Constraining DM-neutrino interactions with IceCube-170922A

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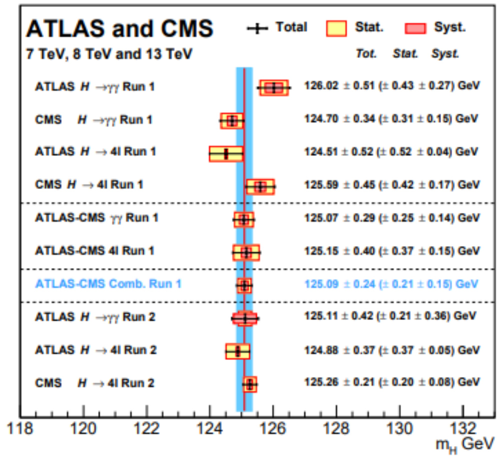
Contents

Standard Model

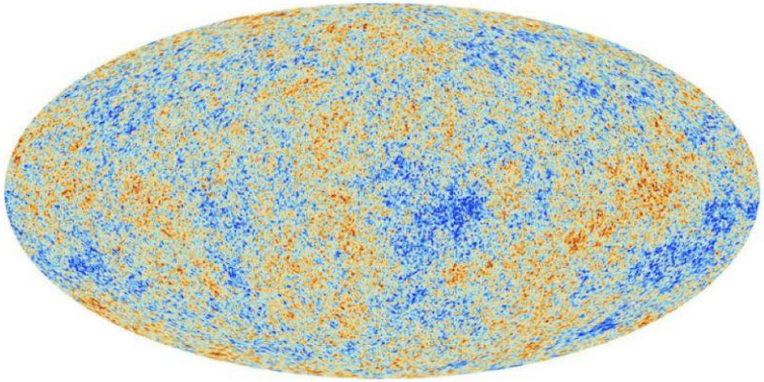
- The standard model is GOOD!!
  - A SM-like Higgs boson was discovered in 2012 @ LHC



- Problems of the SM
  - Neutrino oscillation problem
  - Dark matter problem
  - Matter-antimatter asymmetry problem
  - Hierarchy problem

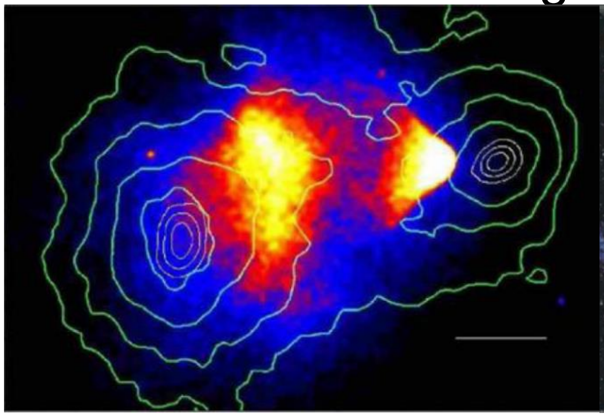
Dark matter

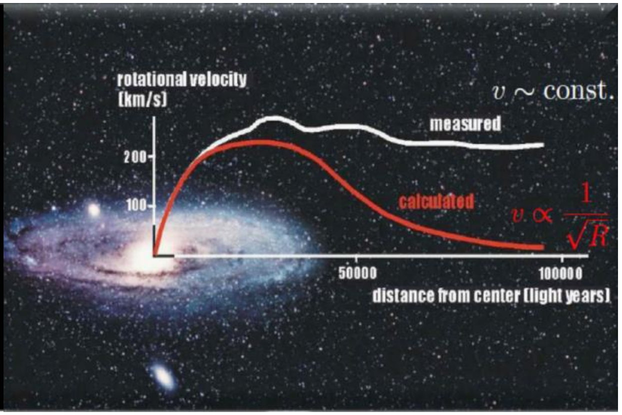
- Dark Matter
  - Suggested by Fritz Zwicky in early 1930s
  - Verified by Vera Rubin in 1970



- Evidences
  - Galaxy clusters
  - Galactic rotational curves
  - Bullet cluster
  - Cosmic Microwave Background: $\Omega_{\mathrm{nbm}} h^2 \quad = \quad 0.1200 \pm 0.0012$

Planck 2018





Neutrino oscillation

- SM neutrino sector
  - No right-handed neutrino
  - No mass terms: $m_\nu \left(\bar{\nu}_L \nu_R + \text{h.c.}\right)$

- Neutrino oscillation
  - At least two neutrinos massive

Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)

PDG 2018

- Simplest solution
  - Introduce RH neutrino
  - Generate **pure Dirac-type mass**: $m_\nu \left(\bar{\nu}_L \nu_R + \text{h.c.}\right)$
  - The required Yukawa couplings are extremely small

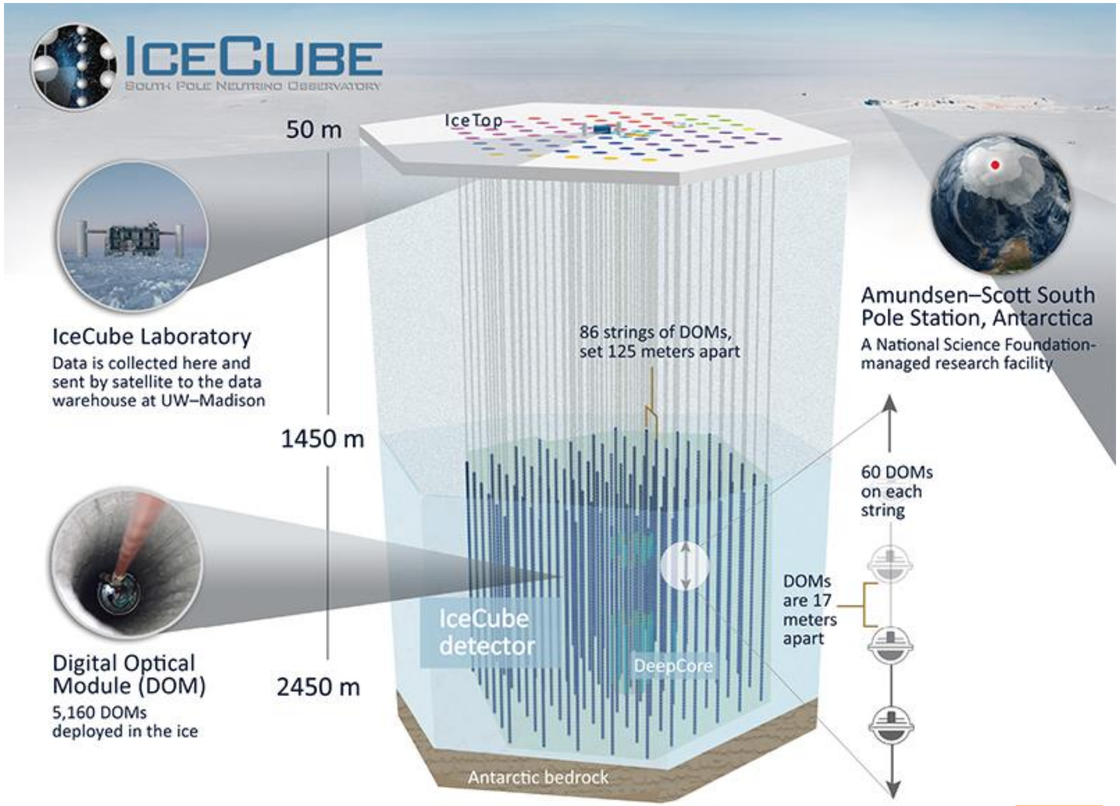
Neutrino observations

- Neutrinos are discovered
  - Terrestrial neutrinos from rock, nuclear reactor, and collider
  - Solar neutrinos and atmospheric neutrinos
  - Recently θ_{13} was detected

- Nobel prizes
  - Discovery of (electron) neutrino (1953)
  - Discovery of muon neutrino (1988)
  - Detection of cosmic neutrinos (2002)
  - Detecting the changing flavors neutrino (2015)
  - …

IceCube Telescope

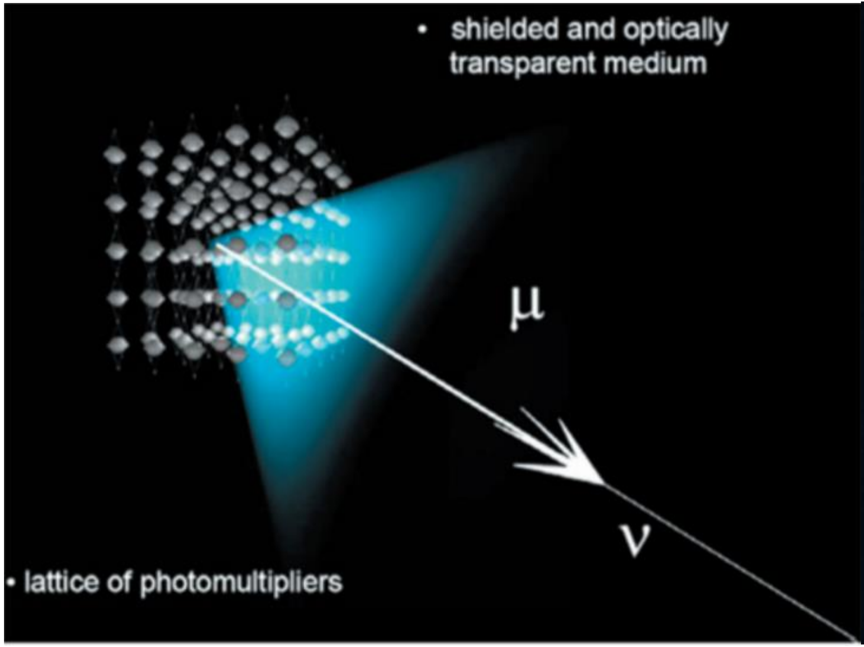
- 5160 Digital optical modules distributed over 86 strings

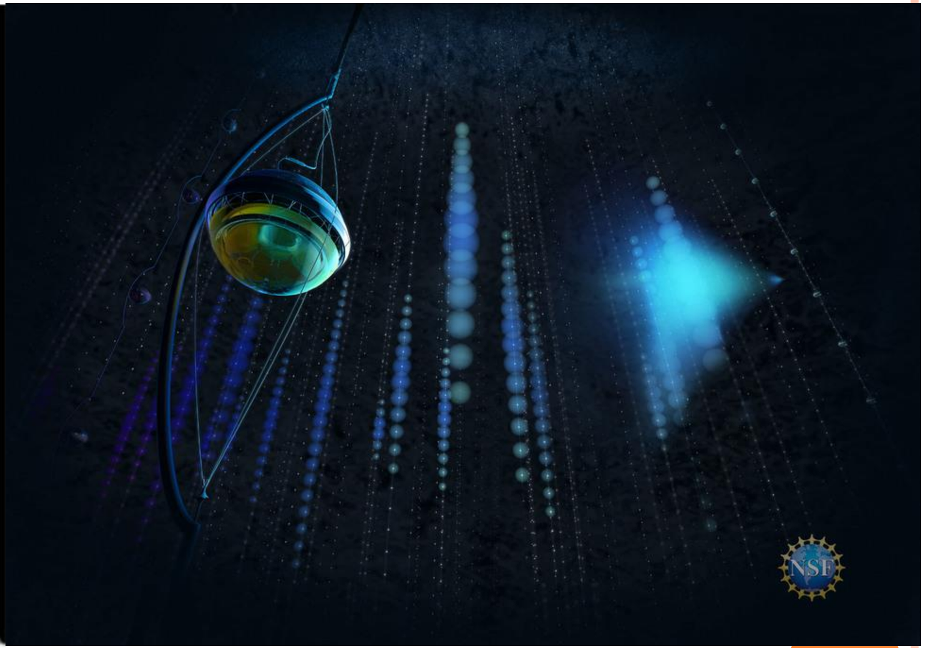


- IceCube Array
  - E_{Thr} ~ 100 GeV
- DeepCore region
  - E_{Thr} ~ 10 GeV
- Tau neutrino is not observed yet
  - $\nu_e : \nu_\mu : \nu_\tau = 2 : 1 : 0$

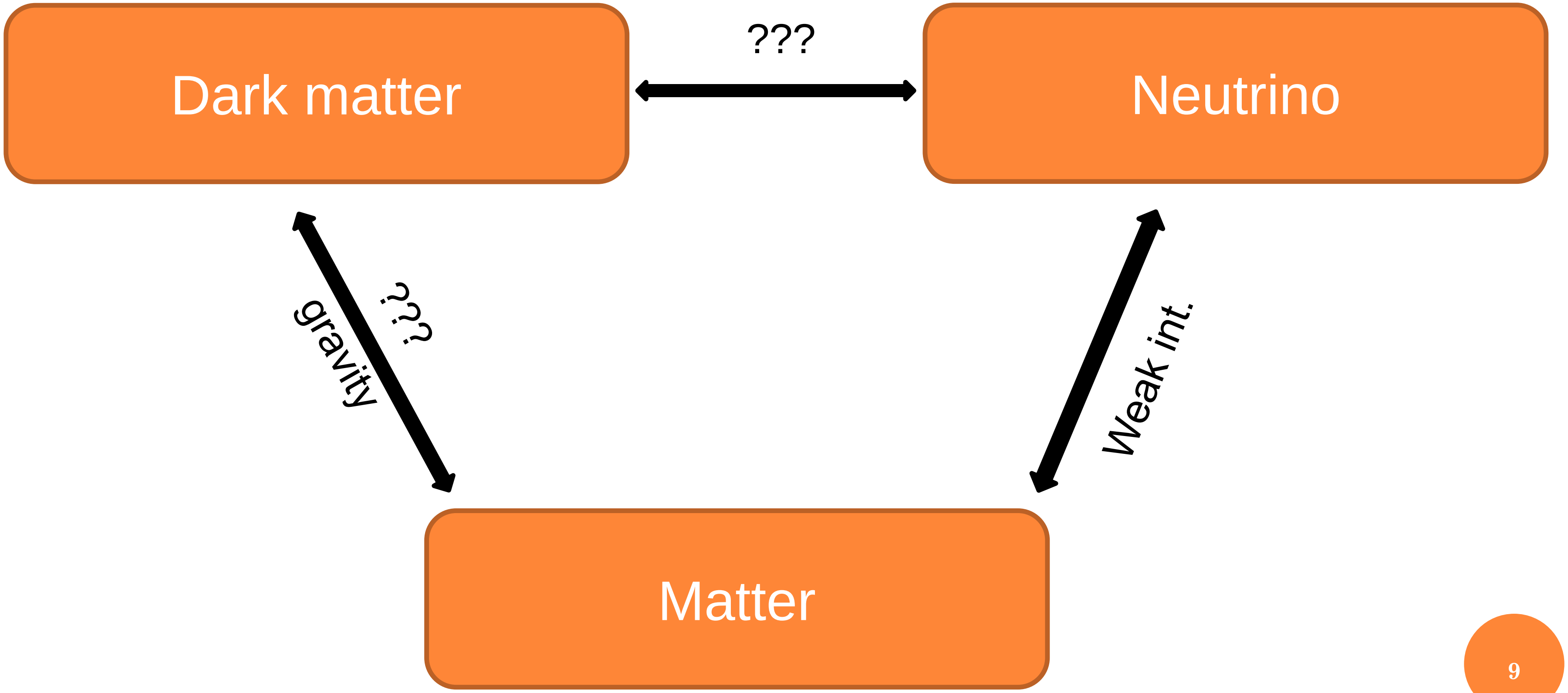
IceCube Telescope

- Neutrinos might interact in or near the detector
- Neutrinos are identified through Cherenkov light emission from secondary particles produced in the neutrino interaction with the ice





New interactions?



Neutrino oscillation effects

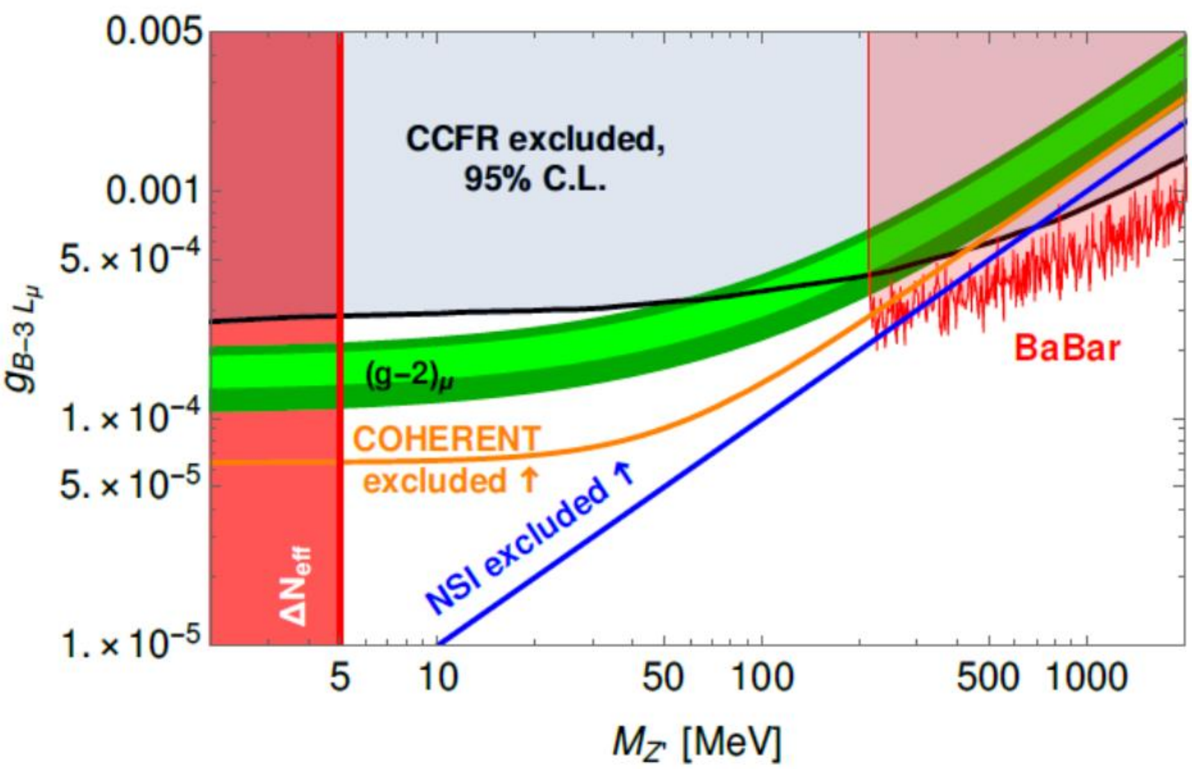
- Neutral current Non-Standard interaction
  - Propagation of neutrinos in matter
  - 4-Fermi interaction: $-2\sqrt{2}G_F\, \epsilon^{fX}_{\alpha\beta}\, (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\, (\bar{f}\gamma_\mu P_X f)$
  - $H_{\rm mat} = \sqrt{2}G_F N_e(r) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sqrt{2}G_F \sum_{f=e,u,d} N_f(r) \begin{pmatrix} \varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau} \\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau} \\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau} \end{pmatrix}$
  - Constraints

Esteban et al., JHEP 1808 (2018) 180

OSC			+COHERENT		
	LMA	LMA $\oplus$ LMA-D		LMA	LMA $\oplus$ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	$[-0.020, +0.456]$	$\oplus[-1.192, -0.802]$	ε^u_{ee}	$[-0.008, +0.618]$	$[-0.008, +0.618]$
			$\varepsilon^u_{\mu\mu}$	$[-0.111, +0.402]$	$[-0.111, +0.402]$
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	$[-0.005, +0.130]$	$[-0.152, +0.130]$	$\varepsilon^u_{\tau\tau}$	$[-0.110, +0.404]$	$[-0.110, +0.404]$
$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.067]$	$\varepsilon^u_{e\mu}$	$[-0.060, +0.049]$	$[-0.060, +0.049]$
$\varepsilon^u_{e\tau}$	$[-0.292, +0.119]$	$[-0.292, +0.336]$	$\varepsilon^u_{e\tau}$	$[-0.248, +0.116]$	$[-0.248, +0.116]$
$\varepsilon^u_{\mu\tau}$	$[-0.013, +0.010]$	$[-0.013, +0.014]$	$\varepsilon^u_{\mu\tau}$	$[-0.012, +0.009]$	$[-0.012, +0.009]$

Neutrino oscillation effects

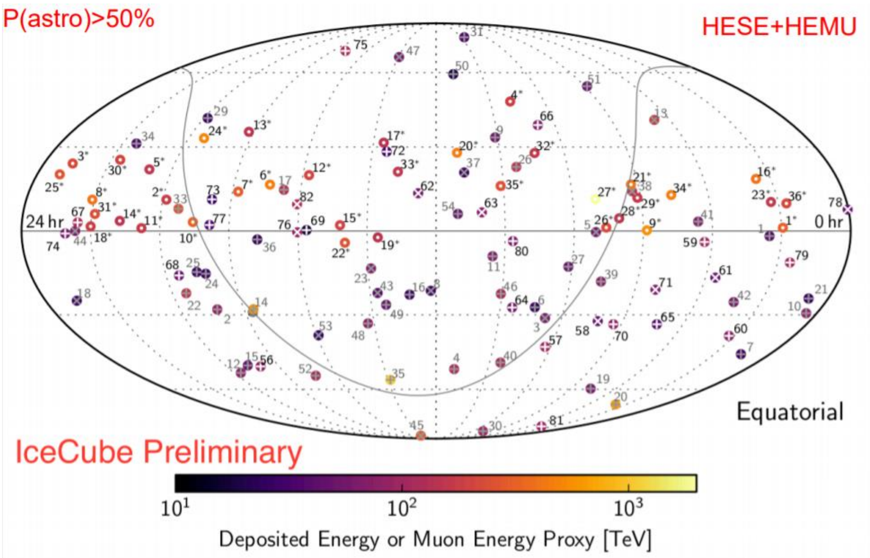
- Anomaly-free theory
  - Violate lepton universality
  - Light Z' boson can be constrained by NSI effects



J. Heeck, M. Lindner, W. Rodejohann and Vogl, arXiv: 1812.04067

High energy neutrinos

- IceCube 6-year high-energy starting events
  - Above 60 TeV

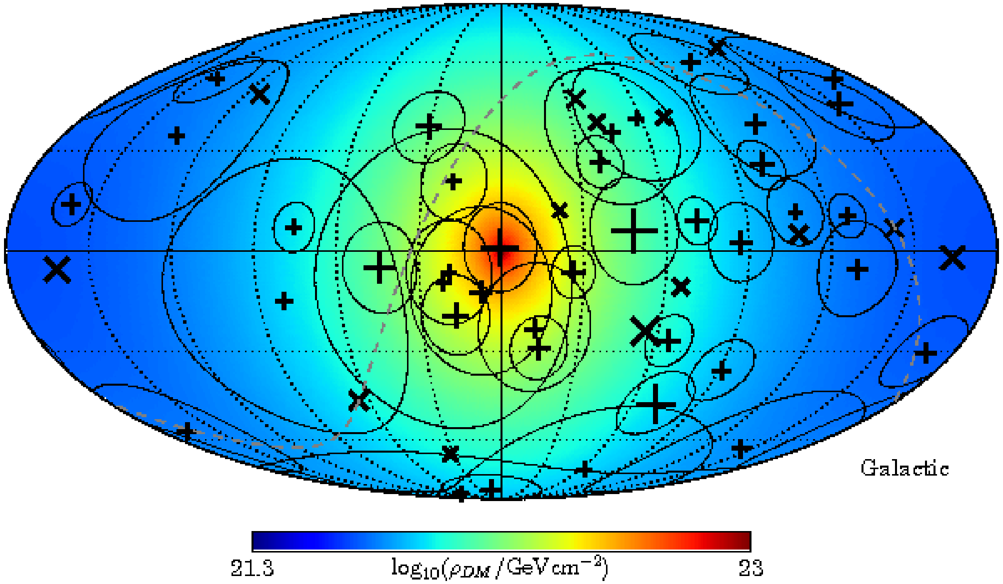


From C. Wiebusch's slide

  - Events arrival directions is compatible with isotropic hypothesis
  - No correlation with Galactic plane
  - Event distribution suggests extragalactic origin for the majority of the events

High energy neutrinos

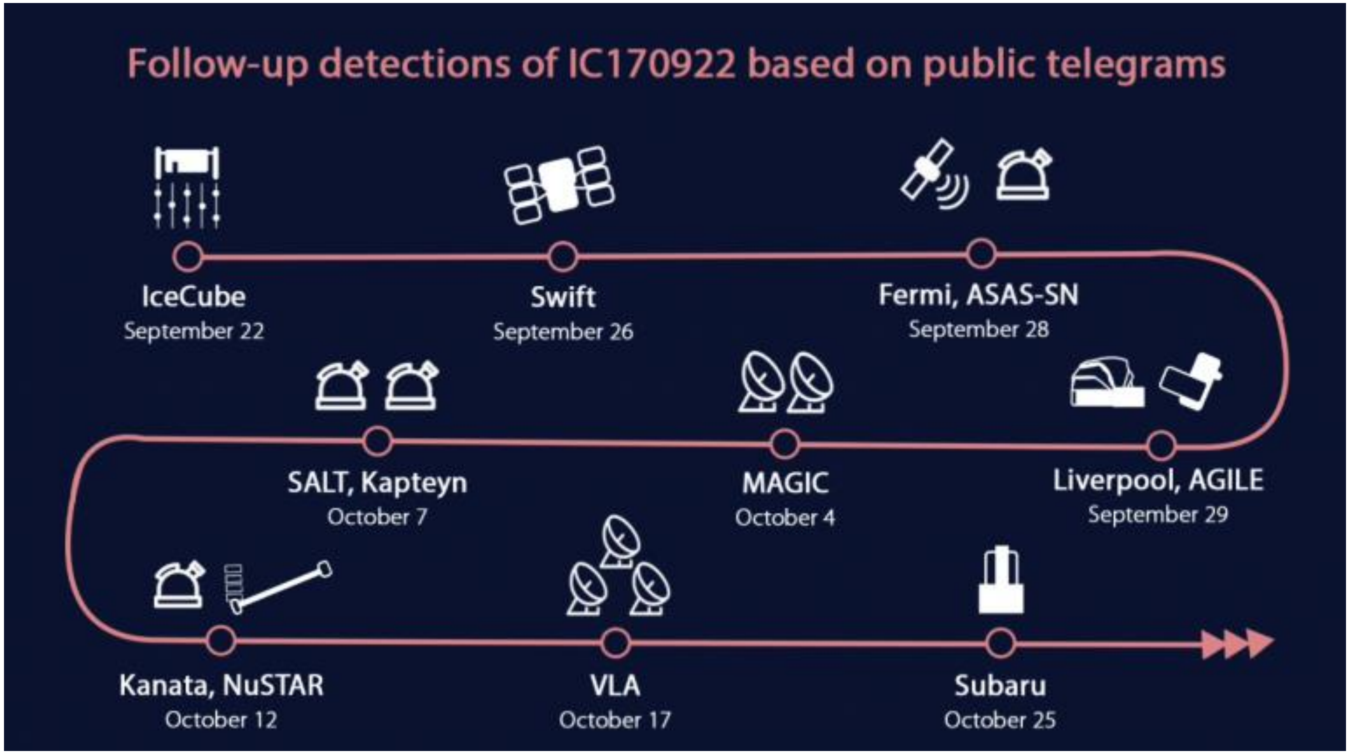
- HESE



C. A. Arguelles,
A. Kheirandish,
B. A. C. Vincent PRL 2017

- DM density is largest in center of the galaxy
- DM-ν interaction will result in scattering of neutrinos from extragalactic sources, leading to anisotropy and energy loss
- 1-100 MeV DM mass model is constrained

IceCube alert



- Unusual high energy neutrino was detected
- Collaboration with another astrophysical experiments

Multi-messenger

- Flaring blazar
  - High energy neutrino
  - Gamma-ray
  - X-ray
  - Optical & radio

배아 발생 과정 세포 단위 추적 연구
RNA 간섭 약물 첫 미국 식품의약국(FDA) 허가
우주 중성미자 기원 '블레이자' 규명
그린란드에 떨어진 빙하기 운석 발견
네안데르탈인-데니소바인의 이종 교배 자손 유전자 확인
세포 안 액상 단백질 기능 규명
DNA 데이터베이스 이용한 과학수사로 미제사건 해결
5억5800만 년 전 생물 화석에서 화학물질 흔적 검출
유기물 분자 구조 알아내는 새로운 분석법
과학계 미투 운동

자료: 사이언스

IceCube-170922A

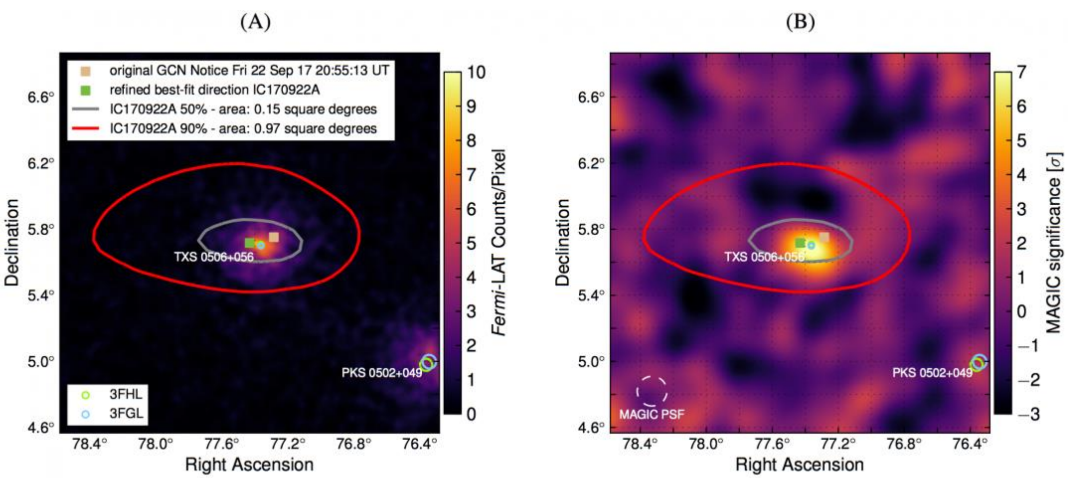
IceCube 2018 Science

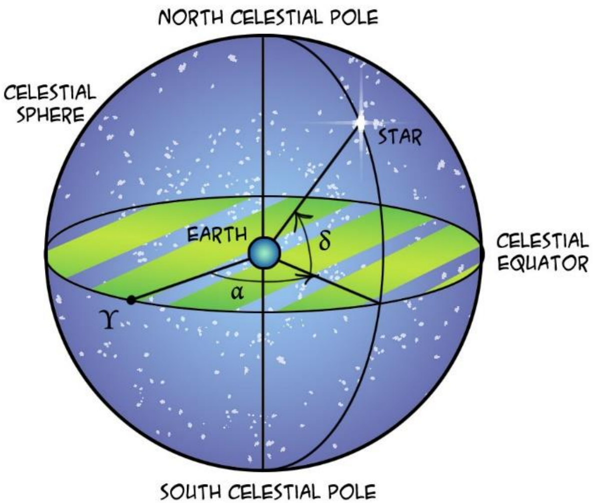
- Icecube-170922A

Redshift: $z = 0.3365 \pm 0.0010$ → $1421^{+1425}_{-1416}\ \mathrm{Mpc}$

right ascension (RA) $77.42^{+0.95}_{-0.65}$ **Declination** (Dec) $+5.72^{+0.50}_{-0.30}$

- Equatorial coordinate system





Coordinate transformation

- From equatorial coordinates to Galactic coordinates

$$\tan(l_0 - l) = \frac{\cos(\delta)\sin(\alpha - \alpha_0)}{\sin(\delta)\cos(\delta_0) - \cos(\delta)\sin(\delta_0)\cos(\alpha - \alpha_0)}$$

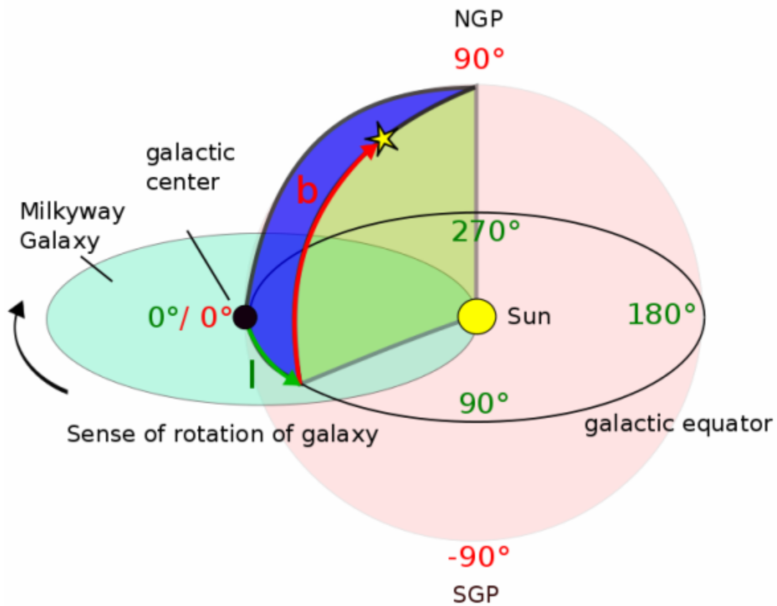
$$\sin(b) = \sin(\delta)\sin(\delta_0) + \cos(\delta)\cos(\delta_0)\cos(\alpha - \alpha_0)$$

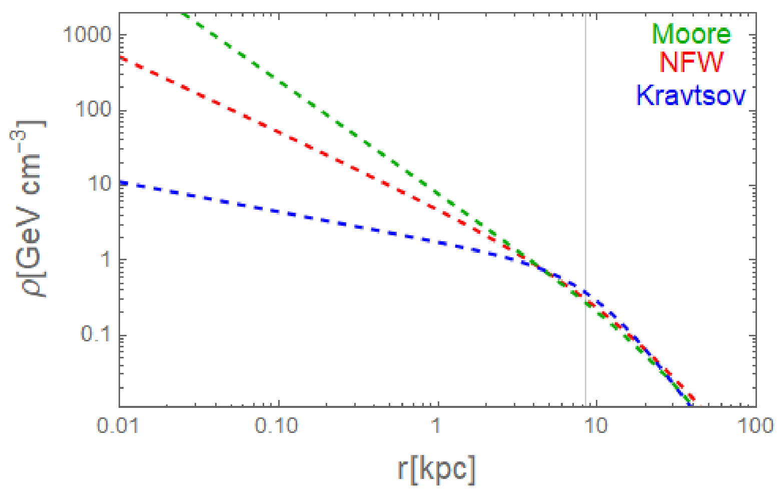
the equatorial coordinates of the Galactic north pole $\alpha_0 \approx 192.8595^\circ$, $\delta_0 \approx 27.1284^\circ$

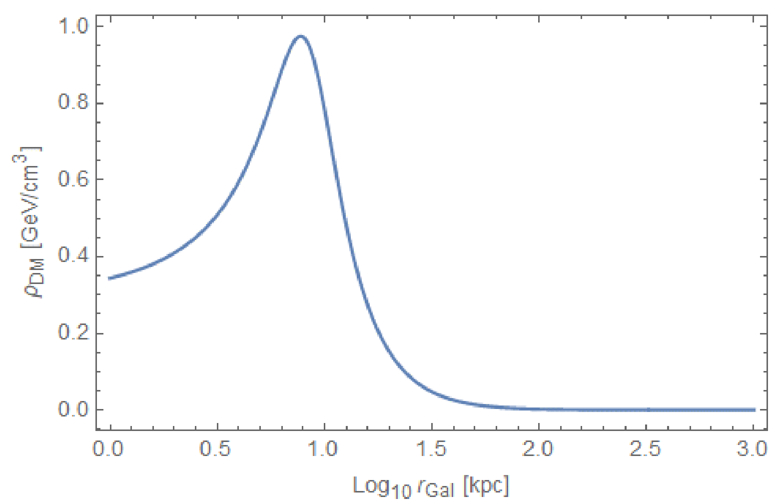
Galactic longitude of the equatorial north pole $l_0 \approx 122.9320^\circ$

Galactic coordinate

- Icecube-170922A
  - b = -19.6 degree
  - l = 15.4 degree
- Not travel through GC
  - Independent on DM profile







Cosmic neutrino background

- If sizable ν-CνB interaction exists, scattering off the ν-CνB can cause a depletion of the detected neutrino events

- Scattering cross section between
  - Icecube-19022A neutrino and Cosmic neutrino background
  - Number density of the CνB: 340/cm^3

- Mean free-path of a 290 TeV neutrino
  - O(10^11) Gpc
  - Negligible effect in the SM
  - Secret neutrino interactions can be tested

Kevin. J. Kelly and Pedro A. Machado, arXiv:1808.02889

Dissipation of neutrino flux

- The interaction of neutrinos with DM can suppress the flux of neutrinos along the path from the source to Earth
  - Scattering cross section → constant

$$\Phi = \Phi_0 e^{-\int_{\text{path}} \sigma n(\mathbf{x}) dl}$$

- The suppression depends on the DM-v scattering cross section as well as the DM number density along the path

- $\int_{\text{path}} \sigma n(\mathbf{x}) dl \lesssim 1$

Dissipation of neutrino flux

- The suppression can be divide into two contributions

$$\int_{\text{path}} \sigma n(\mathbf{x}) dl = n_0 \sigma L + \int_{los} \sigma n_{\text{gal}}(\mathbf{x}) dl,$$

- Suppression from the cosmological DM
  - $$\int_{los} \rho(z)\, dl = \int \rho(z) \frac{cdt}{dz} dz,$$
    $$\simeq 7.2 \times 10^{21}\, \text{GeV}/\text{cm}^2.$$

Dissipation of neutrino flux

- The suppression can be divide into two contributions

$$\int_{\text{path}} \sigma n(\mathbf{x}) dl = n_0 \sigma L + \int_{los} \sigma n_{\text{gal}}(\mathbf{x}) dl,$$

- Galactic DM
  - NFW DM profile
  - $\int_{los} \rho_{\text{gal}}(\mathbf{x}) dl \simeq 3.8 \times 10^{22}\ \text{GeV/cm}^2$

$$\rho_{\text{gal}}(\mathbf{x}) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

- Incidentally both contributions from cosmological DM and Milky Way DM are very comparable
  - Very tiny cosmological DM density is compensated by the long distance

New constraint

- Demand less than 90% suppression of the flux
  - $\int \sigma n dl \lesssim 2.3$
- DM-ν scattering cross section
  - The identification of the source can allow the precise evaluation of the neutrino flux change due to DM- ν scattering cross section

$$\sigma/M_{\rm dm} \lesssim 5.3 \times 10^{-23}\,{\rm cm}^2/\,{\rm GeV}$$

$$\text{at} \quad E_\nu = 290\,{\rm TeV}$$

Constraints

C. Boehm, R. Wilkinson arXiv: 1401.7597

- Lyman-alpha
  - WIMP DM stays in equilibrium with primordial plasma for longer time due to elastic scattering and undergoes acoustic oscillations
  - Suppresses matter perturbations and reduces the amount of small scale structures today
  - constant cross section: $\sigma_{\rm el} < 10^{-36} \left(\frac{m_{\rm DM}}{\rm MeV}\right) \ {\rm cm}^2$
  - T-dependent cross section: $\sigma_{\rm el} < 10^{-48} \left(\frac{m_{\rm DM}}{\rm MeV}\right) \left(\frac{T_\nu}{T_0}\right)^2 \ {\rm cm}^2$

$$T_0 = 2.35 \times 10^{-4} \ {\rm eV}$$

- This constraint can be applied for neutrino energy at around 100 eV.

Constraints

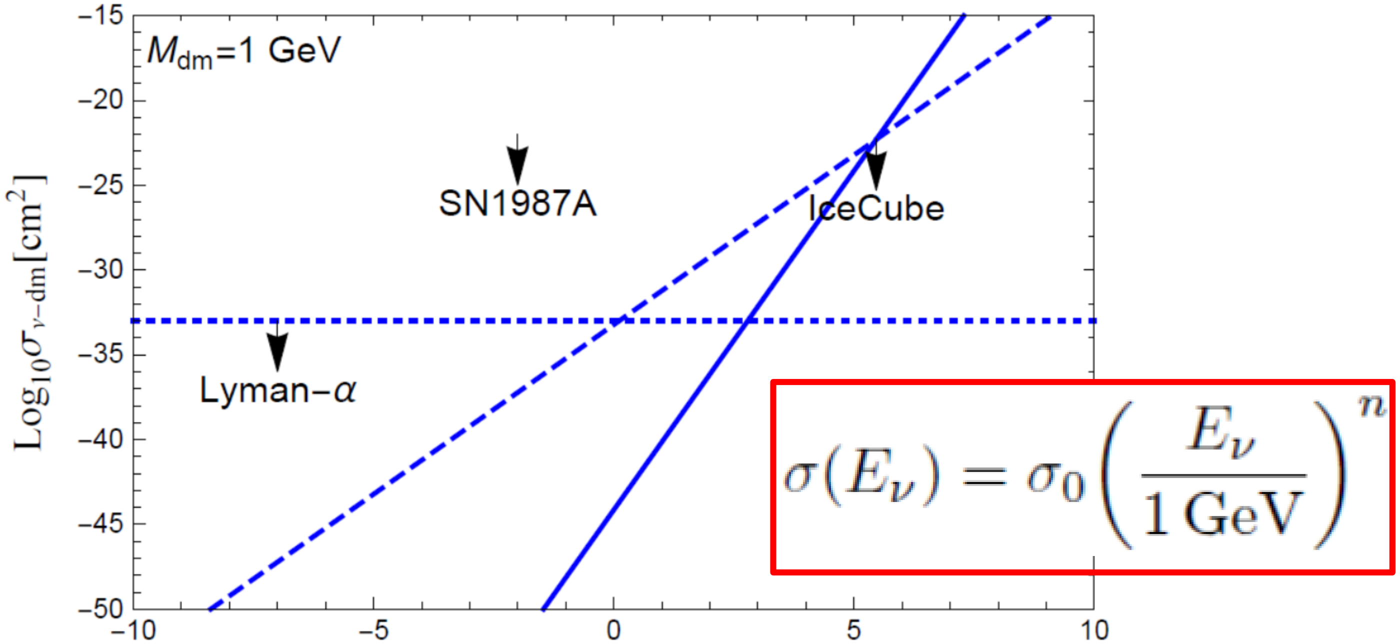
G. Barbiellini, G. Cocconi, 1987

- SN1987A
  - Neutrino energies ~ 10 MeV
  - Distance ~ 50 kpc

- ν-DM interaction can be constrained
- This constraint can be applied for neutrino energy at around 10 MeV.

Neutrino energy	$\sigma/M_{\rm dm}[{\rm cm}^2/{\rm GeV}]$
~ 100 eV	6×10^{-31}
~ 100 eV	10^{-33}
10 MeV	10^{-22}

Scattering cross section

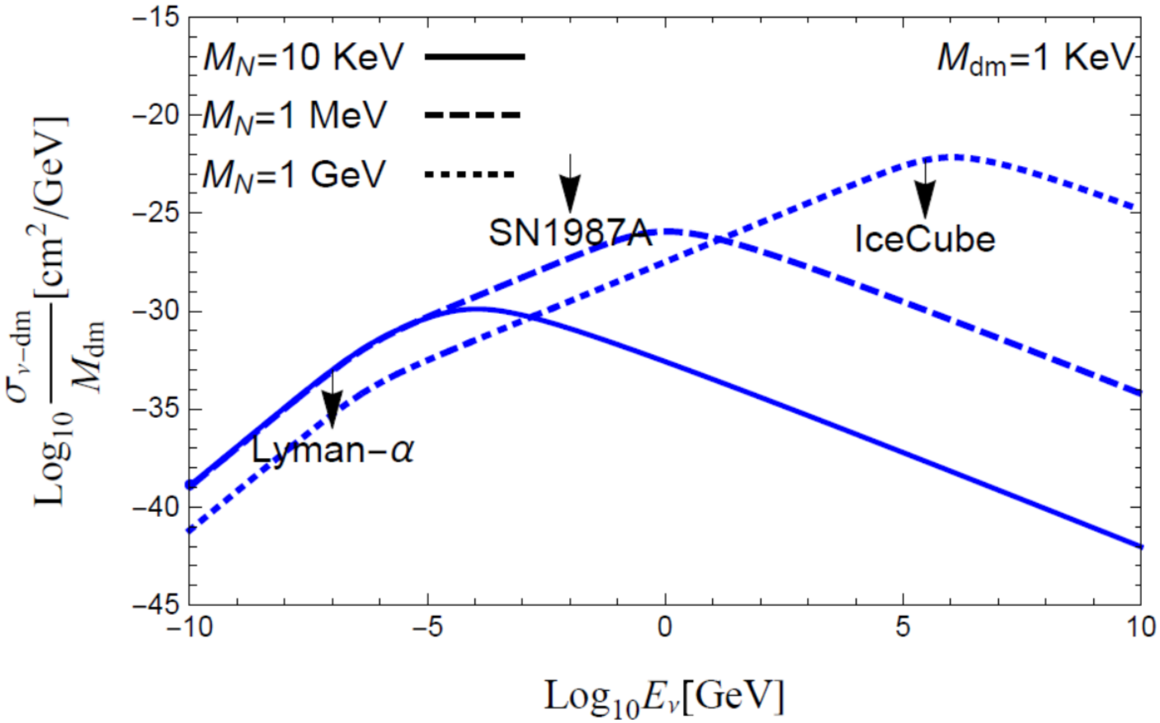


- $$\sigma_0/M_{\rm dm} \lesssim 10^{-33}\,{\rm cm}^2/\,{\rm GeV} \quad {\rm for} \quad n=0,$$
  $$\sigma_0/M_{\rm dm} \lesssim 6.3\times 10^{-34}\,{\rm cm}^2/\,{\rm GeV} \quad {\rm for} \quad n=2,$$
  $$\sigma_0/M_{\rm dm} \lesssim 7.5\times 10^{-45}\,{\rm cm}^2/\,{\rm GeV} \quad {\rm for} \quad n=4.$$
- Stringent constraint depends on the upper bound on DM-neutrino scattering cross section

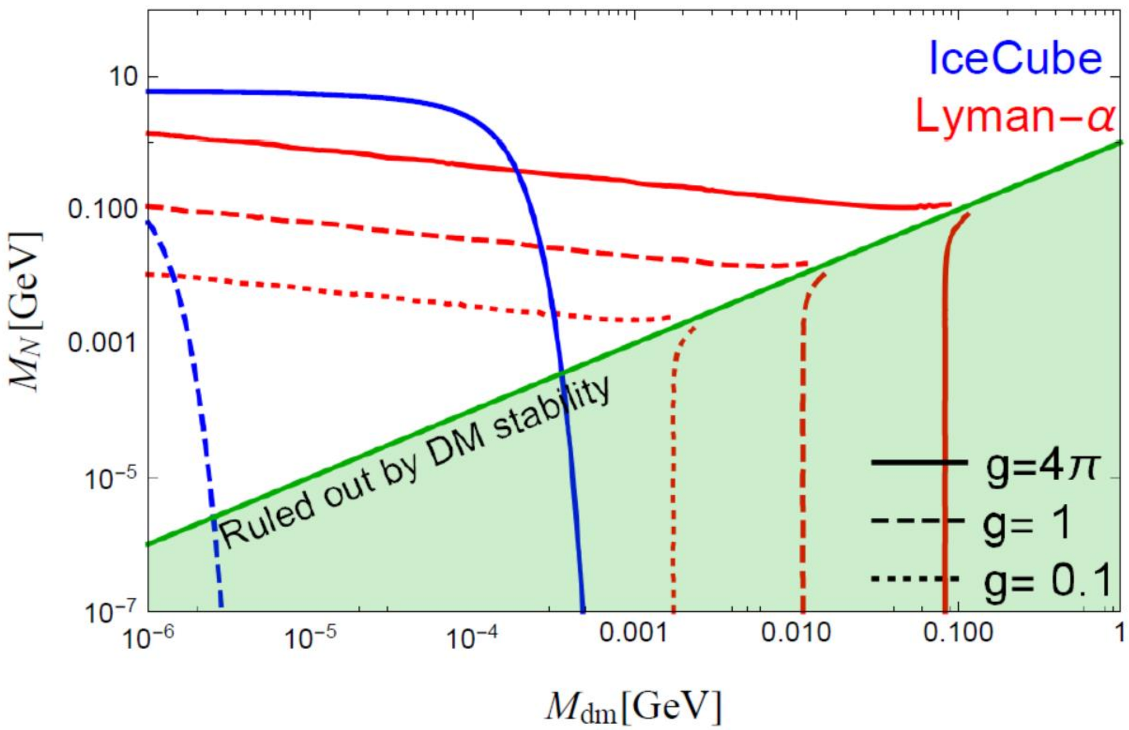
Complex scalar DM model

- A fermion mediator
  - $\mathcal{L}_{\rm int} = -g\chi\overline{N}\nu_L + \text{h.c.},$

- Scattering cross section vs neutrino energy

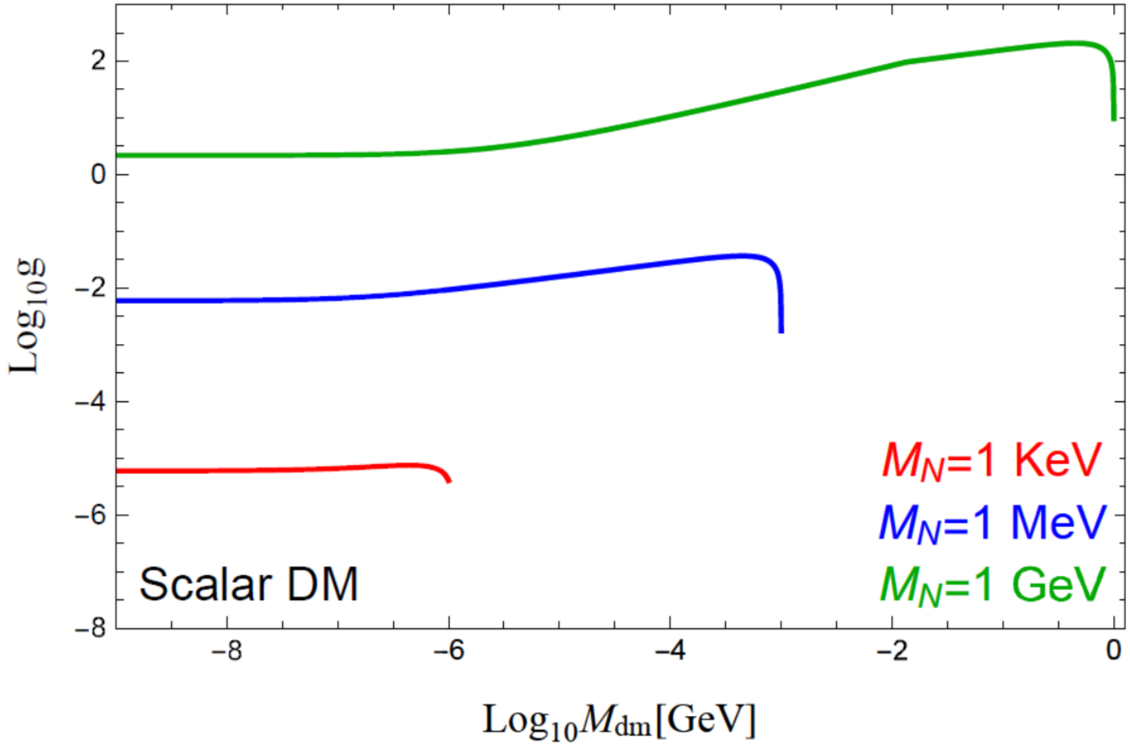


Complex scalar DM model



- Upper & right region are allowed
  - Blue: IceCube-170922A
  - Red: Lyman alpha
- Green region: ruled out by DM stability

Complex scalar DM model



- Maximum values of (g vs m_{DM})

Conclusions

- Identifying sources of astrophysical neutrinos gives us additional information

- New constraint
  - DM-v scattering cross section using Icecube-170922A

$$\sigma / M_{\rm dm} \lesssim 5.3 \times 10^{-23}\,{\rm cm}^2 / \,{\rm GeV}$$

$$\text{at} \quad E_\nu = 290\,{\rm TeV}$$

- Certain classes of new physics models can be probed by high energy neutrinos travelling very long distances
  - Light DM model

Conclusions

- Identifying sources of astrophysical neutrinos gives us additional information

- New constraint
  - DM-ν scattering cross section using Icecube-170922A

$$\sigma / M_{\rm dm} \lesssim 5.3 \times 10^{-23}\,{\rm cm}^2 / {\rm GeV} \quad {\rm at} \quad E_\nu = 290\,{\rm TeV}$$

- Certain classes of new physics models can be probed by high energy neutrinos travelling very long distances

Thank you for your attention~