XIX International Workshop on Neutrino Telescopes, 2021

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

Atri Bhattacharya, University of Liège

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JCAP 05 (2019) 051

AB, Arman Esmaili, Sergio Palomares-Ruiz, and Ina Sarcevic

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References

- Update on decaying and annihilating heavy dark matter with the 6-year IceCube HESE data
  - AB, Arman Esmaili, Sergio Palomares-Ruiz, and Ina Sarcevic
  - **JCAP 05 (2019) 051**
  - e-Print: 1903.12623 [hep-ph]
- Probing decaying heavy dark matter with the 4-year IceCube HESE data
  - AB, Arman Esmaili, Sergio Palomares-Ruiz, and Ina Sarcevic
  - **JCAP 07 (2017) 027**
  - e-Print: 1706.05746 [hep-ph]

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IceCube signals and power-laws

6-yr HESE data

- Interaction vertex in detector
- 80 events
  - 50 with E_{dep} > 60 TeV
- Max. E_{dep}: 2.1 PeV
- Soft-spectrum flux, $\gamma \approx 2.9$

PoS(ICRC2017)981

10-yr through-going μ

- μ-track from ν_μ CC
- Origin outside detector
- 200 TeV+ deposited energy
- Upgoing tracks only
- Harder spectrum, $\gamma \approx 2.3$

PoS(ICRC2019)1017

IceCube signals and power-laws

7.5-yr HESE data

- Interaction vertex in detector
- 102 events
  - 60 with E_{dep} > 60 TeV
- Max. E_{dep}: 2.1 PeV
- Soft-spectrum flux, $\gamma \approx 2.9$

eprint:2011.03545

10-yr through-going μ

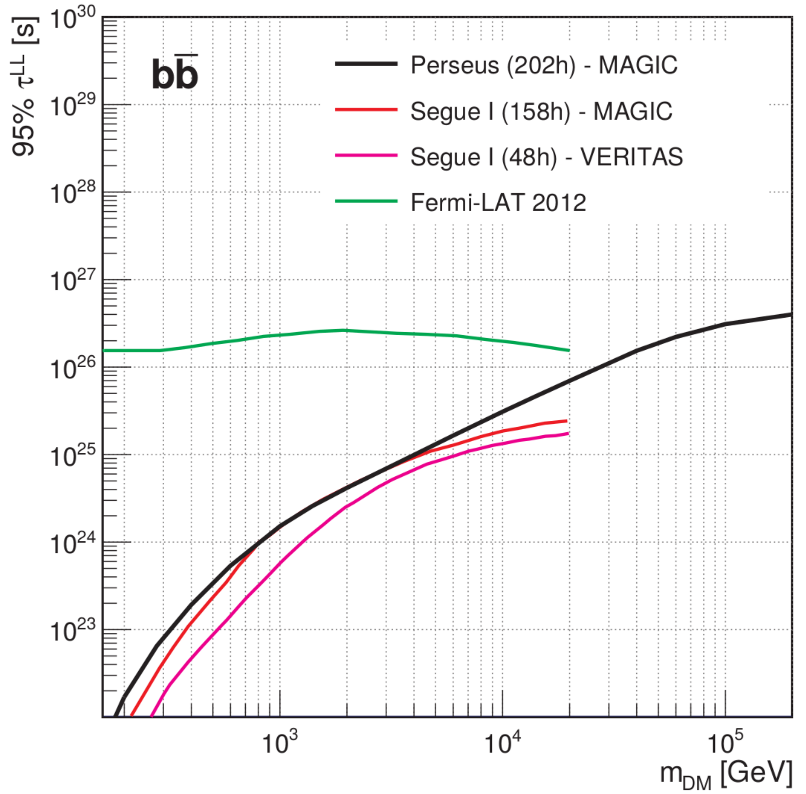
- μ-track from ν_μ CC
- Origin outside detector
- 200 TeV+ deposited energy
- Upgoing tracks only
- Harder spectrum, $\gamma \approx 2.3$

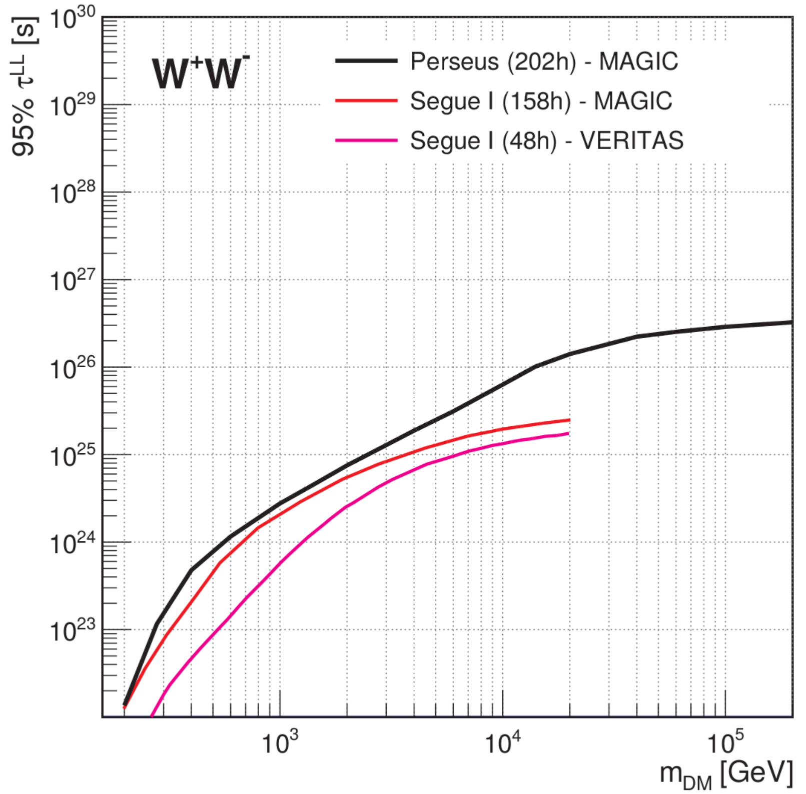
PoS(ICRC2019)1017

Checklist of expectations

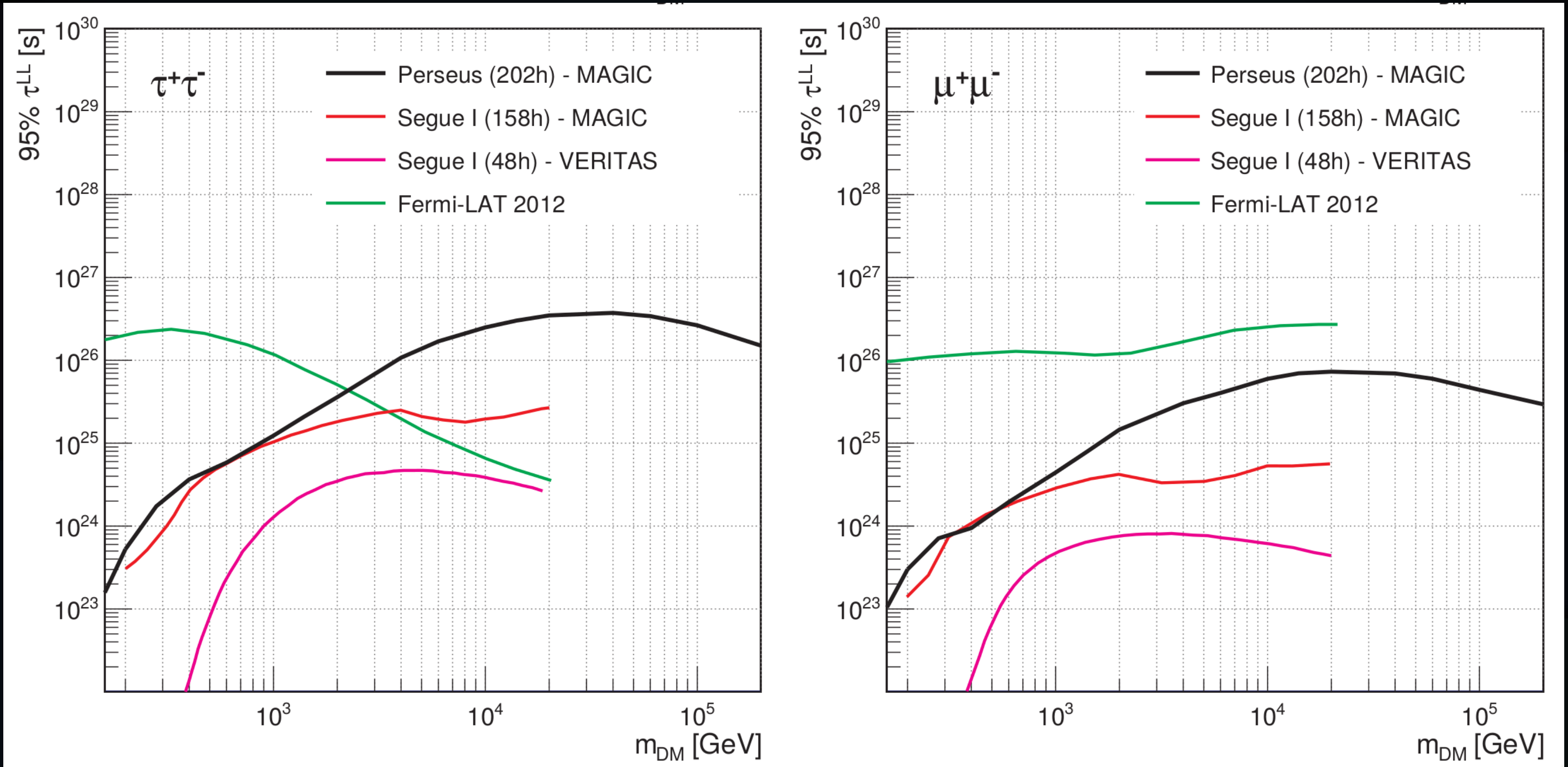
- *Naturally* explain dissonance between HESE and μ-tracks
- Consistent with TeV-scale γ-ray observations

γ-ray constraints





γ-ray constraints



Checklist of expectations

- ☐ *Naturally* explain dissonance between HESE and μ-tracks
- ☐ Consistent with 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

- Simple 2-body decays; scalar parent DM
- Identical final state particles
  - All possible SM particle pairs
  - + Scenarios where DM decays via multiple channels

$$\frac{d\Phi_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{d\Phi^{\mathrm{G}}_{\mathrm{DM},\nu_\alpha}}{dE_\nu} + \frac{d\Phi^{\mathrm{EG}}_{\mathrm{DM},\nu_\alpha}}{dE_\nu}$$

Analysis: Decaying Dark Matter

- Simple 2-body decays; scalar parent DM
- Identical final state particles
  - All possible SM particle pairs
  - + Scenarios where DM decays via multiple channels

$$\frac{d\Phi^{\mathrm{EG}}_{\mathrm{DM},\nu_\alpha}}{dE_\nu} = \frac{\Omega_{\mathrm{DM}}\rho_c}{4\pi m_{\mathrm{DM}}\tau_{\mathrm{DM}}} \int_0^\infty dz\, \frac{1}{H(z)} \frac{dN_{\nu_\alpha}}{dE_\nu}\left[(1+z)E_\nu\right]$$

Analysis: Decaying Dark Matter

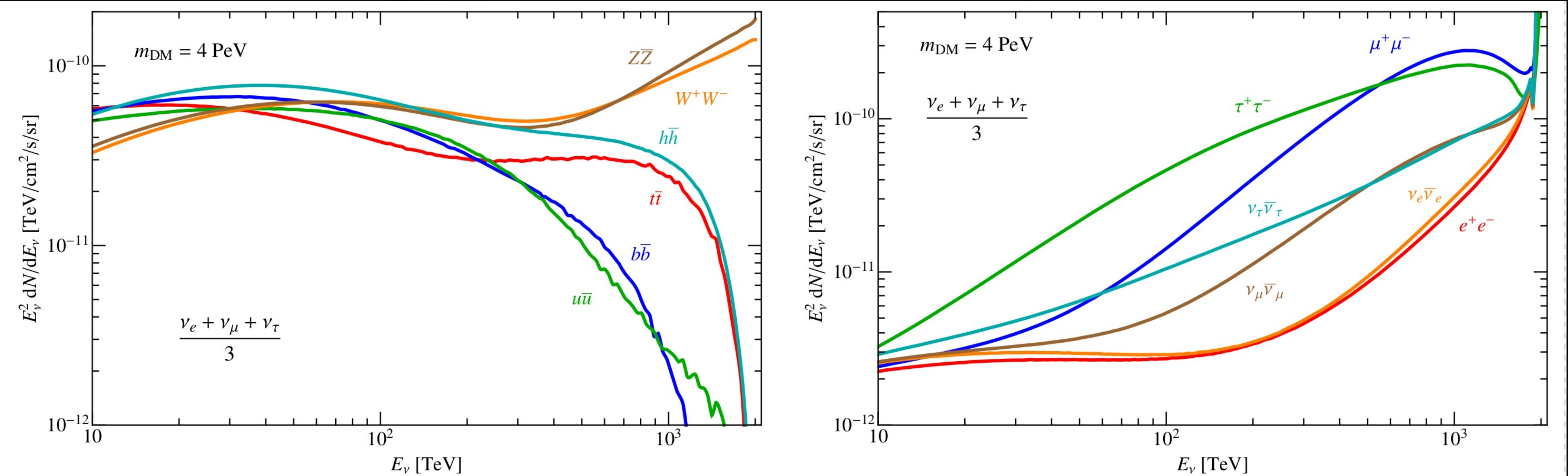
- Simple 2-body decays; scalar parent DM
- Identical final state particles
  - All possible SM particle pairs
  - + Scenarios where DM decays via multiple channels

$$\frac{d\Phi^{\mathrm{G}}_{\mathrm{DM},\nu_\alpha}}{dE_\nu}(E_\nu, b, l) = \frac{1}{4\pi m_{\mathrm{DM}}\tau_{\mathrm{DM}}}\frac{dN_{\nu_\alpha}}{dE_\nu}\int_0^\infty \rho\left[r\left(s, b, l\right)\right] ds$$

Analysis: Decaying Dark Matter

- Simple 2-body decays; scalar parent DM
- Identical final state particles
  - All possible SM particle pairs
  - + Scenarios where DM decays via multiple channels
- Use PYTHIA to generate dN/dE
  - Not an issue for $m_{DM} \lesssim 5$ PeV
  - But see Nicholas Rodd’s plenary talk yesterday for EeV DM

Analysis: Decaying Dark Matter



$$\tau_{\rm DM} = 10^{27} \text{ s}$$

Analysis: Astrophysical flux

- Modelled as simple power-law

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

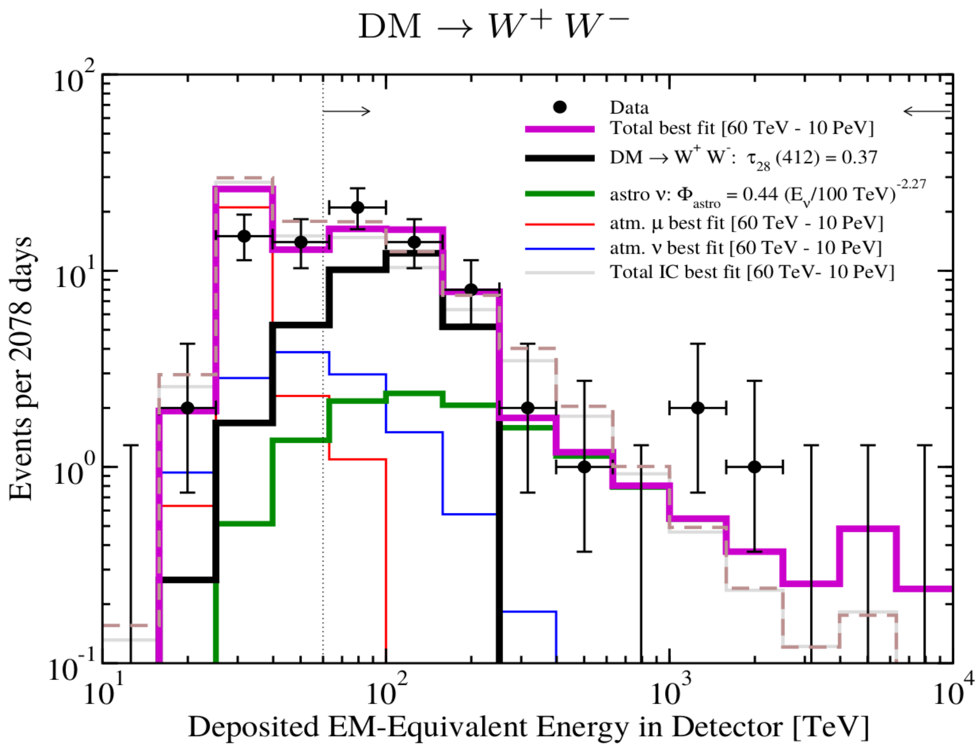
- Fermi shock acc^{n} theory $\Rightarrow \gamma \approx 2.0$
- 10-yr μ-track events $\Rightarrow \gamma \approx 2.3$
- 7.5-yr HESE data $\Rightarrow \gamma \approx 2.9$

Analysis: Fluxes and Events

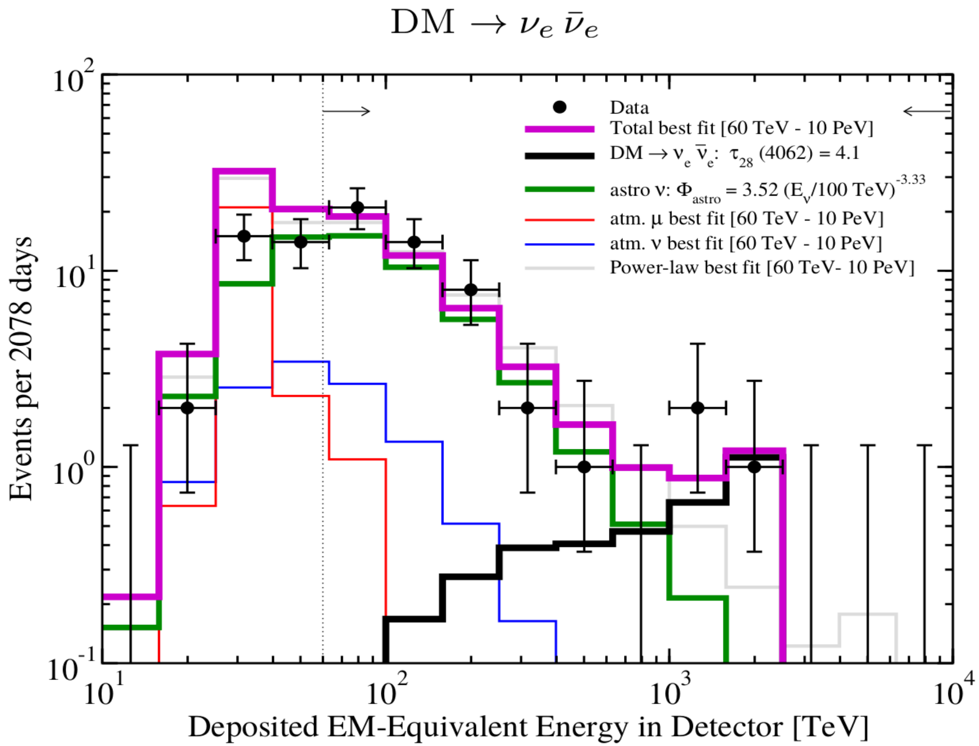
$$\frac{d\Phi^c}{dE_\nu}(E_\nu;\tau_{\mathrm{DM}},m_{\mathrm{DM}},\phi_{\mathrm{astro}},\gamma)=\frac{d\Phi^c_{\mathrm{DM}}}{dE_\nu}(E_\nu;\tau_{\mathrm{DM}},m_{\mathrm{DM}})+\frac{d\Phi_{\mathrm{astro}}}{dE_\nu}(E_\nu;\phi_{\mathrm{astro}},\gamma)$$

- 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
- **Unbinned maximum likelihood analysis**

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_ν/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_ν/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
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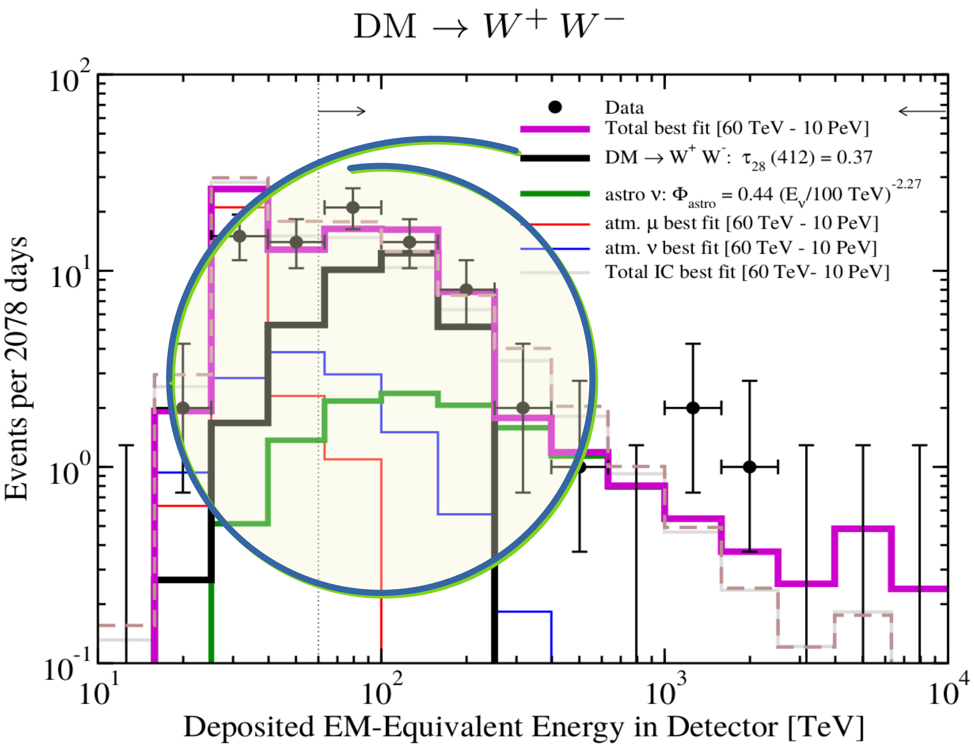
DM → W⁺ W⁻
Data
Total best fit [60 TeV - 10 PeV]
DM → W⁺ W⁻: τ28 (412) = 0.37
astro ν: Φastro = 0.44 (Eν/100 TeV)^-2.27
atm. μ best fit [60 TeV - 10 PeV]
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Total IC best fit [60 TeV- 10 PeV]
Events per 2078 days
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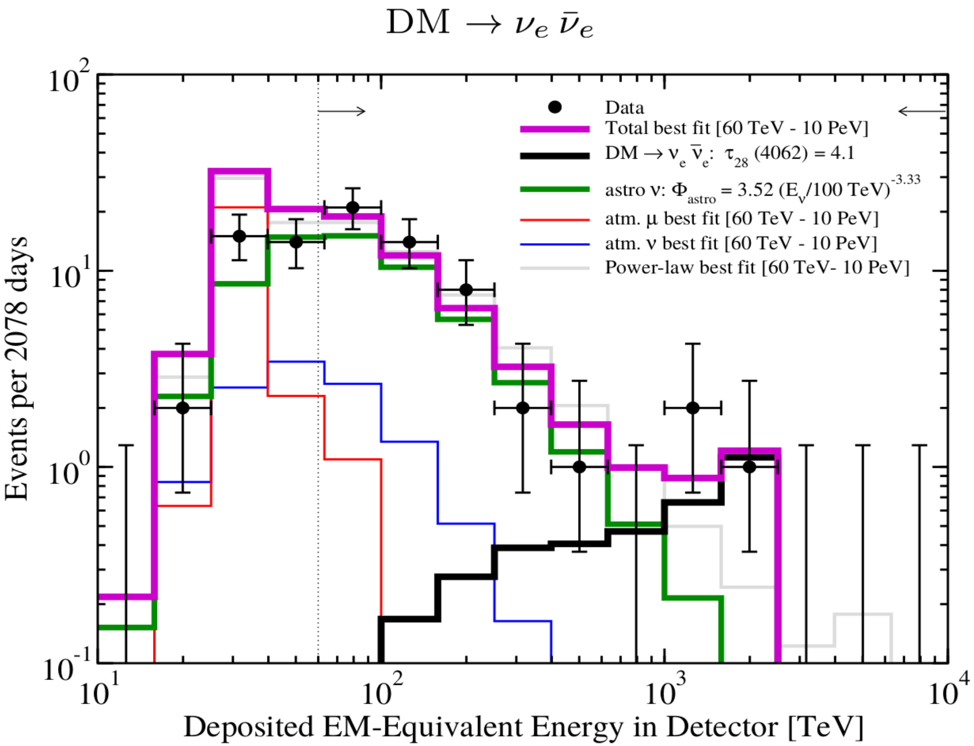
DM → νe ν̄e
Data
Total best fit [60 TeV - 10 PeV]
DM → νe ν̄e: τ28 (4062) = 4.1
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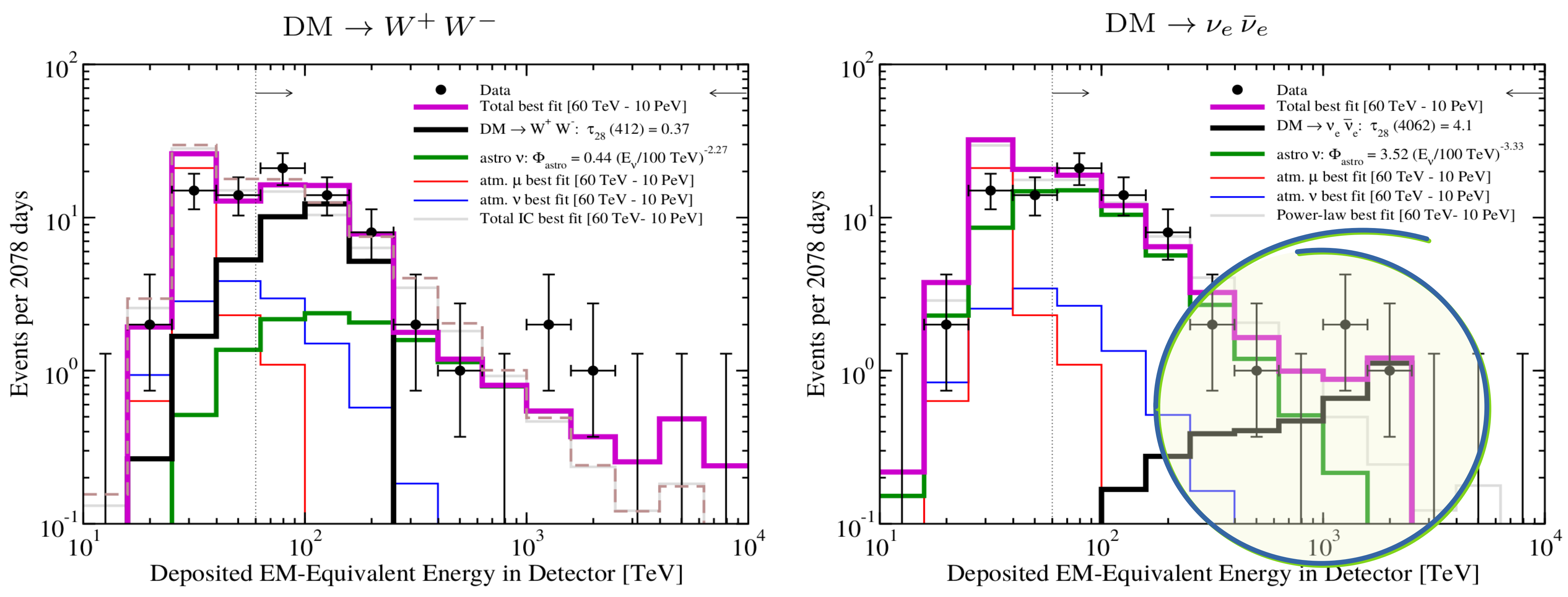
Deposited EM-Equivalent Energy in Detector [TeV]

Results



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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
- m_{DM}: 400 TeV—1.7 PeV

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

DM hard-spectrum channels

- $m_{\mathrm{DM}} \approx 4$ PeV
- PeV+ events: Primary + secondary ν from DM decay
- Sub-PeV events from very soft astro flux ($\gamma > 3$)

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

Results

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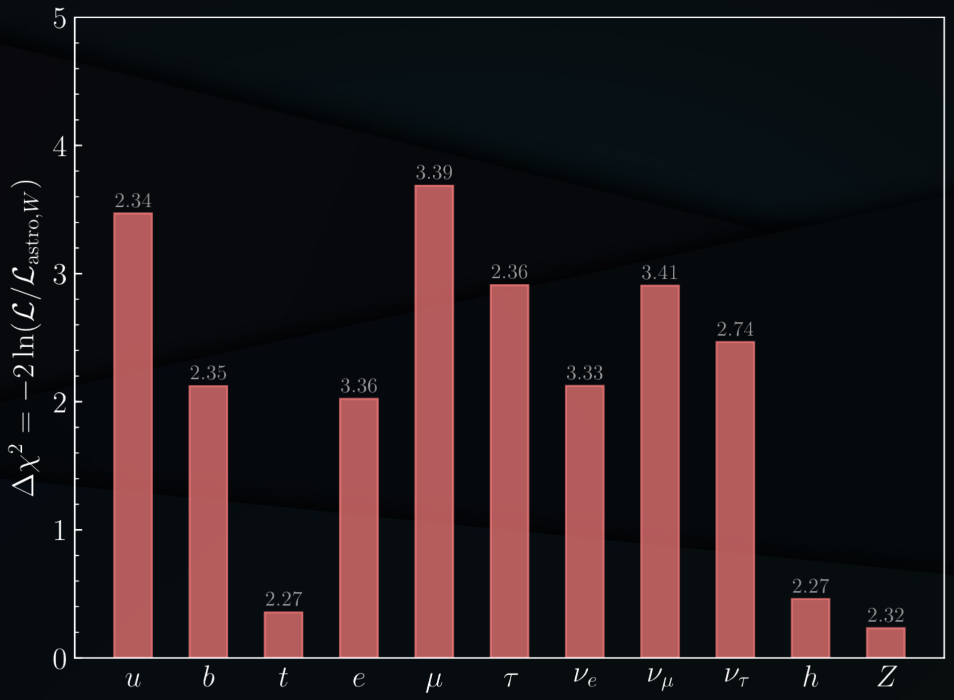
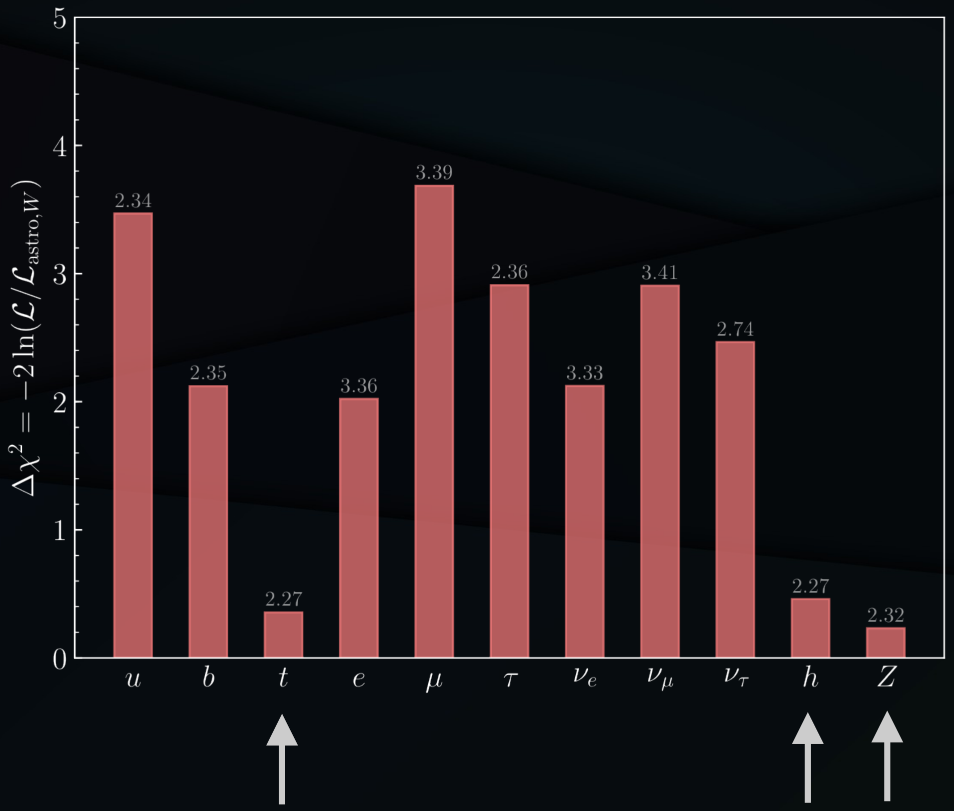


$\Delta\chi^2 = -2\ln(\mathcal{L}/\mathcal{L}_{\mathrm{astro},W})$
0
1
2
3
4
5
2.34
2.35
2.27
3.36
3.39
2.36
3.33
3.41
2.74
2.27
2.32
u
b
t
e
μ
τ
ν_e
ν_μ
ν_τ
h
Z

Results


$\Delta\chi^2 = -2\ln(\mathcal{L}/\mathcal{L}_{\mathrm{astro},W})$
0
1
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3.41
2.74
2.27
2.32
u
b
t
e
μ
τ
ν_e
ν_μ
ν_τ
h
Z

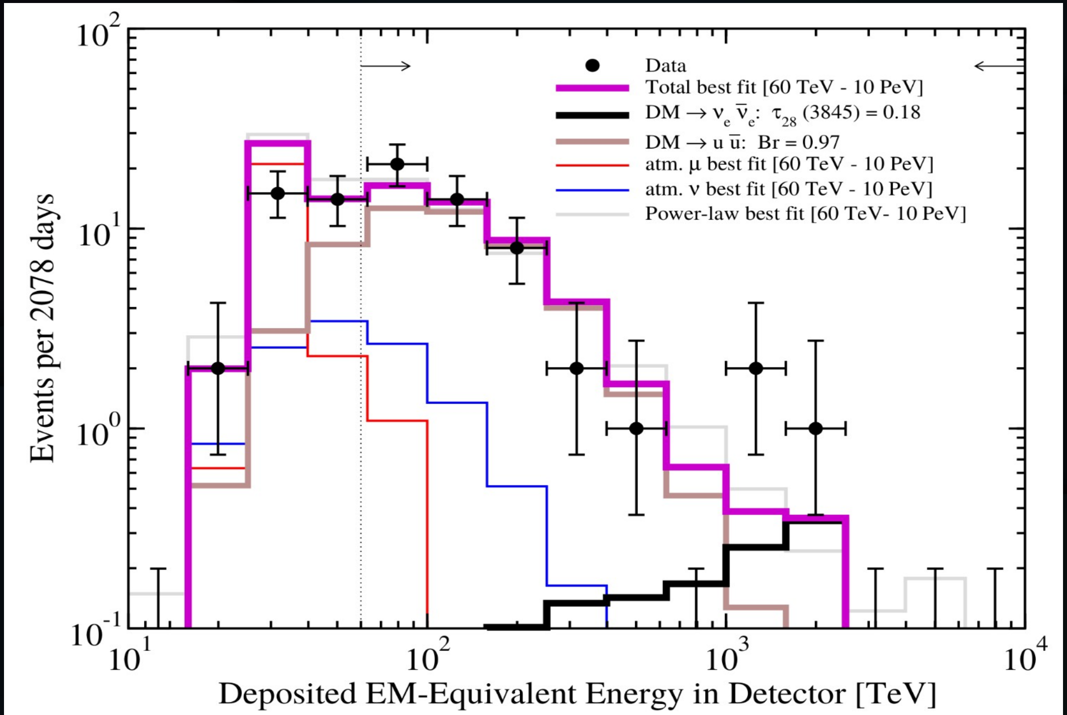
Decays via multiple channels

- Hard + Soft spectrum, both from DM decay
- Assume astrophysical flux to be negligible
- $m_{\mathrm{DM}} \approx 4$ 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
- ☑ Consistent with TeV-scale γ-ray observations
  - Some channels in tension
- ☑ Lack of events at Glashow resonance
- ❓ Confirmation from other indirect searches.

Acknowledgments

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