Indirect dark matter searches: Part II

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Outline

YESTERDAY

- Motivation and methods of indirect detection
- Calculating indirect signals
- Spectra from DM annihilation and decay
- The dark matter distribution — see also Tom Abel's and Louie Strigari's talks

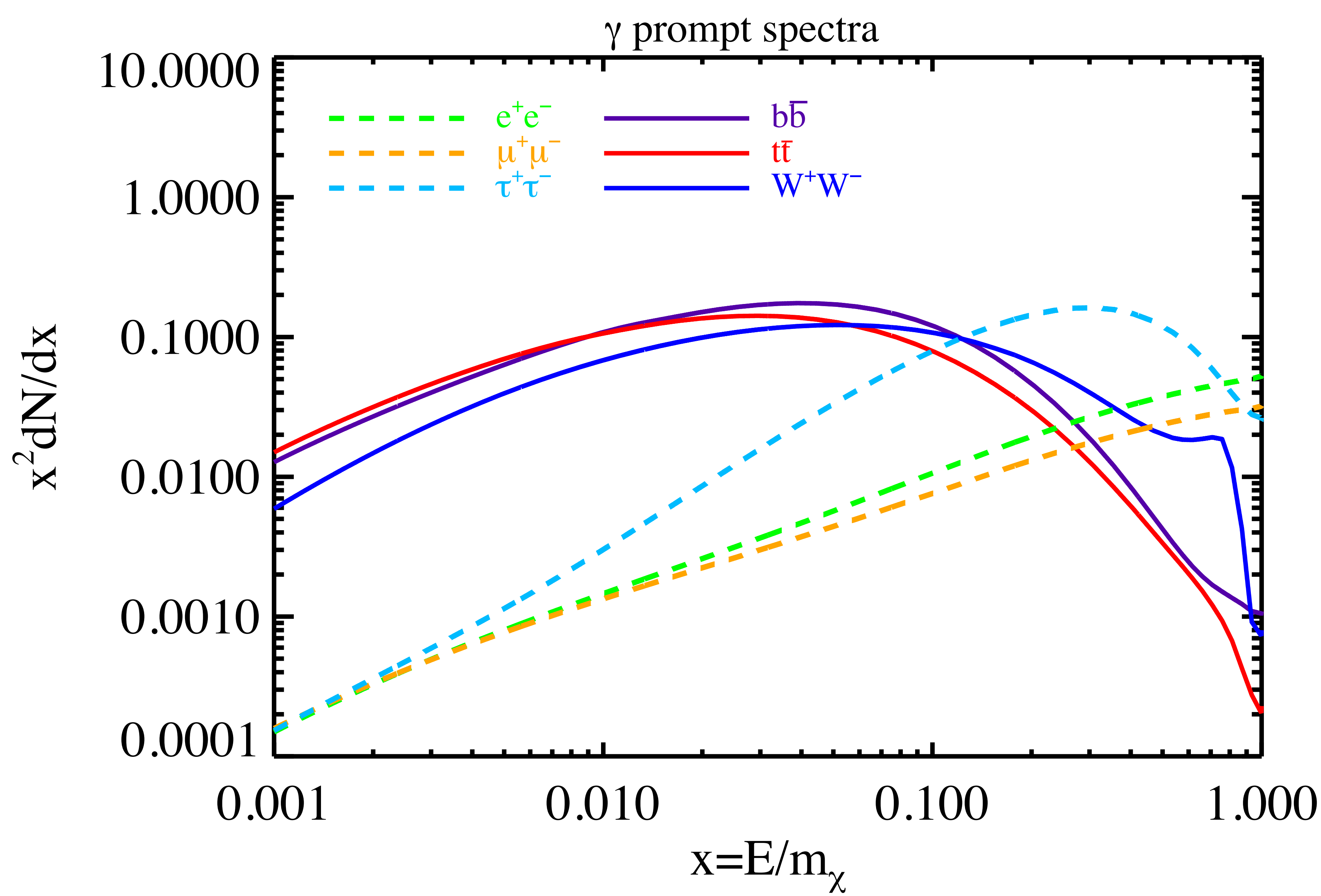
TODAY

- Gamma-ray searches — see also Miguel Sánchez-Conde's and Dan Hooper's talks
- Neutrino searches — see also Justin Vandenbroucke's talk
- Cosmic-ray searches
- Secondary emission
- Anomalies! — see also Dan Hooper's talk

Dark matter photon spectra

Question from yesterday: why always consider bb for limits?

- “soft” channels: produce a continuum gamma-ray spectrum primarily from decay of neutral pions
- “hard channels”: include final state radiation (FSR) associated with charged leptons in the final states
- line emission: γγ, Zγ, hγ (not shown), loop-suppressed



Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

Gamma-ray searches

- look for prompt and sometimes also secondary emission from WIMP annihilation/decay; sift through large, uncertain backgrounds
- to observe gamma rays below about 10 GeV MUST GO TO SPACE: Fermi Large Area Telescope (LAT)
- for high energies, need large effective area: ground-based imaging atmospheric Cherenkov telescopes (IACTs), e.g., H.E.S.S., MAGIC, VERITAS, and CTA

Imaging atmospheric Cherenkov telescopes (IACTs)

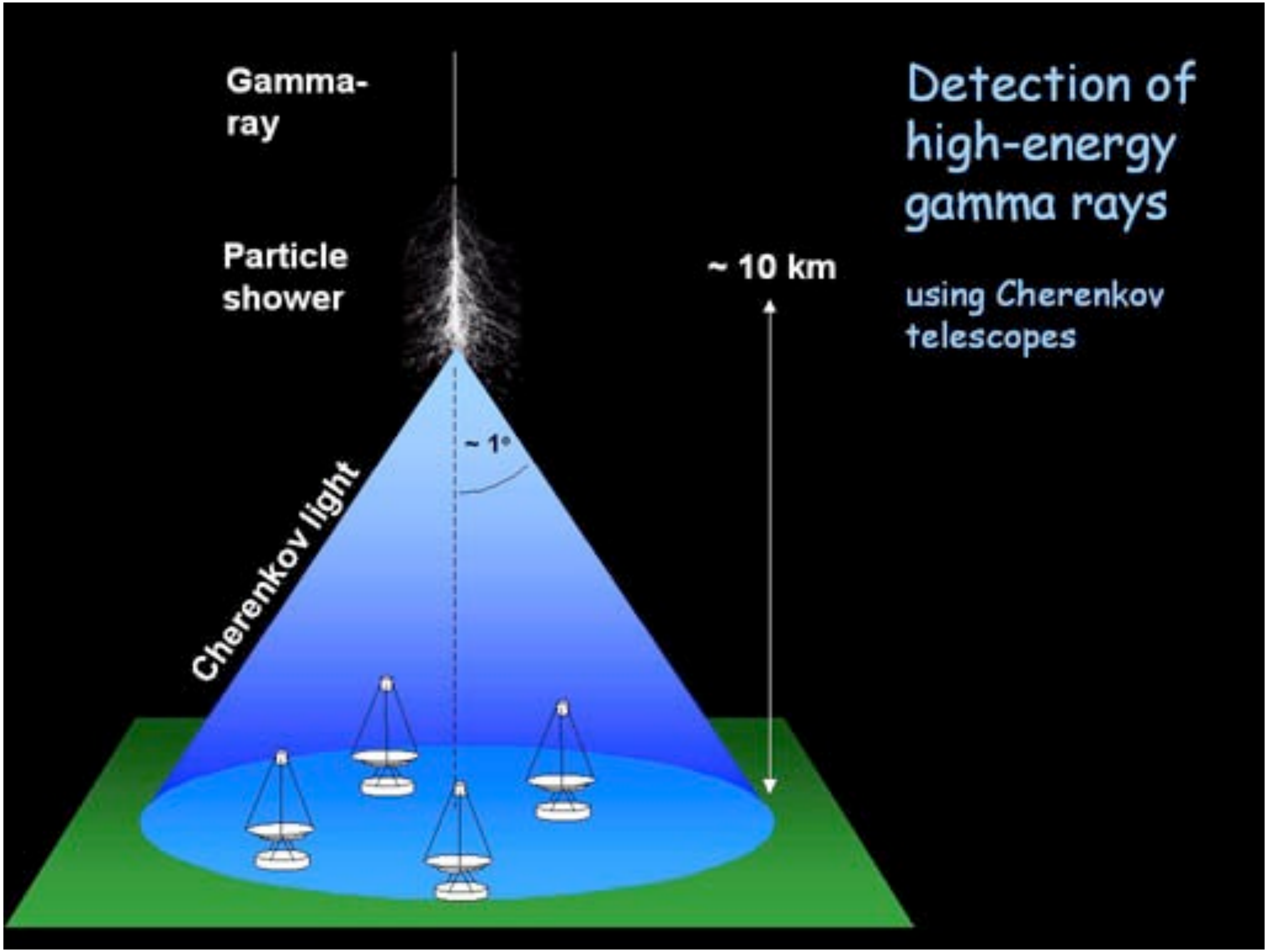


Image credit: H.E.S.S. Collaboration

The Cherenkov Telescope Array (CTA)

- array of many telescopes of various sizes to balance need for effective area while reducing energy threshold
- will trigger as low as ~ few tens of GeV (compared to ~ 100 GeV for current ACTs)

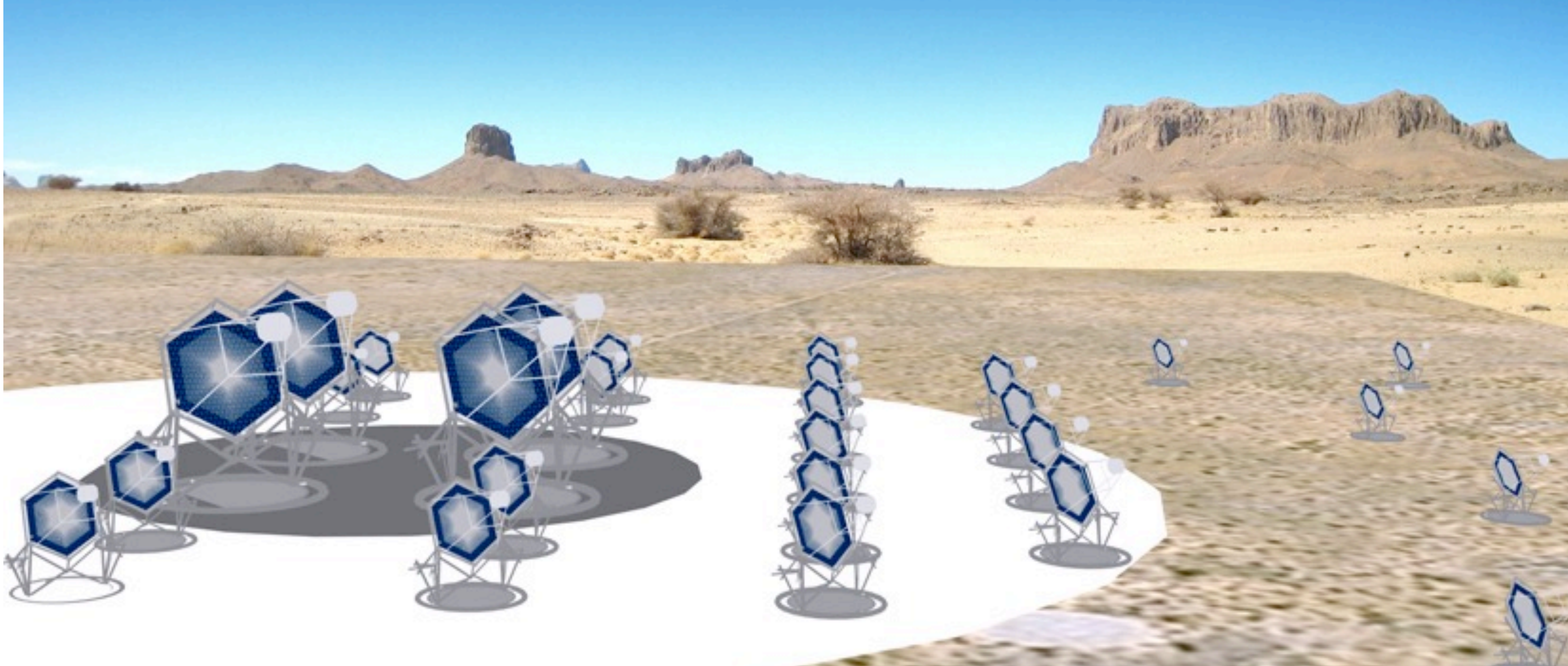
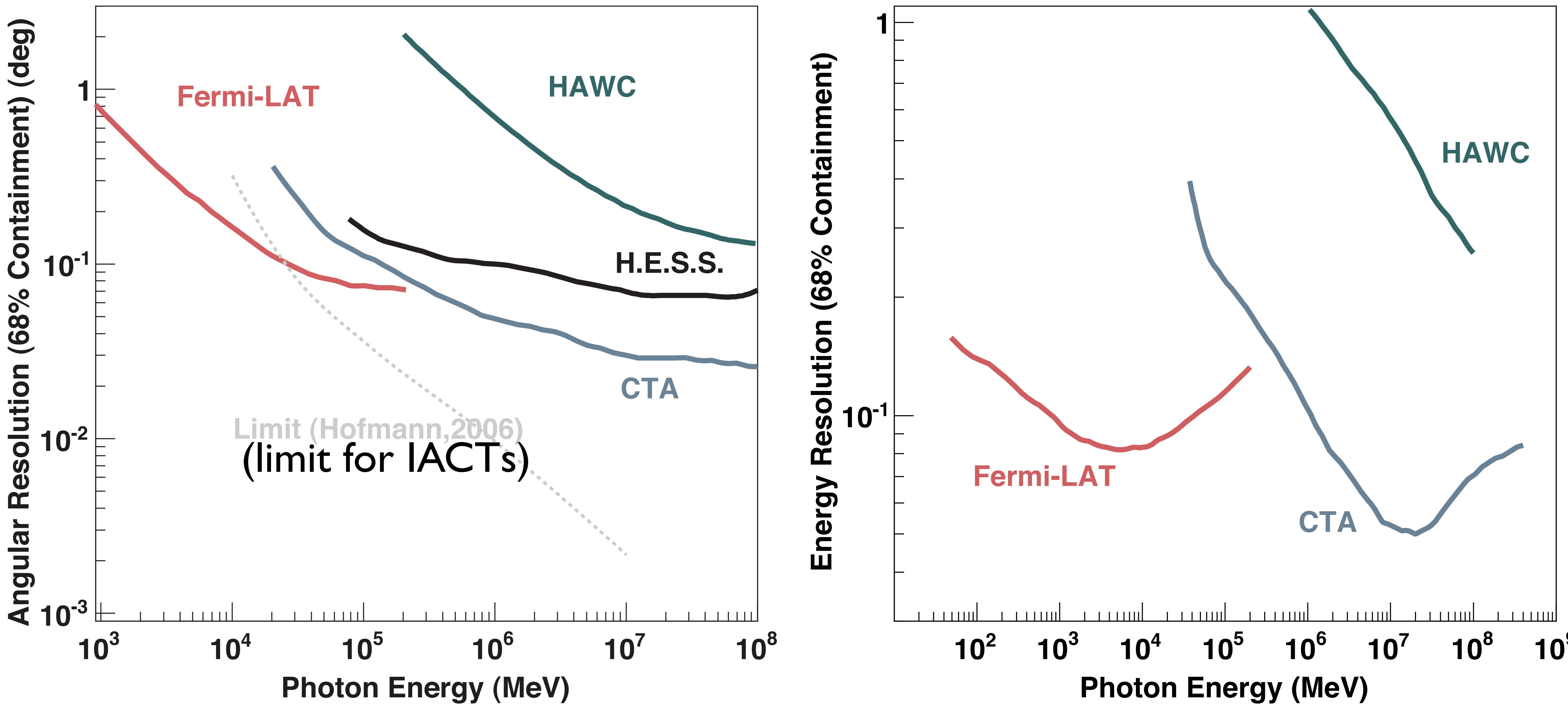


Image credit: CTA Collaboration

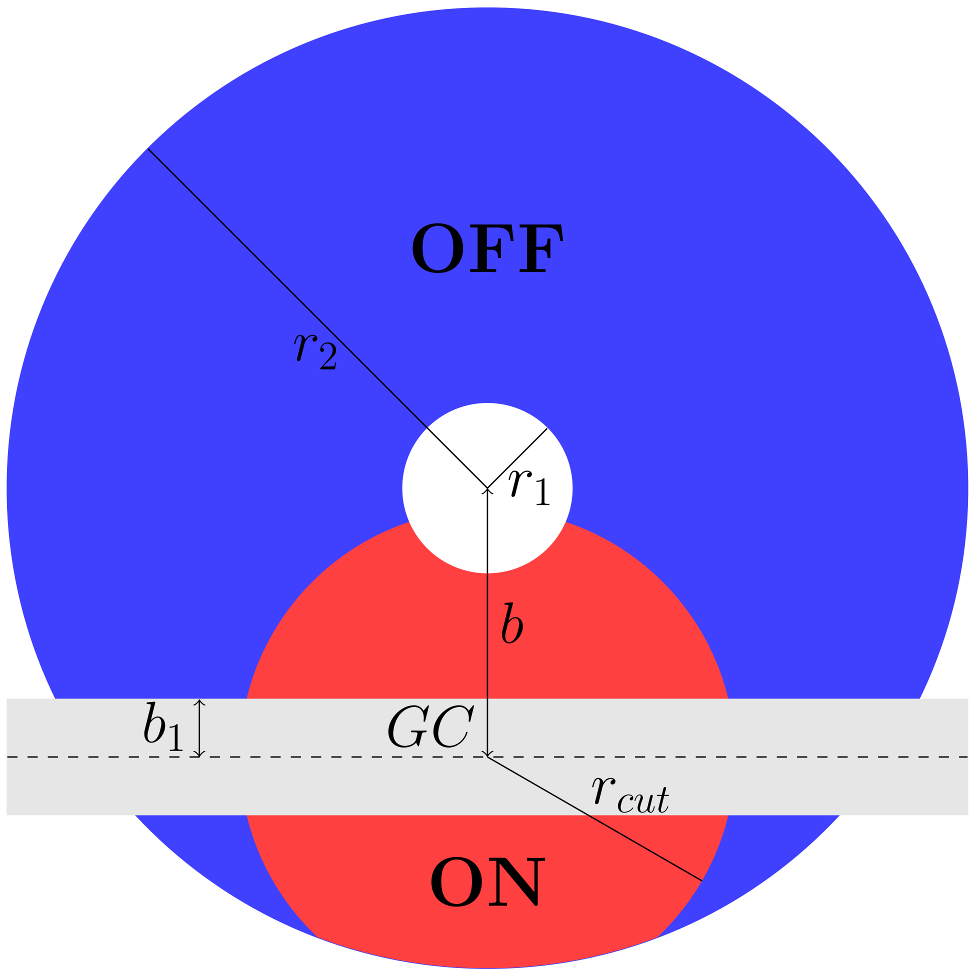
Current and future capabilities



Funk et al. 2012

NB: Fermi LAT effective area ~ 0.8 m^2 vs ~ 10^6 m^2 for CTA

CTA search for dark matter signals



"Ring Method"

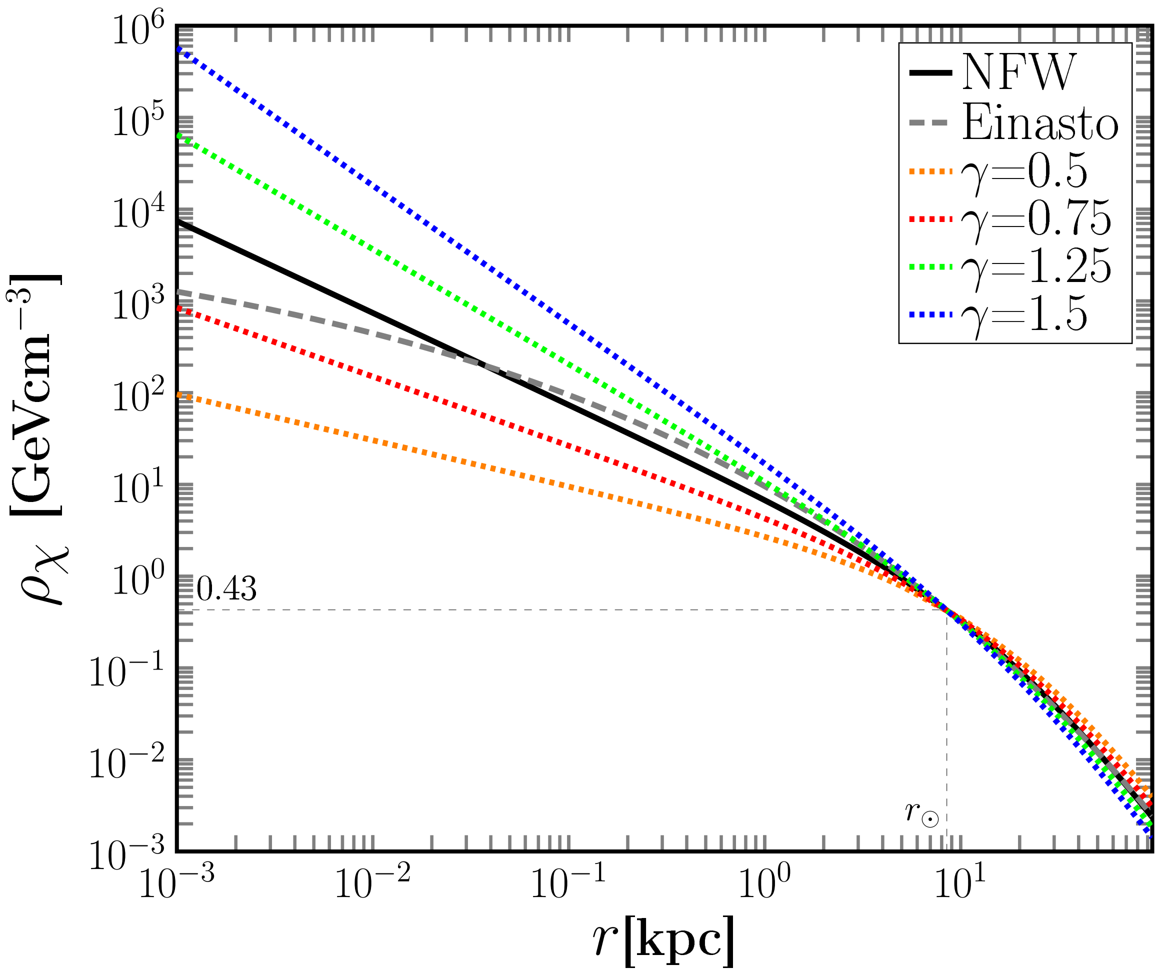
IACTs use "on-off" methods to search for signals due to large irreducible cosmic-ray electron background

The "Ring Method" limits systematics due to uncertainties in the effective area variation across the FOV

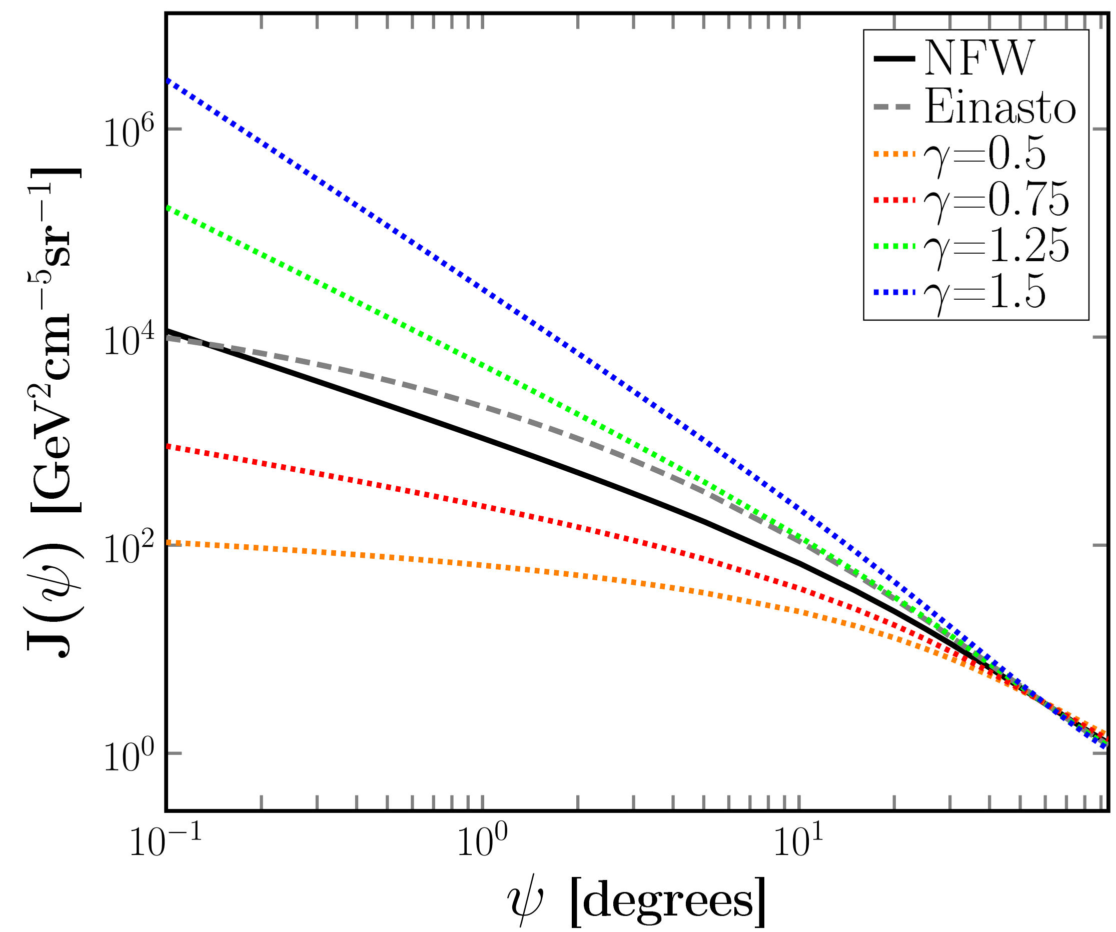
Pierre, JSG, & Scott, 2014

Detecting a Galactic Center DM signal with CTA

Density profile



Annihilation "J-factor"



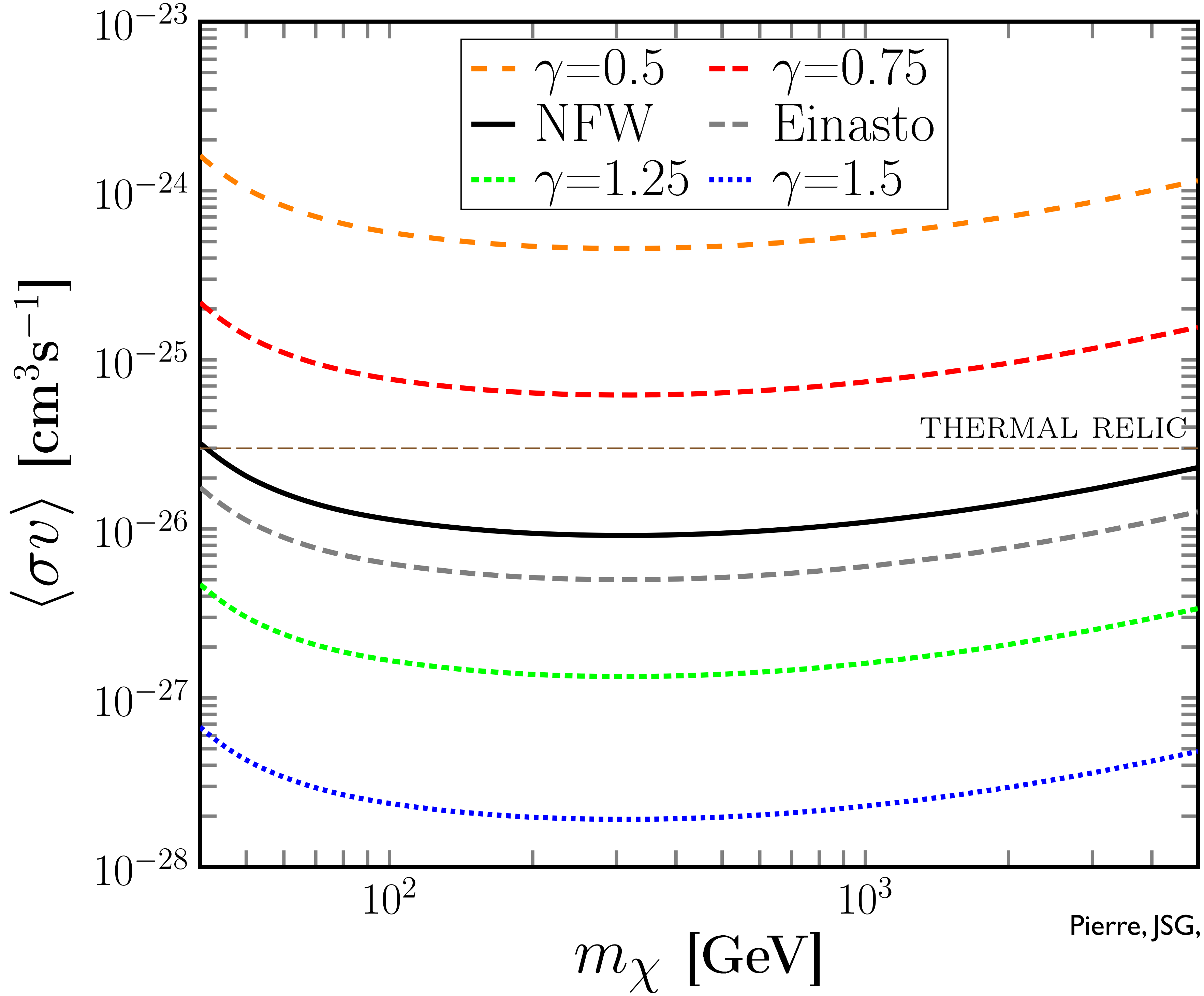
Pierre, JSG, & Scott, 2014

flatter density profiles favored by some observational data and in some DM models could be challenging for CTA

Density profile dependence of sensitivity

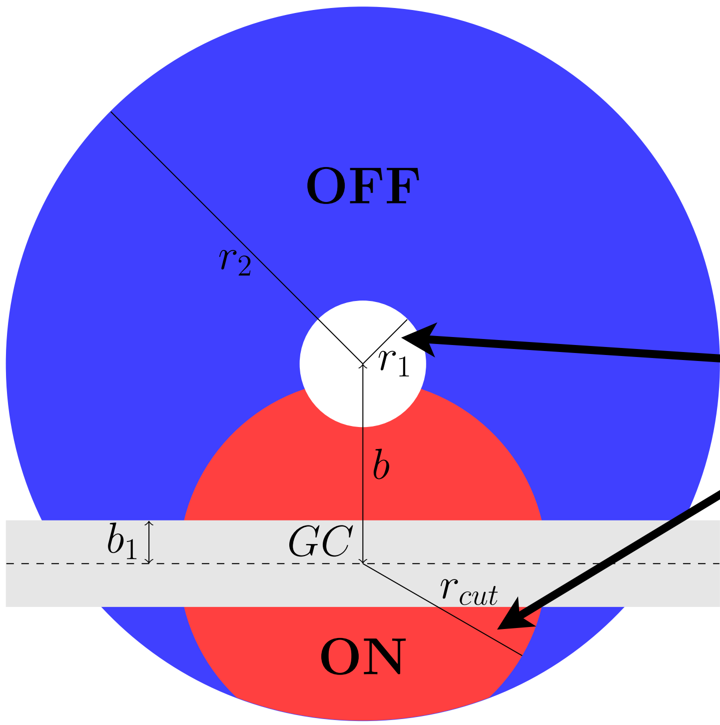
(parameter space ABOVE the curves excluded)

200h, annihilation to $\tau^+\tau^-$



Pierre, JSG, & Scott, 2014

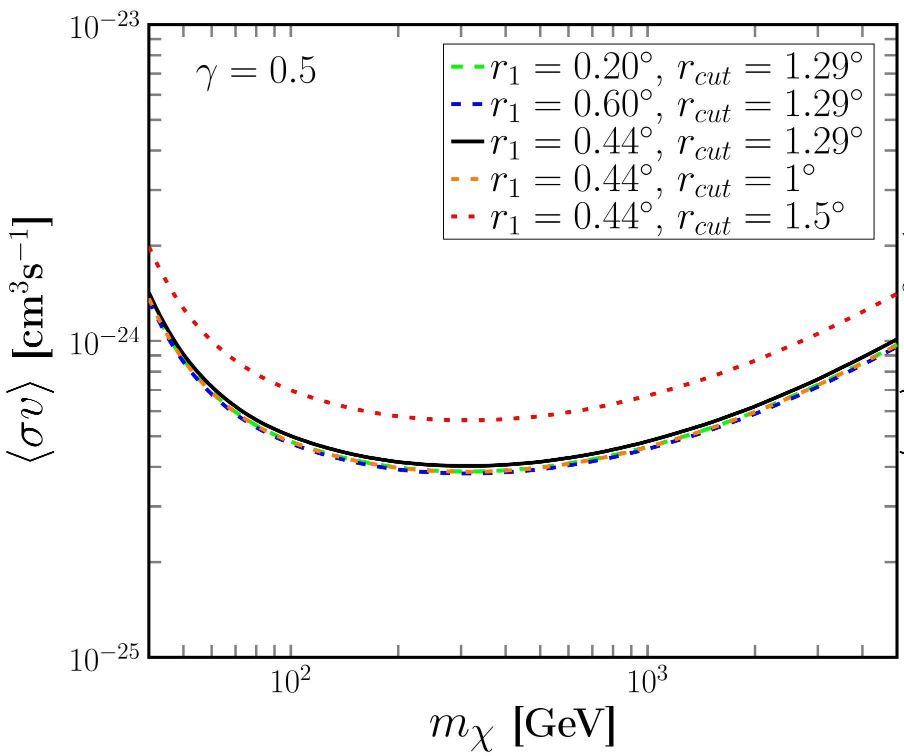
Optimizing the search regions



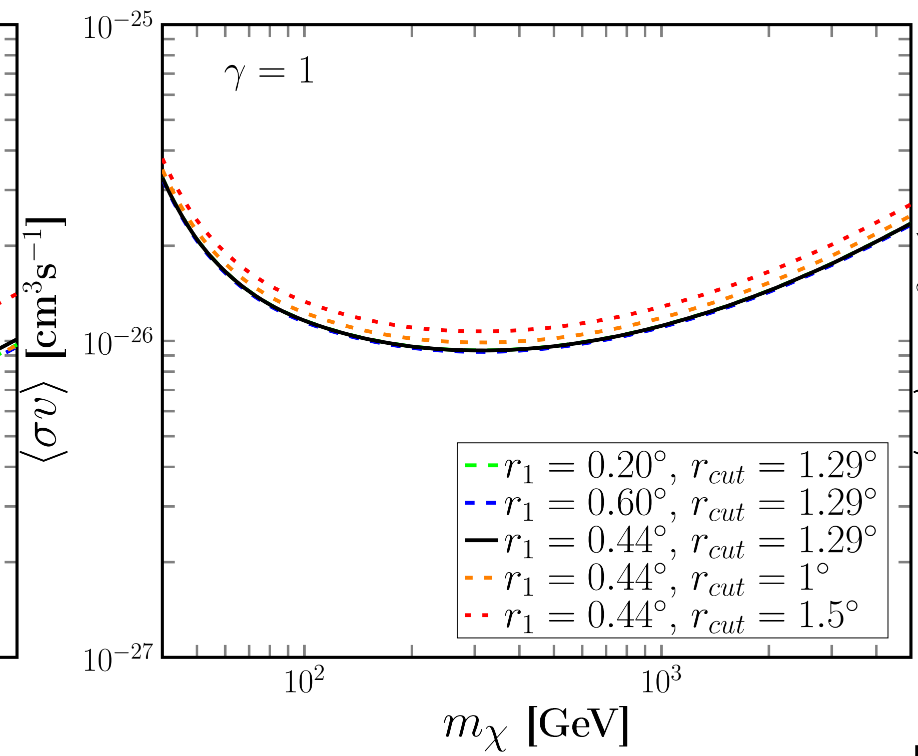
vary these parameters

sensitivity is not strongly dependent on search regions except for a very shallow profile

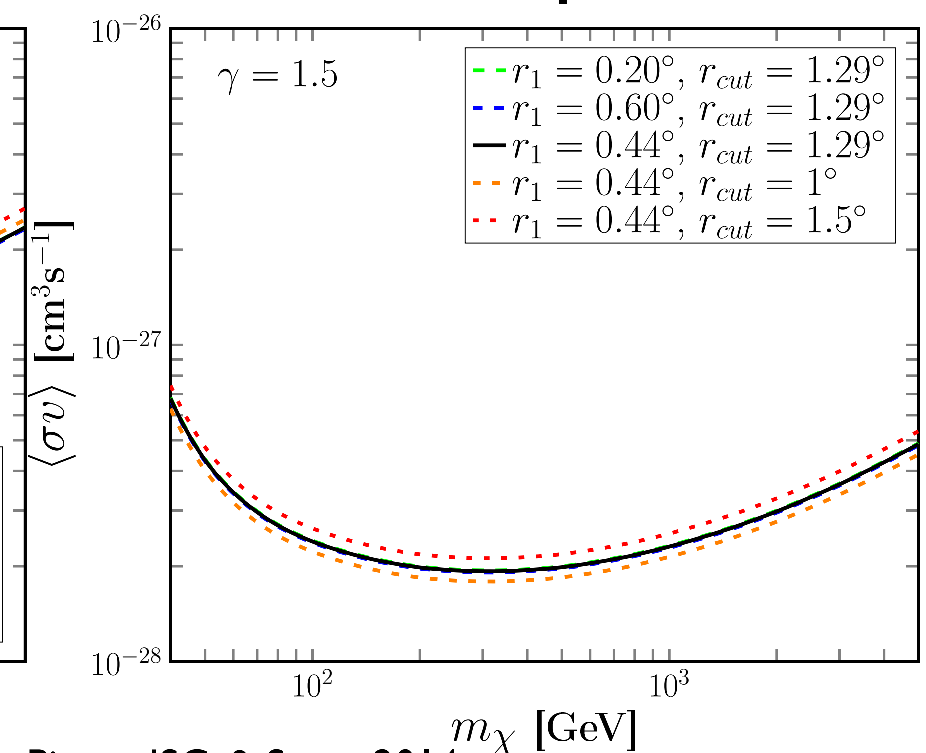
shallower



NFW



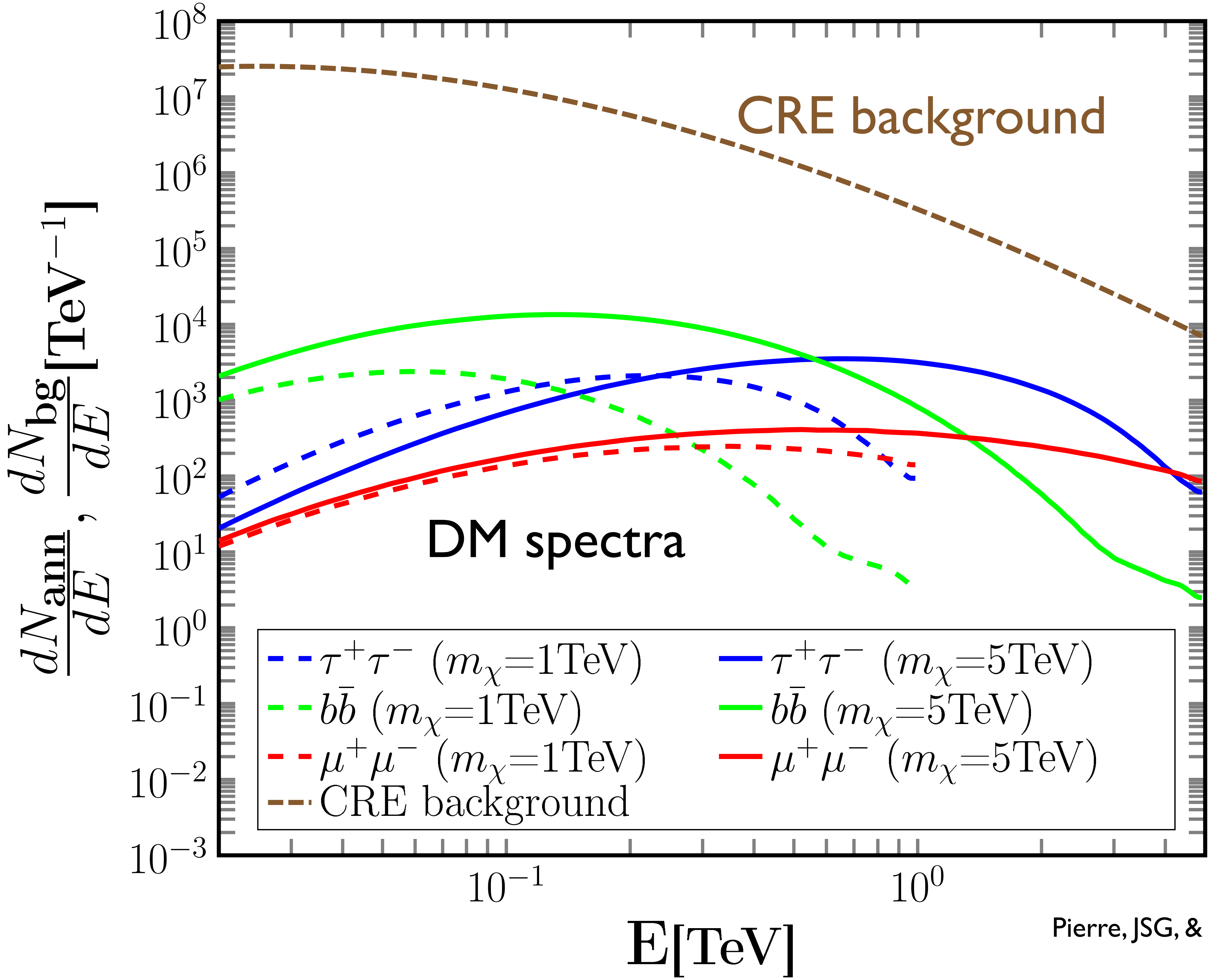
steeper



Pierre, JSG, & Scott, 2014

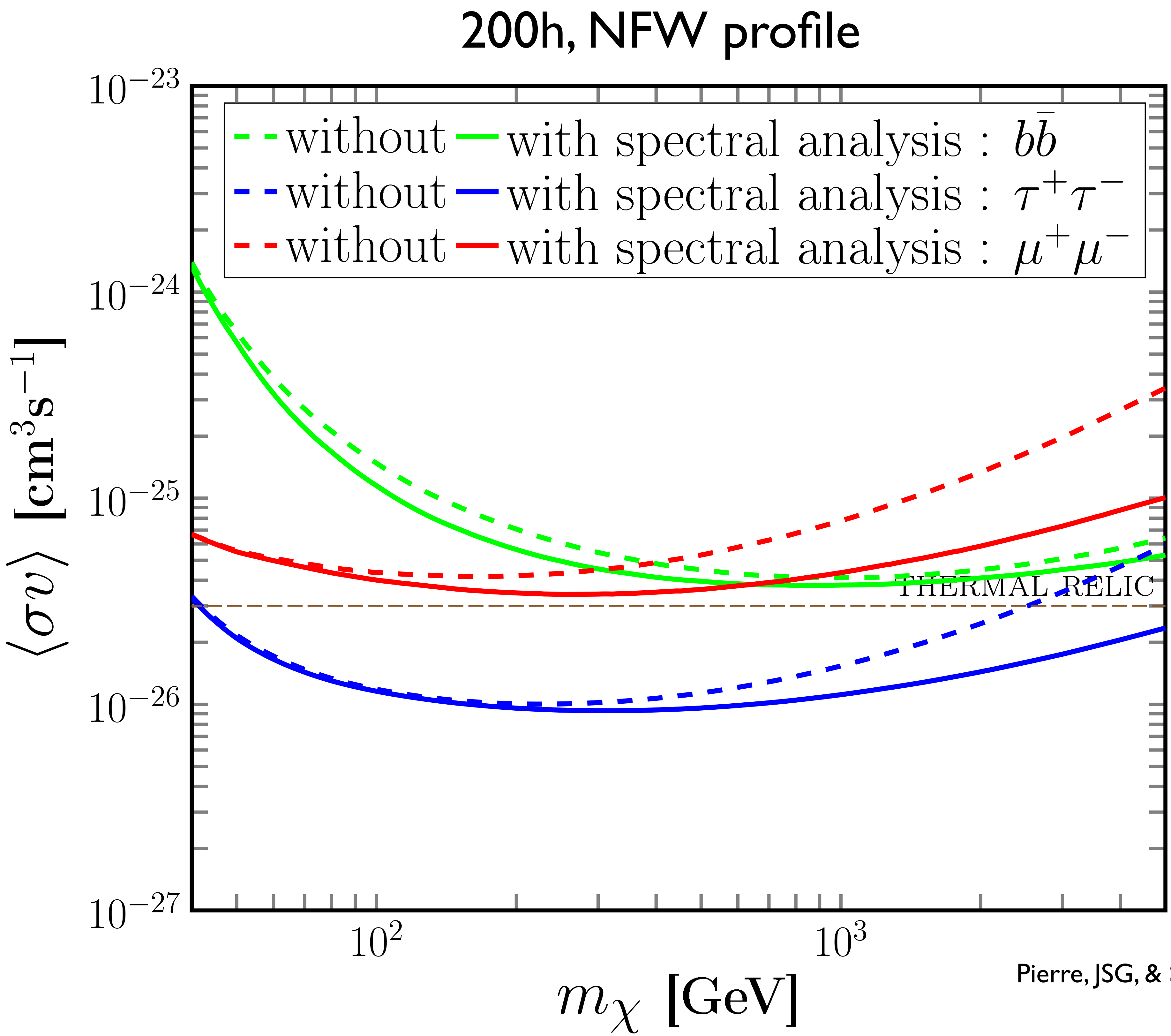
Taking advantage of spectral information

Differential observed counts spectrum



Pierre, JSG, & Scott, 2014

Improvement from spectral analysis

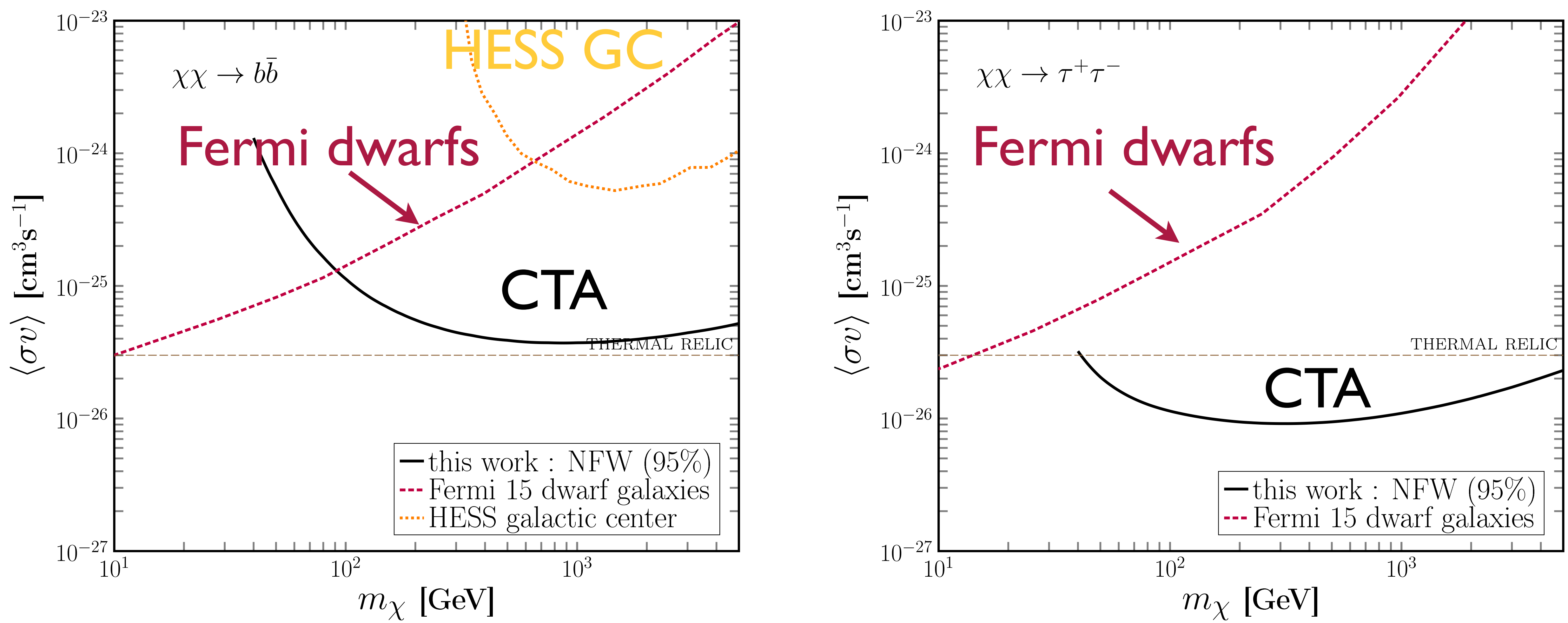


Pierre, JSG, & Scott, 2014

CTA sensitivity to dark matter annihilation

200h w/ CTA, NFW profile

annihilation to bb　　　　annihilation to $\tau^+\tau^-$



Pierre, JSG, & Scott, 2014

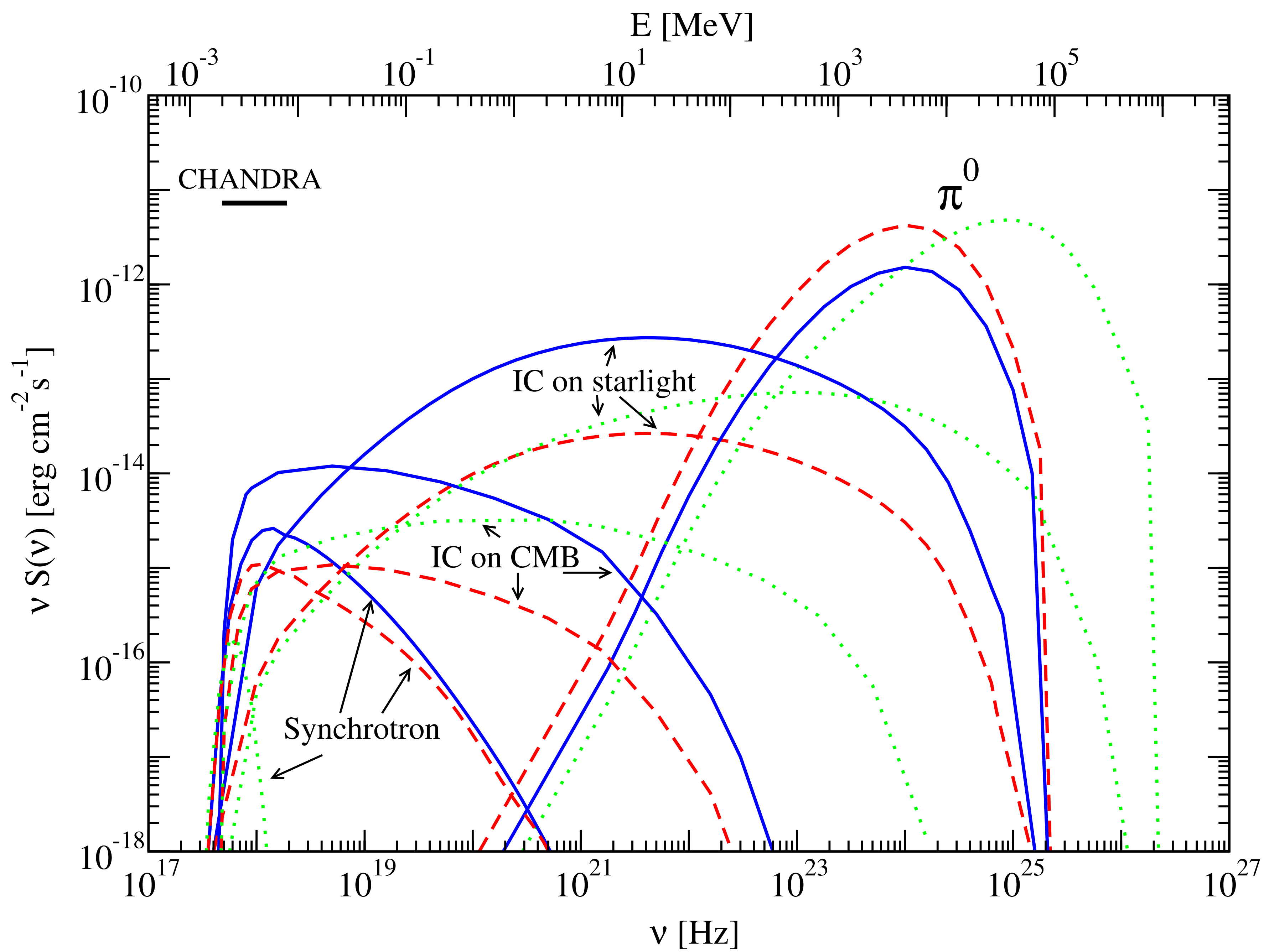
Multi-wavelength searches

- search for secondary lower-energy emission from charged particles produced in WIMP annihilation/decay
- can improve robustness of analyses by testing consistency of DM signals with multiple data sets spanning a broad range of energies
- lower-energy observations can probe much smaller angular scales than gamma-ray observations can, yielding valuable information about cosmic-ray targets that trace diffuse gamma-ray emission
- can detect and constrain gamma-ray source populations using observations at lower energies

Multi-wavelength dark matter photon spectra

- secondary photon emission associated with charged particle final states:
  - inverse Compton scattering of starlight, CMB
  - synchrotron due to magnetic fields
  - Bremsstrahlung on gas
  - hadronic cosmic-ray interactions

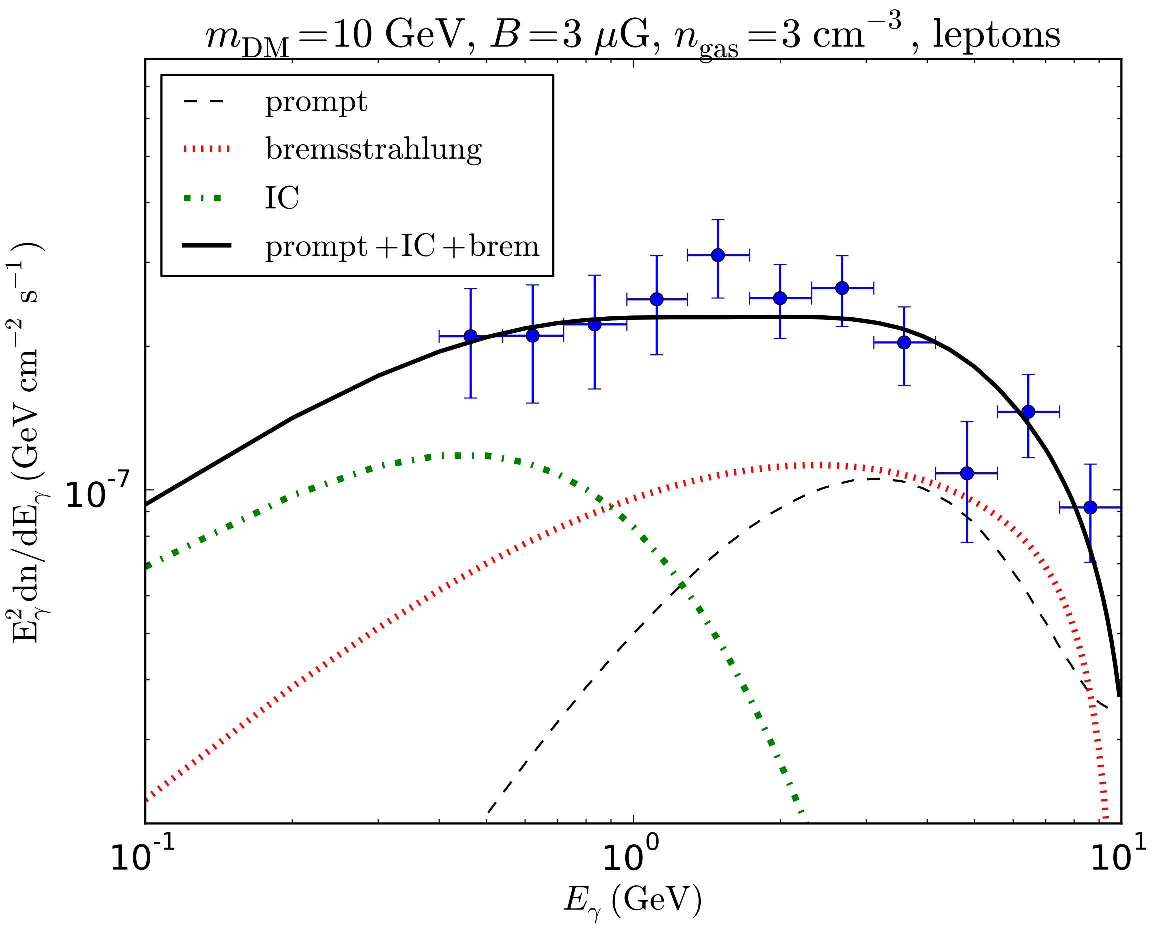
DM spectrum from the Galactic Center

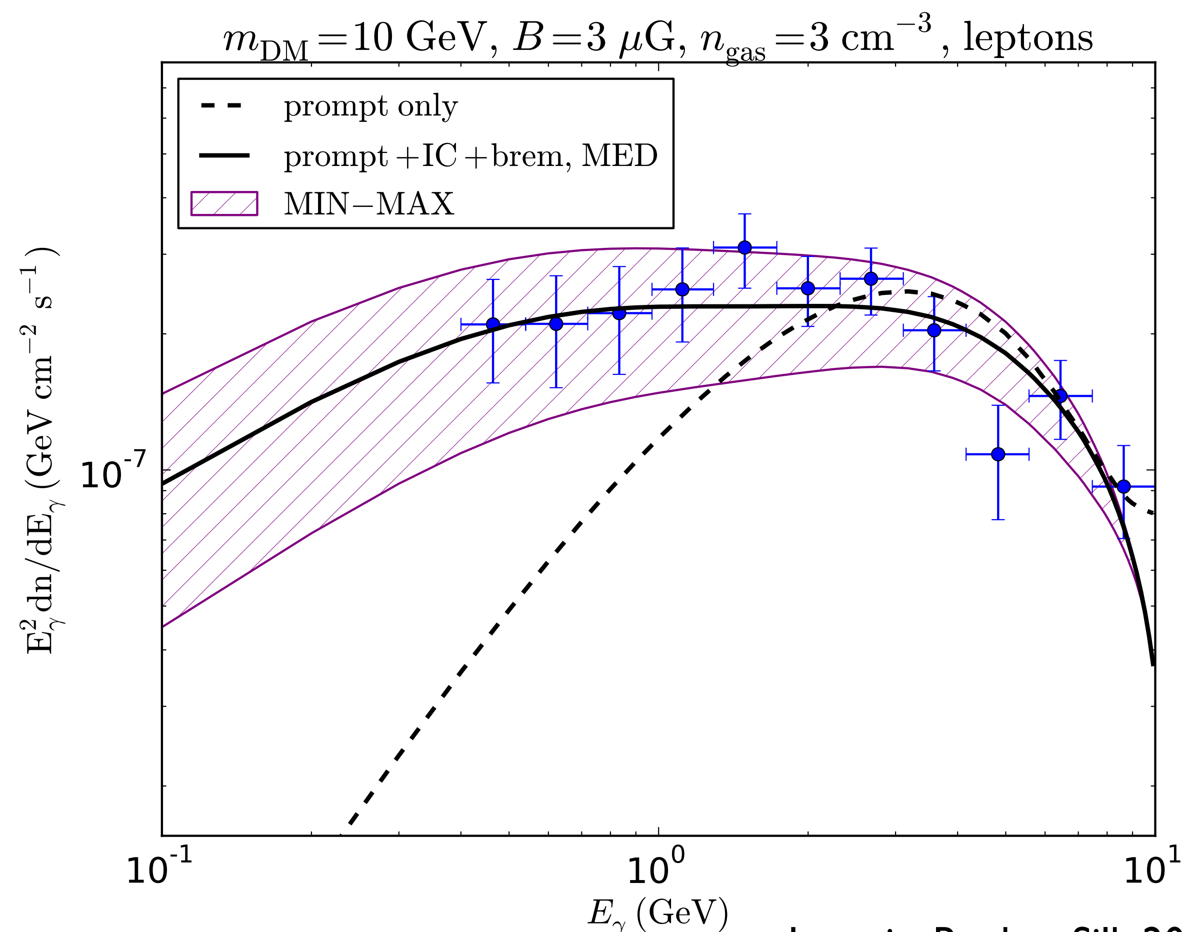


Regis & Ullio 2008

RECAP

Bed of Procrustes





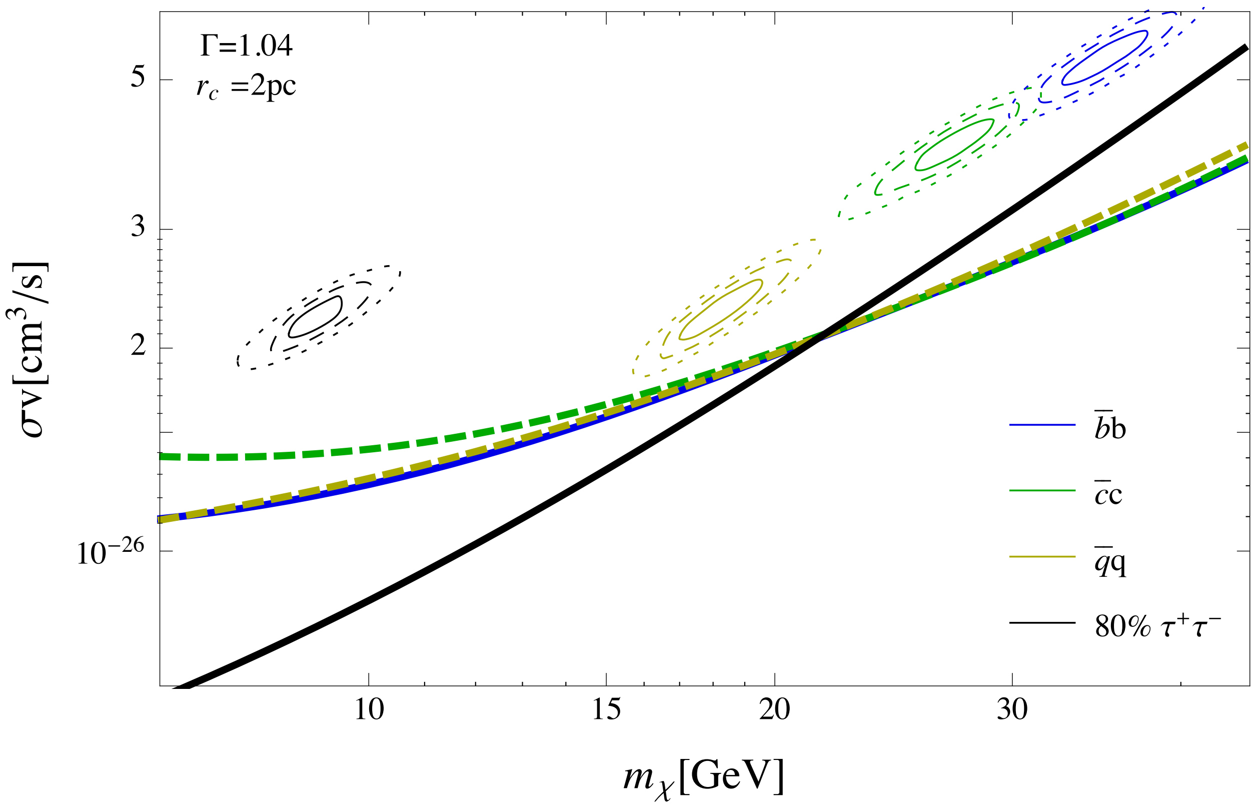
Lacroix, Boehm, Silk 2014

- Lacroix et al. point out importance of:
  - inverse Compton
  - propagation model
  - diffusion (and latitude dependence of secondary emission)

RECAP/UPDATE

Multiwavelength / multi-messenger constraints

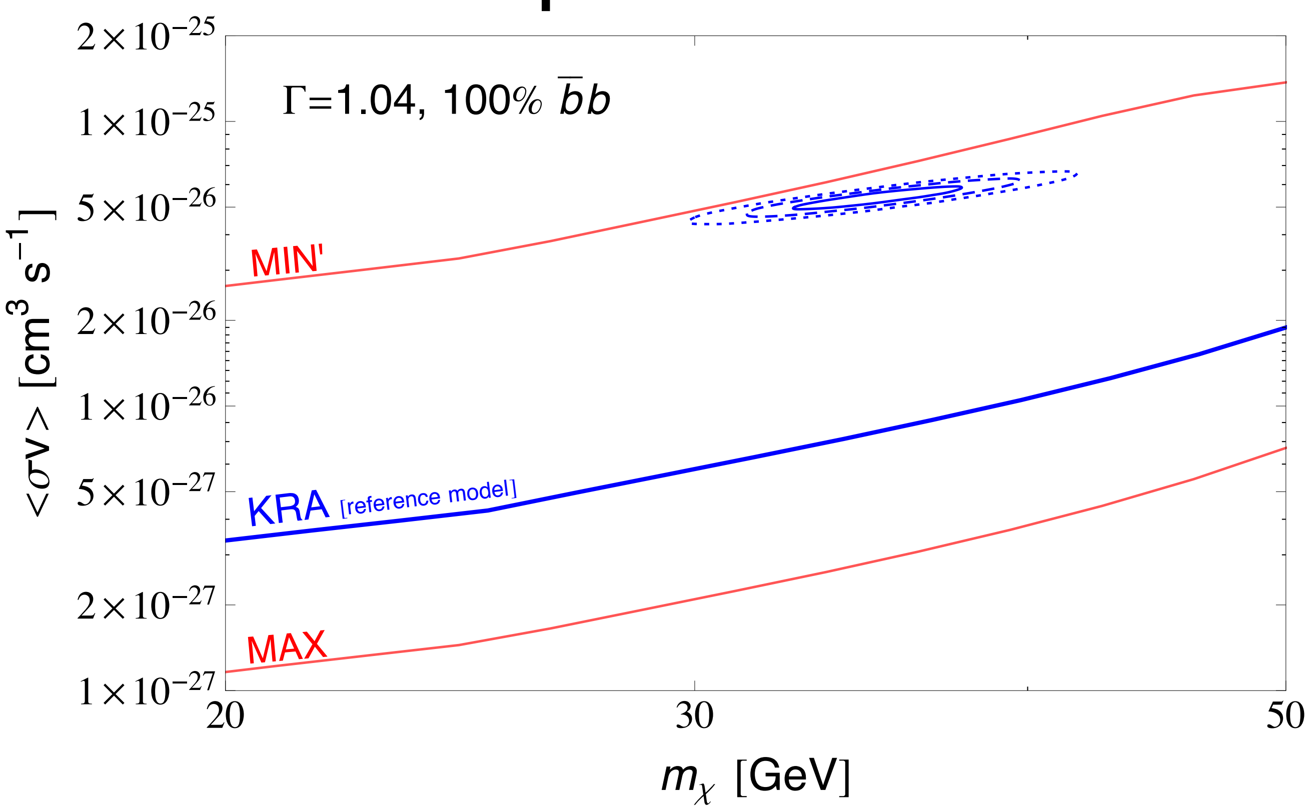
Radio constraints



CAVEAT:
uncertainties in B field?

uncertainties in propagation?

Anti-proton constraints



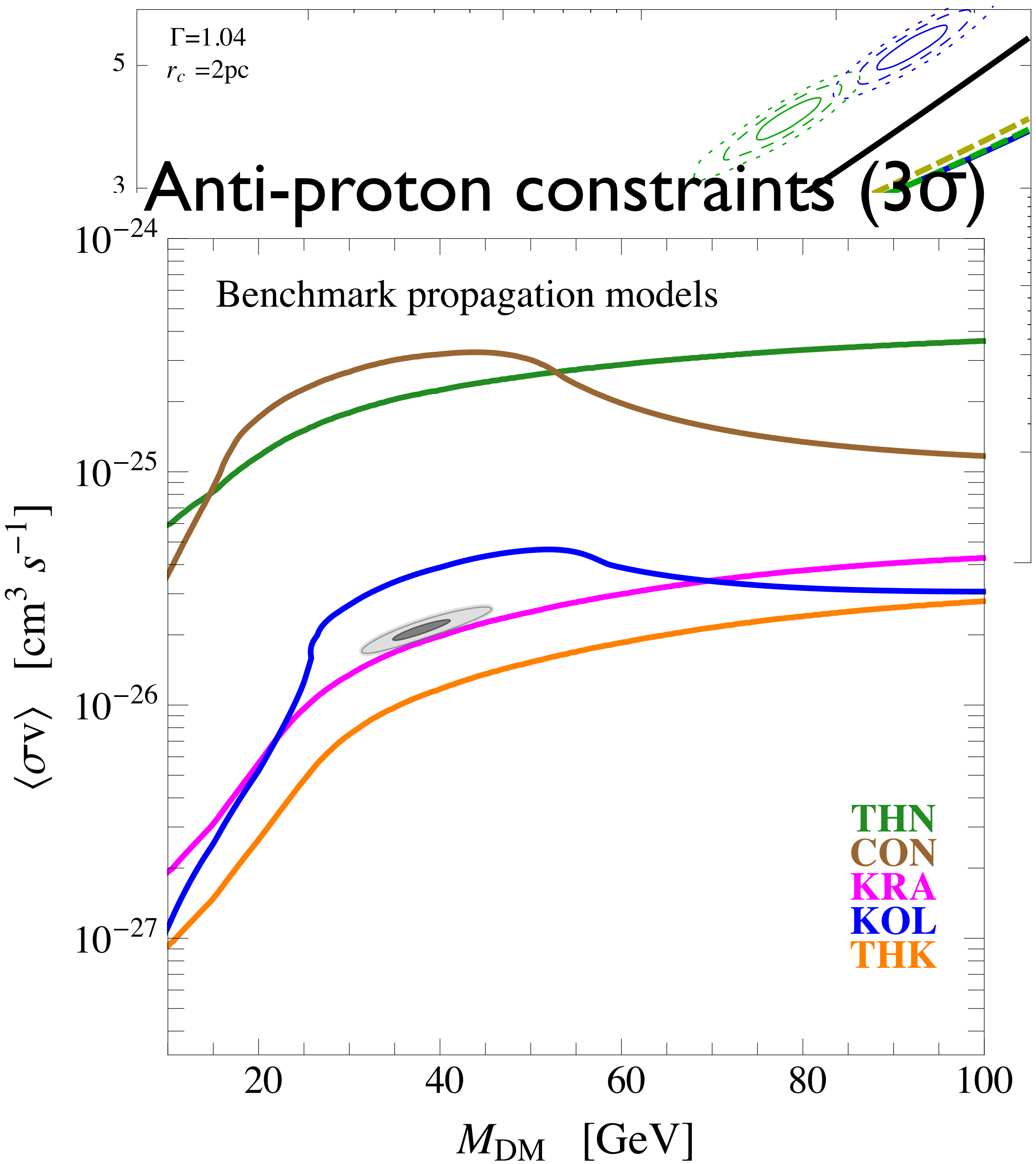
Bringmann et al. 2014

RECAP/UPDATE

Multiwavelength / multi-messenger constraints

Radio constraints

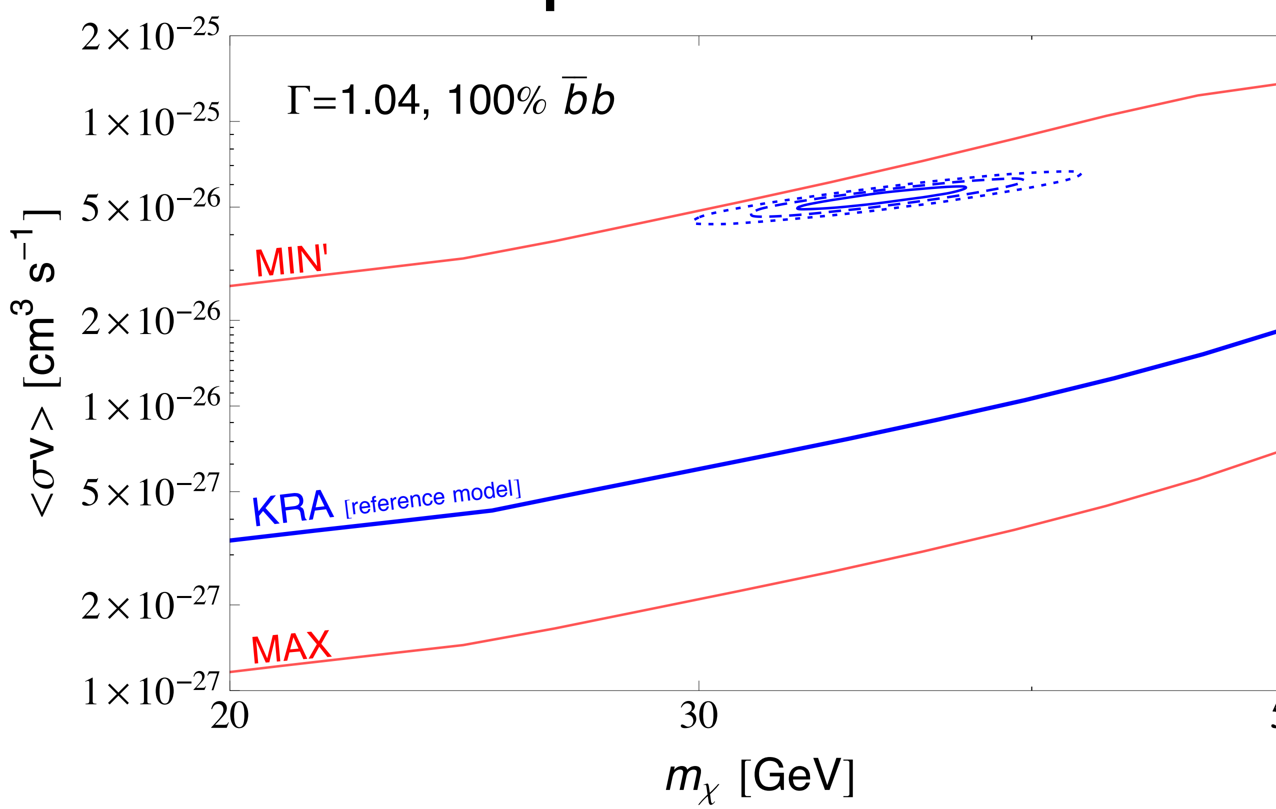
Anti-proton constraints (3σ)



Cirelli et al. 2014

uncertainties in propagation?

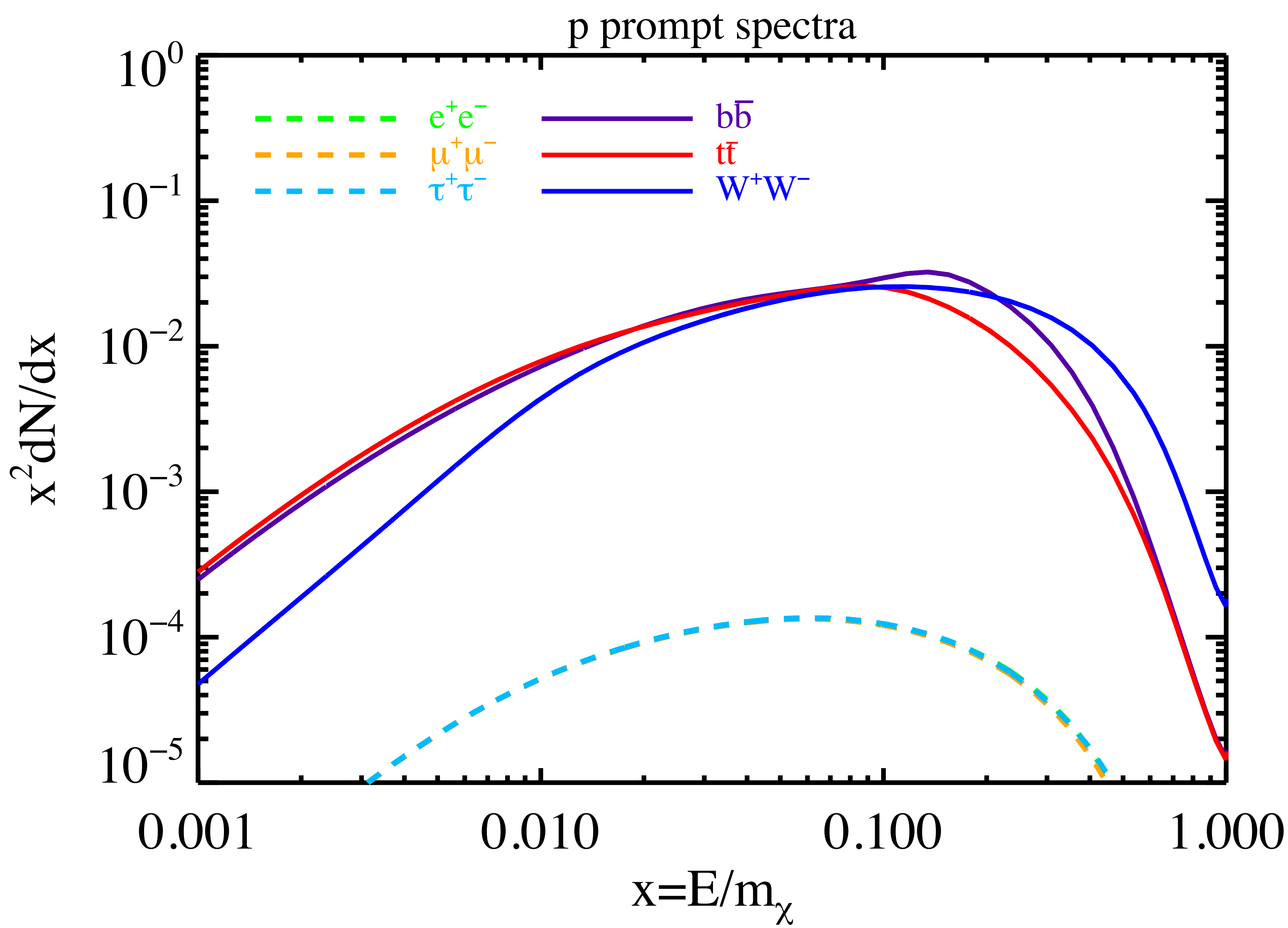
Anti-proton constraints



Bringmann et al. 2014

Dark matter proton/antiproton spectra

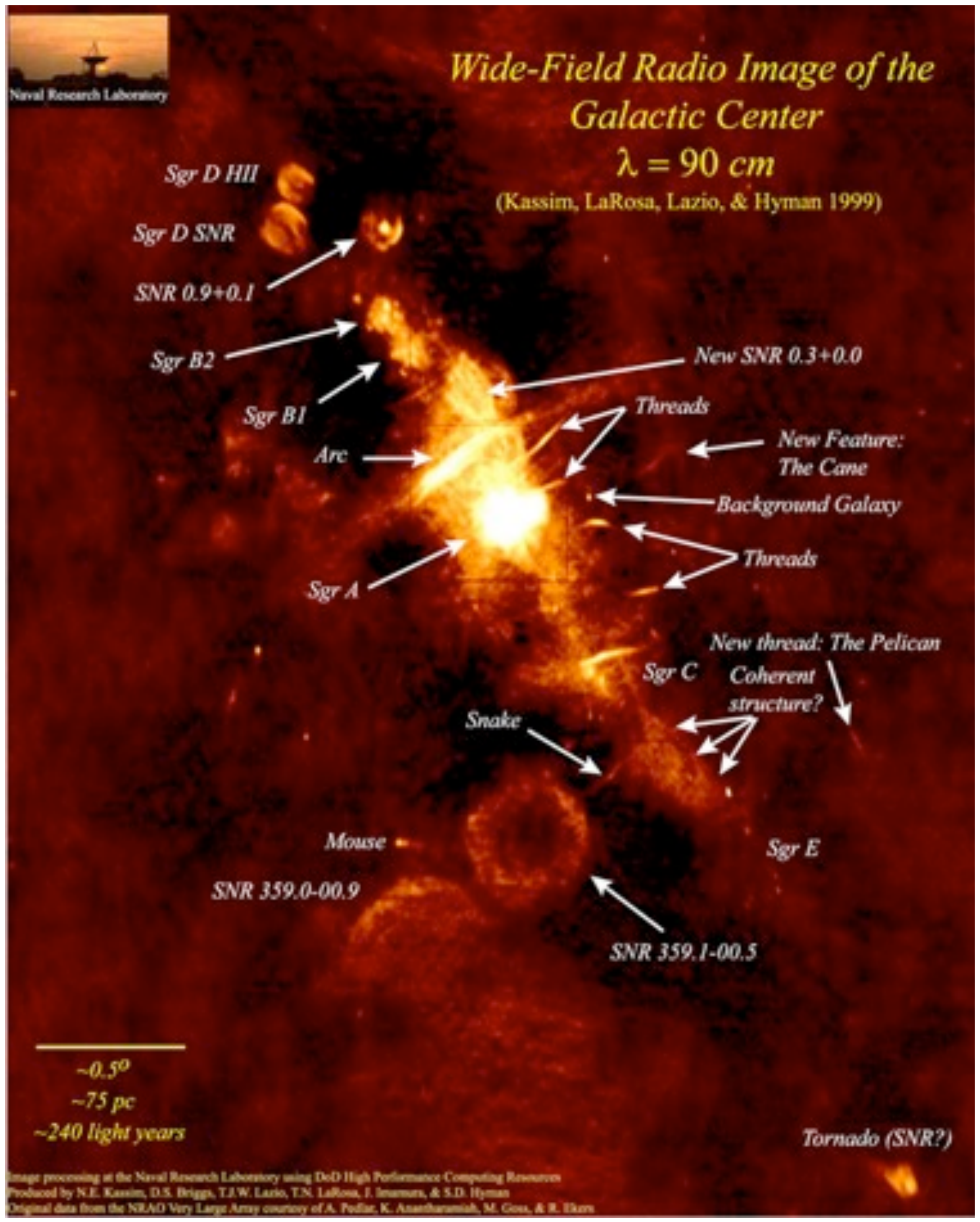
- leptonic channels have negligible proton yields
- hadronic channels generally yield similar spectra



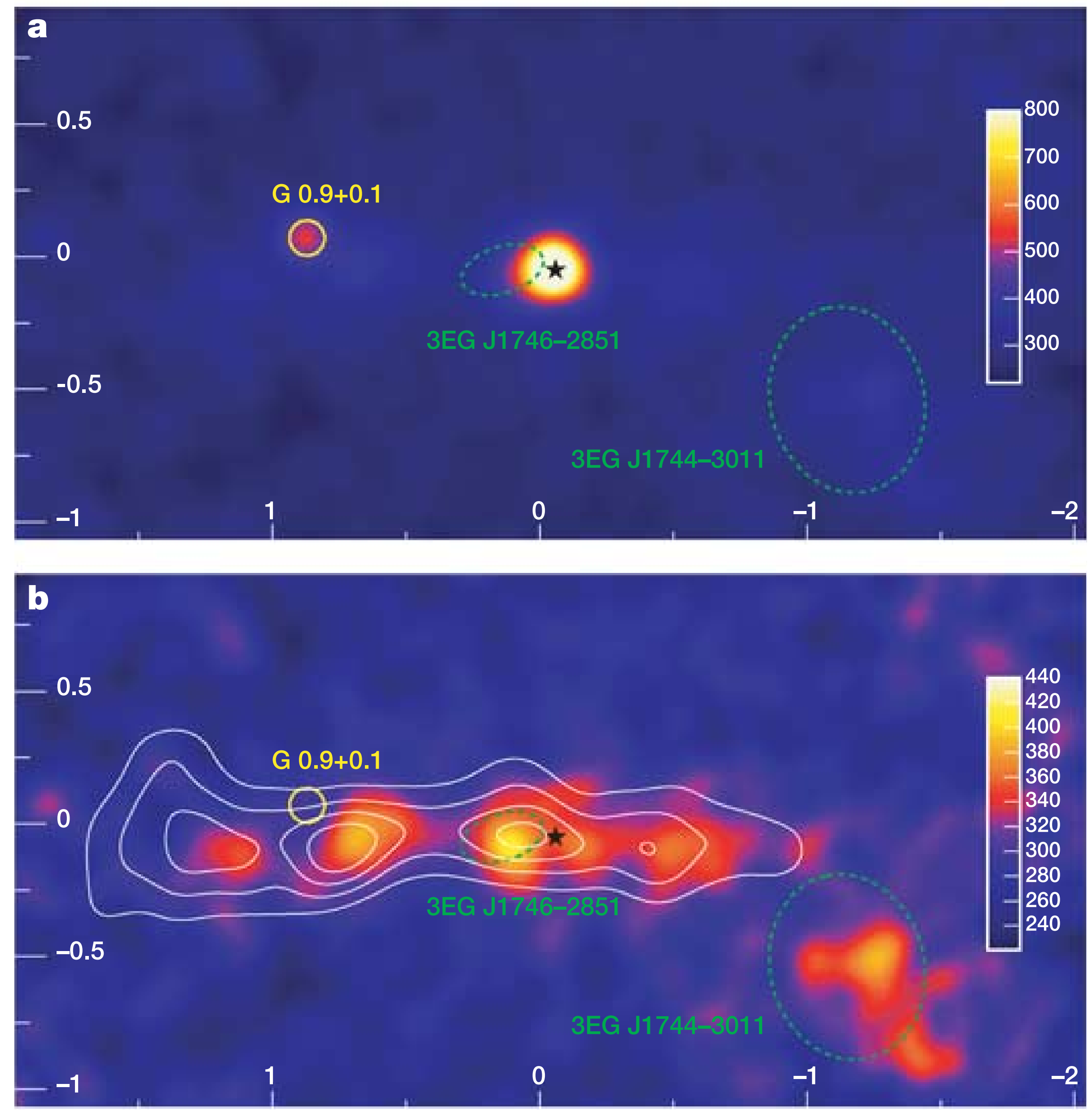
Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

The multi-wavelength Inner Galaxy

VLA @ 330 MHz



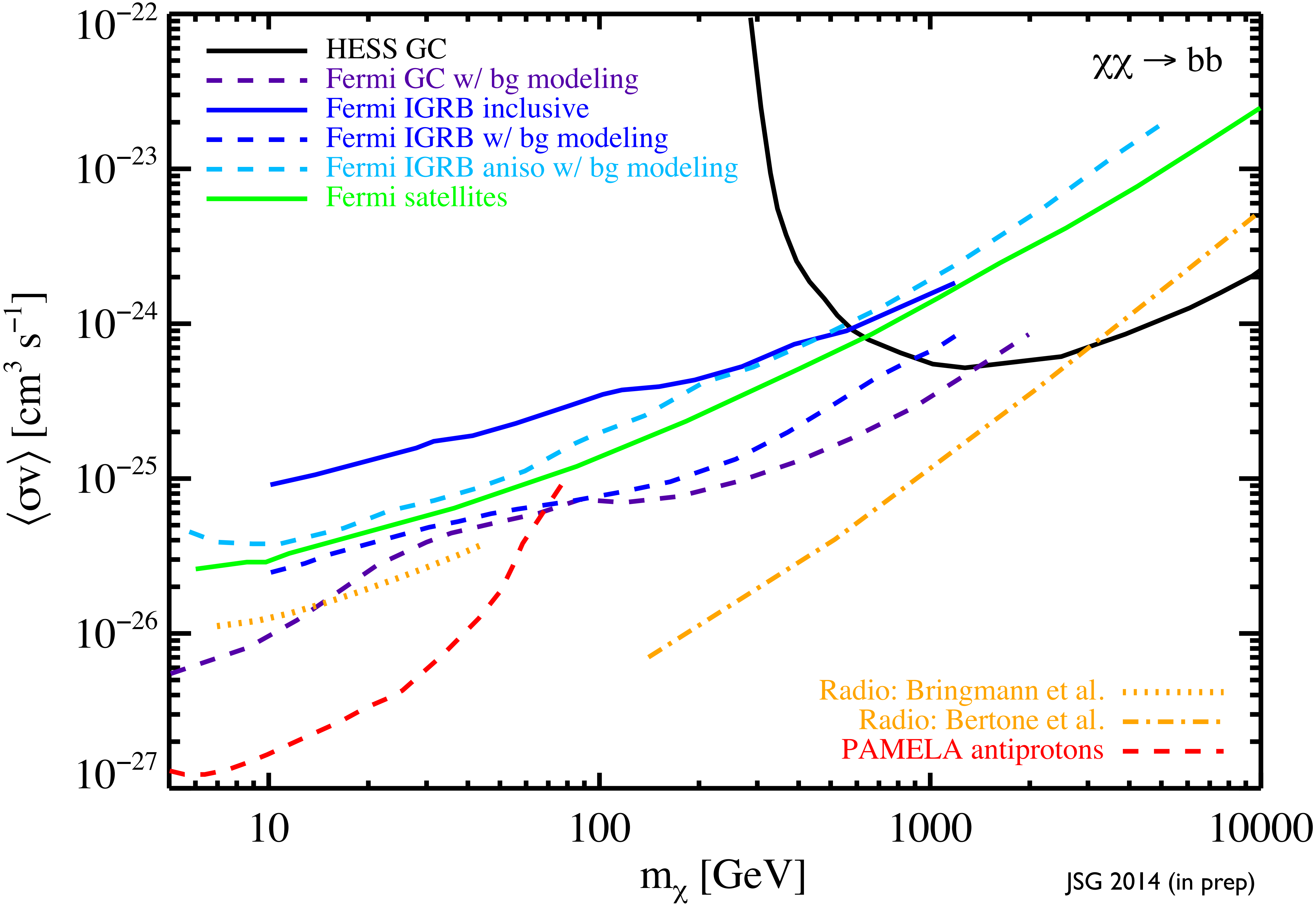
HESS > 380 GeV



Aharonian et al. 2006

RECAP
Current constraints

95% CL upper limits on annihilation cross section to bb



JSG 2014 (in prep)

RECAP

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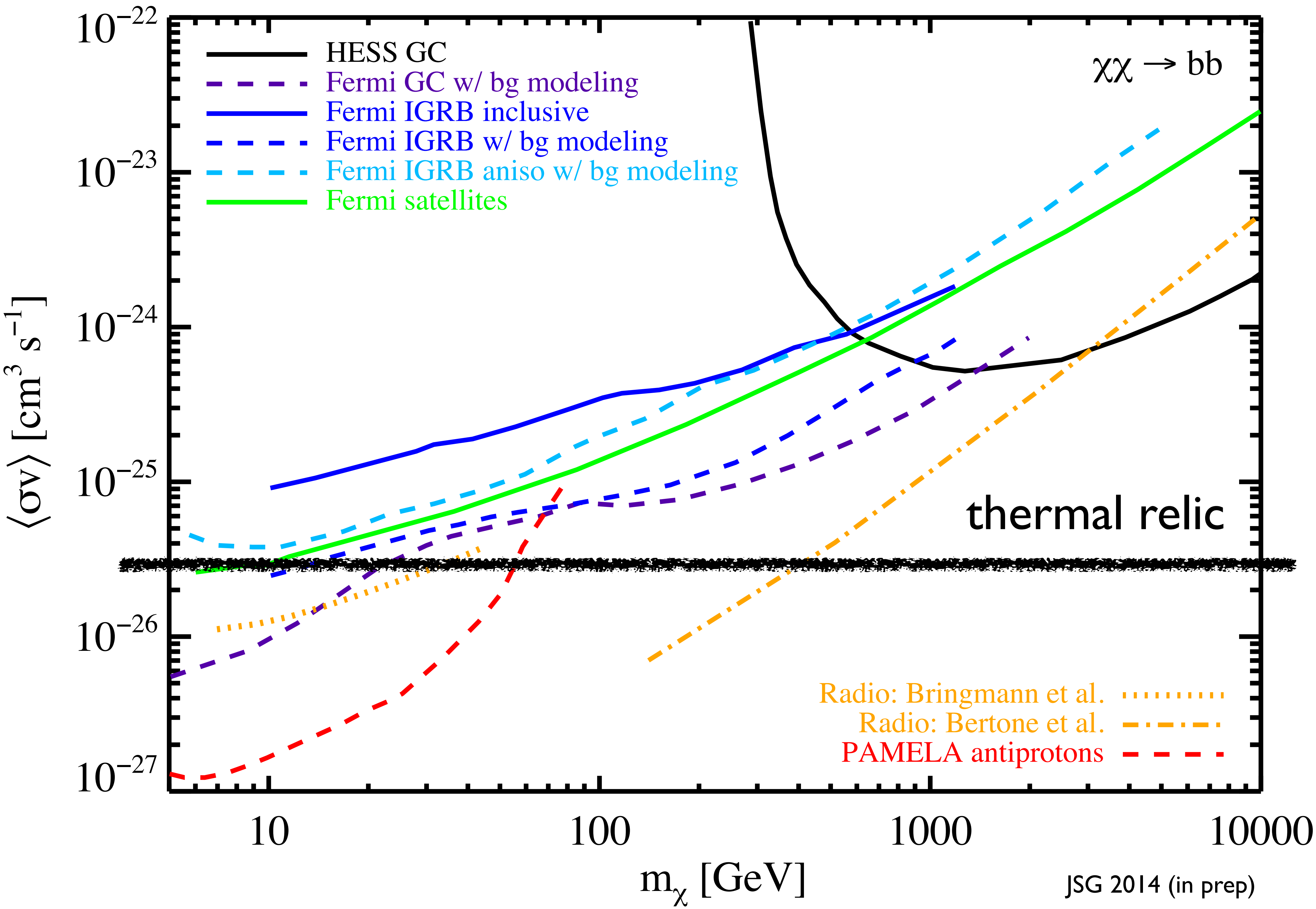


JSG 2014 (in prep)

Tools to calculate cosmic-ray propagation

- GALPROP: http://galprop.stanford.edu
- DRAGON: http://www.dragonproject.org

Cosmic-ray electron searches

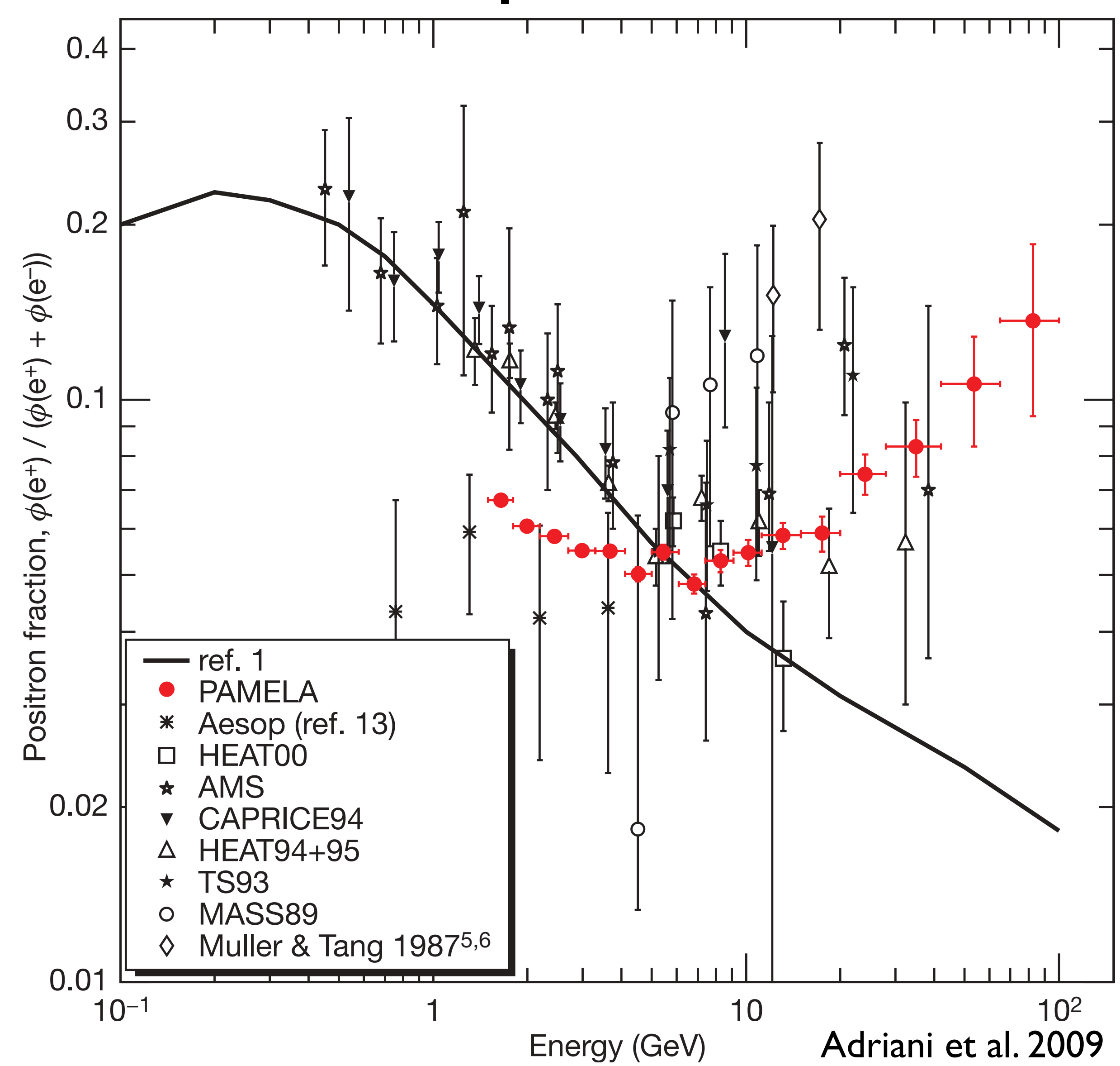
- fluxes of high-energy cosmic-ray electrons probe local volume (within ~ 1 kpc)
- anomalies/excesses detected in the positron fraction and electron+positron spectrum
- anisotropy can be used to test different interpretations
- pulsars probably are an adequate explanation, dark matter seems unlikely

Unexpected features in the cosmic-ray e± spectra?

Unexpected features in the cosmic-ray e± spectra?

- rise in local positron fraction above ~10 GeV disagrees with conventional model for cosmic rays (secondary positron production only); see also arXiv: 1011.4843 for low-energy discrepancy

PAMELA positron fraction



Adriani et al. 2009

Unexpected features in the cosmic-ray e± spectra?

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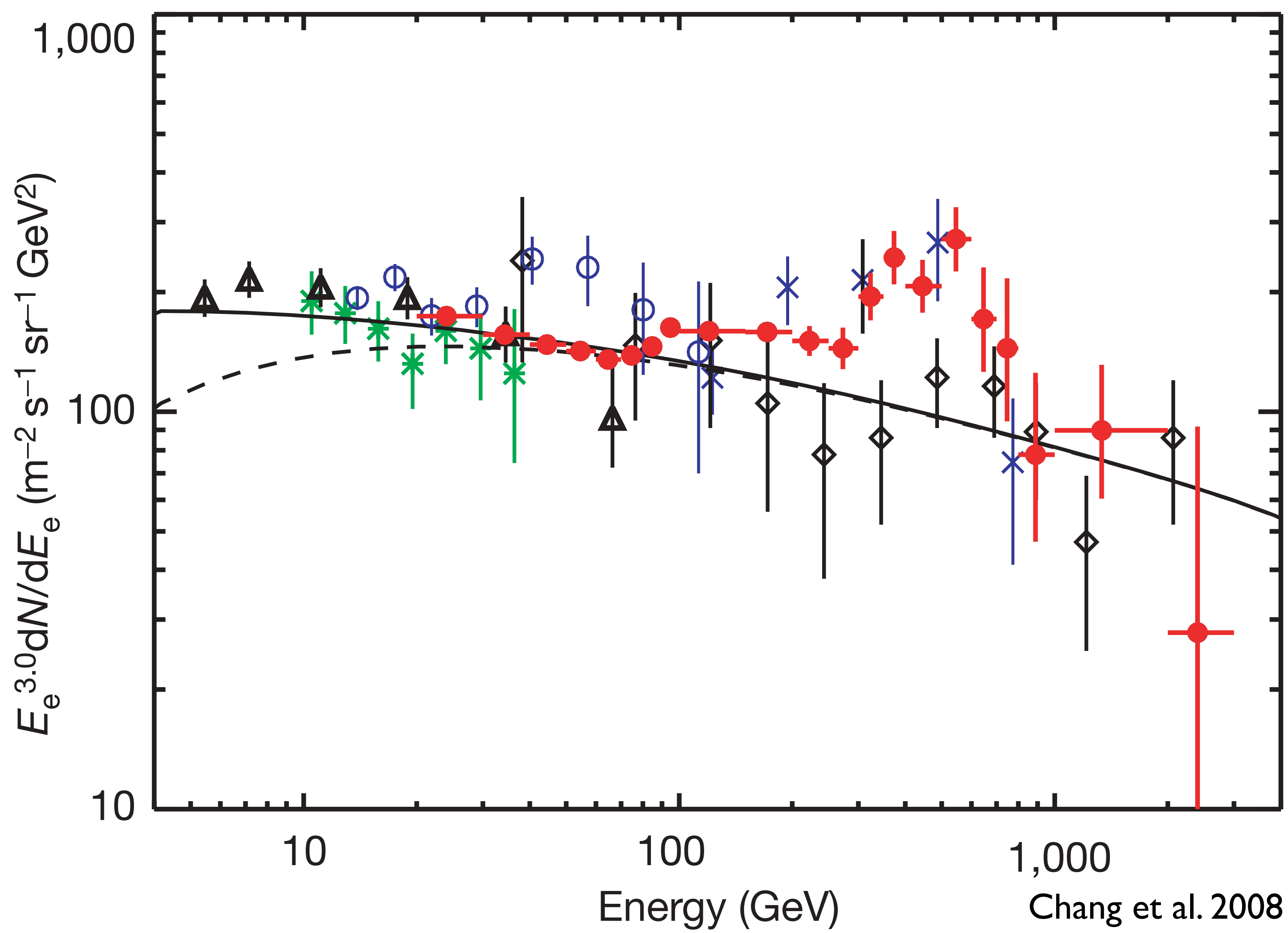
- unexpected bump in total electron + positron spectrum measured by ATIC

ATIC electron + positron spectrum



Chang et al. 2008

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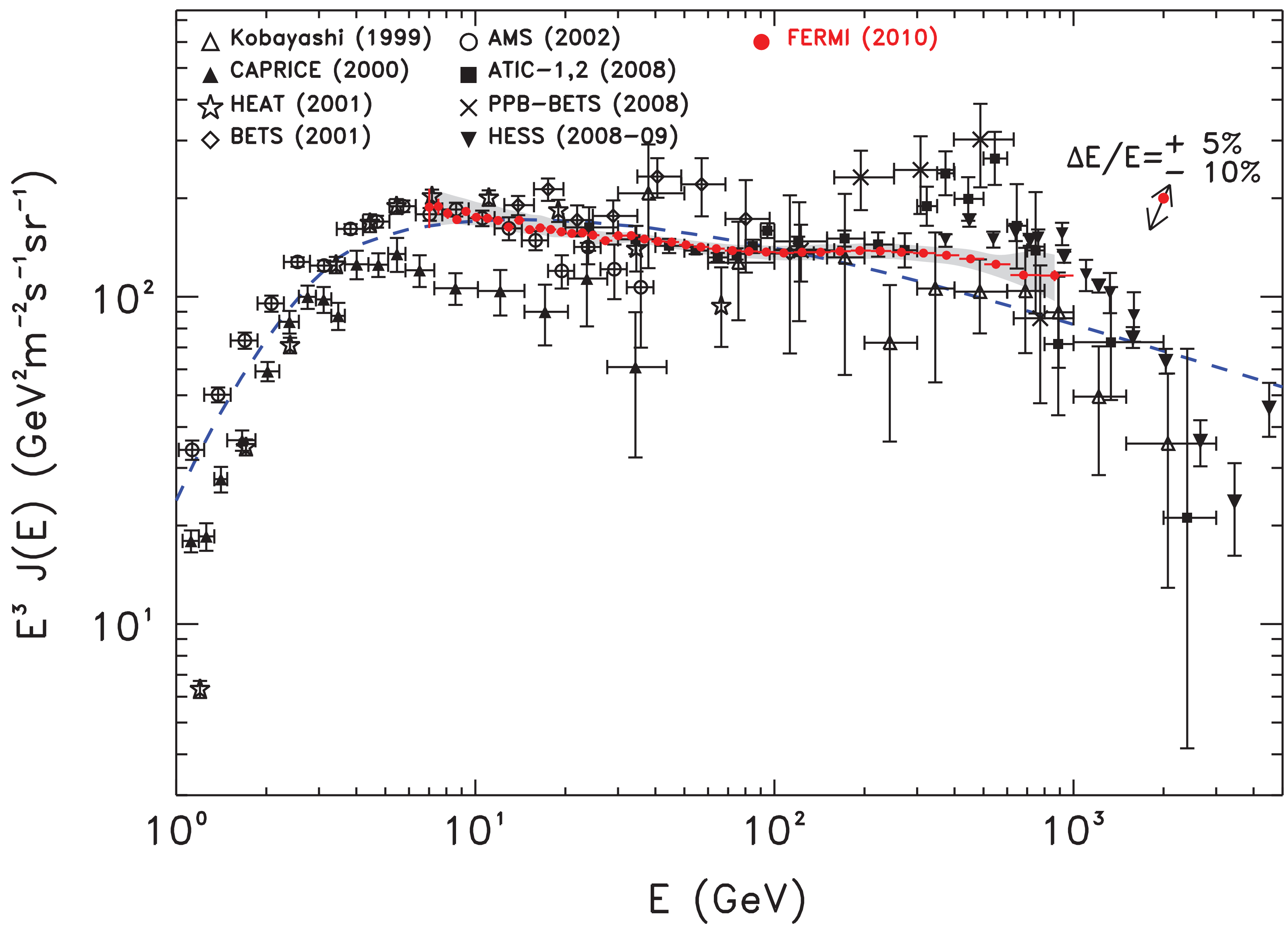
- less prominent feature seen in Fermi cosmic ray electron/ positron spectrum

Fermi electron + positron spectrum



Ackermann et al. [Fermi LAT Collaboration] 2010

Unexpected features in the cosmic-ray e± spectra?

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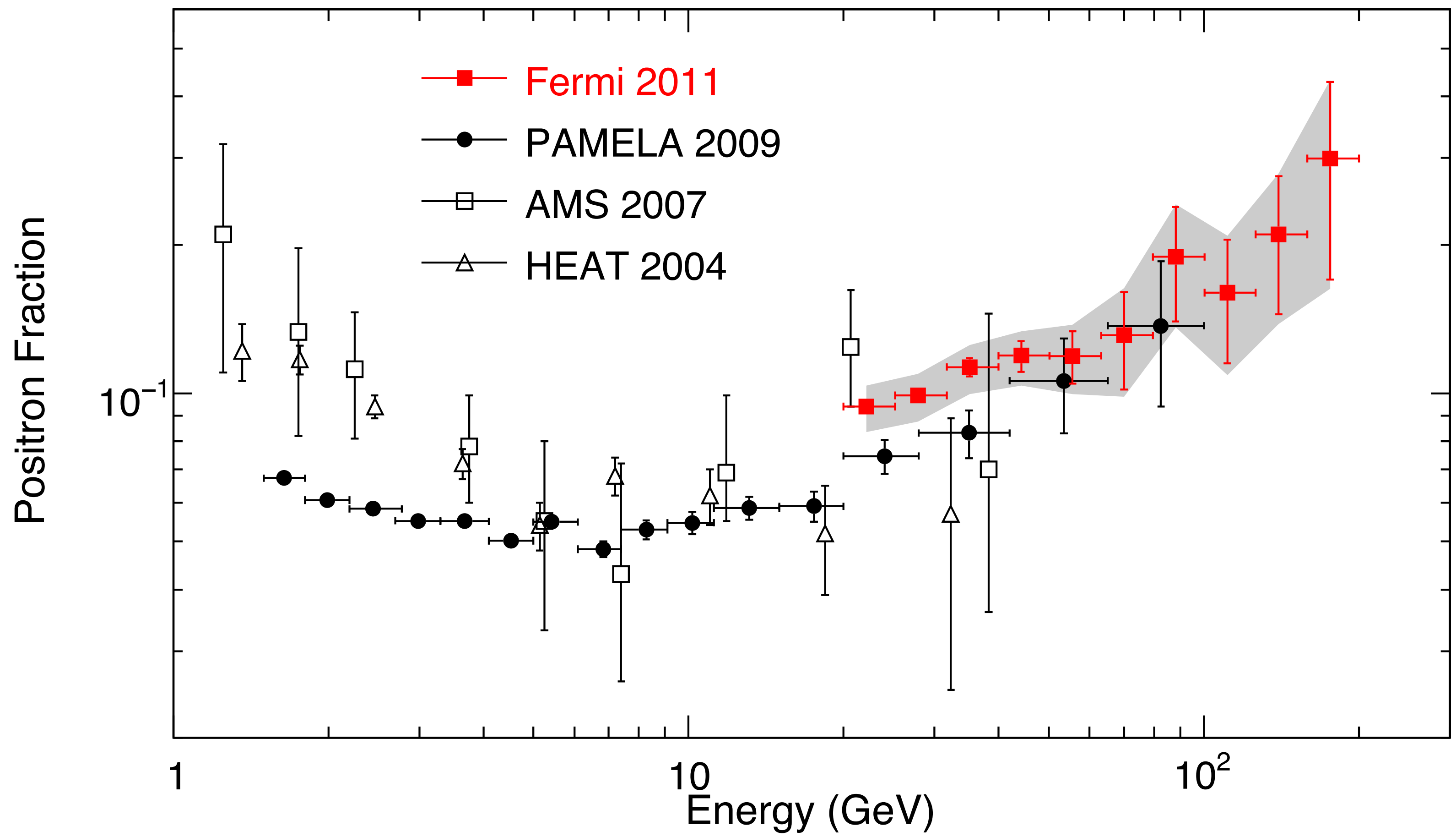
- unexpected bump in total electron + positron spectrum measured by ATIC
- less prominent feature seen in Fermi cosmic ray electron/ positron spectrum
- Fermi positron fraction agrees with PAMELA result, extends to higher energies

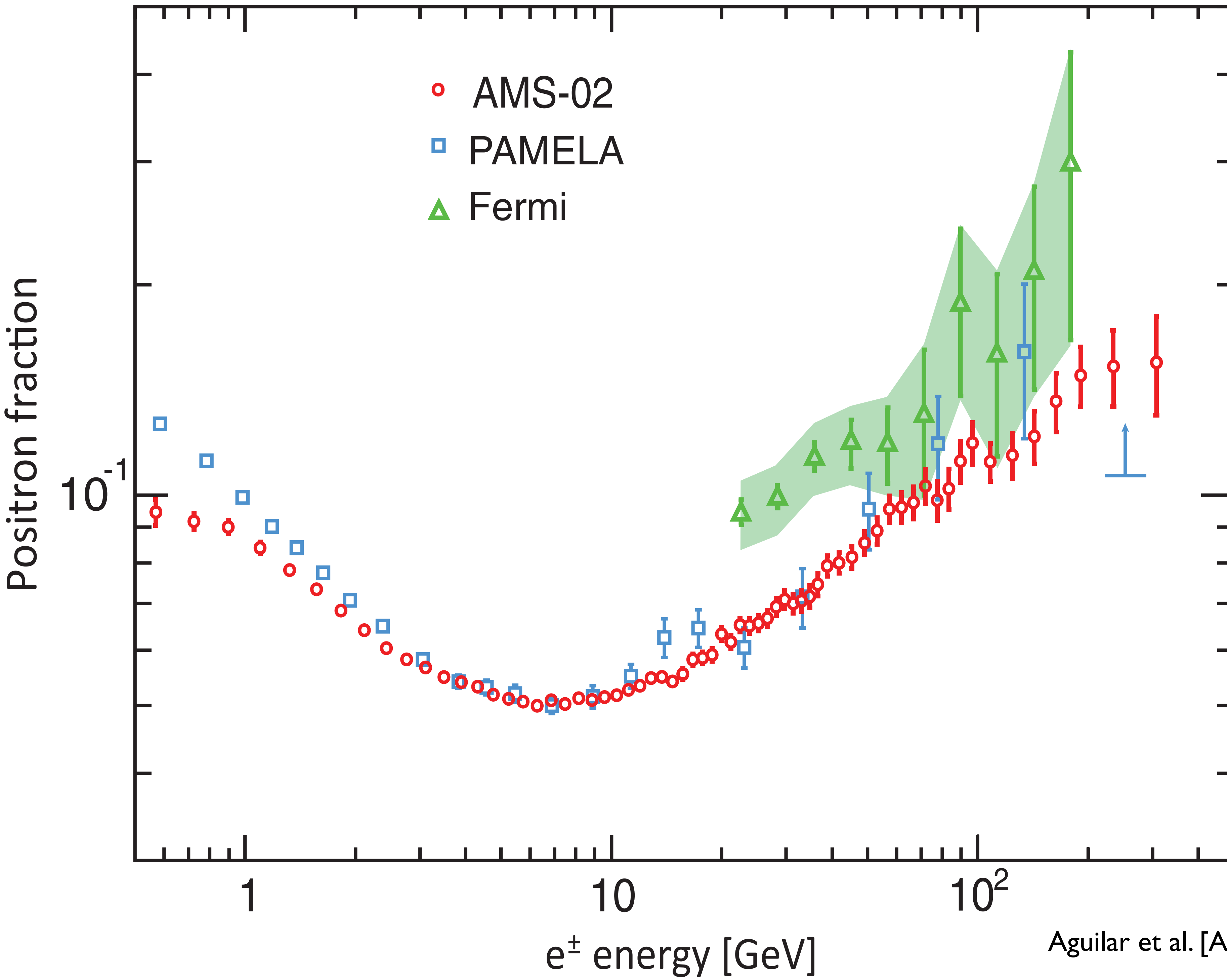
Fermi positron fraction



Ackermann et al. [Fermi LAT Collaboration] 2011

The positron excess persists...

AMS-02 positron fraction measurement



Aguilar et al. [AMS-02 Collaboration] 2013

Hints of a dark matter signal?

The Case for a 700+ GeV WIMP: Cosmic Ray Spectra from ATIC and PAMELA

Ilias Cholis,[1] Gregory Dobler,[2] Douglas P. Finkbeiner,[2] Lisa Goodenough,[1] and Neal Weiner[1]

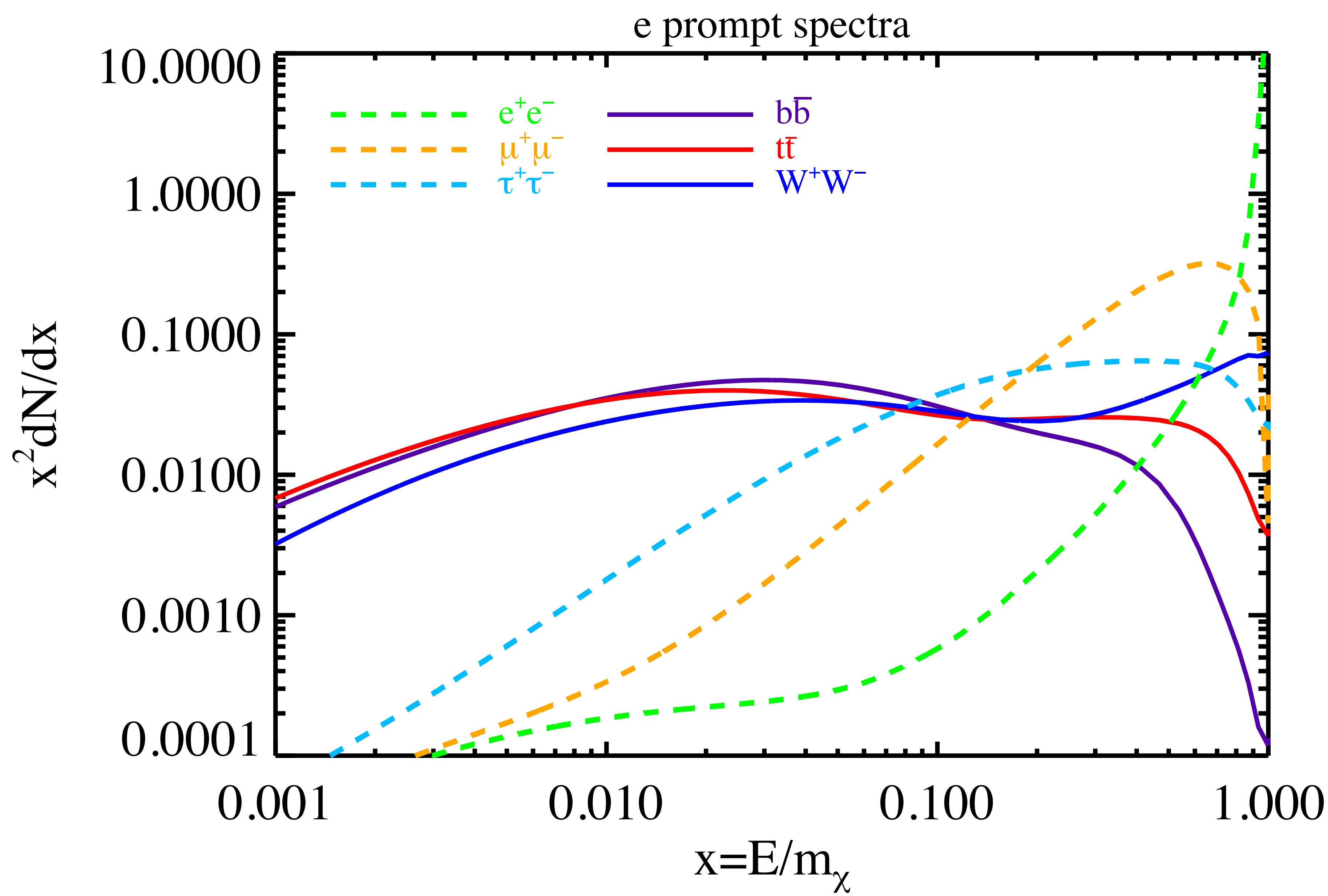
Recent cosmic-ray electron and positron (CRE) results sparked interest in DM explanations (e.g., Arkani-Hamed et al. 2009; Lattanzi & Silk 2009; Cirelli et al. 2009; Cholis et al. 2008; Grasso et al. 2009;...)

To explain the CRE data with DM generally requires:

- leptophilic models
- large annihilation cross-sections; this can arise in "secluded" or "intermediate state" models, in which DM interacts with SM via a new particle (typically a light scalar)

Dark matter electron/positron spectra

- hadronic channels yield few high-energy electrons/positrons

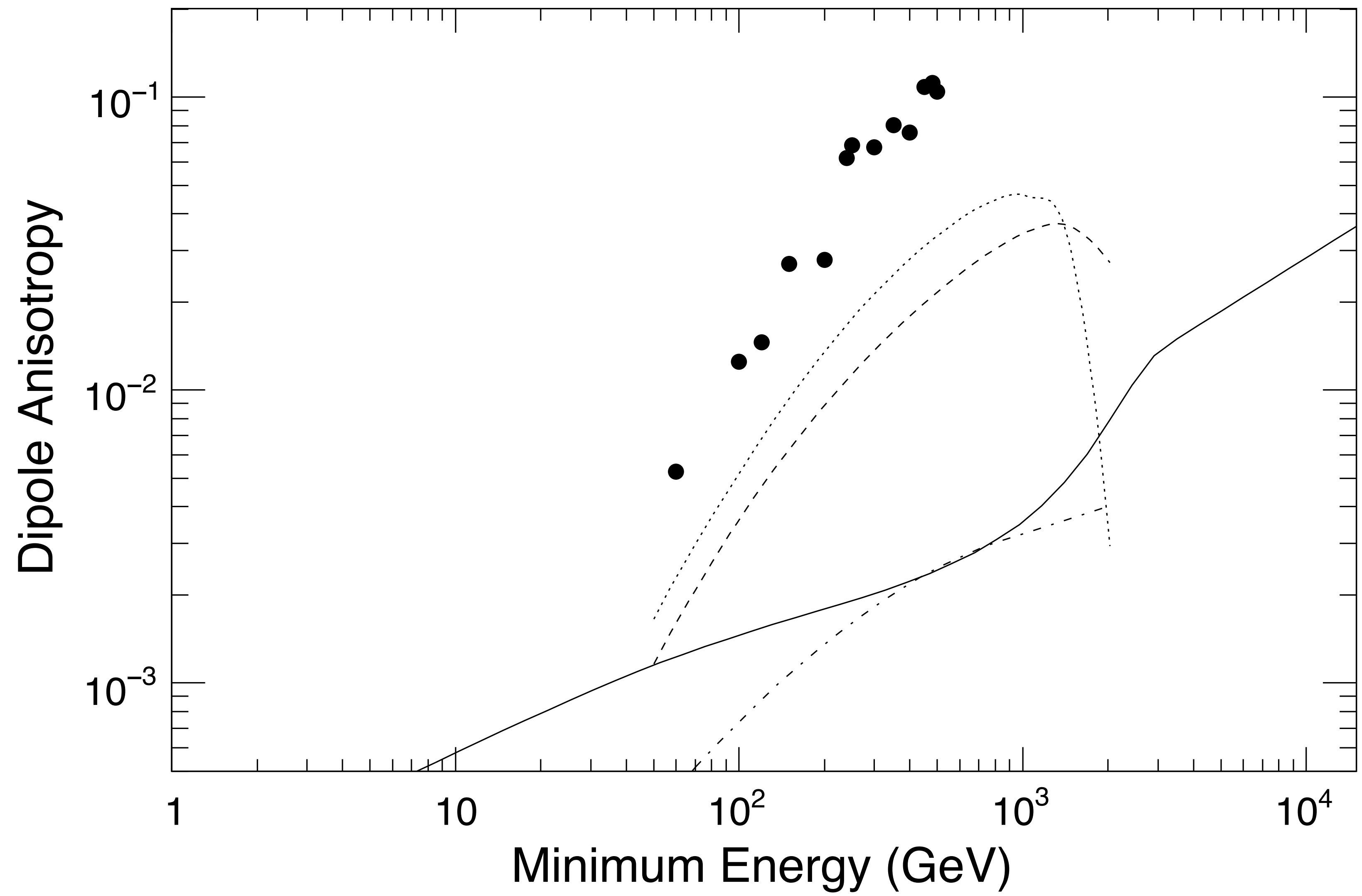


Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

Constraints from CRE dipole anisotropy

- high-energy positrons should originate from "local" sources (within ~ 1 kpc)
- distribution of nearby sources could produce a detectable asymmetry in the arrival direction of CREs
- Fermi LAT / AMS-02 limits on CRE anisotropy could eventually constrain scenarios explaining CRE measurements

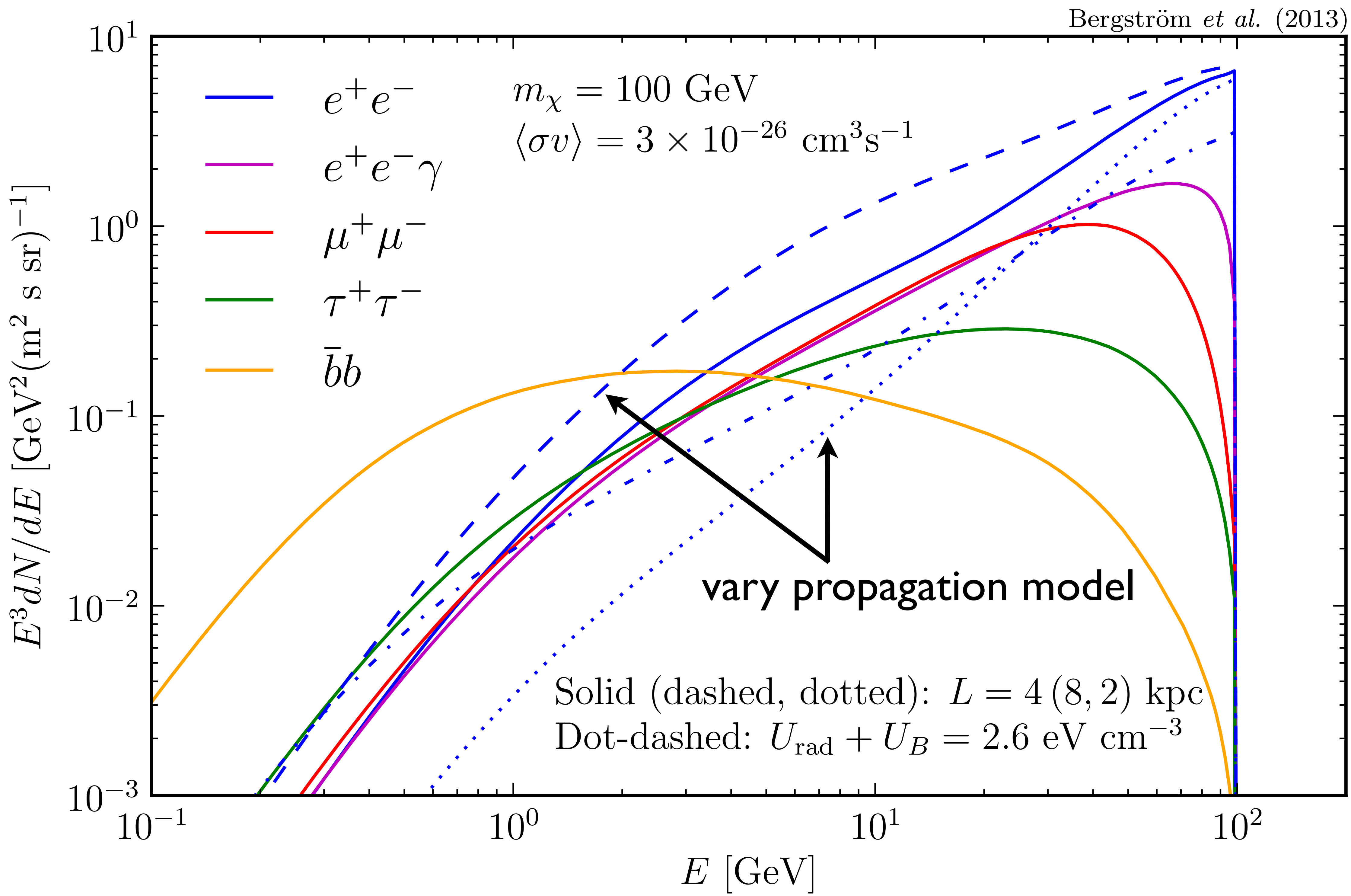
Fermi LAT limits on CRE dipole anisotropy and predictions for some DM scenarios



Ackermann et al. [Fermi LAT Collaboration] 2010
(Phys.Rev.D 82, 092003)

Propagation affects observed spectra

Electron/positron spectra after propagation



Neutrino searches

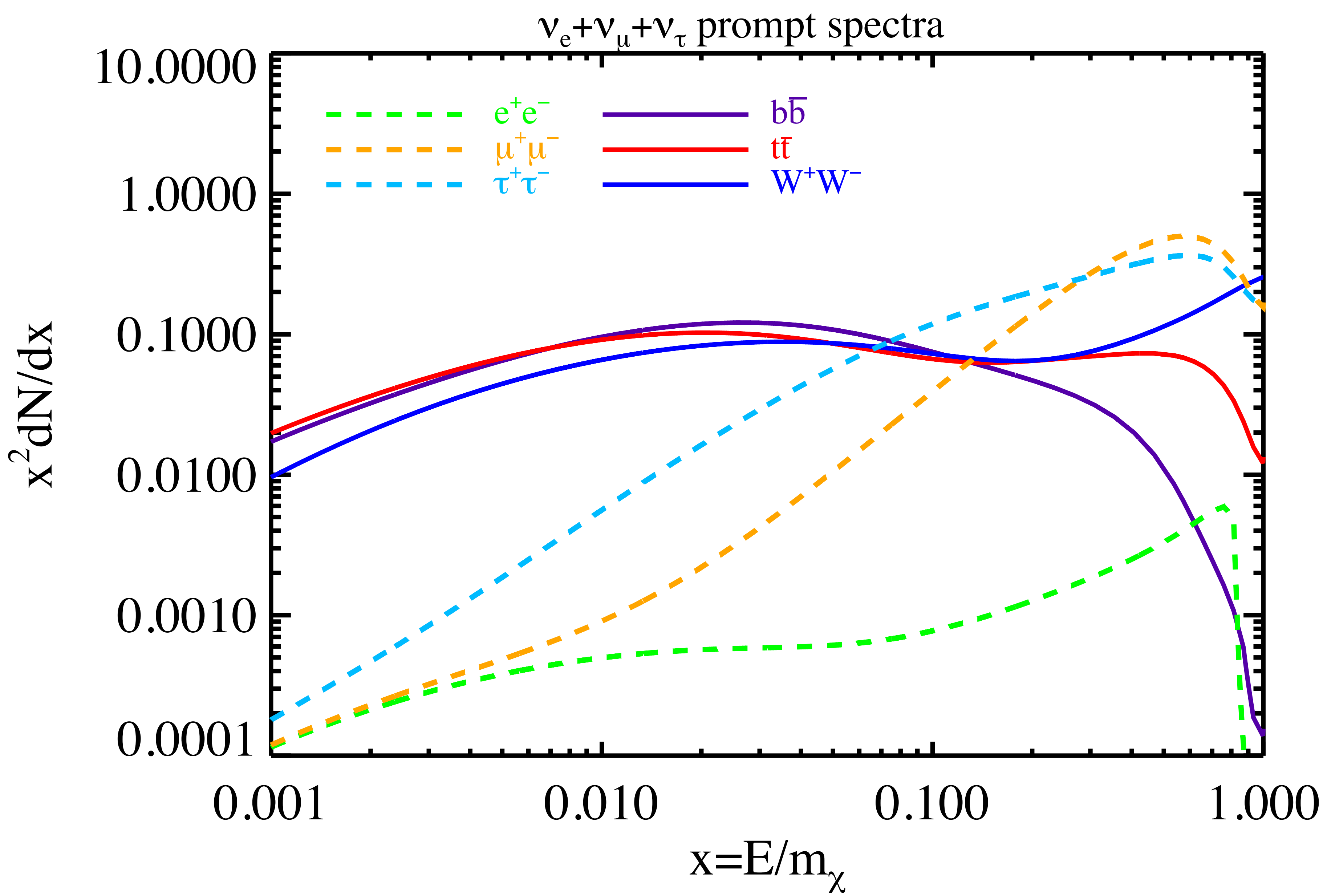
- can use indirect targets already discussed (Galactic Center, halo, galaxy clusters, etc.) and ALSO Sun and Earth
- Sun (and Earth) searches probe DM-nucleon scattering cross section; Sun searches are competitive for SD cross section
- high-energy (> GeV) neutrino searches look for prompt emission

see Justin Vandenbroucke's talk

- low-energy (MeV) neutrino searches are complementary and look for neutrinos from hadronic interactions

Dark matter neutrino spectra

- Ws, muons, and taus are “hard” channels
- mixing changes the ratio of flavors, but over long baselines they become fully mixed and approach a flavor ratio of (1:1:1) -- but not true for Sun/Earth

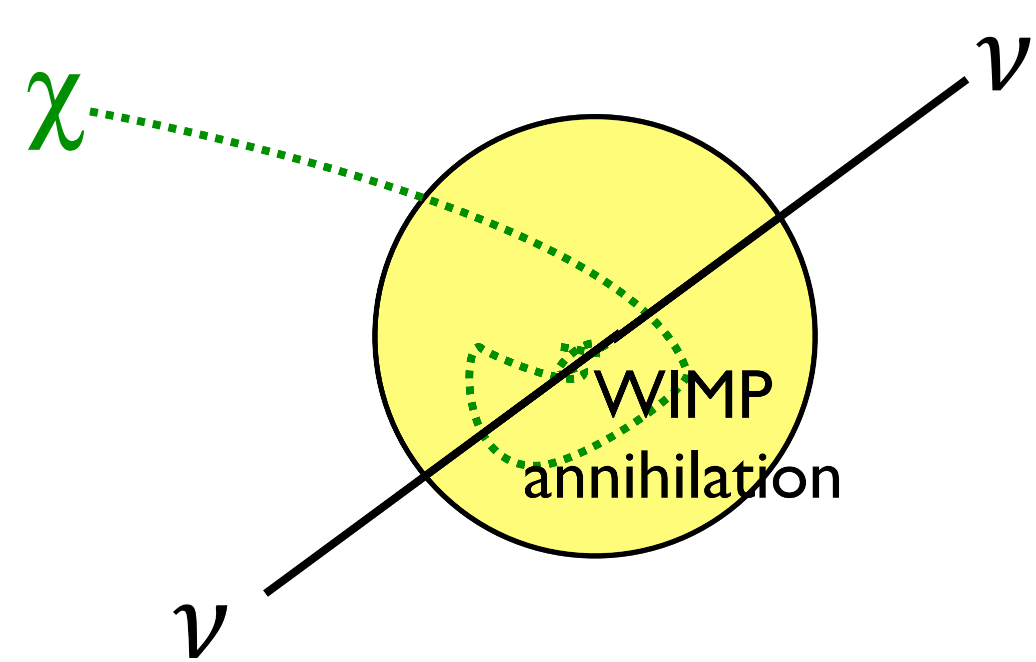


Spectra calculated with PPPC 4 DM ID [Cirelli et al. 2010]

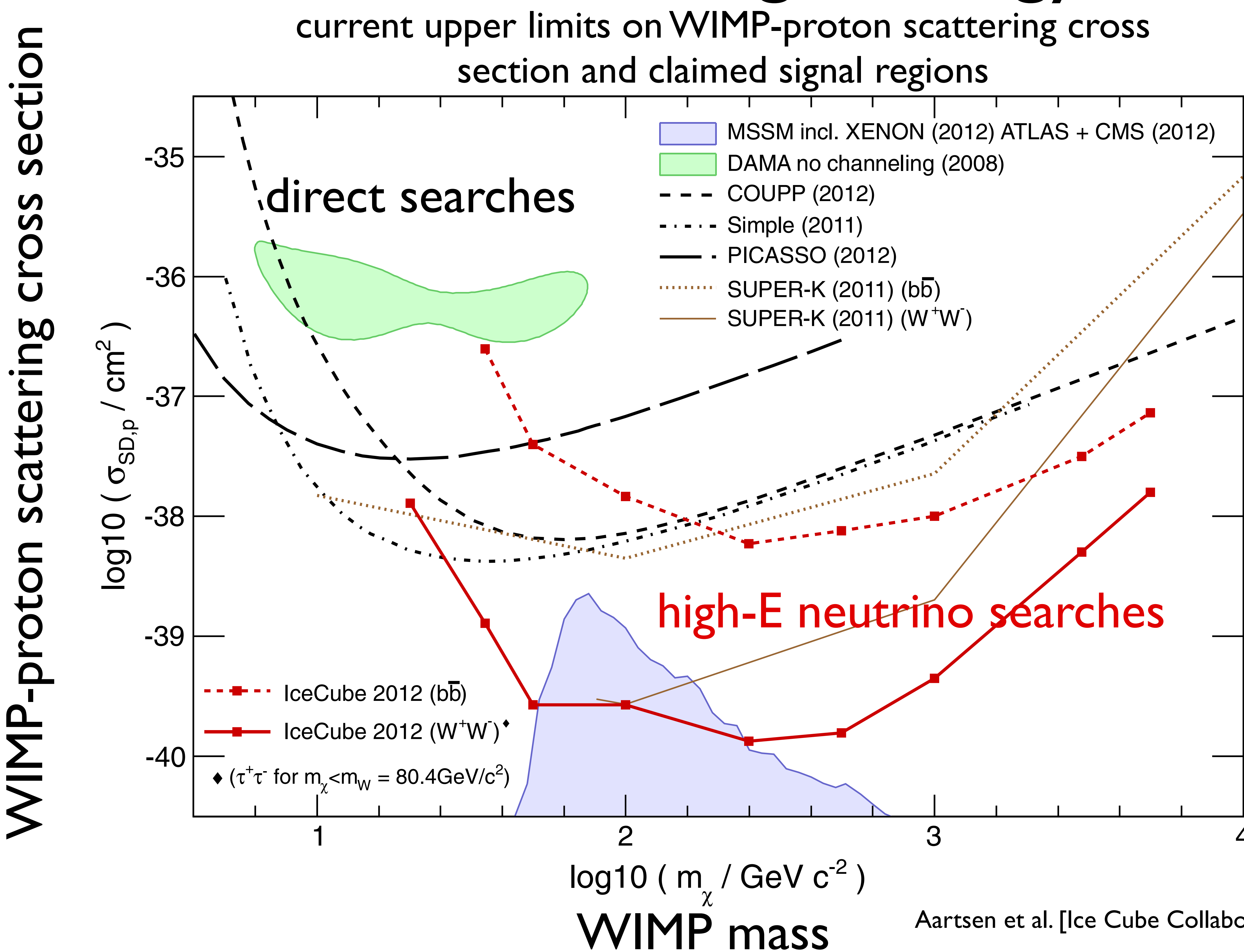
Neutrinos from DM annihilation in the Sun

the standard WIMP capture/annihilation scenario

- WIMP DM particles are captured by the Sun via elastic scattering with nucleons
- the DM particles lose energy with each scattering, and quickly sink to the core of the Sun where they annihilate into standard model (SM) particles
- neutrinos are the only observable signal from DM annihilations in the Sun since they are the only SM particle that can escape from the Sun



Direct detection and high-energy neutrinos



Aartsen et al. [Ice Cube Collaboration], 2013

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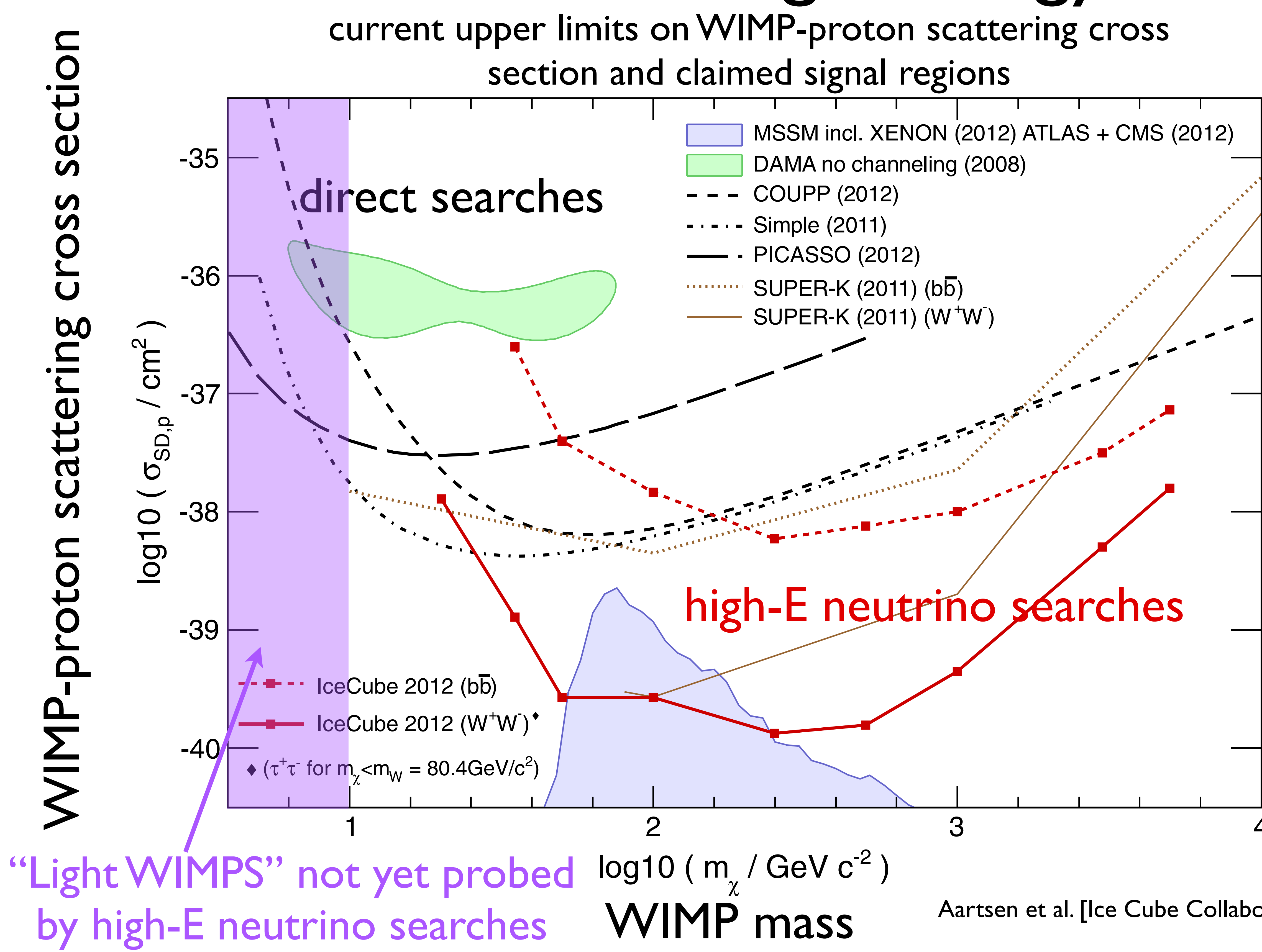
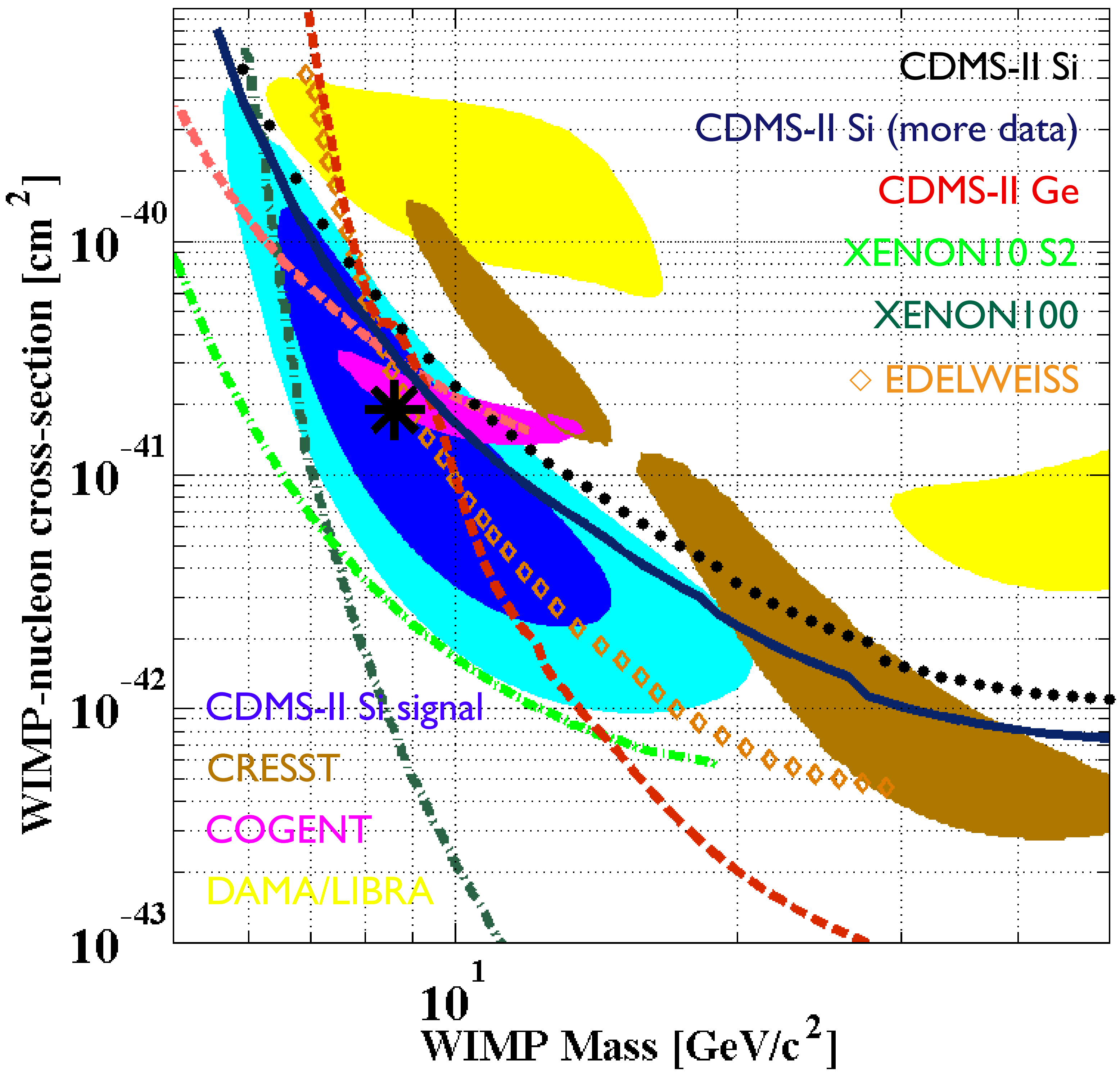


Aartsen et al. [Ice Cube Collaboration], 2013

Light WIMPs: direct searches

- possible direct detection signals are at edge of energy threshold
- direct detection and indirect detection with solar neutrinos are complementary probes with different uncertainties, it would be valuable to cover the same parameter space

current upper limits on WIMP-nucleon scattering cross section and possible signal regions



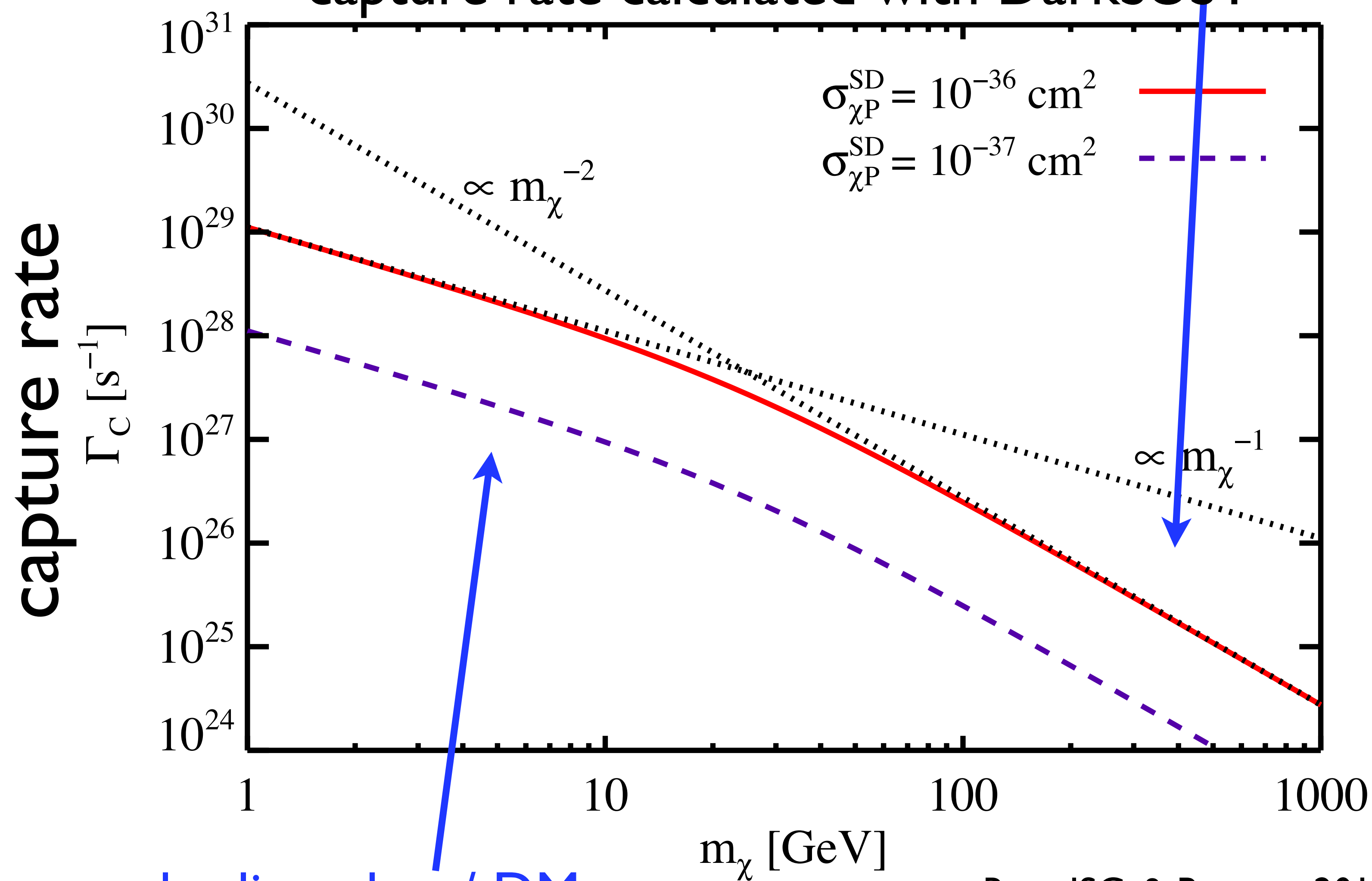
CDMS II Collaboration, 2013

Solar WIMP capture

- capture rate scales linearly with scattering cross-section (if Sun is optically thin to WIMPs)
- for typical WIMP masses and scattering cross-sections, capture and annihilation have reached equilibrium
- in this case, scattering cross-section sets flux of neutrinos; independent of annihilation cross-section

falls faster than 1/m due to kinematic suppression of energy loss

capture rate calculated with DarkSUSY



scales linearly w/ DM number density

WIMP mass

Rott, JSG, & Beacom 2013

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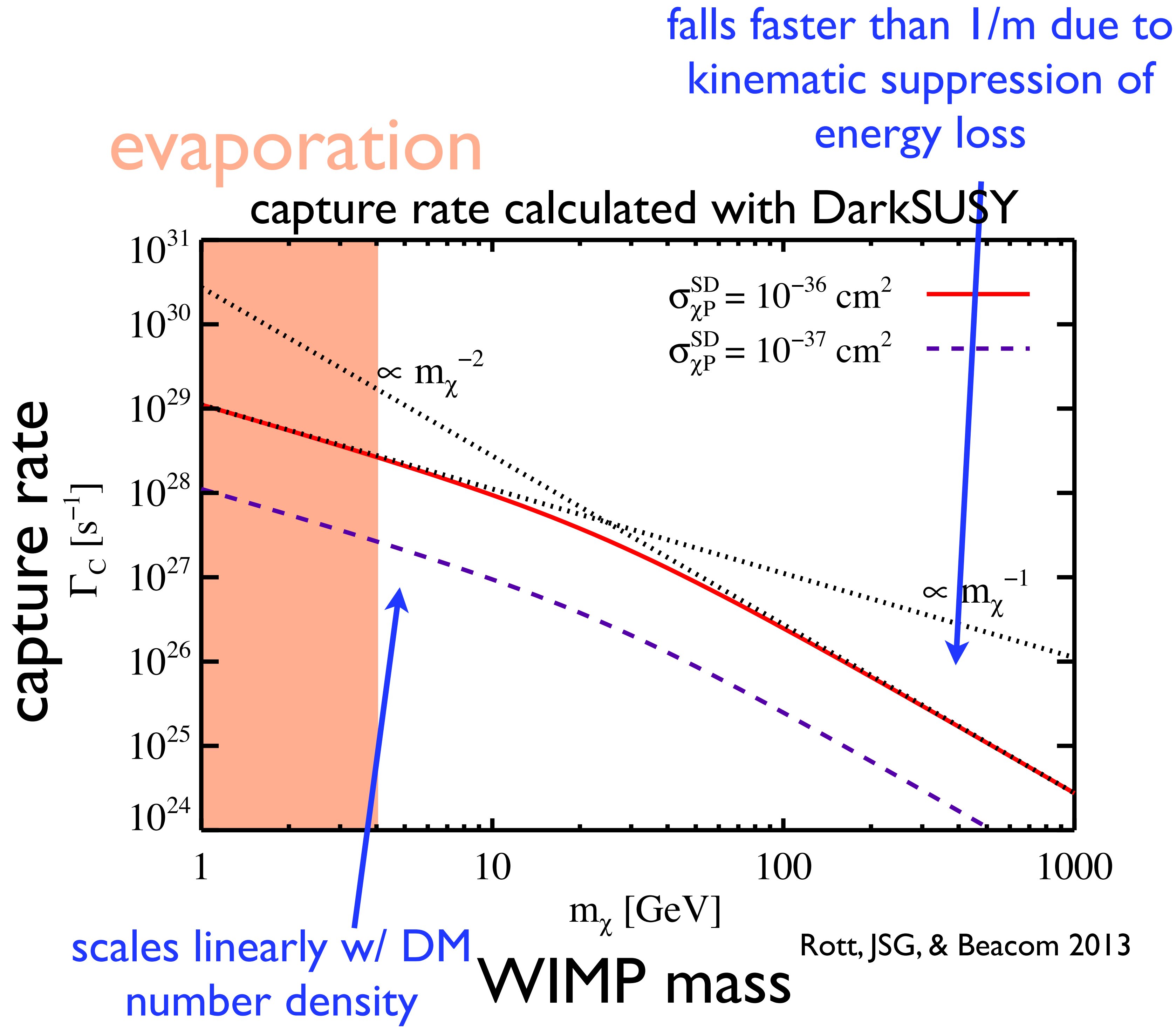
- for typical WIMP masses and scattering cross-sections, capture and annihilation have reached equilibrium
- in this case, scattering cross-section sets flux of neutrinos; independent of annihilation cross-section
- subsequent evaporation of captured low-mass WIMPs can significantly reduce effective capture rate and hence annihilation rate



Rott, JSG, & Beacom 2013

Indirect detection with neutrinos

- high-energy neutrinos ($E \gtrsim 1$ GeV) are produced in annihilation final states and in subsequent hadronization and decay processes for some final states
- the number of high-energy neutrinos produced per annihilation is small, even at high WIMP masses
- (in vacuum, this is the end of the story for neutrino production)

Low-energy neutrinos from the Sun

possible final states:
qq,gg,cc,ss,bb,tt,W^+W^-, ZZ, $\tau^+\tau^-$,$\mu^+\mu^-$, $\nu\nu$, e^+e^-,$\gamma\gamma$

Slide Concept: C. Rott

Low-energy neutrinos from the Sun

possible final states:

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few neutrinos

Slide Concept: C. Rott

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some "high-E" neutrinos from decays BEFORE energy loss → basis of current searches

few neutrinos

Slide Concept: C. Rott

Low-energy neutrinos from the Sun

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dominant decay is into hadrons

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- pions are produced abundantly and rapidly in hadronic final states

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dominant decay is into hadrons

some "high-E" neutrinos from decays BEFORE energy loss → basis of current searches

few neutrinos

- pions are produced abundantly and rapidly in hadronic final states
- roughly equal numbers of π^+, π^-, and π^0 are produced, with far greater multiplicity than other hadrons

Slide Concept: C. Rott

Low-energy neutrinos from the Sun

possible final states:

$q\bar{q}, gg, c\bar{c}, s\bar{s}, b\bar{b}, t\bar{t}, W^+W^-, ZZ, \tau^+\tau^-, \mu^+\mu^-, \nu\nu, e^+e^-, \gamma\gamma$

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some "high-E" neutrinos from decays BEFORE energy loss → basis of current searches

few neutrinos

- pions are produced abundantly and rapidly in hadronic final states
- roughly equal numbers of π^+, π^-, and π^0 are produced, with far greater multiplicity than other hadrons
- what happens to the pions?

Slide Concept: C. Rott

Low-energy neutrinos from the Sun

a plethora of pions!

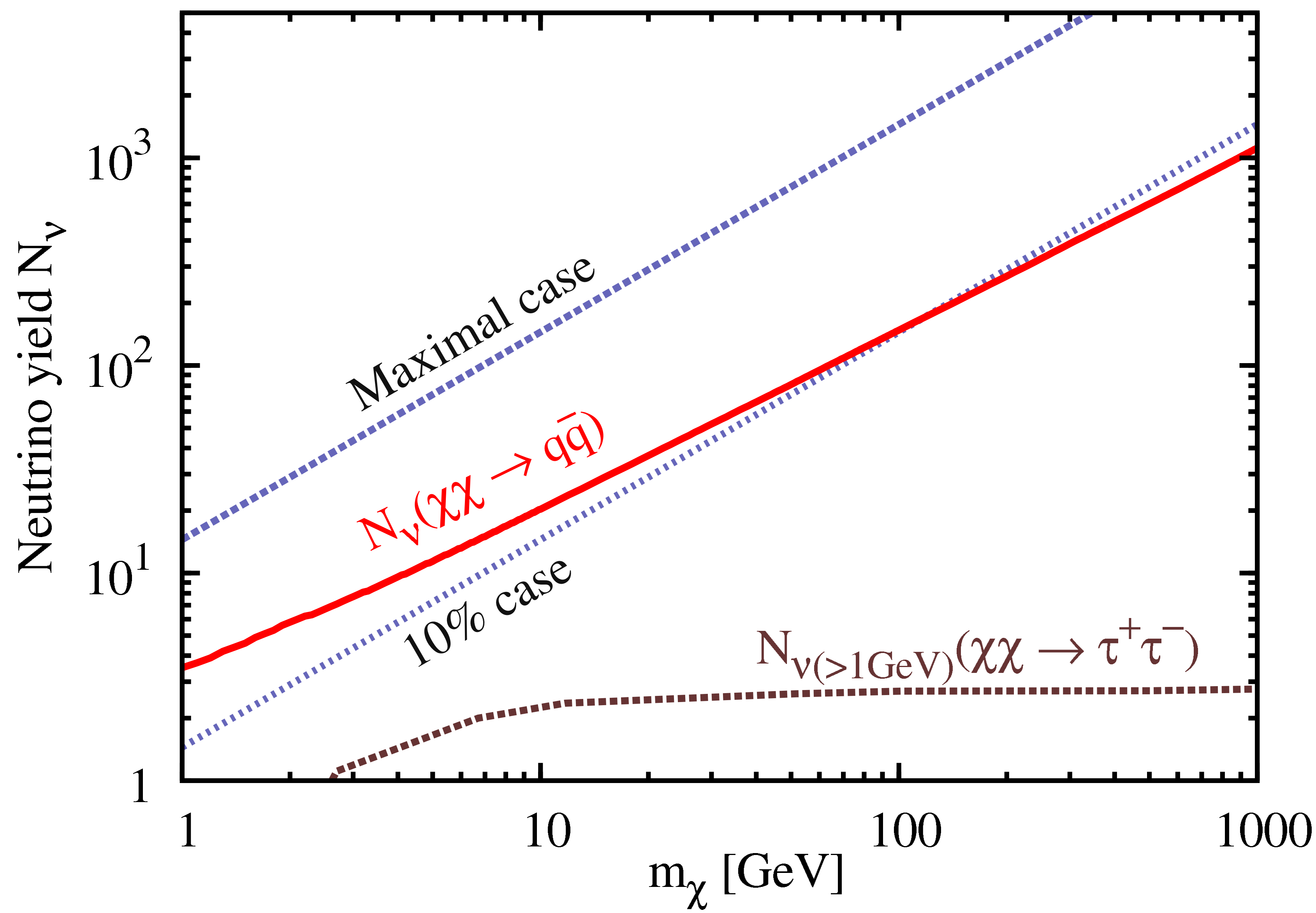
- π^0: decay to 2 photons
- π^- and π^+: in the Sun, the hadronic interaction length for charged pions is shorter than the decay time → charged pions inelastically scatter with protons, producing more pions with each interaction
- once the π^- come to rest, they are Coulomb-captured before decaying
- π^+ finally decay at rest, producing 3 neutrinos in the process, with energies of ~ 20 to ~53 MeV

$$\pi^+ \to \mu^+ \nu_\mu$$

$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$

Multiplicity of neutrinos from Solar WIMPs

- number of low-E neutrinos scales linearly with WIMP mass
- number of high-E neutrinos does not increase noticeably with increasing WIMP mass
- amplitude depends on fraction of annihilation energy going into hadronic final states
- most channels produce some hadronic products (and have a favorable low-E neutrino yield even if not a favorable high-E neutrino yield)

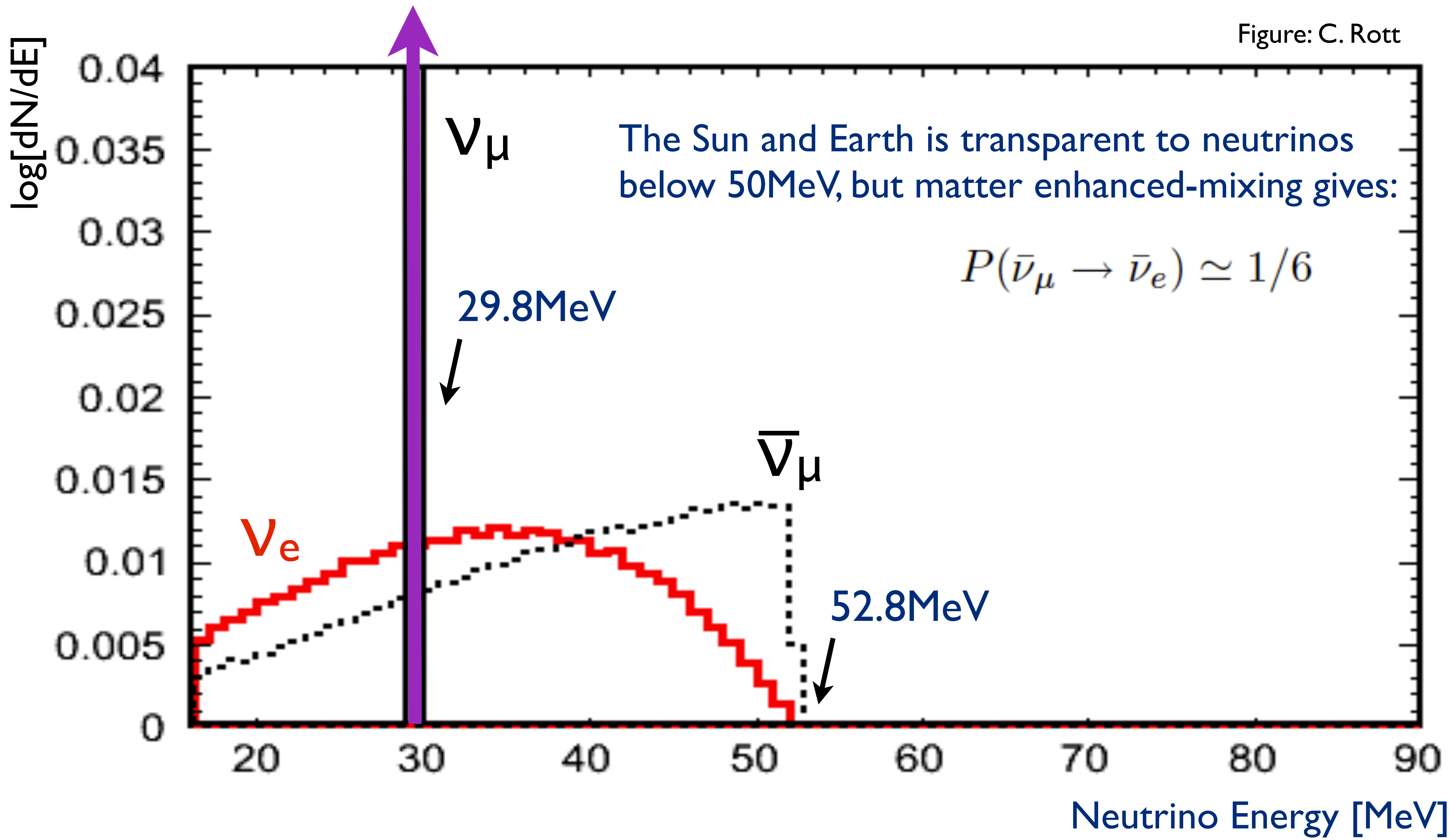


Rott, JSG, & Beacom 2013

Spectrum of low-E neutrinos

Neutrino Spectrum in the Sun (normalized to unity)

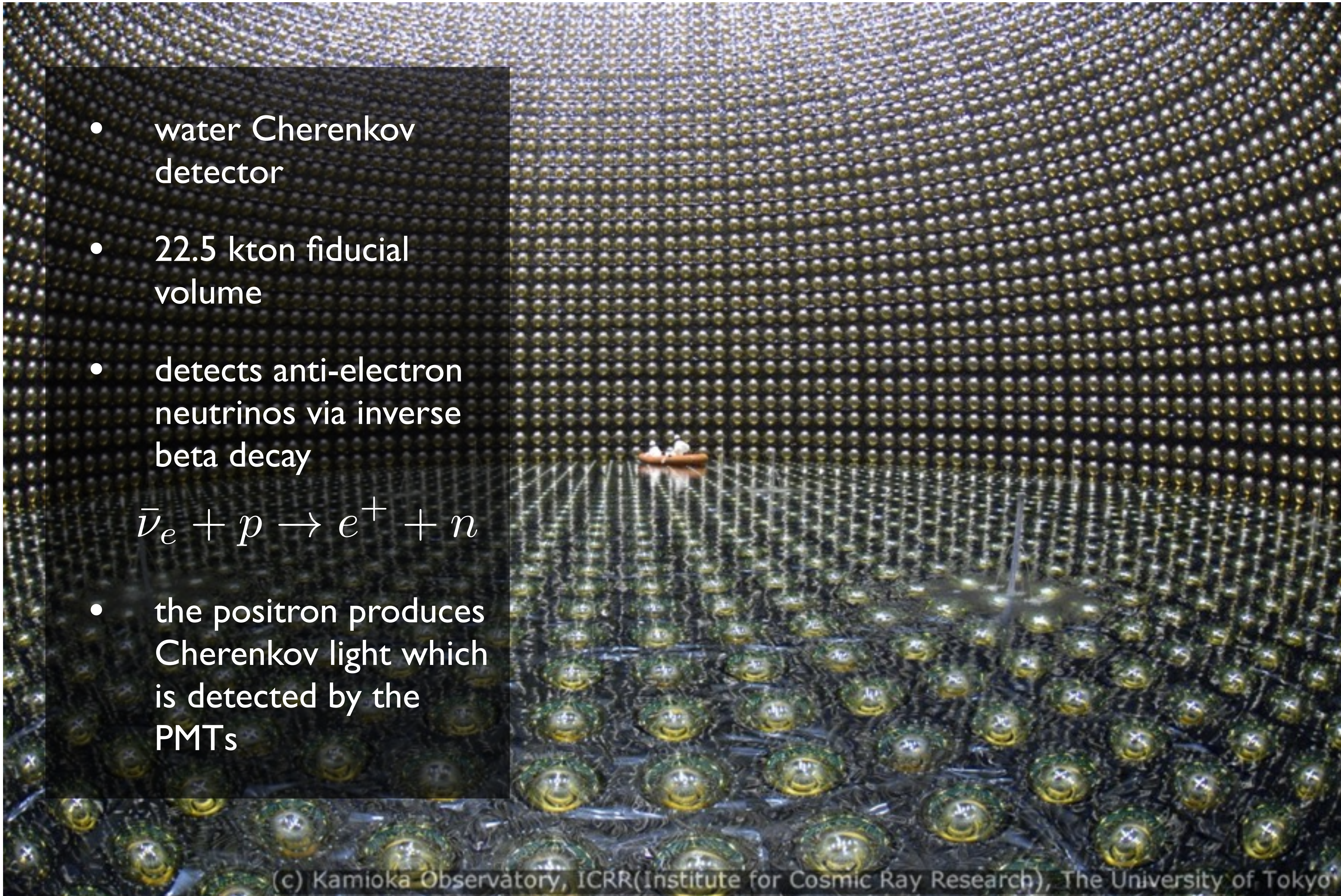
Figure: C. Rott



signal spectral shape does not depend on annihilation channel!

(as long as some energy goes into hadronic products)

Detecting neutrinos with Super-K

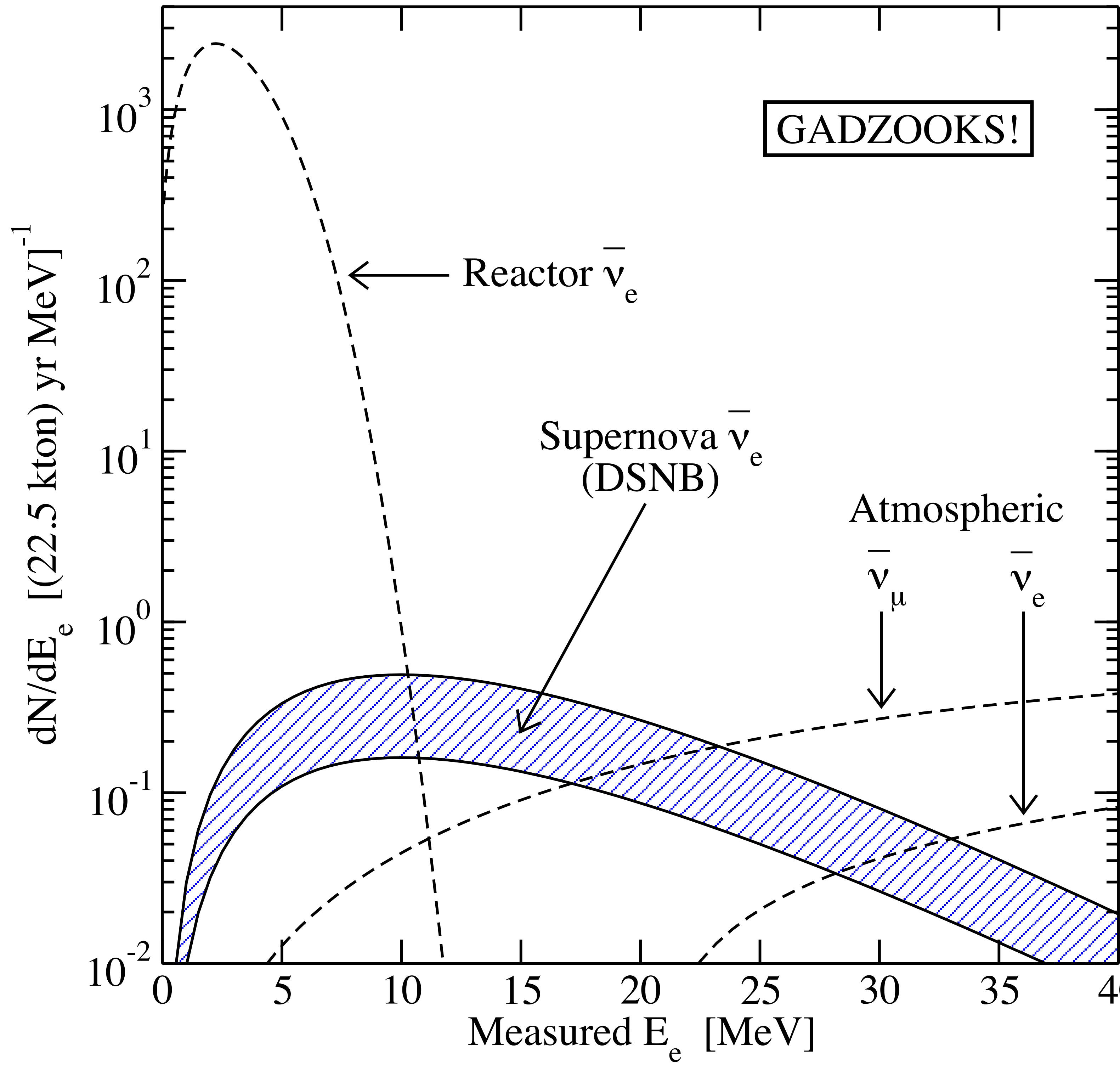


- water Cherenkov detector
- 22.5 kton fiducial volume
- detects anti-electron neutrinos via inverse beta decay

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

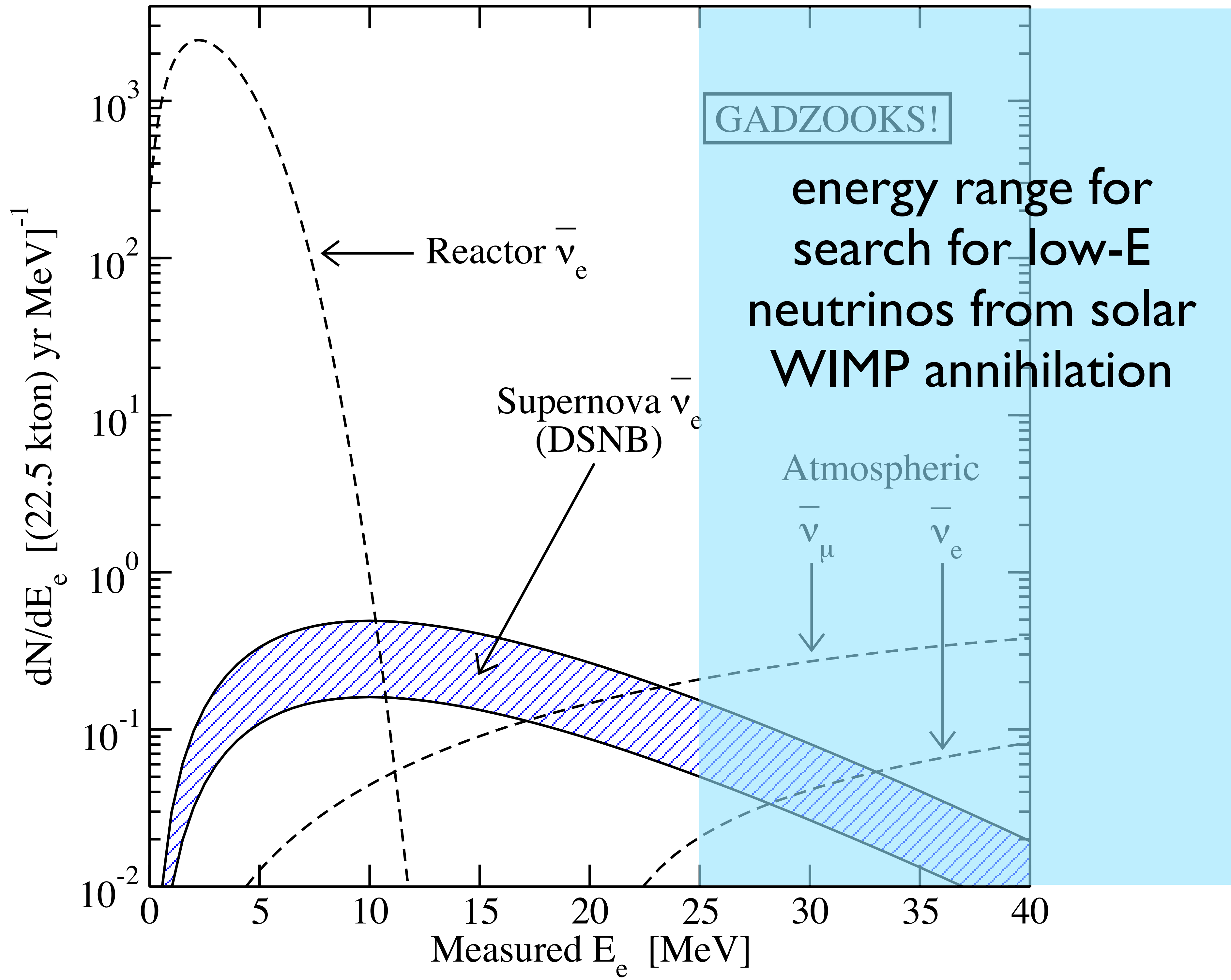
- the positron produces Cherenkov light which is detected by the PMTs

DSNB and other low-E backgrounds



Beacom & Vagins, 2004

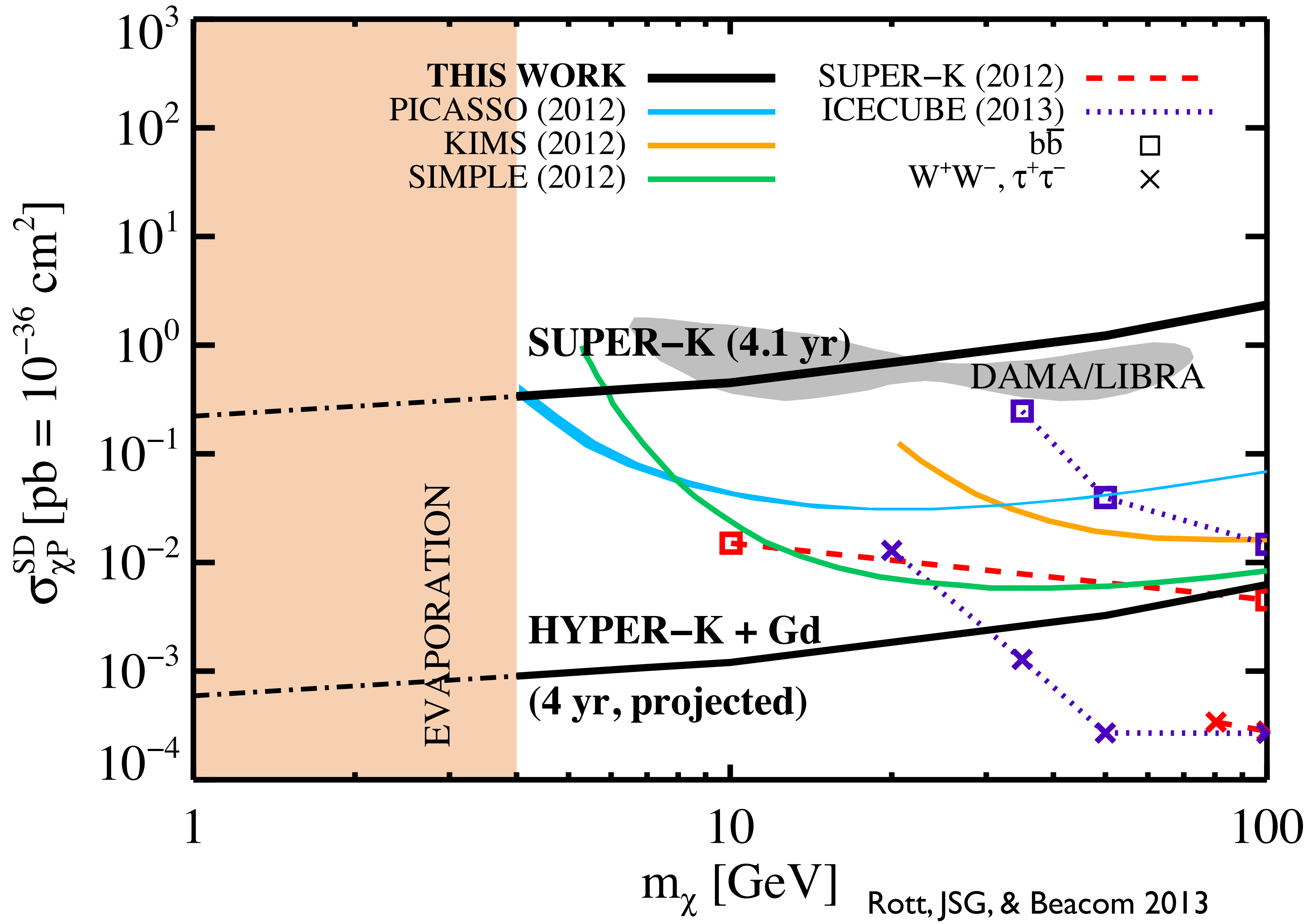
DSNB and other low-E backgrounds



Beacom & Vagins, 2004

New sensitivity using low-energy neutrinos

- sensitivity with low-E neutrino searches continues to improve with decreasing WIMP mass until evaporation becomes important
- minimal dependence on the annihilation channel
- simple sensitivity estimate already tests some of the DAMA signal region
- sensitivity could be improved with dedicated analysis, detector improvements, and larger detectors



Rott, JSG, & Beacom 2013

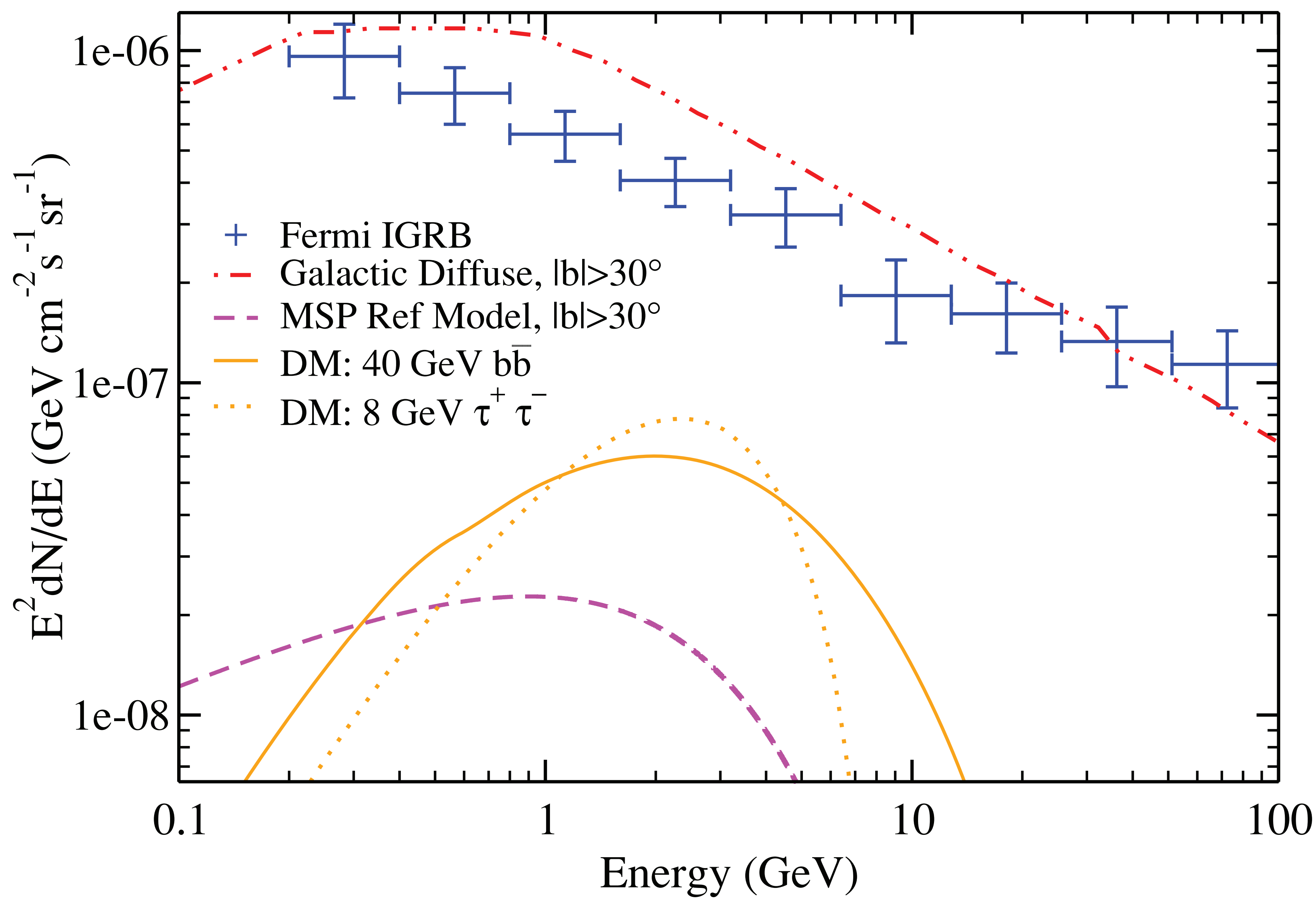
Summary: Part II

- future ground-based gamma-ray searches with CTA are promising
- multiwavelength searches are complementary and can be highly sensitive
- cosmic-ray propagation is a major complication for indirect DM searches with cosmic rays or (multiwavelength) photons
- neutrino searches can access additional targets compared to gamma searches, and are complementary to other indirect searches as well as direct searches
- stay tuned -- the next few years of data will be exciting!

Additional slides

Backgrounds and impostor signals

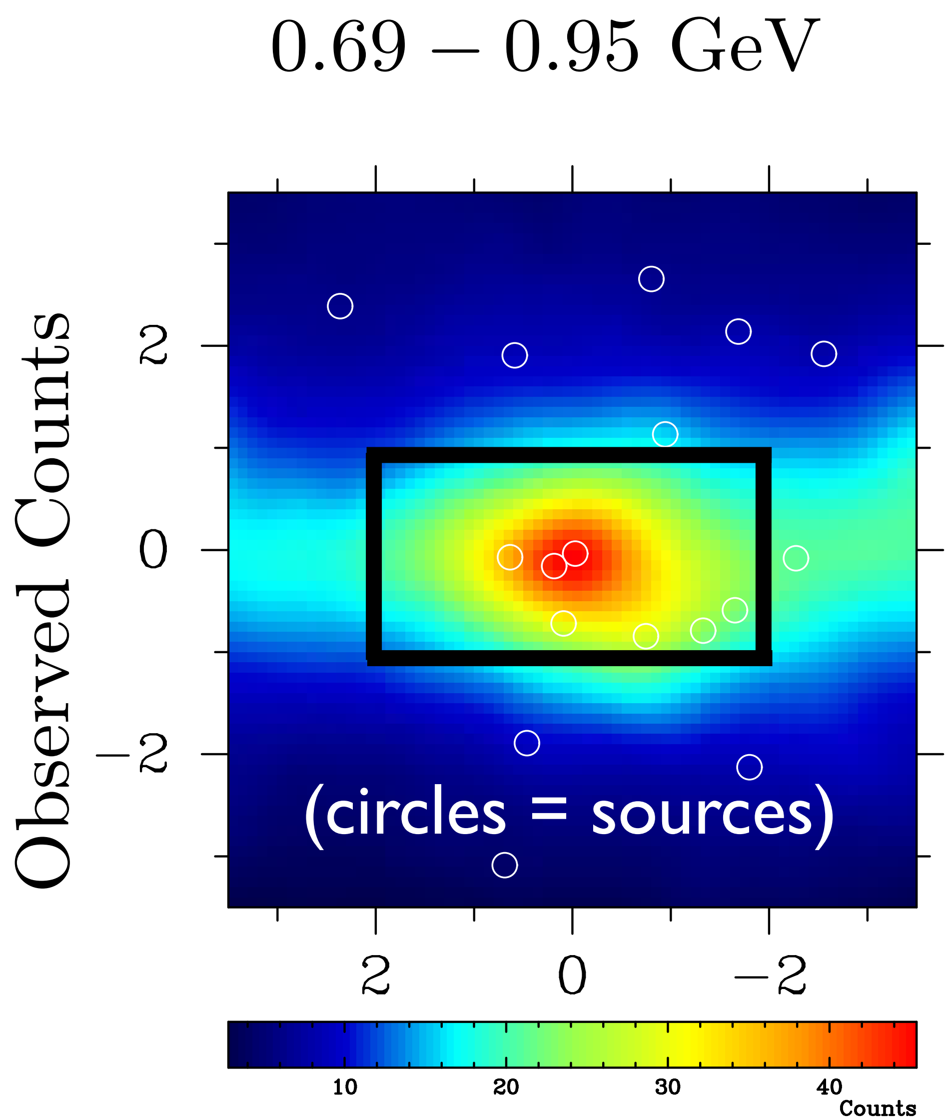
- dark matter makes bumps, lines, cut-offs
- many astrophysical sources make power laws and may have exponential cut-offs
- some astrophysical sources (e.g., pulsars) also make bumps



JSG et al. MNRAS 415, 1074–1082 (2011)

The high-energy inner galaxy

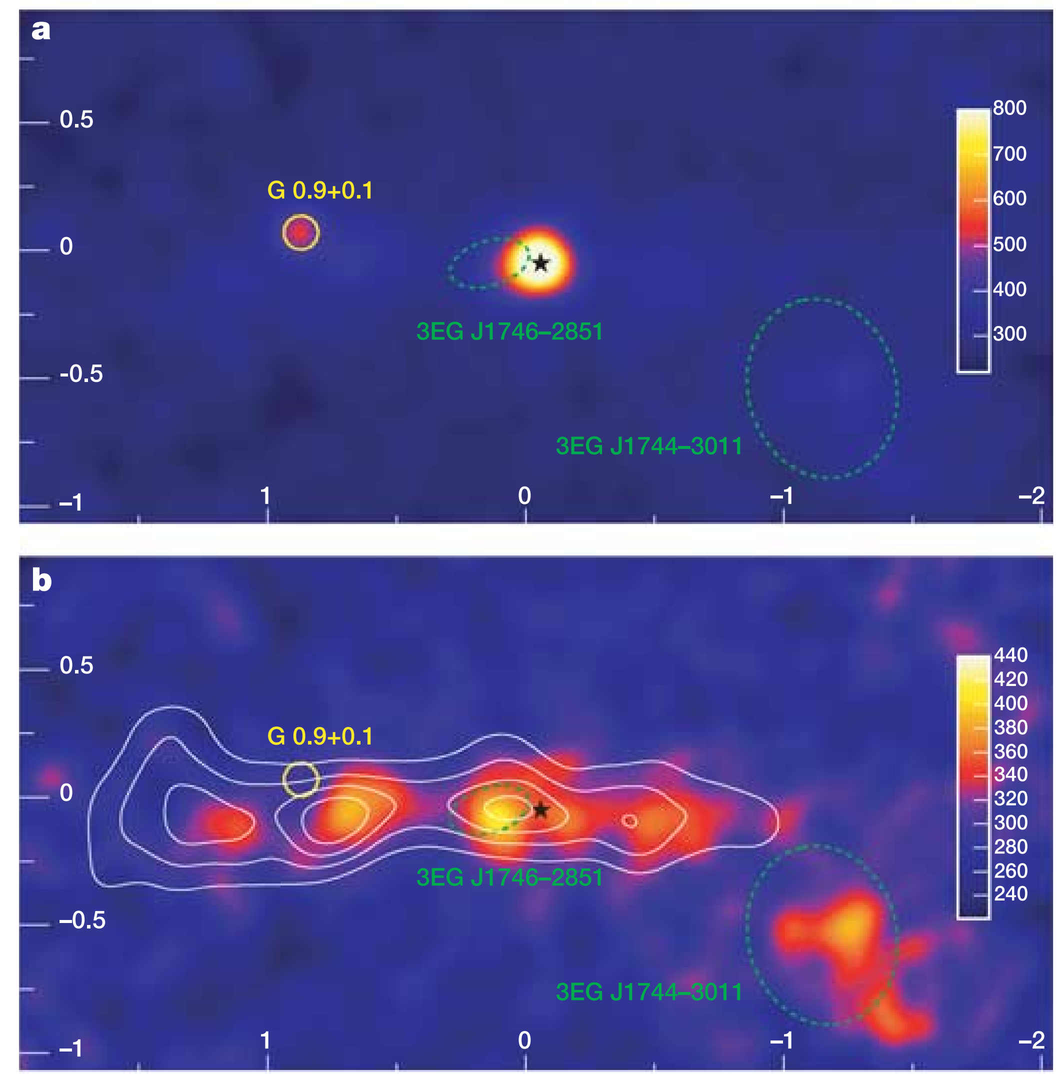
Fermi LAT ~ 1 GeV



Abazajian & Kaplinghat 2012

spatially extended emission

HESS > 380 GeV



Aharonian et al. 2006

consistent with point source

see also: Hooper & Goodenough (2011); Abazajian (2011)