2021年度国立天文台将来シンポジウム
【SG: 横軸5】
宇宙論（宇宙初期、ダークマター、ニュートリノ質量と階層）

素粒子物理学的アプローチ

Cosmology: Particle Physics Approach

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横軸 ◆宇宙論（宇宙初期、ダークマター、ニュートリノ質量と階層）

○ レビュア： [素粒子物理学的アプローチ]

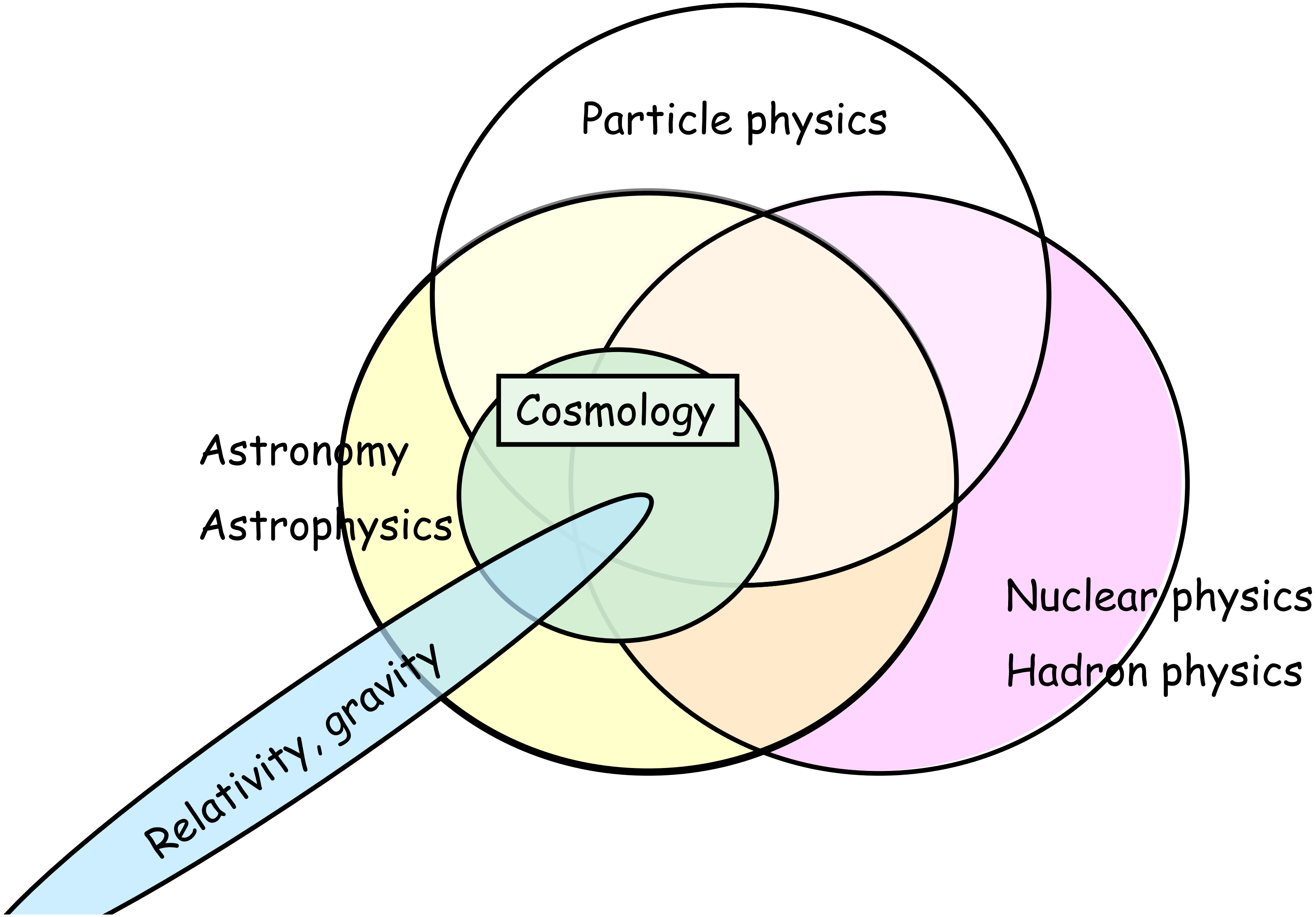
コミュニティ	プロジェクト	（萌芽的テーマ）
高宇連	XRISM （中型） keV axion (X-ray)	MeV天文学
	ATHENA （ESA L2） keV axion (X-ray)	
	FORCE （小型） missing baryon (X-ray)	
	SuperDIOS （中型（予定）） missing baryon (X-ray)	
CRC	CALET (CALorimetric Electron Telescope)	TeV WIMP (e^+, $\overline{p}$)
	TibetAS, Mega ALPACA	PeV DM (CR)
	チェレンコフテレスコープアレイ, MAGIC	TeV DM, PBH (γ-ray)
	IceCube, ARA (Askaryan Radio Array)	PeV DM, ν mass/CP, ν_R
	スーパーカミオカンデ、ハイパーカミオカンデ (KAMIOKA Nucleon Decay Experiment)	proton decay, ν mass/CP, ν_R , ALPs, DM
	KamLAND-2 (Kamioka Liquid scintillator Anti-Neutrino Detector)	ν mass/CP, ν_R , axion, DM
	XMASS (Xenon MASSive detector)	WIMP, ALPs (DD)
	XENON-NT, DARWIN	WIMP, ALPs (DD)
	NEWAGE/CYGNUS (New general WIMP search with an Advanced Gaseous tracker Experiment)	WIMP gas detector (CF_4) dark matter (DD)
	GAPS (General Anti-Particle Spectrometer)	DM, PBH ($\overline{n}$, $\overline{p}$)
	GRAMS	MeVγ DM, PBH (γ-ray)

I am working as a theoretical member of

- KAGRA: A member of Scientific Congress (KSC) / Theory of gravitational waves a(GWs) /Primordial Black Holes (PBHs)
- LiteBIRD: A member of the Publication Board / Theory of Inflation/CMB
- CTA: A leader of dark matter/fundamental physics in CTA-Japan / theory of gamma-ray astrophys and dark matter
- CALET: A member of theoretical analyses / theory of dark matter, antiparticles in cosmic rays
- SKA: A member of Cosmology group in SKA-Japan / theory of neutrino mass , GWs, density perturbation
- DECIGO: Theory of GWs/PBHs produced in the early Universe

Interdisciplinary Subjects in fundamental Physics

COSMOLOGY: An academic field to discuss evolutions of the past, the present and the future of the whole Universe



Concept of values in particle physics

- The ultimate dream: Unification of three forces (electromagnetic, weak and strong interactions, i.e., GUT) and gravity under a symmetry such as SU(3)xSU(2)xU(1), SU(5), SO(10), SUSY, E(8)xE(8) etc.

- Looking for new physics beyond the standard model (the electroweak theory)

- Finding a new physical law by which the current physical law of particle physics must be rewritten

定義により、常に新しい物理学理論を追い求めることを意味する
プロジェクト主義ではなく、目的主義

New Physics beyond the Standard Model

- Inflation
- Dark matter

Today's talk

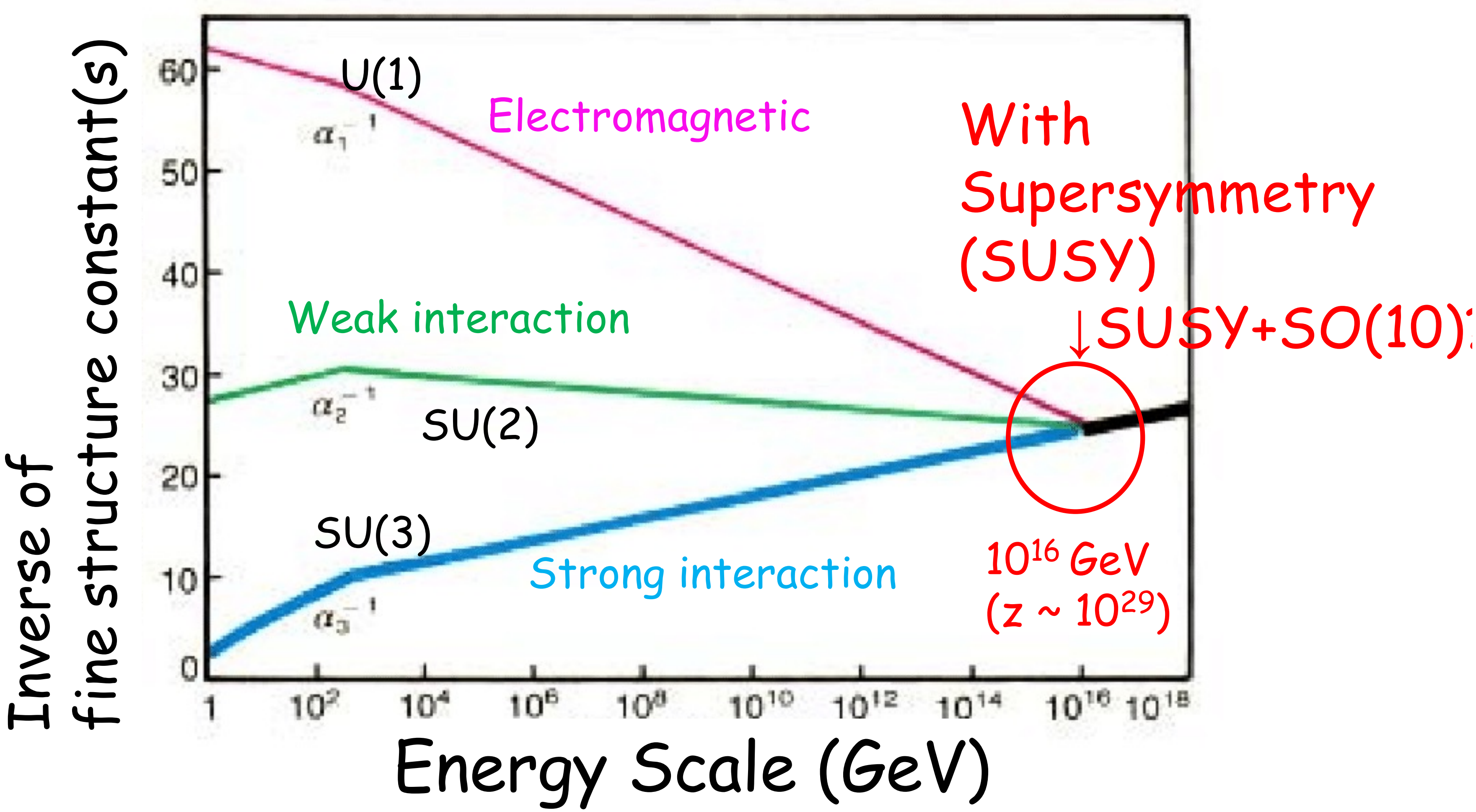
- Neutrino masses/hierarchy and CP violation
- Dark energy
- Matter-antimatter asymmetry
- …

GUT (Grand Unified Theory)

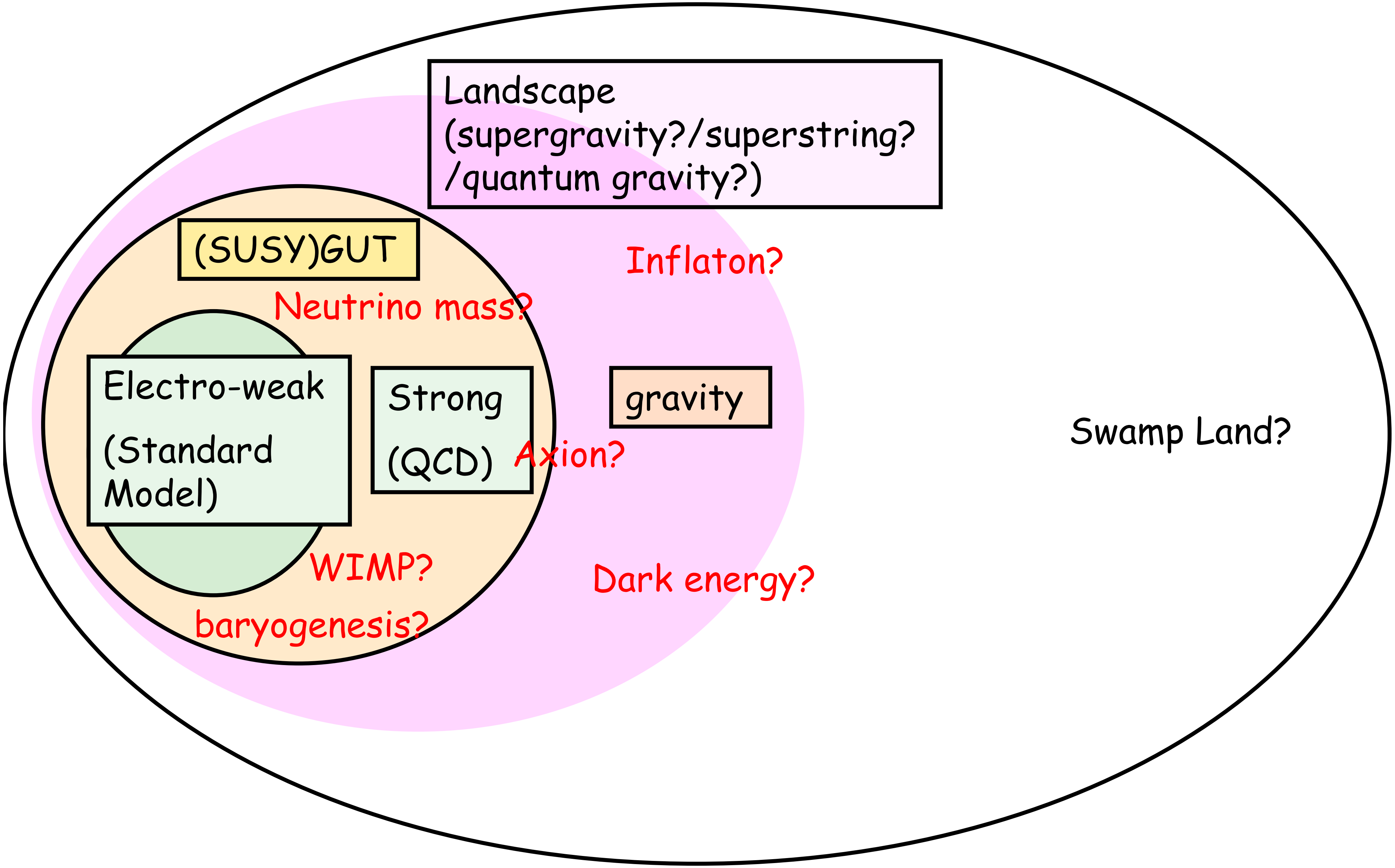
Unification of three coupling constants at 10^{16} GeV

Ugo Amaldi, Wim de Boer, Hermann Furstenau, 1991

Can we confirm it observationally/experimentally?



Further unification?



History of the Universe

Birth of the Universe

Cosmic time	Energy	Event	
10^{-43} sec	10^{19} GeV	Planck scale	Inflation?
10^{-38} sec	10^{16} GeV	GUT phase transition	Neutrino mass?
10^{-11} sec	10^{2} GeV	Electroweak phase transition	Baryogenesis? WIMP? DM?
10^{-5} sec	200 MeV	QCD phase transition	axion DM? PBH DM?
0.1 sec	3 MeV	Neutrino decoupling	Big-bang Nucleosynthesis (BBN)
1 sec	0.5 MeV	Electron-positron annihilation	
10^{10} sec	1 eV	Matter-radiation equality	
10^{12} sec	0.3 eV	Last scatting of CMB	
13.7 Gyr ($\sim 10^{17}$ sec)	2.7°K (-454°F)	Present	dark energy?

Inflation

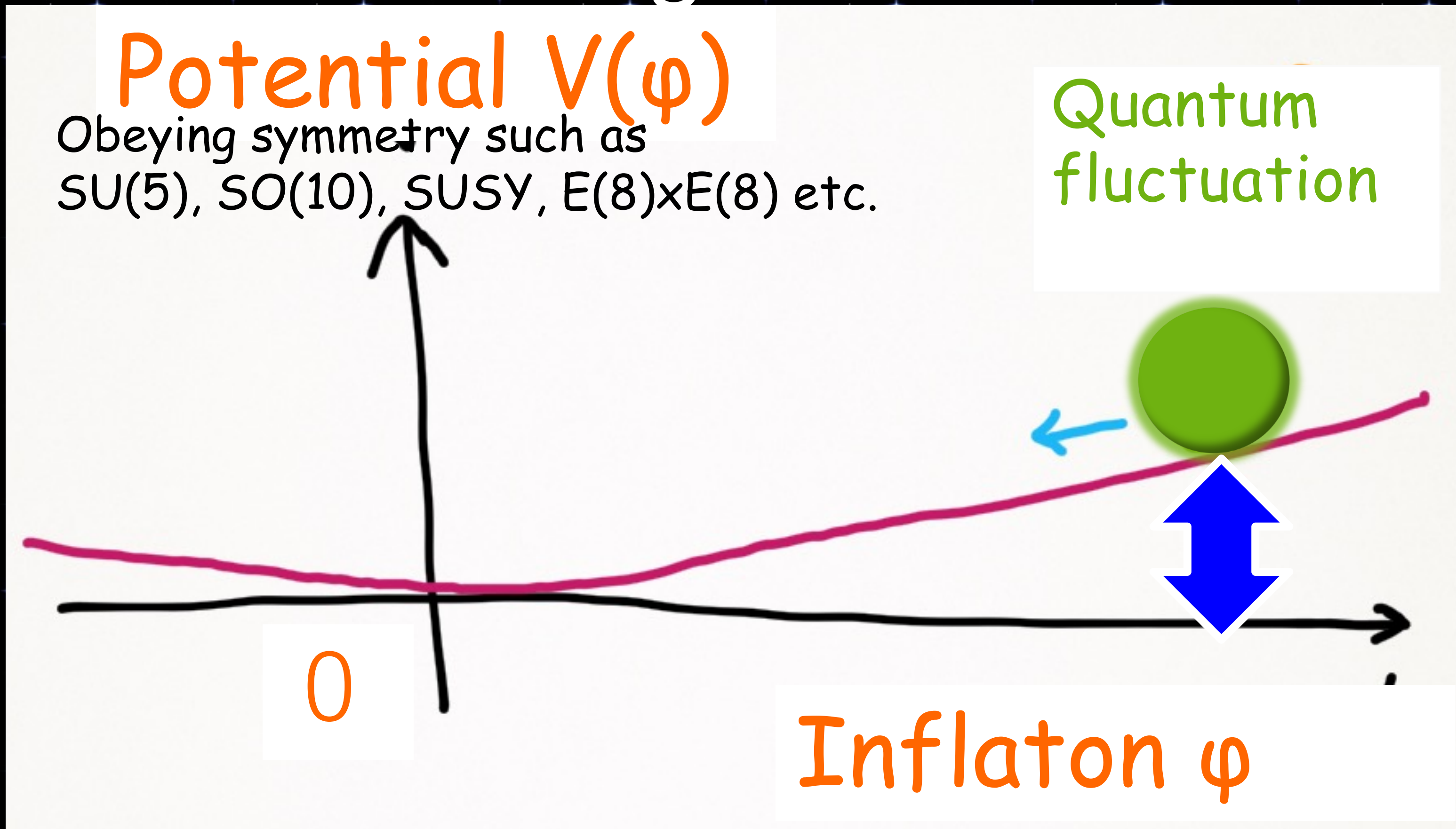
Inflation

- We need an exponentially-growing phase $a(t) \propto e^{Ht}$ in the early Universe, $t \sim 10^{-38}$ sec?, $T \sim V^{1/4} \sim 10^{16}$ GeV? (= GUT scale?) to solve the horizon problem, the flatness problem, to produce primordial density perturbation, …

- [Q] What is the scalar field which induces inflation? What is the model in which the scalar field is embedded?

- [Obs] B-mode polarization in CMB (POLARBEAR-2, Simons Array, Simons Observatory, LiteBIRD, CMB-S4), Primordial stochastic gravitational wave (KAGRA, ET, DECIGO, BBO), …

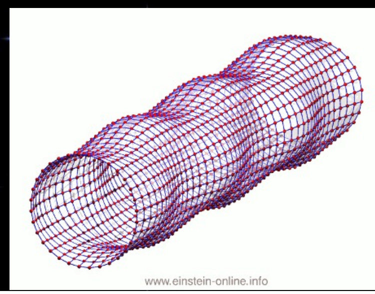
Inflation produces curvature perturbation and gravitational wave



郡和範他、理化学研究所「元素の起源」より

Curvature perturbation P_ζ

GWs



The e-folding number during inflation to be N > 60

- Cosmic expansion

$$a(t) \propto \mathrm{Exp}[N] \qquad N = \int_{t_*}^{t_{end}} H dt = \ln \frac{a(t_{\mathrm{end}})}{a(t_*)}$$

- Lower bound on N

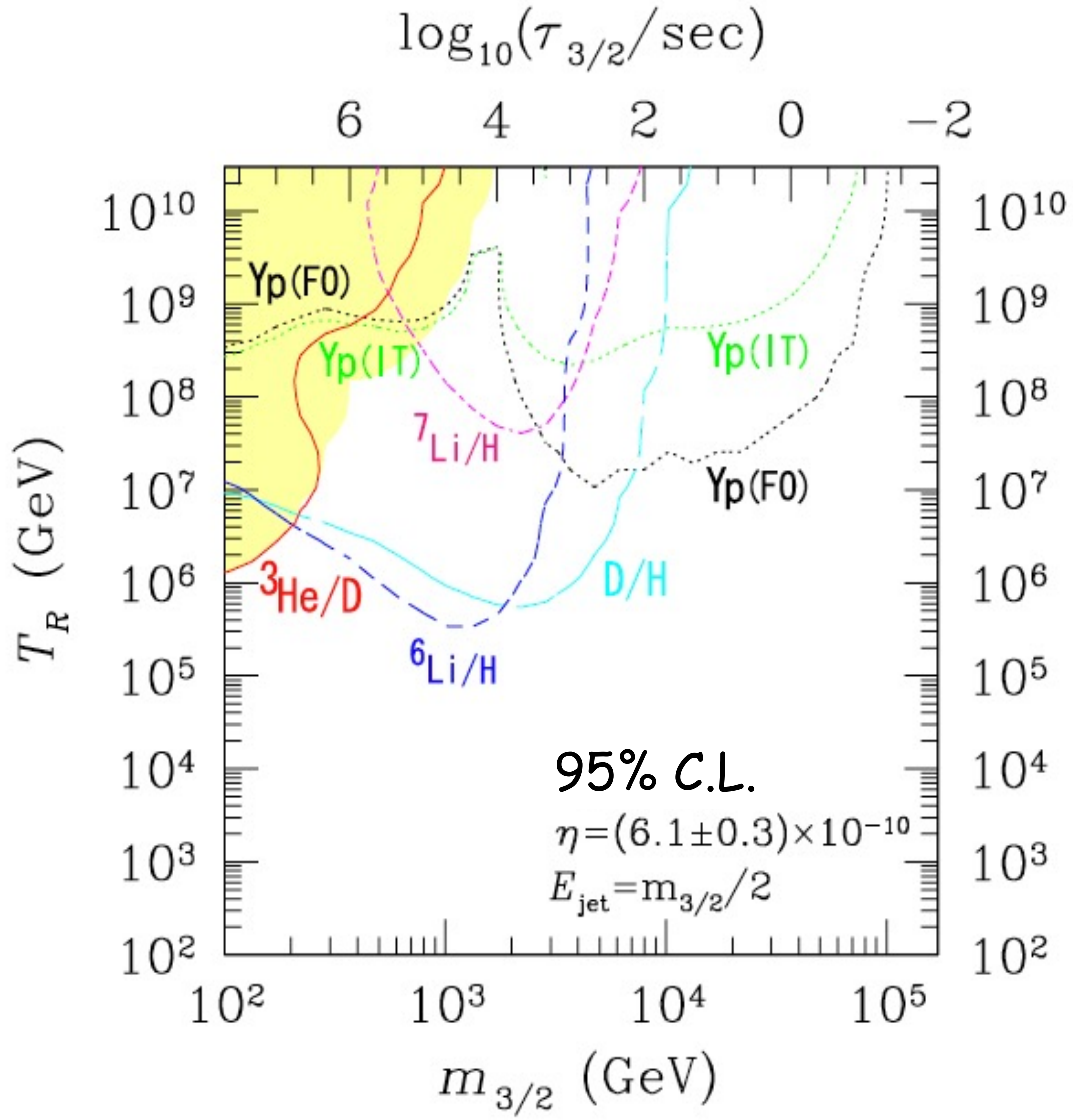
$$N \gtrsim 60 + \frac{2}{3} \ln\left(\frac{V^{1/4}}{10^{16}\mathrm{GeV}}\right) + \frac{1}{3} \ln\left(\frac{T_{\mathrm{Reheat}}}{10^{16}\mathrm{GeV}}\right)$$

- Reheating temperature after inflation

$$T_{Reheat} = ? < 10^{16}\ \mathrm{GeV}$$

Upper bounds on reheating temperature not to produce so many dangerous gravitinos in supersymmetry/supergravity from BBN

Kawasaki, Kohri, and Moroi (2004)



~~4He~~

Predictions from inflation

$$m_{\text{Planck}} = M_p/\sqrt{8\pi} \sim 2.4 \times 10^{18}\text{GeV}$$

$$\epsilon \equiv \frac{1}{2}\left(m_{\text{Planck}}\frac{V'}{V}\right)^2$$

- Temperature (scalar curvature) fluctuation

$$P_{\text{scalar}} = \frac{V}{24\pi^2 m_{\text{Planck}}^4 \varepsilon} = \left[(3.091 \pm 0.025) \times 10^{-5}\right]^2 \sim (\Delta T/T)^2$$

- Spectral index of scalar curvature fluctuation

$P_{\text{scalar}} \propto k^{n_s - 1}$

$$\eta \equiv m_{\text{Planck}}^2 \frac{V''}{V}$$

$$n_s = \frac{d \ln P_{\text{scalar}}}{d\ln k} + 1 = 1 + 2\eta - 6\varepsilon = 0.9639 \pm 0.0047$$

- Tensor (gravitational wave) to scalar ratio (will be observed by CMB B-mode polarization in future)

$$r = P_{\text{tensor}} / P_{\text{scalar}} = 16\varepsilon \lesssim 0.1$$

Energy scale

Potential of infaton field

$$V^{1/4} \simeq 1 \times 10^{16}\mathrm{GeV}\left(\frac{r}{10^{-1}}\right)^{1/4}$$

$$\simeq 3 \times 10^{15}\mathrm{GeV}\left(\frac{r}{10^{-3}}\right)^{1/4}$$

Yes,. we can prove the GUT scale by CMB B-mode polarization

Hubble expansion rate during inflation

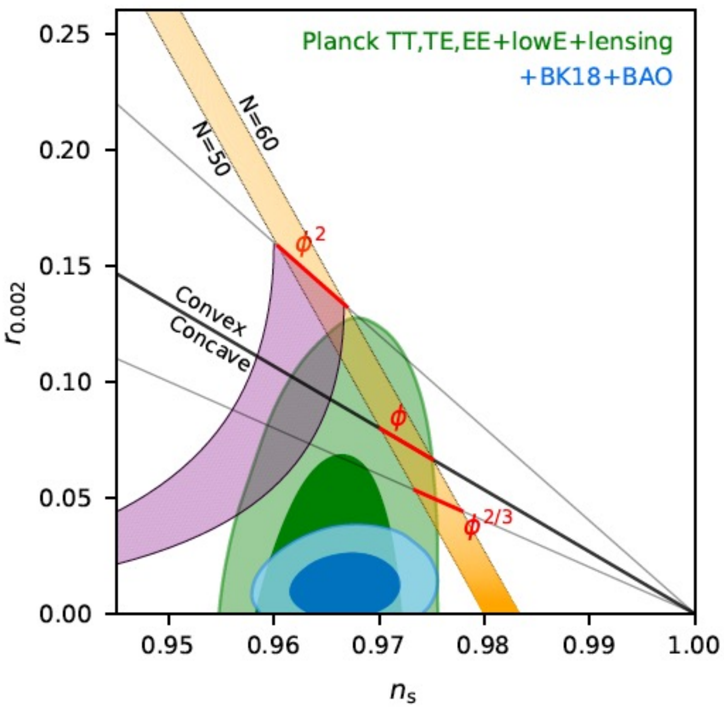
$$H \simeq 10^{14}\mathrm{GeV}\left(\frac{r}{0.1}\right)^{1/2}$$

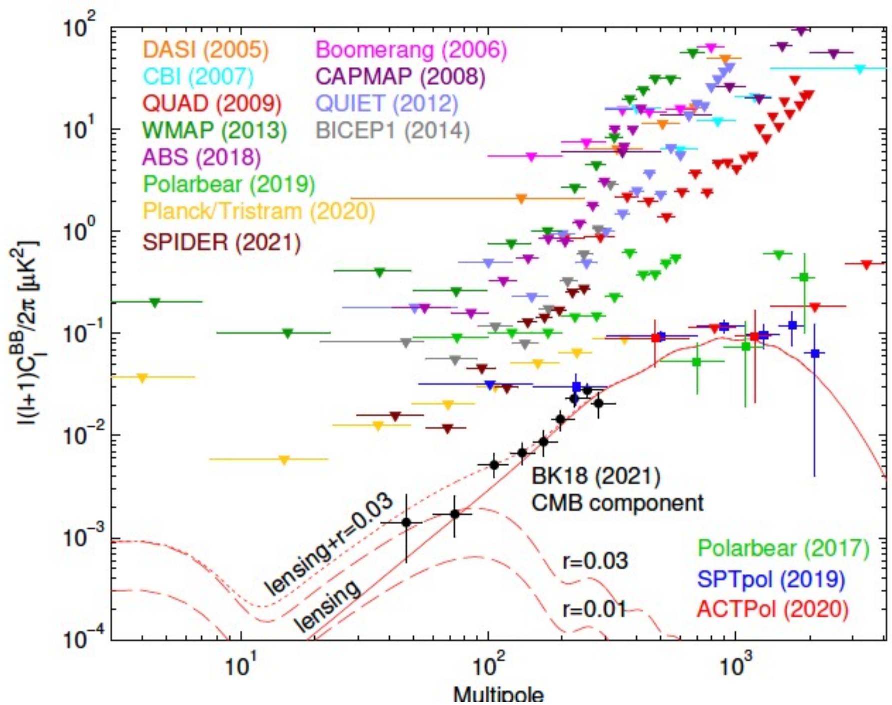
$$\sim 10^{56}\ H_0\ \left(\frac{r}{0.1}\right)^{1/2}$$

BICEP / Keck XIII: Improved Constraints on Primordial Gravitational Waves using Planck, WMAP, and BICEP/Keck Observations through the 2018 Observing Season

BICEP/Keck Collaboration: P.A.R. Ade et al, arXiv:2110.00483 [astro-ph.CO]

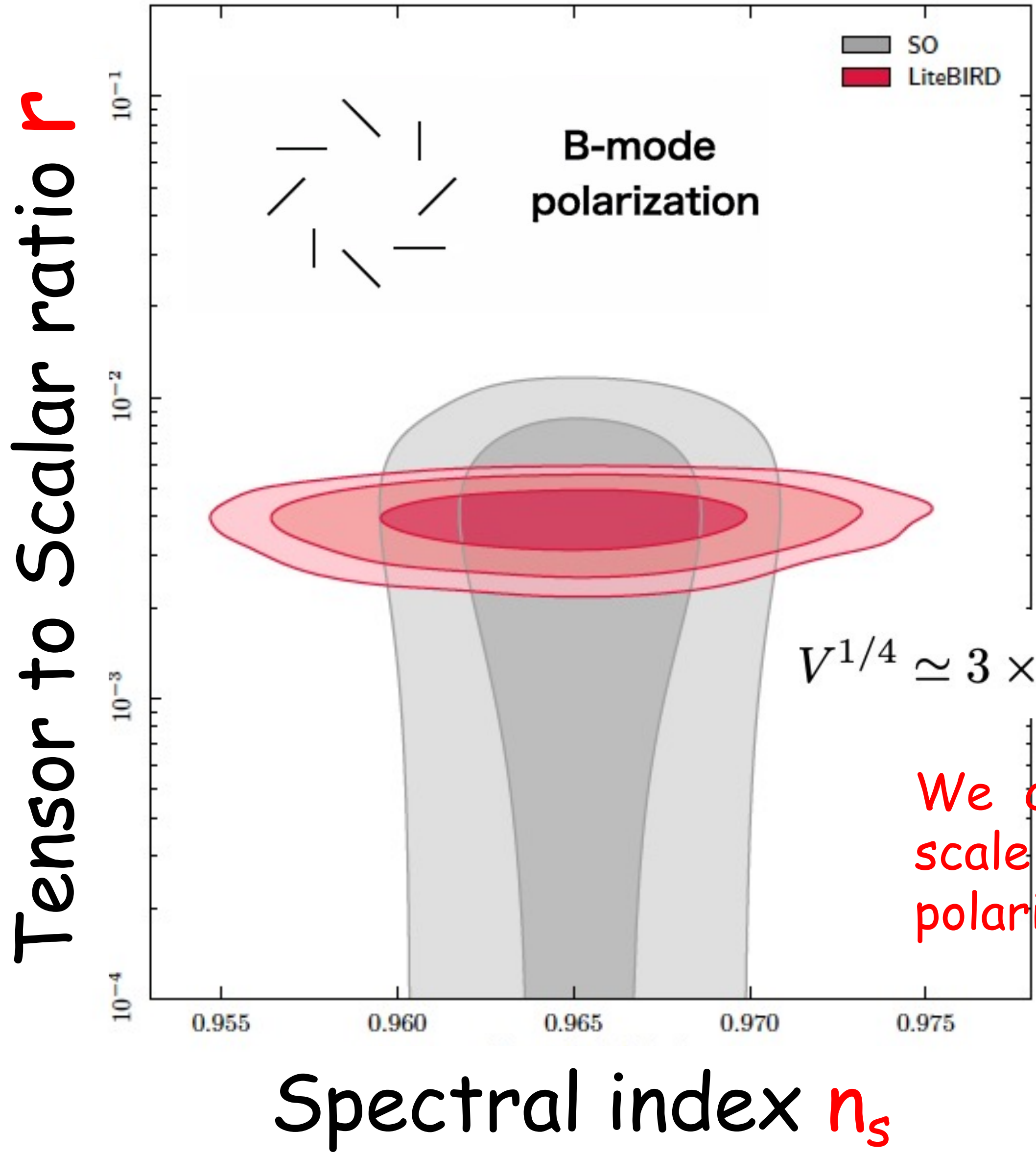
$$r_{0.05} < 0.036 \text{ at } 95\%$$





Future sensitivities on the Tensor mode (B-mode polarization) by LiteBIRD and the Simons Observatory

M. Hazumi, et al, the LiteBIRD collaboration, arXiv:2101.12449



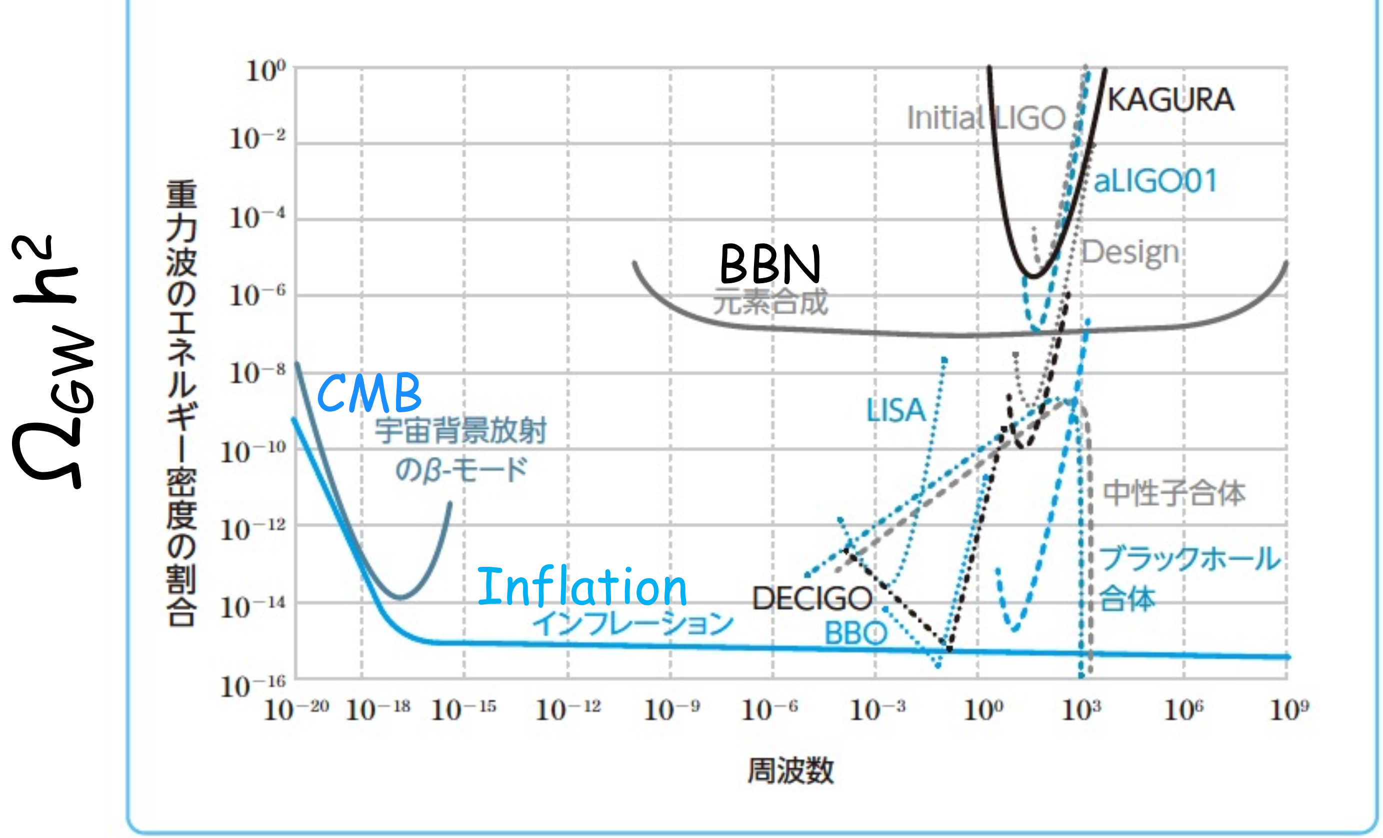
Fiducial value
$r = 4\times10^{-3}$

$$V^{1/4} \simeq 3 \times 10^{15}\text{GeV}\left(\frac{r}{10^{-3}}\right)^{1/4}$$

We can prove the GUT scale by CMB B-mode polarization

Future sensitivities on GWs produced by inflation

図9-2-1● 実験の感度と、様々な理論予言のシグナル



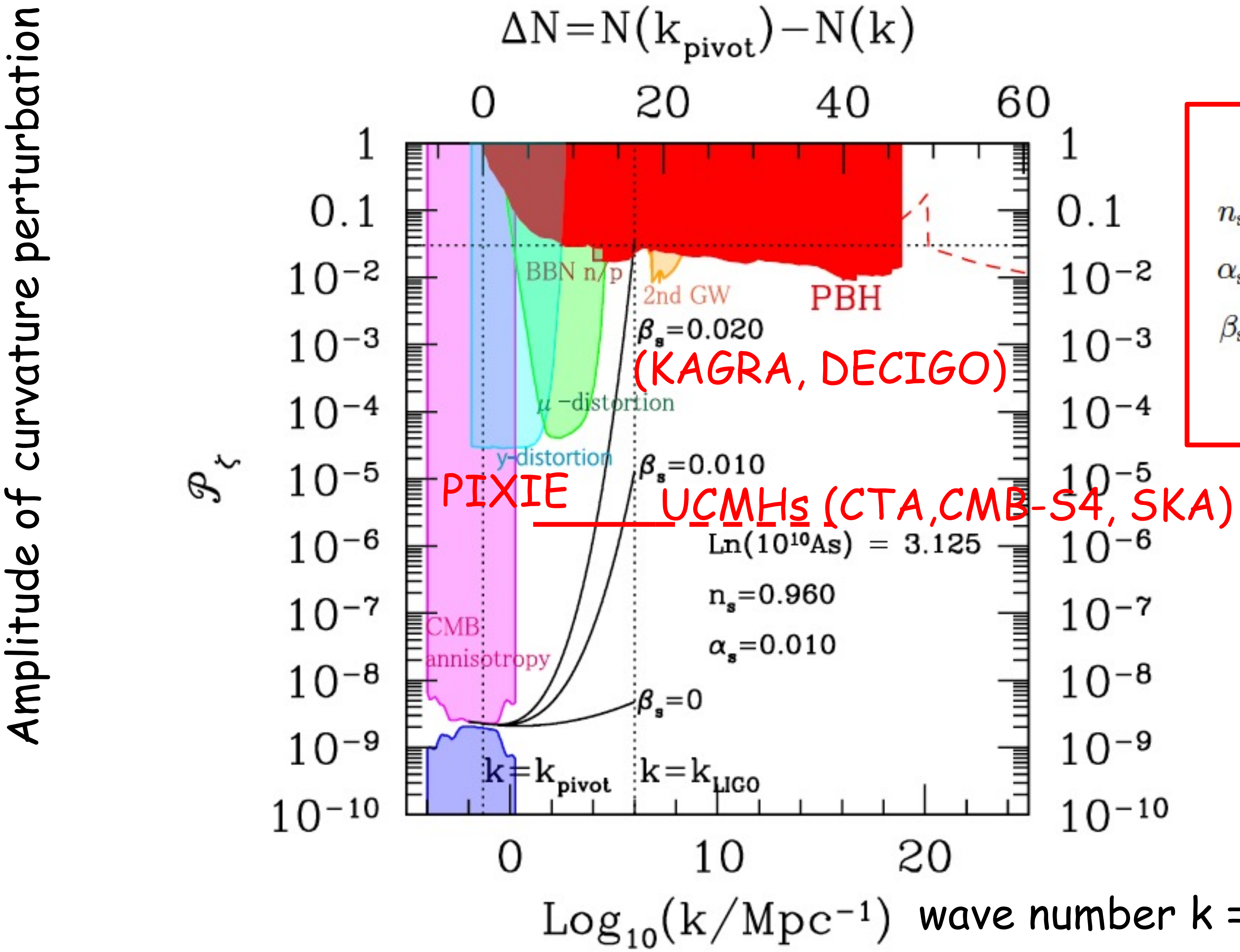
下に平行に伸びているのがインフレーション起源の重力波のシグナルの可能性。将来のCMB実験、DECIGO実験、BBO実験に感度がある。

Kazunori Kohri, “Neutrino and Gravitational wave”
郡 和範 著 「ニュートリノと重力波」ベレ出版 (2021)

Curvature perturbation $P_\zeta(k)$

Small-scales are the new frontier in future cosmology!

Kohri, Lin, Lyth, 2008
Alabidi, Kohri, Sendouda, Sasaki, 2013
Kohri and T.Terada, 2018



Planck

$n_s = 0.9586 \pm 0.0056$,

$\alpha_s = 0.009 \pm 0.010$,

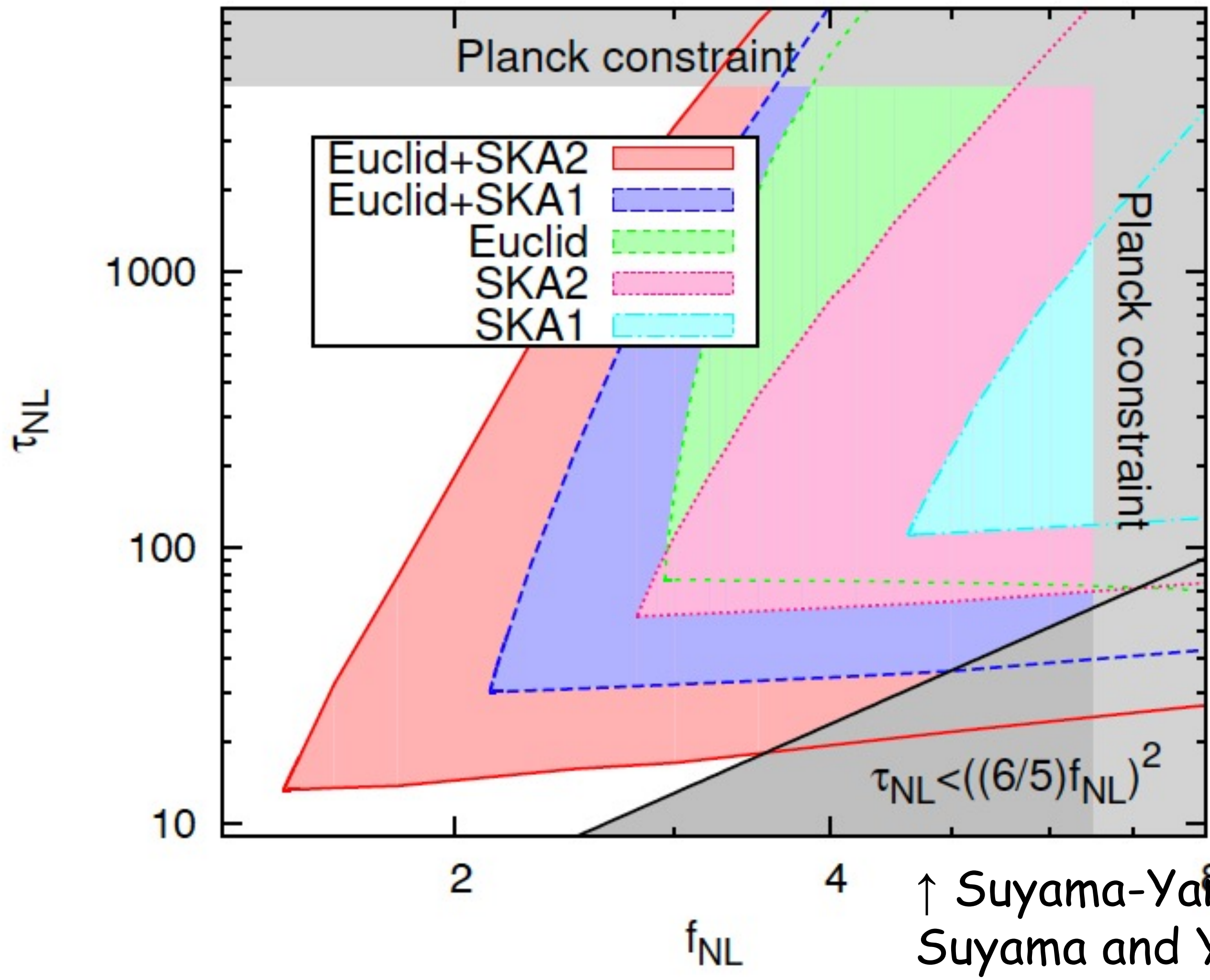
$\beta_s = 0.025 \pm 0.013$.

at 68% C.L.

Multi-field inflation with non-gaussian fluctuation?

Daisuke Yamauchi and Keitaro Takahashi 2015

Daisuke Yamauchi et al, the SKA-Japan collaboration, arXiv:1603.01959



↑ Suyama-Yamaguchi inequality

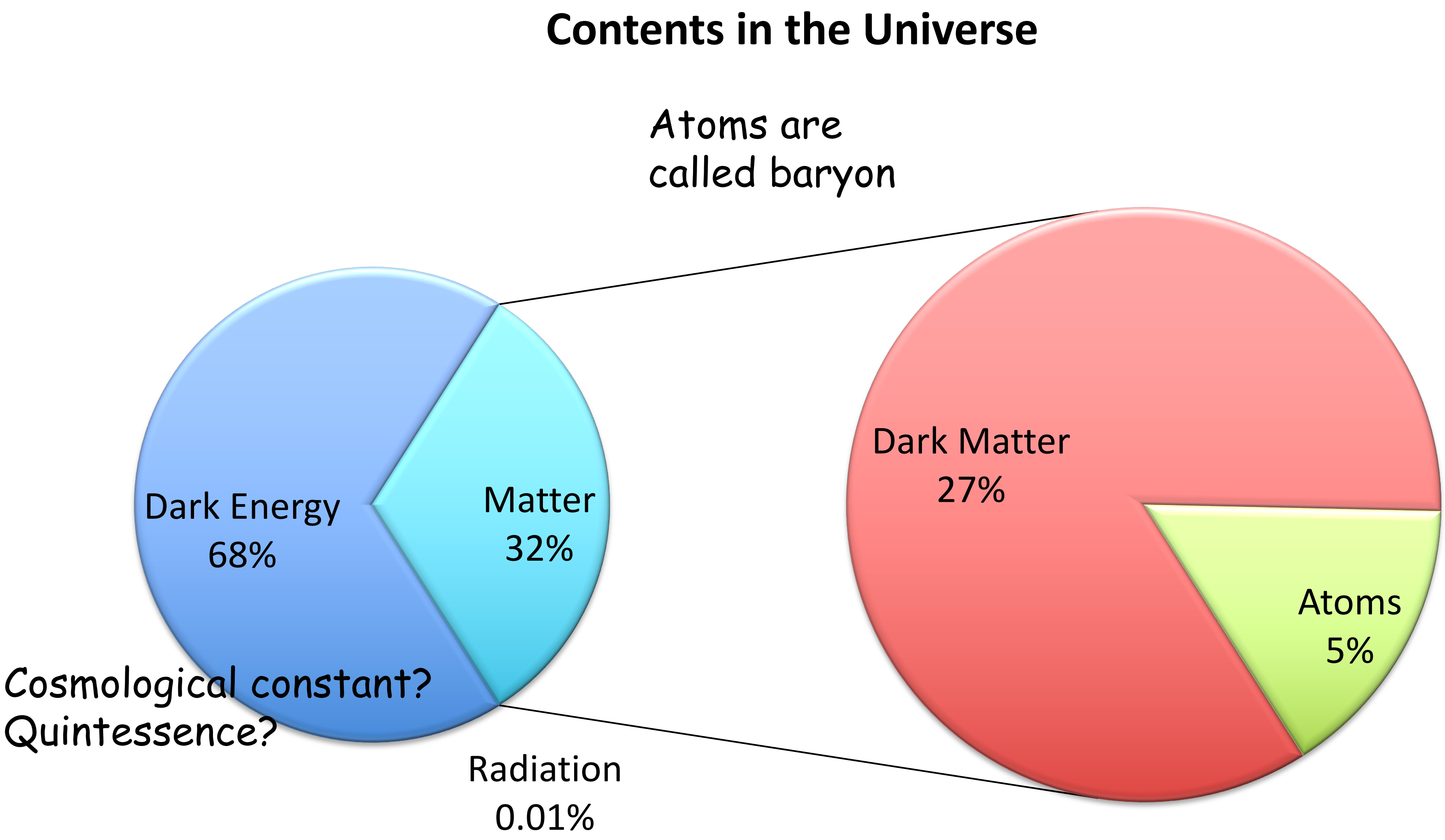
Suyama and Yamauchi, 2008

Dark Matter

Dark Matter

- We need cold dark matter (CDM) to form the large-scale structure (LSS)
- [Q] Revealing the identity of the CDM and the new theory in which the CDM is embedded
- [obs] Collider experiments (HL-LHC, ILC), Direct detections(XMASS, XENON-NT, DARWIN, NEWAGE/CYGNUS), Indirect detections (Calet, CTA, Magic, IceCube, GAPS, GRAMS, SMILE, TibetAS, Mega ALPACA), Consistencies with the cosmic history (HSC,TMT,LiteBIRD,CMB-S4), etc. ...

We are in a minority group



Planck Satellite experiments 2015

Candidate of Dark Matter

- WIMP

HL-LHC, ILC, XMASS, XENON-NT, DARWIN, NEWAGE/CYGNUS, CALET, CTA, Magic, IceCube, GAPS, GRAMS, SMILE, TibetAS, Mega ALPACA

- Axion

XRISM, ATHENA, Fermi, HESS, CTA, Magic, HSC, TMT, CIBER, AKARI KAGRA, …

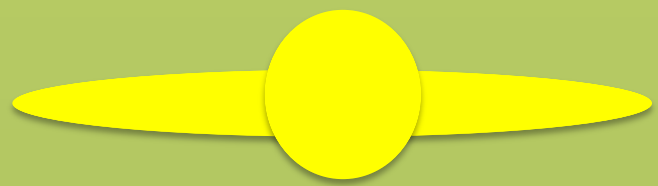
- Primordial Black Hole

XRISM, ATHENA, GRAMS, SMILE Fermi, HESS, CTA, Magic, CALET, GAPS, HSC, TMT, KAGRA, ET LiteBIRD, CMB-S4

- …

Time-evolution of the fluctuation to produce a galaxy

First, dark matter halo was produced in the early universe



Then a galaxy (made by baryons) is produced inside the CDM halo due to the gravity of dark matter

We see $\dfrac{\rho_{DM}}{\rho_{baryon}} \sim 5$

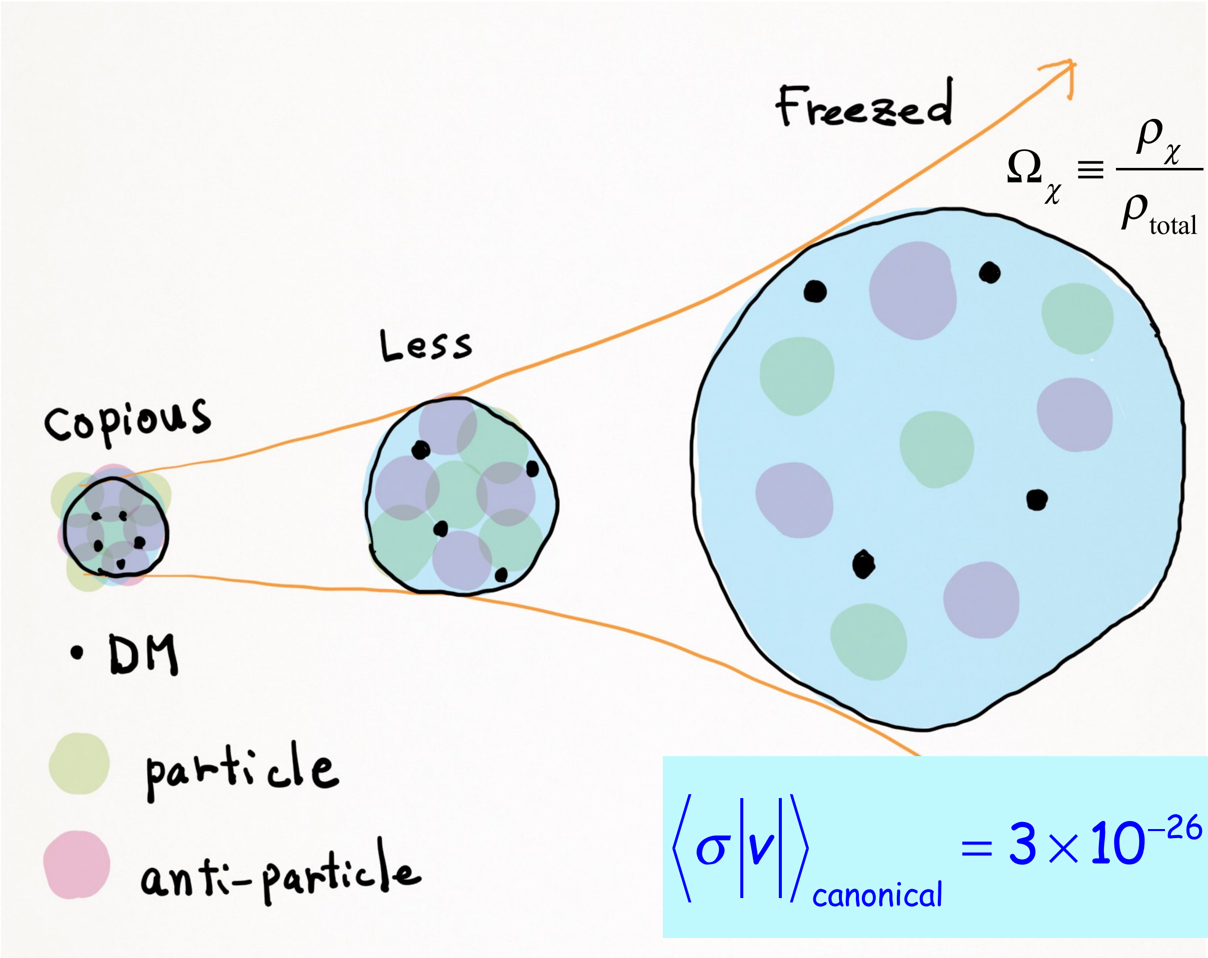
WIMP χ

(neutralino

in SUSY, …)

1) Production of WIMP in the early Universe

- Left from the cosmic expansion (freeze-out)



$$\Omega_\chi \equiv \frac{\rho_\chi}{\rho_{\rm total}} \sim 0.25 \left(\frac{\langle \sigma v \rangle}{\left(0.1/\mathrm{TeV}\right)^2} \right)^{-1}$$

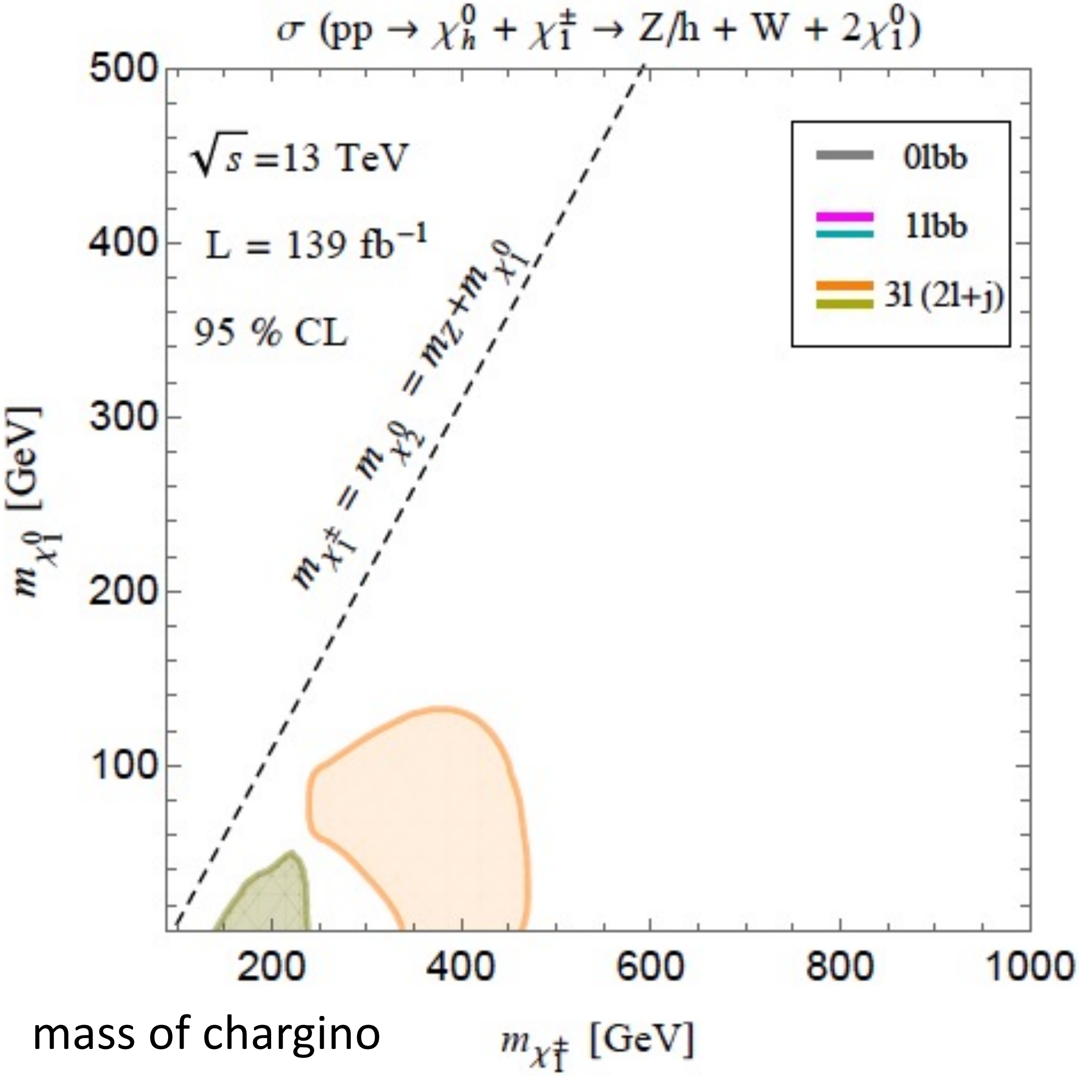
$$\langle \sigma |v| \rangle_{\rm canonical} = 3 \times 10^{-26} \frac{cm^3}{sec} \sim \frac{0.3^4}{(\mathrm{TeV})^2}$$

LHC bounds on WIMP (neutralino)

Jia Liu, Navin McGinnis, Carlos E.M. Wagner, Xiao-Ping Wang, arXiv:2006.07389 [hep-ph]

LHC exp. : p + p → χ + …

mass of DM neutralino χ_1^0



mass of chargino

GAMBIT analyses of LHC data constraining the relic DM density and the SI elastic scattering cross section

The GAMBIT Collaboration: Peter Athron, arXiv:1809.02097 [hep-ph]

LHC exp. : p + p → χ + ...

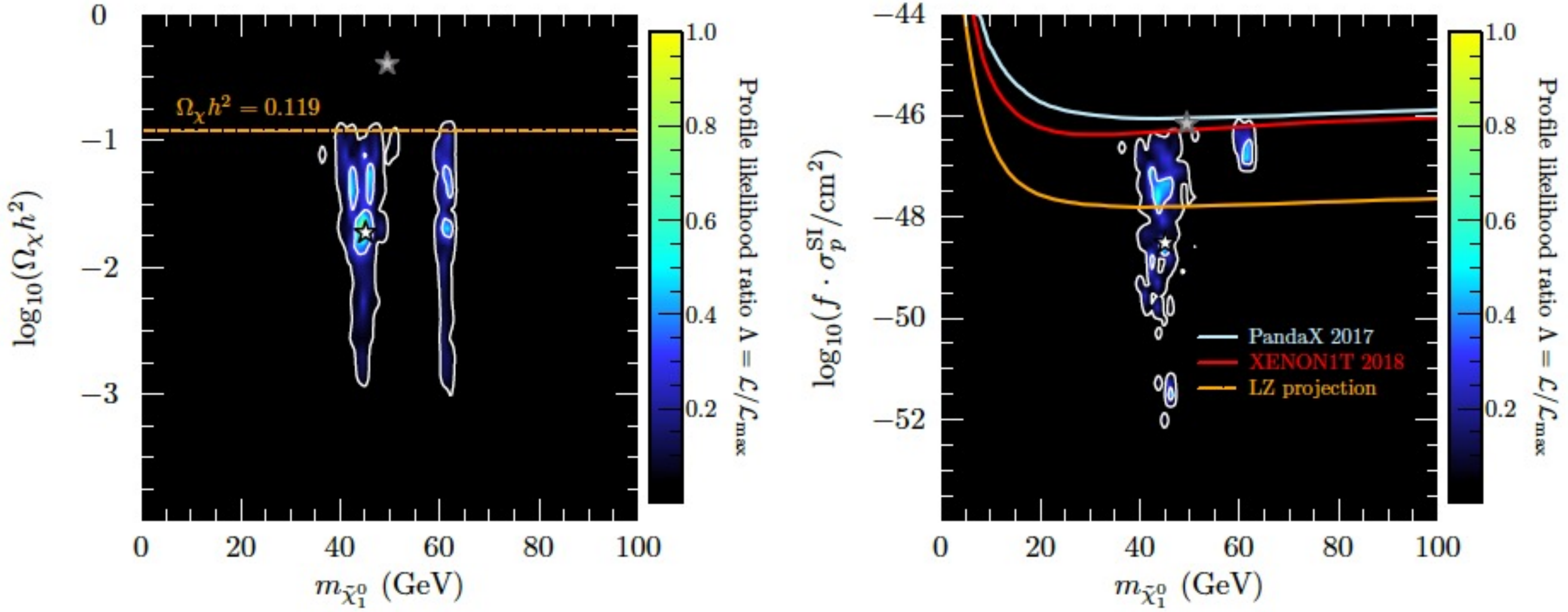
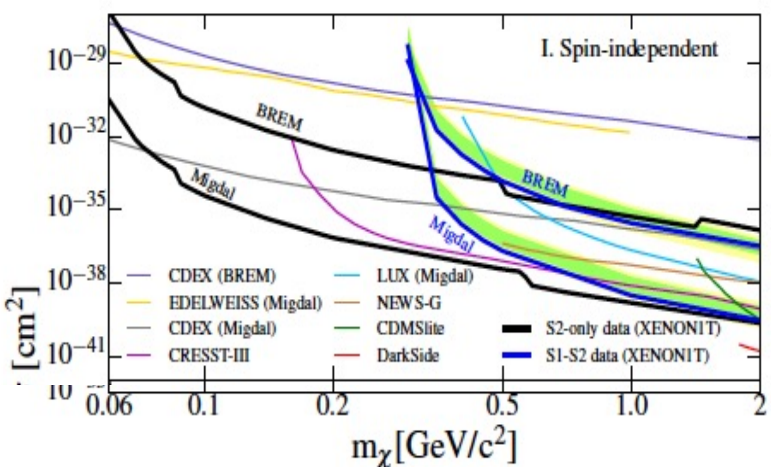


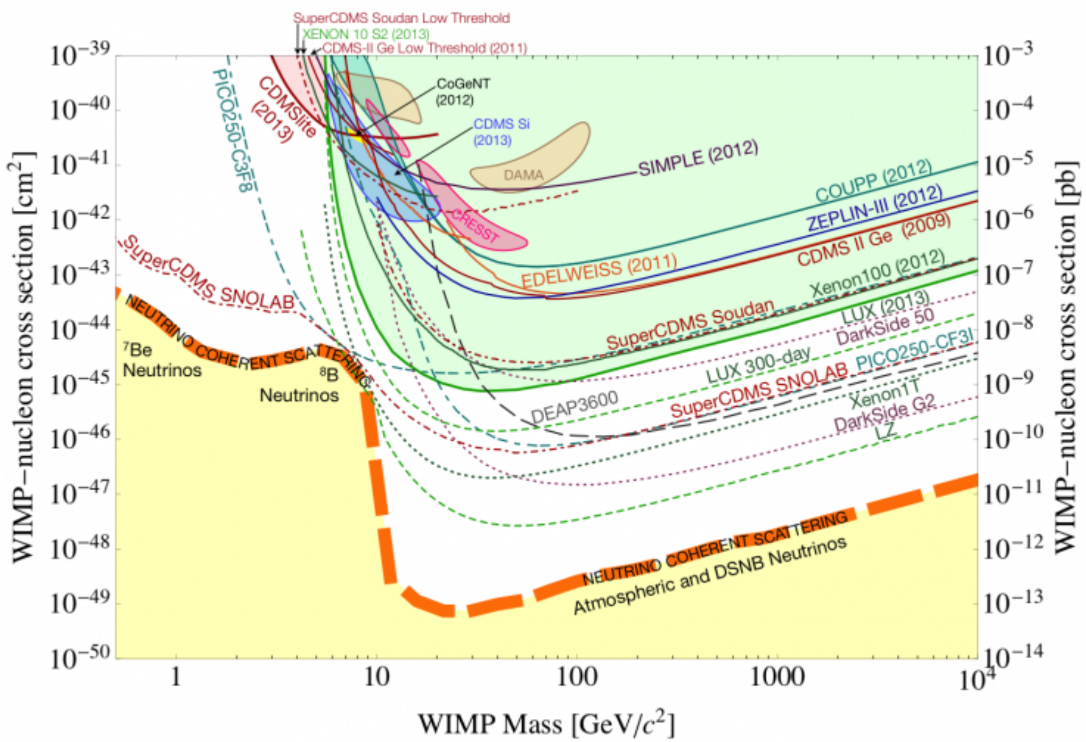
Fig. 15: Combined collider and DM profile likelihood of the relic density of DM (left) and spin-independent direct detection cross-section (right), both plotted against the DM candidate mass. The contours show the 1σ and 2σ regions. The white star marks the point with the highest combined collider-DM likelihood, whereas the grey star marks our collider-only best-fit point. For comparison, we show the current sensitivities of PandaX [146] and XENON1T [147], along with the projected sensitivity of the LZ experiment [154].

Upper bound on (Spin-independent) elastic cross section by Xenon and XMASS

Direct detection : nuclei + χ → nuclei + χ



E. Aprile et al, XENON1T collaborations, arXiv:1907.12771 [hep-ex]

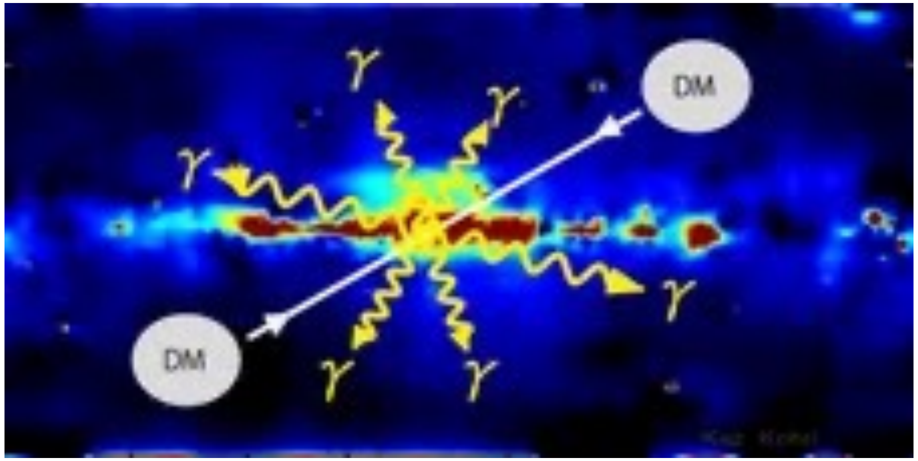


Snowmass Community Summer Study 2013 CF1: WIMP Dark Matter Detection

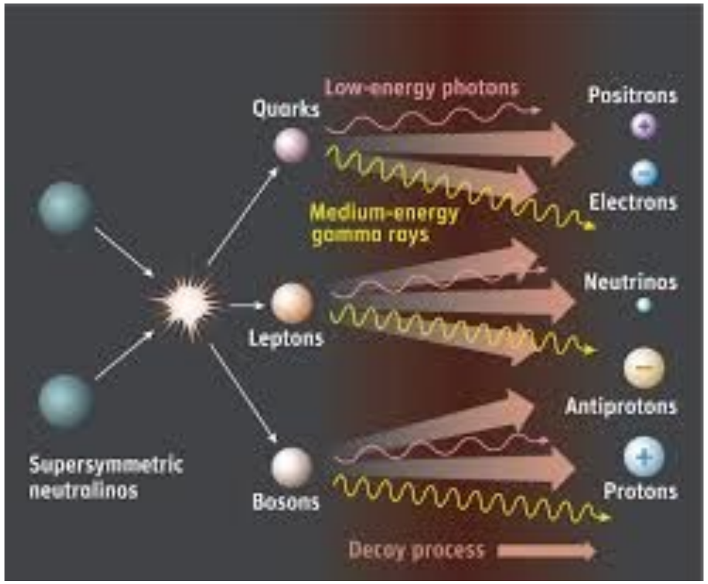
Indirect detection of DM

Indirect detection : $\chi + \chi \rightarrow \gamma$-rays or Cosmic-rays + …

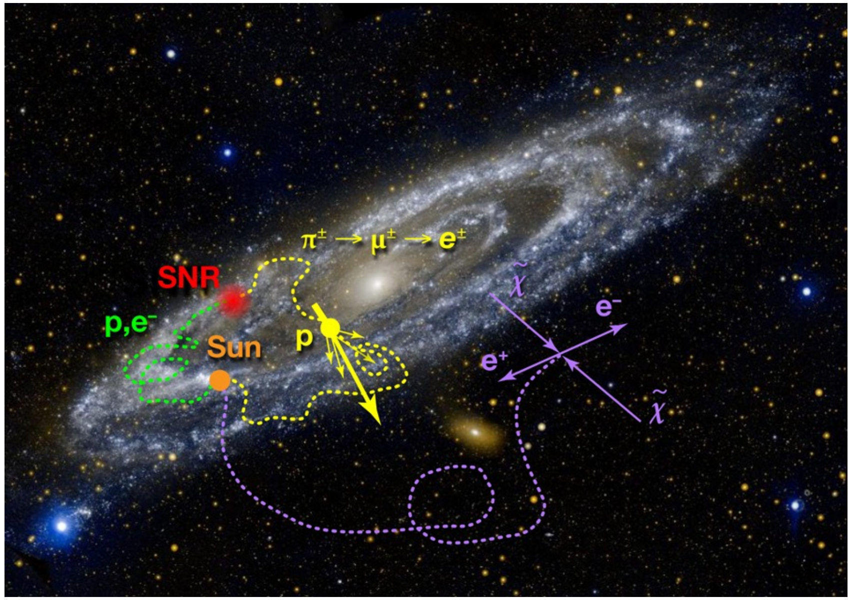
Annihilation or Decay?



Daughter particles

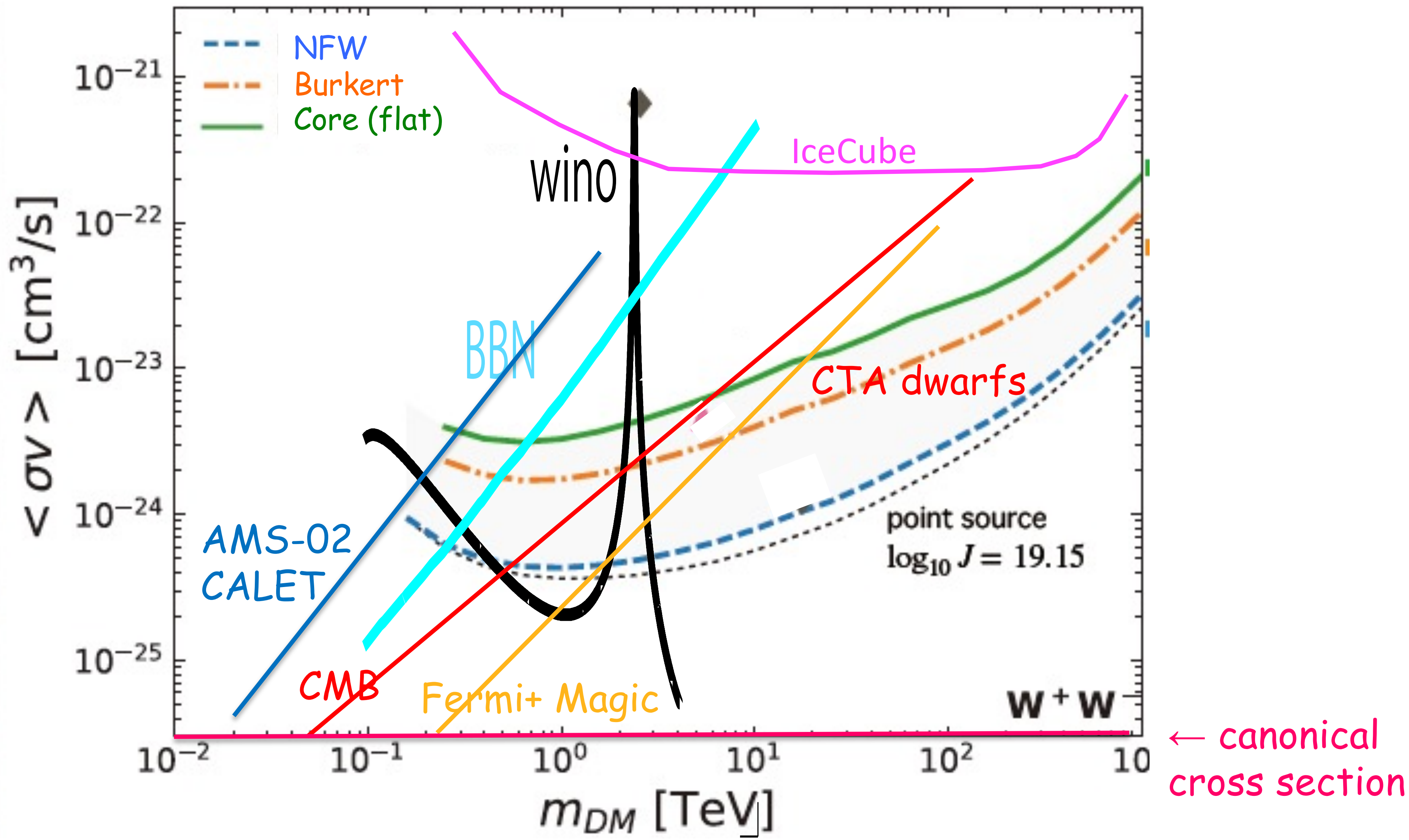


Propagations of charged particles



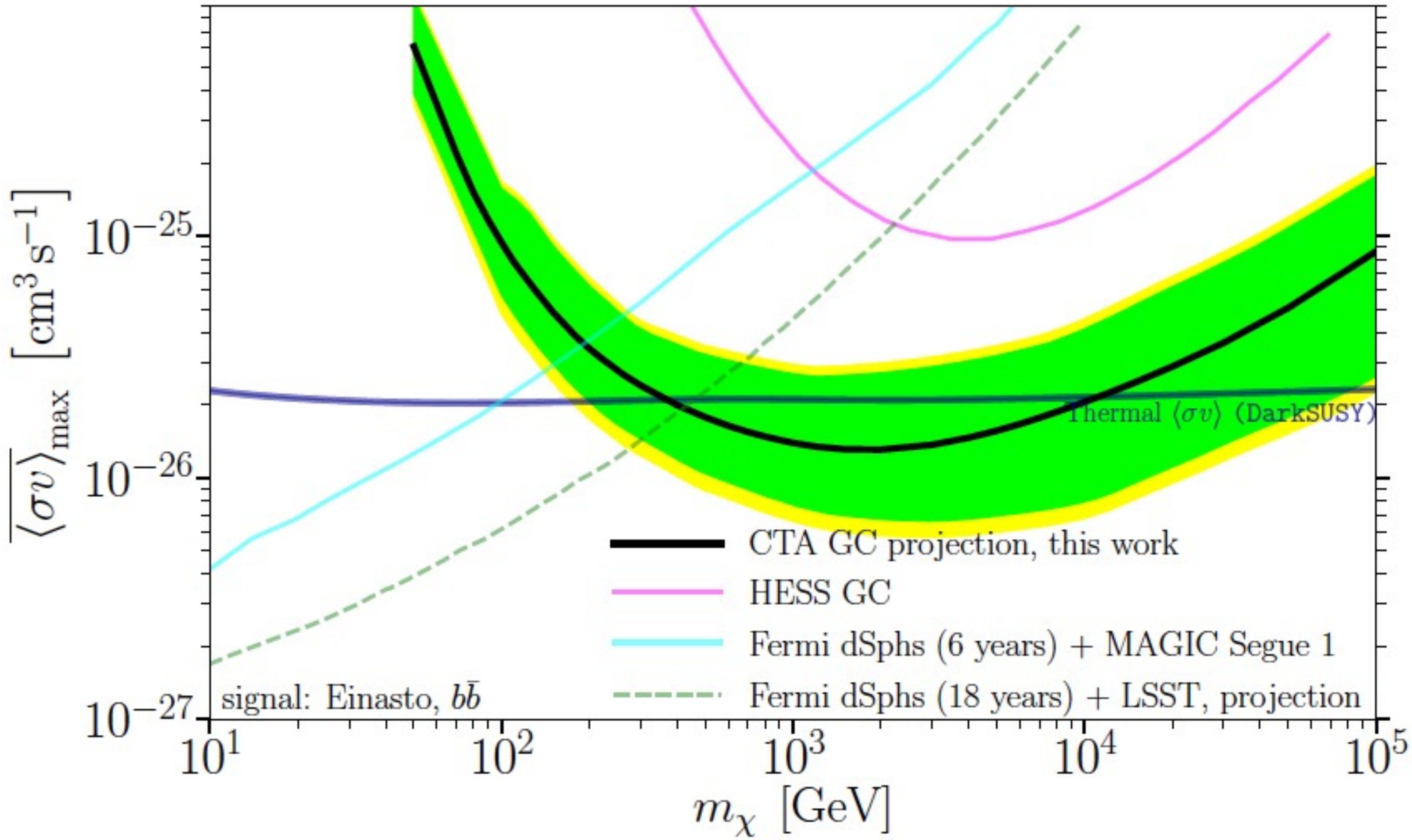
Upper bound on annihilation cross section

N.Hiroshima, M.Hayashida, and KK, arXiv:1905.12940 [astro-ph.HE]



Future sensitivity of upper bouns on annihilation cross section by CTA toward the galactic center

A. Acharyya et al, The Cherenkov Telescope Array Consortium, arXiv:2007.16129 [astro-ph.HE]



Axion

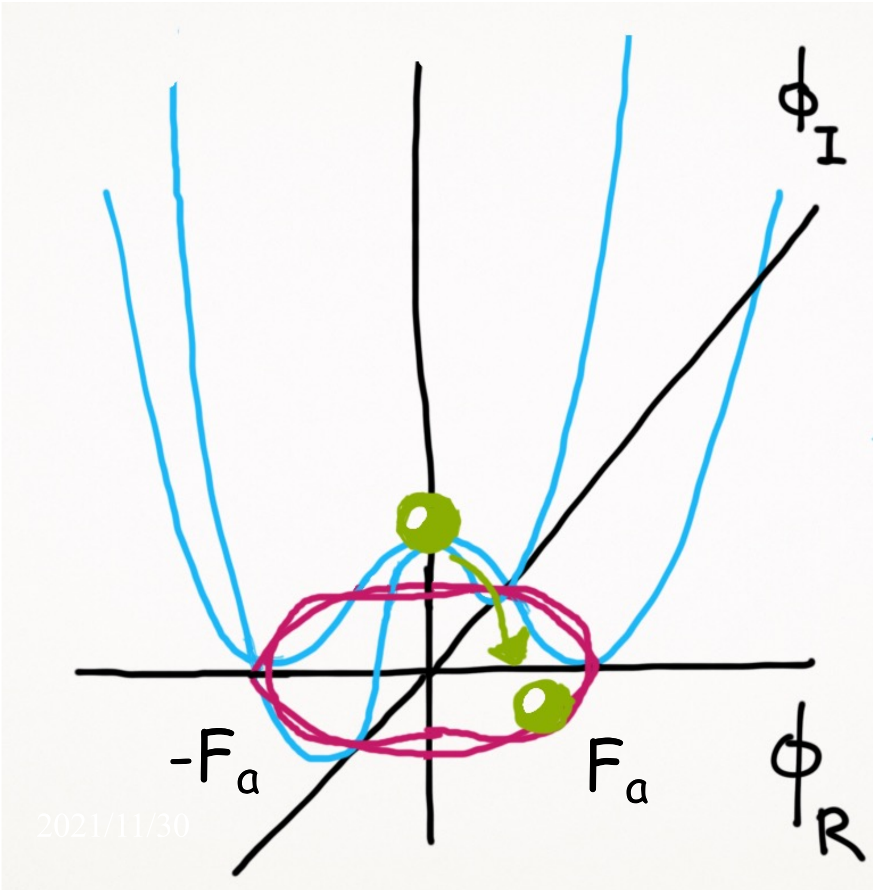
or

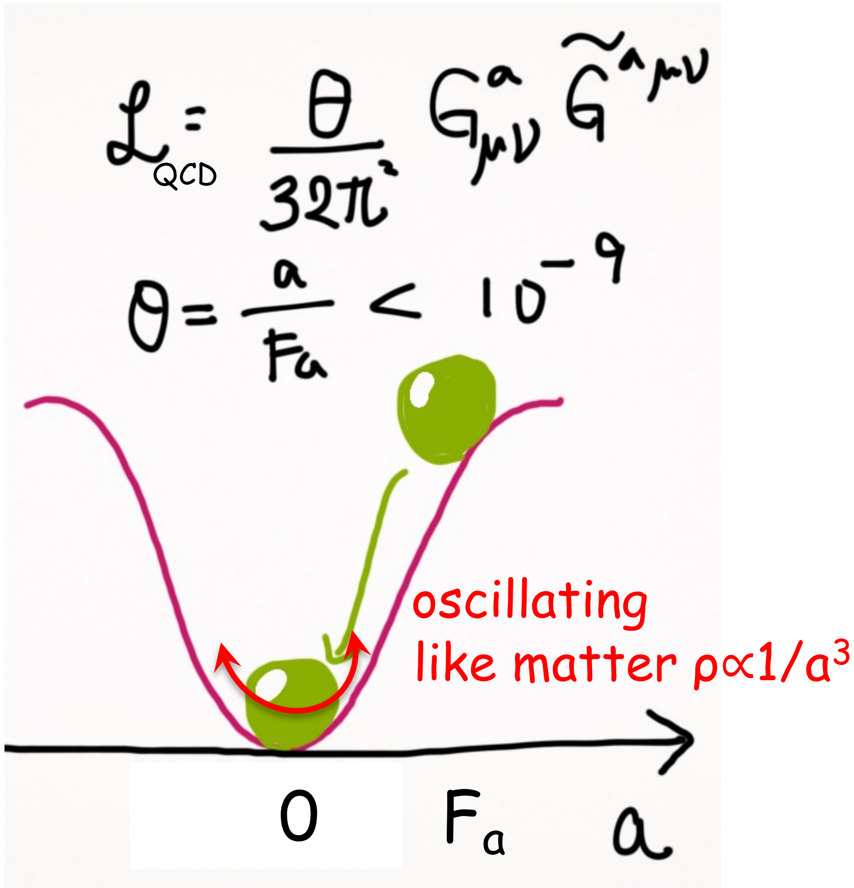
Axion-Like

Particle (ALP)

What is the (QCD) axion?

- Breakdown of the U(1) Peccei-Quinn symmetry
- The Nambu-Goldstone boson (angular component) is called "axion"





Oscillation probability

- Probability

$$P_{a\leftrightarrow\gamma} = \frac{1}{1+\left(\frac{\mathrm{E}_*}{\mathrm{E}_\gamma}\right)^2}\sin^2\left[\frac{g_{a\gamma}Br}{2}\sqrt{1+\left(\frac{\mathrm{E}_*}{\mathrm{E}_\gamma}\right)^2}\right]$$

- For efficient oscillation,

$$E_\gamma > E_* = \frac{m_a^2}{2g_{a\gamma}B} \quad \text{and} \quad r \geq r_{Ha} \equiv \frac{2}{g_{a\gamma}B}$$

ADMX bounds on QCD axions

C. Bartram, et al, the ADMX collaboration, arXiv: 2110.06096
https://arxiv.org/abs/2110.06096

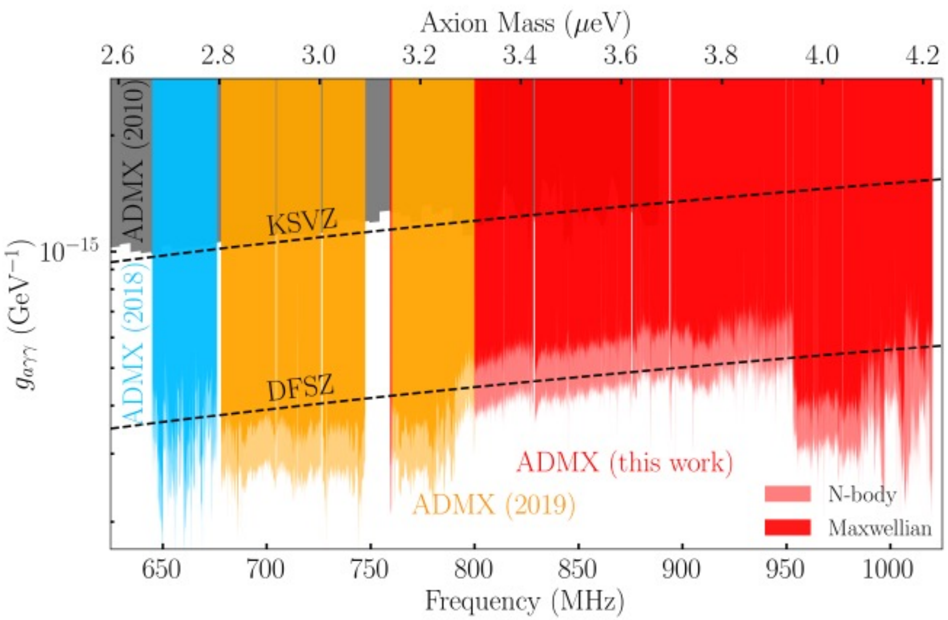


FIG. 4. 90% C.L. upper limits on $g_{a\gamma\gamma}$ as a function of axion mass. The gray-, blue-, and yellow-colored areas represent previous ADMX limits reported in Ref. [28], [32], and [33]. The red-colored area shows the limits of this work. We ruled out KSVZ (DFSZ) axions in the 3.3–4.2 (3.9–4.1)μeV mass range.

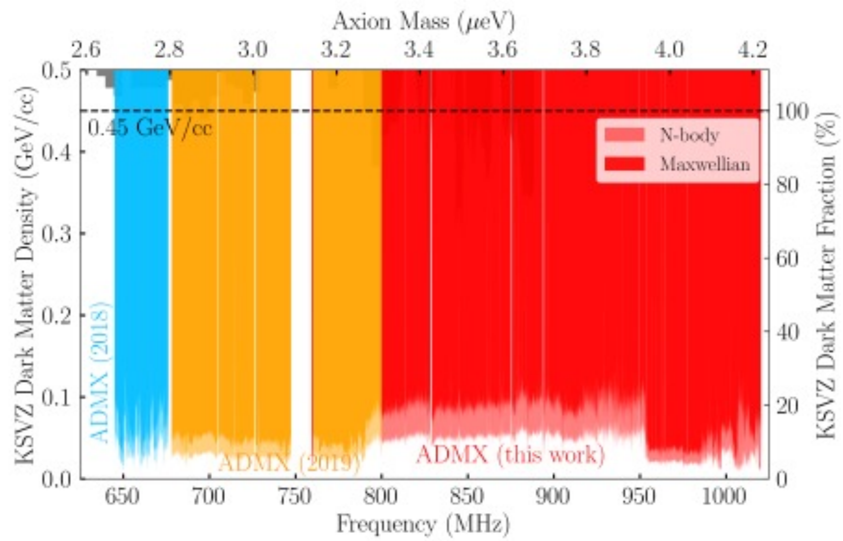
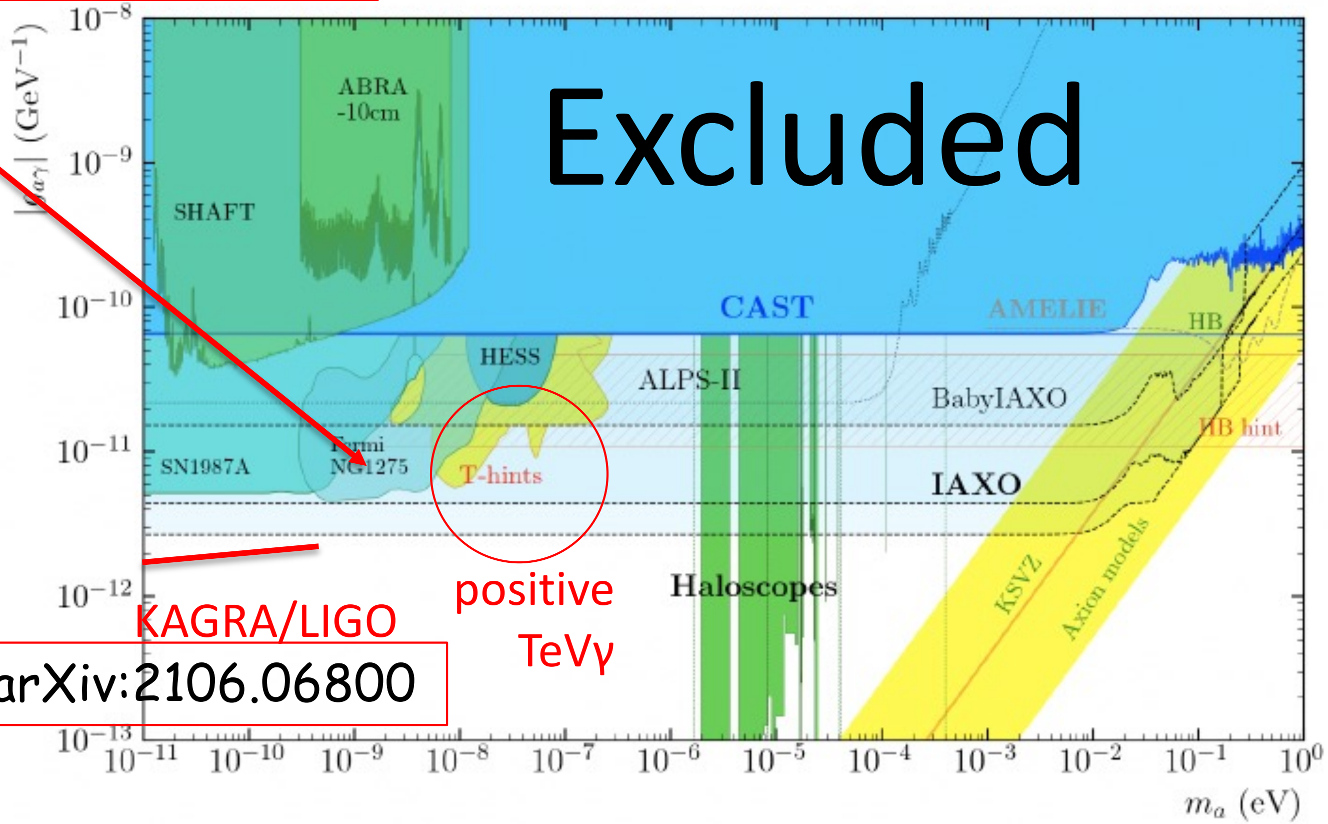


FIG. 5. 90% C.L. upper limits on the dark matter energy density assuming the KSVZ model for axion coupling. The blue- and yellow-colored areas represent previous ADMX limits reported in Ref. [32] and [33], respectively. The red-colored area shows the limits of this work. The KSVZ axions are excluded even though the axion density is 0.1 GeV/cc (20%) of the total dark matter density.

BabyIAXO for axion-like-particles

Kanji Mori, Tomoya Takiwaki, Kei Kotake, arXiv:2107.12661

Javier Galan, arXiv:2110.15668 [hep-ph]



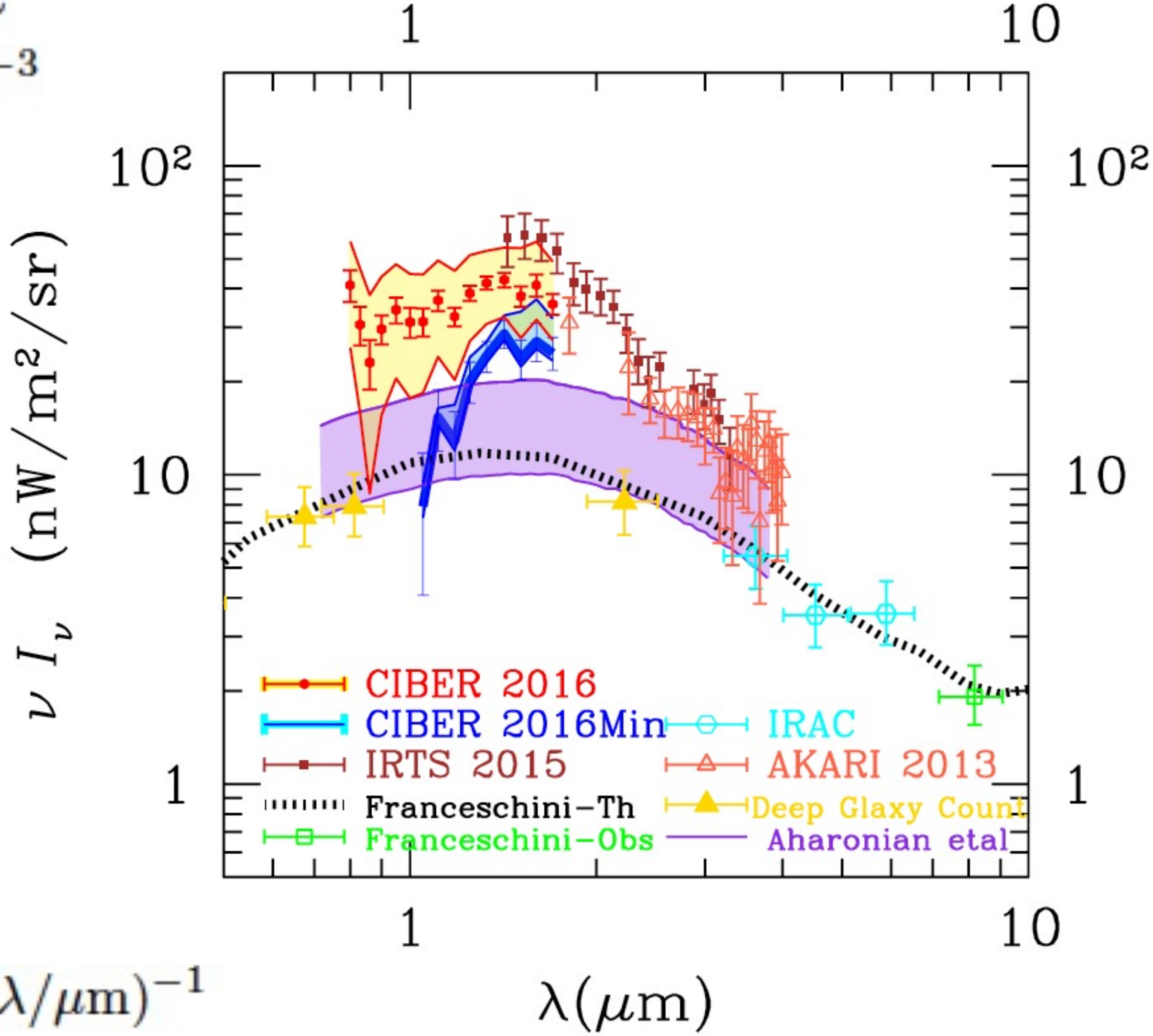
Nagano et al, arXiv:2106.06800

Figure 2. The prospects of the different IAXO setups and its sensitivity to $g_{a\gamma}$ as a function of the axion mass, m_a, including different hints and models described in the text, together with previous and planned experimental searches [12].

Cosmic Infrared Background (CIB) by CIBER 2016, IRTS 2013, Akari 2013

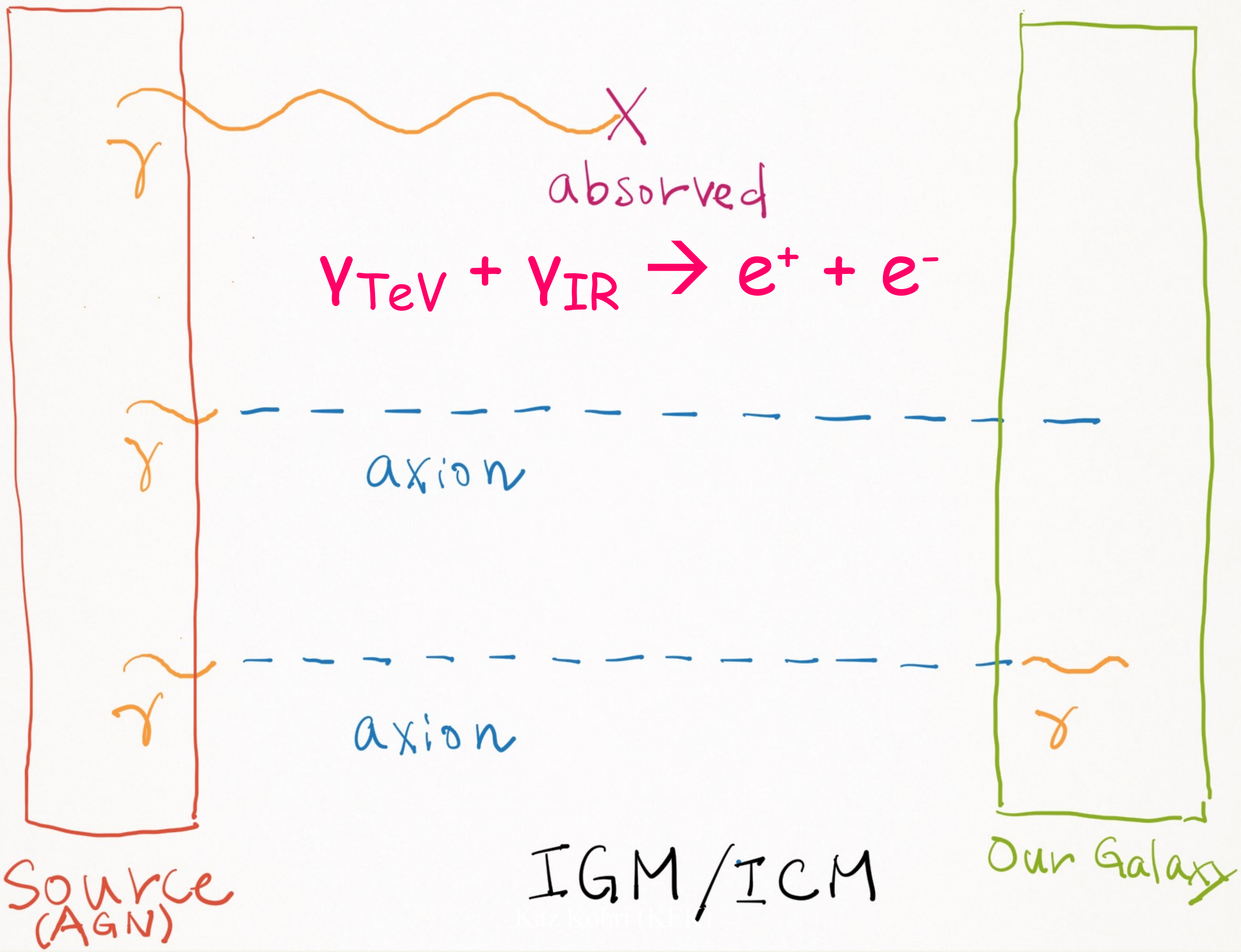
S. Matsuura *et al.* [CIBER Collaboration], Astrophys. J. 839, 7 (2017)

$10 \mathrm{nWcm}^2 \mathrm{sr}^{-1} \sim 2 \times 10^{-3} \mathrm{eVcm}^{-3}$

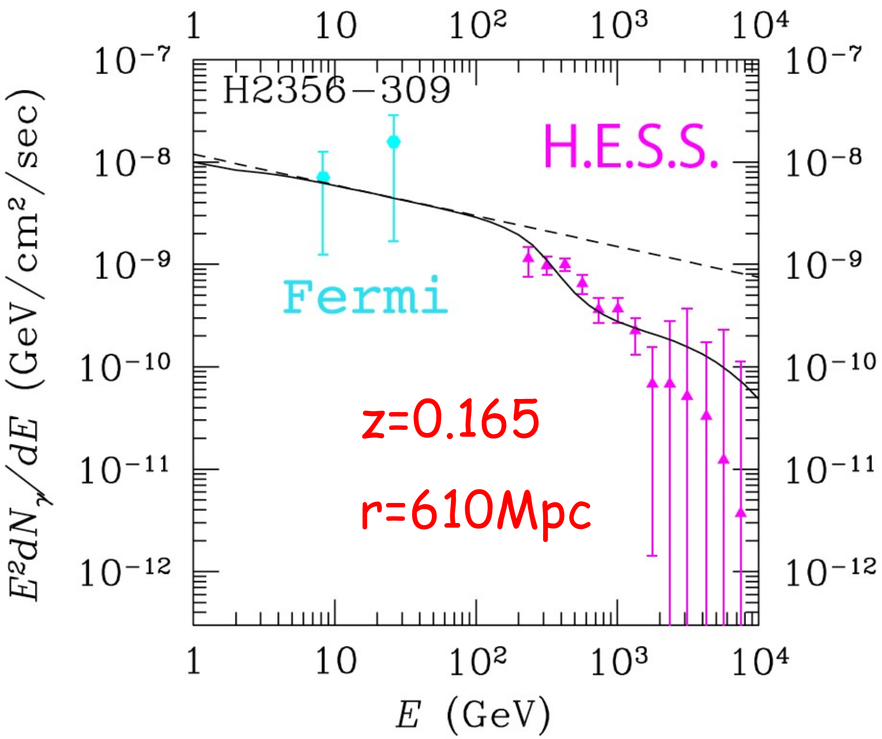


$E_{\gamma \mathrm{BG}} \sim 1.23 \ \mathrm{eV}(\lambda/\mu\mathrm{m})^{-1}$

γ (AGN) →axion (IGM)→γ (Milky-Way)



We need axion or ALPs



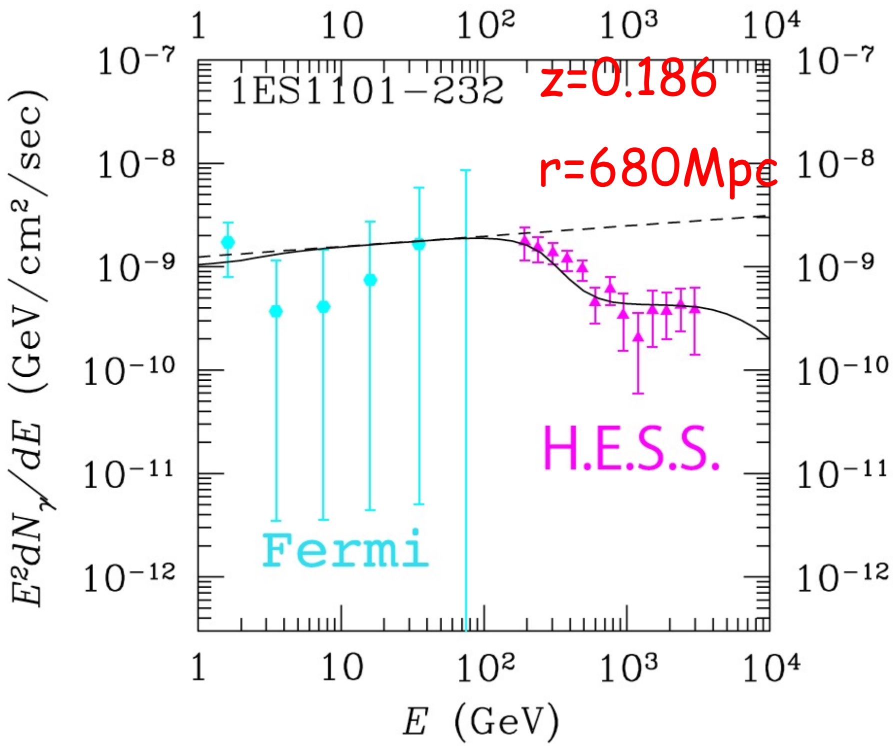


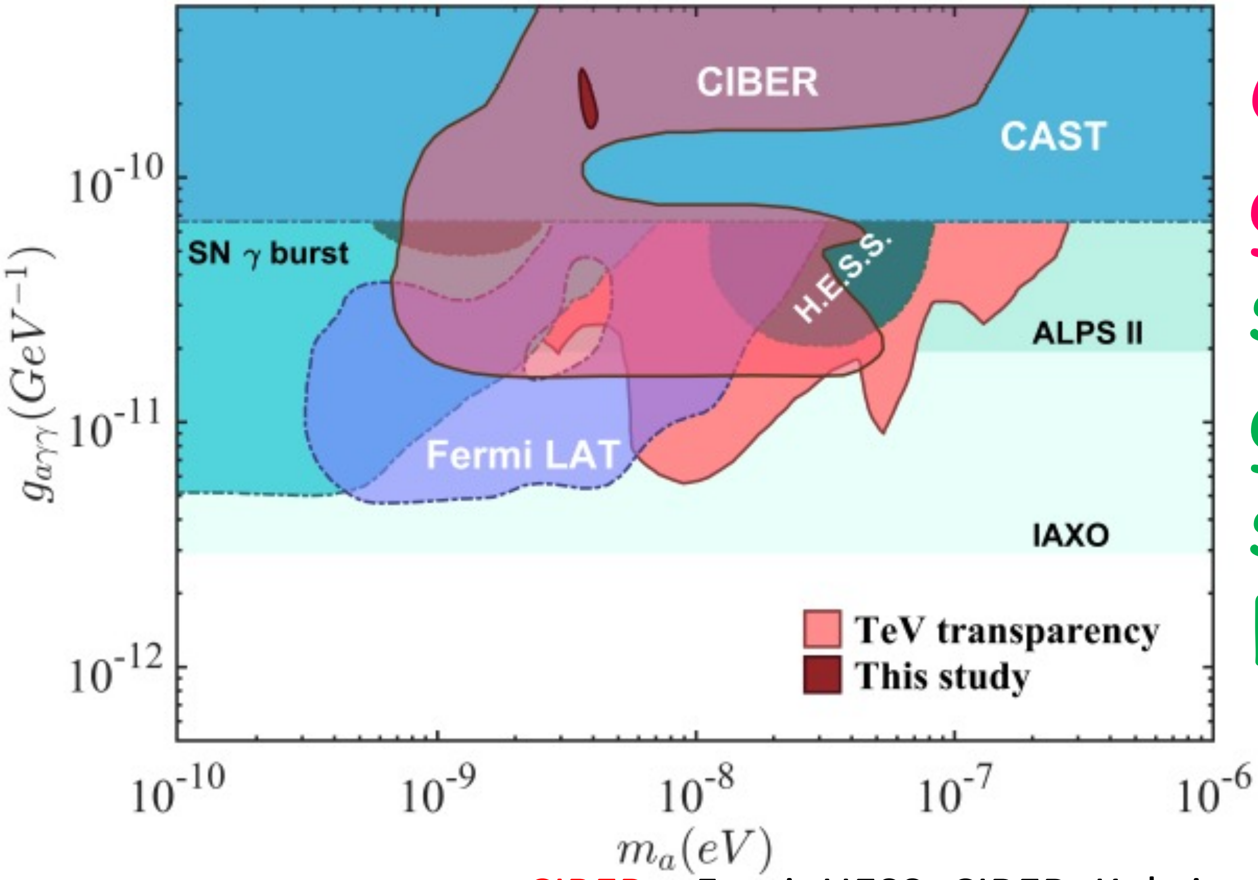
FIG. 3: Gamma-ray spectrum fitted to the data of H2356 309 (the redshift is $z = 0.165$ which gives the distance ~ 610 Mpc). Here, we adopted $g_{a\gamma} = 3.2 \times 10^{-11}\text{GeV}^{-1}$ and $m_a = 3.2 \times 10^{-9}$ eV. The reduced χ^2 is estimated to be $\chi^2/\text{d.o.f} = 1.1$, which is improved from the case without axion $\chi^2/\text{d.o.f} = 2.2$. The fitted value of the photon index is $\Gamma_s = 2.3$. We followed

FIG. 4: Sames as Fig. 3, but for 1ES1101 232 (the redshift is $z = 0.186$ which gives the distance ~ 680 Mpc.). The reduced χ^2 is estimated to be $\chi^2/\text{d.o.f} = 0.69$, which is improved from the case without axion $\chi^2/\text{d.o.f} = 2.0$. The fitted value of the photon index is $\Gamma_s = 1.9$.

Kohri and Kodama, arXiv:2017.05189

Photon-axion mixing through gamma-ray emission from 6 galactic pulsars

Jhilik Majumdar, Francesca Calore, Dieter Horns, arXiv:1801.08813 [hep-ph]



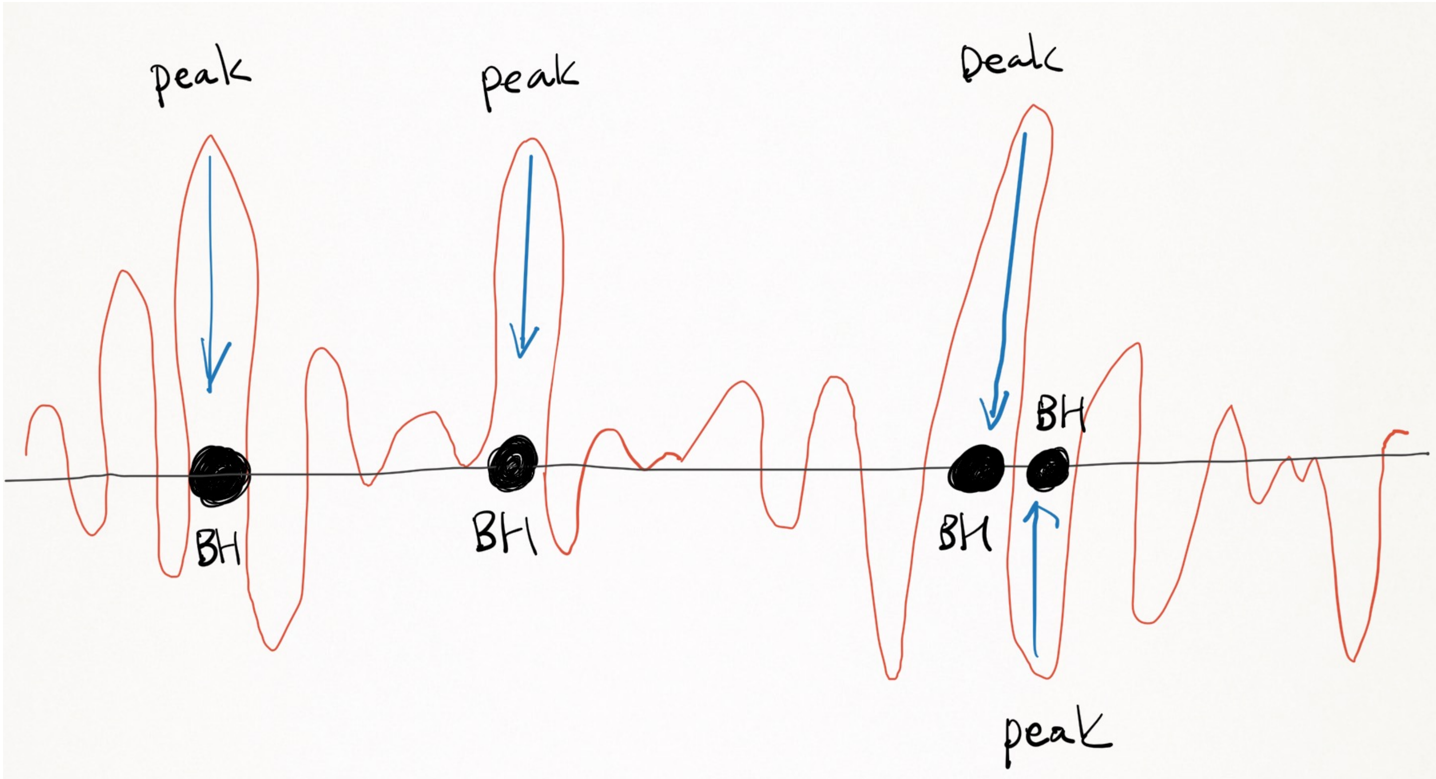
CTA/Magic should give us stronger bounds

CIBER : Femi+HESS+CIBER, Kohri and Kodama (2017)

Primordial Black Holes (PBHs)

Primordial Black Hole (PBH)

- Large perturbation at small scales was produced by Inflation at around > 10^{-36} second

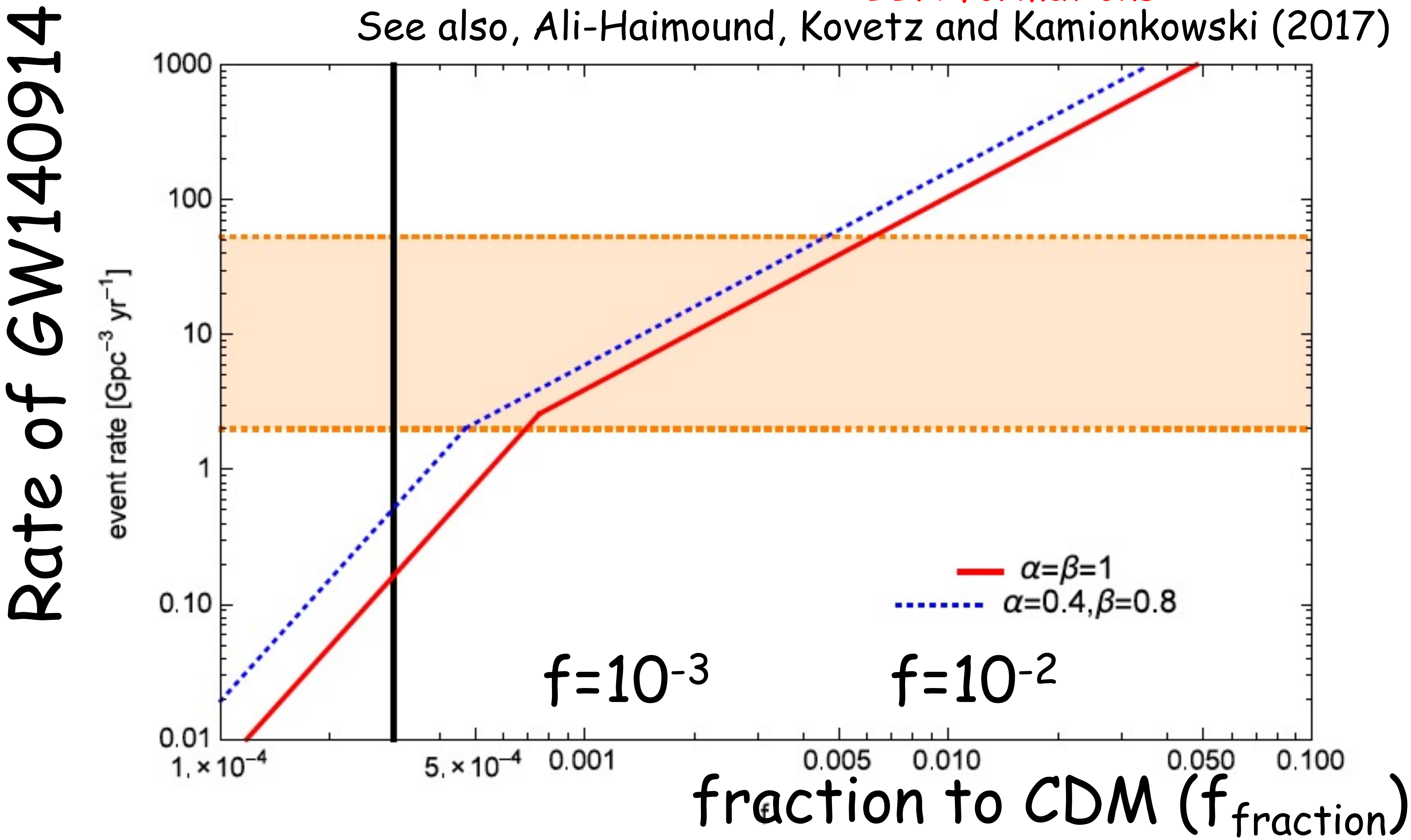


GW150914 and its merger rate

M. Sasaki, T. Suyama, T. Tanaka and S. Yokoyama (2016).

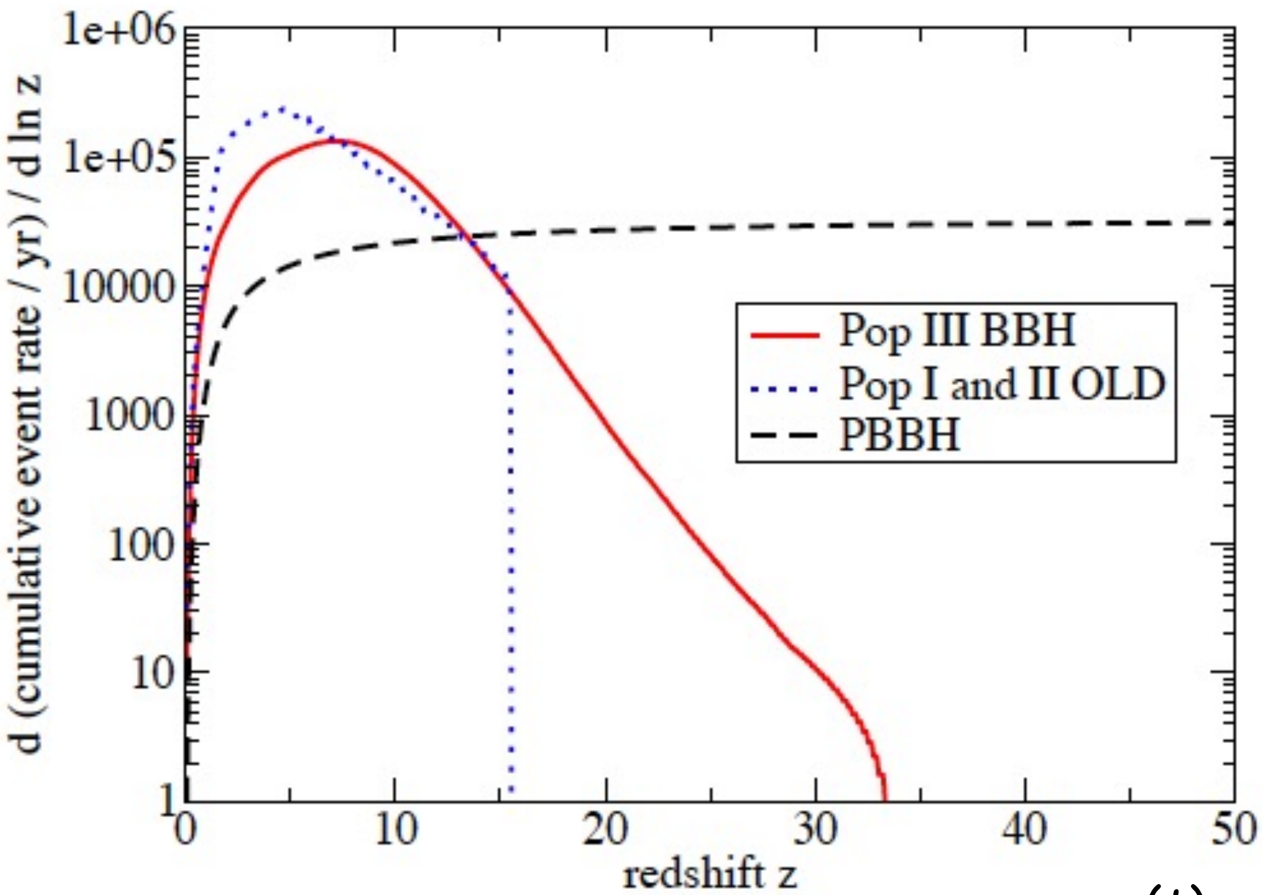
3-body is important for the BBH formations

See also, Ali-Haimound, Kovetz and Kamionkowski (2017)



DECIGO discriminates BPBHs from the normal BBHs

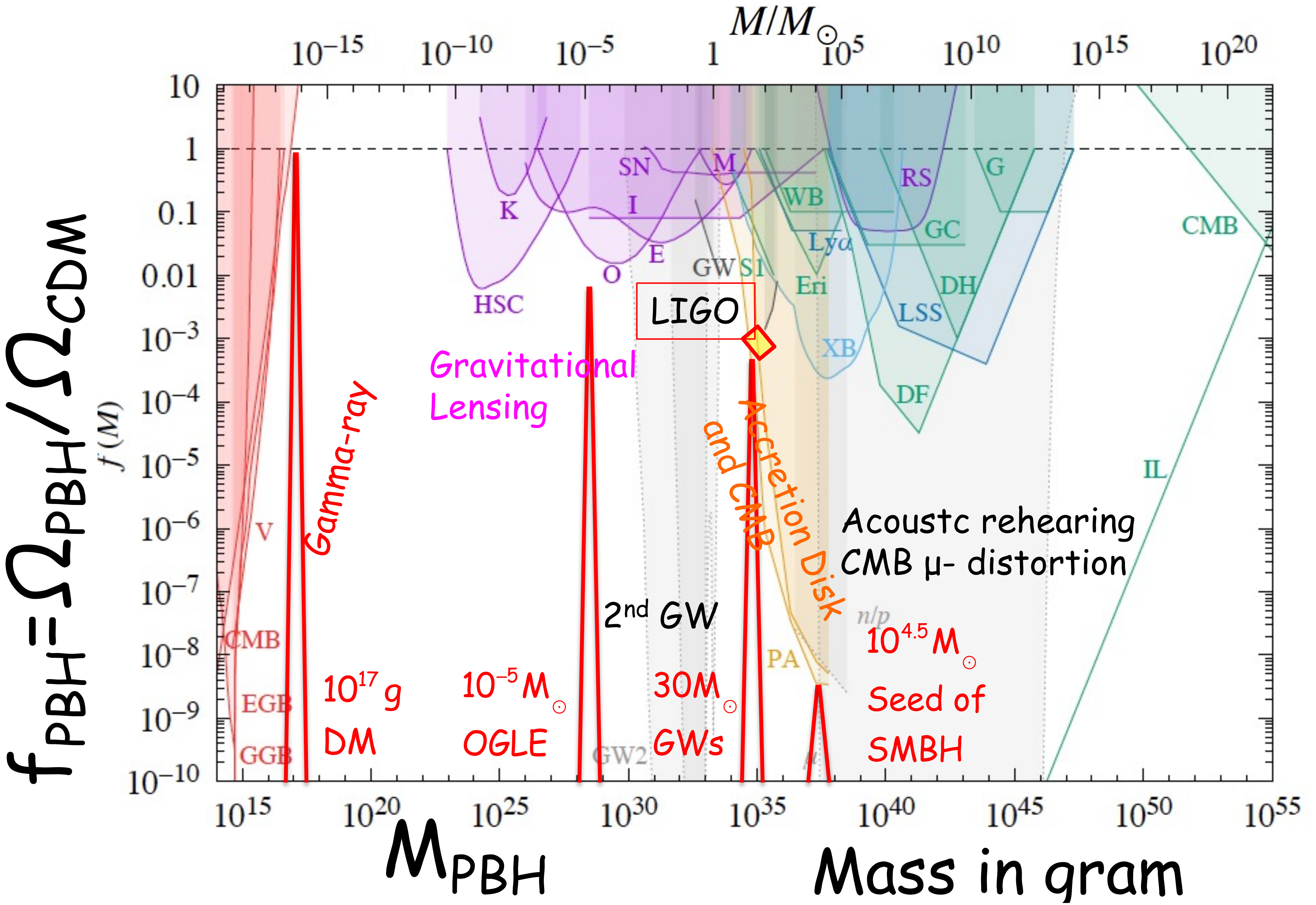
Takashi Nakamura et al, arXiv:1607.00897 [astro-ph.HE]



$$1/z \sim \frac{a(t)}{a(t_0)} \sim \left(t / 10Gyr\right)^{2/3}$$

Upper bounds on the fraction to CDM

Carr, Kohri, Sendouda, J.Yokoyama (2009)(2020)



Type-III Hilltop inflation models

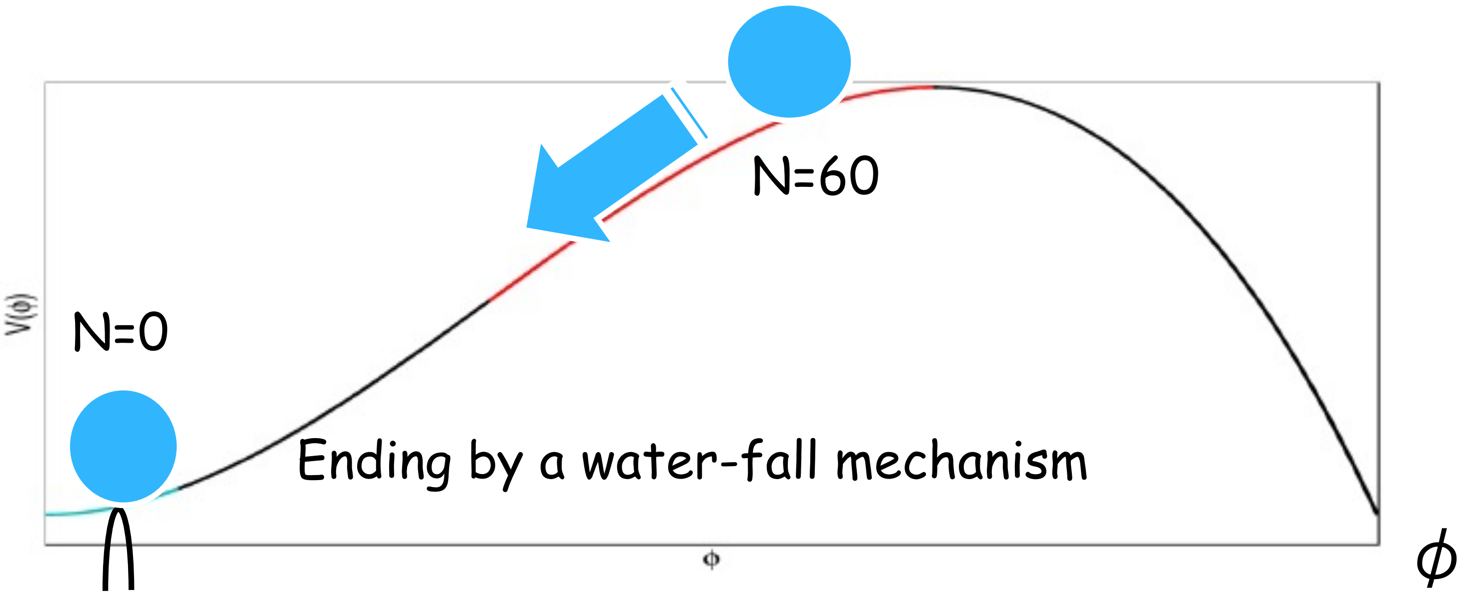
German, Ross, Sarkar (01)
Kohri, Lin and Lyth (07)

- Potential in supergravity, e.g.,

$$V(\phi) \;=\; V_0 + \frac{1}{2}m^2\phi^2 - \lambda\frac{\phi^p}{M_{\rm P}^{p-4}} + \cdots$$

$$W = C\frac{\phi^\rho}{M_{\rm pl}^{p-3}}, \quad \lambda \sim C m_{3/2}/M_{\rm pl}$$ in SUGRA

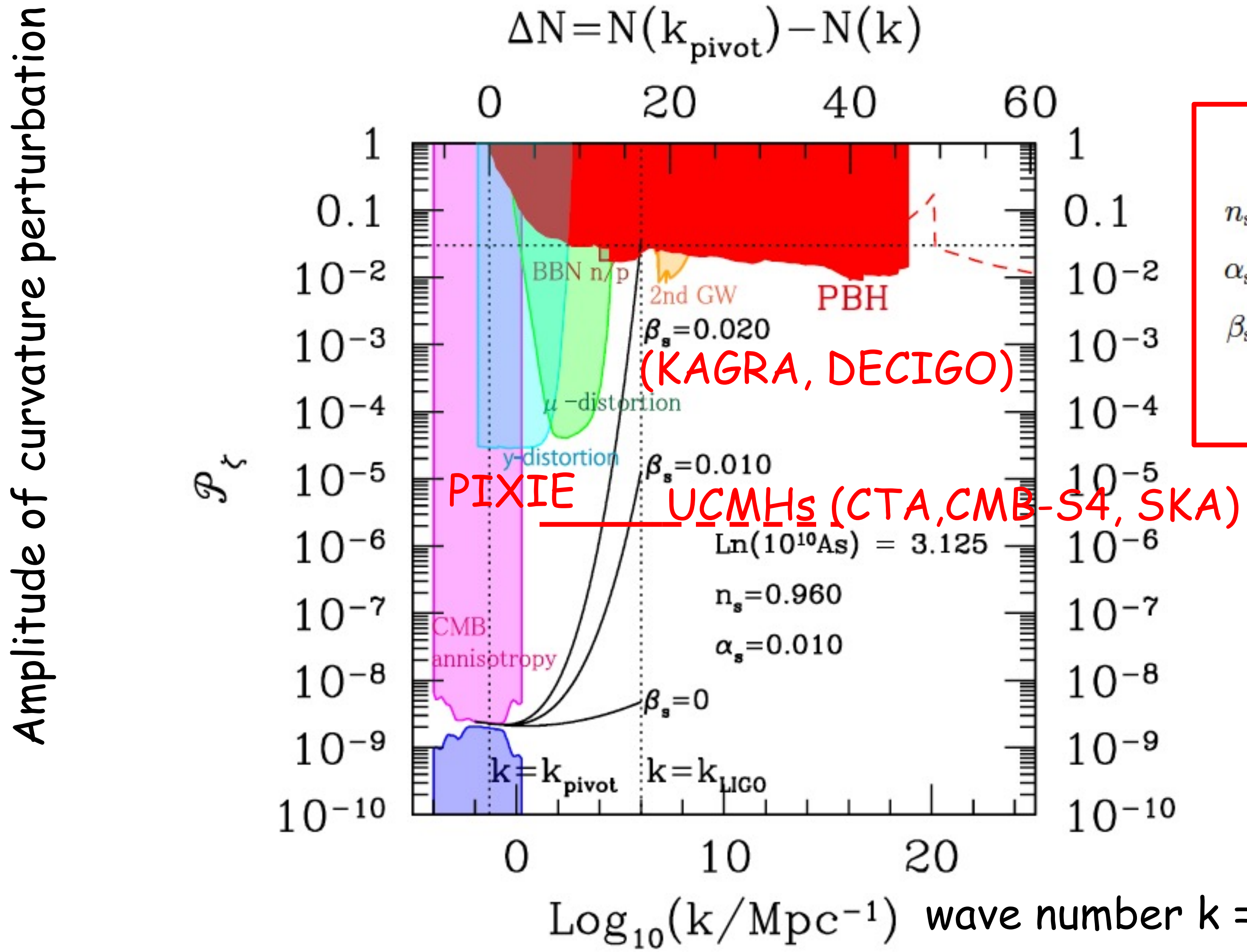
Allahverdi, Kusenko, Mazumdar (06)



Curvature perturbation $P_\zeta(k)$

Small-scales are the new frontier in future cosmology!

Kohri, Lin, Lyth, 2008
Alabidi, Kohri, Sendouda, Sasaki, 2013
Kohri and T.Terada, 2018



Planck

$n_s = 0.9586 \pm 0.0056,$

$\alpha_s = 0.009 \pm 0.010,$

$\beta_s = 0.025 \pm 0.013.$

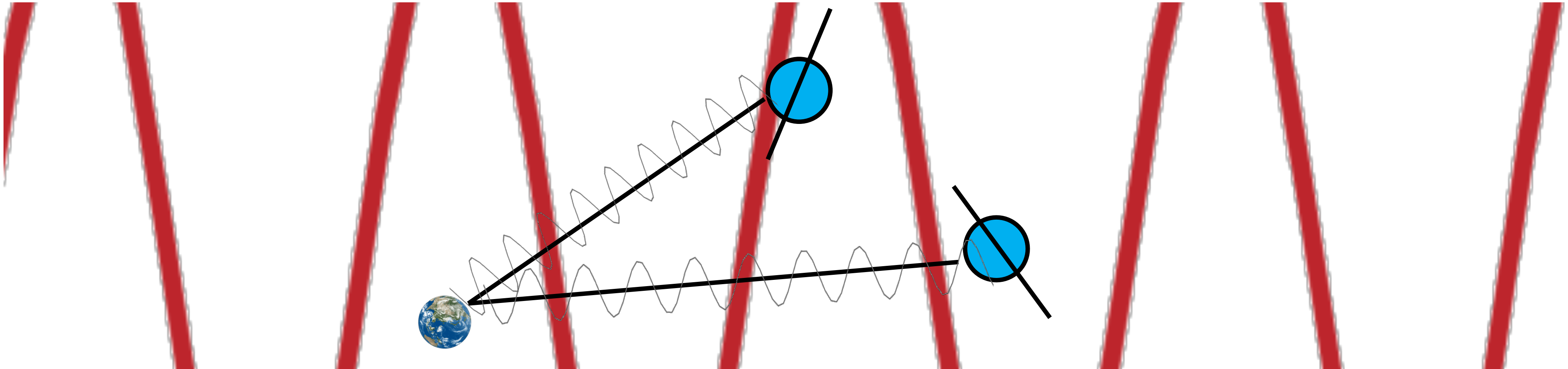
at 68% C.L.

Zaven Arzoumanian, et al, The NANOGrav Collaboration, arXiv:2009.04496

NANOGrav 12.5 yr

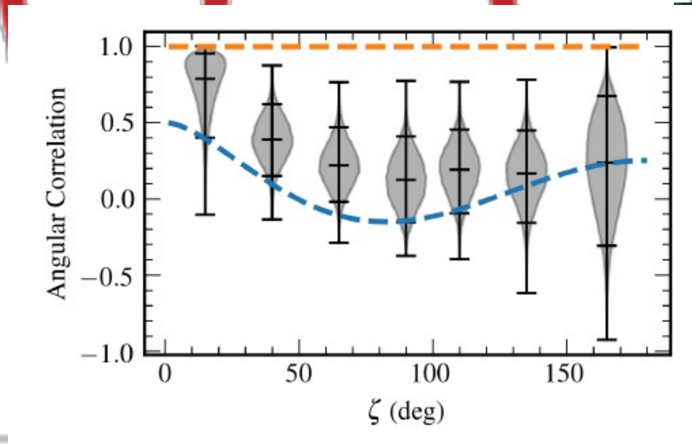
(North American Nanohertz Observatory for Gravitational Waves)

found stochastic GWs through pulsar timing ?



https://www.nasa.gov/sites/default/files/thumbnails/image/arecibo_ao002.jpg

The 305-meter dish of the William E. Gordon Telescope, The Arecibo Obs.



https://science.nasa.gov/science-red/s3fs-public/atoms/files/JLazio_PlanetaryScienceAdvisoryCommittee-February-v2=TAGGED.pdf

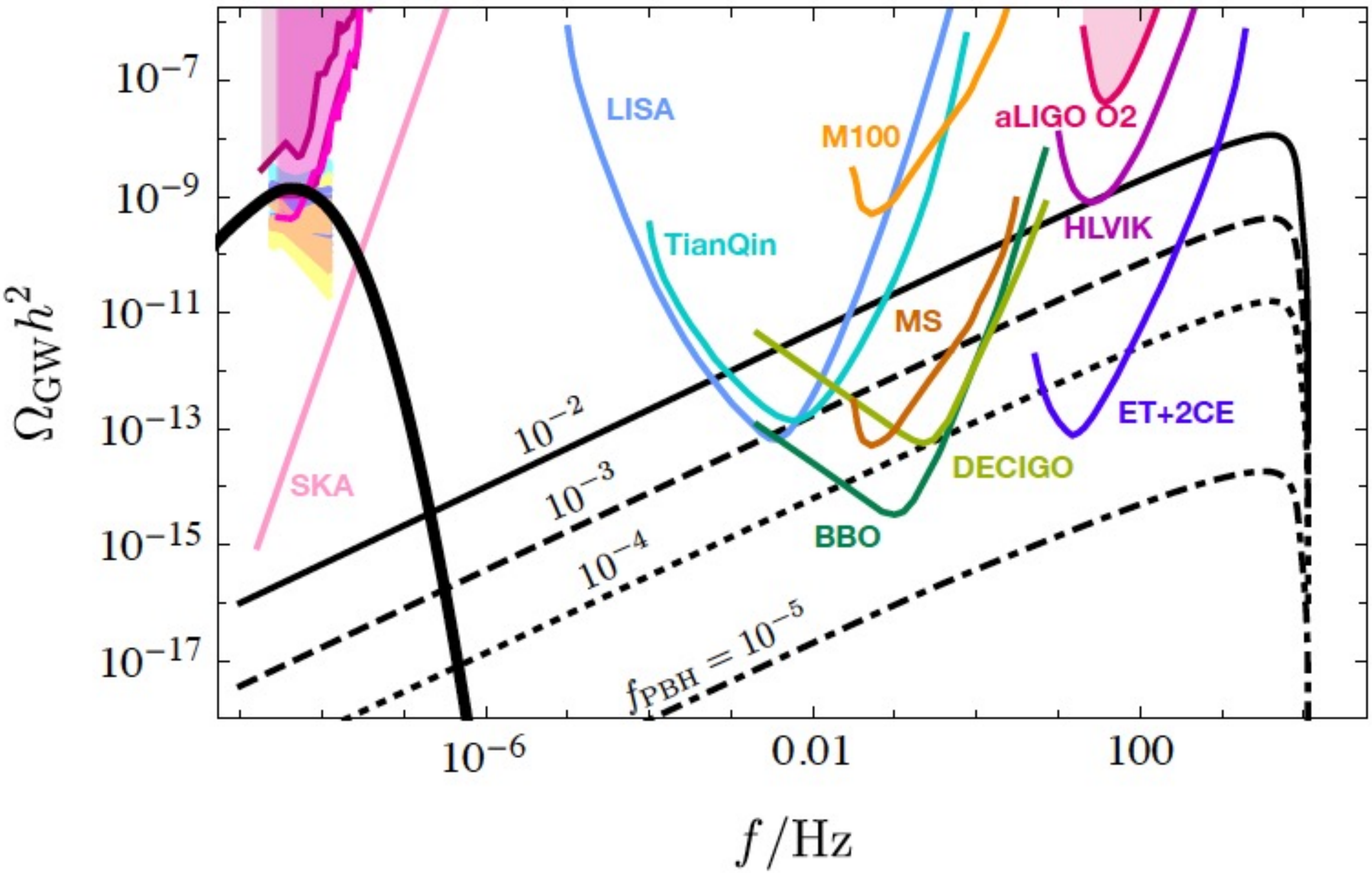
The 100-meter Green Bank Telescope

NANOGrav12.5yr and solar mass PBHs

K. Kohri and T. Terada, arXiv:arXiv:2009.11853

LIGO (H+L) + VIRGO (V) + Indigo (I) + KAGRA (K)

Yoichi Aso, et al, arXiv:1306.6747 [gr-qc]



2^{nd} order GWs enhanced at a sudden transition from MD to RD

Inomata, Kohri, Nakama, Terada, Phys. Rev. D 100, 043532 (2019), arXiv:1904.12879

$\overline{\mathcal{P}_h(\eta,k)}$ ~ $\int\int f^2(u,v,x,x_R)$

$$f(u,v,\bar{x},x_{\rm R}) = \frac{3\left(2(5+3w)\Phi(u\bar{x})\Phi(v\bar{x}) + 4\mathcal{H}^{-1}(\Phi'(u\bar{x})\Phi(v\bar{x}) + \Phi(u\bar{x})\Phi'(v\bar{x})) + 4\mathcal{H}^{-2}\Phi'(u\bar{x})\Phi'(v\bar{x})\right.}{25(1+w)}$$

This is big!

- Gravitational potential

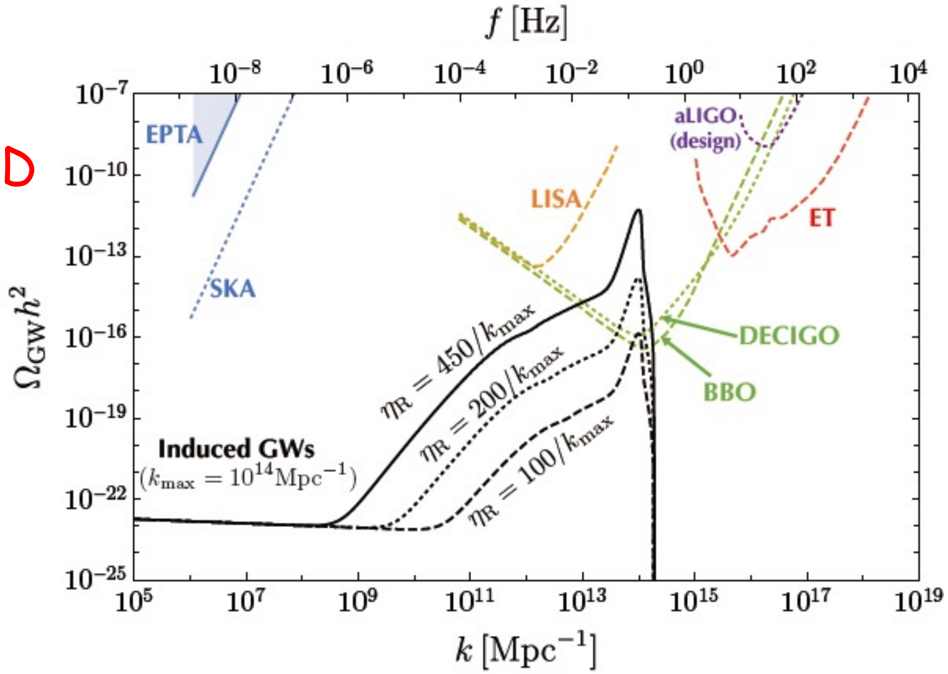
$$\Phi(x,x_{\rm R}) = \begin{cases} 1 & (\text{for } x \le x_{\rm R}), \\ A(x_{\rm R})\mathcal{J}(x) + B(x_{\rm R})\mathcal{Y}(x) & (\text{for } x \ge x_{\rm R}), \end{cases}$$

eMD
RD

- Enhancement at T_R

$$\mathcal{H}^{-2}\Phi'\Phi' \sim (k\eta_{\rm R})^2\Phi^2 \gg \Phi^2$$

Amplitude should be less than unity
The transition occurs in a finite time



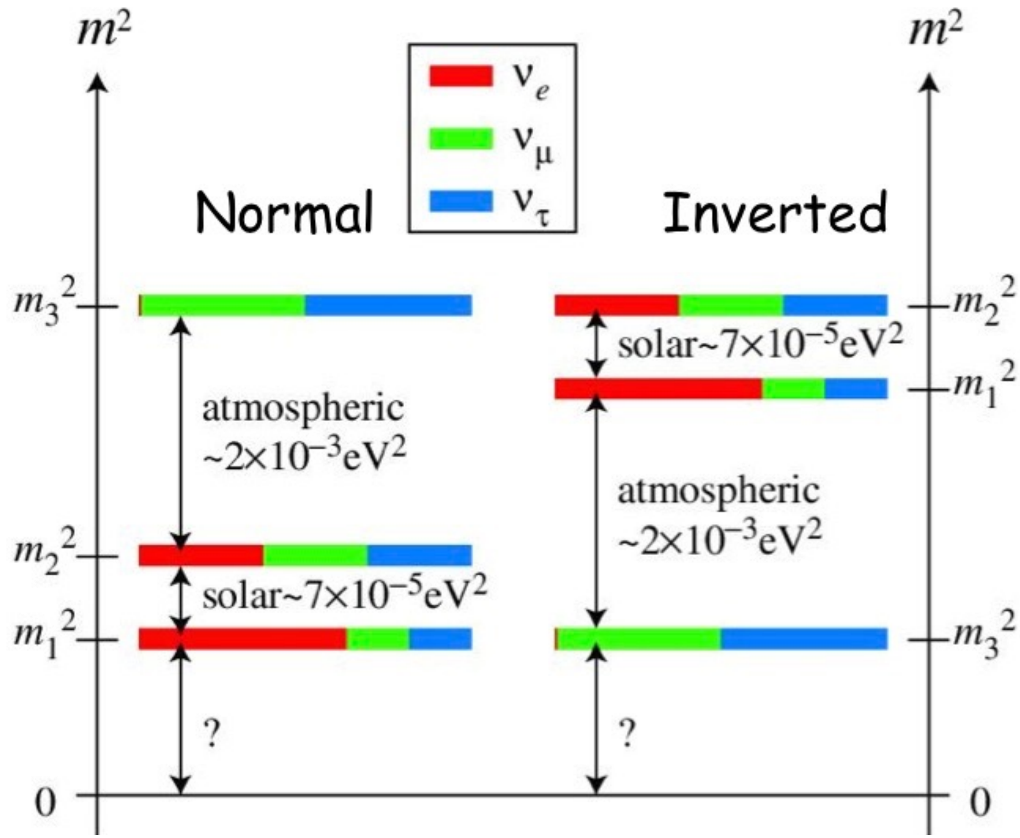
Neutrino masses/hierarchy and CP violation

Neutrino masses m_ν

- The mass differences among neutrinos have been measured by Super-Kamiokande, KamLAND, etc. …
- [Q] How large are the nonzero absolute values of m_ν ? How is the hierarchy among the three masses?
- By measuring them, we can obtain a hint of the new theory which gives m_ν (e.g., GUT, Seesaw mechanism, Leptogenesis etc. …)
- [obs] Cosmological 21cm line (SKA), CMB lensing (POLARBERAR-2, Simons Array/ Observatory, CMB-S4), Ocillation exp. (Hyper-K), the Inverse beta-decay exp. (PTOLEMY), …

Neutrino mass and # of species N_ν

From oscillation experiments



$$\sum_{i=1,2,3} m_{\nu_i} > 0.06 \text{ eV} \qquad \sum_{i=1,2,3} m_{\nu_i} > 0.10 \text{ eV}$$

From the current cosmological observations such as CMB + ...,

$$\sum_{i=1,2,3} m_{\nu_i} < 0.23 \text{ eV } (2\sigma) \qquad N_{\nu,\text{eff}} = 3.3 \pm 0.5 \ (2\sigma)$$

Neutrinos with m_ν=O(0.01) eV become non-relativistic at 3T=m_ν=O(0.01) eV

- Much after the recombination (3T << 0.3eV)
- Much before galaxy formation (3T >> 0.001eV)

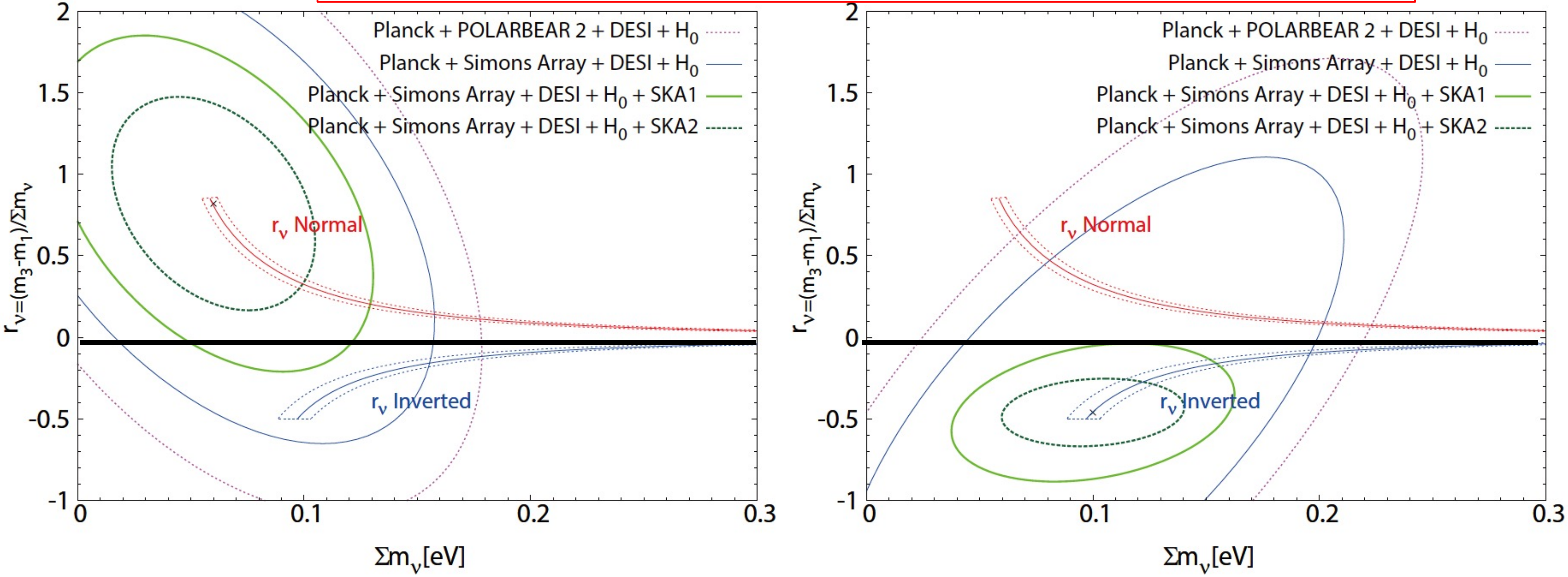
21cm line + CMB lensed B-mode polarization should be the best tool to constrain mass hierarchy with m_ν~0.05 eV

Future constraints on neutrino hierarchy by 21cm, CMB, BAO, H_0

Oyama, Kohri, Hazumi (2015)

- Hierarchy parameter

$$r_\nu \equiv \frac{m_3 - m_1}{\Sigma m_i} = \begin{cases} > 0 & \text{normal hierarchy} \\ < 0 & \text{inverted hierarchy} \end{cases}$$



Dark

Energy

Dark Energy

- We need the source for the accelerating expansion of the Universe at present (～ the cosmological constant)
- Building a theoretical model to explain it
- [Q] We have to reveal it: Why is it so small and constant with $\rho^{1/4} \sim$ meV?
- [Obs] Weak lensing? 21cm? Measurements of masses of axion or neutrino? Modified gravity?

Neutrino mass scale ~ O(1) meV

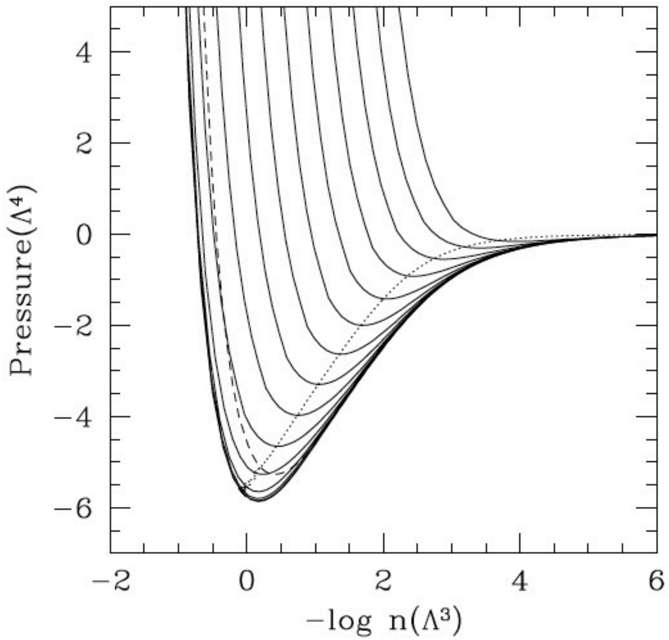
Afshordi, Zaldarriaga, Kohri, arXiv:astro-ph/0506663

- A scalar coupled with neutrinos with $V(\phi)^{1/4} \sim$ O(1) meV
- However, there is an instability which makes DE fragment into dark matter halos

$$\delta \propto \exp[+|c_s| m_\phi t]$$

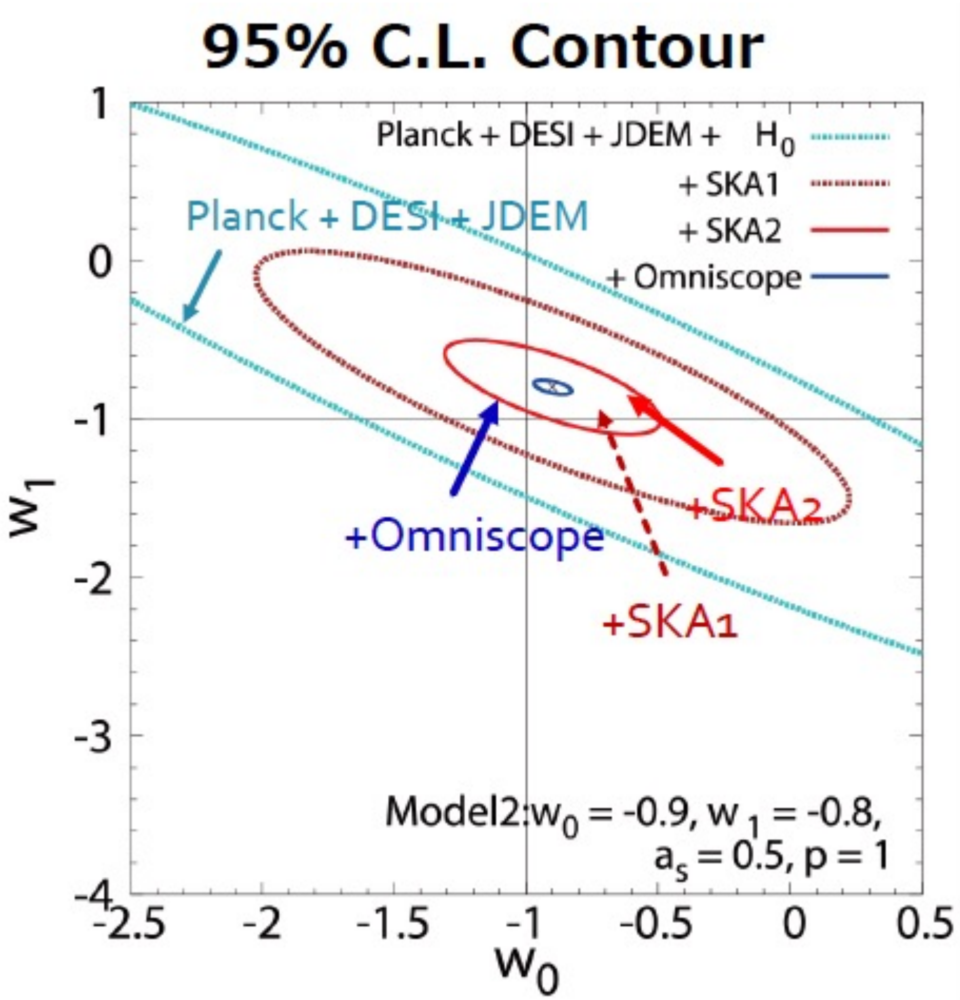
with $c_s^2 < 0$

for $1/m_\phi < 1/k < 1/H_0$



Forecast in future experiments with future 21cm+CMB+BA0+SNeIa+H_0

Kazunori Kohri, Yoshihiko Oyama, Toyokazu Sekiguchi, Tomo Takahashi,
arXiv:1608.01601 [astro-ph.CO]



Matter-antimatter asymmetry

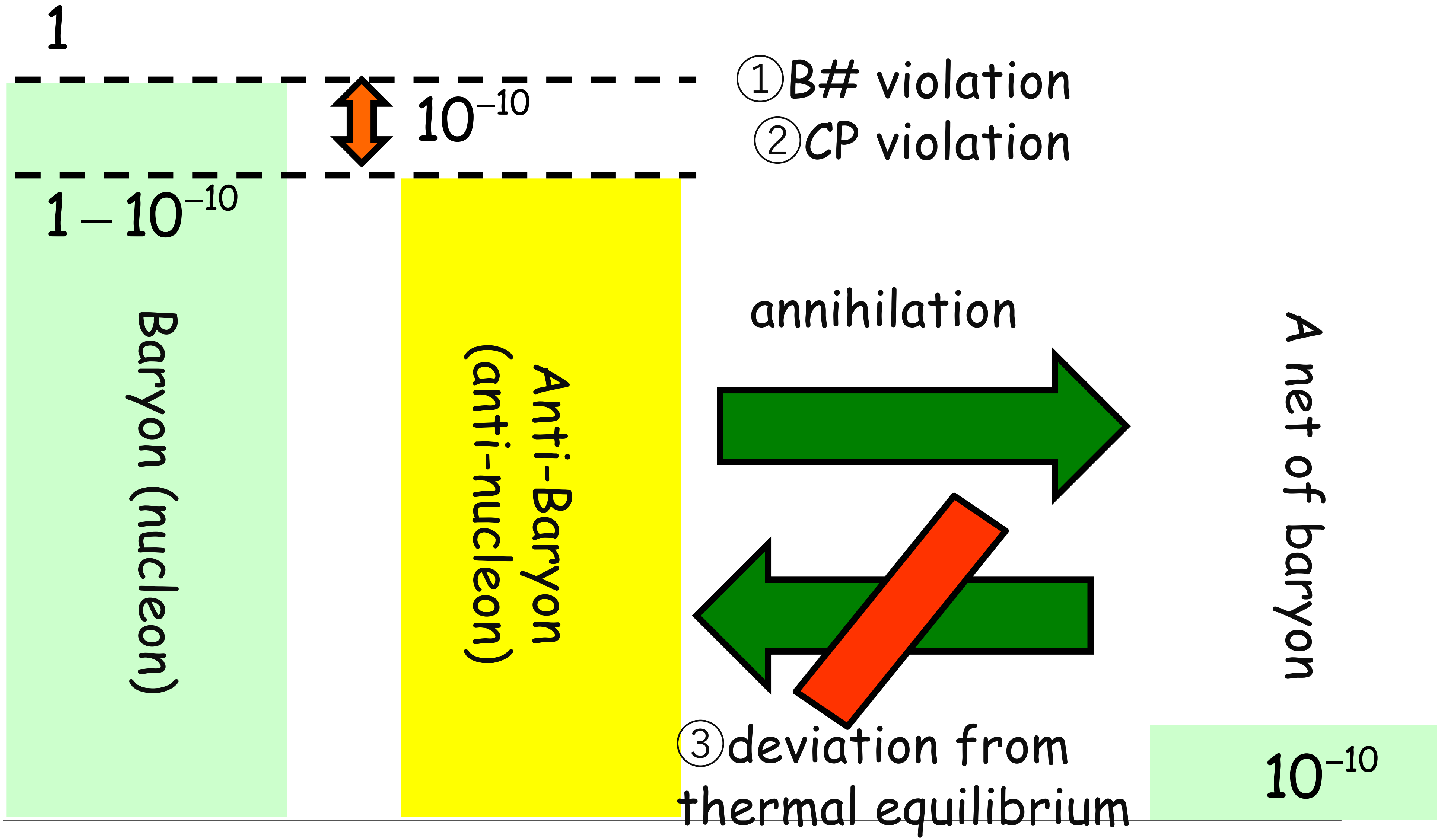
Matter-antimatter asymmetry

- We need n_B/n_γ=baryon # / photon # ~ 10^{-10} suggested by Big Bang Nucleosynthesis (BBN) and CMB

- [Q} How n_B/n_γ was produced from nothing? Building models to produce nonzero n_B/n_γ

- [obs] Measuring another CP phases in quarks, neutrinos (left or right handed) by T2K, Hyper-K or obtaining a hint of nonthermal phenomena such as 1st order phase transition or decaying topological defects (e.g., cosmic string) in the early Universe through GWs by SKA, NANOGrav, KAGRA, ET, DECIGO, ET, CE

Baryogenesis/Leptogenesis and Sakharov's three conditions



Leptogenesis

Fukugita and Yanagida, 1986

- Decay of massive right-handed neutrino ν_R

$$\nu_R \to \nu + h$$
$$\nu_R \to \bar{\nu} + h^*$$

- We need the CP violation in the neutrino sector

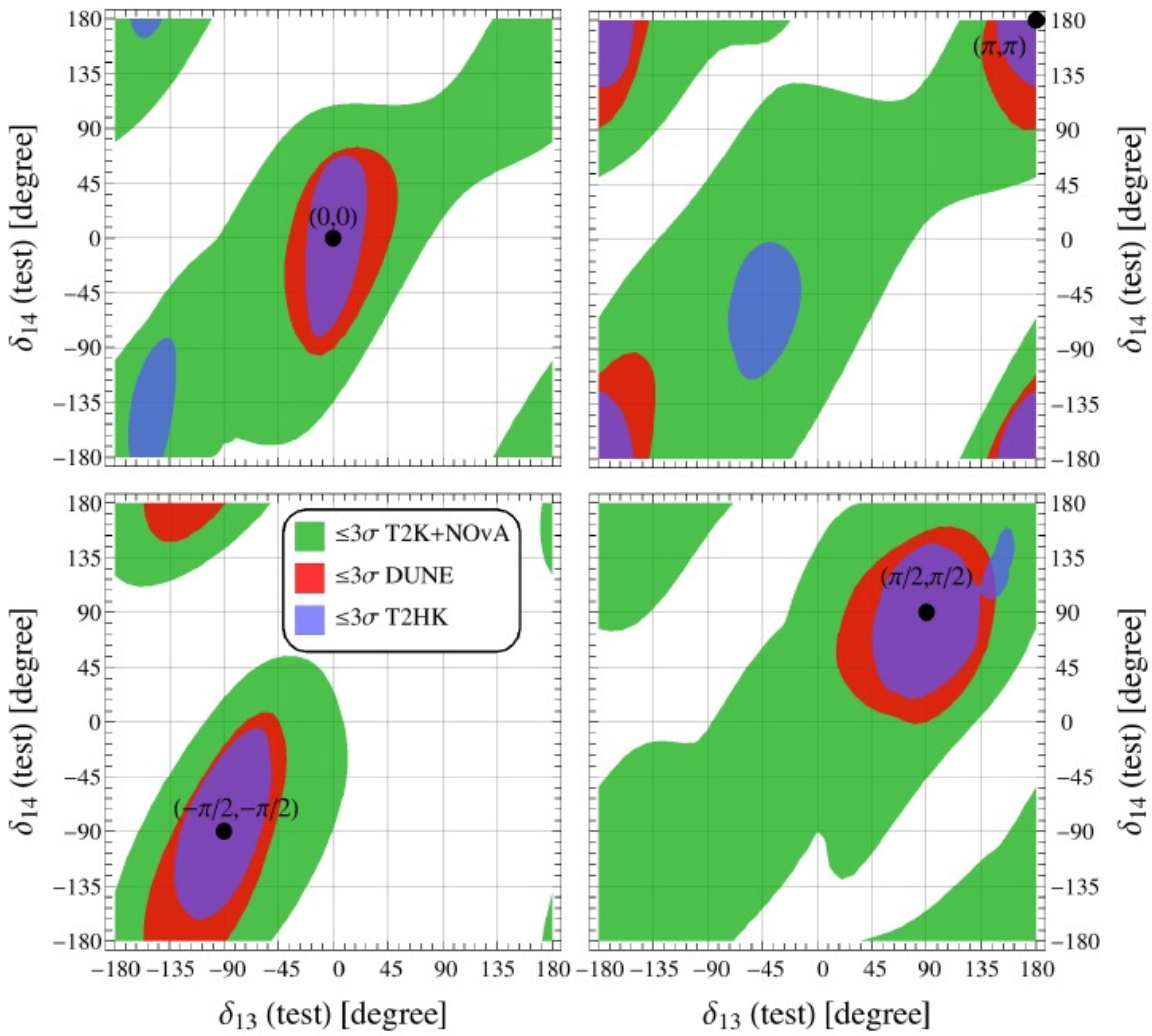
$$\epsilon_1 \equiv \frac{\Gamma(\nu_R \to \nu + h) - \Gamma(\nu_R \to \bar{\nu} + h^*)}{\Gamma_{\rm tree}} \neq 0$$

- Lepton number n_L/s is converted into baryon number n_B/s through the Sphaleron process at T ～O(100) GeV

$$\frac{n_B}{s} = -\frac{28}{79}\frac{n_L}{s} \sim 1 \times 10^{-10} \left(\frac{\kappa}{0.03}\right) \left(\frac{M_1}{10^6 {\rm GeV}}\right) \left(\frac{m_{\nu 3}}{0.05 eV}\right) (-\delta_{\rm eff})$$

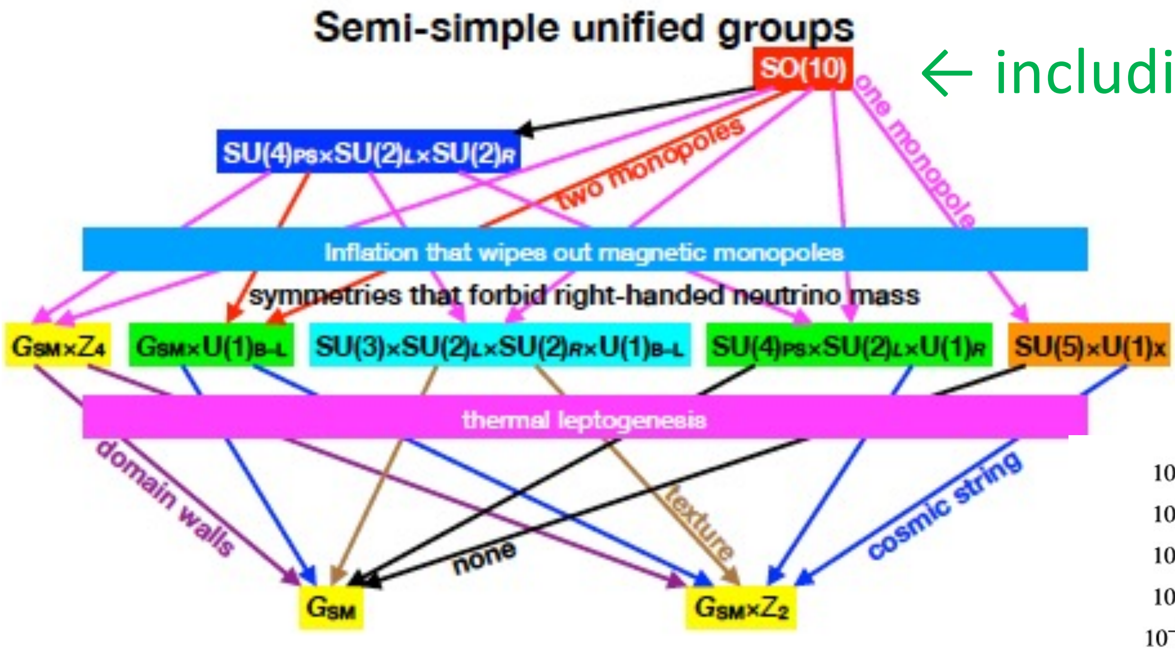
CP phases in active and sterile neutrinos by future T2HK (T2-Hyper-K), Dune, Nova

Sanjib Kumar Agarwalla, Sabya Sachi, Chatterjee, and Antonio Palazzod, arXiv:1801.04855v1



Seesaw and Leptogenesis searched by future GW

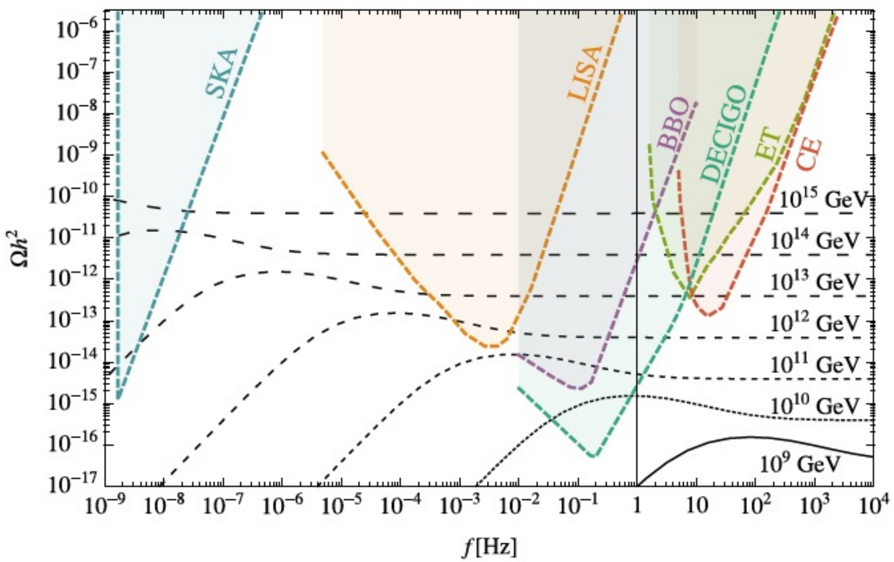
Jeff A. Dror, Takashi Hiramatsu, Kazunori Kohri, Hitoshi Murayama, Graham White, arXiv:1908.03227 [hep-ph]



← including ν_R

Cosmic strings were formed

Decay of cosmic strings → a flat GW spectrum



SKA, NANOGrav, LISA, BB0, DECIGO, ET, CE

素粒子的宇宙論の発展において何が大きな課題か？

What is the most important goal(s) in progress on particle cosmology?

- Building the true model of inflation which should be hopefully verified by future CMB and/or GW observations
- We have to reveal the identity of the CDM
- Measuring neutrino masses with their hierarchy, and CP violation
- Building the true model of dark energy which will be verified by future observations
- Discriminating the true model of baryogenesis/leptogenesis from the others cosmologically
- From astronomy, can we again make a breakthrough in observations which causes a paradigm shift even in fundamental physics (such as DM, or DE)?

どんなアプローチが考えられるのか？
What kind of approaches?

Checking consistencies between observations and predictions in new physics (SUSY, GUT, superstring, modified gravity, etc.) by applying them to cosmology

- By new ideas, launching a new project to astronomically probe new physics such as Inflation (r, etc.), WIMP, axion, PBHs, neutrino mass/CP, dark energy, baryon-asymmetry, which must stimulate the Japanese astronomy communities

- We have to build several leaders who understand concepts of values in both astronomy and fundamental physics from a wide-ranging perspective in the communities

- Not for the project, but for the purpose to look for new physics