The secret life of a pion in the Sun

(New sensitivity to Solar WIMP annihilation using low-energy neutrinos)

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with
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Ohio State University

An era of neutrino astronomy?

IceCube Neutrino Observatory reports first evidence for extraterrestrial high-energy neutrinos

5 hours ago by Jill Sakai
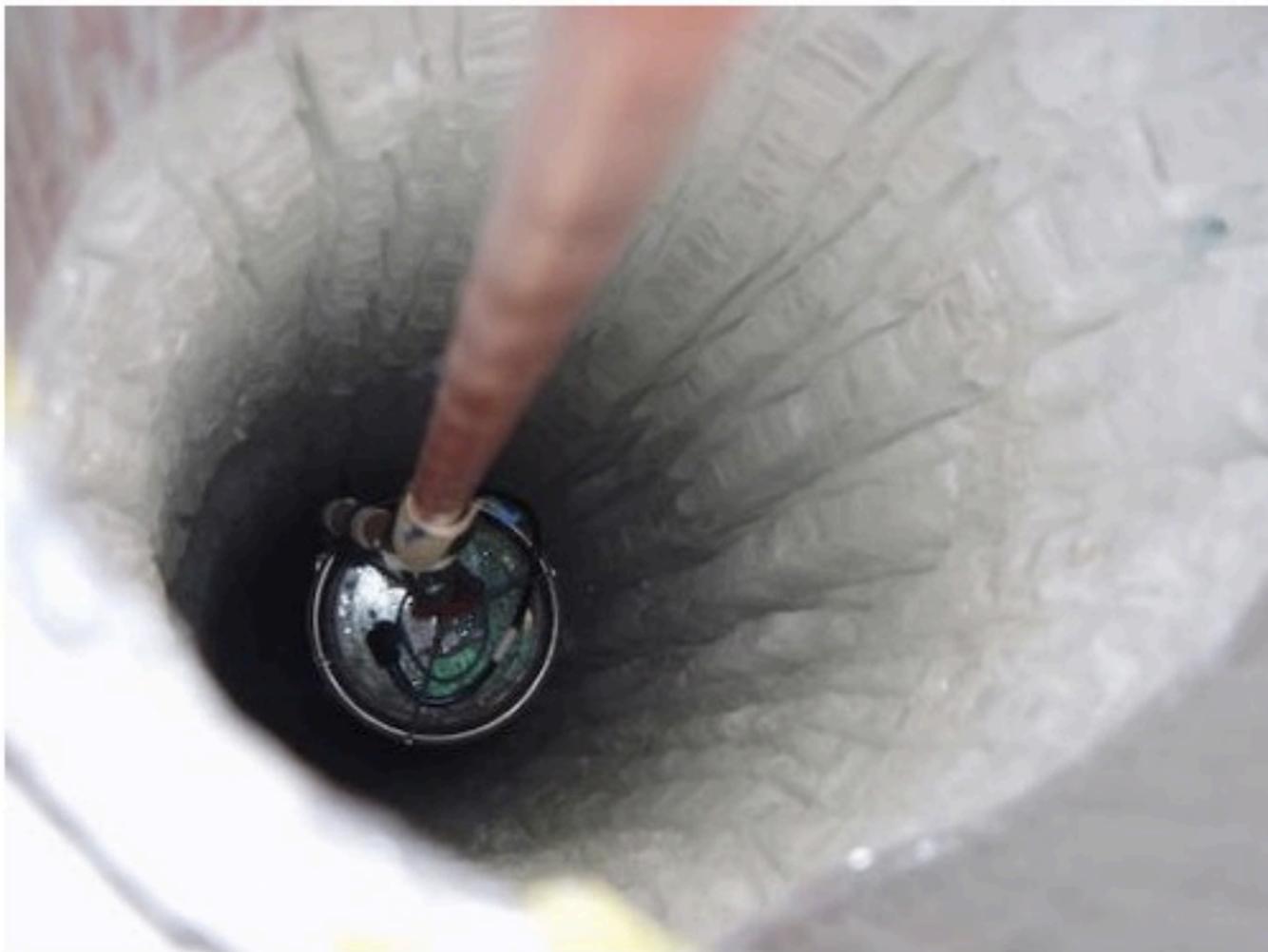
detection reported Wednesday!

The massive IceCube telescope is comprised of more than 5,000 digital optical modules suspended in a cubic kilometer of ice at the South Pole. Credit: IceCube Collaboration/National Science Foundation

New Scientist

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
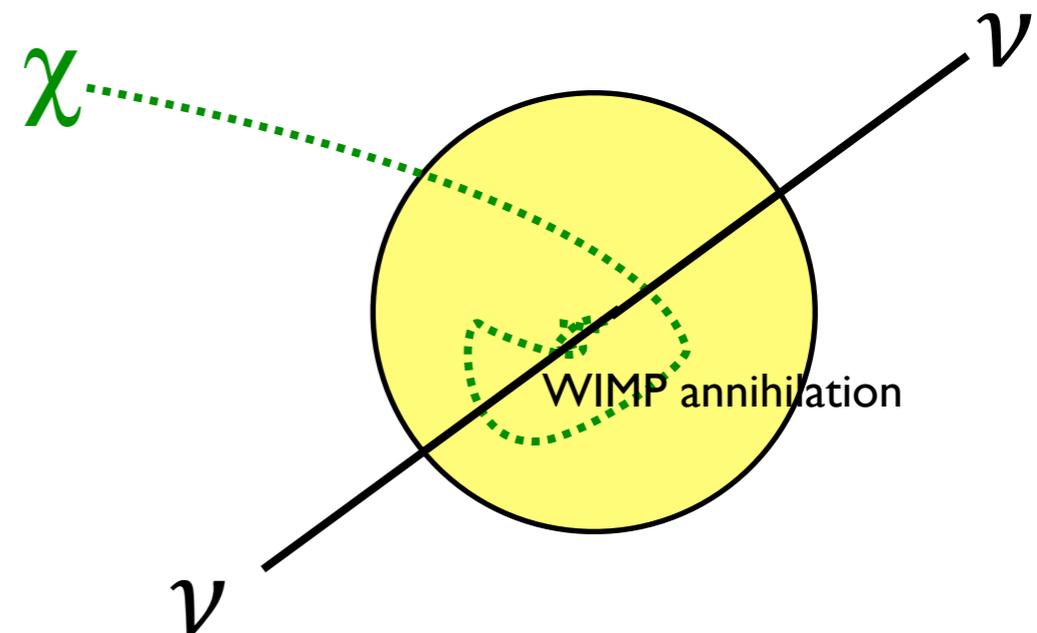
χ ..... ν

WIMP annihilation

ν

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

$\sigma^{SD}_{\chi P} = 10^{-36} \text{ cm}^2$
$\sigma^{SD}_{\chi P} = 10^{-37} \text{ cm}^2$

$\propto m_\chi^{-2}$

$\propto m_\chi^{-1}$

$\Gamma_C \text{ [s}^{-1}\text{]}$

$m_\chi \text{ [GeV]}$
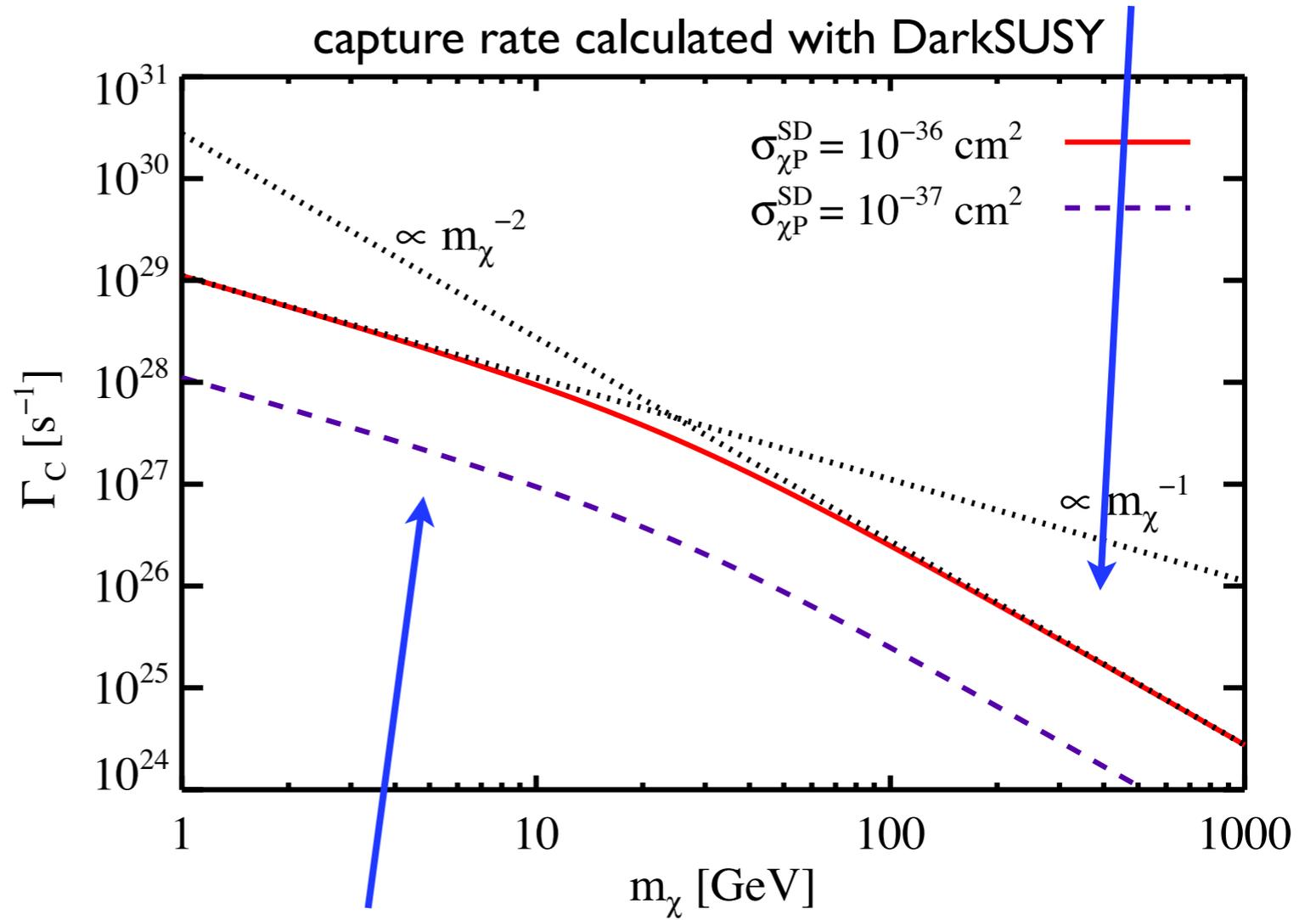
scales linearly w/ DM number density

Rott, JSG, & Beacom 2012

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- subsequent evaporation of captured low-mass WIMPs can significantly reduce effective capture rate and hence annihilation rate

evaporation

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

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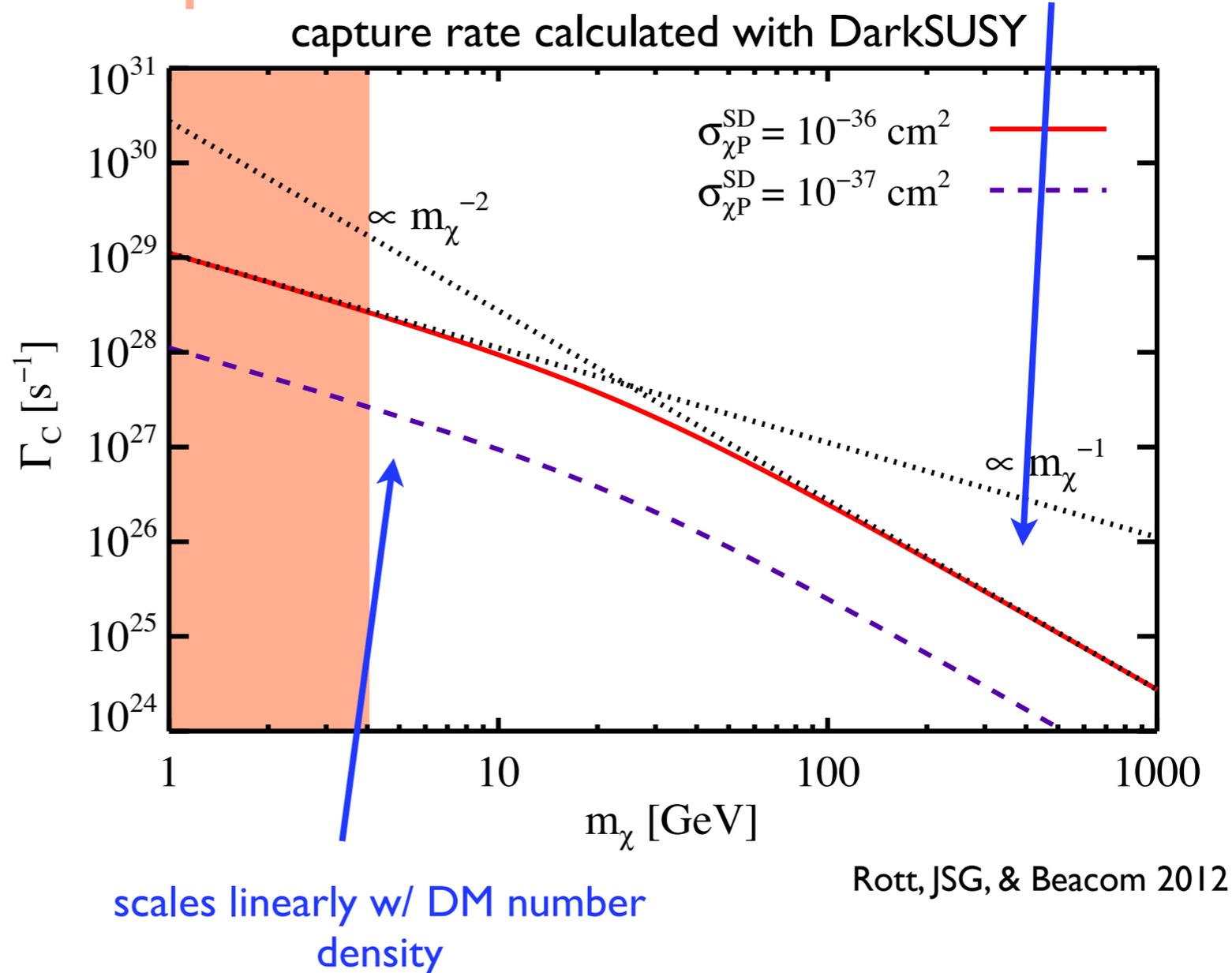
Indirect detection with neutrinos

- high-energy neutrinos (E ≳ 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)
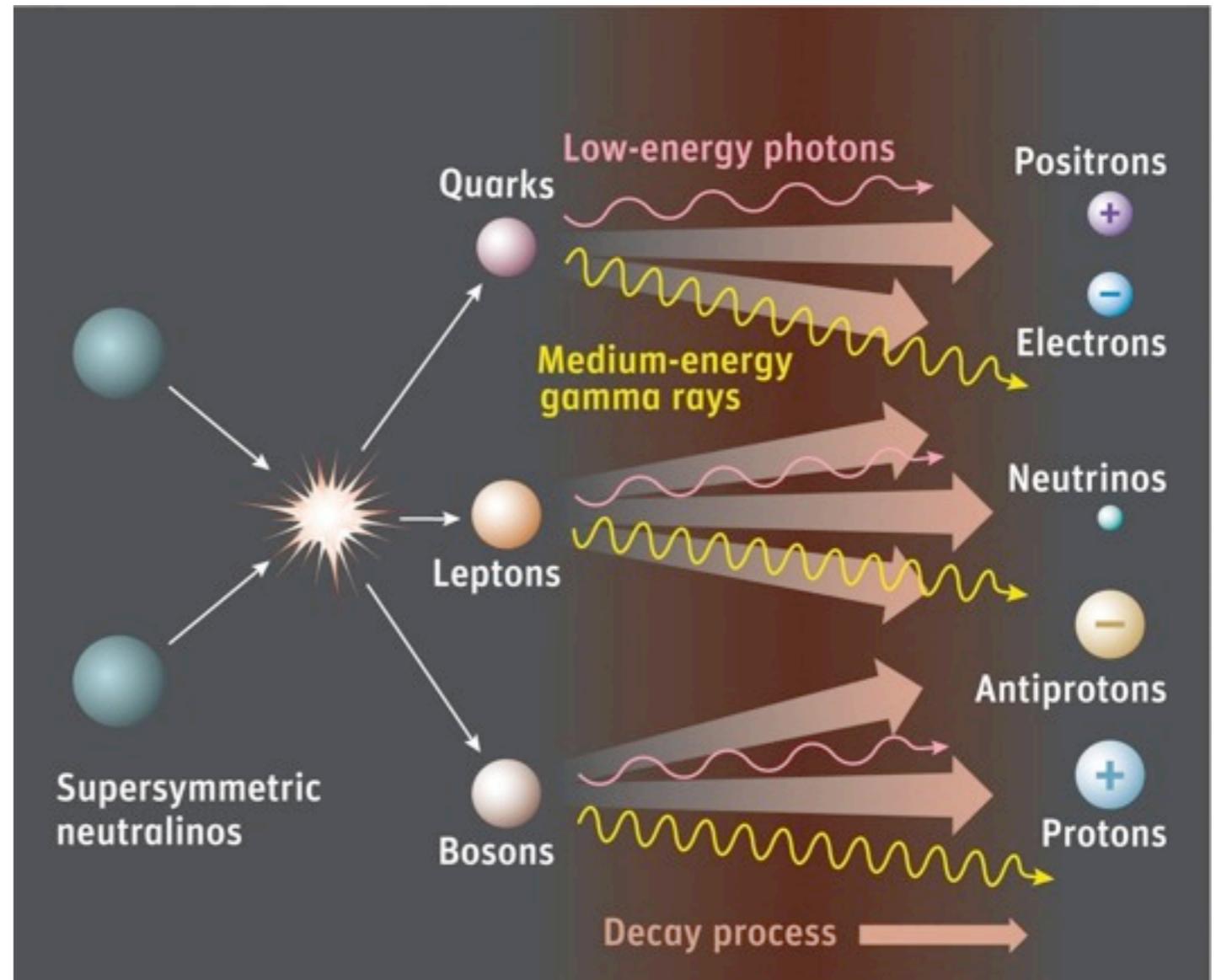
Credit: Sky & Telescope / Gregg Dinderman

Direct detection and high-energy neutrinos
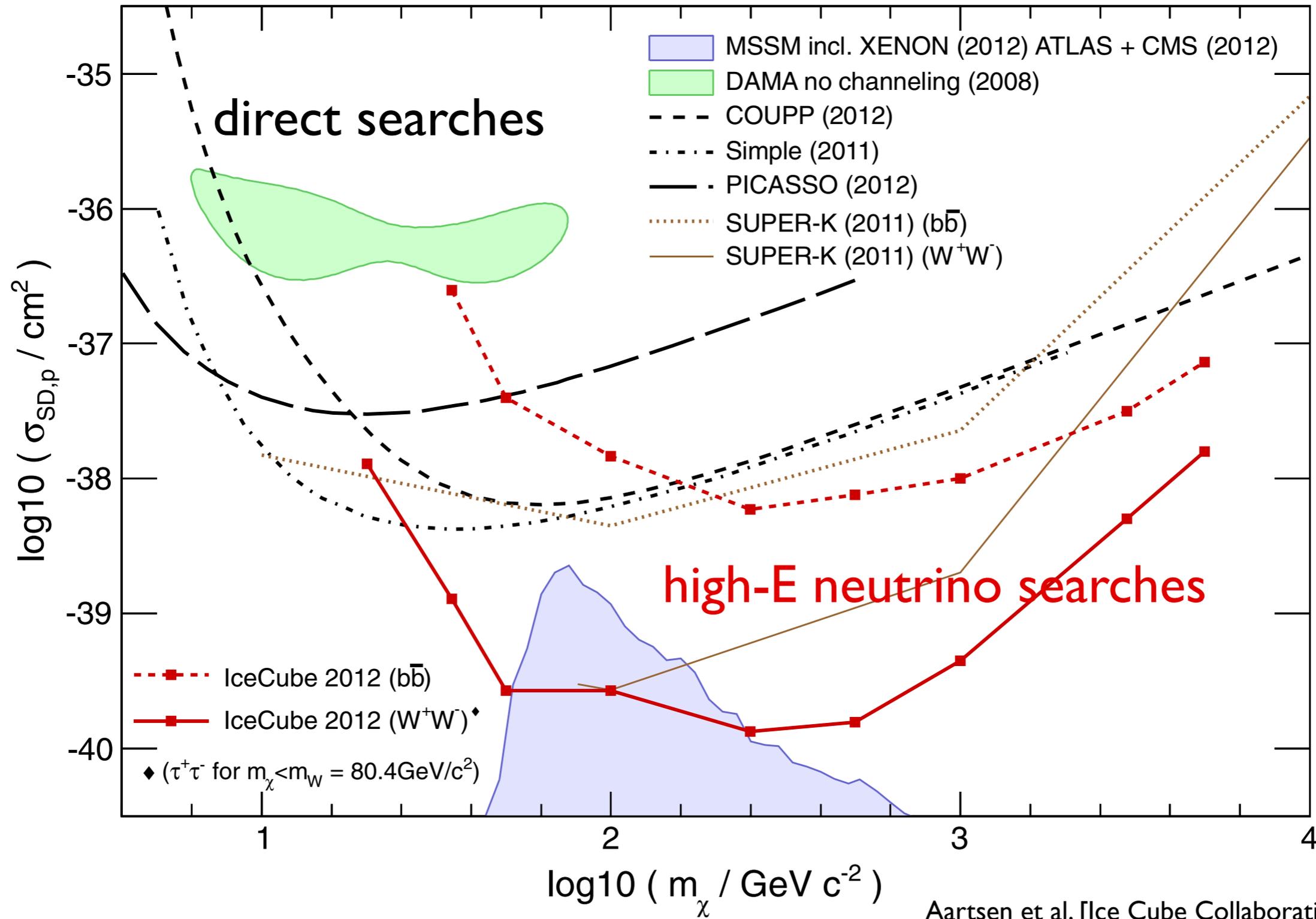

Aartsen et al. [Ice Cube Collaboration], 2013

Direct detection and high-energy neutrinos

direct searches

high-E neutrino searches

not yet probed by high-E neutrino searches

Legend:
- MSSM incl. XENON (2012) ATLAS + CMS (2012)
- DAMA no channeling (2008)
- COUPP (2012)
- Simple (2011)
- PICASSO (2012)
- SUPER-K (2011) ($b\bar{b}$)
- SUPER-K (2011) (W^+W^-)
- IceCube 2012 ($b\bar{b}$)
- IceCube 2012 (W^+W^-)$^\blacklozenge$
- $\blacklozenge$ ($\tau^+\tau^-$ for $m_\chi < m_W = 80.4\,\text{GeV}/c^2$)

Y-axis: $\log_{10}(\sigma_{SD,p} / \text{cm}^2)$
X-axis: $\log_{10}(m_\chi / \text{GeV } c^{-2})$
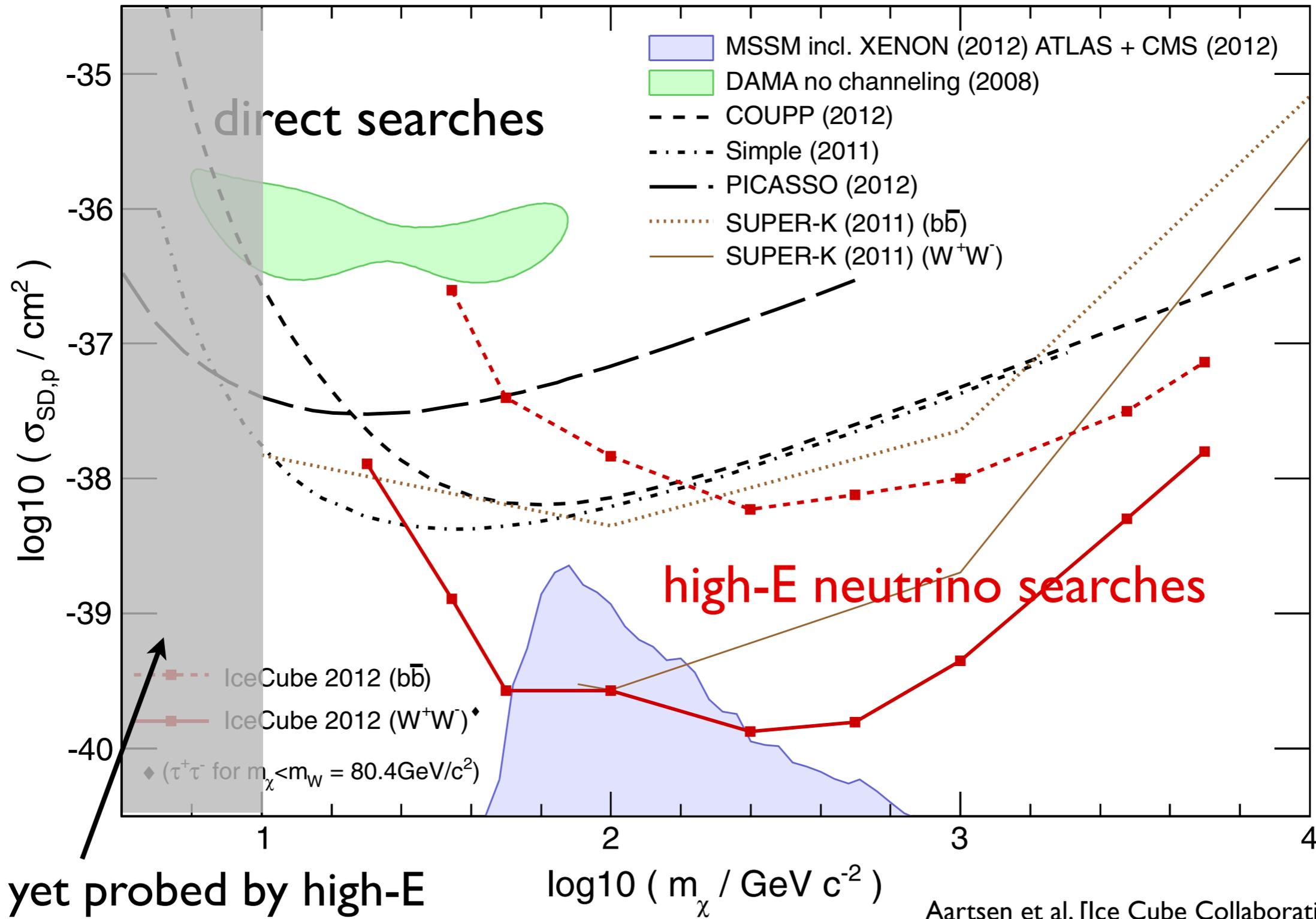
Aartsen et al. [Ice Cube Collaboration], 2013

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
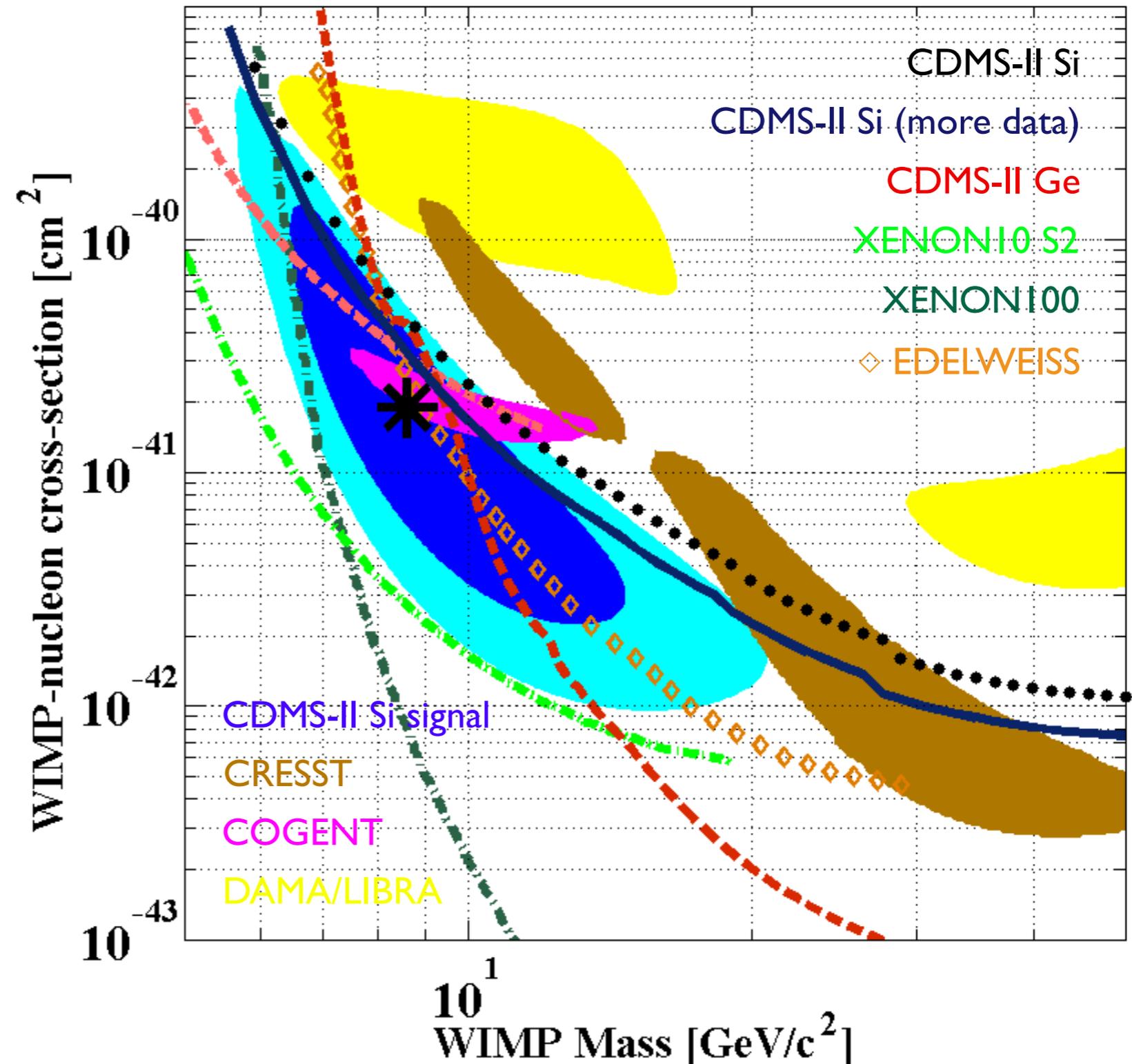
CDMS II Collaboration, 2013

Light WIMPs: gamma-ray signals

$|b| = 10-20$ deg.

E$_\gamma$ (GeV)

E^2 dN/dE (GeV/cm^2/s/sr)

Hooper & Slatyer 2013
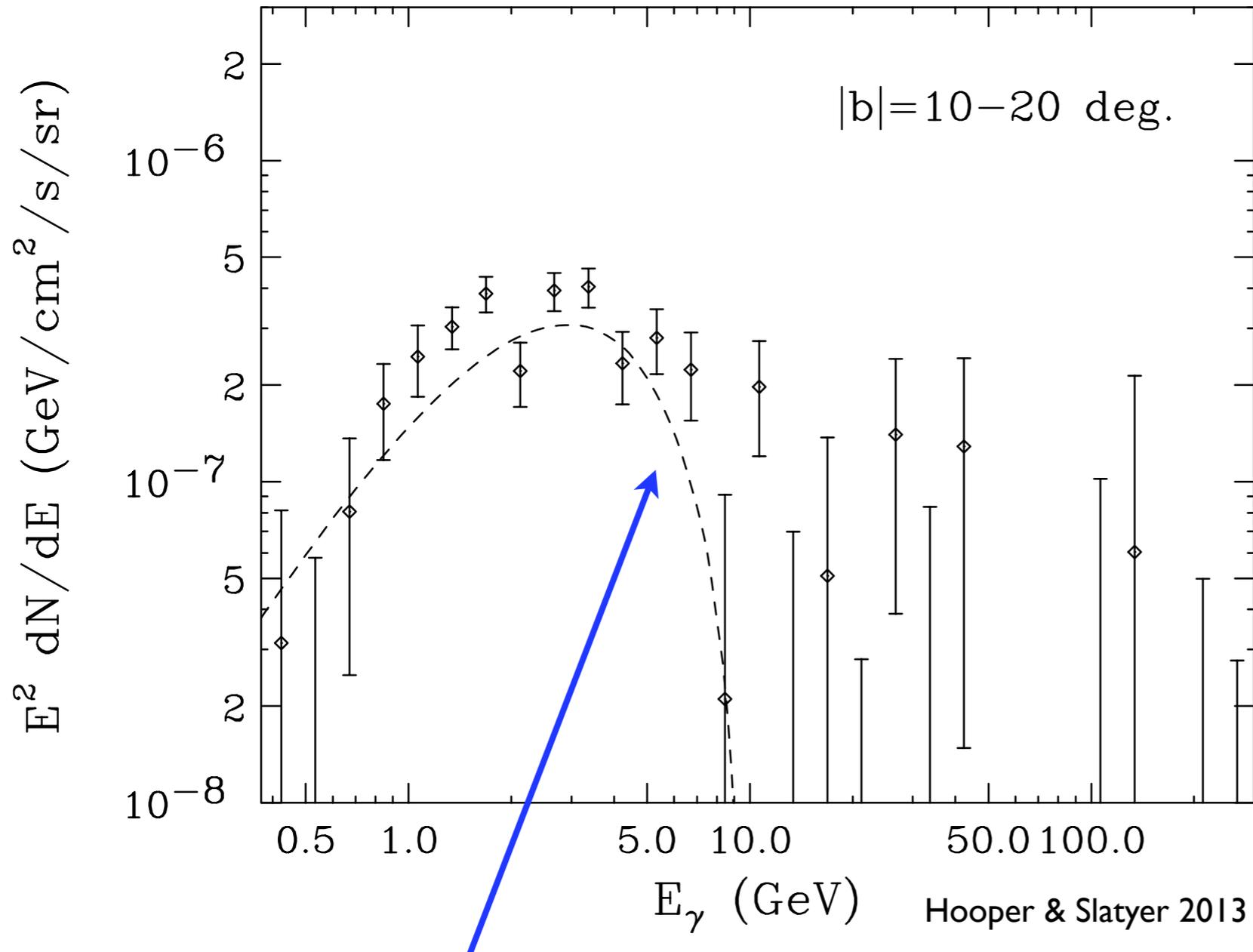
- claimed gamma-ray excesses from the Galactic Center and inner Galaxy are consistent with annihilation of light WIMP DM (e.g., Hooper & Goodenough 2010, Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013)

- again, need for multiple experimental probes

gamma-ray spectrum from annihilation of 10 GeV WIMPs to $\tau^+\tau^-$

$|b|=1-10$ deg.

Low-energy neutrinos from the Sun

possible final states:

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

Slide Concept: C. Rott

Low-energy neutrinos from the Sun

possible final states:
$q\bar{q}, g\bar{g}, c\bar{c}, s\bar{s}, b\bar{b}, t\bar{t}, W^+W^-, ZZ, \tau^+\tau^-, \mu^+\mu^-, \nu\nu, \boxed{e^+e^-, \gamma\gamma}$

few neutrinos

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Low-energy neutrinos from the Sun

possible final states:

$qq, gg, cc, ss,$ [$bb, tt, W^+W^-, ZZ, \tau^+\tau^-, \mu^+\mu^-, \nu\nu$], [$e^+e^-, \gamma\gamma$]

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

few neutrinos

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- roughly equal numbers of π^+, π^-, and π^0 are produced, with far greater multiplicity than other hadrons

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- 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

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

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

Neutrino signals - Example W-Boson
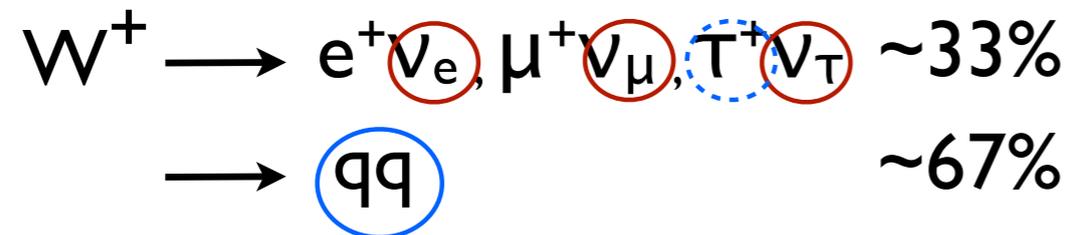
$W^+ \longrightarrow e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau$ ~33%

$\longrightarrow qq$ ~67%

Let's have a closer look at this:

$e^+\nu_e$ 1 high energy ν + em shower

$\mu^+\nu_\mu$ 1 high energy ν + muon

$\tau^+\nu_\tau$ 1 high energy ν + tau decay

qq hadronic shower

Neutrinos from pion decay at rest ~ 20-50MeV

Neutrinos from decay of annihilation final states ~10GeV - 10TeV

MeV   GeV   TeV

$W^+ \longrightarrow e^+ \nu_e, \mu^+ \nu_\mu, \tau^+ \nu_\tau$ ~33%

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Let's have a closer look at this:

$e^+ \nu_e$	1 high energy ν + em shower
$\mu^+ \nu_\mu$	1 high energy ν + muon
$\tau^+ \nu_\tau$	1 high energy ν + tau decay
$q\bar{q}$	hadronic shower

Neutrinos from pion decay at rest ~ 20-50MeV

Neutrinos from decay of annihilation final states ~10GeV - 10TeV

MeV   GeV   TeV

Multiplicity of neutrinos from Solar WIMPs

$N_{\nu(>1\mathrm{GeV})}(\chi\chi \to \tau^+\tau^-)$

Rott, JSG, & Beacom 2012

Multiplicity of neutrinos from Solar WIMPs

all annihilation energy goes into pions

Maximal case

Neutrino yield N_ν

$N_{\nu(>1\text{GeV})}(\chi\chi \rightarrow \tau^+\tau^-)$

m_χ [GeV]
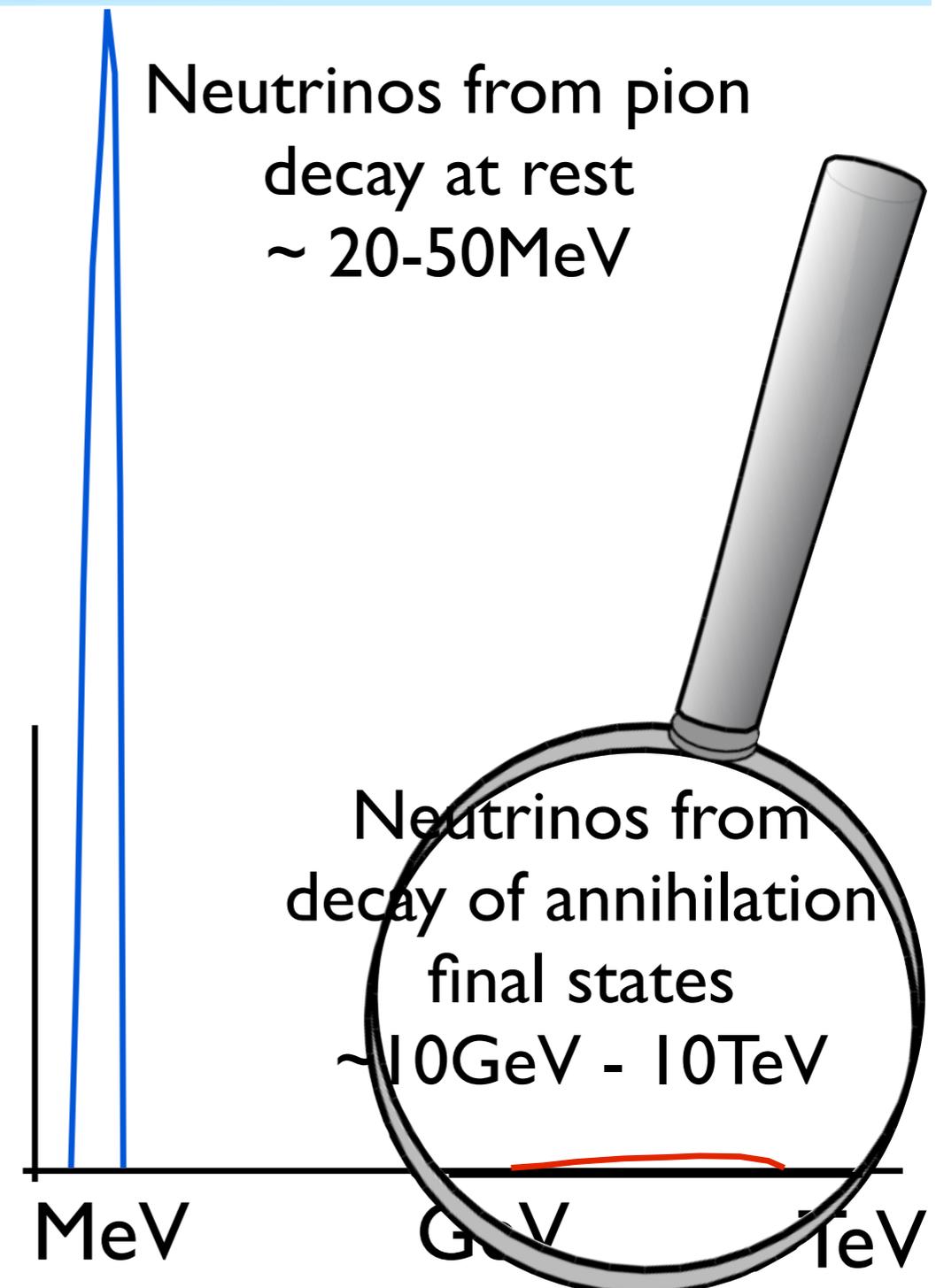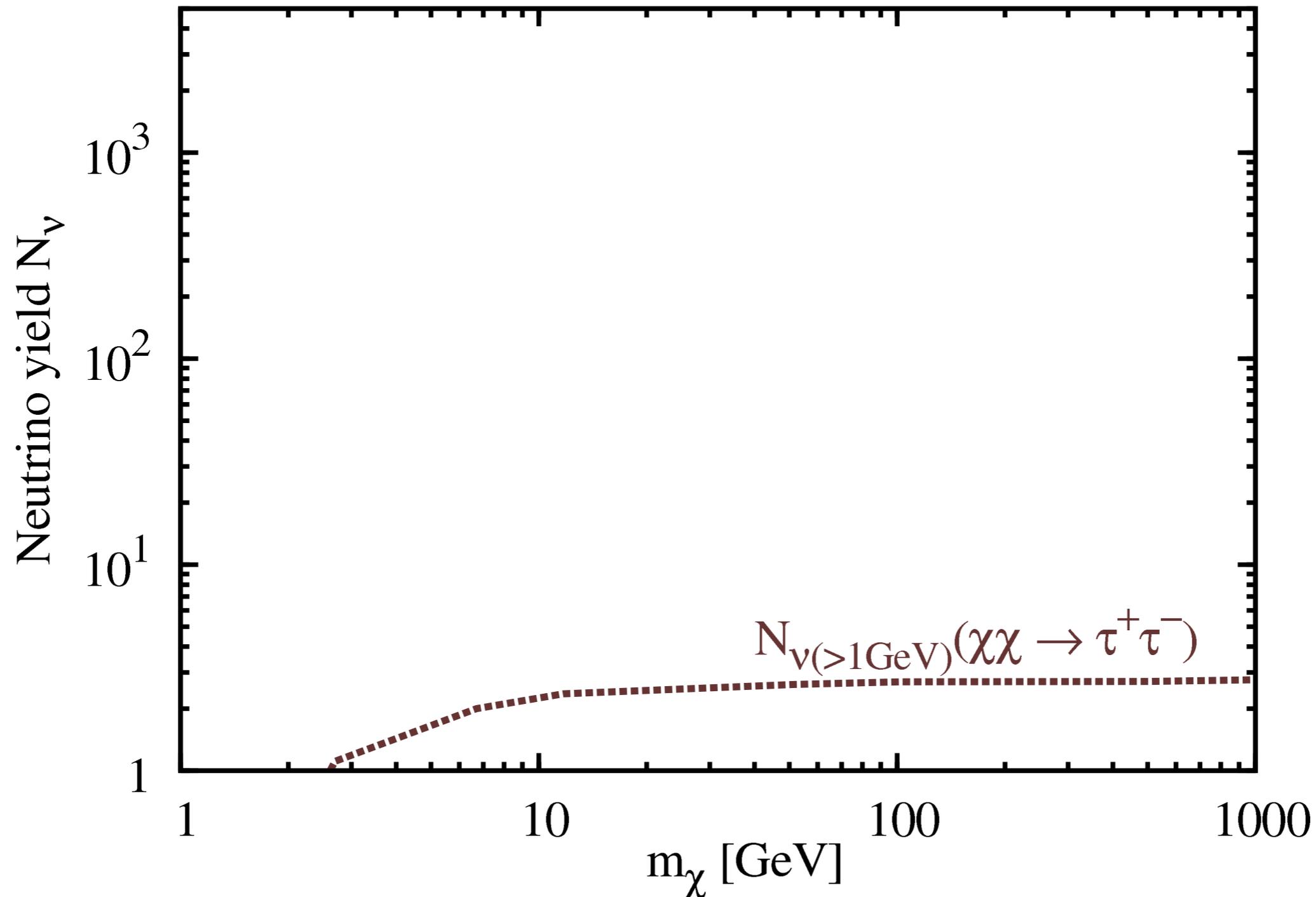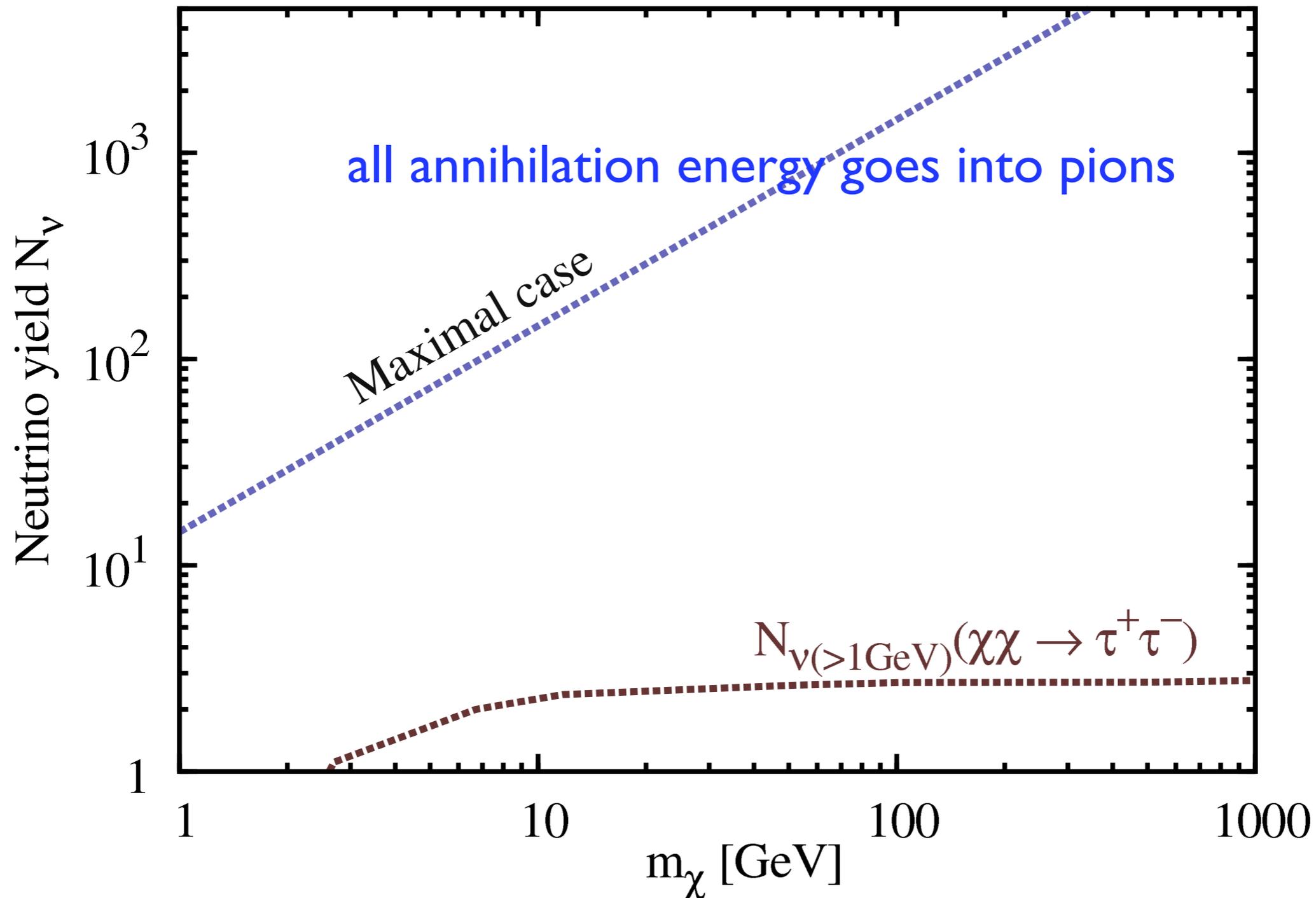
Multiplicity of neutrinos from Solar WIMPs
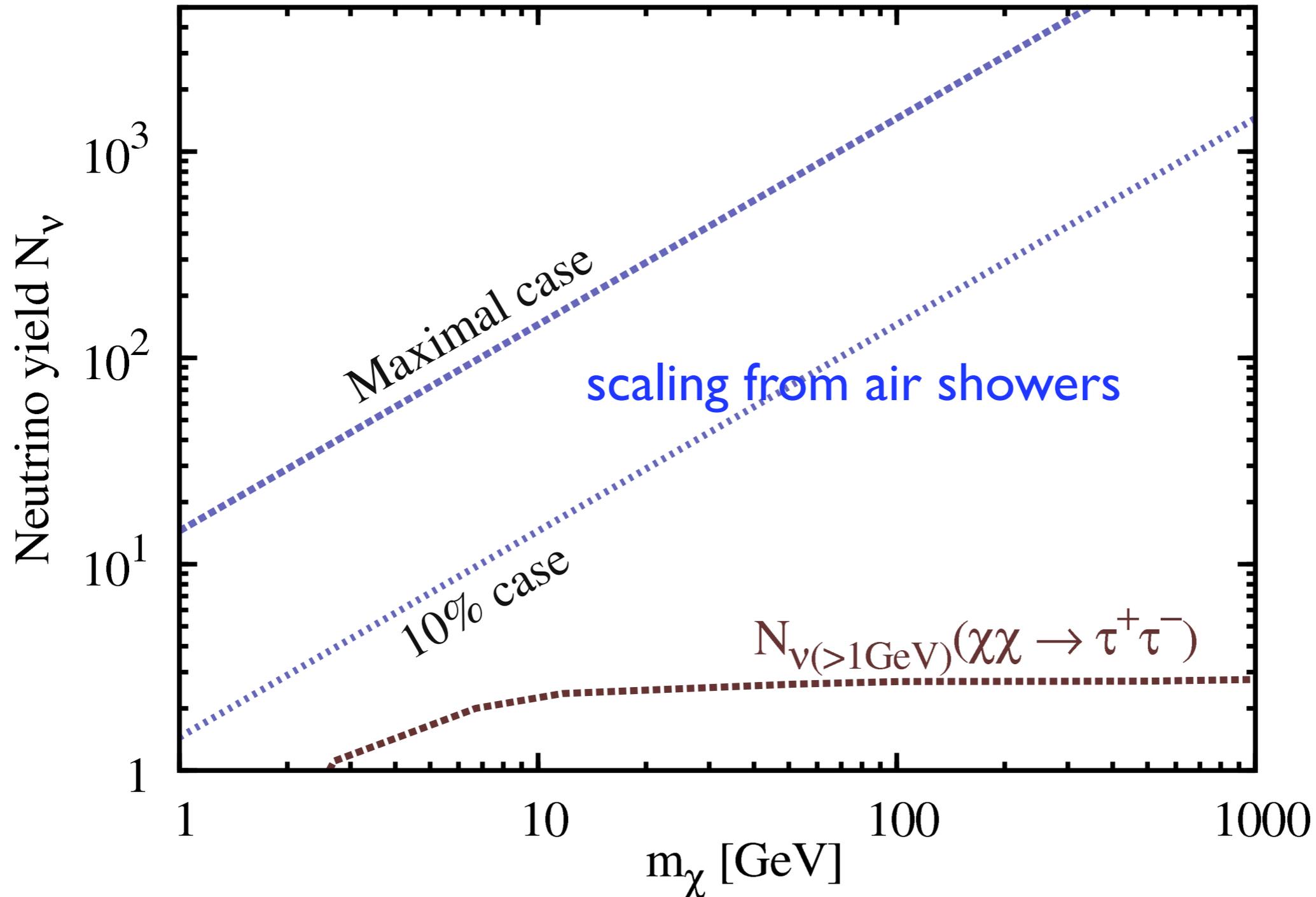
Rott, JSG, & Beacom 2012

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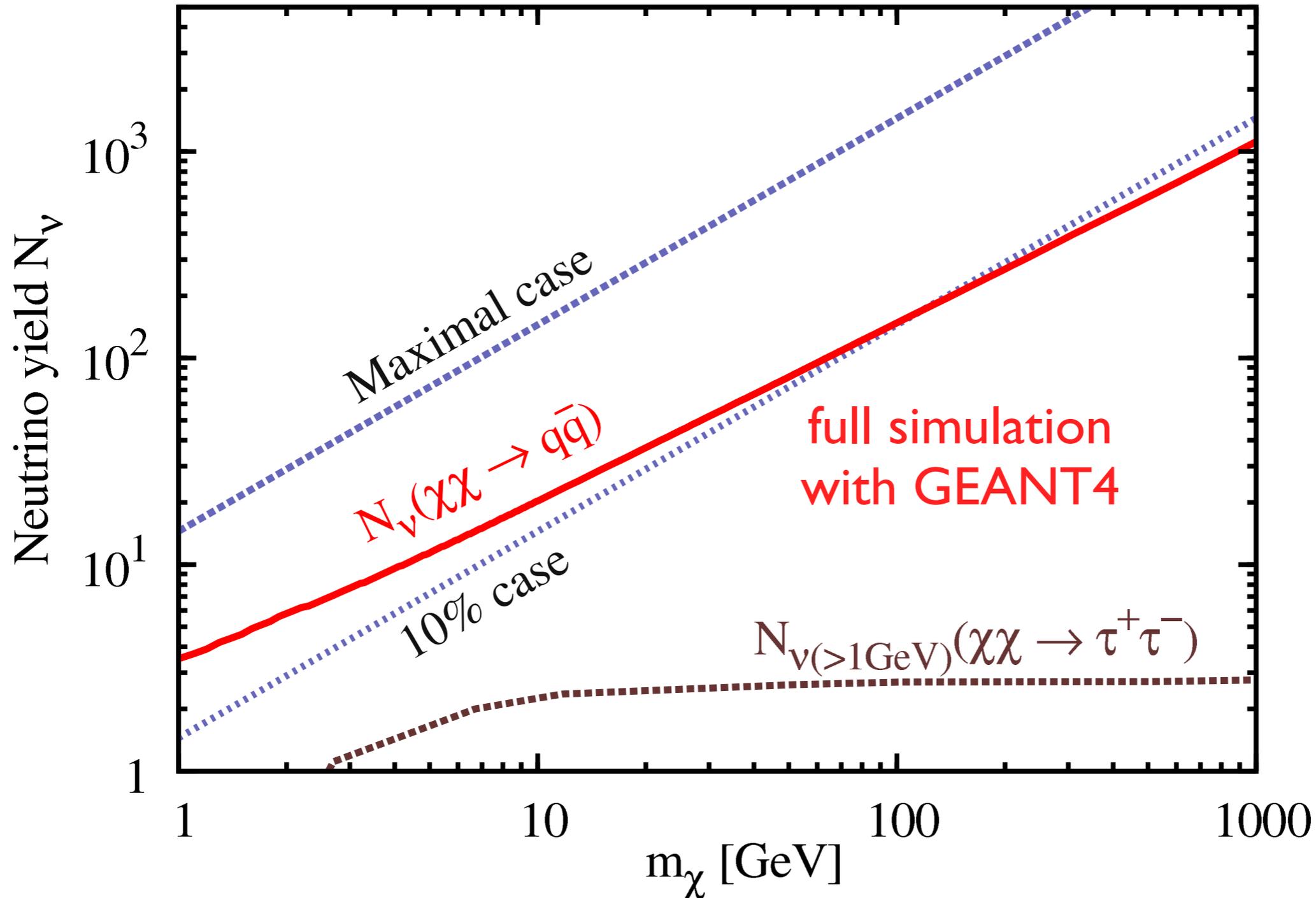
Rott, JSG, & Beacom 2012

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)

Maximal case

$N_\nu(\chi\chi \to q\bar{q})$

10% case

$N_{\nu(>1GeV)}(\chi\chi \to \tau^+\tau^-)$
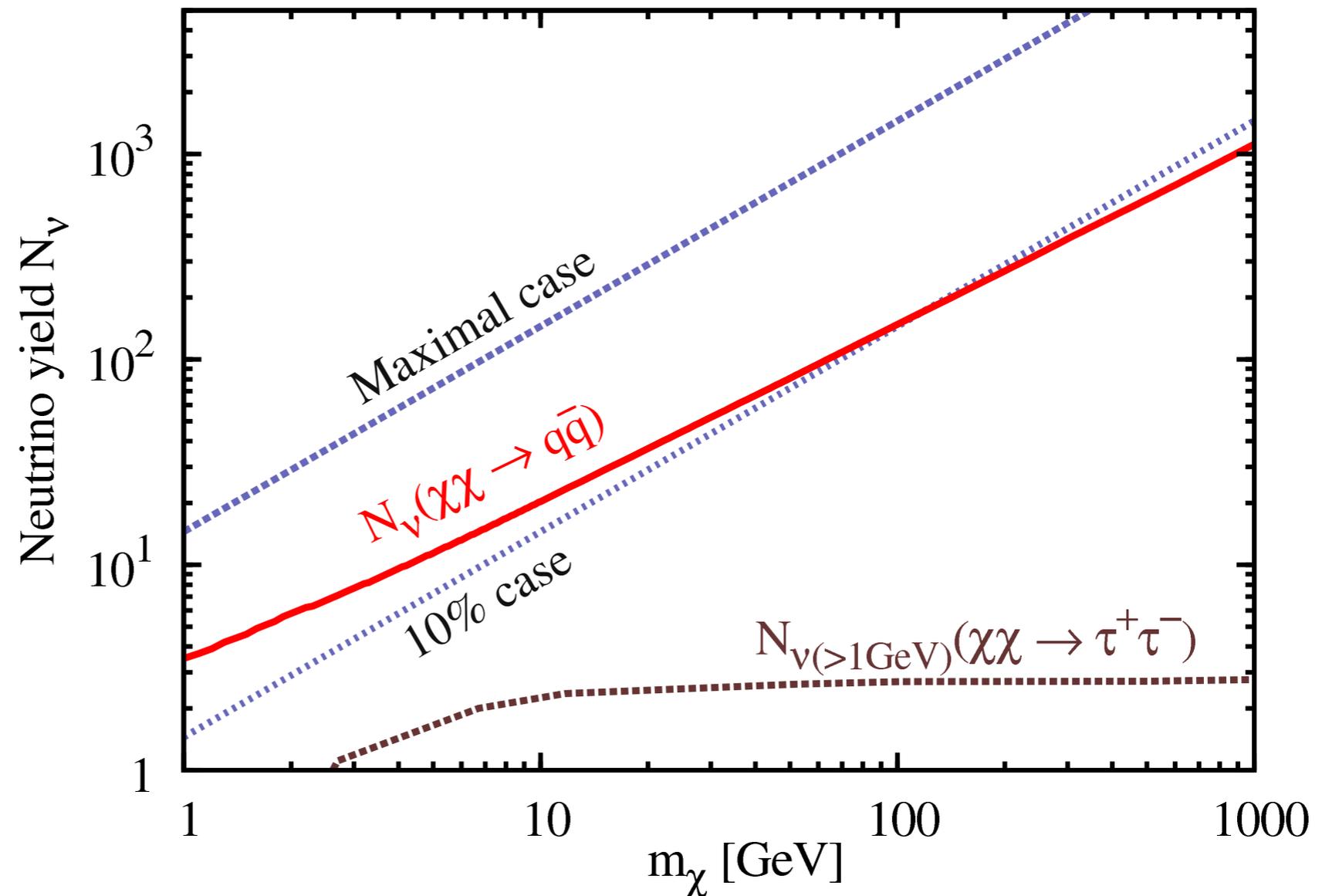
Rott, JSG, & Beacom 2012

Spectrum of low-E neutrinos
Neutrino Spectrum in the Sun (normalized to unity)

Figure: C. Rott

ν_μ

The Sun and Earth is transparent to neutrinos below 50MeV, but matter enhanced-mixing gives:

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 1/6$$

29.8MeV

$\overline{\nu}_\mu$

ν_e

52.8MeV

log[dP/dE]

Neutrino Energy [MeV]
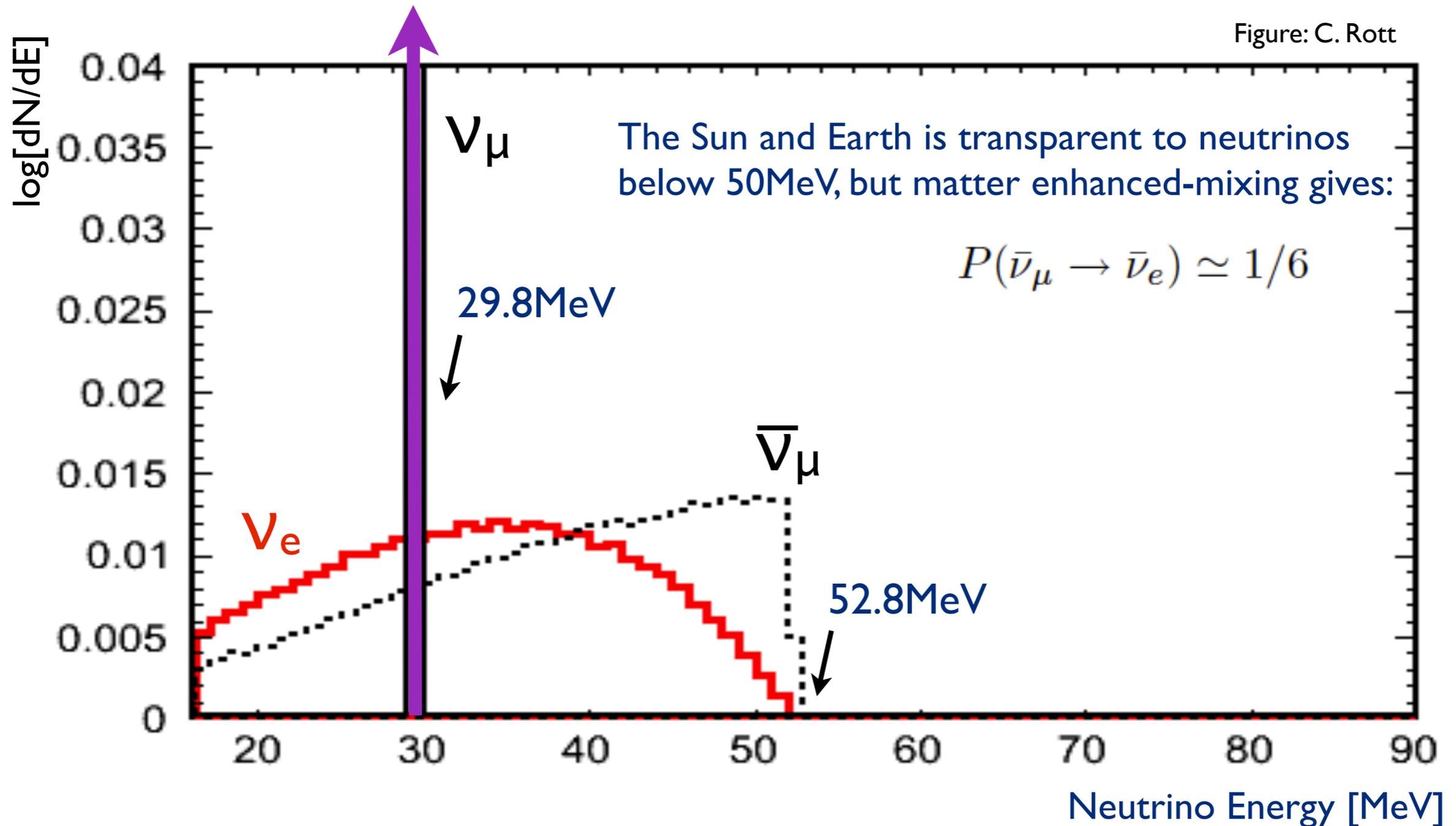
signal spectral shape does not depend on annihilation channel!
(as long as some energy goes into hadronic products)

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
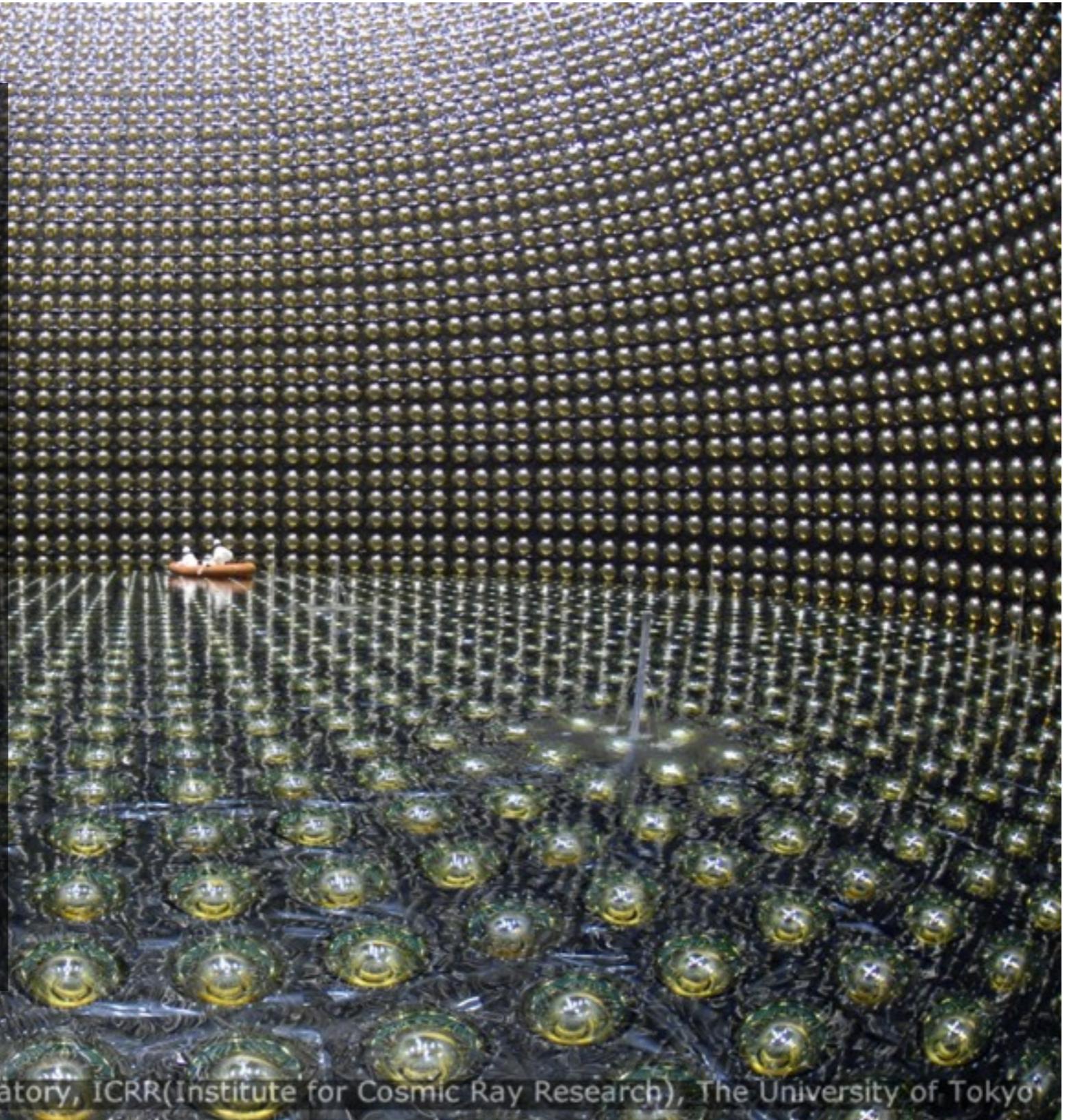
(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

DSNB and other low-E backgrounds
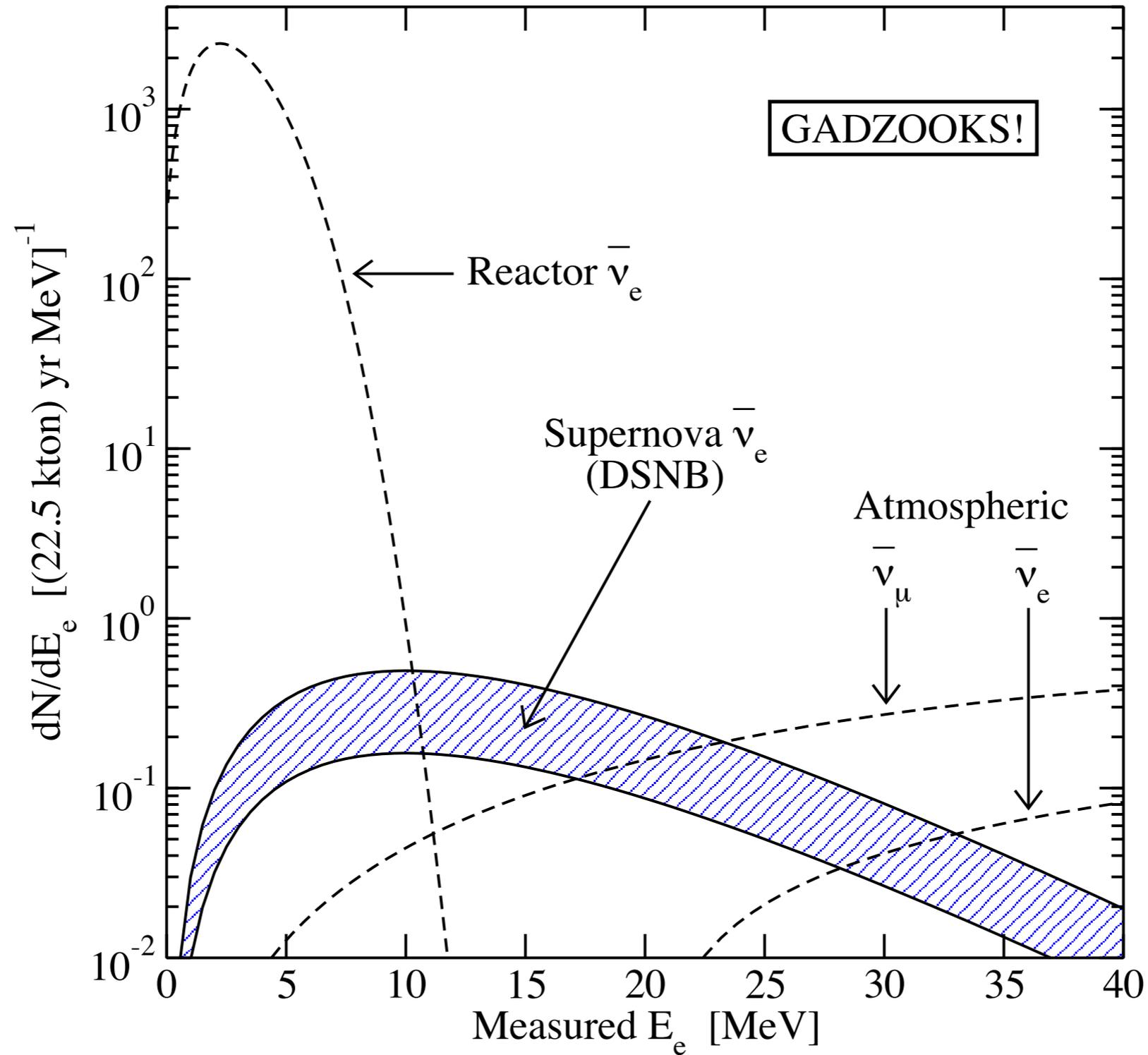
Beacom & Vagins, 2004

DSNB and other low-E backgrounds

GADZOOKS!

energy range for search for low-E neutrinos from solar WIMP annihilation

Reactor $\bar{\nu}_e$

Supernova $\bar{\nu}_e$ (DSNB)

Atmospheric $\bar{\nu}_\mu$ $\bar{\nu}_e$
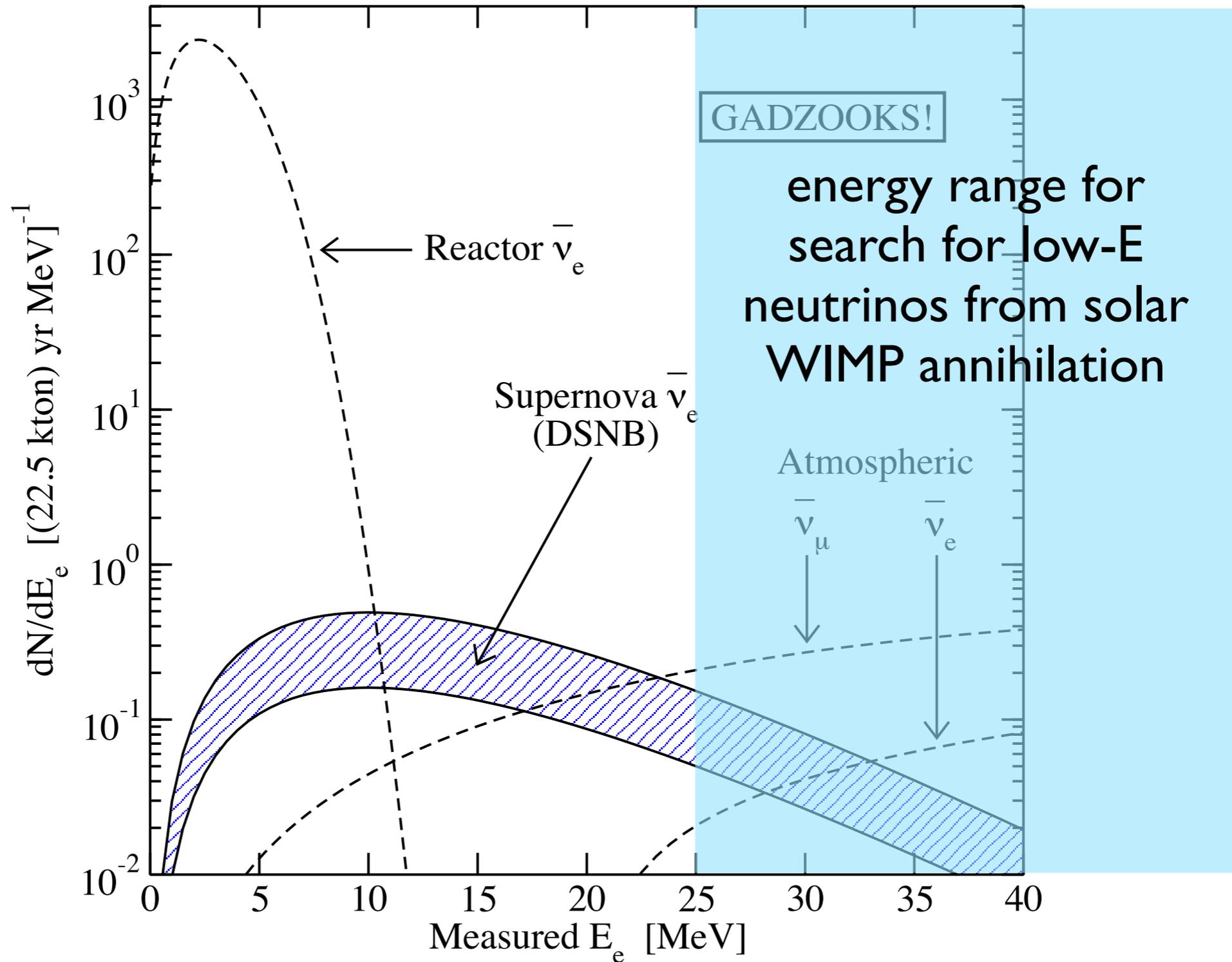
Beacom & Vagins, 2004

Backgrounds

decay electron
atm. muon neutrinos
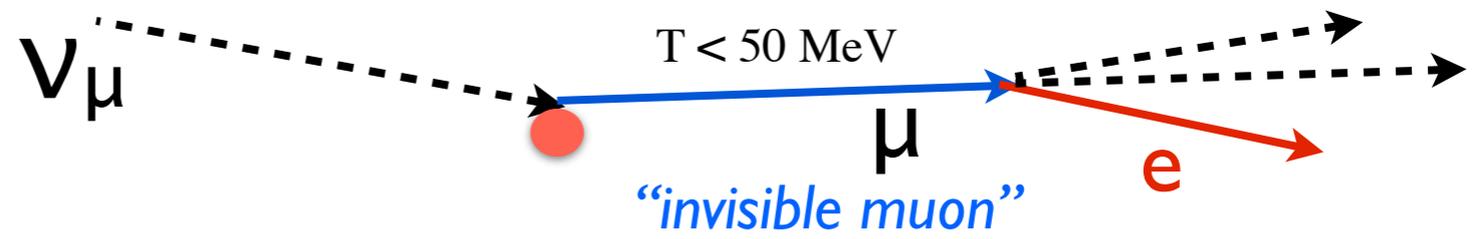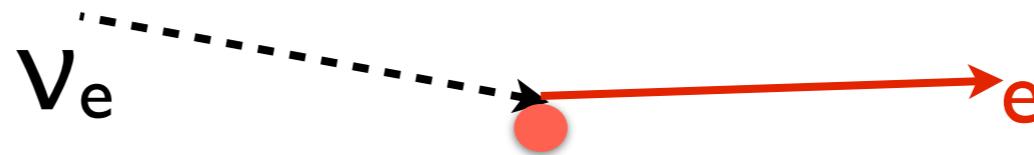
ν_μ T < 50 MeV μ e
"invisible muon"

ν_e CC
atm. electron neutrinos

ν_e e

π / μ
production from atm. neutrinos

ν_x NC ν_x
T > 200 MeV π

ν_μ μ e
"visible short muon track"

Figure: C. Rott

Backgrounds

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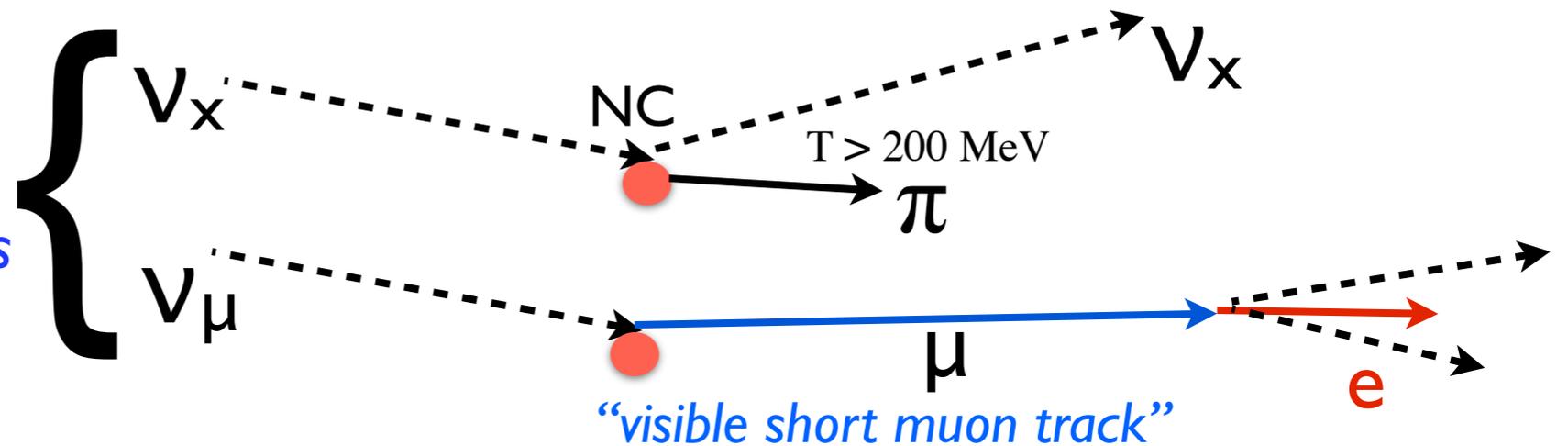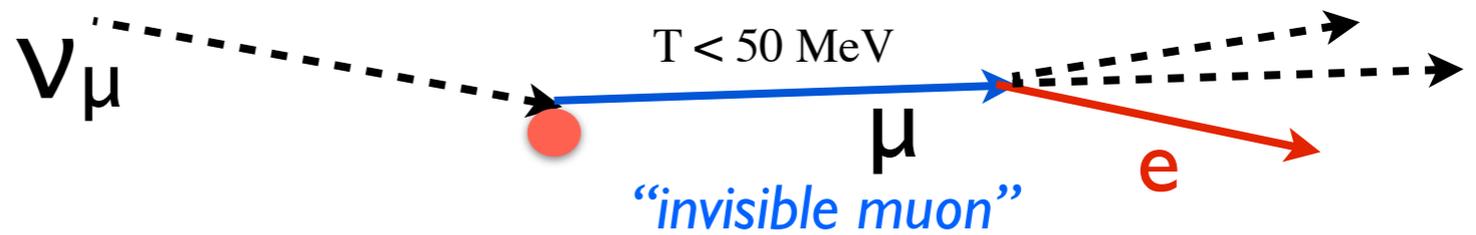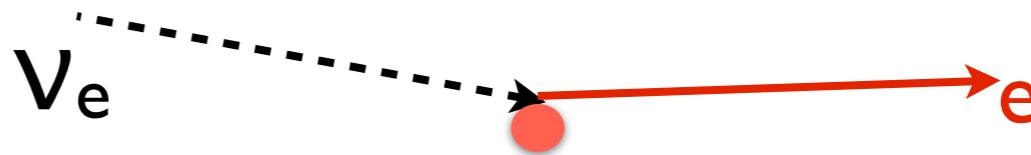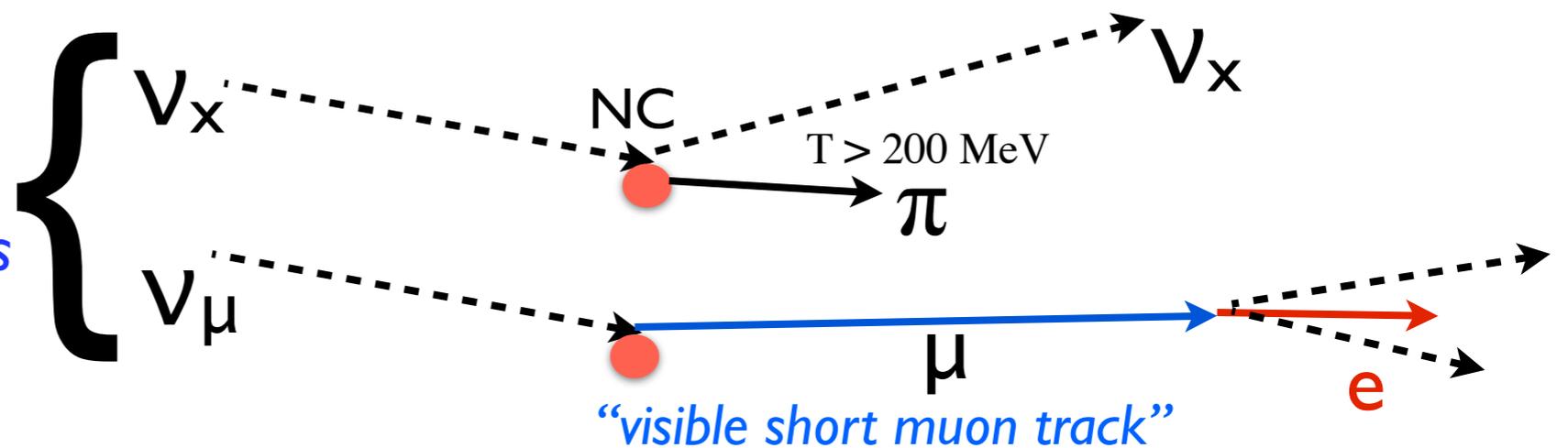
Figure: C. Rott
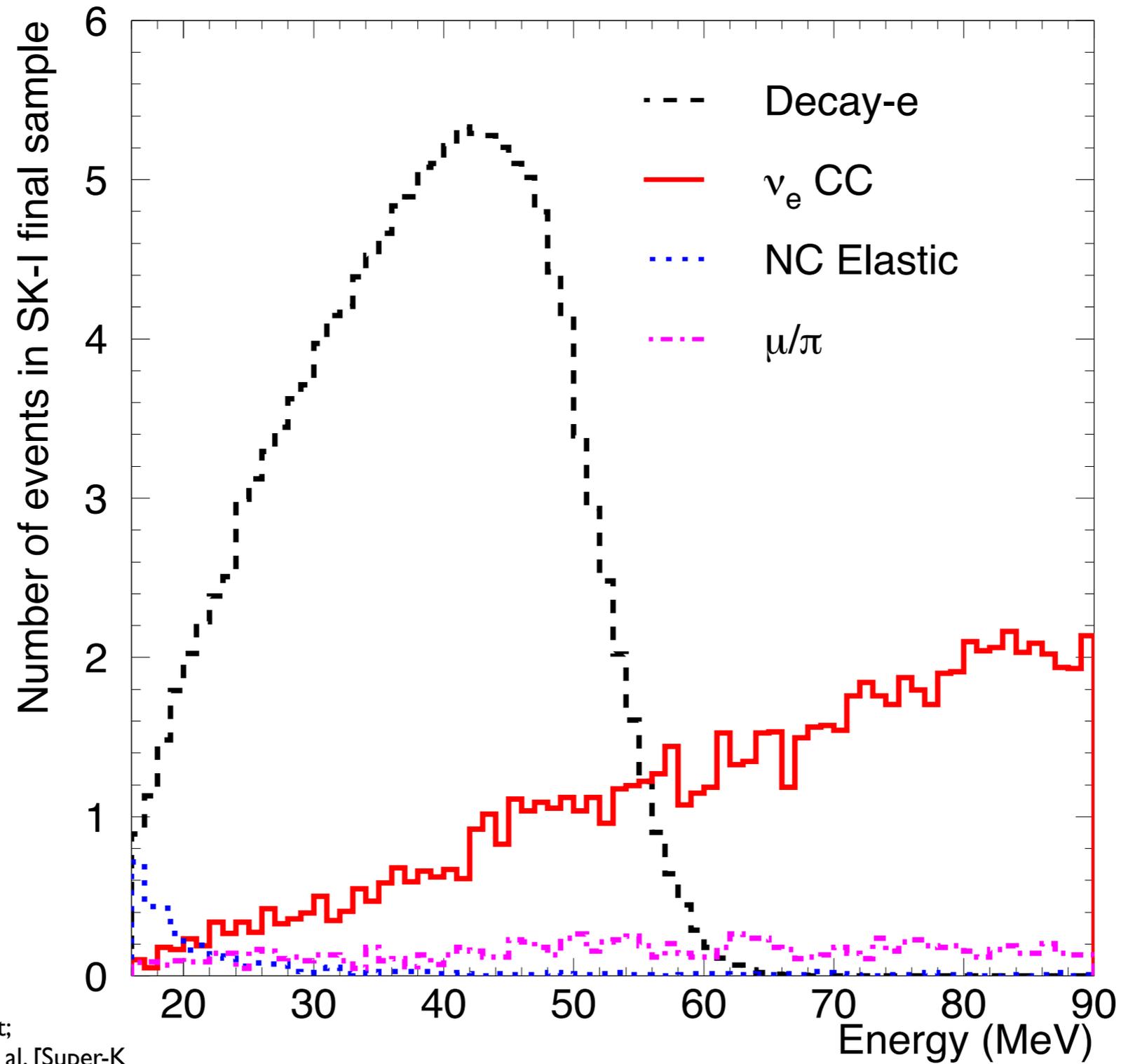
Backgrounds

Figure: C. Rott;
Background data: Bays et al. [Super-K
Collaboration], 2012
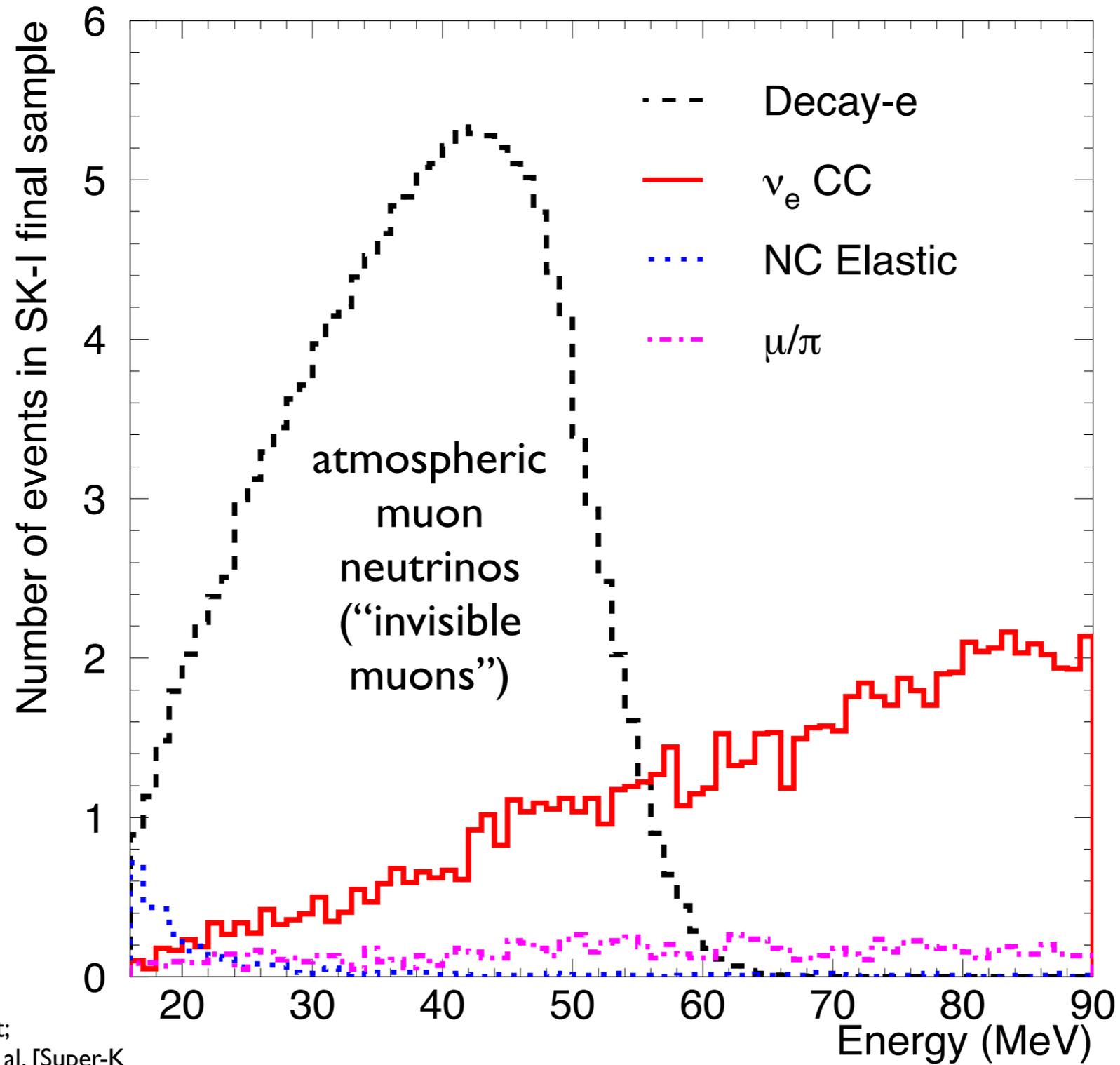
Backgrounds

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Backgrounds

energy range for search for low-E neutrinos from solar WIMP annihilation
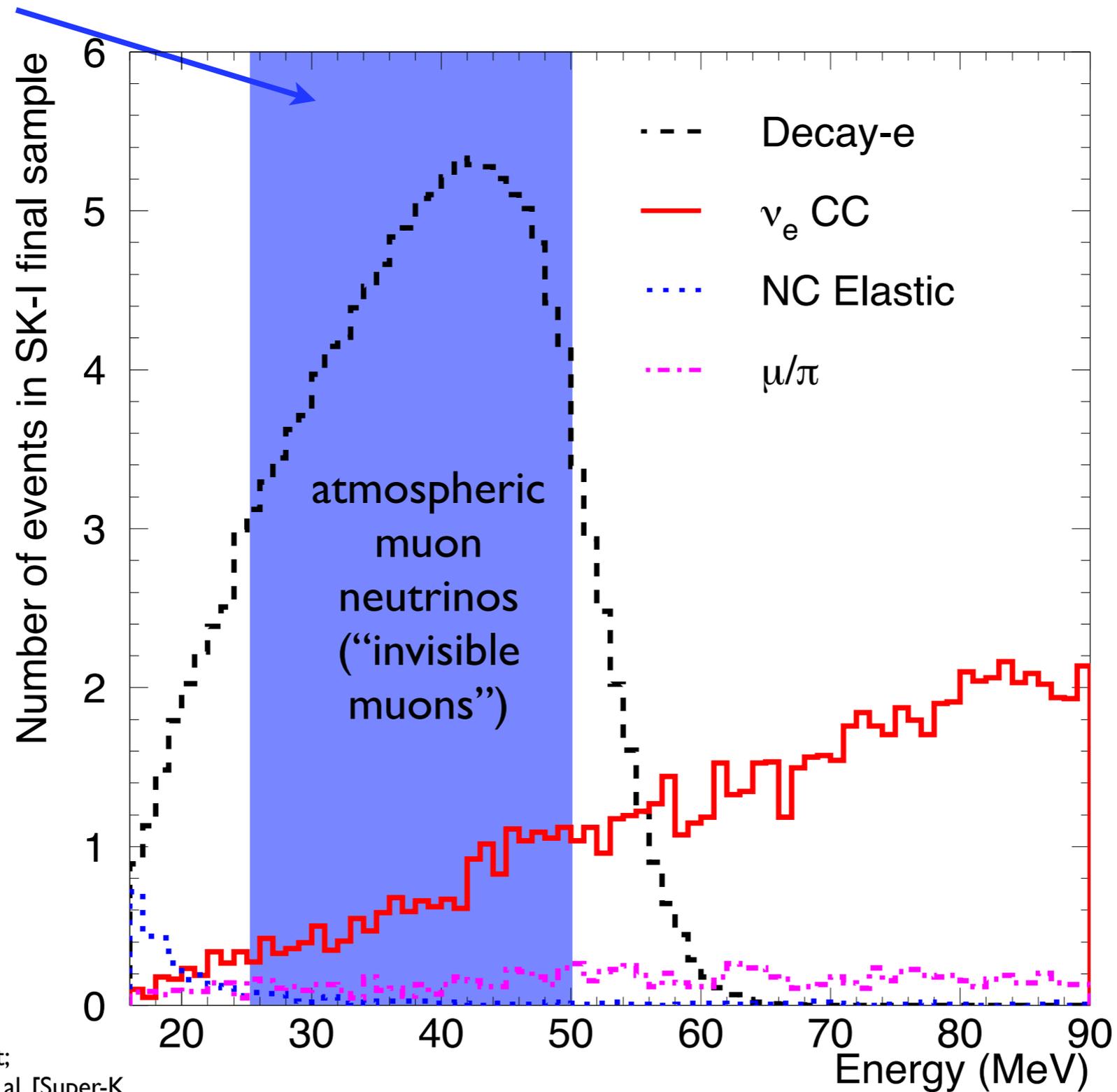
atmospheric muon neutrinos ("invisible muons")

Legend:
- Decay-e
- ν_e CC
- NC Elastic
- μ/π

Y-axis: Number of events in SK-I final sample
X-axis: Energy (MeV)

Figure: C. Rott;
Background data: Bays et al. [Super-K Collaboration], 2012
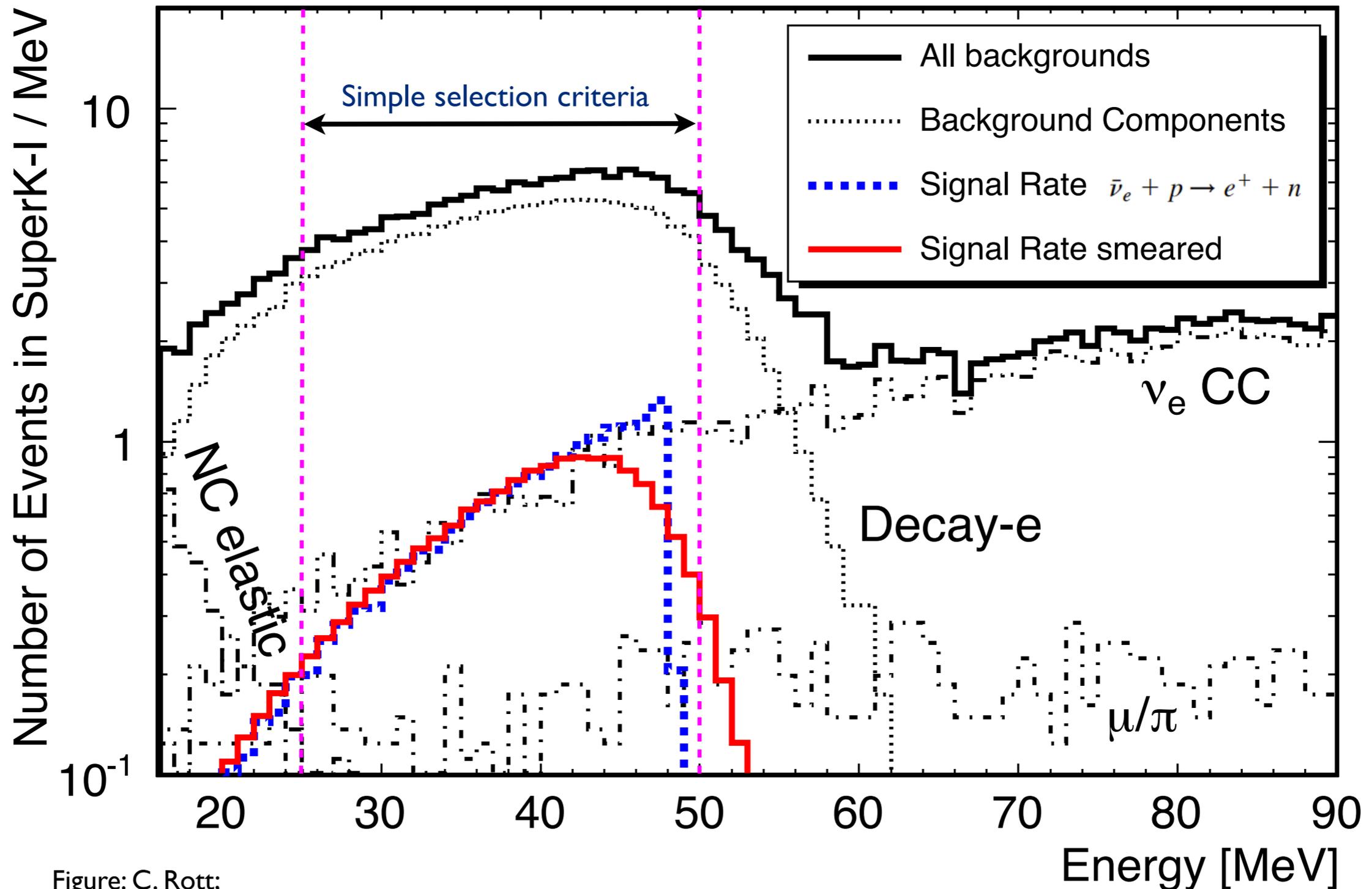
Backgrounds

Figure: C. Rott;
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[Super-K Collaboration], 2012

New sensitivity using low-energy neutrinos

- multiplicity of low-E neutrinos is very large

- backgrounds relatively low at 25-50 MeV

  - most important is "invisible muons"

  - slightly different spectral shape than signal due to signal spectrum being weighted by neutrino interaction cross section

- inverse beta decay has "large" cross section, but little directionality to help reduce backgrounds

- estimate sensitivity by summing background events for SK-1 from 25 to 50 MeV to determine signal amplitude which would reject background-only hypothesis at 90% CL

Signal and background spectra
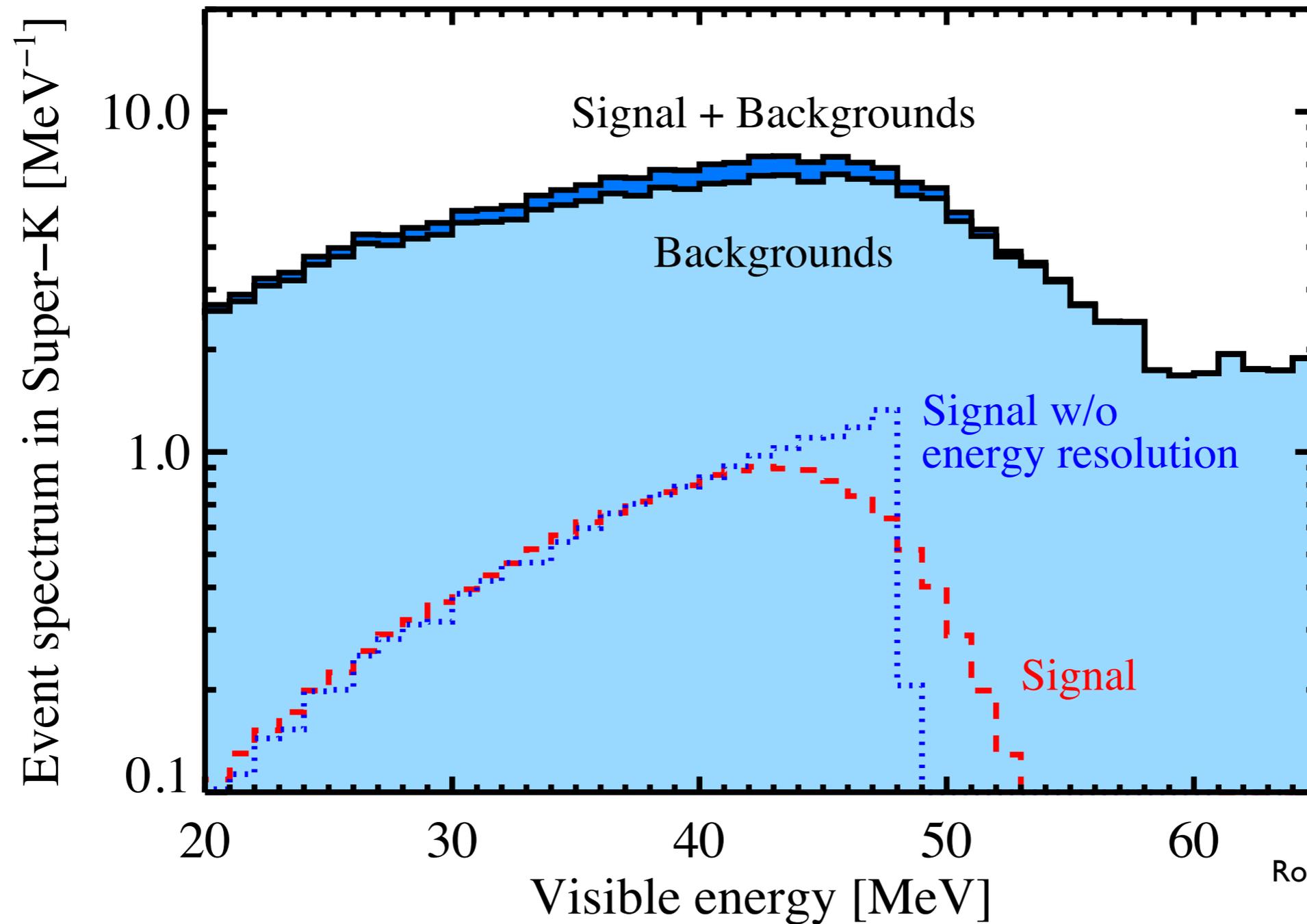
New sensitivity from low-energy neutrinos

- 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
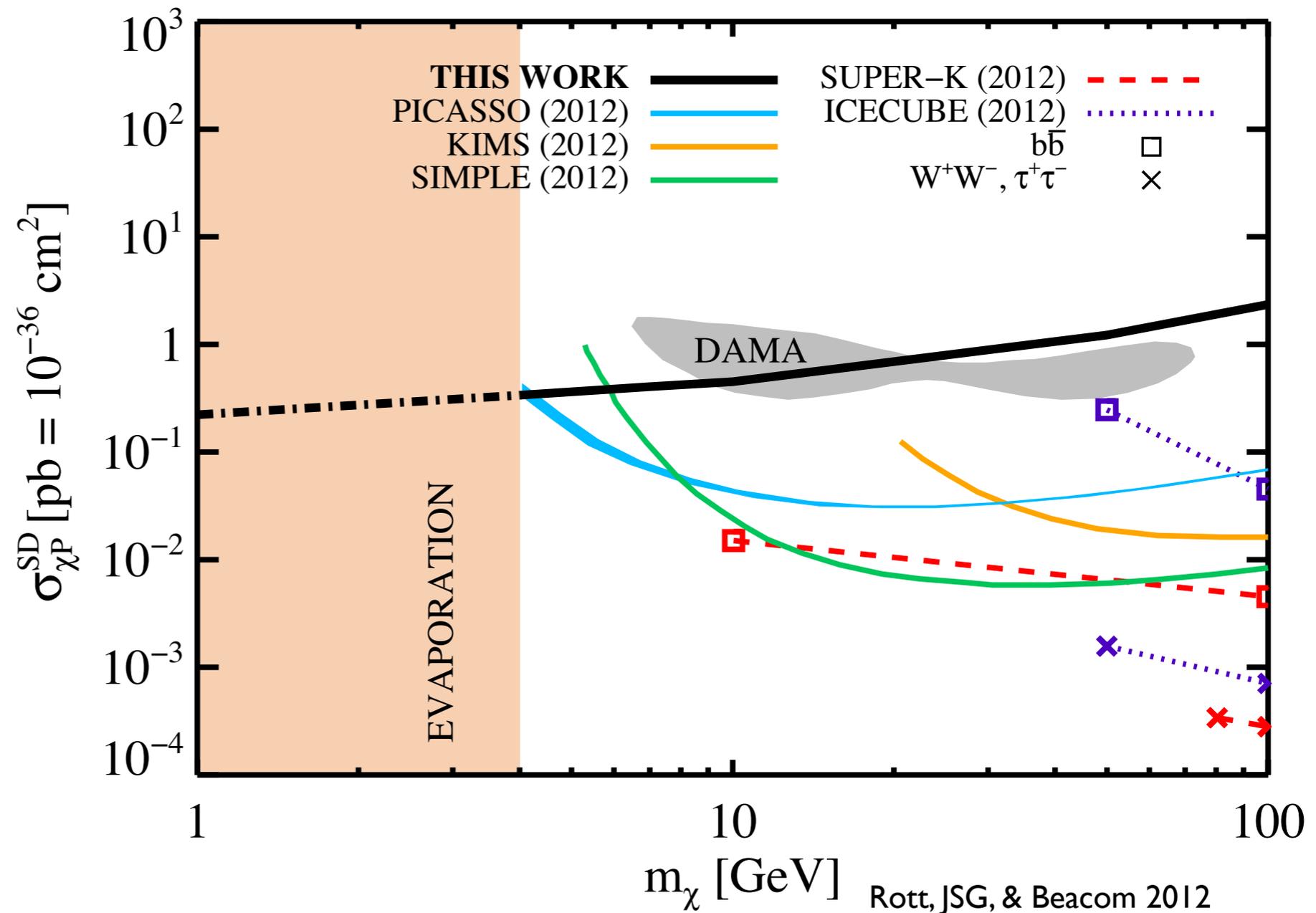
Rott, JSG, & Beacom 2012

Next generation: Hyper-K

- scaling up Super-K (Abe et al. 2011)

- factor of 25 larger fiducial volume

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Rott, JSG, & Beacom 2012

Improving the sensitivity with Gadolinium

- decay electron events are the dominant background

- identifying the neutron in inverse beta decay can discriminate between the signal and the decay electron background

- proposal to add dissolved Gadolinium to Super-K (Beacom and Vagins, 2004)

- neutron capture by Gd emits a 8 MeV photon cascade after a characteristic time

- can reduce background by applying a coincidence cut

Rott, JSG, & Beacom 2012

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Rott, JSG, & Beacom 2012

Summary: low-E neutrinos

- a new channel for indirect detection of WIMP annihilation in the Sun is proposed: low-energy neutrinos

- low-energy neutrinos (up to ~ 53 MeV) result from final states with hadronic content

- low-energy neutrino signal spectrum insensitive to annihilation channel

- provides new sensitivity using neutrinos to final states with minimal high-energy neutrino content but which generate low-energy neutrinos

- eventual observation of both low- and high-energy neutrino signals could help to determine the branching ratios to different final states

- low-mass WIMP scenarios can be tested with neutrino searches

- complementary to direct searches

Constraints on
Sterile Neutrino Dark Matter from the
Fermi Gamma-ray Burst Monitor

in collaboration with

### Kenny Chun Yu Ng
(Ohio State University)

Shunsaku Horiuchi
(UC Irvine)

Rob Preece
(University of Alabama)

Miles Smith
(Penn State)

Indirect searches for sterile neutrinos

- sterile neutrinos can radiatively decay to active neutrinos, producing a photon line signal at half the sterile neutrino mass

- X-ray telescopes can search for spectral lines from keV neutrinos

- (model-dependent) constraints also obtained from Lyman alpha measurements (probing clustering in the early universe) and the dark matter abundance

- a window of parameter space remains...
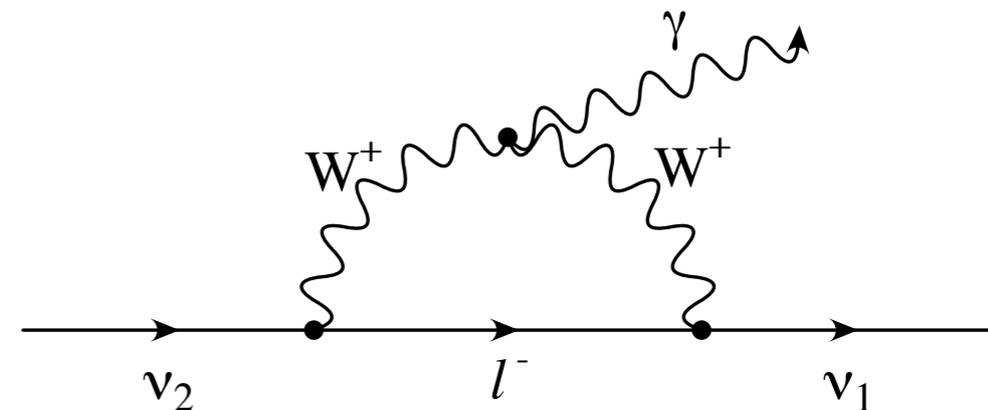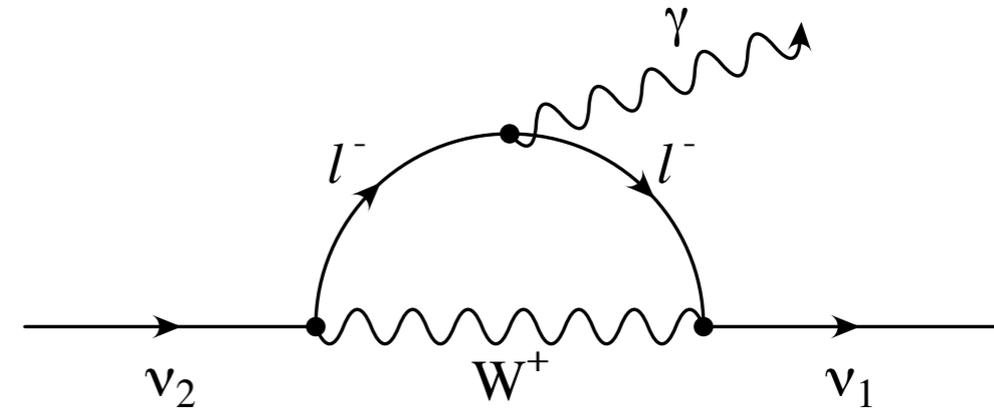
Abazajian, Fuller, & Tucker 2001

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DM abundance: Boyarsky et al. 2009; Lyman alpha: Seljak et al. 2006; INTEGRAL X-ray: Yuksel et al. 2008; MW (HEAO-1): Boyarsky et al. 2006; Ursa Minor X-ray: Loewenstein et al. 2009

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The Fermi Gamma-ray Space Telescope

Credit: NASA/General Dynamics

The Gamma-ray Burst Monitor (GBM)

- 12 sodium iodide (NaI) detectors (8 - 1000 keV, in 128 energy bins)

- 2 bismuth germanate (BGO) detectors (150 keV - 40 MeV)

- GBM observes the entire unocculted sky
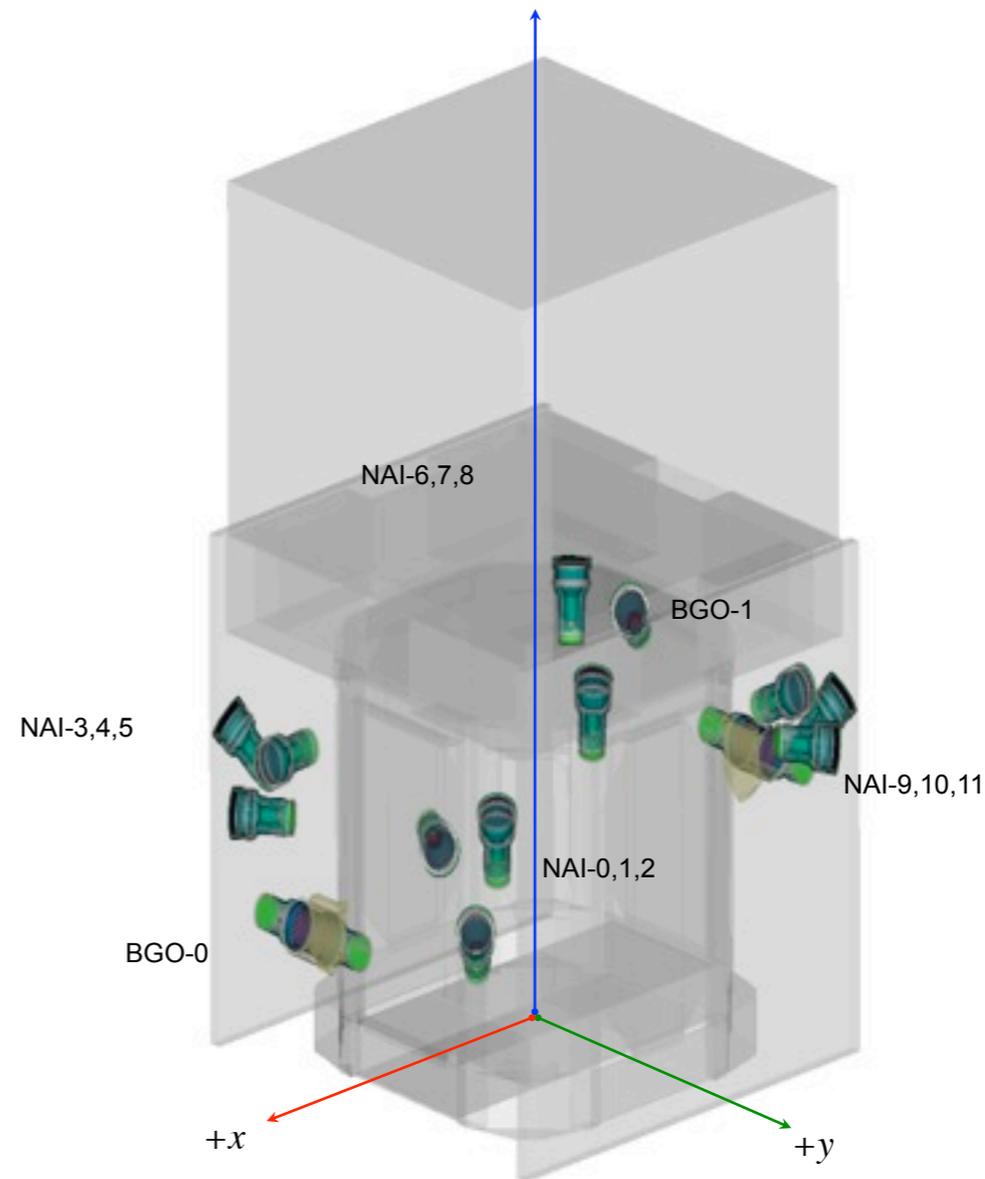
The X-ray sky as seen by ROSAT

c) 1.5 keV (R67)
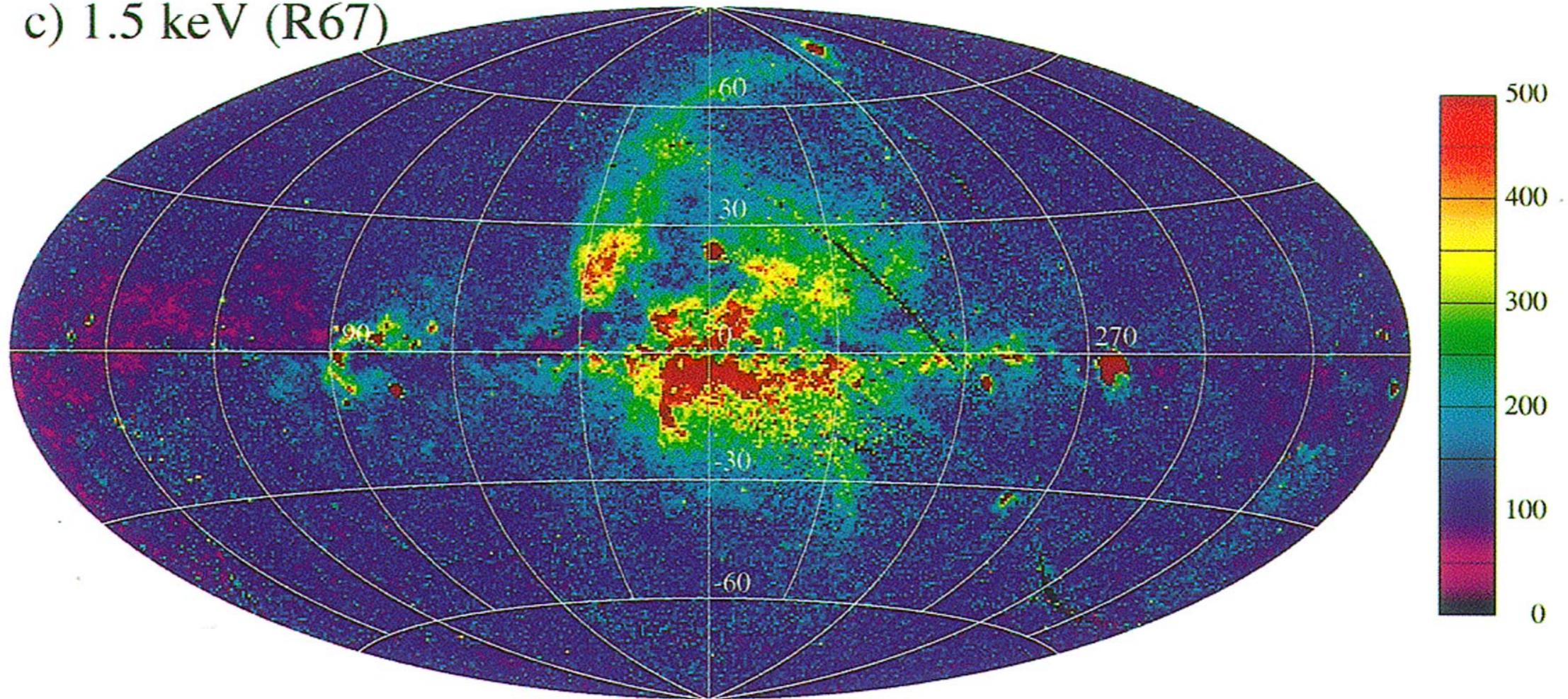
Image Credit: Snowden et al. 1997

The X-ray sky as seen by GBM

GBM count rate in detector pointing direction
(10 keV < E < 20 keV, NaI detector 0, Galactic coordinates)

NB: not a flux map

2.3 ▬▬▬▬▬▬▬▬ 2.6 Log (Count rate [s⁻¹])
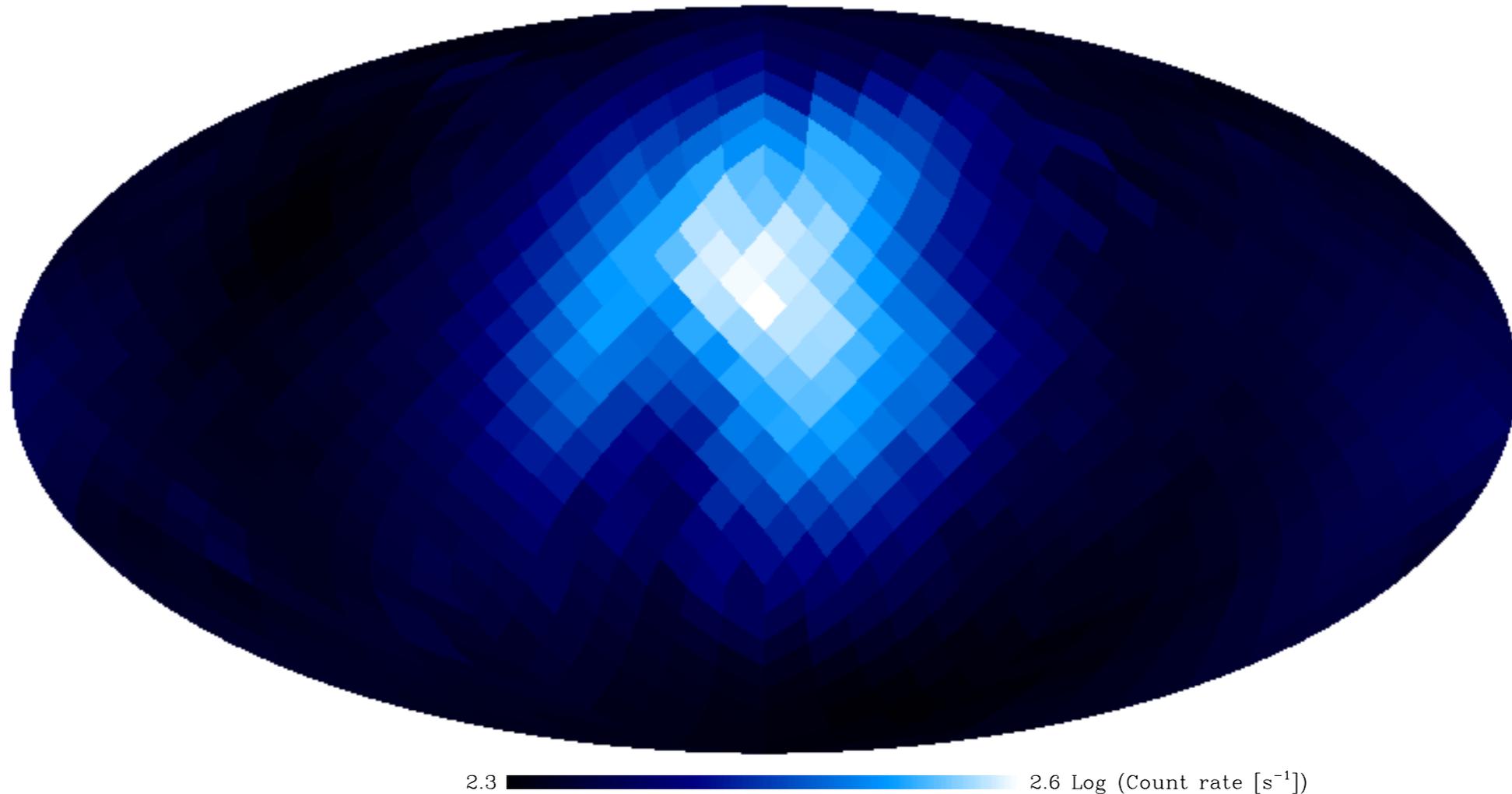
(excluding data time intervals with GRBs, transients, SAA)

Bulk counting analysis

Count rate spectrum

- require that the dark matter signal doesn't exceed the total measured count rate in the energy bin of the line, in the selected ROI

- most robust / conservative limits

ROI = 30 deg around GC

20 keV line
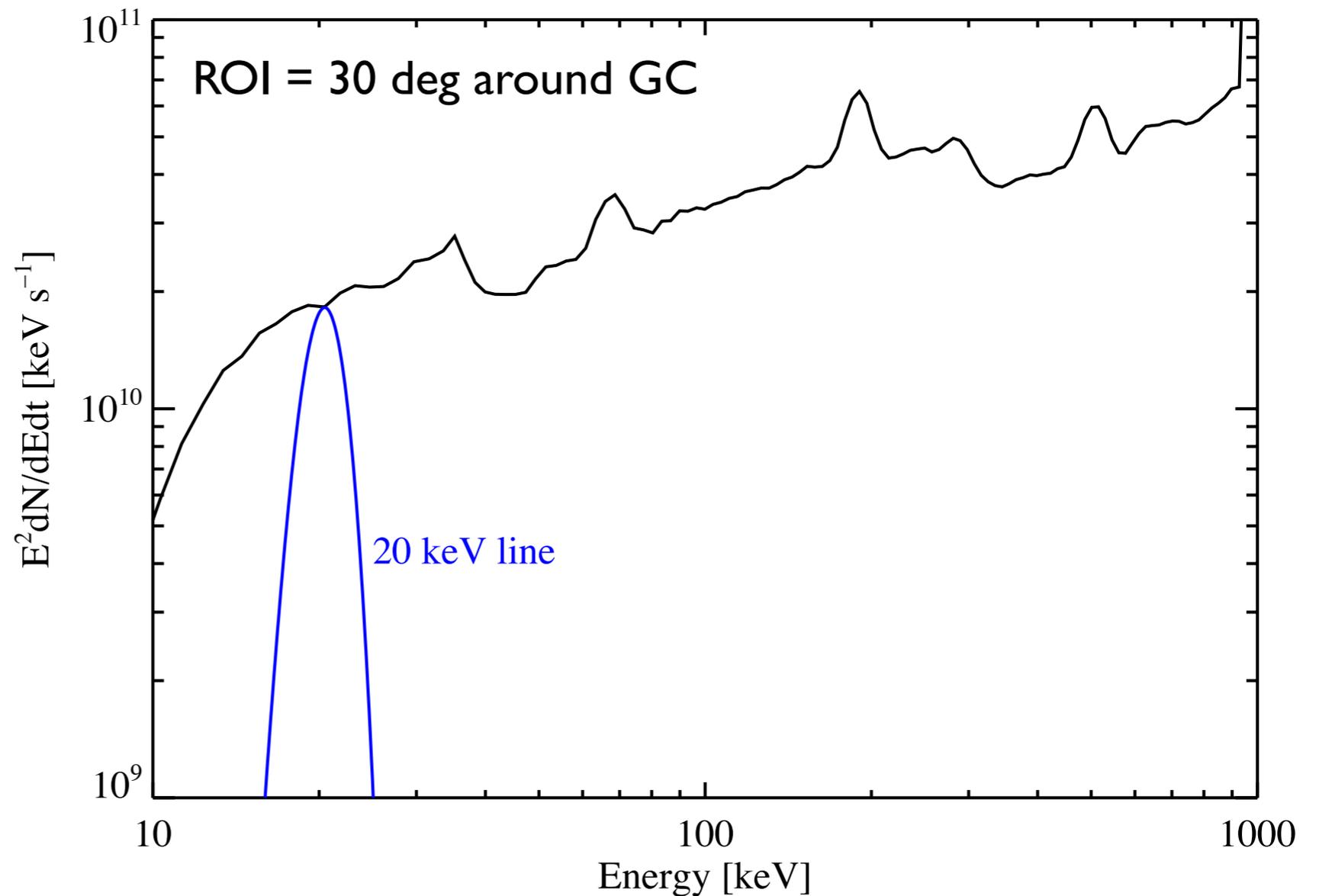
# Bulk counting analysis limits

30 deg ROI
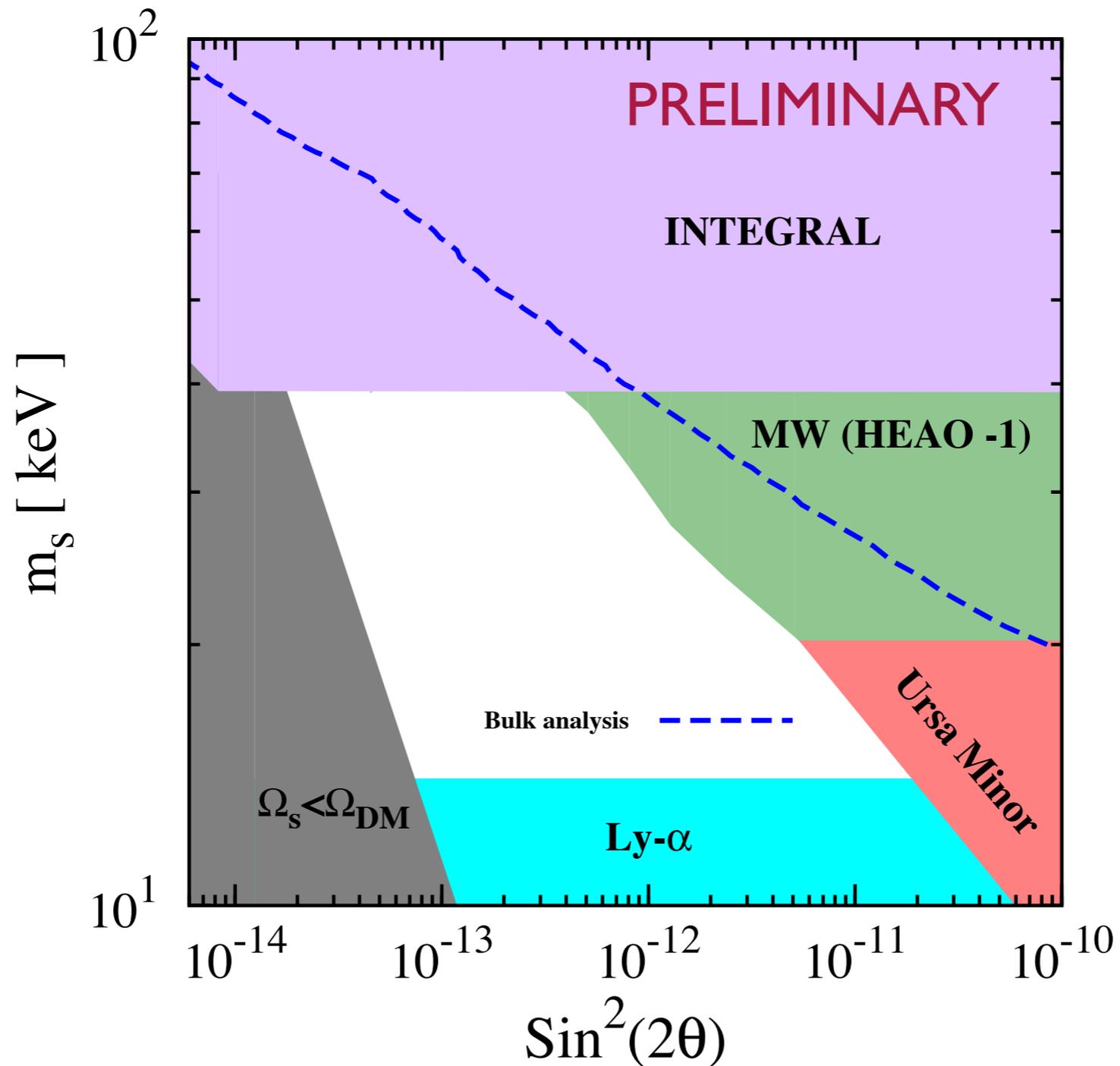
Spectral analysis

Energy windows

- model spectrum as line signal (at fixed energy) + power law

- model parameters are the signal and background normalizations and the power-law index

- choose a window around each line energy (larger than observed line signal width)

- approximate GBM energy response as a Gaussian
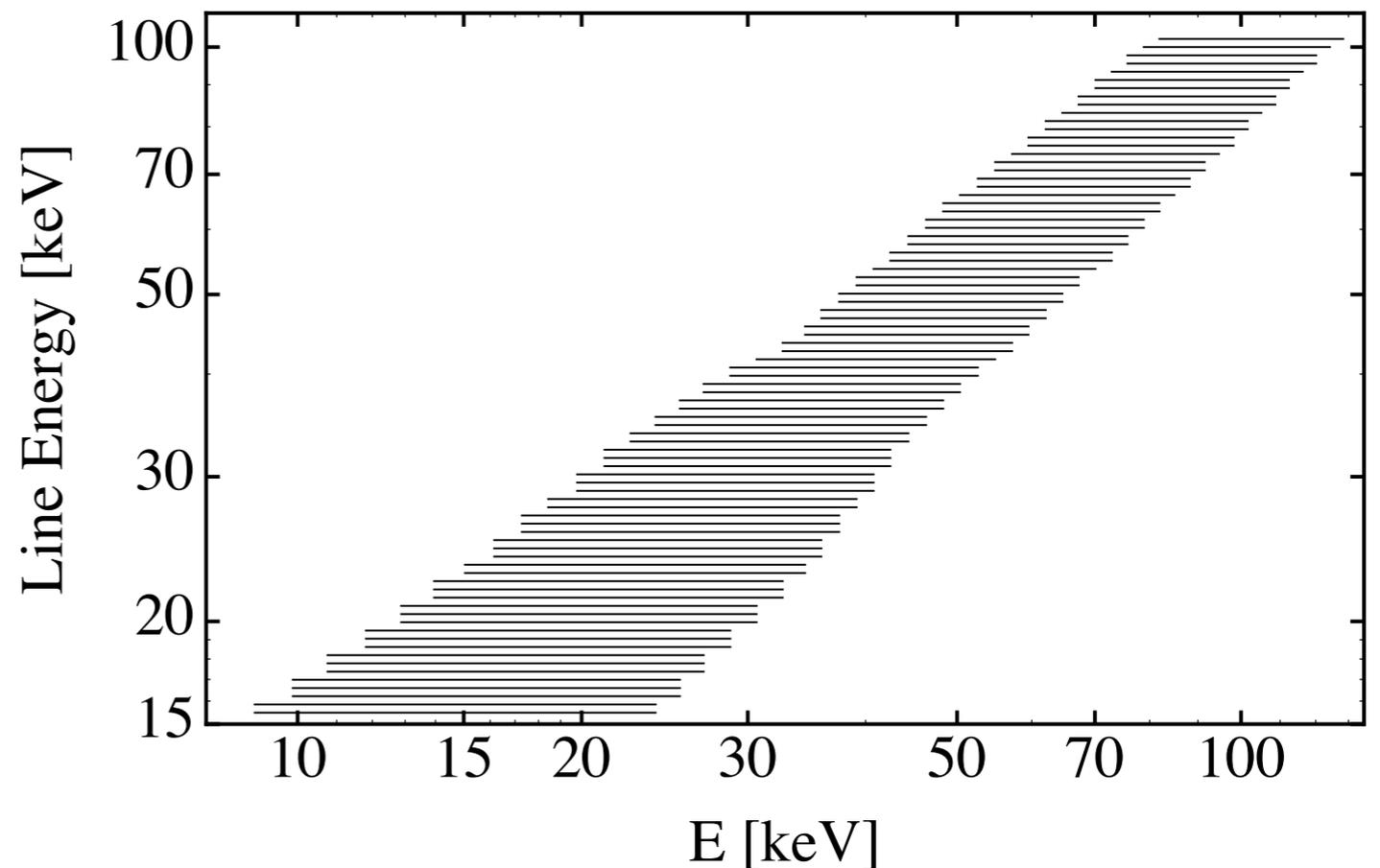

window = ± 6 energy bins around bin of line energy

Spectral analysis limits
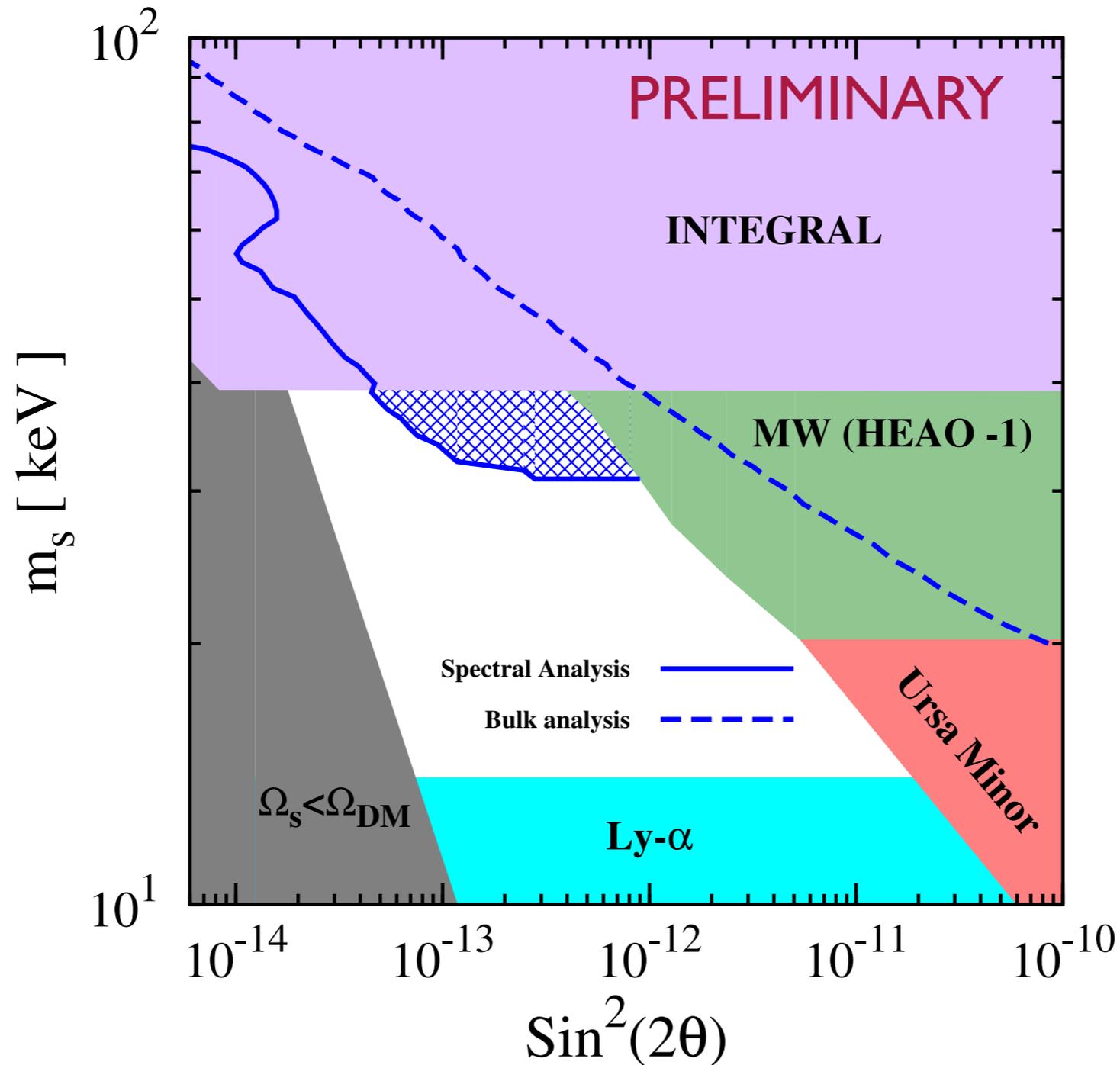
30 deg ROI

Spectral analysis limits

30 deg ROI
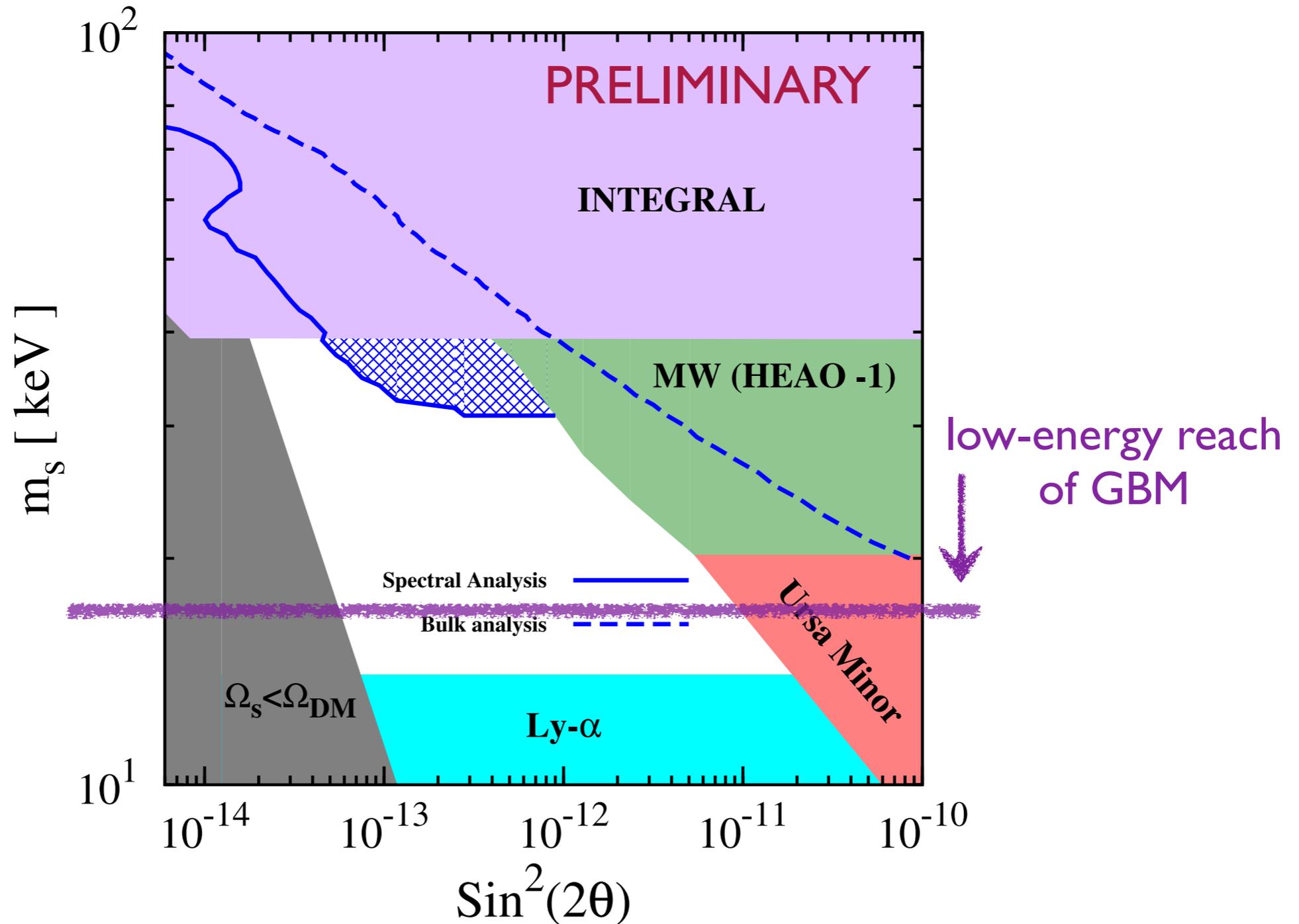
Summary: sterile neutrino line search

- tools to use angular information in GBM data have been developed and applied in the context of a search for lines from sterile neutrino dark matter

- preliminary constraints from GBM data exclude new regions of sterile neutrino dark matter parameter space