

Probing WIMPs in space-based gravitational
wave experiments
空间引力波实验搜寻WIMP暗物质

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With: Cheng-Wei Chiang and Da Huang

Based on: JCAP 01, 035 (2021); PLB 833,137308 (2022);
PRD 106, 055019 (2022)

Outline

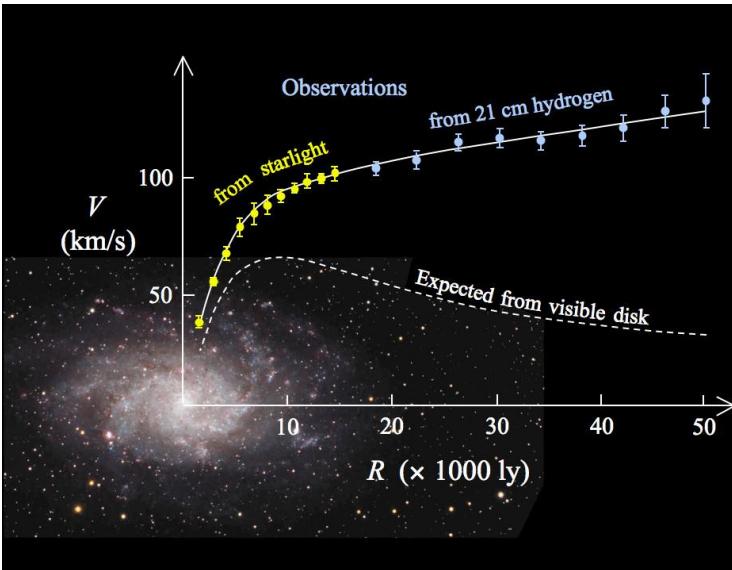
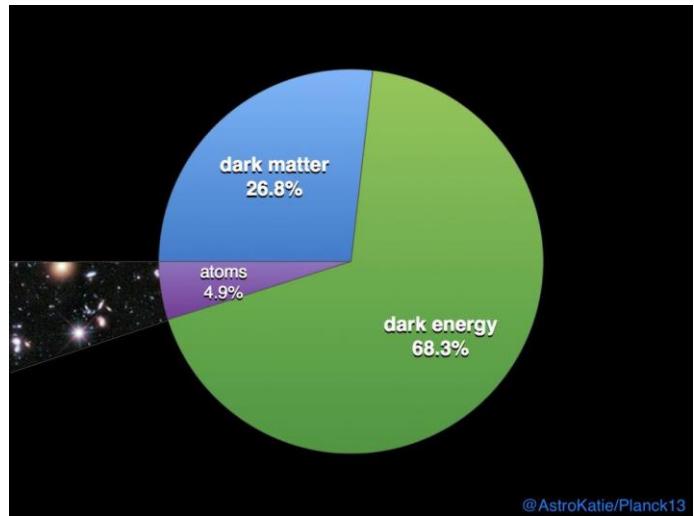
- Observations
- WIMP dark matter
- Dark matter detections
- Cosmological electroweak phase transition
- Space-based gravitational wave detection
- Summary



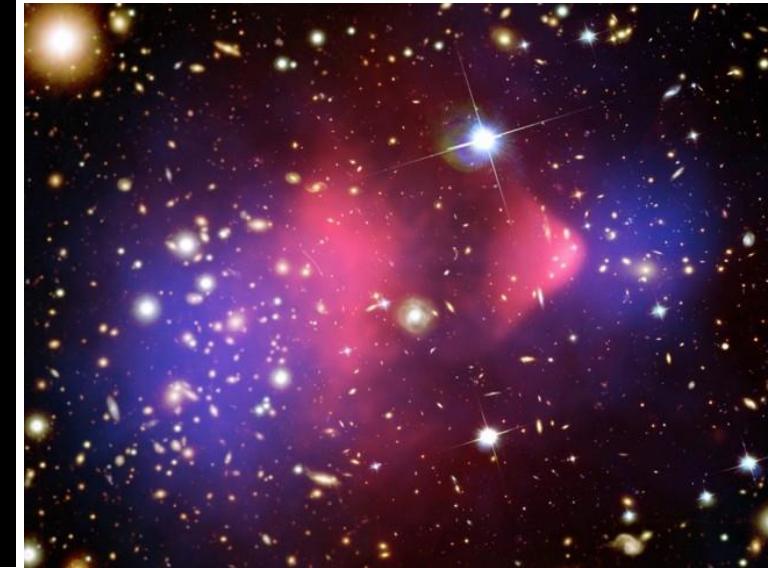
暗物质及其观测证据



1. 星系恒星旋转曲线
2. 宇宙微波背景辐射
3. 引力透镜
4. 宇宙大尺度结构…



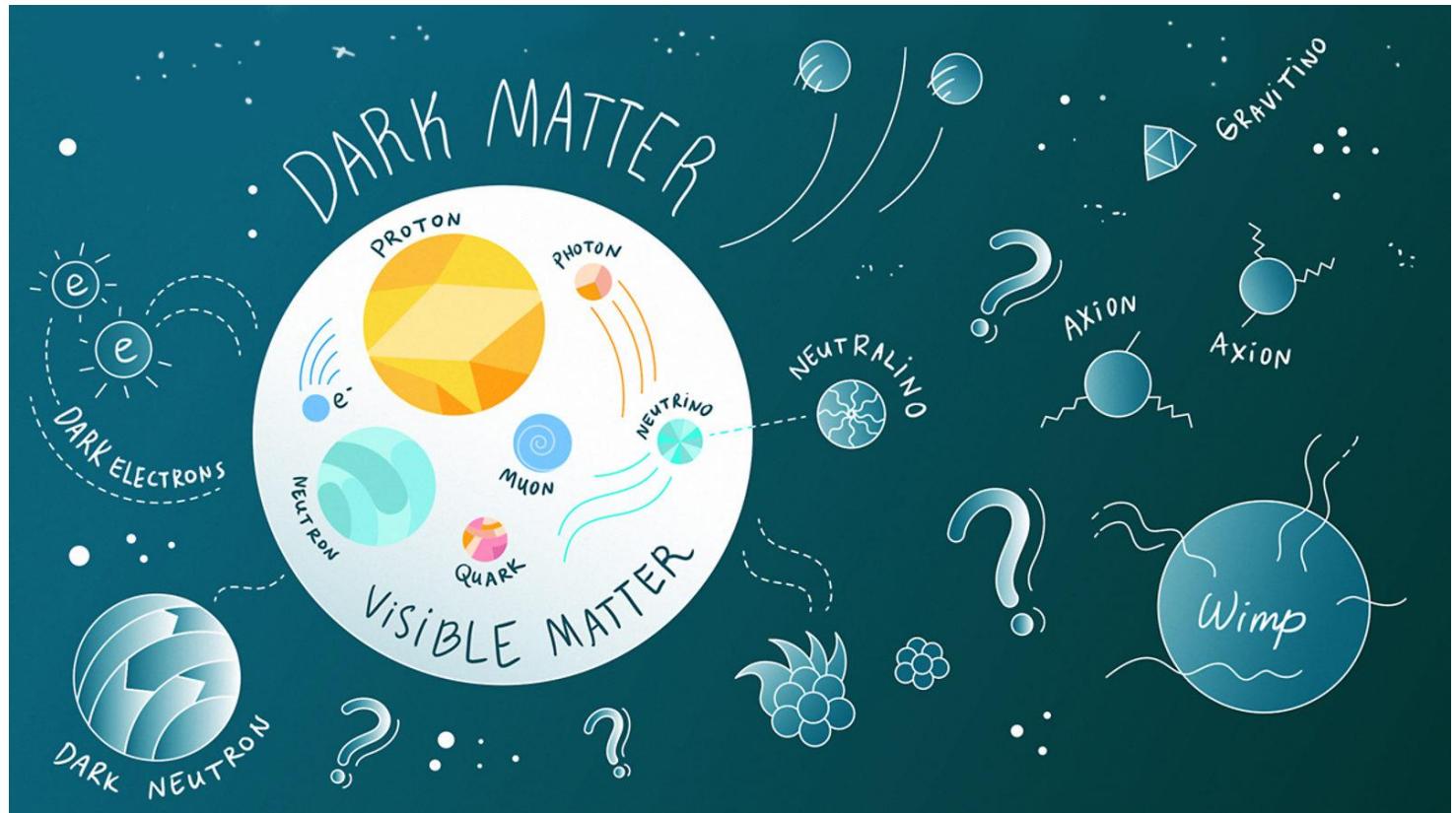
星系旋转曲线



子弹星团的X射线和引力透镜成像

WIMP暗物质

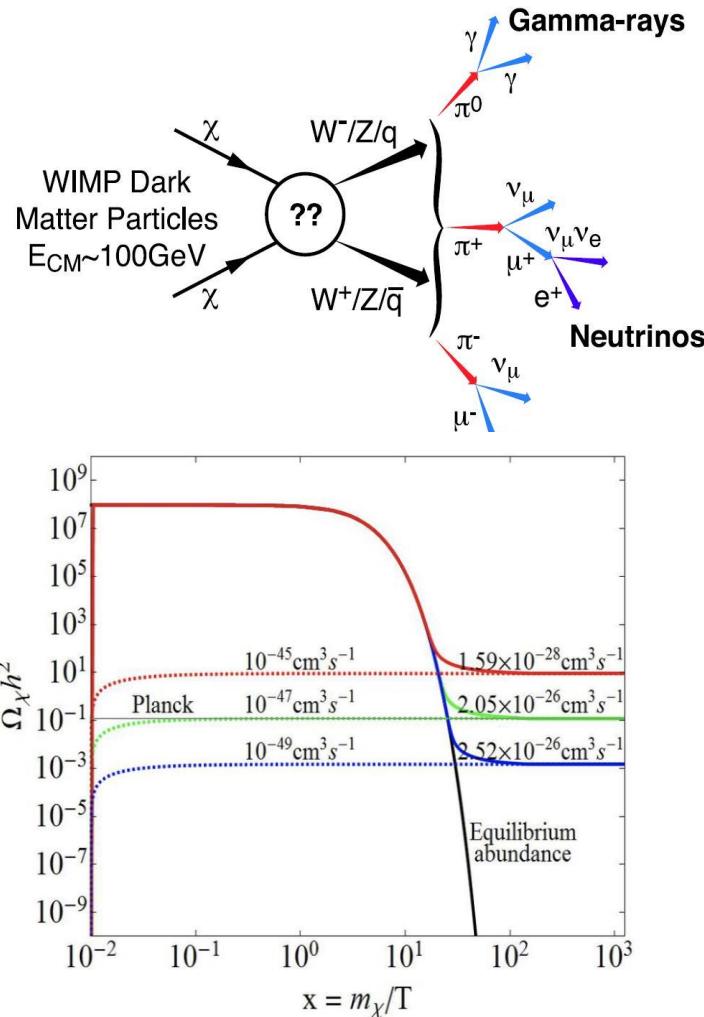
- 暗物质候选者：
 1. 轴子/类轴子粒子
 2. 惰性中微子
 3. 暗光子
 4. Sub-GeV DM
 5. WIMP
 6. 原初黑洞…



较轻暗物质的探测

- 暗光子引起电子谐波振荡—利用FAST搜寻相关信号：
 1. H. An, S. Ge, W.-Q. Guo, X. Huang, J. Liu, and Z. Lu, PRL 130, 181001 (2023).
- 在苏州和哈尔滨建立屏蔽室来探测暗光子暗物质产生的磁场振荡：
 1. Min Jiang et al., arXiv:2305.00890.
- 利用视界望远镜(EHT)对黑洞的观测来搜寻暗光子和轴子等极轻玻色子：
 1. Yifan Chen et al., PRL 124, 061102 (2020).
 2. Yifan Chen et al., Nature Astron. 6, 592 (2022).
- 宇宙线加速的暗物质探测(CR Boosted DM)：
 1. T. Bringmann and M. Pospelov, PRL 122, 171801 (2019);
 2. C. Xia, Y.-H. Xu, Y.-F. Zhou, JCAP 02, 028 (2022);
 3. S.-F. Ge, J.-L. Liu, Q. Yuan, N. Zhou, Phys. Rev. Lett. 126, 091804 (2021).
 4. W. Wang, L. Wu, J. M. Yang, H. Zhou, and B. Zhu, JHEP 12, 072 (2020).
 5. B. Fornal, P. Sandick, J. Shu, M. Su, Y. Zhao, PRL 125, 161804 (2020).

WIMP relic abundance



- **New freeze-out scenario:**

1. Co-annihilation: M. J. Baker et al., JHEP 12, 120 (2015).
2. Co-decaying: J. A. Dror et al., PRL 117, 211801 (2016).
3. Cannibalizing: D. Pappadopulo, et al., PRD 94, 035005 (2016).
4. Secluded DM: M. Pospelov et al., PLB 662, 53–61 (2008).
5. Forbidden DM: R. Tito D'Agnolo et al., PRL 115, 061301 (2015).
6. Self-resonant DM: S.-S. Kim, H. M. Lee, and B. Zhu, JHEP 10, 239 (2021).
7. ...

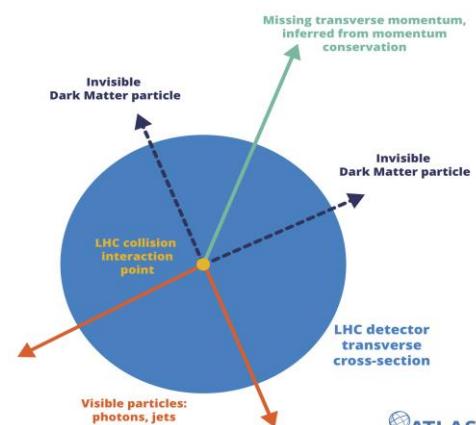
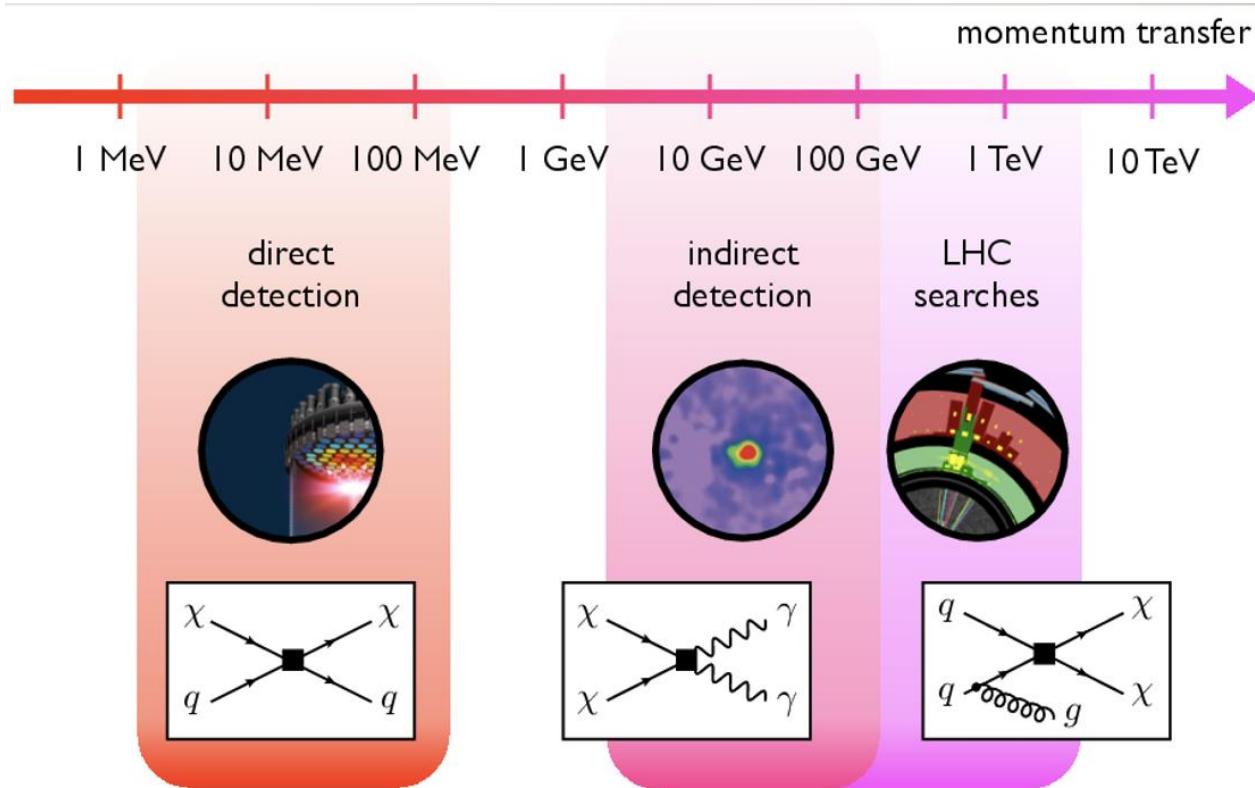
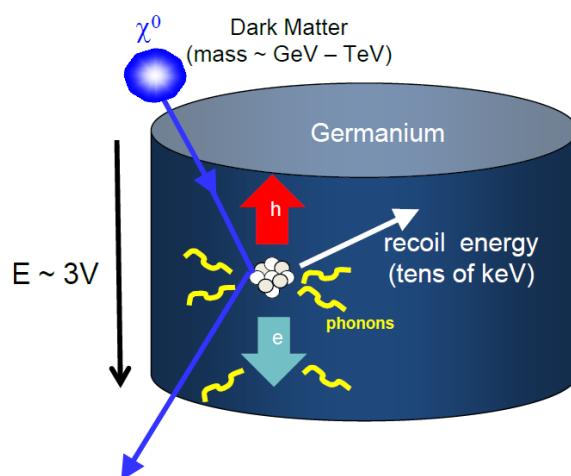
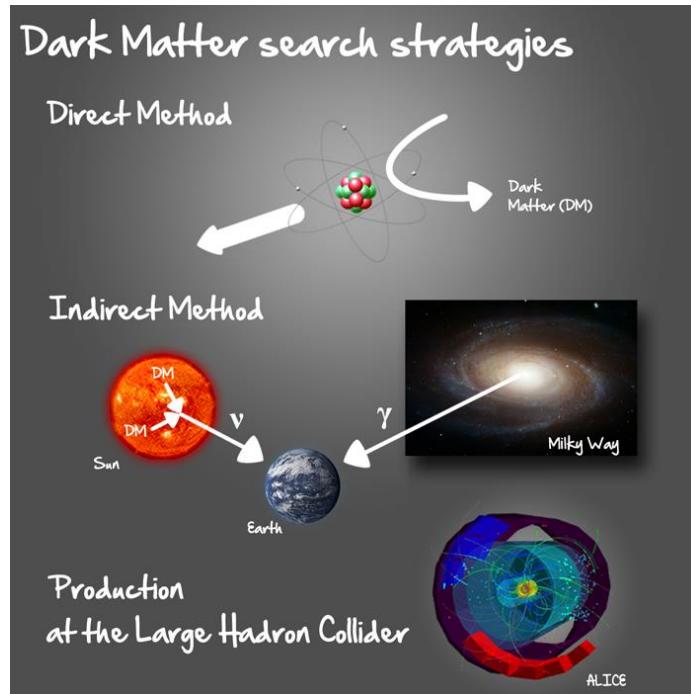
- **Freeze-in DM**

1. Feebly Interacting Massive Particle (FIMP): L. J. Hall, JHEP 03, 080 (2010).
2. Sequential freeze-in: T. Hambye, et al., PRD 100, 095018 (2019).
3. UV freeze-in: C. E. Yaguna, JCAP 02, 006 (2012).
4. Asymmetric freeze-in: L. J. Hall, et al, arXiv:1010.0245.
5. Particle in a plasma...

- **DM produced from a first-order phase transition: Filtered DM**

1. M. J. Baker el at., PRL 125, 151102 (2020).
2. D. Chway, PRD 101, 095019 (2020).
3. W. Chao, X. F. Li, L. Wang, JCAP 06, 038 (2021).
4. S. Jiang, F. P. Huang, C. S. Li, arXiv:2305.02218.

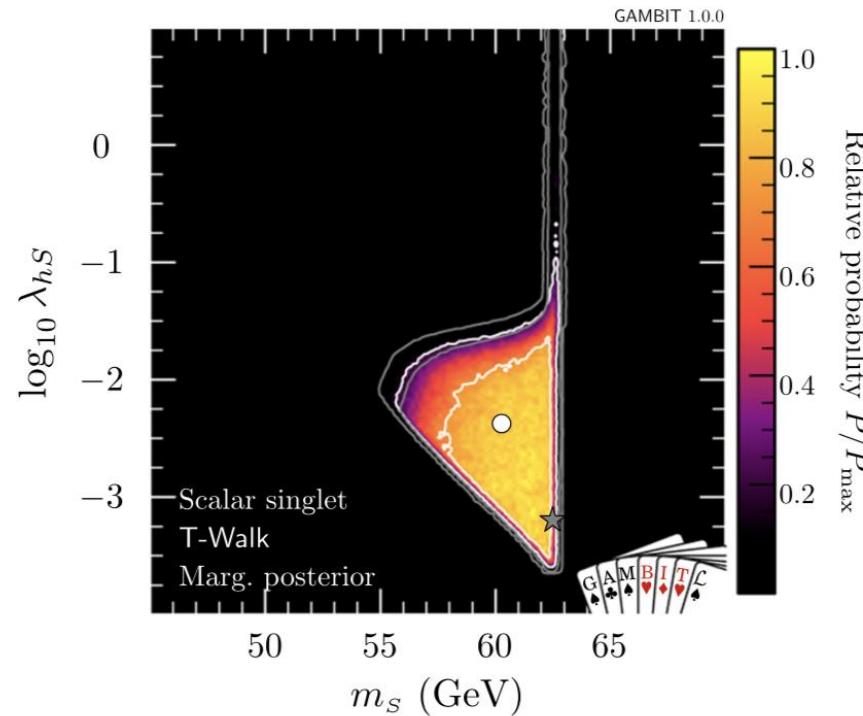
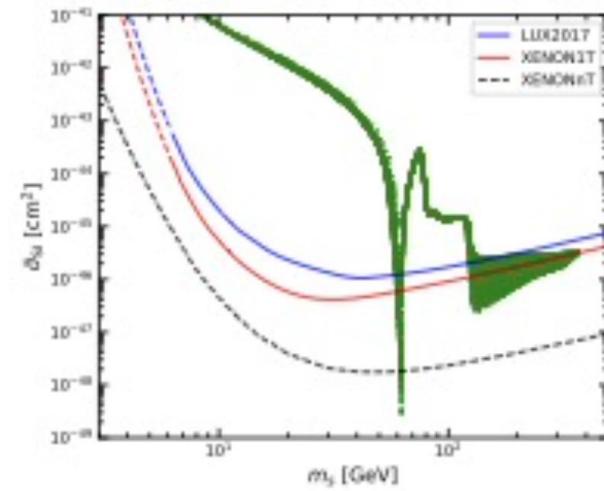
暗物质探测实验



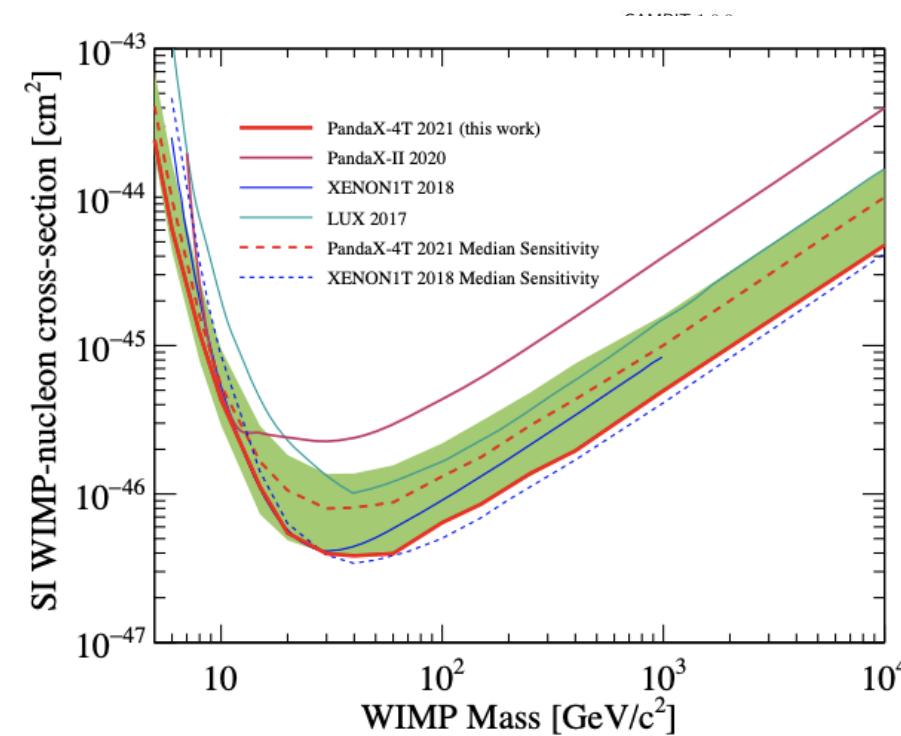
暗物质模型和宇宙一阶电弱相变

Singlet Scalar Extension with a $Z_2/U(1)$ Symmetry

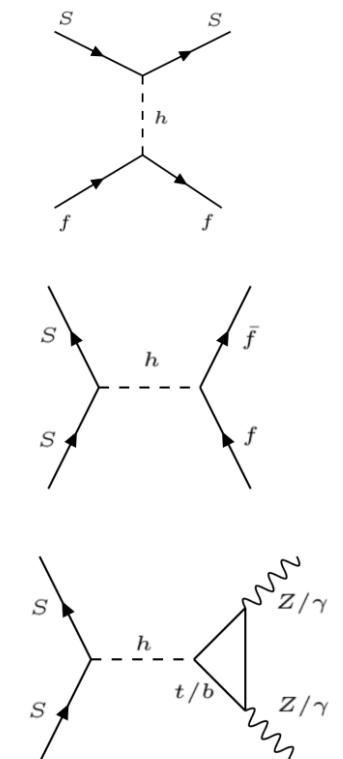
$$V(H, S) = -\mu_h^2 |H|^2 + \lambda_h |H|^4 + \frac{1}{2} \mu_s^2 S^2 + \frac{1}{4} \lambda_s S^4 + \frac{1}{2} \lambda_m |H|^2 S^2,$$



GAMBIT Collaboration EPJC (2017) 77:568



PandaX-4T, PRL 127, 261802 (2021).



暗物质模型和宇宙一阶电弱相变

$U(1)$ softly breaking

C. Gross et al., PRL 119, 191801 (2017)

$$V = V_0 + V_{\text{soft}},$$

$$\begin{aligned} V_0 &= -\frac{\mu_H^2}{2}|H|^2 - \frac{\mu_S^2}{2}|S|^2 + \frac{\lambda_H}{2}|H|^4 \\ &\quad + \lambda_{HS}|H|^2|S|^2 + \frac{\lambda_S}{2}|S|^4, \end{aligned}$$

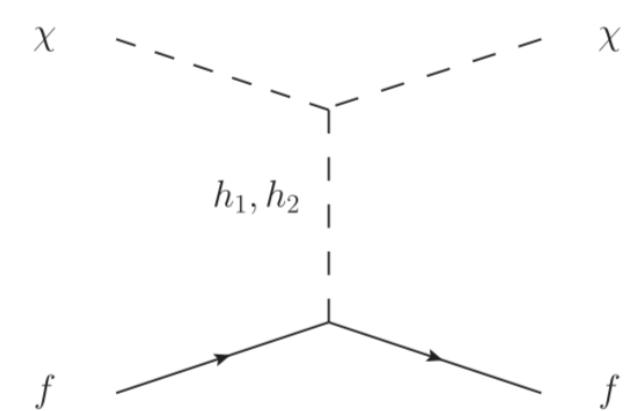
$$V_{\text{soft}} = -\frac{\mu'_S^2}{4}S^2 + \text{H.c.}$$

$$\mathcal{L} \supset -(h_1 \cos \theta + h_2 \sin \theta) \sum_f \frac{m_f}{v} \bar{f} f.$$

$$\mathcal{L} \supset -\frac{v_s}{2} \chi^2 (\kappa_{\chi\chi h_1} h_1 + \kappa_{\chi\chi h_2} h_2),$$

$$\mathcal{A}_{dd}(t) \propto \sin \theta \cos \theta \left(\frac{m_{h_2}^2}{t - m_{h_2}^2} - \frac{m_{h_1}^2}{t - m_{h_1}^2} \right)$$

$$\simeq \sin \theta \cos \theta \frac{t(m_{h_2}^2 - m_{h_1}^2)}{m_{h_1}^2 m_{h_2}^2} \simeq 0,$$



1. The global $U(1)$ symmetry is broken by the soft term.
2. The pseudo Goldstone boson is the WIMP DM candidate since it has a Z_2 symmetry after the spontaneous vacuum symmetry breaking.

暗物质模型和宇宙一阶电弱相变

Singlet Scalar Extension with a CP Symmetry

C.-W. Chiang D. Huang, and B-Q. Lu
JCAP01(2021)035

$$\begin{aligned} V(H, S) = & -\mu_h^2 |H|^2 + \lambda_h |H|^4 - \mu_1^2 (S^* S) - \frac{1}{2} \mu_2^2 (S^2 + S^{*2}) + \lambda_1 (S^* S)^2 + \frac{1}{4} \lambda_2 (S^2 + S^{*2})^2 \\ & + \frac{1}{2} \lambda_3 (S^* S) (S^2 + S^{*2}) + \kappa_1 |H|^2 (S^* S) + \frac{1}{2} \kappa_2 |H|^2 (S^2 + S^{*2}) + \frac{1}{\sqrt{2}} a_1^3 (S + S^*) \\ & + \frac{1}{2\sqrt{2}} b_m |H|^2 (S + S^*) + \frac{\sqrt{2}}{3} c_1 (S^* S) (S + S^*) + \frac{\sqrt{2}}{3} c_2 (S^3 + S^{*3}) , \end{aligned}$$

模型具有 $S \rightarrow S^*$ 对称性，真空自发破缺后 χ 具有 Z_2 对称性而成为 WIMP 暗物质候选粒子

$$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}} (h + iG^0) \end{pmatrix}, \quad \text{and} \quad S = \frac{1}{\sqrt{2}} (s + i\chi).$$

暗物质唯象研究

The evolution of the DM number density is described by the Boltzmann equation

$$\frac{dY}{dT} = \sqrt{\frac{\pi g_*(T)}{45}} M_{\text{pl}} \langle \sigma v_{\text{rel}} \rangle [Y(T)^2 - Y_{\text{eq}}(T)^2],$$

The resulting DM relic density is given by

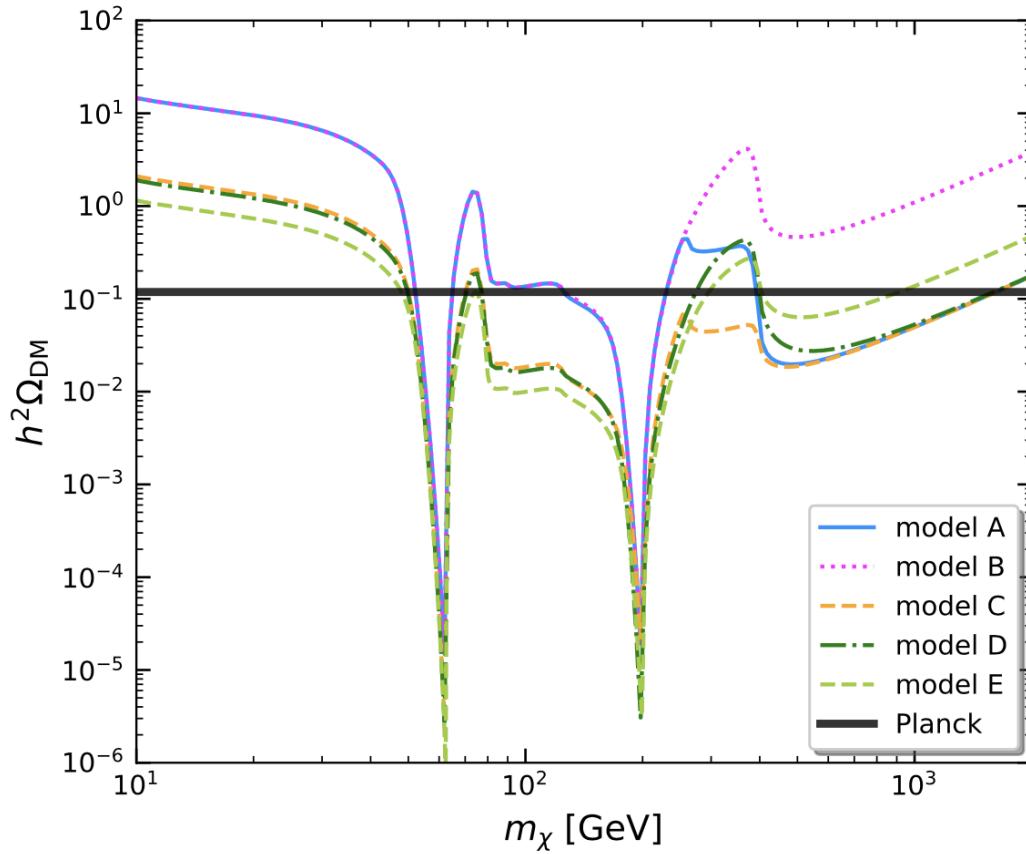
$$h^2 \Omega_{\text{DM}} = 2.742 \times 10^8 Y_0 \frac{m_\chi}{\text{GeV}},$$

The cross-section of the SI DM-nucleon elastic scattering is given by

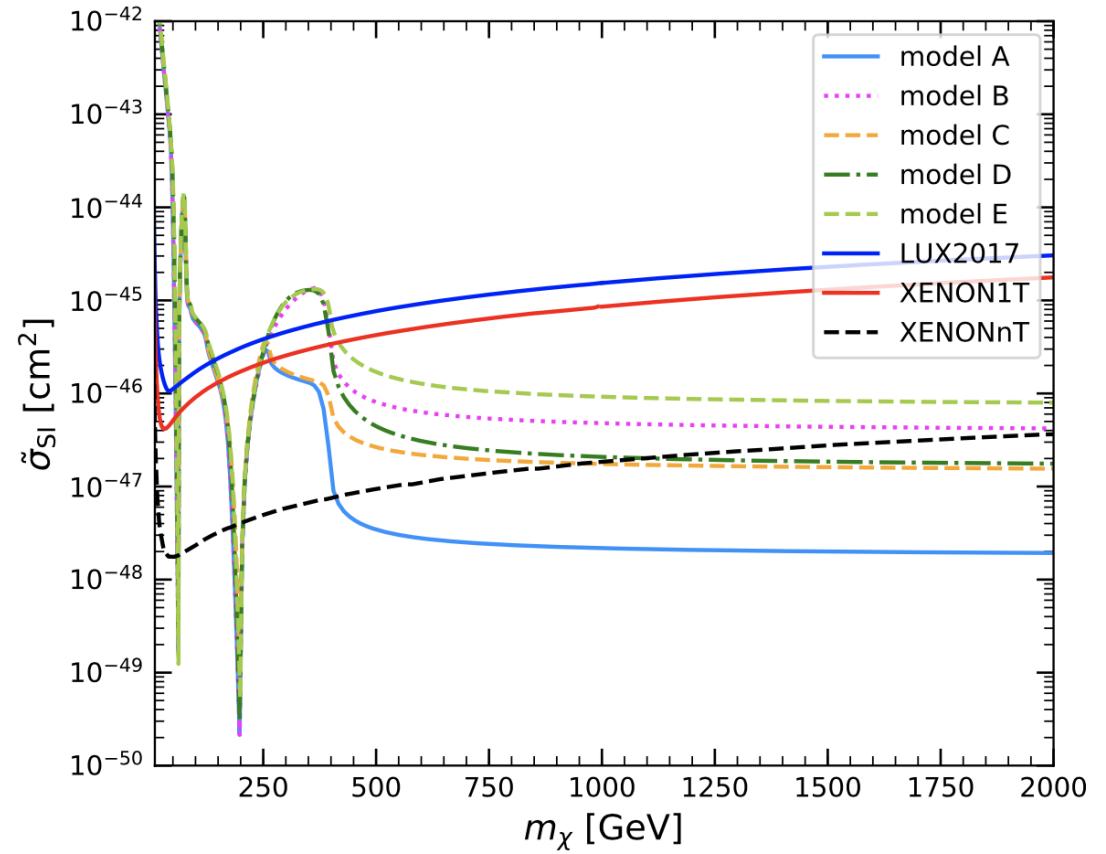
$$\sigma_{\text{SI}} = \frac{\lambda_m^2 m_N^4 f^2}{\pi m_s^2 m_h^4},$$

Scale the scattering cross section as $\tilde{\sigma}_{\text{SI}} = f_X \sigma_{\text{SI}}$, with $f_X \equiv \frac{h^2 \Omega_{\text{DM}}}{h^2 \Omega_{\text{DM}}^{\text{obs}}}$.

暗物质唯象研究

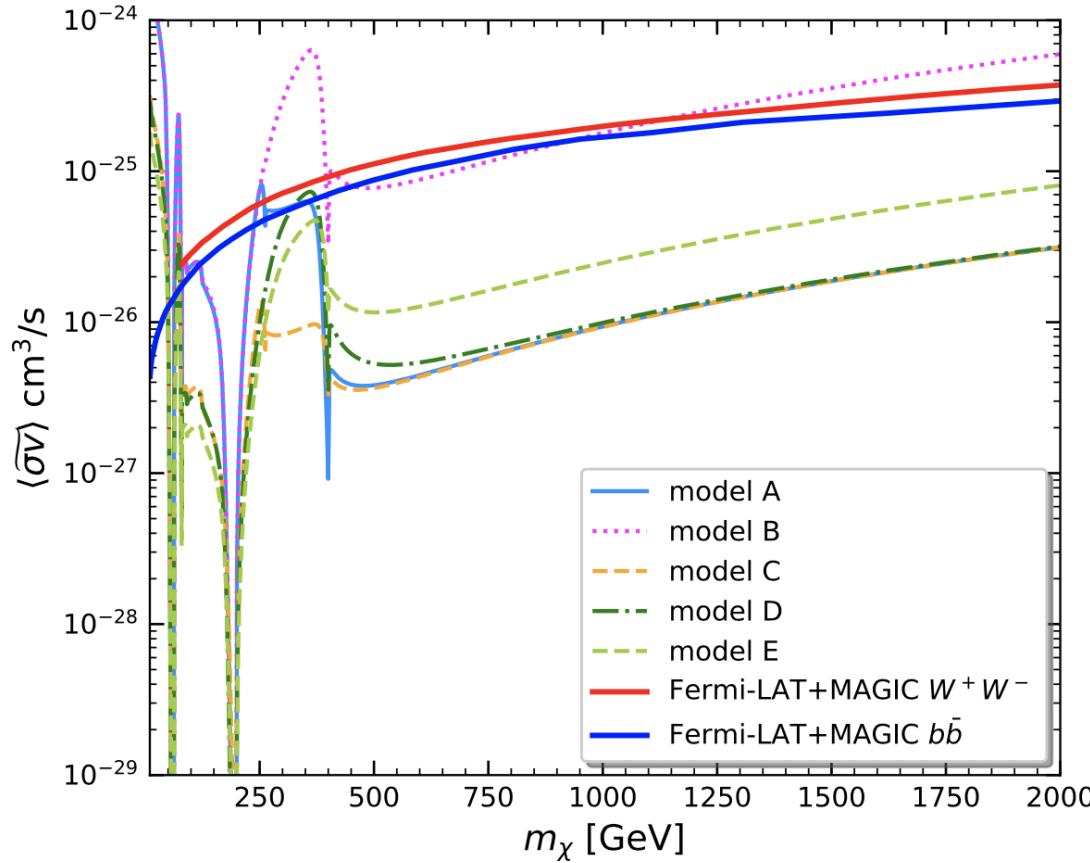


暗物质遗迹密度

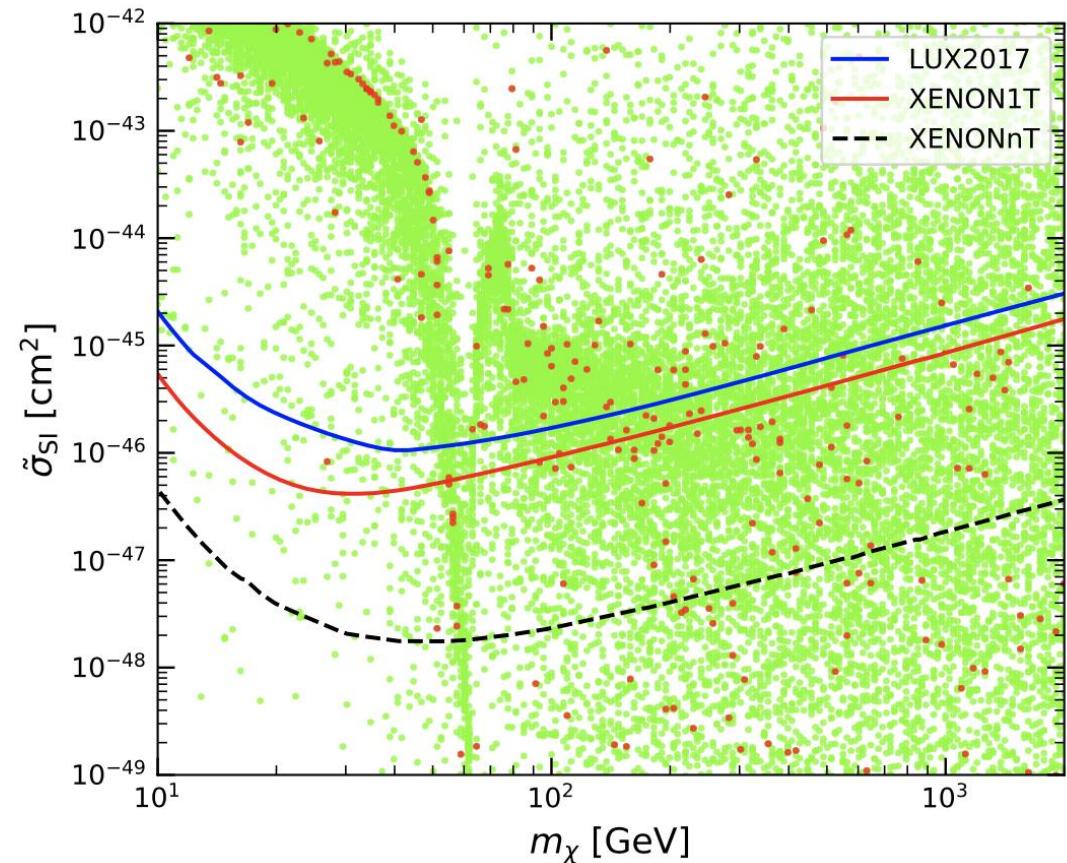


直接探测暗物质-核子散射截面

暗物质唯象研究



暗物质湮灭截面



暗物质探测和暗物质遗迹密度

宇宙一阶电弱相变

- Tree-level scalar potential

B.-Q. Lu, C.-W. Chiang, and D. Huang, PLB 833,137308 (2022)

$$V_0(h, s, \chi) = -\frac{1}{2}\mu_h^2 h^2 - \frac{1}{2}\mu_s^2 s^2 - \frac{1}{2}\mu_\chi^2 \chi^2 + \frac{1}{4}\lambda_h h^4 + \frac{1}{4}\lambda_s s^4 + \frac{1}{4}\lambda_\chi \chi^4 + \frac{1}{2}\lambda_a s^2 \chi^2 \\ + \frac{1}{4}\kappa_s h^2 s^2 + \frac{1}{4}\kappa_\chi h^2 \chi^2 + a_1^3 s + \frac{1}{4}b_m h^2 s + \frac{1}{3}c_s s^3 + \frac{1}{3}c_\chi s \chi^2.$$

- The Coleman-Weinberg potential

$$V_{\text{CW}}(h, s, \chi) = \frac{1}{64\pi^2} \sum_i N_i M_i^4(h, s, \chi) \left[\log \frac{M_i^2(h, s, \chi)}{\mu^2} - C_i \right],$$

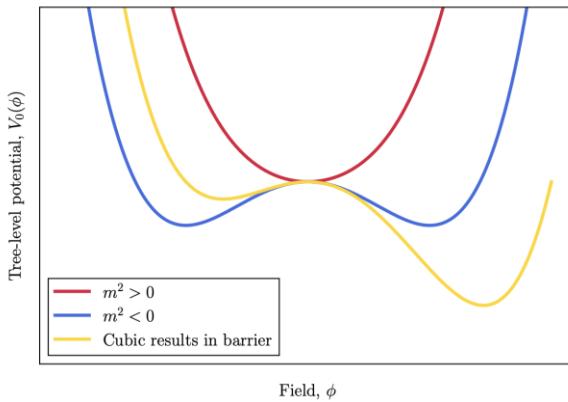
- The finite-temperature contributions to the effective potential at one-loop level

$$V_T(h, s, \chi, T) = \frac{T^4}{2\pi^2} \sum_i N_i J_{B,F} \left(M_i^2(h, s, \chi, T) / T^2 \right),$$

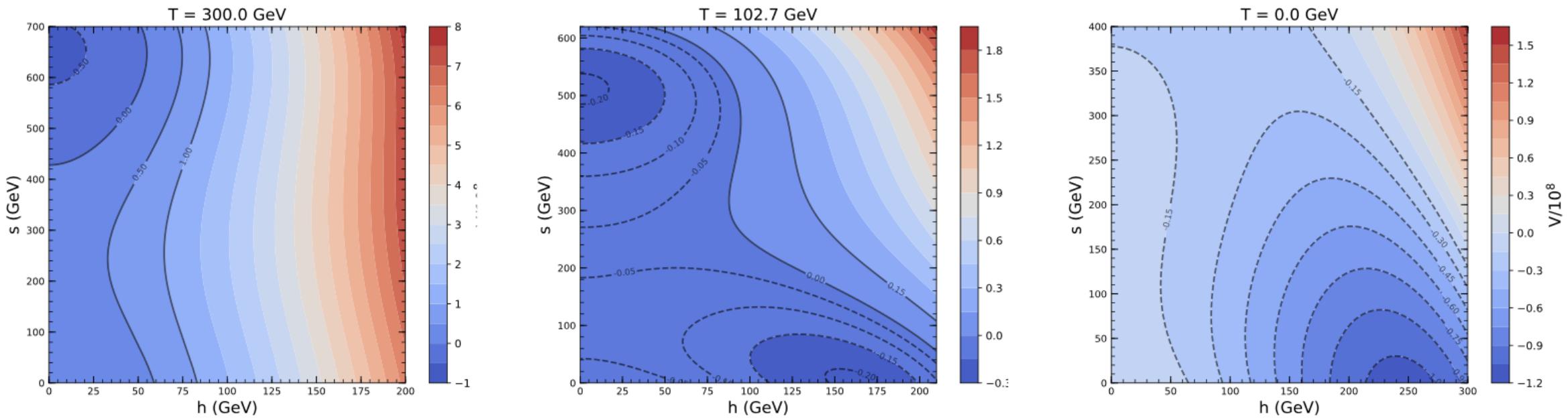
- The leading-order high-temperature expansion

$$V_T(h, s, \chi, T) = \frac{1}{2} \left(g_h h^2 + g_s s^2 + g_\chi \chi^2 + 2m_3 s \right) T^2.$$

宇宙一阶电弱相变



P. Athron, C. Balázs, A. Fowlie,
L. Morris, L. Wu, arXiv:2305.02357



B.-Q. Lu, C.-W. Chiang, and D. Huang, PLB 833,137308 (2022)

宇宙一阶电弱相变

- The decay of the false vacuum can proceed through thermal fluctuations which help overcome the potential barrier. The tunneling rate per unit volume and time element is approximately given by:

$$\Gamma(T) = A(T)e^{-S_3/T},$$

- the probability of bubble nucleations per Hubble volume is defined as

$$p(T) = \int_T^{T_c} \frac{\Gamma(x)}{H^4(x)} \frac{dx}{x} \approx \left(\frac{T}{H}\right)^4 e^{-S_3/T}.$$

- To overcome the dilution due to the expansion of the Universe, we require

$$p(T) \sim 1$$

- This leads to the following condition:

$$\frac{S_3(T_n)}{T_n} \simeq 4 \ln \left(\frac{T_n}{H} \right) \simeq 142 - 4 \log \left(\frac{T_n}{246 \text{ GeV}} \right).$$

宇宙一阶电弱相变

- The Euclidean action for a spherical bubble configuration

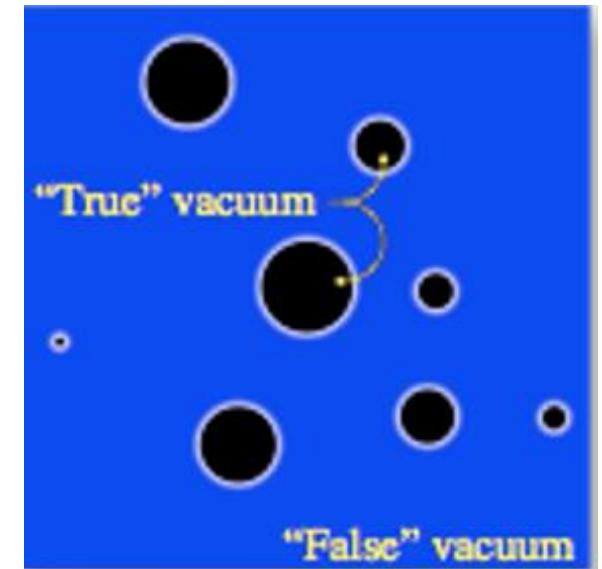
$$S_3(T) = 4\pi \int dr \ r^2 \left[\frac{1}{2} \left(\frac{d\Phi}{dr} \right)^2 + V_{\text{eff}}(\Phi, T) \right].$$

- Equation of motion for the bubble profile

$$\frac{d^2\Phi}{dr^2} + \frac{2}{r} \frac{d\Phi}{dr} - \frac{dV}{d\Phi} = 0,$$

- Boundary condition

$$\left. \frac{d\Phi}{dr} \right|_{r=0} = 0, \quad \left. \Phi \right|_{r \rightarrow \infty} = 0.$$



Gravitational wave

- Two primary gravitational wave (GW) parameters

$$\alpha = \frac{\epsilon(T_*)}{\rho_{\text{rad}}(T_*)} \text{ and } \frac{\beta}{H_*} = T_* \frac{d}{dT} \left(\frac{S_3(T)}{T} \right) \Big|_{T=T_*},$$

$$\epsilon(T) = T \frac{\partial \Delta V_{bs}(T)}{\partial T} - \Delta V_{bs}(T),$$

- GW generation temperature: T_*

Gravitational wave

- 相变过程的引力波源主要有三种：

1. 真空气泡碰撞

$$h^2 \Omega_{\text{col}}(f) = 1.67 \times 10^{-5} \left(\frac{H_*}{\beta} \right)^2 \left(\frac{\kappa_{\text{col}} \alpha}{1 + \alpha} \right)^2 \left(\frac{100}{g_*} \right)^{\frac{1}{3}} \left(\frac{0.11 v_w^3}{0.42 + v_w^2} \right) S_{\text{col}}(f).$$

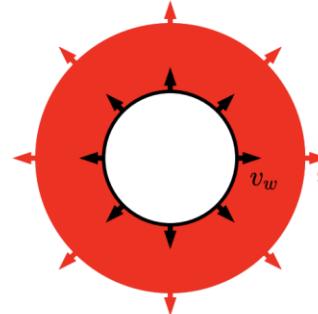
2. 真空气泡碰撞产生的声波

$$h^2 \Omega_{\text{sw}}(f) = 2.65 \times 10^{-6} \left(\frac{H_*}{\beta} \right) \left(\frac{\kappa_{\text{sw}} \alpha}{1 + \alpha} \right)^2 \left(\frac{100}{g_*} \right)^{\frac{1}{3}} v_w S_{\text{sw}}(f).$$

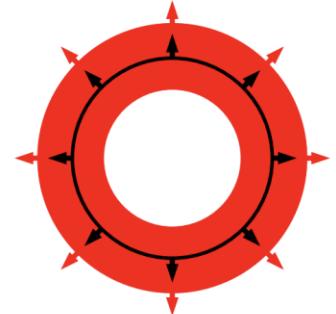
3. 磁流体力学湍流

$$h^2 \Omega_{\text{turb}}(f) = 3.35 \times 10^{-4} \left(\frac{H_*}{\beta} \right) \left(\frac{\kappa_{\text{turb}} \alpha}{1 + \alpha} \right)^{\frac{3}{2}} \left(\frac{100}{g_*} \right)^{1/3} v_w S_{\text{turb}}(f).$$

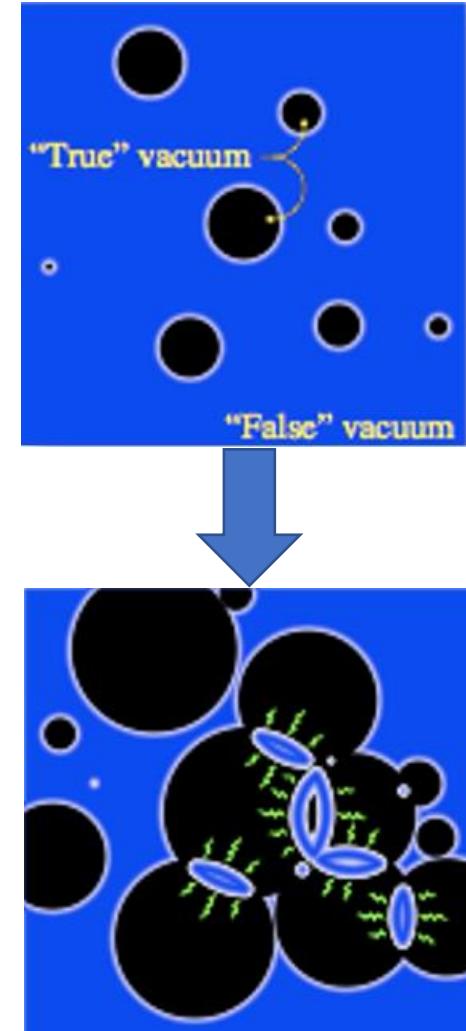
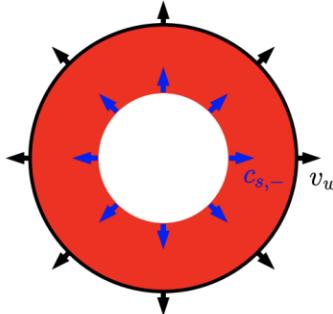
Subsonic deflagration, $v_w < c_{s,-}$



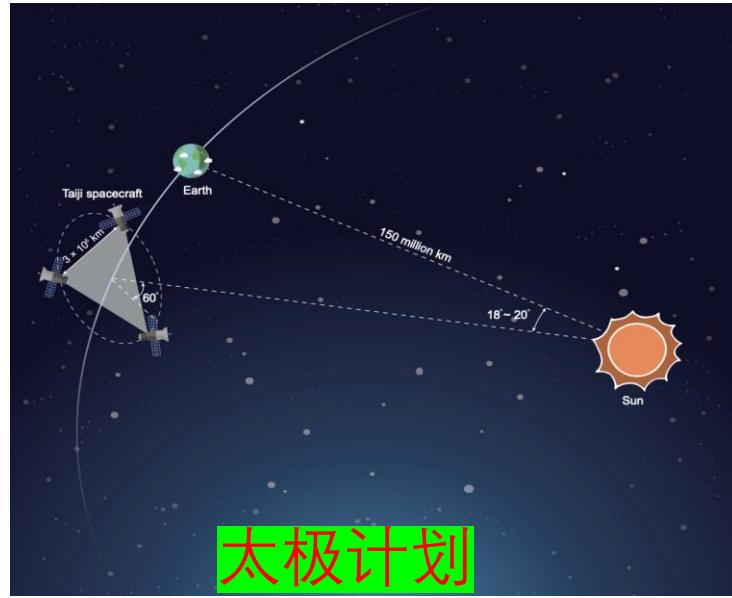
Hybrid, $c_{s,-} < v_w < v_{\text{CJ}}$



Supersonic detonation, $v_w > v_{\text{CJ}}$



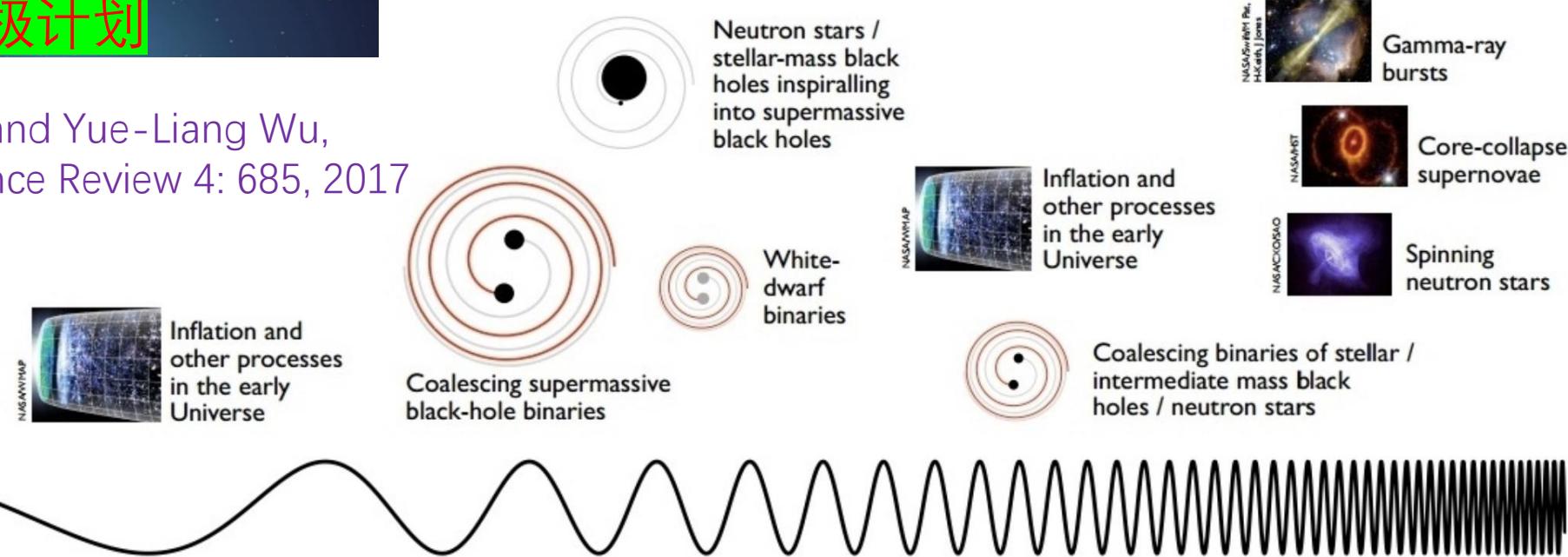
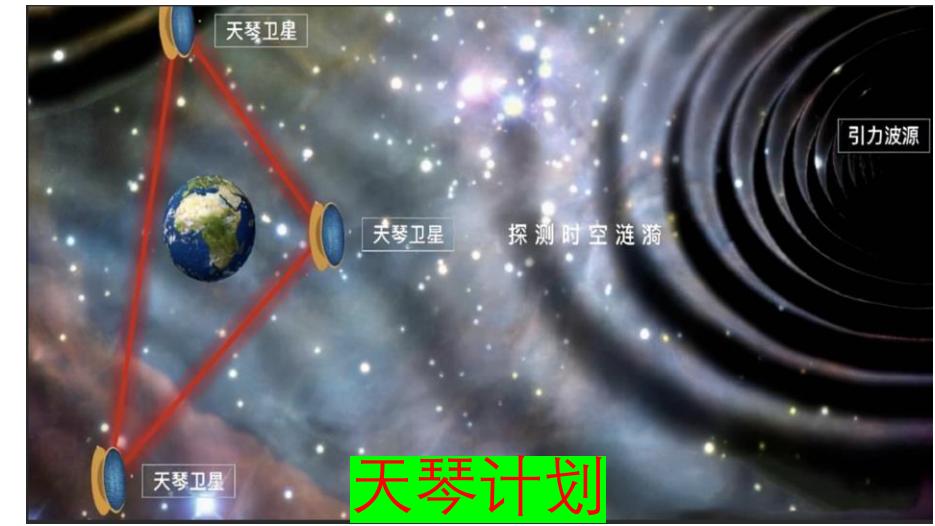
P. Athron, C. Balázs, A. Fowlie,
L. Morris, L. Wu, arXiv:2305.02357



太极计划

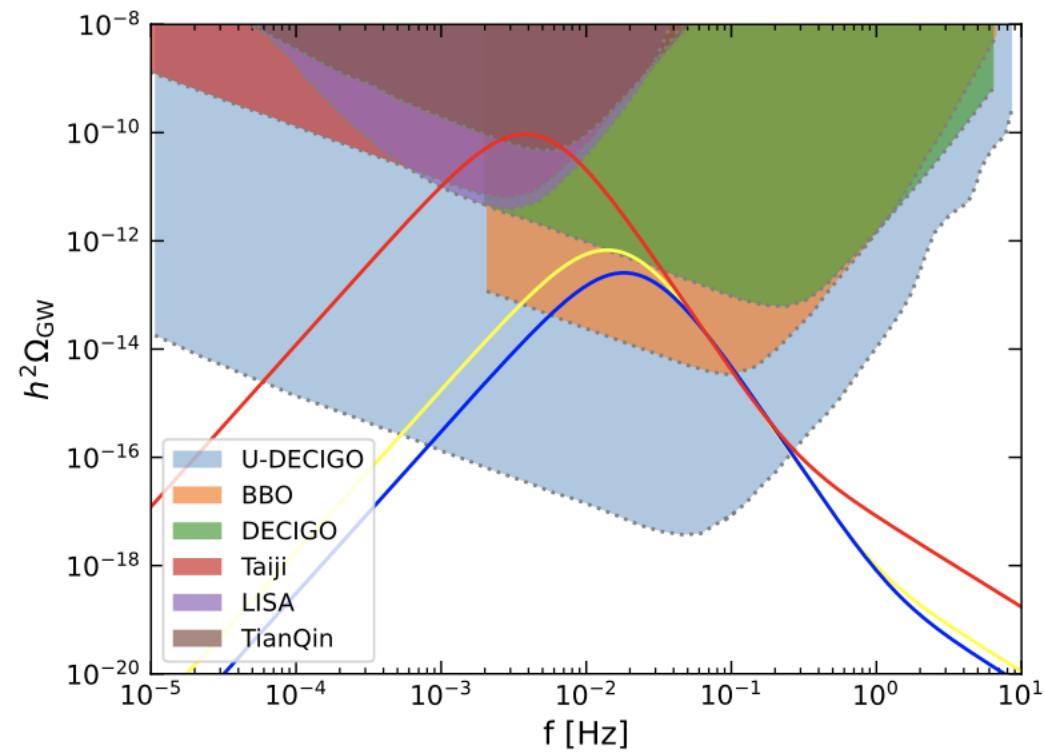
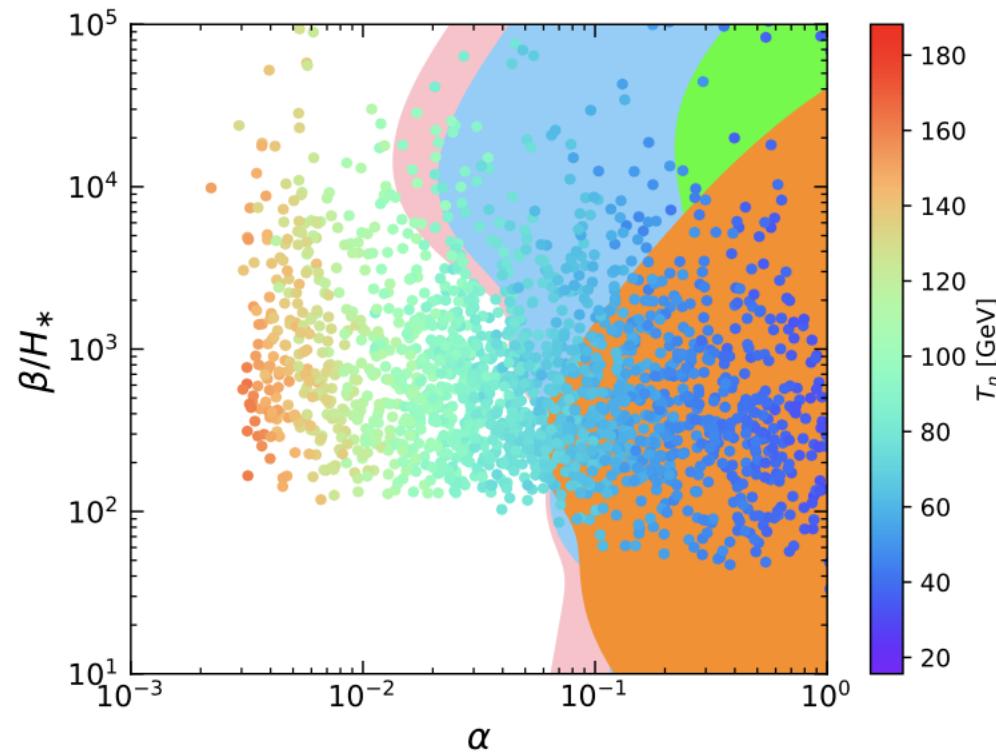
Wen-Rui Hu and Yue-Liang Wu,
National Science Review 4: 685, 2017

- # 空间引力波探测:
1. 太极计划
 2. 天琴计划
 3. LISA
 4. BBO...



Frequency	10^{-16} Hz	$10^{-9} - 10^{-6}$ Hz	$10^{-5} - 10^{-1}$ Hz	$10^{-1} - 1$ Hz	$1 - 10^4$ Hz
Wavelength	10^{21} km	$10^{14} - 10^{11}$ km	$10^{10} - 10^6$ km	$10^6 - 10^5$ km	$10^5 - 10$ km
Detection	CMB Polarization	Pulsar timing	LISA	BBO/DECIGO	LIGO/Virgo/LCGT/ET

WIMP及引力波探测



Scenario	m_S/GeV	m_χ/GeV	θ	λ_a	c_χ/GeV	λ_s	κ_s	c_s/GeV	λ_h
A	182.0	1524.0	0.342	0.467	-403.0	1.3	0.21	-367.0	0.145
B	109.0	984.0	0.279	0.309	162.0	0.71	0.451	-135.0	0.127
C	137.0	1887.1	0.228	0.581	-478.0	0.85	0.403	-200.0	0.130

Scenario	$\sigma_{\text{SI}}/\text{cm}^2$	$\langle \sigma v \rangle_{\text{tot}}/\text{cm}^3\text{s}^{-1}$	v_c/T_c	T_c/GeV	w_c/GeV	T_n/GeV	β/H_*	α
A	1.27×10^{-46}	2.17×10^{-26}	1.32	173.0	194.7	53.57	1343.0	0.139
B	1.23×10^{-47}	2.16×10^{-26}	1.10	196.3	186.2	55.96	1680.8	0.112
C	5.70×10^{-48}	2.17×10^{-26}	1.13	193.4	192.6	38.37	512.8	0.523

- L. Bian, H.-K. Guo, Y. Wu and R. Zhou, *Gravitational wave and collider searches for electroweak symmetry breaking patterns*, *Phys. Rev. D* **101** (2020) 035011 [[1906.11664](#)].
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- L. Bian, Y. Wu and K.-P. Xie, *Electroweak phase transition with composite Higgs models: calculability, gravitational waves and collider searches*, *JHEP* **12** (2019) 028, [[1909.02014](#)].
- X. Wang, F. P. Huang and X. Zhang, *Gravitational wave and collider signals in complex two-Higgs doublet model with dynamical CP-violation at finite temperature*, *Phys. Rev. D* **101** (2020) 015015, [[1909.02978](#)].
- M. Li, Q.-S. Yan, Y. Zhang and Z. Zhao, *Prospects of gravitational waves in the minimal left-right symmetric model*, *JHEP* **03** (2021) 267 [[2012.13686](#)].
- X. Wang, C. Tian and F.P. Huang, *Model-dependent analysis method for energy budget of the cosmological first-order phase transition*, [2301.12328](#).
- Q.-H. Cao, K. Hashino, X.-X. Li, Z. Ren and J.-H. Yu, *Electroweak phase transition triggered by fermion sector*, *JHEP* **01** (2022) 001, [[2103.05688](#)].
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The Georgi-Machacek (GM) model

➤ Scalars

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ -(\xi^+)^* \end{pmatrix},$$

➤ $SU(2)_L \times SU(2)_R$ covariant forms of the fields

$$\Phi \equiv (\epsilon_2 \phi^*, \phi) = \begin{pmatrix} (\phi^0)^* & \phi^+ \\ -(\phi^+)^* & \phi^0 \end{pmatrix}, \quad \text{with} \quad \epsilon_2 = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix},$$

$$\Delta \equiv (\epsilon_3 \chi^*, \xi, \chi) = \begin{pmatrix} (\chi^0)^* & \xi^+ & \chi^{++} \\ -(\chi^+)^* & \xi^0 & \chi^+ \\ (\chi^{++})^* & -(\xi^+)^* & \chi^0 \end{pmatrix},$$

with $\epsilon_3 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & -1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$. (2)

➤ The potential

$$V(\Phi, \Delta) = \frac{1}{2} m_1^2 \text{tr}[\Phi^\dagger \Phi] + \frac{1}{2} m_2^2 \text{tr}[\Delta^\dagger \Delta]$$

$$+ \lambda_1 (\text{tr}[\Phi^\dagger \Phi])^2 + \lambda_2 (\text{tr}[\Delta^\dagger \Delta])^2$$

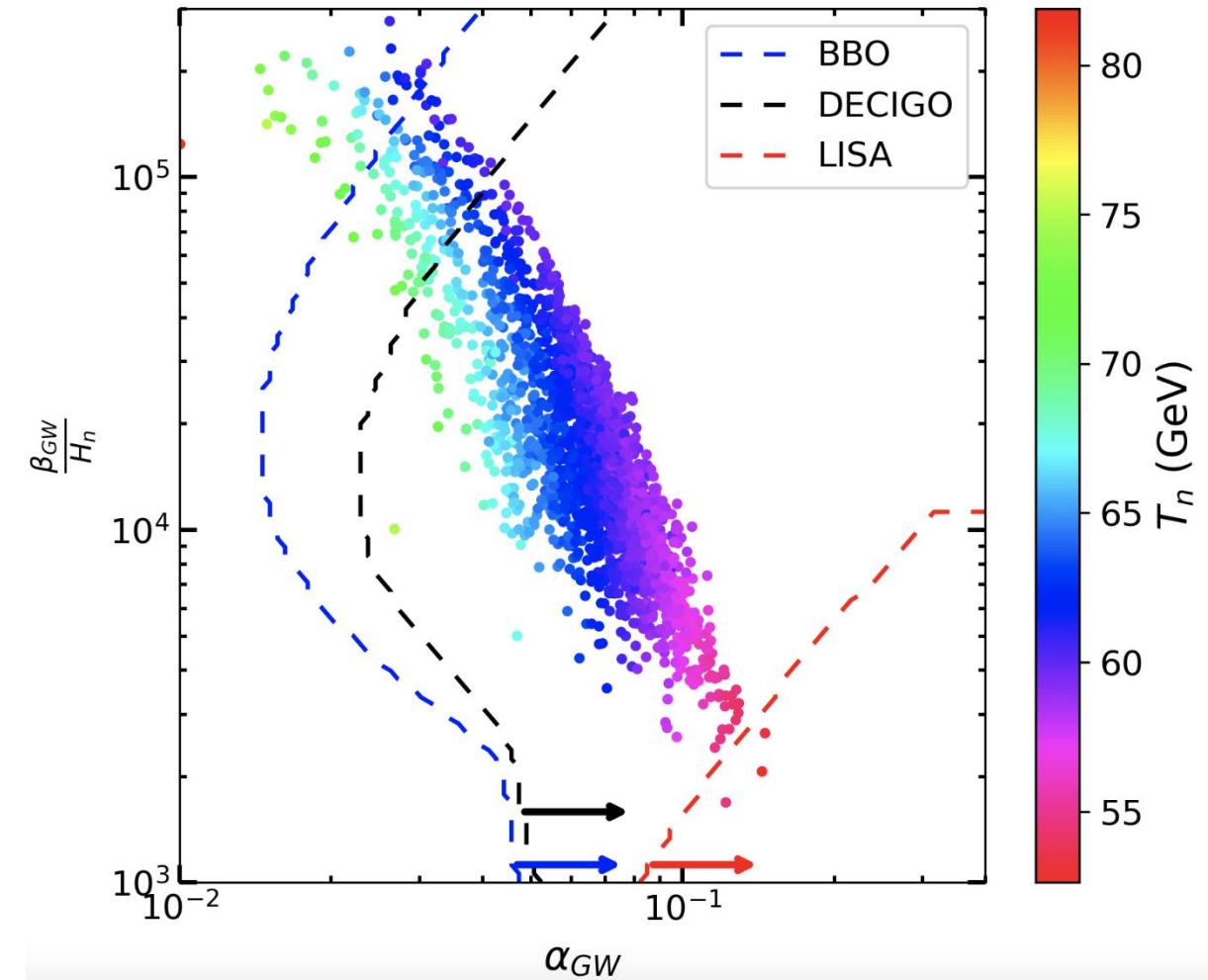
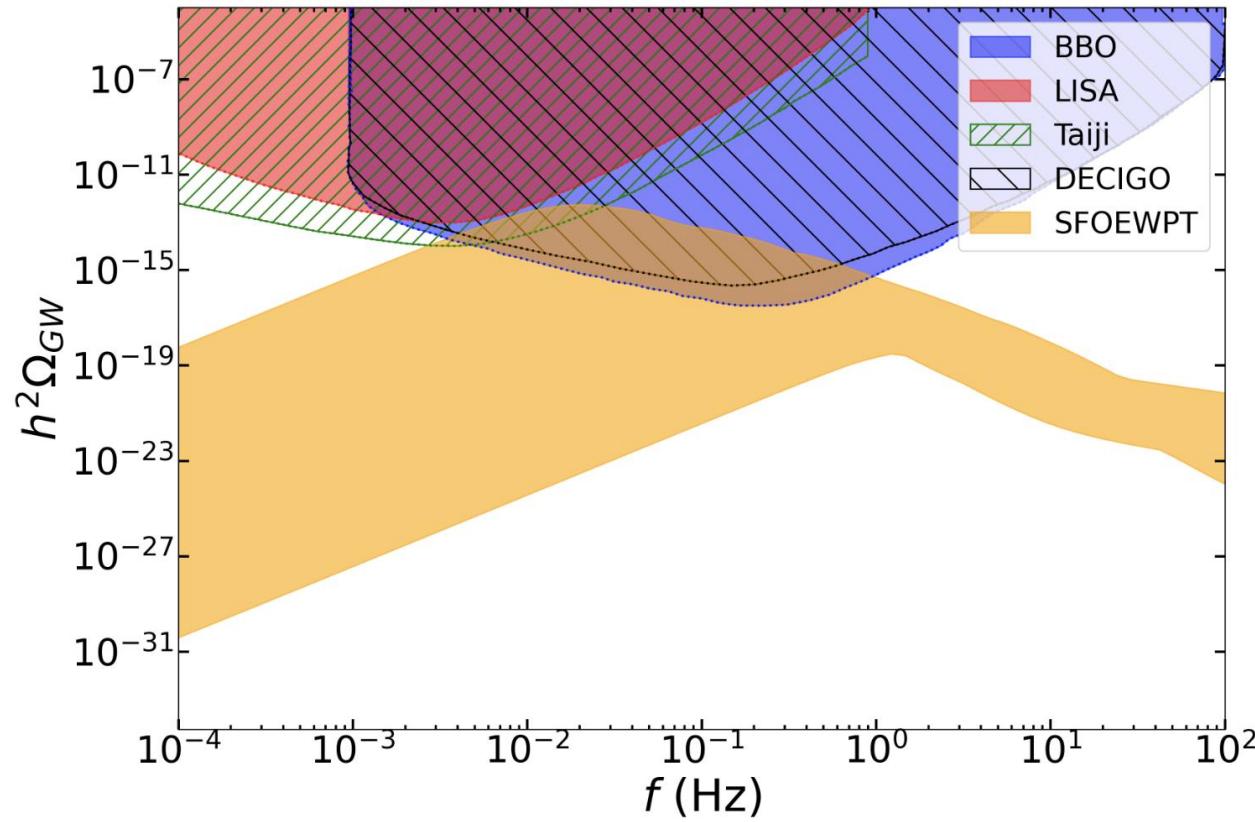
$$+ \lambda_3 \text{tr}[(\Delta^\dagger \Delta)^2] + \lambda_4 \text{tr}[\Phi^\dagger \Phi] \text{tr}[\Delta^\dagger \Delta]$$

$$+ \lambda_5 \text{tr} \left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2} \right] \text{tr}[\Delta^\dagger T^a \Delta T^b]$$

$$+ \mu_1 \text{tr} \left[\Phi^\dagger \frac{\sigma^a}{2} \Phi \frac{\sigma^b}{2} \right] (P^\dagger \Delta P)_{ab}$$

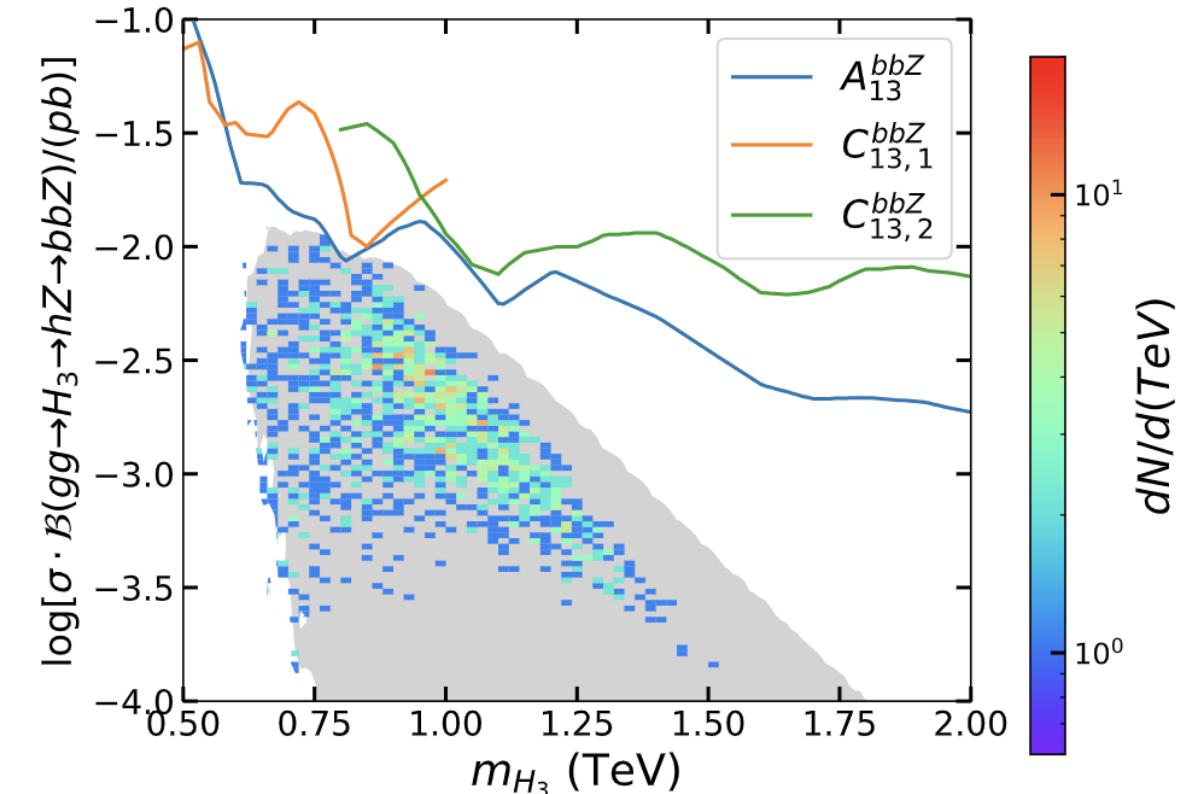
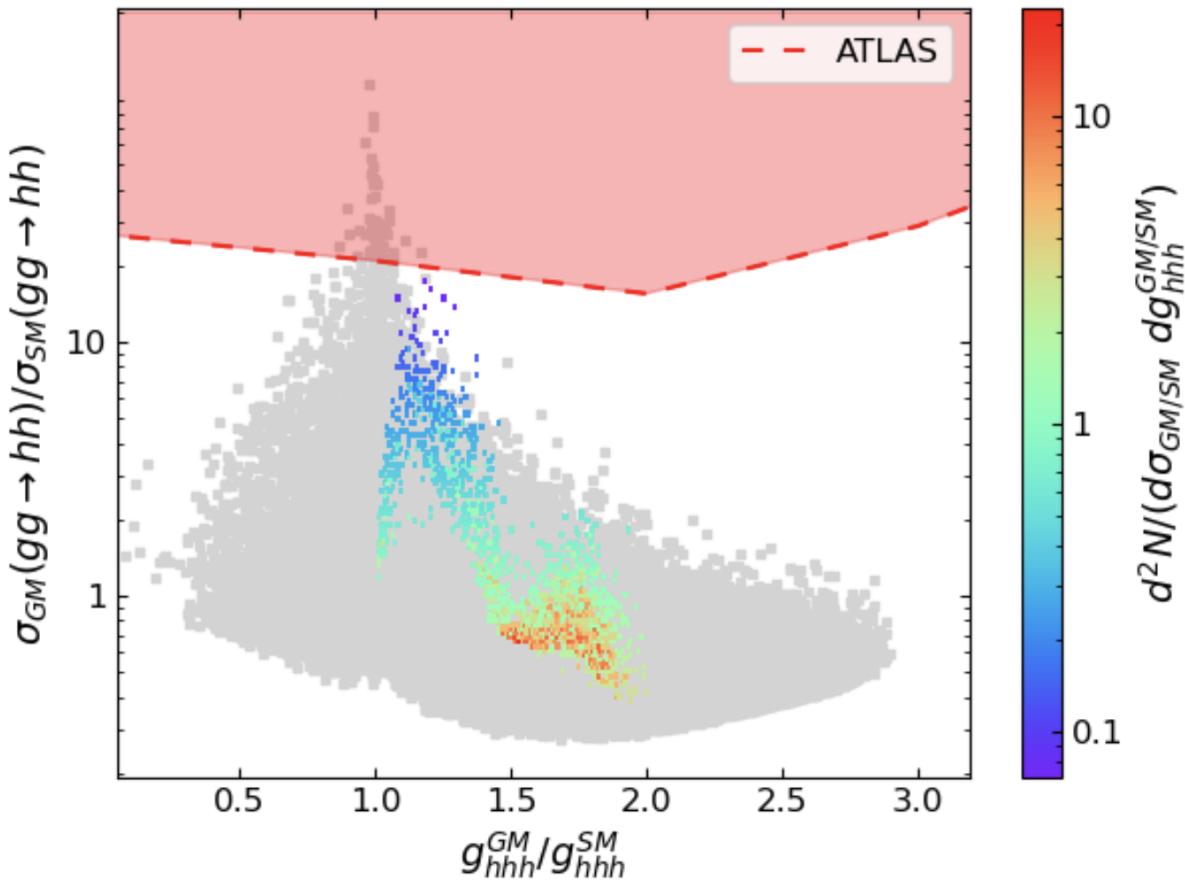
$$+ \mu_2 \text{tr}[\Delta^\dagger T^a \Delta T^b] (P^\dagger \Delta P)_{ab},$$

PT in GM model: Gravitational wave



T. K. Chen, C. W. Chiang, C. T. Huang, and B. Q. Lu PRD 106 055019 (2022).

PT in GM model: LHC constraints and detections



T. K. Chen, C. W. Chiang, C. T. Huang, and B. Q. Lu PRD 106 055019 (2022).

Summary

1. WIMP暗物质是比较流行的暗物质候选粒子之一，已有大量的直接和间接的暗物质实验对WIMP展开搜寻，然而目前仍未探测到明确WIMP信号。
2. 我们研究了一类CP对称性模型，该模型不但能够给出正确的暗物质遗迹密度，满足暗物质相关实验的限制，同时能引发宇宙一阶电弱相变。
3. 宇宙一阶电弱相变产生的引力波信号有可能被太极和天琴等空间引力波实验探测到，因而我们预期将来的空间引力波实验可以作为研究新物理模型和搜寻暗物质的新途径。

谢谢！