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Probing for signs of neutrinos from heavy dark matter decay in the IceCube signal

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IceCube signals and power-laws

6-yr HESE data

- Interaction vertex in instrumented detector volume
- 80 events
- 60 TeV – 2.1 PeV
- Suggests steeply falling flux: $\gamma \approx 2.9$ (7.5-yr data)

$$\frac{d\Phi}{dE_\nu} \propto E_\nu^{-\gamma}$$

Talks at TeVPA 2018: Wood, Ahlers, Murase, Schneider…

IceCube signals and power-laws

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- 60 TeV – 2.1 PeV
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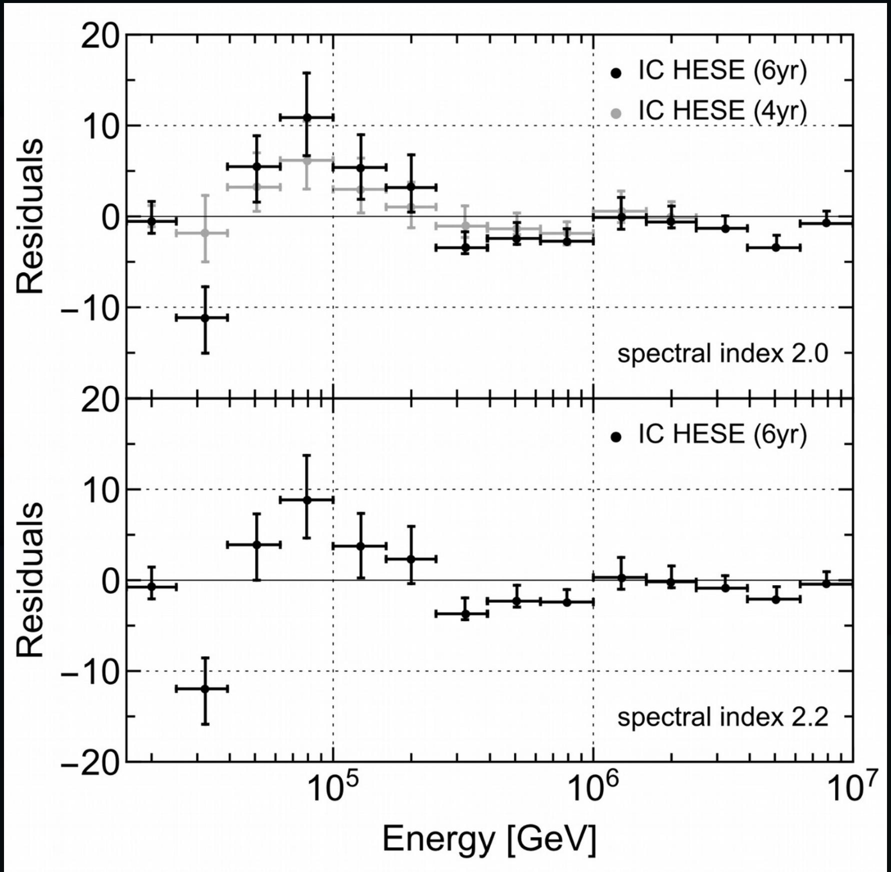
6-yr through-going μ

- μ-track from ν_μ CC interaction outside detector volume
- 200 TeV+ deposited energy
- Suggests $\gamma \approx 2.1$

Talks at TeVPA 2018: Wood, Ahlers, Murase, Schneider…

Low energy excess?

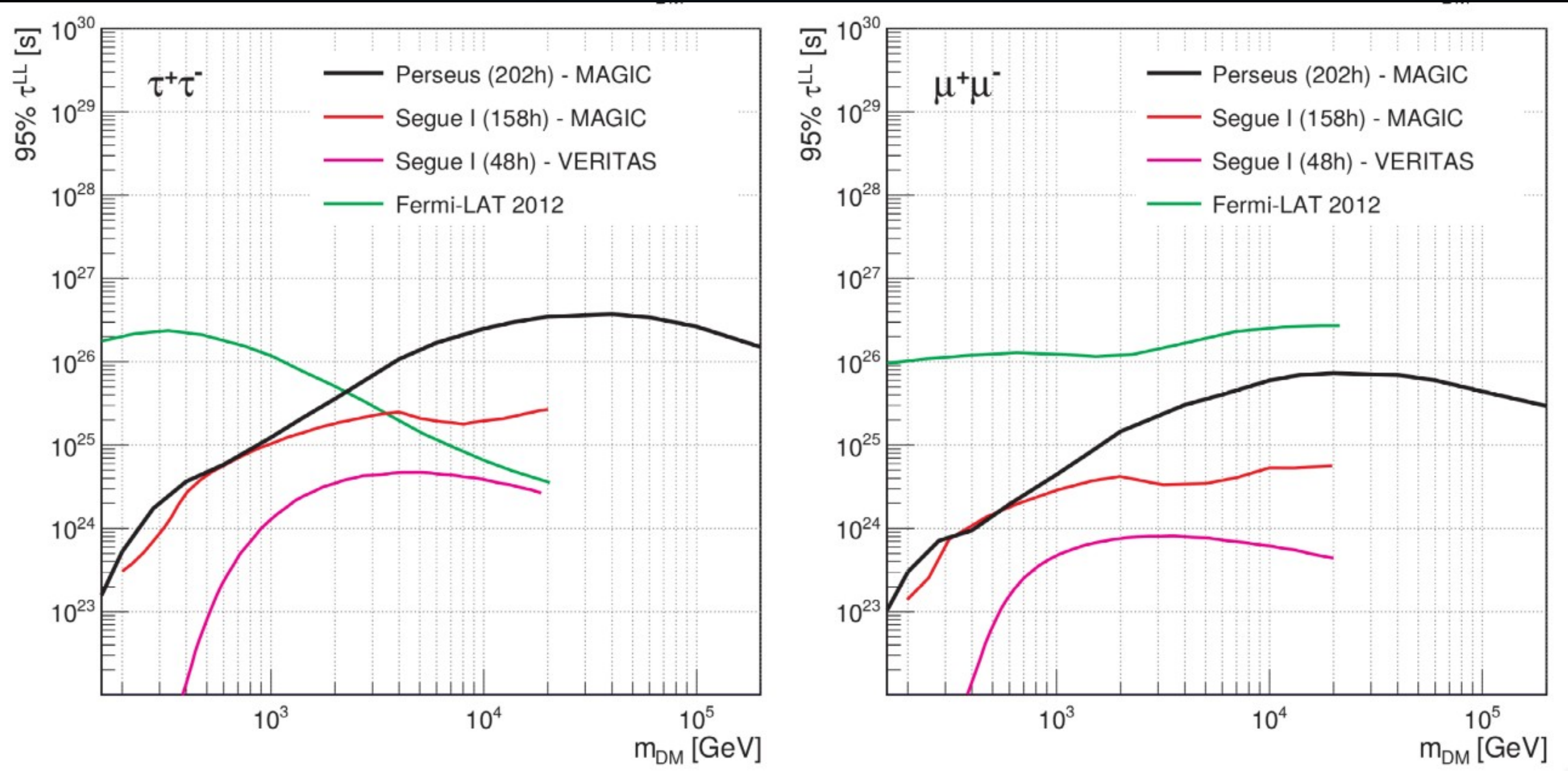


Chianese, et al, arXiv:1707.05241

Adding DM: Expectations

- *Naturally* explain dissonance between HESE and μ-tracks
- Avoid overshooting TeV-scale γ-ray observations

γ-ray constraints



MAGIC coll, arXiv:1806.11063; Fermi-LAT coll, Astrophys. J. 761:91, 2012

Adding DM: expectations

- *Naturally* explain dissonance between HESE and *μ*-tracks
- Avoid overshooting TeV-scale *γ*-ray observations
- Lack of events at Glashow resonance
- Confirmation from other indirect searches.

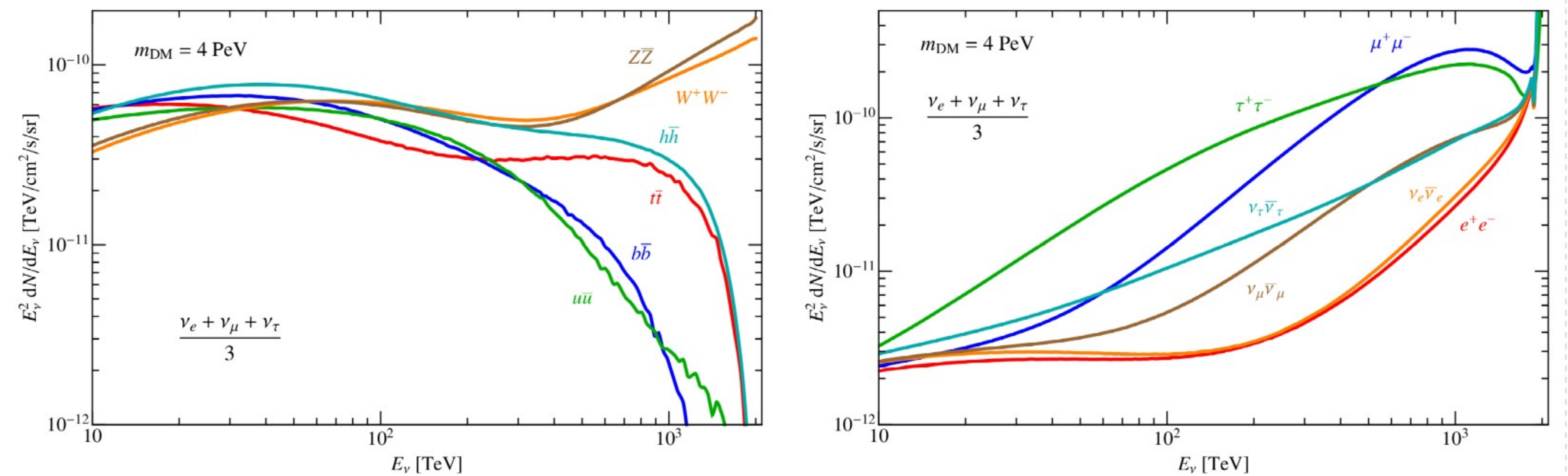
Decaying Dark Matter: Theory

- Decaying DM with m_{DM} ~ 200 TeV+
- Decays necessarily have to be slow
  - Explain relic abundance ($\tau > 10^{18}$ sec)
  - Avoid γ-ray constraints ($\tau \sim 10^{25}$ sec+)
  - Possibly stabilised through global symmetries in a hidden sector broken at the GUT scale or higher

Analysis: Decaying Dark Matter

- Consider simple 2-body decays assuming scalar parent DM
- Identical final state particles
  - All possible SM particle pairs
  - Also look at scenarios where DM may decay via multiple channels
- Use `PYTHIA` to generate flux spectrum

Analysis: Decaying Dark Matter



Analysis: Astrophysical flux

- Model as simple power-law

$$\frac{d\Phi_{\mathrm{astro},\nu_\alpha}}{dE_\nu} = \phi_{\mathrm{astro}} \left(\frac{E_\nu}{100\ \mathrm{TeV}} \right)^{-\gamma}$$

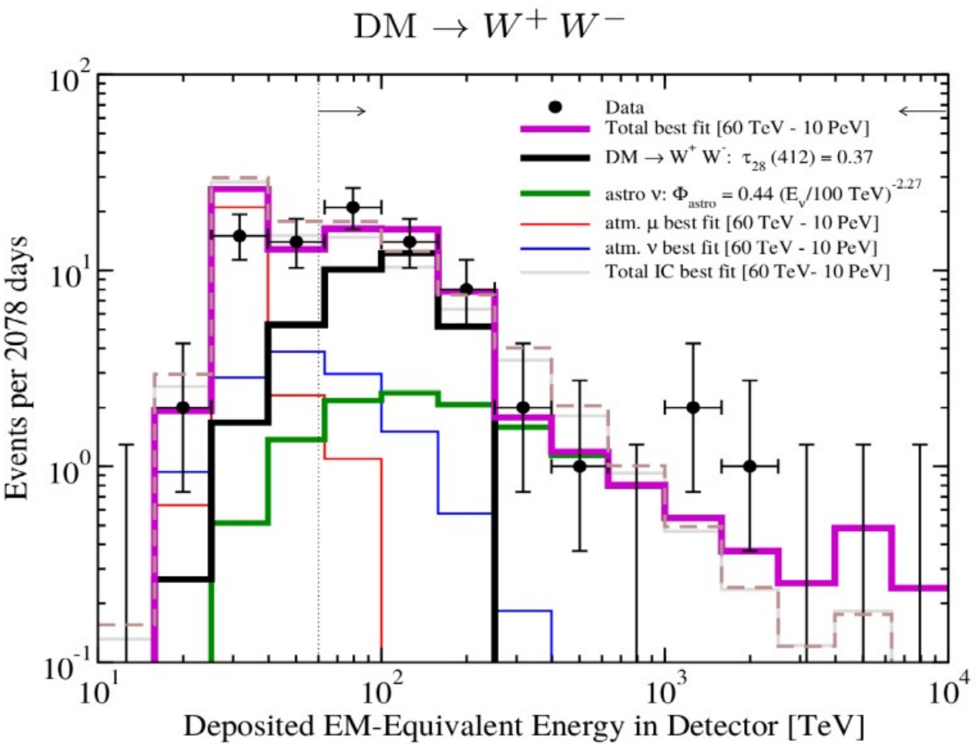
- Shock acc^{n} theory suggests hard spectrum $\gamma \approx 2$
- μ-track events suggest $\gamma \approx 2.1$
- HESE best-fit suggests $\gamma \approx 2.9$ (with 7.5 yrs of data)

Analysis: Fluxes and Events

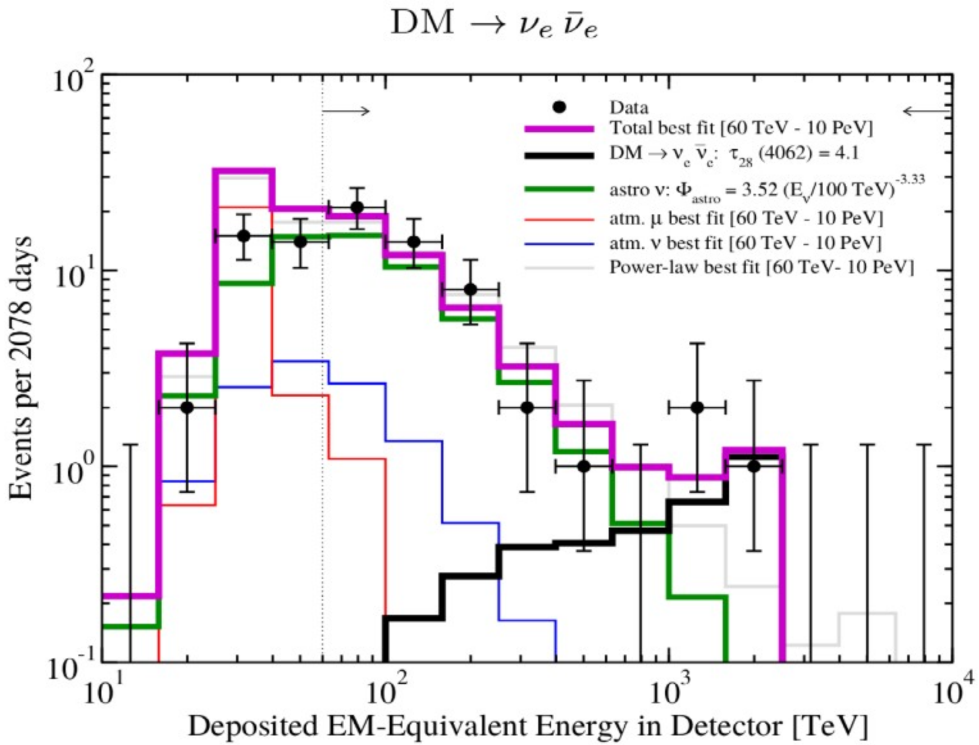
$$\frac{d\Phi^c}{dE_\nu}(E_\nu;\tau_{\rm DM},m_{\rm DM},\phi_{\rm astro},\gamma)=\frac{d\Phi^c_{\rm DM}}{dE_\nu}(E_\nu;\tau_{\rm DM},m_{\rm DM})+\frac{d\Phi_{\rm astro}}{dE_\nu}(E_\nu;\phi_{\rm astro},\gamma)$$

- Use IC published effective areas for event rates
- Use IC best-fit atm. conventional background ν and μ
- Distinguish between event topologies:
  - Tracks and cascades
  - Upgoing and downgoing
- Account for flavour in DM decay flux
- Unbinned maximum likelihood analysis over 4 independent parameters

Results



DM → $W^+ W^-$
Data
Total best fit [60 TeV - 10 PeV]
DM → $W^+ W^-$: τ_{28} (412) = 0.37
astro ν: Φ_{astro} = 0.44 $(E_\nu/100\ TeV)^{-2.27}$
atm. μ best fit [60 TeV - 10 PeV]
atm. ν best fit [60 TeV - 10 PeV]
Total IC best fit [60 TeV- 10 PeV]
Events per 2078 days
Deposited EM-Equivalent Energy in Detector [TeV]



DM → $\nu_e \bar{\nu}_e$
Data
Total best fit [60 TeV - 10 PeV]
DM → $\nu_e \bar{\nu}_e$: τ_{28} (4062) = 4.1
astro ν: Φ_{astro} = 3.52 $(E_\nu/100\ TeV)^{-3.33}$
atm. μ best fit [60 TeV - 10 PeV]
atm. ν best fit [60 TeV - 10 PeV]
Power-law best fit [60 TeV- 10 PeV]
Events per 2078 days
Deposited EM-Equivalent Energy in Detector [TeV]

Results

DM soft-spectrum channels

- Allow flat astro, reduced normalisation
- Secondary ν from DM decay “fills-in” between 60 – 200 TeV
- mDM: 400 TeV—1.7 PeV

Gauge bosons $(u\bar{u})$

DM hard-spectrum channels

- $m_{DM} \approx 4$ PeV
- PeV+ events: Primary + secondary ν from DM decay
- Sub-PeV events almost entirely from astrophysical flux with $\gamma > 3$

Results

Decay channel	$\tau_{\rm DM}[10^{28}\ {\rm s}](N_{\rm DM})$	$m_{\rm DM}$ [PeV]	$\phi_{\rm astro}(N_{\rm astro})$	γ
$u\bar{u}$	0.11 (28.4)	1.761	0.52 (13.0)	2.34
$b\bar{b}$	0.07 (26.9)	1.103	0.58 (14.3)	2.35
$t\bar{t}$	0.11 (28.7)	0.598	0.45 (12.5)	2.27
W^+W^-	0.37 (28.5)	0.412	0.46 (12.6)	2.29
ZZ	0.43 (27.8)	0.407	0.52 (13.3)	2.32
hh	0.12 (28.8)	0.611	0.45 (12.6)	2.27
e^+e^-	2.20 (4.0)	4.160	3.53 (37.3)	3.36
$\mu^+\mu^-$	9.77 (4.9)	6.583	3.51 (36.5)	3.39
$\tau^+\tau^-$	0.89 (27.4)	0.472	0.59 (14.3)	2.36
$\nu_e\bar{\nu}_e$	4.12 (3.6)	4.062	3.52 (37.7)	3.33
$\nu_\mu\bar{\nu}_\mu$	4.63 (5.0)	4.196	3.52 (36.4)	3.41
$\nu_\tau\bar{\nu}_\tau$	0.96 (16.6)	0.341	1.58 (24.9)	2.74

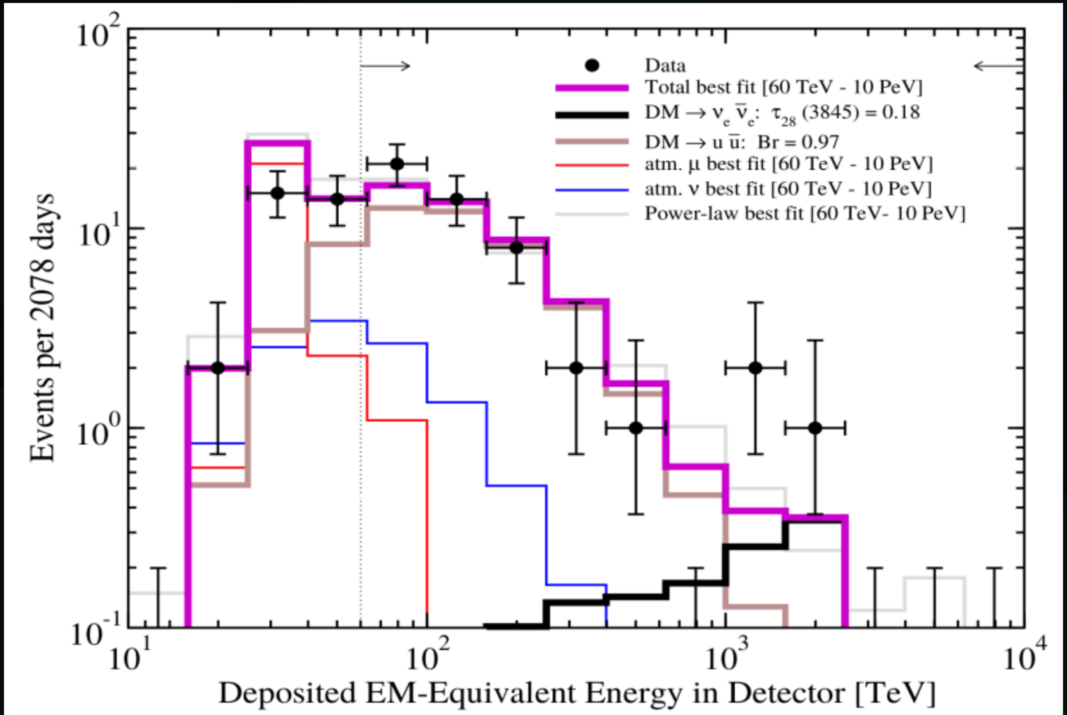
Decays via multiple channels

- Combination of hard and soft spectrum, both from DM decay
- Assume astrophysical flux to be negligible
- $m_{DM} \approx 4$ PeV to explain PeV+ events
  - Hard decay (leptons, neutrinos) explain PeV+ events
  - Soft decay explains sub-PeV events
  - Fit parameters: m_{DM}, τ_{DM}, and branching ratio BR

$$\mathrm{BR} = \Gamma_{\mathrm{DM} \to p_1 \bar{p}_1} / \left(\Gamma_{\mathrm{DM} \to p_1 \bar{p}_1} + \Gamma_{\mathrm{DM} \to p_2 \bar{p}_2} \right)$$

Decays via multiple channels

Best-fits for combination of lightest quarks and neutrinos/leptons



Rounding off: Checklist

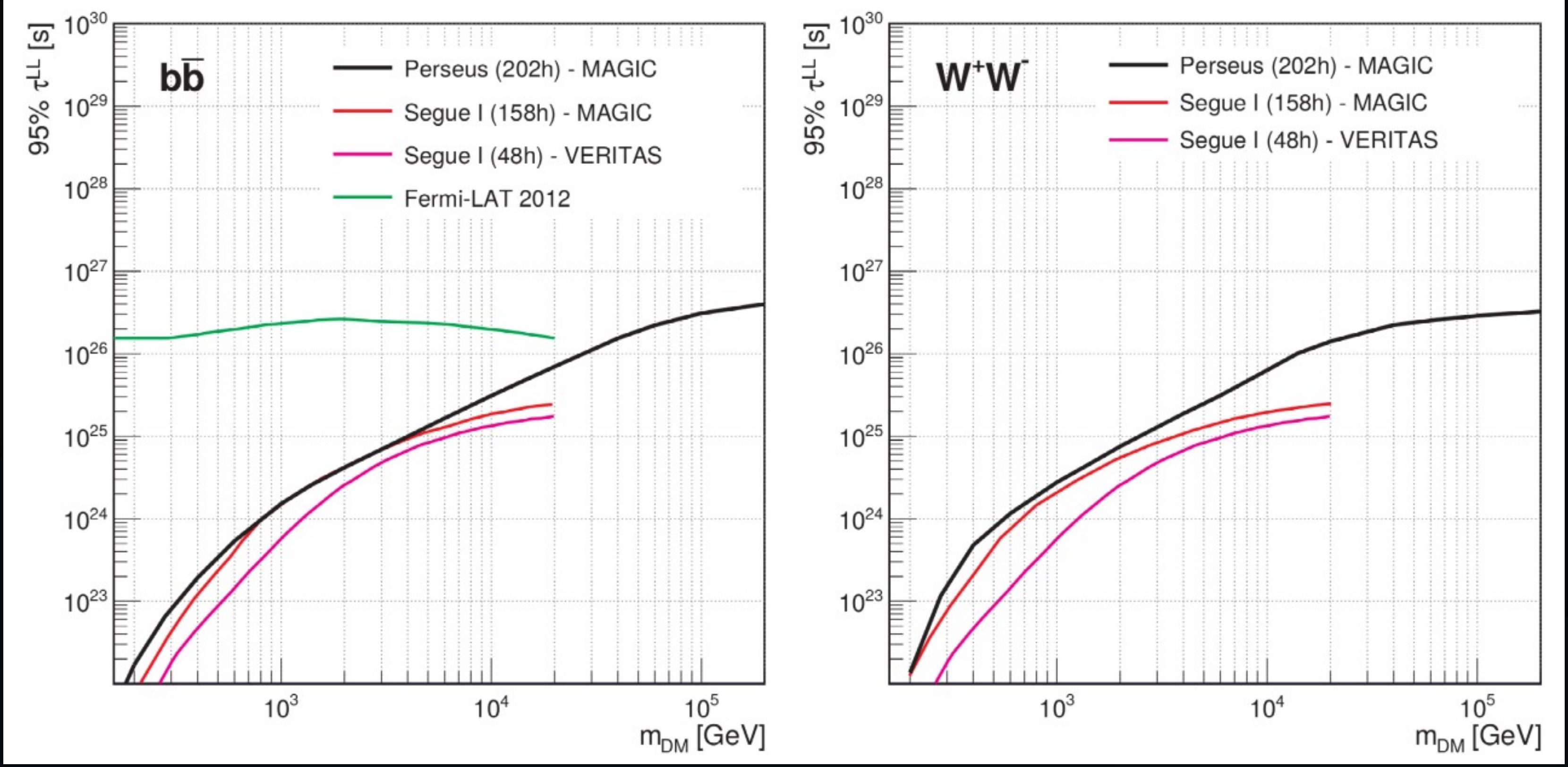
- ☑ *Naturally* explain dissonance between HESE and *μ*-tracks
- ☑ Avoid overshooting TeV-scale *γ*-ray observations
- ☑ Lack of events at Glashow resonance
- ❓ Confirmation from other indirect searches.

Conclusions

- Recent IceCube diffuse neutrino results offer a peek into the UHE universe through the prism of neutrinos
- Extremely soft power-law fit to HESE data suggest the presence of interesting physics at 60–200 TeV
  - Could be astrophysical: hidden sources, choked jets
  - Could be heavy DM decay signatures

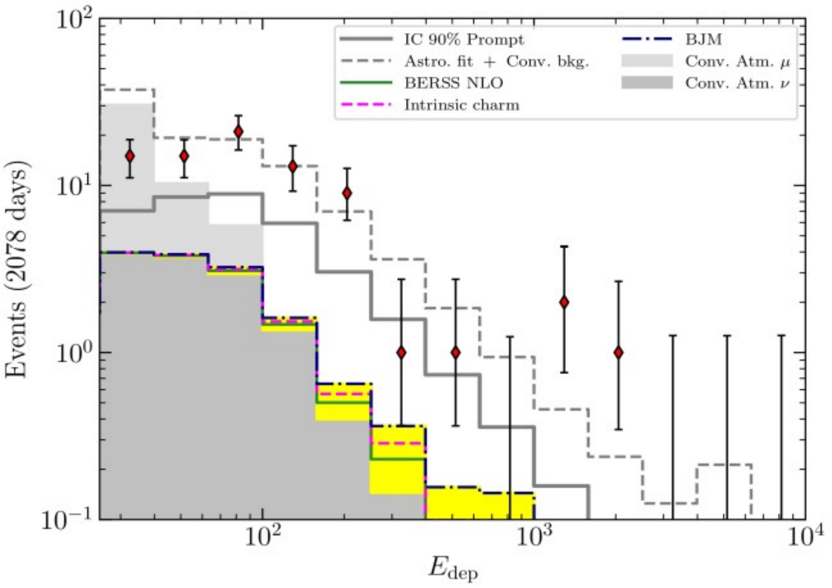
Backup Slides

γ-ray constraints

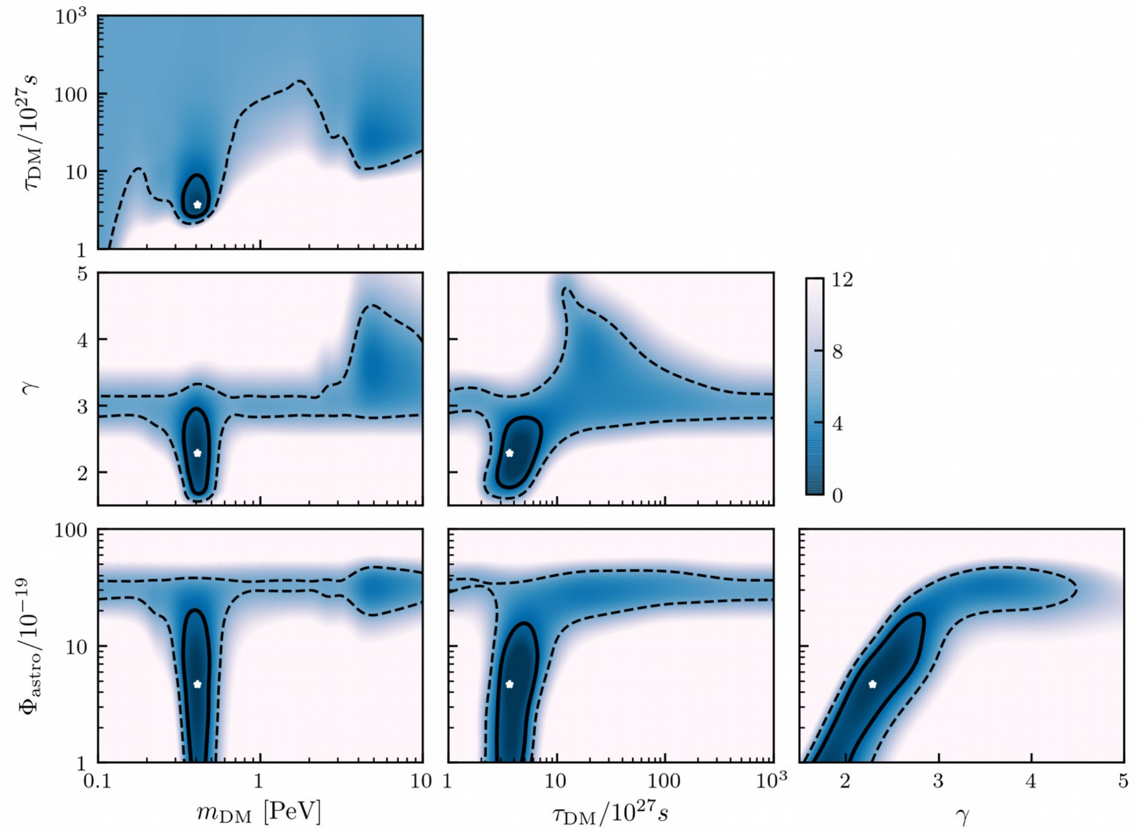


Backgrounds from atm. ν

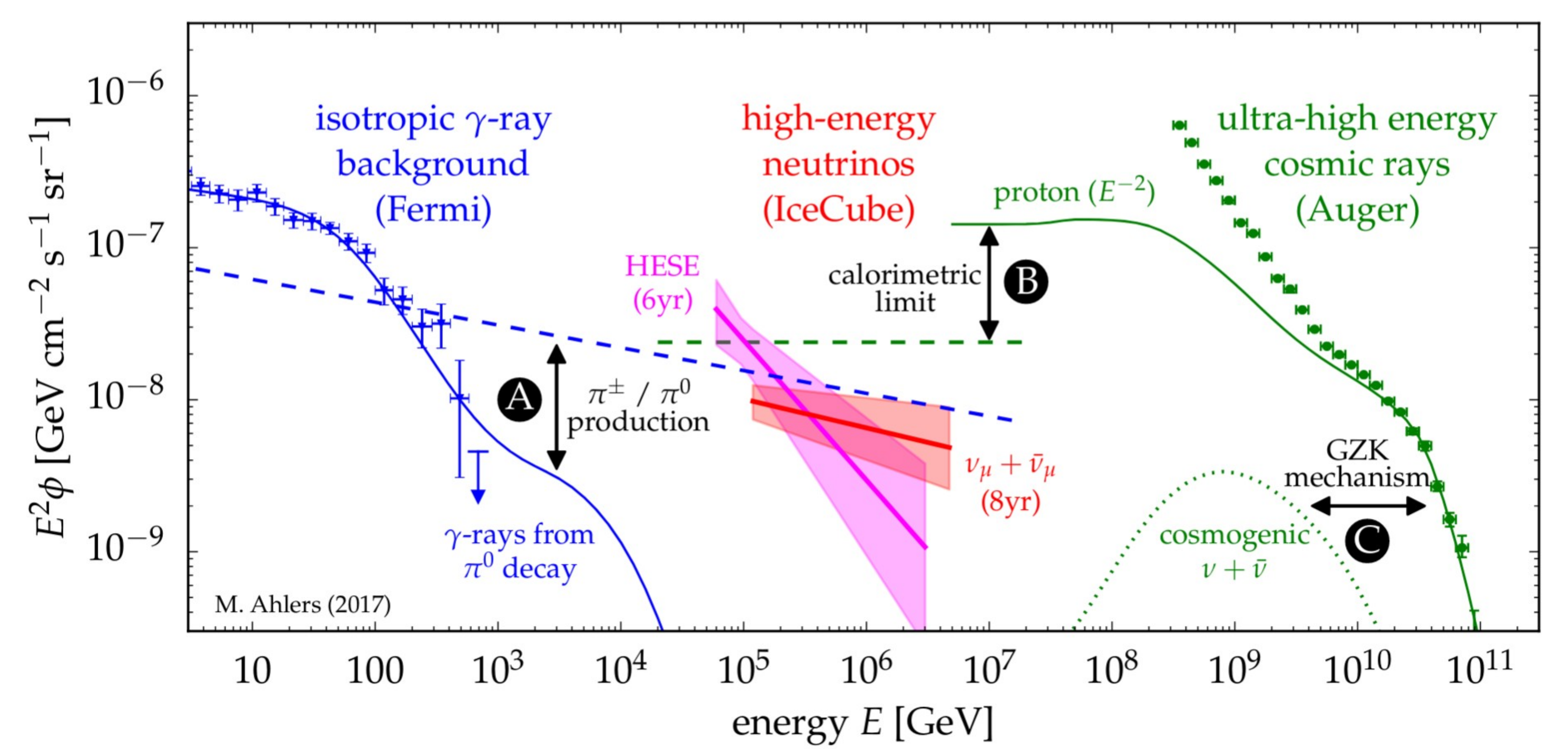
- Conventional flux steeply dropping
- By ~100 TeV prompt dominates, but not significant
- Look at models of diffractive forward charm production
  - Result: No big change



Two-parameter correlations



IceCube vs Fermi



Ahlers, talk on Tuesday