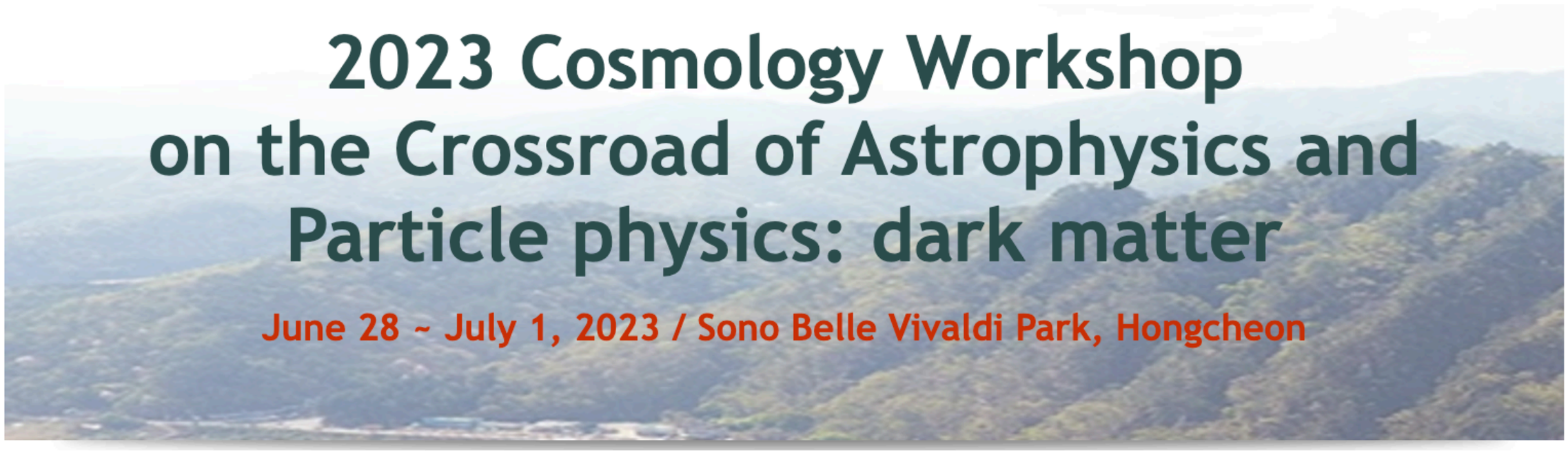
성균관대학교
SUNG KYUN KWAN UNIVERSITY

What is Dark Matter?

Ki -Young Choi



RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

The origin of high-energy cosmic rays, atomic nuclei that continuously impact Earth's atmosphere, is unknown. Because of deflection by interstellar magnetic fields, cosmic rays produced within the Milky Way arrive at Earth from random directions. However, cosmic rays interact with matter near their sources and during propagation, which produces high-energy neutrinos. We searched for neutrino emission using machine learning techniques applied to 10 years of data from the IceCube Neutrino Observatory. By comparing diffuse emission models to a background-only hypothesis, we identified neutrino emission from the Galactic plane at the 4.5σ level of significance. The signal is consistent with diffuse emission of neutrinos from the Milky Way but could also arise from a population of unresolved point sources.

neutrino (ν_τ) with nuclei, as well as scatte
interactions of all three neutrino flavors [ν_e,
muon neutrino (ν_μ), and ν_τ] on nuclei. Because the charged particles in cascade events travel only a few meters, these energy depositions appear almost point-like to IceCube's 125-m (horizontal) and 7- to 17-m (vertical) instrument spacing. This results in larger directional uncertainties than tracks. Tracks are elongated energy depositions (often several kilometers long), which arise predominantly from muons generated in cosmic-ray particle interactions in the atmosphere or muons produced by interactions of ν_μ with nuclei. The energy deposited by cascades is often contained within the instrumented volume (unlike tracks), which provides a more complete measure of the neutrino energy (*19*).

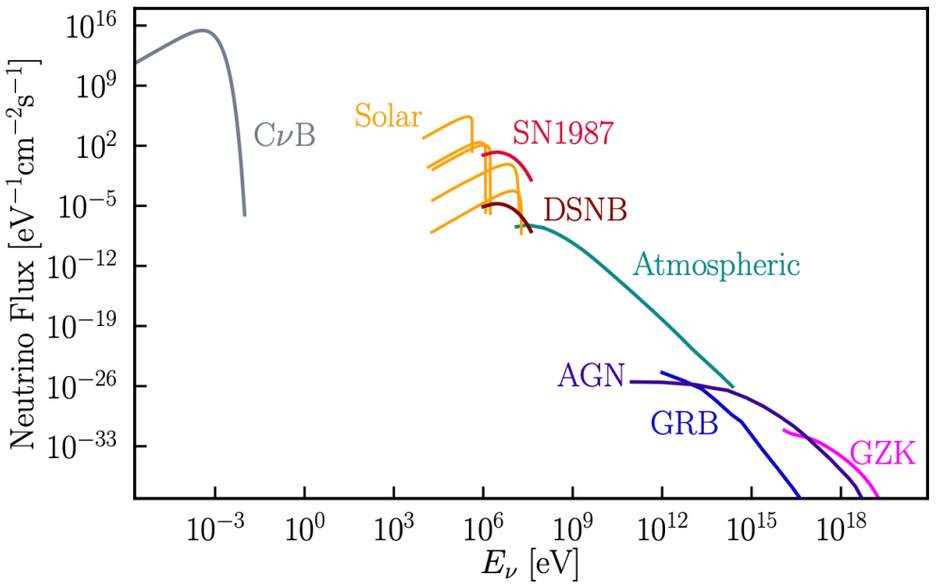
Searches for astrophysical neutrino sources are affected by an overwhelming background of muons and neutrinos produced by cosmic-

Downloade

We identified neutrino emission from the Galactic plane at the 4.5 sigma level of significance by comparing diffuse emission model to a background-only hypothesis.

IceCube

Halzen etal, 2202.00694



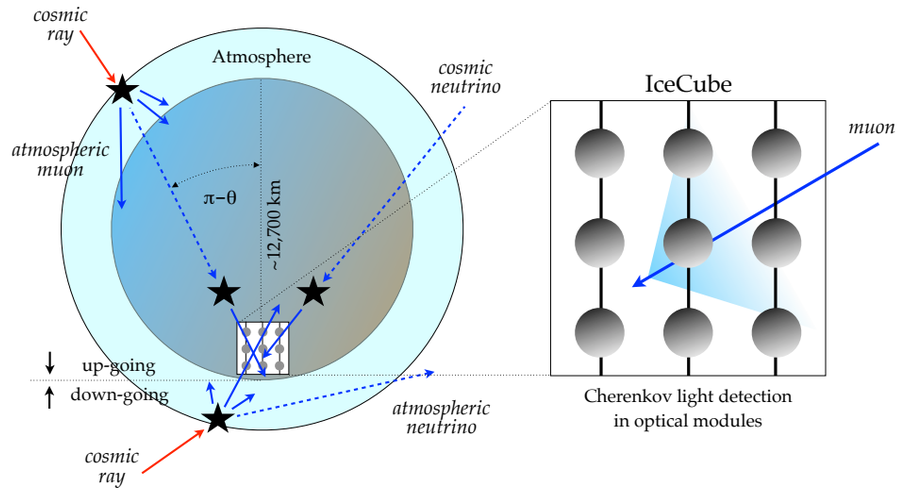
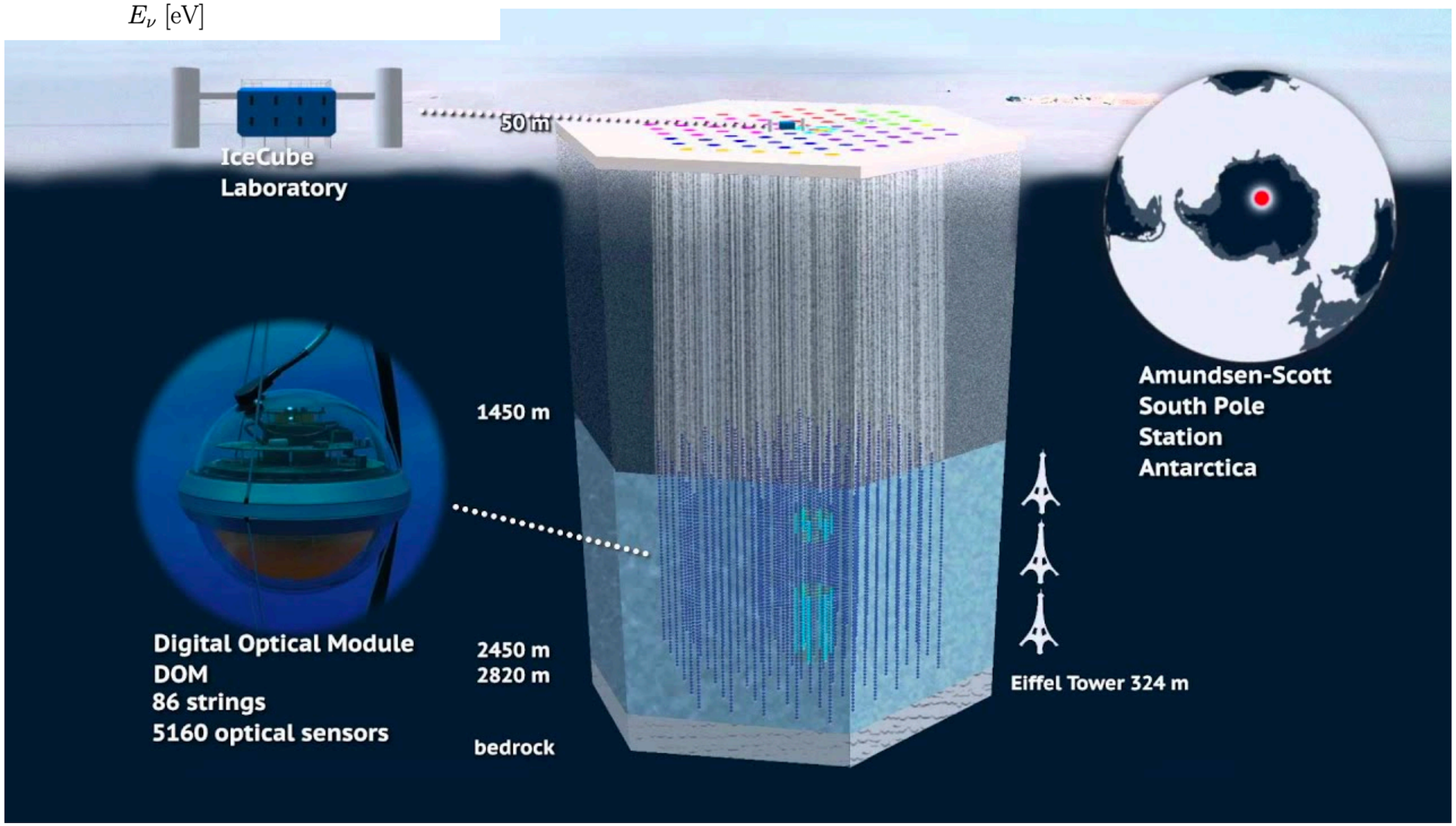


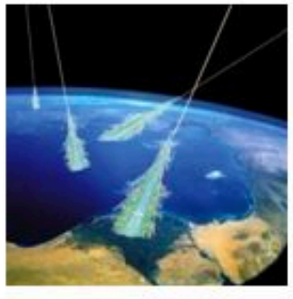
Fig. 9. The concept of a neutrino telescope from the point of view of IceCube located at the



Neutrino sources



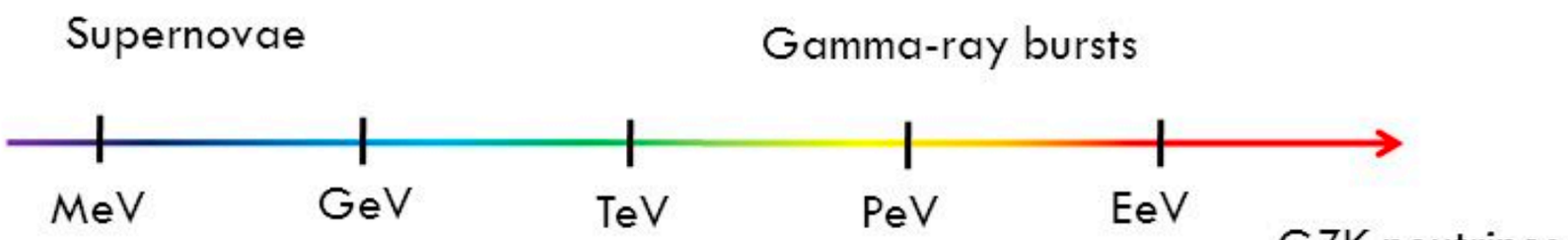
Supernovae



Atmospheric neutrinos



Gamma-ray bursts



GZK neutrinos

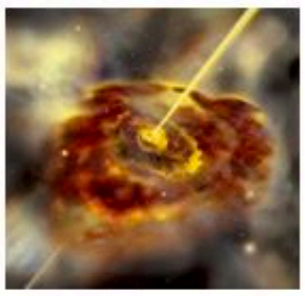
Dark matter



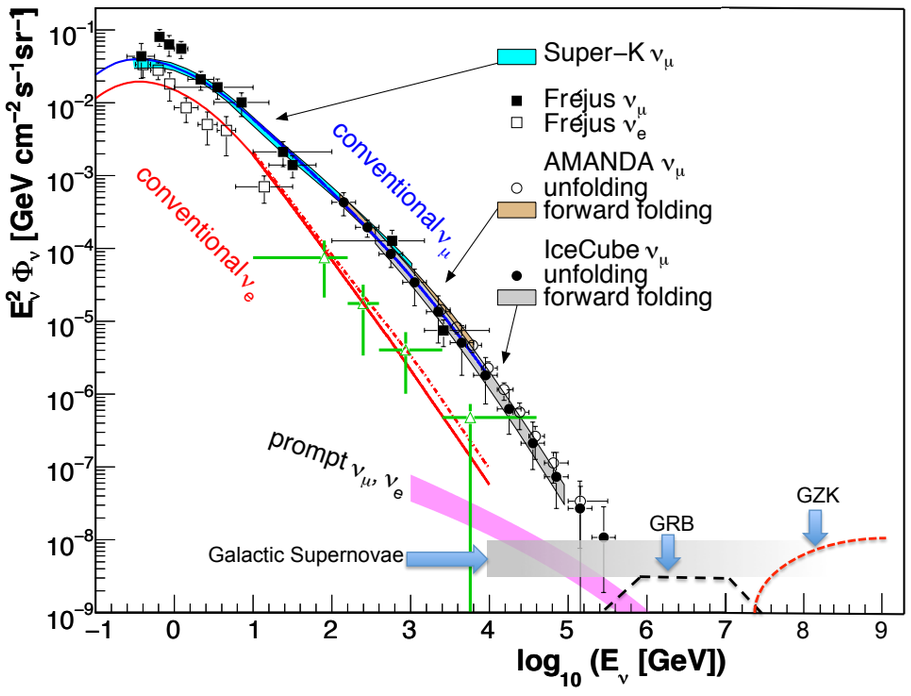
Supernova remnants



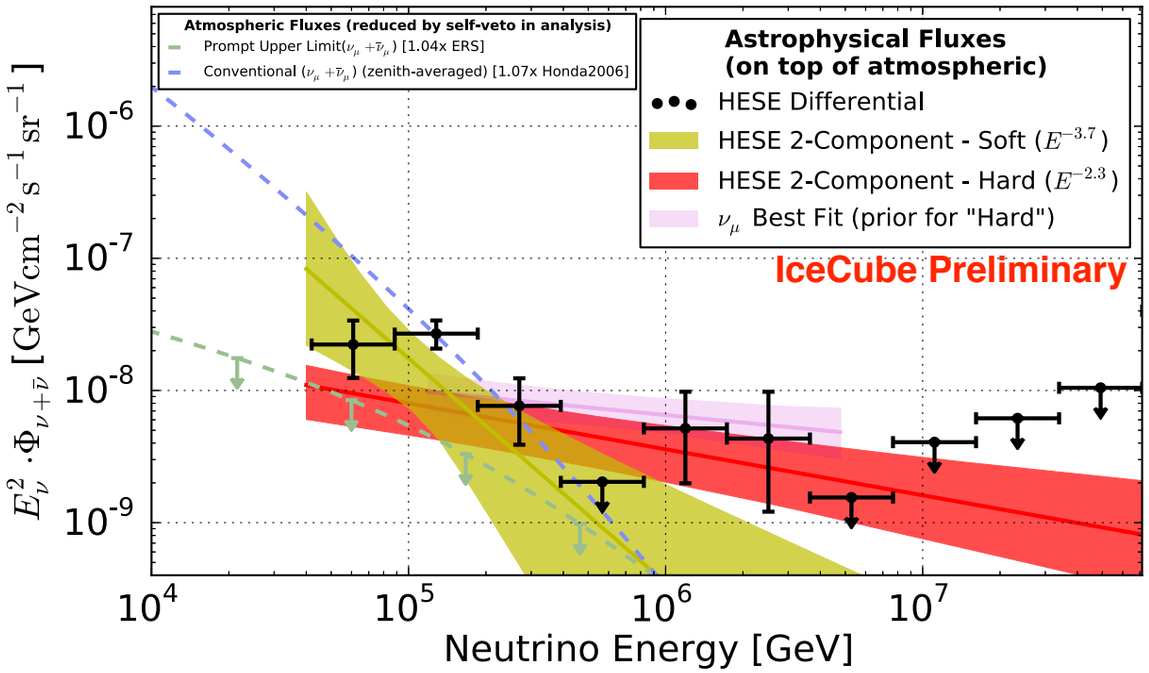
Active galactic nuclei



Atmospheric neutrinos



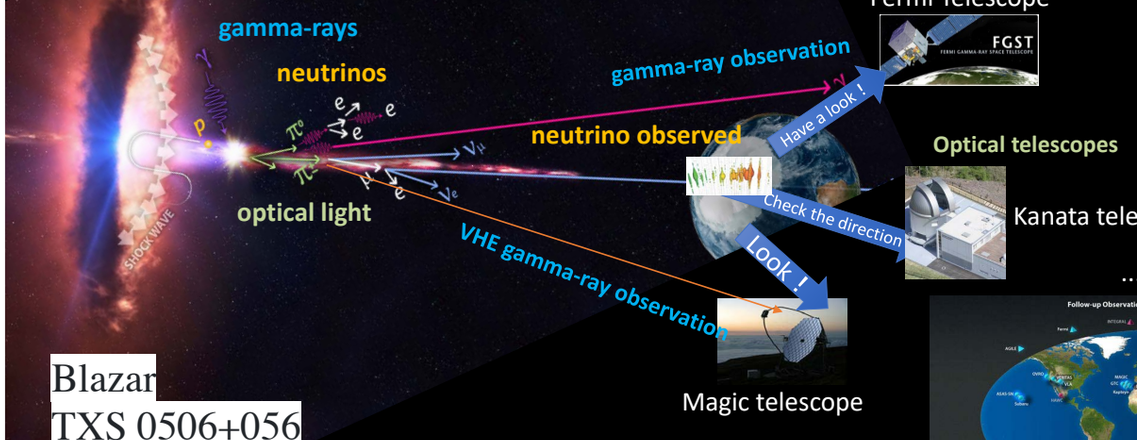
Astrophysical neutrinos



Science 361, eaat1378 (2018)

IceCube-170922A alert to worldwide telescopes

- 2017/9/22 20:54:30.43 UTC
- 5th and the most cosmic neutrino signal like EHE alert
- automated alert was distributed to observers just 43 seconds later





Science — Nov.4, 2022

RESEARCH

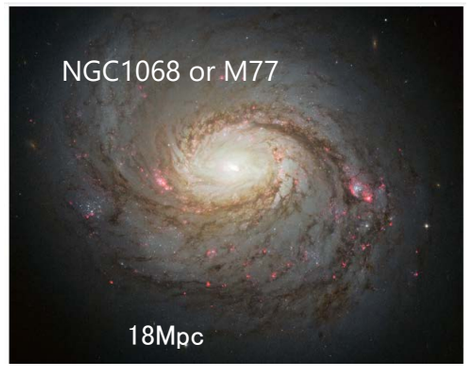
RESEARCH ARTICLE

NEUTRINO ASTROPHYSICS

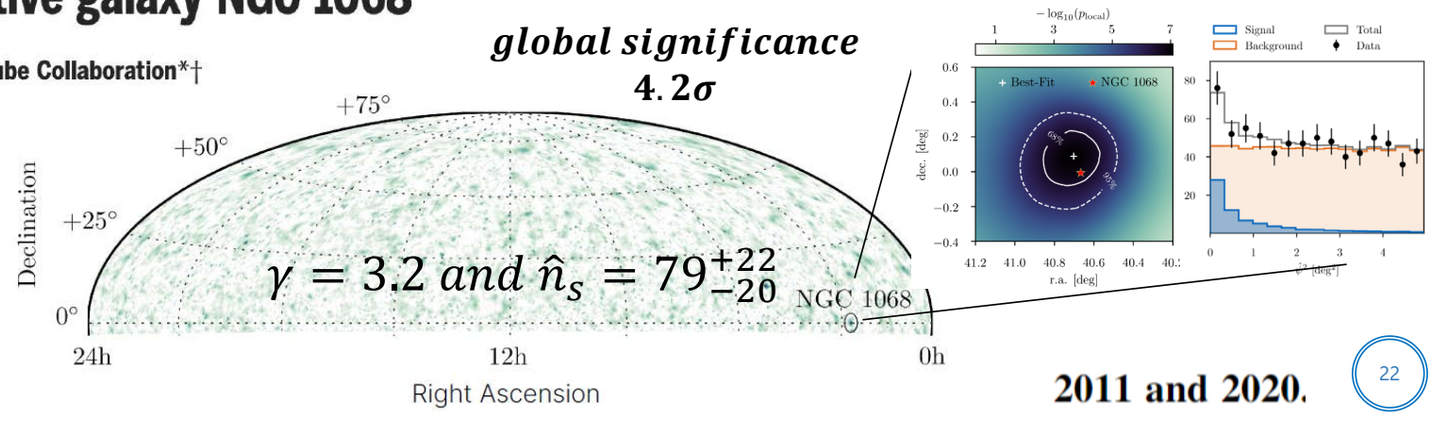
Evidence for neutrino emission from the nearby active galaxy NGC 1068

IceCube Collaboration*†

Very bright, well studied, spiral galaxy



global significance
4.2σ



2011 and 2020.

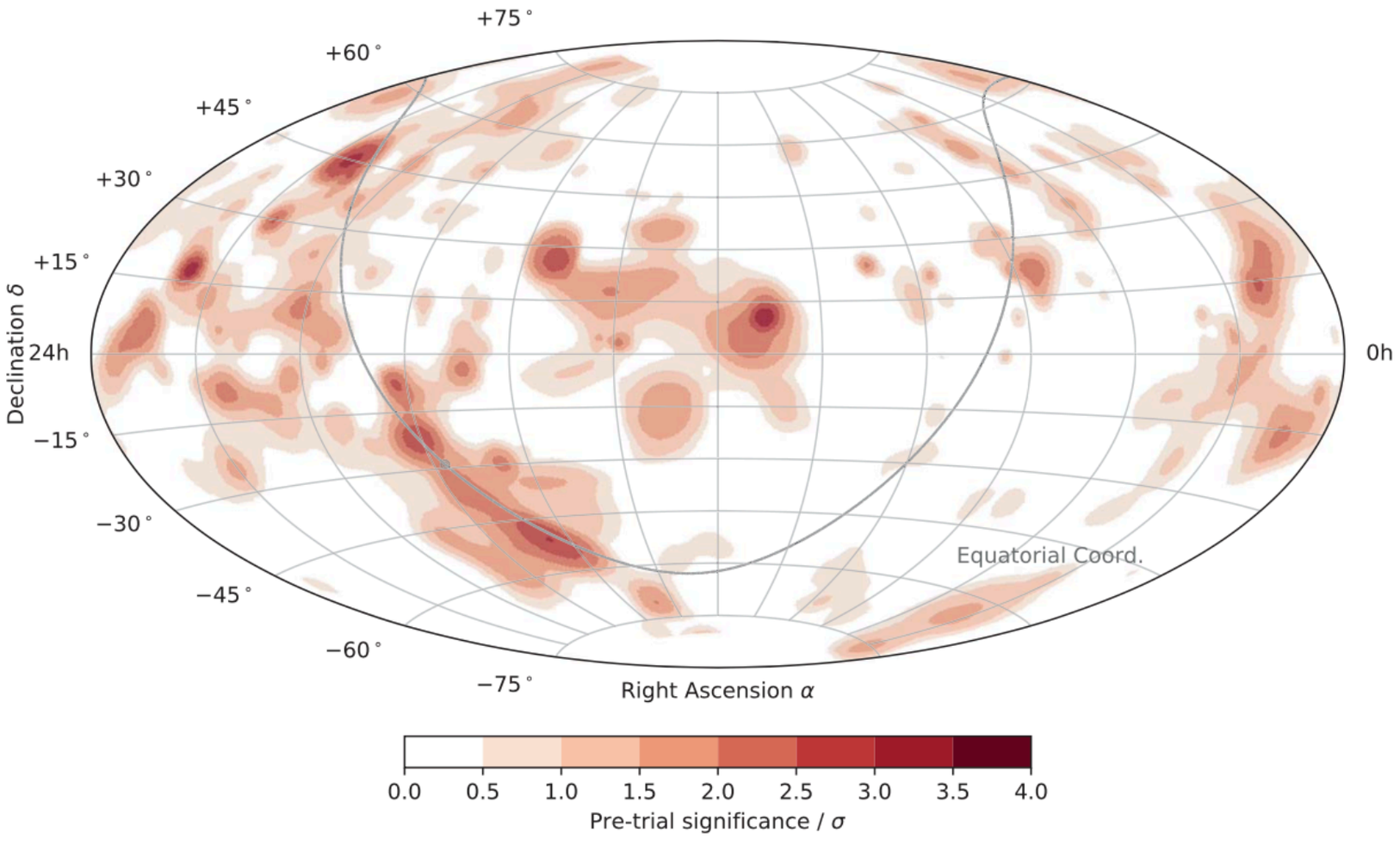
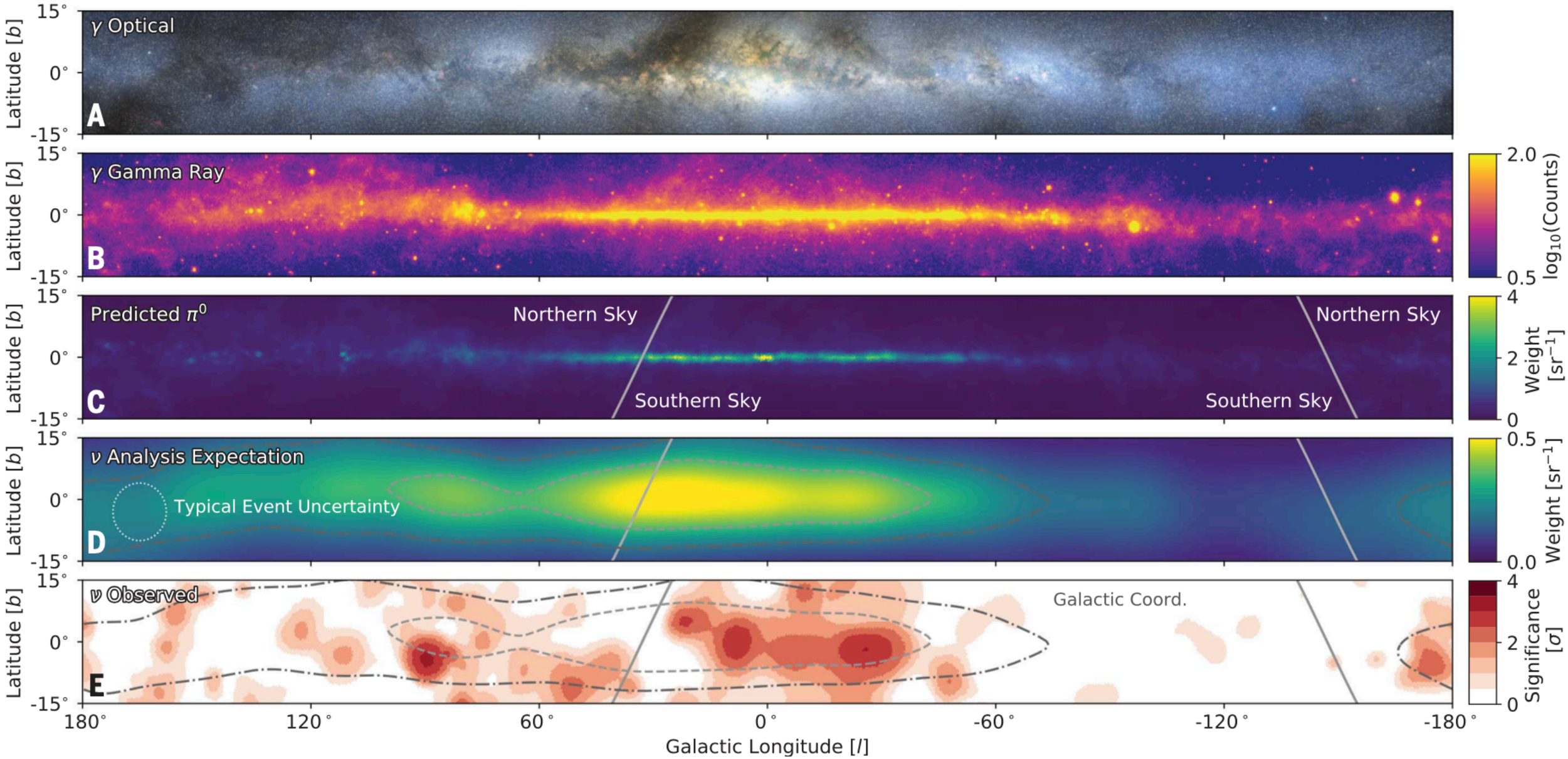


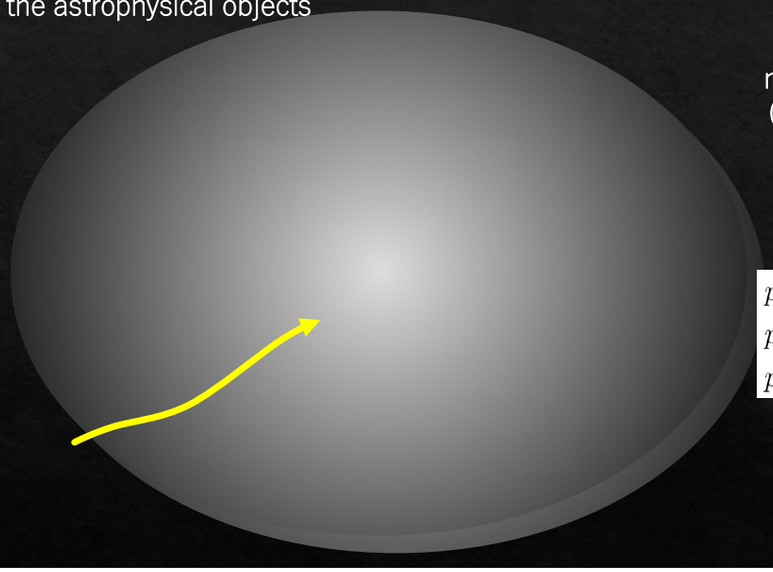
Fig. 4. All-sky point source search. A map of the best-fitting pretrial significance for the all-sky search, shown on an Aitoff projection of the celestial sphere, in equatorial coordinates (J2000 equinox). The Galactic plane is indicated with a grey curve, and the Galactic Center is indicated with a gray dot. Although some locations appear to have significant emission, the trial factor for the number of points searched means that these points are all individually statistically consistent with background fluctuations.



748, 276, 211 signal events for the model of π^0, KRA_γ^5, and KRA_γ^{50} models, respectively.

How to create the high energy neutrinos

high energy (1〜10^8TeV) cosmic-rays (proton and nuclei) interact with matter (gas, plasma) and photon field in the astrophysical objects



mesons (pions) are created
(both charged and neutral)

$$p + \gamma \rightarrow n + \pi^+$$
$$p + \gamma \rightarrow p + \pi^0$$

$$p + p \rightarrow p + p + \pi^0$$
$$p + p \rightarrow p + n + \pi^+$$
$$p + p \rightarrow p + p + \pi^+ + \pi^- \ldots$$

From slides of Aya Ishihara, PPC2023

How to create the high energy neutrinos

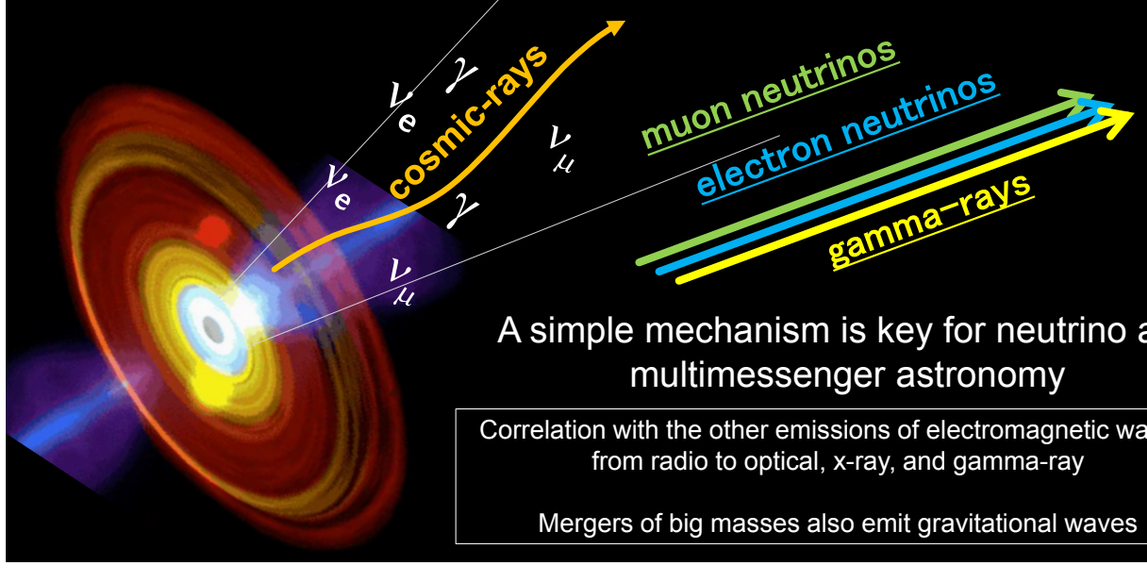
a charged pion decays into muon and neutrino, a muon decays into positron and (anti) neutrinos

$$\pi^0 \rightarrow \gamma + \gamma$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

charge neutral pions creates gamma-rays

When **neutrinos** are born, so are **gamma-rays**, from the **cosmic-rays**!



A simple mechanism is key for neutrino and multimessenger astronomy

Correlation with the other emissions of electromagnetic waves; from radio to optical, x-ray, and gamma-ray

Mergers of big masses also emit gravitational waves

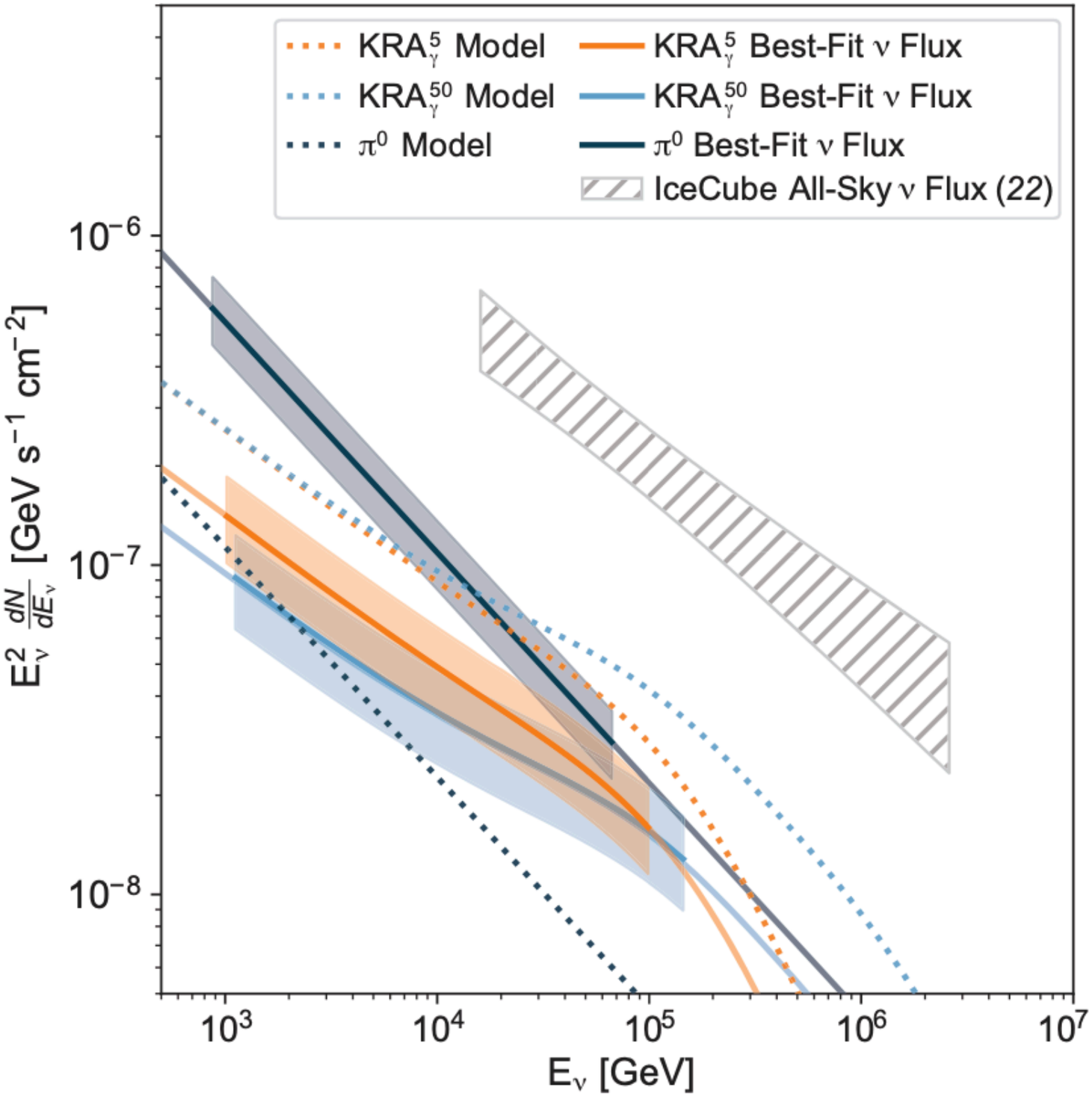
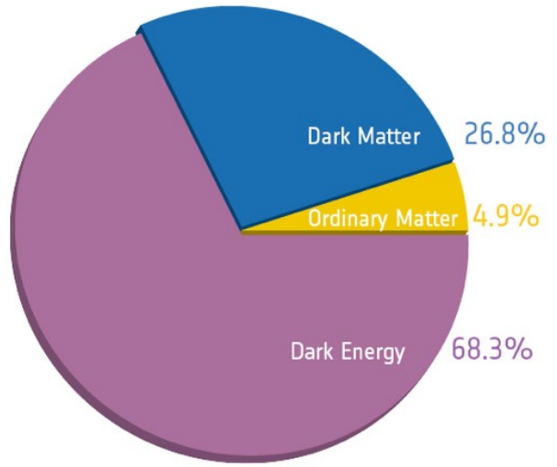


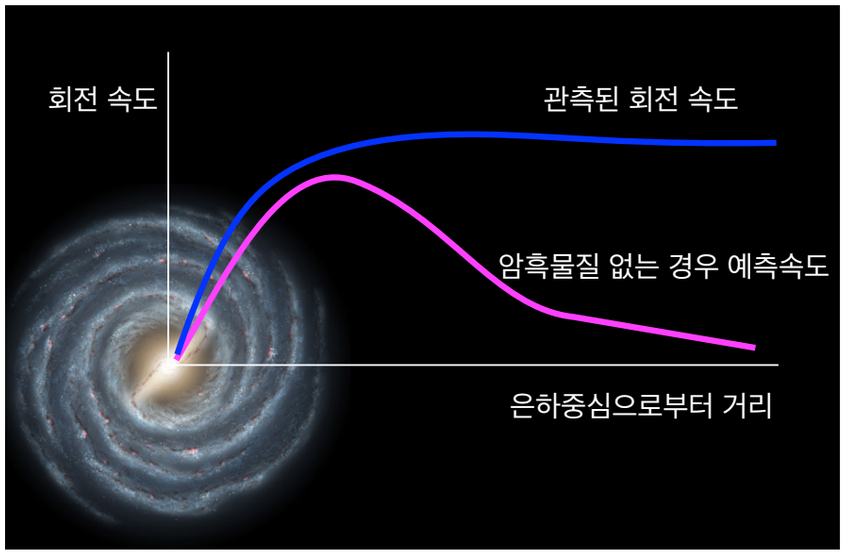
Fig. 5. Energy spectra for each of the Galactic plane models. Energy-scaled, sky-integrated, per-flavor neutrino flux is shown as a function of neutrino energy (E_ν) for each of the Galactic plane models. Dotted lines are the predicted values for the π^0 (dark blue), KRA$_\gamma^5$ (orange), and KRA$_\gamma^{50}$ (light blue) models. Solid lines are our best-fitting flux normalizations from the IceCube data. Shaded regions indicate the 1σ uncertainties; they extend over the energy range that contributes to 90% of the significance. These results are based on the all-sky (4π sr) template and are presented as an all-sky flux. For comparison, the gray hatching shows the IceCube total neutrino flux (*22*), scaled to an all-sky flux by multiplying by 4π, with its 1σ uncertainty.

Dark Matter

Cold Collisionless Dark Matter

We can observe the DM with only gravitation.





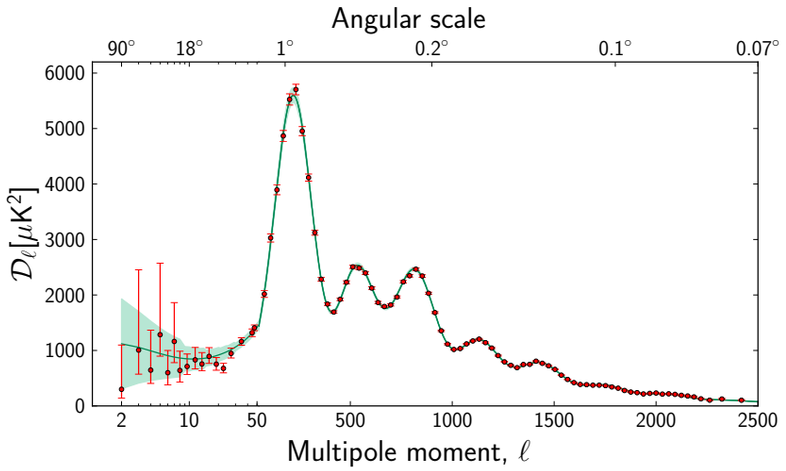
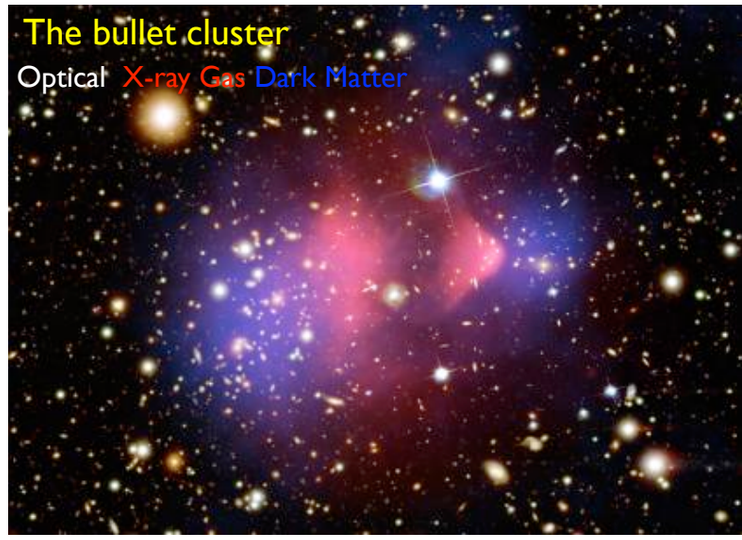
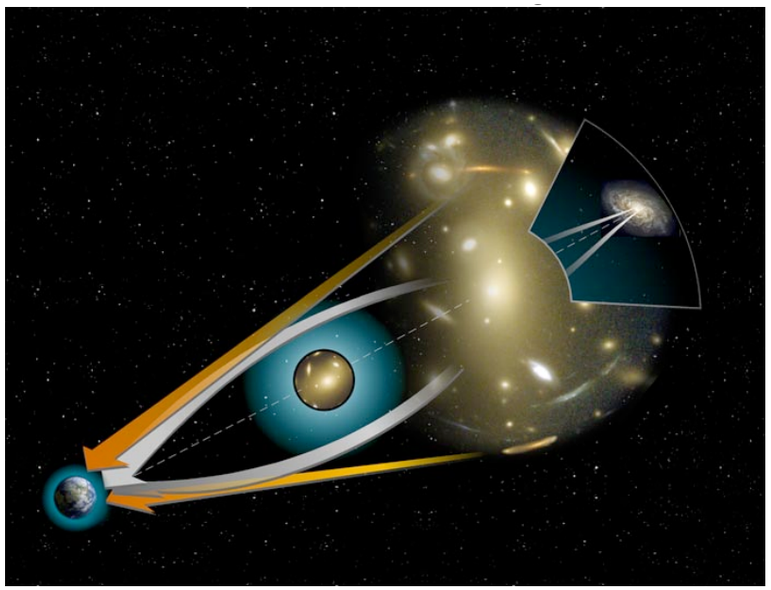
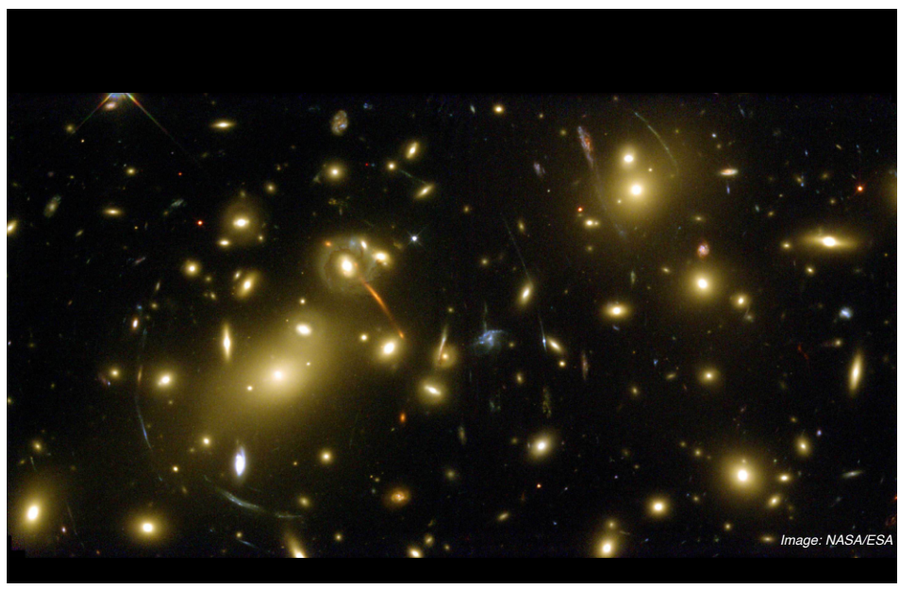
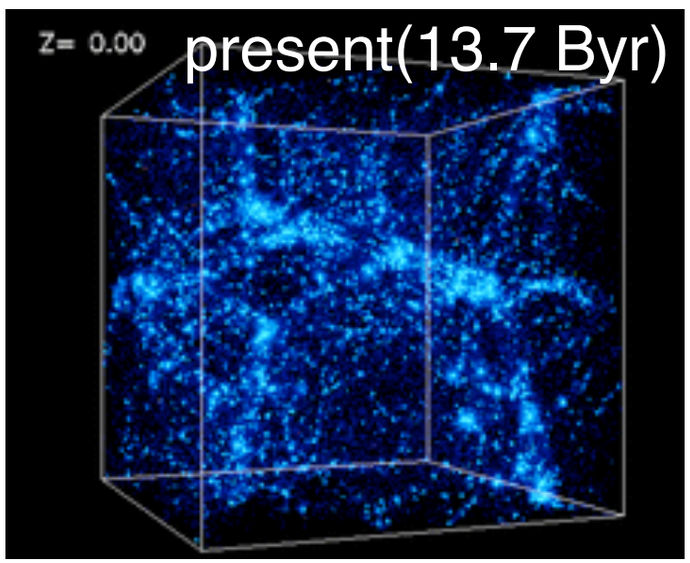


Fig. 19. The temperature angular power spectrum of the primary CMB from *Planck*, showing a precise measurement of seven acoustic peaks, that are well fit by a simple six-parameter ΛCDM theoretical model (the model plotted is the one labelled [Planck+WP+highL] in Planck Collaboration XVI (2013)). The shaded area around the best-fit curve represents cosmic variance, including the sky cut used. The error bars on individual points also include cosmic variance. The horizontal axis is logarithmic up to $\ell = 50$, and linear beyond. The vertical scale is $\ell(\ell+1)C_l/2\pi$. The measured spectrum shown here is exactly the same as the one shown in Fig. 1 of Planck Collaboration XVI (2013), but it has been rebinned to show better the low-ℓ region.







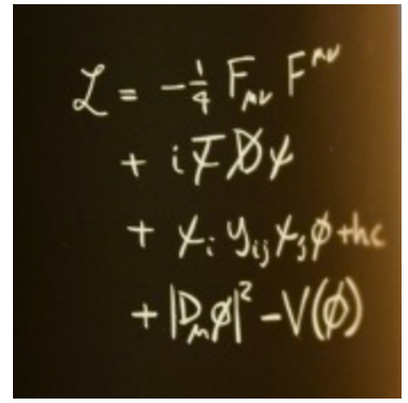


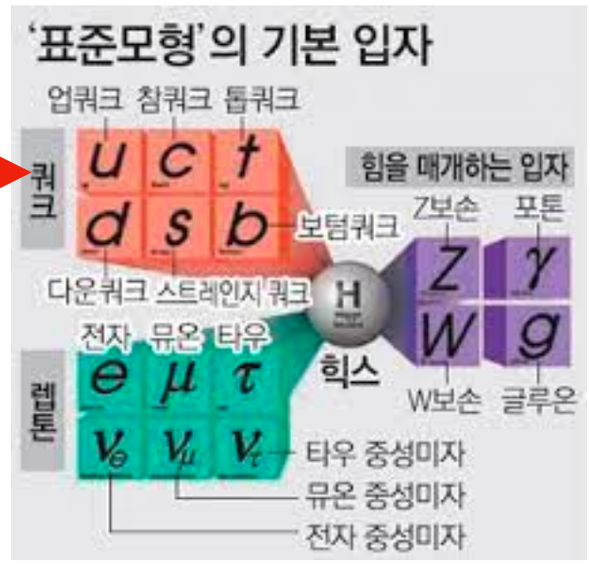
공기 (바람)같은 암흑물질

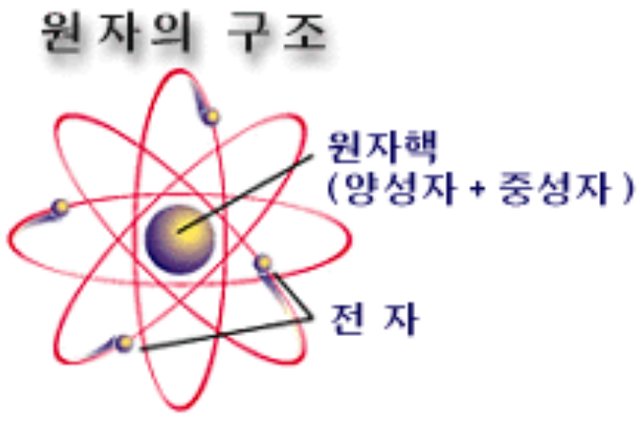
Fundamental Particles of the World

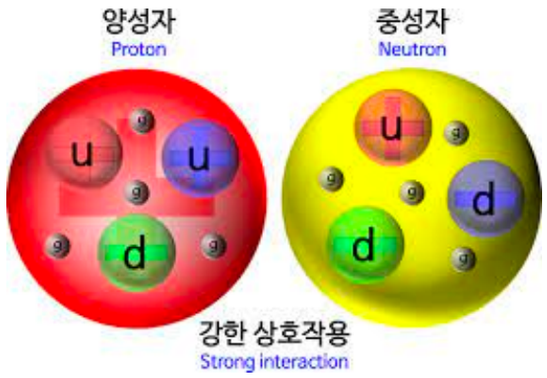












Deconstructed Standard Model Lagrangian

1 $$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$

2 $$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j -$$

3 $$\bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] +$$

4 $$\frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) +$$

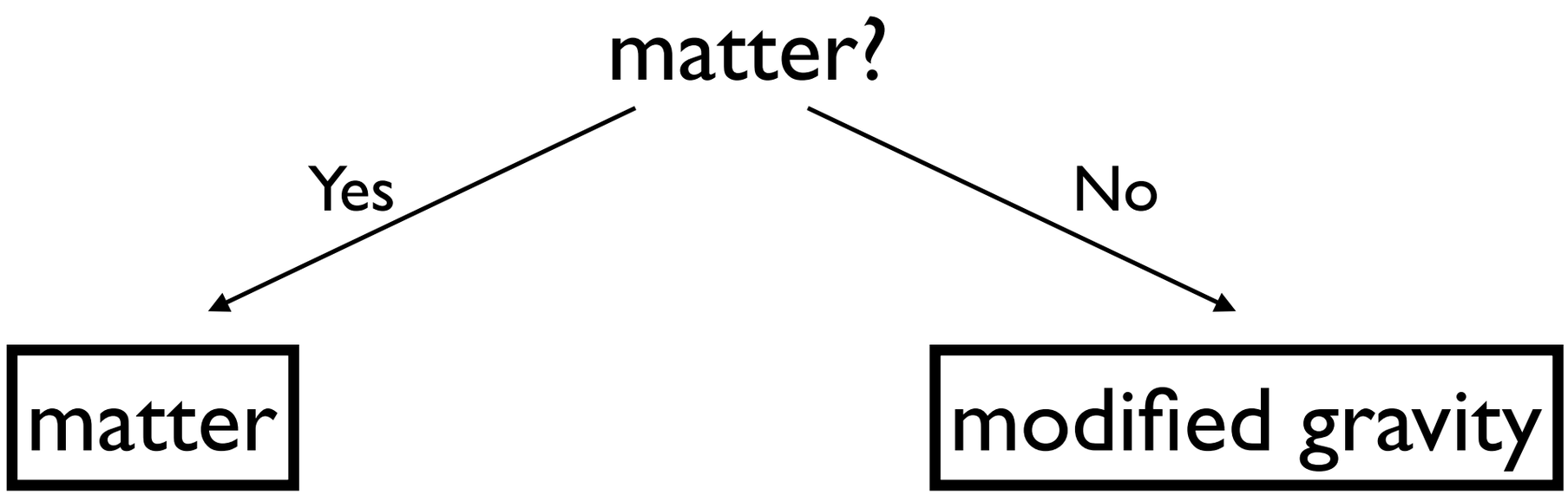
5 $$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]$$

Lagrangian standard model

Courtesy of T.D. Gutierrez

What is (dominant) Dark Matter?

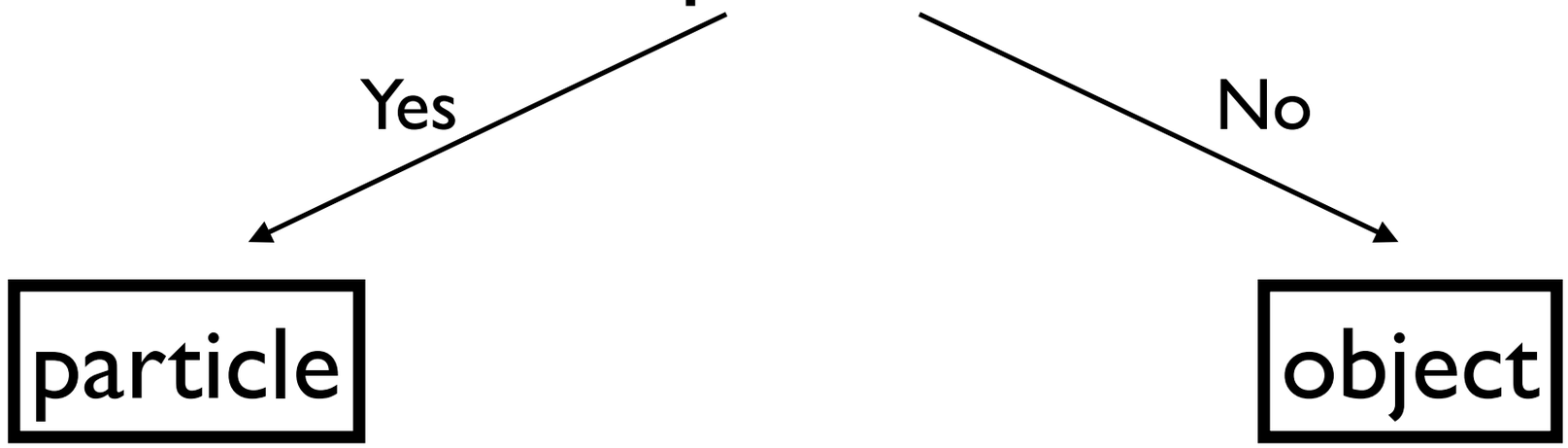
What is Dark Matter?



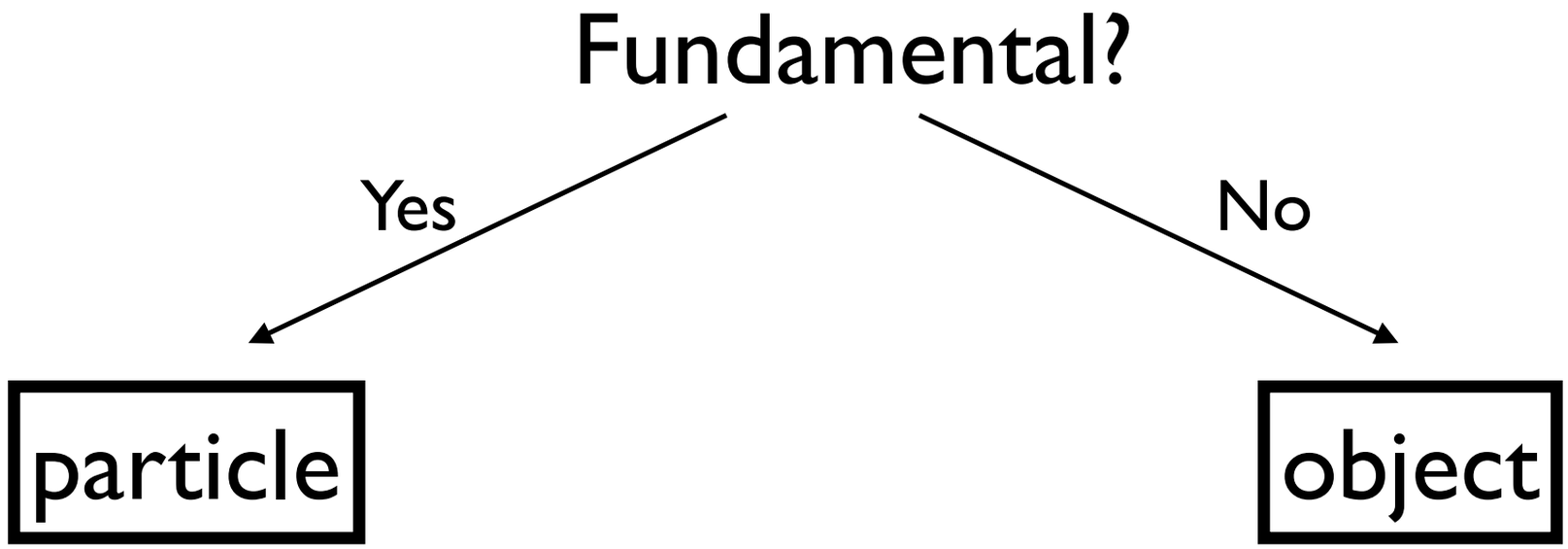
or others?

If Dark Matter is matter,

particle?



If Dark Matter is matter,



Massive Astrophysical Compact Halo Object (MACHO), Compact DM, Baryonic DM
: Black hole, neutron star, brown dwarfs, etc

If Dark Matter is MACHO,

Baryonic?

Yes

What about the baryon density?

CMB, BBN predicts

$$\Omega_b h^2 \simeq 0.02$$

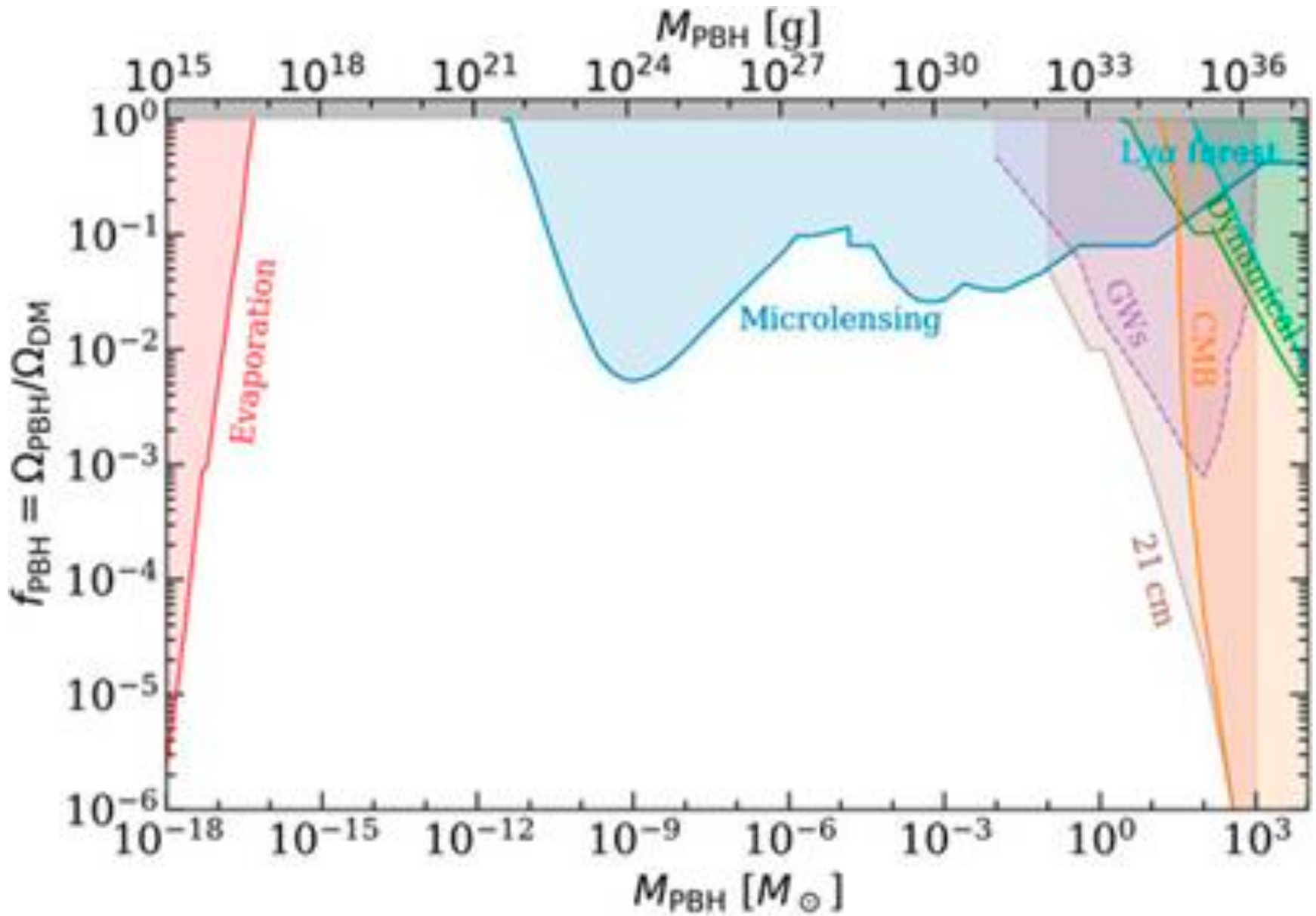
cannot be 100 % of DM

No

Made of new matters?

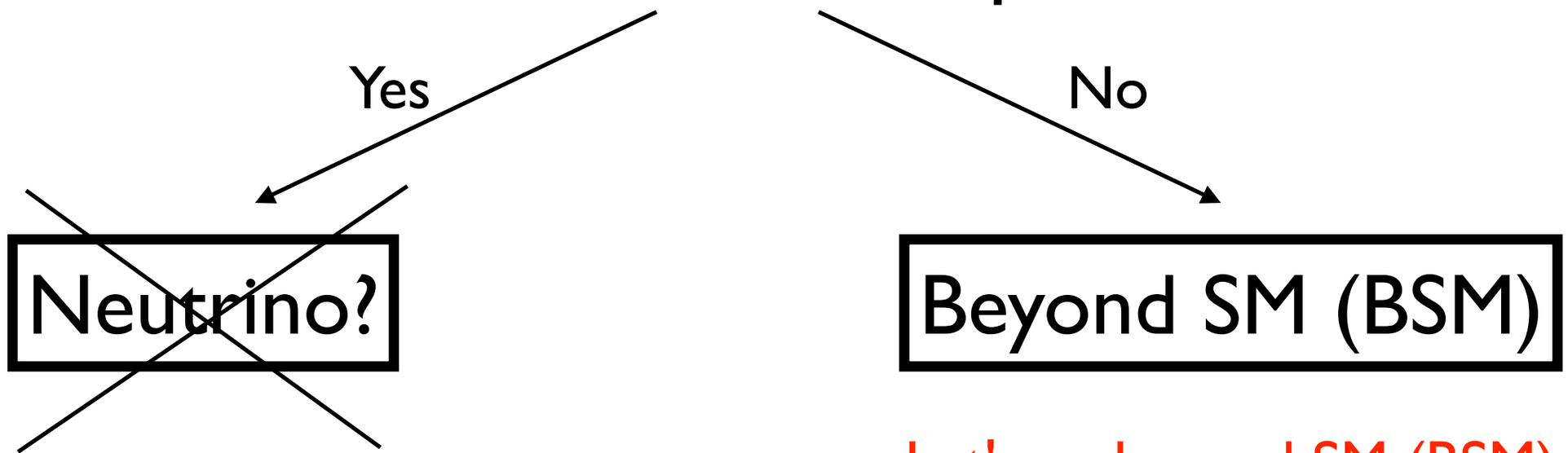
→ Except primordial black hole (PBH) produced before BBN

Primordial Black Hole as Dark Matter



If Dark Matter is particle,

Standard Model can explain DM?



Let's go beyond SM (BSM)

If Dark Matter is particle in BSM,

elementary?

Yes

No

elementary particle

composite

A point-like particle

Bound state of elementary particles

introduce new particle and interaction
in the Lagrangian of BSM

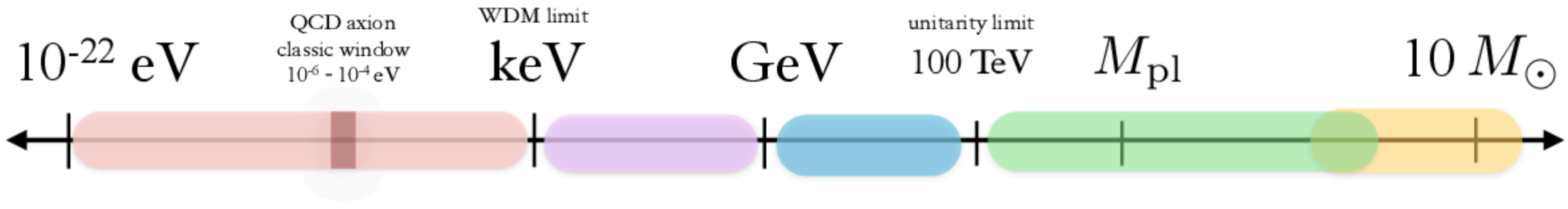
: Strongly coupled Composite DM

such as dark meson, dark baryon,
dark glueballs, etc

Mass scale of dark matter

(not to scale)

* Number density is inversely proportional to DM mass



``Ultralight" DM

non-thermal
bosonic fields

Fuzzy DM

``Light" DM

dark sectors
sterile ν
can be thermal

WIMP

Composite DM

(Q-balls, nuggets, etc)

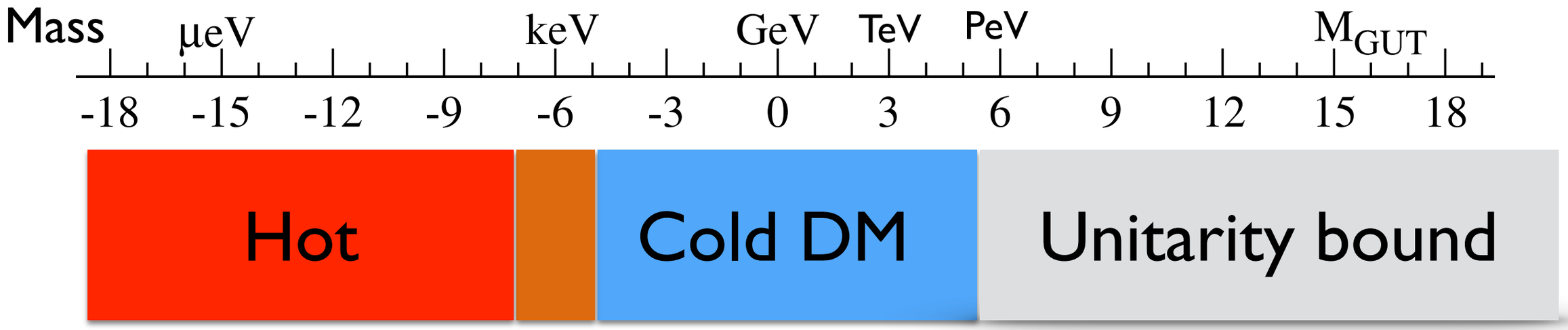
Primordial
black holes

Fermion DM
(phase space bound)

Boson DM
(de Broglie wave length)

Produced from thermal plasma

DM with thermal distribution



WIMP

Warm DM

Neutralino in supersymmetric models
: Bino, Zino, Higgsino-like DM

neutrino

sterile neutrino

ADM

FIMP

gravitino

axino

gravitino

axino

gravitino

axino

Production of Dark Matter

The relic density of DM is calculated by solving Boltzmann equation in the expanding Universe. Clue to the non-gravitational interaction of DM?

Thermal production: produced from thermal particles

WDM (Warm DM)

$$\Omega_{\rm WDM}h^2 \simeq \left(\frac{m}{1\ {\rm keV}}\right)\left(\frac{106.75}{g_*}\right)$$

ADM (Asymmetric DM)

$$\Omega h^2 \sim \frac{\eta}{10^{-8}}\frac{m}{\rm GeV} \qquad \eta = \frac{n-\bar{n}}{s}$$

WIMP

(Weakly Interacting Massive Particles)

$$\Omega h^2 \simeq \frac{3\times 10^{-27}{\rm cm}^3{\rm sec}^{-1}}{\langle\sigma v\rangle}$$

FIMP(super-WIMP, E-WIMP)

(Feebly Interacting Massive Particles)

$$Y(T_0) = \int_{T_0}^{T_{\rm reh}} \frac{\langle\sigma v\rangle n_{eq}^2}{s(T)H(T)T}dT \propto M_P\frac{T_{\rm reh}}{M_P^2}, \qquad M_P\frac{T_{\rm reh}}{f_a^2}$$

$$\Omega h^2 = \frac{\rho}{\rho_c}h^2 = mY\frac{sh^2}{\rho_c} = 2.8\times\left(\frac{Y}{10^{-8}}\right)\left(\frac{m}{\rm GeV}\right)$$

Non-thermal production

- Coherent oscillation
- Decay of heavy particles
- Primordial Black Hole

Interaction with SM particles

..... Portal to DM



scalar

vector

Higgs

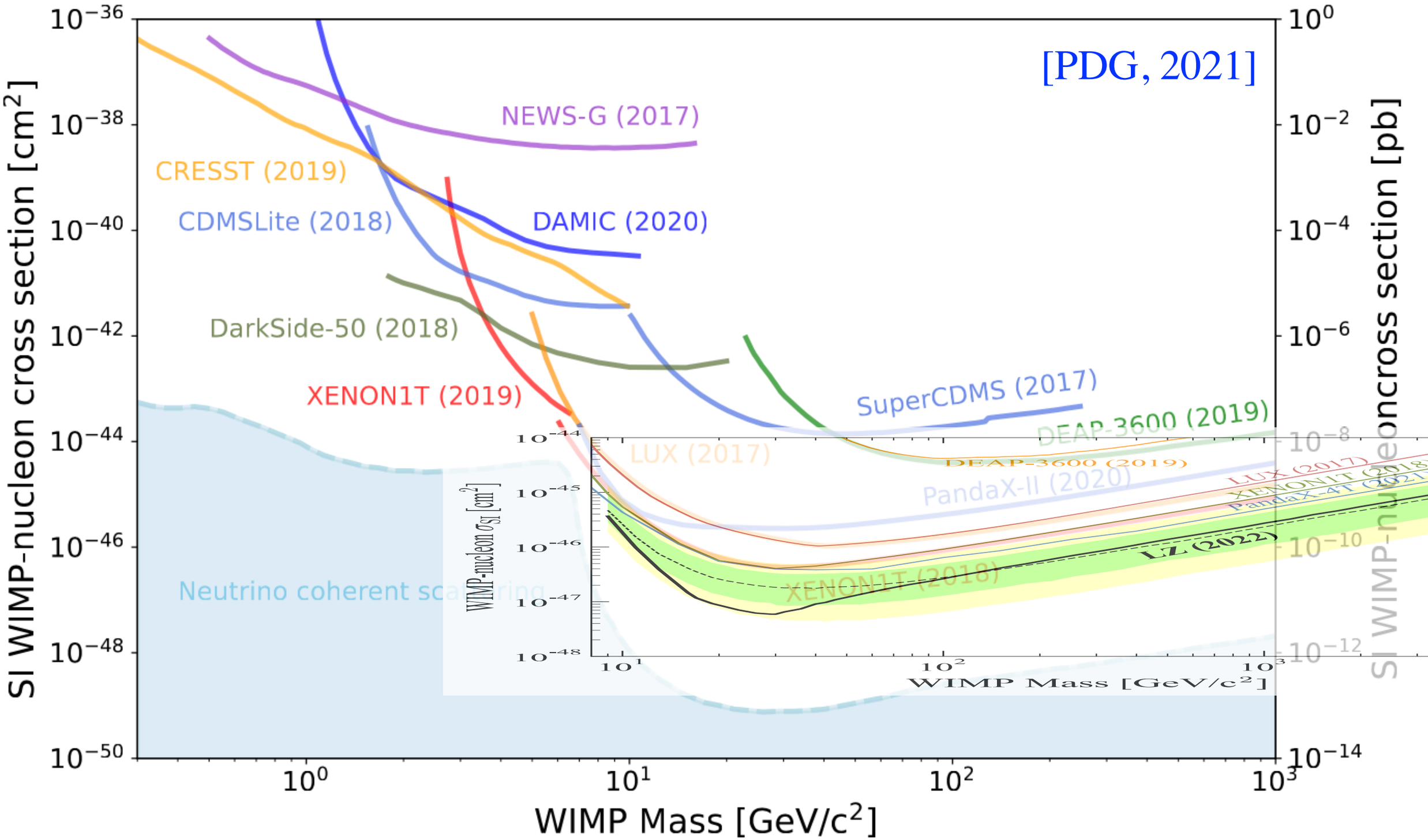
neutrino

gravity

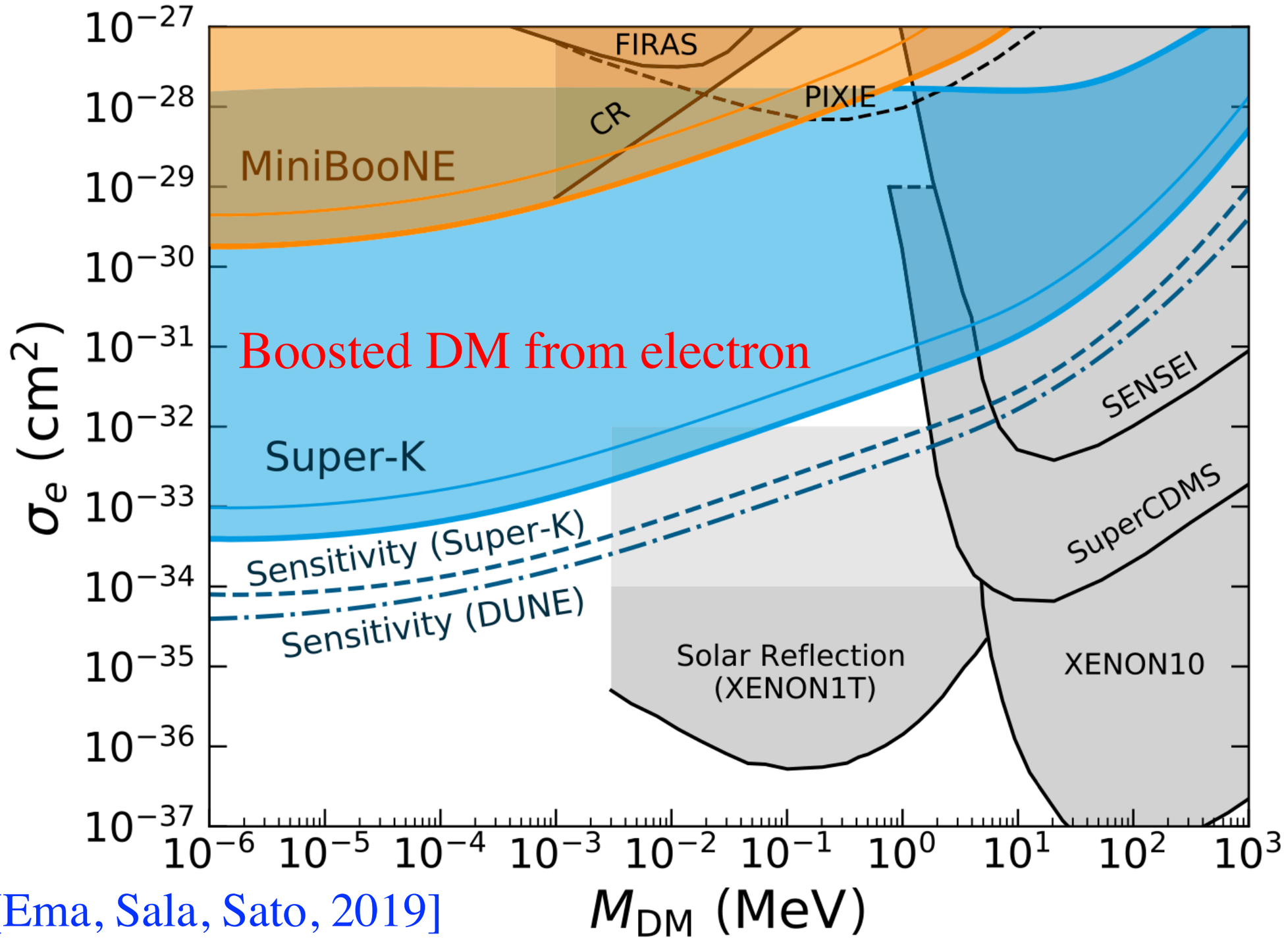
Z'-boson

Dark Matter

DM Direct Detection with Nucleon



DM Direct Detection with electron



[Ema, Sala, Sato, 2019]

DM detection with Neutrino

Constraints on the DM-neutrino interaction from CMB anisotropy, Lyman-alpha, SN1987A, IceCube etc.

[KYChoi, Jongkuk Kim, CarstenRott, 2019]

Neutrino energy	$\sigma/M_{\rm dm}[{\rm cm}^2/{\rm GeV}]$	Exp. [Ref.]
~100 eV	6×10^{-31}	CMB [13–15]
~100 eV	10^{-33}	Lyman-α [11]
10 MeV	10^{-22}	SN1987A [9]
290 TeV	5.1×10^{-23}	IceCube-170922A [1]
PeV	10^{-27}	IceCube [2107.11491]
	10^{-17}	Davis,Silk [1505.01843]

More at [2209.02173] and [2209.06339]
Cosmic Neutrino Boosted DM [Jho etal, 2101.11262]

Motivated by experiments/observations

Small scale problems: WDM, SIDM, SIMP, Fuzzy DM, ...

Neutrino mass and baryogenesis: sterile neutrino

Baryon Asymmetry: Asymmetric DM

Anomaly in the cosmic ray, neutrino, gamma ray: decaying DM, ...

Theory-motivated candidates of DM
beyond Standard Model

Strong CP problem : axion

Neutrino mass : sterile neutrino, RH neutrino, Majoron

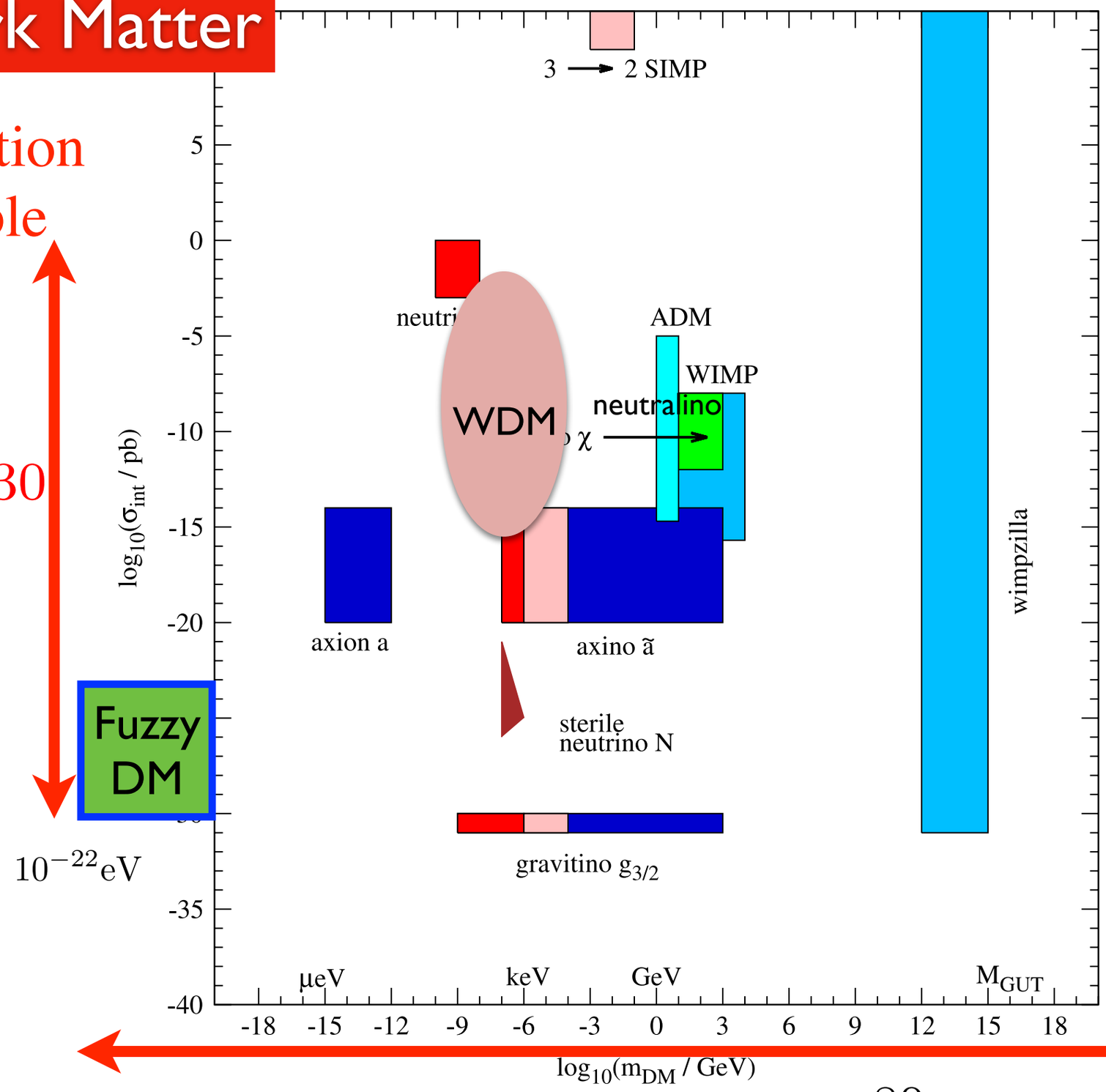
Supersymmetry : neutralino, gravitino, axino, scalar neutrino

Extra dimension : Kaluza-Klein particle

and mores.....

Candidates of Dark Matter

H. Baer et al. / Physics Reports 555 (2015) 1–60



Interaction to visible matter

10^{30}

10^{-22}eV

Fuzzy DM

10^{80}

DM Mass

HDM

WDM

CDM

WIMP is generic name: neutralino,KKDM, sneutrino,⋯

PBH DM

$10^{-10} M_\odot \sim 10^{60}$GeV

originally from

[Baer etal, Physics Reports (2014)]

“Streetlight Effect”

Lost your key
under the lamp?



NO, I lost in the park.
But, here is light.

Thank You!