Neutrino Source Searches with Likelihood Landscapes

Neutrino Source Searches

- Hypothesis H0: background only flux
  - Atmospheric neutrino's
  - (Misreconstructed) Atmospheric Muons
- Hypothesis H1: background + signal flux
  - (High energy) Cosmic Neutrinos

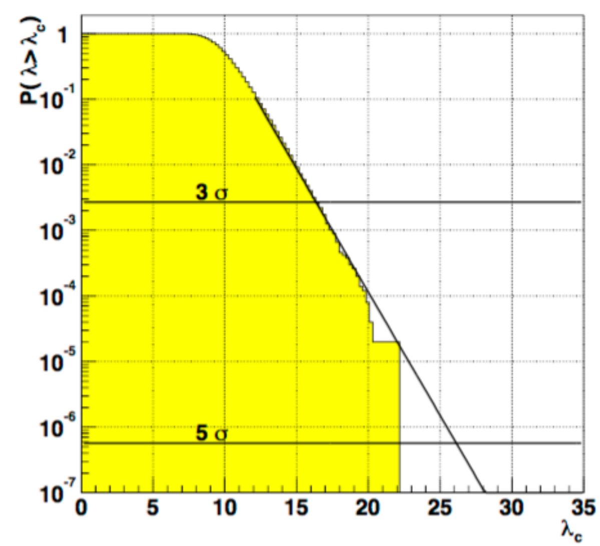
General Procedure

- How compatible is data with H0 or H1?

$$\lambda = \log\left[\frac{P(\mathrm{data}|H_1)}{P(\mathrm{data}|H_0)}\right]$$

- When to claim an observation?
  - Accept H1 if $\lambda > \lambda_c$
  - λ_c such that

    P(accept H1 | H0 = true) < 0.00…1



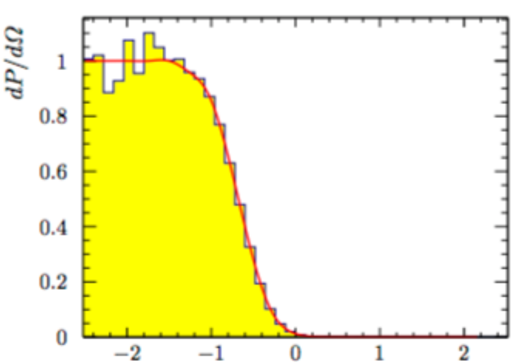
$$\lambda = \log\left[\frac{P(\text{data}|H_1)}{P(\text{data}|H_0)}\right]$$

Test Statistic (Conventional)

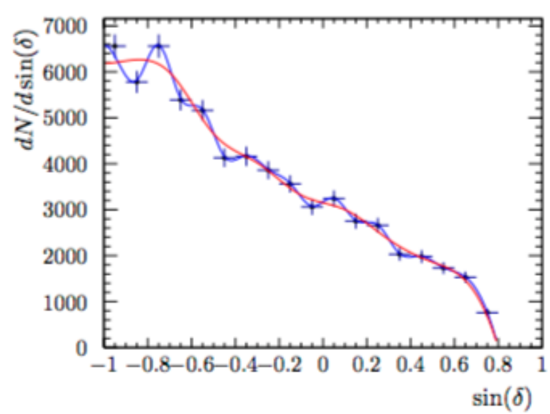
- Given detected (and selected) events $\{ev_i\}$

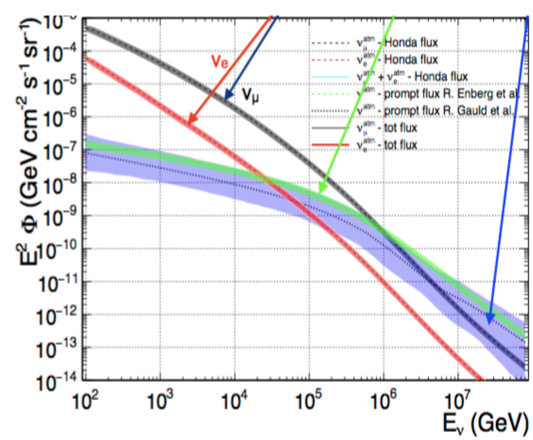
$$P(data|H) = \sum_i \left[\log \int P(x_{reco,i}|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true} \mid H)\, dx_{true}\right] - \mu^{tot}(H)$$

Reconstruction — Detection efficiency — Expected flux



log(angle reco,true)





$$\lambda = \log\left[\frac{P(\text{data}|H_1)}{P(\text{data}|H_0)}\right]$$

Test Statistic

- Given detected (and selected) events $\{ev_i\}$

$$P(data|H) = \sum_i \left[\log \int \underbrace{P(x_{reco,i}|\, x_{true})}_{\text{Reconstruction}} \cdot \underbrace{P^{det}(x_{true})}_{\text{Detection efficiency}} \cdot \underbrace{\mu(x_{true}\,|\,H)}_{\text{Expected flux}}\, dx_{true}\right] - \mu^{tot}(H)$$

- New method:

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\,|\,H)\, dx_{true}\right] - \mu^{tot}(H)$$

- No big deal?

New vs. Conventional

Conventional

- Only best solution kept from reconstruction
- Selection criteria needed to select well-reconstructed events -> events are lost

- Different reconstruction algorithms (showers/tracks/tau double bang) patched together
- Event identification by BDT's and other black magic algorithms

- Parameterizations of MC events
- Fast

New Method

- Detailed knowledge of event likelihood landscape
- All events can be used

- Single 'reconstruction' algorithm for all events

- Neutrino flavour identification automatically taken into account

- Event-by-event
- Probably slow

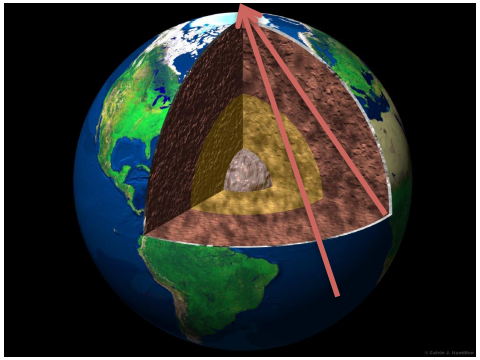
Likelihood Ingredients

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\ |\, H)\, dx_{true}\right] - \mu^{tot}(H)$$

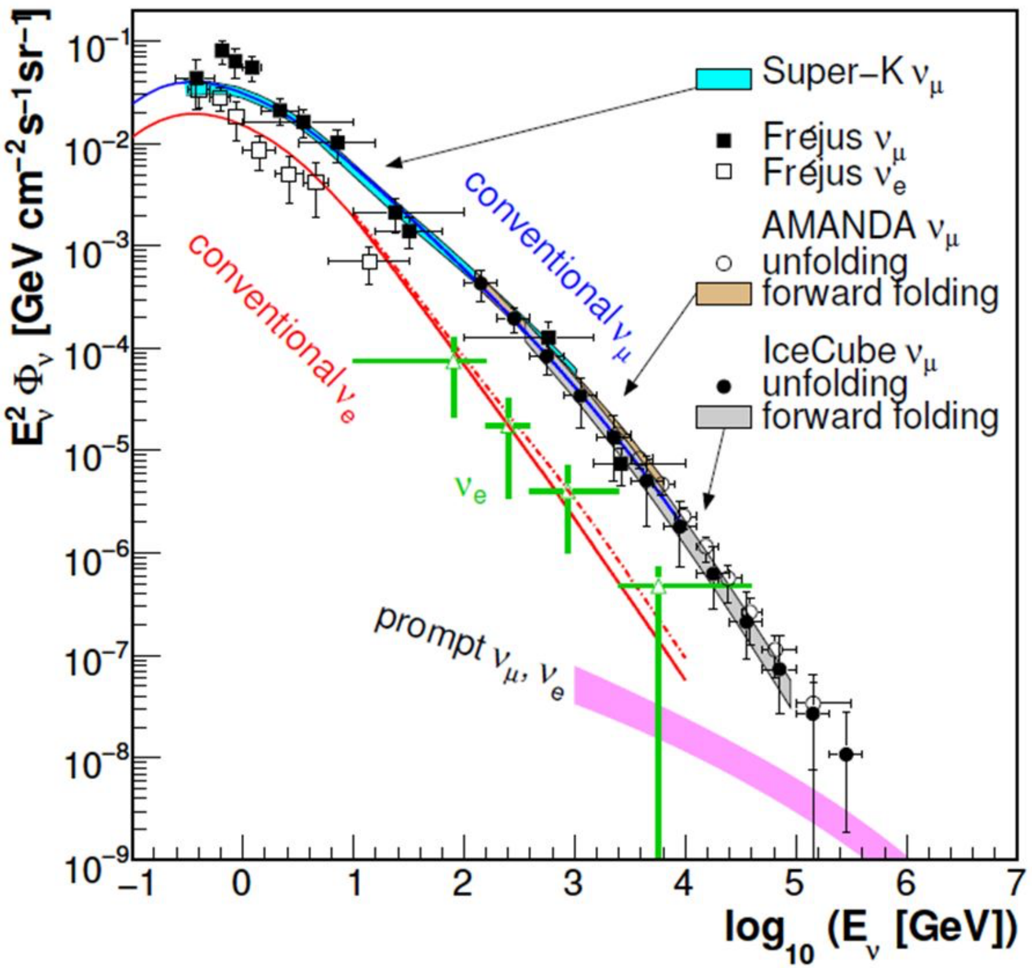
$\mu(x_{true}\ |\, H)$ Number of expected background or signal events in our detector (can)

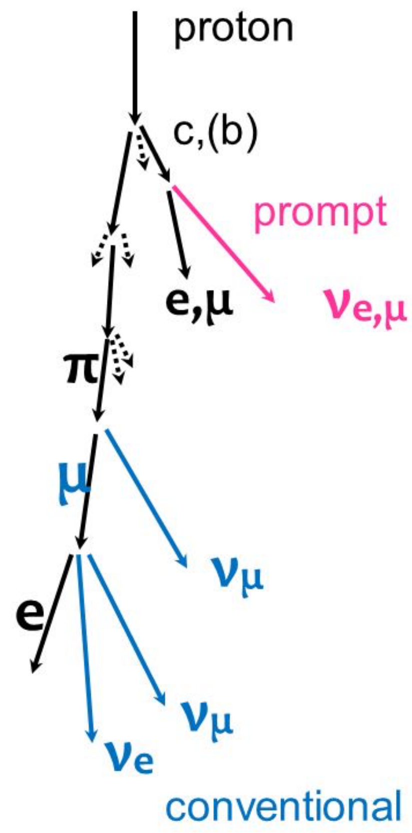
$P^{det}(x_{true})$

$P(ev_i|\, x_{true})$



Atmospheric Neutrinos

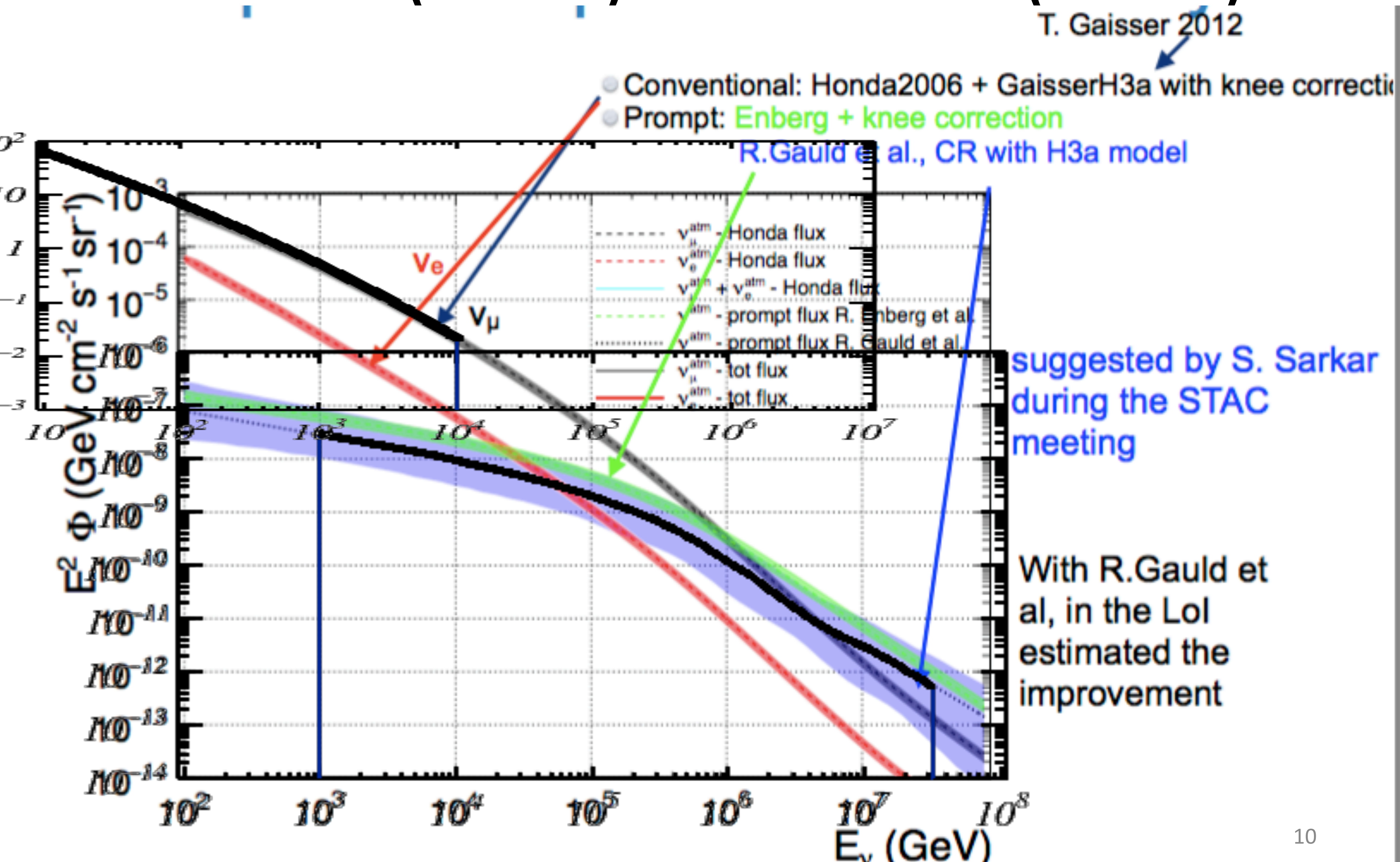




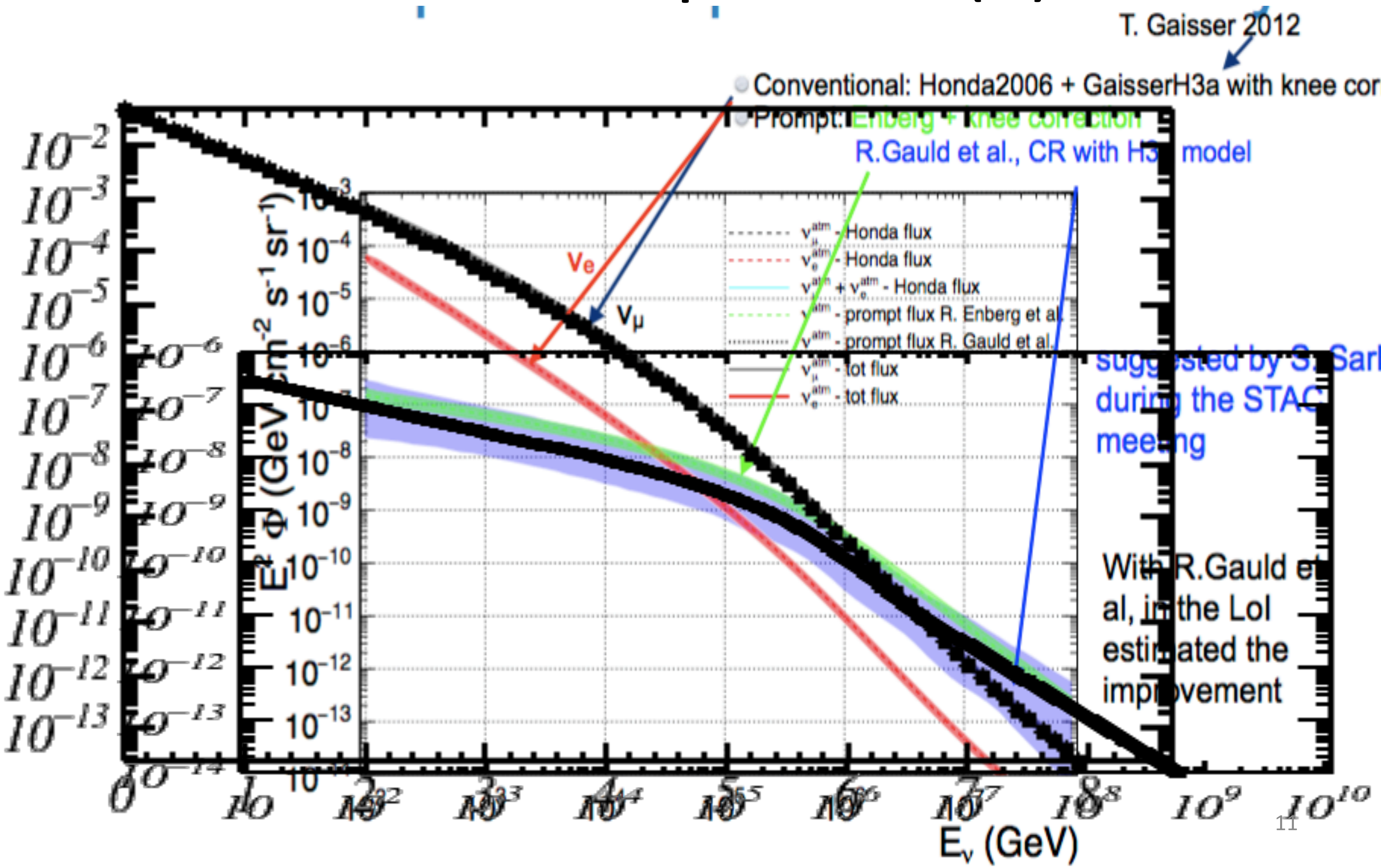
Current Parameterization

- KM3NeT Letter of Intent
- Based on Seatray
- Polynomial fit of Honda tables
  - Extrapolation to higher energy ranges
  - Outdated? Honda 2006 used.
  - Gaisser H3a knee correction
- Polynomial fit of Gauld tables 2015
  - From PromptNuFlux, L. Rottoli

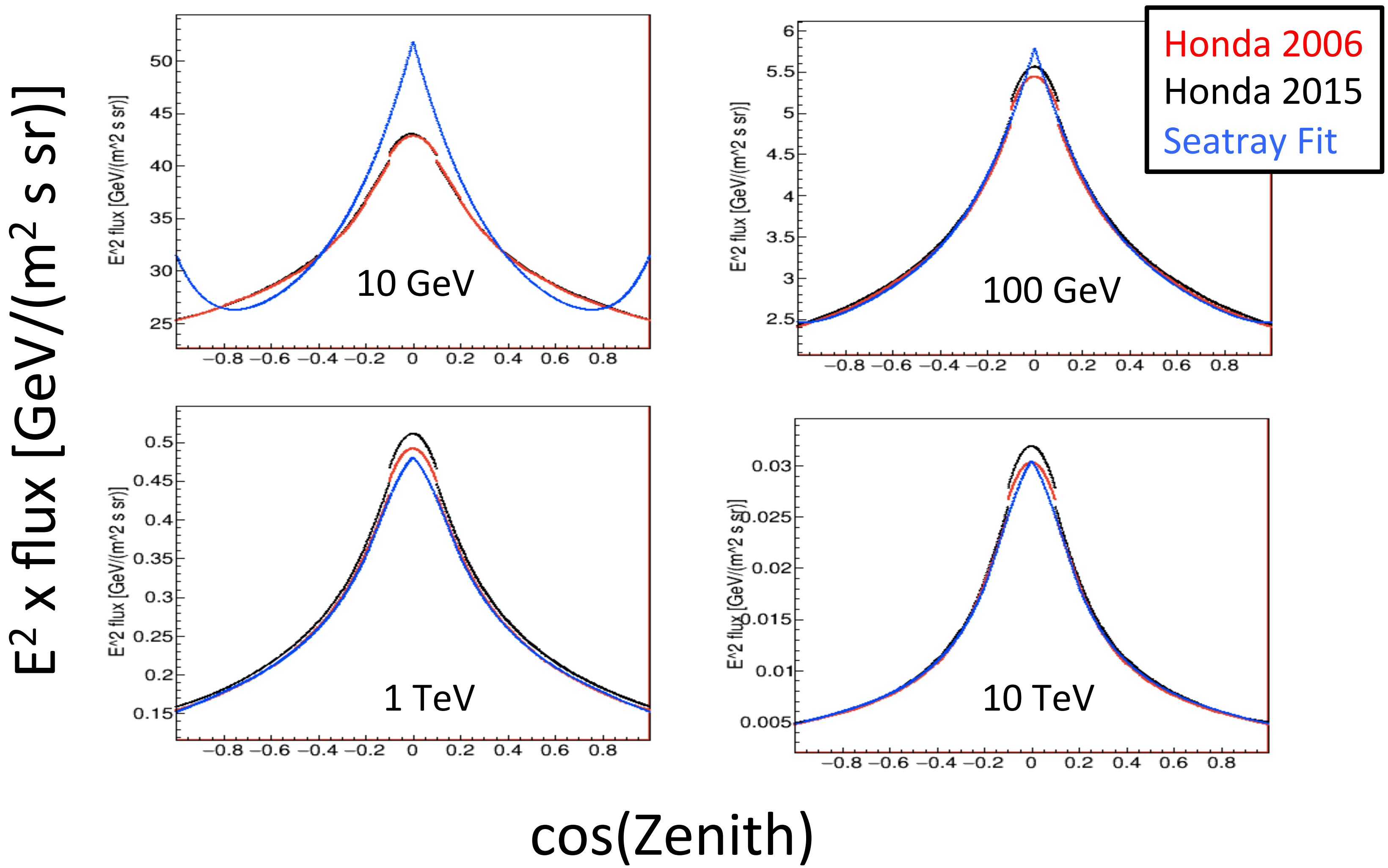
Honda (2006) and Gauld (2016)



Both Extrapolated (2)



Honda: Zenith Dependence



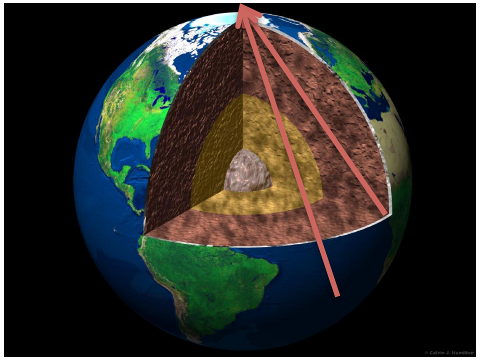
Likelihood Ingredients

$$P(data|H) = \sum_i \left[\log \int P(ev_i |\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true} \mid H)\, dx_{true}\right] - \mu^{tot}(H)$$

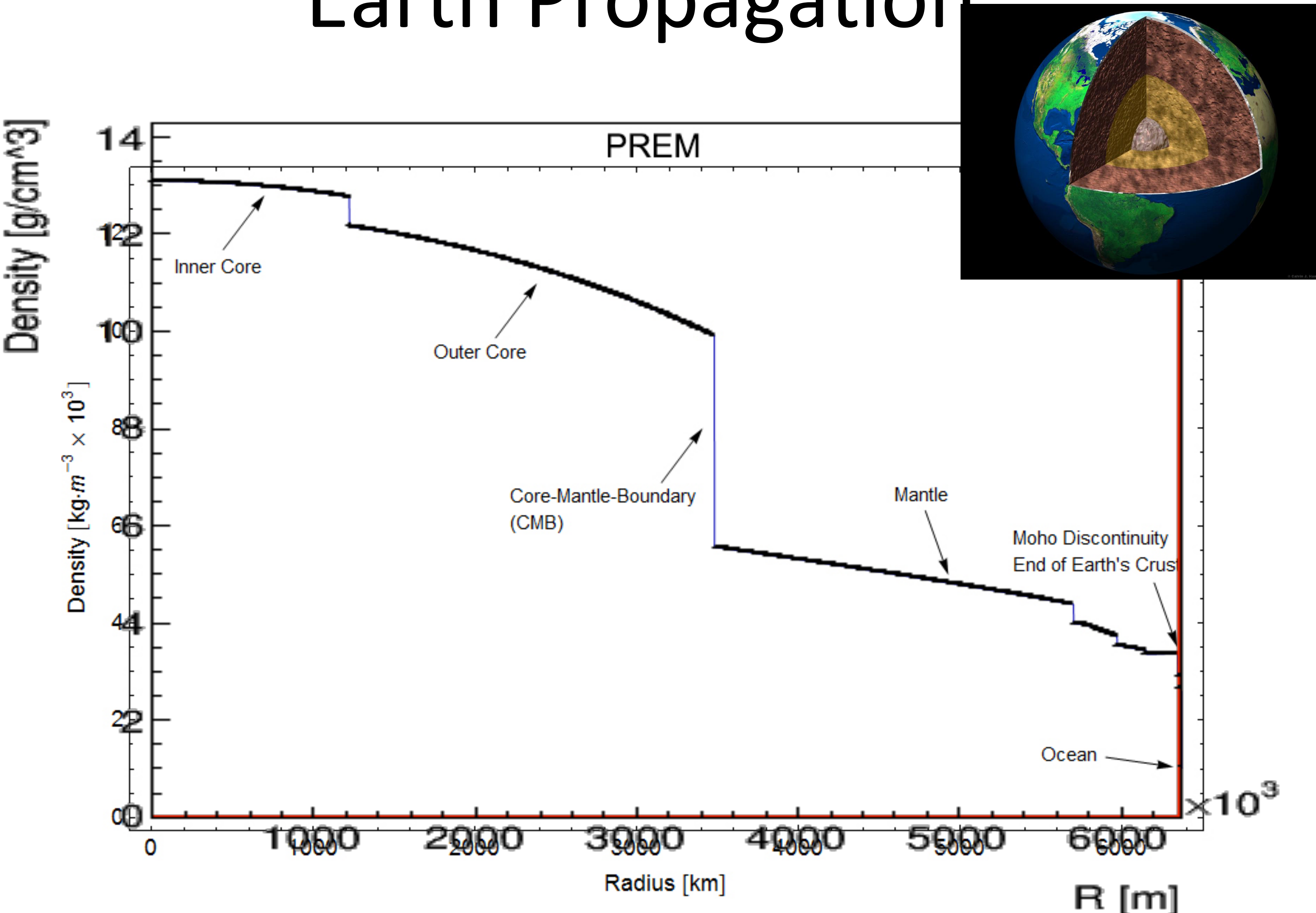
$\mu(x_{true} \mid H)$ Number of expected background or signal events in our detector (can)

$P^{det}(x_{true})$

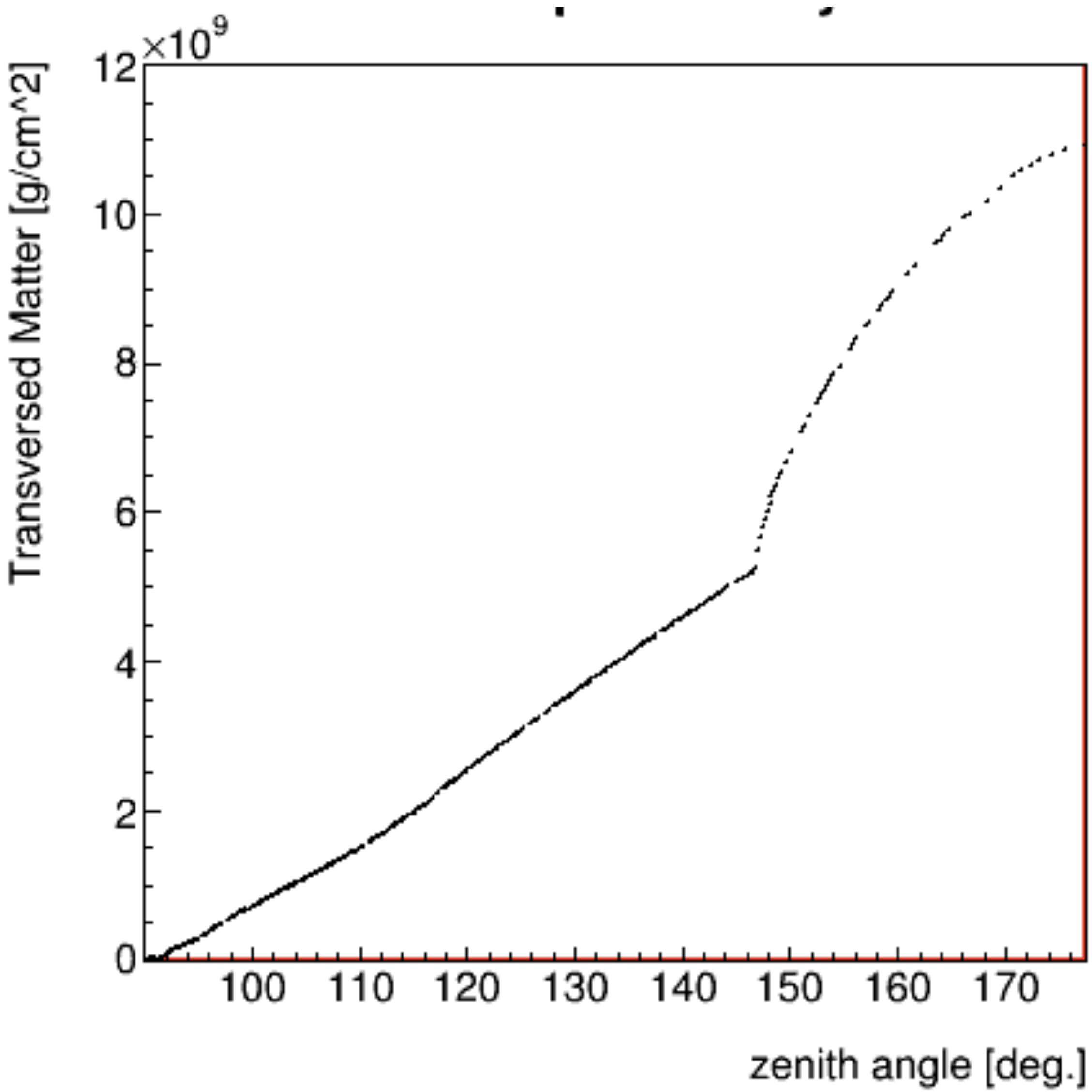
$P(ev_i |\, x_{true})$

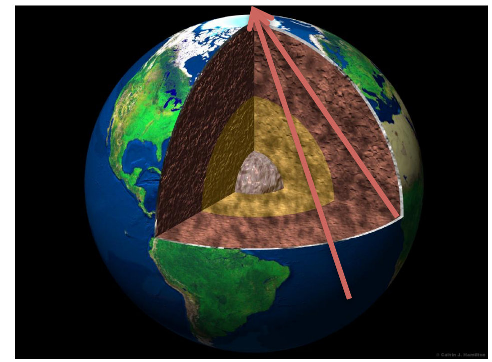


Earth Propagation



Transversed Matter Density

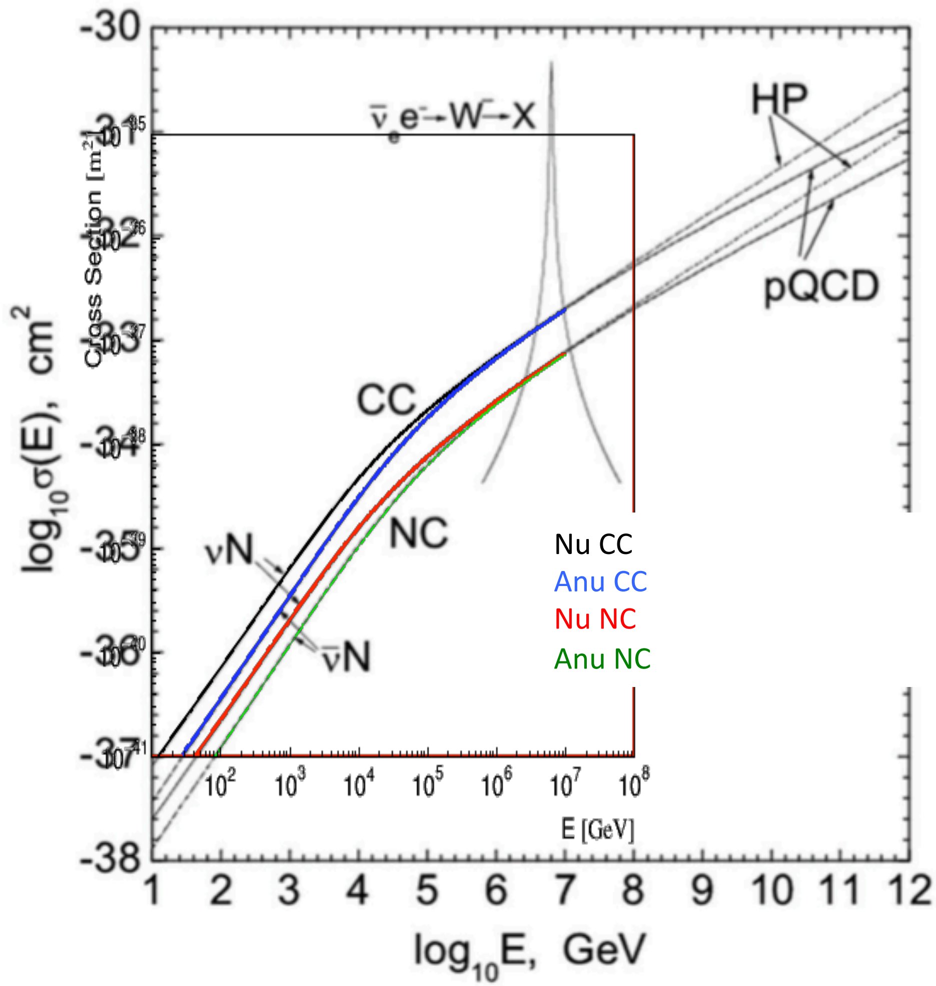




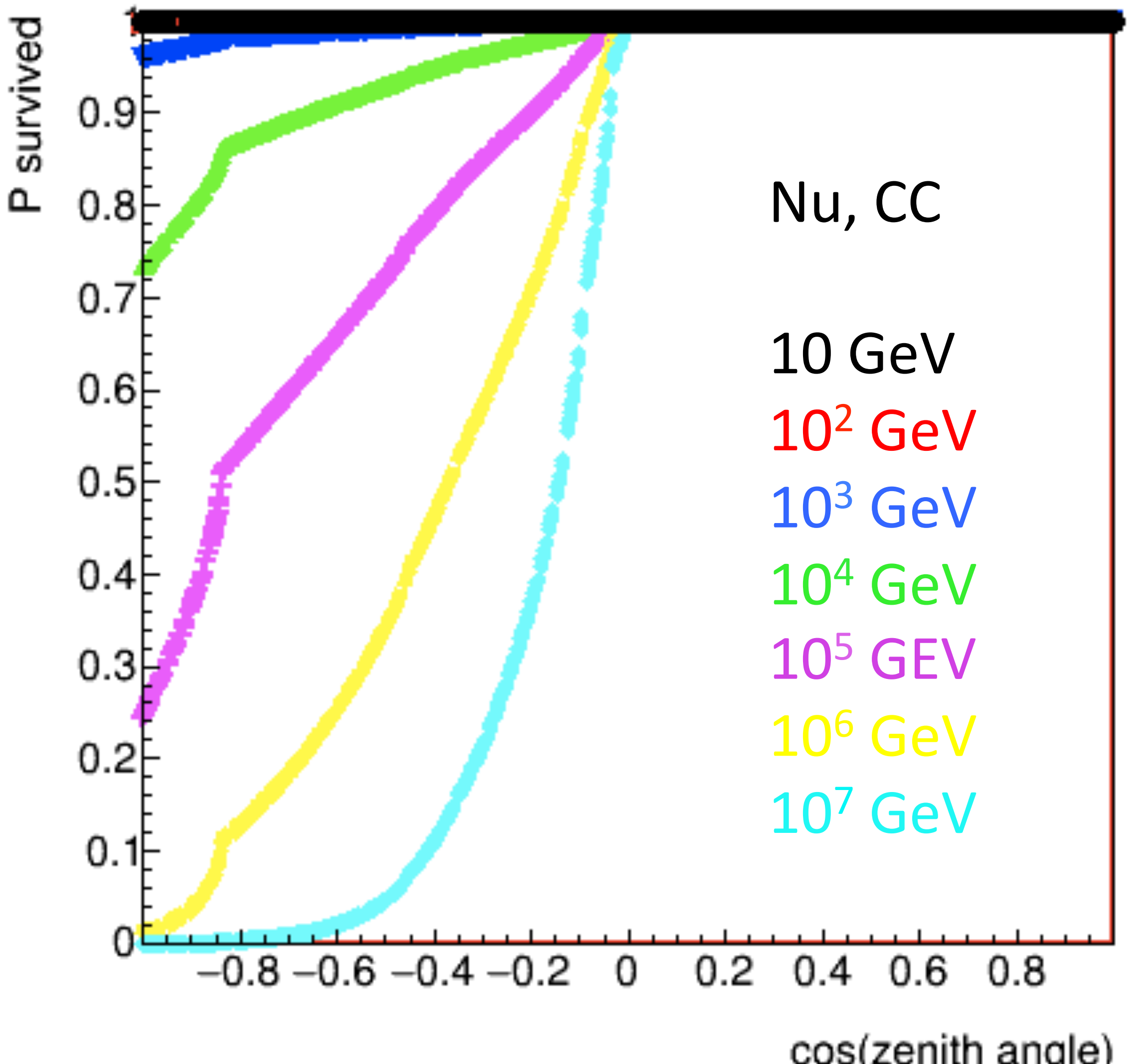
Analytically derived -> very fast

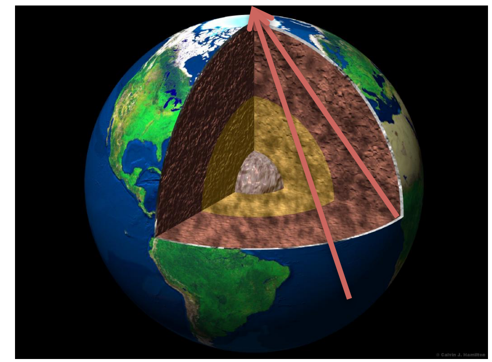
ANIS, Kowalski 2003
Figure from Colnard 2009

Neutrino Cross Sections

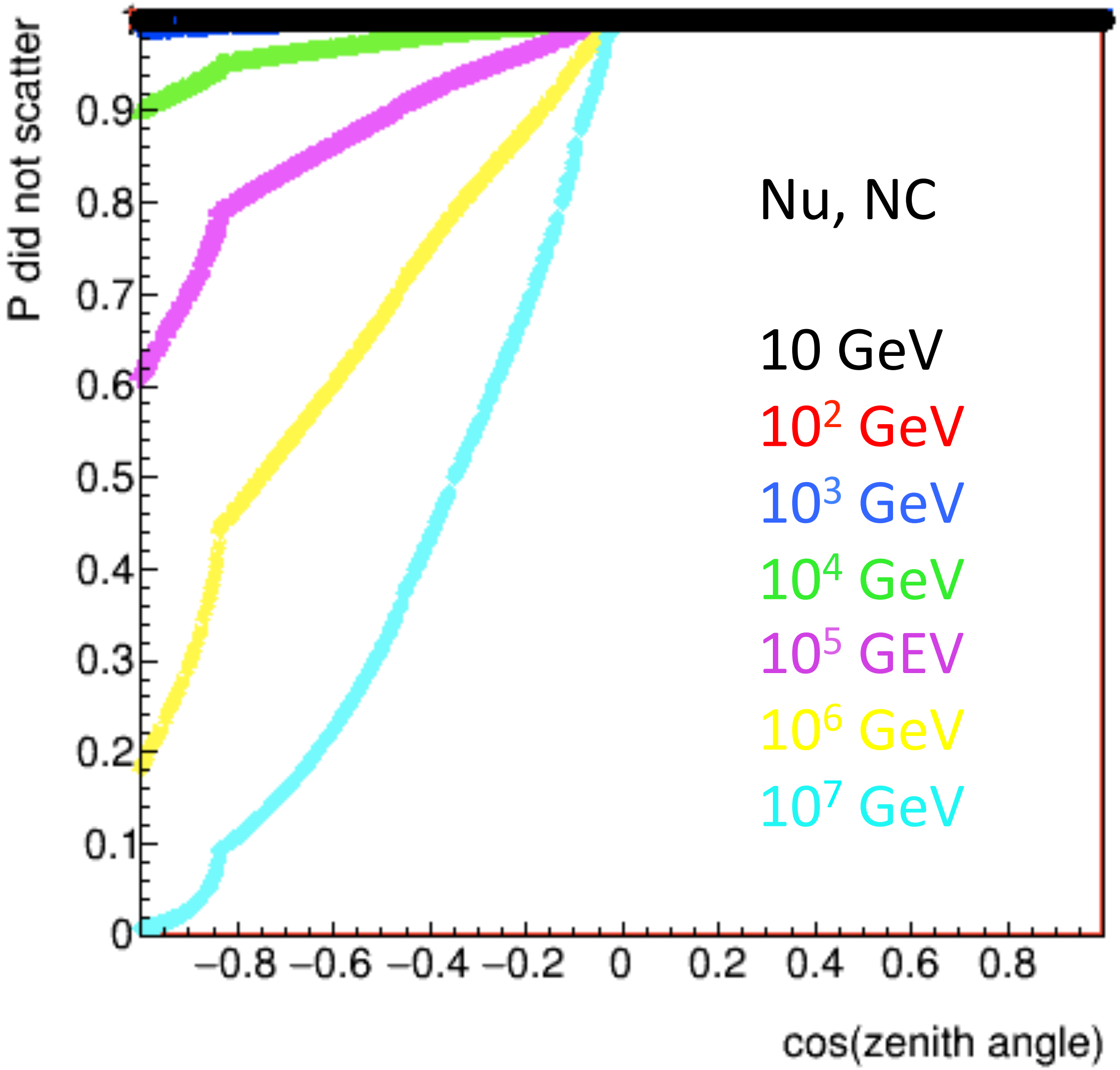


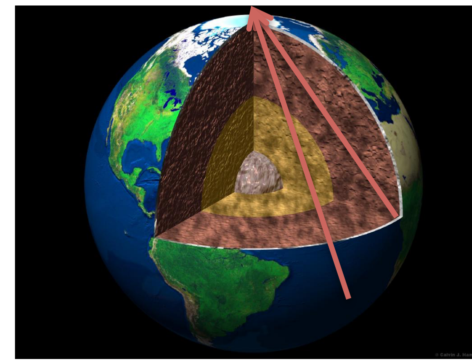
Neutrino Absorption



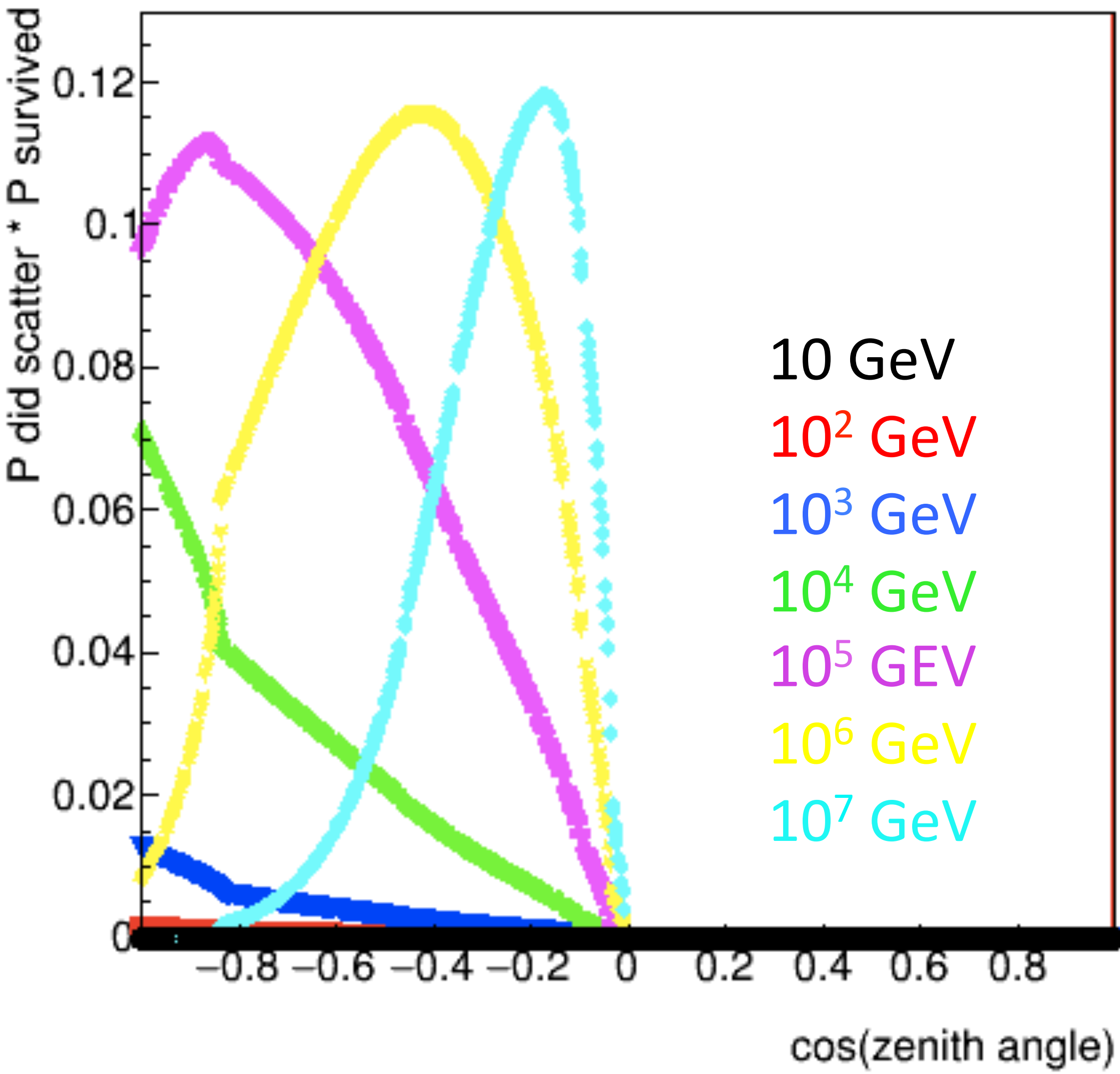


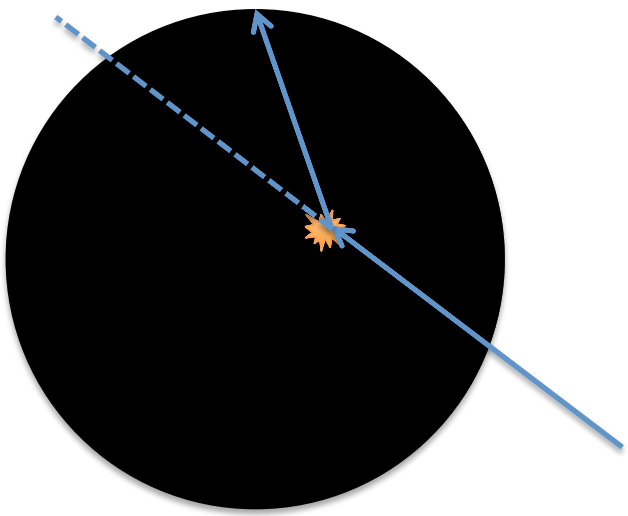
Neutrino NC Scattering (1)



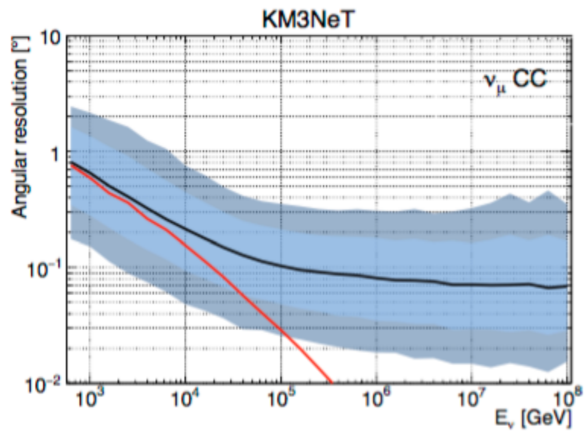


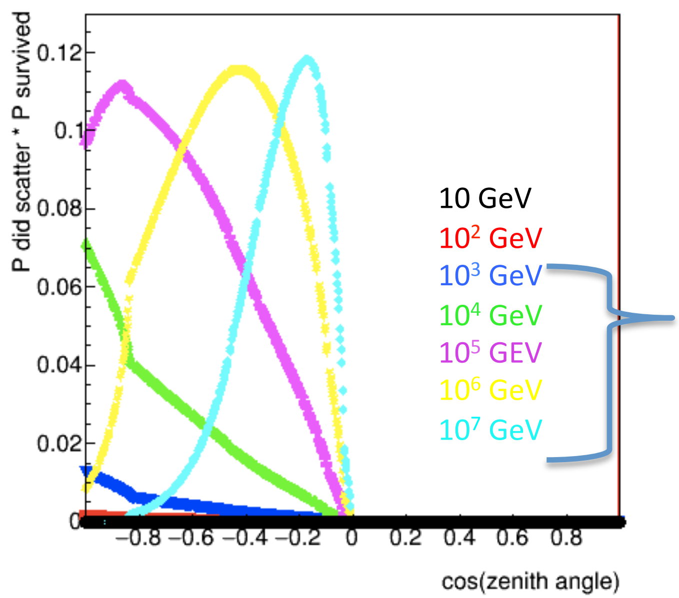
Neutrino NC Scattering (2)

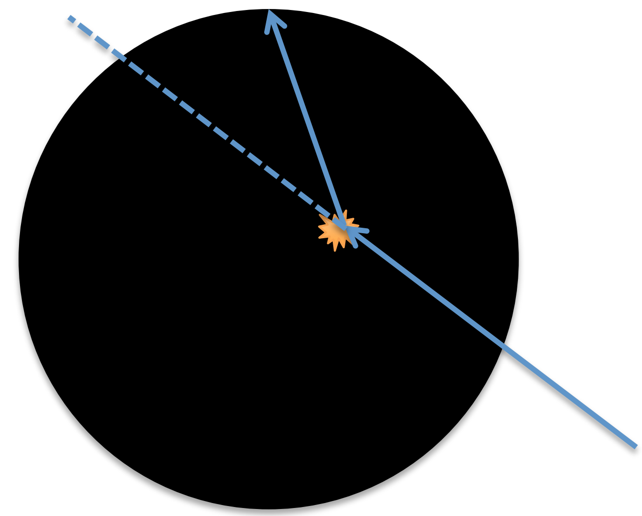




Neutrino NC Scattering (3)







- Change in direction: <≈ 0.6 degrees for Enu > 10^3 GeV
- Change in Energy???

Effects on expected atm. Neutrino flux neglected

Neutrino Oscillations

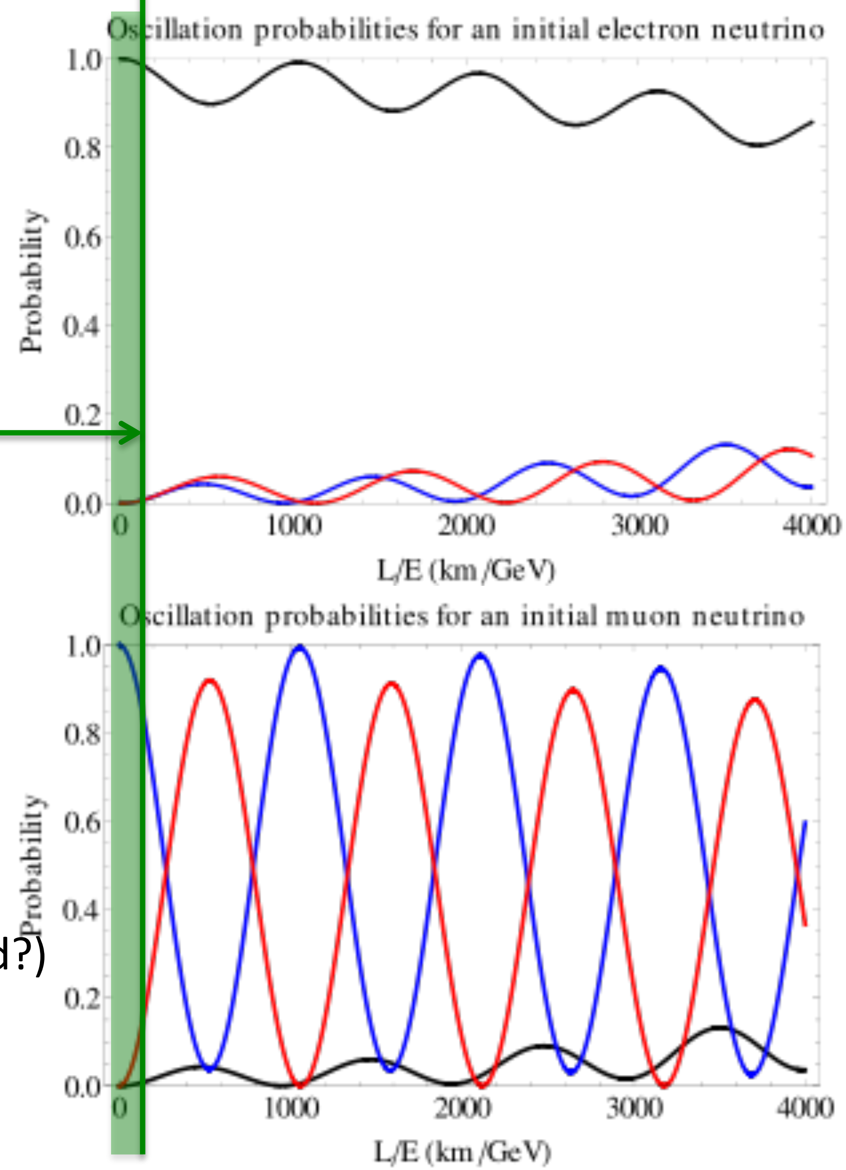
Earth radius=6.4 * 10^3 km
100 GeV neutrino

L/E = 1.28 * 10^2 km/GeV

Earth covers one oscillation period
P(oscilate) up to:

- ~0.01 (electron -> muon/tau)
- ~0.2 (muon -> tau)
- ~0.2 (tau -> muon)

For now: Ignore…. (to be continued?)



Likelihood Ingredients

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\ |\, H)\, dx_{true}\right] - \mu^{tot}(H)$$

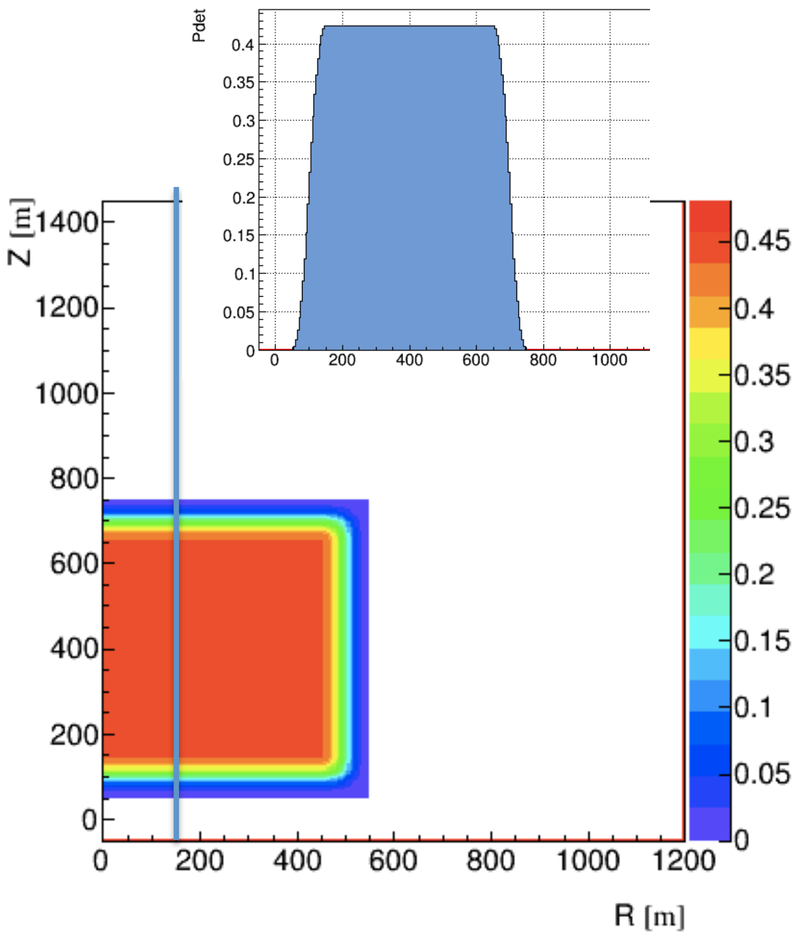
$\mu(x_{true}\ |\, H)$ Number of expected background or signal events in our detector (can)

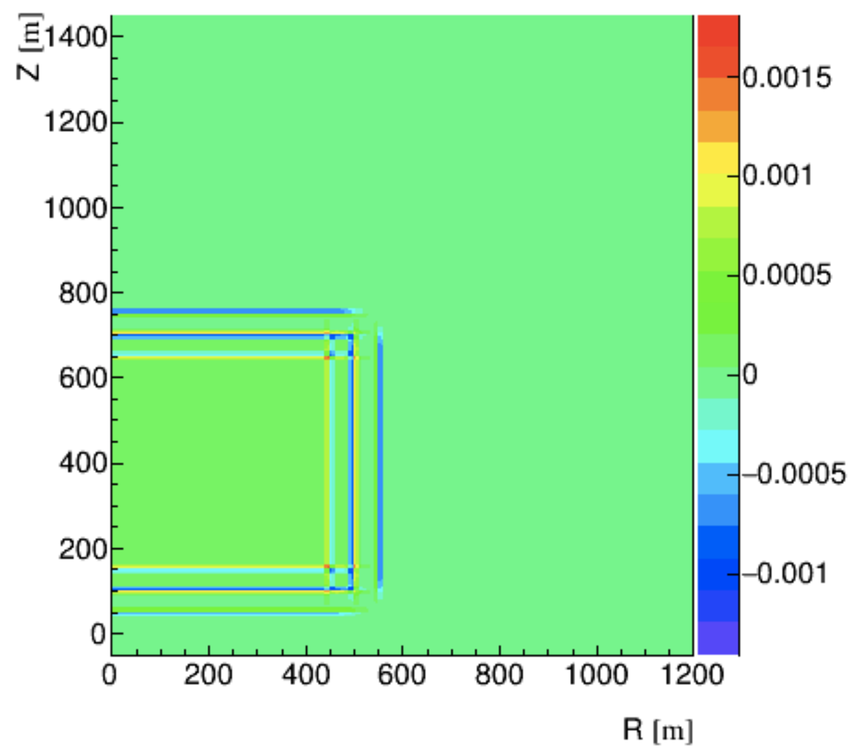
$P^{det}(x_{true})$ Probability to detect (=trigger) and select event

6-D Interpolation from tabulated values -> fast

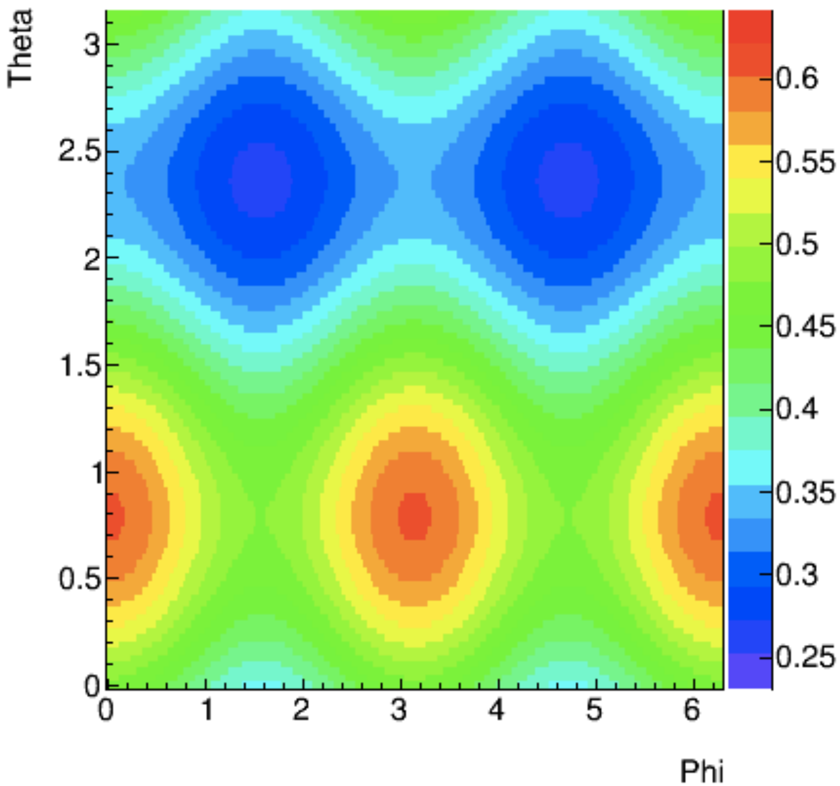
$P(ev_i|\, x_{true})$

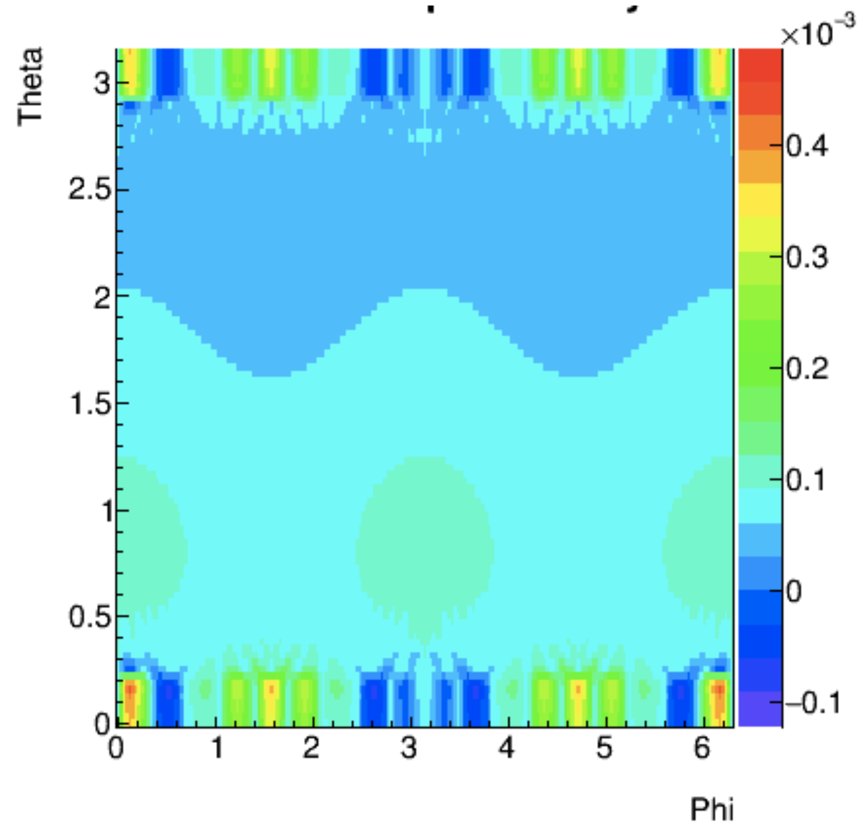
Detection Efficiency (1)





Detection Efficiency (2)





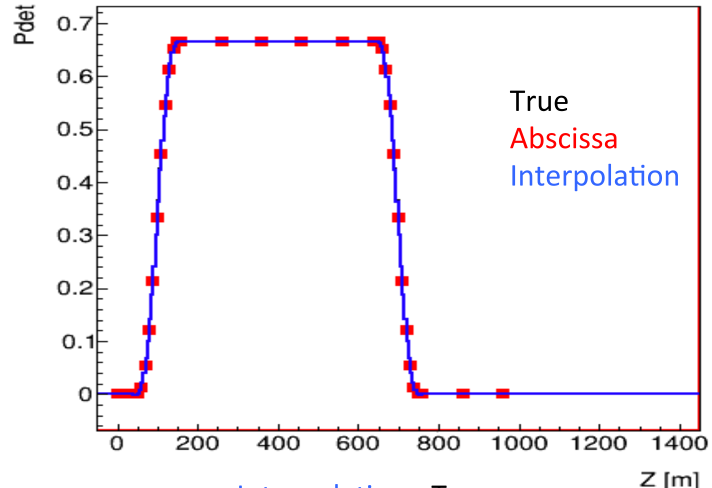
What is Pdet?

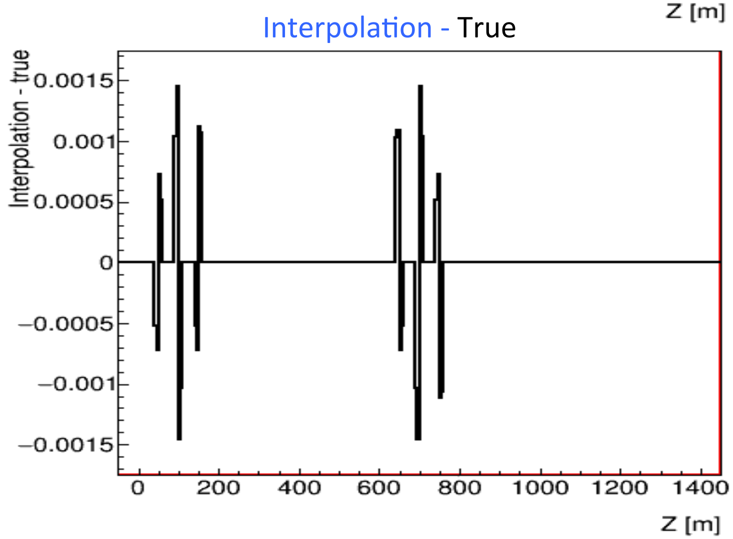
- Probability that an event:
  - Causes hits in detector: Jsirene
  - Leads to a trigger: JTriggerEfficiency
  - Is selected (reject atm. Muons): ??

- Get Pdet(x_{true}) by running MC events

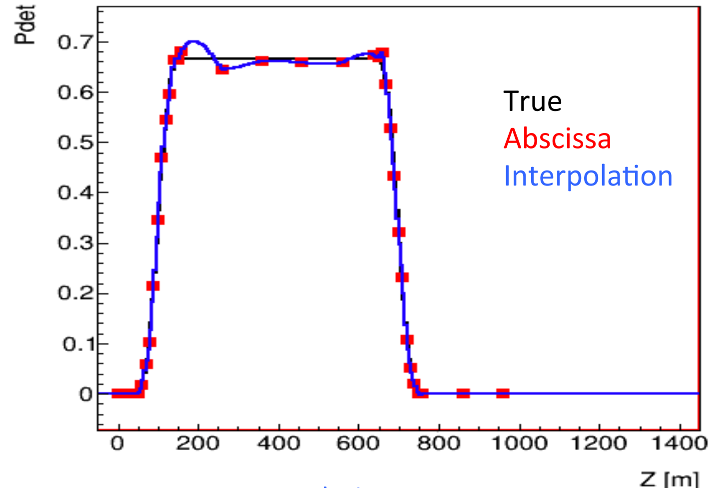
Statistical Fluctuations

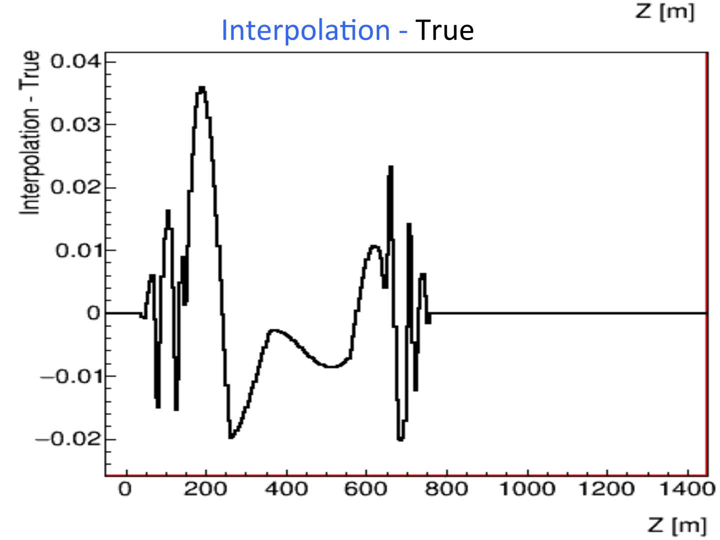
Ideal case: Infinite statistics



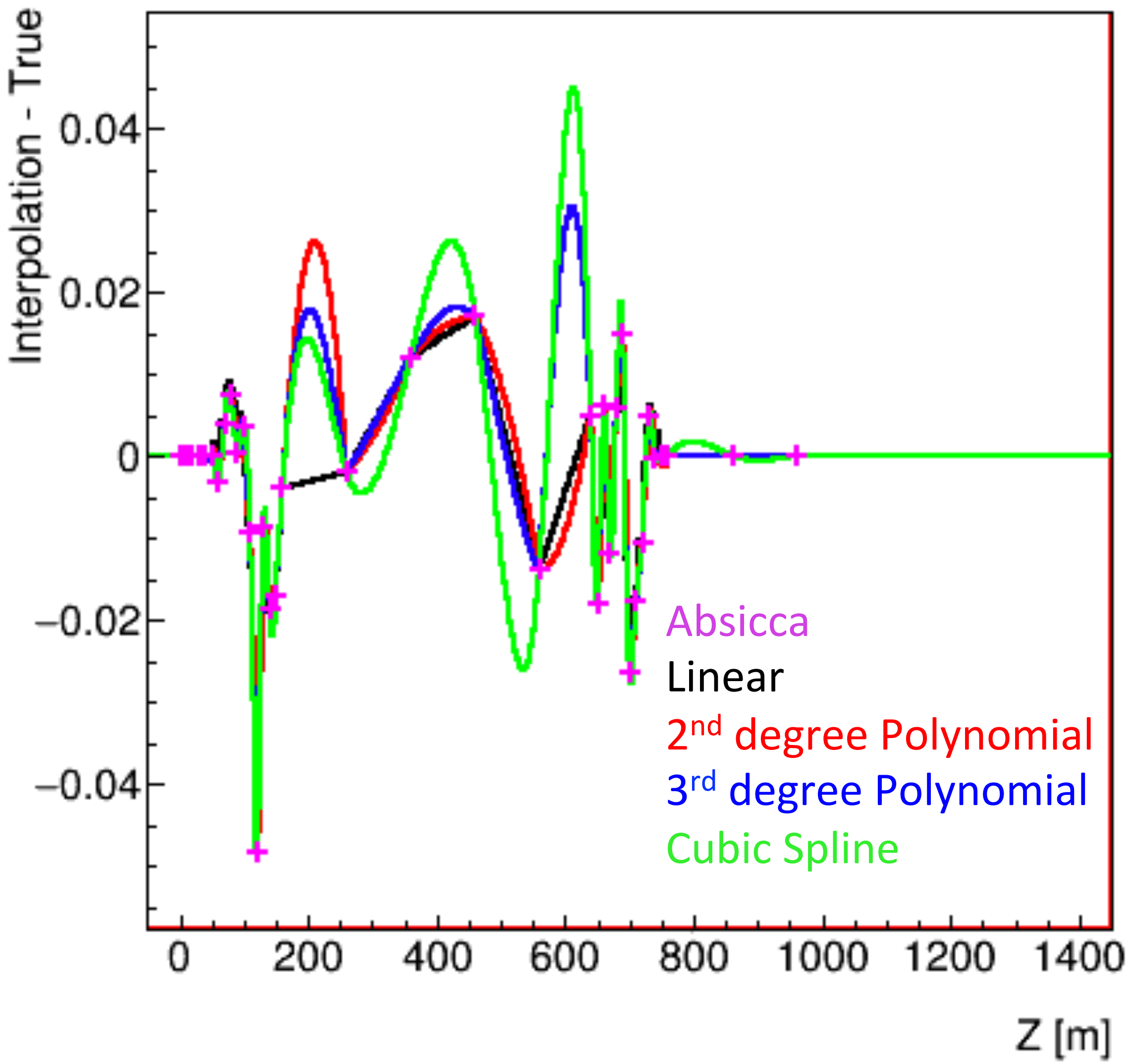


Realistic case: 1000 simulated events





Different Interpolation Techniques

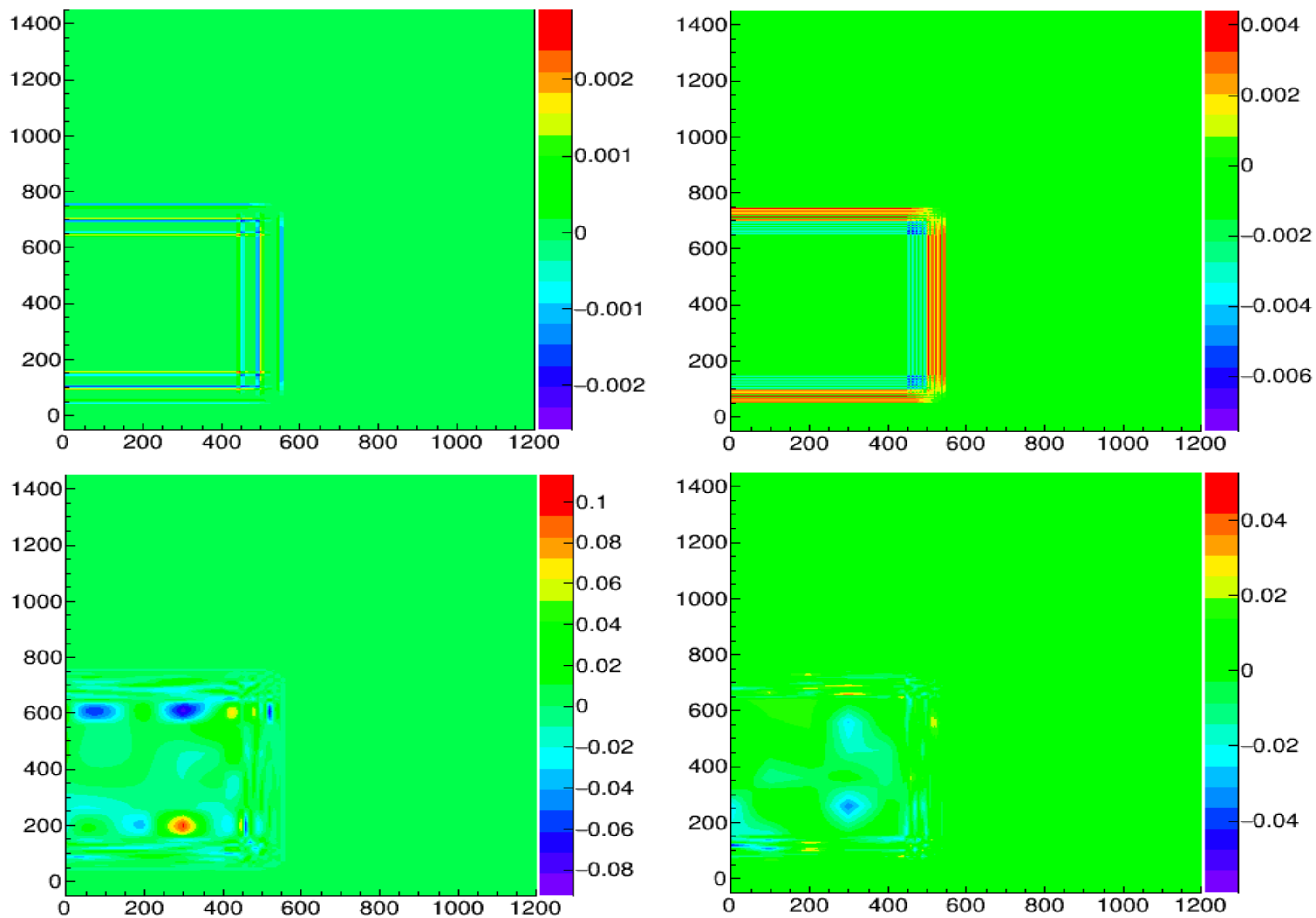


Polynomial vs linear fit

3rd degree polynomial | Linear fit

No stat. fluctuations

With stat. fluctuations



Time Consumption

```
Scanning over 72000 Positions * 98 Directions * 1 Energy-bins = 7056000 points... Done in

624169.543 ms elapsed
623814.165 ms user
    12.998 ms system
 99%CPU
```

3rd degree polynomial interpolation of 7 million points in 10 minutes

```
Scanning over 72000 Positions * 98 Directions * 1 Energy-bins = 7056000 points... Done in

 16068.632 ms elapsed
 16057.558 ms user
     4.999 ms system
 99%CPU
```

Linear interpolation of 7 million points in 16 seconds

Likelihood Ingredients

$$P(data|H) = \sum_i \left[\log \int P(ev_i|\, x_{true}) \cdot P^{det}(x_{true}) \cdot \mu(x_{true}\ |\, H)\ dx_{true}\right] - \mu^{tot}(H)$$

$\mu(x_{true}\ |\, H)$ Number of expected background or signal events in our detector (can)

$P^{det}(x_{true})$ Probability to detect (=trigger) and select event

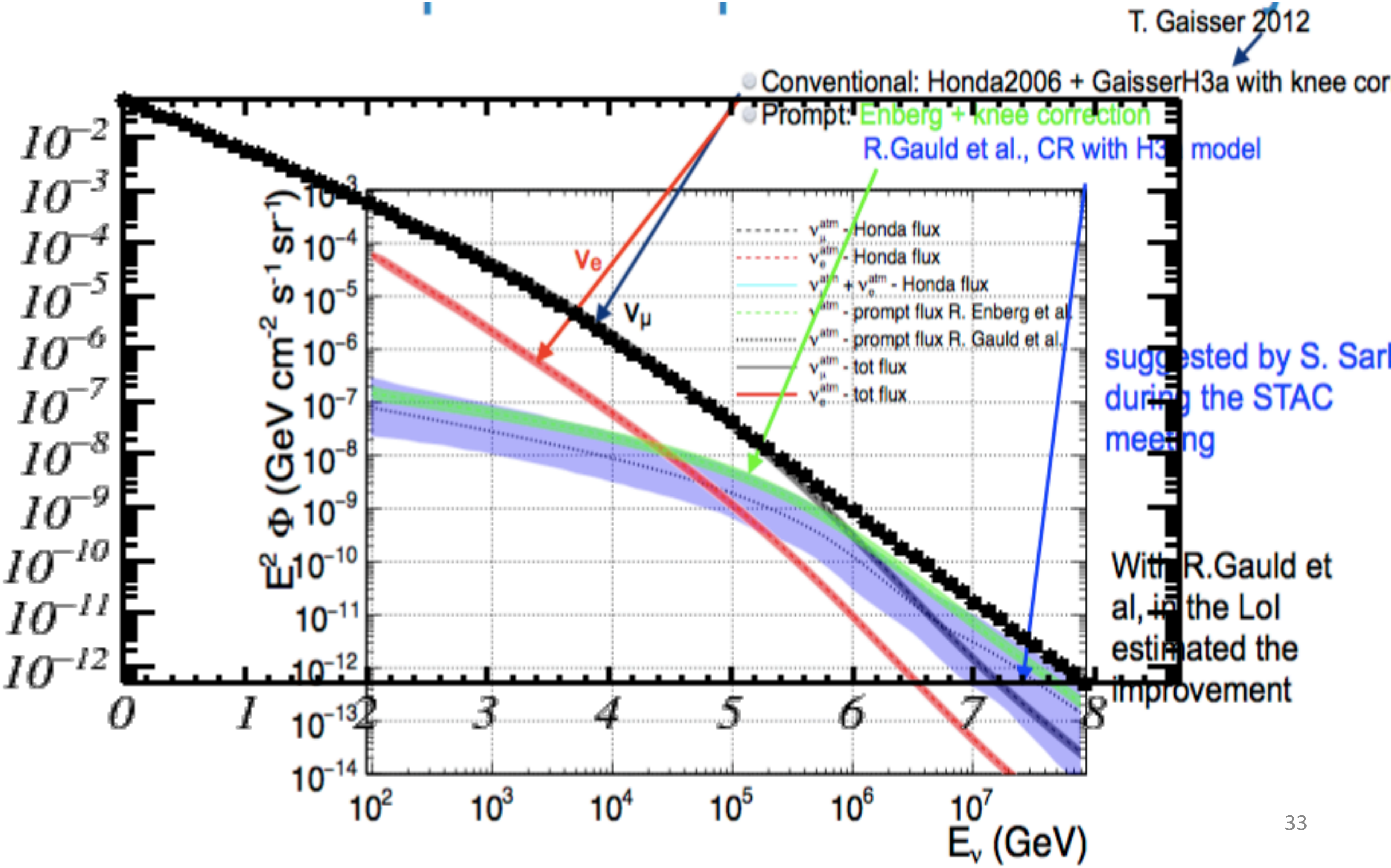
$P(ev_i|\, x_{true})$ Reconstruction, loop over PMTs. Phit * Ptime -> to do

Conclusions

- New method seems promising
- Most ingredients in place
- ‘Reconstruction’ part to be done

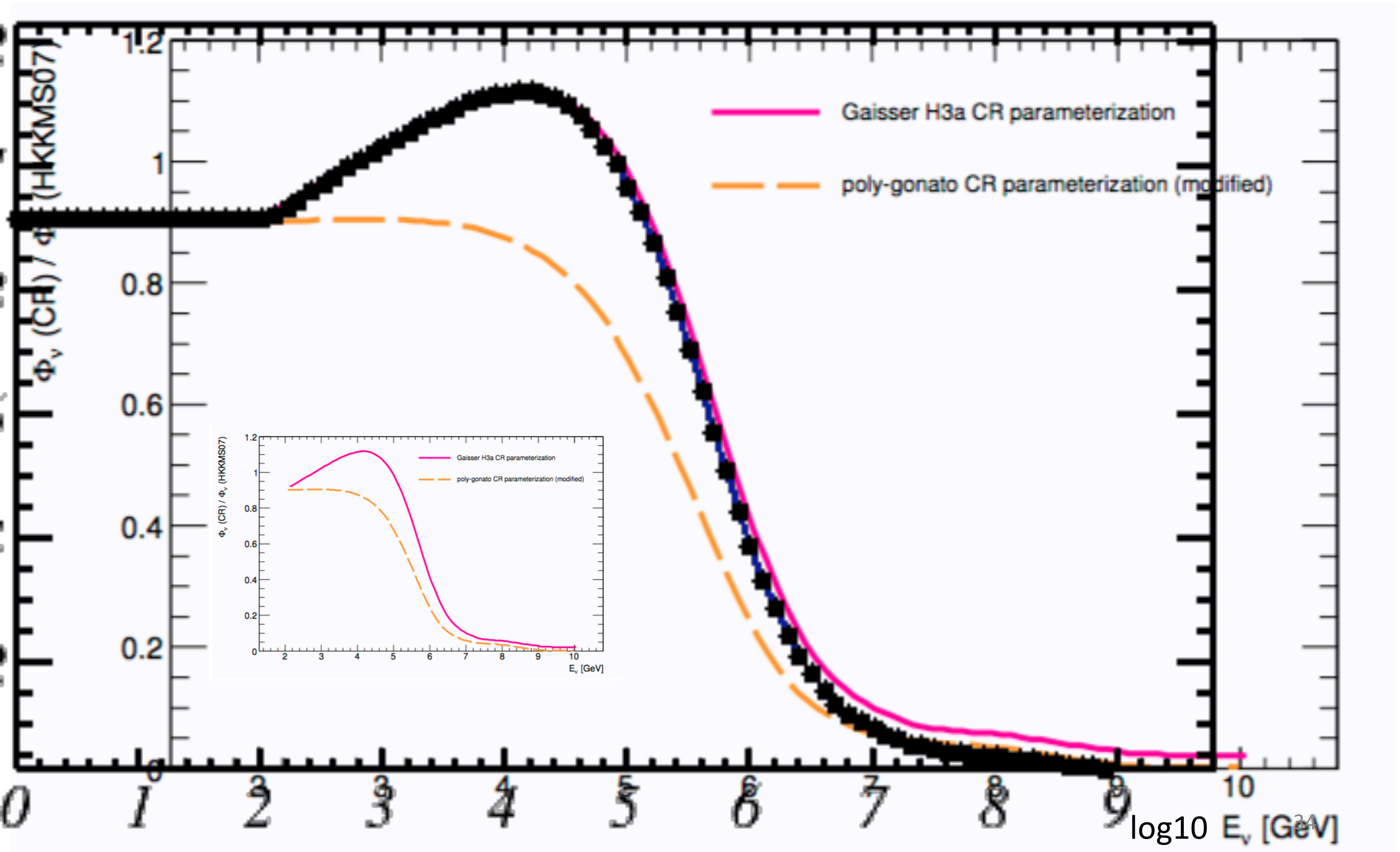
Backup

Honda extrapolated

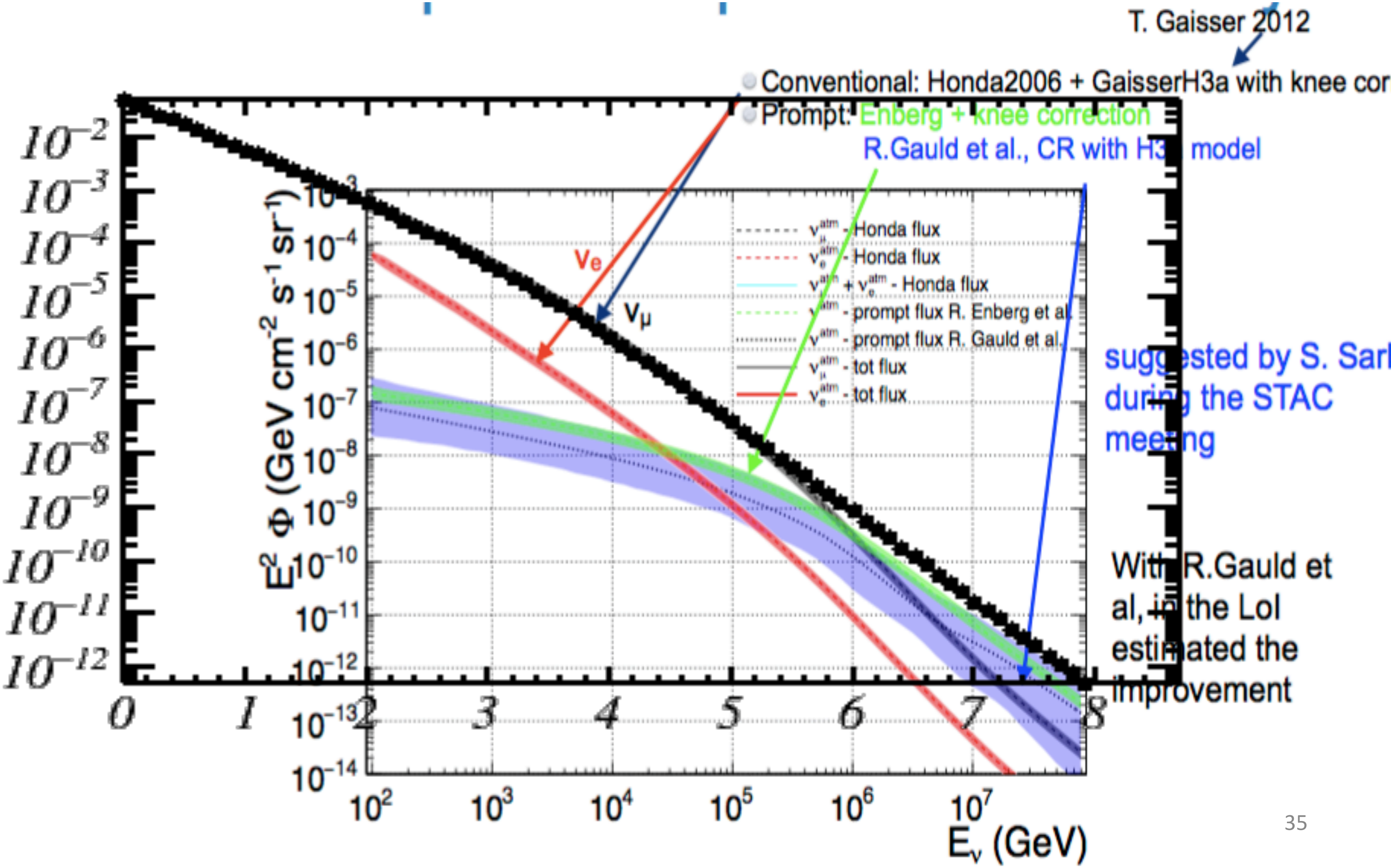


arXiv:1311.7048

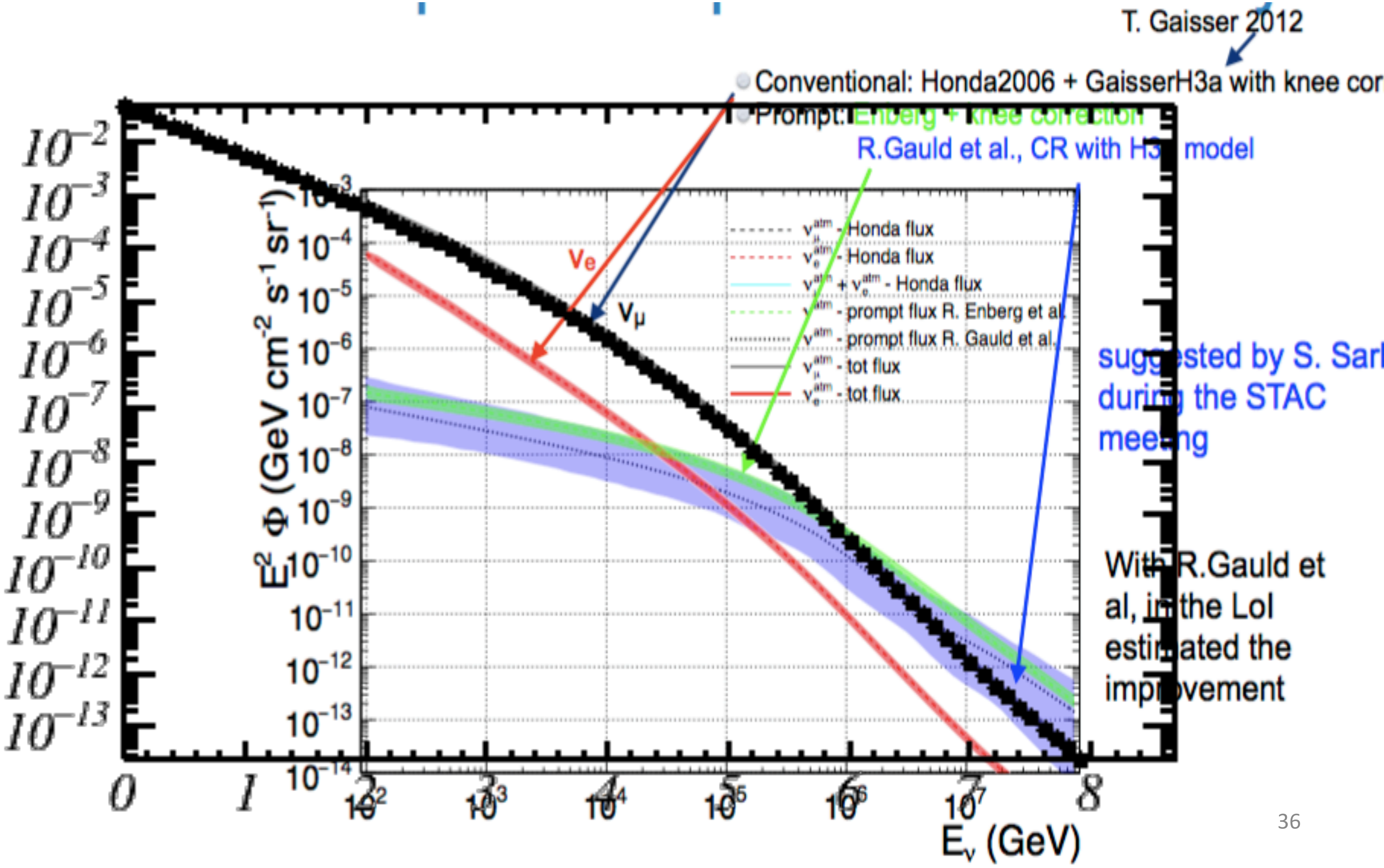
Knee Correction (Gaisser H3a)



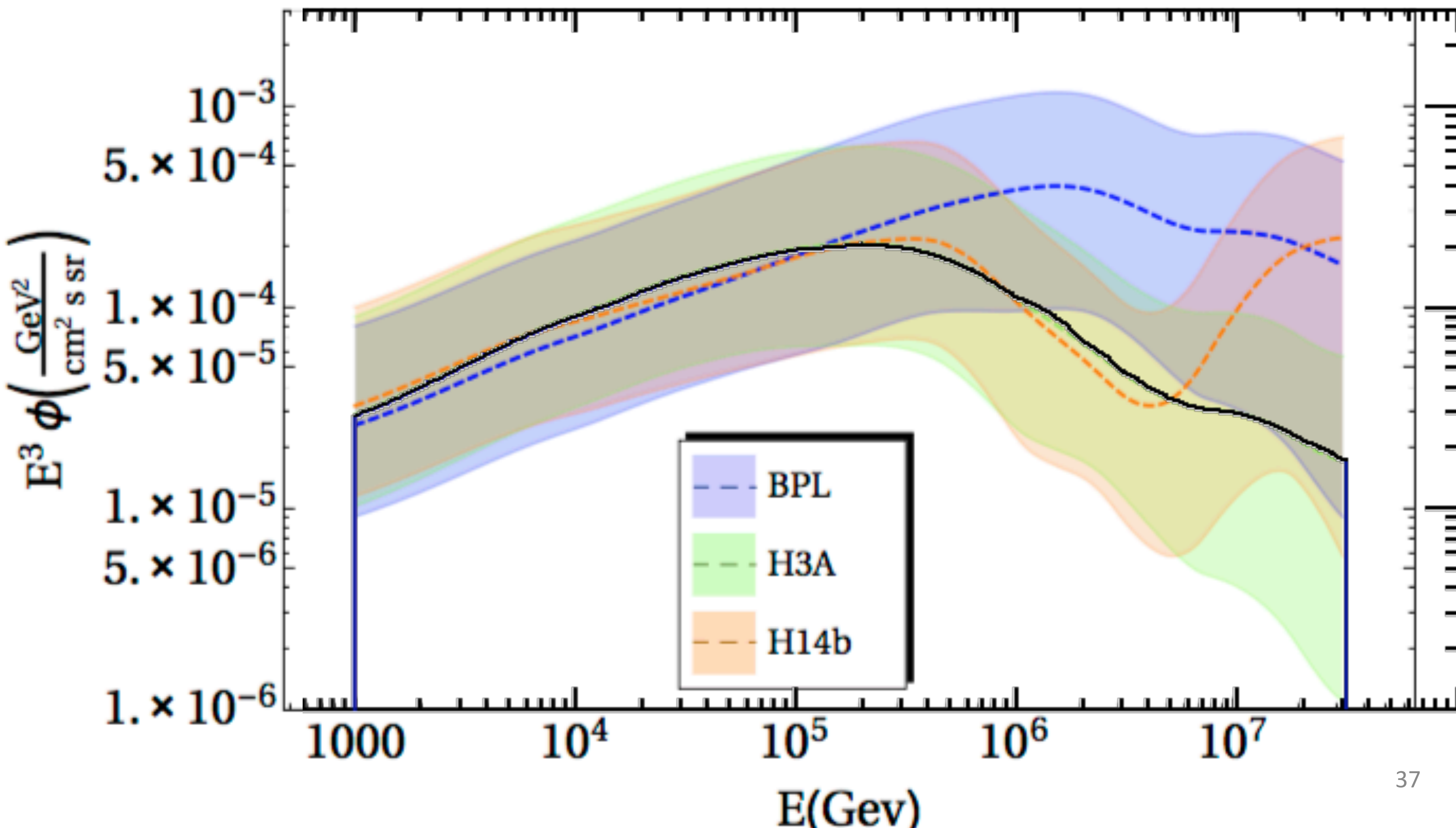
Honda extrapolated



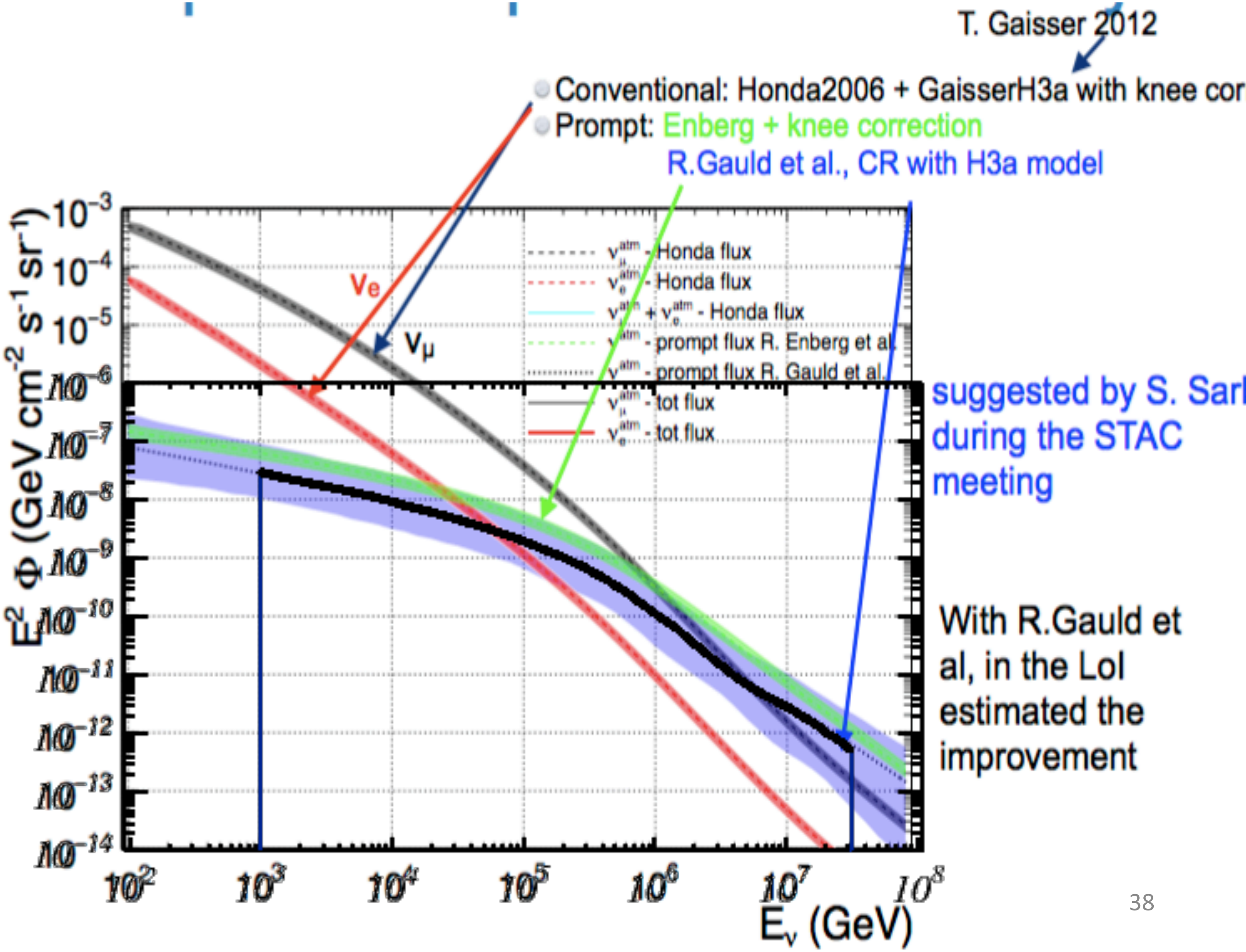
Honda extrapolated + knee correction



Prompt: Gauld Flux (2016)

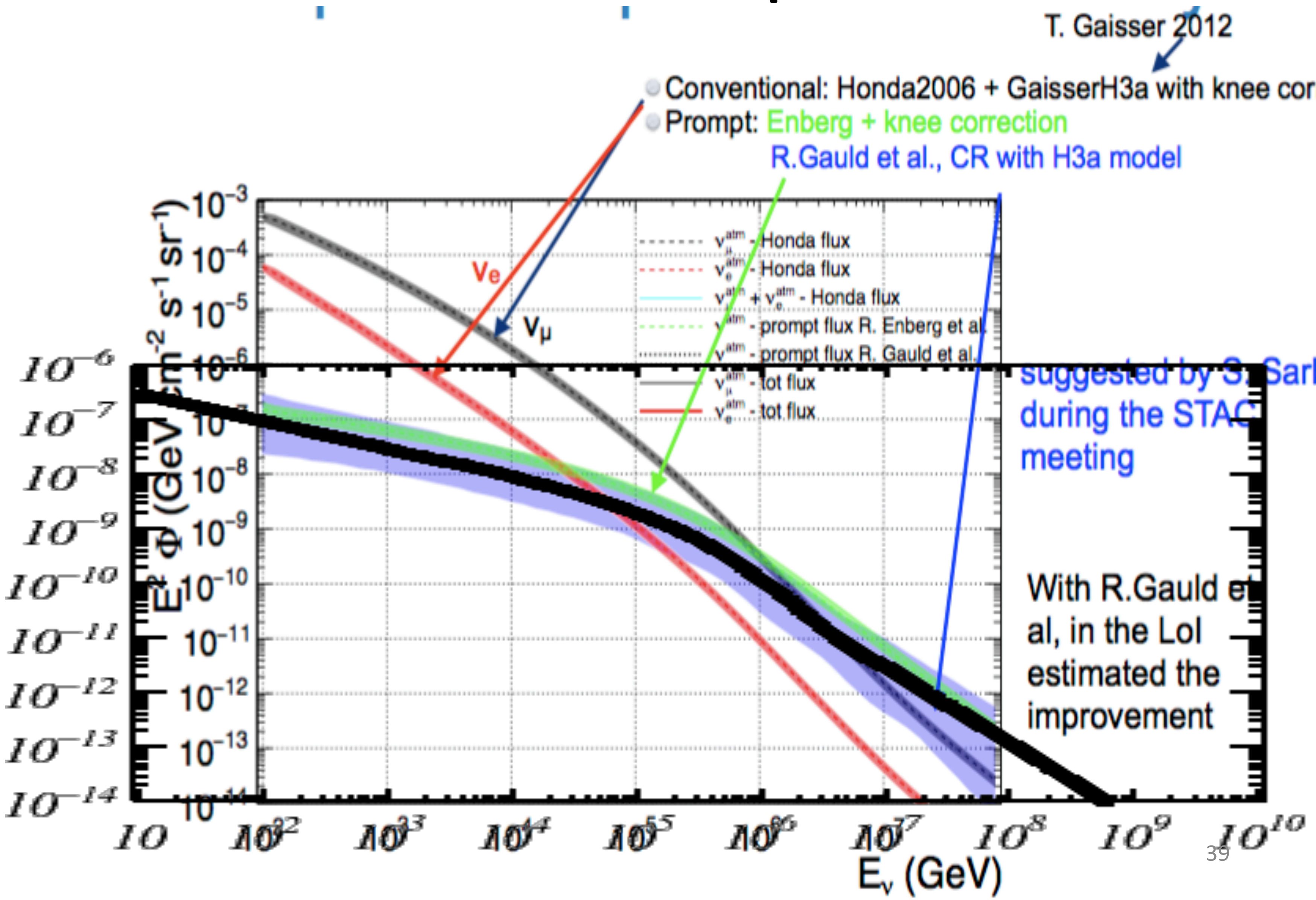


Gauld 2016

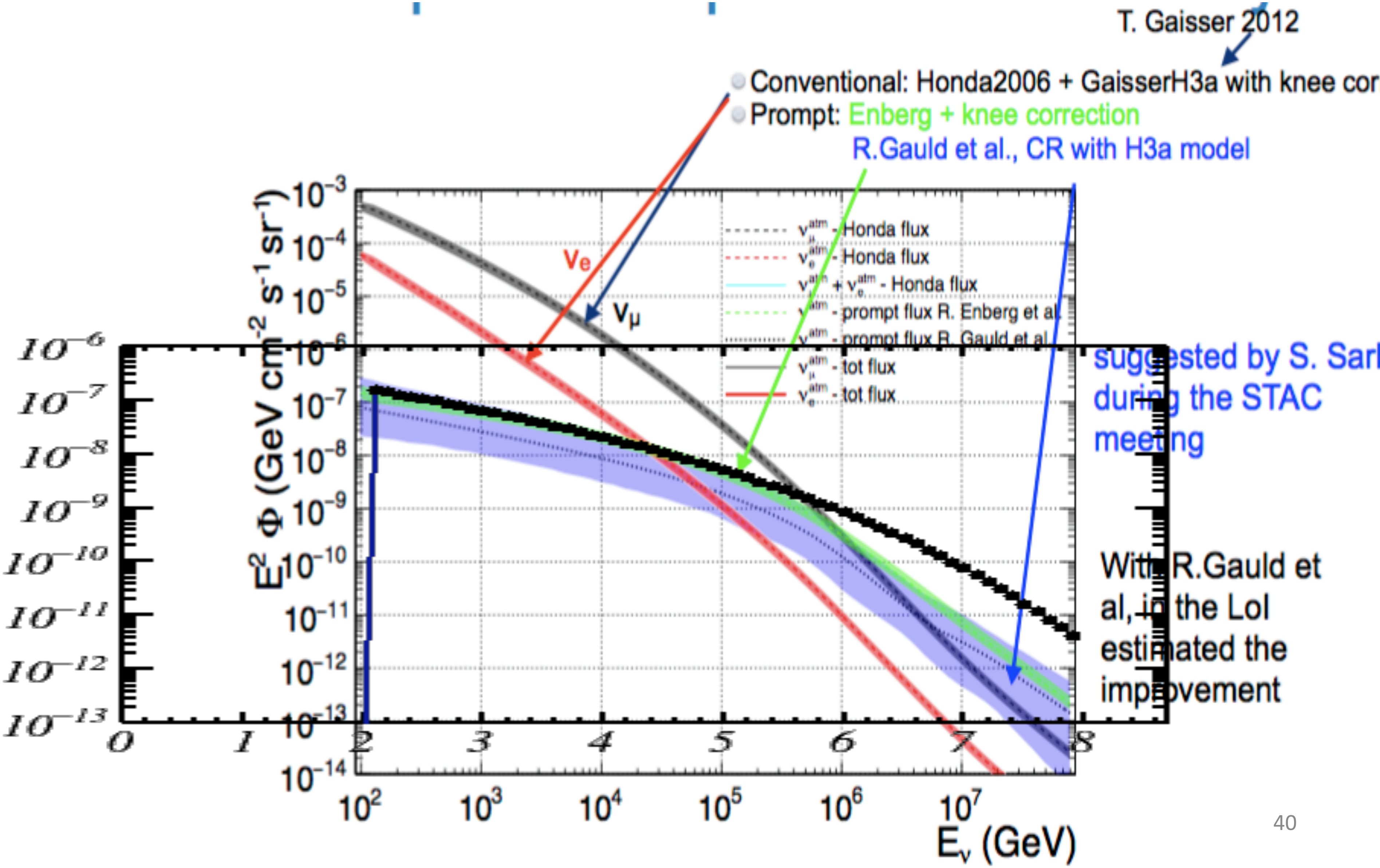


T. Gaisser 2012
Conventional: Honda2006 + GaisserH3a with knee cor
Prompt: Enberg + knee correction
R.Gauld et al., CR with H3a model
ν_e
ν_μ
ν_μ^{atm} - Honda flux
ν_e^{atm} - Honda flux
ν_μ^{atm} + ν_e^{atm} - Honda flux
ν_μ^{atm} - prompt flux R. Enberg et al.
ν_μ^{atm} - prompt flux R. Gauld et al.
ν_μ^{atm} - tot flux
ν_e^{atm} - tot flux
$E^2\,\Phi$ (GeV cm^{-2} s^{-1} sr^{-1})
E_ν (GeV)
suggested by S. Sarl
during the STAC
meeting
With R.Gauld et
al, in the LoI
estimated the
improvement

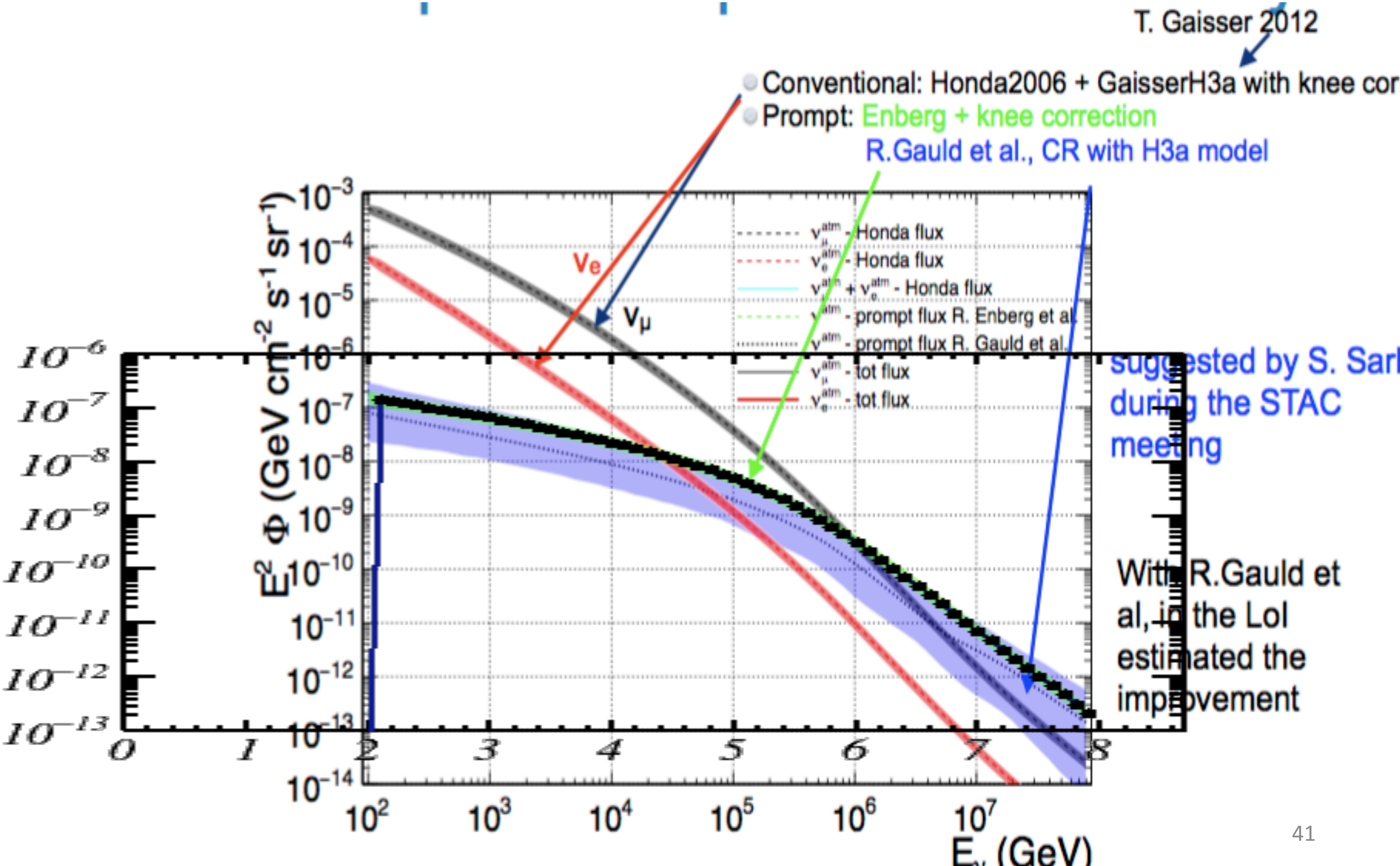
Gauld 2016 extrapolated



Enberg extrapolated



Enberg extrapolated + knee correction



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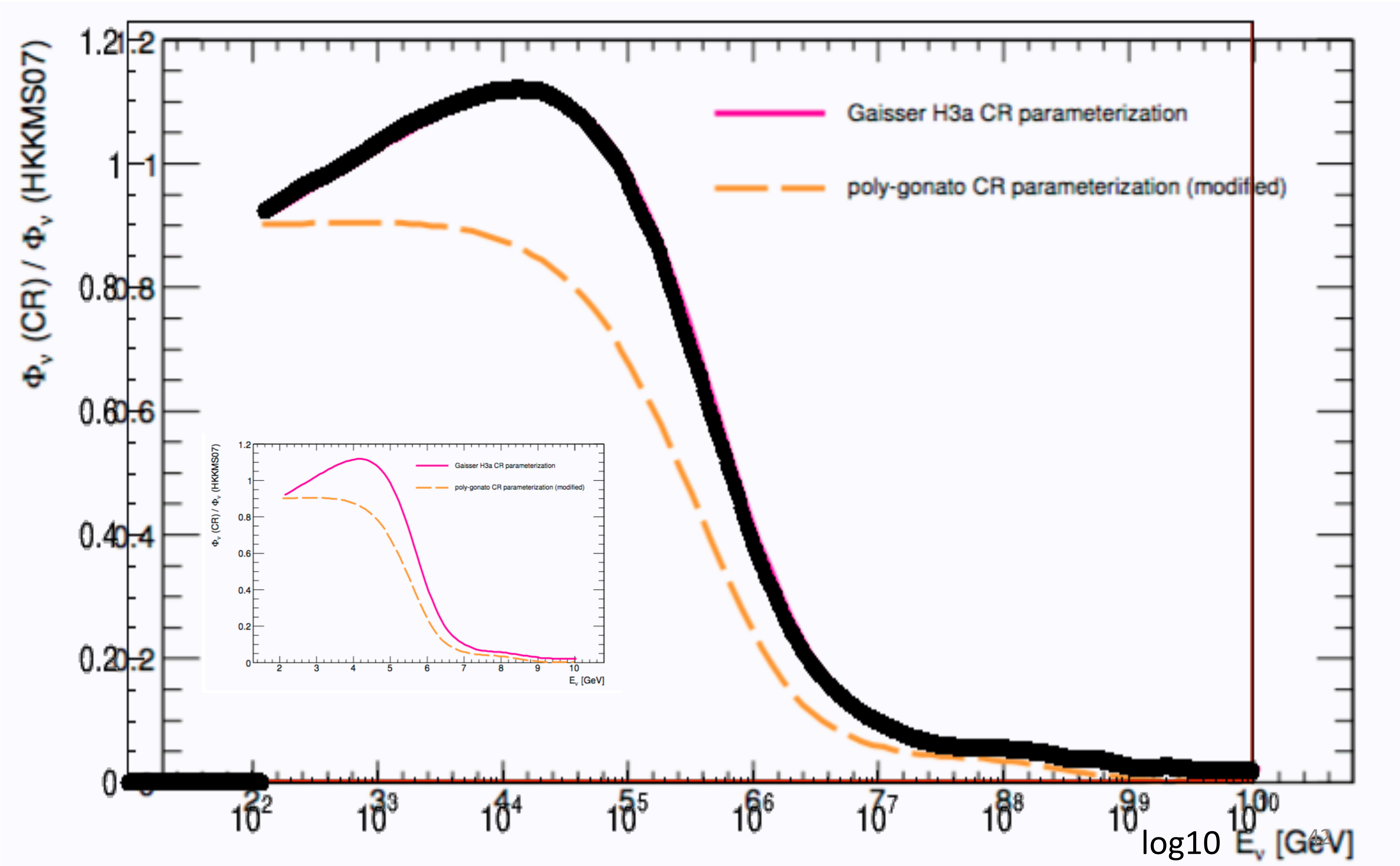
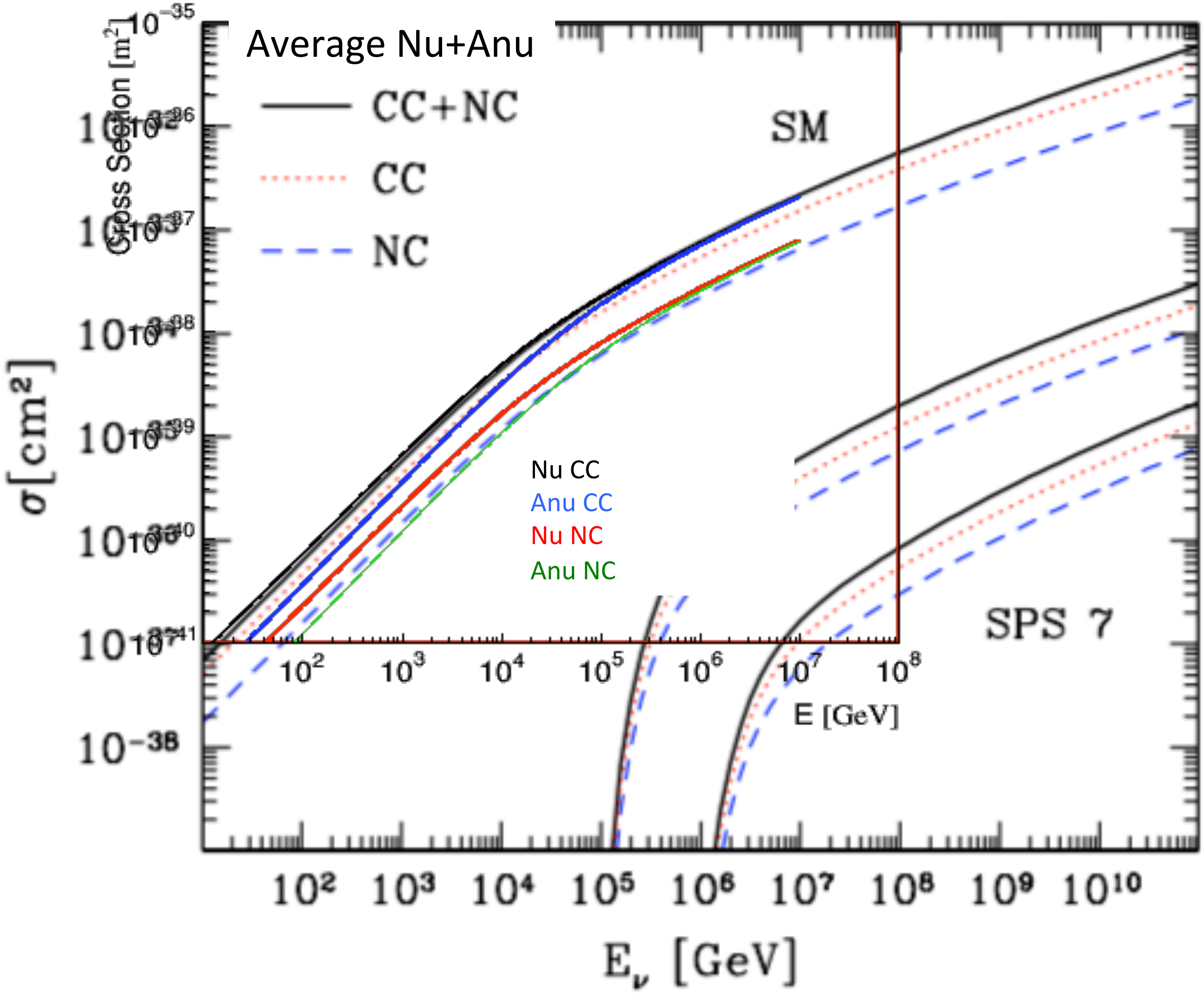


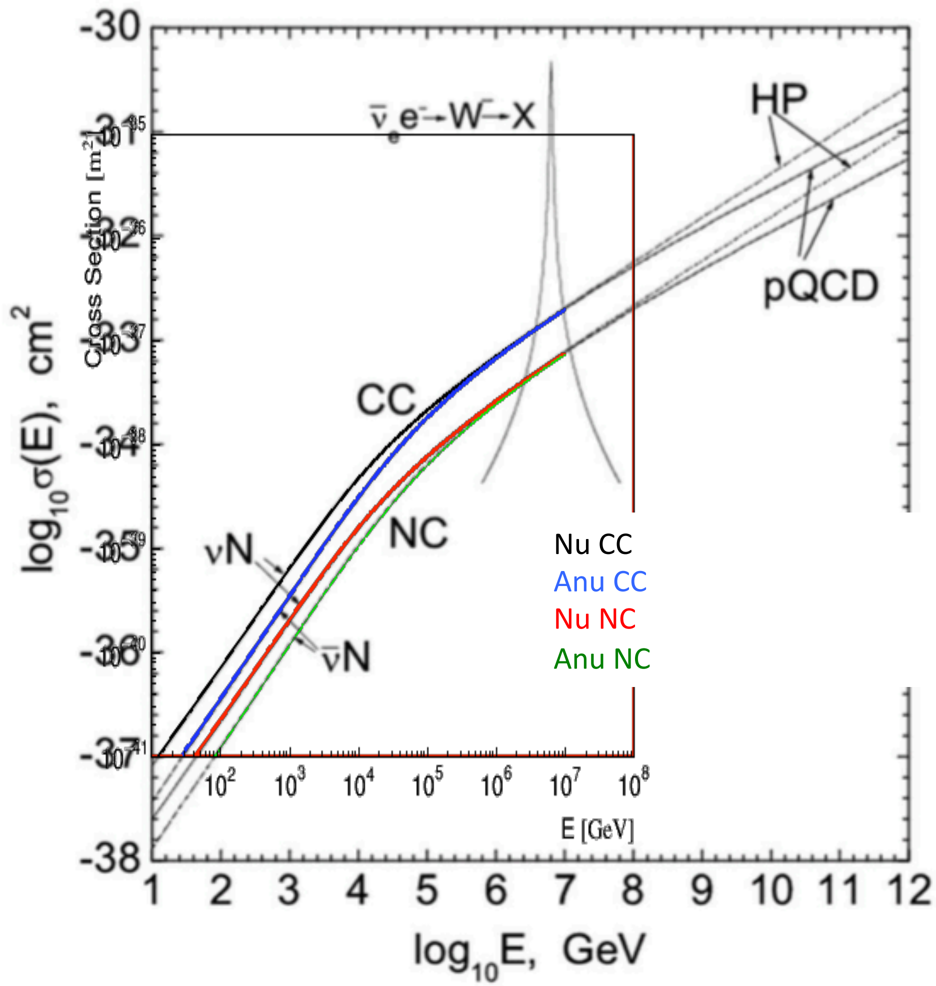
https://arxiv.org/pdf/hep-ph/0604188.pdf

Neutrino Cross Sections



ANIS, Kowalski 2003
Figure from Colnard 2009

Neutrino Cross Sections



Neutrino Cross Sections