Probing dark matter and baryon asymmetry of the universe by SKA-like and LISA-like experiments

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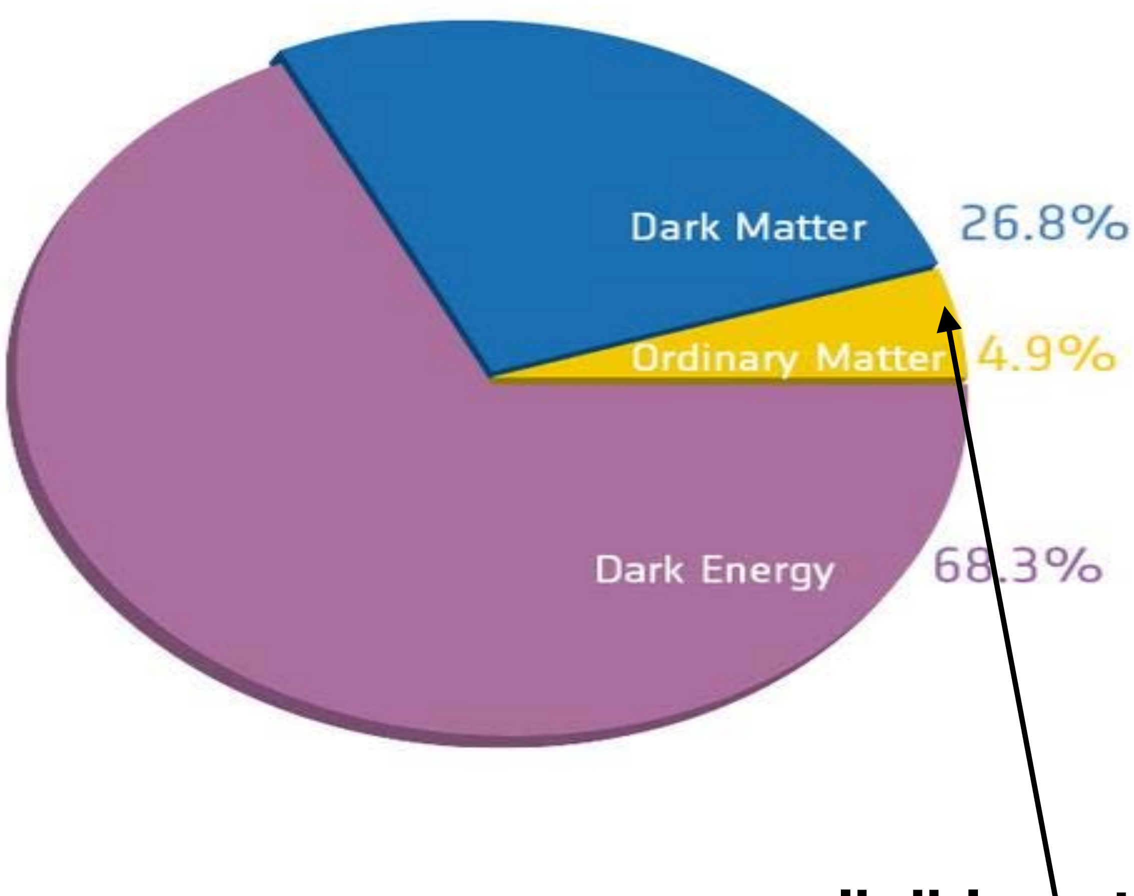
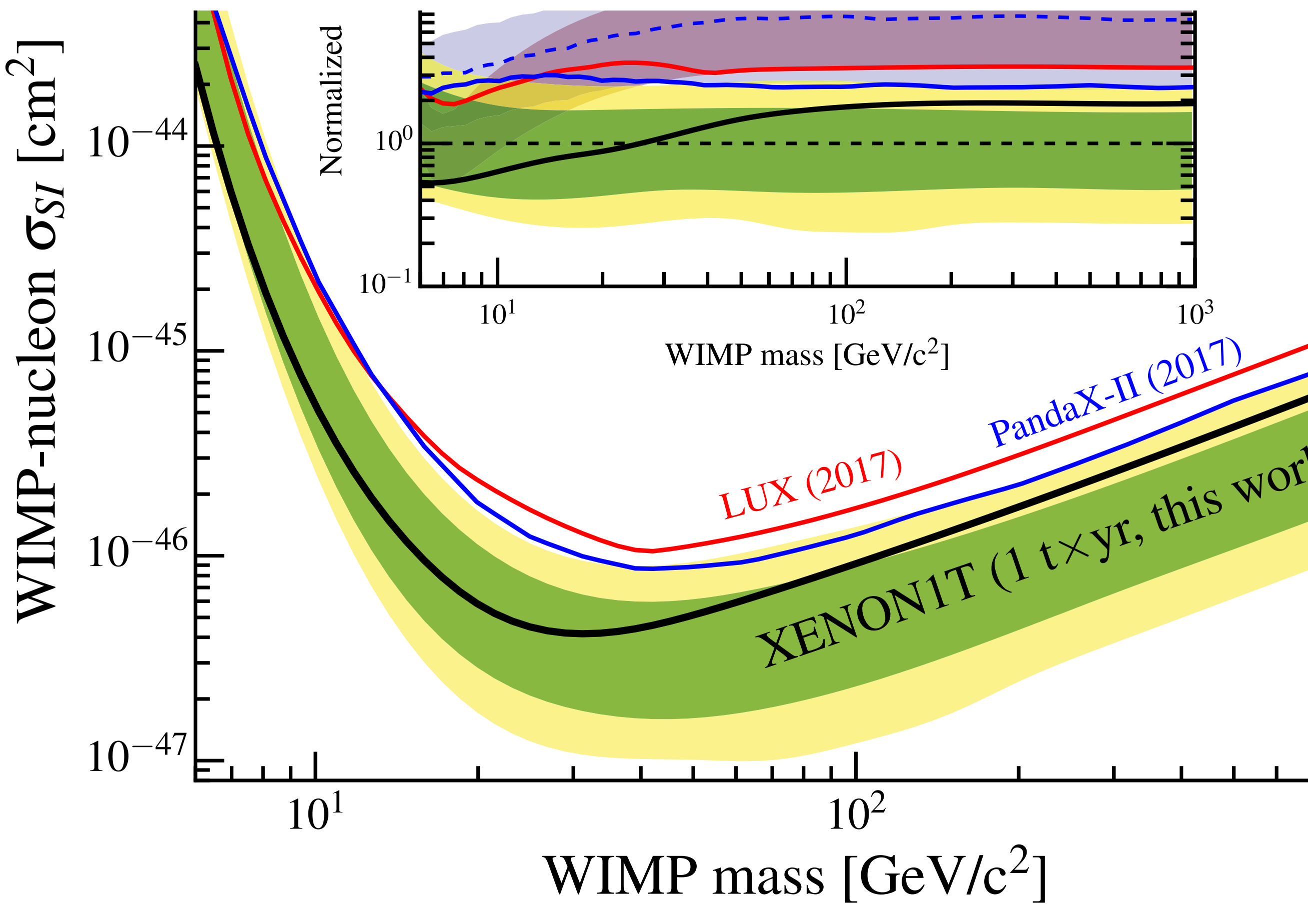
Motivation

Obvious shortcomings in our understanding of particle cosmology (such as the dark matter and the baryon asymmetry of the universe), and no evidence of new physics at LHC and DM direct search may just point us towards new approaches, especially
the Radio telescope experiments (SKA, FAST, GBT…) and
the Laser Interferometer experiments (LISA, Tianqin, Taiji…)



negligible antimatter,
baryon asymmetry of the universe

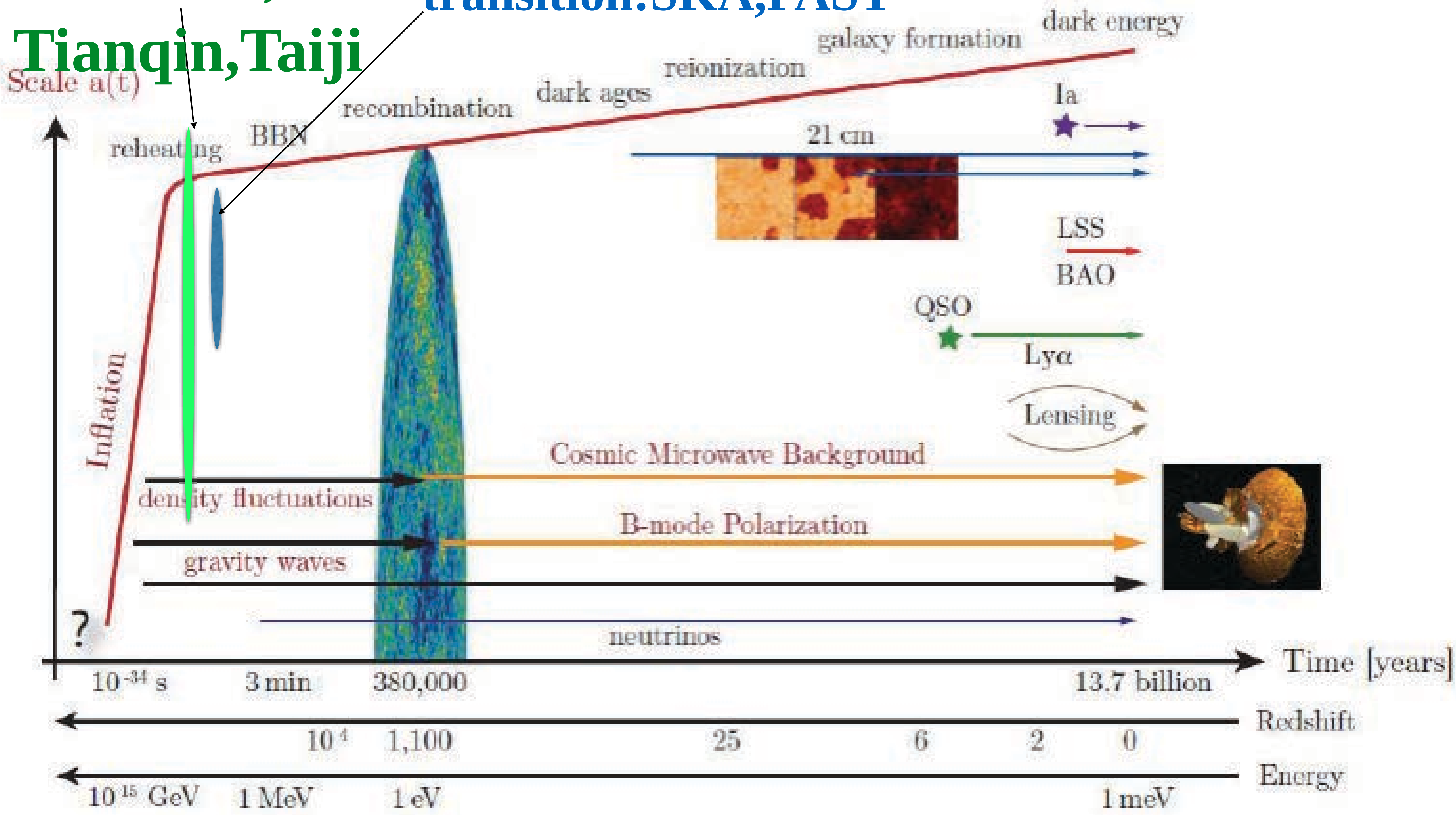


Phys.Rev.Lett. 121 (2018) no.11, 111302

Motivation

EW phase transition/ baryogenesis :LISA, Tianqin,Taiji

QCD phase and axion dark matter transition:SKA,FAST



The axion cold dark matter and strong-CP

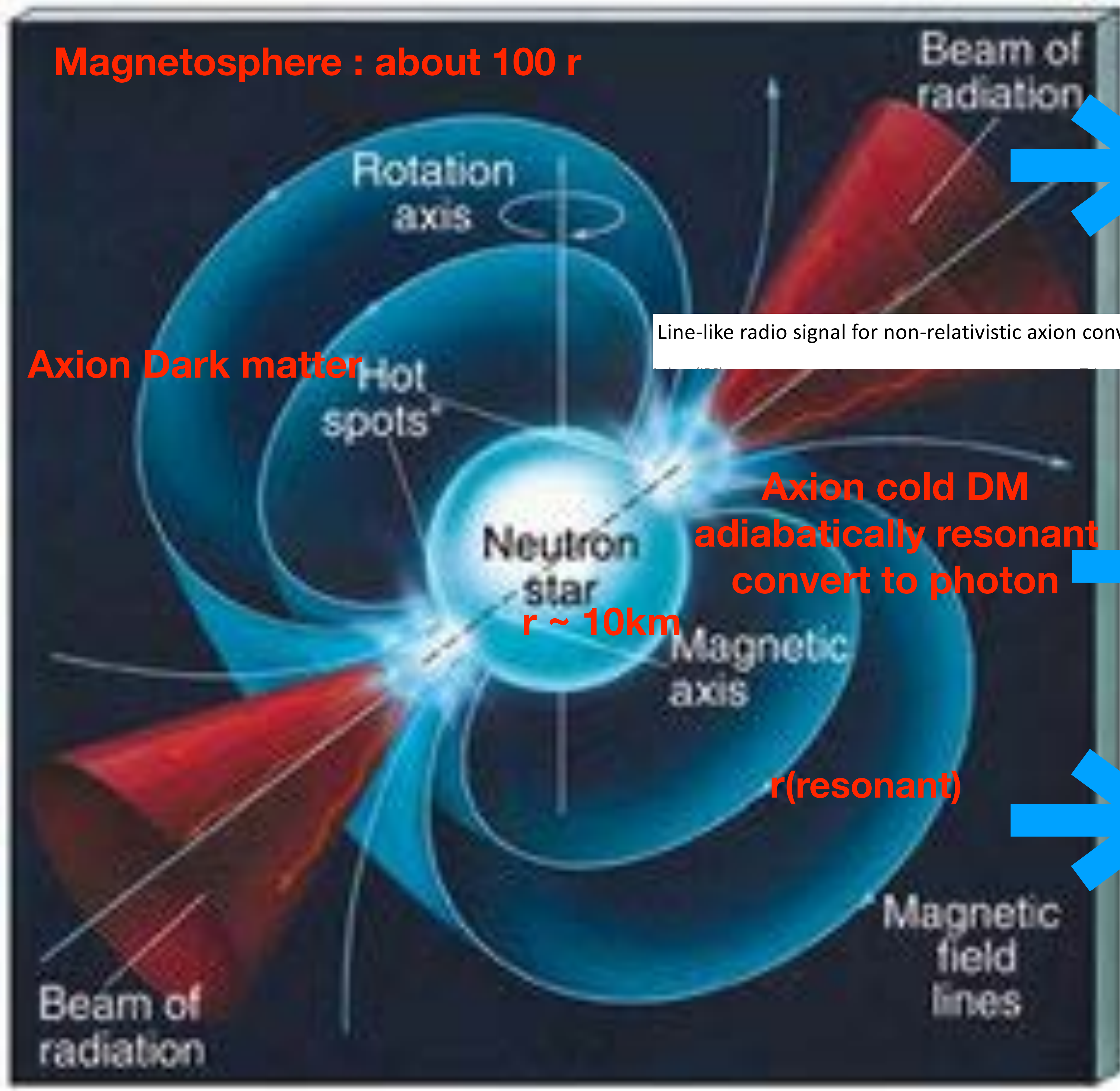
The two famous DM candidates which have pretty beautiful physics motivation

- **WIMP DM from SUSY:Unfortunately, DM search and collider experiments disfavor this candidate**
- **Axion or Axion-like DM from strong-CP problem or string-theory: still favored by current data, most promising DM candidate**

We firstly study using the SKA-like experiments to explore the resonant conversion of cold DM axions from magnetized astrophysical sources, such as neutron star, magnetar, pulsar.

FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001

Magnetosphere of Neutron star, pulsar or Magnetar



Line-like radio signal for non-relativistic axion conversion: $f \sim \frac{m_a}{2\pi} \sim 240 \left(\frac{m_a}{\mu eV}\right)$MHz

FAST

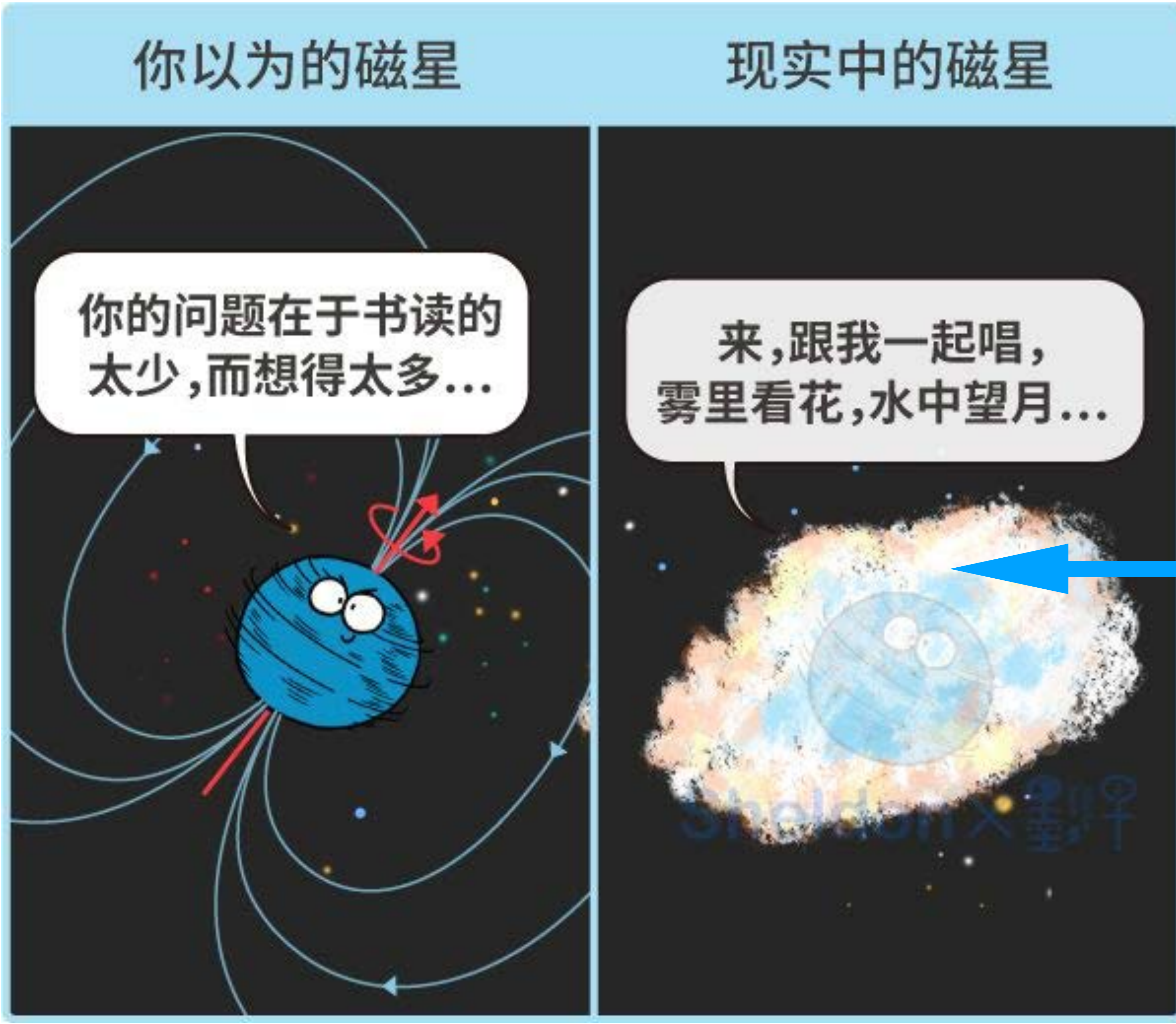
0.1–100 GHz

GBT

SKA

FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001

Neutron star, Pulsar,Magnetar: the strongest magnetic field



Magnetosphere

Credit: 量子沙龙

Axion-photon conversion in magnetosphere

The Lagrangian for axion-photon conversion the magnetosphere

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu a \partial^\mu a - m_a^2 a^2) + L_{\rm int} + L_{\rm QED}$$

Massive Photon in the magnetosphere of the neutron star obtains the effective mass in the magnetized plasma.

$$L_{\rm QED} = \frac{\alpha^2}{90 m_e^4}\frac{7}{4}(F_{\mu\nu}\tilde{F}^{\mu\nu})^2$$

$$Q_{\rm QED} = \frac{7\alpha}{45\pi}\omega^2\frac{B^2}{B_{\rm crit}^2}$$

$$m_\gamma^2 = Q_{\rm pl} - Q_{\rm QED}$$

$$Q_{\rm plasma} = \omega_{\rm plasma}^2 = 4\pi\alpha\frac{n_e}{m_e}$$

$$\frac{Q_{\rm pl}}{Q_{\rm QED}} \sim 5\times 10^8 \left(\frac{\mu{\rm eV}}{\omega}\right)^2 \frac{10^{12}\ {\rm G}}{B}\frac{1\ {\rm sec}}{P}$$

$$L_{\rm int} = \frac{1}{4}g\tilde{F}^{\mu\nu}F_{\mu\nu}a = -g\mathbf{E}\cdot\mathbf{B}a,$$

Axion-photon conversion in magnetosphere

The axion-photon conversion probability

$$p_{a\to\gamma} = \sin^2 2\tilde{\theta}(z)\sin^2[z(k_1 - k_2)/2]$$

$$\sin 2\tilde{\theta} = \frac{2gB\omega}{\sqrt{4g^2B^2\omega^2 + (m_\gamma^2 - m_a^2)^2}}$$

$$B(r) = B_0\left(\frac{r}{r_0}\right)^{-3} \qquad m_\gamma^2(r) = 4\pi\alpha\frac{n_e(r)}{m_e}$$

$$n_e(r) = n_e^{\mathrm{GJ}}(r) = 7\times 10^{-2}\,\frac{1s}{P}\,\frac{B(r)}{1\ \mathrm{G}}\,\frac{1}{\mathrm{cm}^3}$$

Here, we choose the simplest magnetic field configuration and electron density distribution to clearly see the underlying physics.

The Adiabatic Resonant Conversion

The resonance radius is defined at the level crossing point

$$m_\gamma^2(r_{\rm res}) = m_a^2$$

At the resonance, $|m_\gamma^2 - m_a^2| \ll gB\omega$ and $m_{1,2}^2 \approx m_a^2 \pm gB\omega$.

Near the resonance region, the axion-photon conversion is greatly enhanced due to large mixing angle.

$$\sin 2\tilde{\theta} = \frac{(2gB\omega/m_\gamma^2)}{\sqrt{(4g^2B^2\omega^2/m_\gamma^4) + (1-(m_a/m_\gamma)^2)^2}}$$

$$\equiv \frac{c_1}{\sqrt{c_1^2 + (1-f(r))^2}},$$

The adiabatic resonant conversion requires that the region in which the resonance is approximately valid inside the resonance width.

$$\delta r > l_{\rm osc}$$

$$|d\ln f/dr|_{\rm res}^{-1} > 650[m]\left(\frac{m_a}{\mu{\rm eV}}\right)^3\left(\frac{v_{\rm res}}{10^{-1}}\right)\left(\frac{1/10^{10}\ {\rm GeV}}{g}\right)^2$$

$$\times\left(\frac{10^{12}\ {\rm G}}{B(r_{\rm res})}\right)^2\left(\frac{\mu{\rm eV}}{\omega}\right)^2$$

$$l_{\rm osc} = \frac{2\pi}{|k_1 - k_2|_{\rm res}}$$

$$|d\tilde{\theta}/dr|_{\rm res} < l_{\rm osc}^{-1}$$

The Photon flux search by the radio

Signal: For adiabatic resonant conversion, and the photon flux density can be estimated to be of order

$$S_\gamma = \frac{dE/dt}{4\pi d^2 \Delta\nu} \sim 4.2\mu Jy \frac{\left(\frac{r_{\rm res}}{100\ {\rm km}}\right)\left(\frac{M}{M_{\rm sun}}\right)\left(\frac{\rho_a}{0.3\ {\rm GeV/cm^3}}\right)\left(\frac{10^{-3}}{v_0}\right)\left(\frac{g}{1/10^{10}\ {\rm GeV}}\right)\left(\frac{B(r_{\rm res})}{10^{12}\ {\rm G}}\right)\left(\frac{\omega}{\mu{\rm eV}}\right)\left(\frac{\mu{\rm eV}}{m_a}\right)^2}{\left(\frac{d}{1\ {\rm kpc}}\right)^2\left(\frac{m_a/2\pi}{\mu{\rm eV}/2\pi}\right)\left(\frac{v_{\rm dis}}{10^{-3}}\right)},$$

where d represents the distance from the neutron star to us. The photon flux peaks around the frequency $\nu_{\rm peak} \sim m_a/2\pi$, and $\Delta\nu \sim \nu_{\rm peak} v_{\rm dis}$ represents the spectral line broadening around this peak frequency due to the DM velocity dispersion $v_{\rm dis}$.

Sensitivity: The smallest detectable flux density of the radio telescope (SKA, FAST, GBT) is of order

$$S_{\rm min} \approx 0.29\mu Jy \left(\frac{1\ {\rm GHz}}{\Delta B}\right)^{1/2}\left(\frac{24\ {\rm hrs}}{t_{\rm obs}}\right)^{1/2}\left(\frac{10^3\ {\rm m^2/K}}{A_{\rm eff}/T_{\rm sys}}\right)$$

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The FAST (Five Hundred Meter Aperture Spherical Radio Telescope) covers 70 MHz–3 GHz, the SKA (Square Kilometre Array) covers 50 MHz–14 GHz, and the GBT (Green Bank Telescope) covers 0.3–100 GHz, so that the radio telescopes can probe axion mass range of 0.2–400 μeV

The Photon flux search by the radio

Signal: For a trial parameter set, $B_0 = 10^{15}$ G, $m_a = 50\ \mu$eV

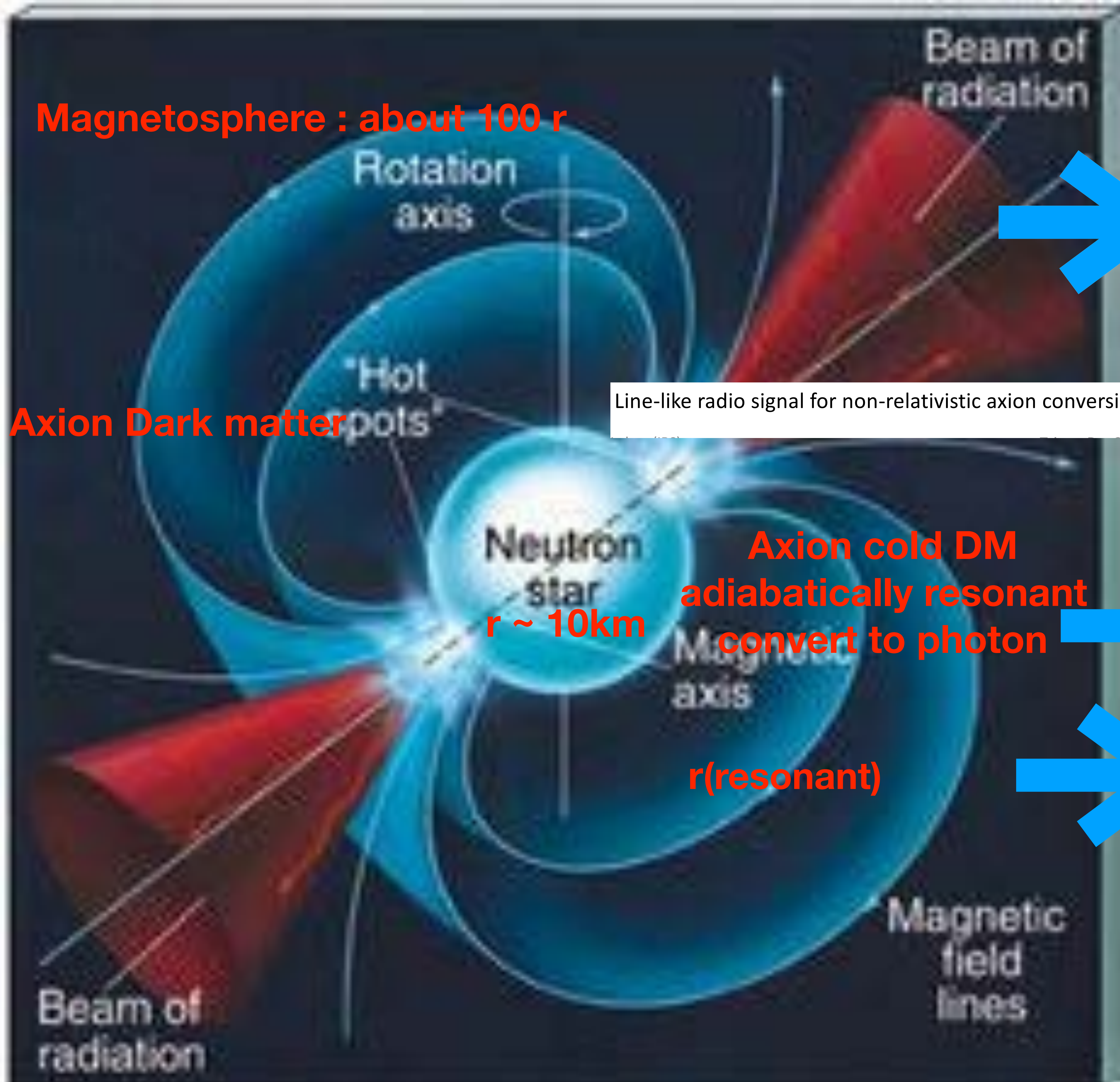
$P = 10$ s, $g = 5 \times 10^{-11}$ GeV^{-1}, $r_0 = 10$ km, $M = 1.5 M_{sun}$

satisfies the conditions for the adiabatic resonance conditions with S_γ~0.51 μJy.

Sensitivity: $S_{\min} \sim 0.48 \mu Jy$ for the SKA1

$S_{\min} \sim 0.016 Jy$ for the SKA2 with 100 hour observation

There are more and more detailed study including the magnetic profile of the neutron star, the dark matter density around the neutron star, the location of the neutron star…
More and more following work…



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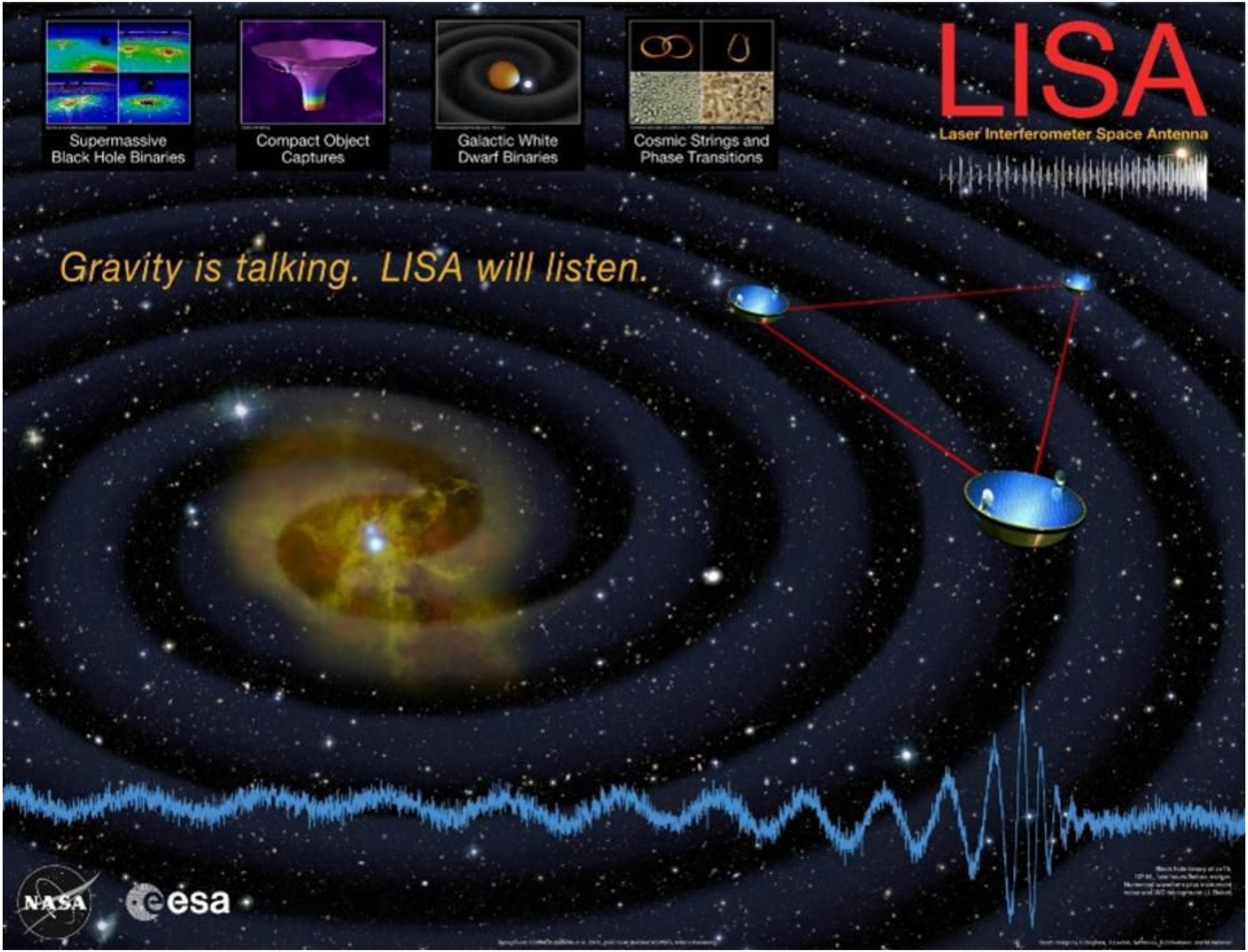
FPH, K. Kadota, T. Sekiguchi, H. Tashiro, Phys.Rev. D97 (2018) no.12, 123001,
There are more and more detailed study on this new approach.


Supermassive Black Hole Binaries
Compact Object Captures
Galactic White Dwarf Binaries
Cosmic Strings and Phase Transitions
LISA
Laser Interferometer Space Antenna
Gravity is talking. LISA will listen.
NASA
esa

Powerful LISA experiments

- ➢**The true shape of Higgs potential (Exp: complementary check with CEPC)**
- ➢ Baryon **asymmetry of the universe (baryogenesis)**
- ➢**Gravitational wave (Exp:LISA 2034)**
- ➢**Dark Matter blind spots** **Phys.Rev. D98 (2018) no.9, 095022, FPH,Jianghao Yu**
- ➢ **Asymmetry dark matter**

(The cosmic phase transition with Q-balls production mechanism can explain the baryogenesis and DM simultaneously, where constraints on DM masses and reverse dilution are significantly relaxed.
FPH, Chong Sheng Li, Phys.Rev. D96 (2017) no.9, 095028)

LISA in synergy with CEPC helps to explore the evolution history of the universe at several hundred GeV temperature, dark matter and baryogenesis.

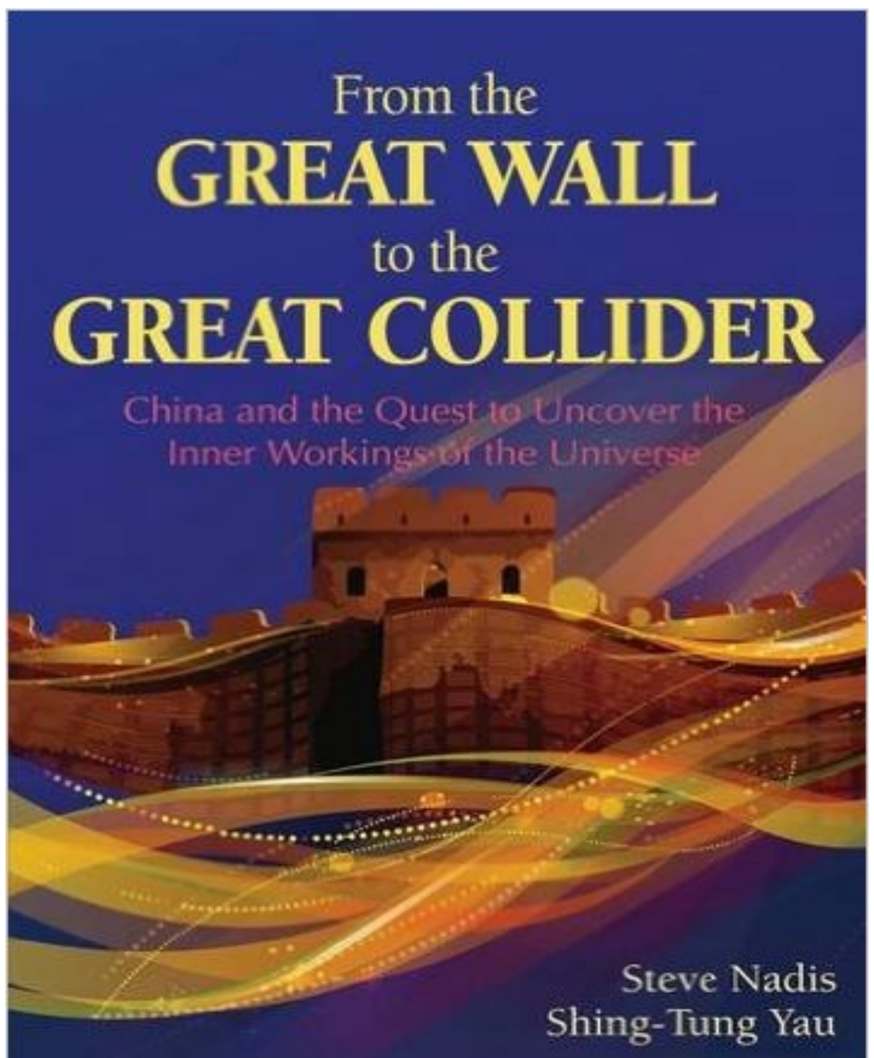
Current particle collider has no ability to unravel the true potential of the Higgs boson, we need new experiments.

Particle approach

we can build more powerful colliders, such as planned

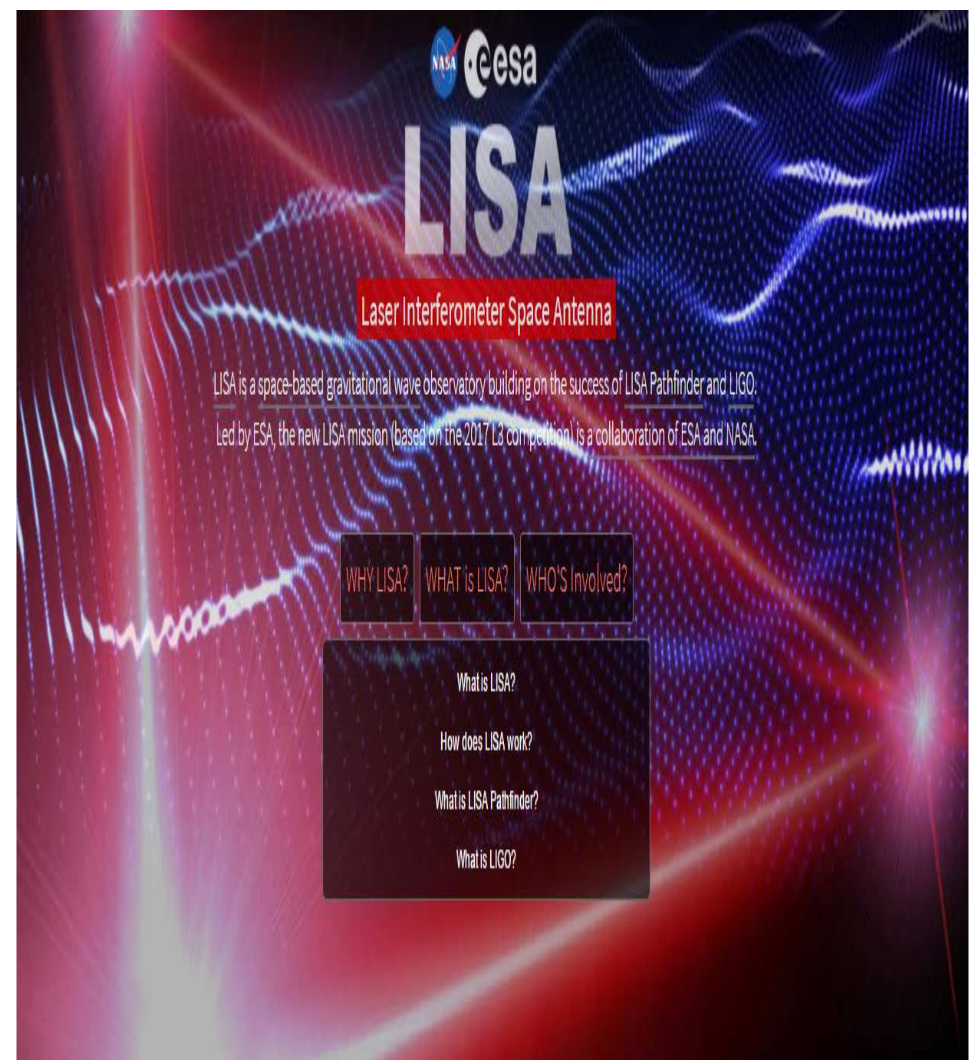
Wave approach

GW detectors can test Higgs potential as complementary approach. (LISA launch 2034)

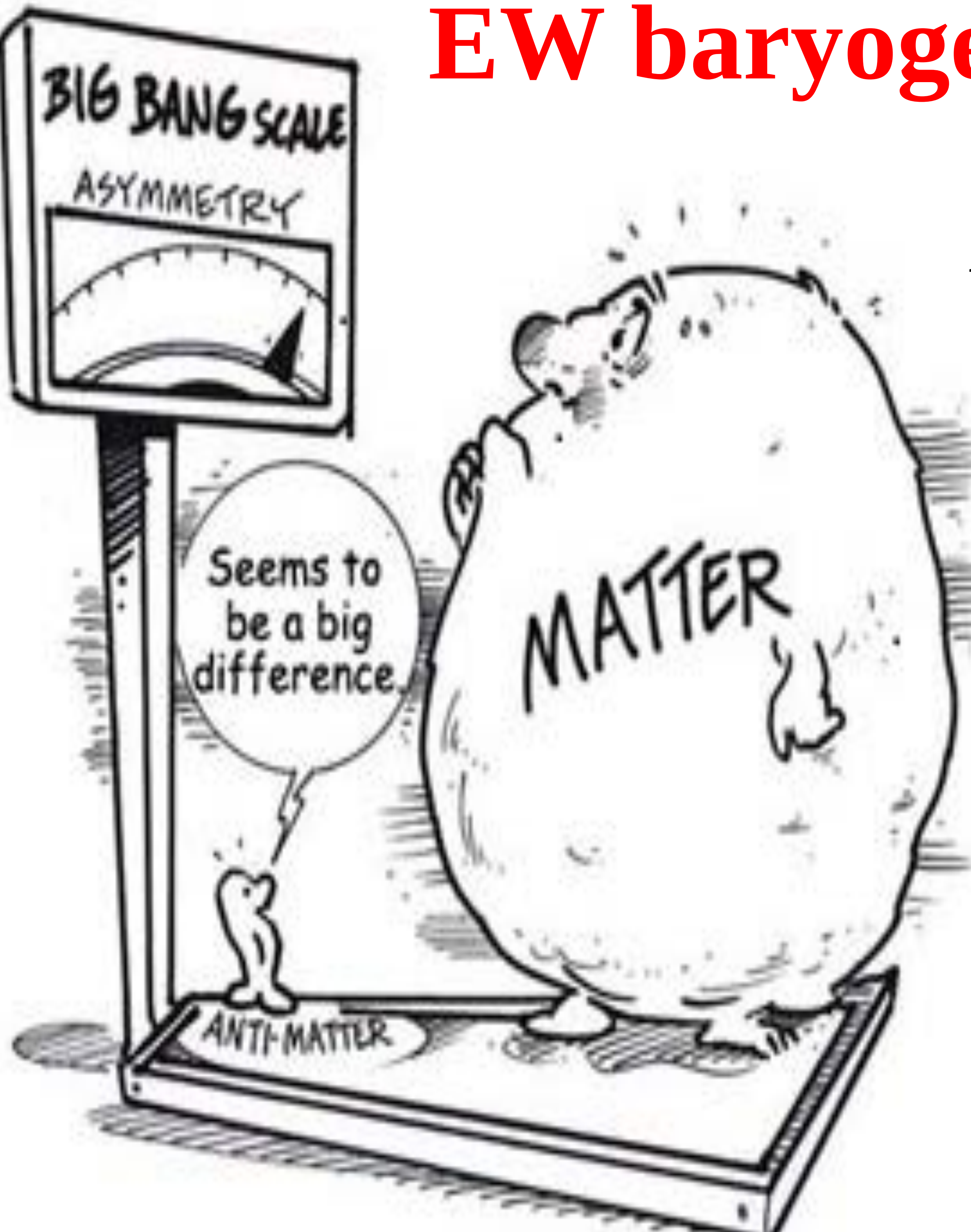


Relate by EW phase transition/ baryogenesis

Double test on the Higgs potential and baryogenesis



EW baryogenesis in a nutshell



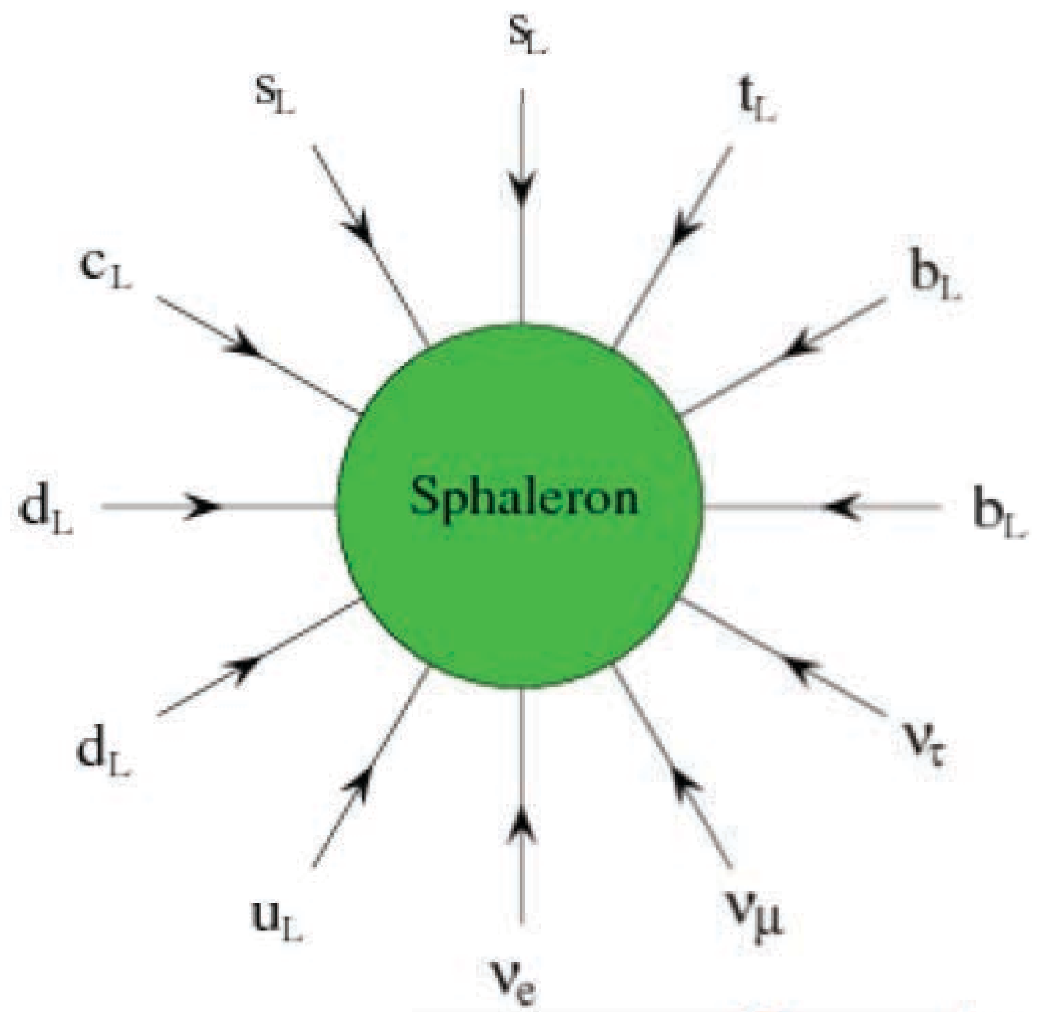
A long standing problem in particle cosmology is the origin of baryon asymmetry of the universe (BAU).

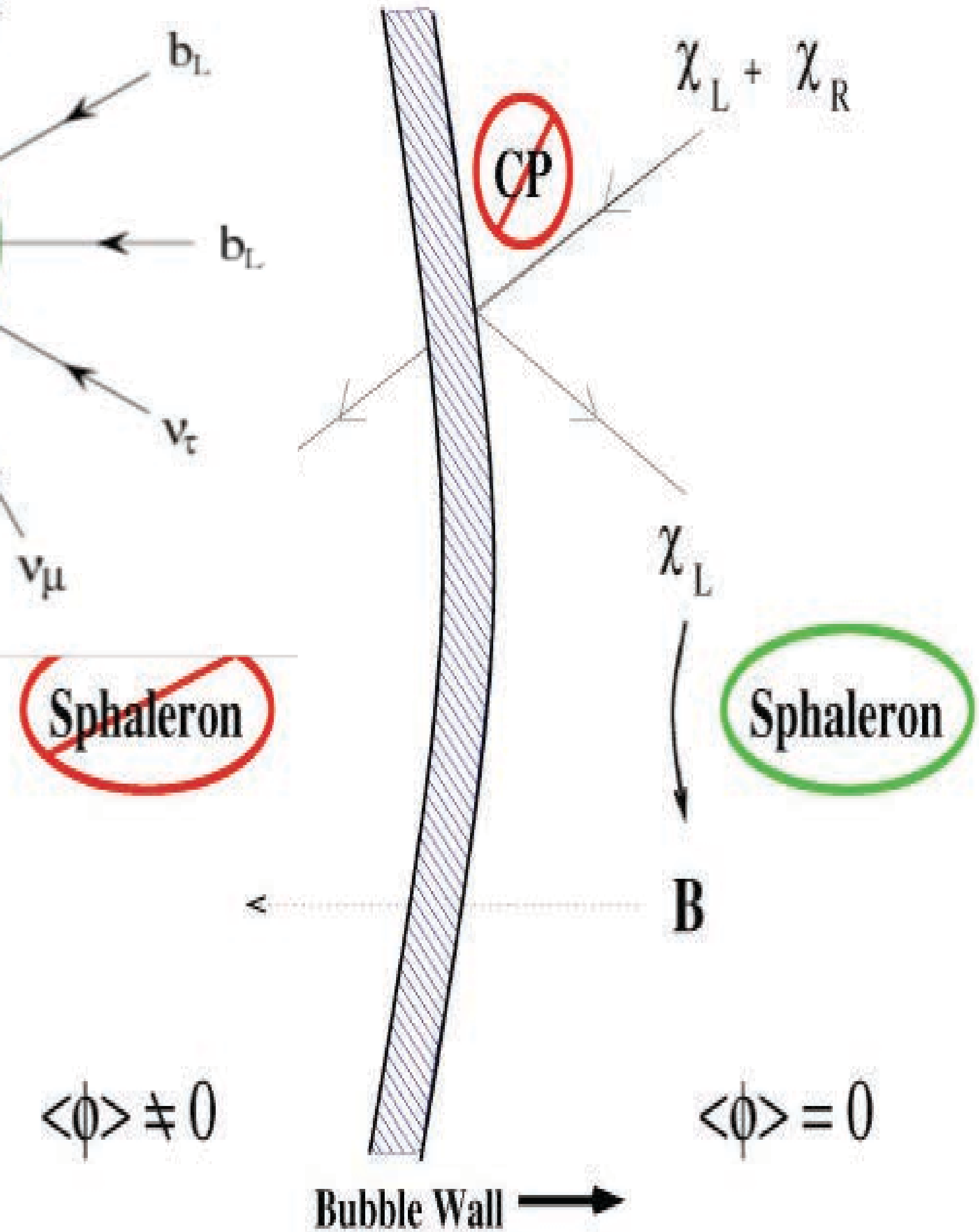
After the discovery of the Higgs boson by LHC and gravitational waves (GW) by aLIGO, EW baryogenesis becomes a timely and testable scenario for explaining the BAU.

$$\eta_B = n_B/n_\gamma = 5.8 - 6.6 \times 10^{-10} \quad \text{(CMB, BBN)}$$

EW baryogenesis:

SM technically has all the three elements for baryogenesis , (Baryon violation, C and CP violation, Departure from thermal equilibrium or CPT violation) but not enough.

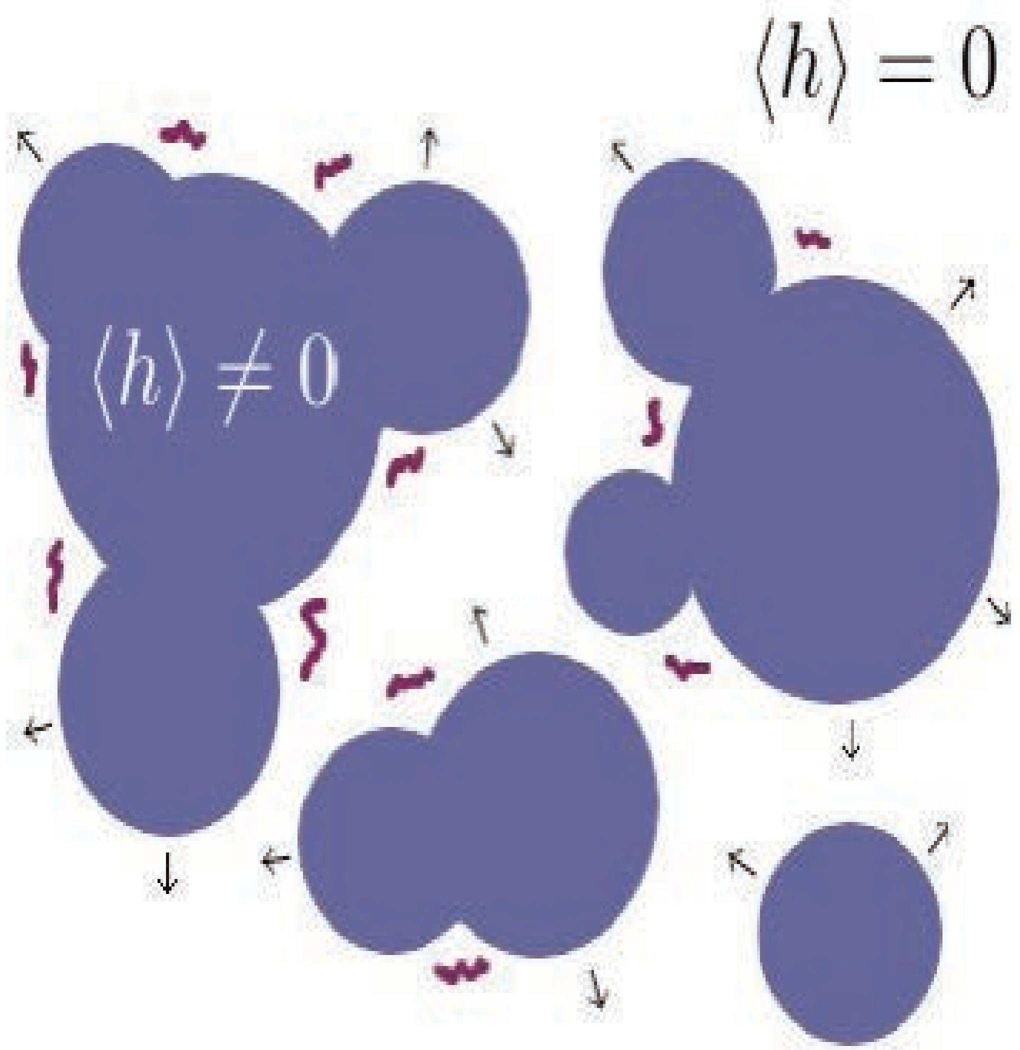




- **B violation from anomaly in B+L current.**
- **CKM matrix, but too weak.**
- **strong first-order phase transition (SFOPT) with expanding Higgs Bubble wall.**

D. E. Morrissey and M. J. Ramsey-Musolf, New J. Phys. 14, 125003 (2012).

phase transition GW in a nutshell



Strong First-order phase transition (FOPT) can drive the plasma of the early universe out of thermal equilibrium, and bubbles nucleate during it, which will produce GW.

E. Witten, Phys. Rev. D 30, 272 (1984)
C. J. Hogan, Phys. Lett. B 133, 172 (1983); M. Kamionkowski, A. Kosowsky and M. S. Turner, Phys. Rev. D 49, 2837 (1994))

EW phase transition GW becomes more interesting and realistic after the discovery of Higgs by LHC and GW by LIGO.

Mechanisms of GW during phase transition

- Bubble collision: **well-known source from 1983**

- **Turbulence in the plasma fluid**: **a fraction of the bubble wall energy converted into turbulence.**

- Sound wave in the plasma fluid: **after the collision a fraction of bubble wall energy converted into motion of the fluid (and is only later dissipated).**
  New mechanism of GW：**sound wave**
  Mark Hindmarsh, *et al*., PRL 112, 041301 (2014);

Sufficient CP-violation for baryogenesis v.s. electric dipole moment (EDM) measurement

Current EDM data put severe constraints on many baryogenesis models. For example, the ACME Collaboration's new result, i.e. $|d_e| < 1.1\times 10^{-29}$ cm $\cdot$ e at 90% C.L. (Nature vol.562,357,18th Oct.2018) , has ruled out a large portion of the CP violation parameter space for many baryogenesis models.

$$|d_e| < 8.7 \times 10^{-29}\ \mathrm{cm}\cdot\mathrm{e}$$ **(ACME 2014)**

$$|d_e| \sim< 1 \times 10^{-29}$$ **(ACME 2018)**

Large enough CP-violating source for successful EW baryogenesis

Strong tension in most cases

pretty small CP-violation to avoid strong EDM constraints

How to alleviate this tension for successful baryogenesis?

Question: How to *alleviate* the tension between sufficient CP violatio for successful electroweak baryogenesis and strong constraints from current electric dipole moment measurements ?

Answer: Assume the CP violating coupling evolves with the universe. In the early universe, CP violation is large enough for successful baryogenesis. When the universe evolves to today, the CP violation becomes negligible !

Large enough CP-violating source in the early universe for successful EW baryogenesis

***alleviate* by assuming the CP-violating source is time dependent**

Dynamical/cosmological evolve

Negligible CP-violating source at current time to avoid strong EDM constraints

- I. Baldes, T. Konstandin and G. Servant, arXiv:1604.04526,
- I. Baldes, T. Konstandin and G. Servant, JHEP 1612, 073 (2016)
- S. Bruggisser, T. Konstandin and G. Servant, JCAP 1711, no. 11, 034 (2017)

First, we study the following case as a representative example:

Phys.Rev. D98 (2018) no.1, 015014
(**FPH**, Zhuoni Qian, Mengchao Zhang)

$$\mathcal{L}_{\rm SM} - y_t \frac{\eta}{\Lambda} S \bar{Q}_L \tilde{\Phi} t_R + {\rm H.c} + \frac{1}{2}\partial_\mu {\rm S} \partial^\mu {\rm S} + \frac{1}{2}\mu^2 {\rm S}^2 - \frac{1}{4}\lambda {\rm S}^4 - \frac{1}{2}\kappa {\rm S}^2 (\Phi^\dagger \Phi)$$

$$\eta = a + ib$$

The singlet and the dim-5 operator can come from many types composite Higgs models arXiv:0902.1483 , arXiv:1703.10624 ,arXiv:1704.08911,

Firstly, a second-order phase transition happens, the scalar field S acquire a vacuum exception value (VEV) and the dim-5 operator generates a sizable CP-violating Yukawa coupling for successful baryogenesis.

Secondly, SFOPT occurs when vacuum transits from (0,<S>) to (<Φ>,0).

1. During the SFOPT, detectable GW can be produced.

2. After the SFOPT, the VEV of S vanishes at tree-level which avoids the strong EDM constraints, and produces abundant collider phenomenology at the LHC and future lepton colliders, such as CEPC, ILC, FCC-ee.

J. M. Cline and K. Kainulainen, JCAP **1301**, 012 (2013)

J. R. Espinosa, B. Gripaios, T. Konstandin and F. Riva, JCAP **1201**, 012 (2012)

- I. Baldes, T. Konstandin and G. Servant, arXiv:1604.04526,
- I. Baldes, T. Konstandin and G. Servant, JHEP 1612, 073 (2016)
- S. Bruggisser, T. Konstandin and G. Servant, JCAP 1711, no. 11, 034 (2017)
- S. Bruggisser, B. Von Harling, O. Matsedonskyi and G. Servant, arXiv:1803.08546

Benchmark points, which can give SFOPT and produce phase transition GW

Benchmark set	κ	m_S [GeV]	T_N [GeV]	α	$\tilde{\beta}$
I	2.00	115	106.6	0.035	107
II	2.00	135	113.6	0.04	120

After the first step of phase transition, S field obtains a VEV, and then the CP violating top quark Yukawa coupling is obtained.

Thus, during the SFOPT, the top quark has a spatially varying complex mass $m_t(z) = \frac{y_t}{\sqrt{2}} H(z) \left(1 + (1+i)\frac{S(z)}{\Lambda}\right) \equiv |m_t(z)| e^{i\Theta(z)}$

$$\eta_B = \frac{405\Gamma_{\rm sph}}{4\pi^2 \tilde{v}_b g_* T} \int dz \, \mu_{B_L} f_{\rm sph} \, e^{-45\,\Gamma_{\rm sph}|z|/(4\tilde{v}_b)}$$

We choose reasonably small relative velocity $\tilde{v}_b$~ 0.2, which is favored by the EW baryogenesis to guarantee a sufficient diffusion process in front of the bubble wall, and large enough bubble wall velocity $v_b \sim 0.5$ to produce stronger phase transition GW (Roughly speaking, for deflagration case, a larger bubble wall velocity v_b gives stronger GW)

$$\tilde{v}_b(0.2) < v_b(0.5) < c_s(\sqrt{3}/3)$$

- J. M. No, Phys. Rev. D 84, 124025 (2011)

From the roughly numerical estimation, we see that the observed BAU can be obtained as long as $\Delta\sigma/\Lambda \sim 0.1 - 0.3$, where $\Delta\sigma$ is the change of σ during the phase transition

Particle phenomenology induced by CP-violating top loop

After the SM Higgs obtains a VEV v at the end of the phase transition, we have

$$\mathcal{L}_{Stt} = -\left(\frac{m_t}{\Lambda} + \frac{m_t H}{\Lambda v}\right) S \left(a\bar{t}t + ib\bar{t}\gamma_5 t\right)$$

The one-loop effective operators can be induced by covariant derivative expansion method

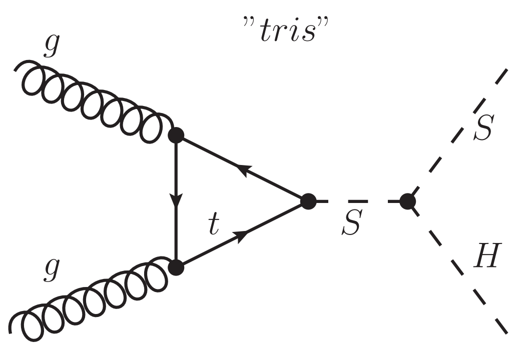
$$\begin{aligned}\mathcal{L}'_{SVV} &= \frac{a\alpha_S}{12\pi\Lambda} S G^a_{\mu\nu} G^{a\mu\nu} - \frac{b\alpha_S}{8\pi\Lambda} S G^a_{\mu\nu} \tilde{G}^{a\mu\nu} \\ &+ \frac{2a\alpha_{EW}}{9\pi\Lambda} S F_{\mu\nu} F^{\mu\nu} - \frac{b\alpha_{EW}}{3\pi\Lambda} S F_{\mu\nu} \tilde{F}^{\mu\nu}\end{aligned}$$

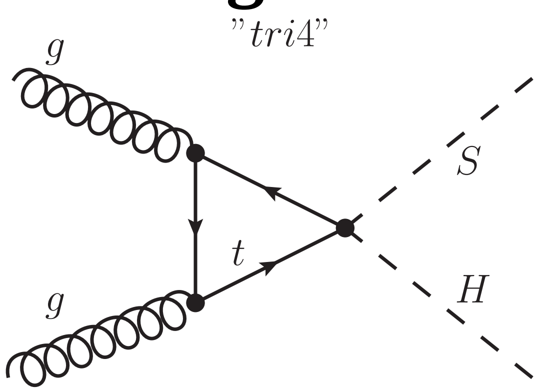
Mixing for H and S from one-loop contribution

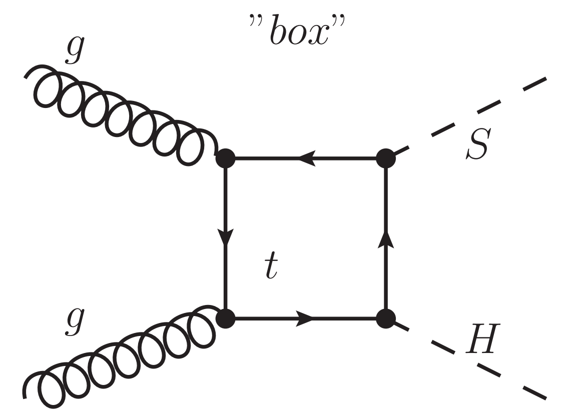
Abundant collider signals

Hadron collider:

$$pp \to HS$$



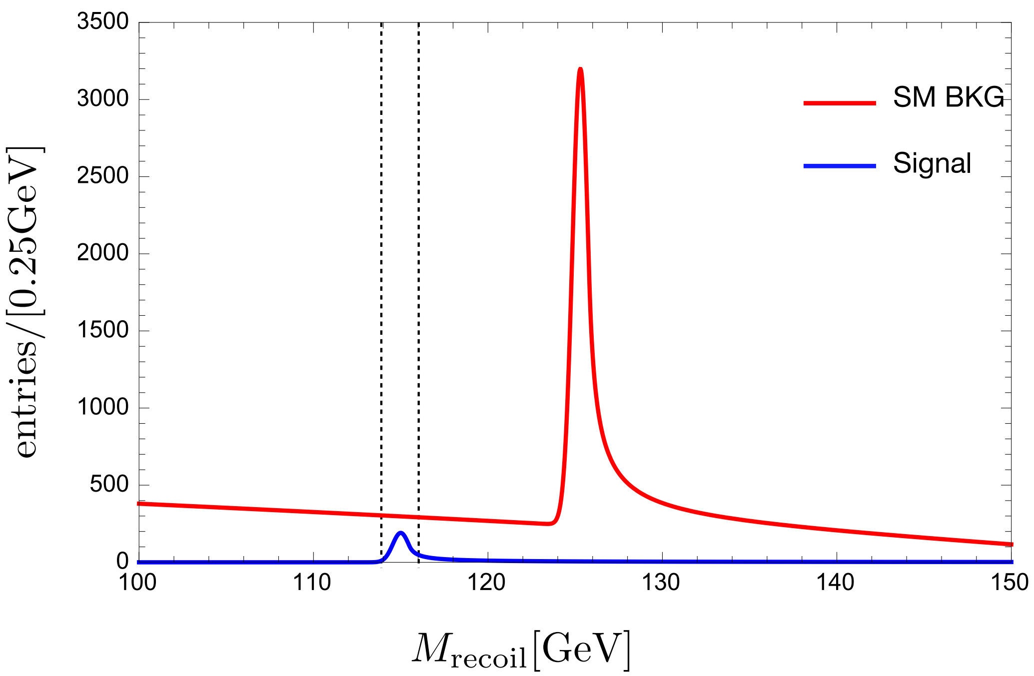


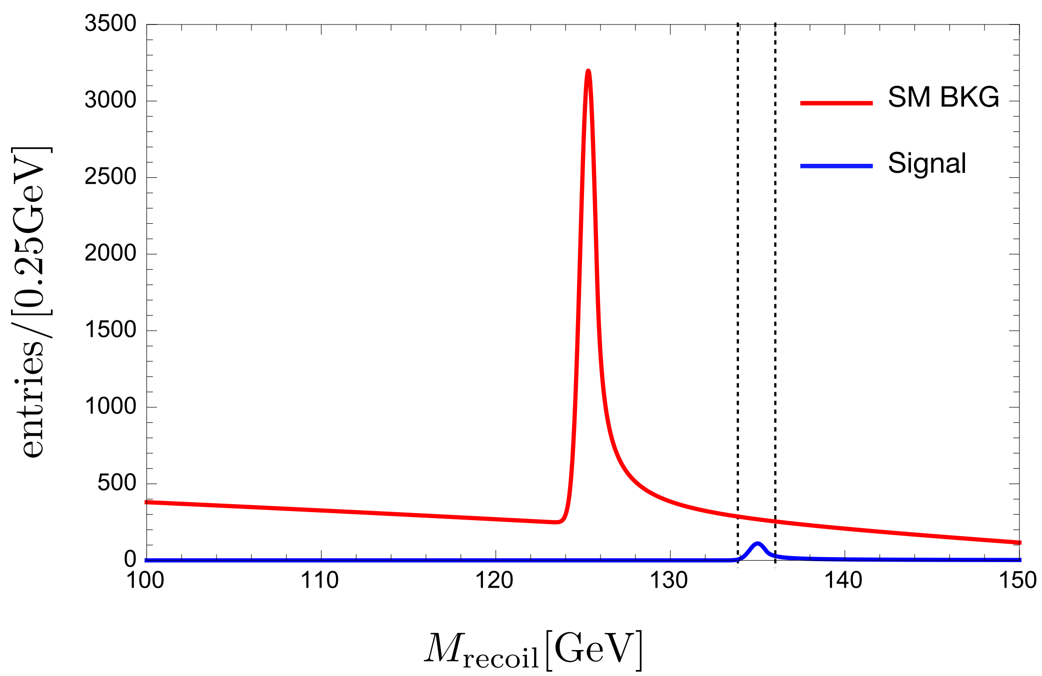


Lepton collider (CEPC for example):

1.Direct search: ZS production recoiled muon pair mass distribution:

$$\sigma(e^+e^- \to ZS) = \frac{G_F^2 m_Z^4}{96\pi s}(v_e^2 + a_e^2)|\mathcal{O}_{12}|^2 \sqrt{\tilde{\lambda}}\, \frac{\tilde{\lambda} + 12m_Z^2/s}{(1-m_Z^2/s)^2}$$

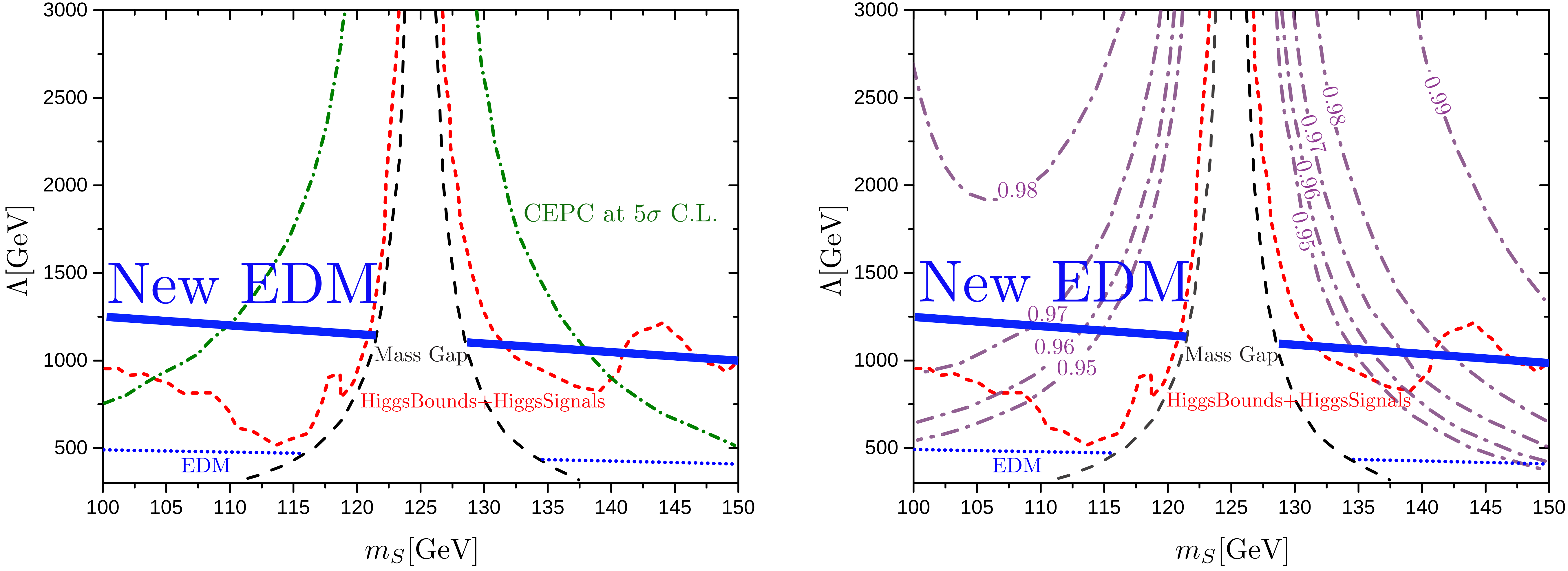




2.Indirect search: ZH cross section deviation from mixing and field strength renormalization:

$$\mathcal{Z} = 1 + \frac{\kappa^2 v^2}{32\pi^2 m_H^2}\left(1 - \frac{4m_S^2}{m_H^2}\frac{1}{\sqrt{\frac{4m_S^2}{m_H^2}-1}}\arctan\frac{1}{\sqrt{\frac{4m_S^2}{m_H^2}-1}}\right)$$

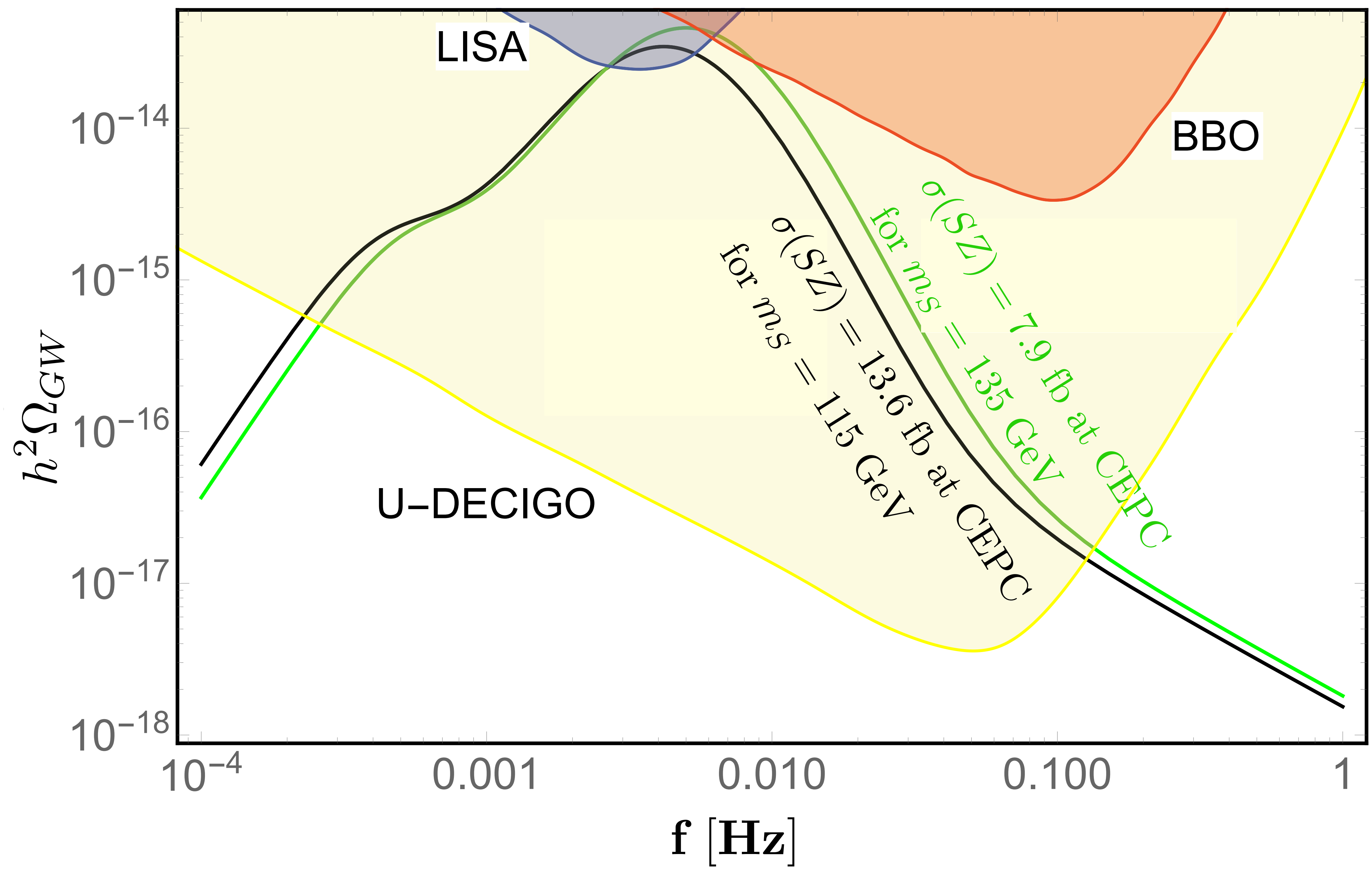
So $\sigma(e^+e^- \to HZ)$ will be rescaled by a factor $|\mathcal{O}_{22}|^2\mathcal{Z}$



Current exclusion limit and future search sensitivity projected on Λ versus ms plane.The regions below dotted blue lines have been excluded by EDM measurement; regions below dashed red lines have been excluded by collider scalar searches and Higgs data. In the left plot, regions below dash dotted olive lines can be observed from ZS production at 5 ab^{-1} CEPC with a C.L. higher than 5σ. In the right plot, we show the ratio of ZH cross section with purple dash dotted contour lines.

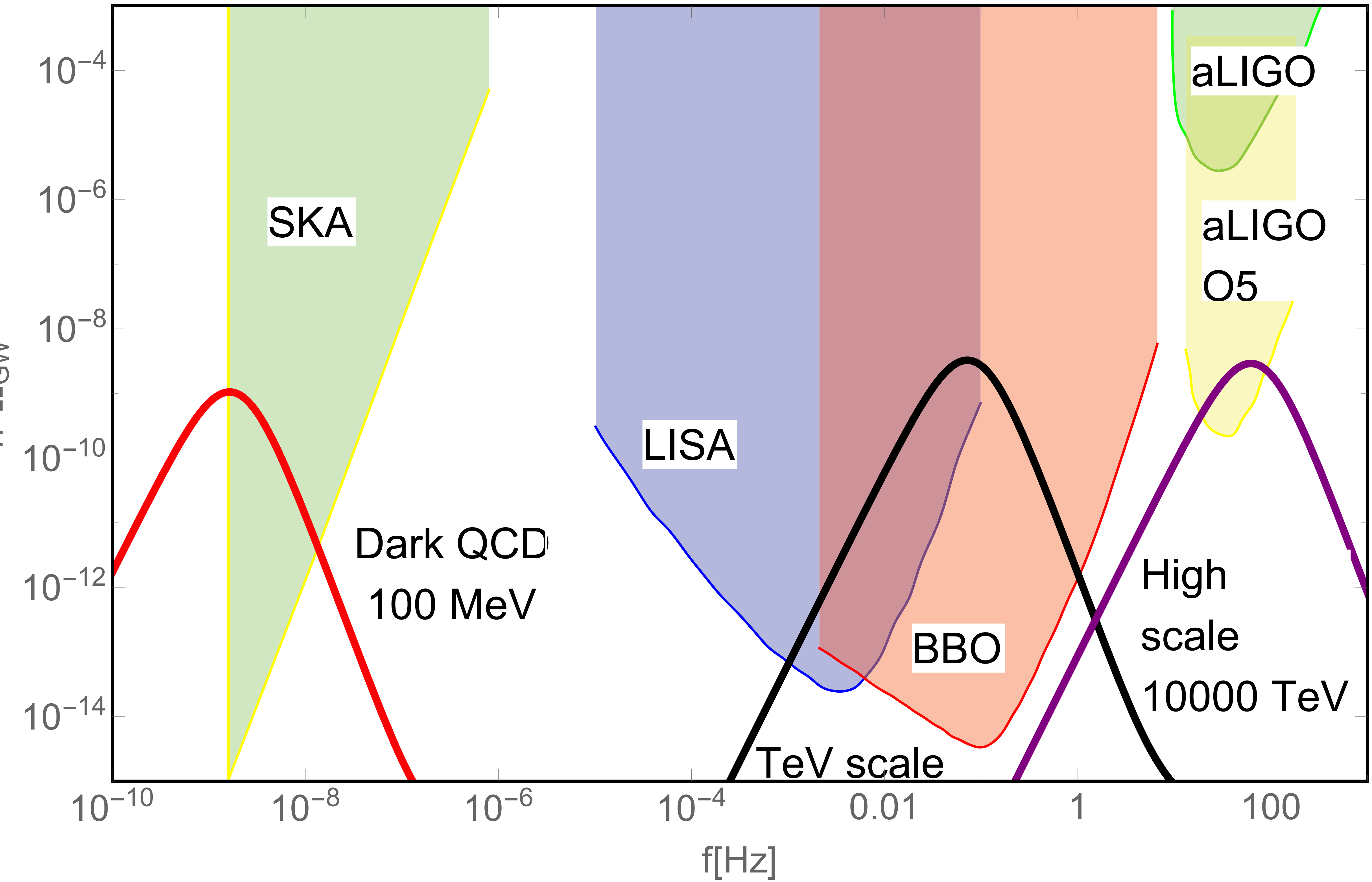
N.B. Limit from EDM is much weaker than Higgs data, due to the fact the contributions to EDM in this scenario come from three-loop contributions

The correlation between the future GW and collider signals



For example taking benchmark set I, the GW spectrum is represented by the black line, which can be detected by LISA and U-DECIGO. The black line also corresponds to $0.9339\sigma_{SM}(HZ)$ of the HZ cross section for $e^+e^- \to HZ$ process and 115 GeV recoil mass with 13.6 fb cross section for the $e^+e^- \to SZ$ process, which has a 5σ discovery potential with 5 ab^{-1} luminosity at CEPC.

More general



Schematic phase transition GW spectra

FPH, Xinmin Zhang, Physics Letters B 788 (2019) 288-294

Conclusion

The SKA-like and LISA-like experiments (more and more experiments, SKA, FAST,GBT, aLIGO, LISA, Tianqin, Taij) can provide new approaches to explore the nature of dark matter and baryon asymmetry of the universe.

Thanks for your attention!

Comments and collaborations are welcome!