Beyond Dark Matter Detection with Neutrino Telescopes

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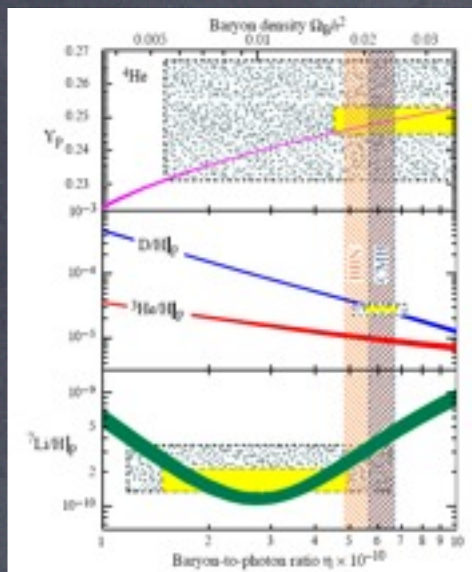
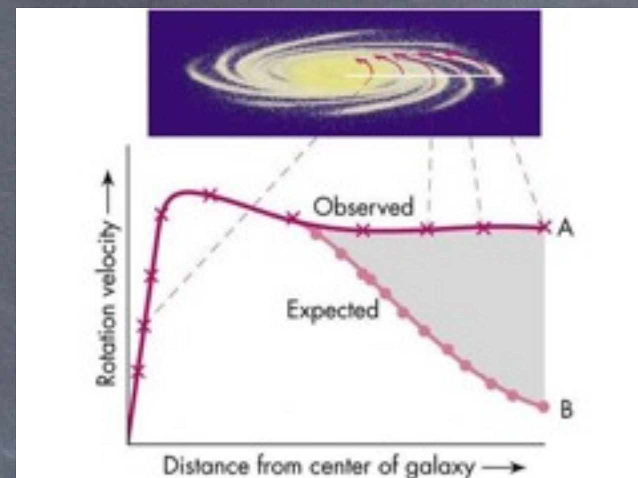
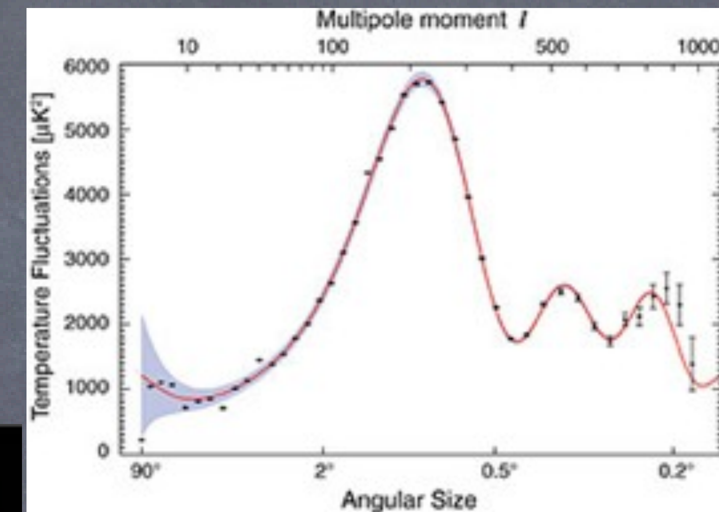
Bethe Forum
LHC, Dark Matter and Unification
Bonn, November 17, 2011

Astro/Cosmo Evidences of DM

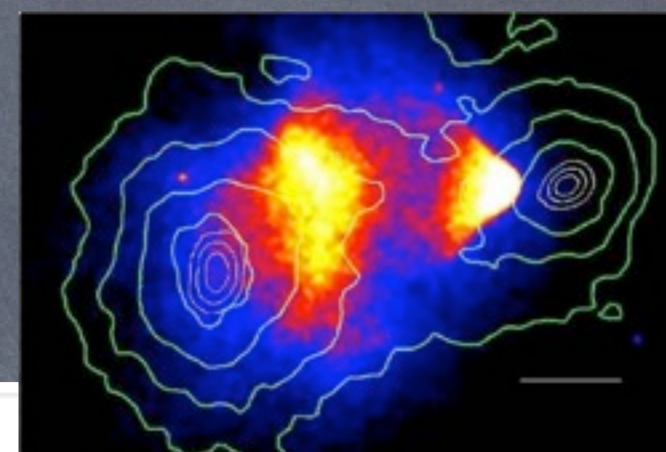


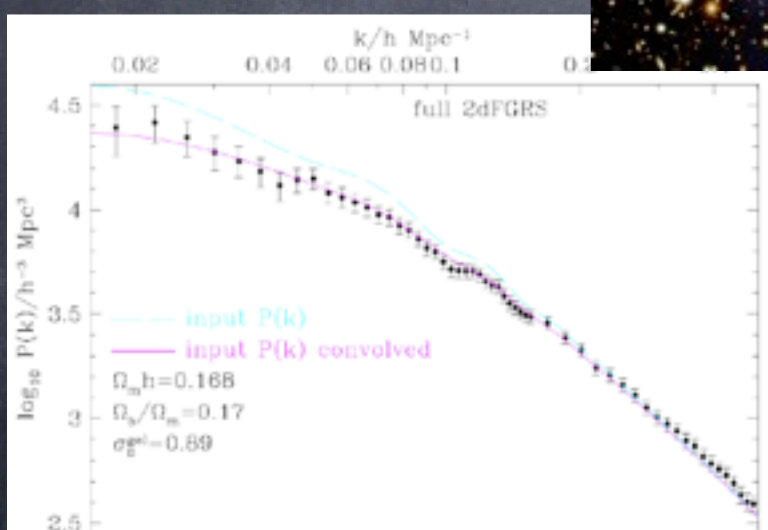
B. D. Fields and S. Sarkar, *PDG*



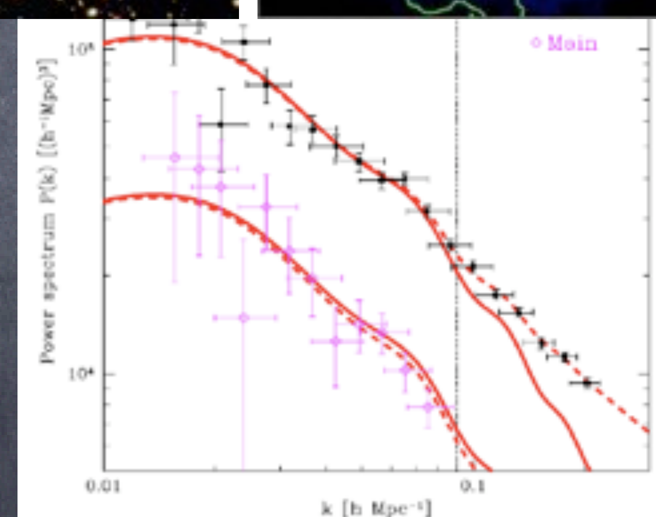


NASA/WMAP Science Team

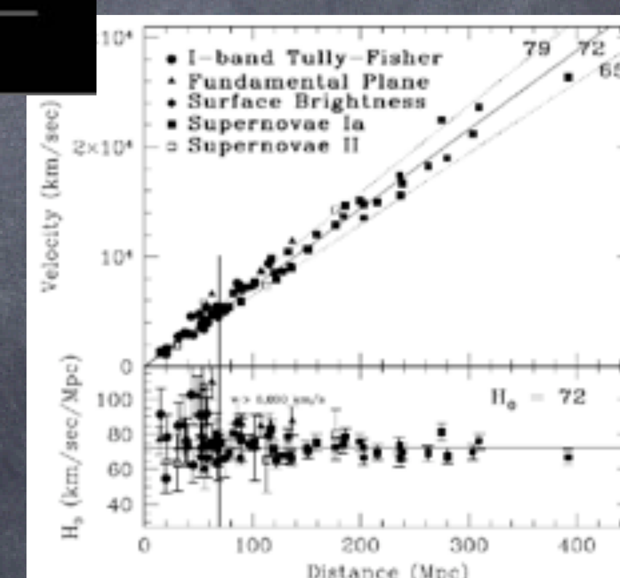




S. Cole *et al.* [2dFGRS Collaboration],
Mon. Not. Roy. Astron. Soc. 362:505, 2005

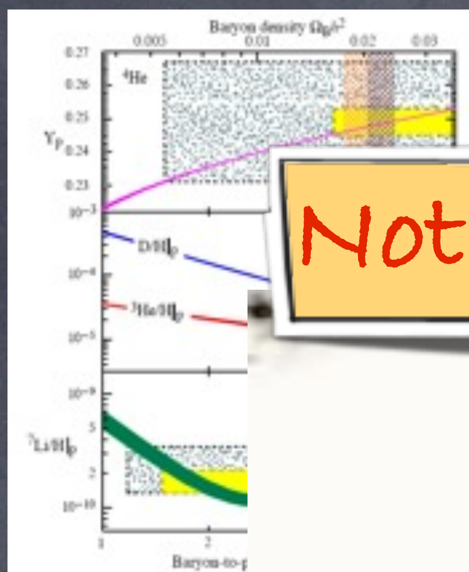


M. Tegmark *et al.* [SDSS Collaboration],
Phys. Rev. D74:123507, 2006



W. L. Freedman *et al.* [HST Collaboration],
Astrophys. J. 553:47, 2001

Astro/Cosmo Evidences of DM



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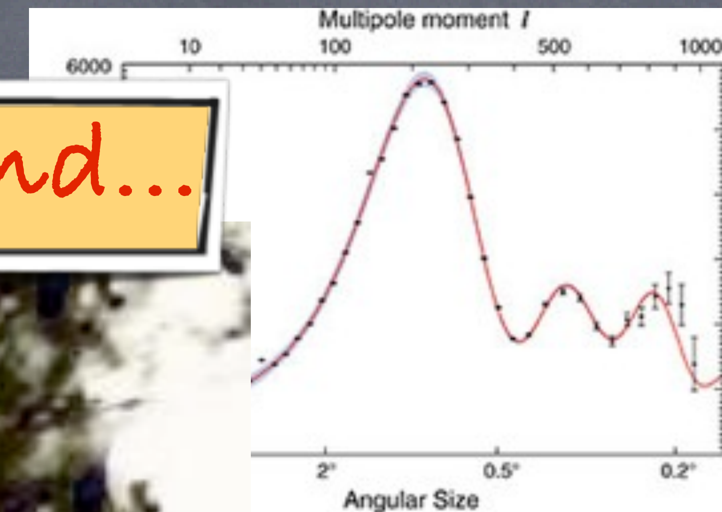
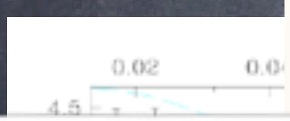
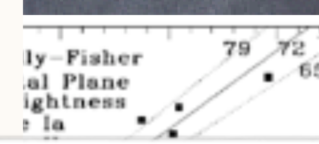


WMAP Science Team

Not the only Dark Matter around...



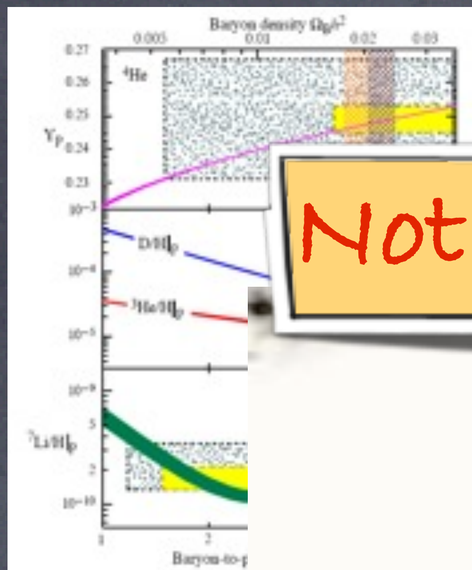


"The genomes of multicellular animals are big and complex, but functions have been defined for only a small proportion of them. Only 1% of the human genome is transcribed into protein-coding messenger RNA (mRNA) and non-protein-coding RNA (ncRNA), and DNA elements that control the expression of genes occupy another ~0.5%, suggesting that the remaining "dark genome" is nonfunctional padding."

M. Blaxter, "Revealing the Dark Matter of the Genome", Science 330, 1758, 2010

n],

Astro/Cosmo Evidences of DM



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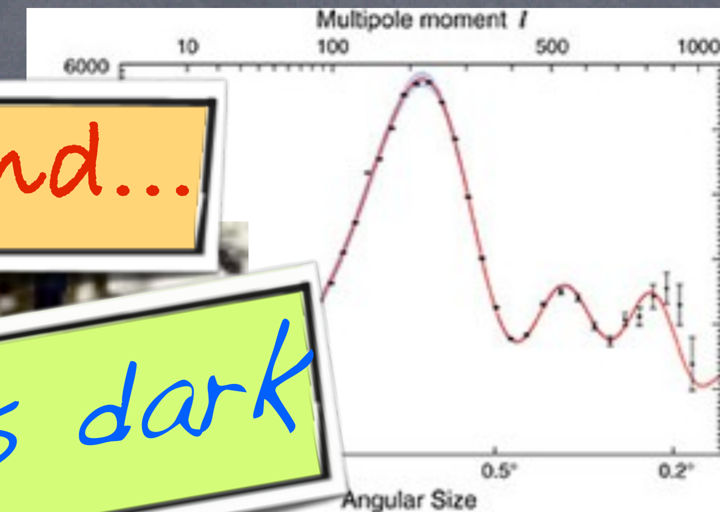
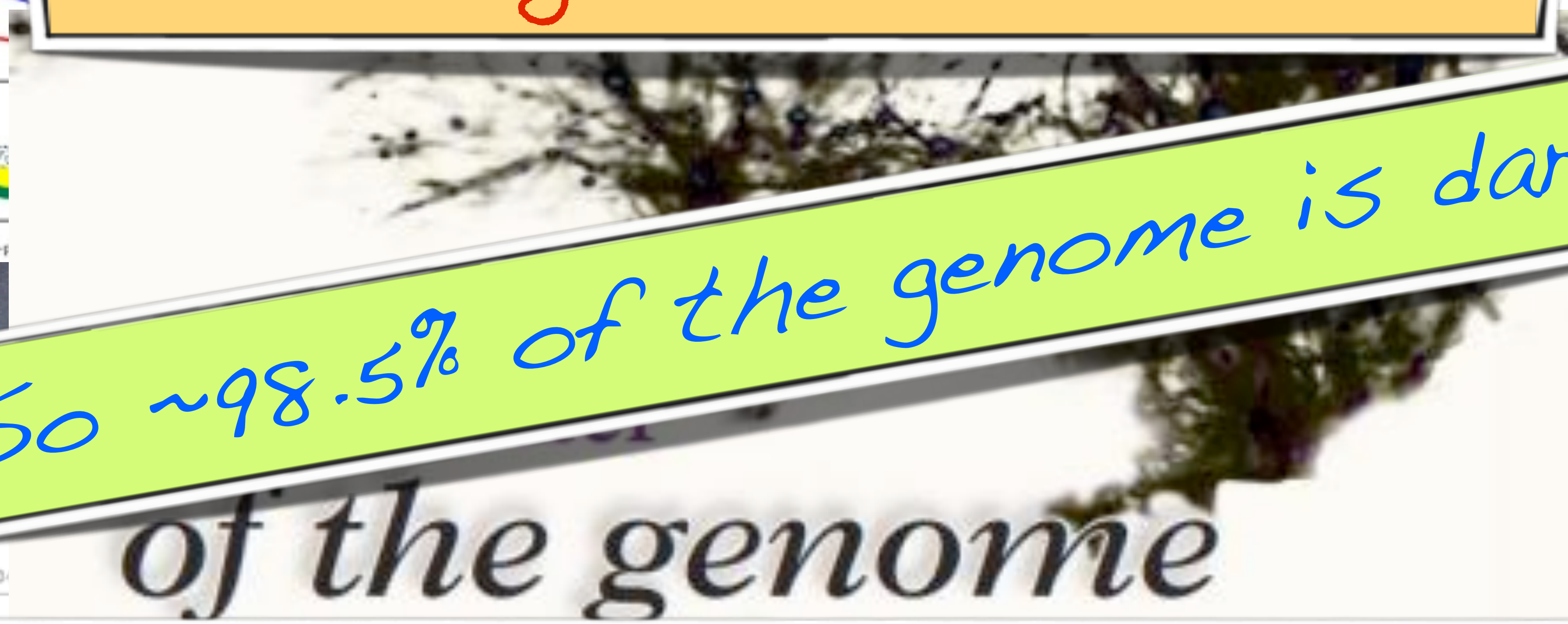
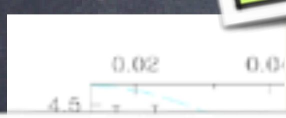
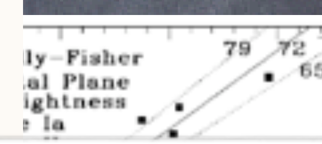


WMAP Science Team







Not the only Dark Matter around...

So ~98.5% of the genome is dark

"The genomes of multicellular animals are big and complex, but functions have been defined for only a small proportion of them. Only 1% of the human genome is transcribed into protein-coding messenger RNA (mRNA) and non-protein-coding RNA (ncRNA), and DNA elements that control the expression of genes occupy another ~0.5%, suggesting that the remaining "dark genome" is nonfunctional padding."

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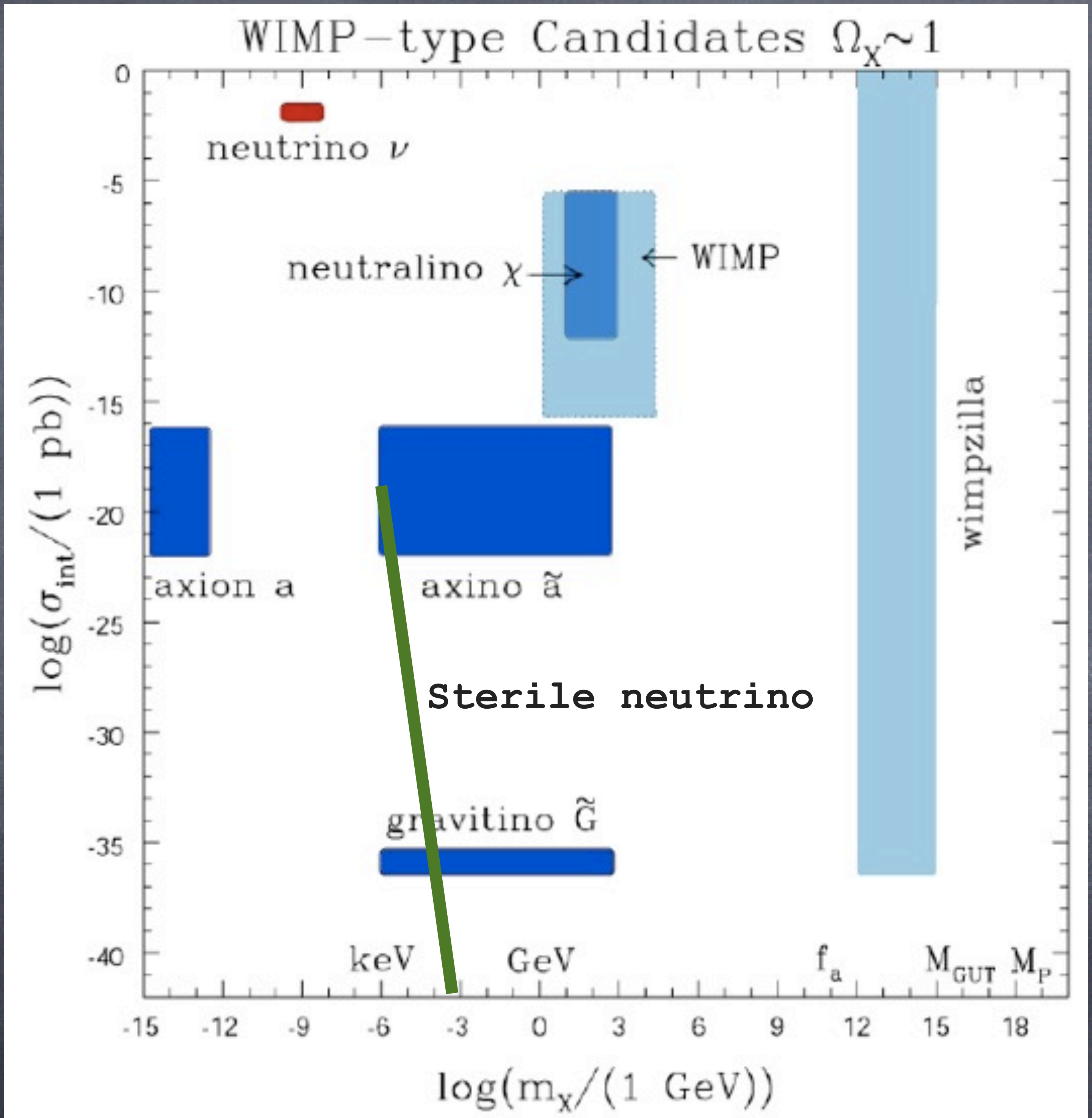
n],

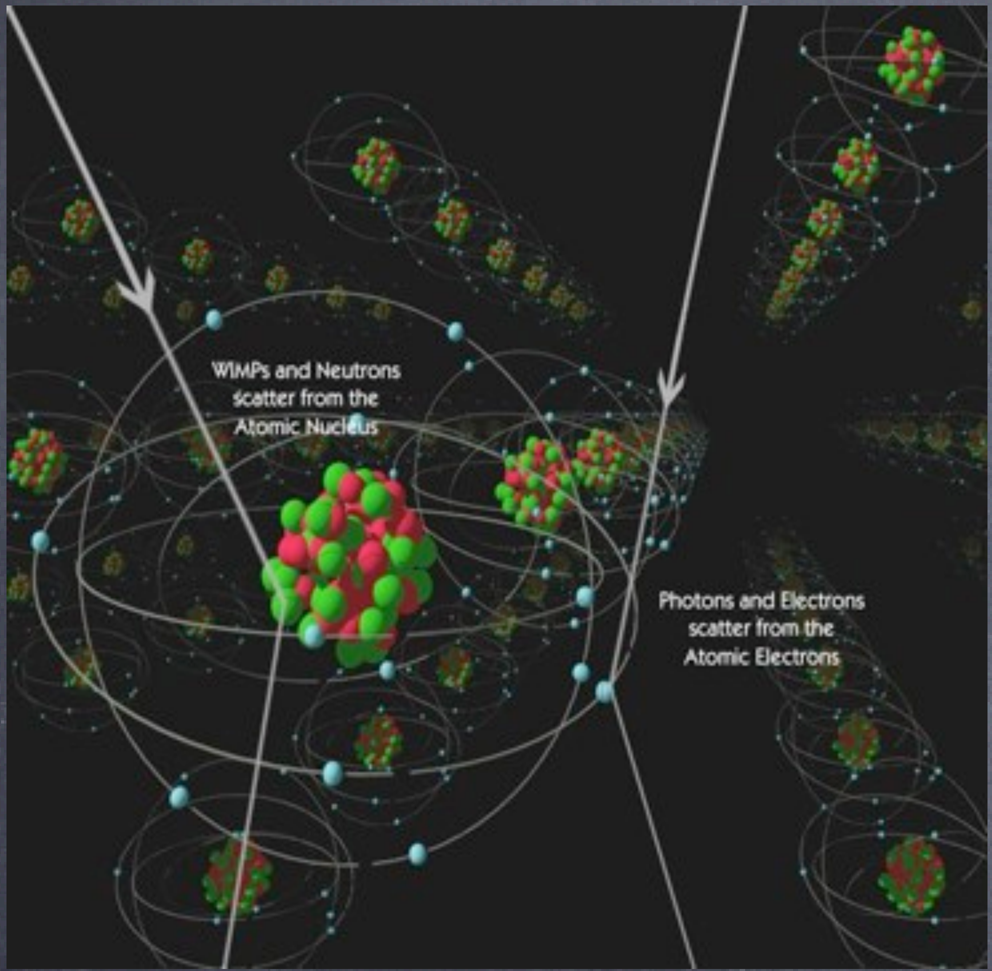
Dark Matter candidates



L. Roszkowski, *Pramana 62:389, 2004*

Direct Detection

Direct Detection of WIMPs



Expected signal:

nuclear recoil: few 10's of keV
featureless exponential
low rates <0.1 events/kg/day

Challenges:

low energy thresholds
large radioactive backgrounds

Need to know:
local density, velocity distribution, local circular velocity

Spin dependence

Spin-independent cross section (coherent interaction)

Scattering amplitudes (same for neutrons and protons) add coherently

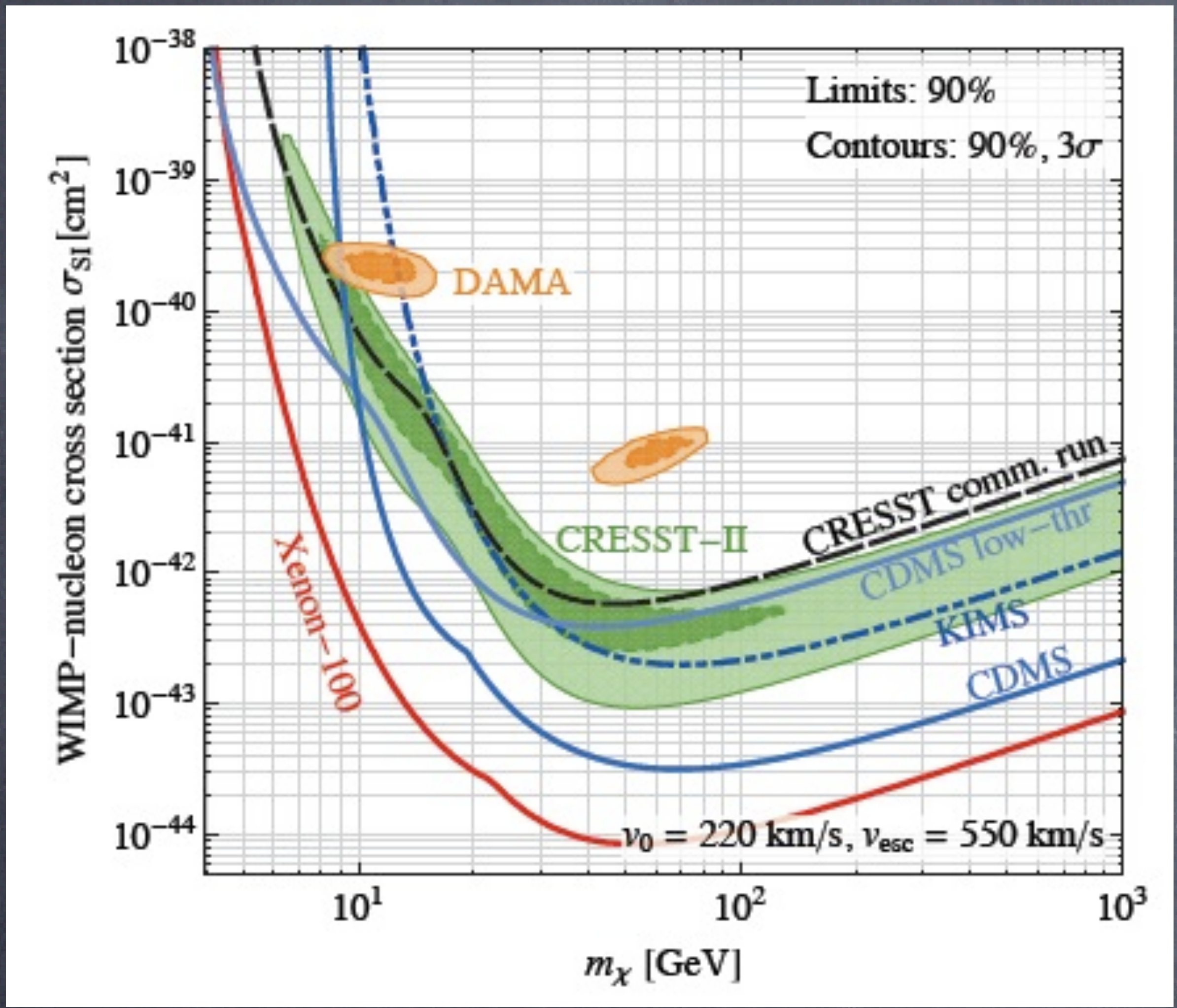
$$\sigma_{SI} \propto \left(Z f_p + (A - Z) f_n \right)^2$$

Spin-dependent cross section

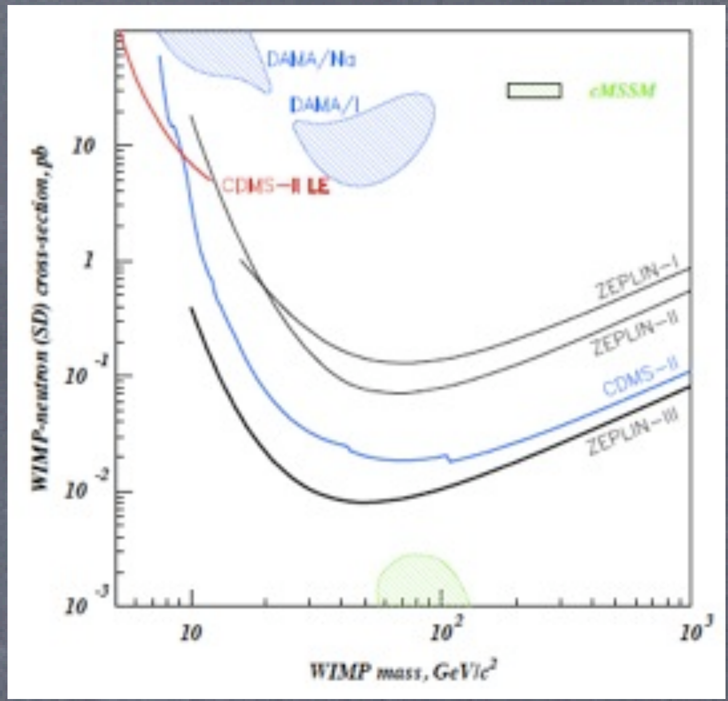
Scattering amplitude changes sign with spin direction, so paired nucleons do not contribute: only the residual unpaired nucleons

$$\sigma_{SD} \propto J(J+1)$$

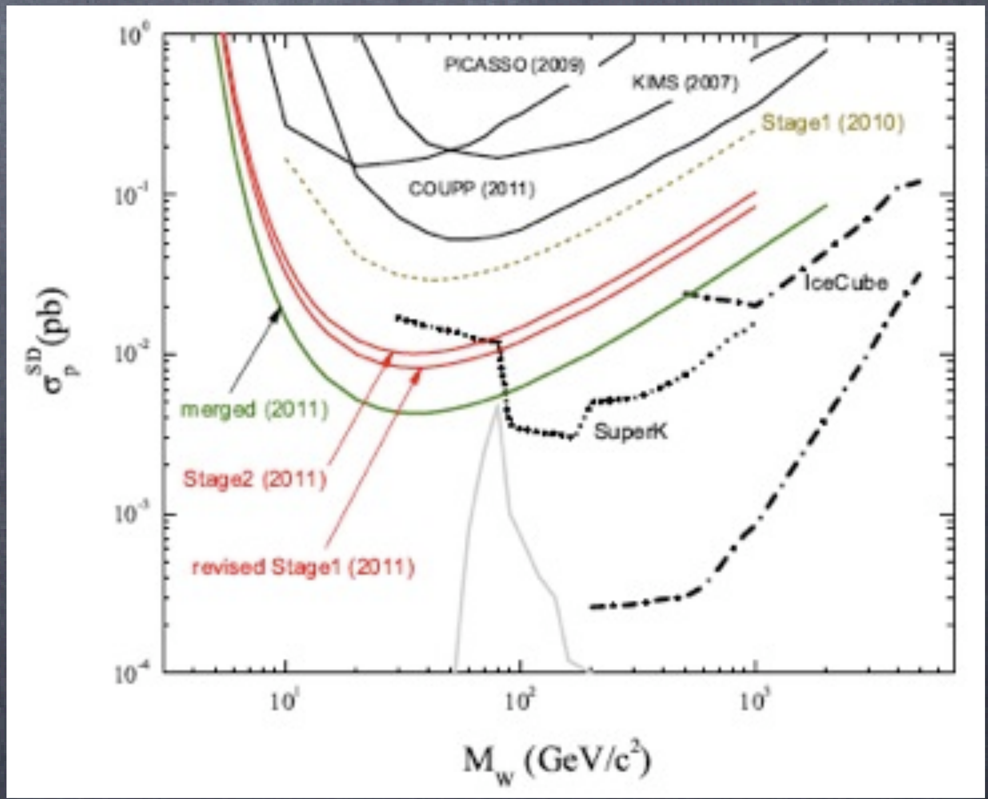
Current Direct Detection searches



J. Kopp, T. Schwetz and J. Zupan, *arXiv:1110.2721*



D. Yu. Akimov *et al.* [ZEPLIN Collaboration], *arXiv:1110.4769*



M. Felizardo *et al.* [SIMPLE Collaboration], *arXiv:1106.3014*

Indirect Detection

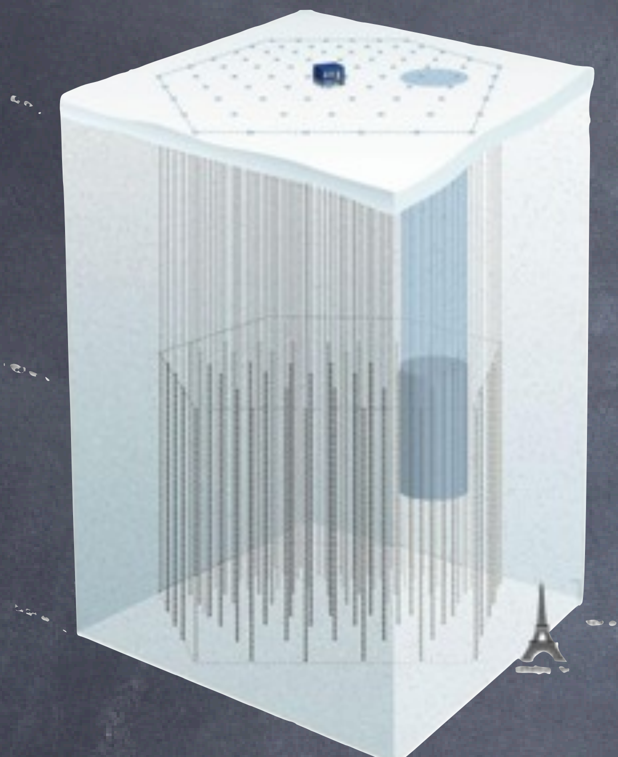
Gamma-rays

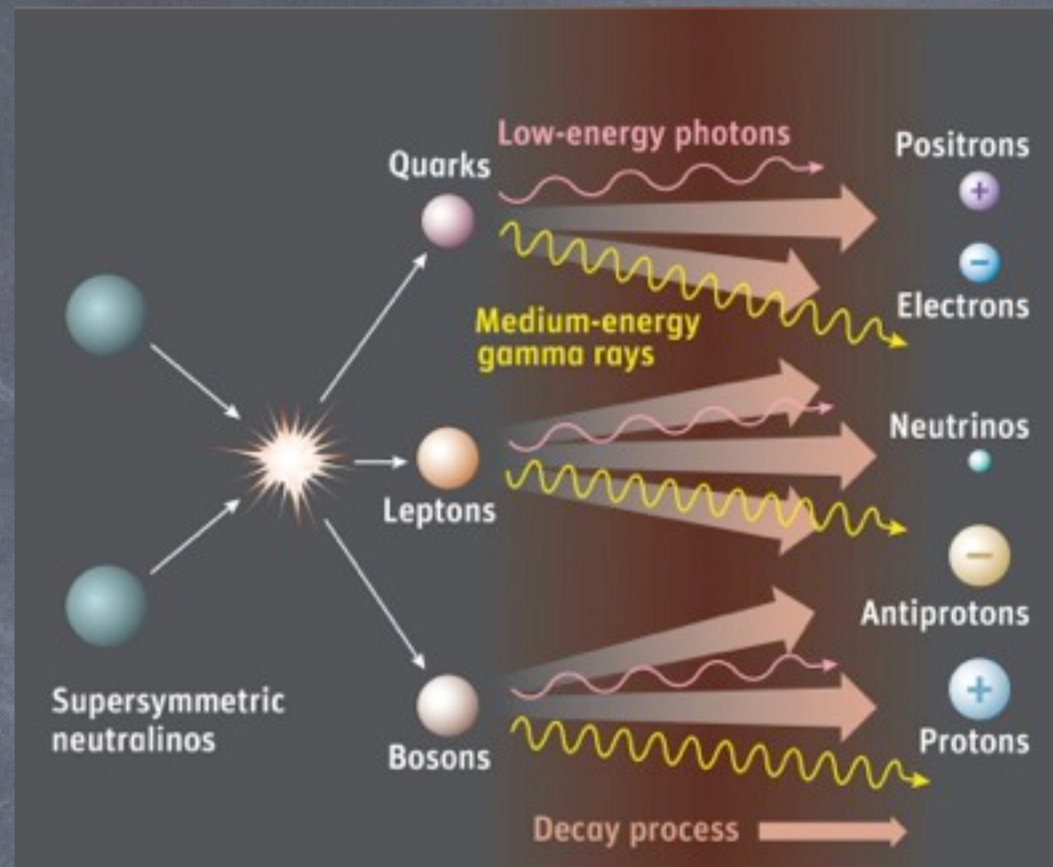
Antimatter

Neutrinos

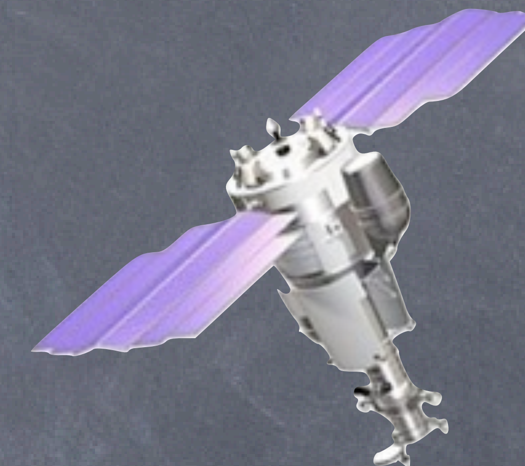
Indirect Detection of WIMPs

IceCube



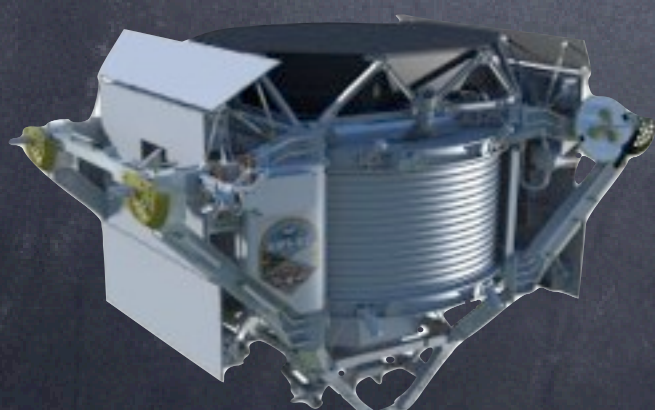


PAMELA



Fermi-LAT

AMS



Expected signal:
annihilation (decay) products

Challenges:
absolute rates
discrimination against other sources

Need to know:
local density, halo profile, amount of substructure...

Indirect Detection

Gamma-rays

Antimatter

Neutrinos

Indirect Detection

Gamma-rays

Rather high rates
No attenuation
Point directly to the sources: clear spatial signatures
Clear spectral signatures to look for

Where to look?

Galactic halo

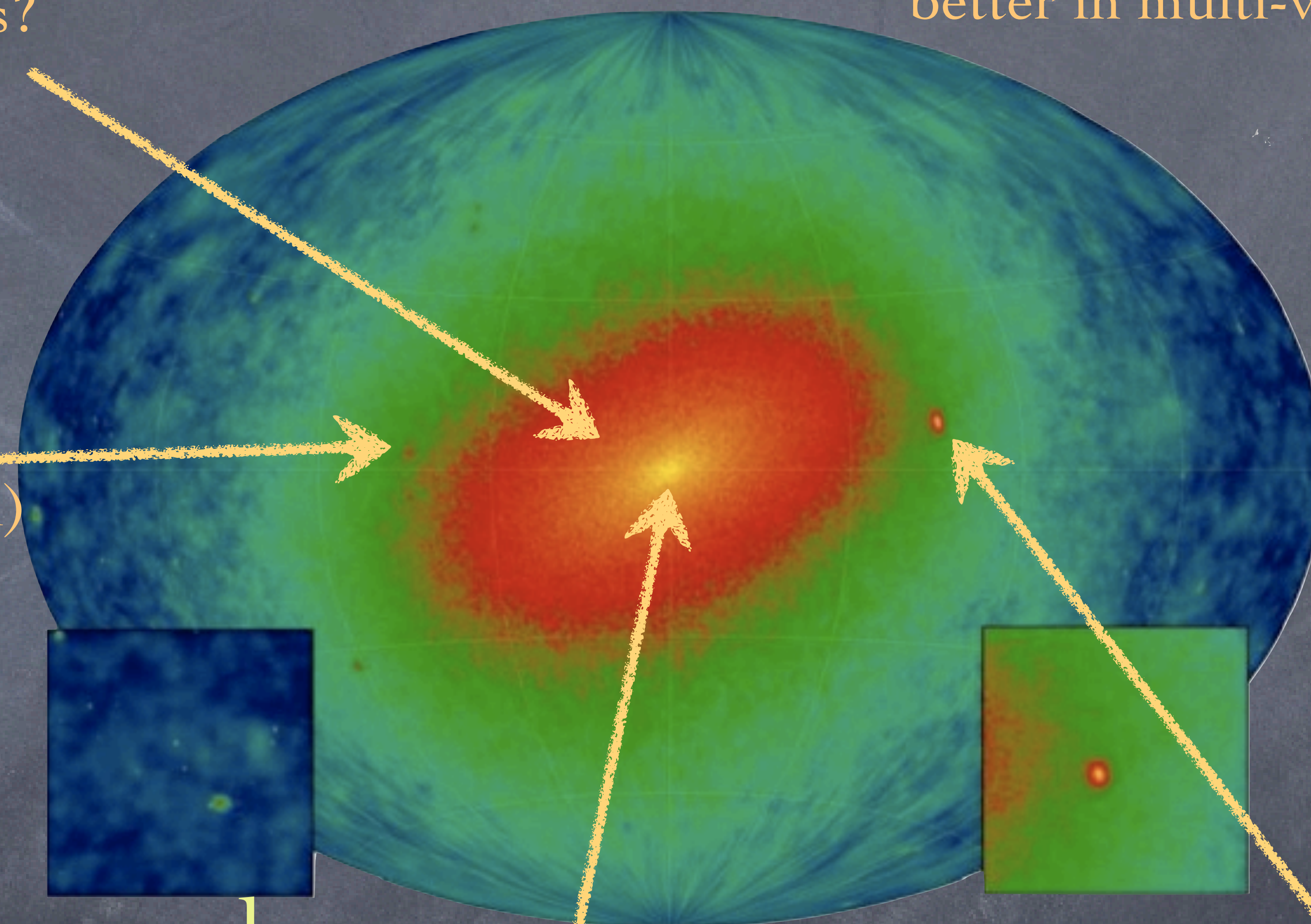
good statistics, angular information
galactic backgrounds?

Galaxy clusters

cosmic ray contamination
better in multi-wavelength?

DM clumps

easy discrimination (if found)
bright enough?



Extragalactic background

DM contribution from all z
background difficult to model

Galactic center

brightest DM source
large backgrounds and uncertainties

Dwarf galaxies

DM dominated

Figure from J. Diemand, M. Kuhlen and P. Madau, *Astrophys. J. 657:262, 2007*

Indirect Detection

Gamma-rays

Antimatter

Neutrinos

Indirect Detection

Confined by galactic magnetic fields

Low backgrounds

Antimatter

After propagation, no directional information

Spectral information is slightly washed out

Secondaries

Antiprotons

No significant astrophysical sources
For E>10 GeV completely diffusion dominated
Very efficient to set constraints
Cannot be used to discriminate among DM candidates

Positrons

Energy losses dominate: locally produced
Some sensitivity to discriminate among DM models
Efficient to set constraints
Many astrophysical sources of primary positrons: pulsars, old supernova remnants, GRB...

Indirect Detection

Gamma-rays

Antimatter

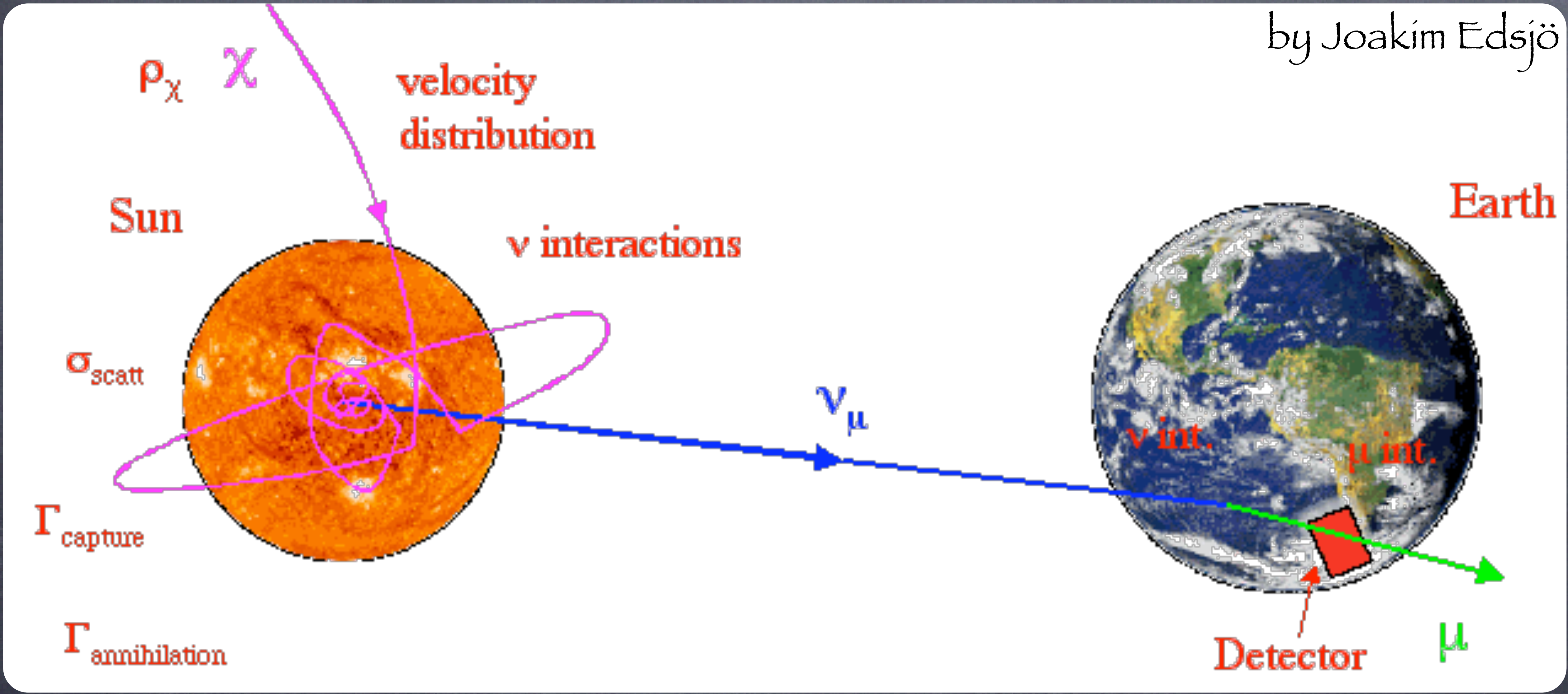
Neutrinos

Indirect Detection

Low rates
Understood background
Only detectable products from DM in the Sun
Spectral signatures

Neutrinos

Neutrinos from DM annihilation in the Sun



Neutrinos from DM annihilation in the Sun

- WIMPs elastically scatter with the nuclei of the Sun to a velocity smaller than the escape velocity, so they remain trapped inside

  Additional scattering give rise to an isothermal distribution

$$C_\odot \simeq 9\times 10^{-25}\,\mathrm{s}^{-1}\left(\frac{\rho_0}{0.3\ \mathrm{GeV/cm^3}}\right)\left(\frac{270\ \mathrm{km/s}}{\bar{v}_{local}}\right)^3\left(\frac{\sigma_{\chi A}}{10^{-3}\ \mathrm{pb}}\right)\left(\frac{50\ \mathrm{GeV}}{m_\chi}\right)^2$$

- Trapped WIMPs can annihilate into SM particles

- After some time, annihilation and capture rates equilibrate

$$\Gamma_{ann} = \frac{1}{2} C_\odot \tanh^2\left(\frac{t_\odot}{t_{eq}}\right)$$

- Only neutrinos can escape

Density matrix treatment

M. Cirelli, N. Fornengo, T. Montaruli, I. Sokalski, A. Strumia and F. Vissani, *Nucl. Phys. B727:99, 2005*
V. Barger, W. Y. Keung, G. Shaughnessy and A. Tregre, *Phys. Rv. D76:095008, 2007*
V. Barger, J. Kumar, D. Marfatia and E. M. Sessolo, *Phys. Rev. D81:115010, 2010*

$$\dot{\rho} = -i\left[H,\rho\right] - \frac{1}{2}\left\{\Gamma,\rho\right\} + \dot{\rho}_{reg}$$

Neutrino oscillations
H is the oscillation hamiltonian

Neutrino absorption
Γ (diagonal) containts the neutrino interaction rates

Regeneration term
Describes the production of new neutrinos due to interactions with matter

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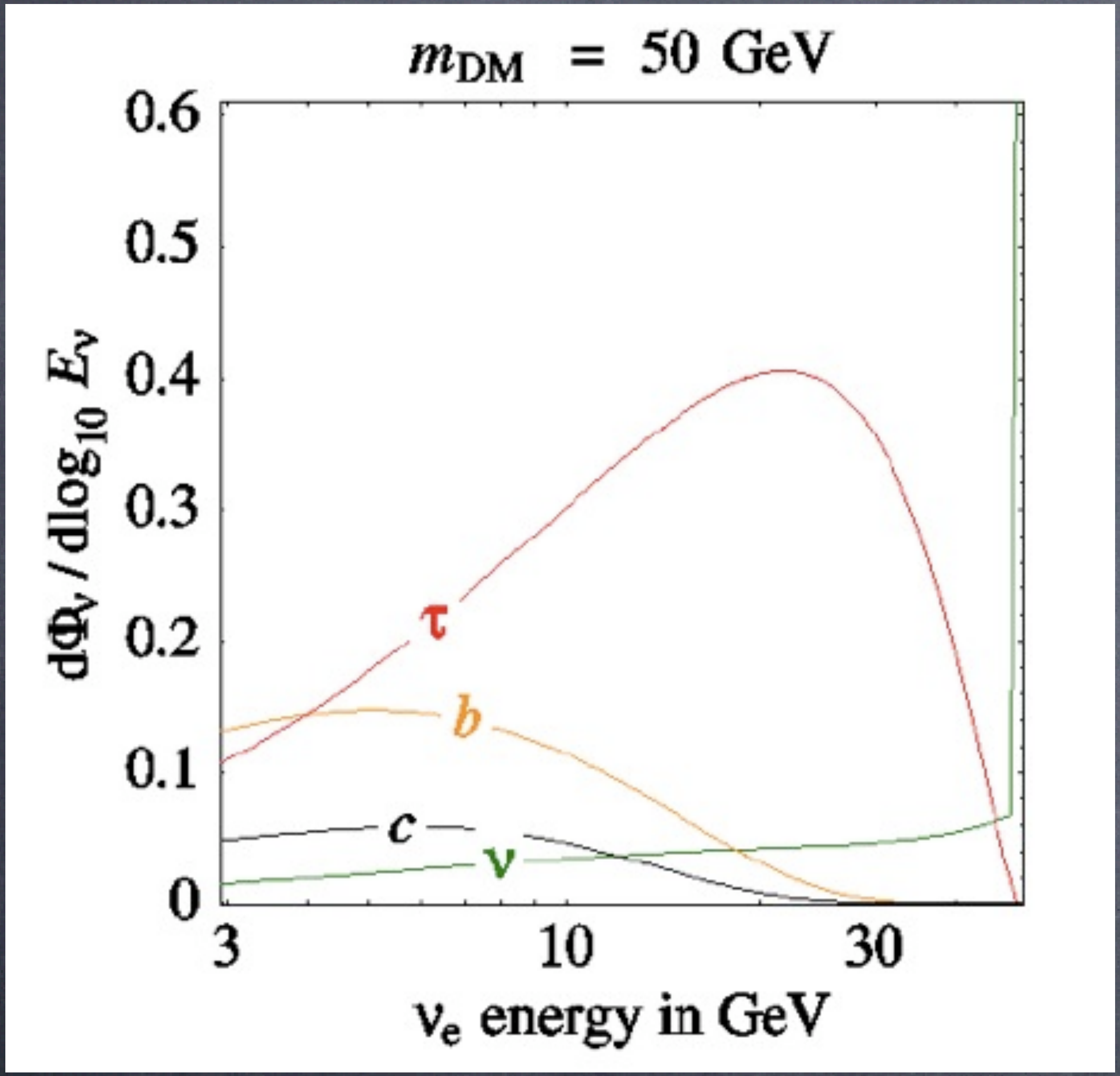
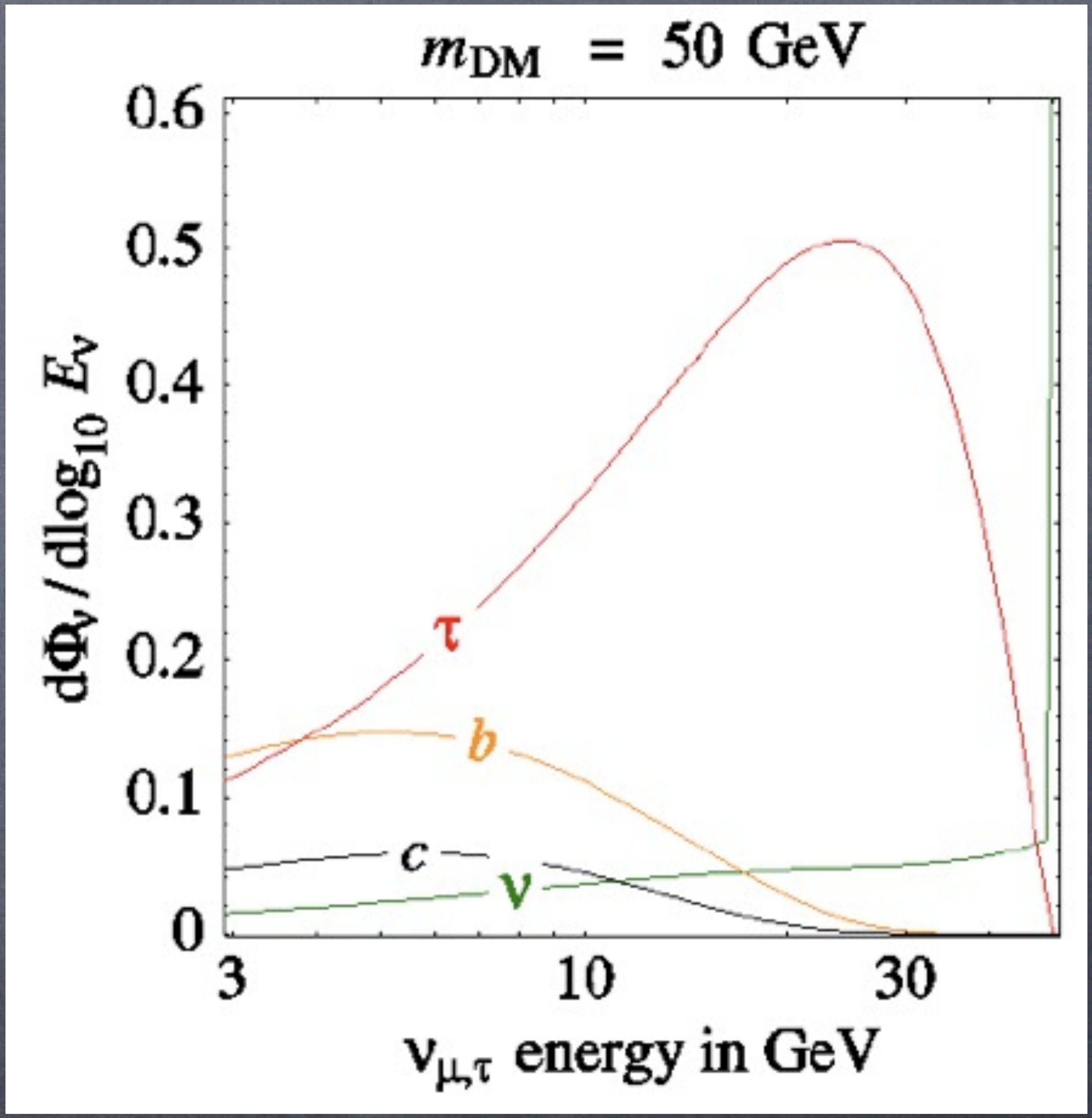
Neutrino Spectra at Detection

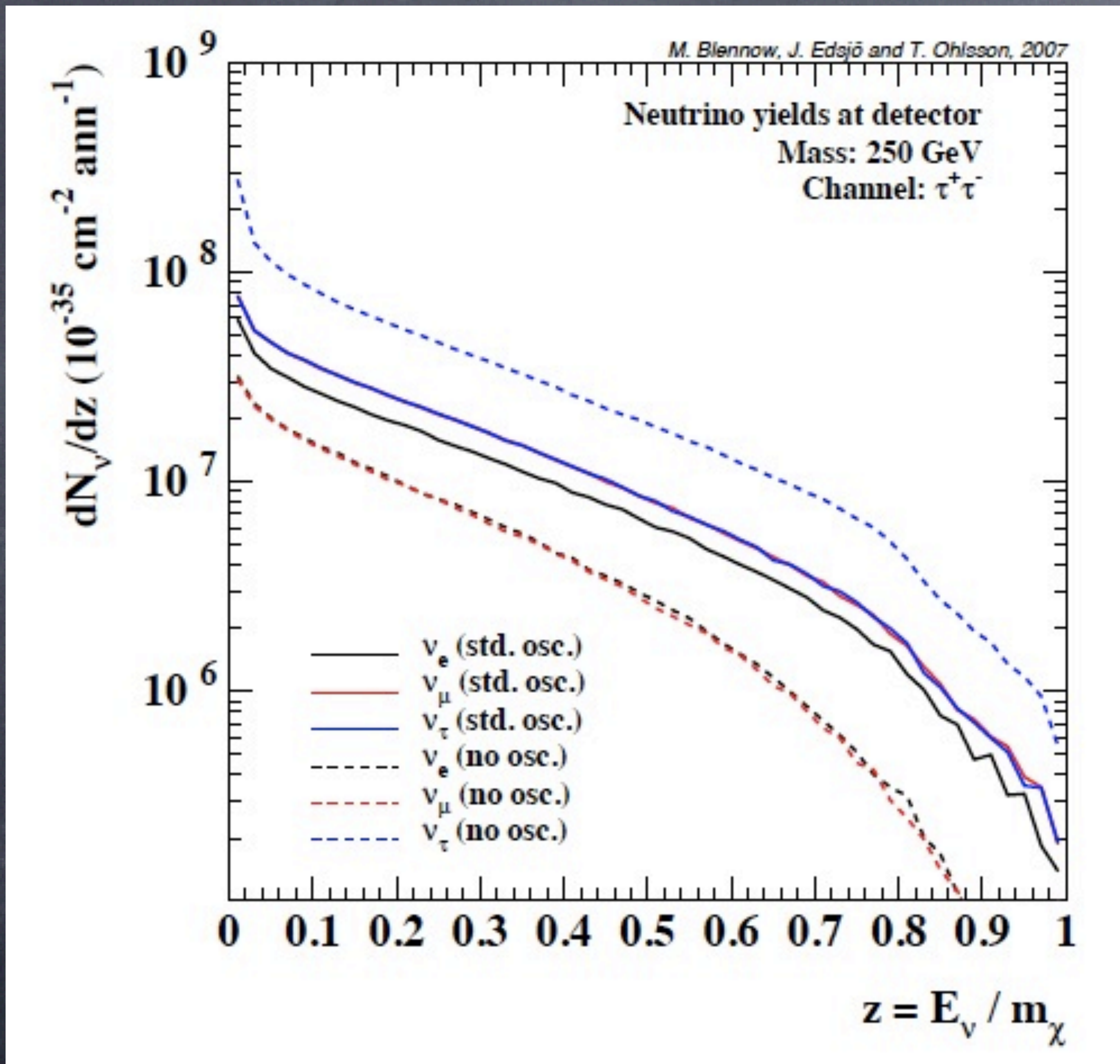
Neutrino oscillations taken into account



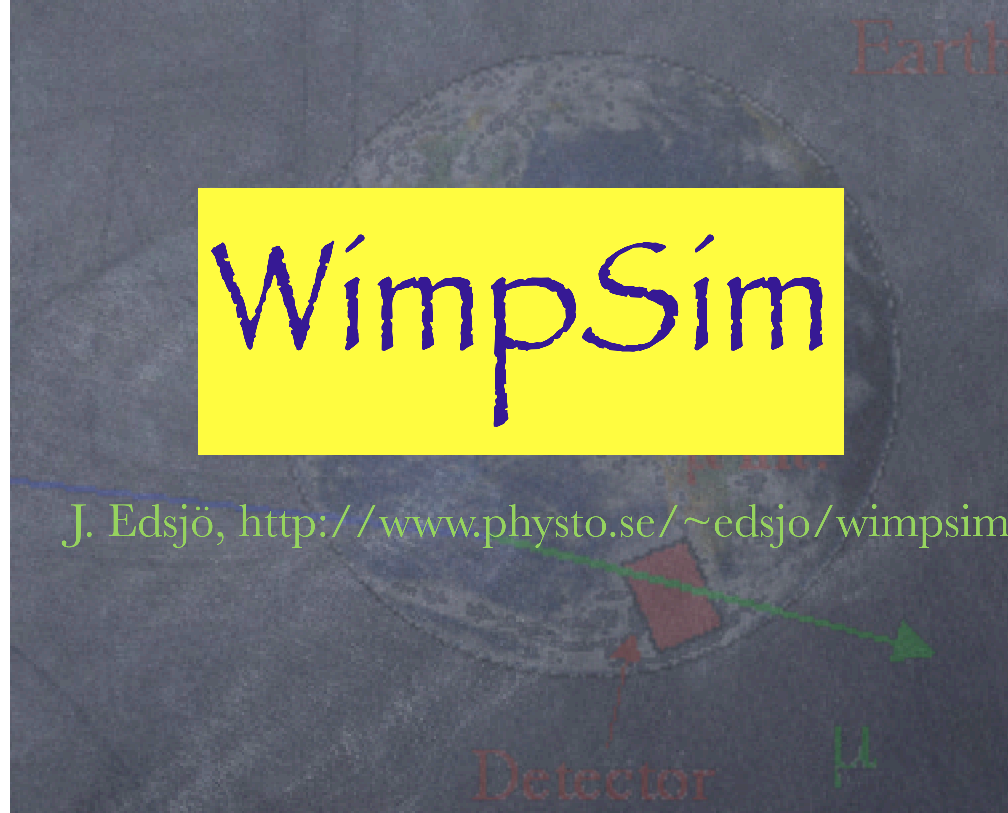


M. Cirelli, N. Fornengo, T. Montaruli, I. Sokalski, A. Strumia and F. Vissani, *Nucl. Phys. B727:99, 2005*

Event-based framework



M. Blennow, J. Edsjö and T. Ohlsson, *JCAP 0801:021, 2008*



J. Edsjö, http://www.physto.se/~edsjo/wimpsim/

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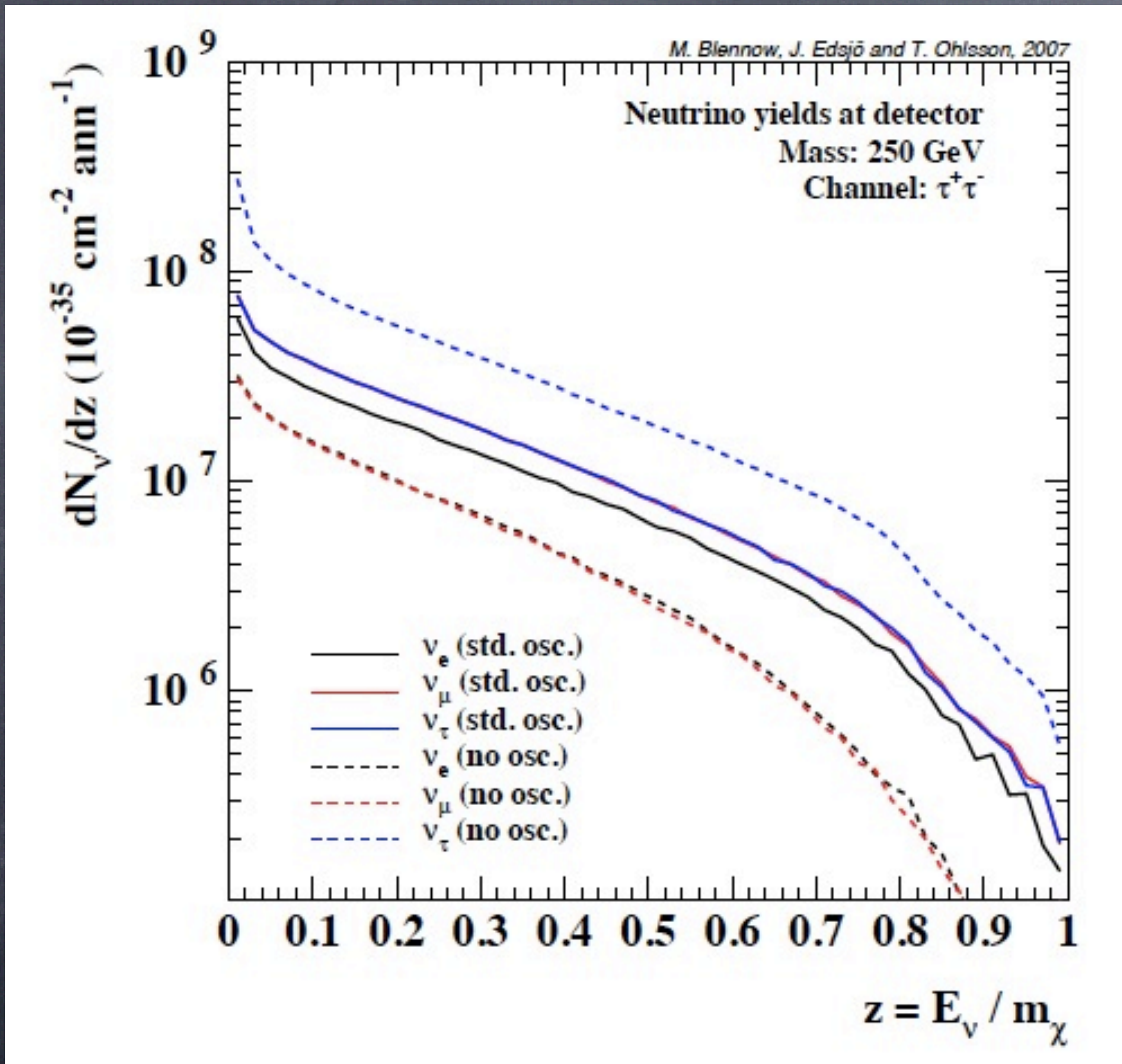
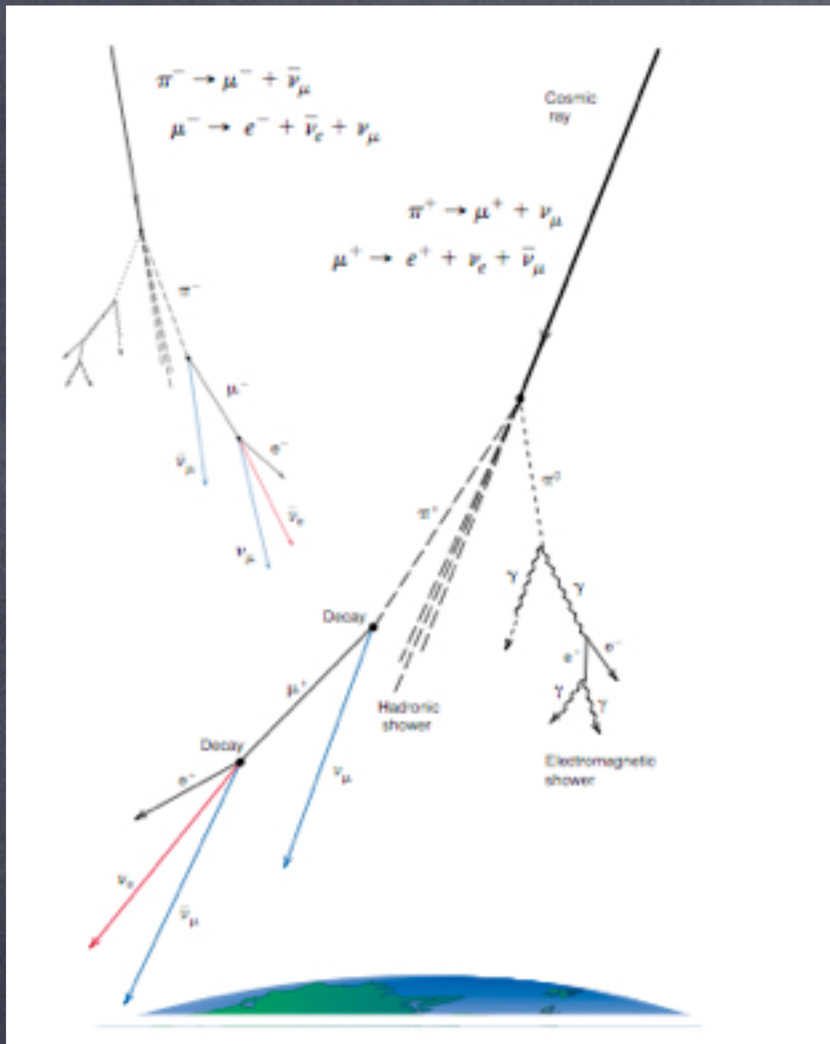


M. Blennow, J. Edsjö and T. Ohlsson, *JCAP 0801:021, 2008*

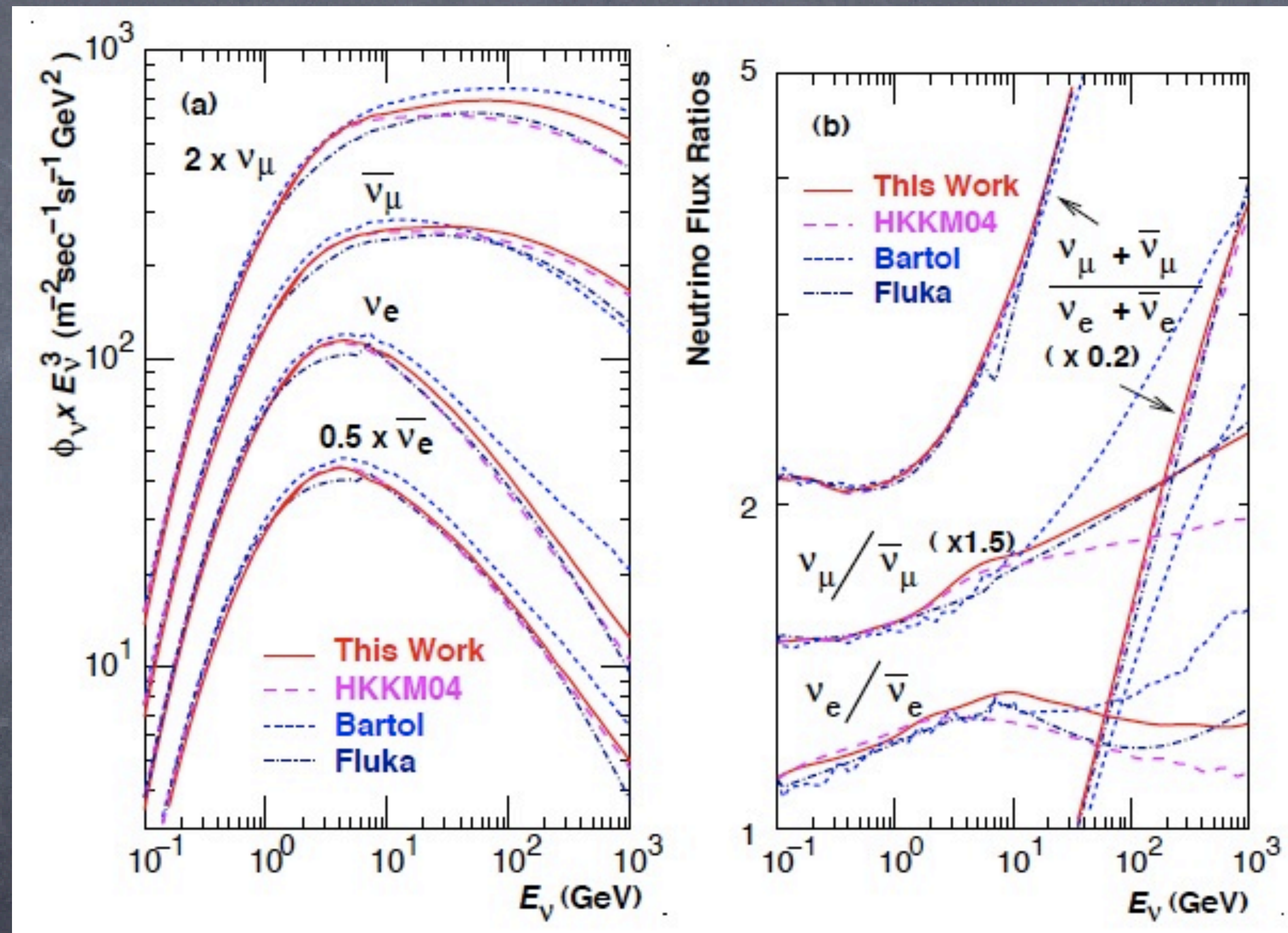
WimpSim

J. Edsjö, http://www.physto.se/~edsjo/wimpsim/

Background: atmospheric neutrinos



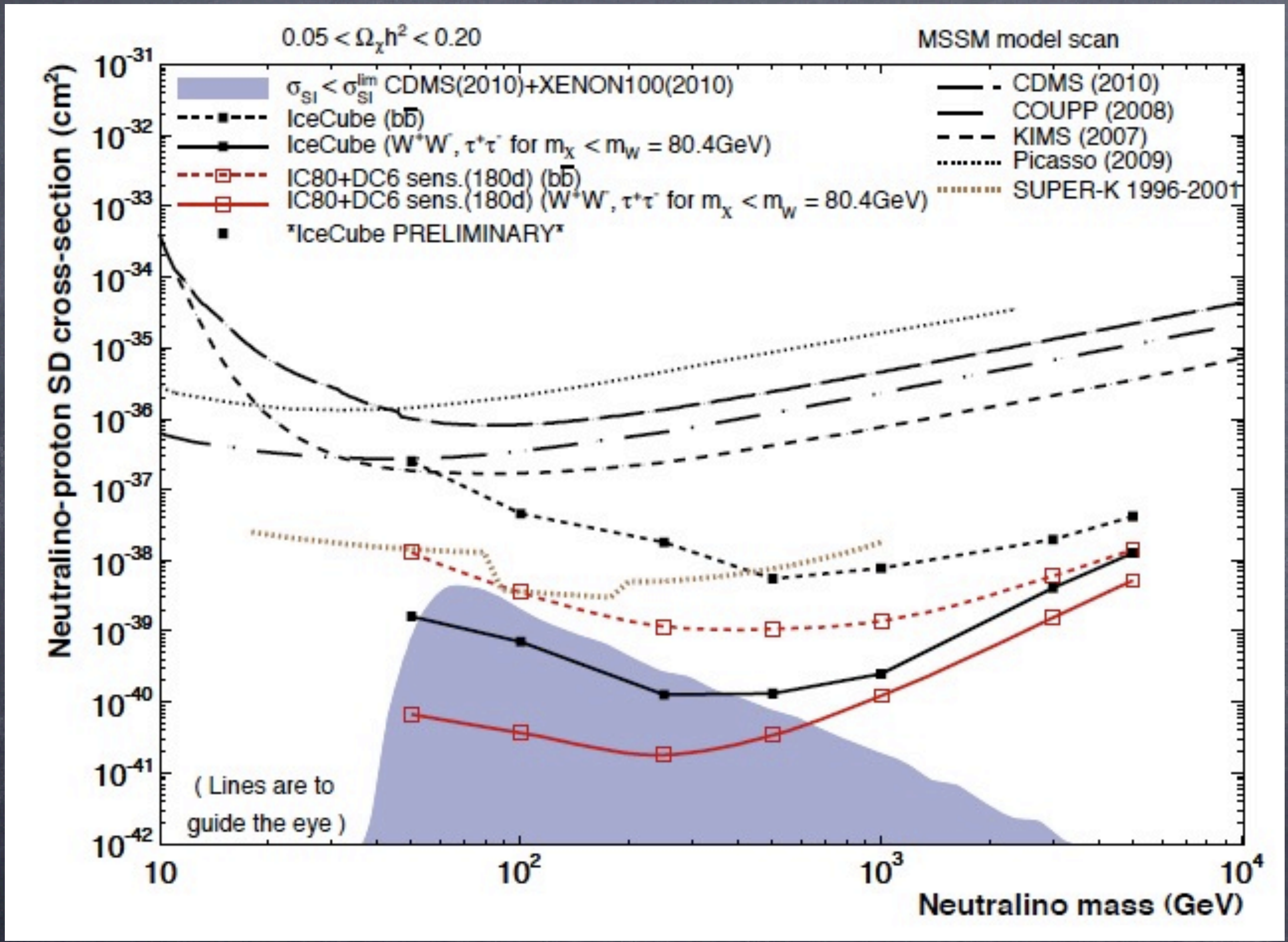
Los Alamos Science No. 25, 1997

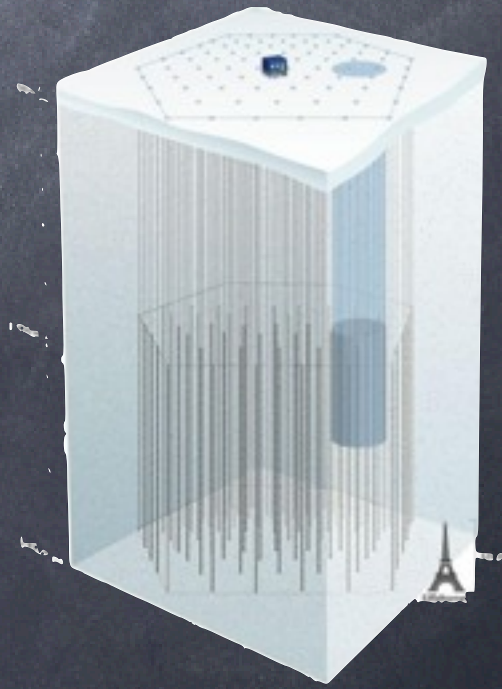


M. Honda, T. Kajita, K. Kasahara, S. Midorikawa and T. Sanuki, *Phys. Rev. D75:043006, 2007*

Neutrino Indirect Detection Searches

IceCube and Super-Kamiokande: neutrinos from the Sun





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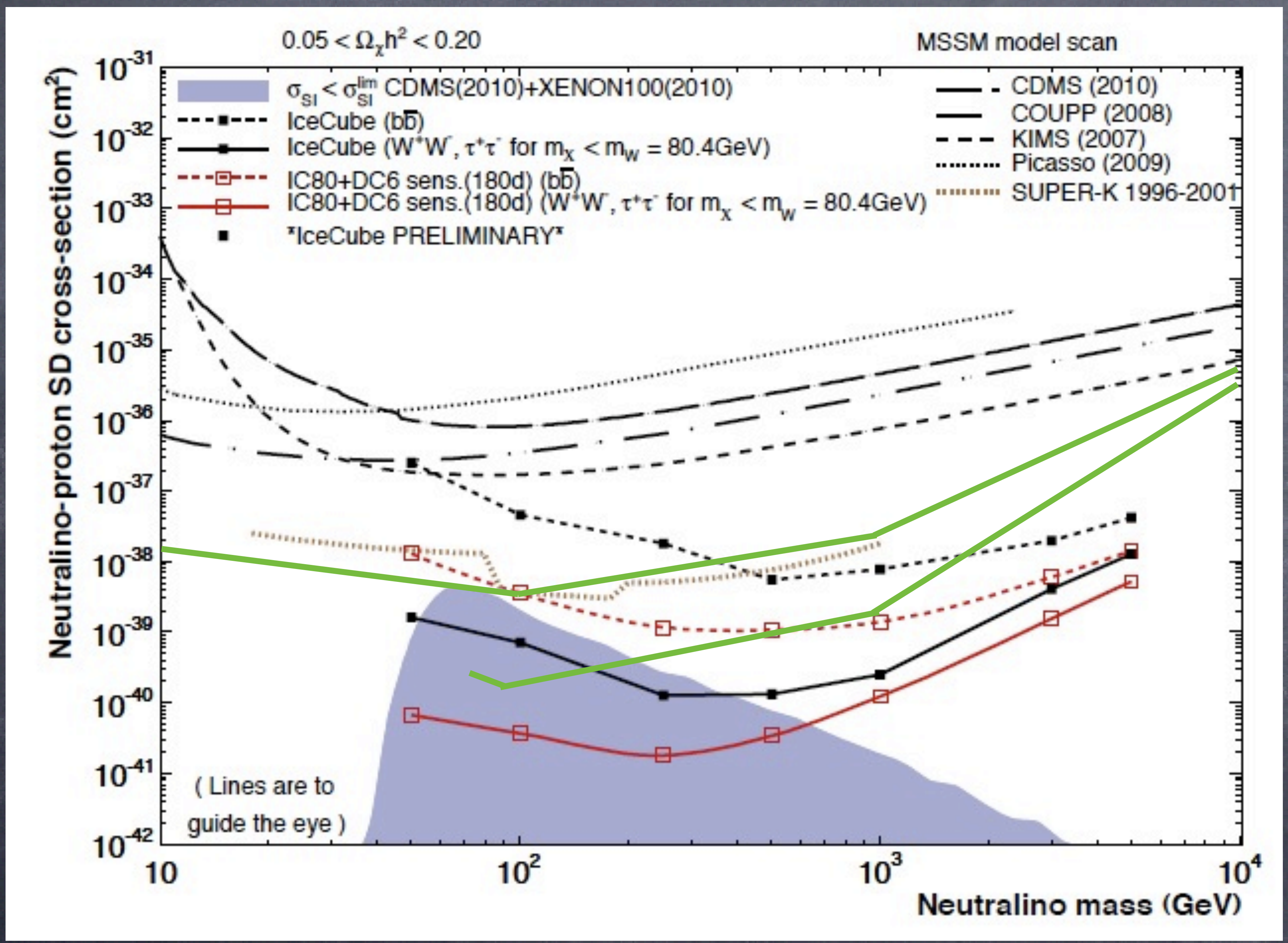
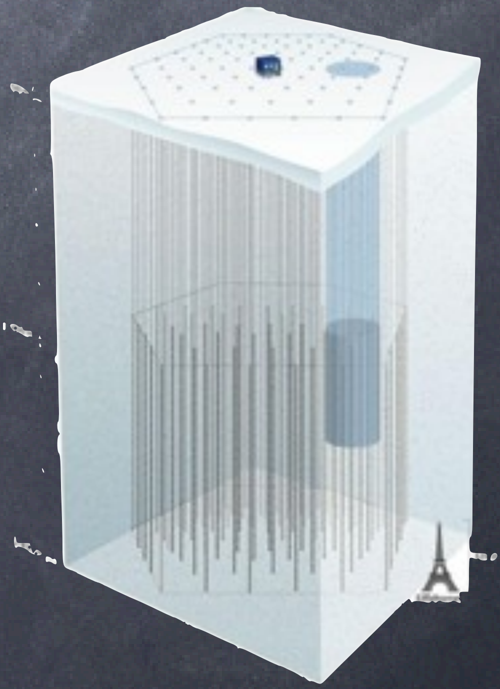


New SK analysis

T. Tanaka *et al.* [Super-Kamiokande Collaboration], *arXiv:1108.3384*



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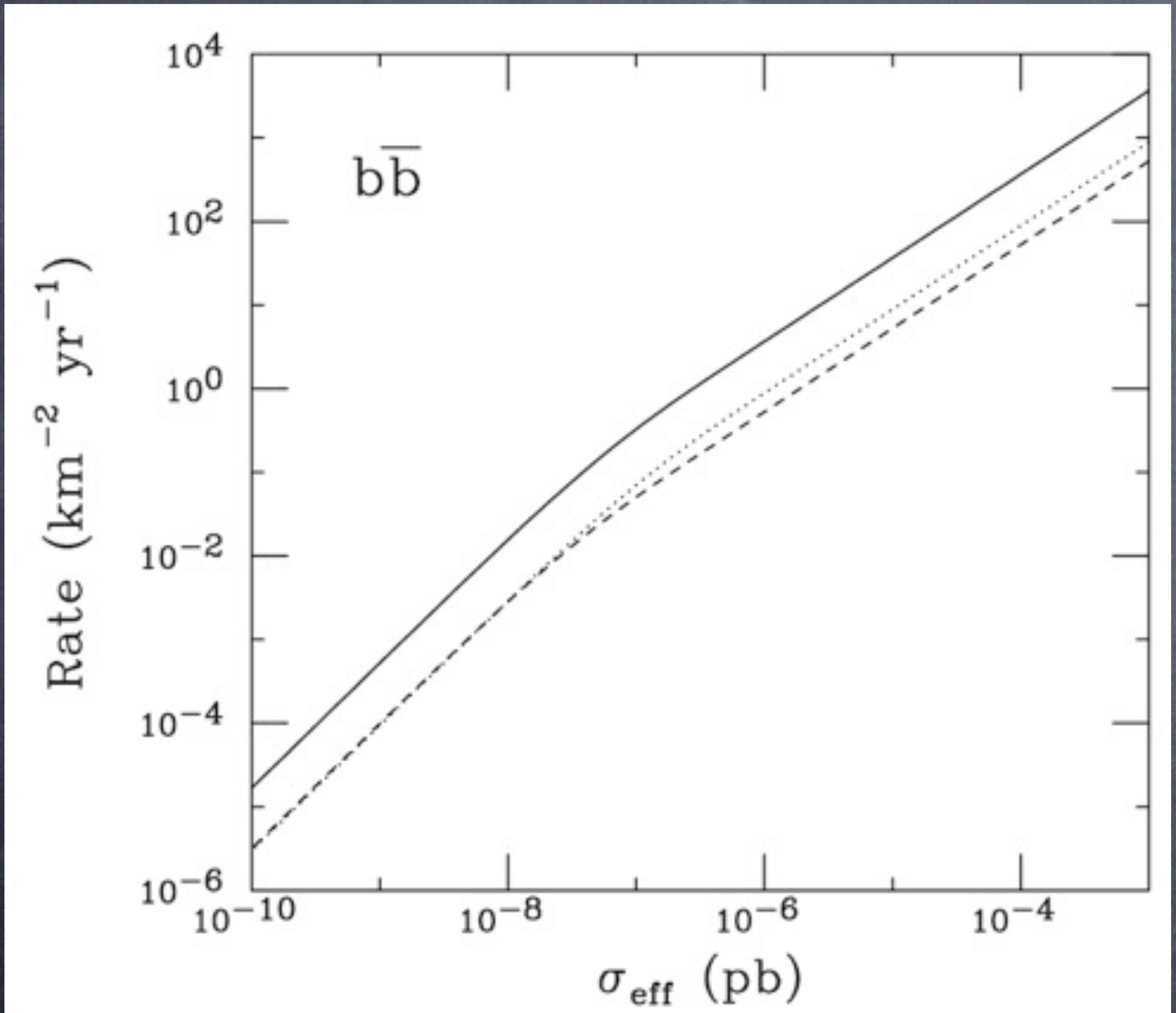
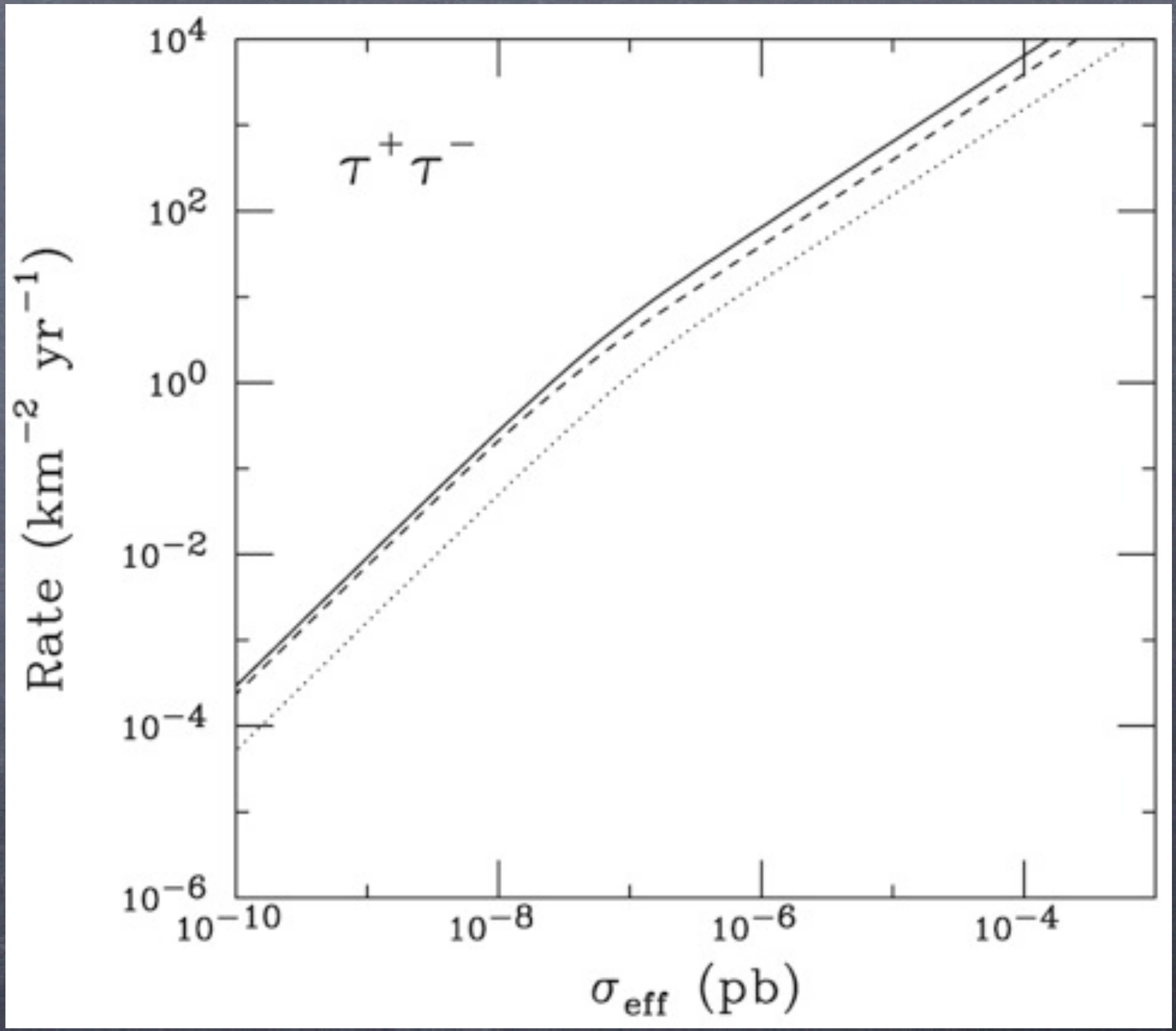
Rates in a Neutrino Telescope

$$N_{\rm events} \approx \int\int \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} \frac{d\sigma_\nu}{dy}(E_{\nu_\mu}, y) \left[R_\mu(E_\mu) + L\right] A_{\rm eff}\, dE_{\nu_\mu}\, dy$$
$$+ \int\int \frac{dN_{\bar\nu_\mu}}{dE_{\bar\nu_\mu}} \frac{d\sigma_{\bar\nu}}{dy}(E_{\bar\nu_\mu}, y) \left[R_\mu(E_\mu) + L\right] A_{\rm eff}\, dE_{\bar\nu_\mu}\, dy$$





F. Halzen and D. Hooper, *Phys. Rev. D73:123507, 2006*

Rates in a Neutrino Telescope

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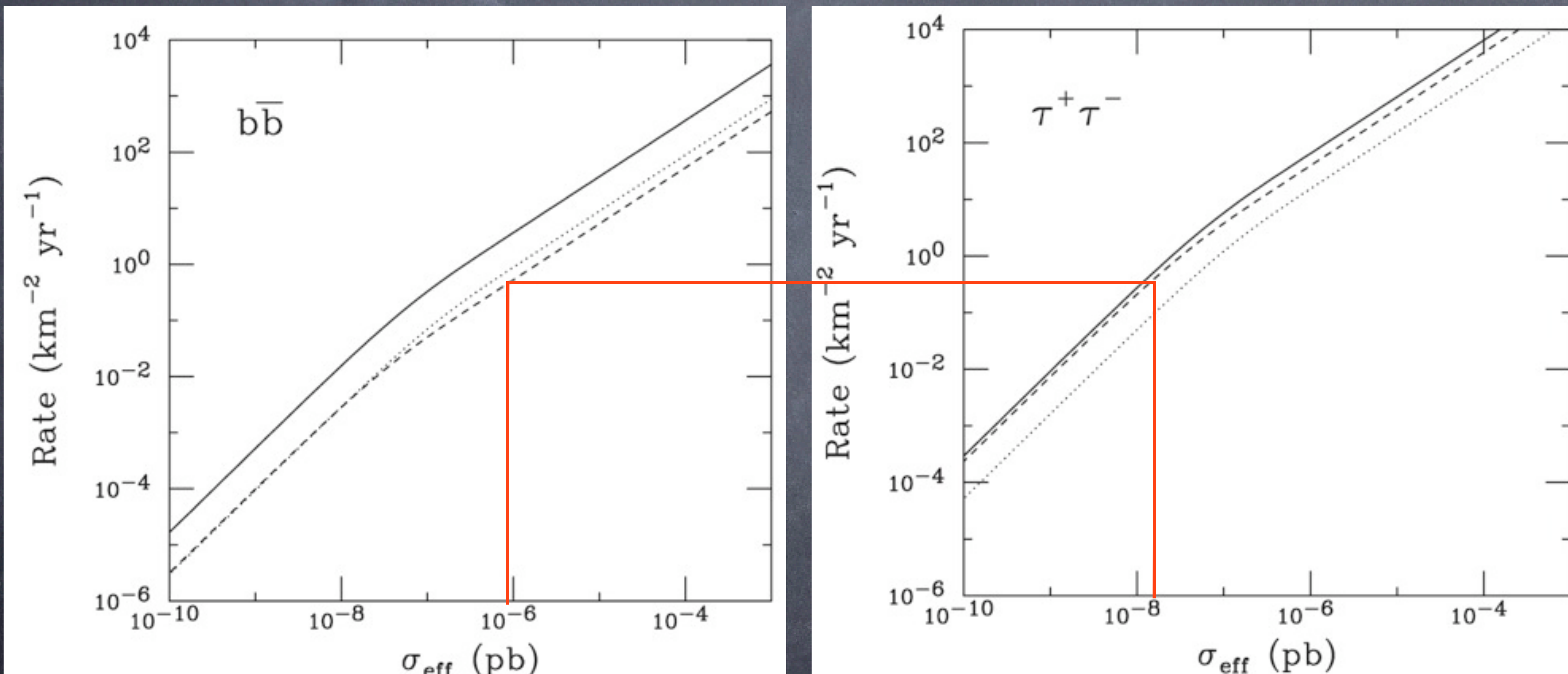

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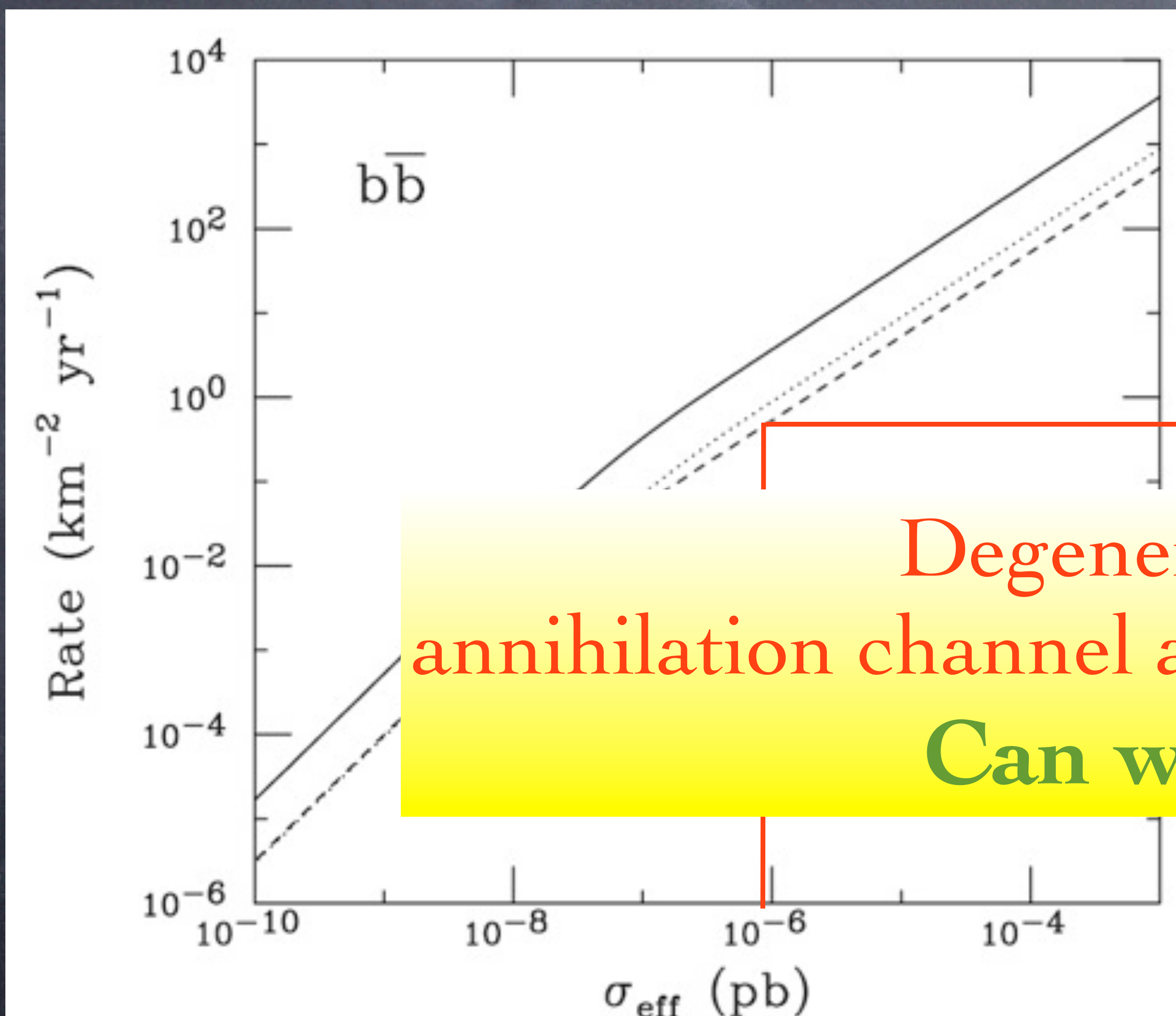
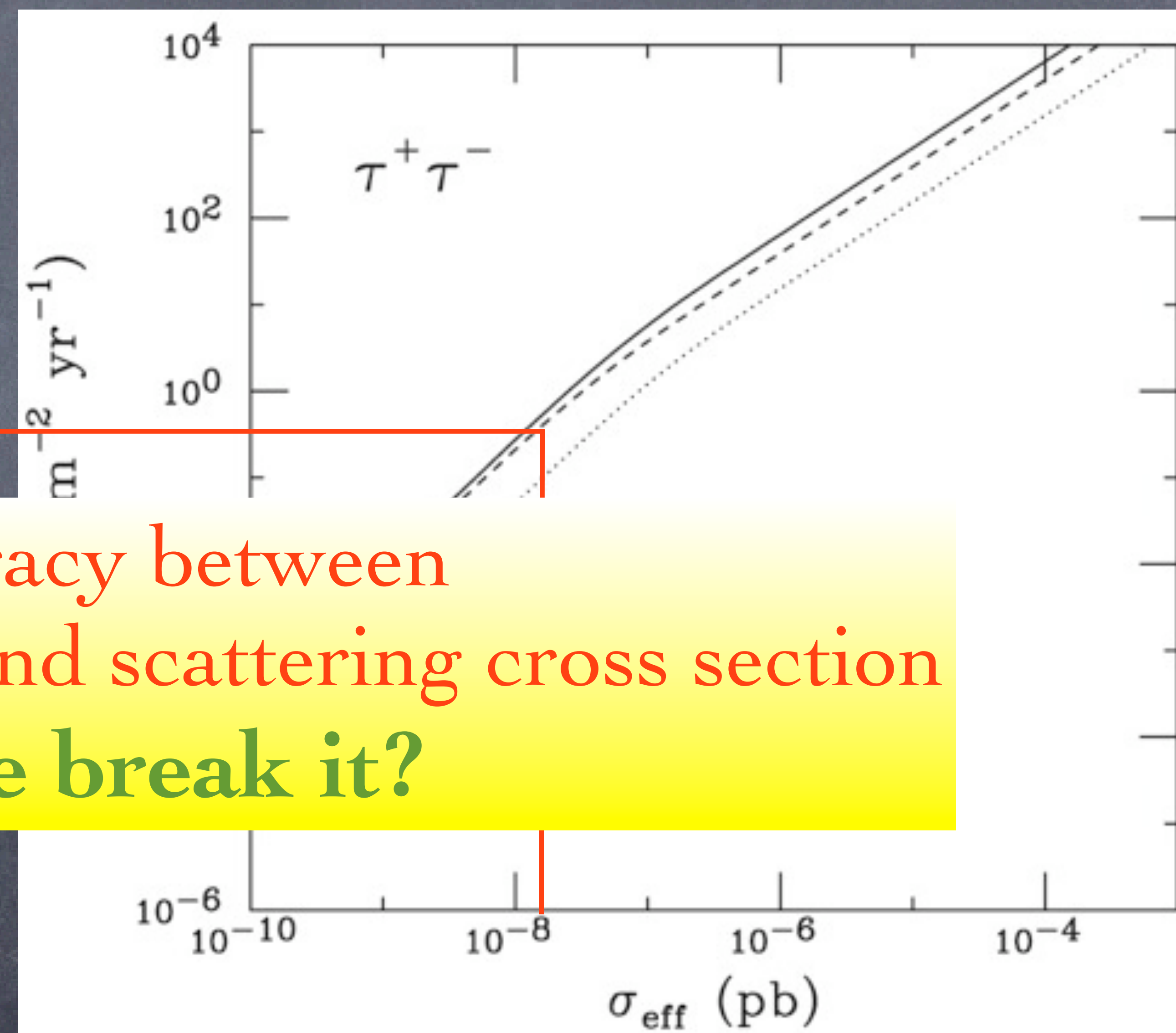




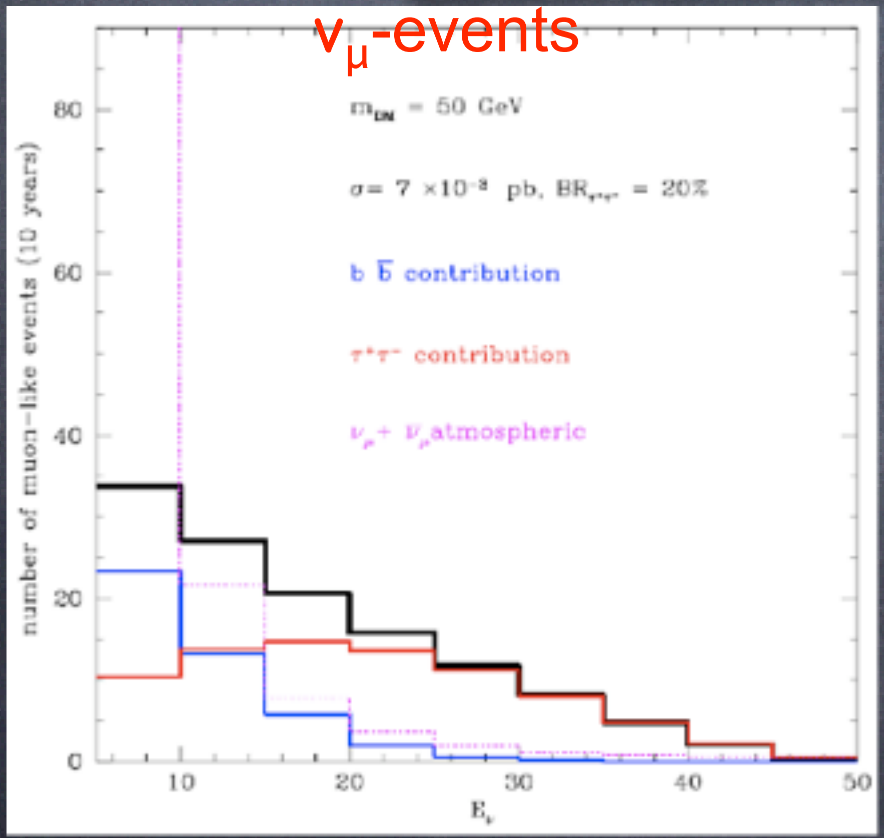
Degeneracy between
annihilation channel and scattering cross section
Can we break it?

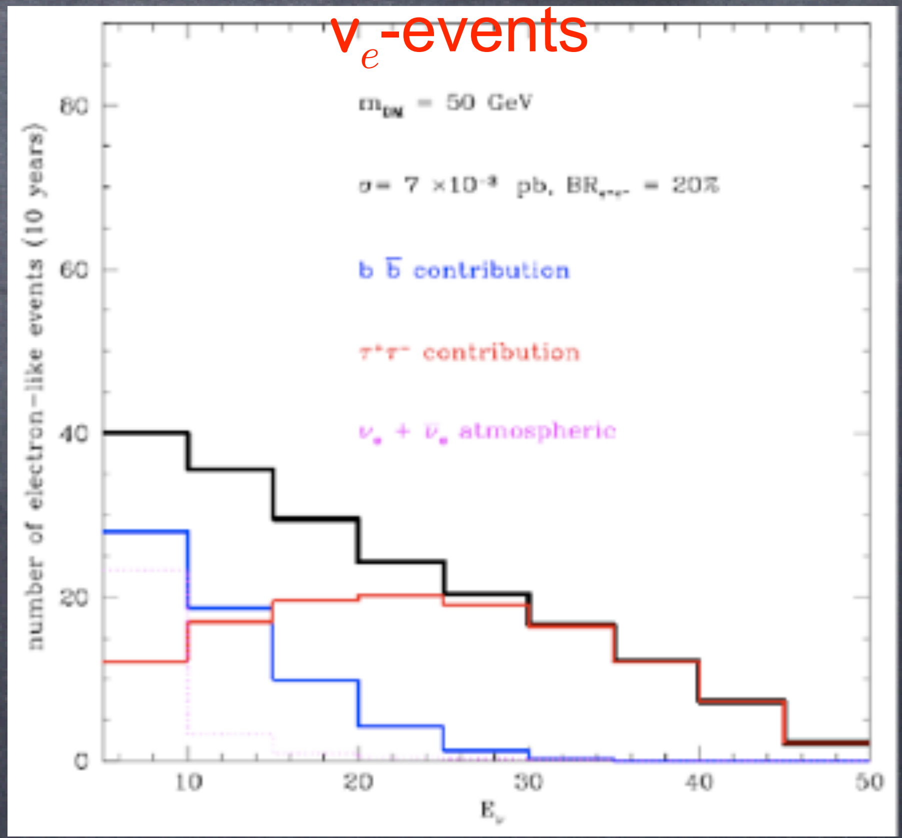
F. Halzen and D. Hooper, *Phys. Rev. D73:123507, 2006*

Future Neutrino Detectors

- Magnetized Iron Calorimeters (MINOS-like, INO…)
- Totally Active Scintillator Detectors (NOvA, MINERvA…)
- Liquid Argon Time Projection Chamber (GLACIER…)

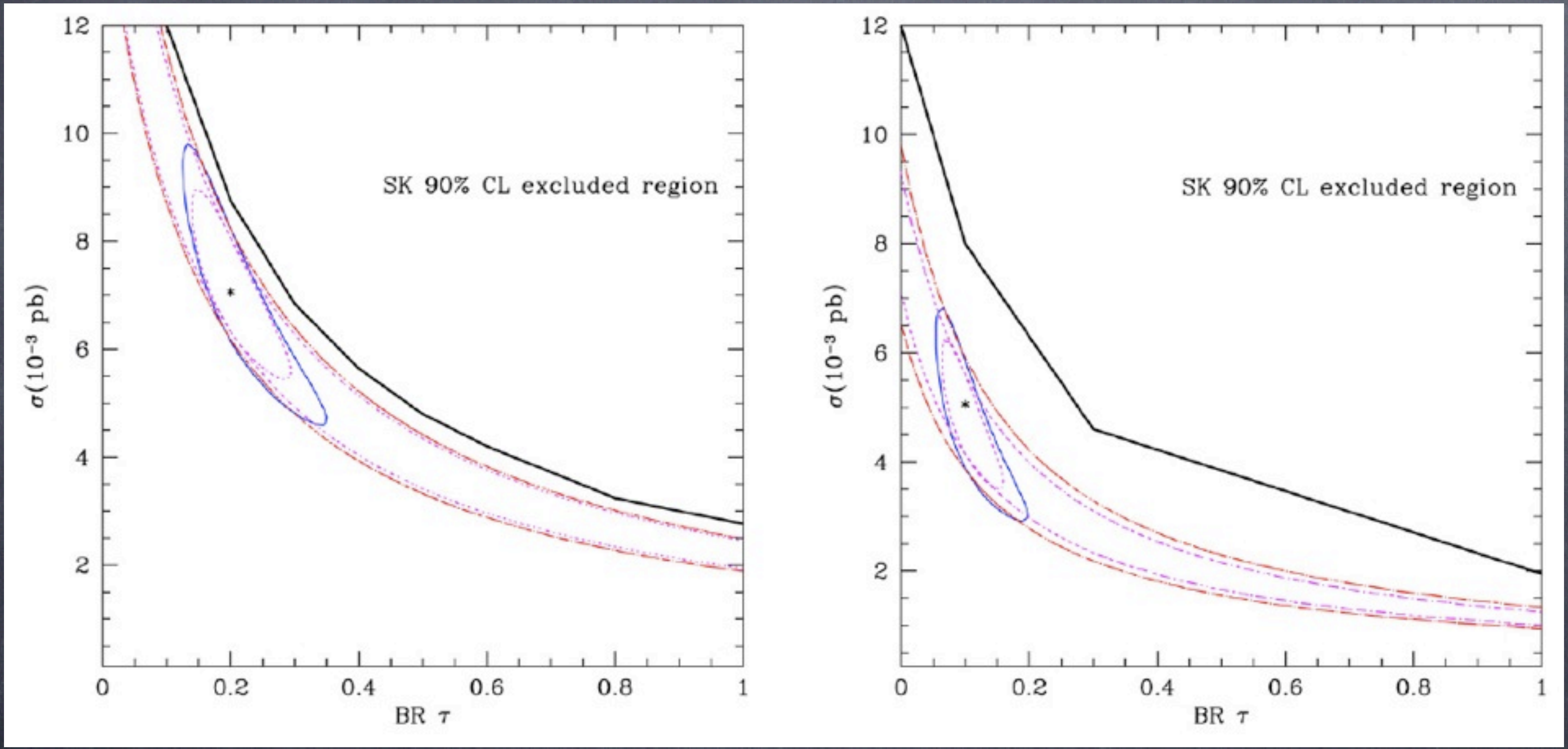
Very good angular and energy resolution for ν_e and/or ν_μ for 10's of GeV → suitable for low mass WIMPs





$$m_\chi = 50\,\mathrm{GeV}$$
$$\mathrm{Br}_{\tau^+\tau^-}(\mathrm{hard}) = 20\%$$

$$m_\chi = 70\,\mathrm{GeV}$$
$$\mathrm{Br}_{\tau^+\tau^-}(\mathrm{hard}) = 10\%$$

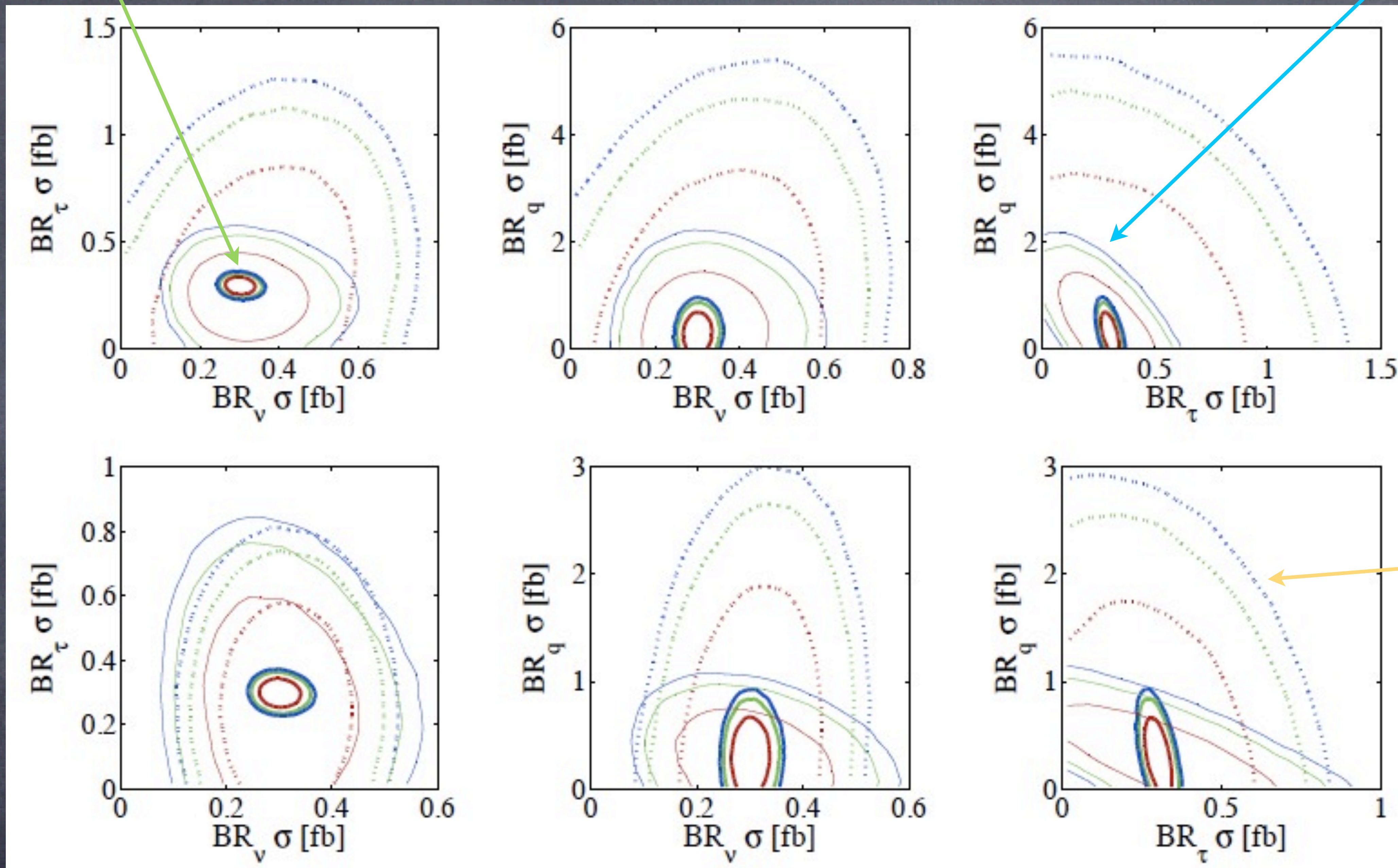


O. Mena, SPR and S. Pascoli, *Phys. Lett. B664:92, 2008*

GLACIER

$m_\chi = 10$ GeV $\quad Br_{\tau^+\tau^-} = 100\%$

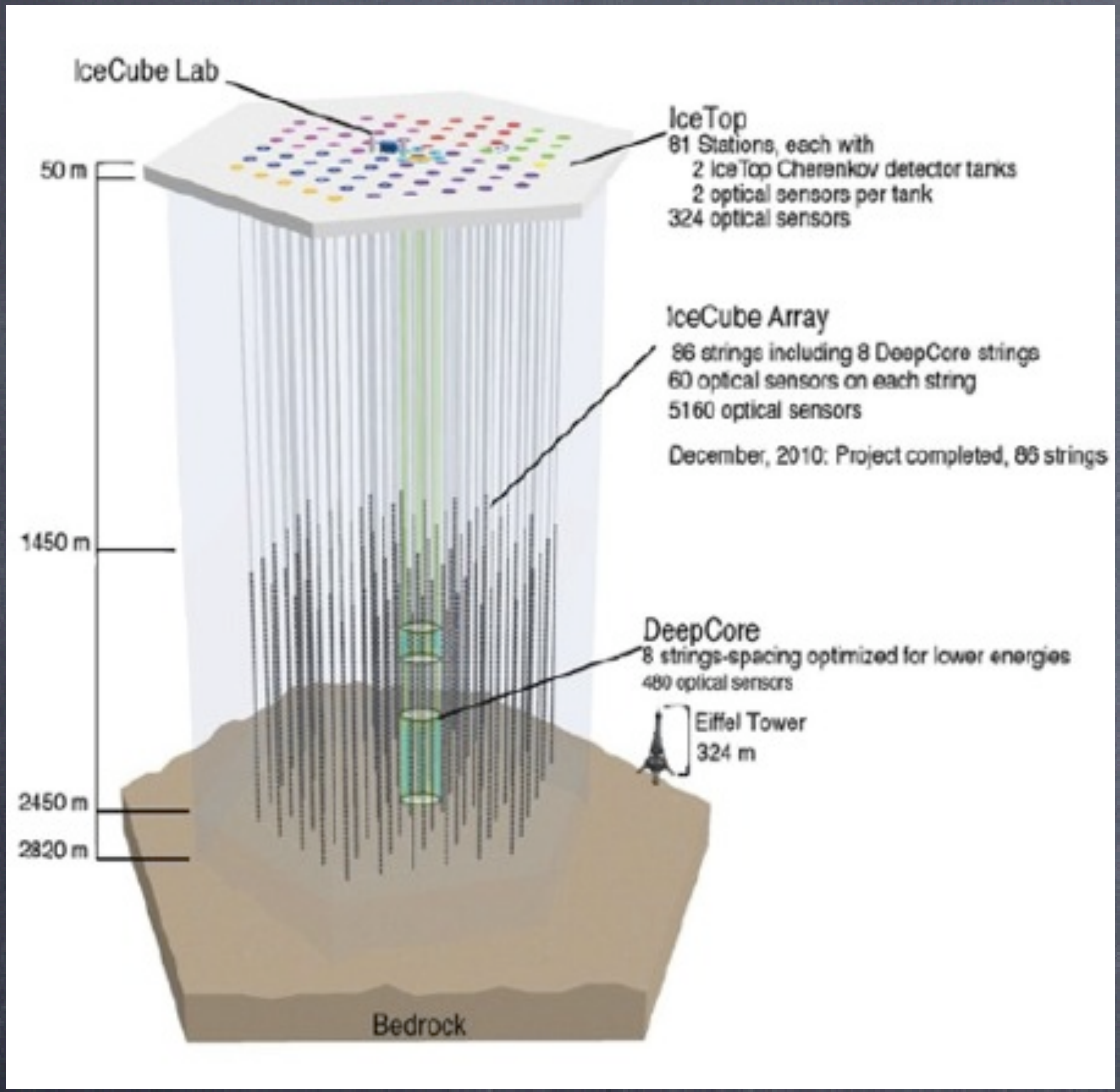
LArTPC



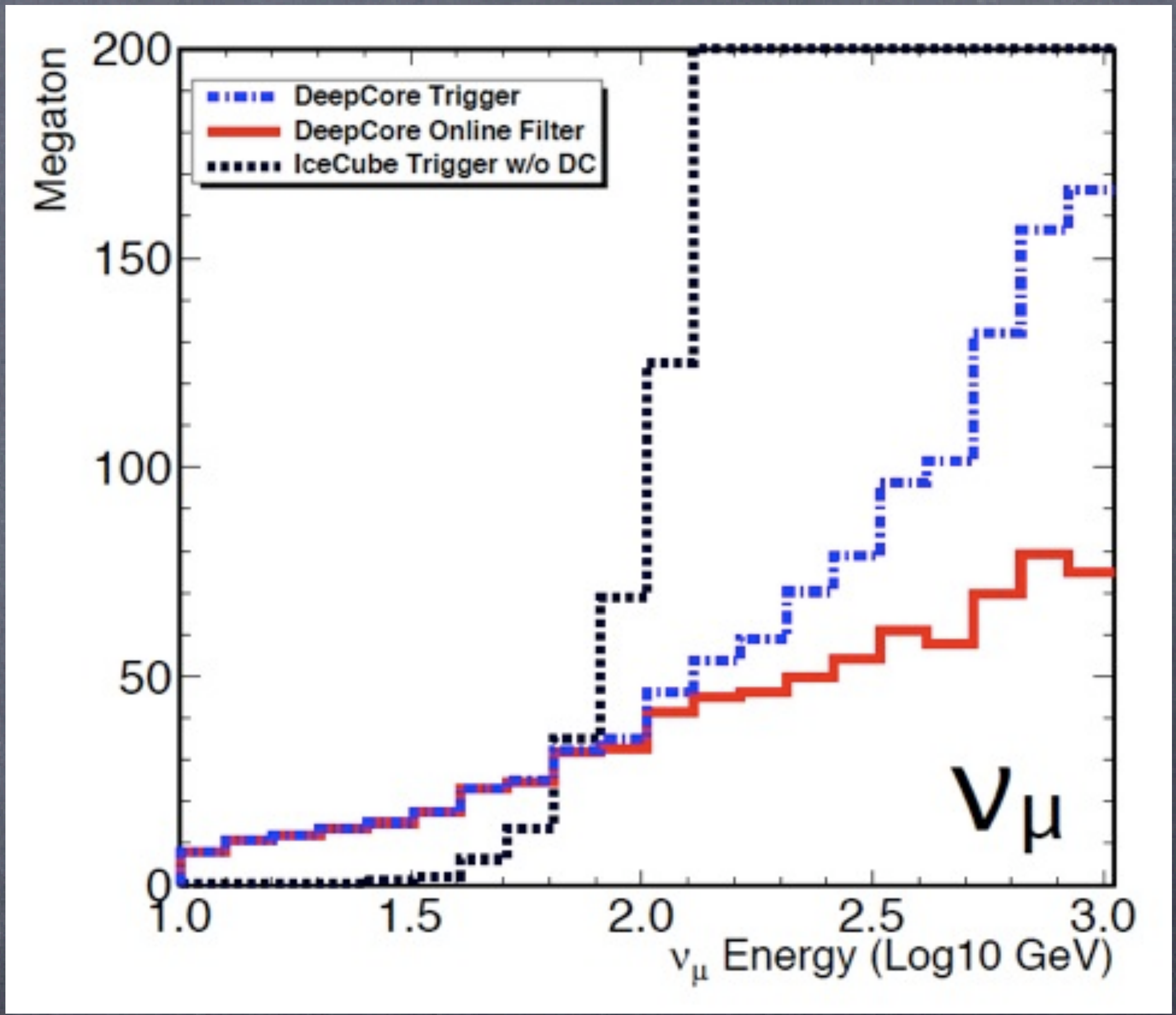
$m_\chi = 25$ GeV $\quad Br_{\tau^+\tau^-} = 100\%$

S. K. Agarwalla, M. Blennow, E. Fernández-Martínez and O. Mena, *JCAP 1109:004, 2011*

Determining the WIMP mass with DeepCore



C. Rott, *Intensity Frontier Workshop, Fermilab, Batavia (USA) October 2011*



T. DeYoung, *RICAP 2011, Rome (Italy), May 2011*

Angular Resolution:

dominated by the scattering between the incoming neutrino and outgoing muon

$$\theta_{rms} \simeq \sqrt{\frac{\mathrm{GeV}}{E_\nu}}$$

Energy Resolution:

not estimated yet, but it will rely on track length rather than track brightness. Assuming the track estimation to be good to 50 m, we take 10-GeV bins

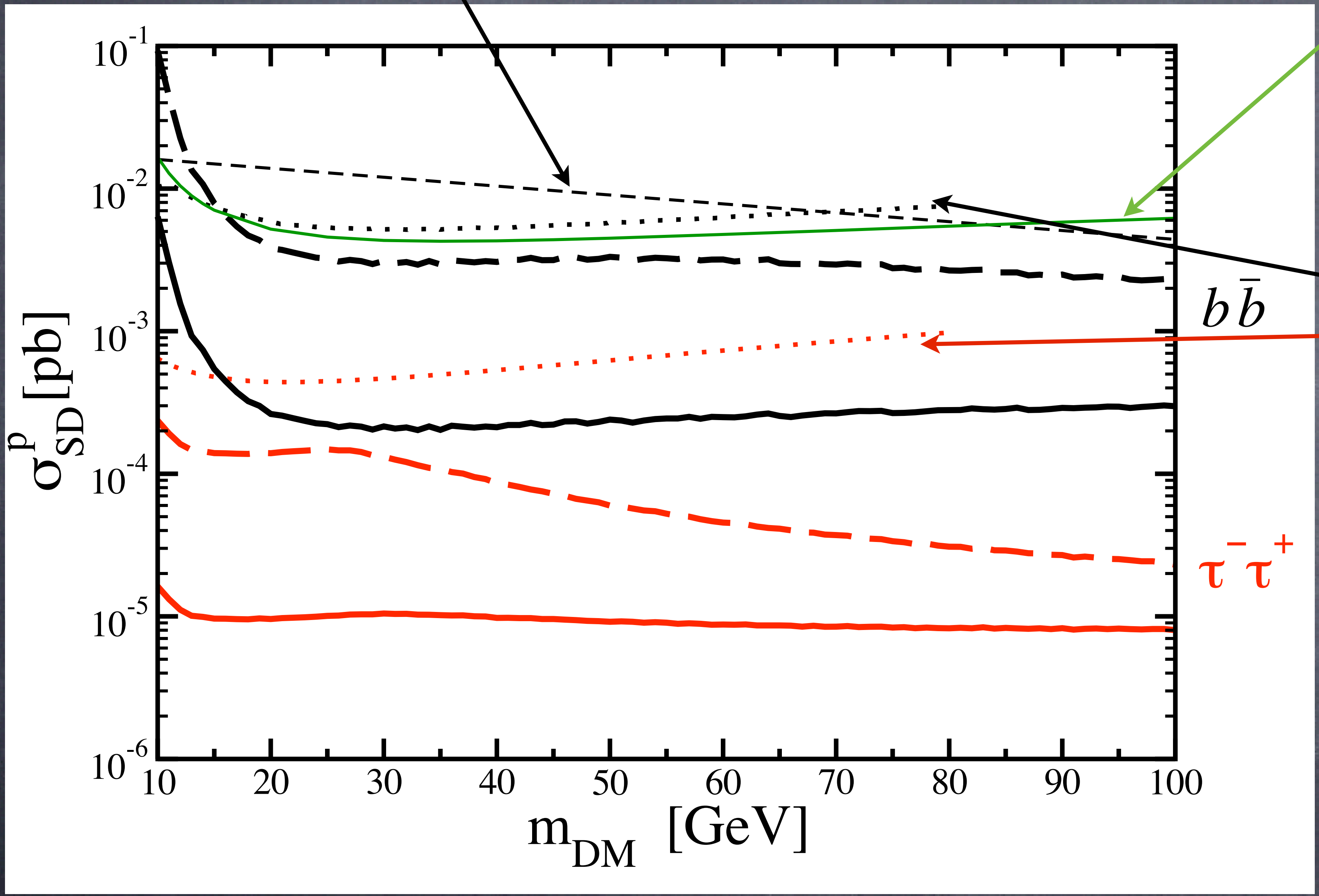
DeepCore Sensitivity to low mass WIMPs

Stopping and through-going muons in SK

T. Tanaka *et al.* [Super-Kamiokande Collaboration], *arXiv:1108.3384*

Direct DM searches

M. Felizardo *et al.* [SIMPLE Collaboration], *arXiv:1106.3014*



Fully-contained and stopping muons in SK

R. Kappl and M. W. Winkler, *Nucl. Phys. B850:505, 2011*

C. R. Das, O. Mena, SPR and S. Pascoli, *arXiv:1110.5095*

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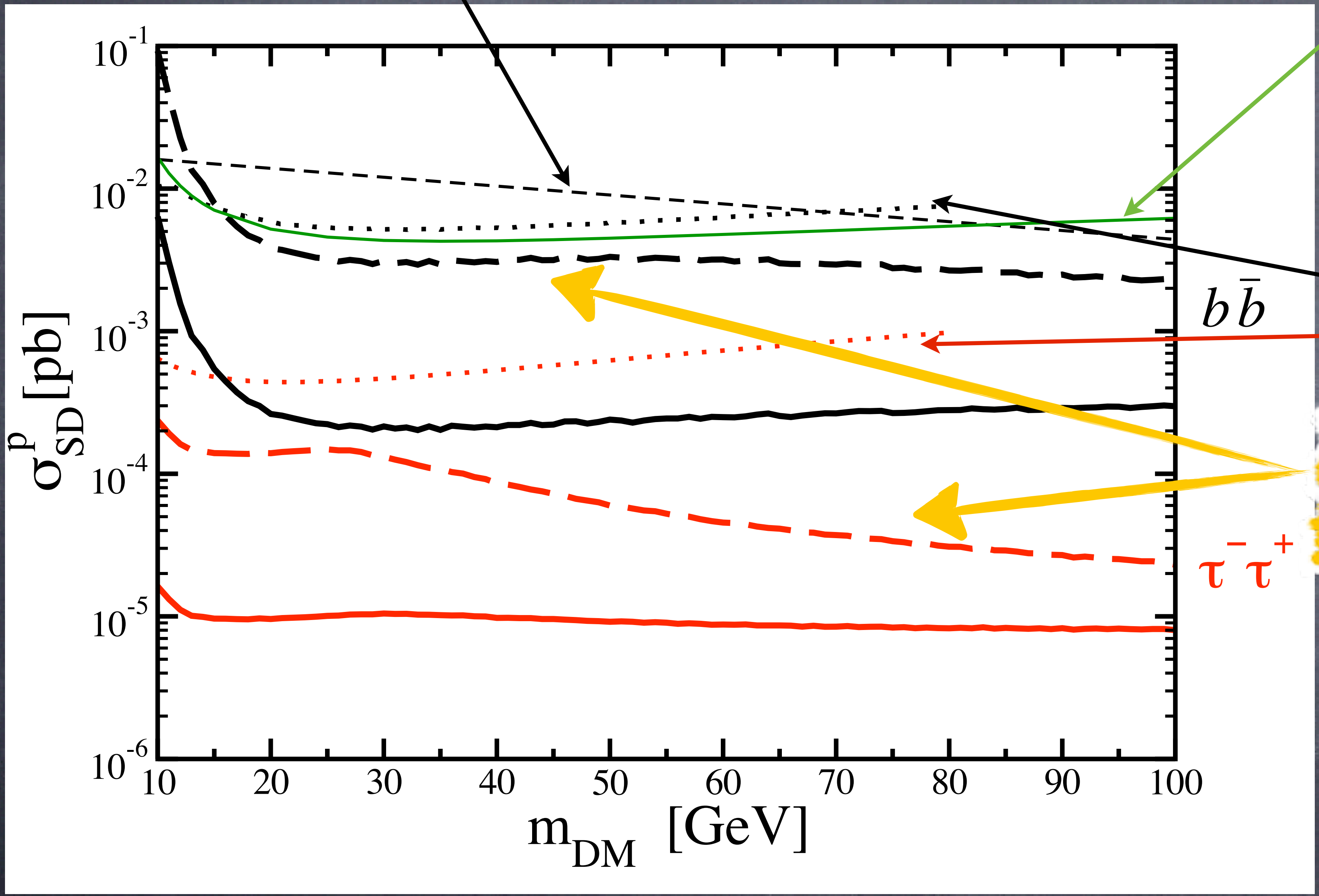

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Systematic error = 15%

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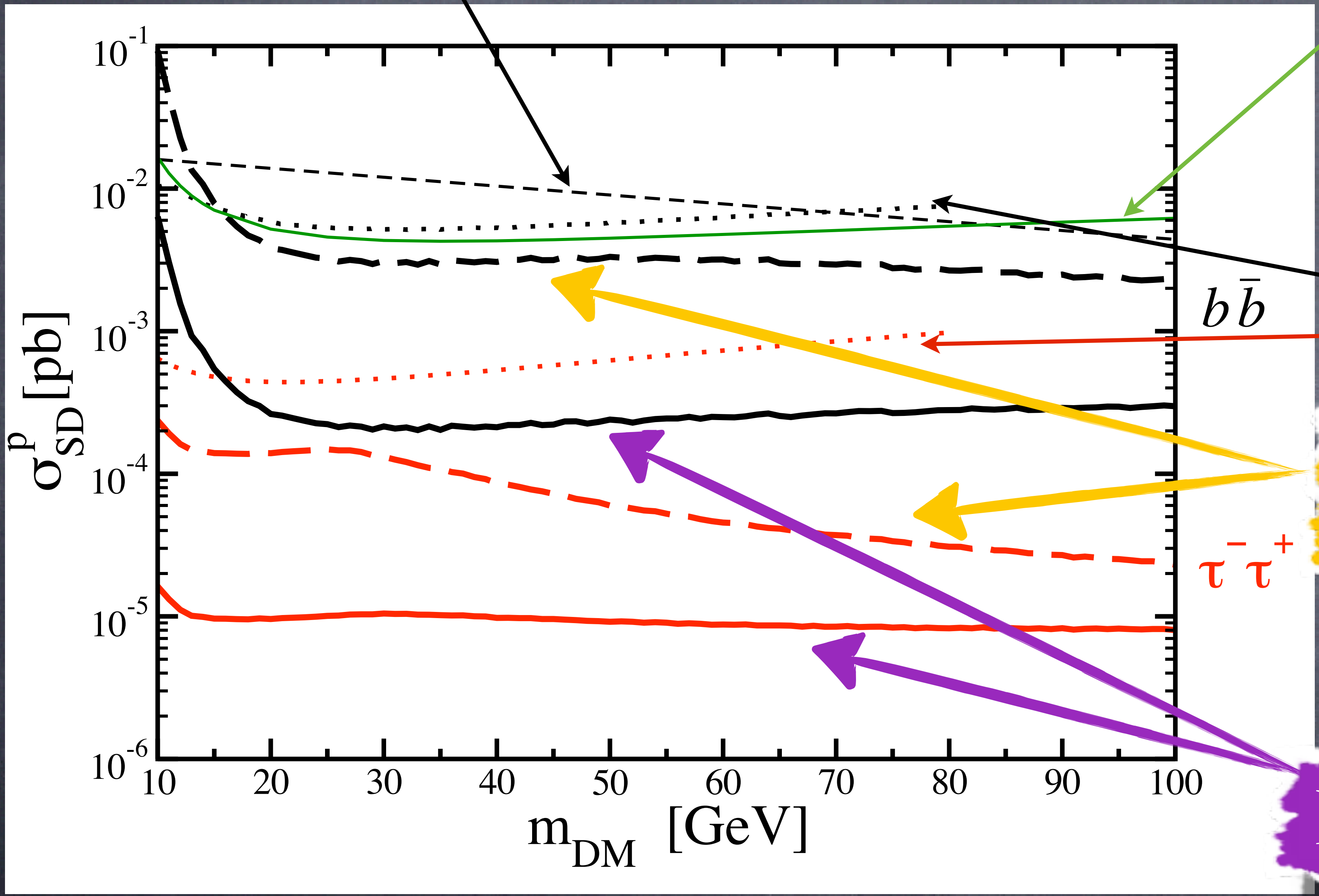


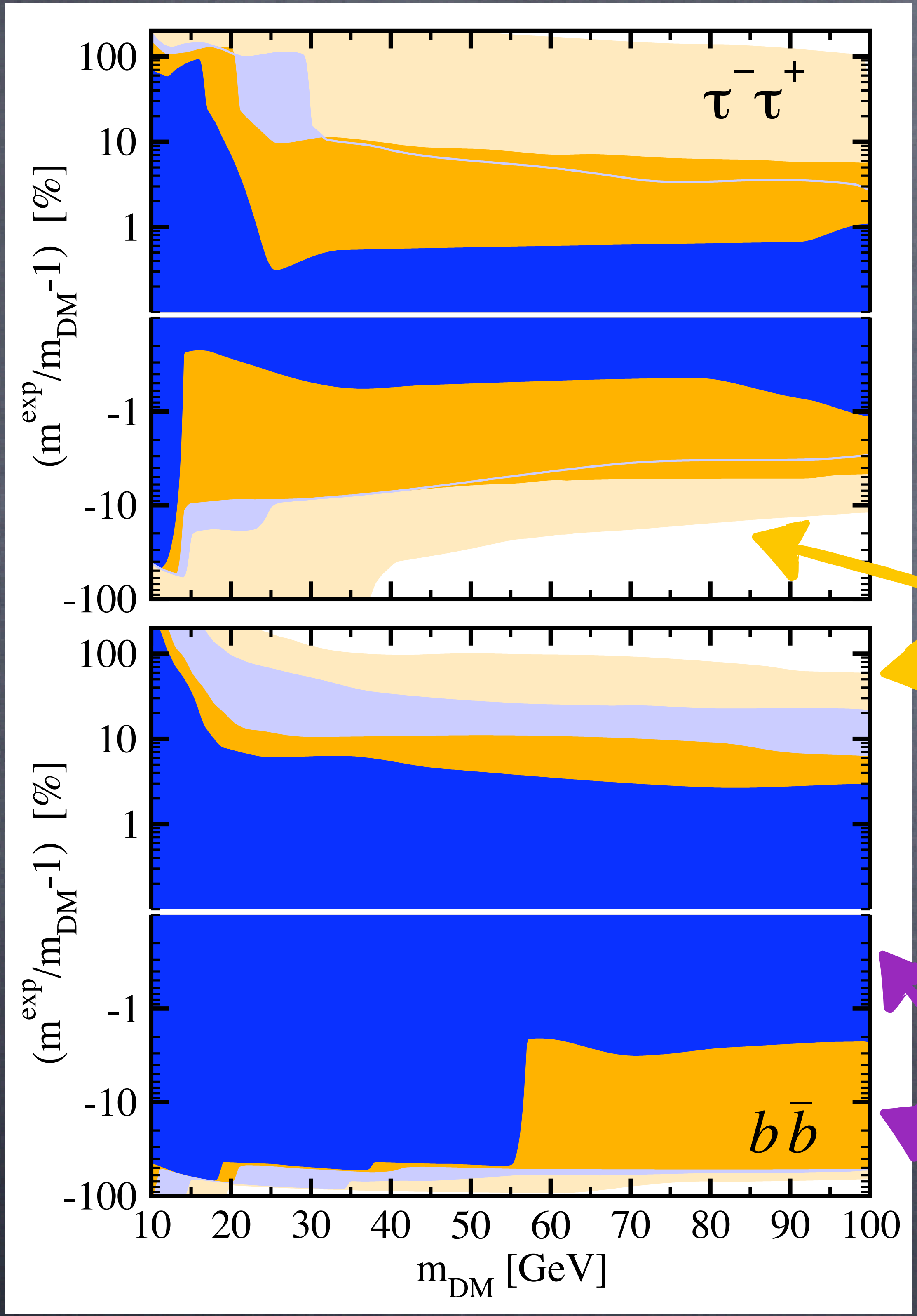
Systematic error = 15%

No systematic error

C. R. Das, O. Mena, SPR and S. Pascoli, *arXiv:1110.5095*

Determination of the DM mass at DeepCore

(after marginalizing with respect to cross section and annihilation channel)



$\sigma_{SD}^{p} = 10^{-3}\,pb$

$\sigma_{SD}^{p} = 10^{-4}\,pb$

Systematic error = 15%

$\sigma_{SD}^{p} = 10^{-2}\,pb$

$\sigma_{SD}^{p} = 4\times10^{-3}\,pb$

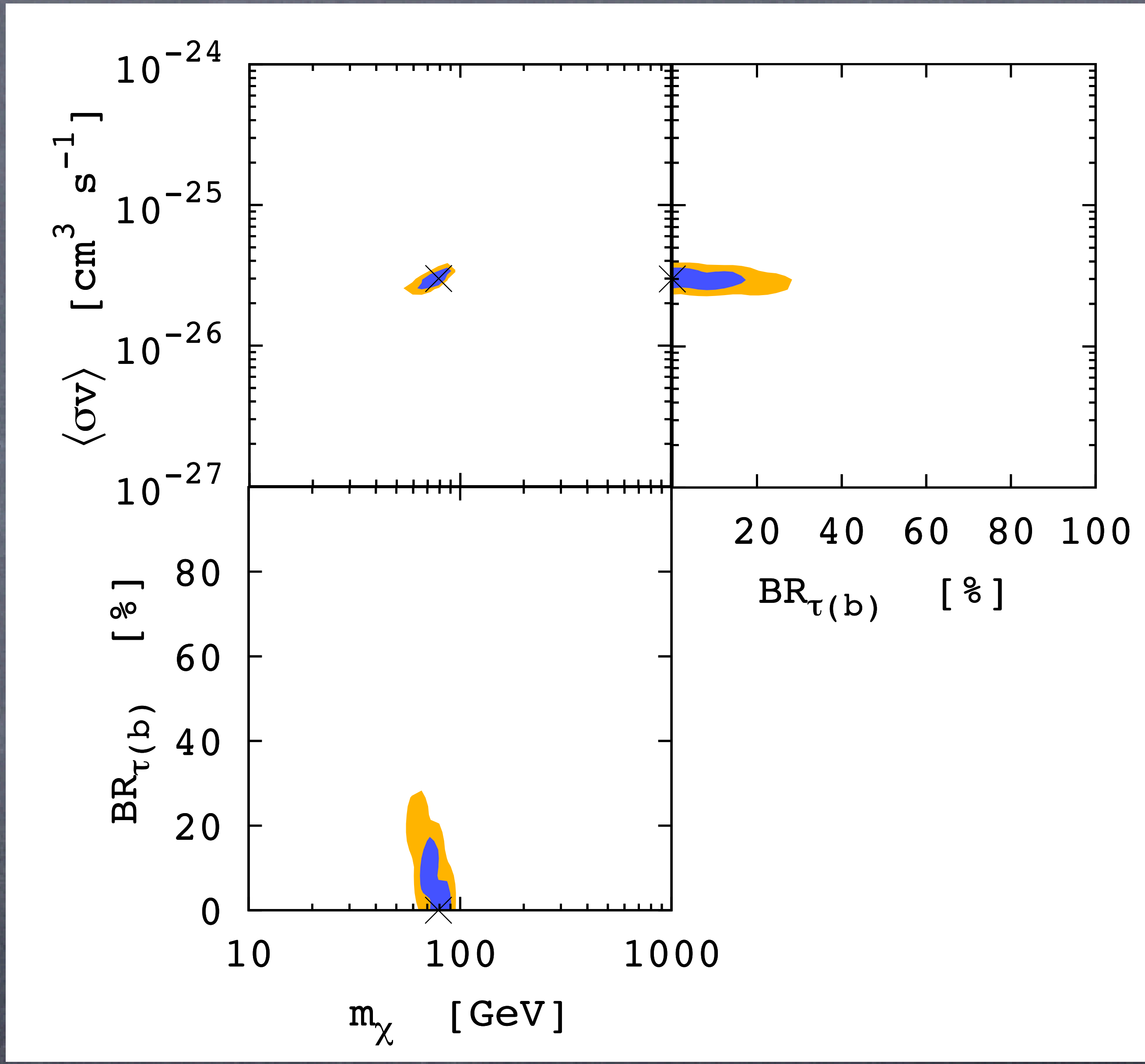
No systematic error

C. R. Das, O. Mena, SPR and S. Pascoli, *arXiv:1110.5095*

Comments on uncertainties: signal

- Uncertainties on the capture rate calculation: important for masses >> 100 GeV
- Uncertainties on the overall normalization, e.g., local DM density
- Contribution due to EW corrections: important for masses >>100 GeV
- Contribution of more annihilation channels

Example: gamma rays



N. Bernal and SPR, *arXiv:1006.0477* and *arXiv:1103.2377*

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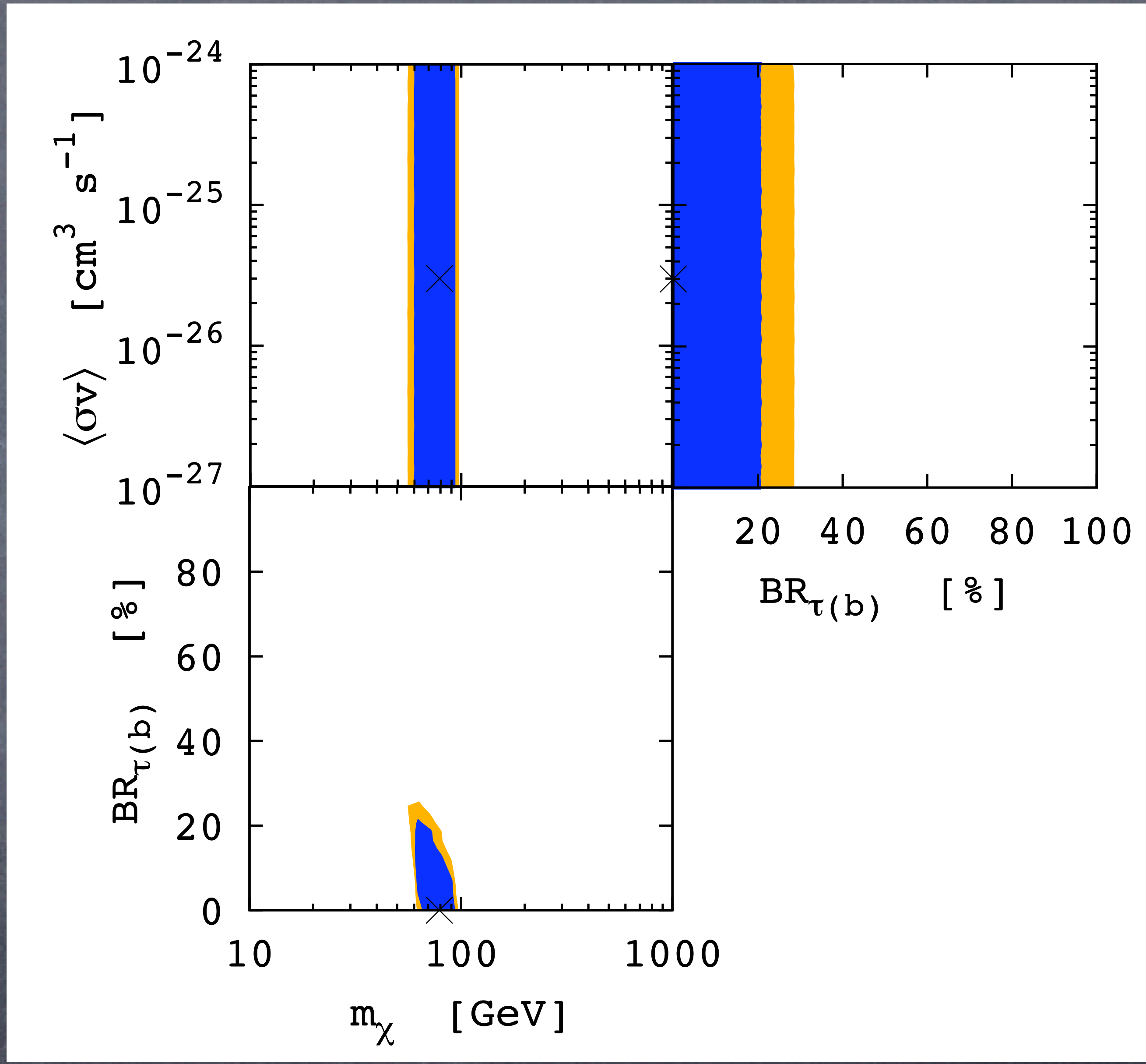
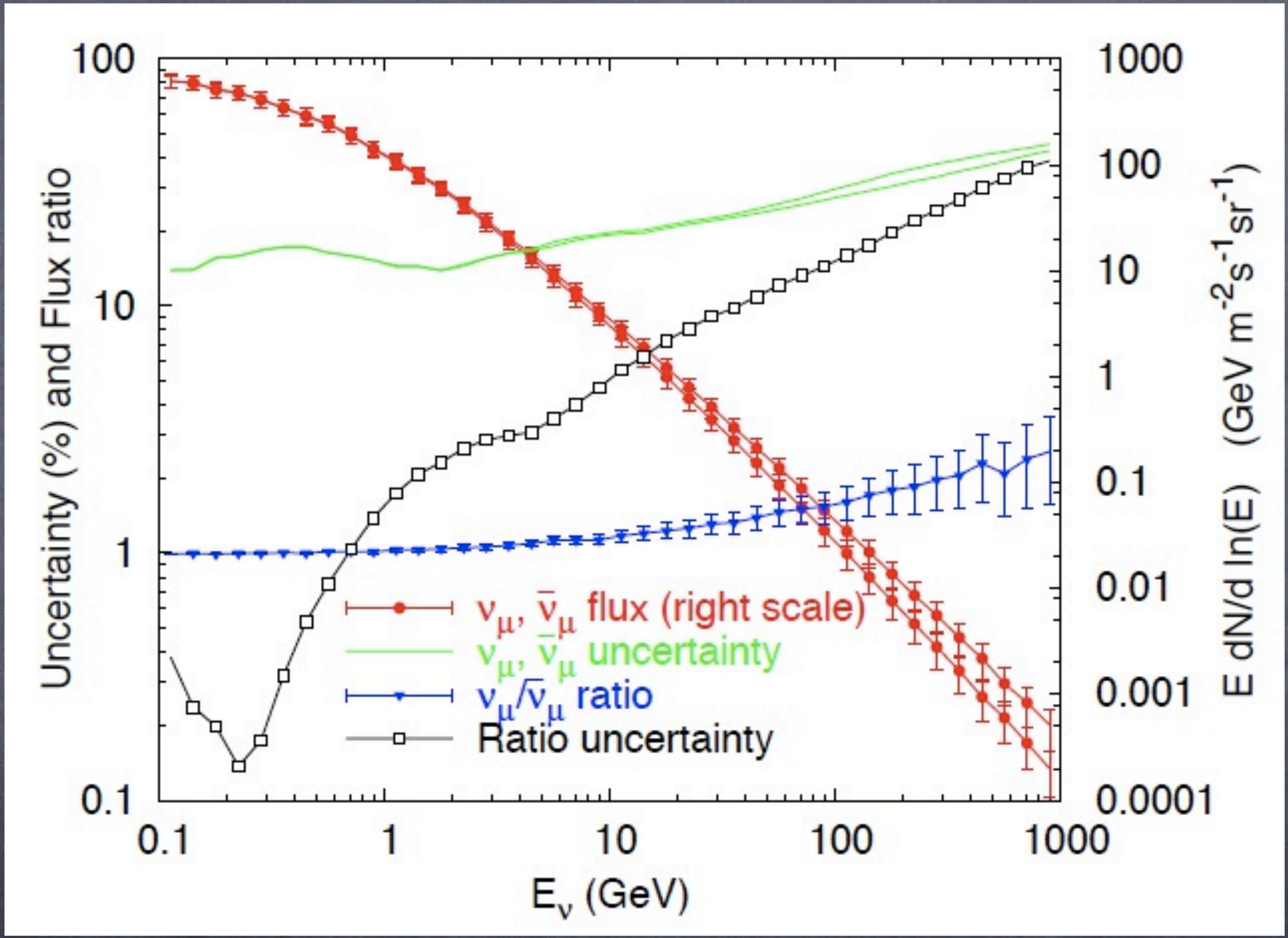


N. Bernal and SPR, *arXiv:1006.0477* and *arXiv:1103.2377*

Comments on uncertainties: background



G. D. Barr, T. K. Gaisser, S. Robbins and T. Stanev, *Phys. Rev. D74:094009, 2006*

Other ways to determine the DM mass

- Colliders

G. Polesello and D. R. Tovey, *JHEP 05:071, 2004*
N. M. Nojiri, G. Polesello and D. R. Tovey, *JHEP 03:063, 2006*
E. A. Baltz, M. Battaglia, M. E. Peskin and T. Wizansky, *Phys. Rev. D74:103521, 2006*
G. Belanger, O. Kitter, S. Kraml, H. U. Martyn and A. Pukhov, *Phys. Rev. D78:015011, 2008*
R. L. Arnowitt, B. Dutta, A. Gurrola, T. Kamon, A. Krislock and D. Toback, *Phys. Rev. Lett. 100:231802, 2008*
B. Altunkaynak, M. Holmes and B. D. Nelson, *JHEP 10:013, 2008*
N. Alster and M. Battaglia, *arXiv:1104.0523*

- Direct searches

A. M. Green, *JCAP 0708:022, 2007* and *JCAP 0807:005, 2008*
M. Drees, C.-L. Shan, *JCAP 0806:012, 2008*
L. E. Strigari and R. Trotta, *JCAP 0911:019, 2009*
A. H. G. Peter, *Phys. Rev. D81:087301, 2010*
Y.-T. Chou and C.-L. Shan, *JCAP 1008:014, 2010*
J. Billard, F. Mayet and D. Santos, *Phys. Rev. D83:075002, 2011*

- Indirect gamma-ray searches

S. Dodelson, D. Hooper and P. D. Serpico, *Phys. Rev. D77:063512, 2008*
T. E. Jeltema and S. Profumo, *JCAP 0811:003, 2008*
N. Bernal, A. Goudelis, Y. Mambrini and C.Muñoz, *JCAP 0901:046, 2009*
SPR and J. Siegal-Gaskins, *JCAP 07:023, 2010*
N. Bernal and SPR, *arXiv:1006.0477, arXiv:1103:2377*

- Neutrinos from the Sun:

Using the angular distribution/Using seasonal variation

J. Edsjö and P. Gondolo, *Phys. Lett. B357: 595, 1995* A. Esmaili and Y. Farzan, JCAP 1104:007, 2011

Conclusions

- Searches of neutrinos from DM annihilations taking place in the Sun could constitute powerful probes of WIMP properties
- Icecube (DeepCore) is starting having data
- SK and future neutrino detectors will also play a role, mainly for low masses
- Uncertainties need to be taken into account, although an uncertainty in the normalization of the flux does not (significantly) affect the determination of the DM mass, which might be achieved at the O(10%) level
- We just need... a signal!