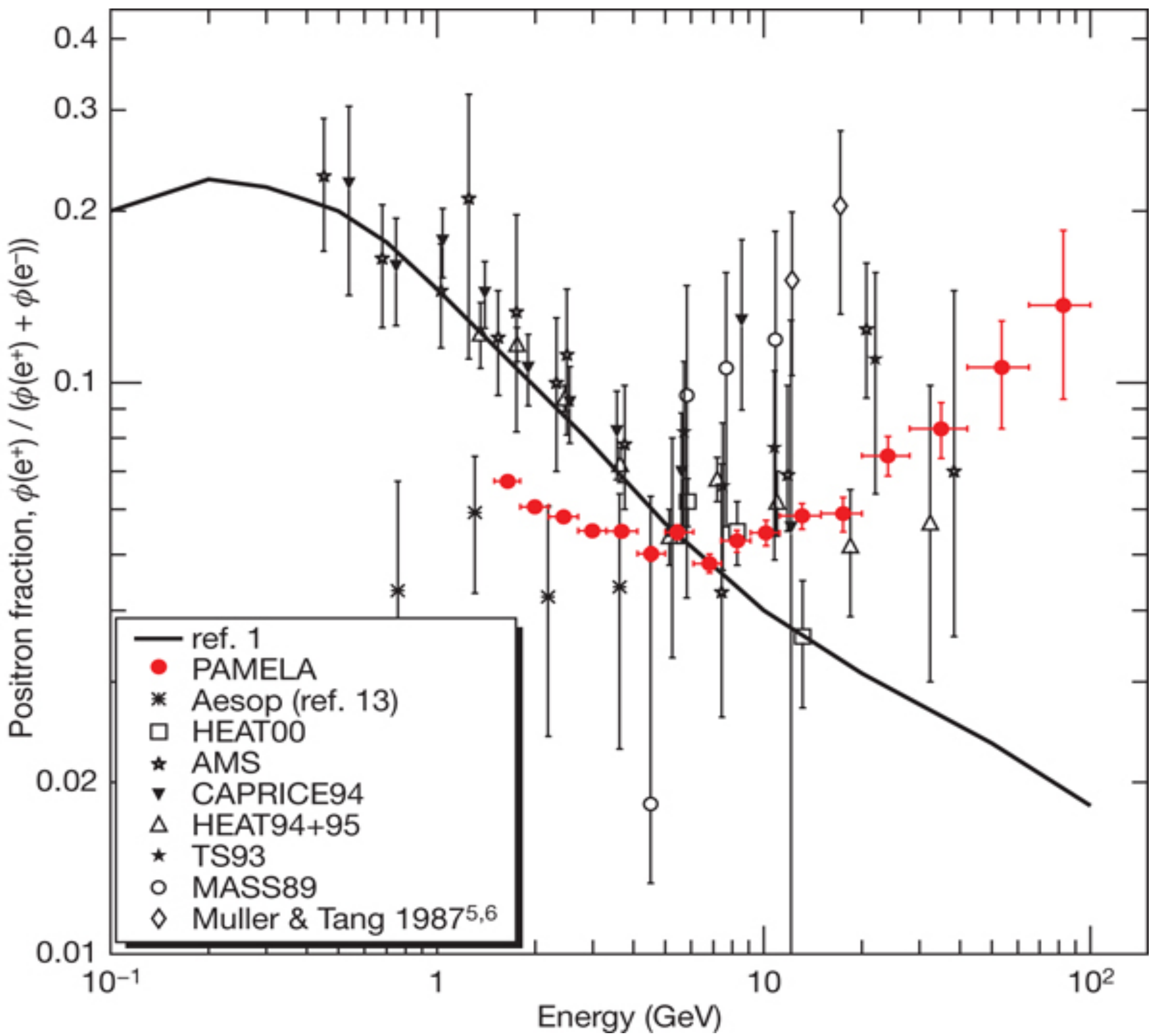
$$\frac{\phi_{e^+}}{\phi_{e^+} + \phi_{e^-}}$$

Anomaly ⇒ excess above 'astrophysical background'

Source of anomaly:

- DM decay/annihilation?
- Pulsars?
- Nearby SNRs?

… over 150 papers!



Nature 458:607,2009

Dark matter as source of $e^{\pm}$

Dark matter annihilation

Annihilation rate $\propto n_{\rm DM}^2$

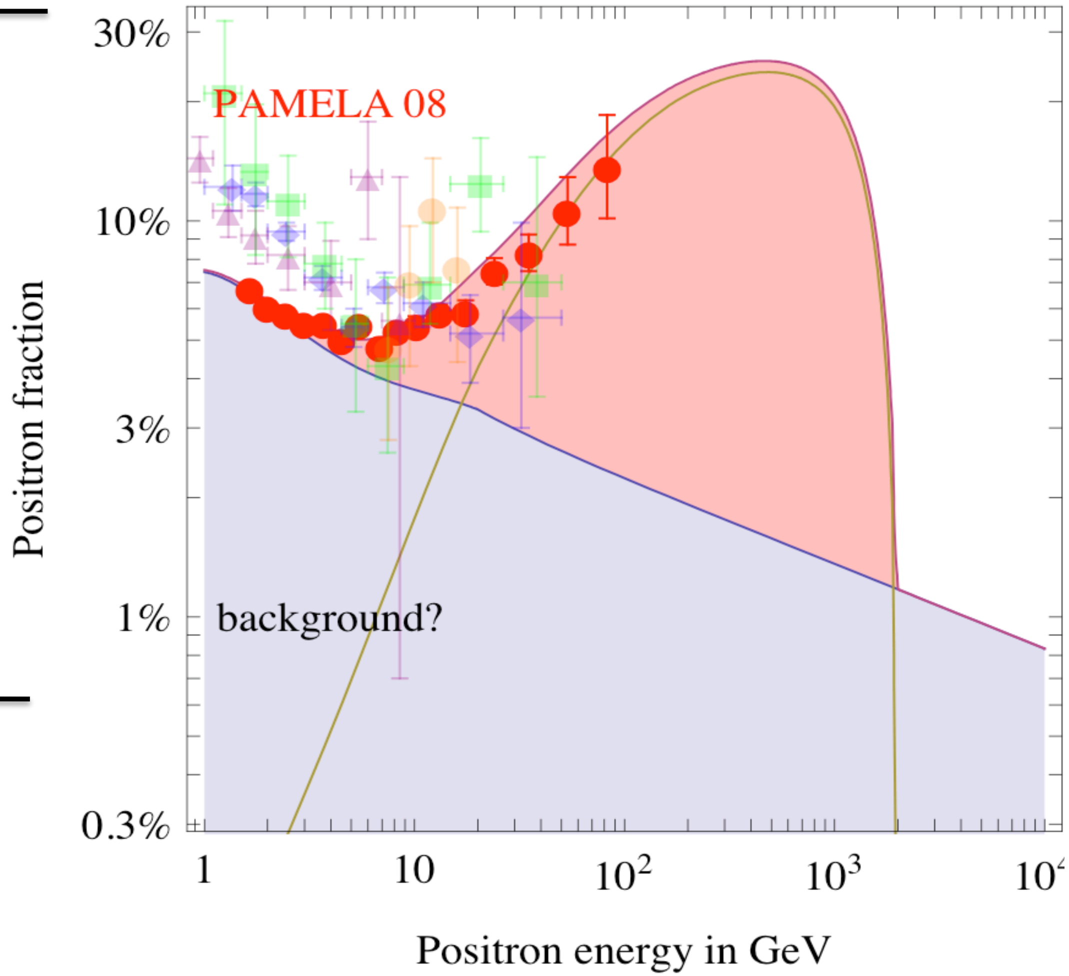
Leads eventually to SM particles

If WIMPs produced thermally, need astrophysical (clumping) or particle physics (Sommerfield enhancement) to yield 'boost factor' of $O(100)$

Dark matter decay

Similar, but decay rate $\propto n_{\rm DM}$

Lifetime ~ 10^9 x age of universe
(dim-6 operator suppressed by $M_{\rm pl}$)



Nardi, Sannino & Strumia, JCAP 0901:043,2009

Dark Matter, lightest superpartner wino dark matter, satellite data, string theory moduli, non-thermal cosmological history, and LHC

Gordy Kane

RICAP 2009

IF THE PAMELA EXCESS IS INDEED DUE TO A LIGHT WINO LSP THE IMPLICATIONS ARE REMARKABLE

- Would have learned that the dark matter, about a fifth of the universe, is (mainly) the W superpartner, and its approximate mass
- Discovery of supersymmetry!

  -- guarantees can study superpartners at LHC
- Would have learned that the universe had a non-thermal cosmological history, one we can probe
- Suggests form of underlying theory – M-Theory "G_2 – MSSM" construction a concrete example

"There is something fascinating about science. One gets such wholesome returns of conjectures out of such trifling investment of fact."

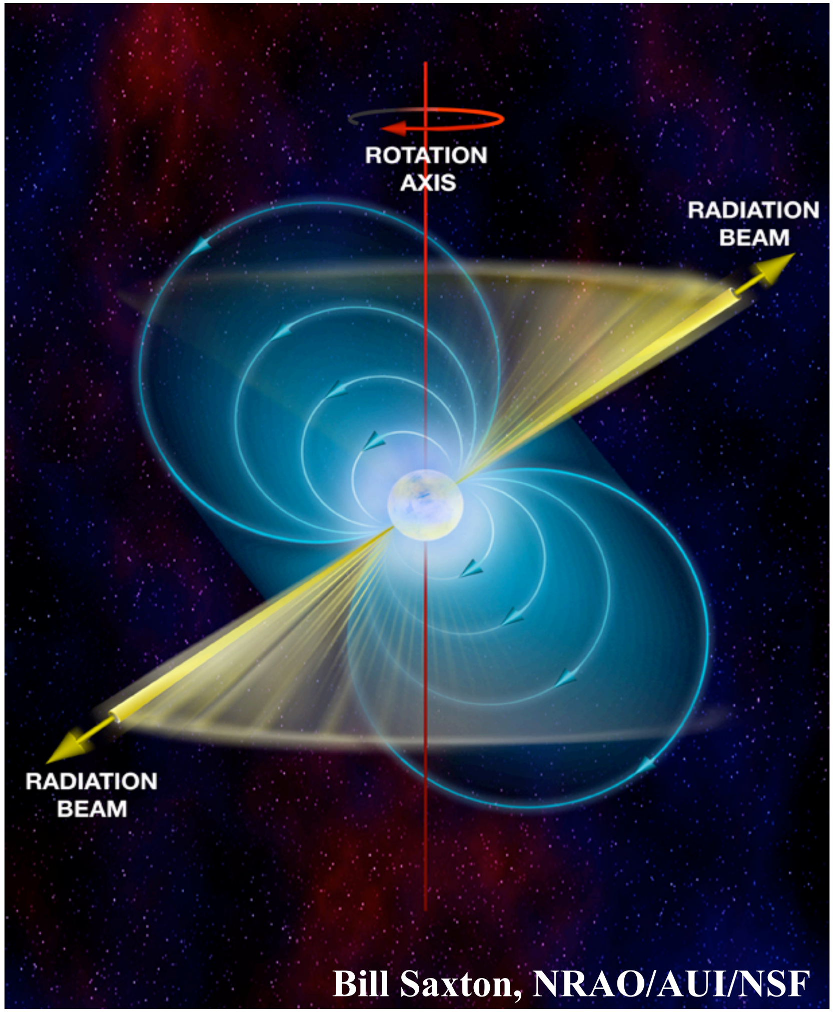
Mark Twain

"Get your facts first and then you can distort them as much as you wish ..."

Nearby pulsars as source of $e^{\pm}$

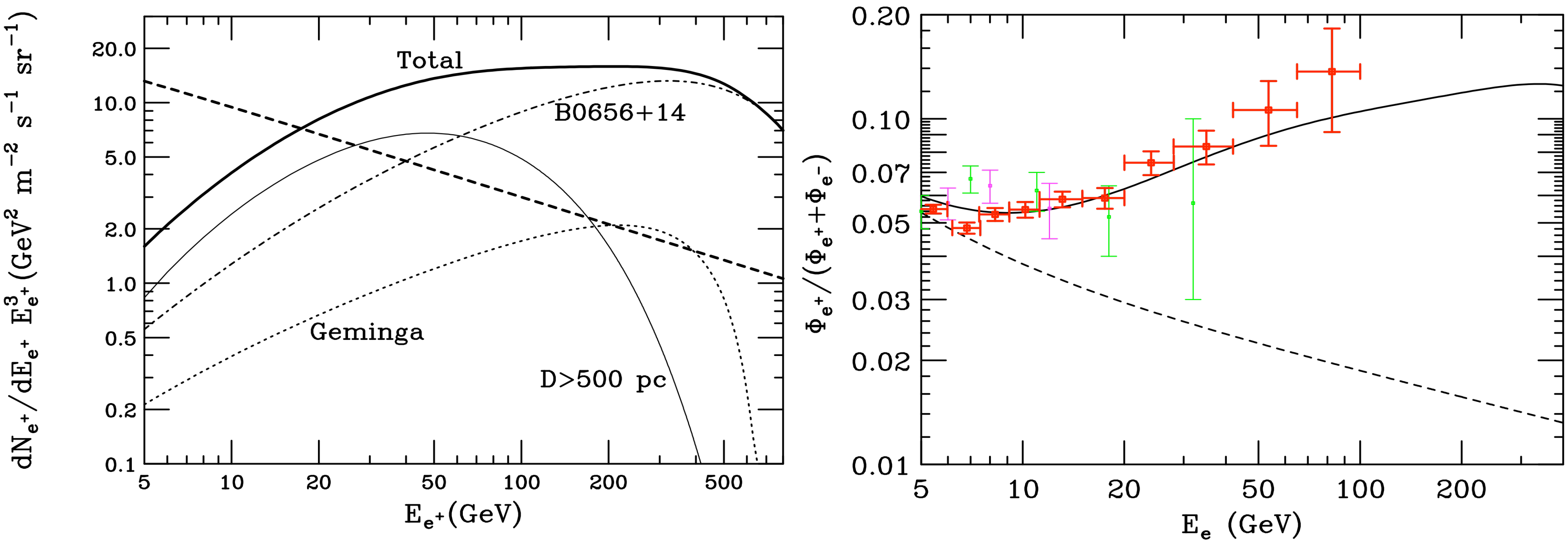
- Highly magnetized, fast spinning neutron stars
- γ rays and electron/ positron pairs produced along the magnetic axis
- Spectrum expected to be harder than background from propagation, *viz.*

$$N \propto E_e^{\pm\,-1.6} e^{-E_e^{\pm}/100\,\mathrm{GeV}}$$



Combination of galactic contribution and two nearby mature pulsars, **Geminga** (157 pc) and **B0656+14** (290 pc), *can* fit PAMELA excess

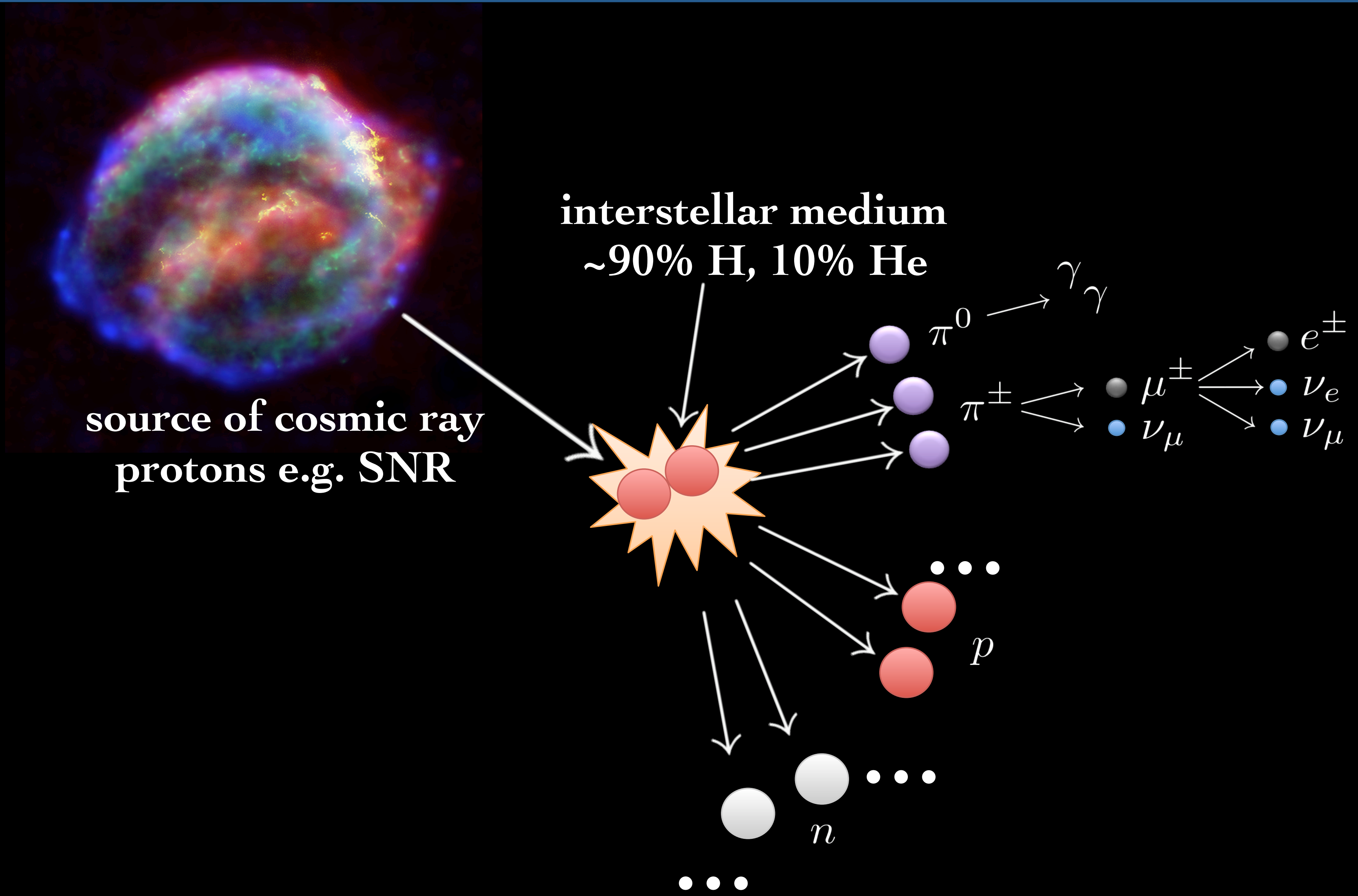
Hooper, Blasi, Serpico, JCAP 0901:025,2009



Parameters of pulsars, are however not well known …

Possible test: FERMI may be able to detect expected anisotropy towards B0656+14 within 5 years

Secondary $e^{\pm}$ during propagation



The 'Leaky Box Model' (Cowsik *et al* 1967)

* Cosmic rays confined in galaxy but with small (constant) escape probability (due to diffusion in tangled magnetic fields)
$\Rightarrow$ Exponential distribution of path lengths between cosmic ray source and Earth

* If the average column density depends on energy/rigidity as: $\lambda(E) = \lambda_0 E^{-\delta}$,

… then with $\delta \sim 0.4\text{-}0.6$ can account for both:

- energy dependence of observed ratios of secondary-to-primary nuclei, *and*
- spectrum of observed cosmic rays

GALPROP (Moskalenko & Strong 1998) solves the 3-D time-dependent transport equation and yields ~the same answer for the equilibrium fluxes

Secondary-to-Primary Ratios

Transport equation:

$$\frac{\mathrm{d}N_i}{\mathrm{d}t} = -\frac{N_i}{\tau_i} - \Gamma_i N_i + \sum \Gamma_{j\to i} N_j + Q_i$$

Primary spectrum:

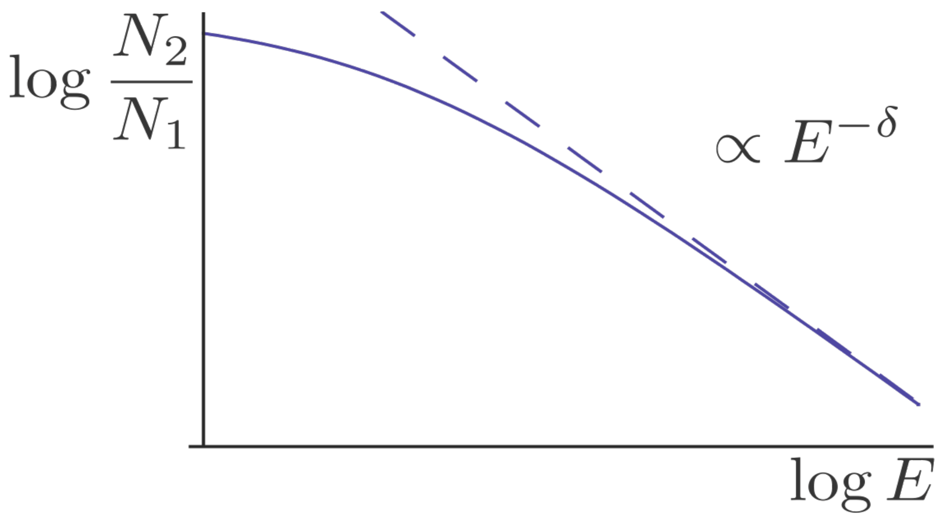
$$N_1 = \frac{Q_1 \tau_1}{1 + \lambda_1^{\mathrm{esc}}/\lambda_1^{\mathrm{tot}}}$$

Secondary spectrum:

$$N_2 = \left(\frac{1}{\lambda_2^{\mathrm{esc}}} + \frac{1}{\lambda_2}\right)^{-1} \frac{N_1}{\lambda_{1\to 2}}$$

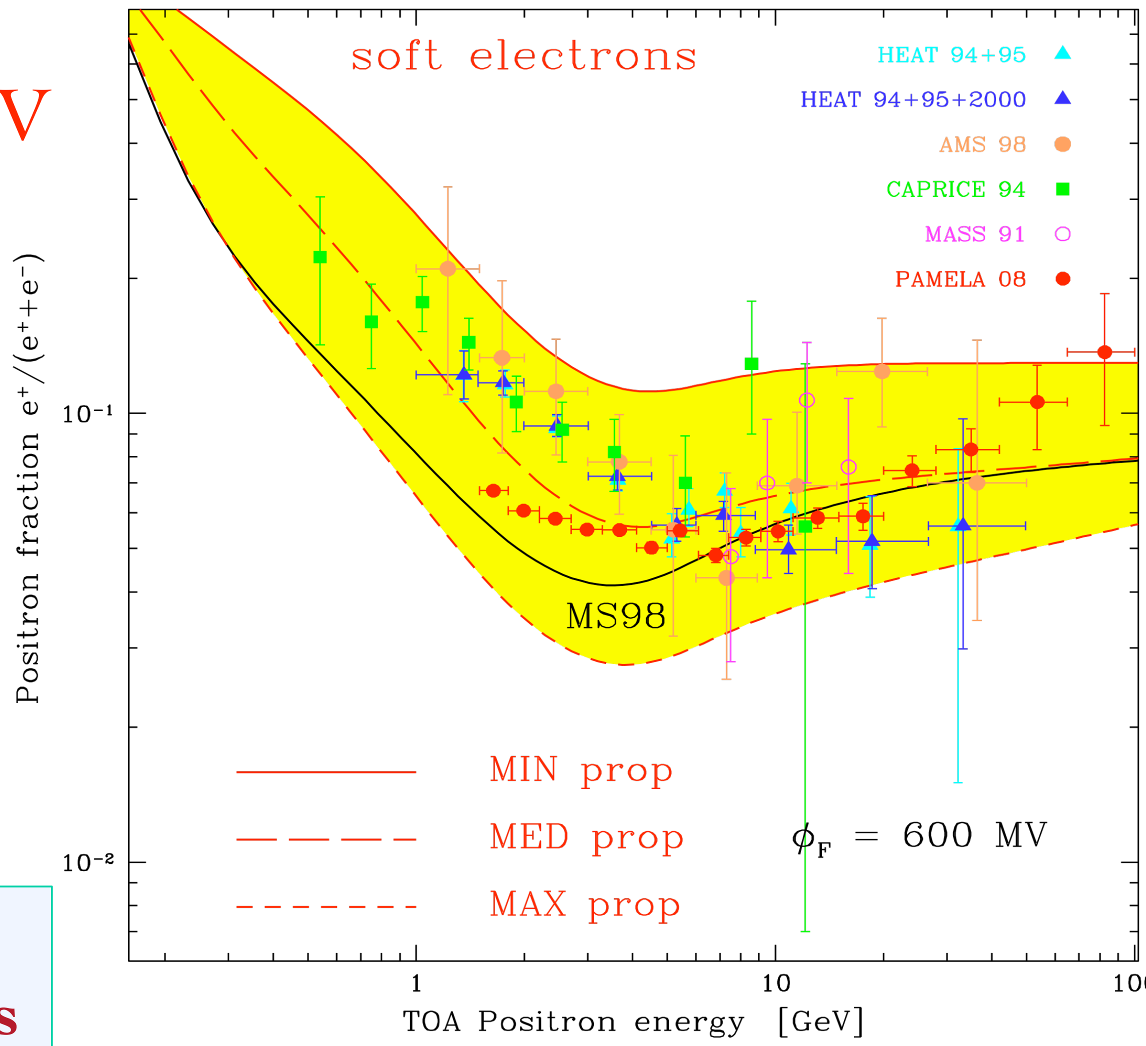
Secondary-to-primary ratio:

$$\frac{N_2}{N_1} = \Bigg(\underbrace{\frac{\lambda_{1\to 2}}{\lambda_2^{\mathrm{esc}}}}_{\propto E^{\delta}} + \frac{\lambda_{1\to 2}}{\lambda_2}\Bigg)^{-1}$$



Uncertainties in background estimate

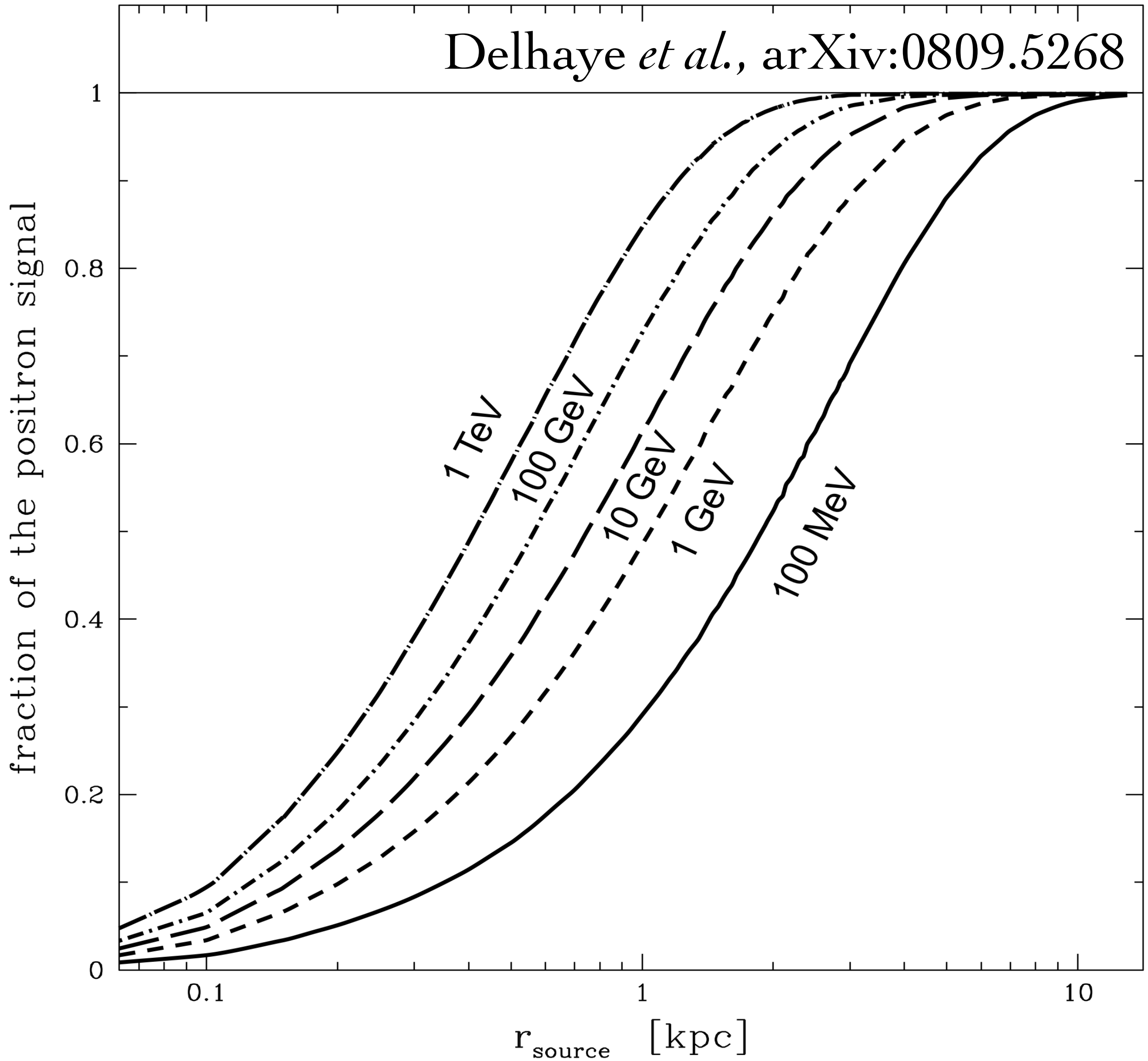
- Nuclear cross-sections: factor ~2-3 above 10 GeV
- Primary electron flux: factor ~4 at 100 GeV
- $e^{\pm}$ energy losses
- Propagation model



Delhaye *et al.*, arXiv:0809.5268

NB: positron fraction from secondary production always *decreases* with energy

However $e^{\pm}$ lose energy readily, so *nearby* sources dominate at high energies … the steady state solution is then irrelevant!



Nearby cosmic ray accelerator?

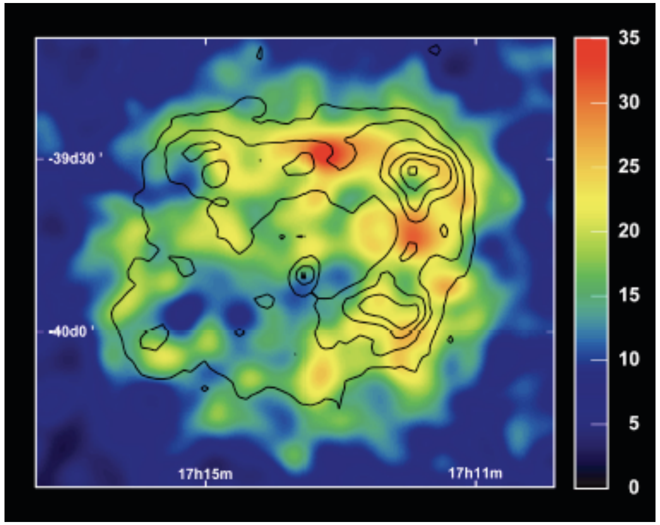
Rise in e^+ fraction could be due to secondaries being produced *during* acceleration … which are then accelerated along with the primaries

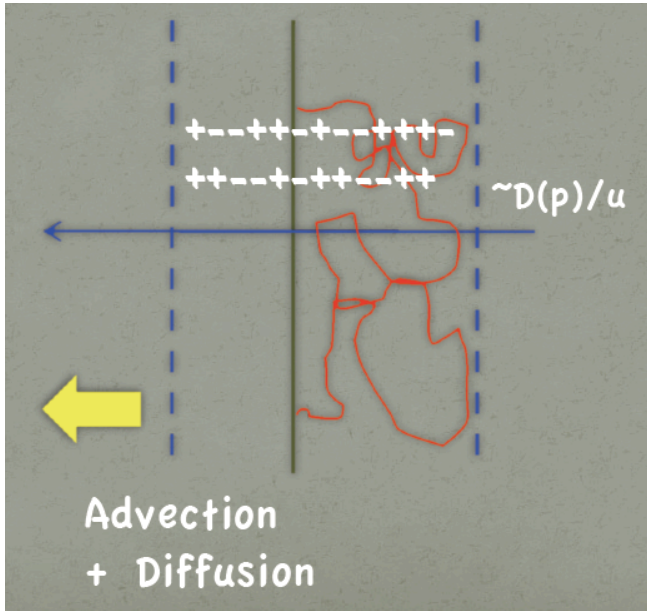
Blasi, arXiv:0903.2794

… assuming the sources of galactic cosmic rays are SNR, the PAMELA positron fraction can be well fitted

This is a generic feature of any *stochastic* acceleration process, if

$$\tau_{acc} > \tau_{1\to 2}$$ (Cowsik 1979, Eichler 1979)



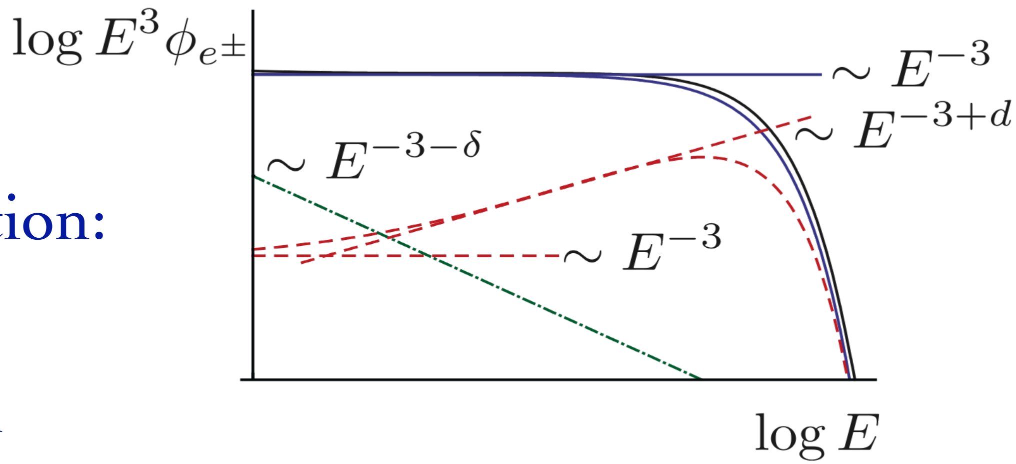


Acceleration of secondary $e^{\pm}$

Blasi, arXiv:0903.2794

Total electron + positron flux:

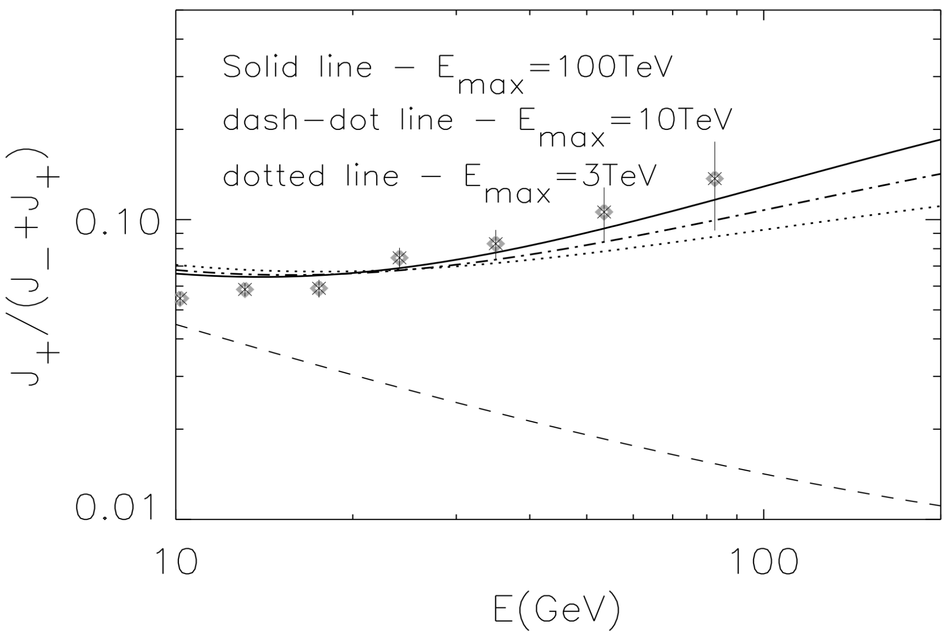
- primary electrons: $\sim E^{-3}$
- secondary $e^{\pm}$ from propagation: $\sim E^{-3-\delta}$
- secondary $e^{\pm}$, accelerated in source: $\sim E^{-\delta} + E^{d}$



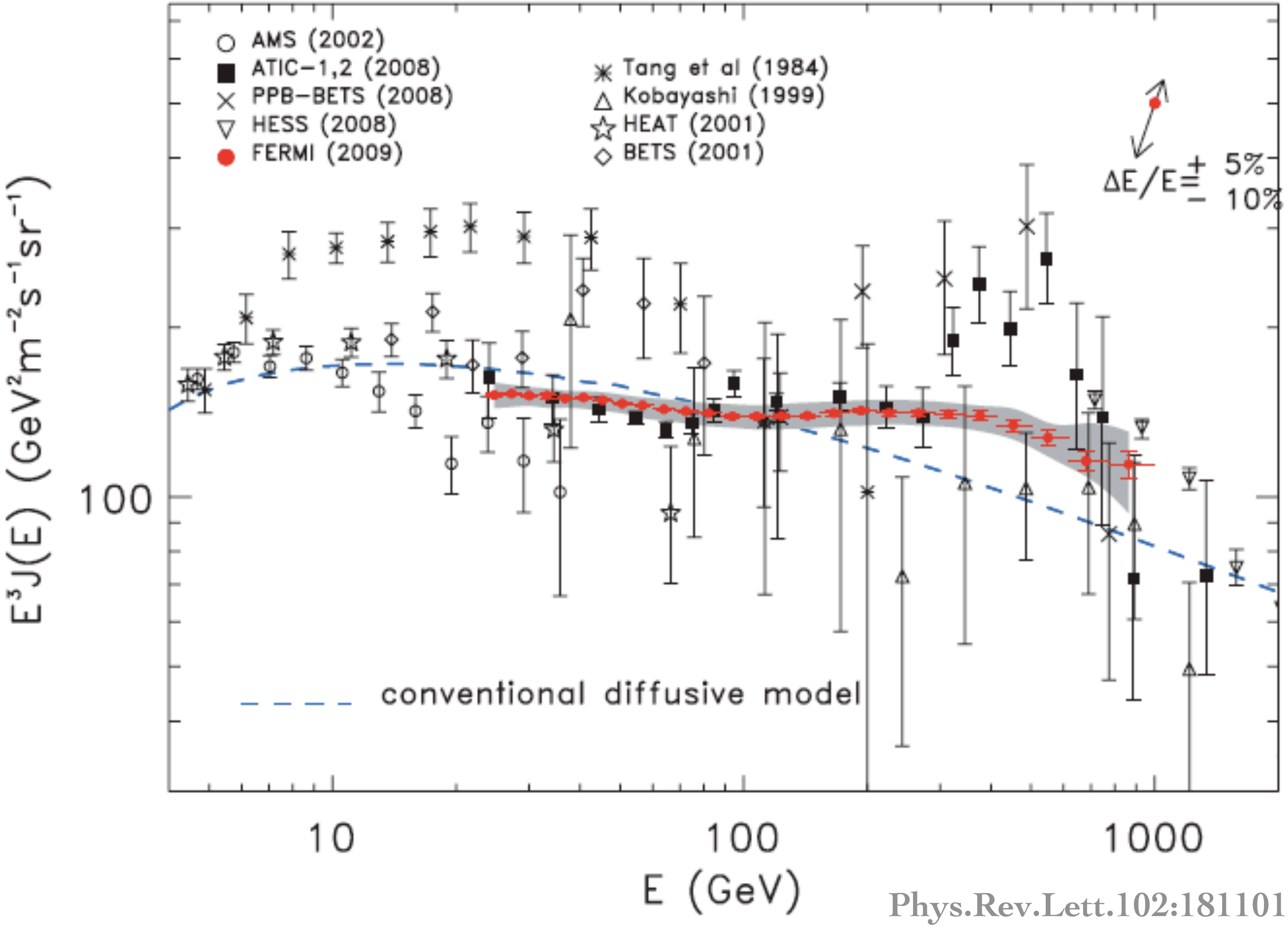
Positron ratio:

$$\frac{\phi_{e+}}{\phi_{e+} + \phi_{e-}} \simeq \frac{\phi_{e+}}{\phi_{e-}}$$

$$\sim \frac{E^{-3-\delta} + E^{-3+d}}{E^{-3}} \sim E^{-\delta} + E^{d}$$



Electron spectrum consistent with FERMI LAT data …



Phys.Rev.Lett.102:181101,2009

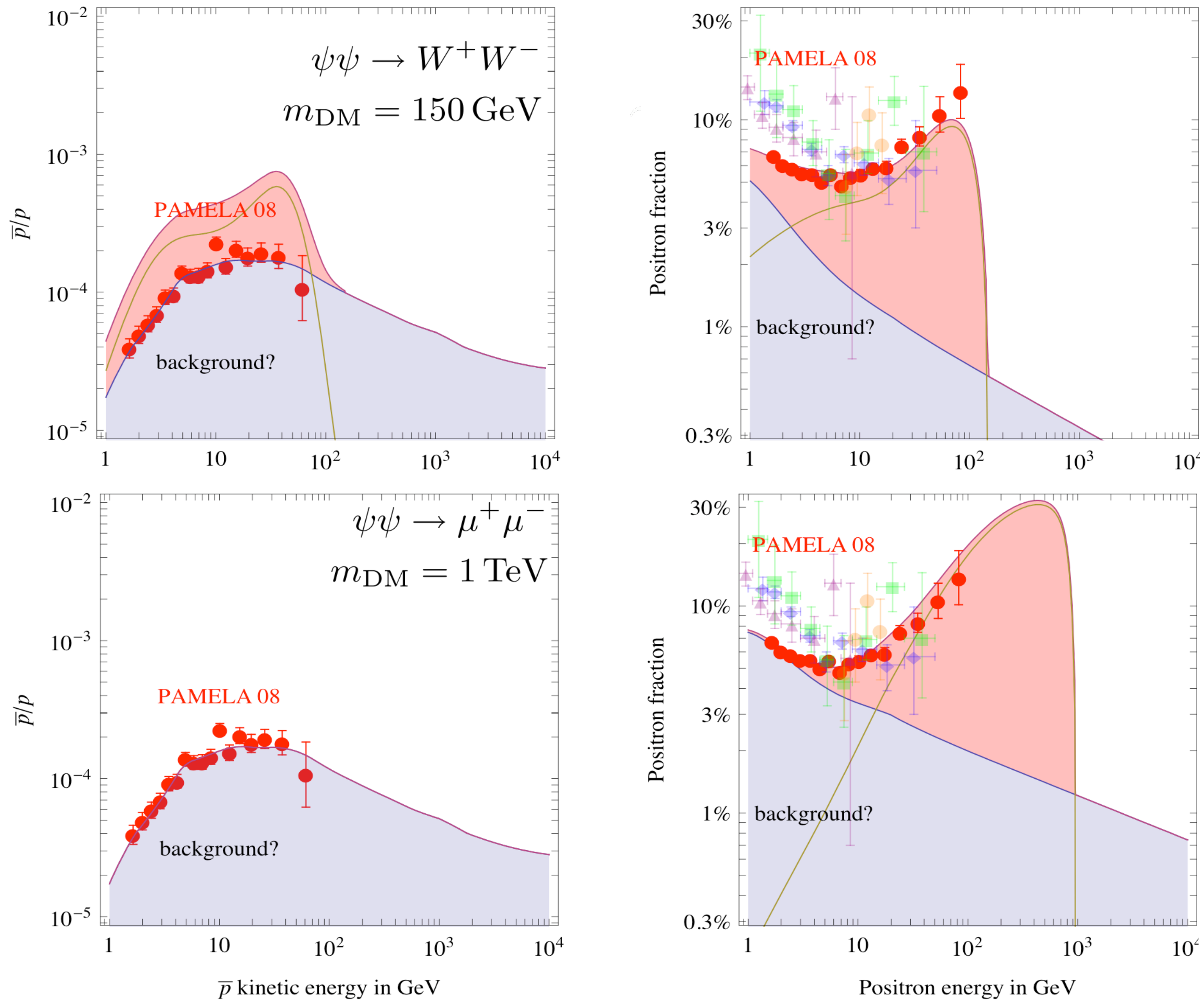
Explanations for PAMELA excess

	e^+/e^-		
DM	✓		
Pulsars	✓		
Acceleration of Secondaries	✓		

Antiproton-to-proton Ratio

Cirelli *et al.*, Nucl.Phys.B813:1,2009

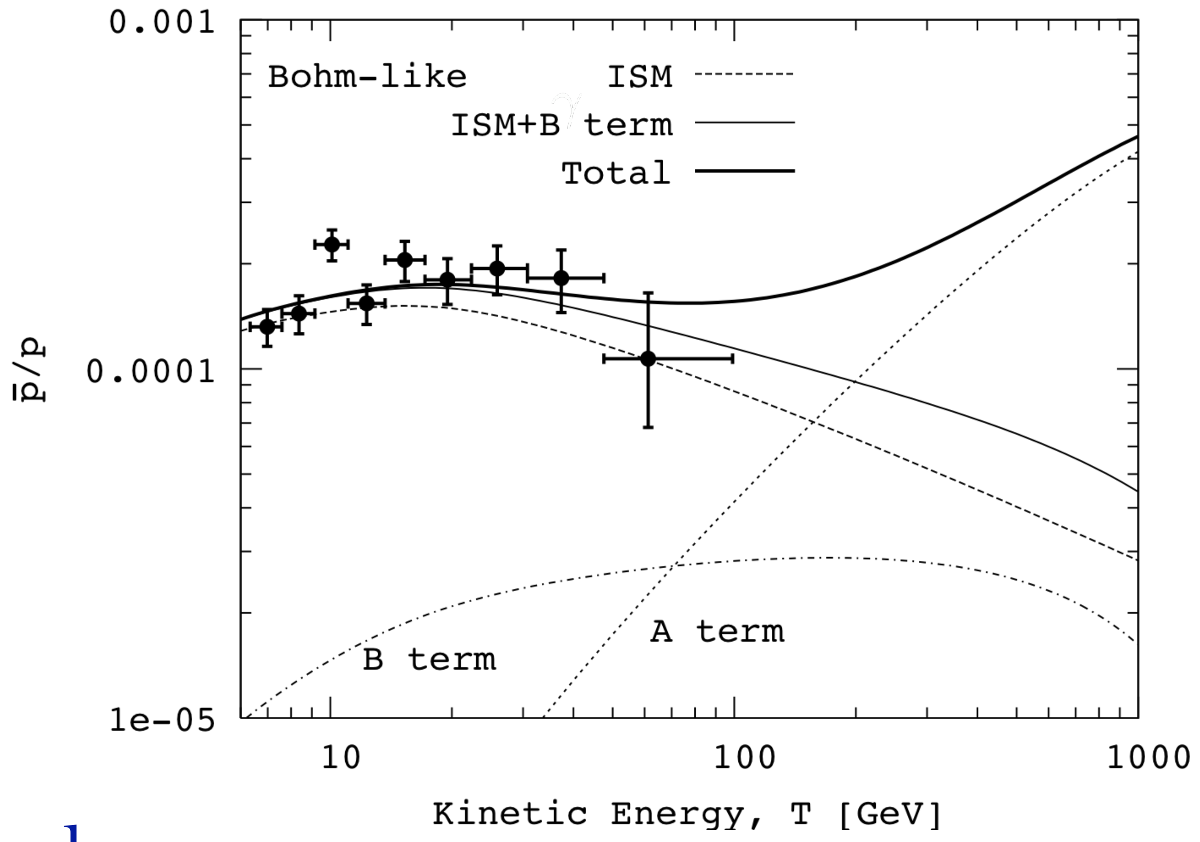
	$\bar{p}/p$
DM	(✓)
Pulsars	✗



… can fit by tuning DM parameters appropriately

Antiproton-to-proton ratio

	$\bar{p}/p$
DM	(✓)
Pulsars	✗
Acceleration of Secondaries	✓



… more *natural* in secondary acceleration model – predicts rise beyond 100 GeV (AMS?)

Blasi & Serpico, arXiv0904.0871

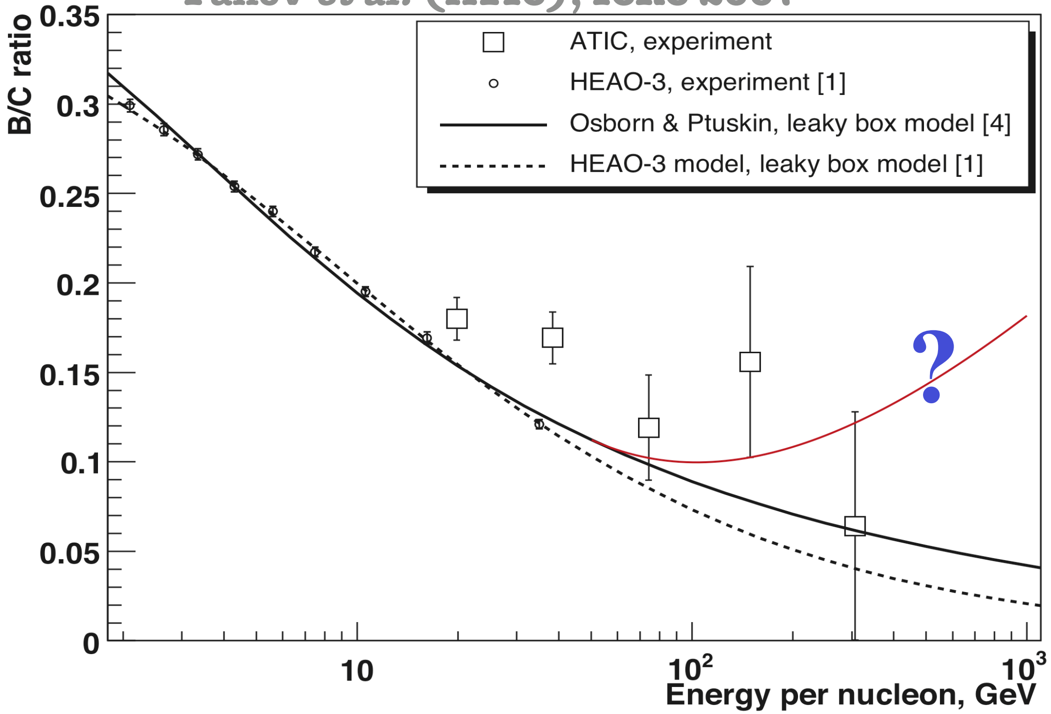
Nuclear secondary-to-primary Ratios

	nuclei
DM	✗
Pulsars	✗
Acceleration of Secondaries	✓

If we see this, it would rule out both the dark matter and pulsar models!

If nuclei are accelerated in the same sources as electrons and positrons, nuclear ratios must also *rise* …

Panov *et al.* (ATIC), ICRC 2007



Can solve problem analytically (no need for numerical code!)

Mertsch & Sarkar, arXiv:0905.3152

- Transport equation

$$u\frac{\partial f_i}{\partial x} = D_i \frac{\partial^2 f_i}{\partial x^2} + \frac{1}{3}\frac{du}{dx} p \frac{\partial f_i}{\partial p} - \Gamma_i f_i + q_i$$

with boundary condition $f_i(x,p) \xrightarrow{x\to-\infty} Y_i \delta(p-p_0)$

- Solution:

$$f_i^+ = f_i^0 + \frac{q_i^+(x=0) - \Gamma_i^+ f_i^0}{u_+} x$$

where

$$\begin{aligned} f_i^0(p) &= \int_0^p \frac{\mathrm{d}p'}{p'} \left(\frac{p'}{p}\right)^\gamma \mathrm{e}^{-\gamma(1+r^2)(D_i^-(p)-D_i^-(p'))\Gamma_i^-/u_-^2} \\ &\quad \times \gamma \frac{D_i^-(p')}{u_-^2} \left[(1+r^2) q_i^-(x=0) + \Gamma_i^- Y_i \delta(p'-p_0)\right] \end{aligned}$$

$$\sim \text{“}q_i^-(p) + D_i^-(p) q_i^-(p)\text{”}$$

Diffusion near shock front

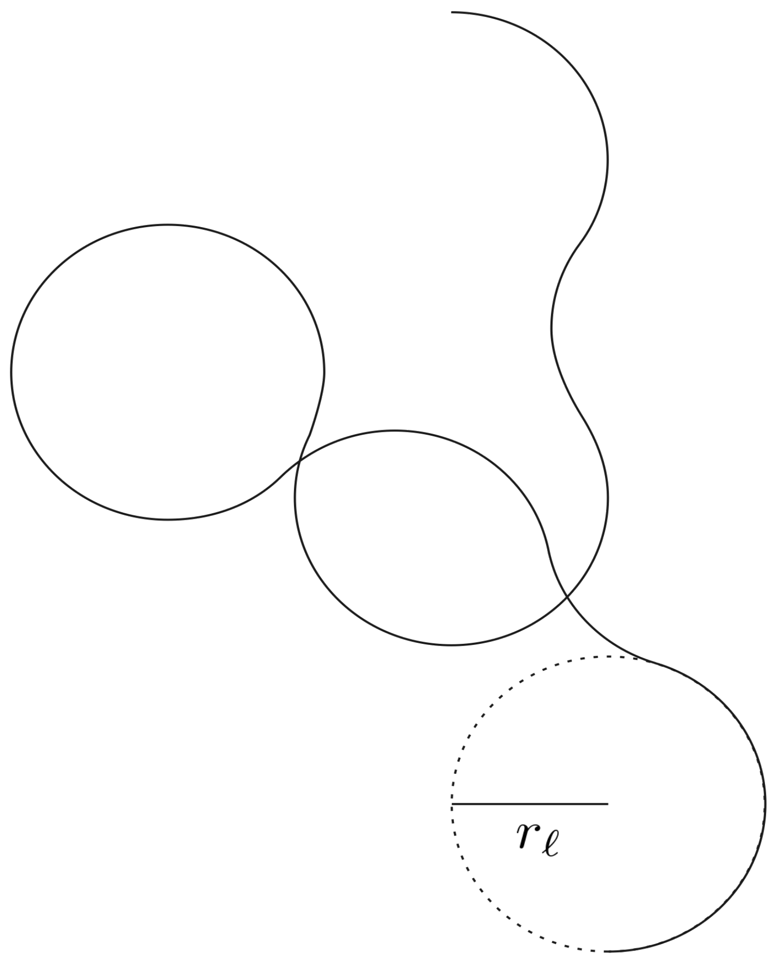
- Diffusion coefficient not known *a priori*
- Bohm diffusion sets *lower* limit

$$D^{\mathrm{Bohm}} = r_\ell \frac{c}{3} \propto \frac{E}{Z}$$

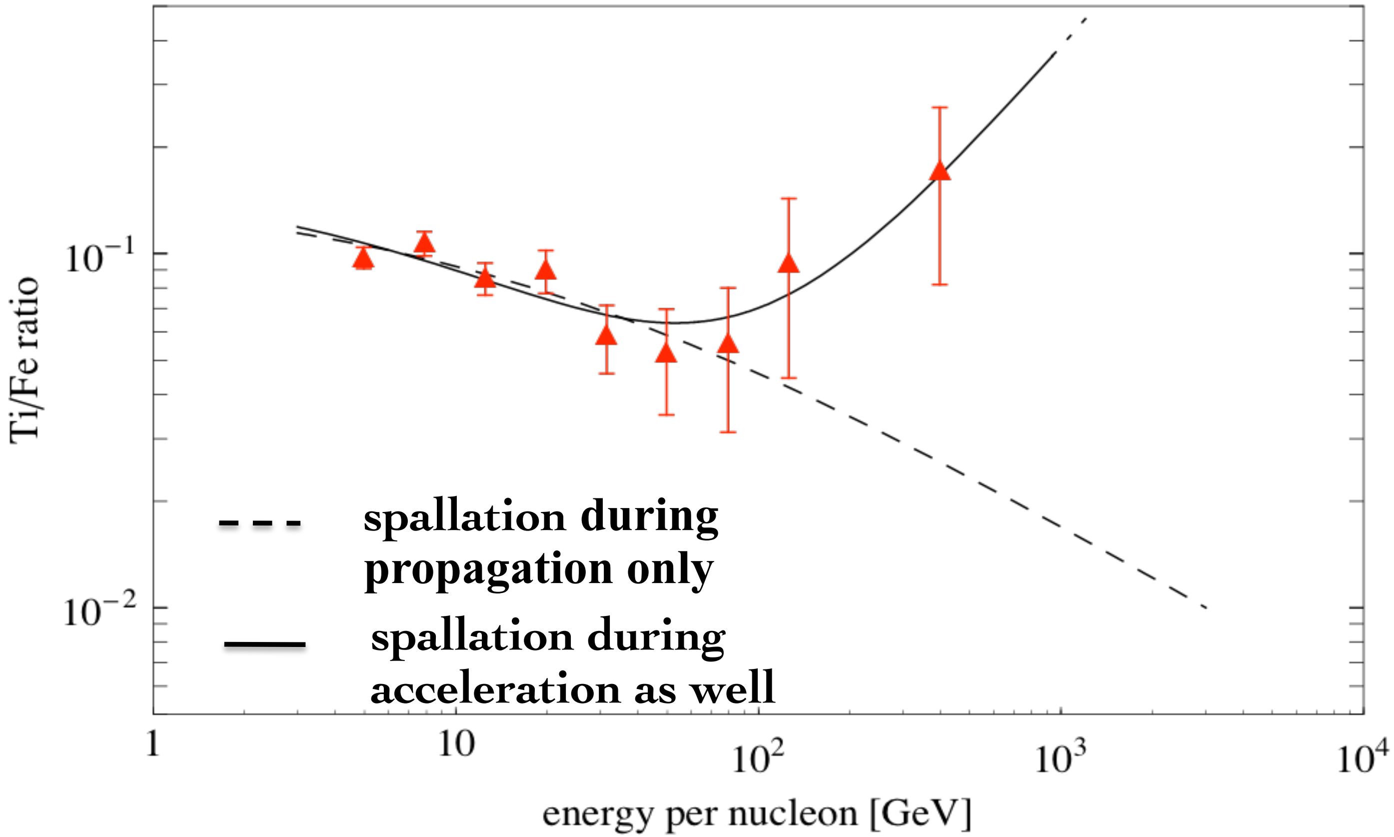
- Difference parametrised by fudge factor $\mathcal{F}^{-1}$

$$D = D^{\mathrm{Bohm}} \mathcal{F}^{-1}$$

- $\mathcal{F}^{-1}$ determined by fitting to one ratio … allows prediction to be made for other ratios



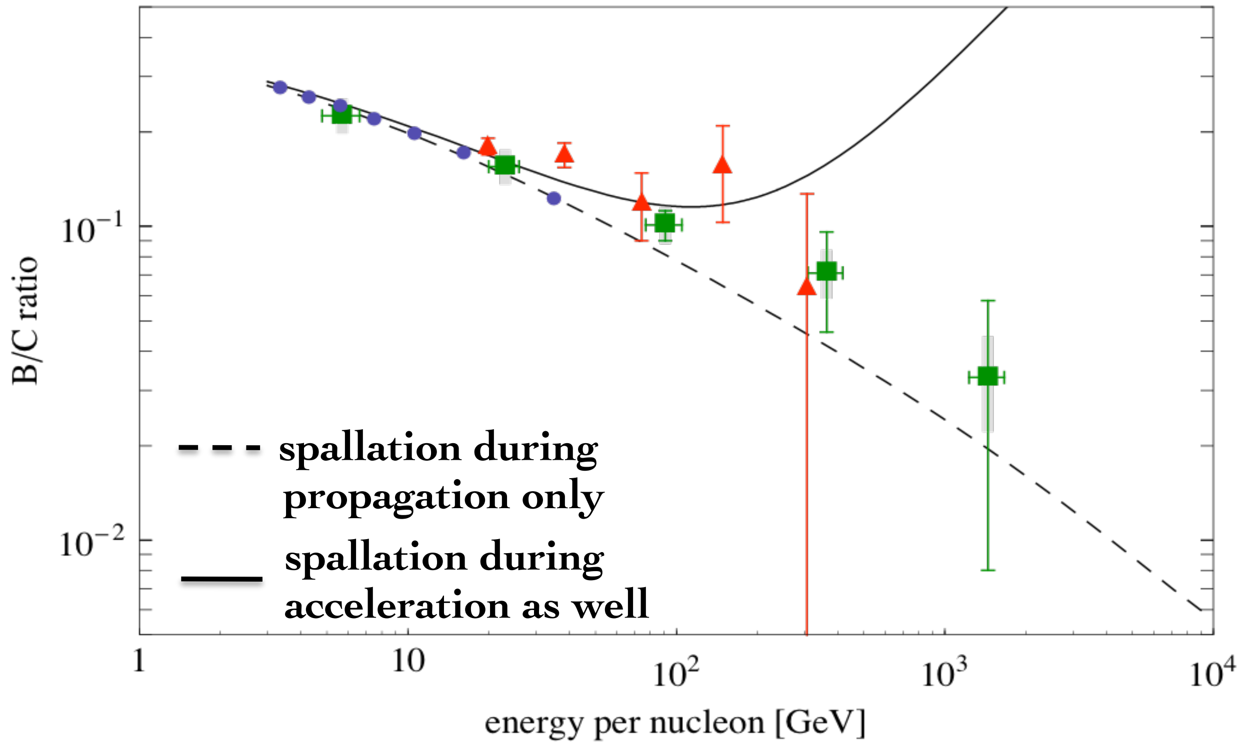
Titanium-to-Iron Ratio



Titanium-to-iron ratio used to fix diffusion coefficient to be $\mathcal{F}^{-1} \simeq 40$ (NB: this is ~the same value that fits the e^+ excess

Mertsch & Sarkar, arXiv:0905.3152

Boron-to-Carbon Ratio



● **HEAO-3**
Engelmann *et al.*,
A&A 233:96,1990

▲ **ATIC-2**
Panov *et al.*, ICRC 2007

■ **CREAM**
Ahn *et al.*,
Astropart.Phys.
30:133,2008

PAMELA is currently measuring B/C with unprecedented accuracy
A rise would *rule out* the DM and pulsar explanation of the e^+ excess

Mertsch & Sarkar, arXiv:0905.3152

Explanations for PAMELA Excess

	e^+/e^-	$\bar{p}/p$	nuclei
DM	✓	✓	✗
Pulsars	✓	✗	✗
Acceleration of Secondaries	✓	✓	✓

The high energy frontier

The LHC will soon achieve 14 TeV cms …

But 1 EeV (= 10^{18} eV) cosmic ray initiating giant air shower
$\Rightarrow$ 50 TeV cms (rate ~ 10/day in 3000 km^2 array)

New physics would be hard to see in hadron-initiated showers

(#-secn TeV^{-2} vs GeV^{-2})

… but may have a dramatic impact on *neutrino* interactions

$\rightarrow$ can probe new physics both **in and beyond the Standard Model** by observing **ultra-high energy cosmic neutrinos**

Where there are high energy cosmic rays, there *must* also be high energy neutrinos …

GZK interactions of extragalactic UHECRs on the CMB

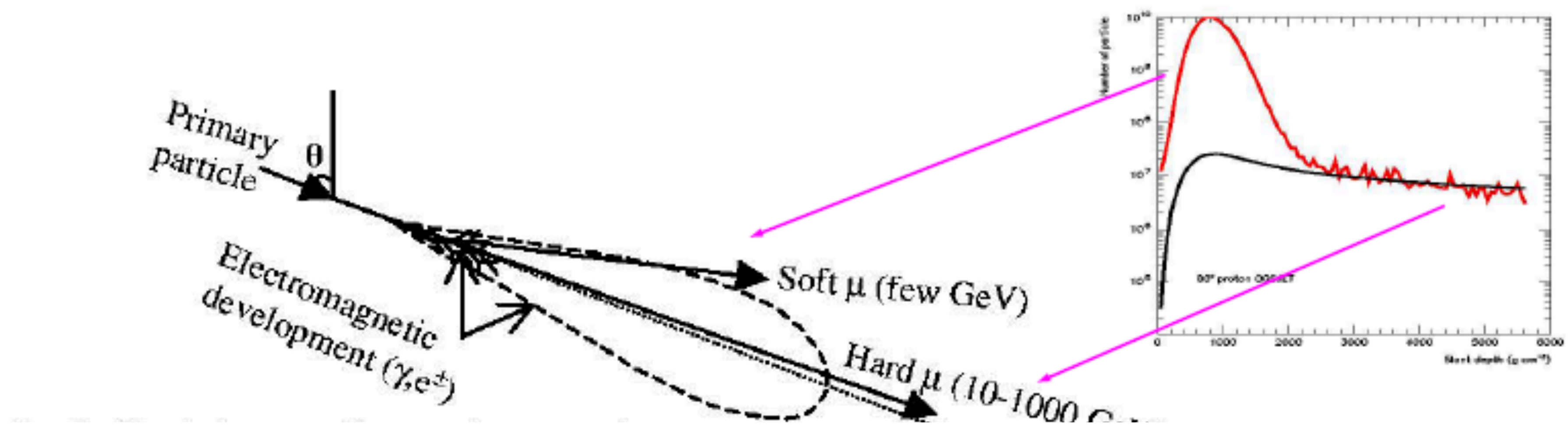
("guaranteed" cosmogenic neutrino flux … but may be altered significantly if the primaries are heavy nuclei rather than protons)

UHECR candidate accelerators (γ-ray bursts, active galactic nuclei, micro-quasars, …)

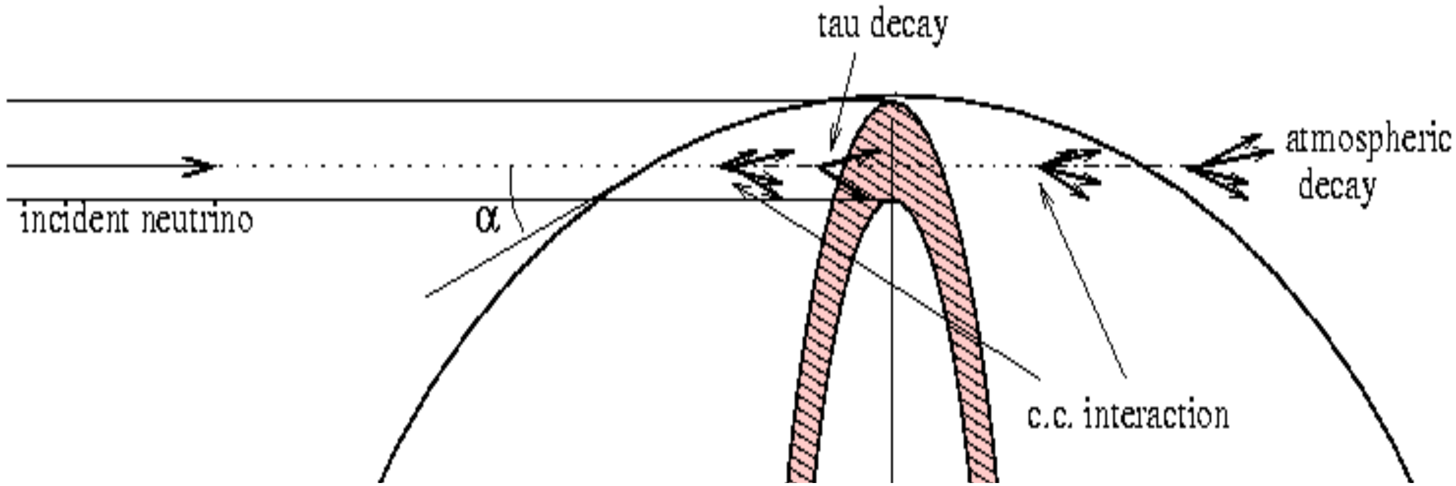
("Waxman-Bahcall flux" - normalised to extragalactic UHECR flux … sensitive to galactic-extragalactic 'cross-over' energy)

An unexpected bonus – neutrino detection with Auger surface array

Auger can see ultra-high energy neutrinos as inclined deeply penetrating showers
- Rate ∞ cosmic neutrino flux, ∞ ν-N #-secn

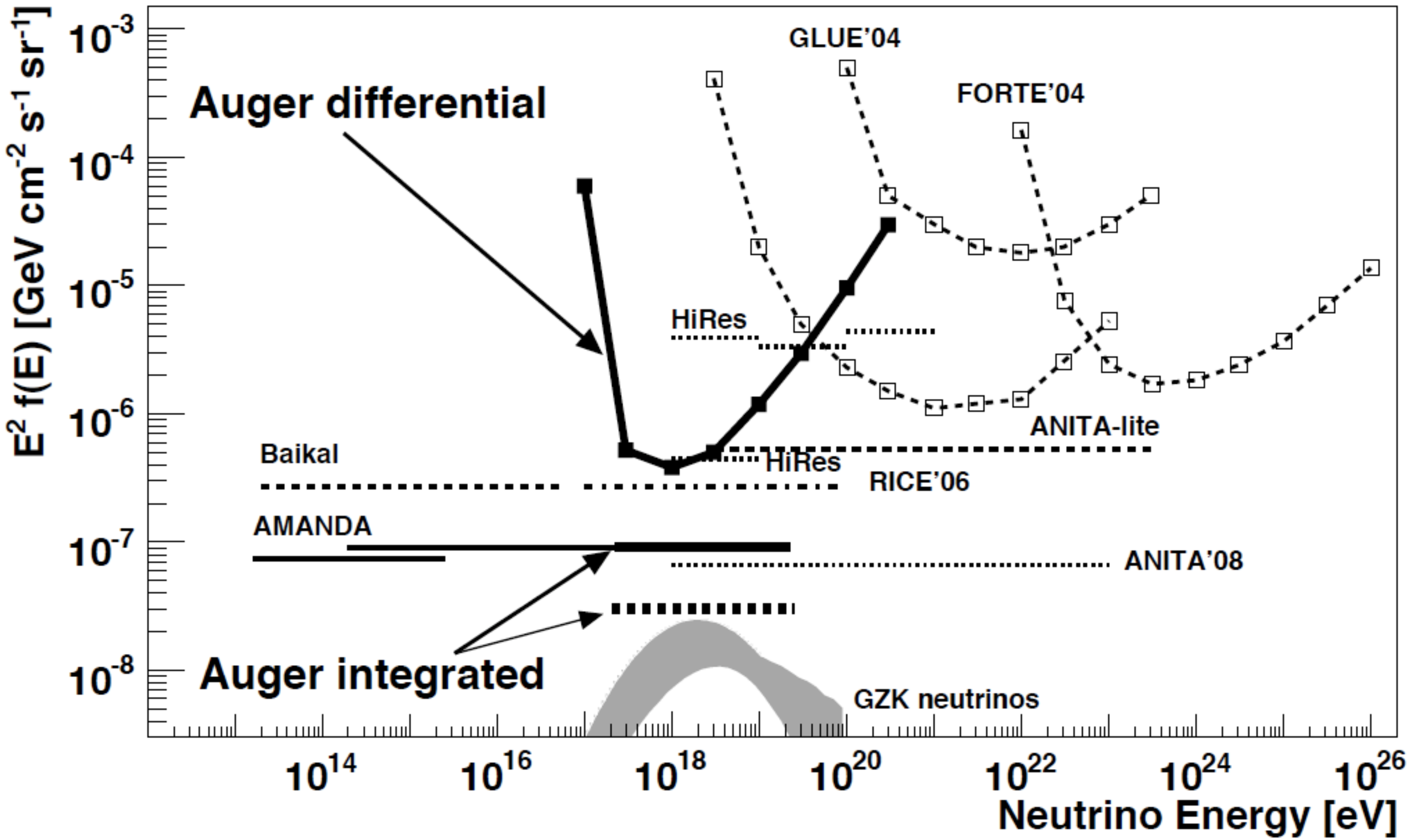


Auger can also see Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower -
- Rate ∞ cosmic ν flux, but ~independent of ν-N #-secn



No neutrino events yet … but getting close to "guaranteed" cosmogenic flux

PhysRevD79:102001,2009



(NB: To do this we have to know ν-N cross-section at ultrahigh energies)

ν-*N* deep inelastic scattering

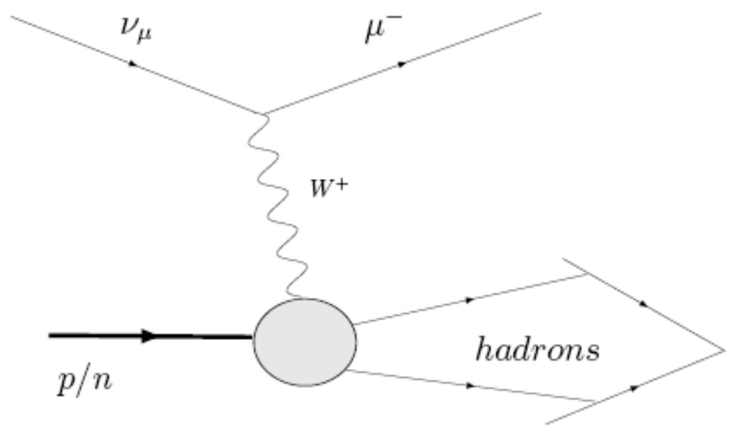
$$\frac{\partial^2 \sigma^{CC,NC}_{\nu,\bar\nu}}{\partial x \partial y} = \frac{G_F^2 M E}{\pi}\left(\frac{M_i^2}{Q^2+M_i^2}\right)$$

Q^2 ↑, propagator ↓

$$[\frac{1+(1-y)^2}{2} F_2^{CC,NC}(x,Q^2) - \frac{y^2}{2} F_L^{CC,NC}(x,Q^2)$$

$$\pm y\left(1-\frac{y}{2}\right) x F_3^{CC,NC}(x,Q^2)]$$

Q^2 ↑, parton distrib. fns ↓



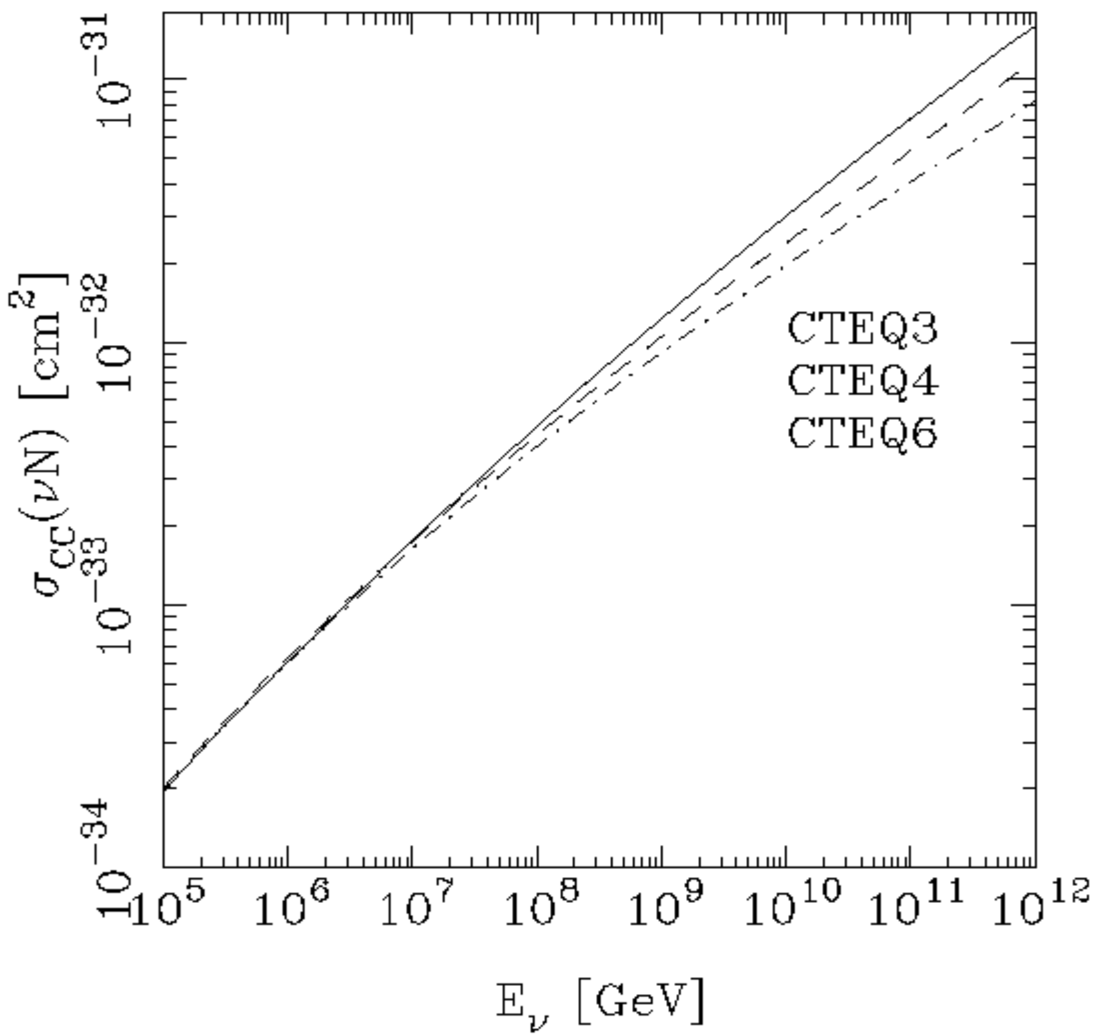
Most of the contribution to #-secn comes from: $Q^2 \sim M_W^2$ *and* $x \sim \dfrac{M_W^2}{M_N E_\nu}$

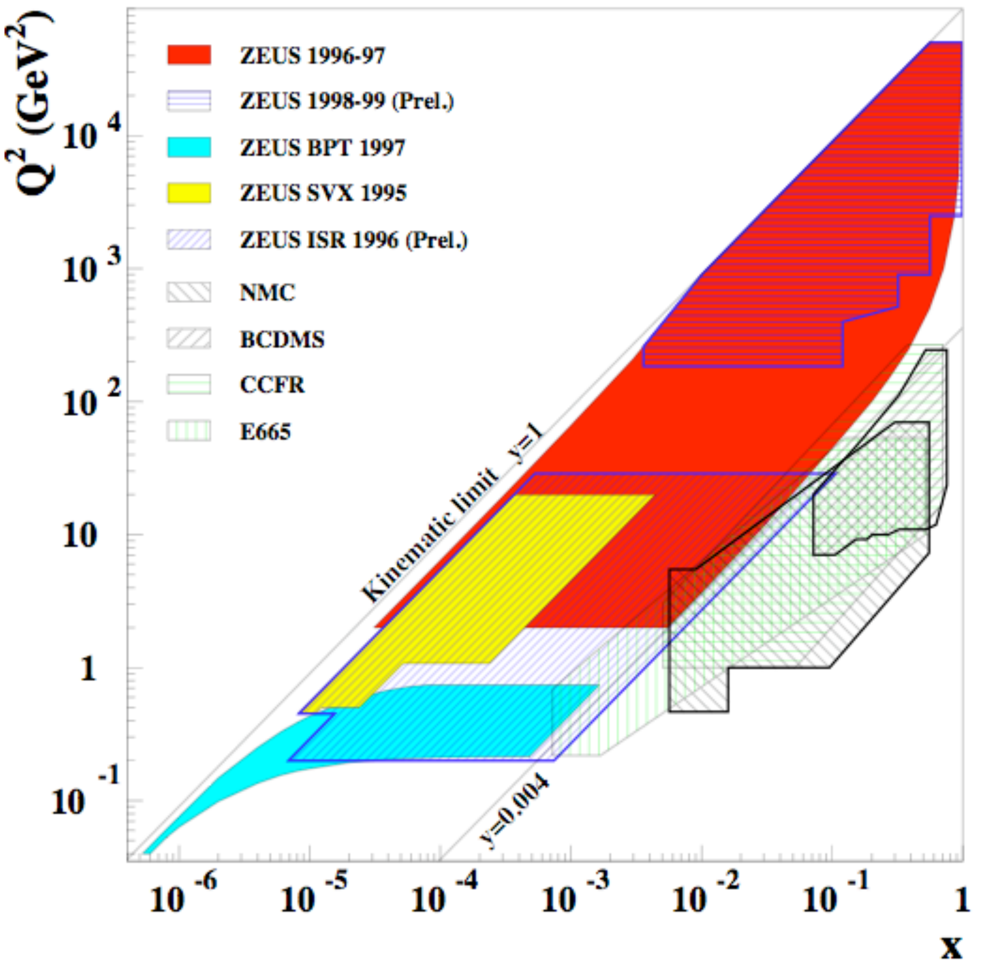
At leading order (LO) : $F_L = 0$, $\quad F_2 = x(u_v + d_v + 2s + 2b + \bar u + \bar d + 2\bar c)$,

$$xF_3 = x(u_v + d_v + 2s + 2b - \bar u - \bar d - 2\bar c) = x(u_v + d_v + 2s + 2b - 2\bar c)$$

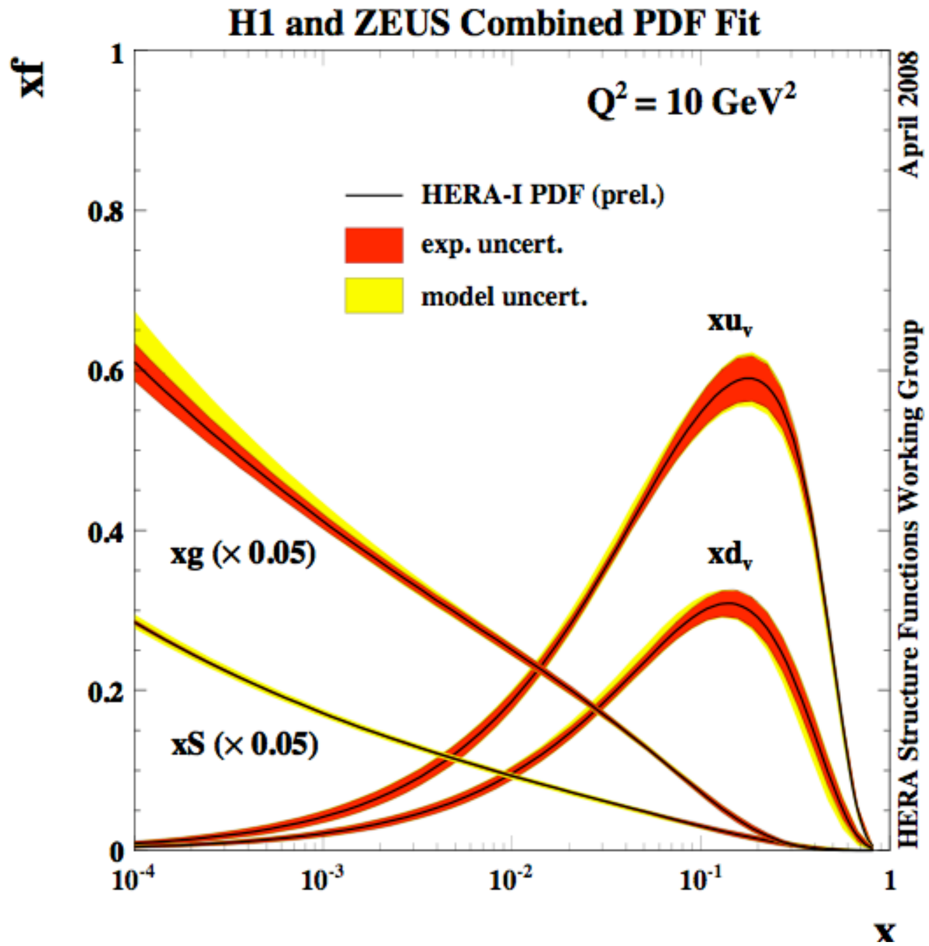
At NLO in α_s, it gets more complicated . . . but is still calculable

Many estimates have been made using available "off the shelf" parameterisations of PDFs by e.g. the CTEQ group … most are based on ***out-of-date data*** and have ***no estimates of uncertainties***



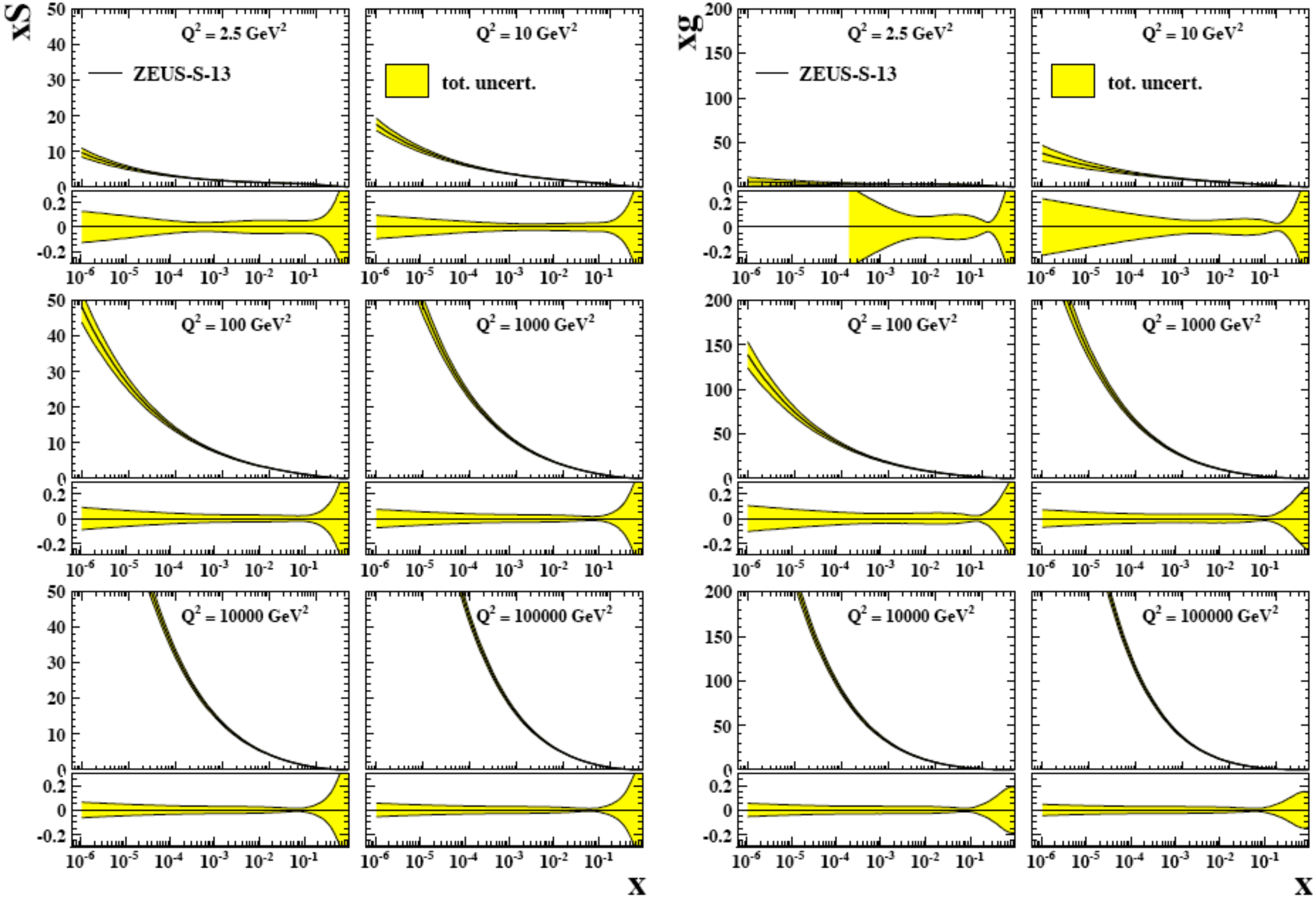


The H1 and ZEUS experiments at HERA have made great progress by probing a much deeper kinematic region



Most surprising result is the steep rise of the gluon structure function at low Bjorken x ➔ significant impact on ν DIS

Parton distribution functions from the ZEUS-S global data analysis

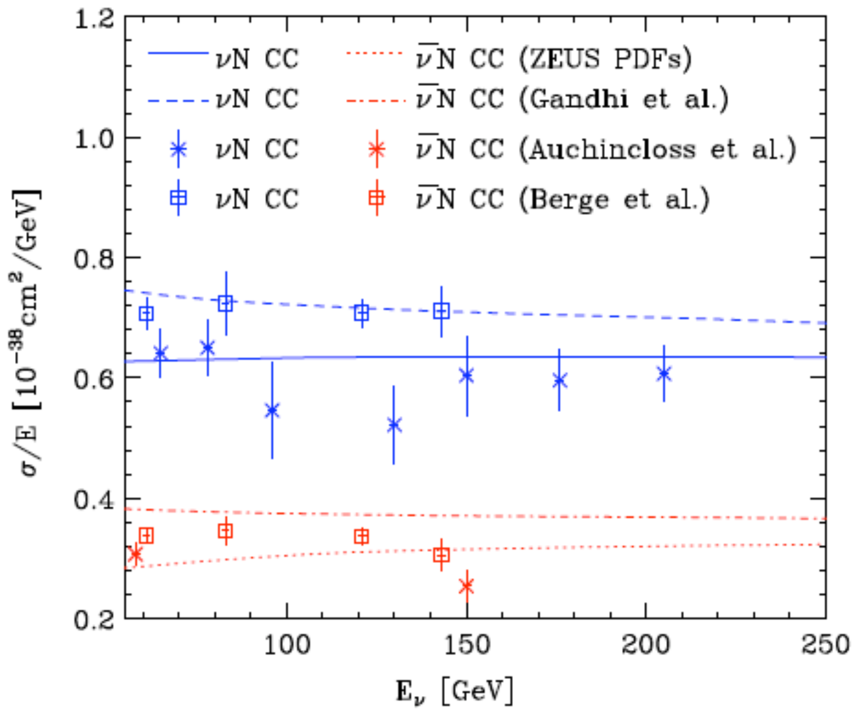


Cooper-Sarkar & Sarkar, JHEP01:075,2008

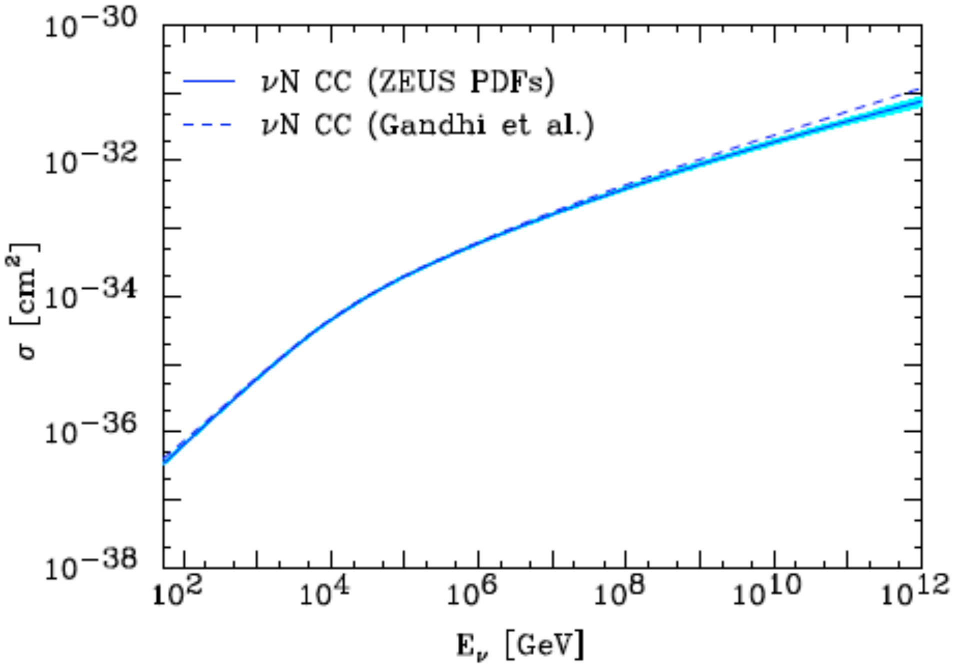
using DGLAP evolution of the PDFs (at NLO, incl. heavy quark corrections)

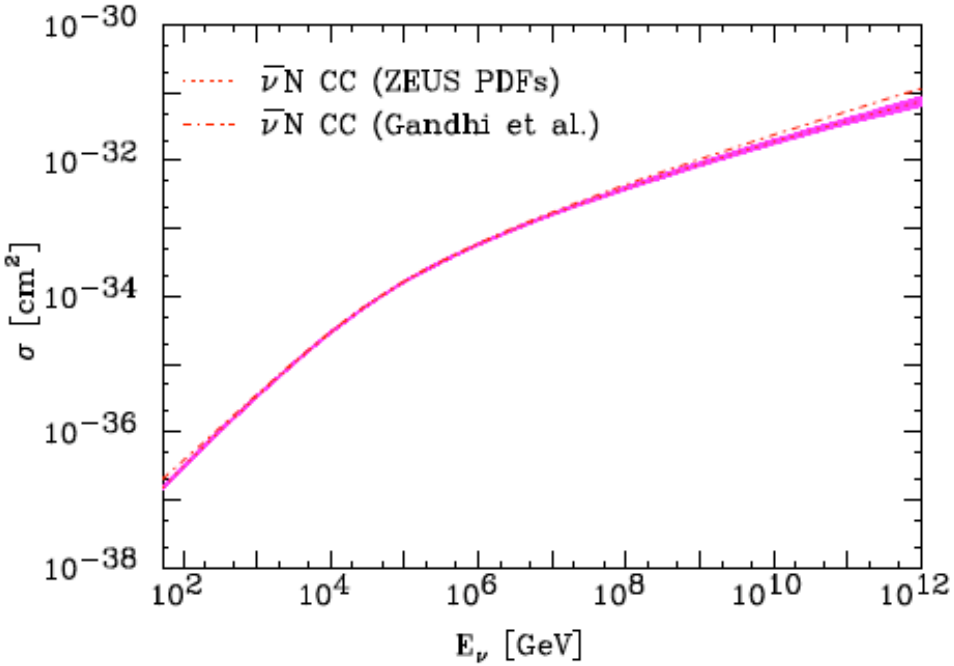
The #-section is up to ~40% *below* the previous 'standard' calculation by Gandhi *et al* (1996) … more importantly the (perturbative SM) *uncertainty* has now been determined

Cooper-Sarkar & Sarkar, JHEP 01:075,2008

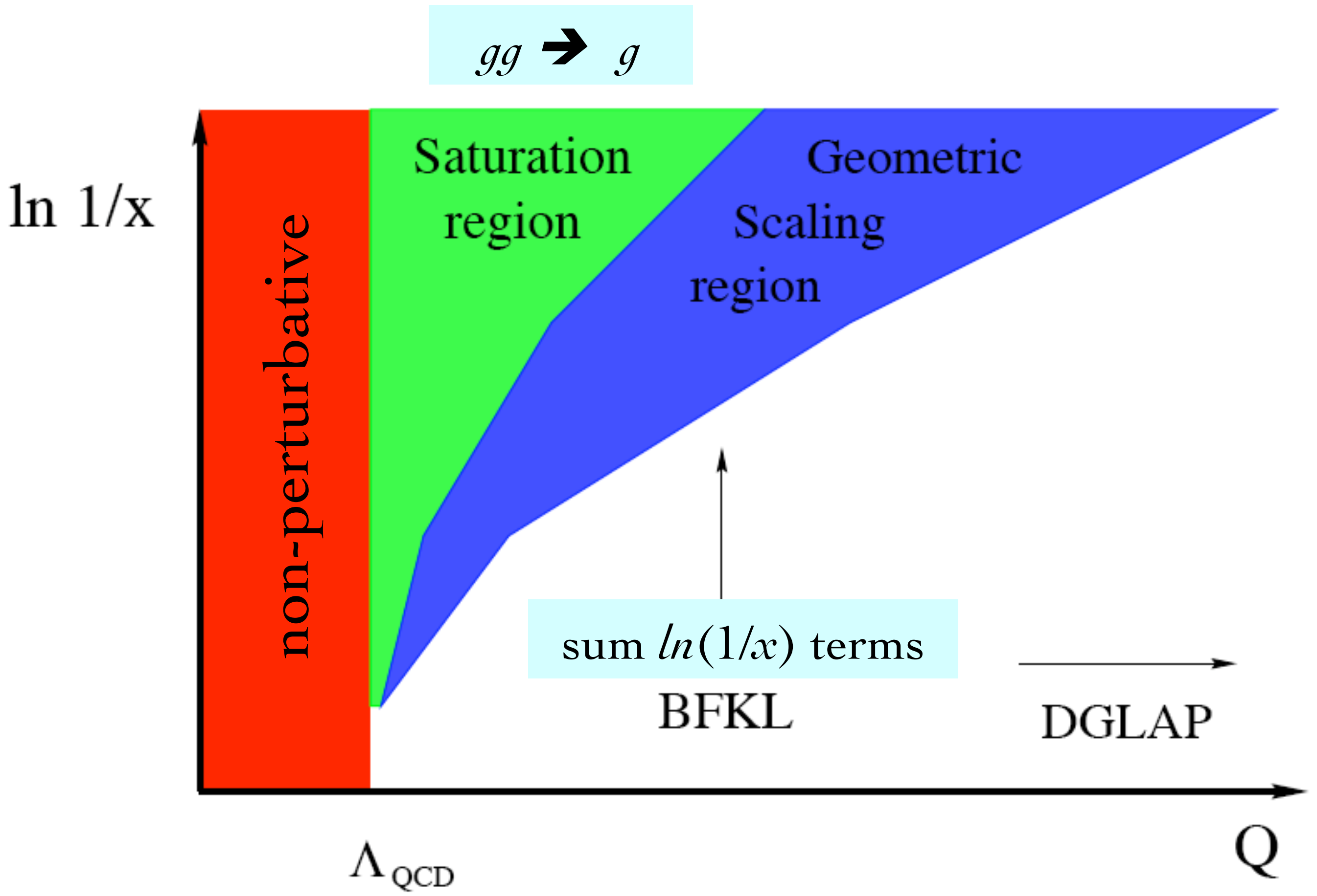


Being used by Auger and IceCube (to be incorporated in ANIS MC)



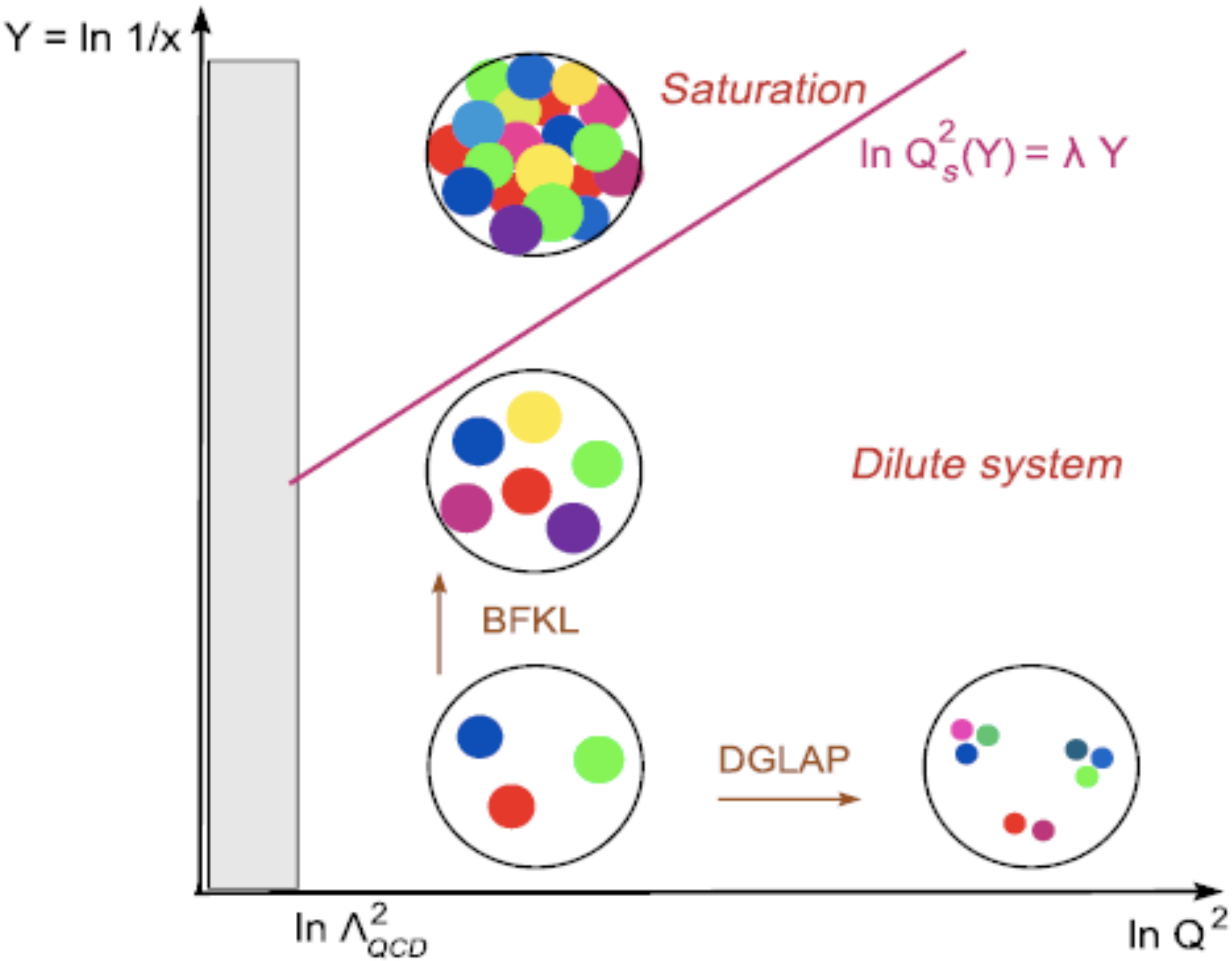


As the gluon density increases at low x, screening/ recombination effects become important
... a new phase - Colour Gluon Condensate - may form



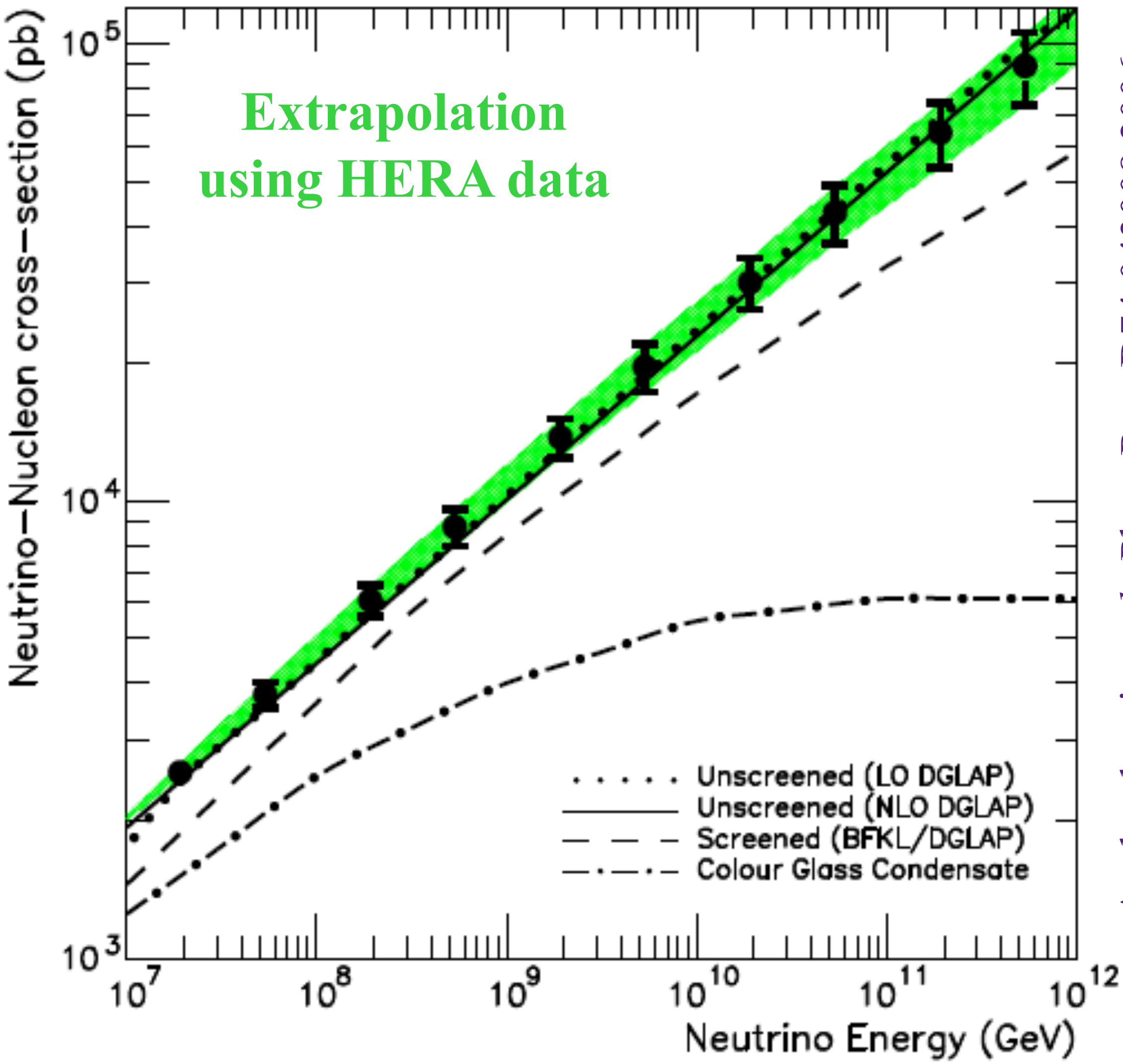
This would *suppress* the ν-*N* #-secn below its (unscreened) SM value

Very challenging theoretical area … and very active (mainly because of related physics of 'glasma' ➔ significant experimental developments at RHIC … soon LHC)



The steep rise of the gluon density at low-x *must* saturate (unitarity!)

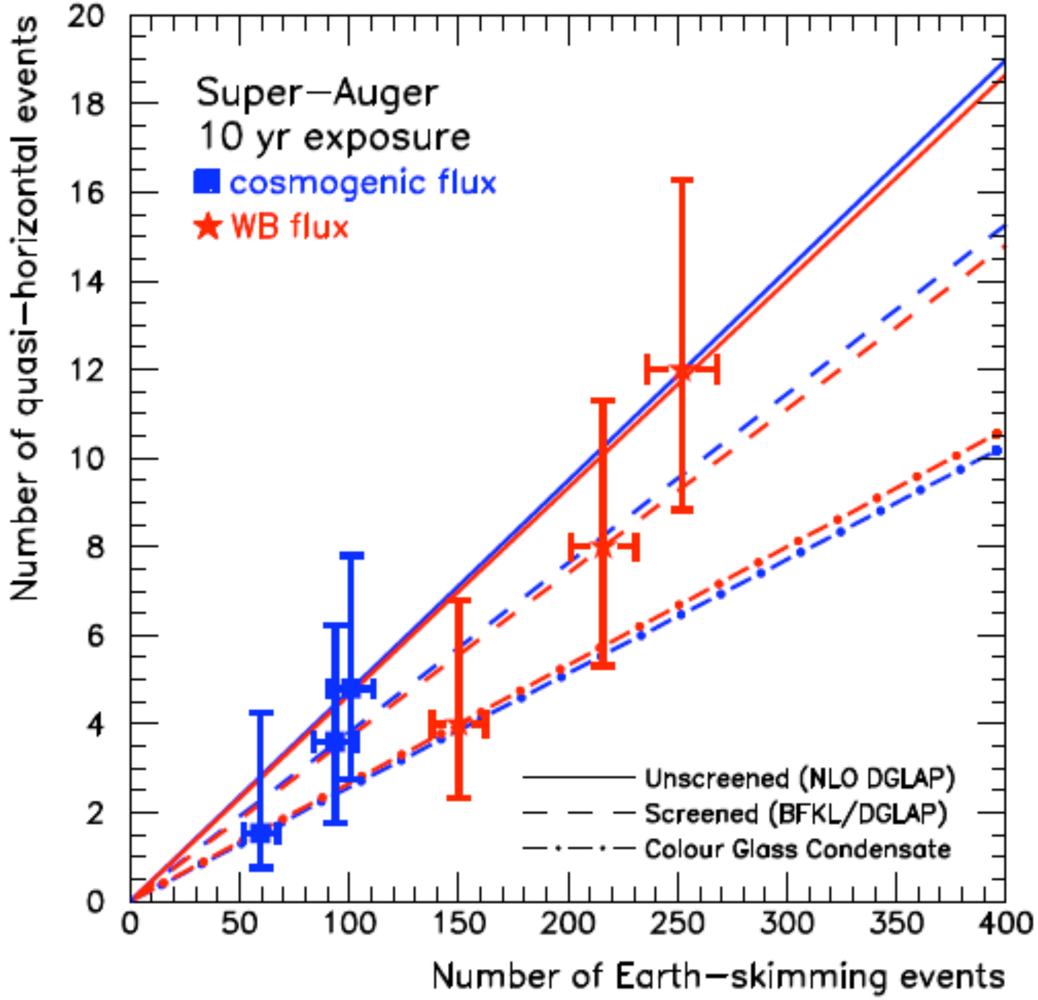
➔ **suppression of the ν-N cross-section at ultrahigh energies**



Anchordoqui, *et al.*, Phys. Rev. D74:043008,2006

Can we test these possibilities *experimentally* using cosmic neutrinos?

The ratio of quasi-horizontal (all flavour) and Earth-skimming (ν_τ) events *determines* the ν-N #-section (even when the primary flux is not well known!)



Anchordoqui, *et al.*, Phys. Rev. D74:043008,2006

… this will require however an exposure of ~10^6 Linsleys (km^2 sr yr)!

Can also be done with a ~10^2-10^3 km^3 "IceRay"

Summary

Astroparticle physics is enormously exciting but to make progress in answering old questions – e.g. the origin of cosmic rays – will require much better understanding of the relevant astrophysical issues

The reward for particle physicists who make the effort would be access to the high energy (but not high intensity!) frontier