SIGNS OF OUTLANDISH DARK MATTER BEHAVIOUR NEAR THE FIRST STARS

work in progress with:
P. Graham, R. Harnik & S. Rajendran
and with:
P. Graham, S. Rajendran, R. Sundrum & L. Vecchi

It's a good time to be a bit crazy

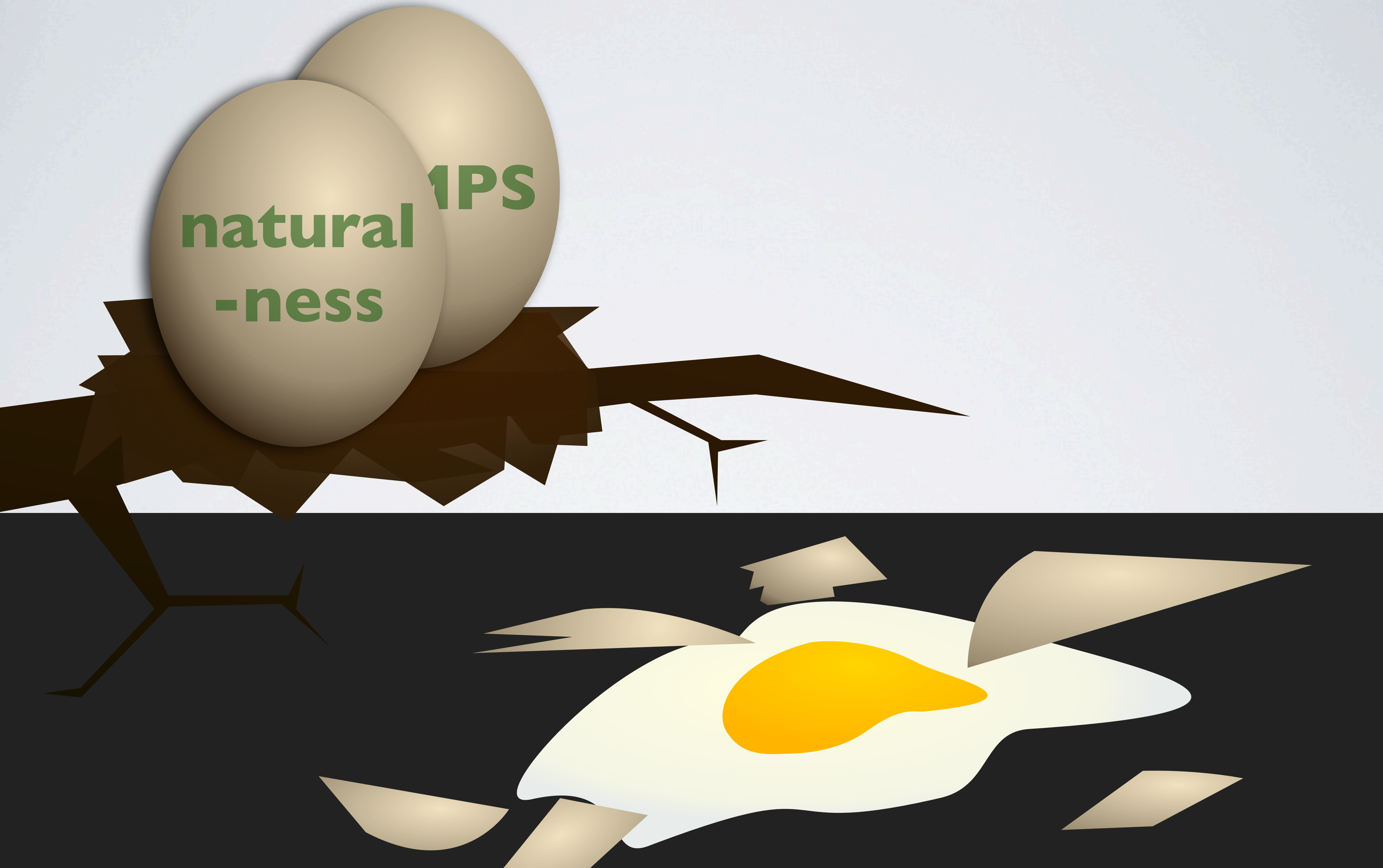
For the last 30 years we've been expecting new physics at the Weak scale:

a natural solution to the hierarchy problem

and

WIMP dark matter

It's a good time to be a bit crazy



Pop III Stars

First generation of stars

- **Pop I :** the sun and sun-like stars
- **Pop II :** older, metal-poor stars
- **Pop III :** first generation of stars forming from primordial metal-free gas. Unobservable (but uncontroversial!)

Formation (oversimplified)

- DM halo + gas
- lack of metals makes cooling inefficient (no molecular lines)
- results in a **single, very massive star per halo?** (Abel et al 2002)
- **~30-300 $M_\odot$?**
- **form at redshift z~10-20**?
- lives ~1 Myr , then fate depends on mass:

  140-260 $M_\odot$: Pair Instability Supernova with no remnant?

  30-140, 260+ $M_\odot$: forms black hole without a supernova?

(Heger et al 2003)

Enhanced DM densities in Pop III

Gas collapses in center of DM halo

- already a high DM density environment

Gravitational density enhancement

- inefficient cooling → slow collapse
  → **"adiabatic contraction" of DM**

(Blumenthal et al 1986)

Naive estimate:

- circular orbits + spherical symmetry+ adiabatic collapse:
- cons. of ang. mom.: $M'(r')r' = M(r)r$

ENHANCED DM DENSITIES IN POP III

Taking NFW initial profile ($\rho \sim r^{-1}$)

"DARK STARS"

Spolyar, Freese & Gondolo 0705.0521
and many others since

DM feedback on gas:

- more DM contraction → more DM annihilation
- DM annihilation energy → pressure in gas

In a "Dark Star", this pressure prevents further gas collapse

- May result in supermassive stars ($>10^5\ M_\odot$), observable with JWST? (e.g. Ilie et al 1110.6202)
- very uncertain (see e.g. Iocco 1103.4384 for a review)

For now imagine Pop-III star forms what happens *after* the Dark Star stage

- assume $\sim 100\ M_\odot$ stars (more mass will help)

OTHER SIGNALS?

Amazingly high DM densities in vicinity of Pop-III star
→ inner region where *all* DM annihilates

Neutrino signal:

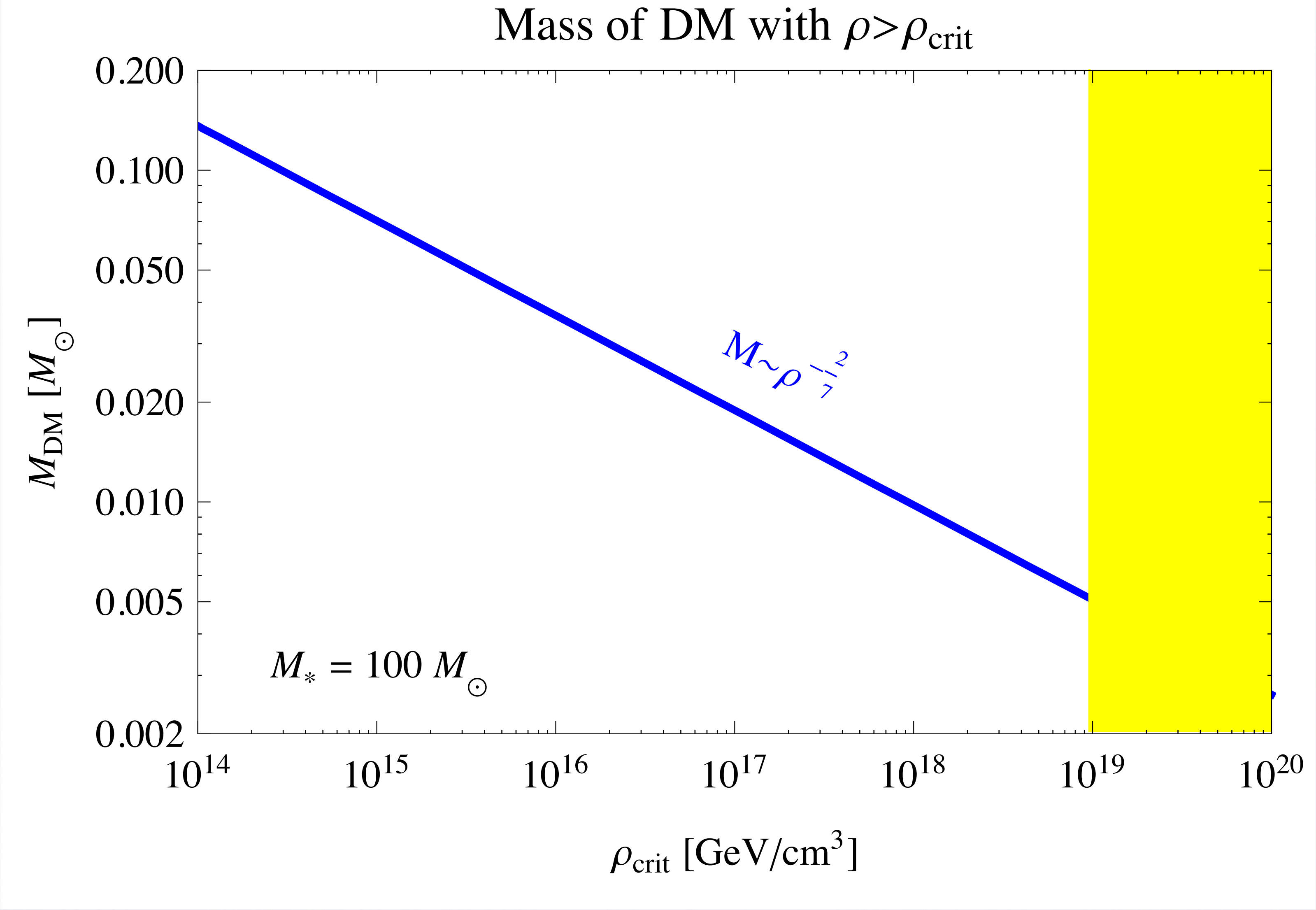
- neutrinos can reach us without scattering
- ***double-bump signal:***
  redshifted neutrinos from Pop-III halos
  + *unredshifted* neutrinos from annihilation in Milky Way?

Gamma ray signal:

- Gammas and electrons shower with CMB if E>3 TeV x 10/(1+z)
  (Kribs & Rothstein hep-ph/9610468)
- Shower down to E~3 TeV x 10/(1+z), then gammas travel freely
- Energy redshifts to $E_{today}=E_0/(1+z)$
- ***gamma signal at E~300 GeV***

DM Annihilation Rate Estimate

Total DM mass annihilated:



$$\rho_{\rm crit} = 10^{16}\,{\rm GeV\,cm^{-3}}\left(\frac{m_{\rm DM}}{\rm PeV}\right)\left(\frac{10^{-23}\,{\rm cm^3\,s^{-1}}}{\sigma v_{\rm ann}}\right)\left(\frac{10^6\,{\rm yr}}{t_*}\right)$$

WARNING! uncertainties

how good is the approximation of spherical adiabatic contraction with circular orbits?

- not circular orbits
- not adiabatic
- not spherical
- ...but basically agrees with (limited) simulations (e.g. Gnedin et al 04)

single Pop-III star or fragmentation into many?

- fragmentation of gas cloud is bad for DM contraction
- controversial whether it happens or not
- DM annihilation should actually reduces fragmentation

(see Smith et al 1210.1582 ; Freese et al 1304.7415)

Also

- initial DM profile (how cuspy?)
- mass of Pop-III stars

WARNING! More uncertainties

Halo formation rate

- large variation in literature

Continued annihilation around remnant?

- Size of remnant (depends on star mass)
- Disruption by merger?

The IceCube anomaly

Jeremy Mardon, SITP, Stanford

ICECUBE DETECTOR

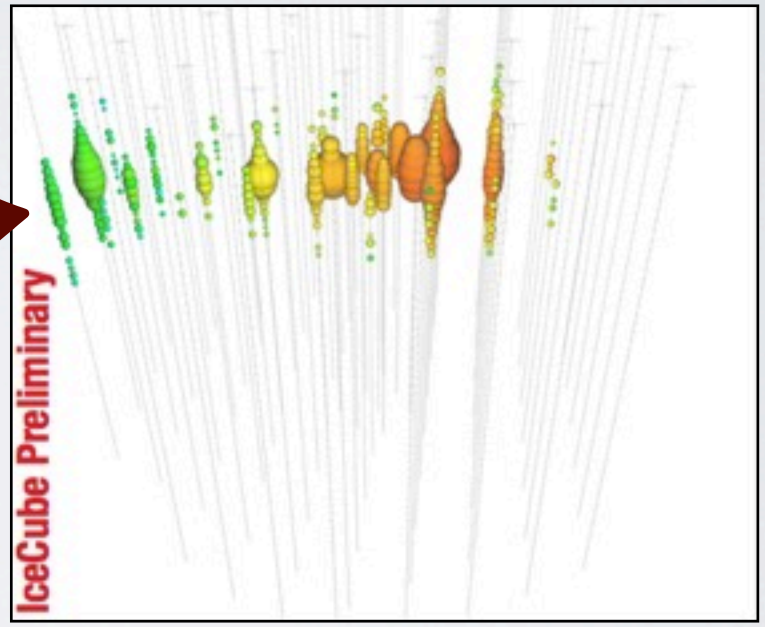
~km^3 of ice instrumented with PMTs

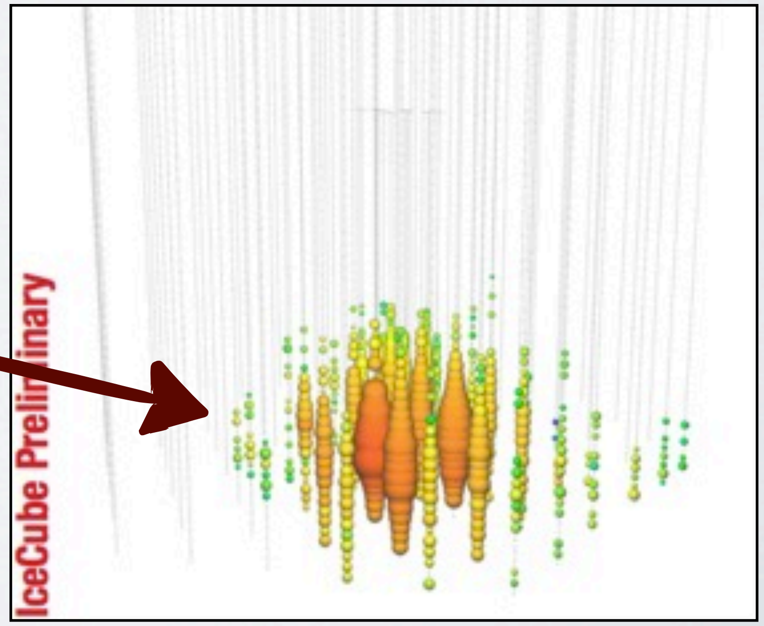
sees Cherenkov light from charged particles

energy threshold 10s of TeV

Types of event:

- **muon tracks**
  stopping distance is several km
  distinctive track of PMT hits
  O(10%) of energy is deposited
  dE/dx can give total energy
- **EM & hadronic showers**
  much better contained
  O(10%) energy resolution





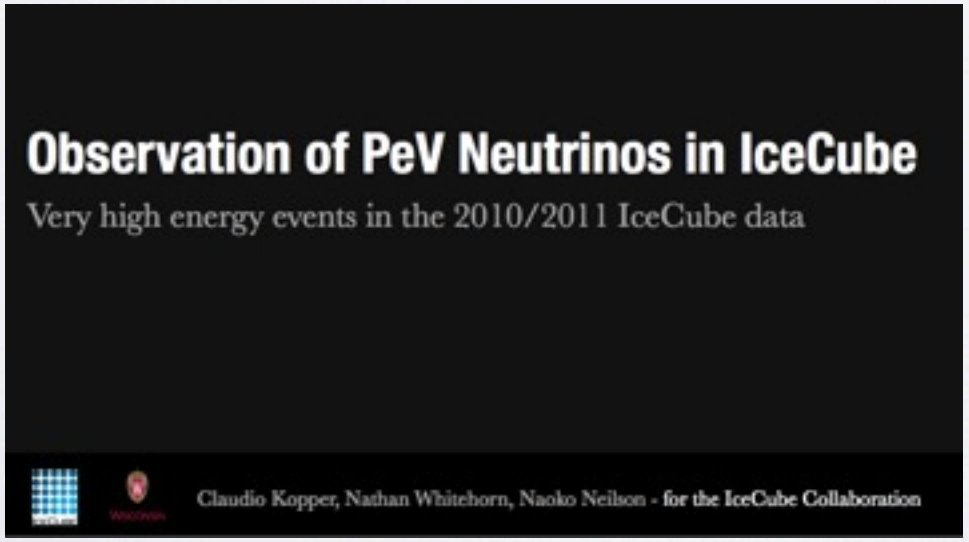
ICECUBE ANOMALY

"First Observation of PeV-energy neutrinos with IceCube"
1304.5356

- high-energy search (energy threshold ~PeV) with 616 days data
- **2 shower events with ~PeV energy**: "Bert" and "Ernie"
- **expected total background: 0.08 events**

Lower energy analysis:

- Preliminary results given in talks
- energy threshold ~30 TeV
- **26 new events**
- **expected background ≈11 ± 4**

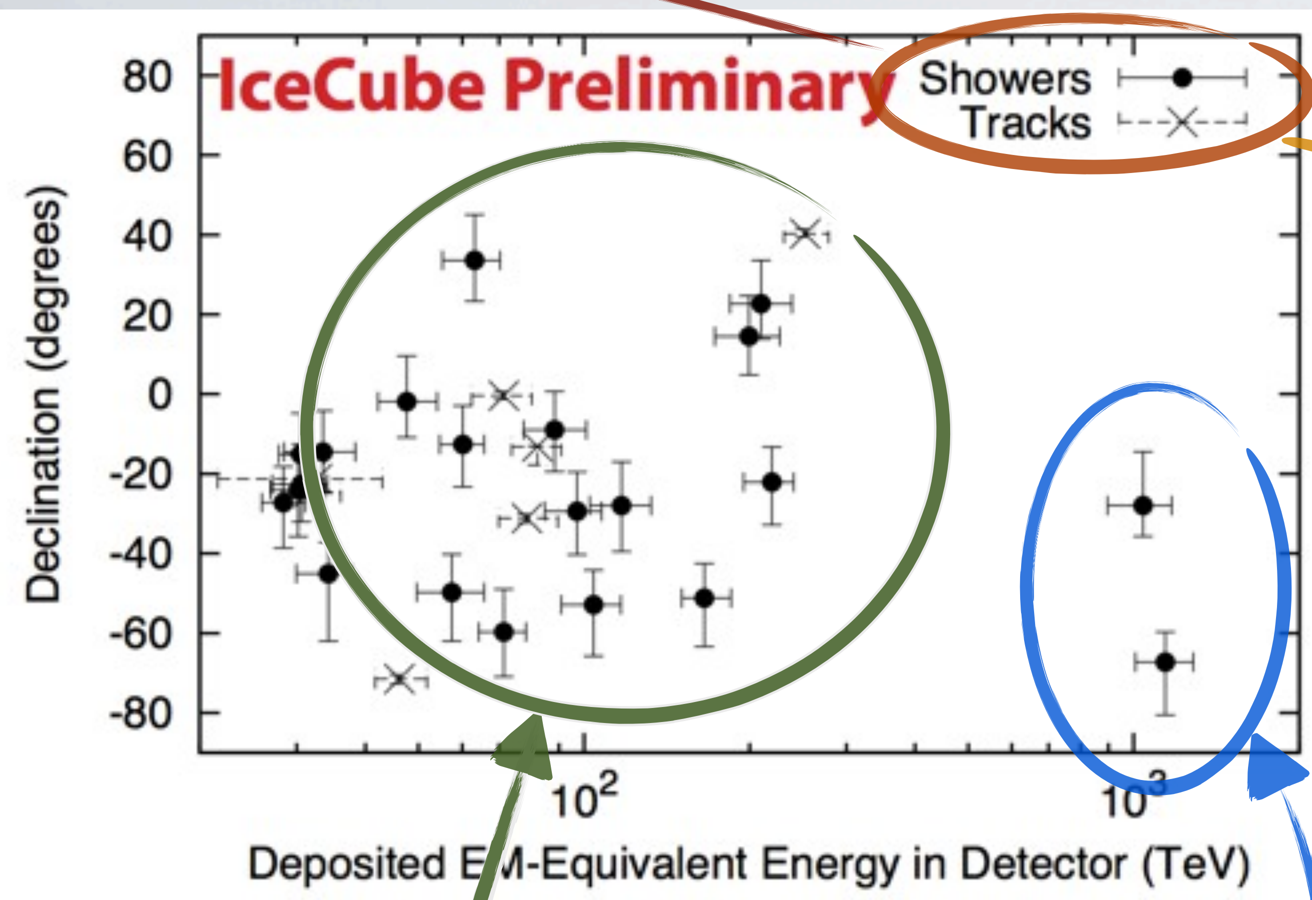


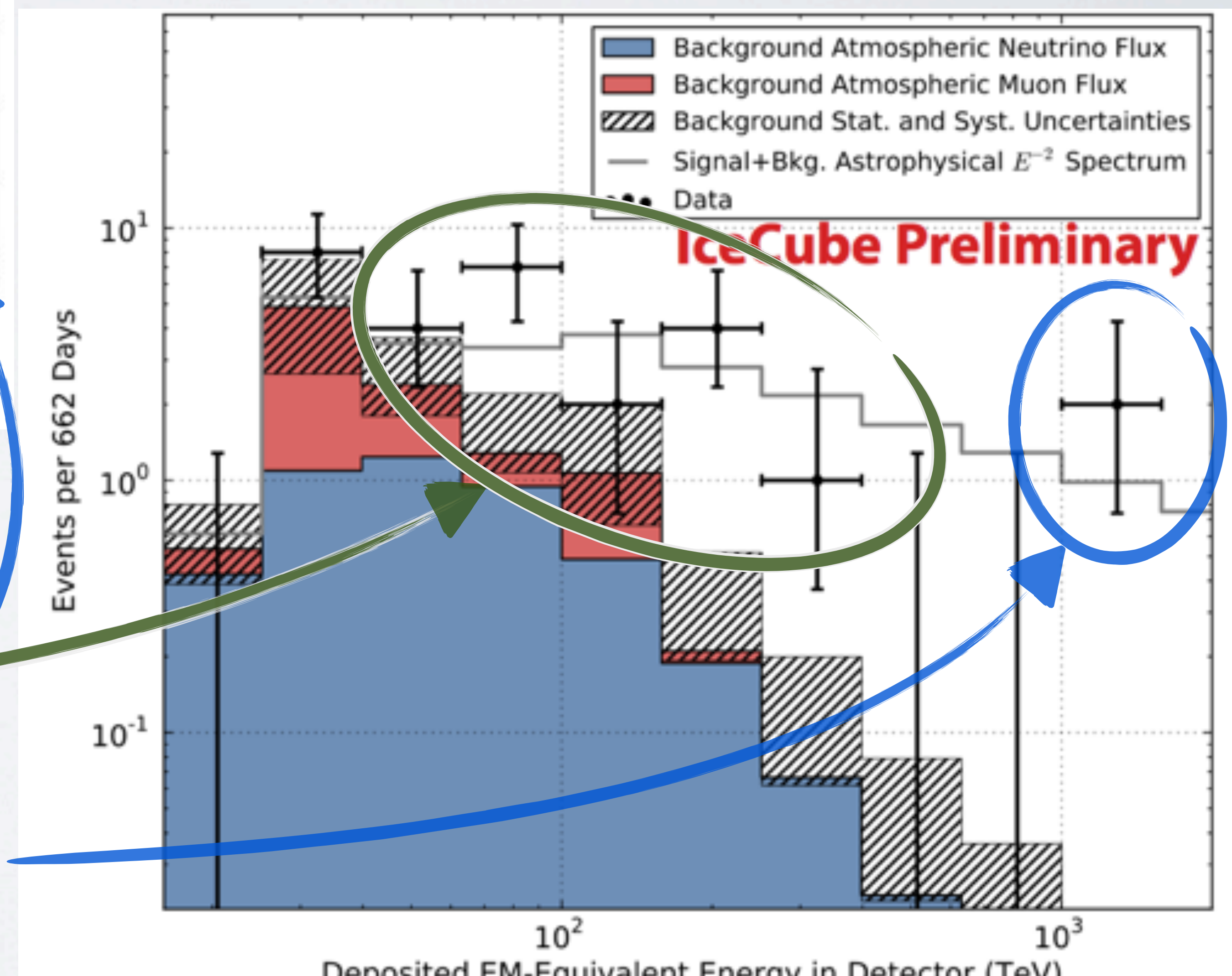
“Track” = contained shower with muon track coming out

ν_μ CC scattering
ν_τ CC scattering with soft μ
unvetoed μ

$\nu_{e,\mu,\tau}$ NC scattering

“Shower” = contained shower





significant excess around 50-250 TeV

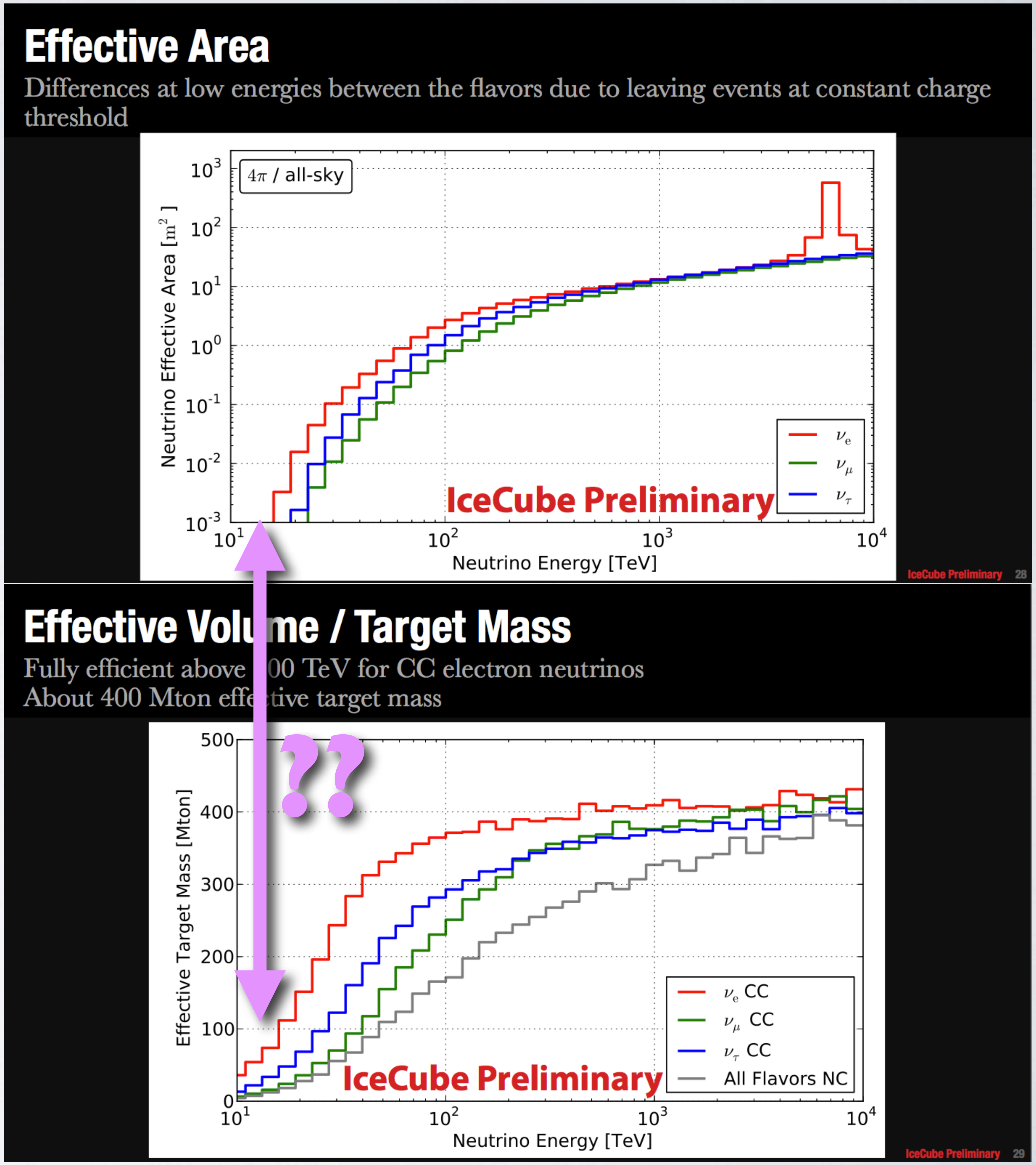
Bert & Ernie

MISSING DETAILS

Effective area is inconsistent with effective mass

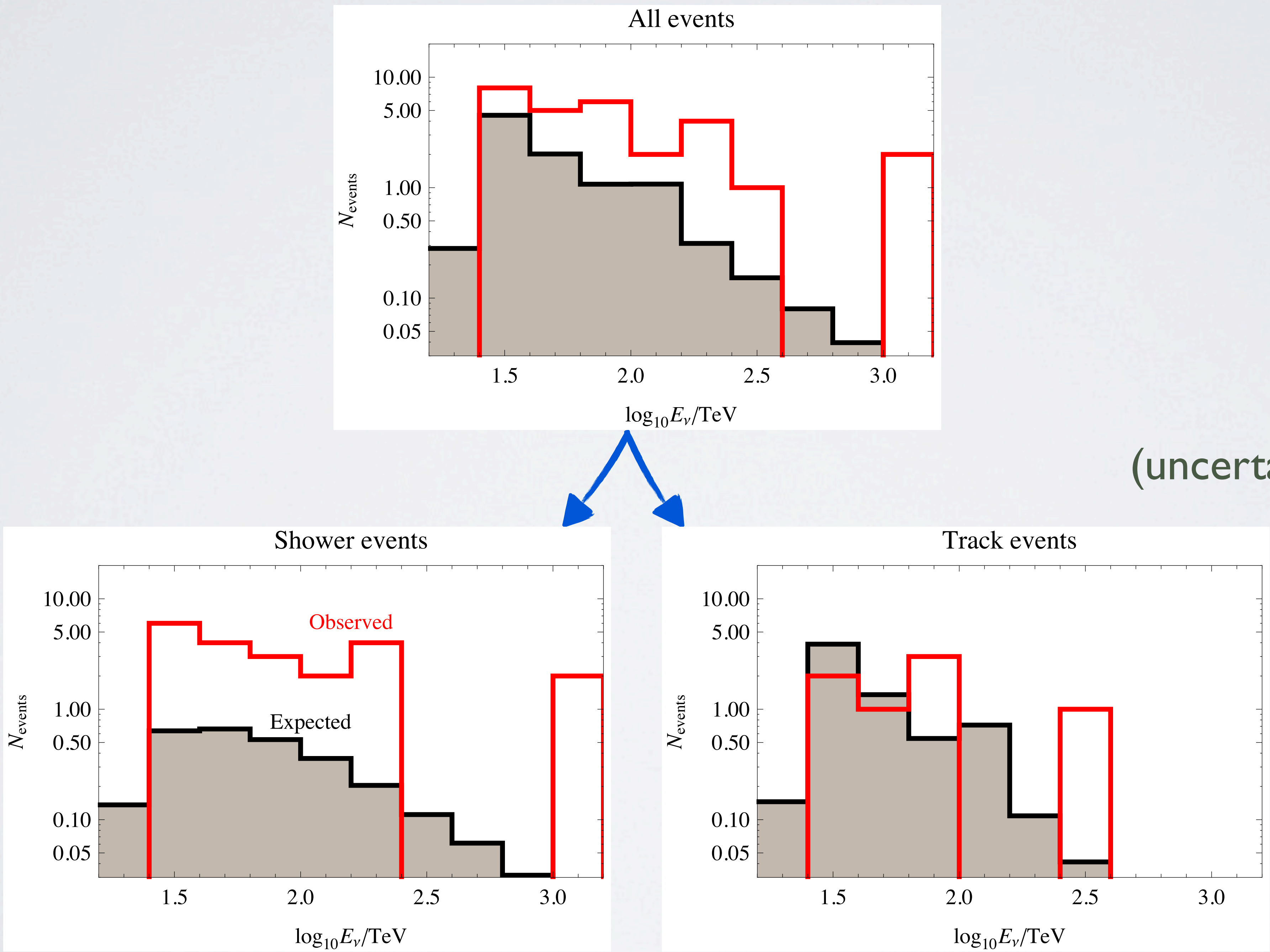
Track energy information from dE/dx?

Breakdown of backgrounds by shower vs track?



Showers vs Tracks: dirty analysis

Excess looks especially significant in shower events! (?)



(uncertainties not shown!)

What's causing the excess?

Detector issues?

- probably not

(Atmospheric) background prediction is wrong?

- PDF uncertainties at O(30%) -- not enough to explain excess

Astrophysical sources

- GRBs, AGNs, ... (e.g. Kistler et al 1301.1703, Laha et al 1306.2309, Chen et al 1309.1764, ...)
- If "expected" flux parametrized with $E^{-\gamma}$ spectrum, can give good fit

"Glashow resonance" (W^-)

- 6.3 PeV ν_e is on resonance with an electron
- not clear how this could explain 2 events at PeV (Barger et al 1207.4571)

BSM physics?

- decaying DM (Feldstein et al 1303.7320; Esmail & Serpico1308.1105)
- leptoquark resonance (Barger & Keung 1305.6907)

COULD IT BE DM ANNIHILATION?

Looks tantalizingly like the double-bump spectrum!

line at ~1.1 PeV from galactic annihilations
+ redshifted 50-250 TeV excess from Pop-III halos?

Approach

- First try to fit "line" with galactic signal
- then come to Pop-III signal

Disclaimer: statistical fits aren't very good with 2 events points...

GALACTIC NEUTRINO SIGNAL

Flux from galactic annihilations:

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{2(4)} \frac{\sigma v_{\rm ann}}{4\pi m_{\rm DM}^2} \frac{dn_{\nu_i}}{dE_\nu} \int d\Omega \, J(\theta, \phi)$$

$$\text{where } J(\theta,\phi) \equiv \int_{\rm l.o.s.} dl \rho_{\rm DM}^2(\vec{r})$$

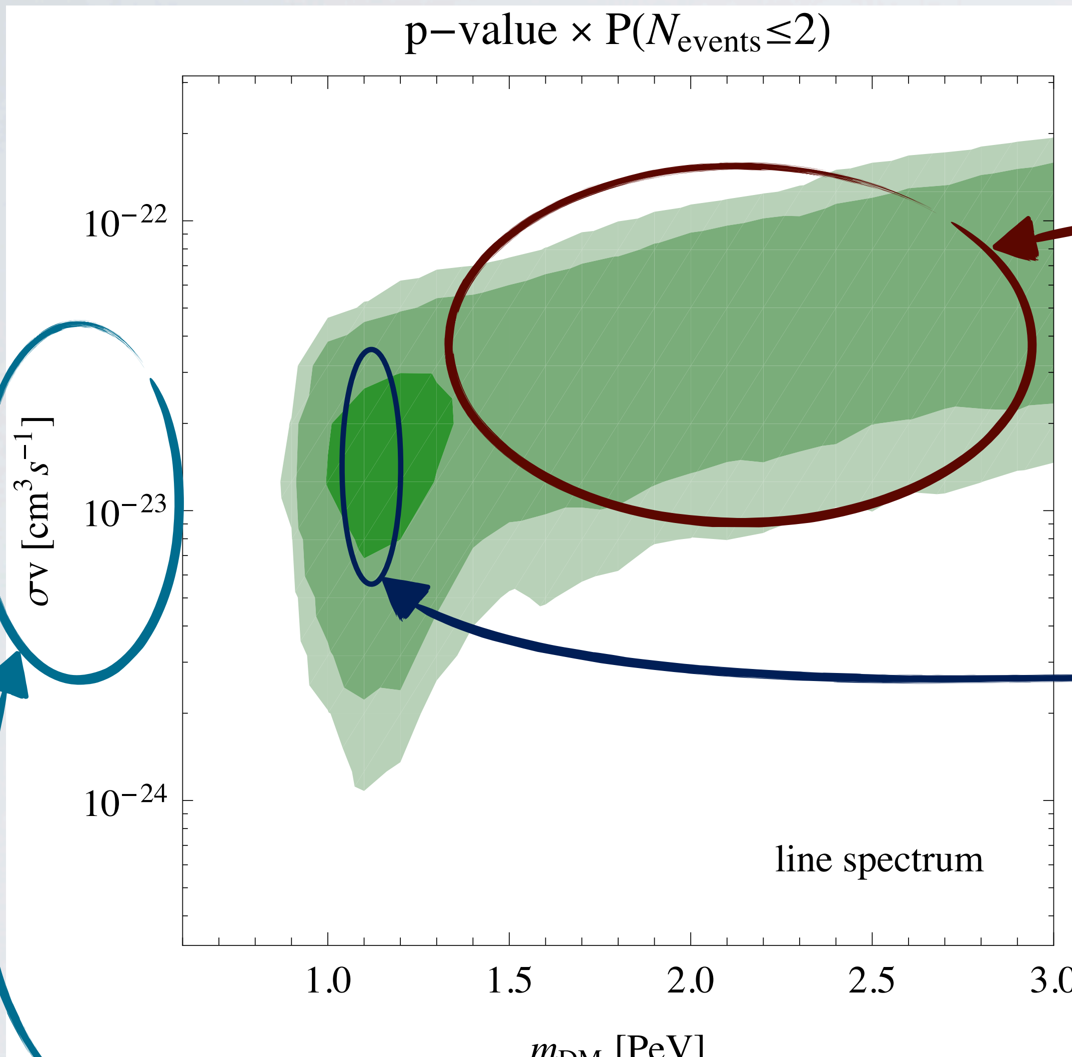
uncertainty in halo profile → factor 3 or more off?

DM substructure → could boost J by orders of magnitude

For now take typical NFW profile

FITTING THE DATA: LINE SPECTRUM

Try to fit to the data *above 300 TeV* (i.e. just 2 events!)

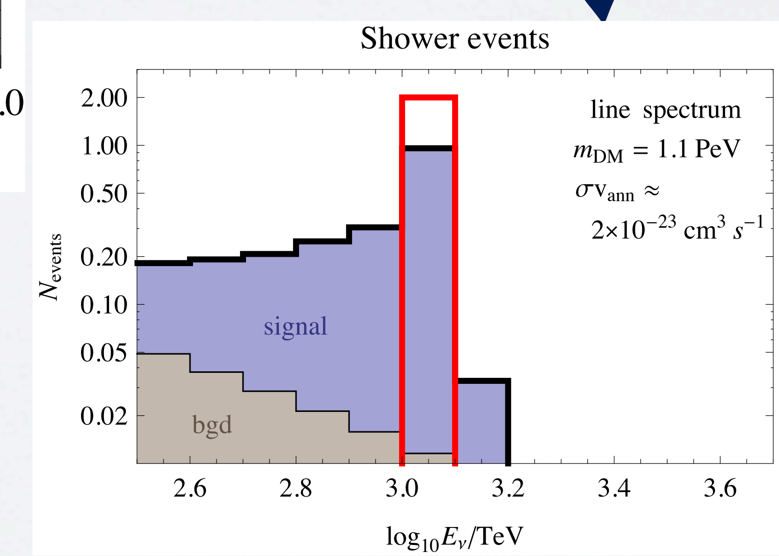


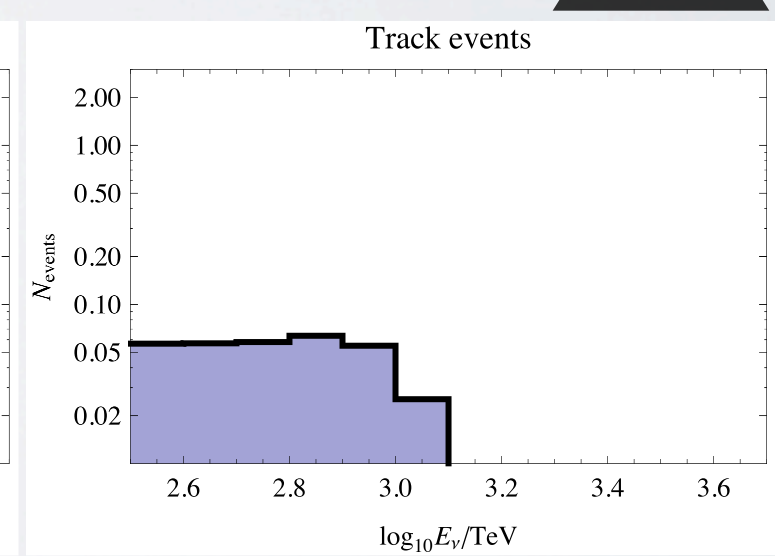
2 events do not make a line:
a broader spectrum works too

if it's really a line

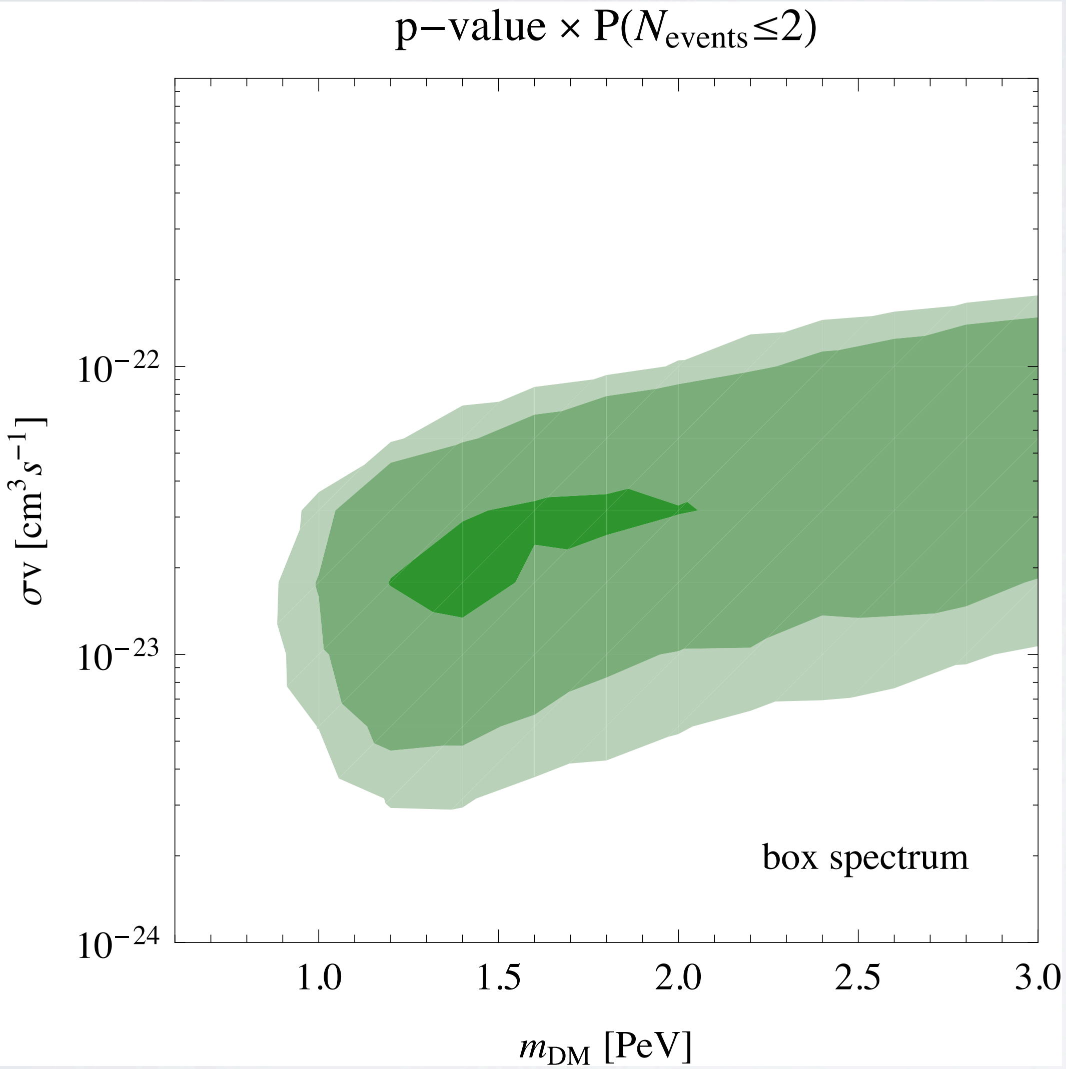
enormous annihilation cross-section!

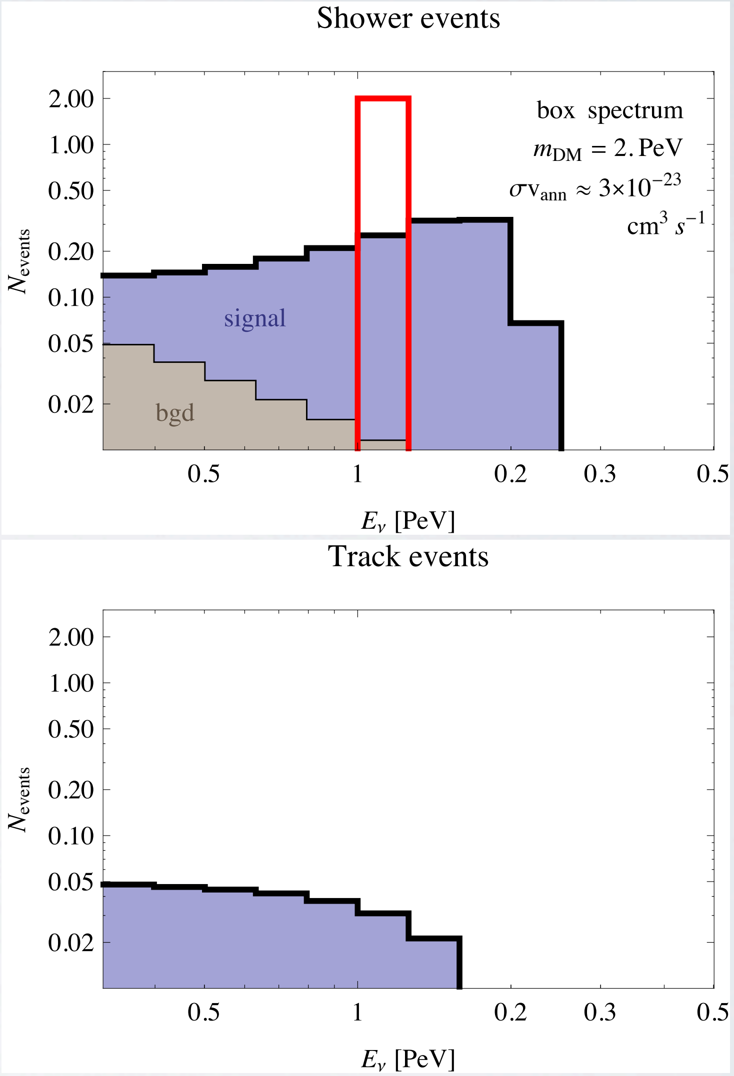
pre-liminary!





FITTING THE DATA: BOX SPECTRUM





pre-liminary!

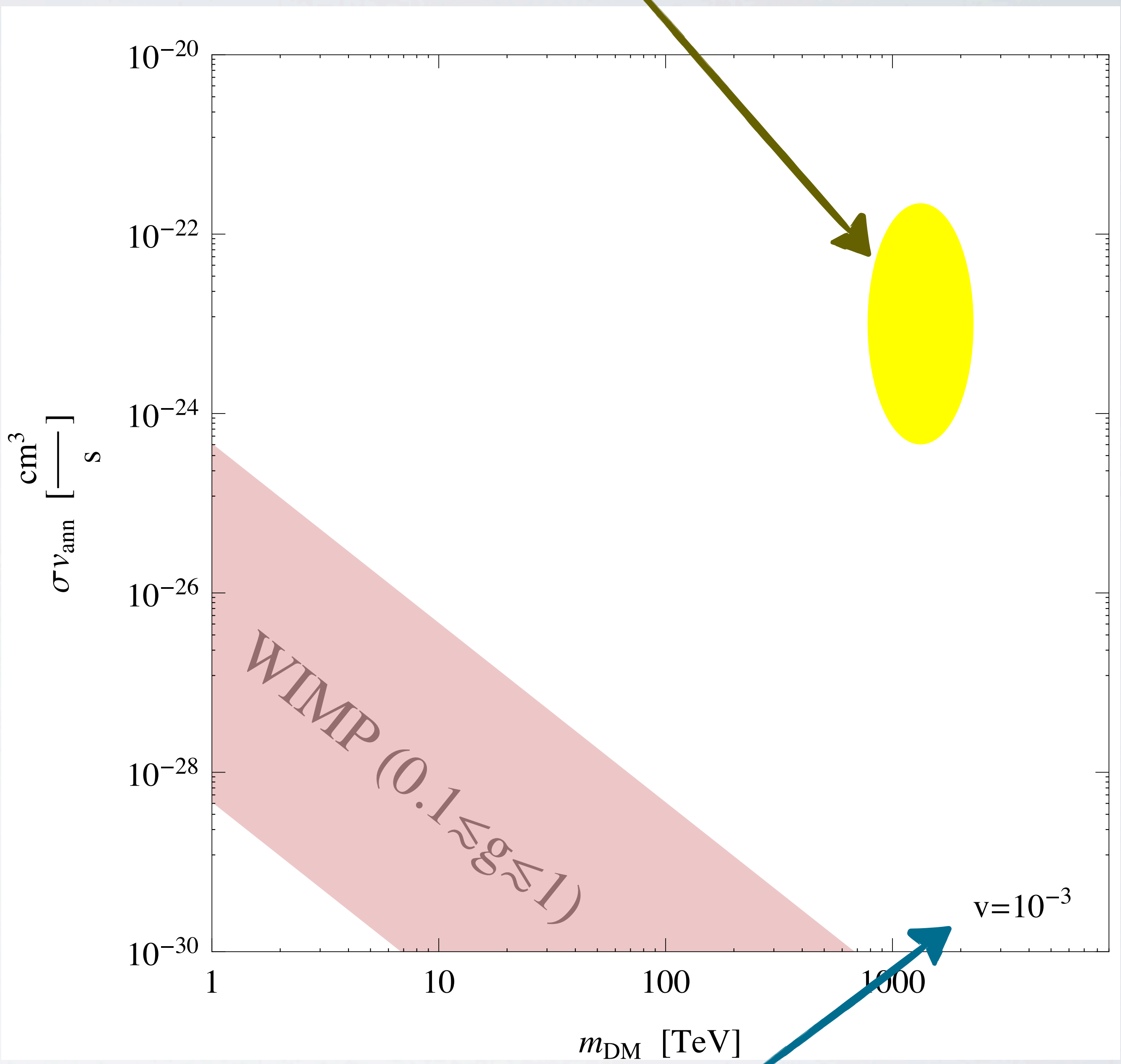
Can DM have such a huge cross-section?

(work in progress with
P. Graham, S. Rajendran, R. Sundrum & L. Vecchi)

CAN DM HAVE SUCH A HUGE CROSS-SECTION?

WIMP: $\sigma v_{\rm rel} \approx \dfrac{g^4}{8\pi m_{\rm DM}^2}$

goal



typical velocity in galaxy
and around Pop-III star

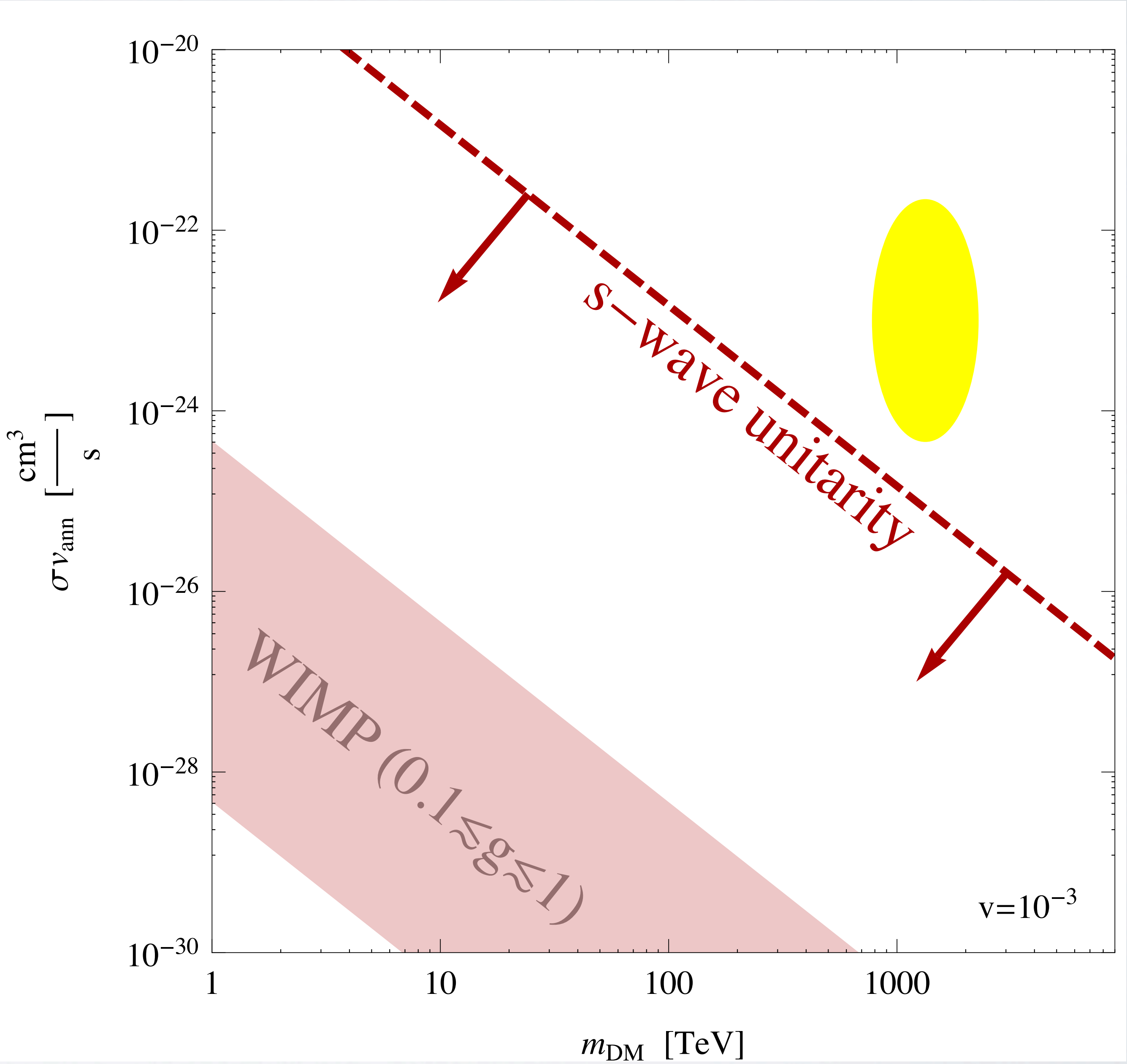
Can DM have such a huge cross-section?

WIMP: $$\sigma v_{\rm rel} \approx \frac{g^4}{8\pi m_{\rm DM}^2}$$

s-wave unitarity:

(Griest & Kamionkowski 1990)

$$\sigma v_{\rm rel} < \frac{4\pi}{m_{\rm DM}^2 v_{\rm rel}}$$



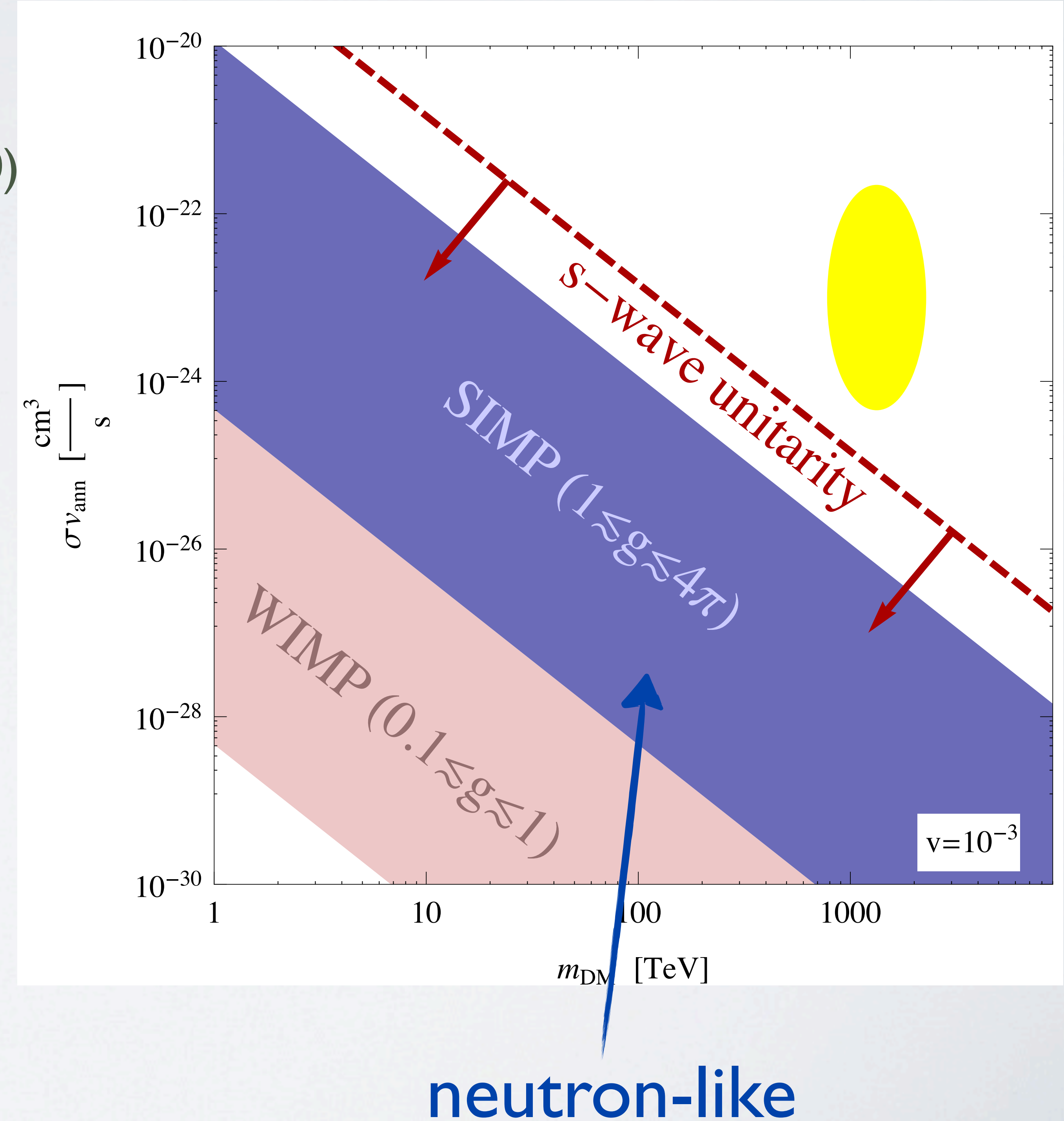
Can DM have such a huge cross-section?

WIMP: $$\sigma v_{\rm rel} \approx \frac{g^4}{8\pi m_{\rm DM}^2}$$

s-wave unitarity:

(Griest & Kamionkowski 1990)

$$\sigma v_{\rm rel} < \frac{4\pi}{m_{\rm DM}^2 v_{\rm rel}}$$



CAN DM HAVE SUCH A HUGE CROSS-SECTION?

WIMP: $\sigma v_{\rm rel} \approx \dfrac{g^4}{8\pi m_{\rm DM}^2}$

s-wave unitarity:

(Griest & Kamionkowski 1990)

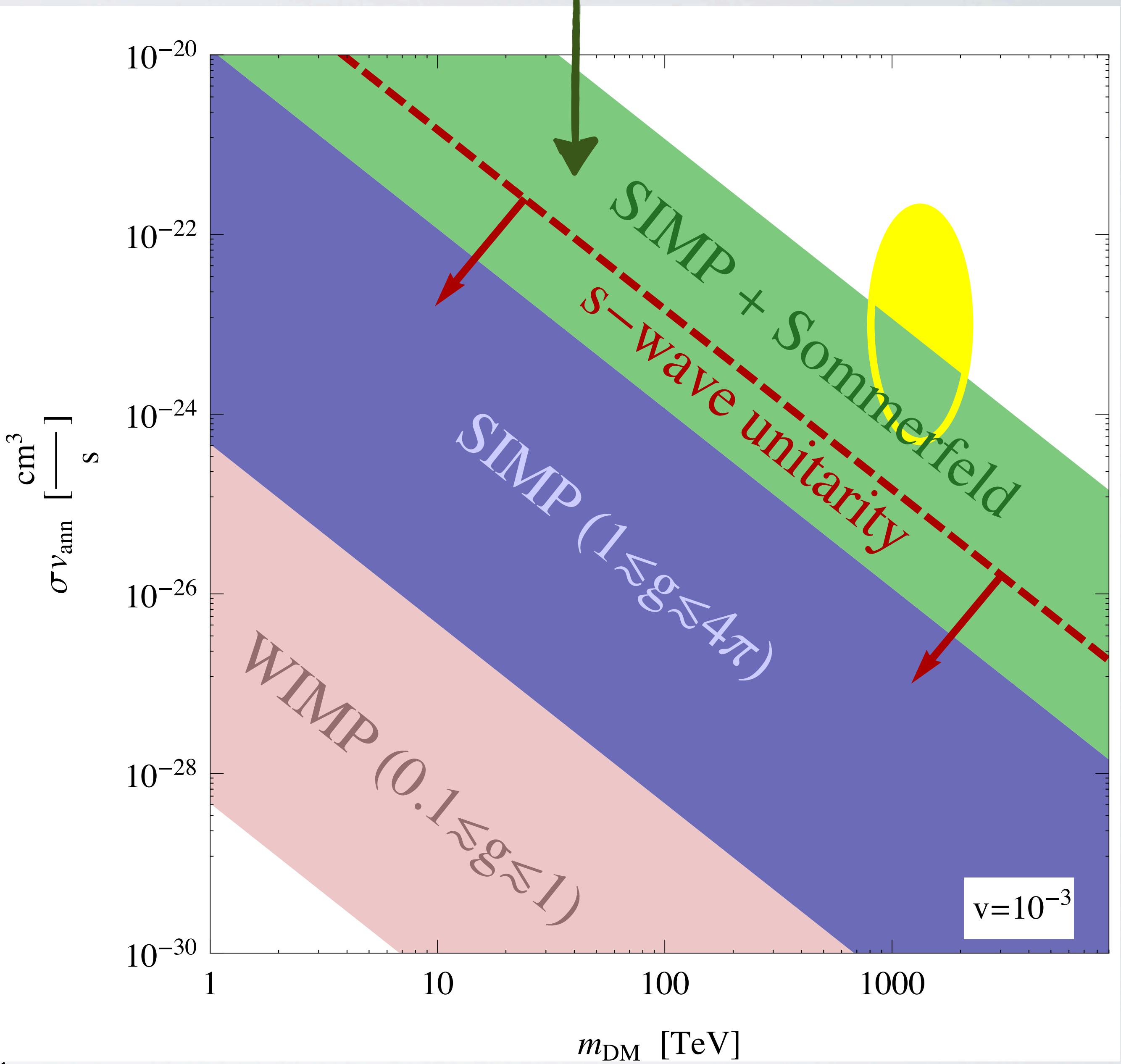
$$\sigma v_{\rm rel} < \frac{4\pi}{m_{\rm DM}^2 v_{\rm rel}}$$

Sommerfeld enhancement:

$$\sigma v_{\rm rel} \to \sigma v_0 \times \frac{\lambda^2}{4 v_{\rm rel}}$$

- N.B. at freeze out, $v_{\rm rel}$ is about 300 × larger
- $\sigma v_{\rm rel}$ is about 300 × smaller
- $\sigma v_{\rm rel} \sim 3 \times 10^{-26}\,{\rm cm^3\,s^{-1}}$

proton-like



Can DM have such a huge cross-section?

WIMP: $$\sigma v_{\rm rel} \approx \frac{g^4}{8\pi m_{\rm DM}^2}$$

s-wave unitarity:

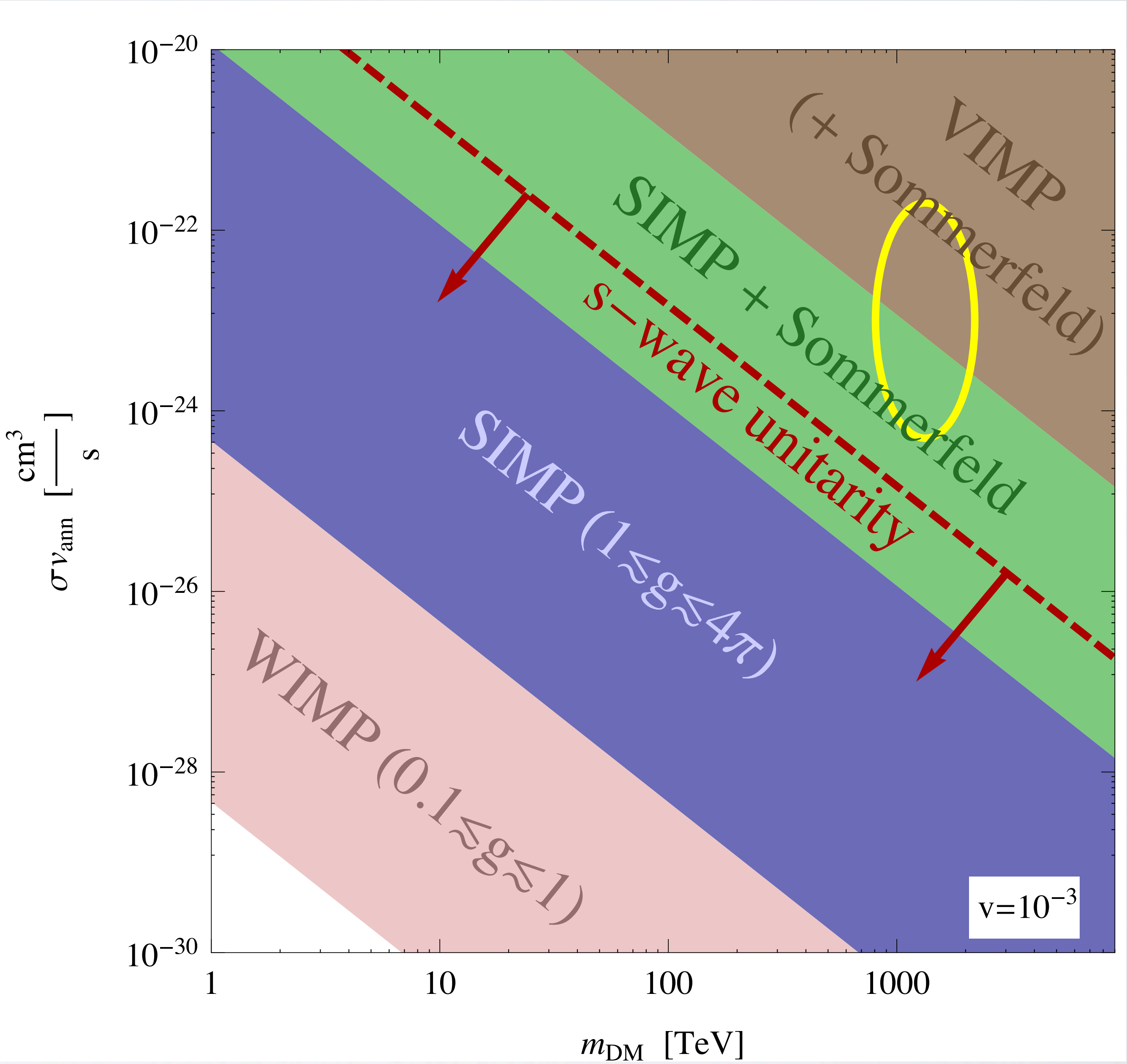
(Griest & Kamionkowski 1990)

$$\sigma v_{\rm rel} < \frac{4\pi}{m_{\rm DM}^2 v_{\rm rel}}$$

Sommerfeld enhancement:

$$\sigma v_{\rm rel} \to \sigma v_0 \times \frac{\lambda^2}{4 v_{\rm rel}}$$

Beyond proton-like composites: VIMPs



Very Important Massive Particles

What are they?

- very massive particles surrounded by an entourage of lighter particles
- **geometric cross section MUCH bigger than compton wavelength**
- I just made up the name

How do they arise?

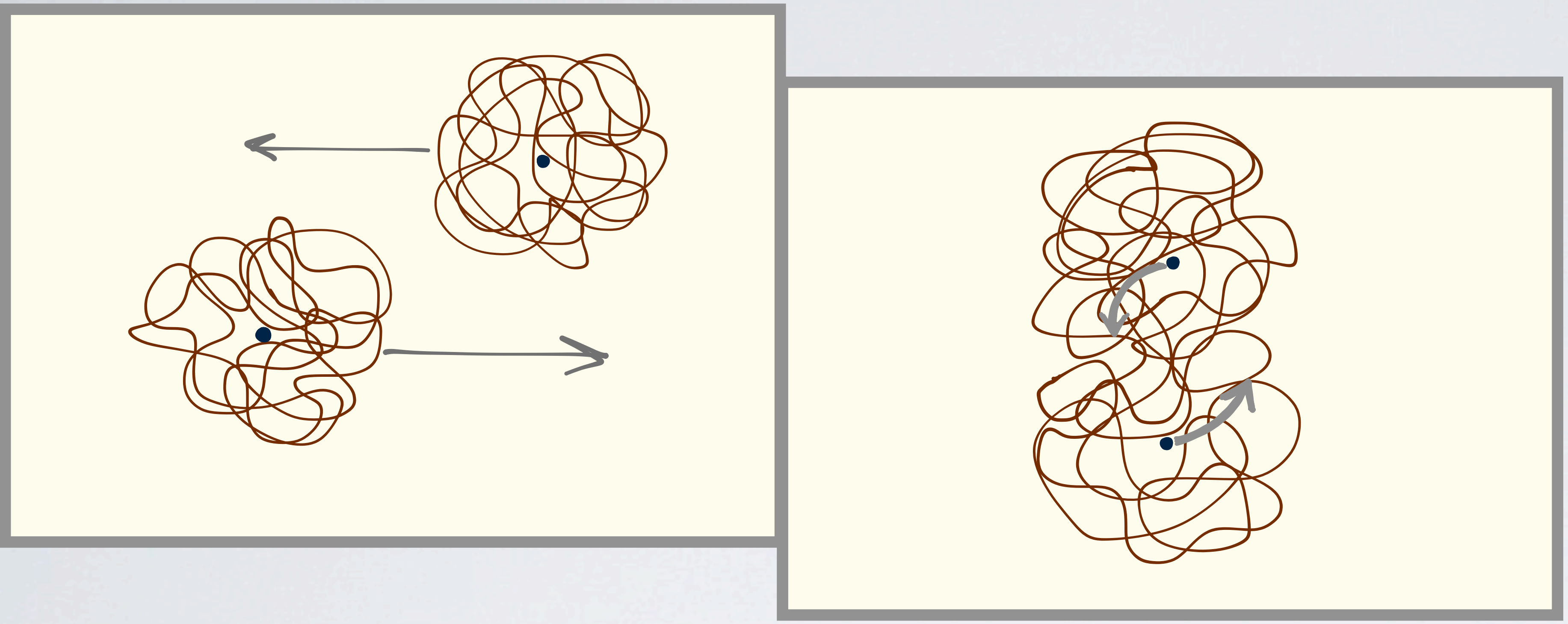
- **like B mesons:**
  confining interaction with stable heavy quarks
  heavy quarks hadronized by "brown muck" of light quarks

Previously work:

- cosmology of massive coloured relics

Kang, Luty & Nasri hep-ph/0611322 , Jacoby & Nusinov 0712.2681

ANNIHILATION OF 2 VIMPs



Can the particles become bound?

estimate:

$$\frac{\Delta E}{E} \approx \frac{F \Delta x}{m_{\mathrm{DM}} v^2} \approx \frac{\Lambda^2 \times \Lambda^{-1}}{m_{\mathrm{DM}} v^2}$$

$$\implies \Lambda > m_{\mathrm{DM}} v^2 \sim \mathrm{TeV}$$

ANNIHILATION OF 2 VIMPS

Annihilation cross section is geometric

$$\sigma v_{\rm rel} \sim \frac{\pi}{\Lambda^2} v_{\rm rel} \gg \frac{4\pi}{m_{\rm DM}^2 v_{\rm rel}}$$

How to get a hard neutrino spectrum

Issue with SIMPs / composite DM

- only get large cross-section by using strong coupling interactions

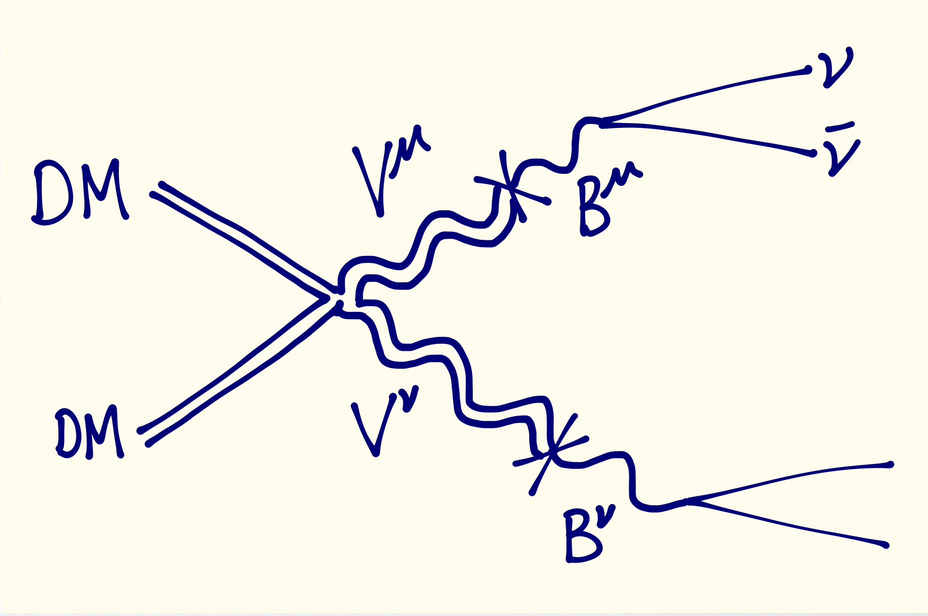
SOME IDEAS:

Leptons are composite at scale of DM

- can have large couplings to composite DM particles
- maximal coupling → DM annihilates to spray of soft leptons
- sub-maximal coupling: DM prefers to annihilate to 2 or 4 leptons

Composite DM annihilates into composite vectors

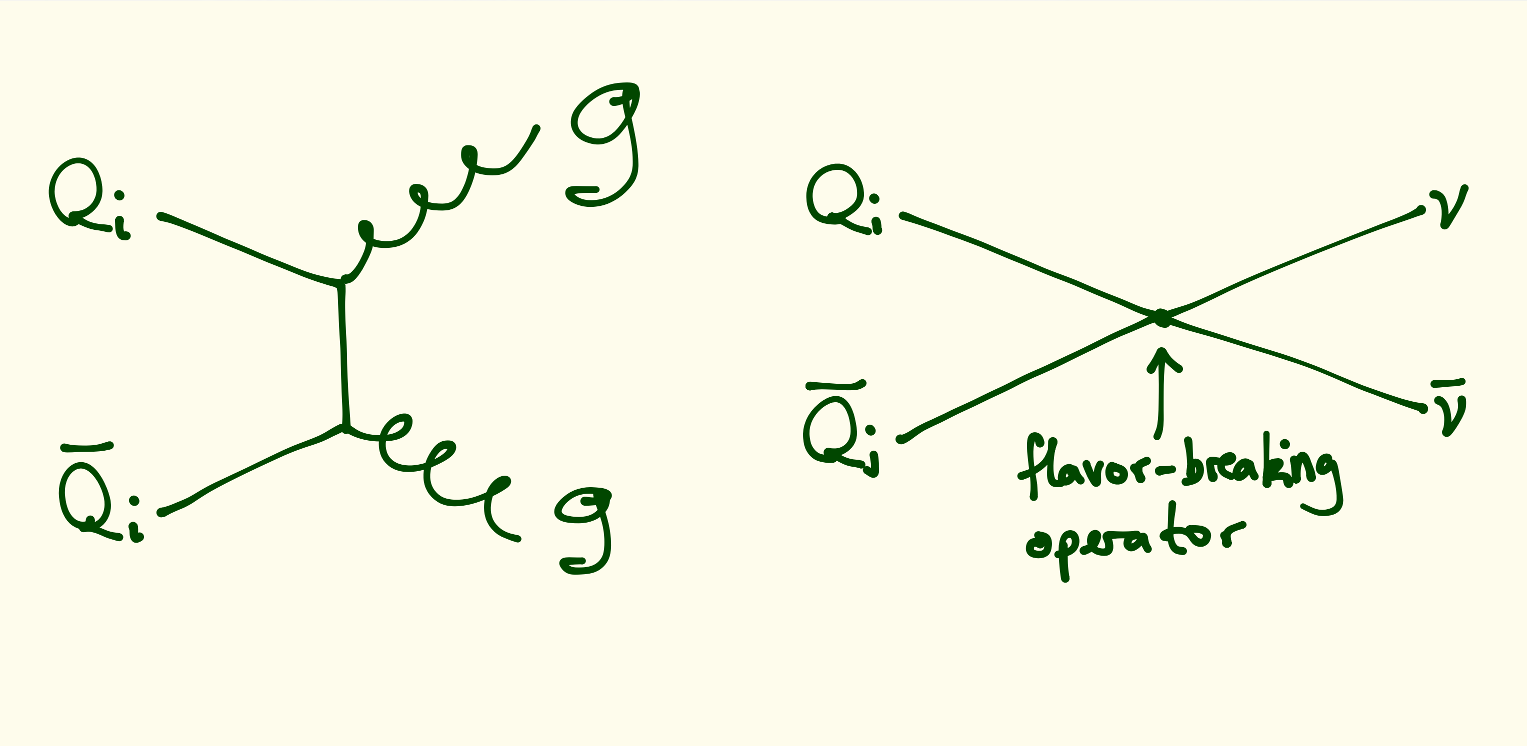
- vectors decay through weak mixing in to SM



HOW TO GET A HARD NEUTRINO SPECTRUM

VIMPs:

- annihilation and scattering can occur though quite different interactions
- e.g. same-flavor heavy quarks annihilated to hidden-sector gluons
- different flavor heavy quarks annihilate through flavor-violating interactions



QUICK SUMMARY

PeV DM

with

"unitarity"-beating cross-section

- not just easy to come up with: it's actually SM-like

Hard or monochromatic neutrino spectrum

- can be achieved without too much trouble

More details for another day

Does it Fit with Pop III?

Pop III physics very uncertain

Best we can do:

- see what Pop III physics we would need to explain IceCube
- see if it fits with what we learn in the future about Pop III stars

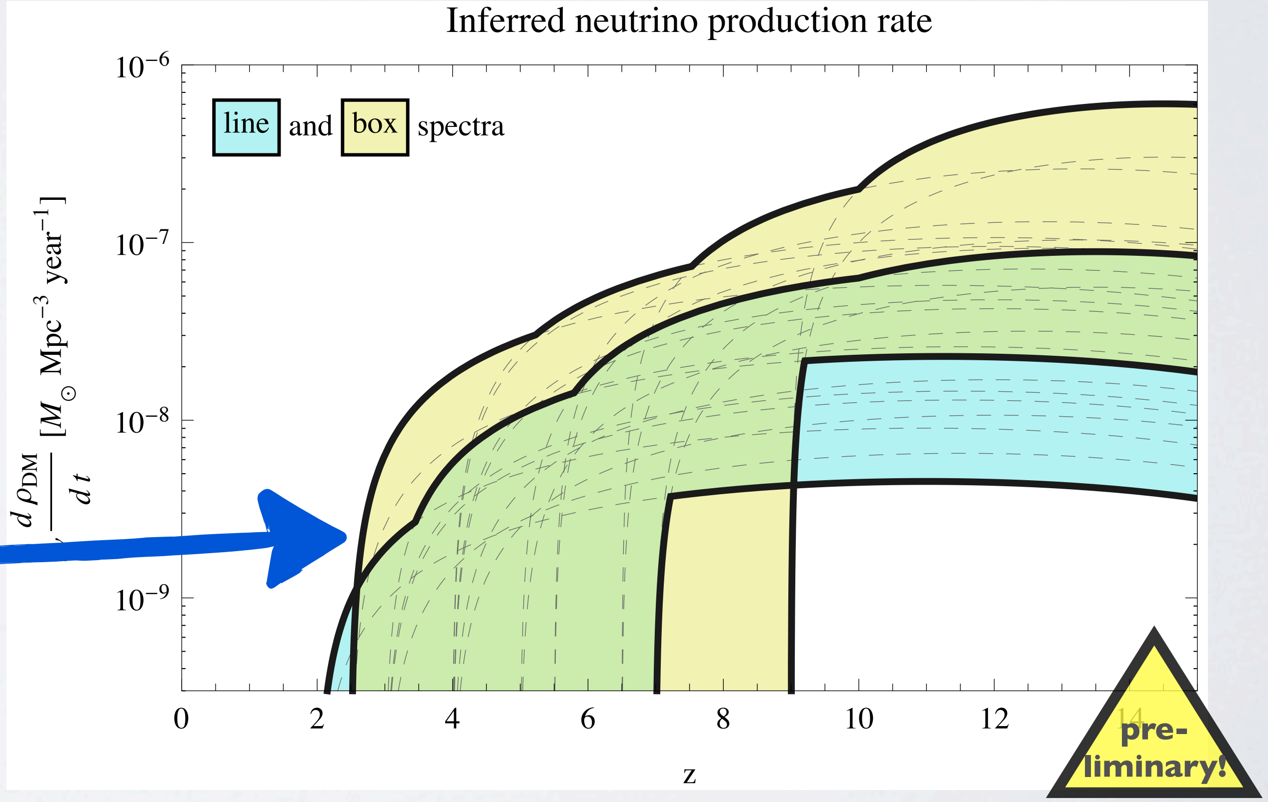
Inferring the Neutrino Production Rate

What would the cosmic rate of neutrino production from DM annihilations need to be to fit the excess?

Take simple parametrization and fit to data

- quadratic function
- production begins at z=25 (not very important)
- continues until z_{end}
- overall normalization A

This is the spread of what fits (approximate)



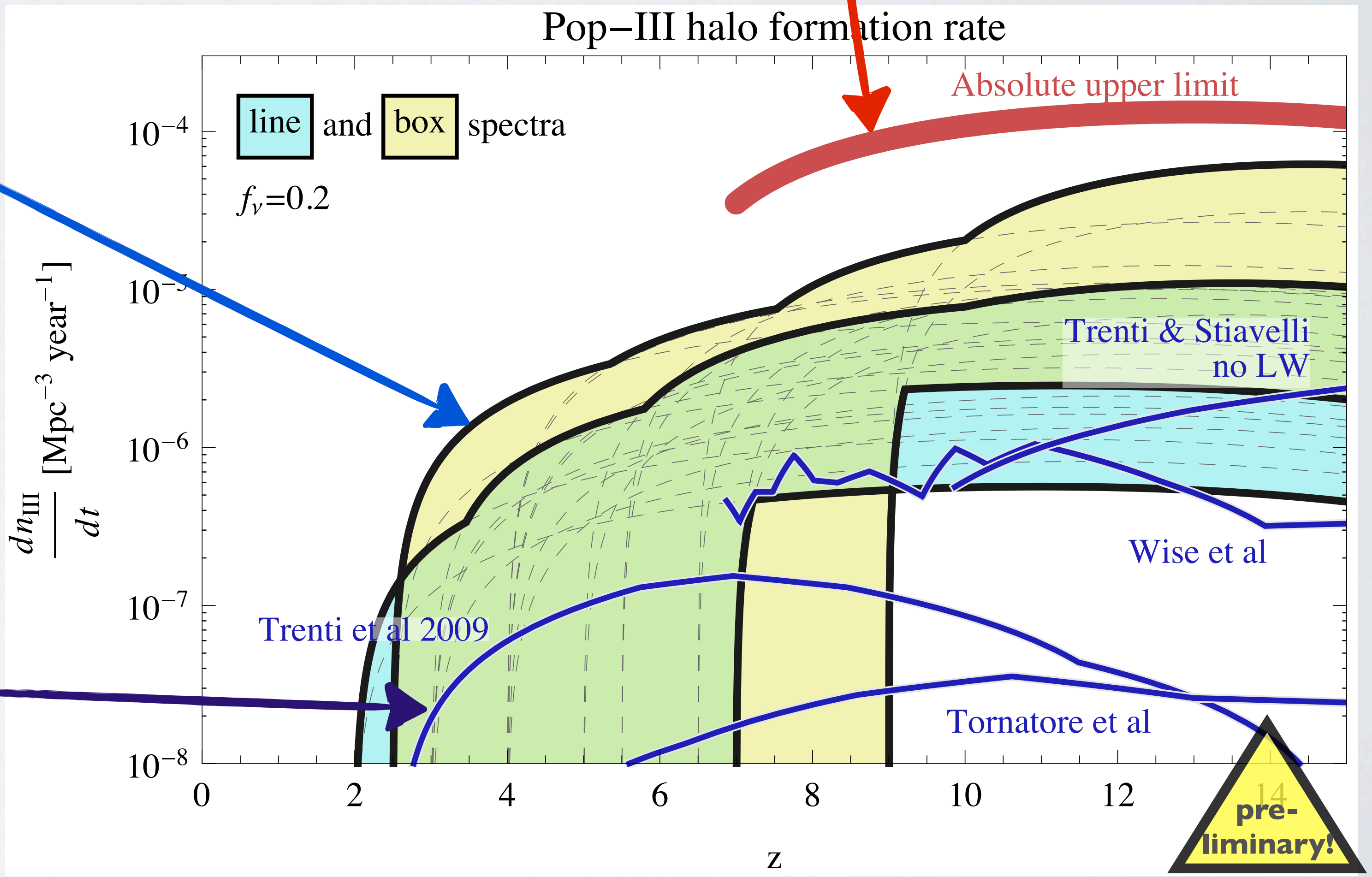
WHAT POP-III FORMATION RATE DO WE NEED?

Divide by DM mass annihilated per Pop-III halo to get halo formation rate

red curve: if all matter formed a Pop-III halo

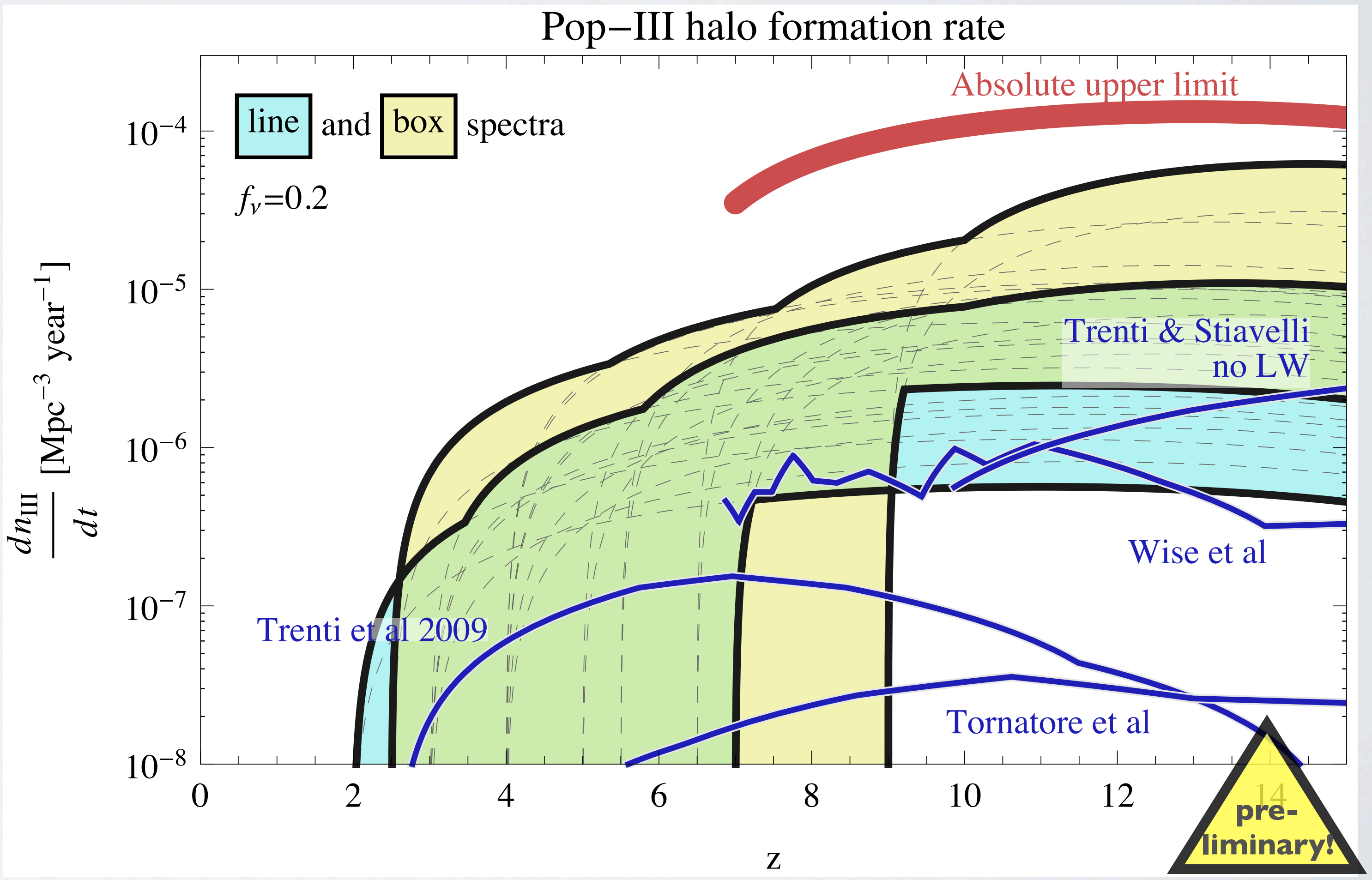
Results using simple adiabatic contraction model from initial NFW profile

some models in the literature (should be taken with salt)



WHAT POP-III FORMATION RATE DO WE NEED?

Divide by DM mass annihilated per Pop-III halo to get halo formation rate

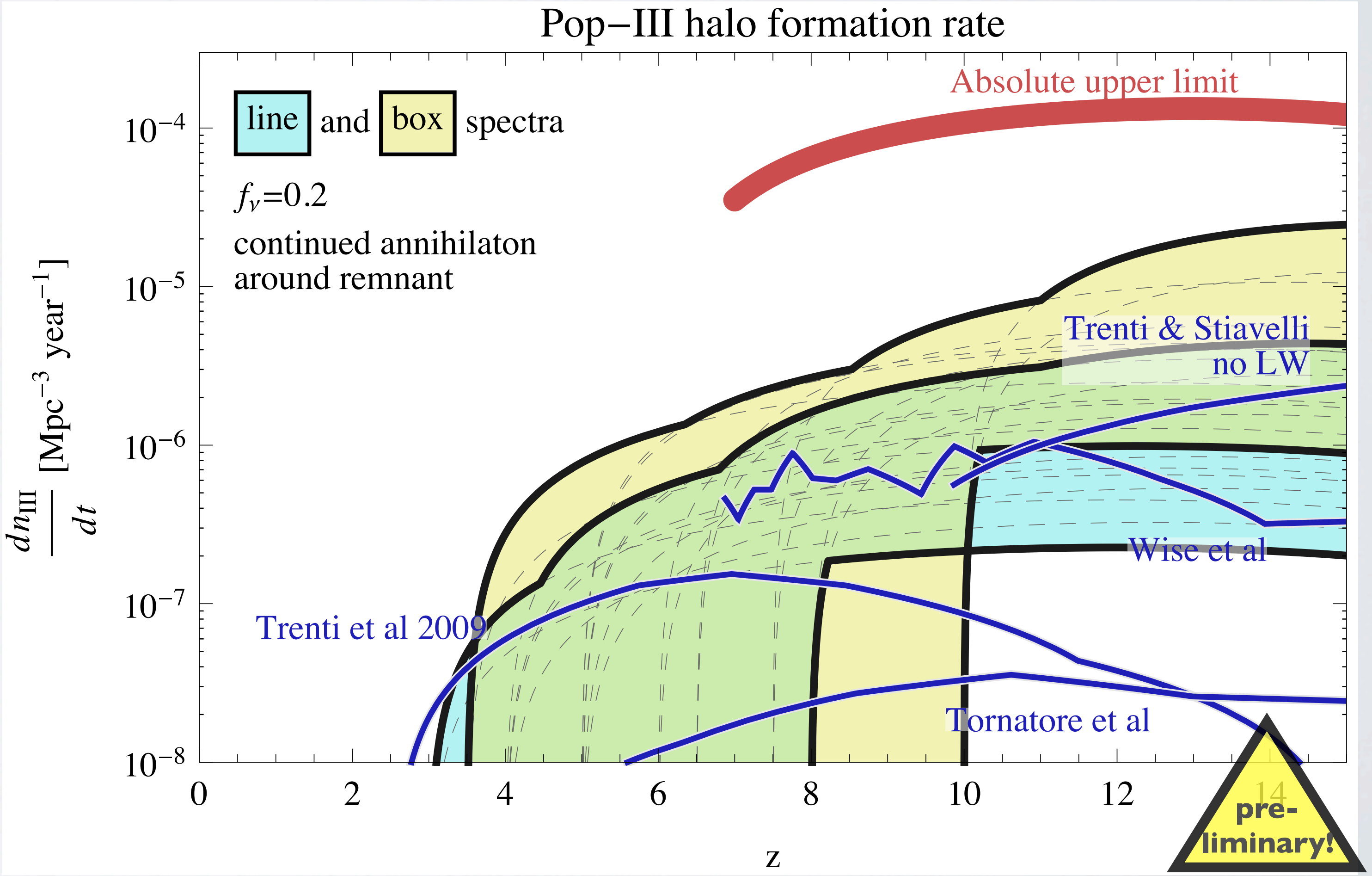


WHAT POP-III FORMATION RATE DO WE NEED?

Enhanced DM densities survive around Pop-III remnant

Annihilation continues until disrupted by merger

Take $z_{merge} = (z_{form} - 1.2)/1.08$ (Lacey & Cole 1993; Yuan et al 1104.1233)



Looks almost believable!

Testing Pop-III origin with Gamma rays

Gamma ray signal

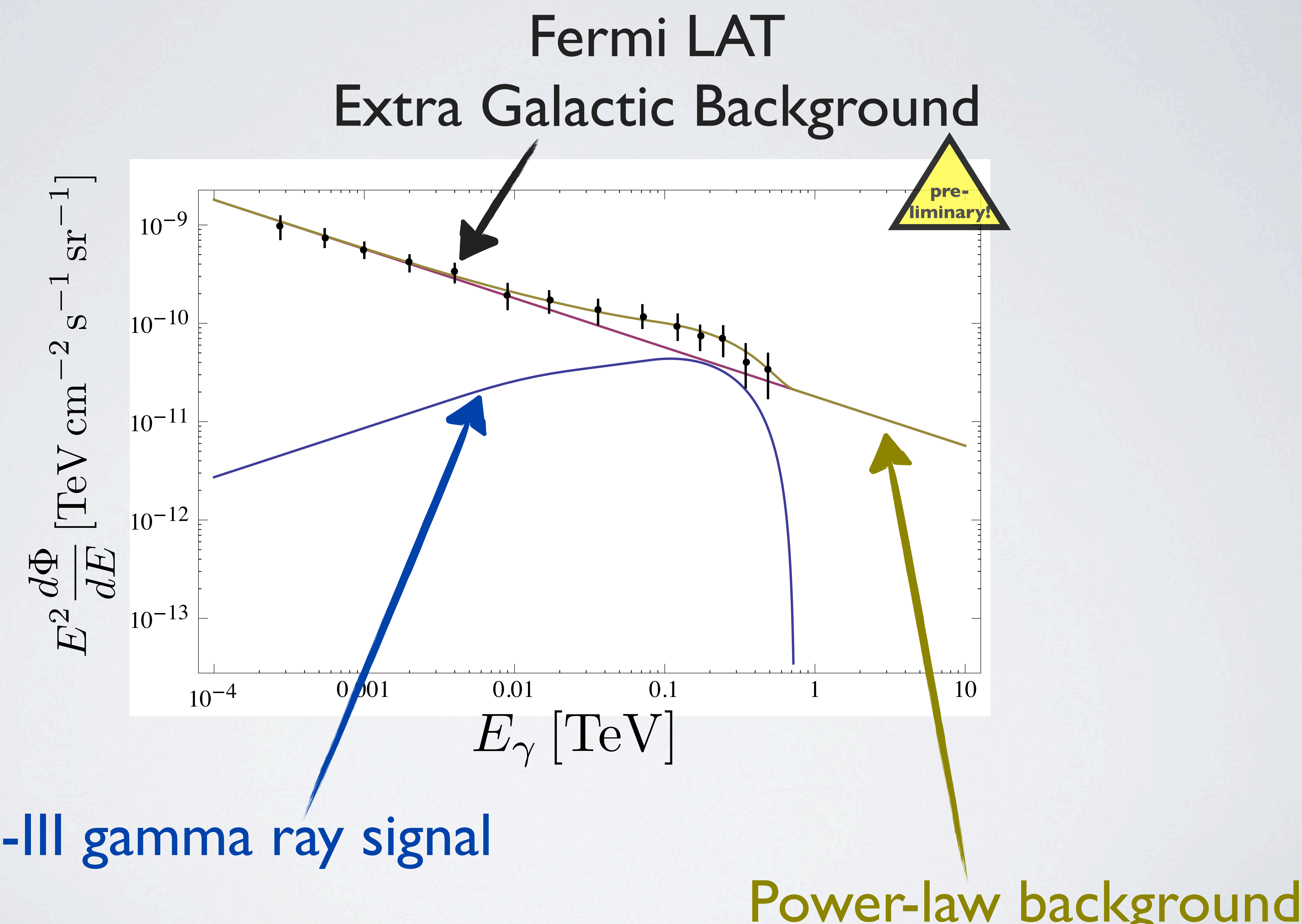
- γs from DM annihilations will scatter with CMB photons
- so will e^+/e^- if they can escape halo without syncrotron loss
- at z=10, a **single PeV $\gamma/e^+/e^-$ showers into about 300 $(\gamma/e^+/e^-)$'s** with ~3 TeV energy each
- redshift to give **signal at ~300 GeV**

(Kribs & Rothstein hep-ph/9610468)

PeV gammas from annihilation in Milky Way?

- impossible (?) to distinguish from cosmic rays with air/water Cherenkov telescopes

Testing Pop-III origin with Gamma rays



Testing Pop-III origin with Gamma rays

Q: How robust is it?

- depends on neutrino production rate (function of z)
  fit this from neutrino signal
  does NOT depend on Pop-III astrophysics!
  learn about Pop-III formation history from this? ($E_\gamma \sim 1/(1+z)^2$)
- depends on production of γs and e^+e^- relative to **ν**s
  hard to avoid producing e^+e^- when there is a channel to **ν**s
  may be increased with larger BR to γs
  (may be decreased if there are **B**-fields in halo causing syncrotron losses)

A: Quite robust!

Other possibilities

Is all the IceCube excess from Pop-III DM annihilation?

- would need mDM ~ 5-20 PeV
- $\sigma v_{ann} \sim 10^{-22}\ cm^3\ s^{-1}$?
- gamma signal roughly unchanged

Is all the IceCube excess from galactic DM annihilations?

- requires softer initial neutrino spectrum
- $\sigma v_{ann} \sim 10^{-22}\ cm^3\ s^{-1}$?

What's Next

Need more IceCube data...

- is there a line at ~1 PeV ?
- is there a gap from ~300 TeV - PeV?
- does it extend beyond 1 PeV?
- does it come from Milky Way?

...data will triple in a couple of years

Need more gamma ray data

- Fermi pass-8 will reduce uncertainties and go to higher E
- as more point sources are discovered, EGB will go *down*

Need better simulations of Pop III stars and halos

Conclusion

The sites where the first stars (Pop-III) form may be the most remarkable places in the universe for DM

- gravitational contraction enhances density
- may be a region near star where *all* DM annihilates

If we journey beyond perturbative WIMPs, a much bigger range of DM masses and cross-sections is possible.

- s-wave unitarity is *not* the limit

Could this explain the IceCube neutrino excess?

- a line at ~1 PeV would be a smoking gun for DM
- how to test a Pop-III origin:
  double-bump signature of galactic+Pop-III DM annihilation
  gamma bump in Fermi at ~300 GeV

May find out in the next year or two

BACKUP

DM Annihilation Rate Estimate

Significant fraction of star's mass
may remain in remnant black hole

Heger & Woosley 2002

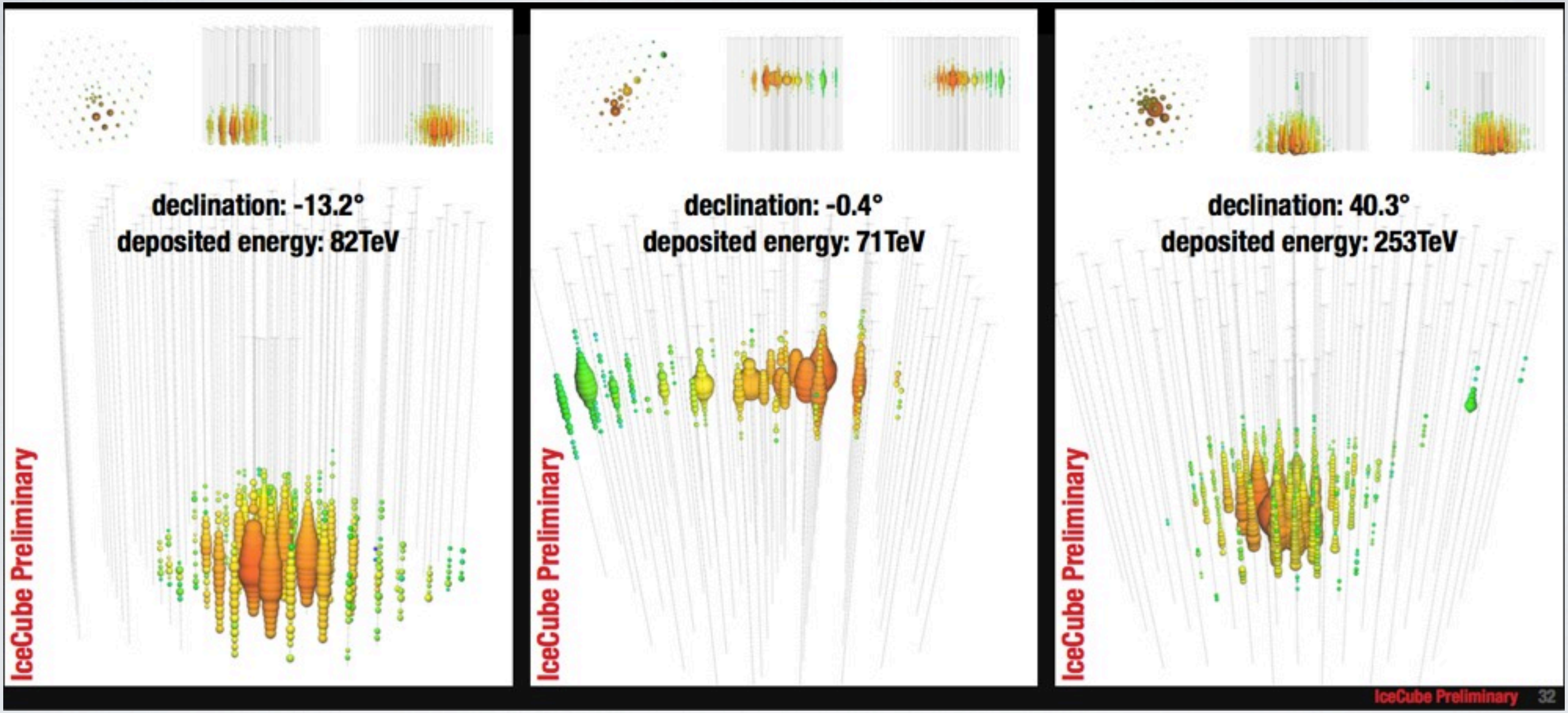
O(1) fraction of bound DM may remain bound

- Survives until merger, at about $z_{merge}=(z_{form}-1.2)/1.08$

Yuan et al 1104.1233

- increases mass of DM annihilated (by about 3)
- annihilation continues to lower z (by about 1)

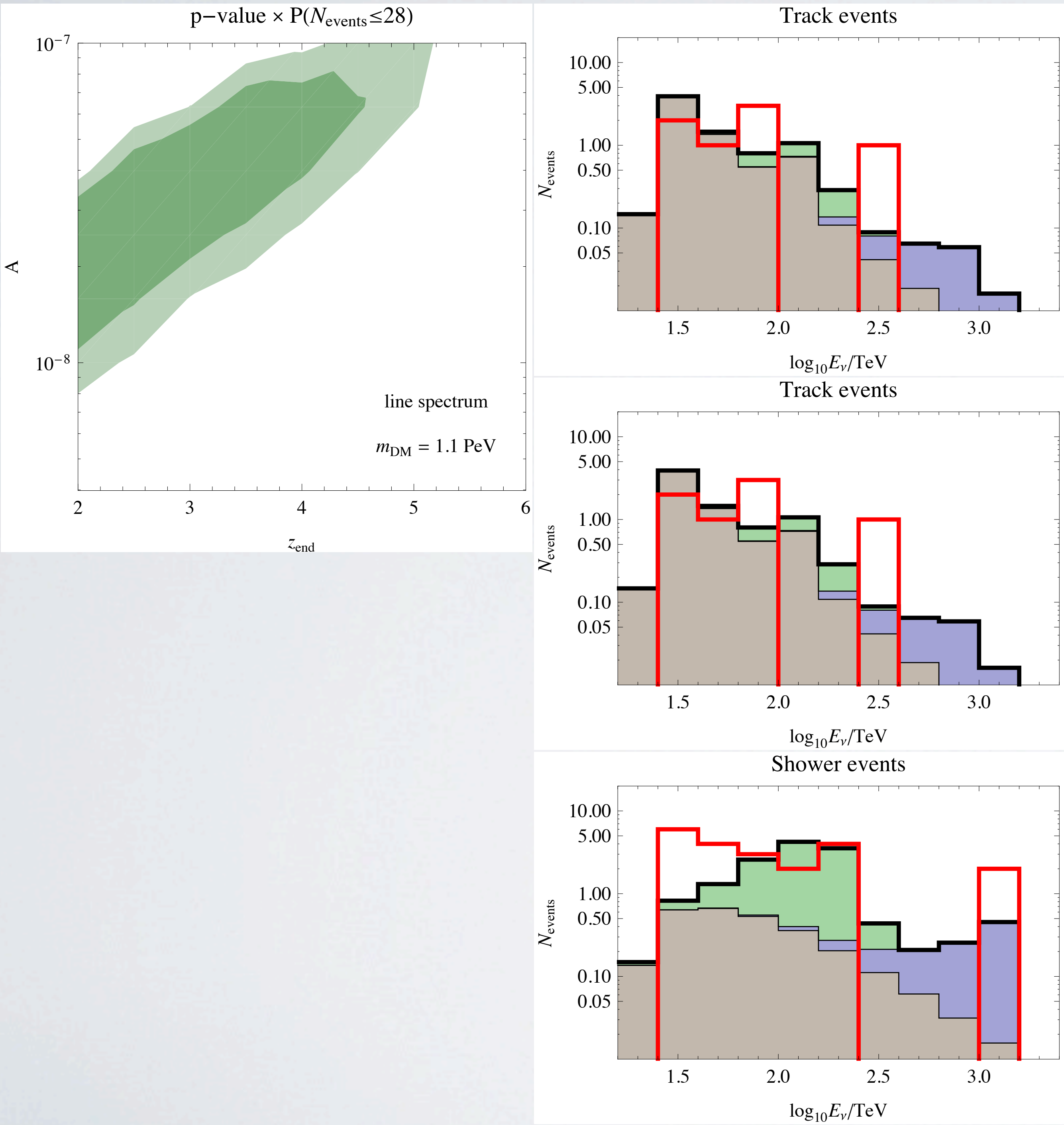
SHOWERS & TRACKS



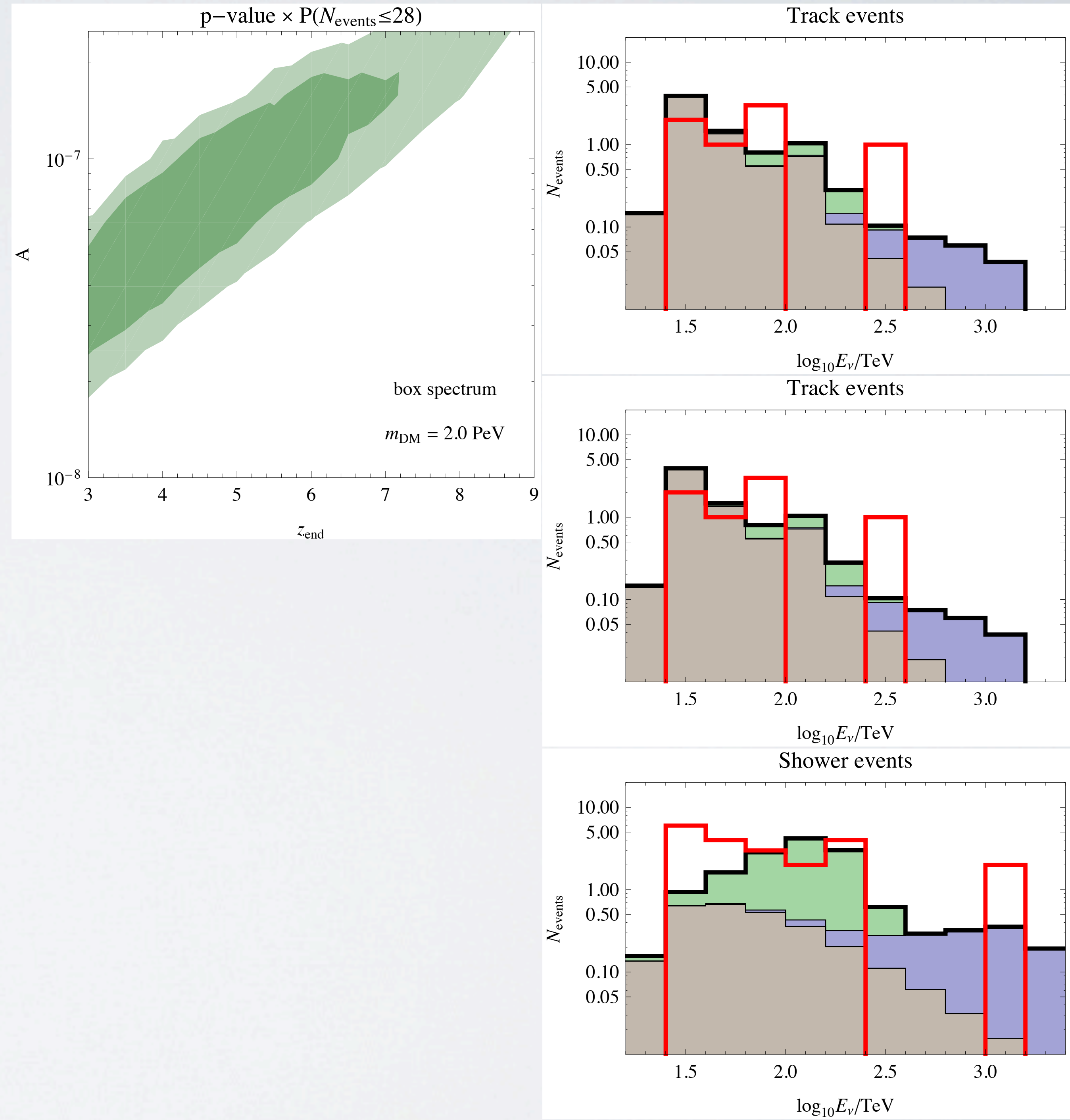
SAMPLE FITS

pre-liminary!

Line spectrum, m=1.1PeV



Box spectrum, m=2.0PeV



PROTONS VS. S-WAVE UNITARITY