Beyond Dark Matter Detection with Neutrino Telescopes

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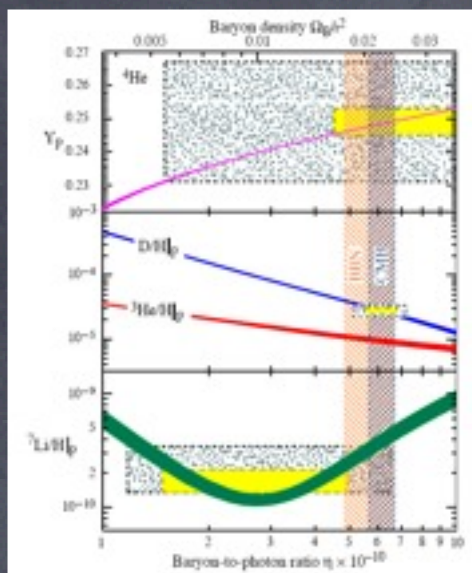
Instituto Superior Técnico, Lisboa

What is ν?

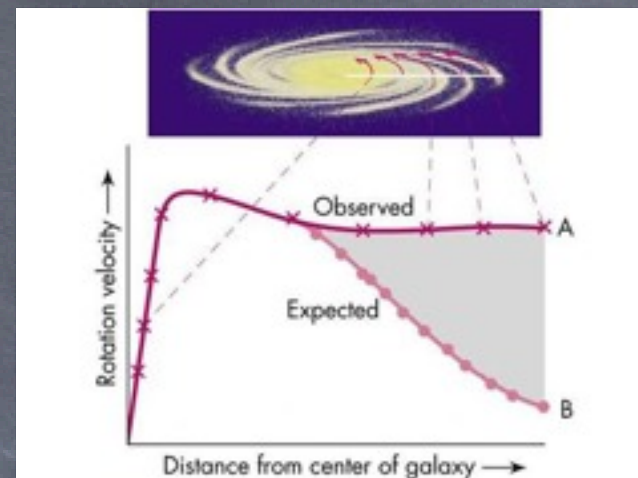
From new experimental neutrino results to a deeper understanding of theoretical physics and cosmology

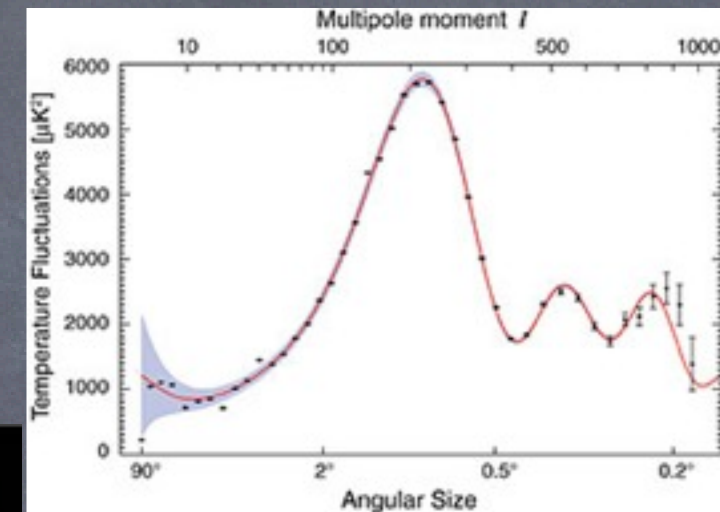
Florence, July 9, 2012

Astro/Cosmo Evidences of DM

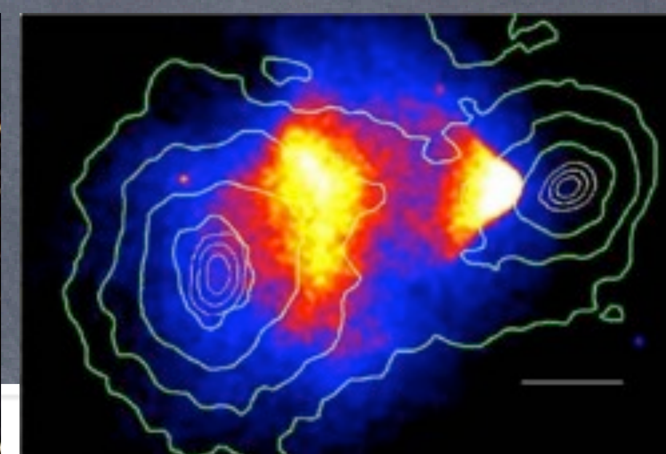


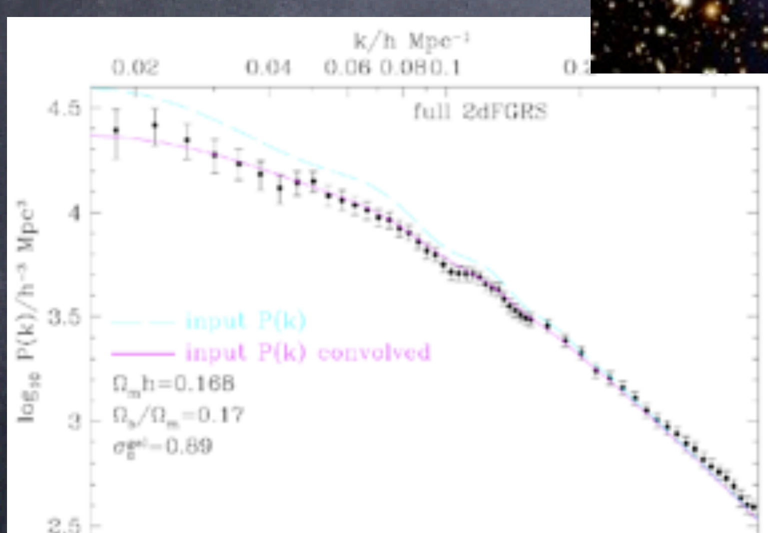
B. D. Fields and S. Sarkar, *PDG*



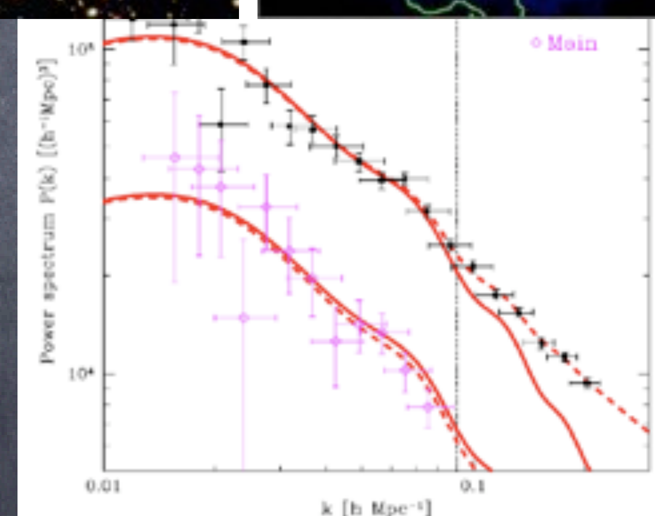


NASA/WMAP Science Team

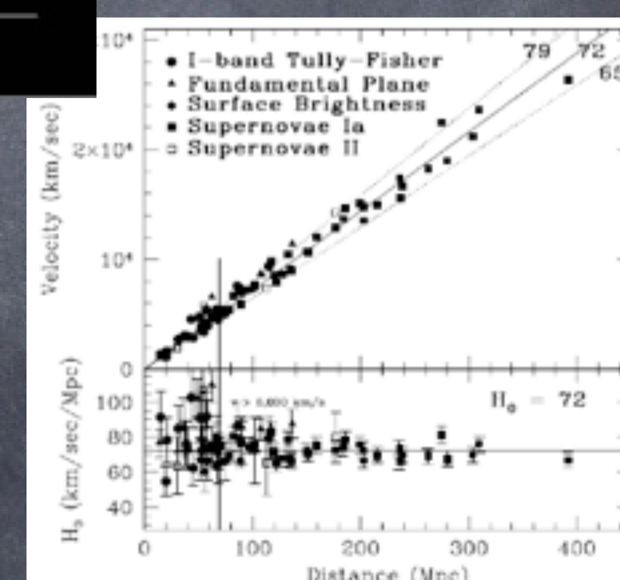




S. Cole *et al.* [2dFGRS Collaboration], *Mon. Not. Roy. Astron. Soc. 362:505, 2005*

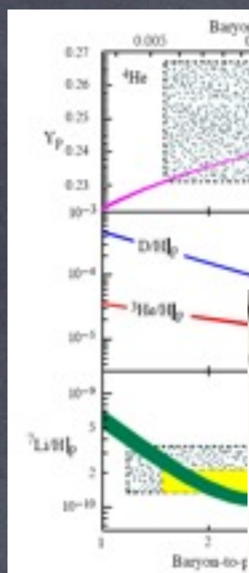


M. Tegmark *et al.* [SDSS Collaboration], *Phys. Rev. D74:123507, 2006*



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

Astro/Cosmo Evidences of DM



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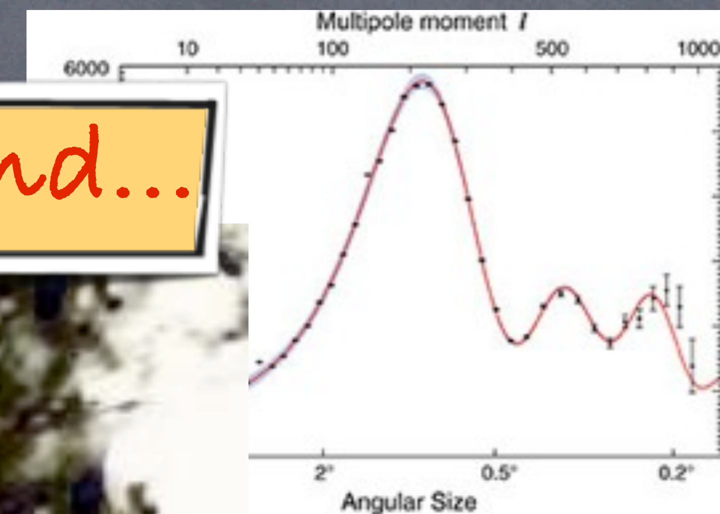
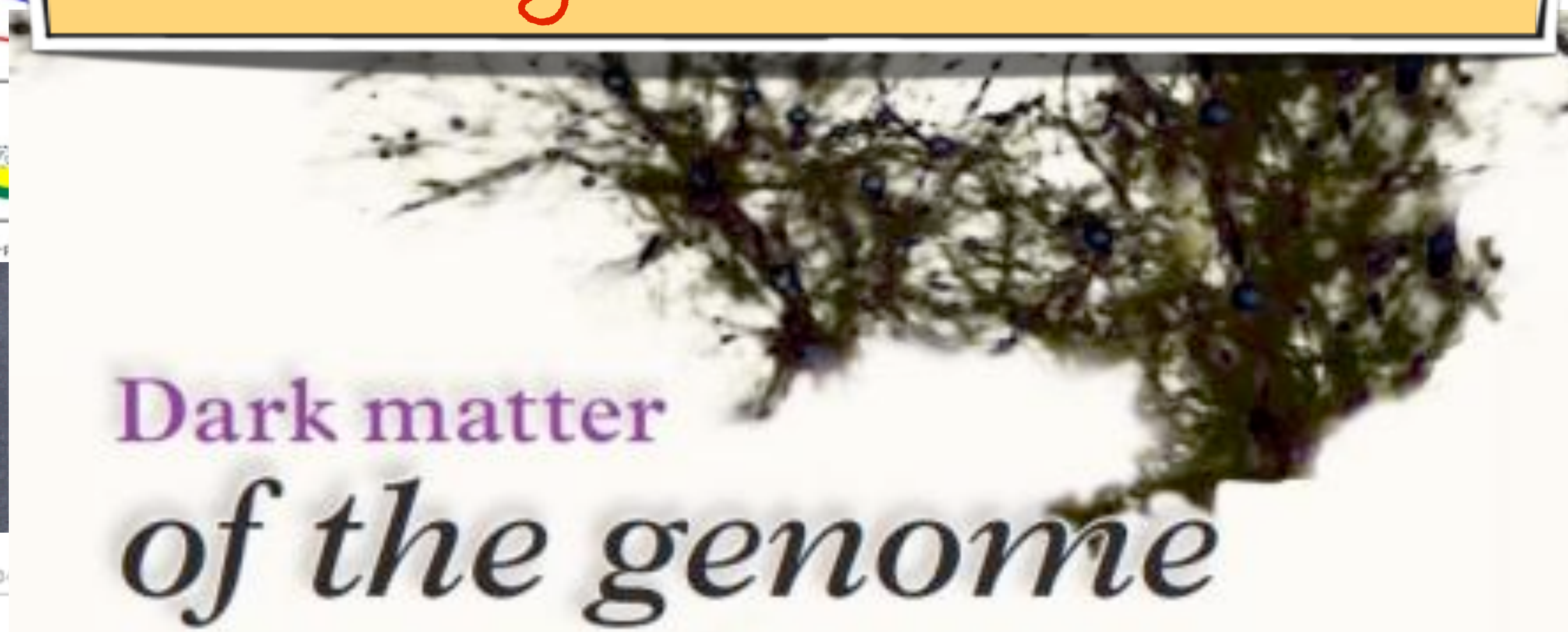
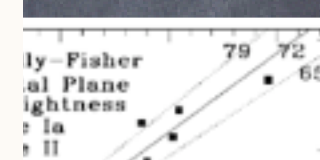


WMAP Science Team

Not the only Dark Matter around...



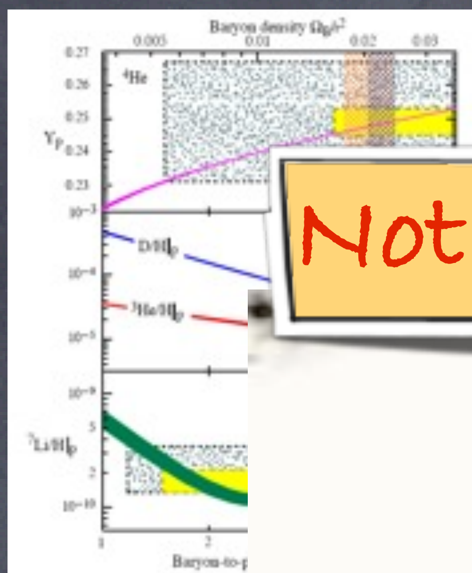


"The genomes of multicellular animals are big and complex, but functions have been defined for only a small proportion of them. Only 1% of the human genome is transcribed into protein-coding messenger RNA (mRNA) and non-protein-coding RNA (ncRNA), and DNA elements that control the expression of genes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

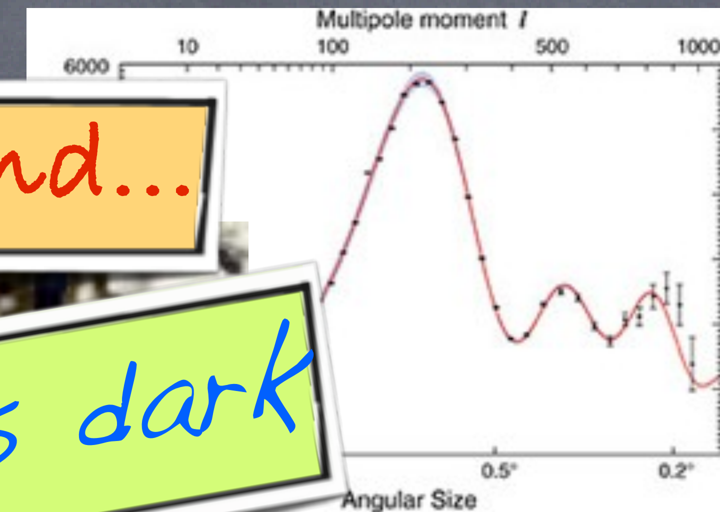
M. Blaxter, "Revealing the Dark Matter of the Genome", Science 330, 1758, 2010

n],

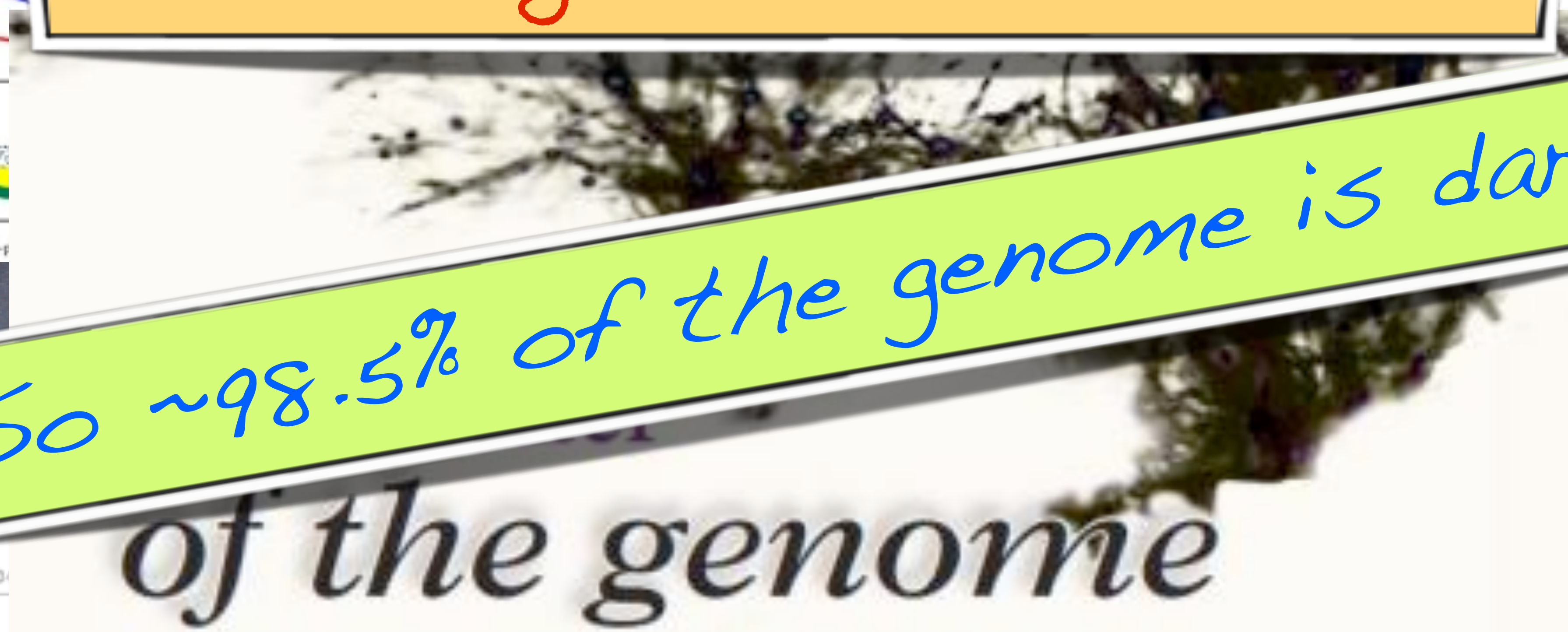
Astro/Cosmo Evidences of DM

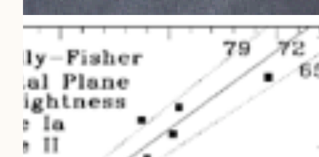


B. D. Fields and



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."

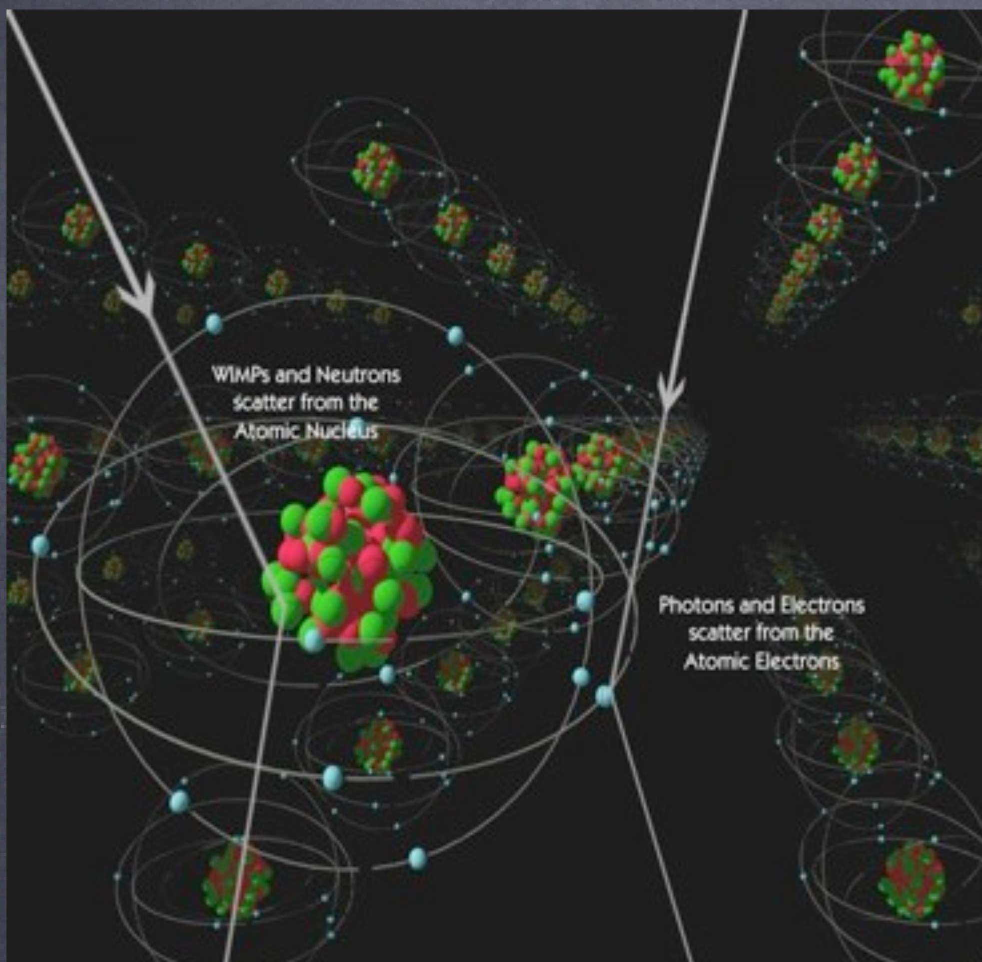
M. Blaxter, "Revealing the Dark Matter of the Genome", Science 330, 1758, 2010

n],

Detecting Dark Matter

- Collider Searches
  - Missing Energy (Tevatron, LHC, ILC?)
- Direct Detection
  - Nuclear Recoil produced by DM scattering (CDMS, CRESST, XENON, DAMA/LIBRA, KIMS, CoGeNT, COUPP...)
- Indirect Detection
  - Observation of annihilation/decay products
    - Gamma-ray telescopes (Fermi-LAT, MAGIC, VERITAS, HESS, CANGAROO-III, EGRET...)
    - Antimatter experiments (PAMELA, HEAT, BESS...)
    - Neutrino detectors/telescopes (IceCUBE, ANTARES, AMANDA, Super-Kamiokande...)

Direct Detection of WIMPs



Expected signal:

nuclear recoil: few 10's of keV

featureless exponential

low rates <0.1 events/kg/day

Challenges:

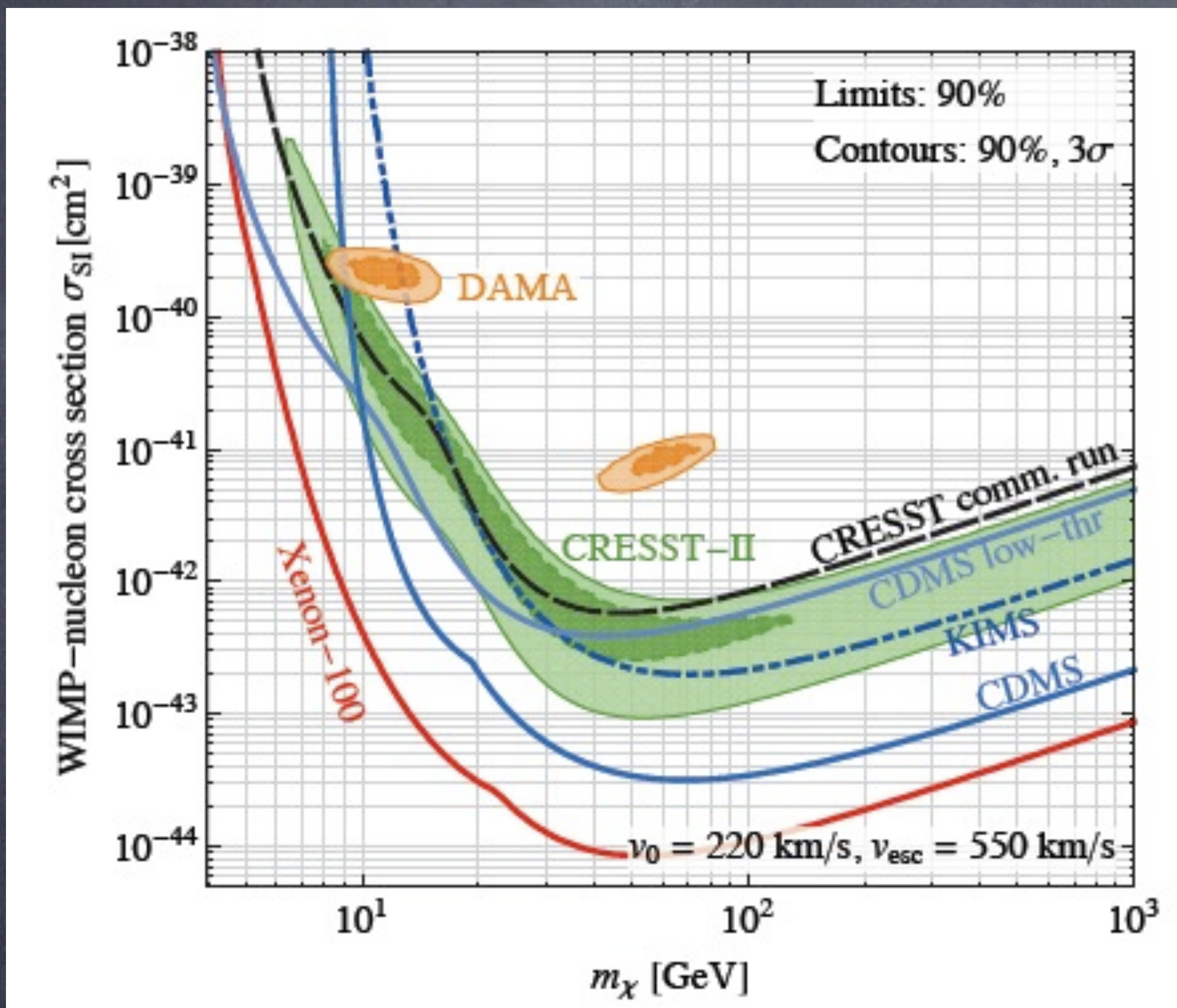
low energy thresholds

large radioactive backgrounds

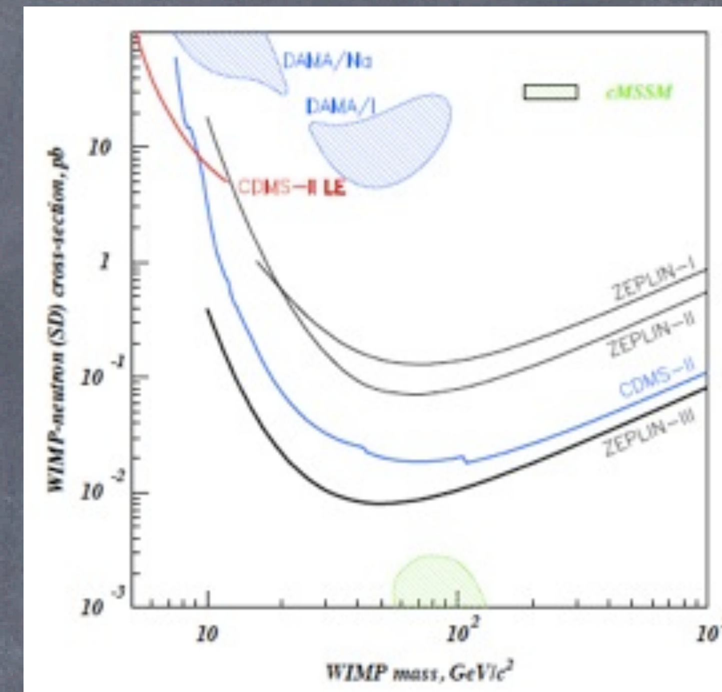
Need to know:

local density, velocity distribution, local circular velocity

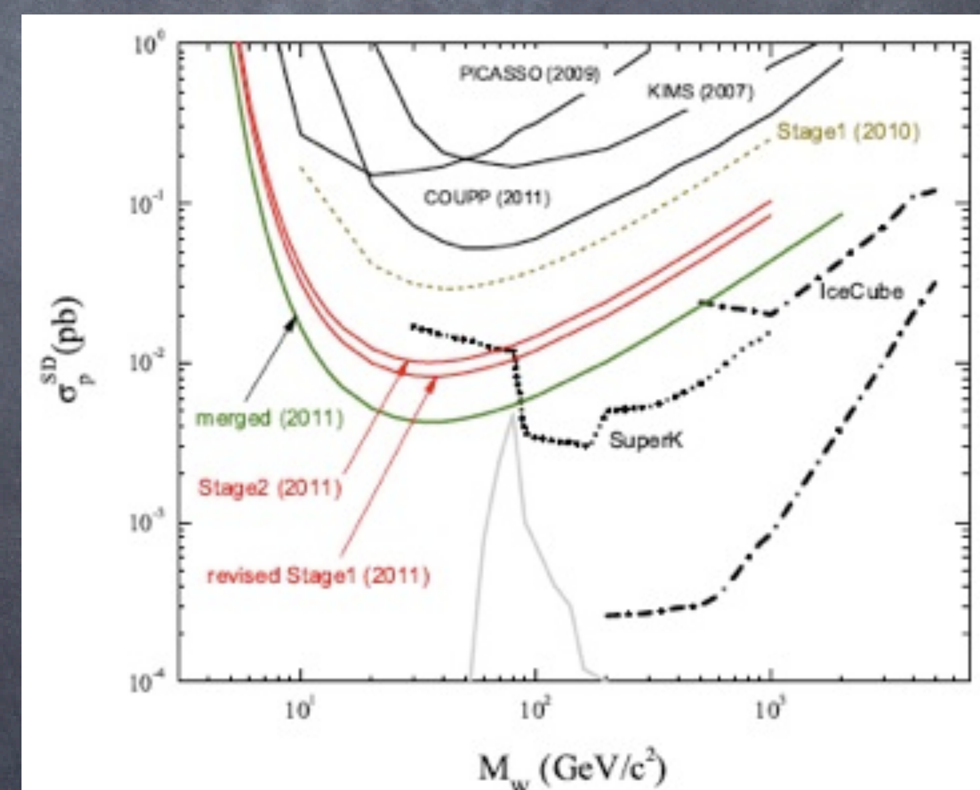
Current Direct Detection searches



J. Kopp, T. Schwetz and J. Zupan, *JCAP 1203:001, 2012*



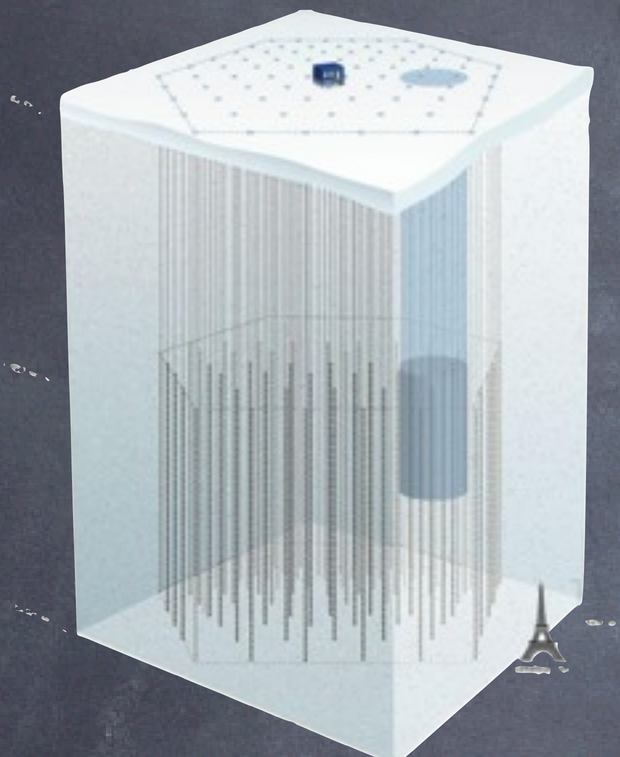
D. Yu. Akimov *et al.* [ZEPLIN Collaboration], *Phys. Lett. B709:14, 2012*

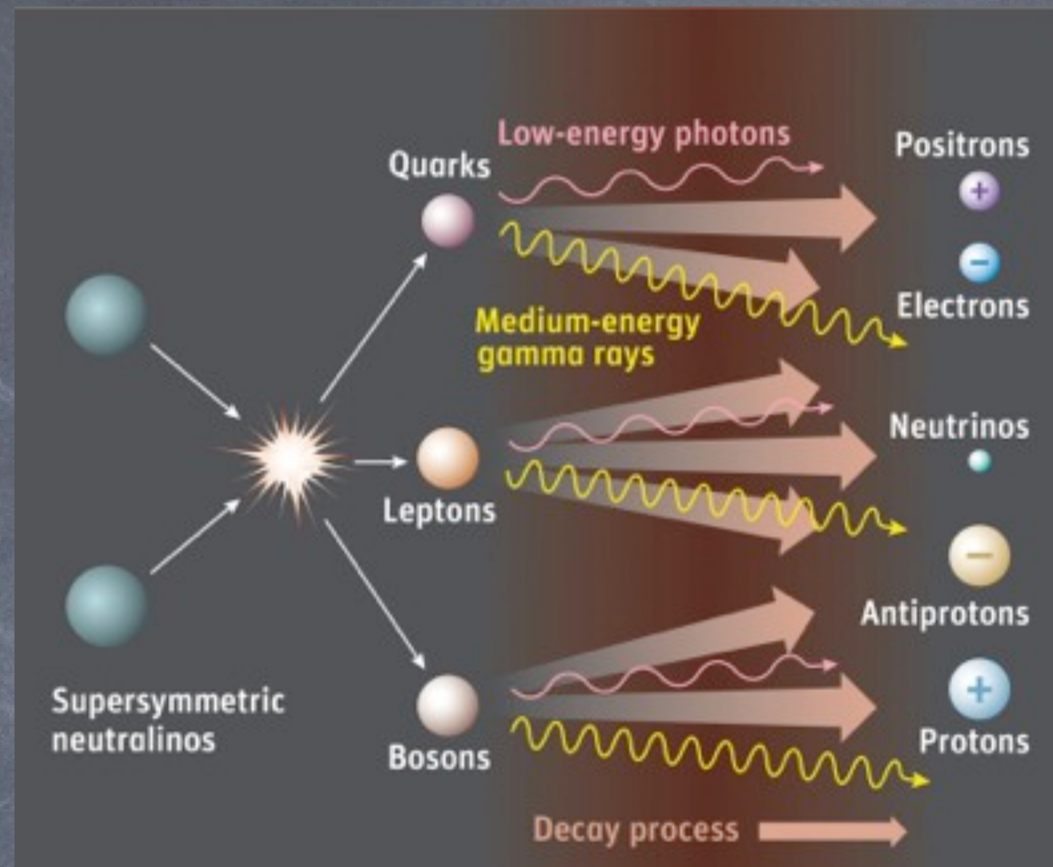


M. Felizardo *et al.* [SIMPLE Collaboration], *arXiv:1106.3014*

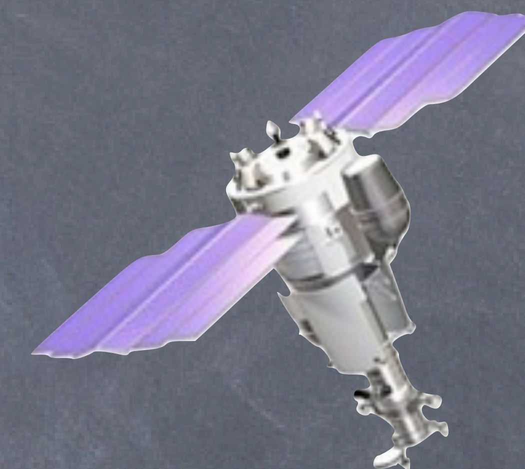
Indirect Detection of WIMPs

IceCube



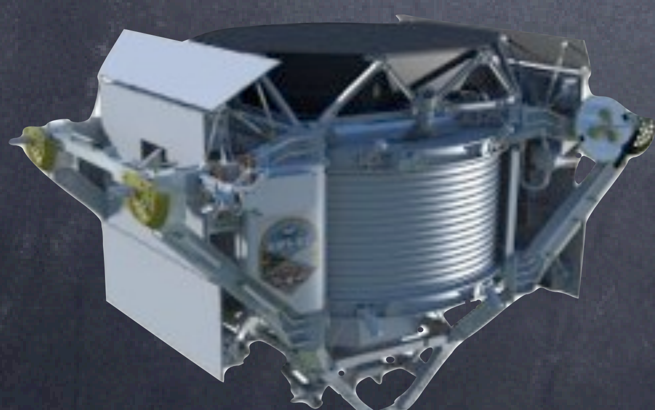


PAMELA



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

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

Indirect Detection

Gamma-rays

Antimatter

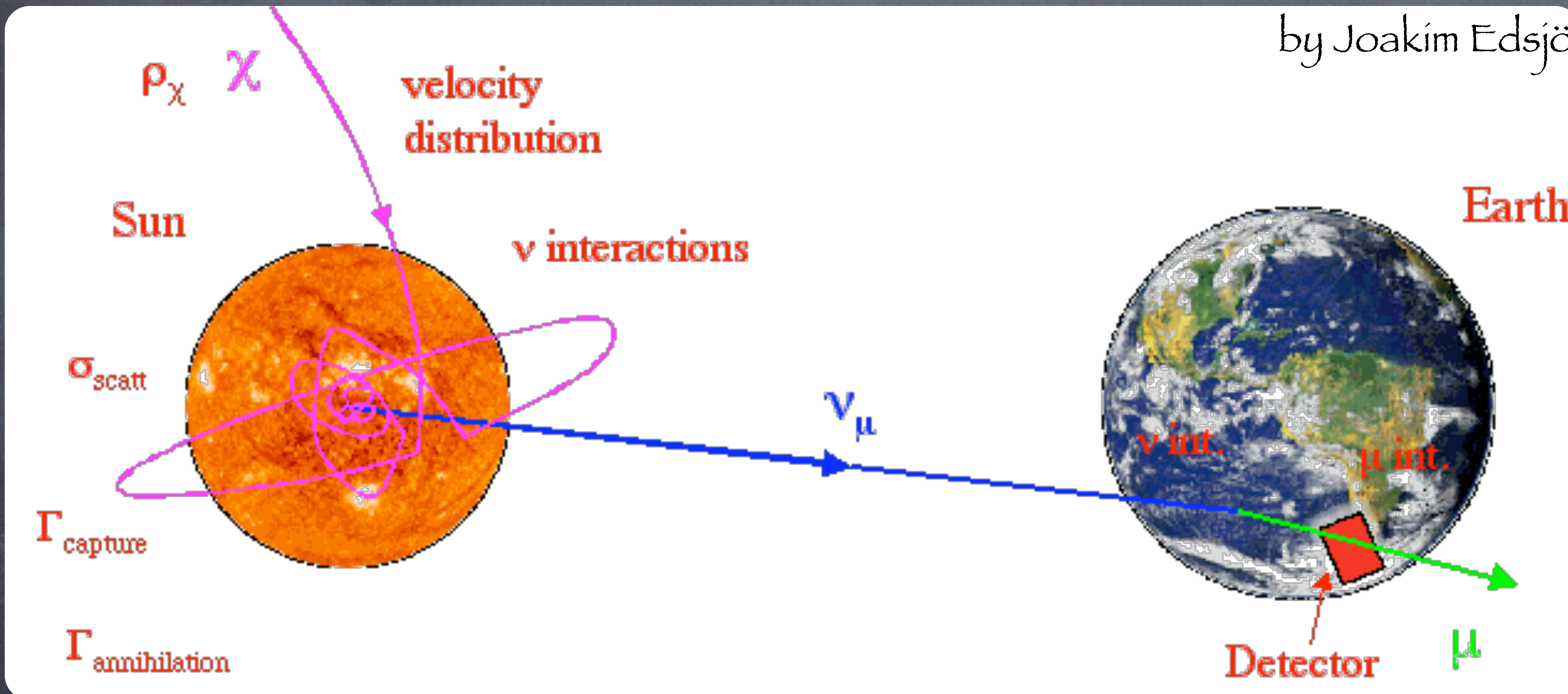
Neutrinos

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*

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

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

Density matrix treatment

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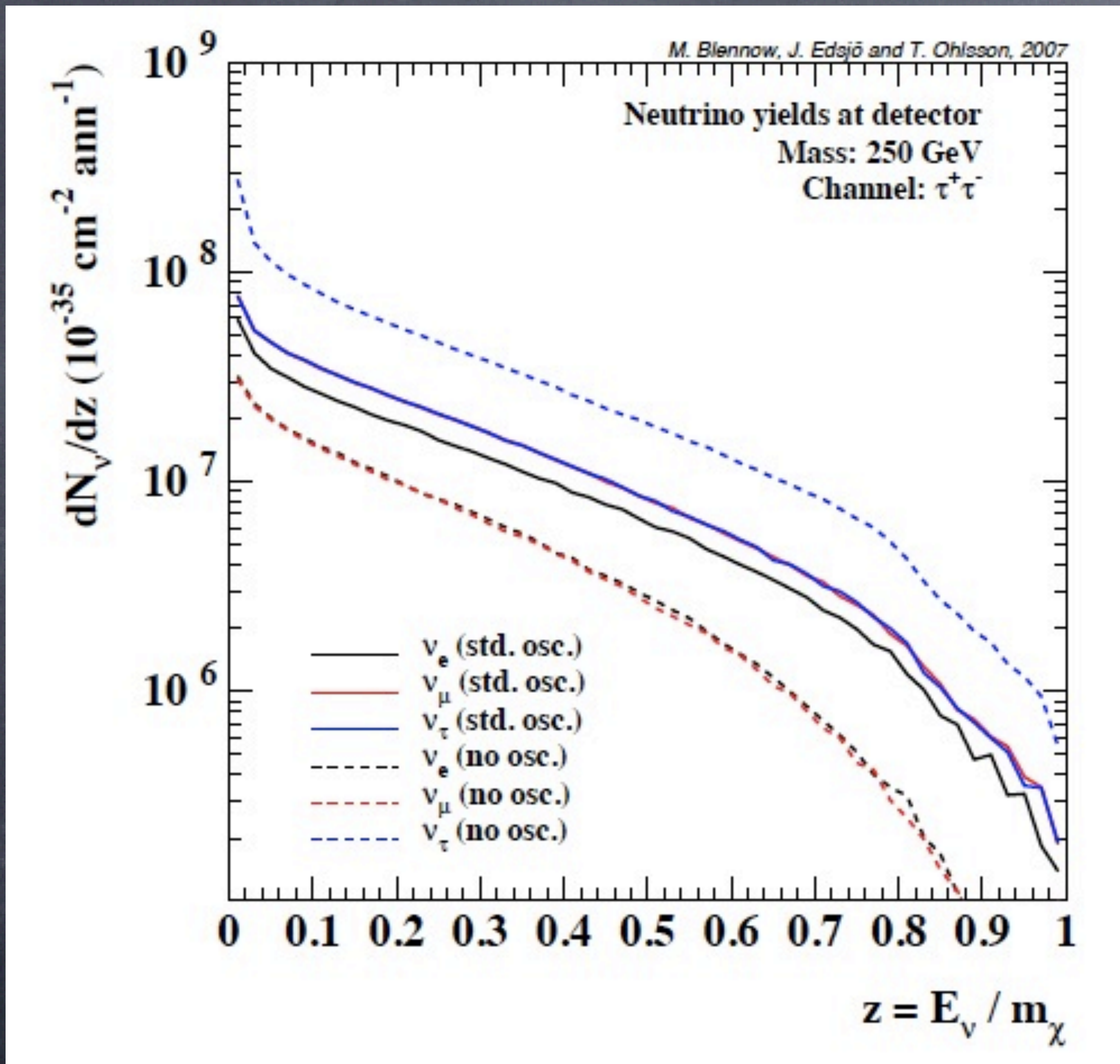
Event-based framework

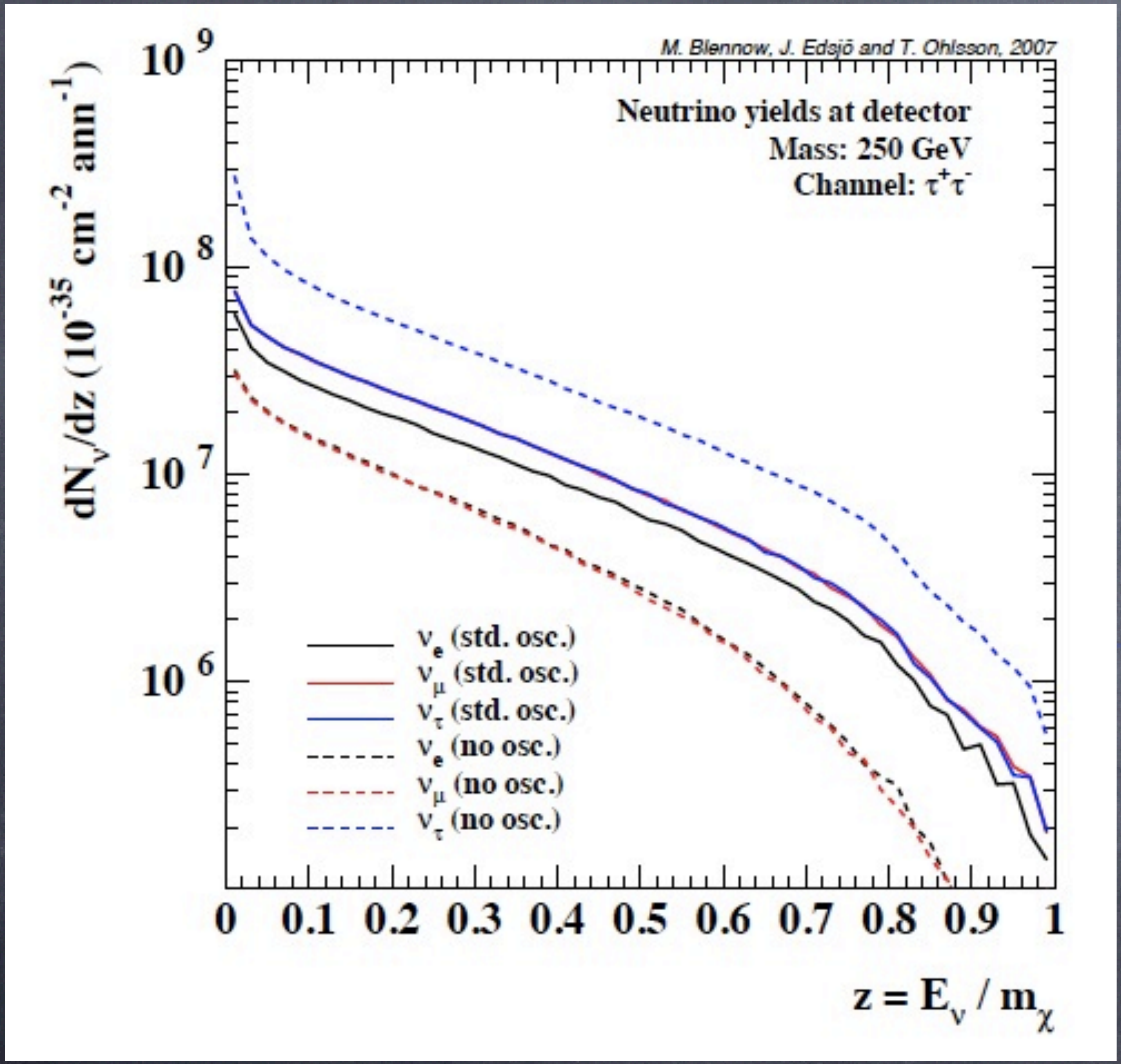


WimpSim

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

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

Event-based framework

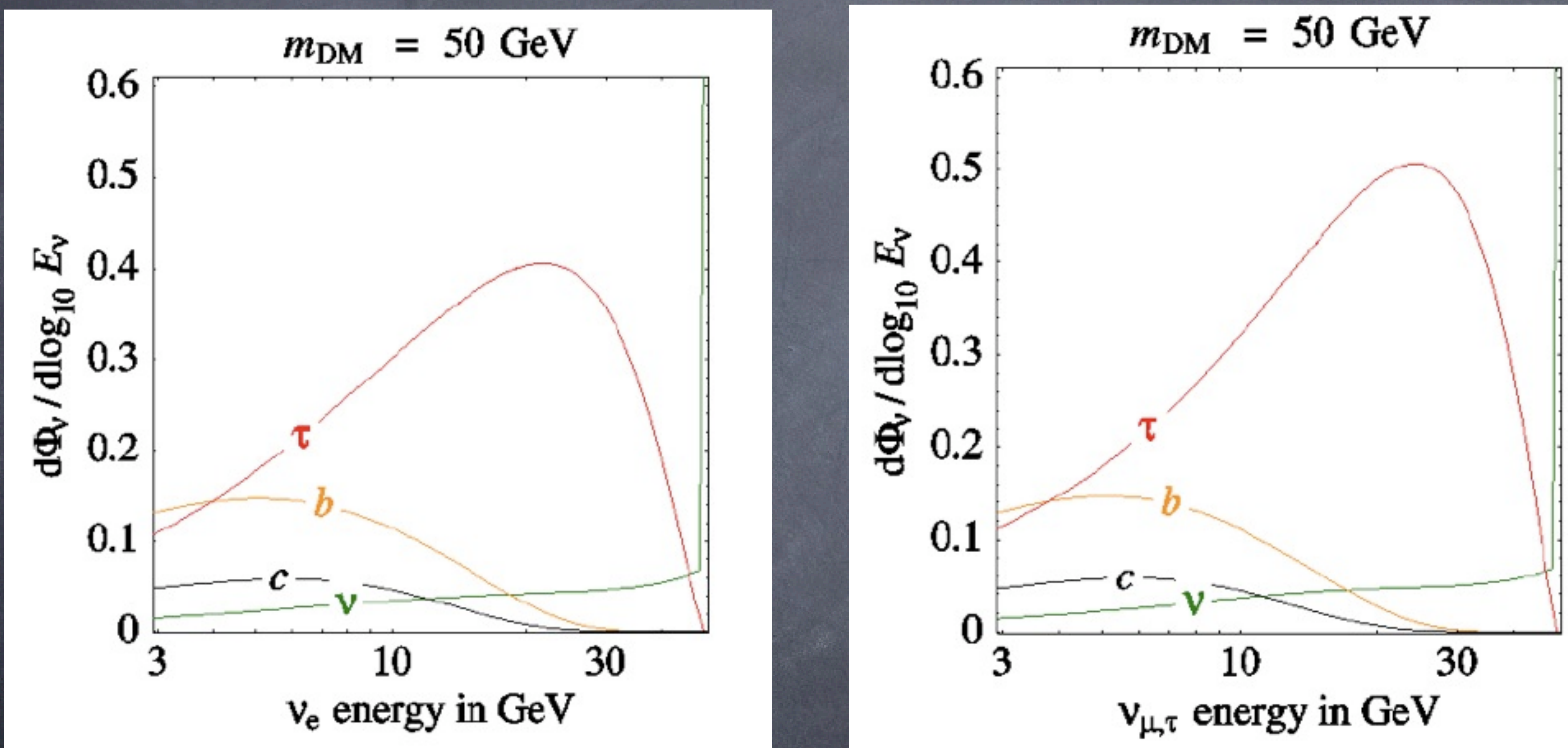


J. Edsjö, http://www.physto.se/~edsjo/wimpsim/

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

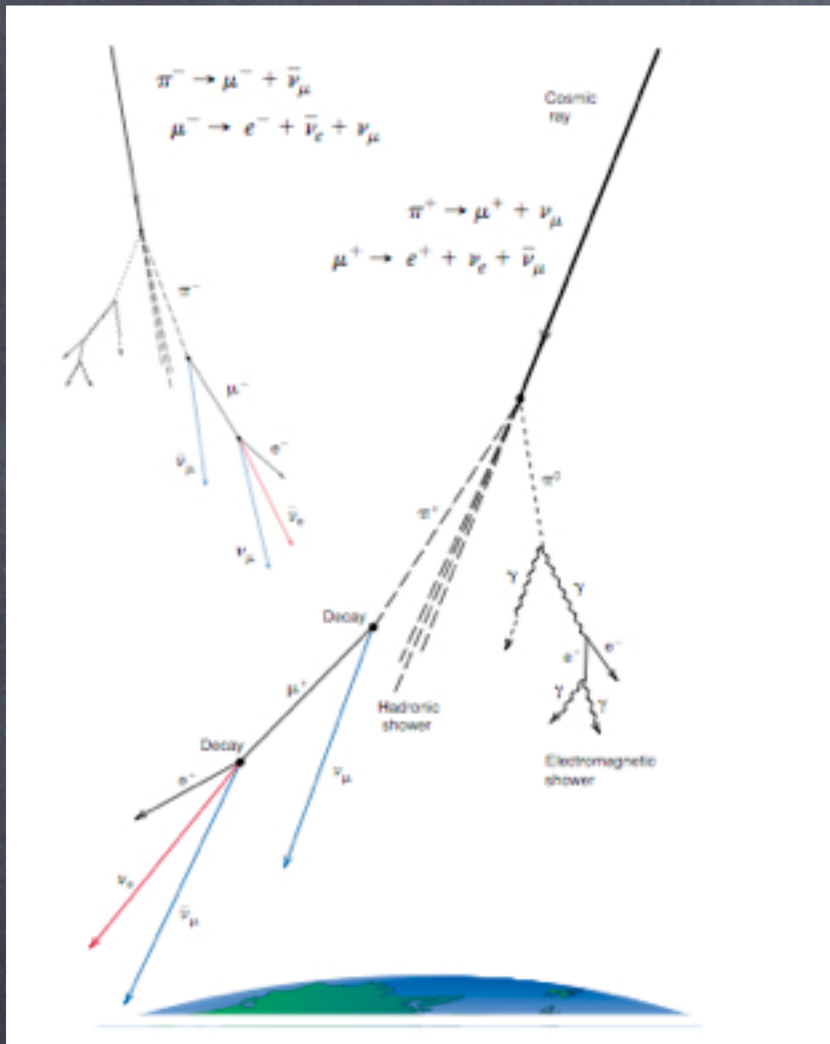
Neutrino Spectra at Detection

Neutrino oscillations taken into account

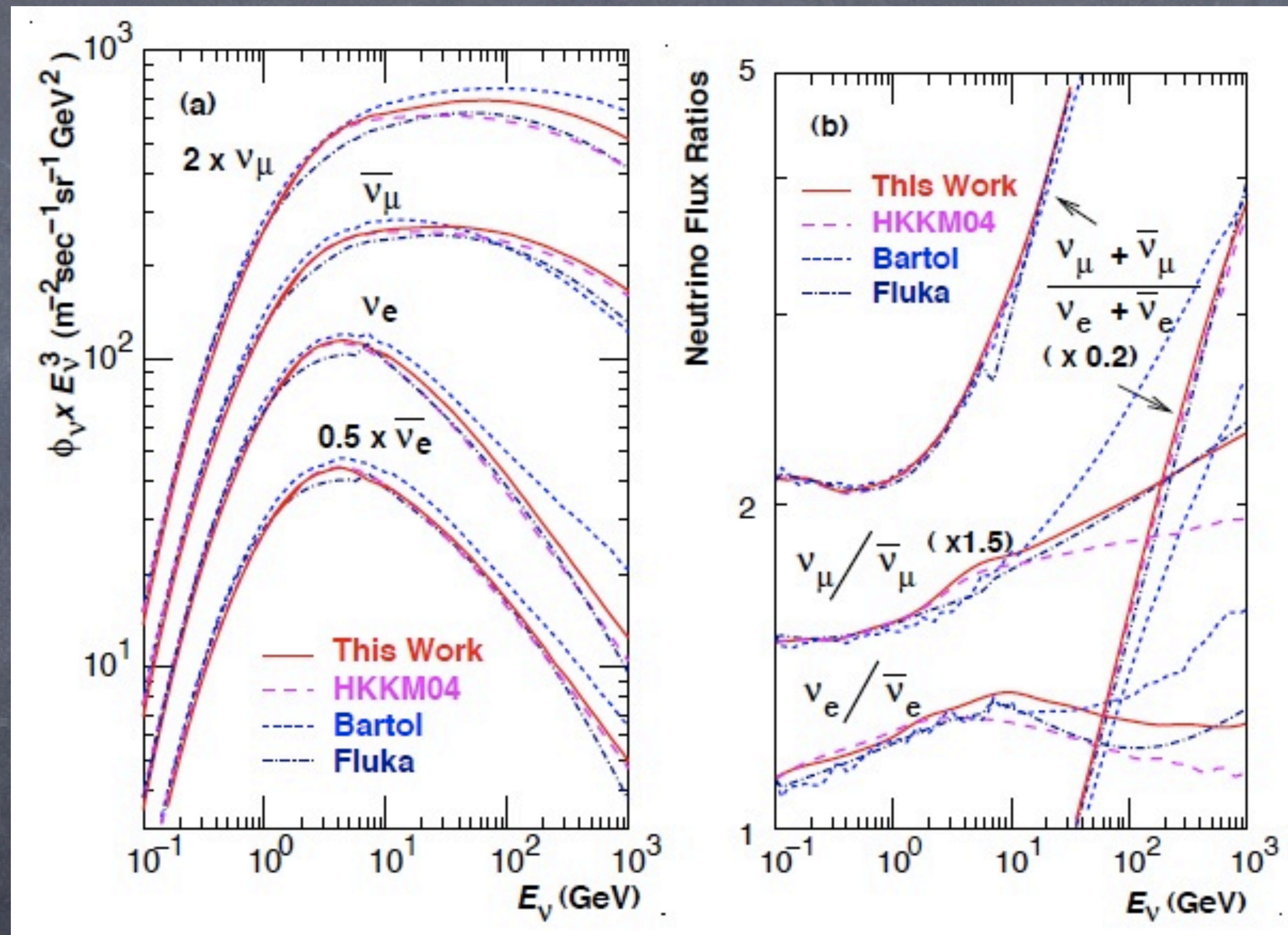


M. Cirelli, N. Fornengo, T. Montaruli, I. Sokalski, A. Strumia and F. Vissani, *Nucl. Phys. B727:99, 2005*

Background: atmospheric neutrinos

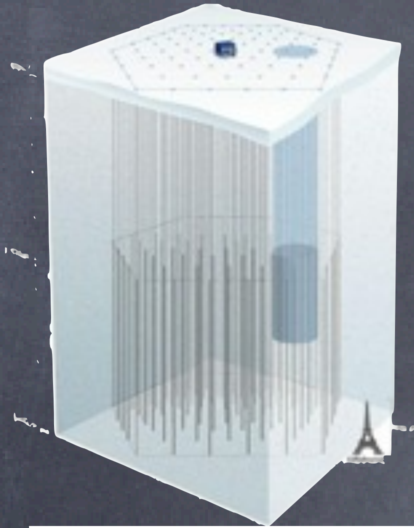


Los Alamos Science No. 25, 1997

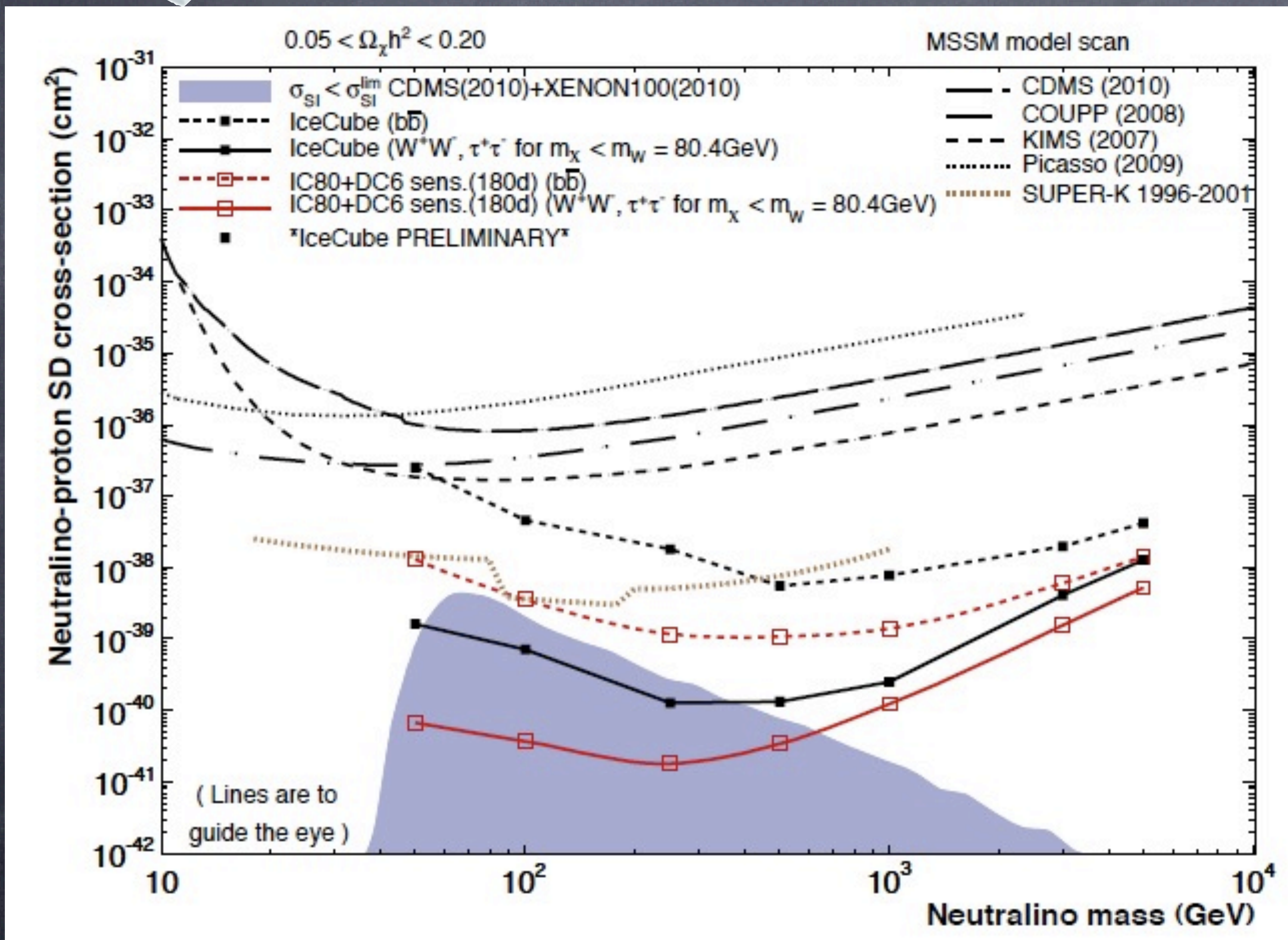


M. Honda, T. Kajita, K. Kasahara, S. Midorikawa and T. Sanuki, *Phys. Rev. D75:043006, 2007*

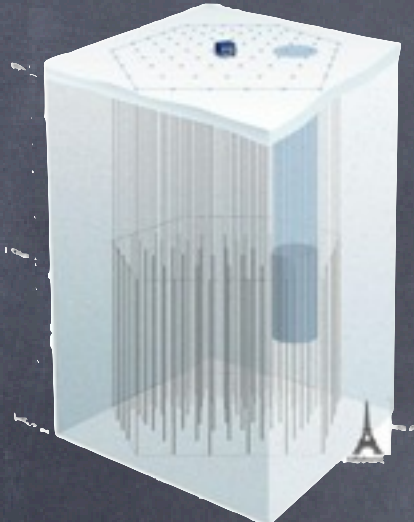
Neutrino Indirect Detection Searches



IceCube and Super-Kamiokande: neutrinos from the Sun



M. Danninger, E. Strahler *et al.* [IceCube Collaboration],
32nd ICRC, Beijing, 2011, arXiv:1111.2738



Neutrino Indirect Detection Searches

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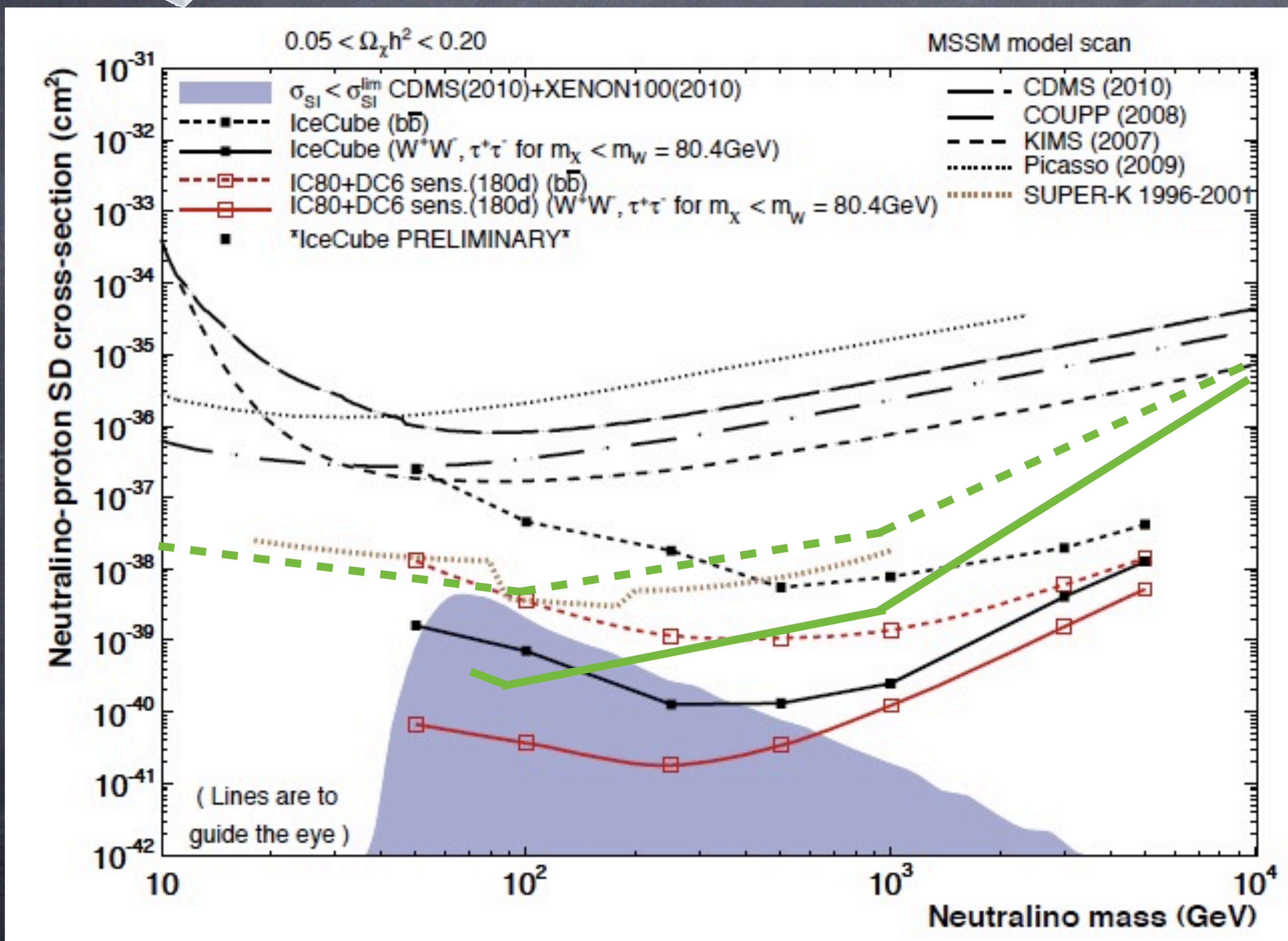
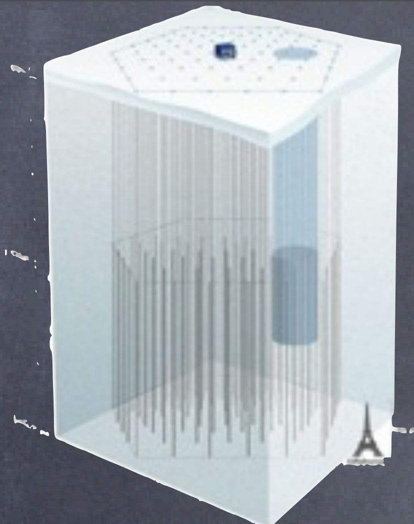


New SK analysis

T. Tanaka *et al.* [Super-Kamiokande Collaboration], *Astrophys. J. 742:78, 2011*

M. Danninger, E. Strahler *et al.* [IceCube Collaboration], *32nd ICRC, Beijing, 2011, arXiv:1111.2738*



Neutrino Indirect Detection Searches

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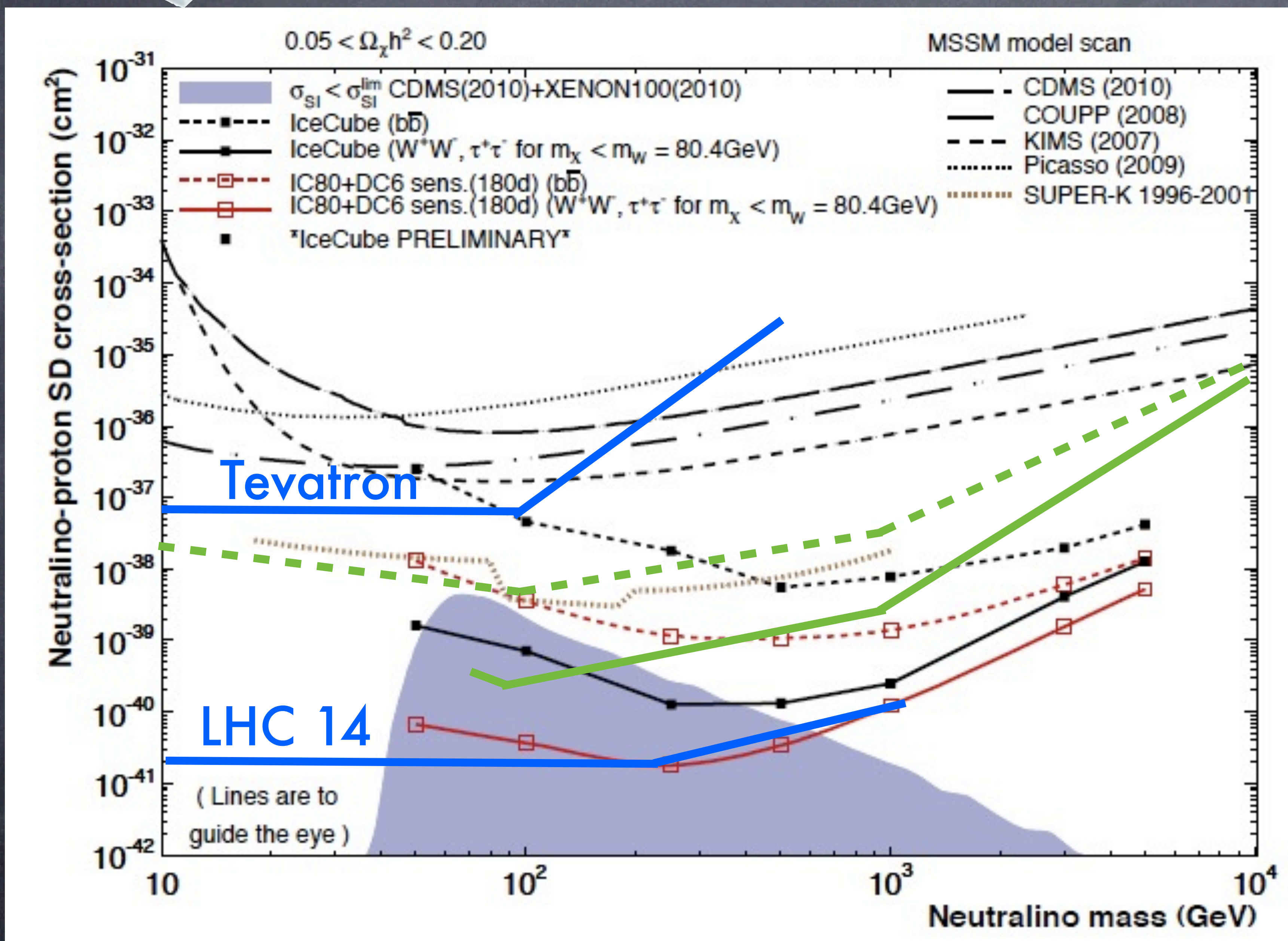

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Tevatron bounds and LHC discovery reach

A. Rajaraman, W. Shepherd, T. M. P. Tait and A. M. Wijangco, *Phys. Rev.D84:095013, 2011*

See also:

Q.-H. Cao, C.-R. Chen, C. S. Li and H. Zhang, *JHEP 08:018, 2011*

P. Agrawal, Z. Chack, C. Kilic and R. K. Mishra, *arXiv:1003.1912*

J. Goodman, M. Ibe, A. Rajaraman, W. Shepherd, T. M. P. Tait, H.-B. Yu, *Phys. Lett. B695:185, 2011* and *Phys. Rev. D82:116010, 2010*

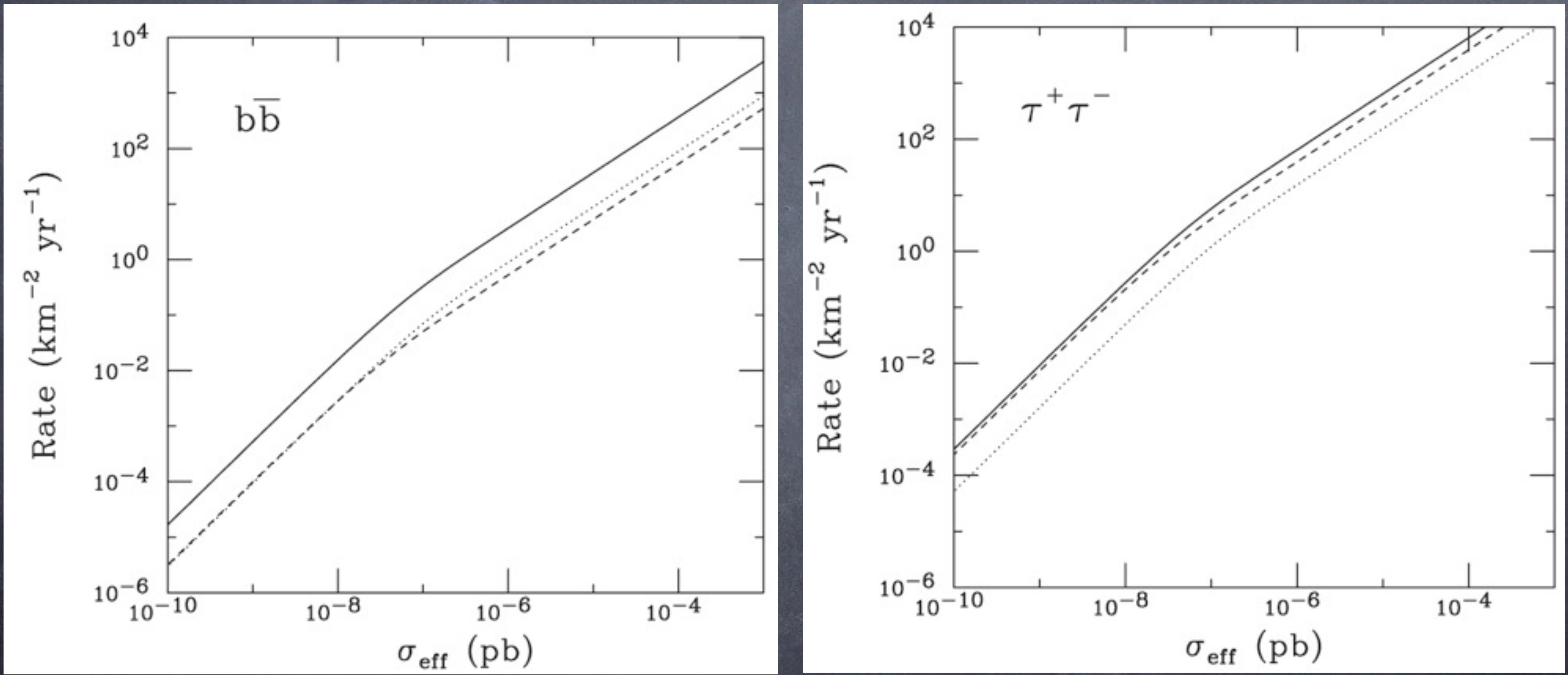
Y. Bai, P. J. Fox and R. Harnik, *JHEP 12:048, 2010*

P. J. Fox, R. Harnik, J. Kopp, Y. Tsai, *Phys. Rev. D85:056011, 2012*

M. Danninger, E. Strahler *et al.* [IceCube Collaboration], *32nd ICRC, Beijing, 2011, arXiv:1111.2738*

Rates in a Neutrino Telescope

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



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

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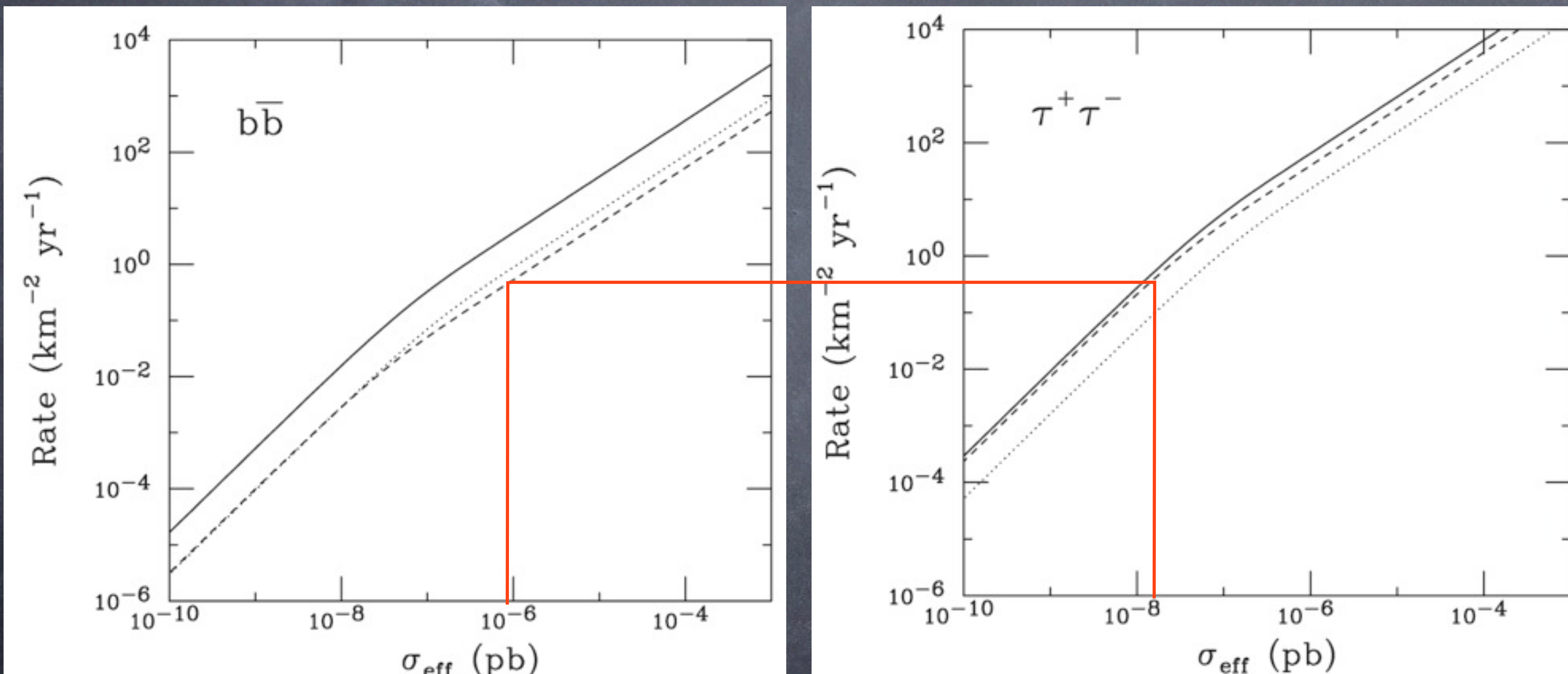

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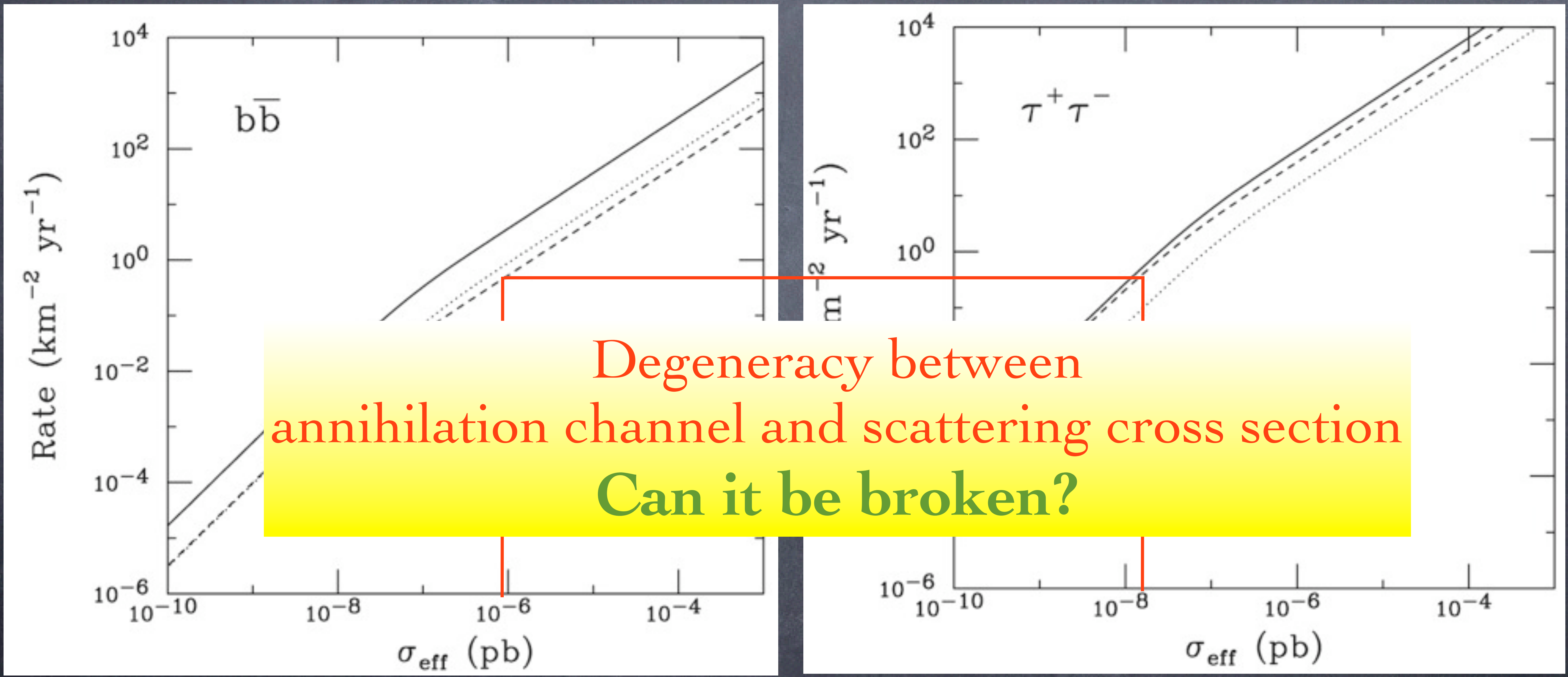


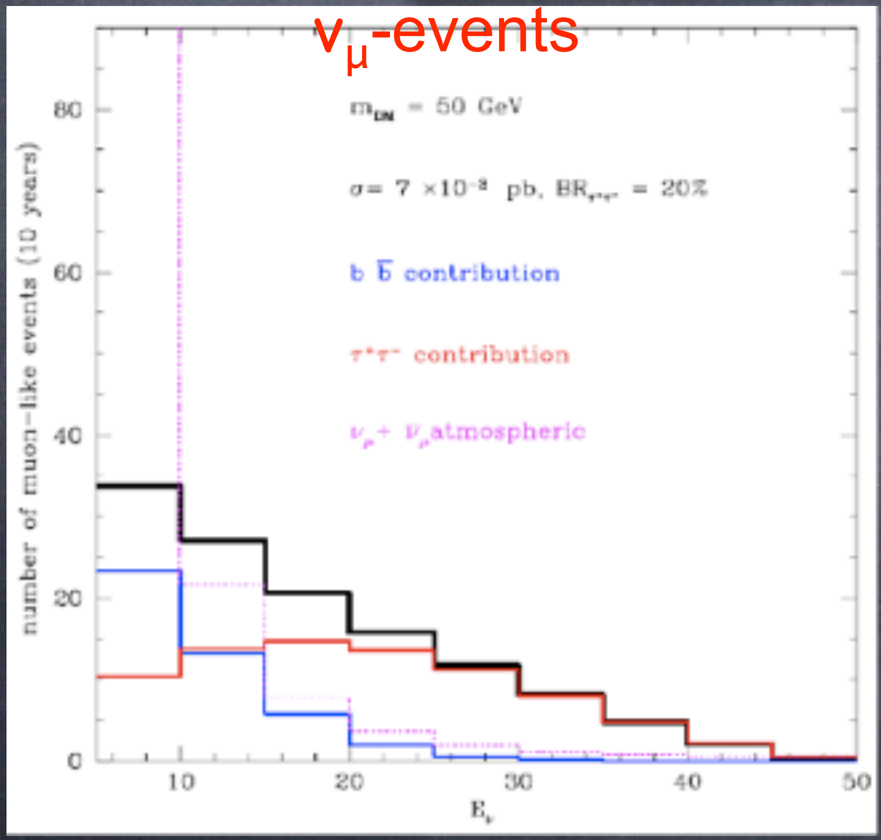
Degeneracy between
annihilation channel and scattering cross section
Can it be broken?

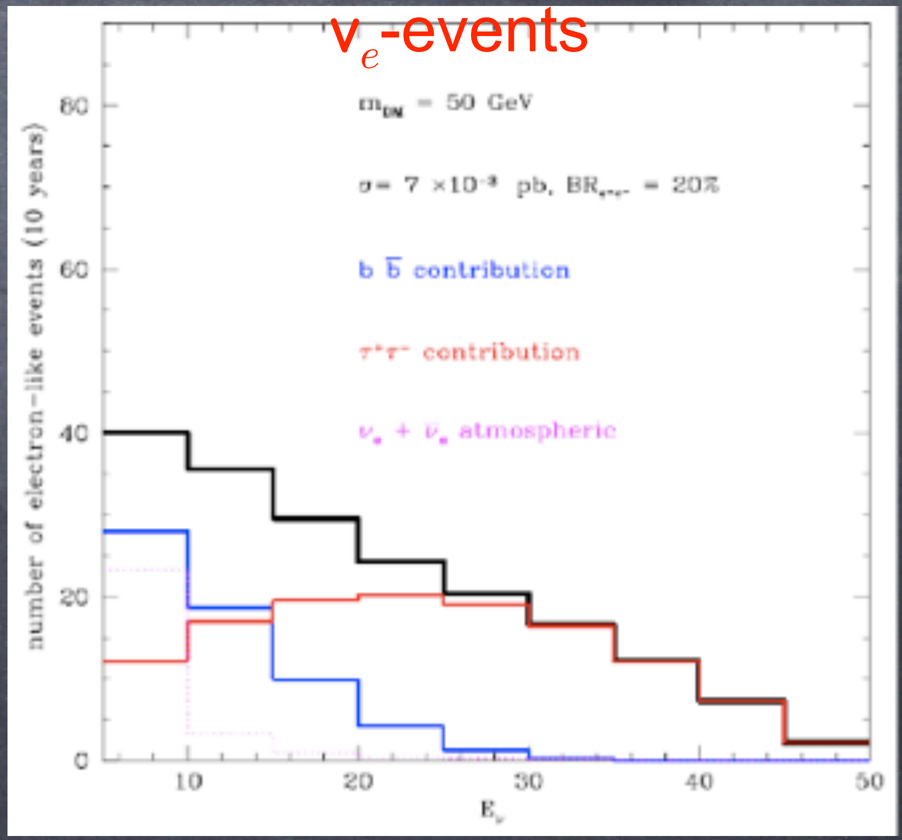
F. Halzen and D. Hooper, *Phys. Rev. D73:123507, 2006*

Future Neutrino Detectors

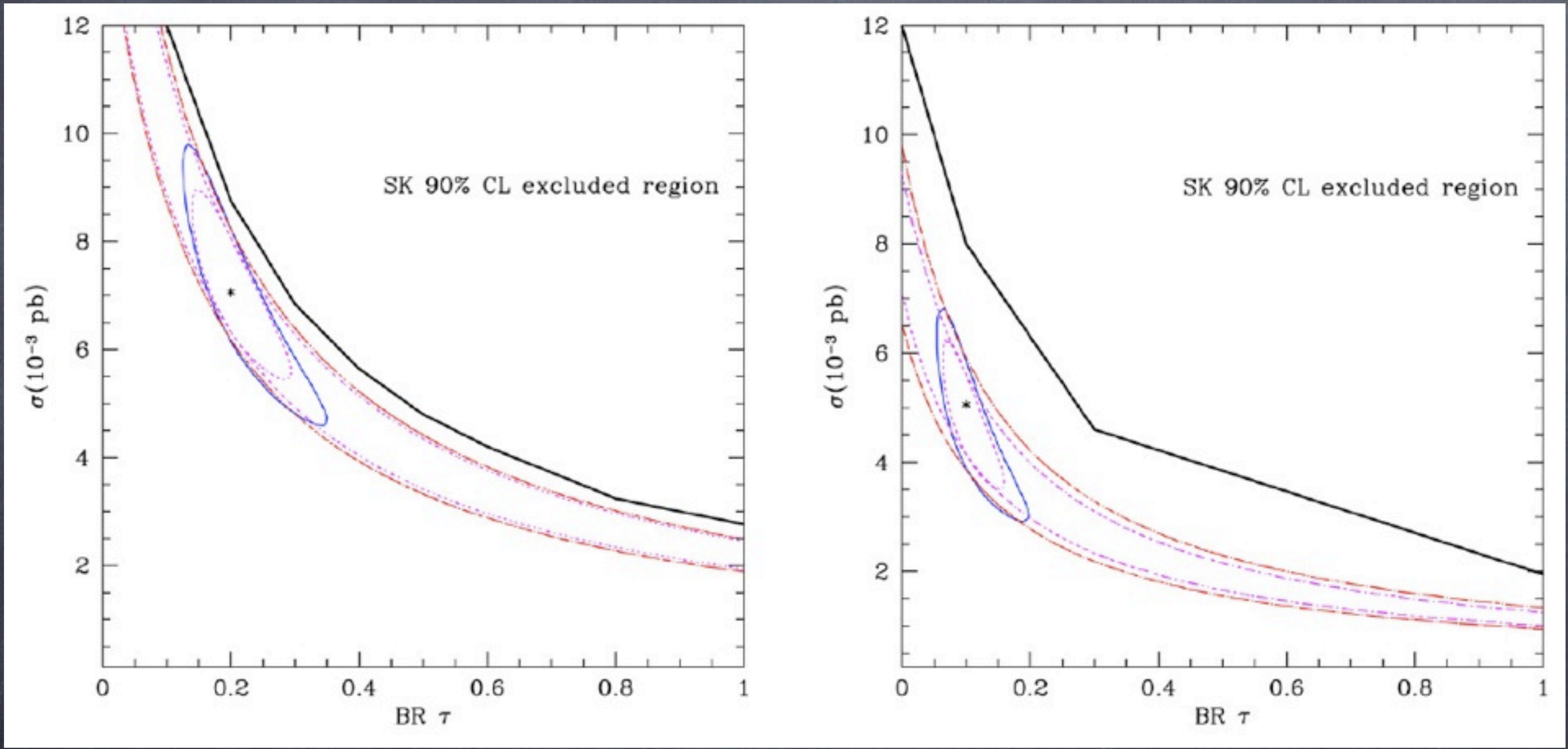
- Magnetized Iron Calorimeters (MINOS-like, INO...)
- Totally Active Scintillator Detectors (NOvA, MINERvA...)
- Liquid Argon Time Projection Chamber (GLACIER...)

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





$$m_\chi = 50\,\mathrm{GeV} \qquad\qquad m_\chi = 70\,\mathrm{GeV}$$
$$\mathrm{Br}_{\tau^+\tau^-}(\mathrm{hard}) = 20\% \qquad\qquad \mathrm{Br}_{\tau^+\tau^-}(\mathrm{hard}) = 10\%$$

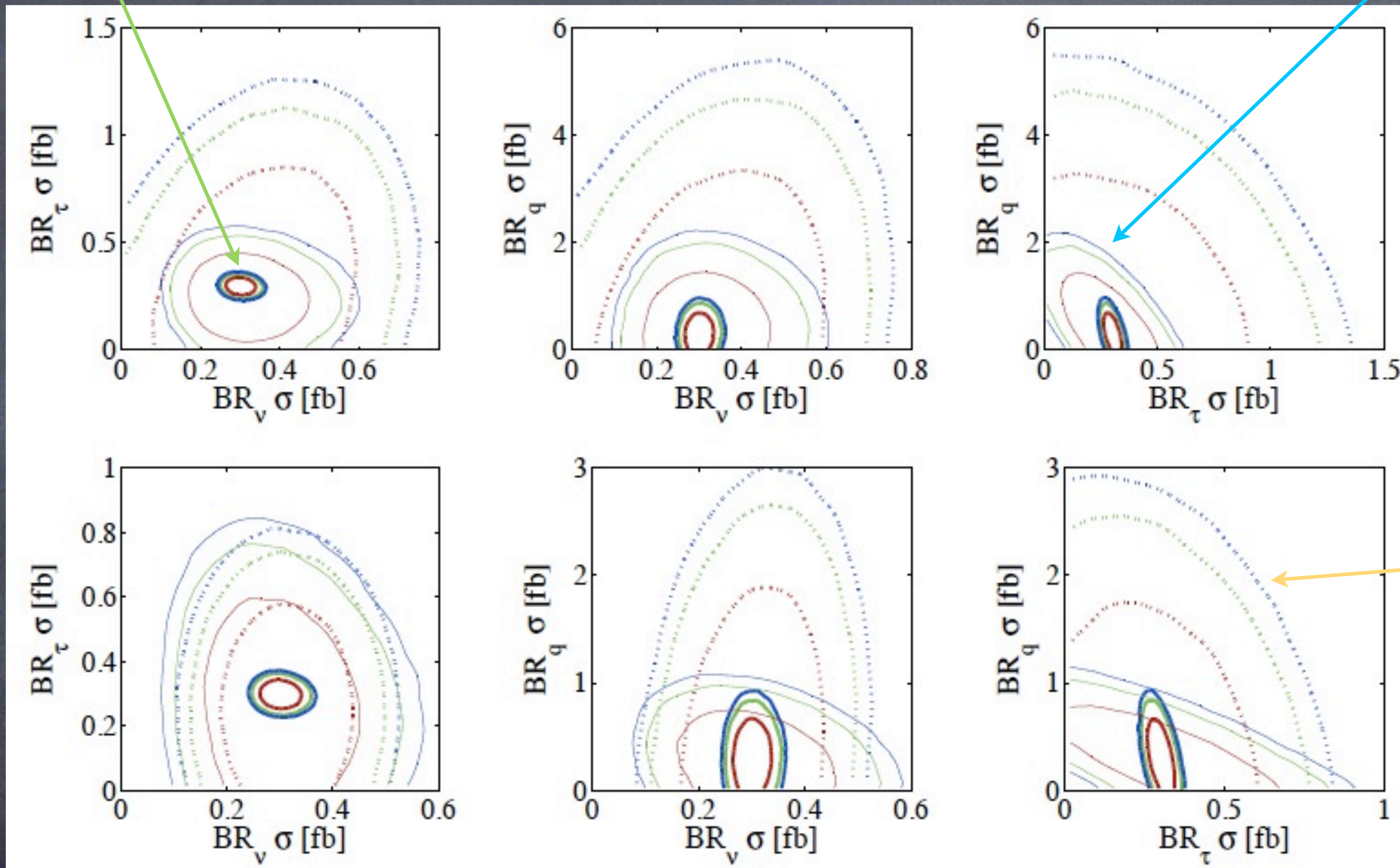


O. Mena, SPR and S. Pascoli, *Phys. Lett. B664:92, 2008*

GLACIER

$m_\chi = 10\ \mathrm{GeV} \qquad \mathrm{Br}_{\tau^+\tau^-} = 100\%$

LArTPC

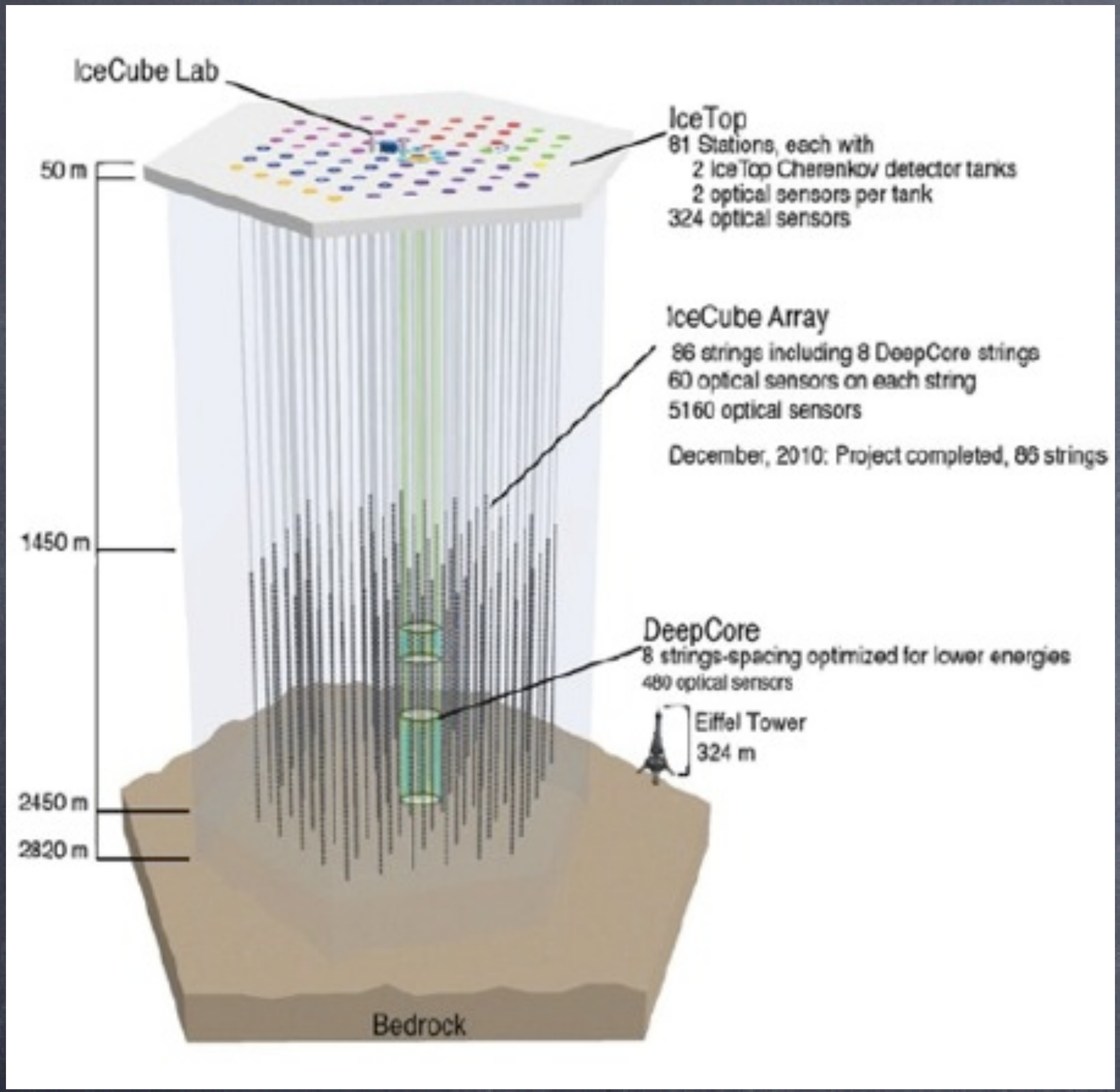


MIND

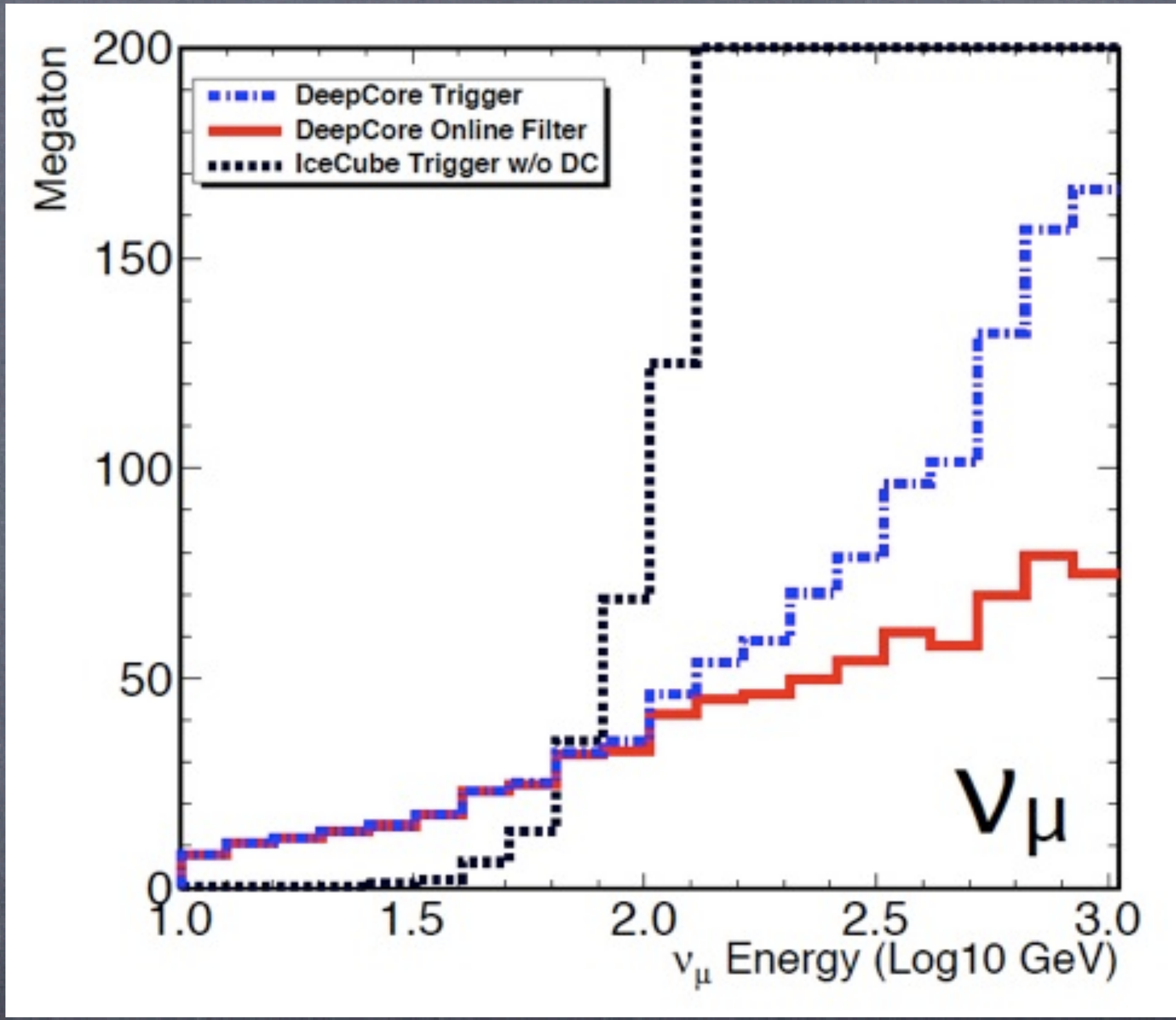
$m_\chi = 25\ \mathrm{GeV} \qquad \mathrm{Br}_{\tau^+\tau^-} = 100\%$

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

Determining the WIMP mass with DeepCore



Effective volume



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

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

We assume 50% efficiency

IceCube Collaboration, *arXiv:1109.6096*

Angular Resolution:

dominated by the scattering between the incoming neutrino and outgoing muon

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

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], *Astrophys. J. 742:78, 2011*

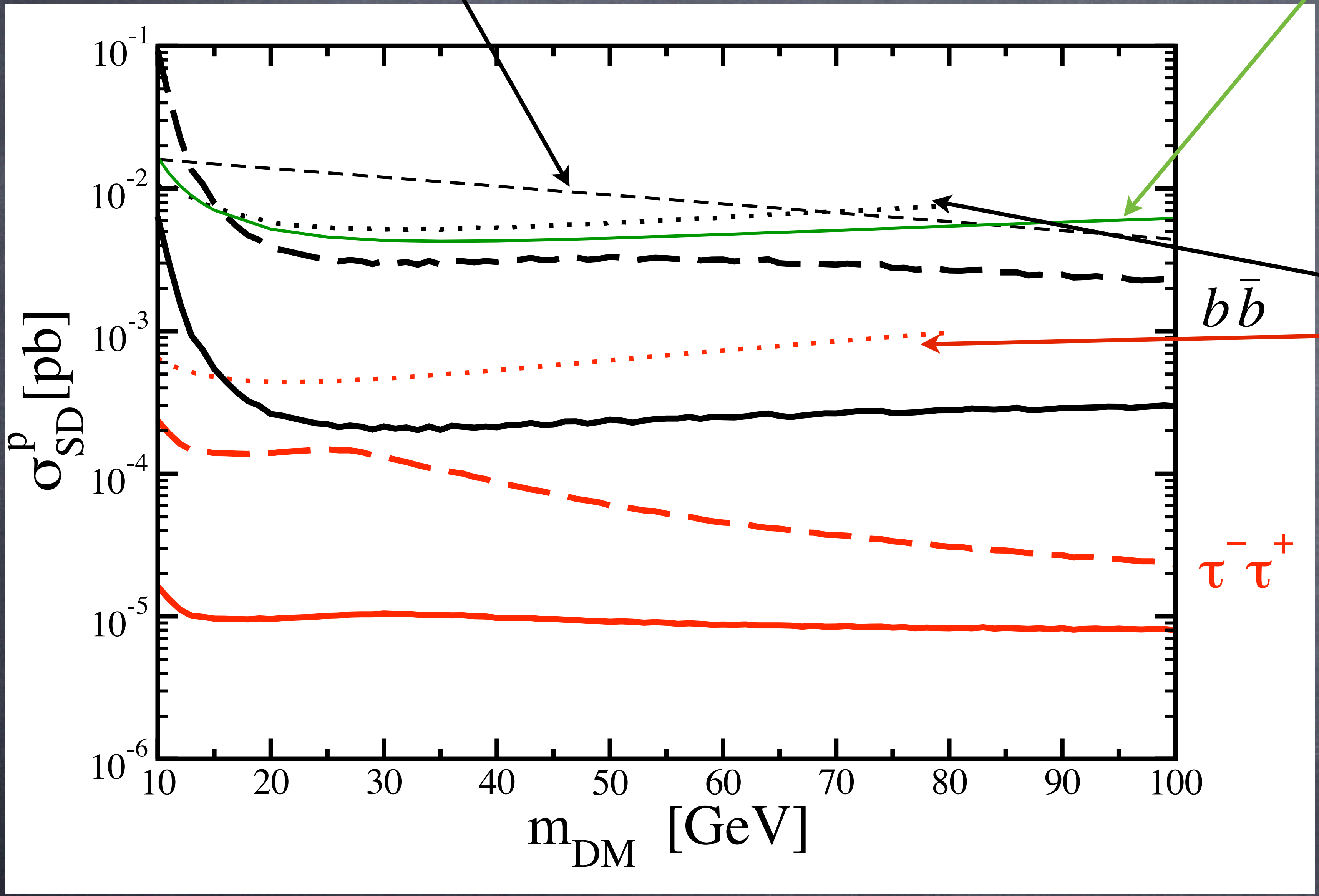
Direct DM searches

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

See however,
J. Collar, *arXiv:1106.3559*
C. E. Dahl, J. Hall and W. H. Lippincott, *arXiv:1111.6192*

Fully-contained and stopping muons in SK

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



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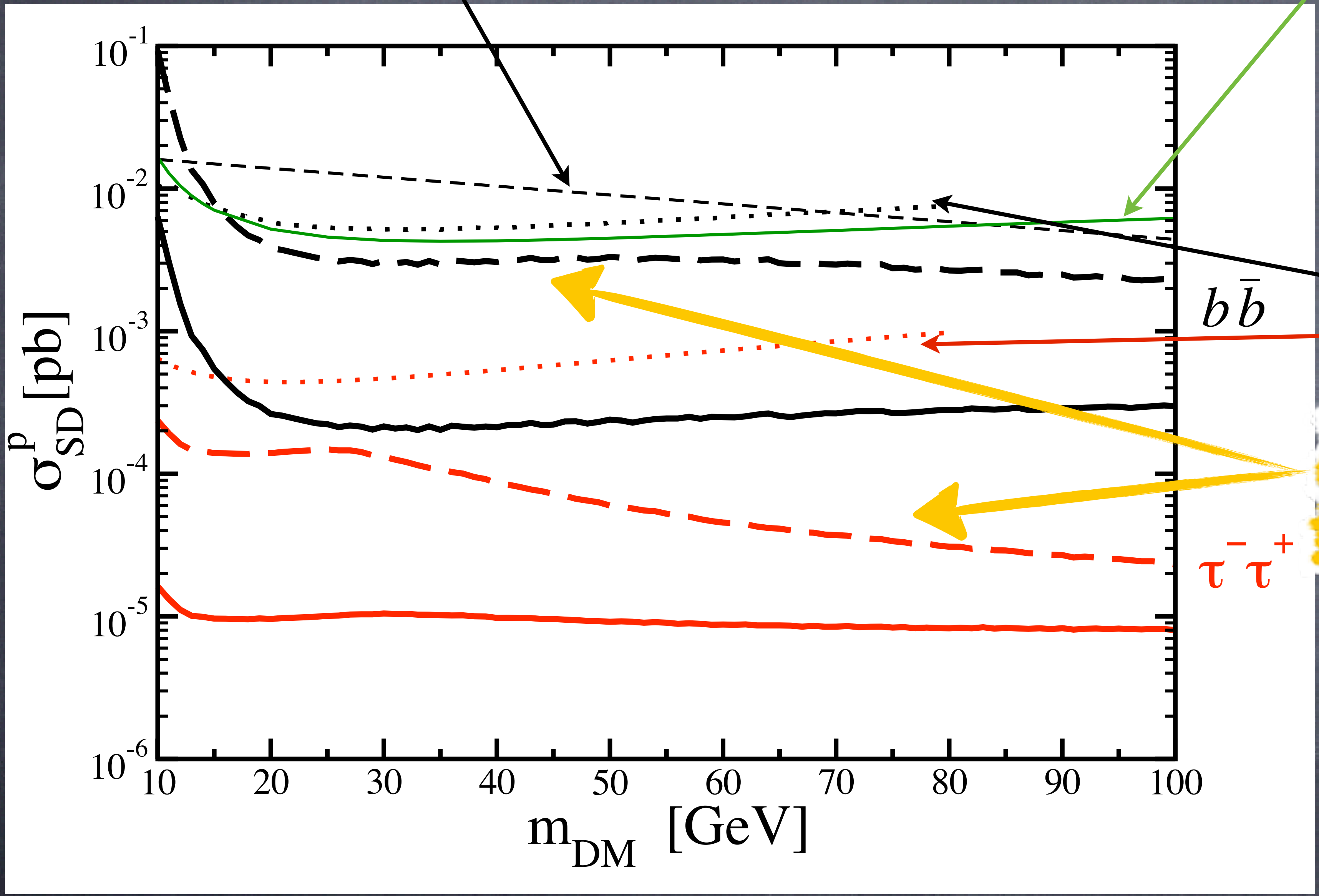

Systematic error = 15%

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

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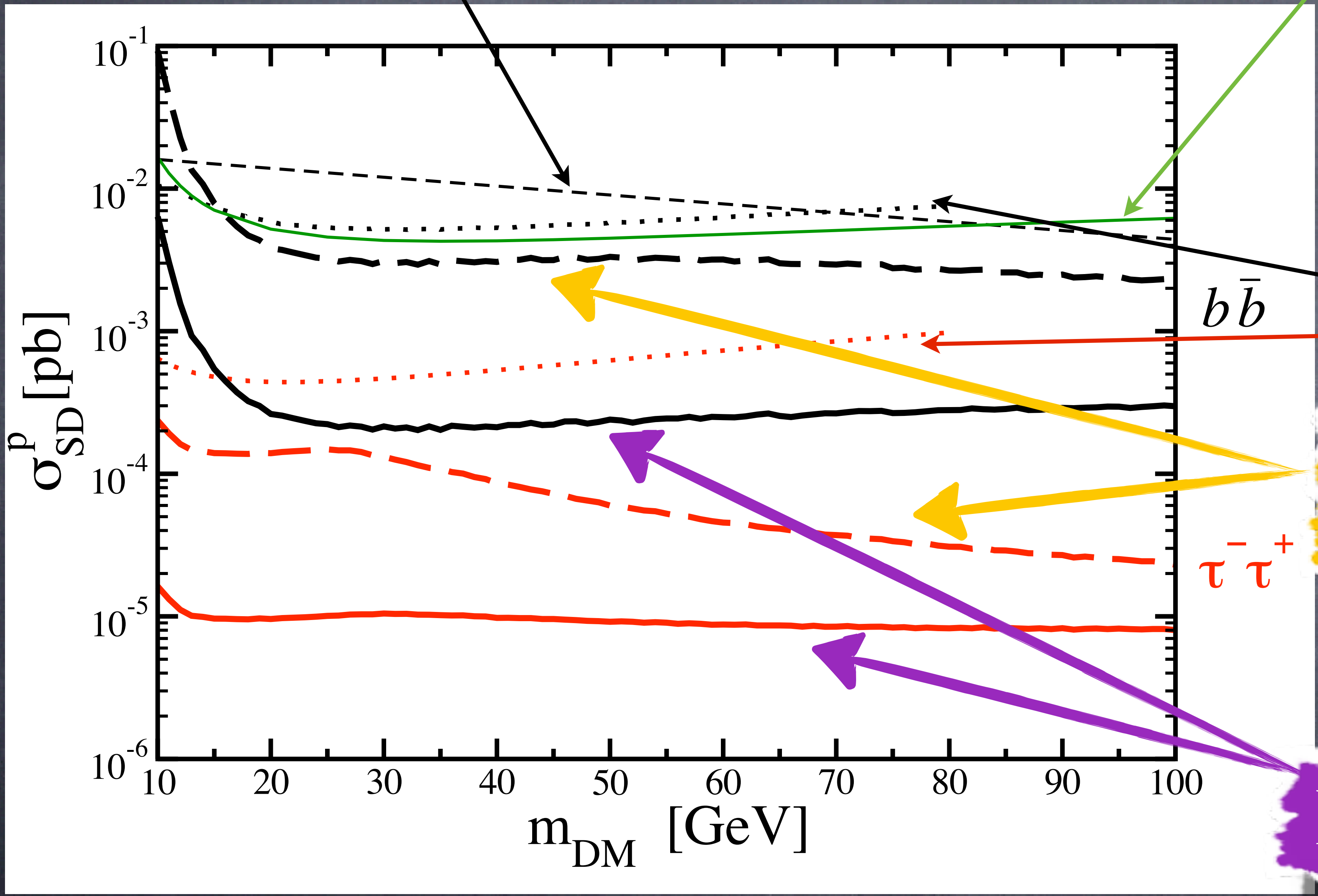
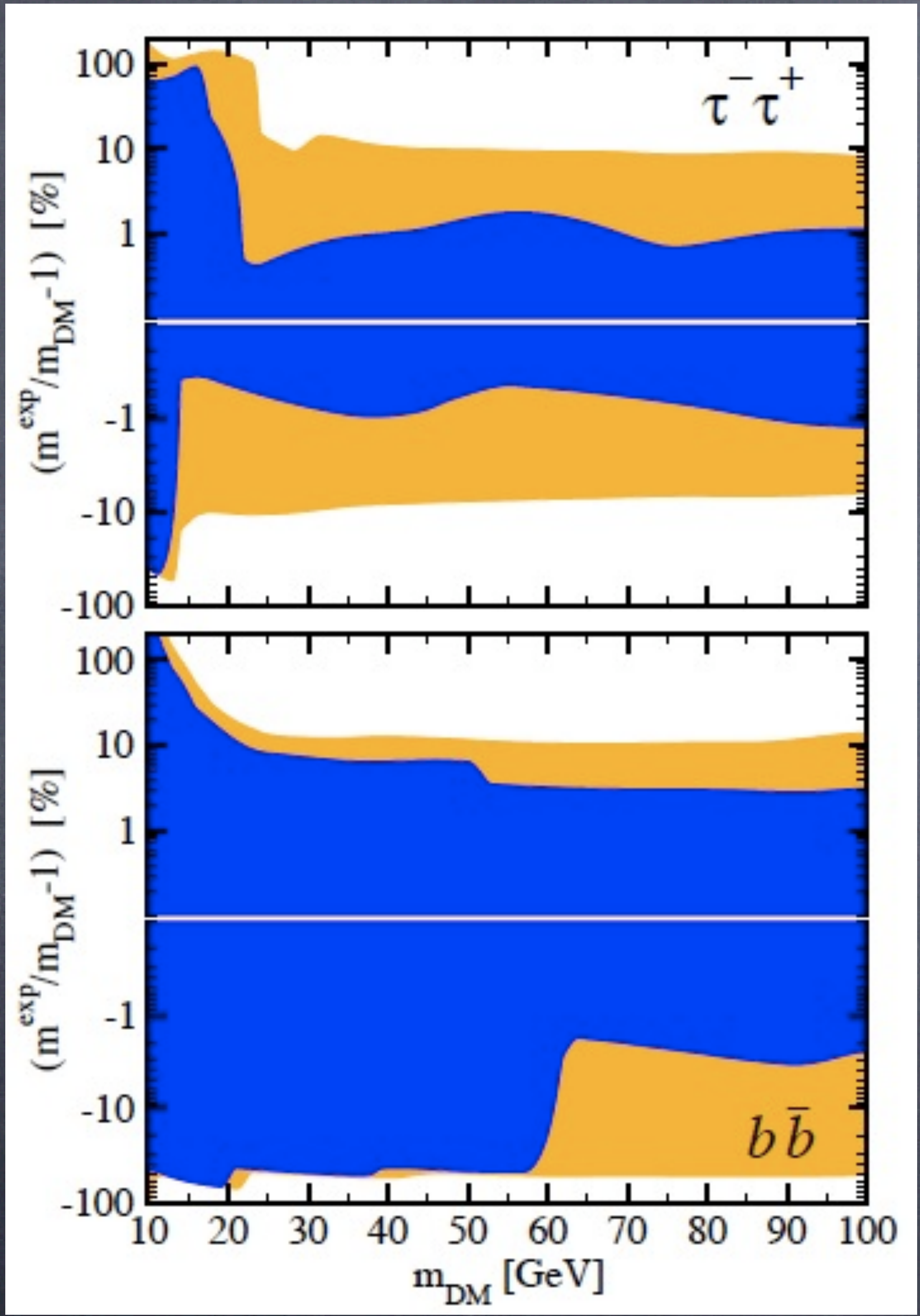


Systematic error = 15%

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)

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

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

No systematic error

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

$\sigma_{SD}^{p} = 4\times 10^{-3}\, pb$

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

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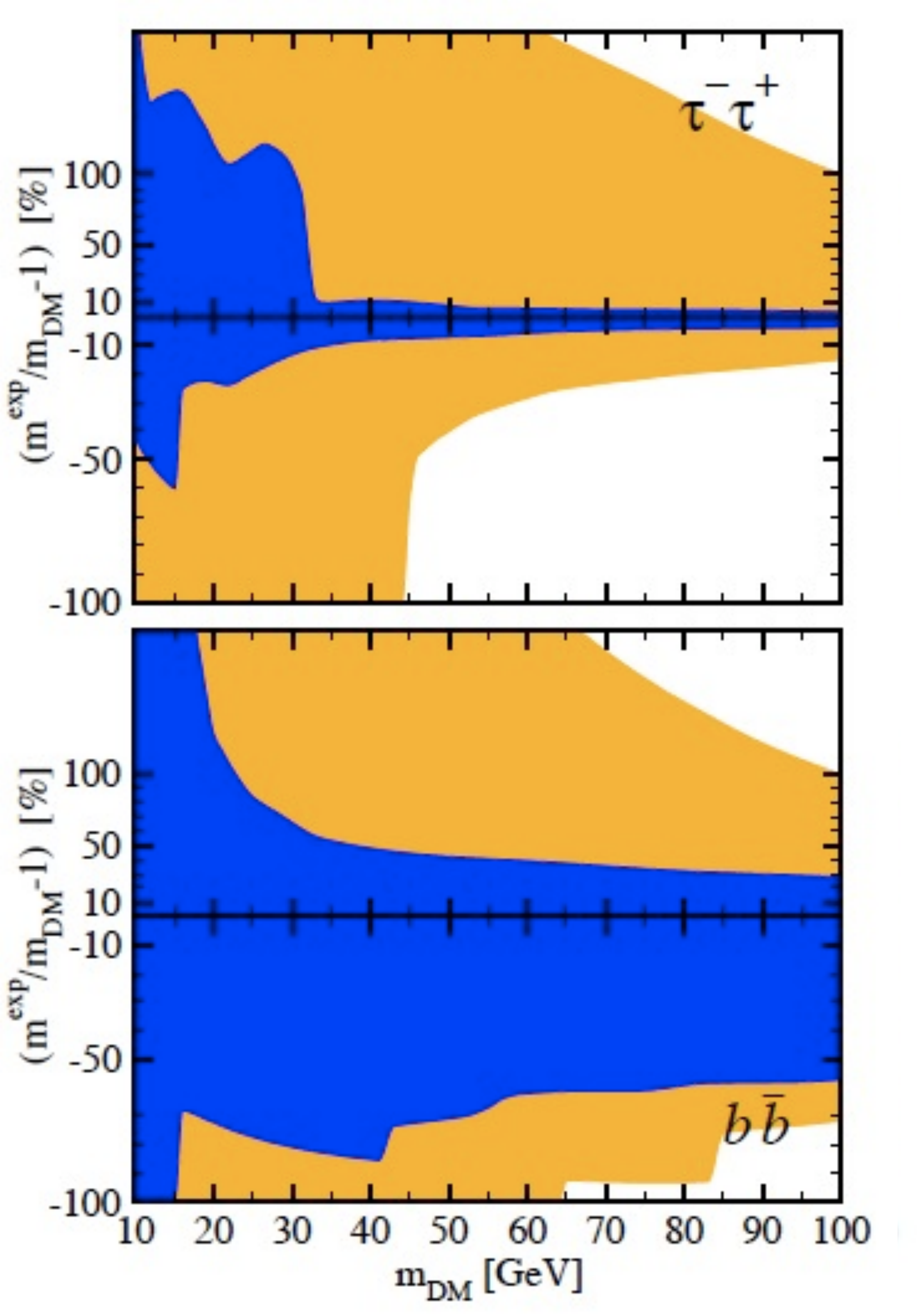

(after marginalizing with respect to cross section and annihilation channel)

$\sigma^p_{SD} = 10^{-3}\, pb$

$\sigma^p_{SD} = 10^{-4}\, pb$

Systematic error = 15%

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$\sigma^p_{SD} = 4 \times 10^{-3}\, pb$

Adapted from 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

  A. H. G. Peter, *Phys. Rev. D79:103532, 2009*
  S. Sivertsson and J. Edsjö, *arXiv:1201.1895*
  J. Edsjö, talk at Bethe Forum, Bonn, November 15, 2011

- Contribution due to EW corrections: important for masses >>100 GeV

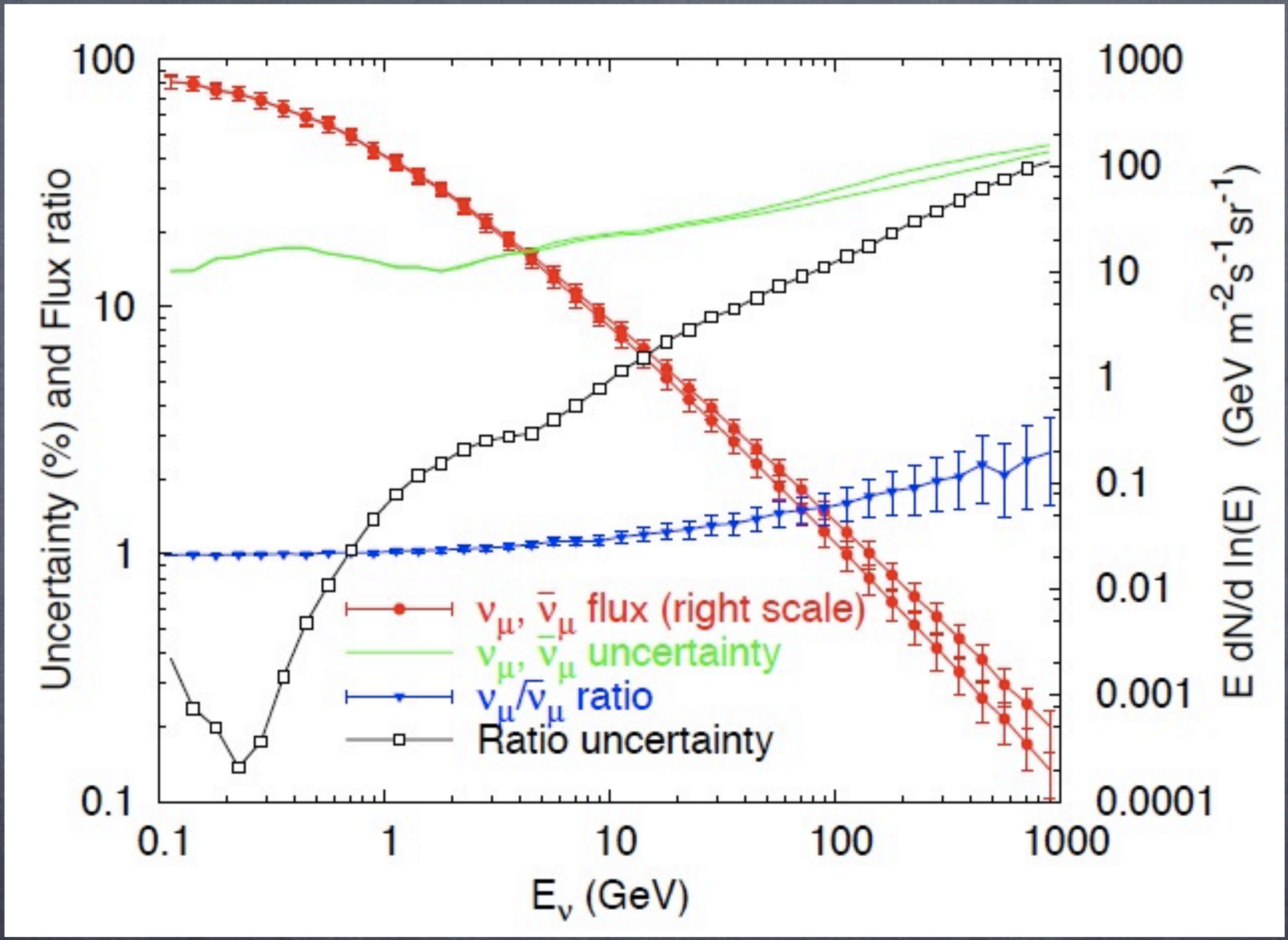
  X.-L. Chen and M. Kamionkowski, *JHEP 9807:001, 1998*
  M. Kachelriess and P. D. Serpico, *Phys. Rev. D76:063516, 2007*
  N. F. Bell, J. B. Dent, T. D. Jaques and T. J. Weiler, *Phys. Rev. D78:083540, 2008*
  J. B. Dent, R. J. Scherrer and T. J. Weiler, *Phys. Rev. D78:063509, 2008*
  P. Ciafaloni and A. Urbano, *Phys. Rev. D82:043512, 2010*
  M. Kachelriess, P. D. Serpico and M. A. Solberg, *Phys. Rev. D80:123533, 2009*
  C. E. Yaguna, *Phys. Rev. D81:075024, 2010*
  P. Ciafaloni, D. Comelli, A. Riotto, F. Sala, A. Strumia and A. Urbano, *JCAP 1103:019, 2011*
  N. F. Bell, J. B. Dent, T. D. Jaques and T. J. Weiler, *Phys. Rev. D83:013001, 2011* and *Phys. Rev. D84:103517, 2011*
  P. Ciafaloni, M. Cirelli, D. Comelli, A. De Simone, A. Riotto and A. Urbano, *JCAP 1106:018, 2011*

- Uncertainties on the local DM density

  R. Catena and P. Ullio, *JCAP 1008:004, 2010* — $\rho_\odot = 0.39 \pm 0.03$ GeV/cm^3
  L. E. Strigari and R. Trotta, *JCAP 0911:019, 2009* — $\rho_\odot = 0.32 \pm 0.07$ GeV/cm^3
  P. Salucci, F. Nesti, G. Gentile and C. F. Martins, *Astron. Astrophys. 523:A83, 2010* — $\rho_\odot = 0.43 \pm 0.15$ GeV/cm^3
  P. J. McMillan, *Mon. Not. Roy. Astron. Soc. 414:2446, 2011* — $\rho_\odot = 0.40 \pm 0.04$ GeV/cm^3
  J. Bovy and S. Tremaine, *arXiv:1205.4033* — $\rho_\odot = 0.30 \pm 0.10$ GeV/cm^3

- Contribution of more annihilation channels

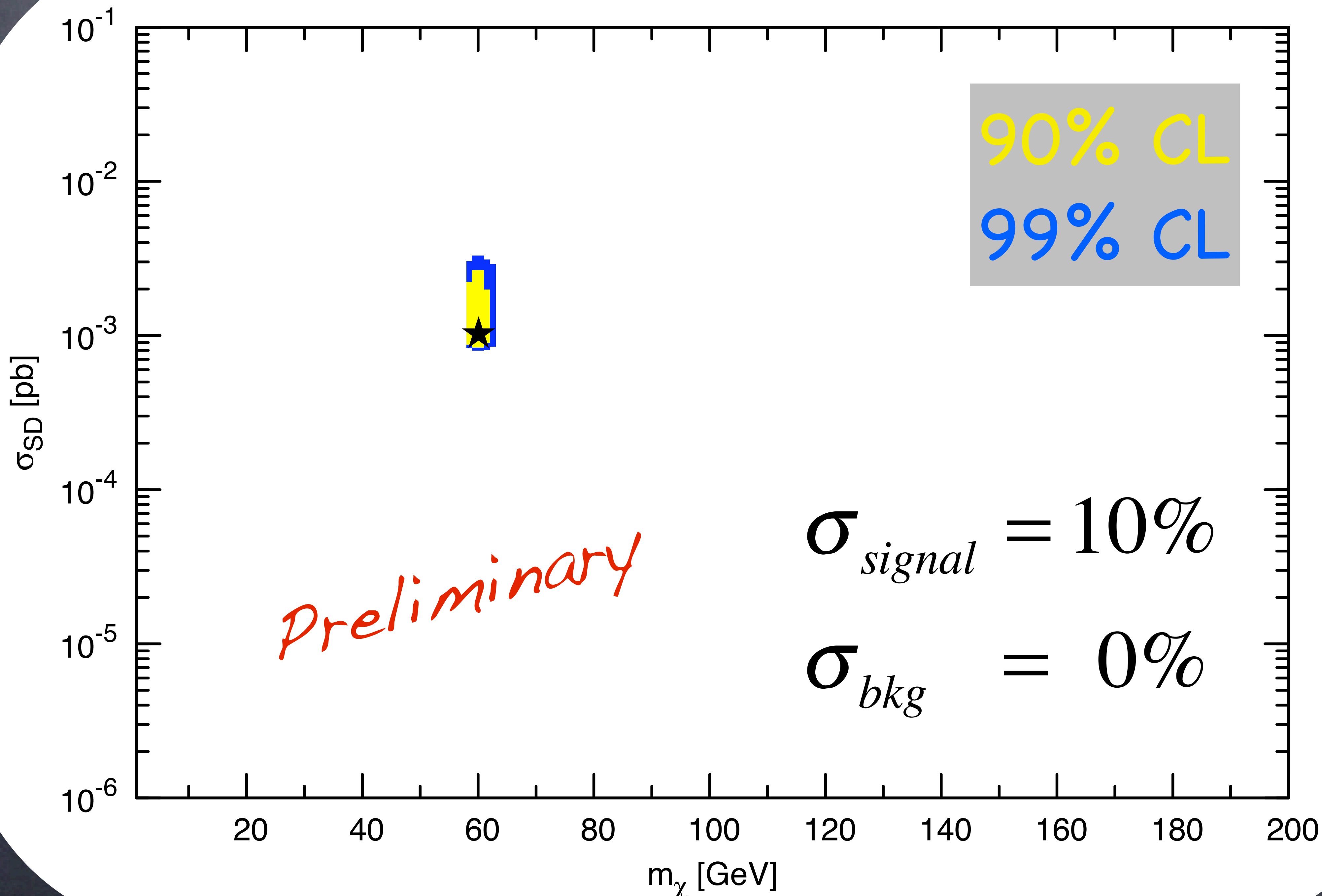
Comments on uncertainties: background



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

Anihilations into τ

Reconstruction with τ and b



C. R. Das et al., *in preparation*

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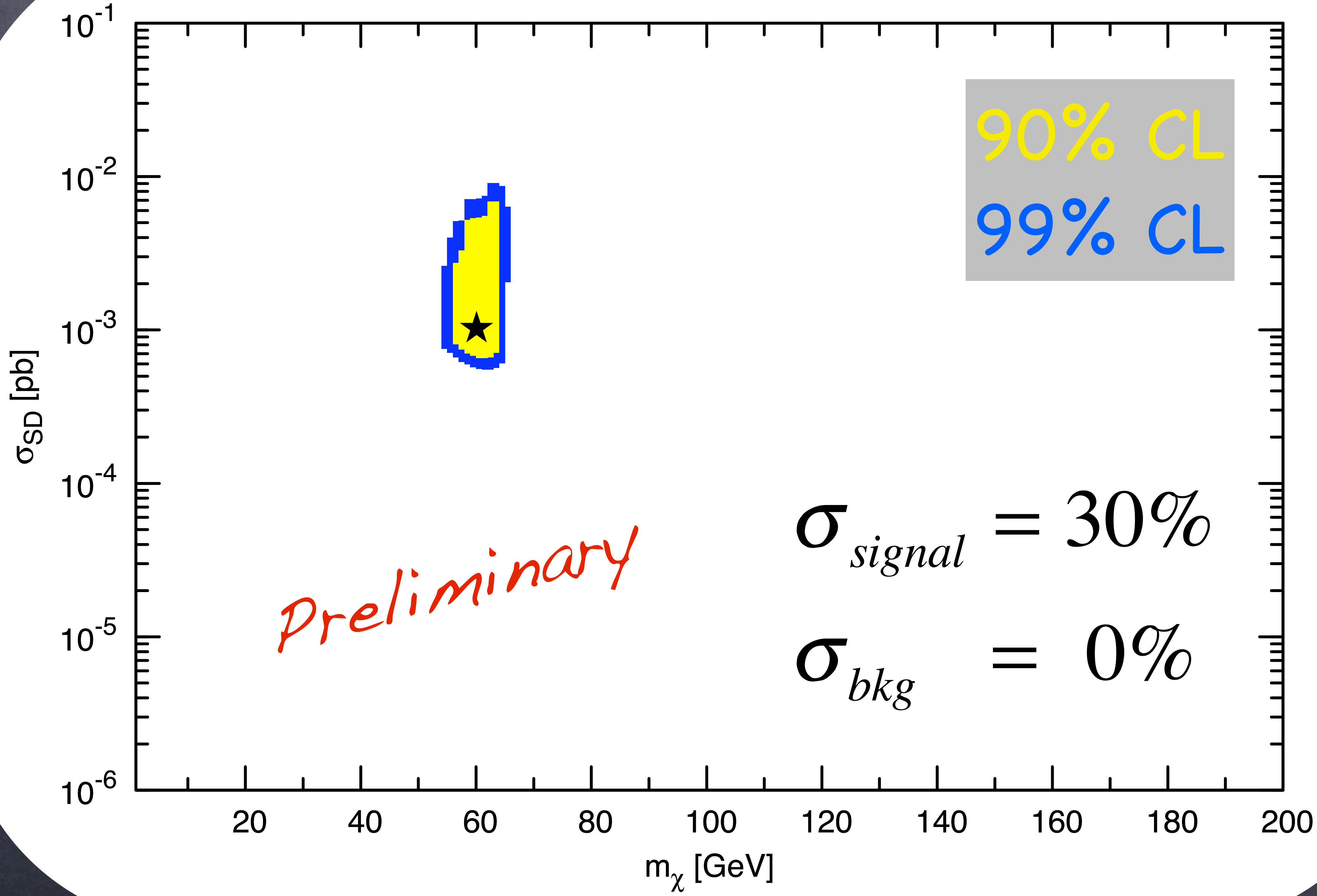

C. R. Das et al., *in preparation*

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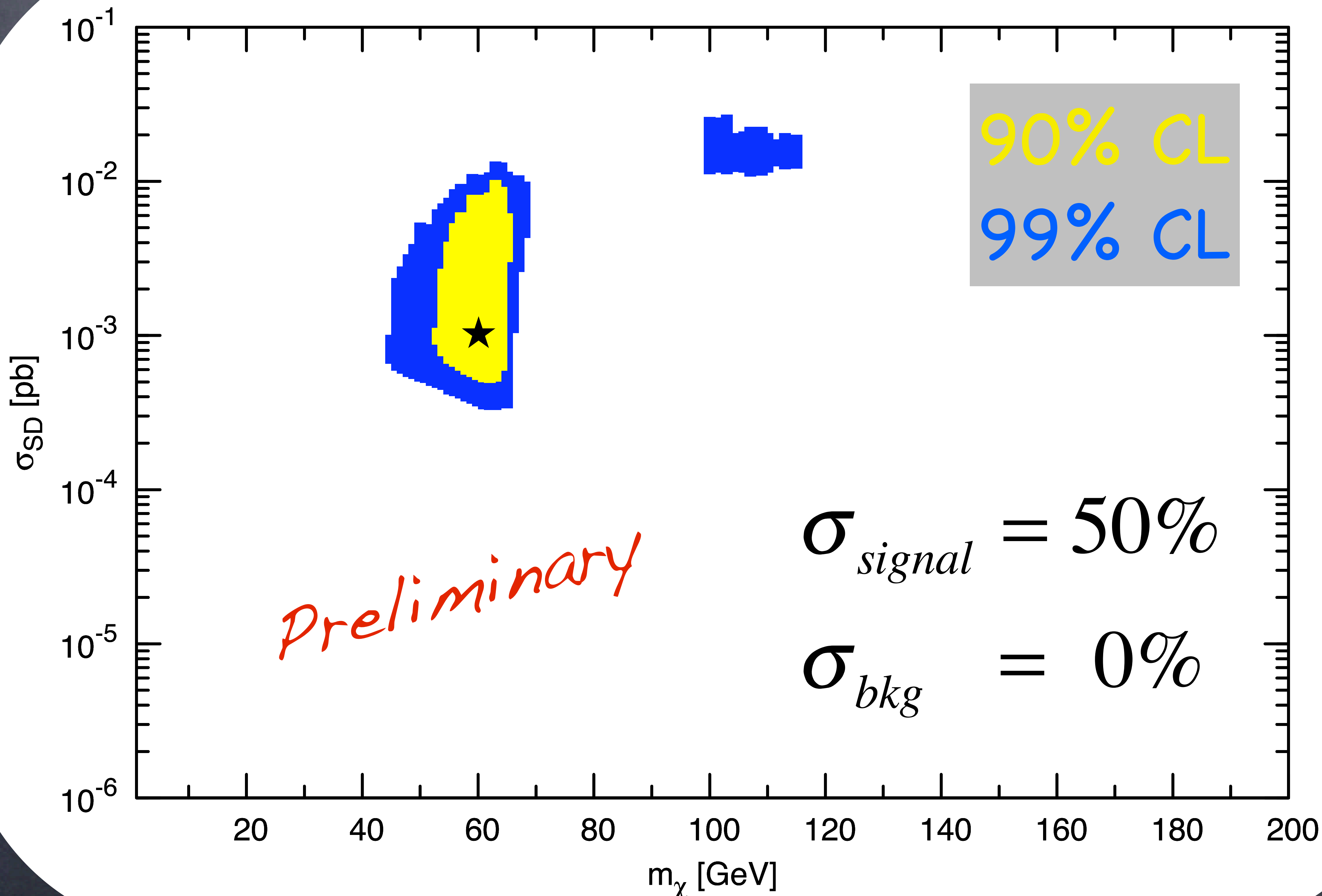

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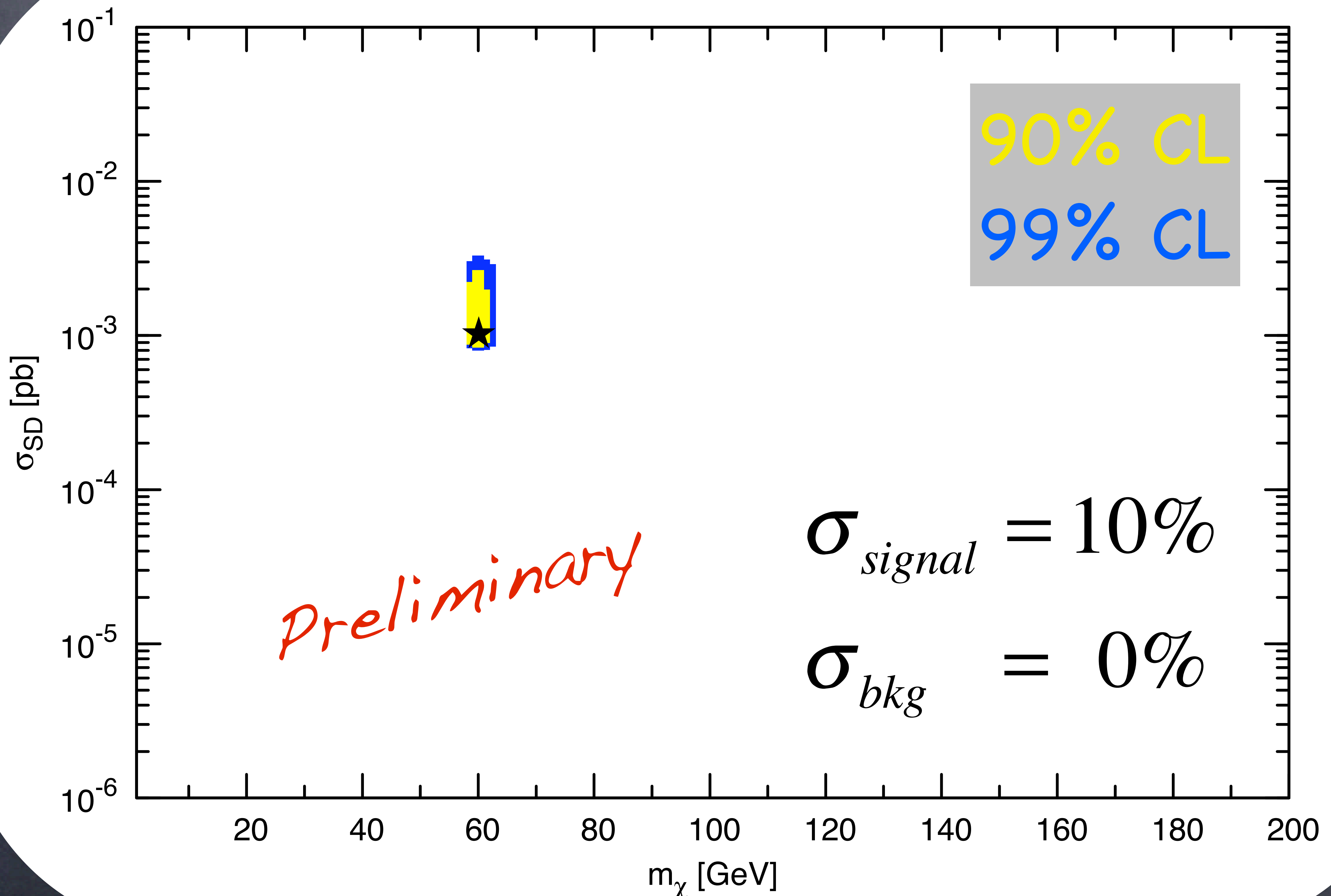

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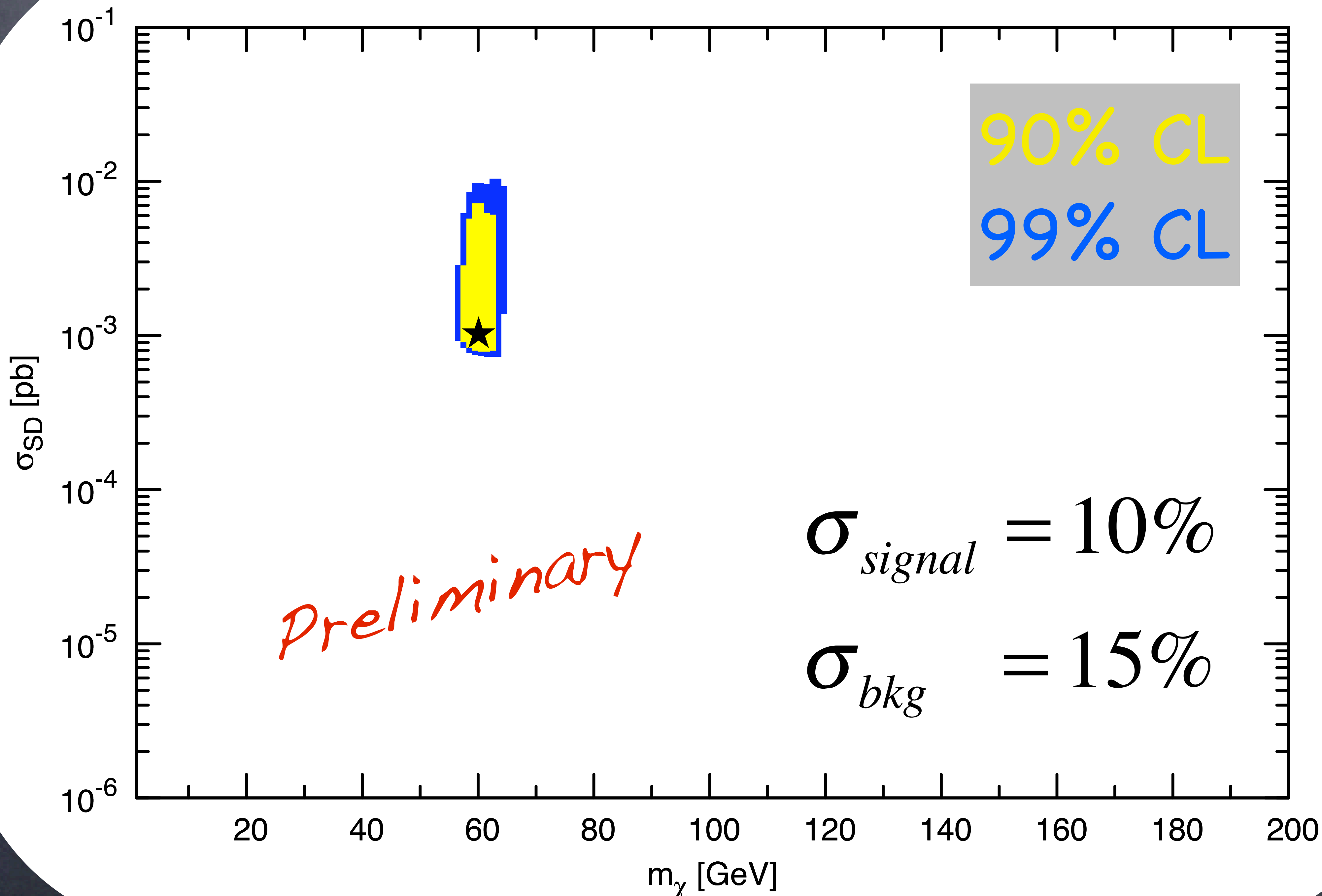

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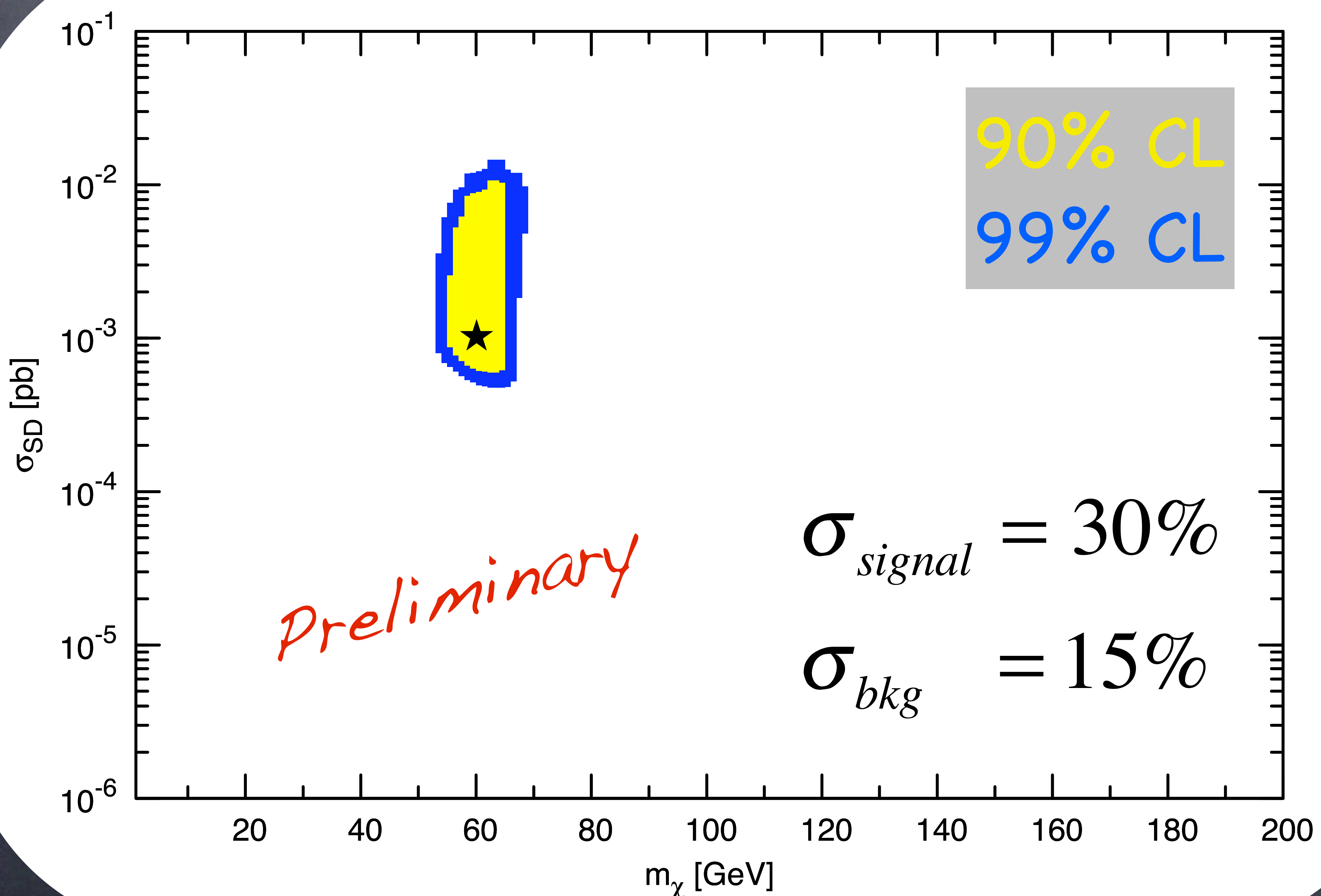

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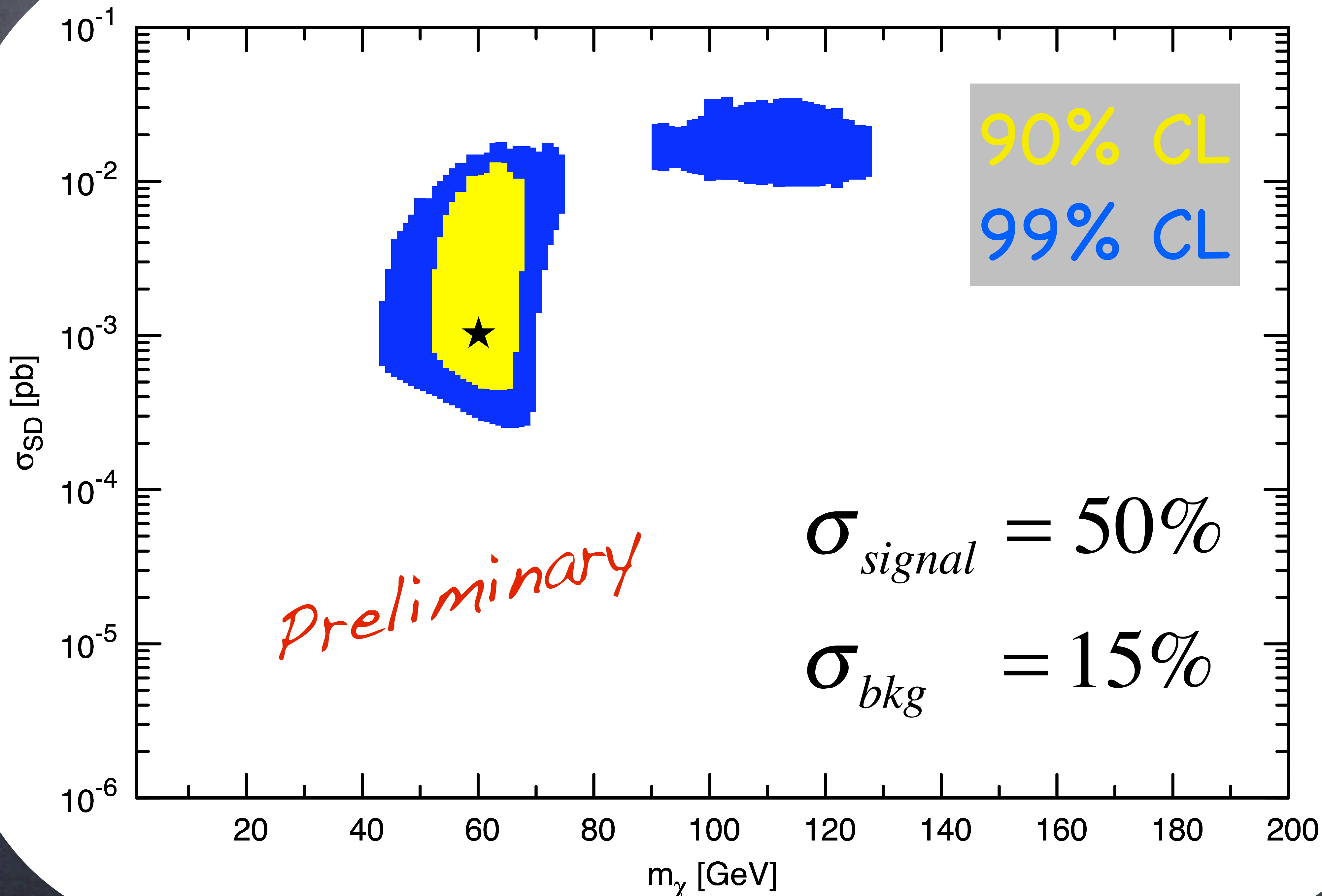

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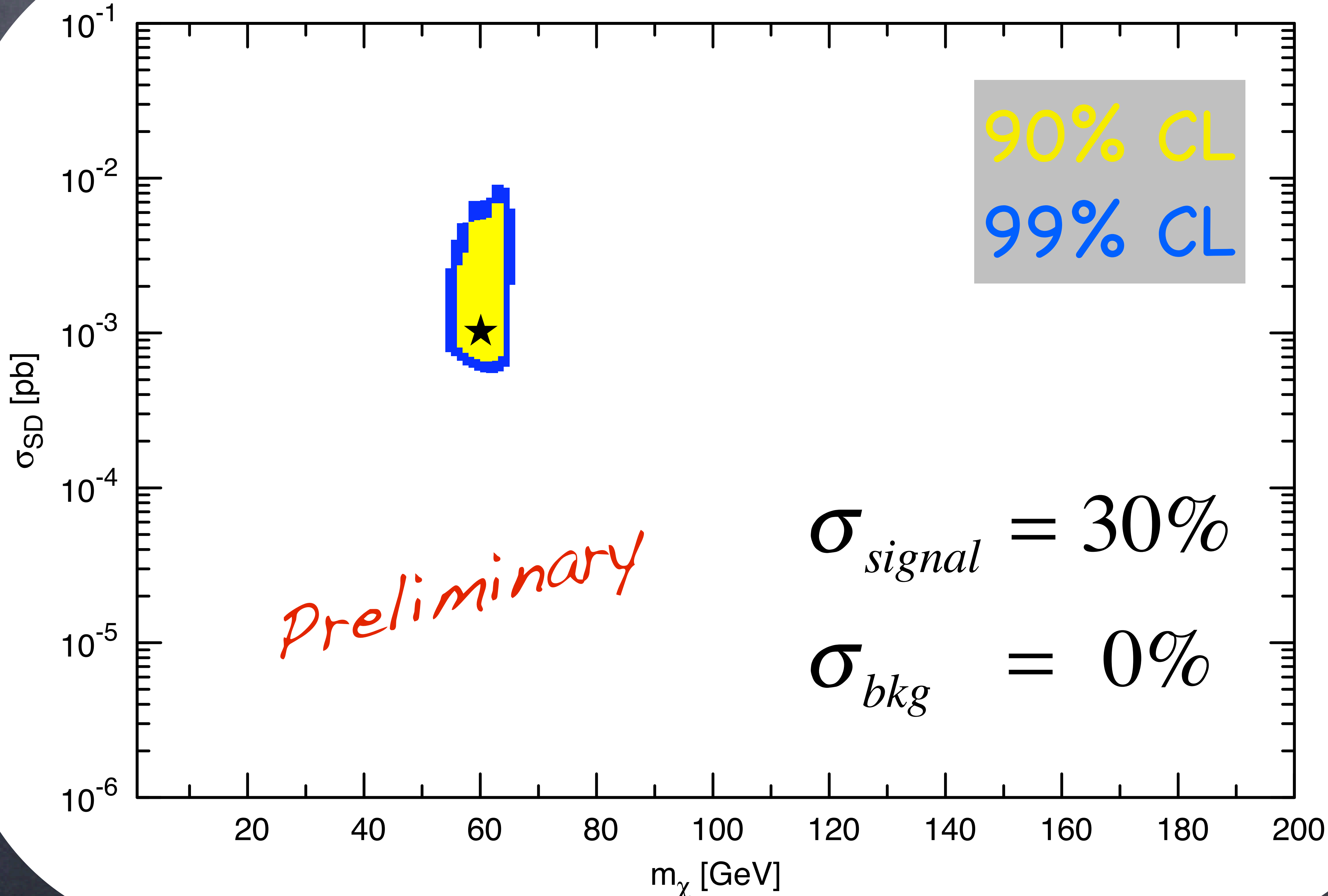
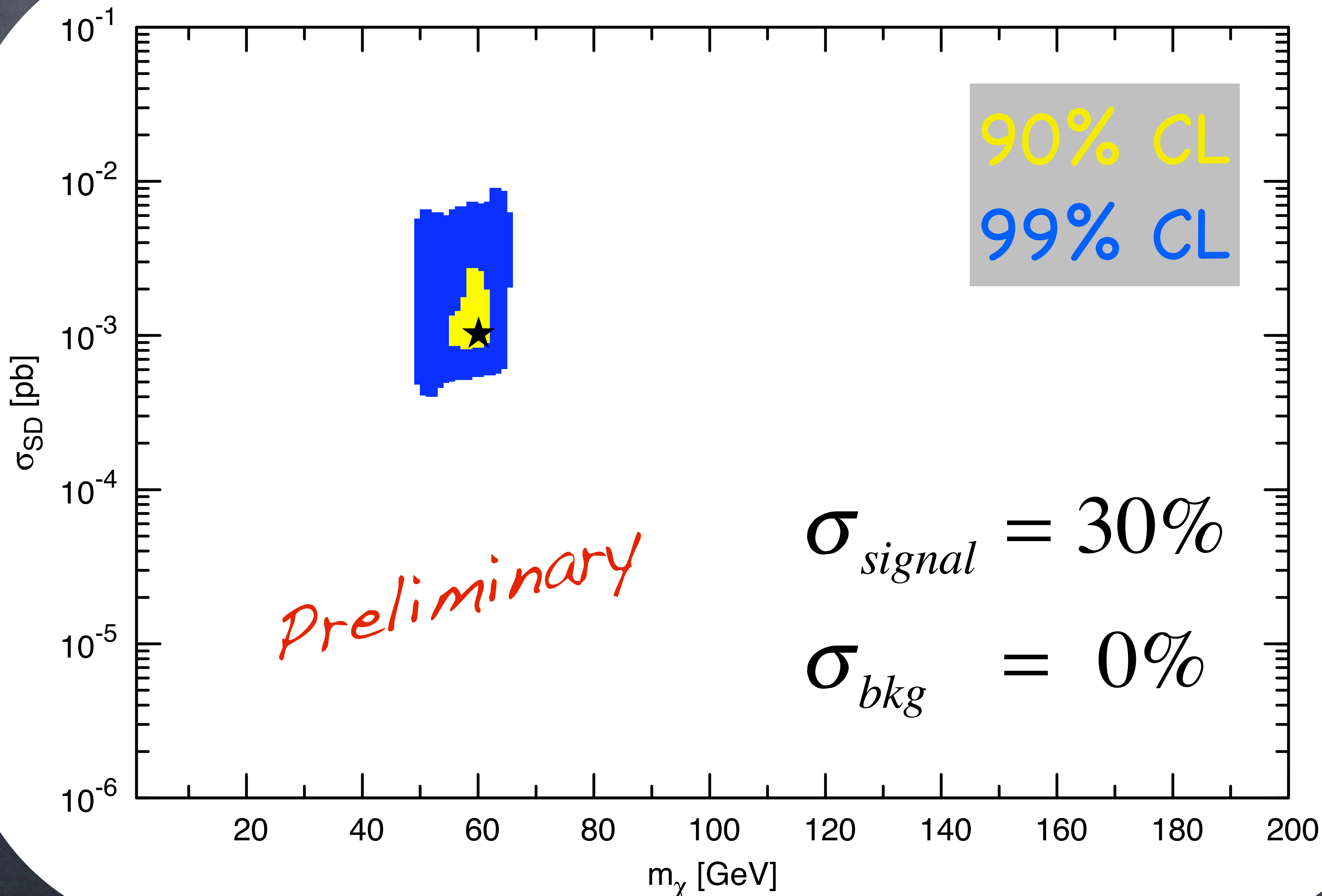
Anihilations into τ

Reconstruction with τ and b



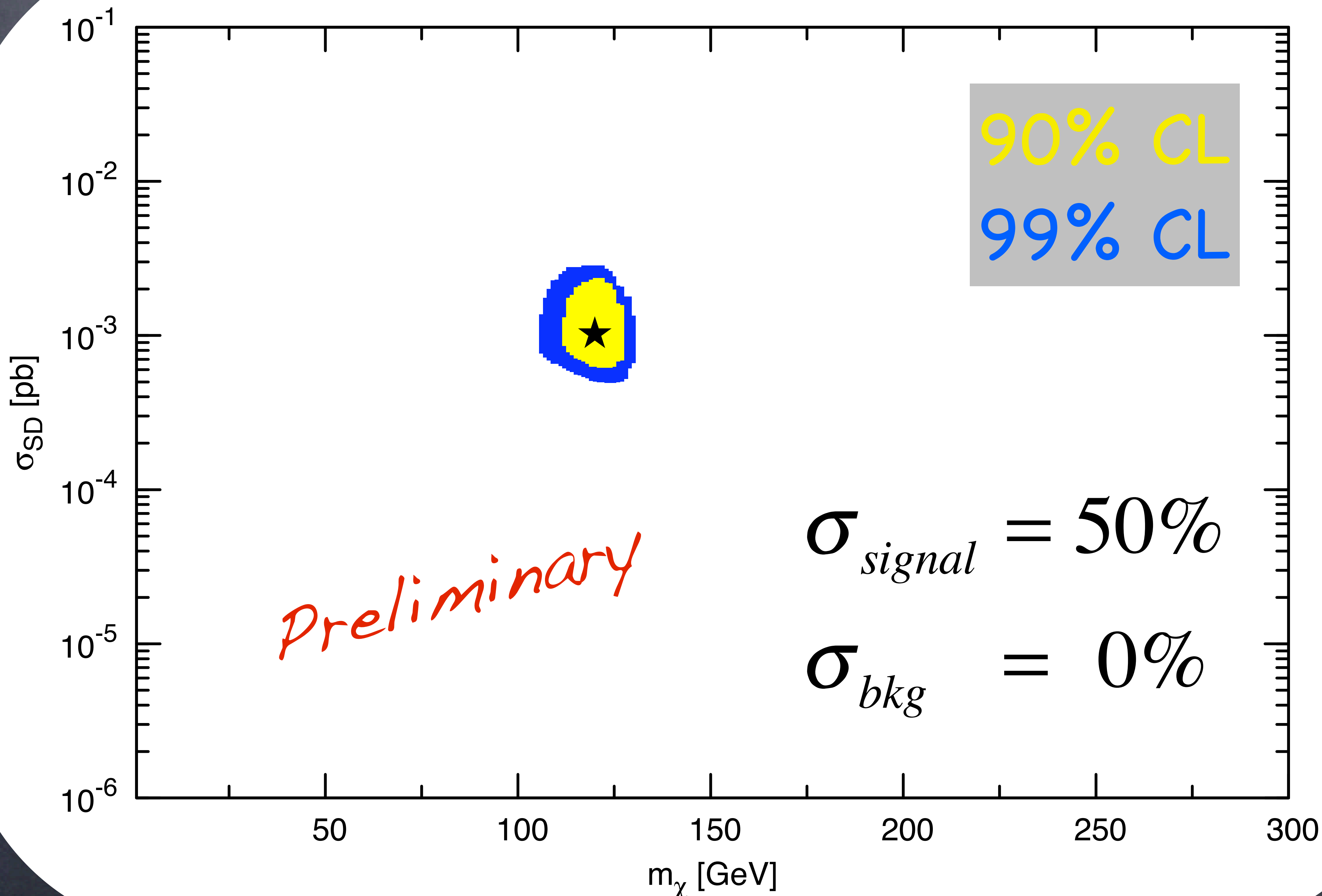
C. R. Das et al., *in preparation*

Anihilations into τ
Reconstruction with τ, b and ν



C. R. Das et al., *in preparation*

Anihilations into τ
Reconstruction with τ and W



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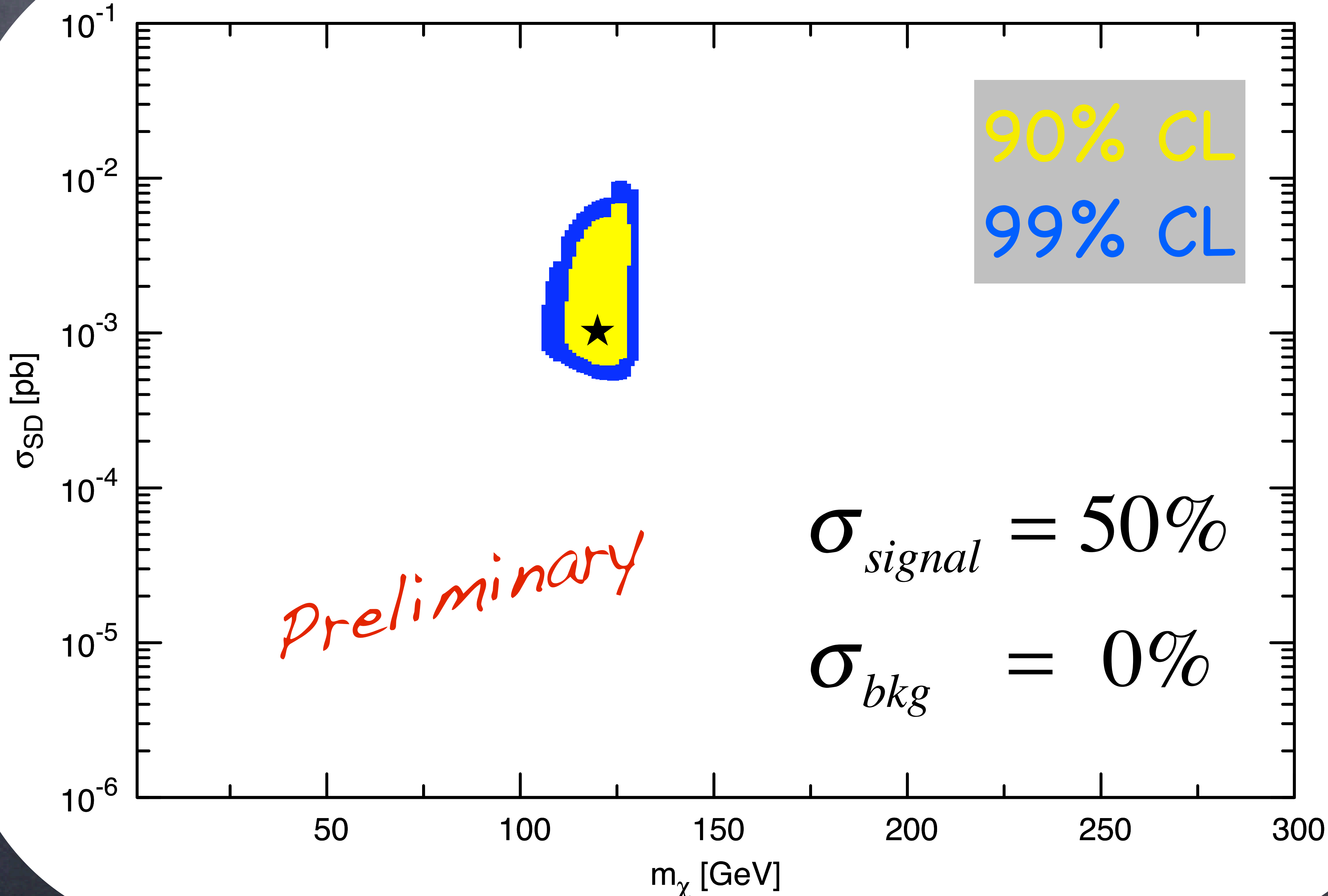
Anihilations into τ

Reconstruction with τ and b



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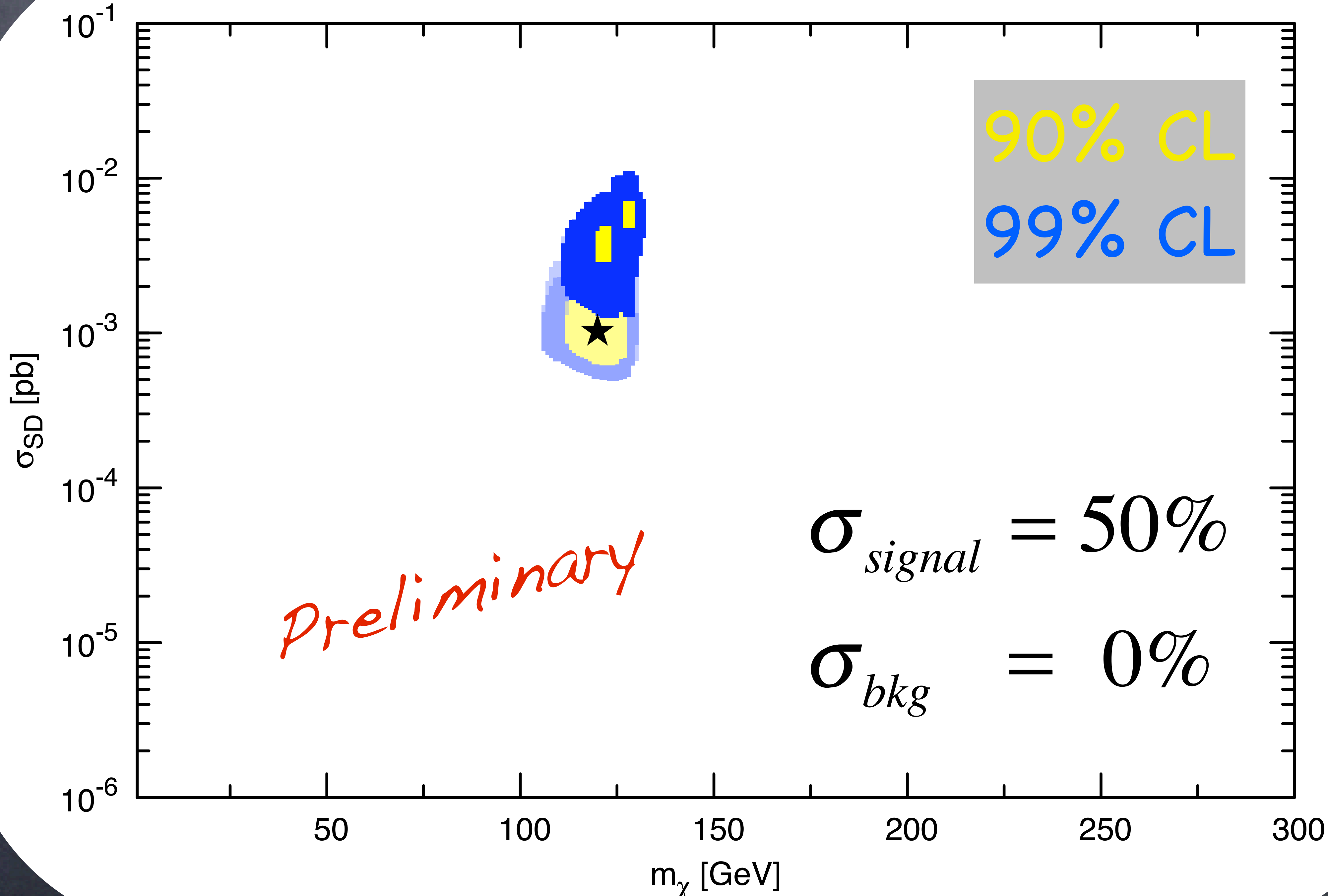
Anihilations into τ

Reconstruction with b and W



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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!