New Developments on Baryogenesis

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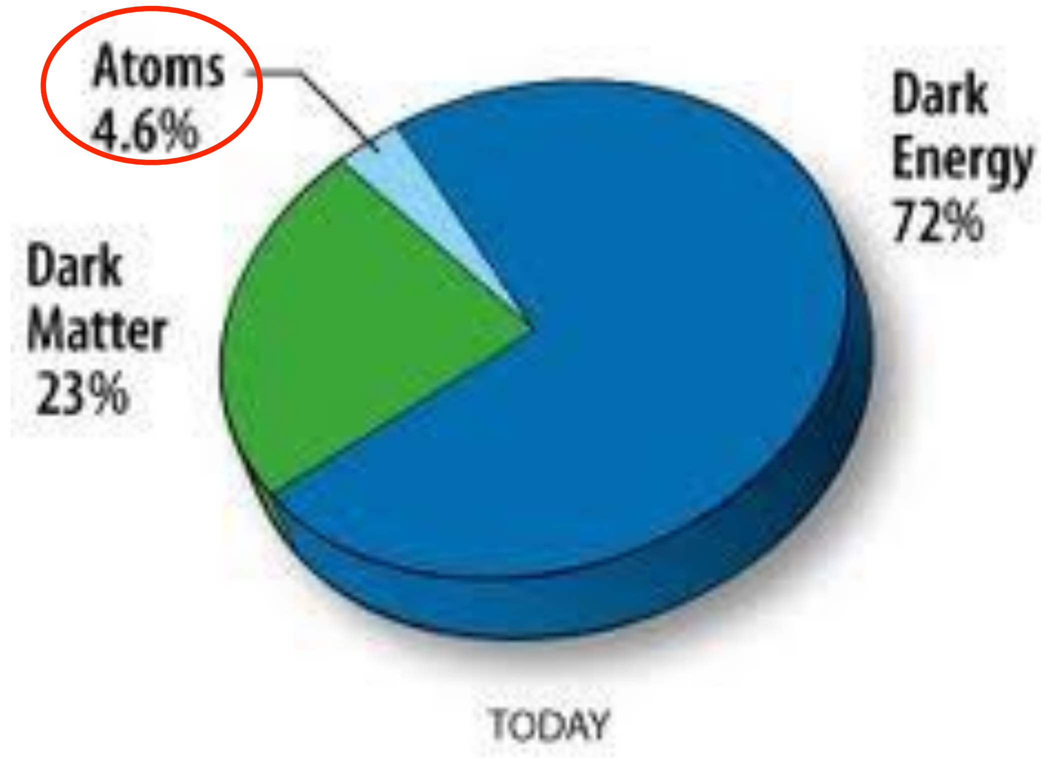
The Cosmic Puzzle of Ω_B

—**Dark** secret of the visible matter

- **Baryon (atomic matter):** $\Omega_B \approx 4\%$
- **Dark Matter:** $\Omega_{DM} \approx 23\%$



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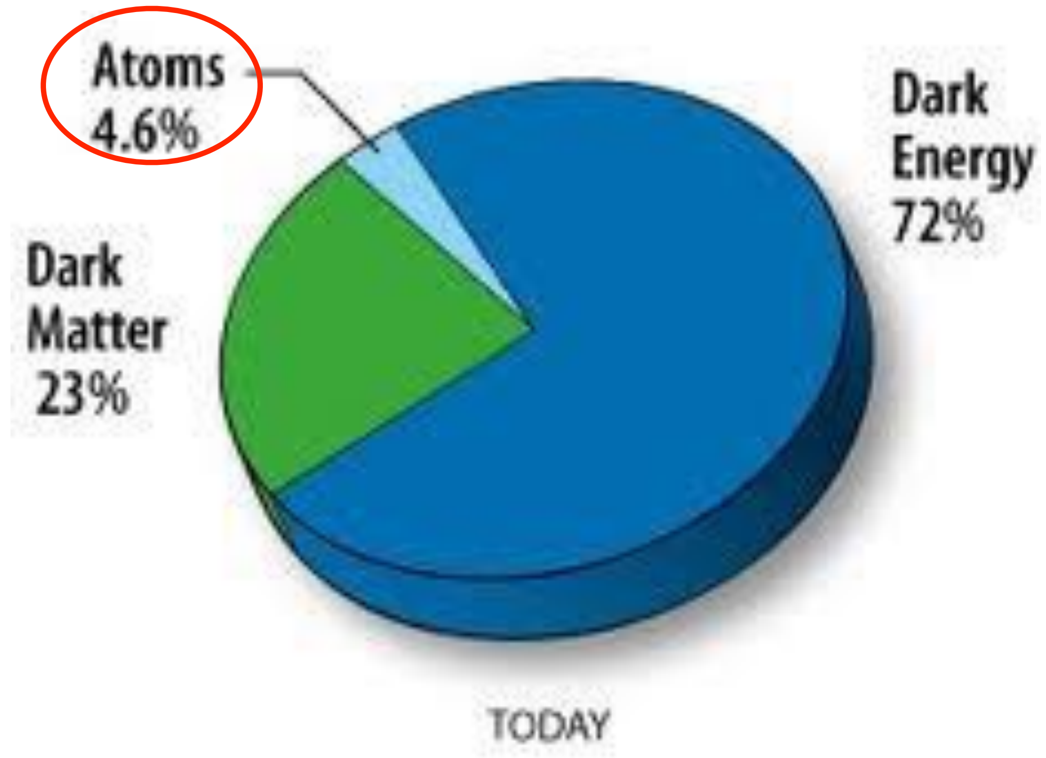
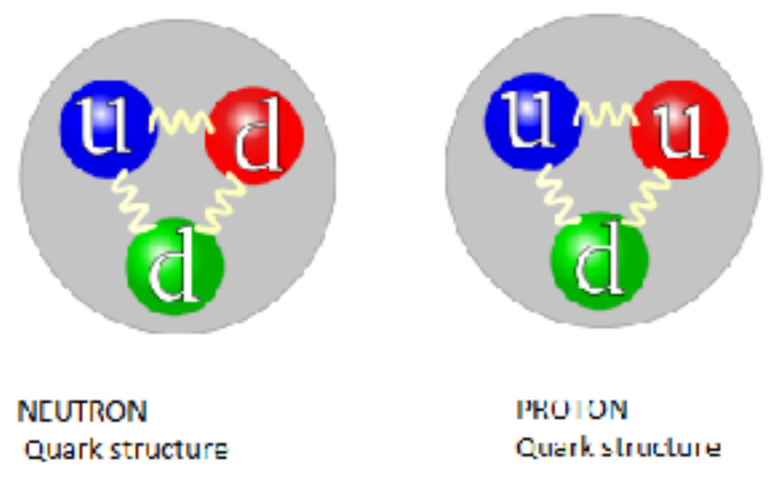


Ω_B: the unknown of the known



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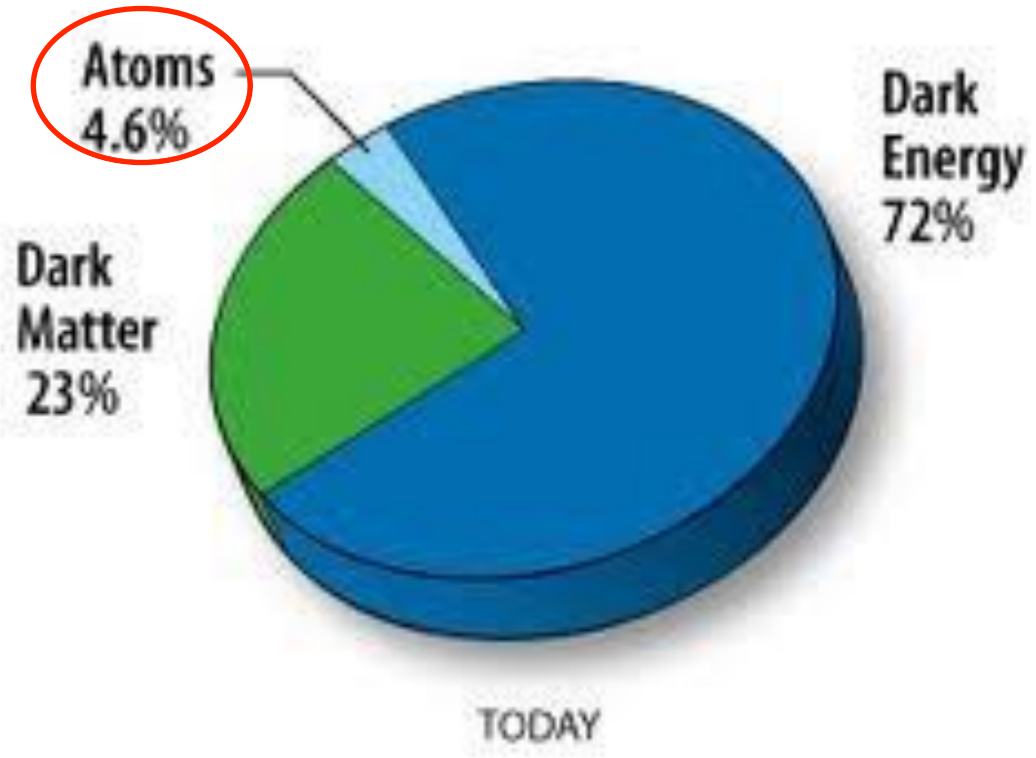

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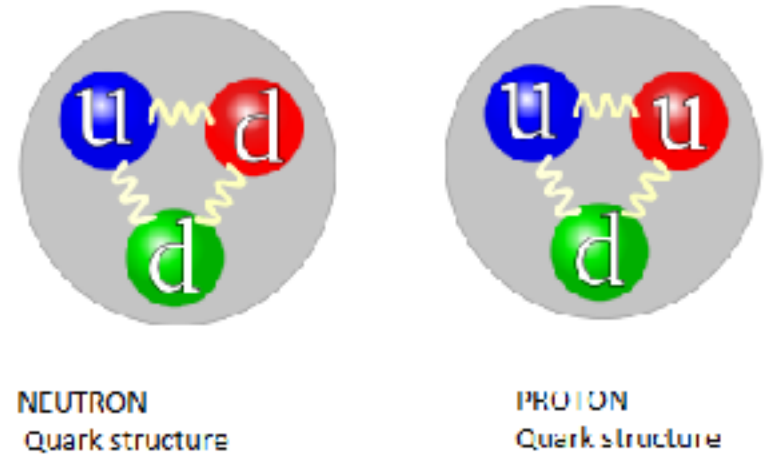

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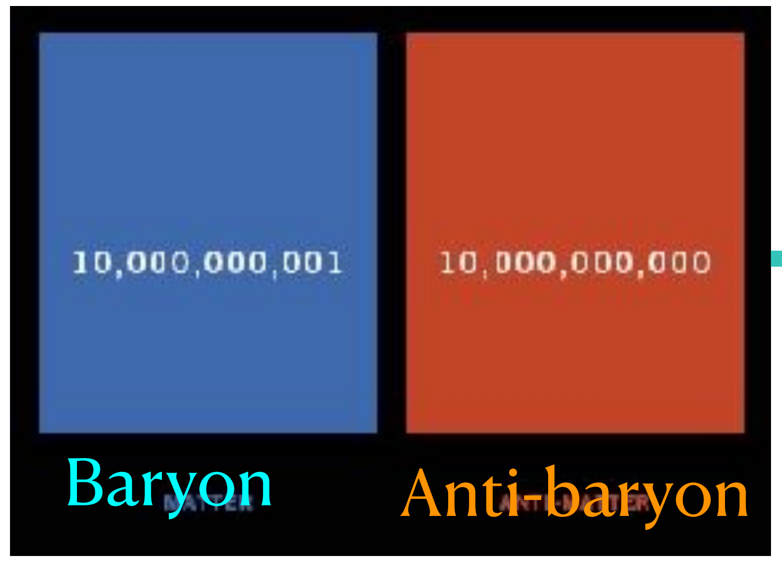
$\eta_B = (n_B - n_{\bar{B}})/n_\gamma \sim 10^{-10}$



symmetric annihilation

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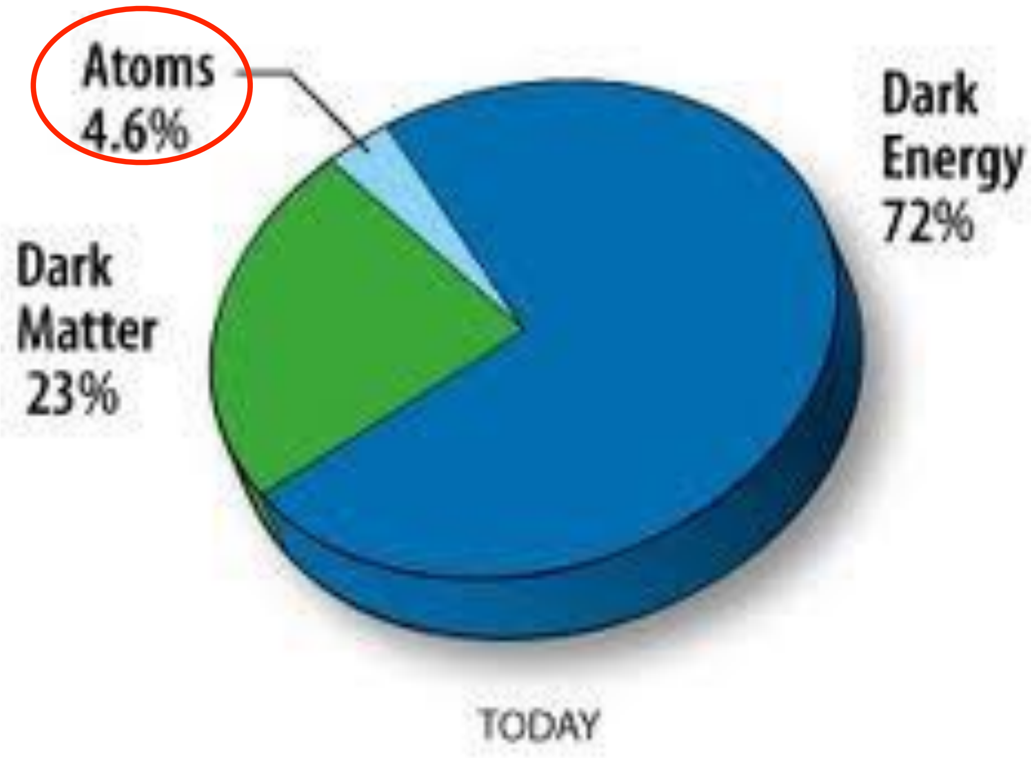

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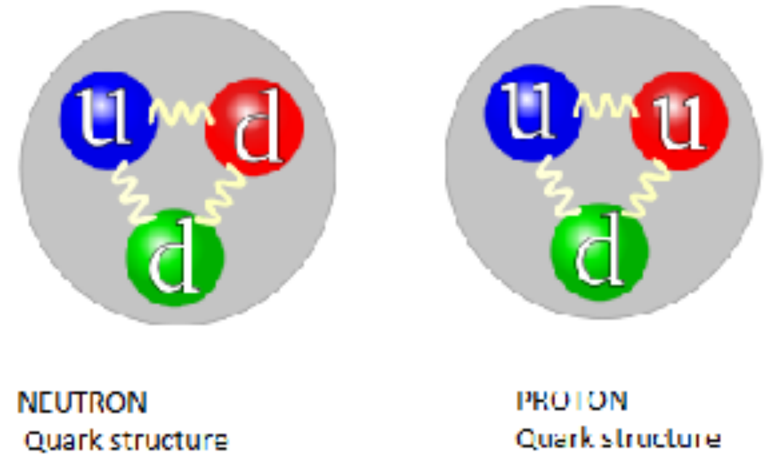

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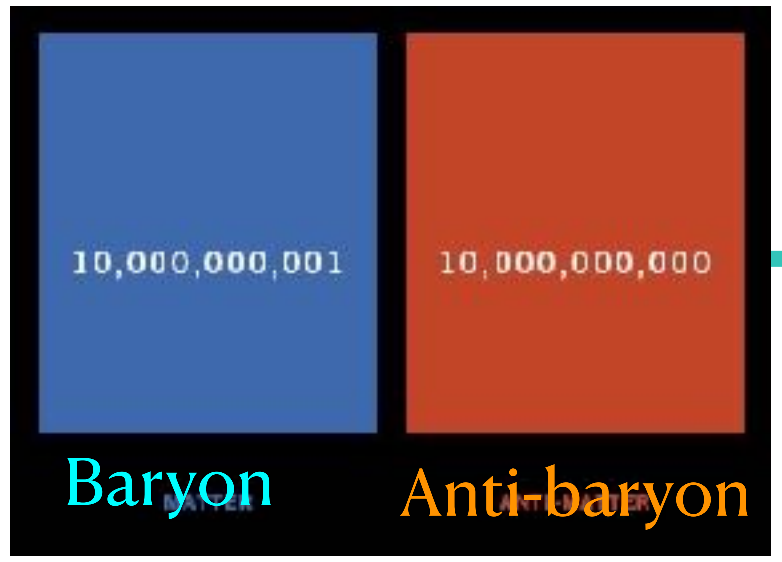

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Where does Ω_B come from? =Where do we come from?

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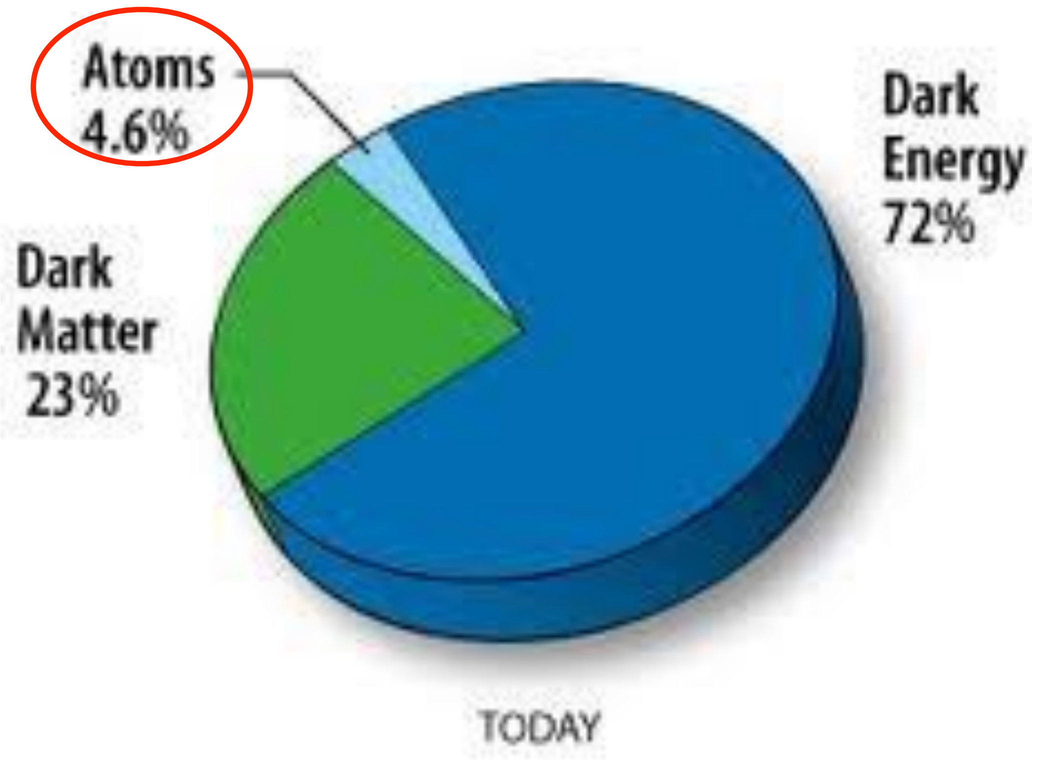

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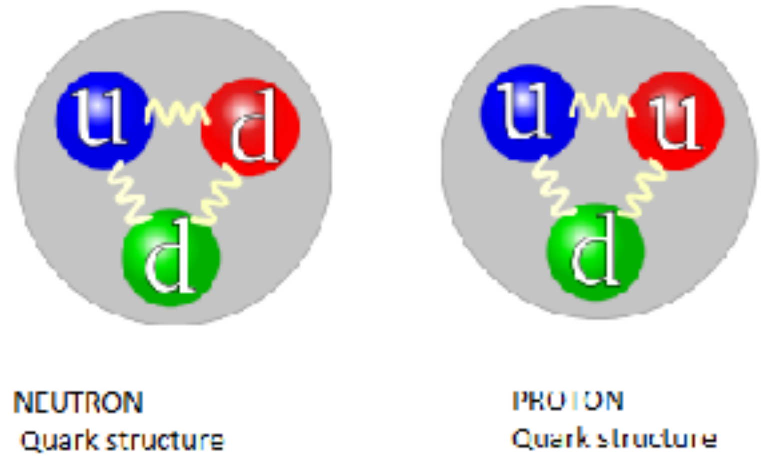

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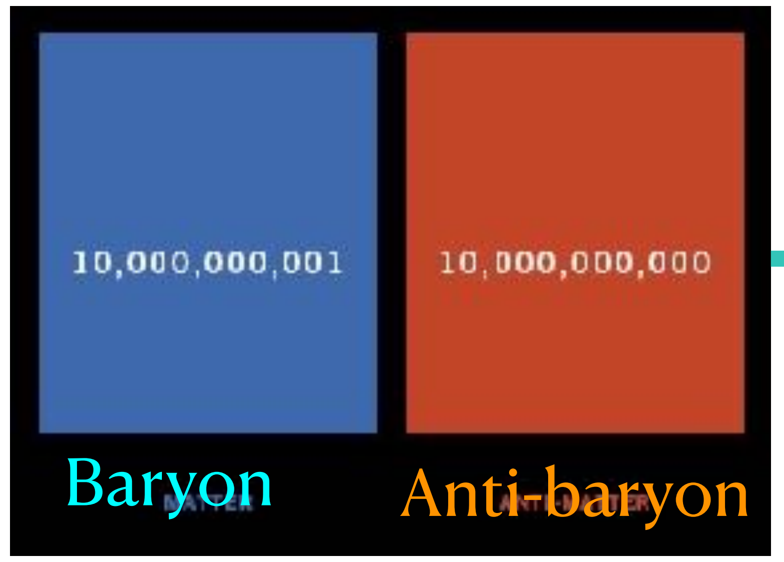

symmetric annihilation

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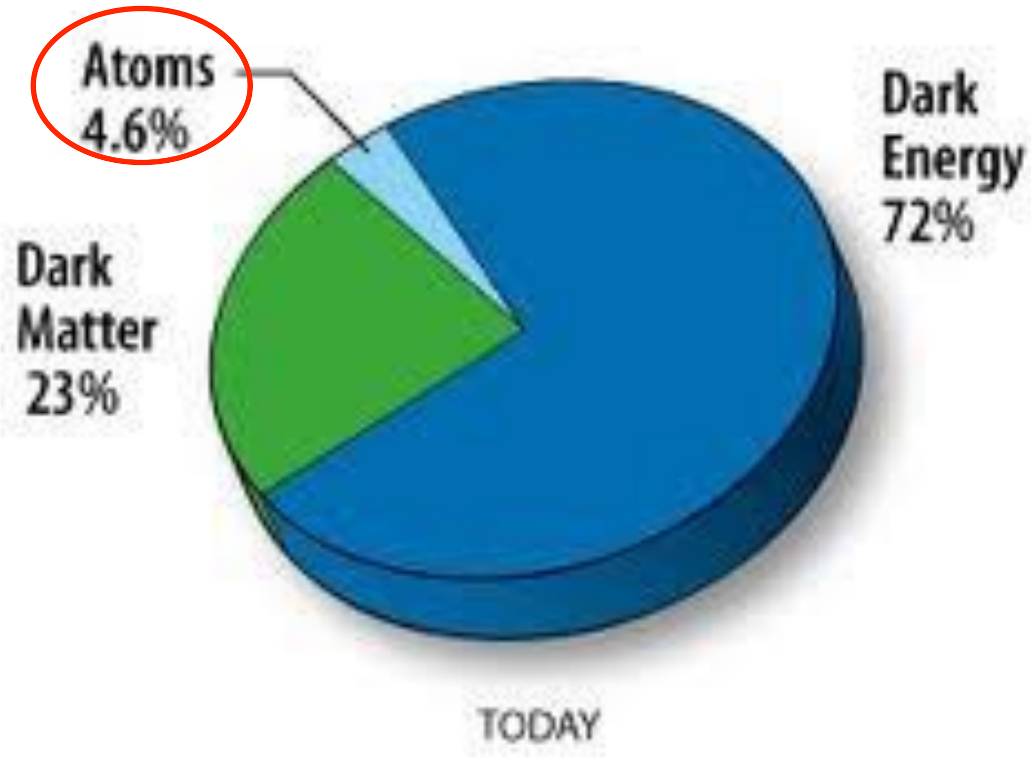
We do not know!

The Cosmic Puzzle of Ω_B

—Dark secret of the visible matter

The triple puzzle about cosmic matter:

- **Baryon (atomic matter):** $\Omega_B \approx 4\%$
- **Dark Matter:** $\Omega_{DM} \approx 23\%$
- **Coincidence:** $\Omega_{DM} \sim \Omega_B$



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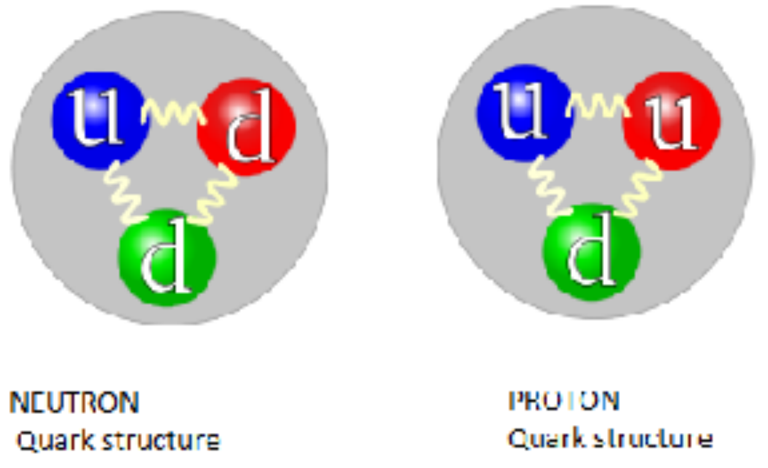

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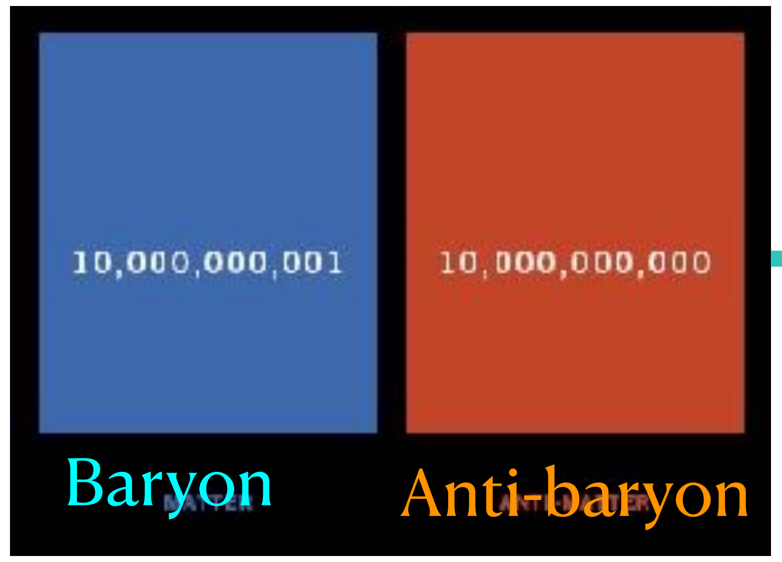

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The "coincidence": A deep connection between Ω_{DM} and Ω_B?

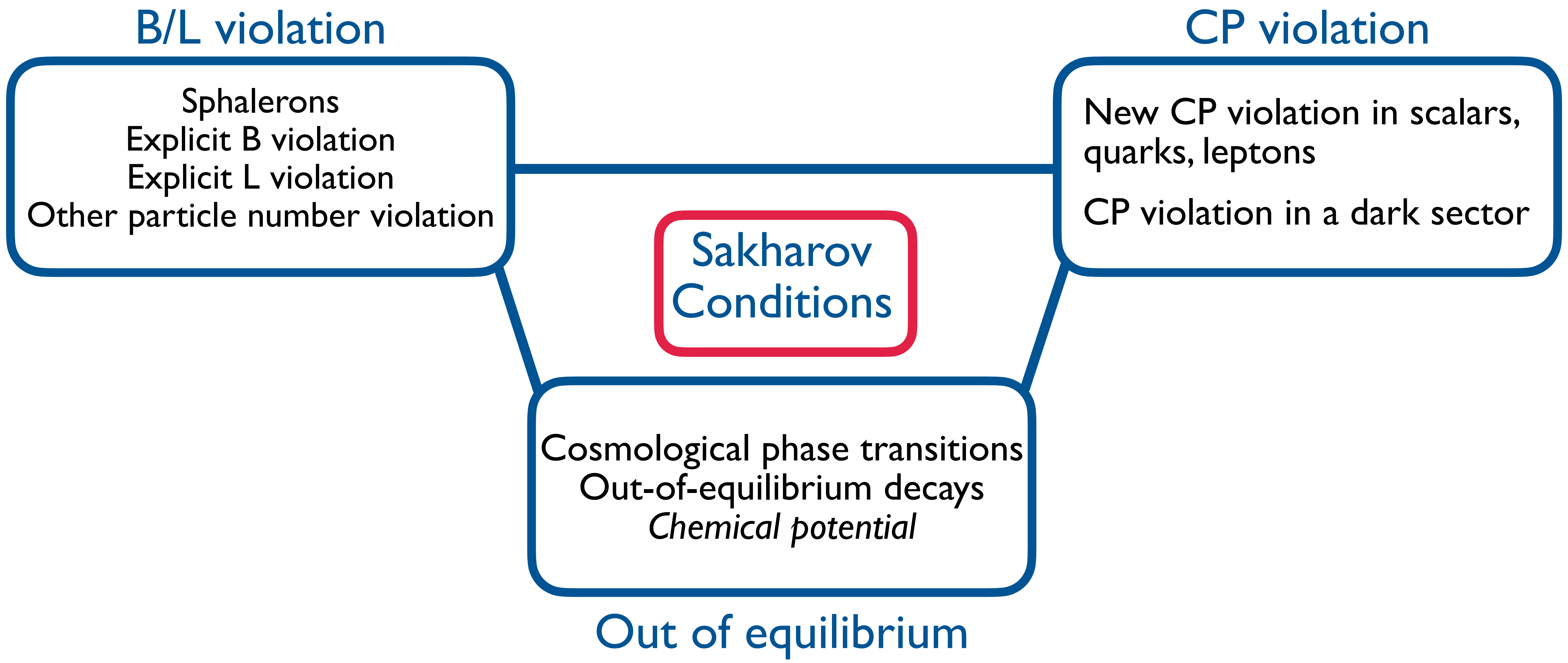
Baryogenesis

- **What is origin of the matter-antimatter asymmetry? (Baryogenesis)**

— the Universe starts with $B = 0$ *(inflation)* $\xrightarrow{?} B \neq 0$

- **Sakharov conditions for BG (1967):** B violation, CP violation, out of equilibrium

Requires BSM new physics to explain $\Omega_B \approx 4\,\%$!



Examples of BSM ingredients evoked to satisfy Sakharov conditions and explain Ω_B (arxiv: 2203.05010)

Traditional Baryogenesis

— Model and Pheno

A general summary of representative BG mechanisms developed in the past decades

(Not a complete list!)

- **GUT baryogenesis:** decay of GUT scale massive particles; challenged by constraints on inflation scale and subsequent T_{RH} ; direct test challenging (high scale)
- **Electroweak baryogenesis**: EW sphaleron + bubble collisions during 1st order PT; minimal models ruled out (SM+MSSM) with LHC data *(extensions being investigated)*
- **Leptogenesis:** decay of heavy RH neutrinos; intriguing connection to neutrino physics (Seesaw); direct test challenging (high scale)
- **Affleck-Dine baryogenesis:** evolution/decay of the VEV of scalar condensates in SUSY models; direct test challenging (high scale)

— Well-studied, well-motivated, attractive models; yet some challenged by recent data, others are yet challenging to test (indirect signals better studied: e.g. EDM, $n-\bar{n}$ oscillation, proton decay)

☞ Further pursuits are required!

New Developments on Baryogenesis

Recent progress in solving the Ω_B puzzle, driven by:

- **Big question persists:** Ω_B no less important than Ω_{DM} !
- **Some of the paradigms challenged/constrained by recent data:** e.g. GUT BG, minimal EWGB; new theoretical ideas beyond the known: worthy intellectual pursuit
- Traditional mechanisms typically assume high scale: BG at T_{EW} (100 GeV) or much higher; In reality, BG can occur as late as just before BBN (MeV)!
  ☞ The uncharted/under-explored low-scale BG landscape (theory and observables)!
- Traditional mechanisms generally involve very high energy physics ($\gg \Lambda_{EW}$): challenging/impossible to directly test with terrestrial probes
  ★ Imprints from the very early/high energy Universe? New opportunity with the era of precision cosmology/astrophysics observatories (CMB, LSS...) + gravitational wave astronomy!
- Increasing attention on **the coincidence problem**: $\Omega_B \sim \Omega_{DM}$ (e.g. asymmetric DM), connection/inspiration/synergy with recent developments in dark matter studies?

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✤ Echos the recent developments in DM studies, driven by: increasing constraints on WIMP paradigm + new signals with new experimental designs/technology

A Snowmass White Paper (arxiv: 2203.05010)

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

New Ideas in Baryogenesis: A Snowmass White Paper

Editors: Gilly Elor,[1] Julia Harz,[2] Seyda Ipek,[3] Bibhushan Shakya.[4]

Authors: Nikita Blinov,[5] Raymond T. Co,[6] Yanou Cui,[7] Arnab Dasgupta,[8] Hooman Davoudiasl,[9] Fatemeh Elahi,[1] Gilly Elor,[1] Kåre Fridell,[2] Akshay Ghalsasi,[8] Keisuke Harigaya,[10] Julia Harz,[2] Chandan Hati,[2] Peisi Huang,[11] Seyda Ipek,[3] Azadeh Maleknejad,[10] Robert McGehee,[12] David E. Morrissey,[13] Kai Schmitz,[10] Bibhushan Shakya,[4] Michael Shamma,[13] Brian Shuve,[14] David Tucker-Smith,[15] Jorinde van de Vis,[4] Graham White.[16]

- **New ideas in BG models**
- **New ideas in testing traditional BG models**

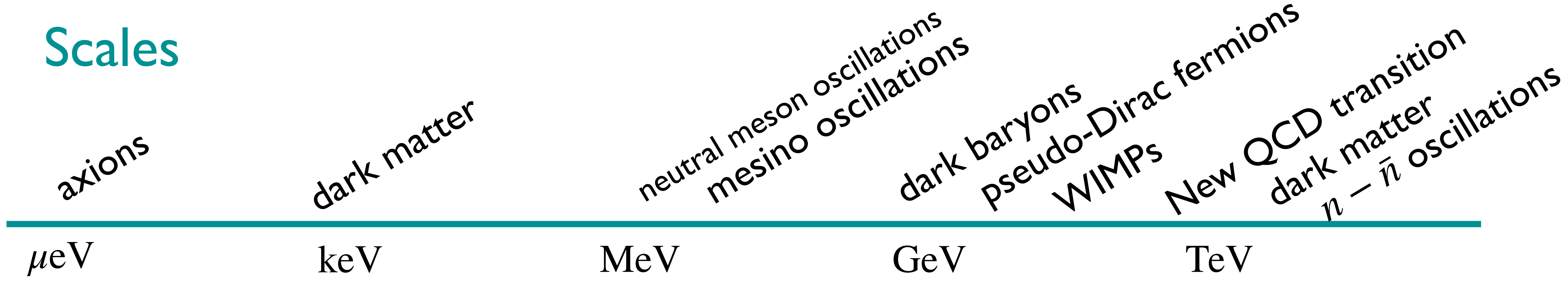
New physics ingredients

B/L violation	*CP* violation	Out-of-equilibrium conditions
Dark baryons RPV terms Sphalerons Direct B/L violation	Axions CKM phase Oscillations DM oscillations DM chemical potential CPV couplings	Freeze-in processes Long-lived particles QCD phase transition EW phase transition Particle decays

Observables

LLP searches; exotic hadron decays; same-sign dilepton asymmetry; new SU(3)-charged particles; new scalar-Higgs mixing; same-sign tops; $0\nu\beta\beta$ decay; missing momentum; induced nucleon decays; Higgs triple coupling; lepton flavor violation; multijet signals; CPV observables at B factories + LHCb; gravitational waves; structure formation; X-ray signals; $n-\bar{n}$ oscillations

Scales



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Contents

Many great new ideas!

Outline: A Glimpse of New Developments on Baryogenesis

Disclaimer: this is a small, representative sampler set! See our Snowmass WP for many other examples

- **New ideas in baryogenesis models:**
  - WIMP triggered BG and variations, e.g. WIMP cogenesis, Dark freezeout cogenesis
  - Axiogenesis

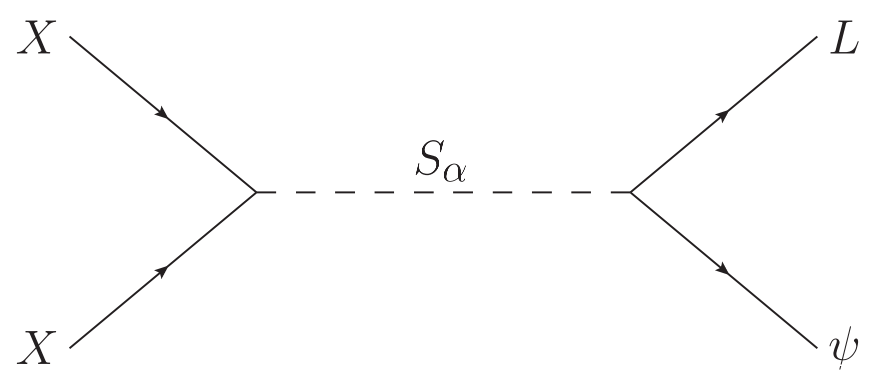
- **New ideas in testing traditional baryogenesis models:**
  - Cosmological probes for high scale leptogenesis: cosmological collider physics (LSS, 21 cm)
  - Gravitational waves as a probe for BG models: leptogenesis, EWBG, Affleck-Dine

New ideas in baryogenesis models

WIMP Triggered Baryogenesis-1

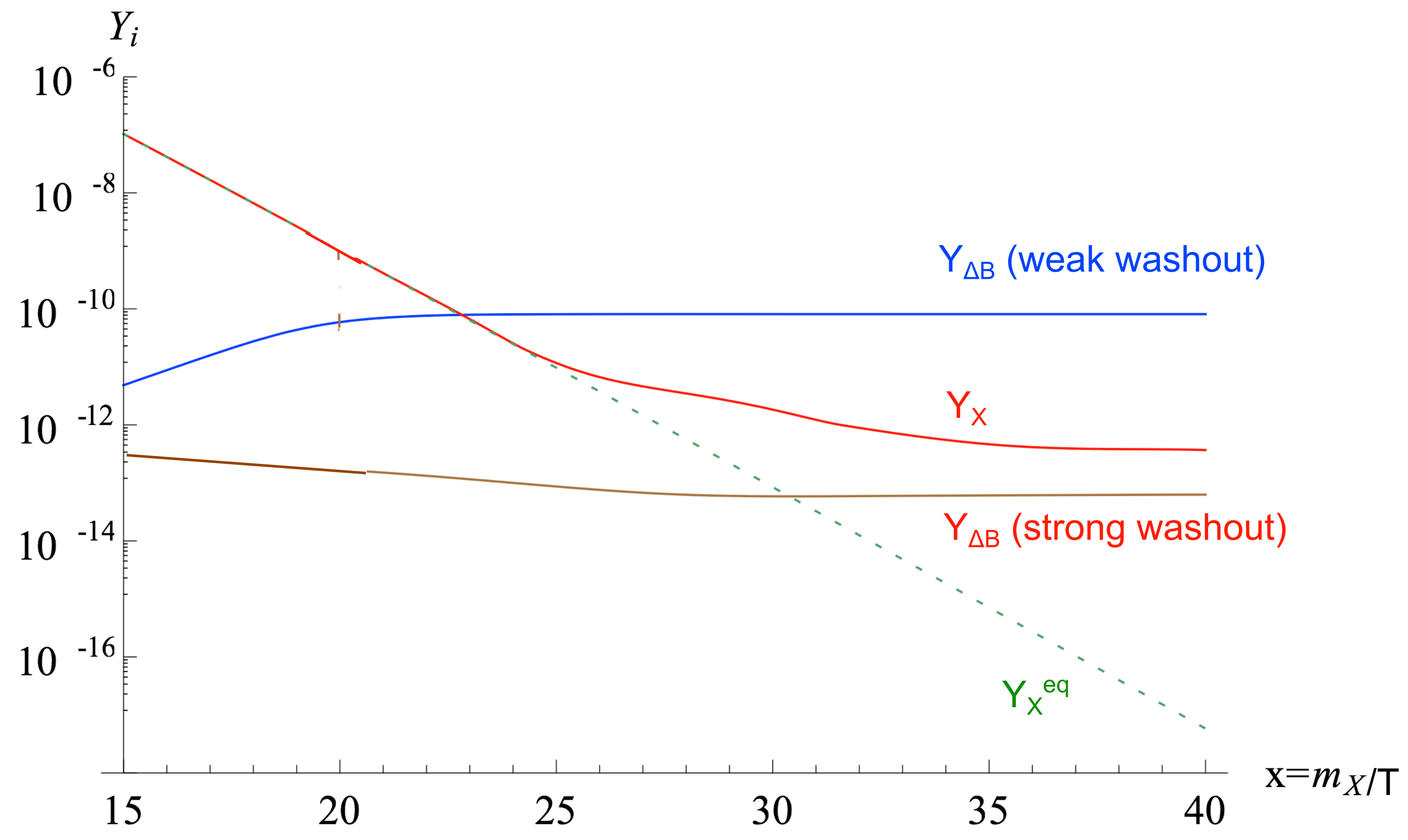
- **Motivation:** New mechanisms for addressing $\Omega_B \sim \Omega_{DM}$ *(alternative to asymmetric DM)*, while preserving the merit of WIMP miracle (the absolute Ω from thermal freezeout)
- **First attempt:** WIMP DM freeze-out (i.e. out-of-equilibrium annihilation) as a new way realizing Sakharov conditions for BG (vs. out-of equil decay)?

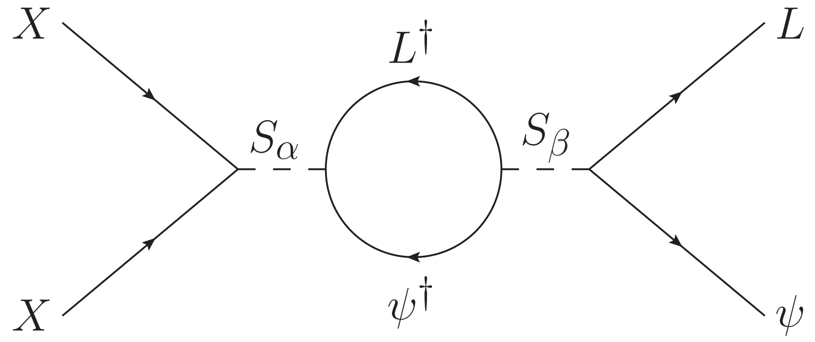
☞ **WIMPy Baryogenesis** *(YC w/L. Randall, B. Shuve 2011)*

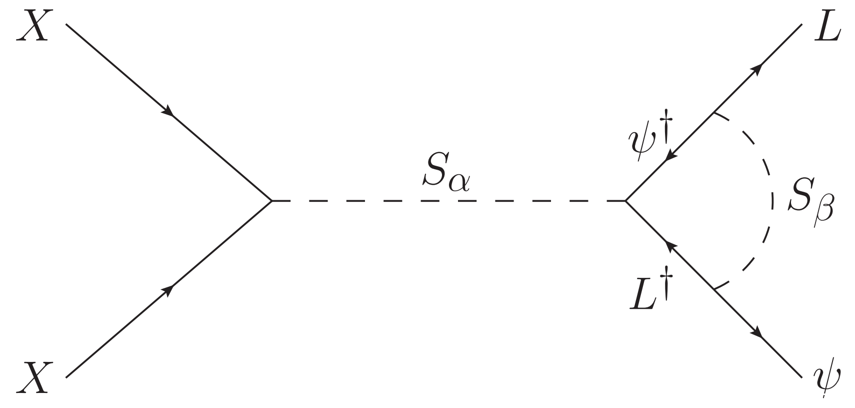


$\not{B}, \not{CP}$ encoded in the annihilation of DM X (tree-level+interference w/loop processes)

$\Rightarrow \Delta B$ generated during the X freezeout



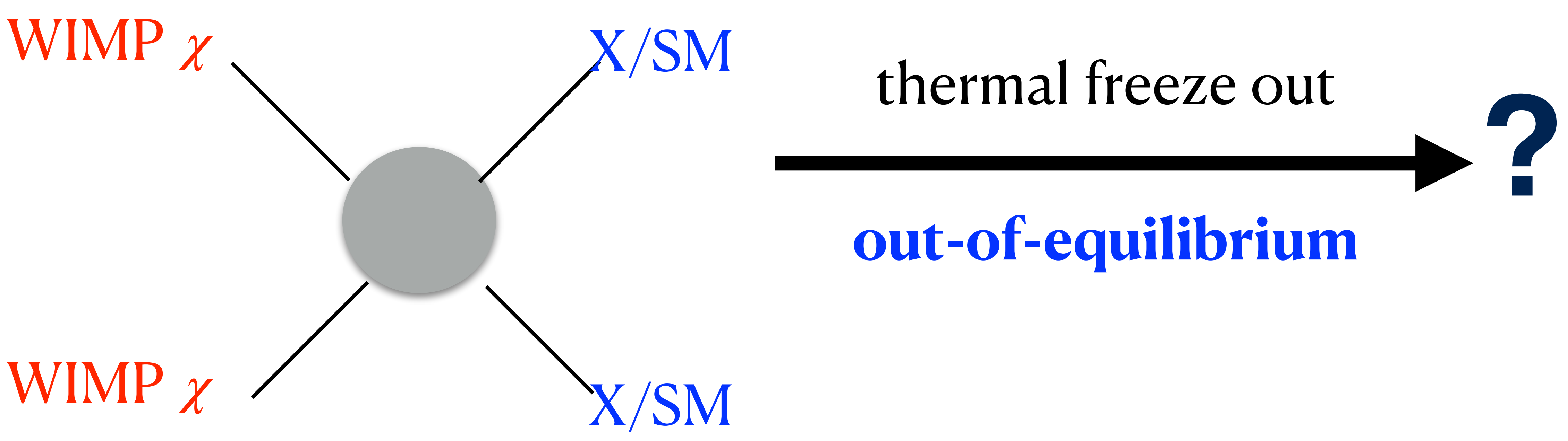




- Novel mechanism with close connection to DM physics + rich pheno: collider, DM detection, EDM...
- ΔB sensitive to details of washout process $\Rightarrow$ restricted parameter region

WIMP Triggered Baryogenesis-2

- **Baryogenesis from metastable WIMP decay** (YC w/R. Sundrum 2012): A robust WIMP miracle for baryons, post-f.o. decay of long-lived WIMP (not WIMP DM!) triggers BG, insensitive to washout details



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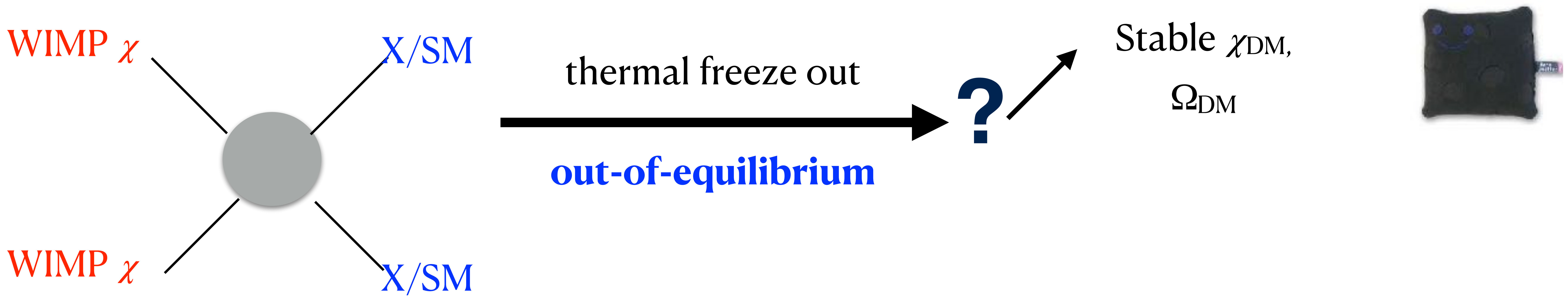

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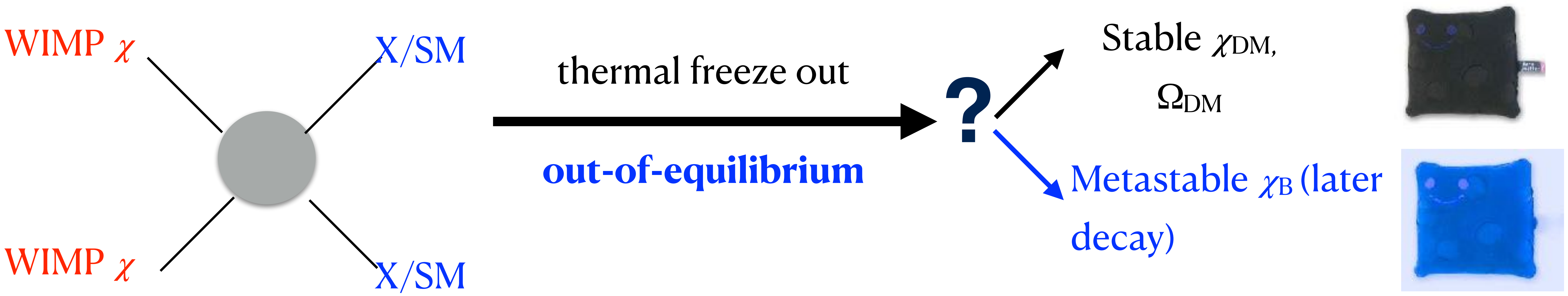

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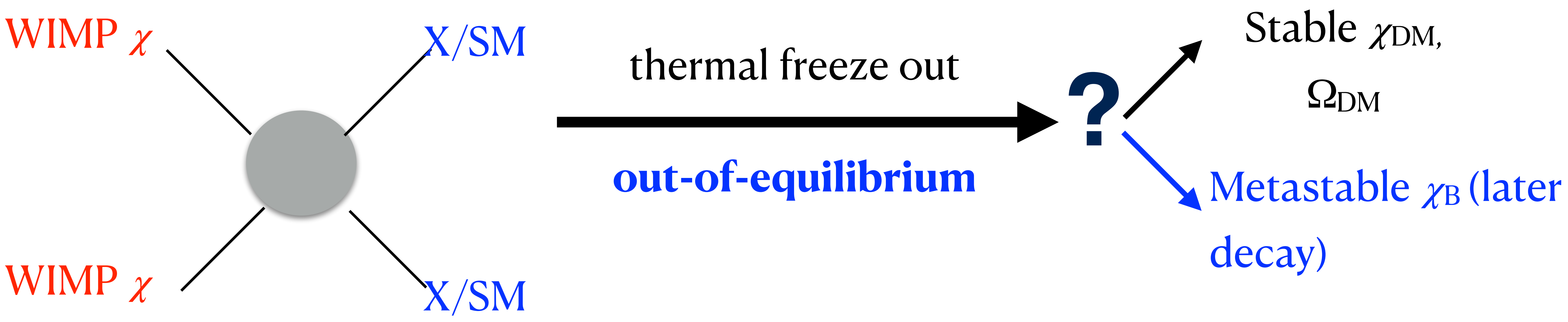

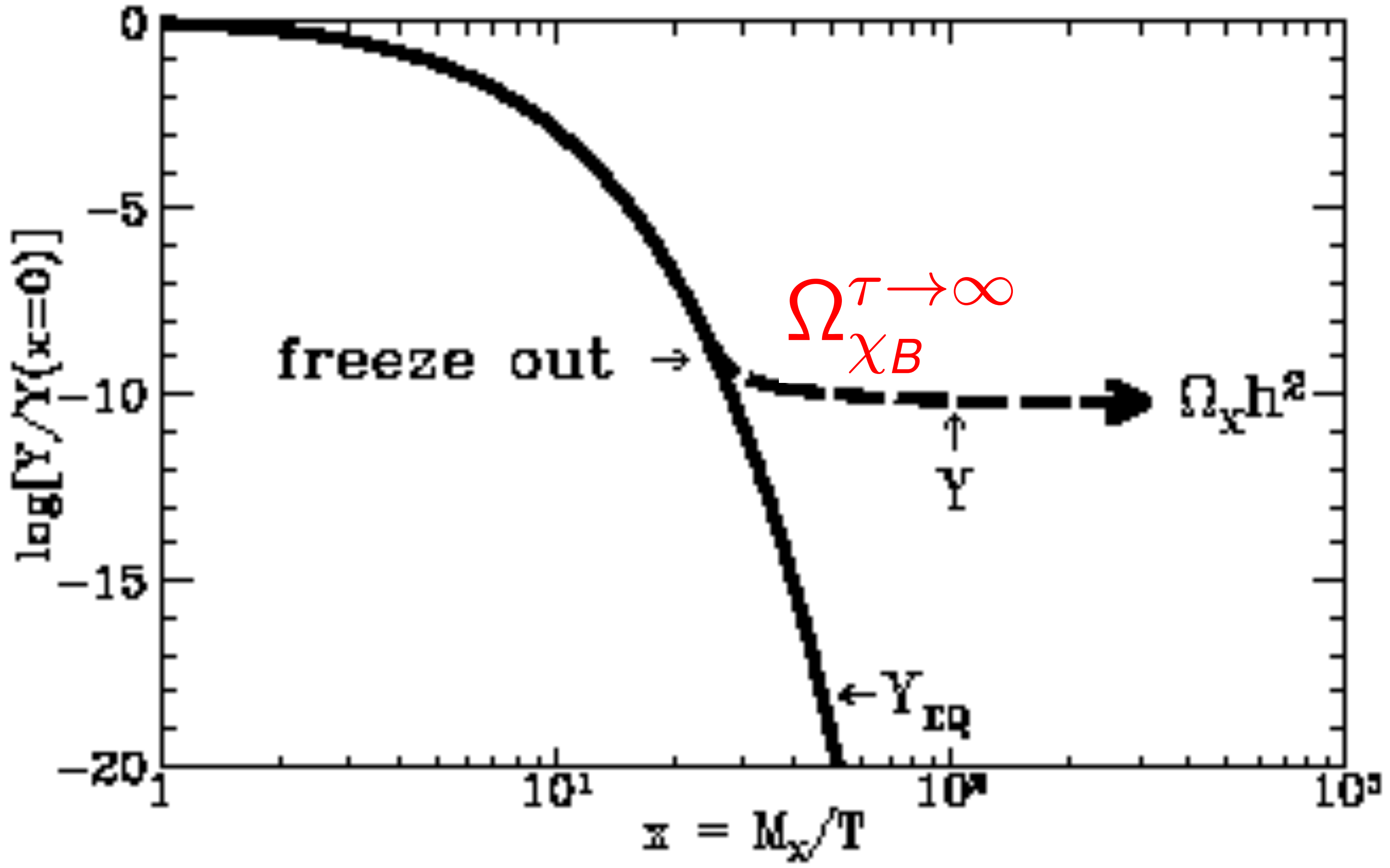

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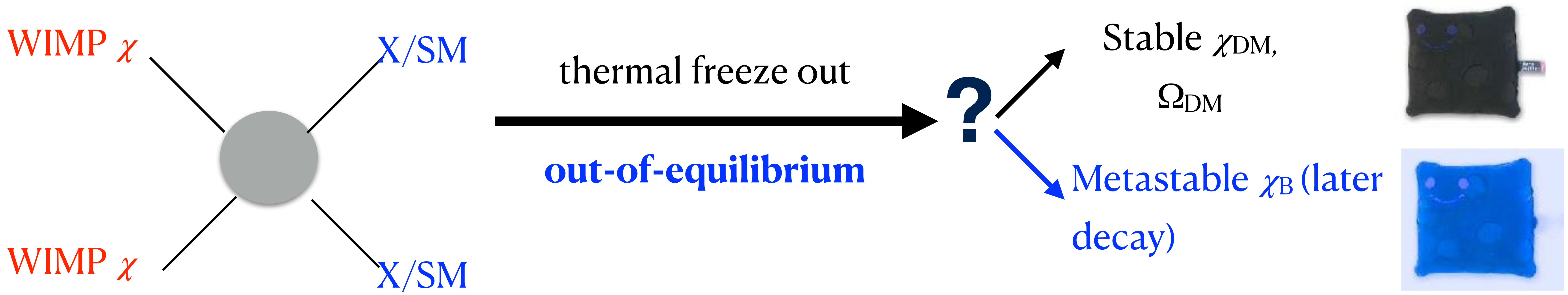

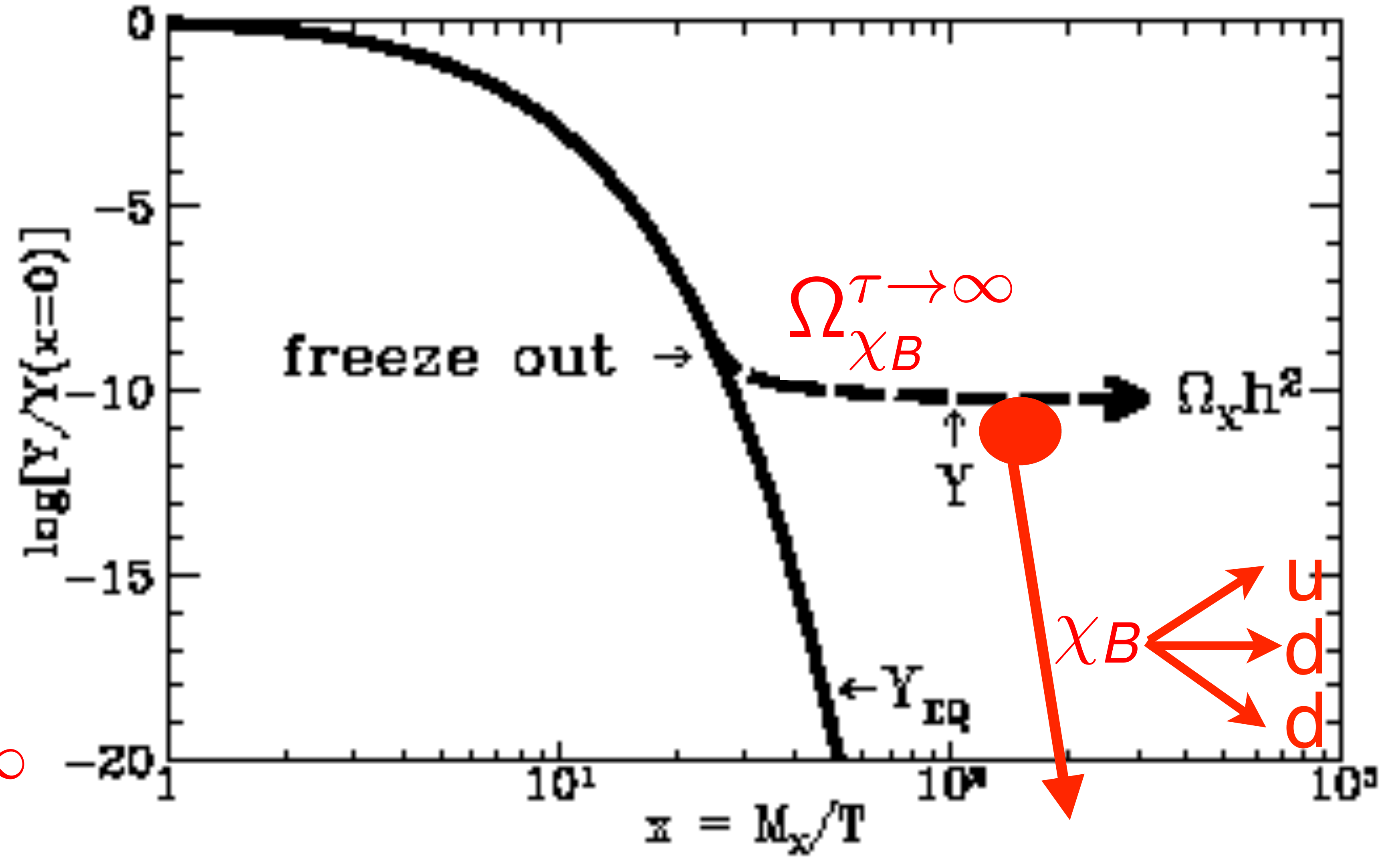

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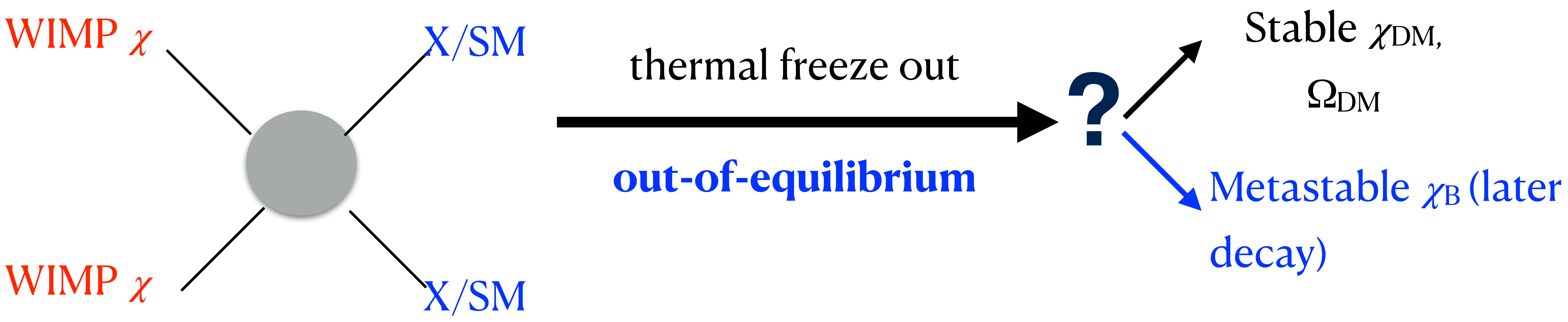

- **Novel baryogenesis**

  Ω_B ✅

- **Generalized WIMP miracle**

  (assume: + stable WIMP DM Ω_{DM} ✅)

  $\Omega_B \sim \Omega_{DM}$ ✅

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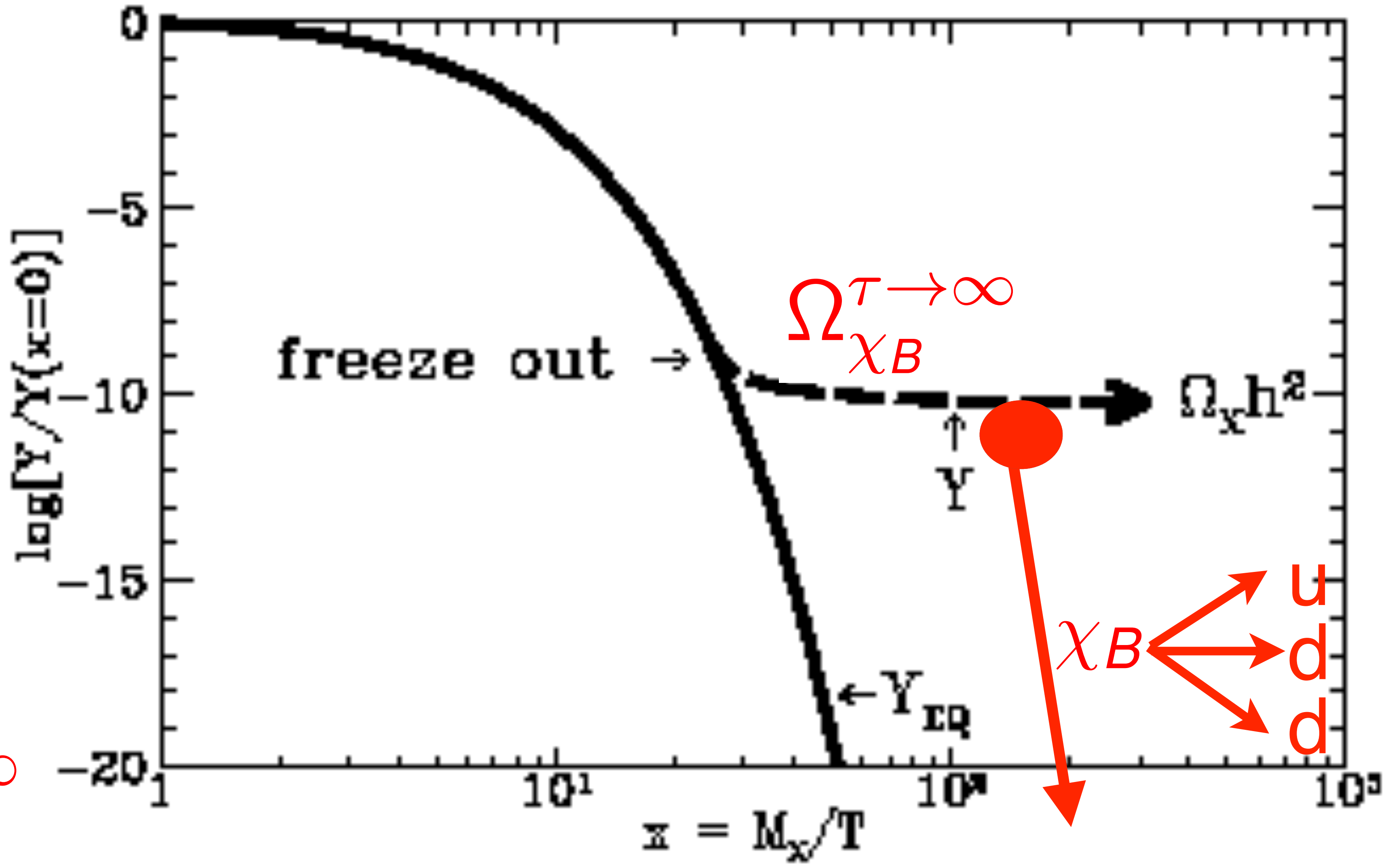

Baryogenesis from Metastable WIMP Decay

- **Realization in SUSY models:** in RPV MSSM+singlet (YC, Sundrum 2011), in mini-split MSSM with RPV (YC 2013)
- **Distinct collider phenomenology (LLP) with cosmological motivation** (YC, Shuve 2014)

For χ of weak scale mass, χ lives beyond its thermal freeze out time ☞ $\Gamma_\chi < H(T = M_\chi)$ ⟷ $c\tau_\chi \gtrsim \mathrm{mm}$ LHC tracking resolution!

— **A generic connection** between cosmological slow rates at T ~100 GeV and displaced vertices at colliders!

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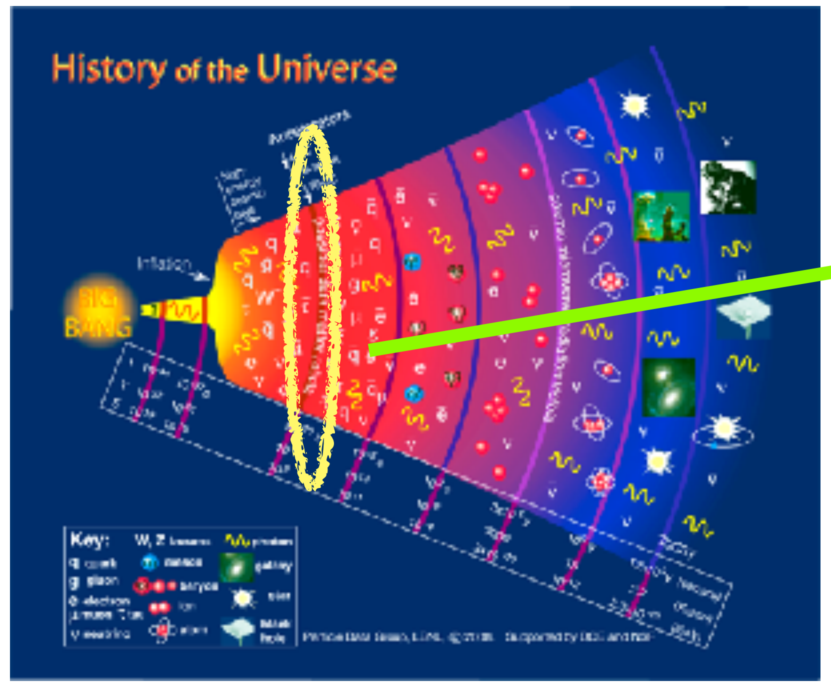

Our universe around EW phase transition was just slightly bigger than LHC tracking resolution!

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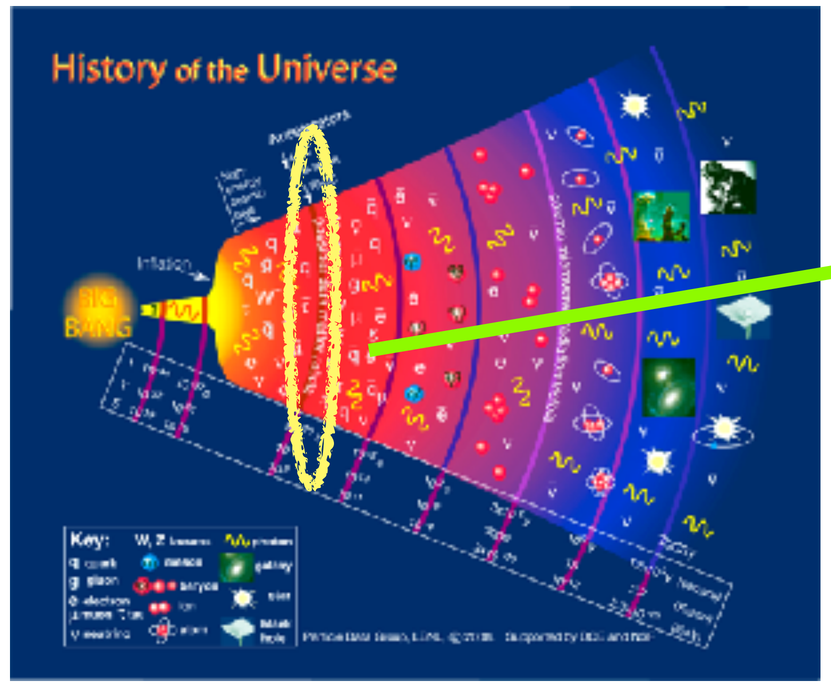

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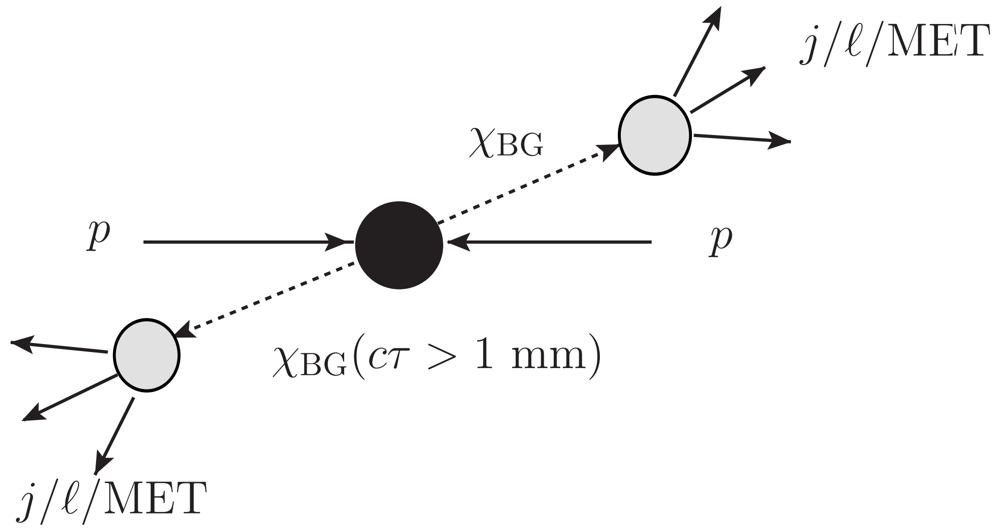
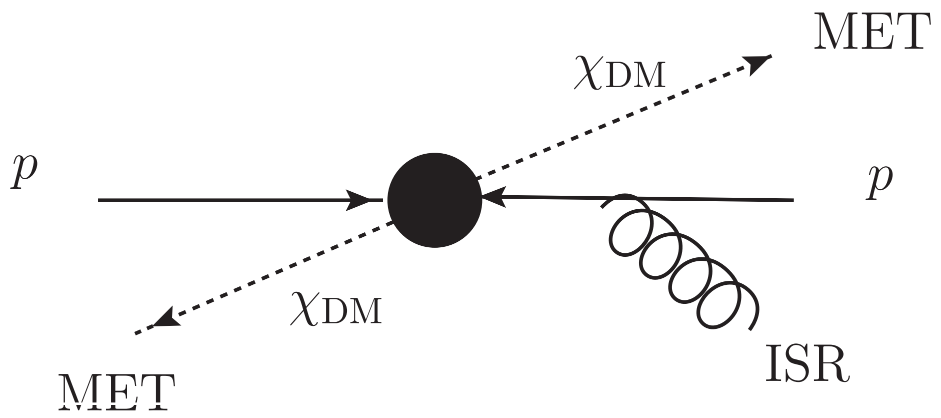
Reproduce early Universe BG at the LHC!

(WIMP BG adopted by ATLAS LLP WG as a benchmark →first official ATLAS report 2019)

Metastable WIMP baryon parent@LHC: displaced vertex



Stable WIMP DM@LHC: missing energy (analogy)



WIMP Cogenesis

Further development beyond WIMP BG-2: <u>incorporate specifics of dark matter</u>

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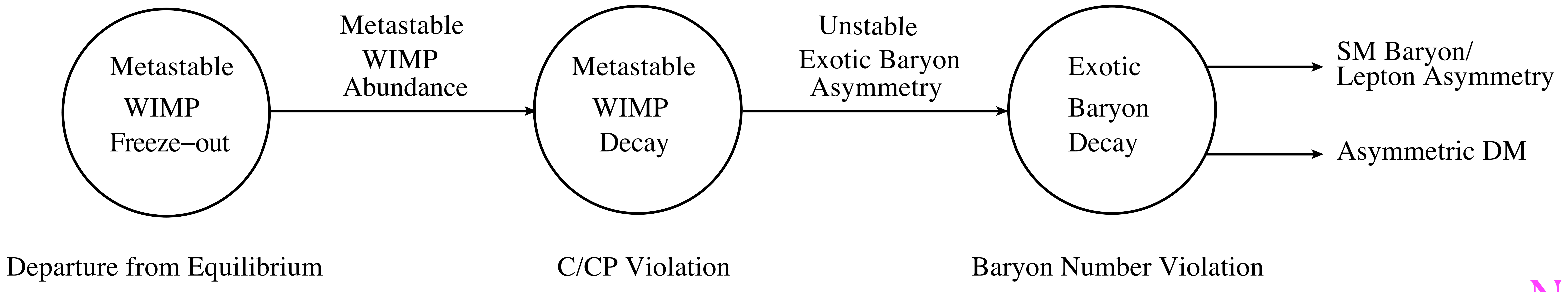
  —Echos: e.g. Davoudiasl et al. 2010 (Hylogenesis), YC&Randall, Shuve 2011



Three Sakharov conditions realized in sequential steps

$$\Omega_\chi(\infty) = \frac{2m_\chi s_0}{\rho_c}\epsilon_1 Y_{Y_1,\rm f.o.}$$
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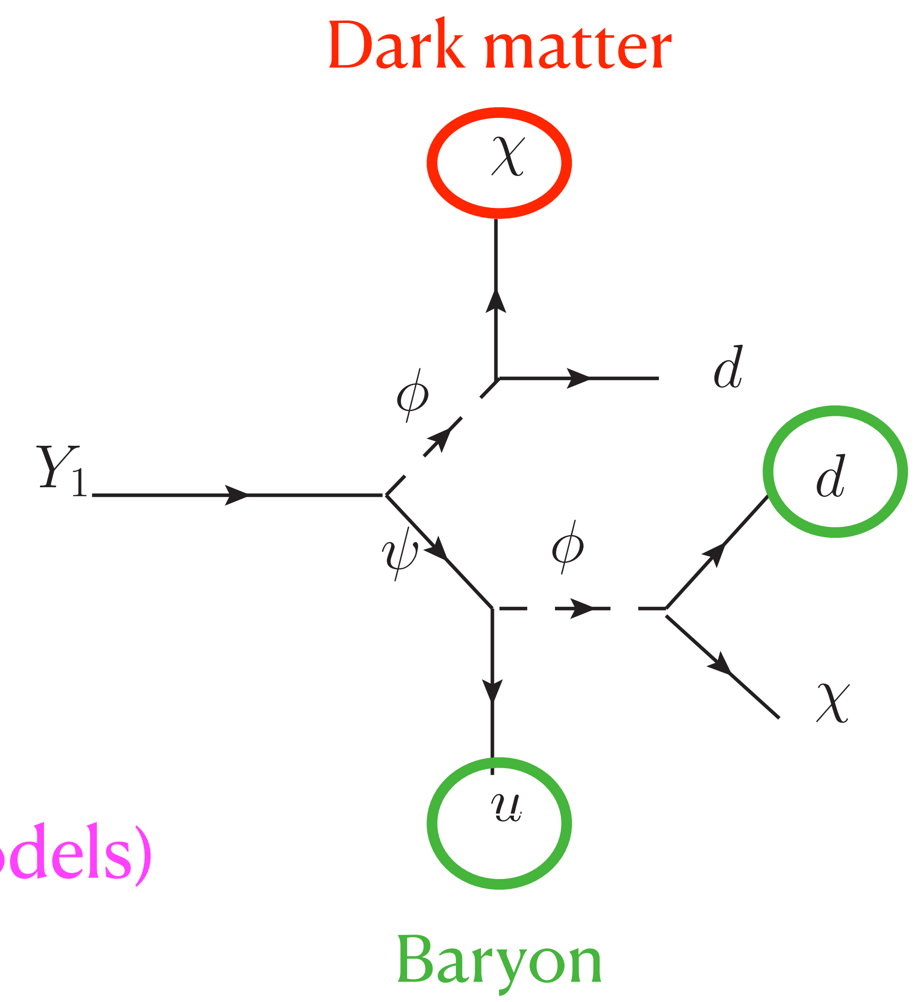
Neat prediction for sub-GeV-GeV ADM
(mechanism different from most ADM models)



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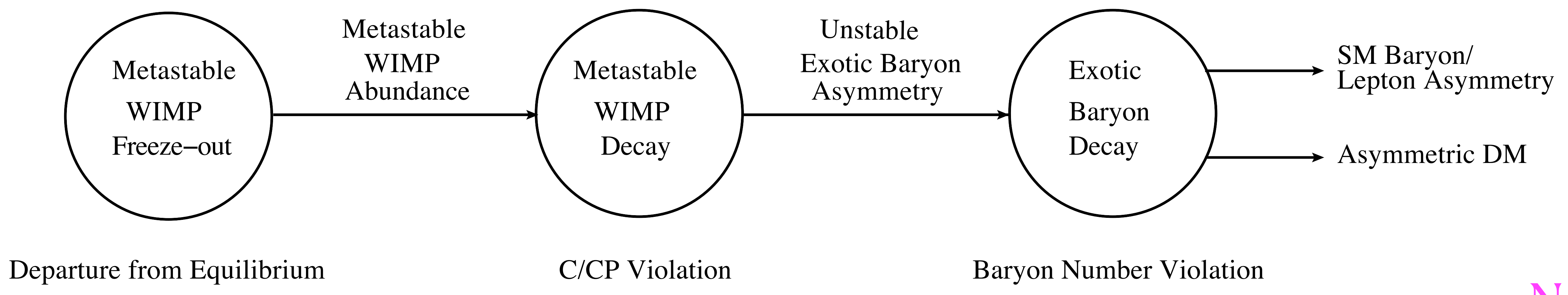

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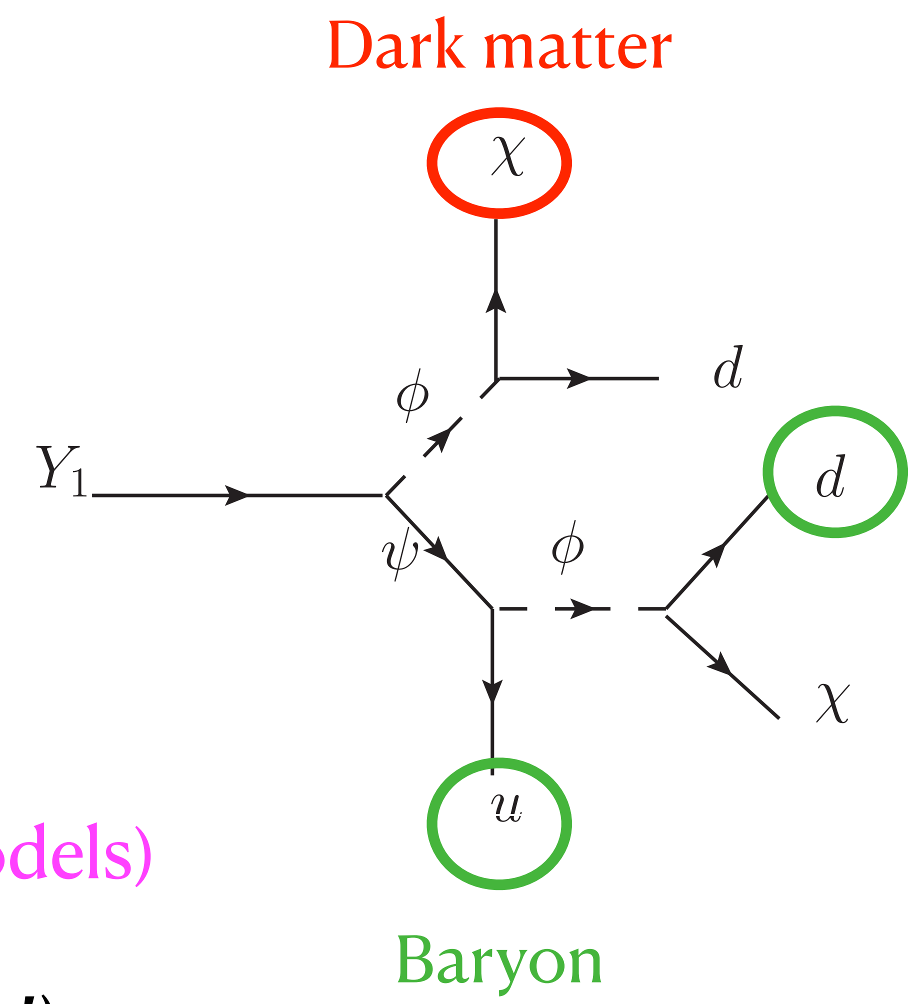
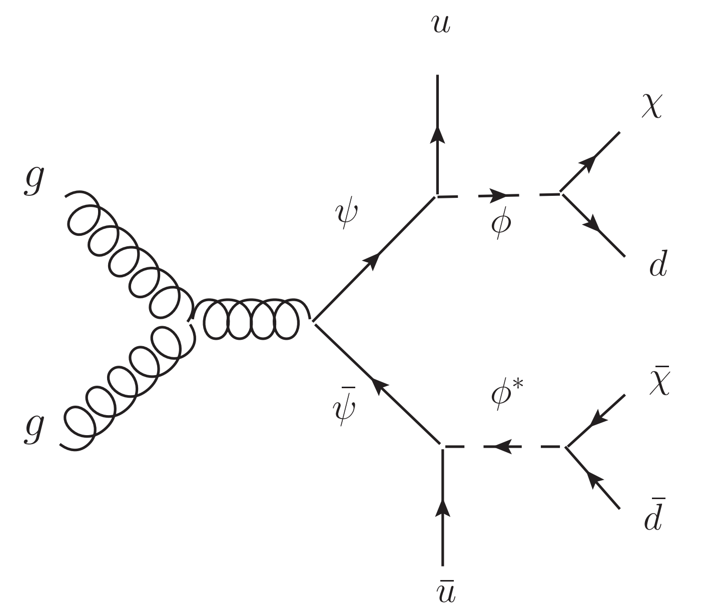
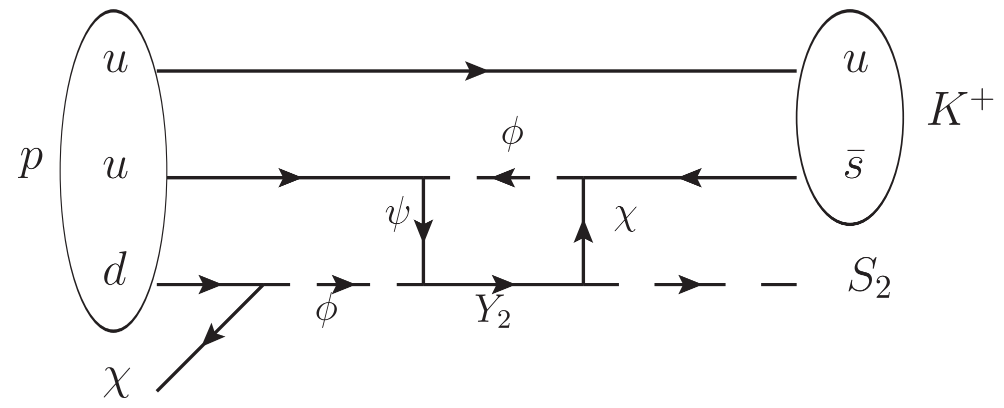
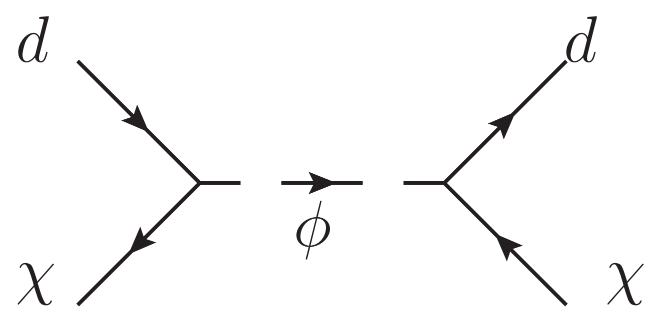


- Rich signals for LHC, induced nucleon decay, DM direct detection *(sub-GeV to GeV range!)*…







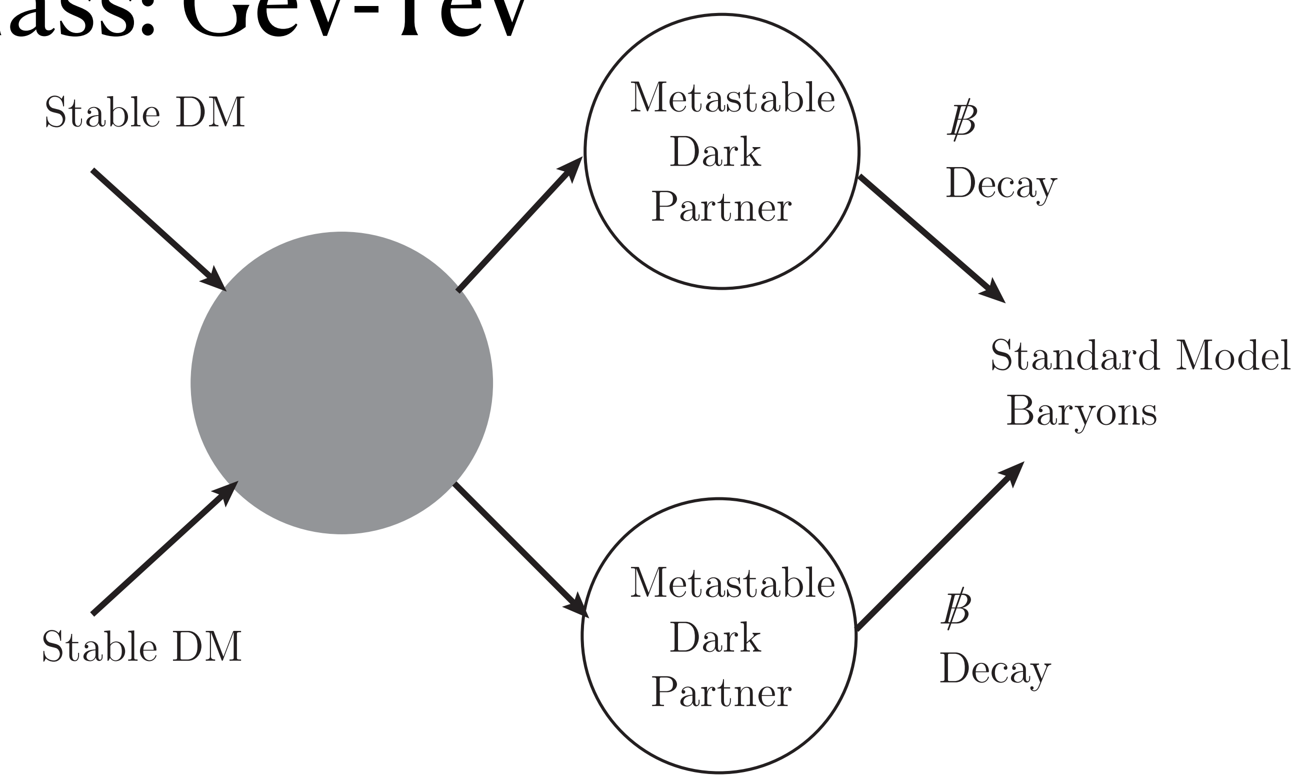
Dark Freeze-out Cogenesis

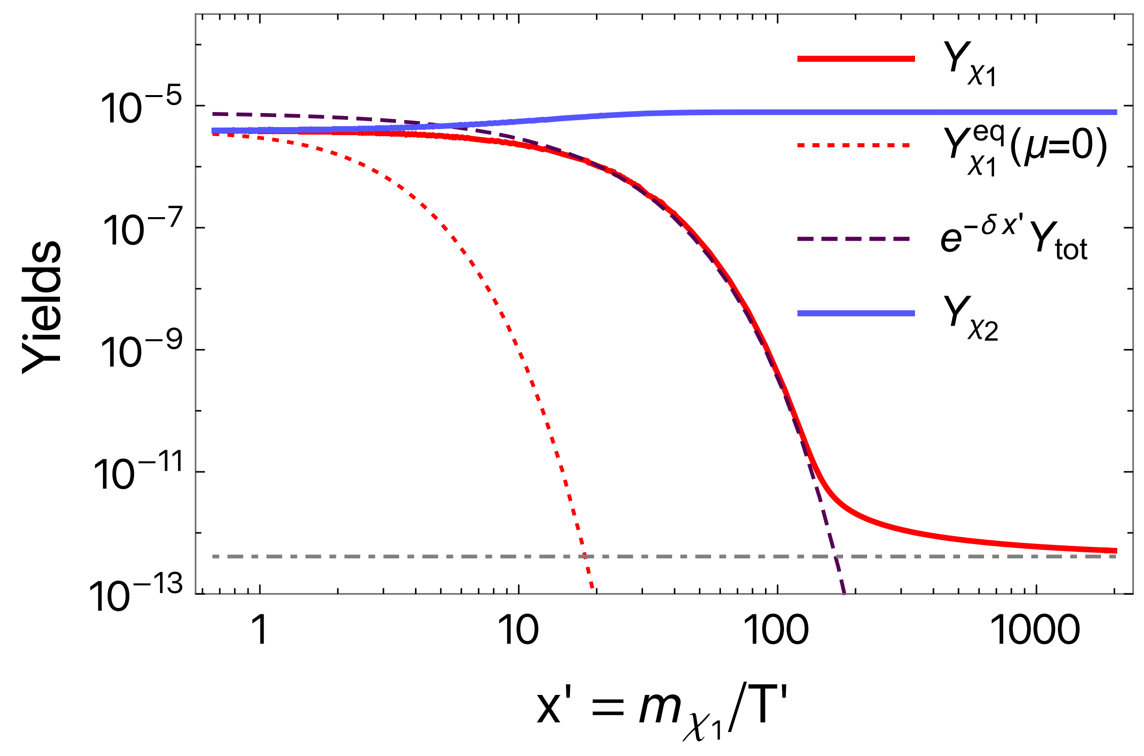
(Also see M. Shamma's parallel talk yesterday)

Further inspiration from WIMP BG: common origin of DM, baryons from a decoupled dark sector

☞ **Dark Freeze-out Cogenesis** *(X. Chu, YC, J. Pradler and Shamma 2112.10784 JHEP)*

- Freeze-out of DM via annihilating into a metastable dark partner $\Rightarrow \Omega_{DM}$ *(New f.o. dynamics! Conserved number in dark sector)* + Out-of-equilibrium condition for Ω_B *, via late decay of the dark partner*
- Accommodate wide range of DM mass: GeV-TeV





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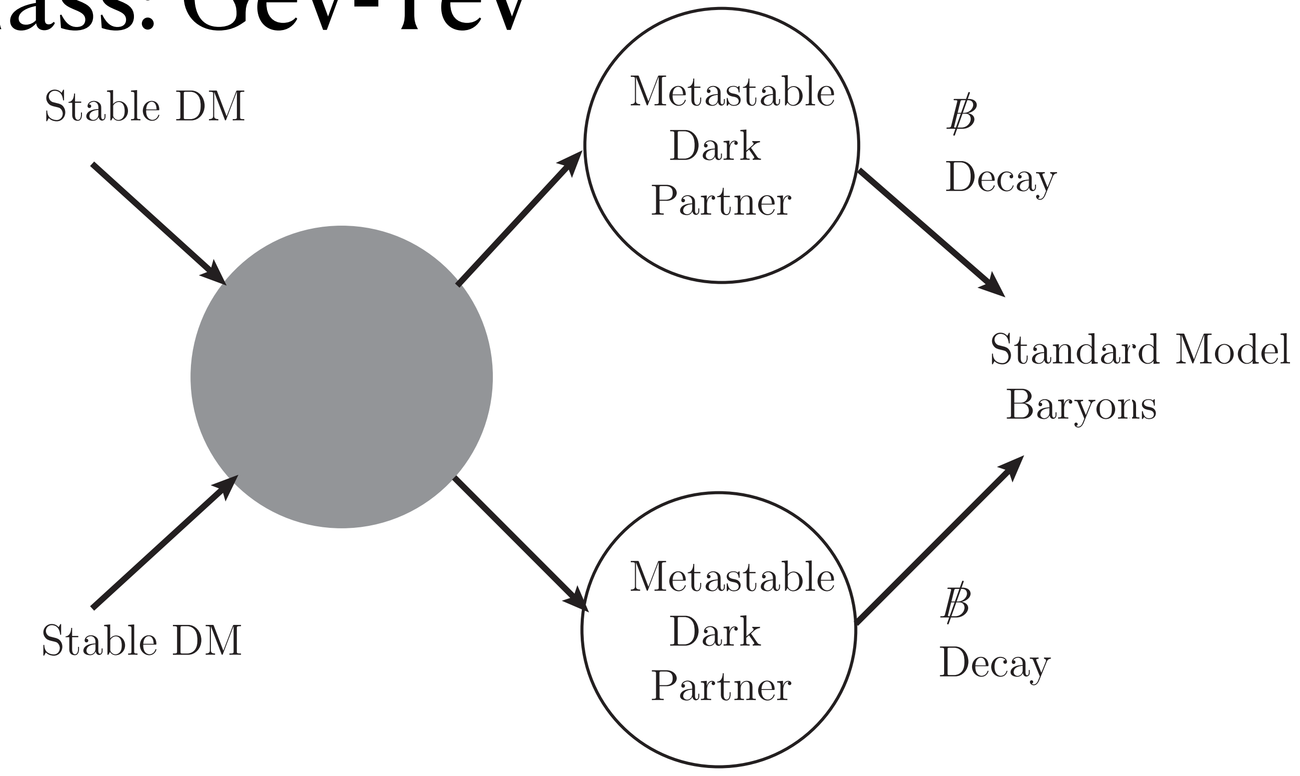
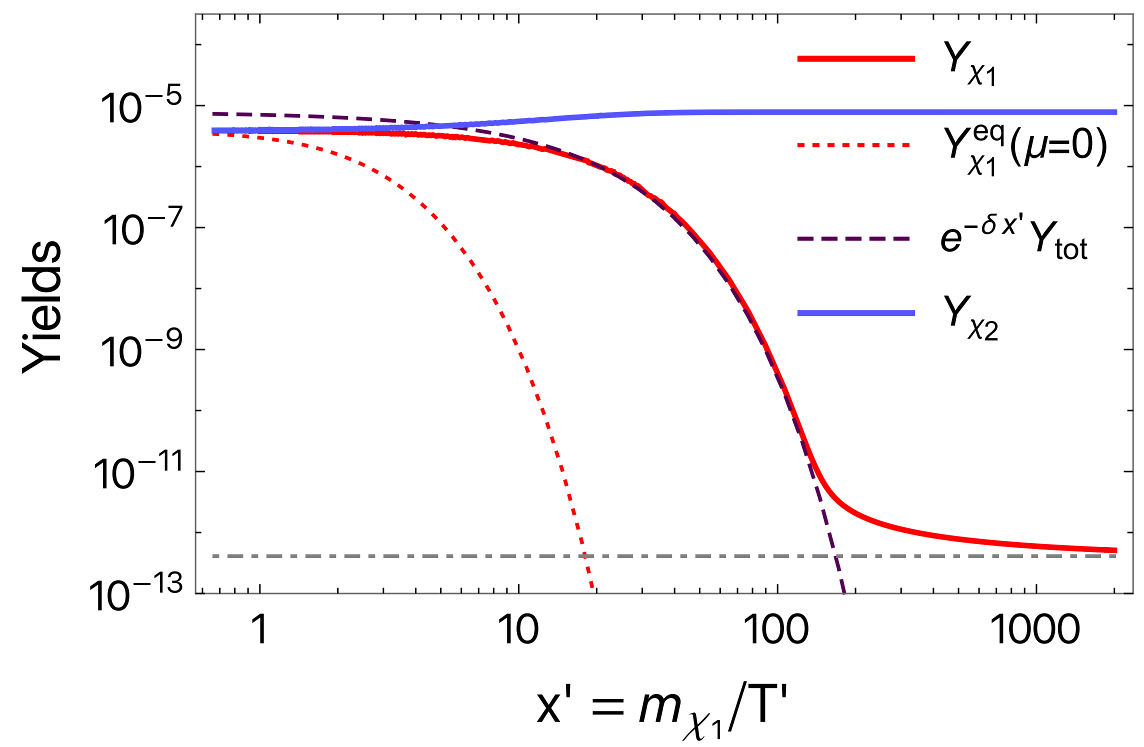
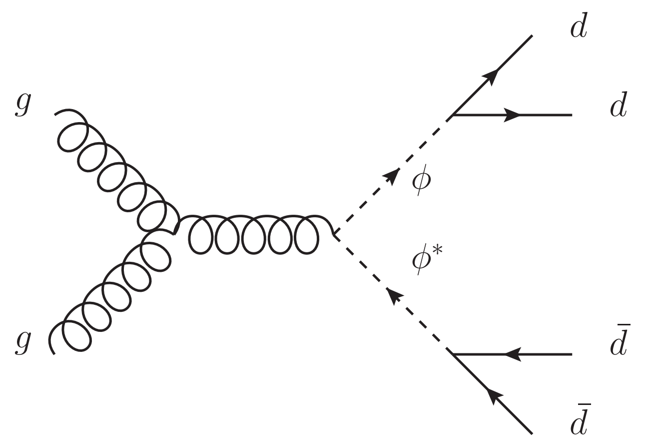
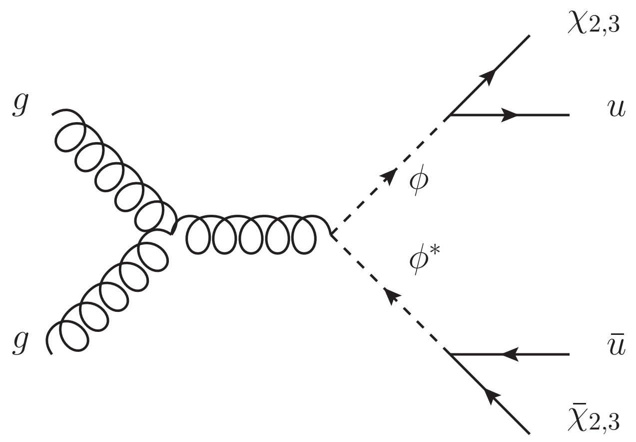
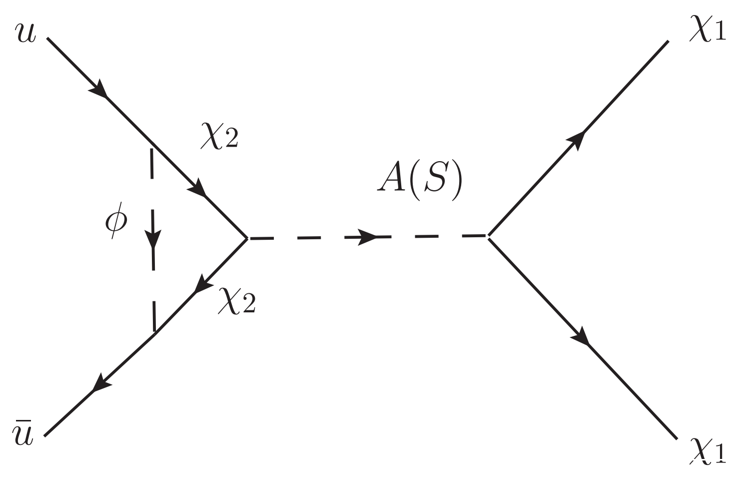


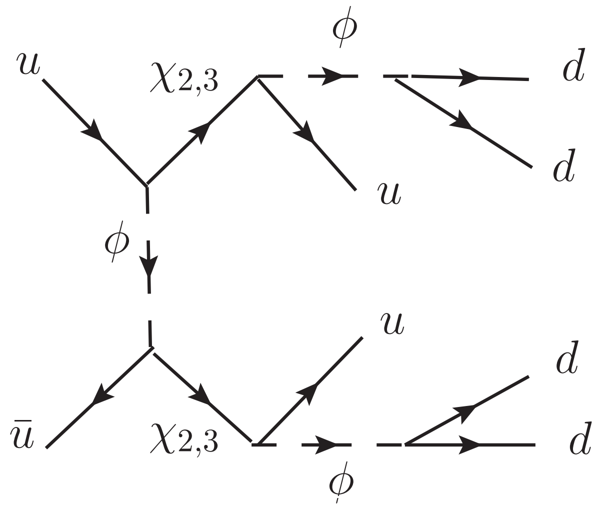


- Rich cosmology+pheno: Early matter dominated era driven by the metastable dark partner before its decay *(observable effect on structure formation)*, collider signals most promising with future high-E, high-Lum colliders









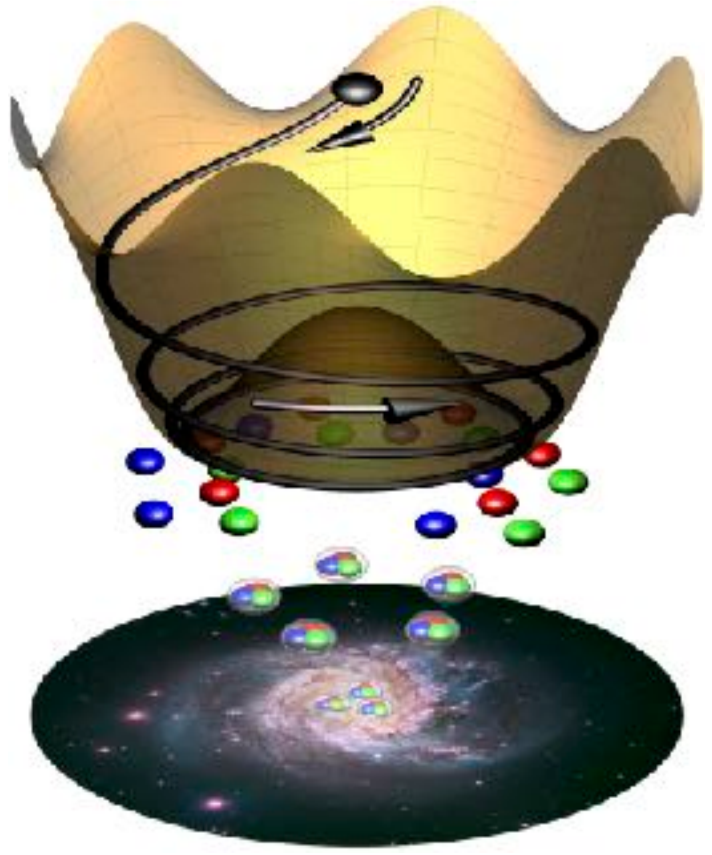
Axiogenesis

- **Kinetic misalignment** (Co, Hall and Harigaya 2019; Chia-Feng Chang and YC 2019)**:** Axion field with a non-zero initial velocity $\dot{\theta}_i \neq 0$ (vs. conventional misalignment: $\dot{\theta}_i = 0$), can originate from an explicit PQ breaking (OK/expected for an approximate, global symmetry) $\Rightarrow$ Alters the prediction for $\Omega_a(f_a)$

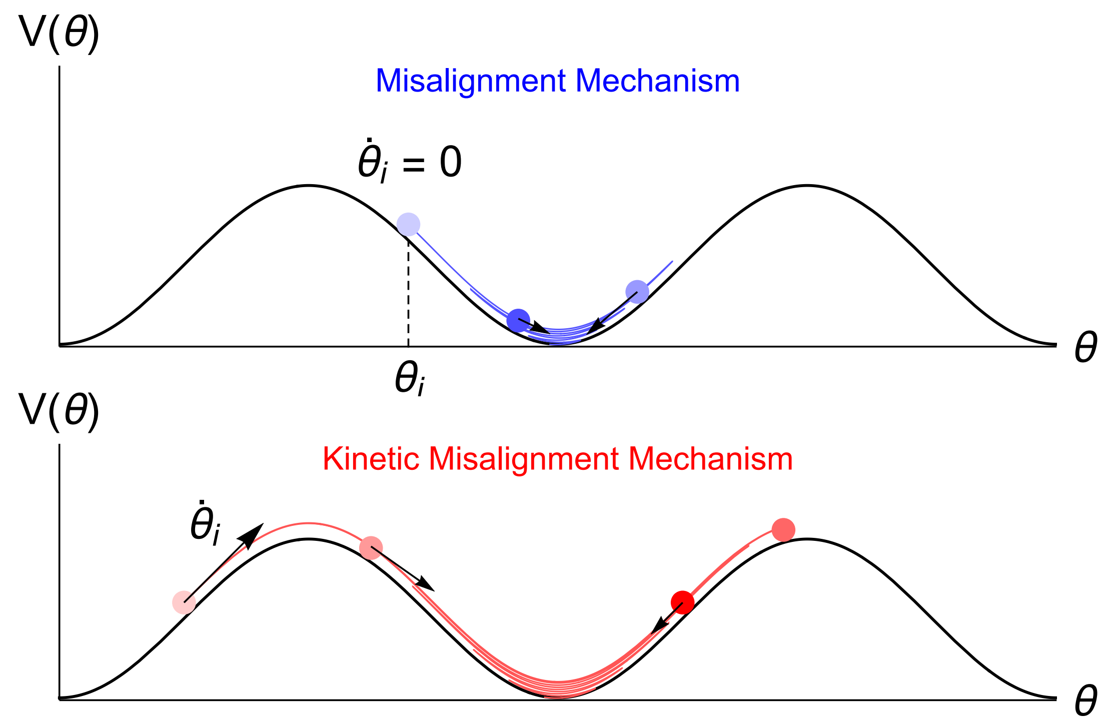
- **Axiogenesis** (Co and Harigaya 2019)**:** generate Ω_B in kinetic misalignment scenario

PQ charge ($\dot{\theta}_i \neq 0$) $\xrightarrow{\text{Strong sphaleron}}$ Quark chiral asymmetries $\xrightarrow{\text{EW sphaleron}}$ Baryon asymmetry

$$Y_B = \frac{n_B}{s} = \frac{45 c_B}{2 g_* \pi^2} \frac{\dot{\theta}}{T}\bigg|_{T=T_{\rm EW}}$$



Credit: Harigaya's website

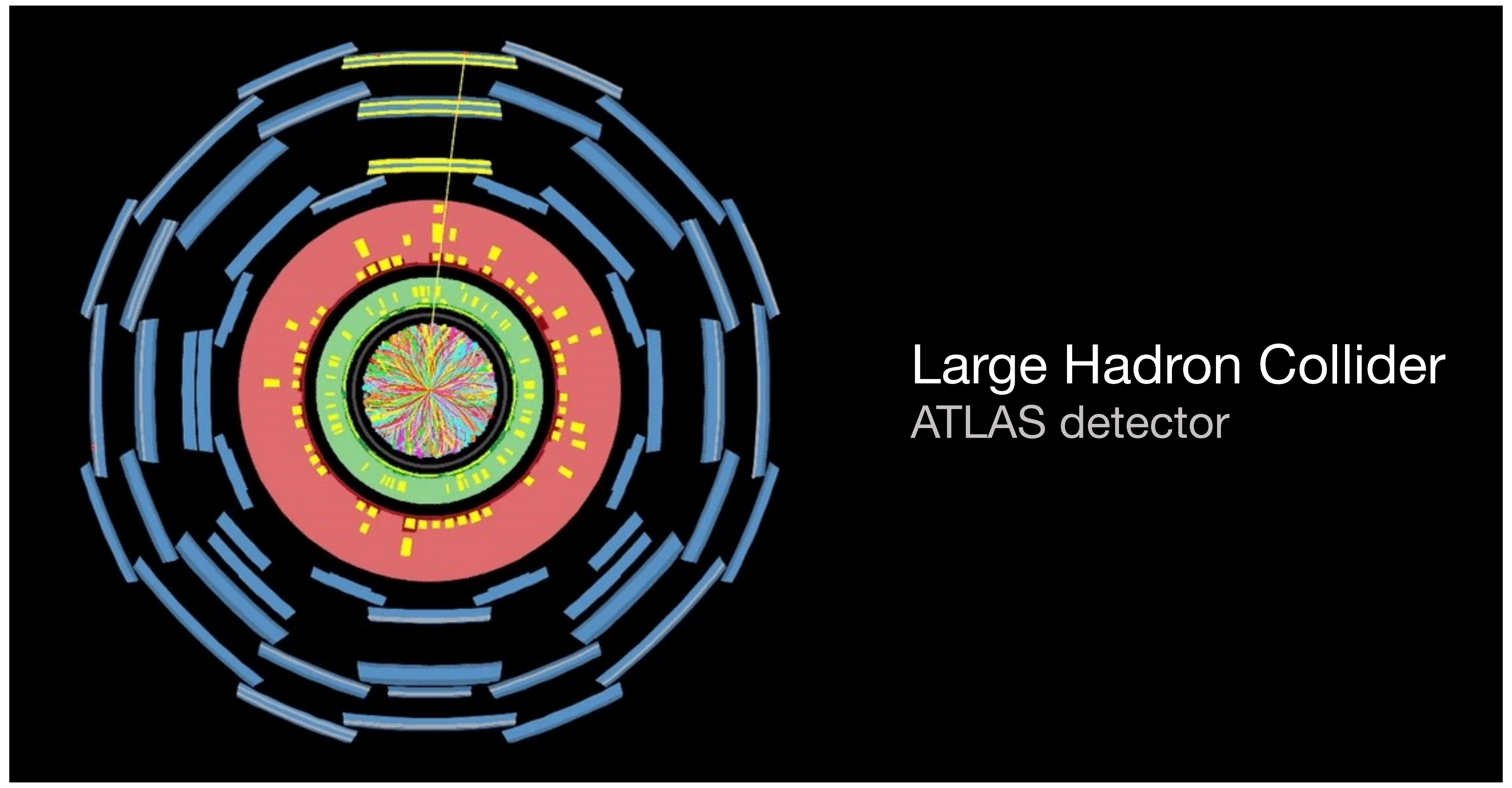


New ideas in testing traditional baryogenesis models

Probing Leptogenesis with the Cosmological Collider

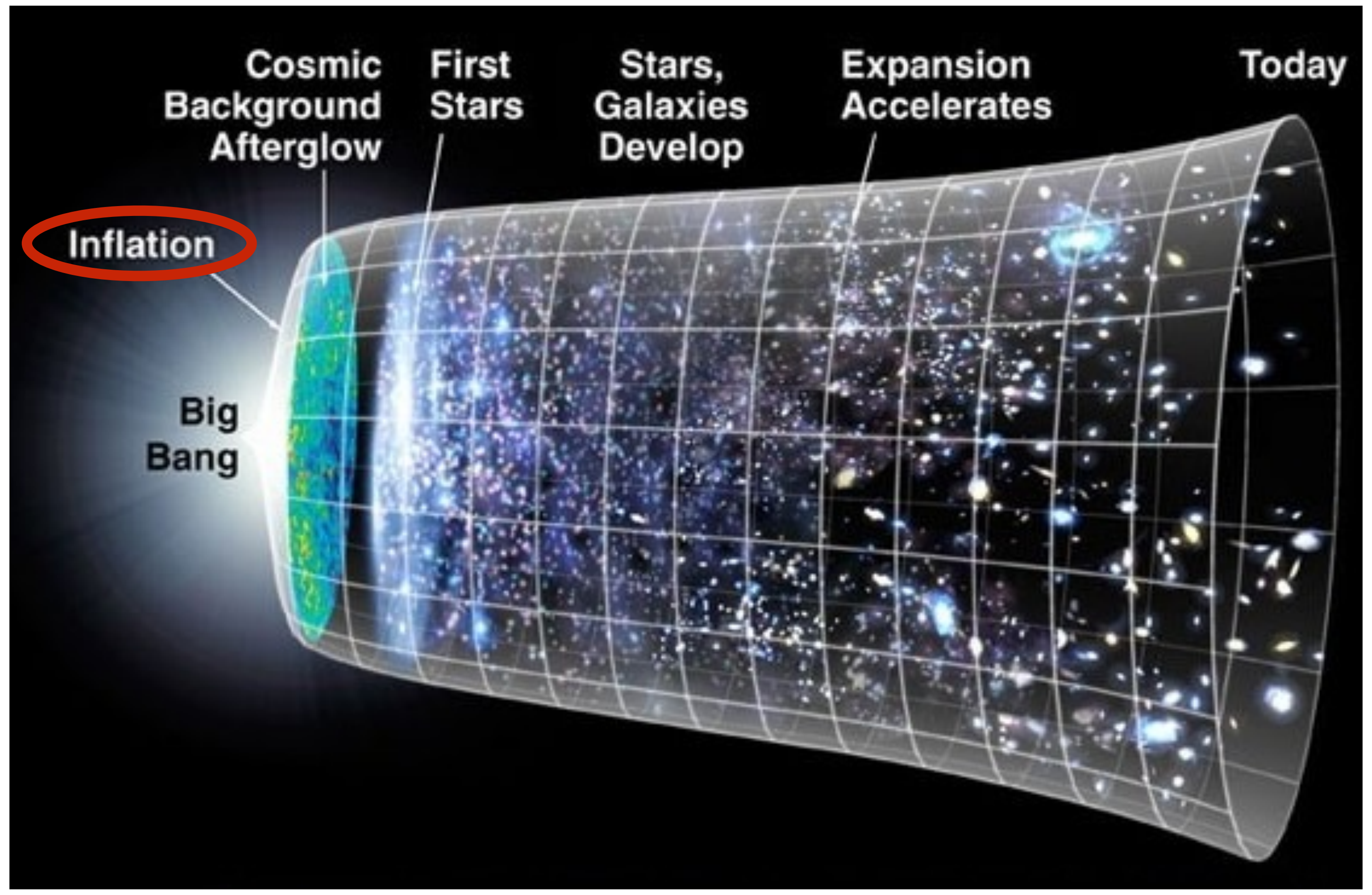
(arxiv: 2112.10793, submitted to PRL, YC w/Zhong-Zhi Xianyu)

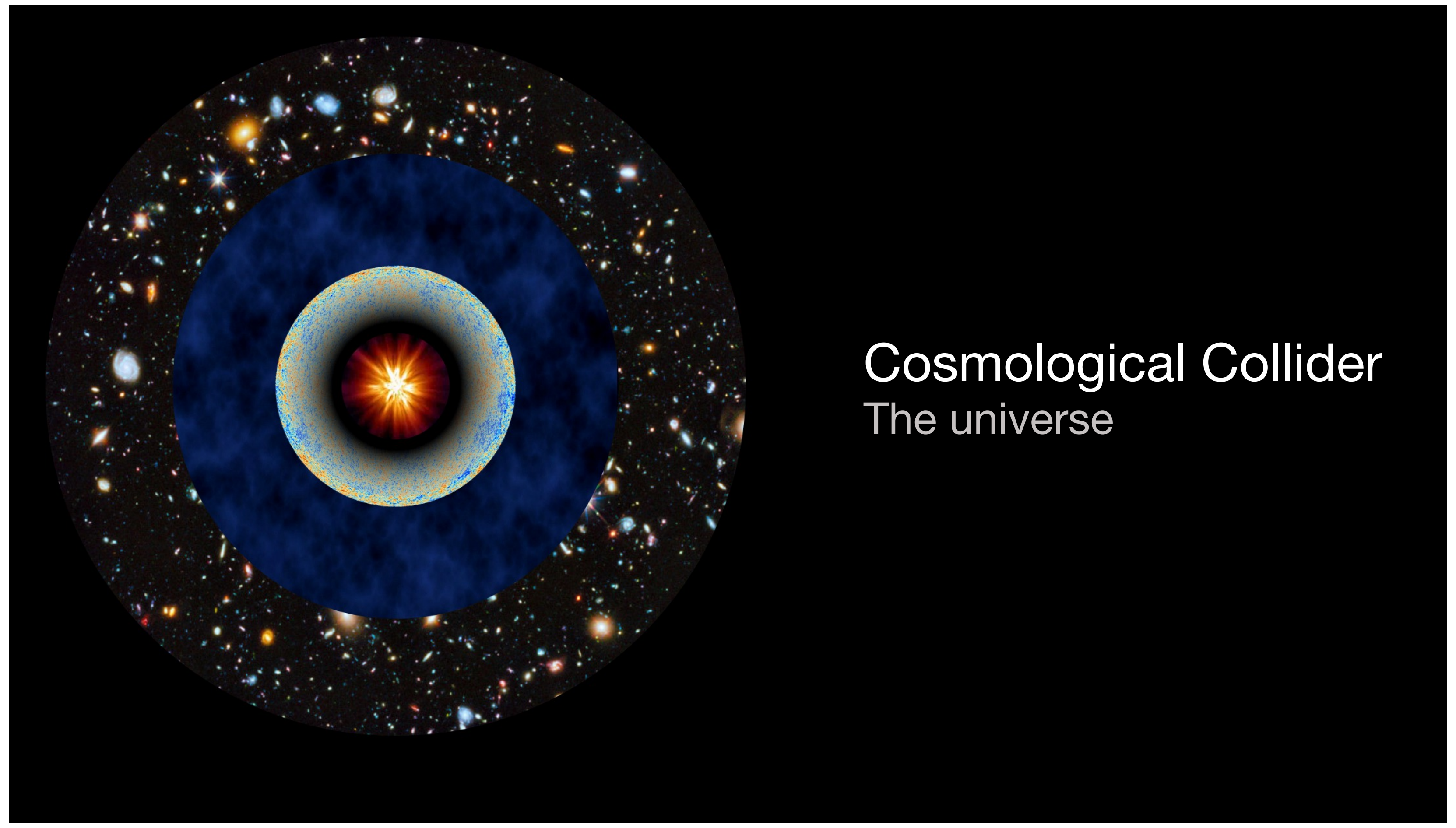
- **A Short intro to CC physics** (Chen, Wang 2009; Baumann, Green 2011 Arkani-Hamed; Maldacena 2015...)



▸ **Man-made, terrestrial collider physics:**
2D map of energy deposition in calorimeters→ physics of high energy collision (short distance): interactions, masses of new particles

▸ **Cosmological collider physics:**
2D map of CMB or galaxy distribution (sourced by primordial fluctuation)→ physics of ultra high energy inflationary Universe: particle masses/interactions...

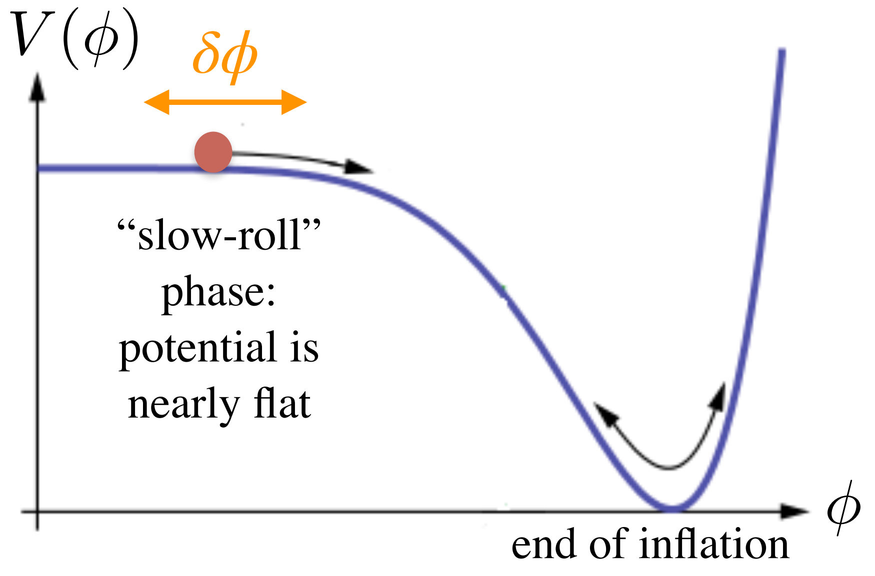




$E = mc^2$
Hubble expansion energy (H) during inflation: up to $O(10^{13})$ GeV!
→production of heavy particles well beyond the reach of LHC!

- **A Short intro to CC physics** (cont'd):

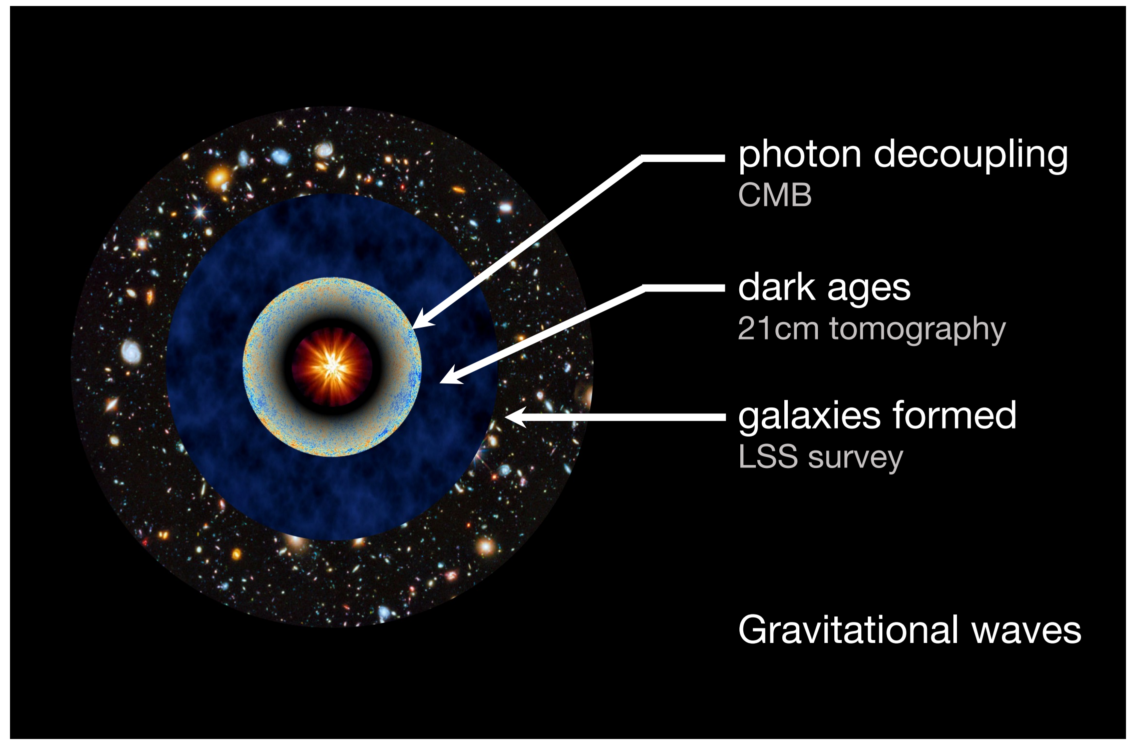
Primordial quantum fluctuation of a scalar field(s) ϕ (e.g. inflaton), $\delta\phi$: seeds CMB anisotropies, structure formation (inhomogeneities)



$\delta\phi(\mathbf{x})$

$\delta\rho_m(\mathbf{x})$ — LSS

$\delta T(\mathbf{x})$ — CMB



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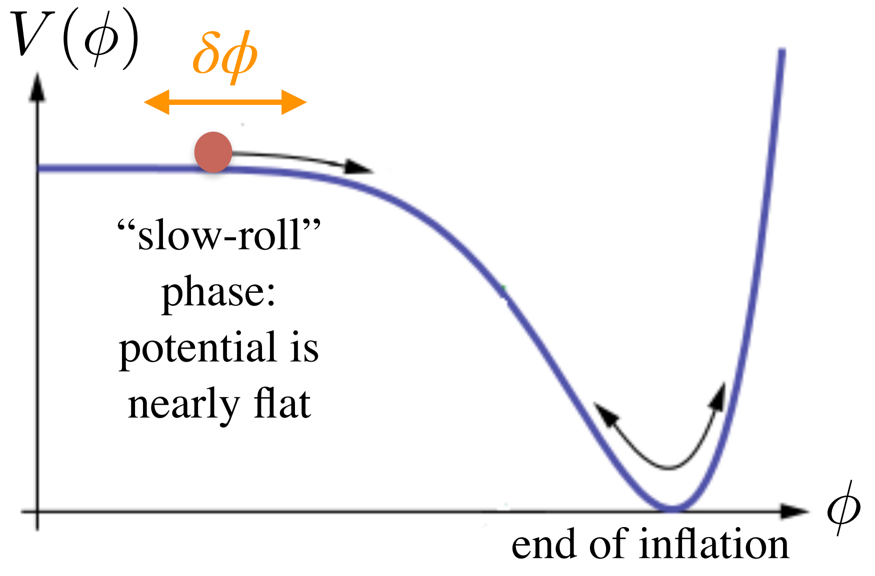
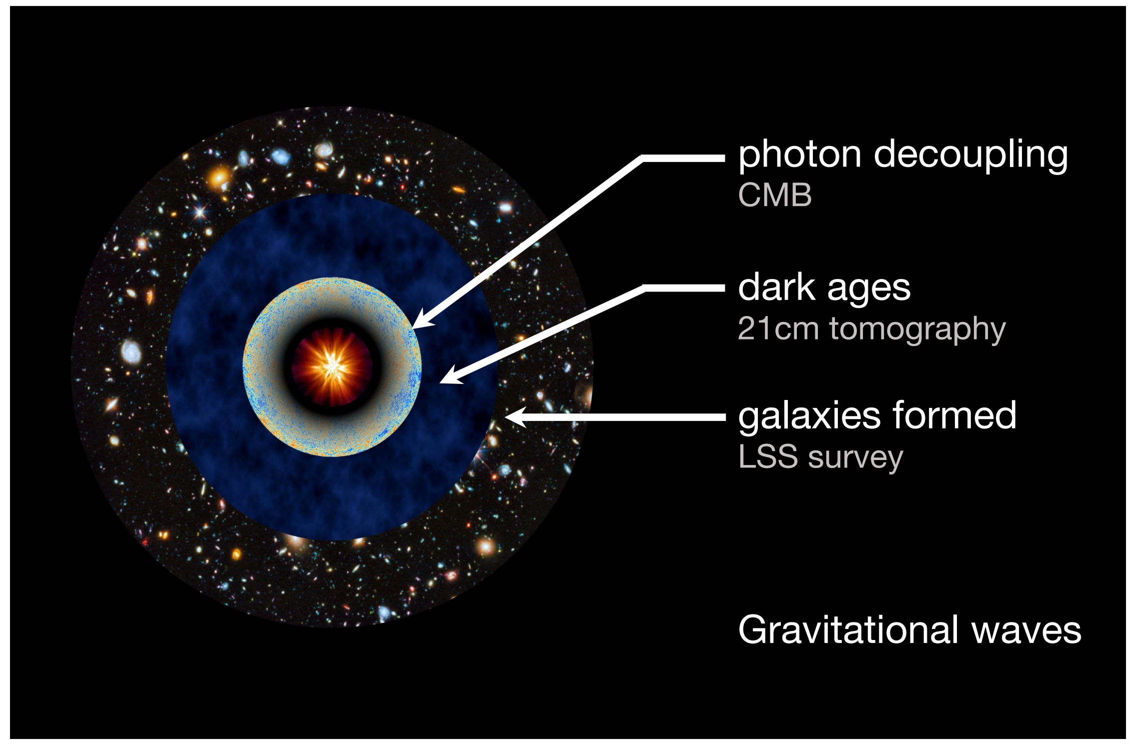
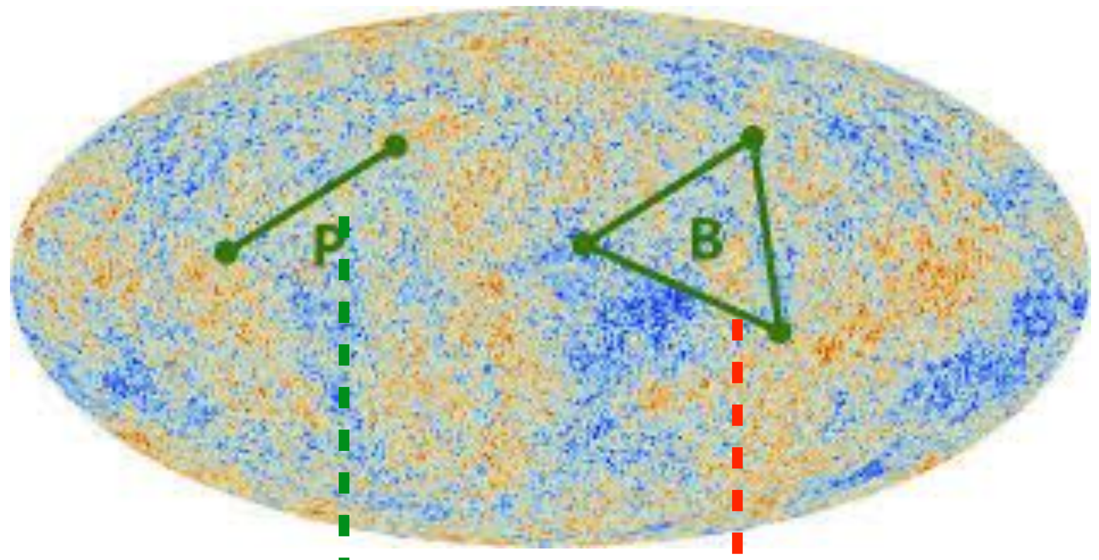


$\delta\phi(\mathbf{x})$ → $\delta\rho_m(\mathbf{x})$ LSS ; $\delta T(\mathbf{x})$ CMB →

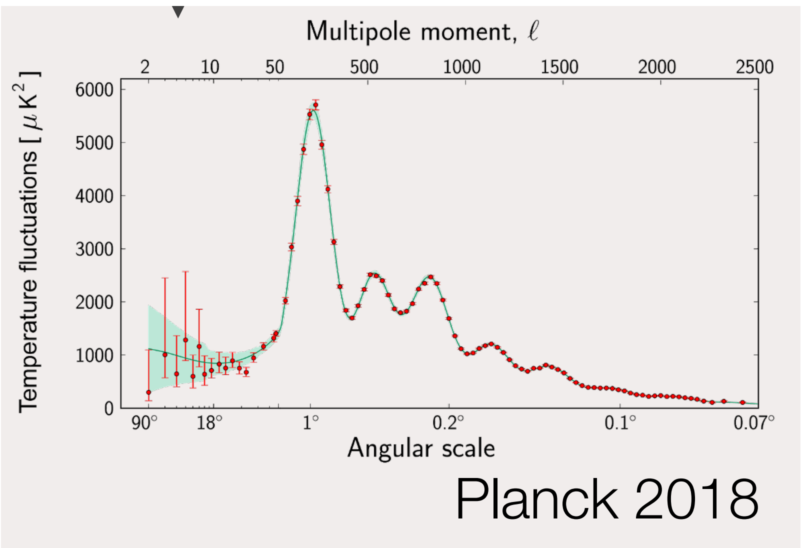


Example: How we extract information about primordial fluctuation from the CMB



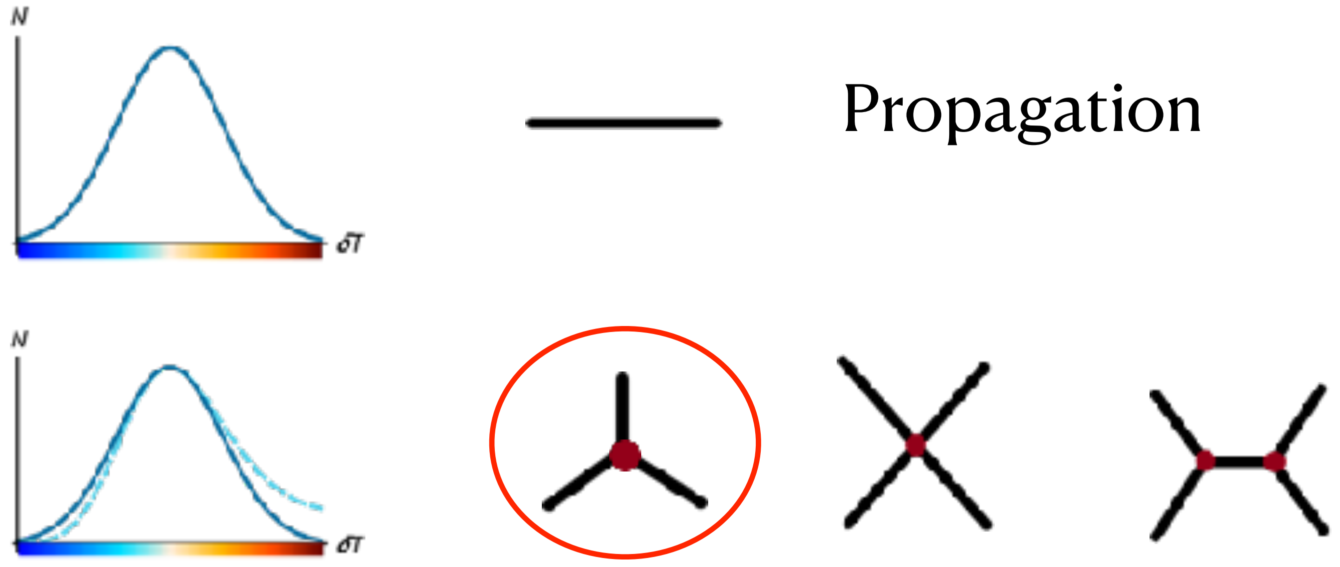
$\langle \delta T(x_1)\cdots\delta T(x_n)\rangle \rightarrow \langle \zeta(x_1)\ldots\zeta(x_n)\rangle$ *Fourier transform* → $\langle \delta T(k_1)\ldots\delta T(k_n)\rangle$ $\langle \zeta(k_1)\ldots\zeta(k_n)\rangle$

$\zeta(x)$: curvature perturbation due to $\delta\phi$



- n=2: 2-point correlator ☞ power spectrum
- n>2: Higher order correlations, bispectrum (3-pt), trispectrum (4-pt)☞ **Non-Gaussianity!**

★ Reveal info about **interactions** of the field(s) contributing to primordial fluctuation *(inflaton+...)*



Collision (interactions!)

- **A Short intro to CC physics** (cont'd):

  - Original CC: an inflaton collider

    — inflaton fully responsible for the source of inhomogeneity

  - Beyond the minimal (yet motivated!): primordial fluctuation (partially) sourced by another field *("Modulated reheating", Dvali, Gruzinov, Zaldarriaga 2003),*

Application in CC: Cosmological Higgs Collider (CHC) (Lu, Wang and Xianyu 2019); Curvaton collider (Kumar, Sundrum 2019)

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SM particles *(Chen, Wang, Xianyu 2016),* GUT physics *(Kumar, Sundrum 2018),* Higgs potential at high energy *(Hook, Huang, Racco 2019)*…

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Opportunities for high scale baryogenesis?

A benchmark: Leptogenesis

(arxiv: 2112.10793, submitted to PRL, YC w/Zhong-Zhi Xianyu)

(Naturally suitable for CHC: heavy RH neutrino, SM ν coupling to SM Higgs)

Probing Leptogenesis with the Cosmological Collider

- **Essence of leptogenesis (Type-I Seesaw): heavy RH Majorana neutrino N**, SM lepton doublet $L = (\nu, e^-)^T$, couple to the SM Higgs $\mathbf{H}$; N decay (post-inflation, before EWPT)⇒$\Omega_{\Delta L}$⇒$\Omega_{\Delta B}$ (EW sphaleron)

- **Distinct story when applying to CHC:**

  During inflation Higgs gets a large VEV $v \sim H$! H: Hubble, quantum fluctuation *(e.g. Bunch, Davies 1978)*

  ➜ Distinct pattern of neutrino mass matrix/couplings, different from both leptogenesis era ($v = 0$) and today ($v = v_{\rm EW}$)

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Take 1 generation of N as a toy example: parametrize the Higgs as $\mathbf{H}=(0,(v+h)/\sqrt{2})^T$

$$\Longrightarrow \quad \Delta\mathscr{L}=\nu^\dagger \mathrm{i}\bar{\sigma}^\mu\partial_\mu\nu+N^\dagger \mathrm{i}\bar{\sigma}^\mu\partial_\mu N+\Big[m_D\big(1+\frac{h}{v}\big)\nu N-\frac{1}{2}m_N NN+\mathrm{c.c.}\Big] \qquad m_D\equiv yv/\sqrt{2}$$

Rotate to mass eigenstates $\psi_\pm$:

$$\mathscr{L}\supset\frac{m_D h}{v\sqrt{m_N^2+4m_D^2}}\Big[m_D(\psi_-^2-\psi_+^2)+m_N\psi_-\psi_+\Big] \qquad m_\pm=\tfrac{1}{2}\big(m_N\pm\sqrt{m_N^2+4m_D^2}\big)$$

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★ $m_D \sim m_N \sim H$ during inflation— no Seesaw! $\Rightarrow m_+ \sim m_-$

★ Mass matrix and Higgs Yukawa couplings cannot be simultaneously diagonalized

Sizable Yukawa coupling mixing mass eigenstates!

☞ **Novel pattern of CHC signal**

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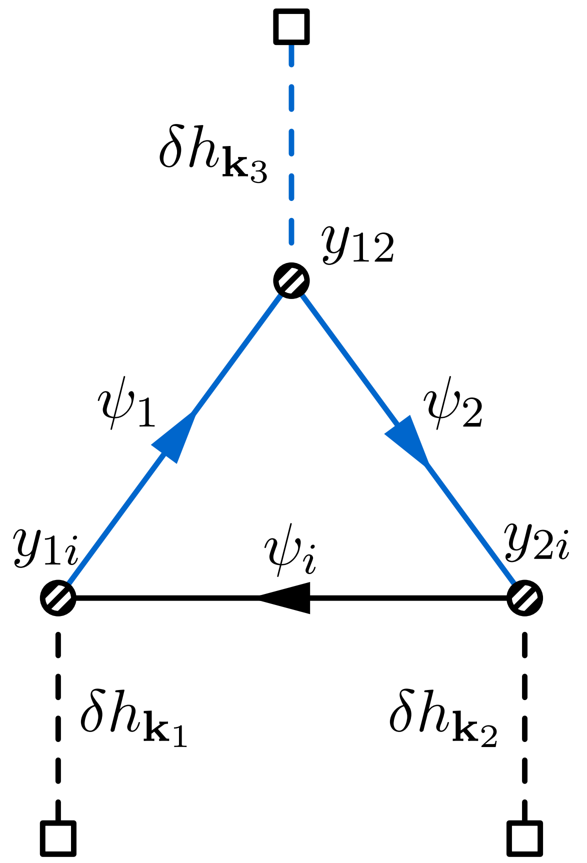
☞ **Novel pattern of CHC signal**

Generalize to realistic 3 generation N's: mixed Yukawa couplings persist, plus CP phases

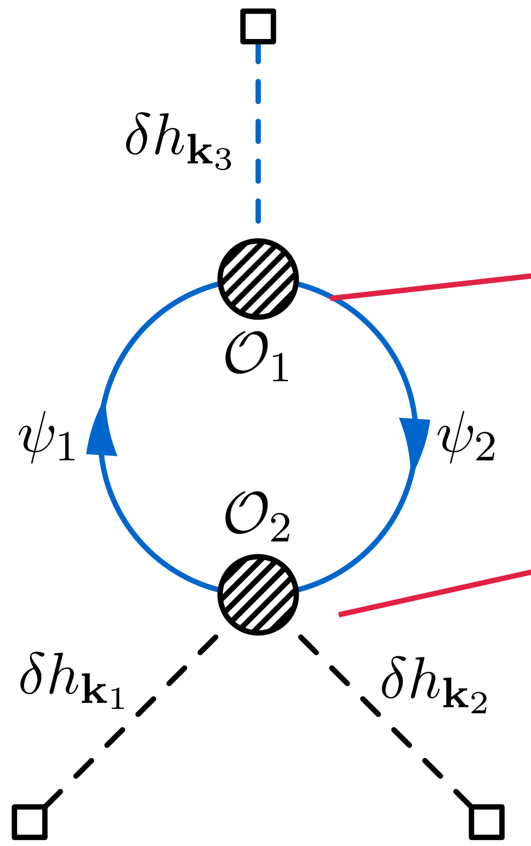
Cosmological (Higgs) Collider Signals of Leptogenesis

- **Central task for finding CHC signal: calculate the 3-pt correlator of δh**



Squeezed limit

Integrate out a "local" neutrino



$$\mathcal{O}_1 \equiv y_{12}(e^{i\varphi_{12}}\psi_1\psi_2 + \text{c.c.})$$

φ_{12}, φ_5: CP phases

$$\mathcal{O}_2 \equiv \frac{1}{\Lambda}(e^{i\varphi_5}\psi_1\psi_2 + \text{c.c.})$$

$$1/\Lambda \sim y_{12}(y_{11}/m_1 + y_{22}/m_2)$$

$$\langle \mathcal{O}_1(x)\mathcal{O}_2(y)\rangle = -\frac{4y_{12}}{\Lambda}\Big[\cos(\varphi_{12}+\varphi_5)g_{m_1}(x,y)g_{m_2}(x,y) + \cos(\varphi_{12}-\varphi_5)f_{m_1}(x,y)f_{m_2}(x,y)\Big]$$

☞ How the CHC signal depends on m_1, m_2, CP phases

$$\mathrm{i}f_m(x,y) = 2\mathrm{Re}\left\{\frac{\Gamma(2-\mathrm{i}\widetilde{m})\Gamma(\frac{1}{2}+\mathrm{i}\widetilde{m})}{4\pi^{5/2}}\left(\frac{\tau_1\tau_2}{X^2}\right)^{3/2-\mathrm{i}\widetilde{m}} \times\left[1+\frac{\big(3-4\widetilde{m}(2\mathrm{i}+\widetilde{m})\big)(\tau_1^2+\tau_2^2)-6\tau_1\tau_2}{2(1-2\mathrm{i}\widetilde{m})X^2}\right]\right\},$$

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$$\widetilde{m} = m/H$$

Cosmological (Higgs) Collider Signals of Leptogenesis

Result-1: Shape function of the primordial bispectrum ($S(k_1, k_2, k_3)$):

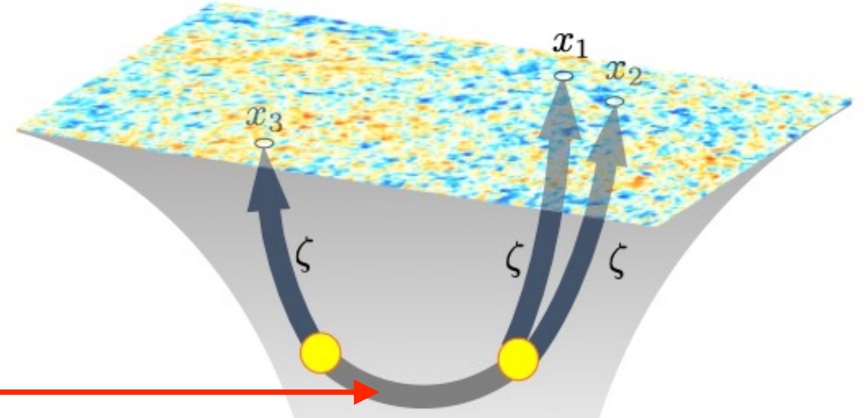
Squeezed limit of bispectrum: $k_1 \simeq k_2 \gg k_3$

☞ Key for revealing new heavy particles (mass, coupling!)

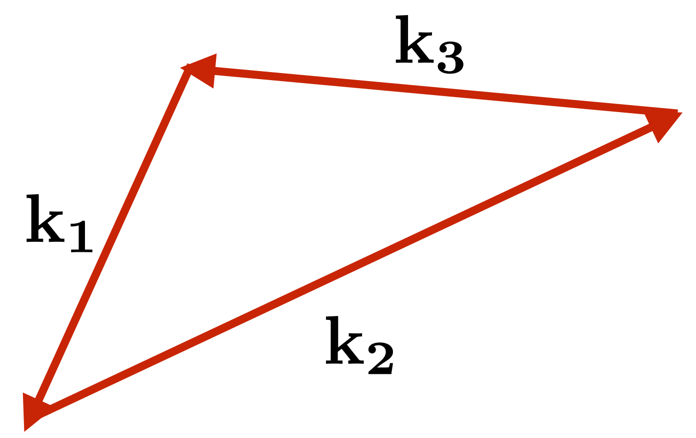
$$S(k_1, k_3) \propto e^{-\pi m/H} e^{im\Delta t}$$

— **Mass measurement via oscillation pattern!**

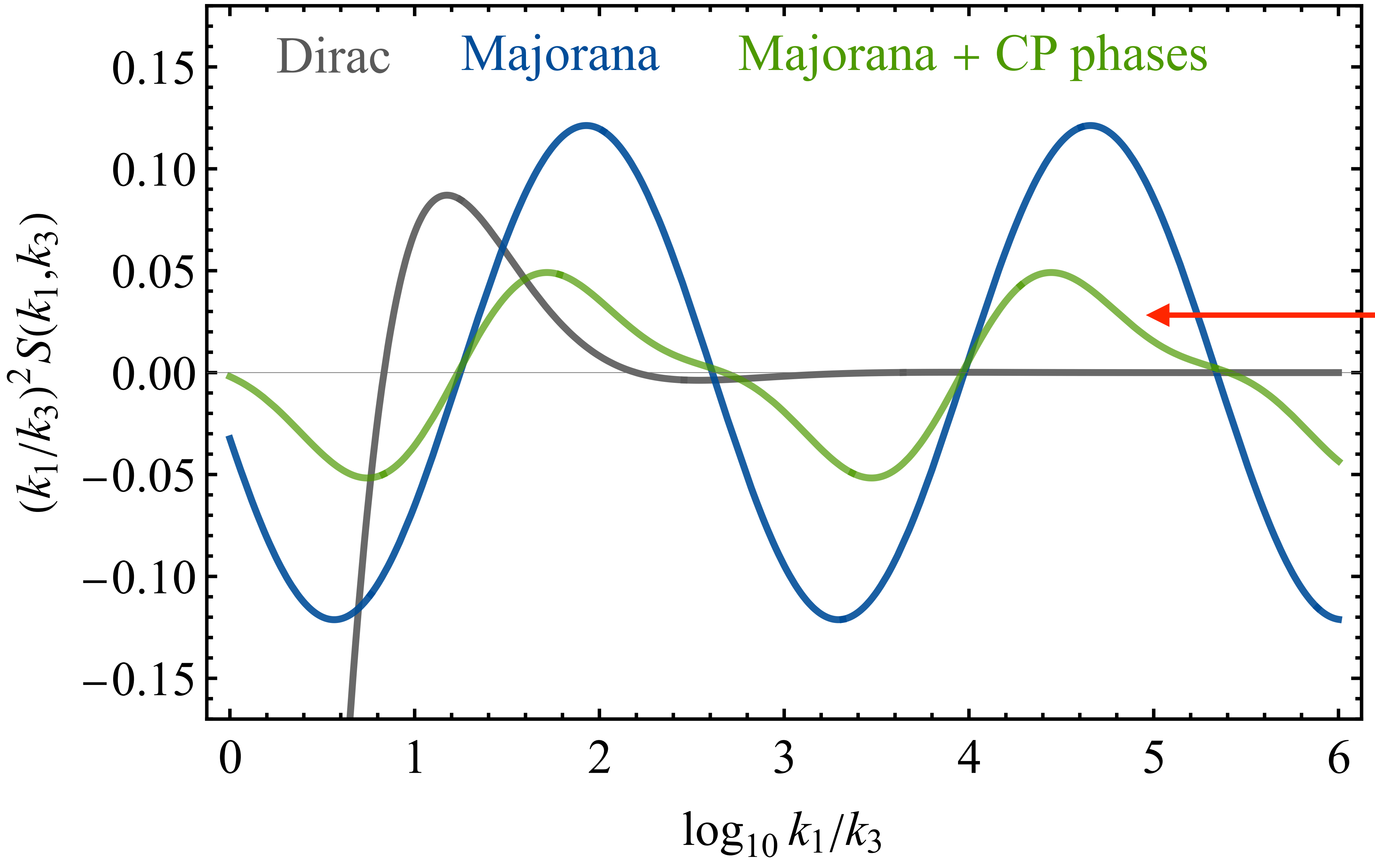
(C.f. bump hunting at the LHC)



Intermediate heavy particle



3-pt function in Fourier space



Three cases:

- Pure Dirac mass: known case, signal dies fast
- Majorana mass w/o CP phases (new): single mode oscillation
- Majorana mass w/ CP phases (new, leptogenesis): two distinct modes of lasting oscillation

  ☞ Information about **heavy RH neutrino mass**!

With 3 generations, more oscillation modes possible, but generally expect one pair of mass eigenstates dominate the signal

Cosmological (Higgs) Collider Signals of Leptogenesis

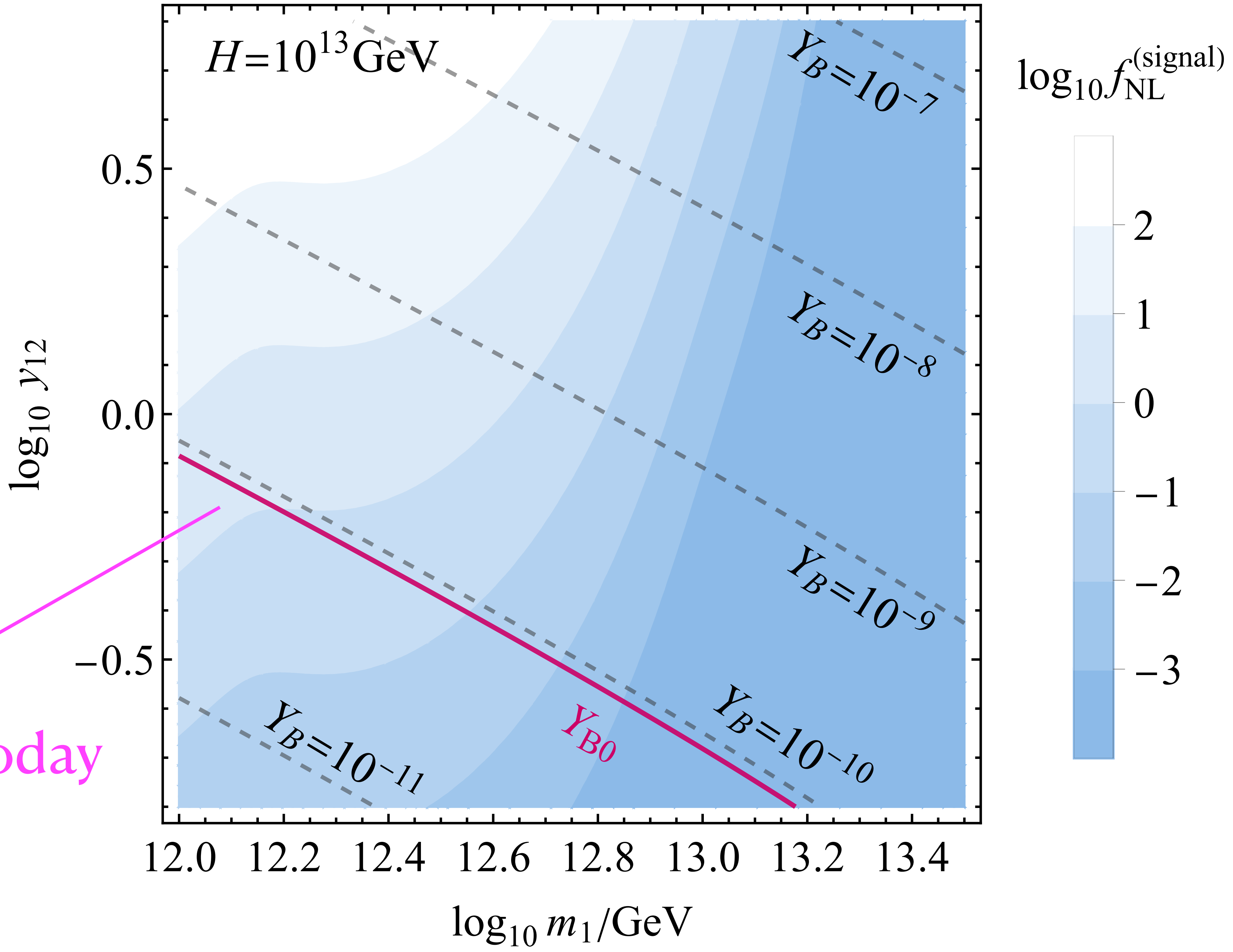
Result-2: CHC signal strength $f_{\rm NL}$ VS. Y_B predicted by leptogenesis

$f_{\rm NL}$: amplitude of the shape function $S(k_1, k_3)$, increase with couplings

$$Y_B = \frac{c_s}{c_s - 1}\kappa\frac{\epsilon_1}{g_*}$$

- c_s : sphaleron conversion
- ϵ_1 : asymmetry from N_1 decay
- κ: washout efficiency, decreases as couplings increase

Observed Y_B today



$\Rightarrow$ A potential tension for observable f_{NL} vs. Sufficient Y_B

Scan over perturbative Yukawa couplings, mass range

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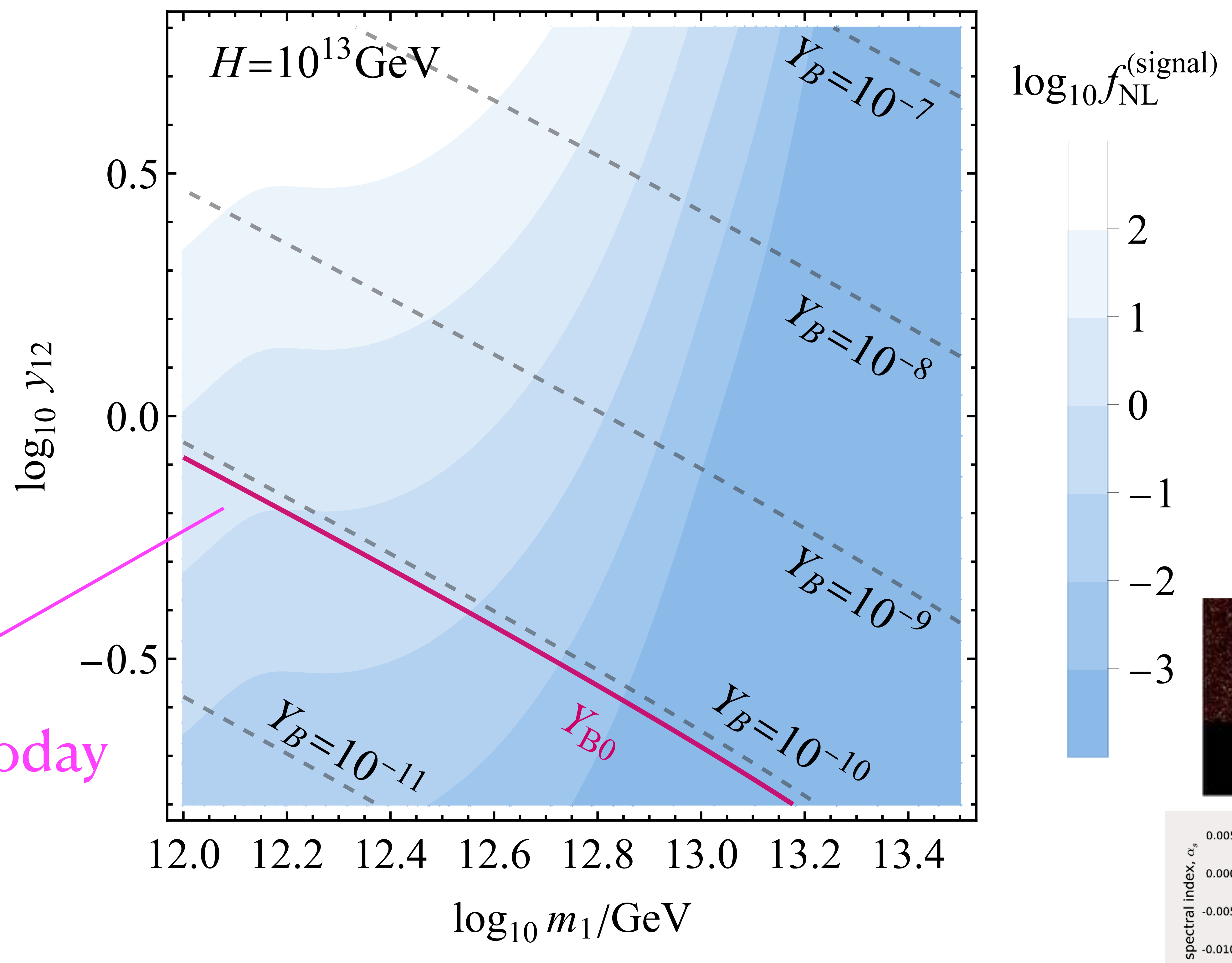
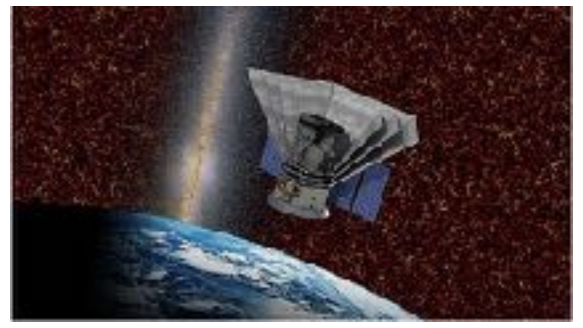
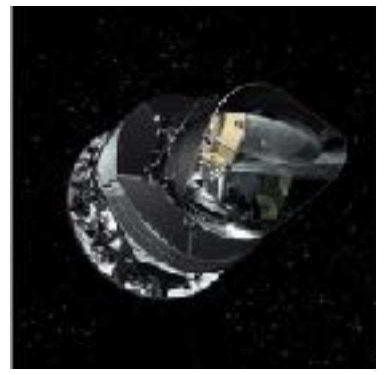


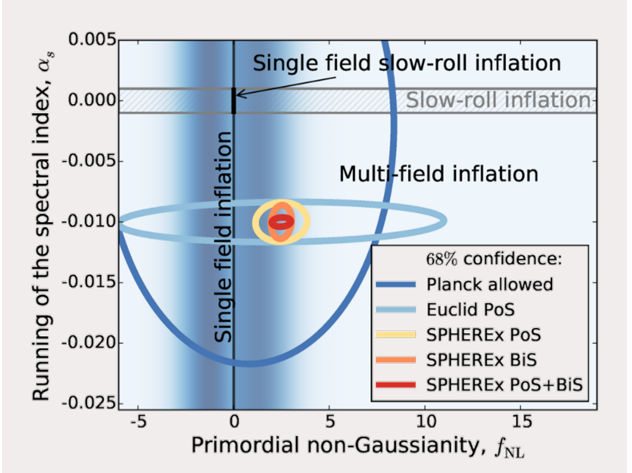
Scan over perturbative Yukawa couplings, mass range

☞ Viable leptogenesis models can lead to signals detectable by future CMB/LSS/21 cm experiments!

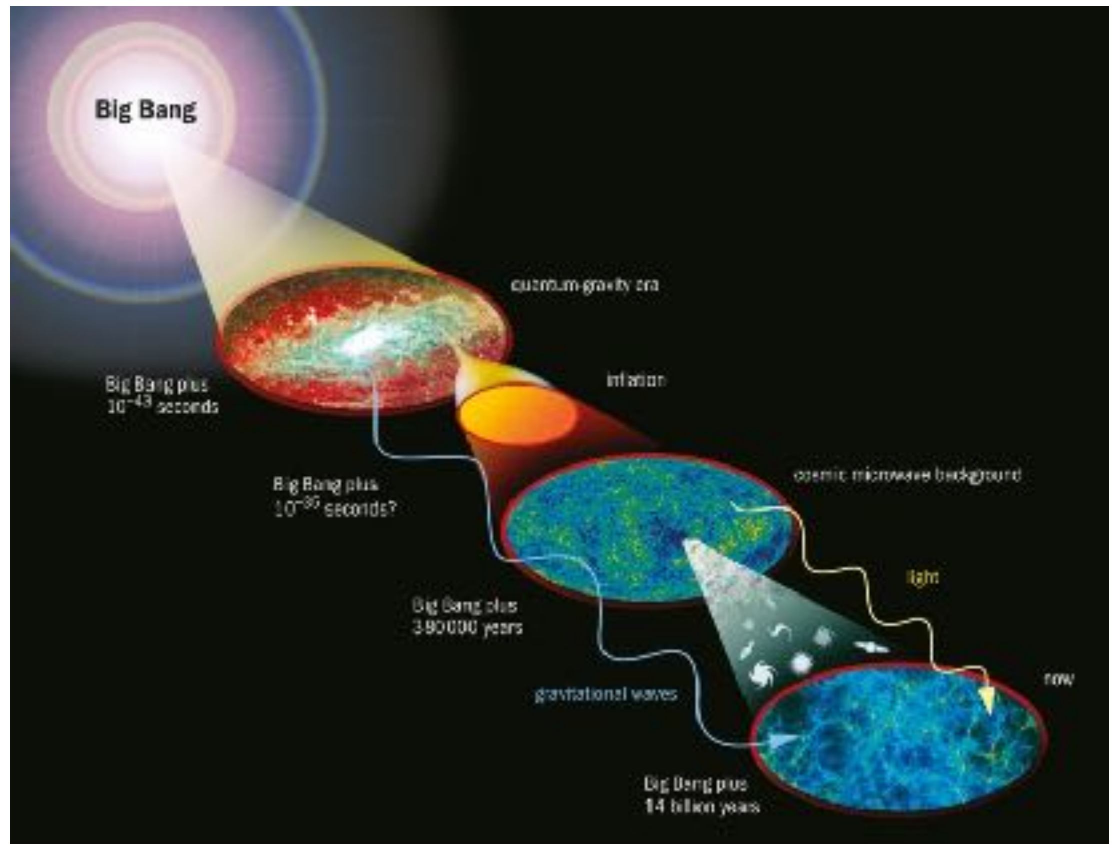
($f_{NL} \gtrsim O(0.01)$)







Probing High-scale Baryogenesis with Gravitational Waves



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Snowmass WP on GW probes for BSM: arxiv: 2203.07972, LISA science book: arxiv: 2204.05434

+ Nobu's talk tomorrow

✳GW: Unique tool for probing the pre-BBN primordial dark age; the only messenger that can travel freely throughout space since the Big Bang *(gravity: weakest force)*

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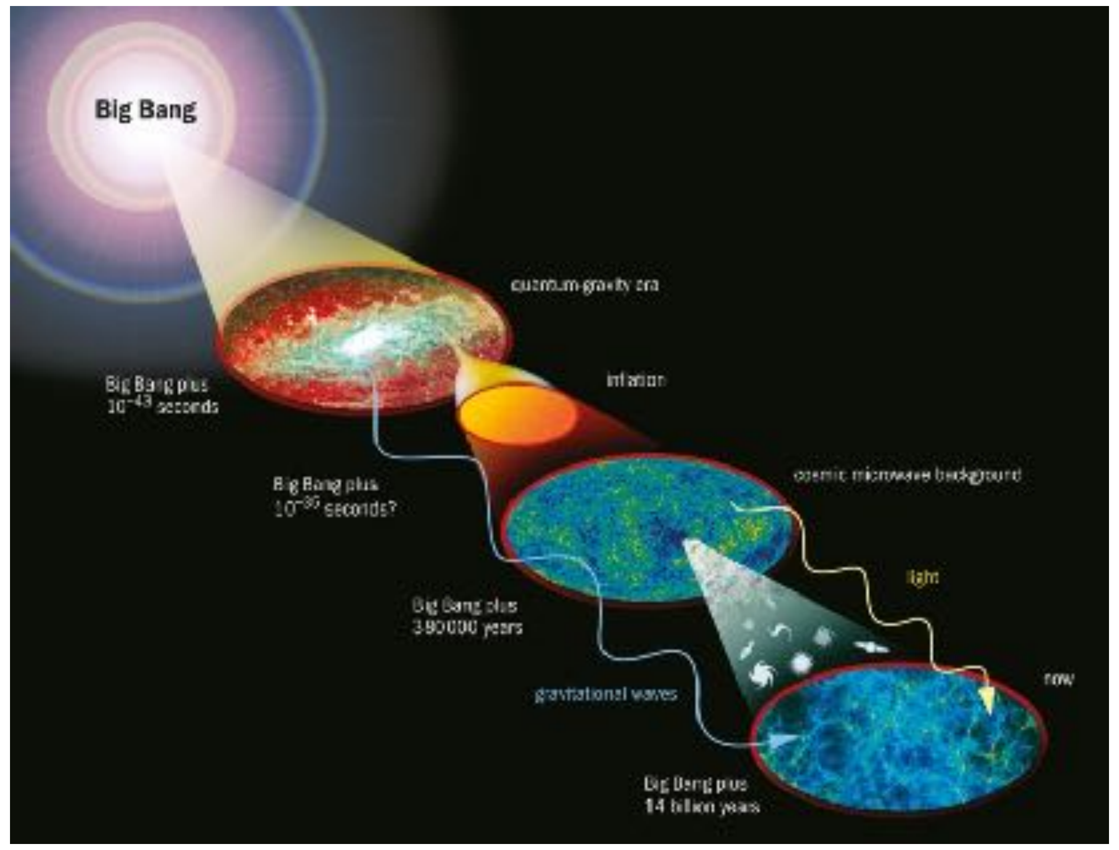

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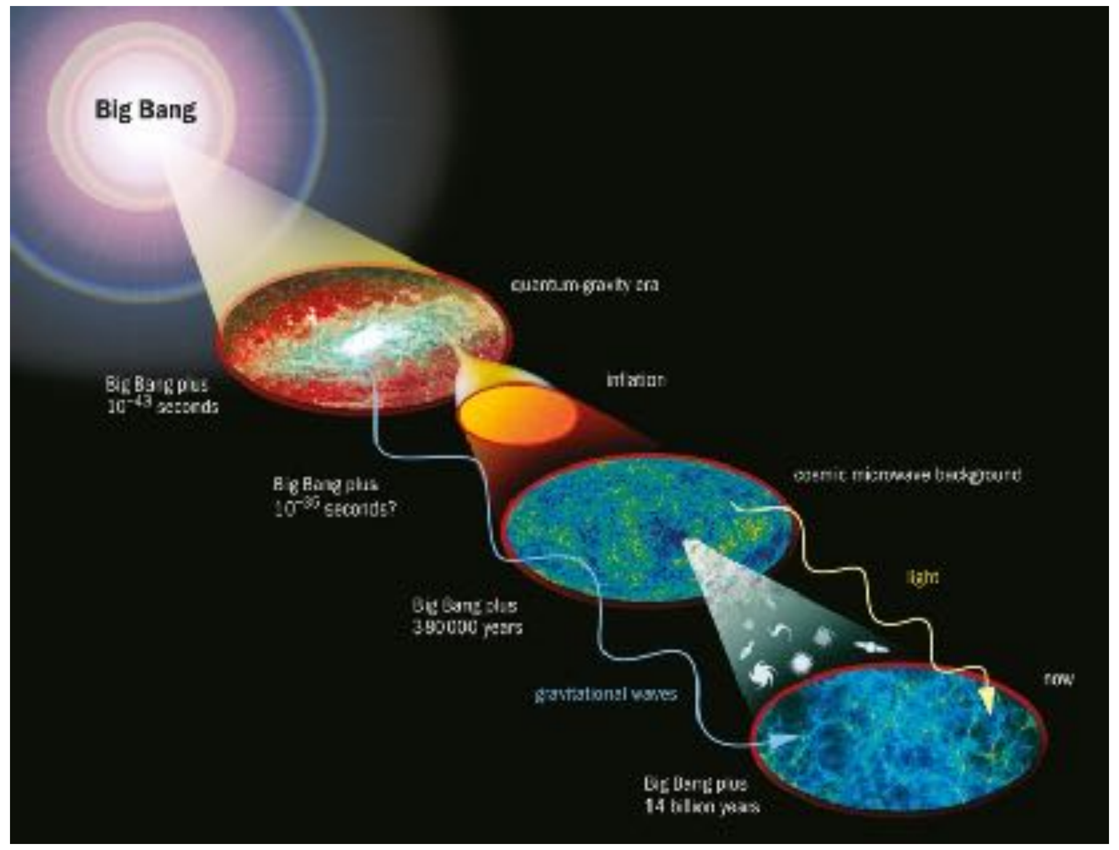

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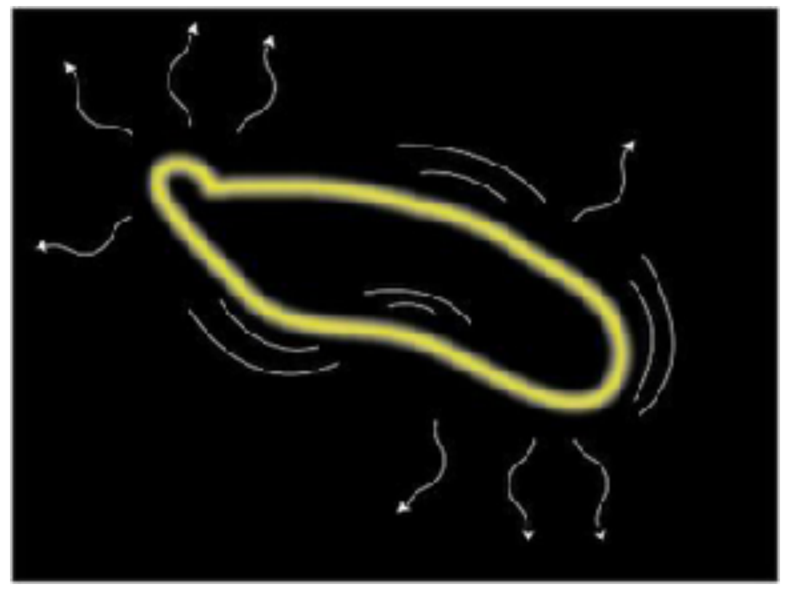
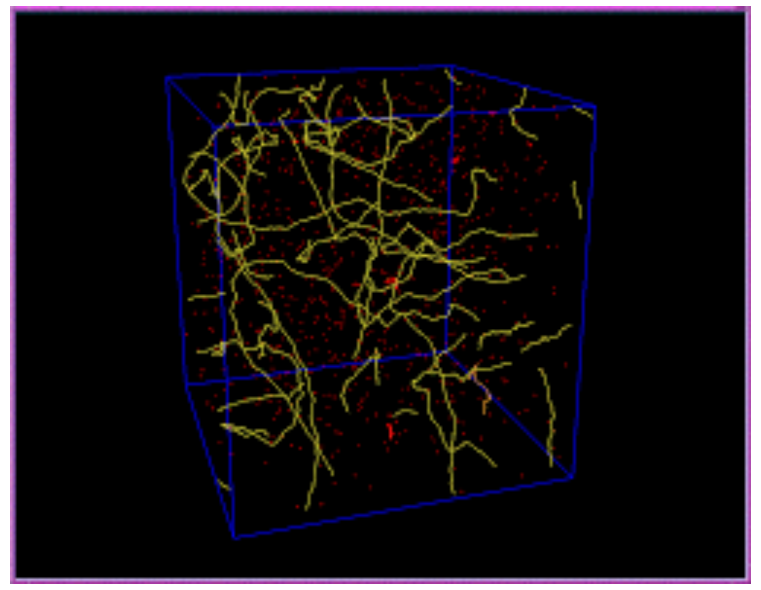
- **Example-1: Leptogenesis** (Dror, Hiramatsu, Kohri, Murayama, White 2019)

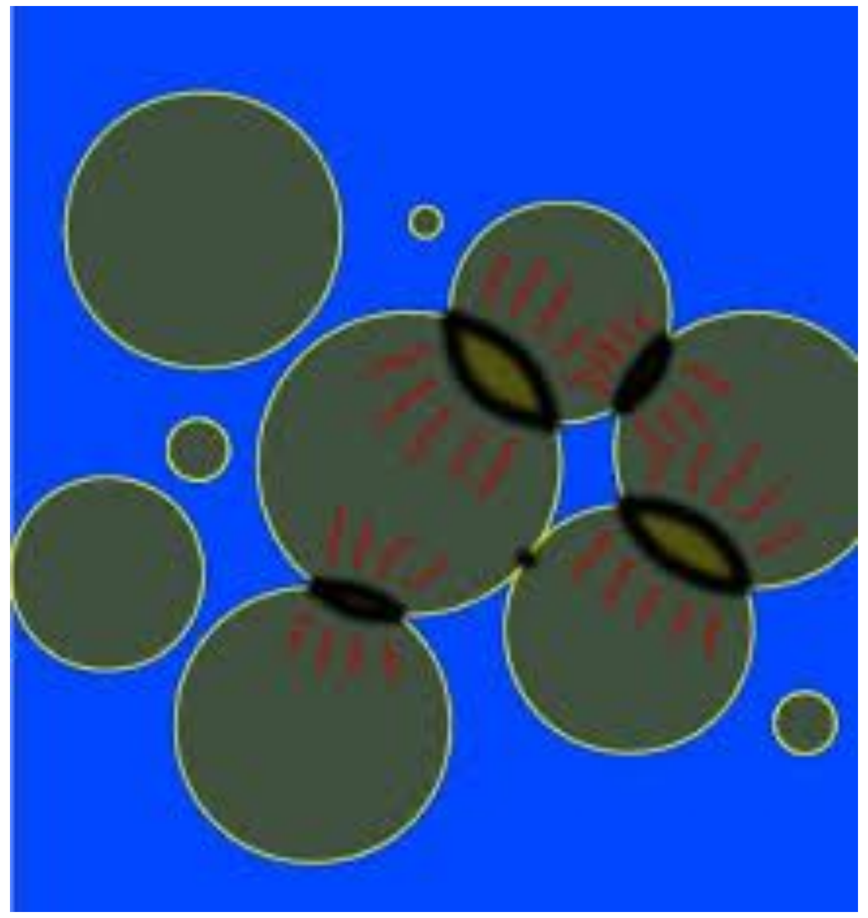
  - Cosmic strings generically predicted in LG with spontaneously broken $U(1)_{B-L}$
  - Cosmic strings are well-studied, potentially strong source of GW signals (e.g. NANOGrav, recent review by LISA CosWB: arxiv: 1909.00819; *cosmic archaeology*: YC et al. 2017, C. Chang+YC 2021...)
  - A wide range of leptogenesis models of this type can be probed with future GW experiments *(LISA, ET, BBO, SKA...)* (Dror et al. 2019)





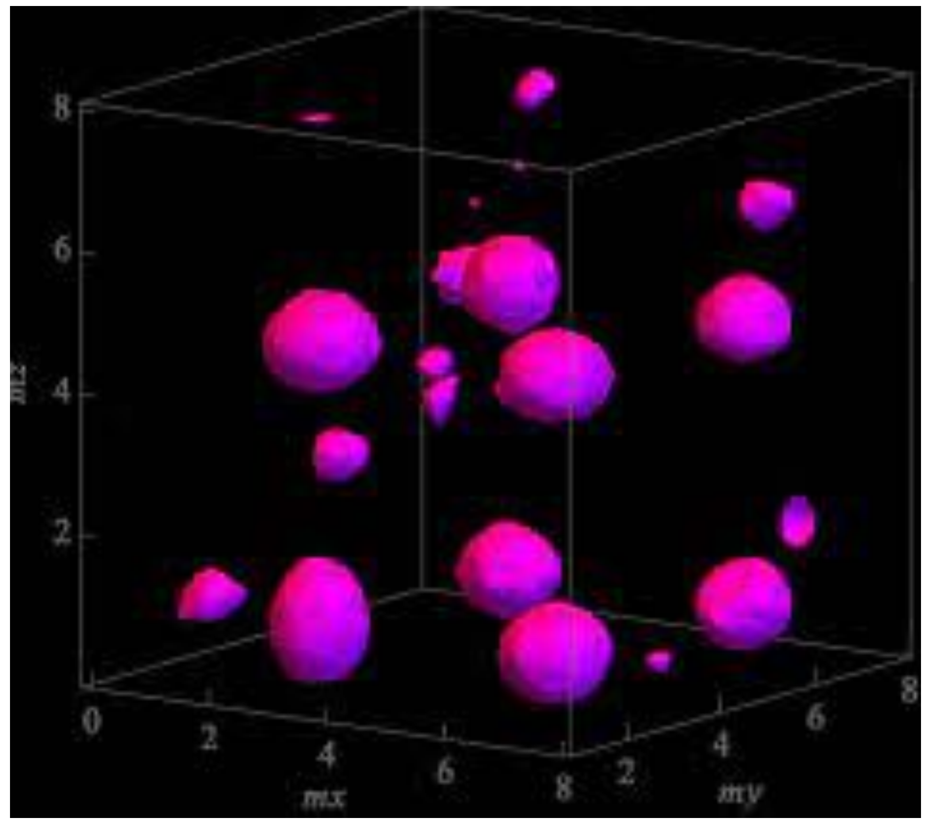
Probing High-scale Baryogenesis with Gravitational Waves

- **Example-2: BG from first-order phase transitions**



- EWBG: an attractive BG mechanism, out-of-equilibrium condition met by first order EWPT; minimal versions (SM, MSSM) not viable with LHC constraints, can work in extended models (see review in arxiv: 2203.05010)
- Bubble dynamics during (strong) 1st order PT ☞ Detectable GW signals; e.g. GW signal from EWPT can be within reach of LISA (recent review: arXiv:1909.00819, 2204.05434)

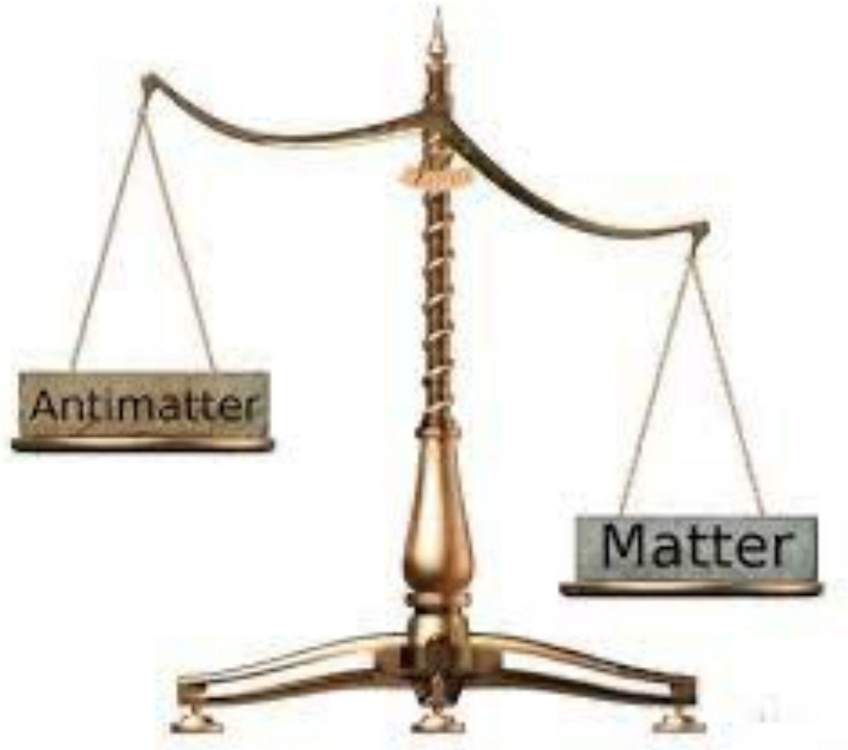
- **Example-3: Affleck-Dine BG** (Zhou 2015, White, Pearce, Vagie, Kusenko 2021)



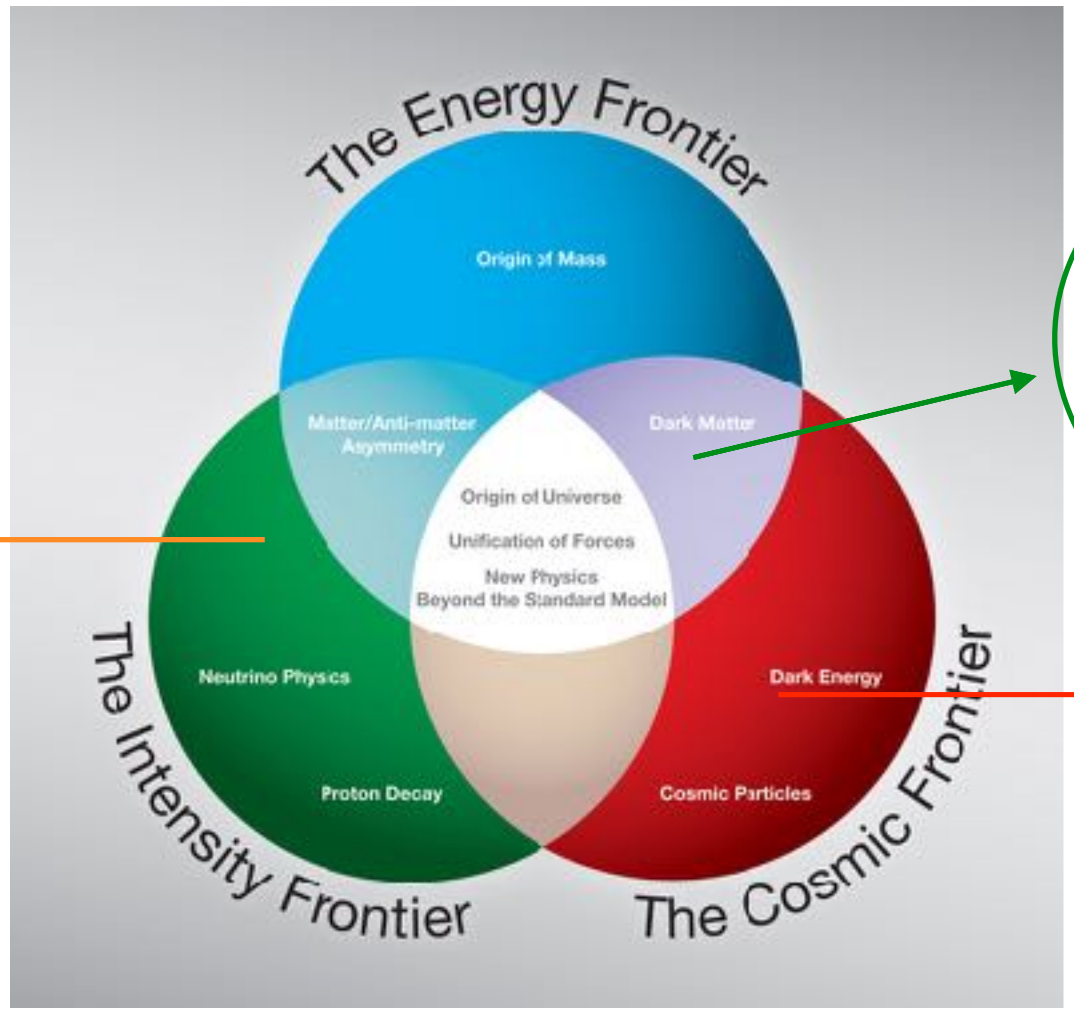
- AD scalar condensate generally fragments into non-topological solitons, Q-balls, which later decay
- Q-ball dynamics (formation, rapid decay) can lead to distinct GW signals

Conclusion

- **Baryogenesis persists as a profound puzzle in particle physics** *(just like dark matter!)*, ample opportunities for further exploration (some of the prevailing models constrained or hard to test with old methods, new experimental probes available)
- **Recent developments:**
  - **New model building:** low-scale physics, dark matter inspired, coincidence $\Omega_{\rm B} \sim \Omega_{\rm DM}$ inspired...
  - **New phenomenology:** for the new models and for traditional (high-scale) models; distinct collider signals (LLP etc.), intensity frontier, astrophysical/cosmological probes (LSS, GW...)...
- **Exciting time ahead for unraveling the cosmic matter puzzle (Ω_B, Ω_{DM}, $\Omega_{DM} \sim \Omega_B$)!**



+...



+ The Theory frontier, neutrino frontier

+ GWs, 21 cm line...

Thank you!

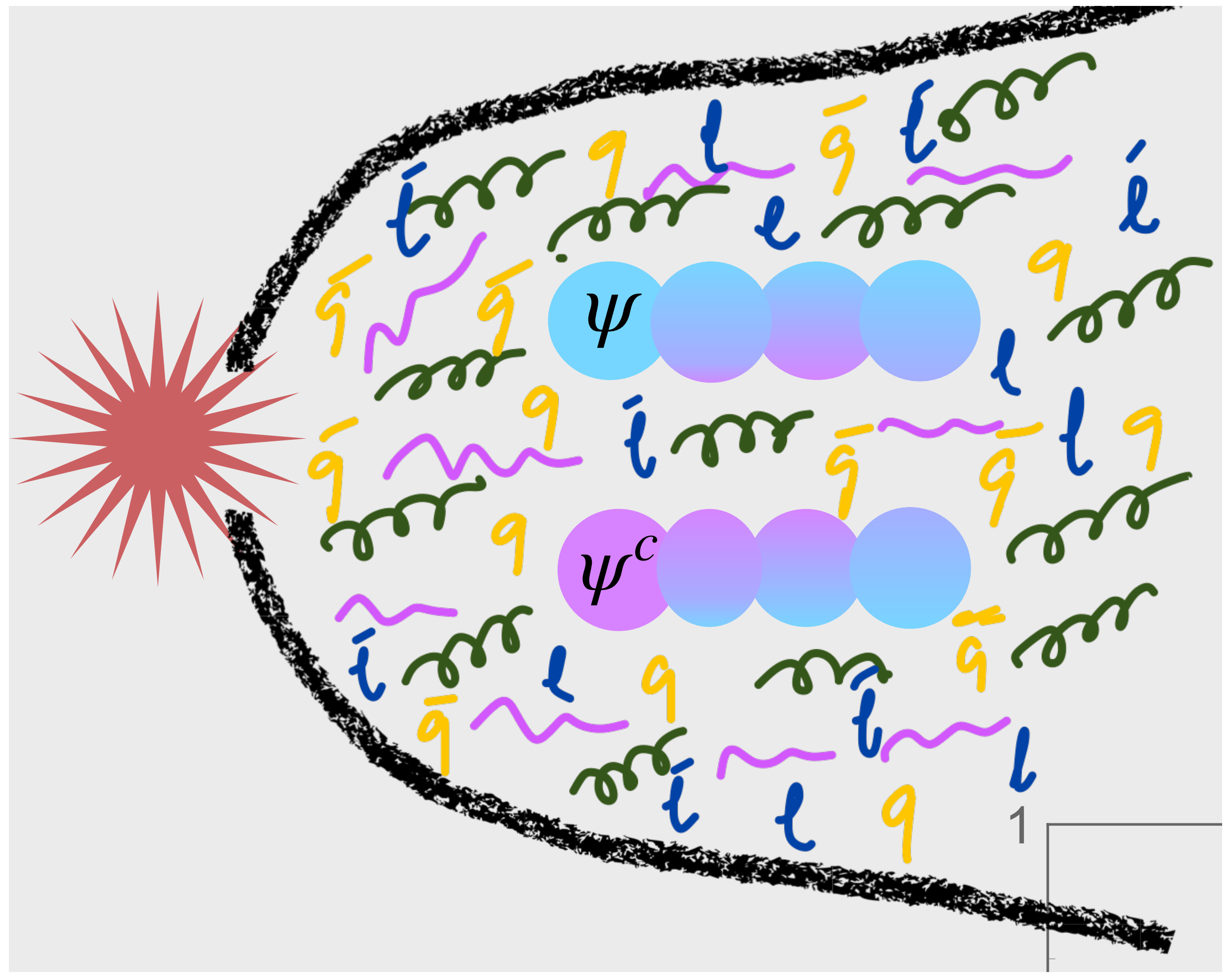
Backup Slides

Baryogenesis from $X - \bar{X}$ Oscillation

- **Baryogenesis from particle-antiparticle oscillation**
  - From mesino oscillation (Ghalasasi, Mckeen, Nelson 2015)
  - From pseudo Dirac fermion oscillation: e.g. SUSY Bino (Ipek and March-Russell 2016)
  - From B-meson oscillation (Alonso Alverez et al. 2019)
  - From dark matter oscillation (Shuve and Tucker-Smith 2020)

Inspiration from meson oscillations in the SM: oscillation is optimal when $\delta m \sim \Gamma \Rightarrow$ Enhanced CP violation

Complex oscillation dynamics in the early Universe:
Hubble expansion, oscillation, scattering...



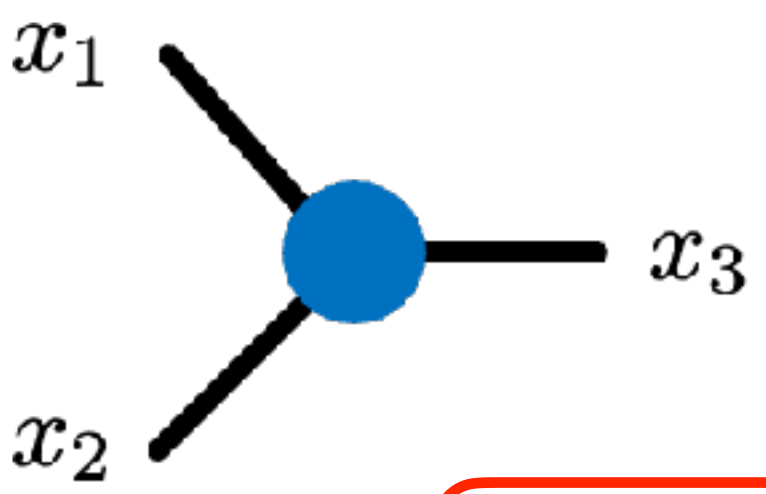
- Oscillation $\Rightarrow$ out-of-equilibrium and $\not{B}$ or $\not{L}$ decay $\Rightarrow \Omega_B$

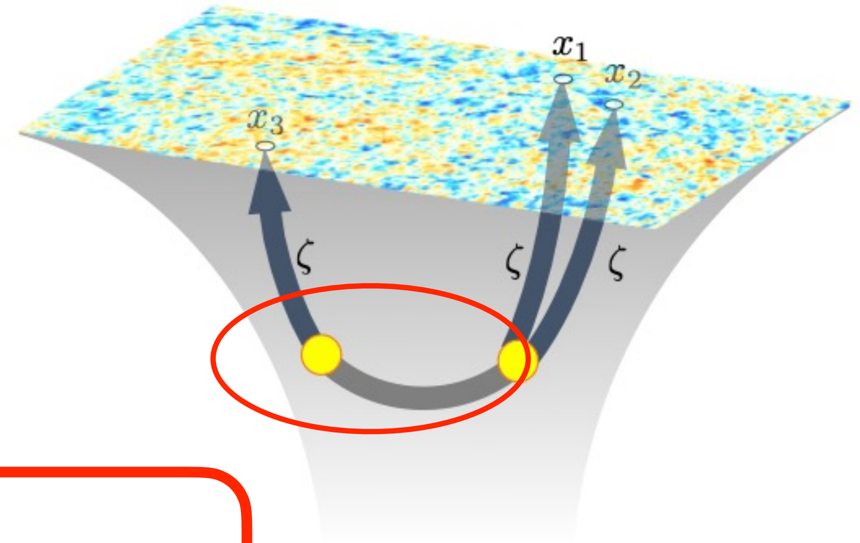
- Rich pheno (depends on model): LLPs and other LHC signals, CPV observable at B-factories, structure formation, X-rays...

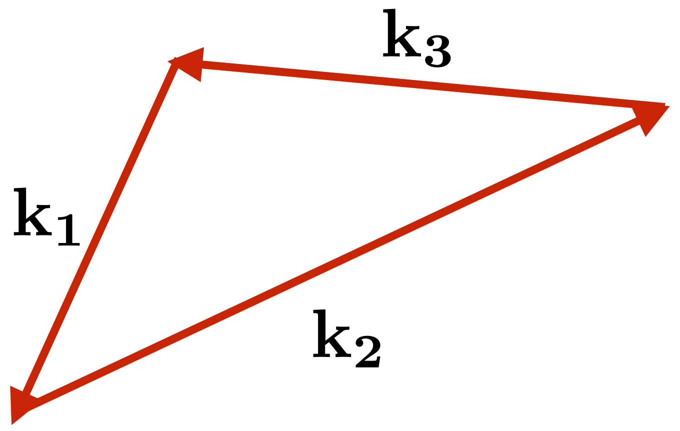
Cosmological Collider (CC) Physics 101

- How we discover new heavy particles with CC

3-pt correlation function:







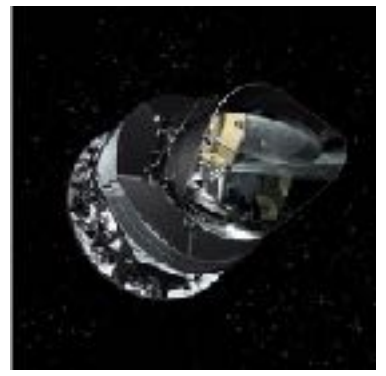
$$\langle \zeta_{\mathbf{k}_1}\zeta_{\mathbf{k}_2}\zeta_{\mathbf{k}_3}\rangle' \equiv (2\pi)^4 P_\zeta^2 \frac{1}{(k_1k_2k_3)^2} S(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3)$$

$S(k_1, k_2, k_3)$: shape function

★**Amplitude** of non-G: $f_{\mathrm{NL}} \simeq |S(\mathbf{k},\mathbf{k},\mathbf{k})|$

Observational prospect for f_{NL} :

Planck 2018:



$$f_{\mathrm{NL}}^{(\mathrm{local})} = -0.9 \pm 5.1$$
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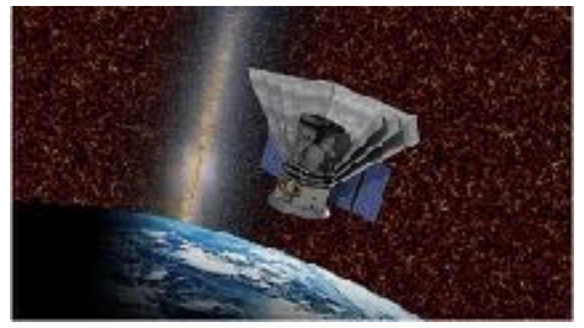
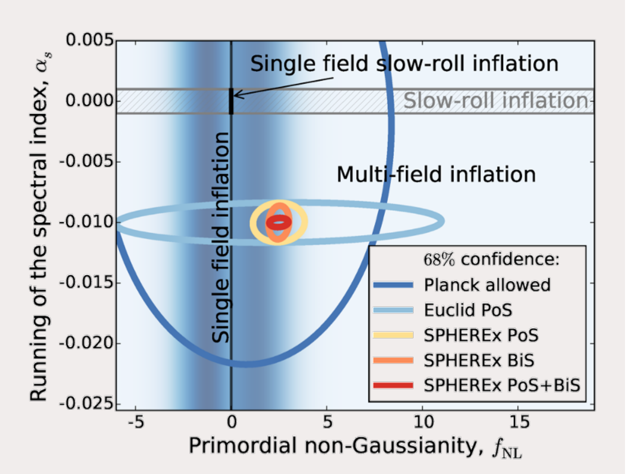
O(1) in 10 yrs?

SPHEREx: launch ~2024





O(0.01) ultimately

21 cm tomography

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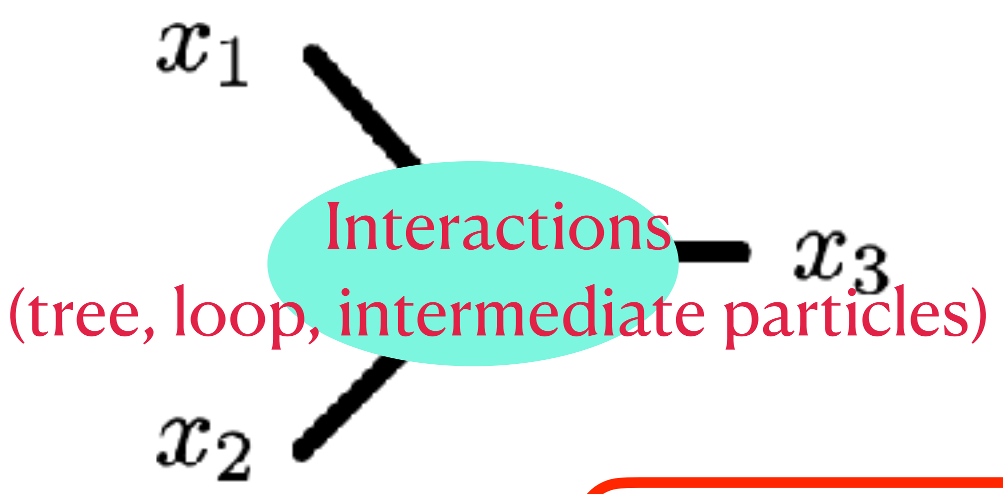

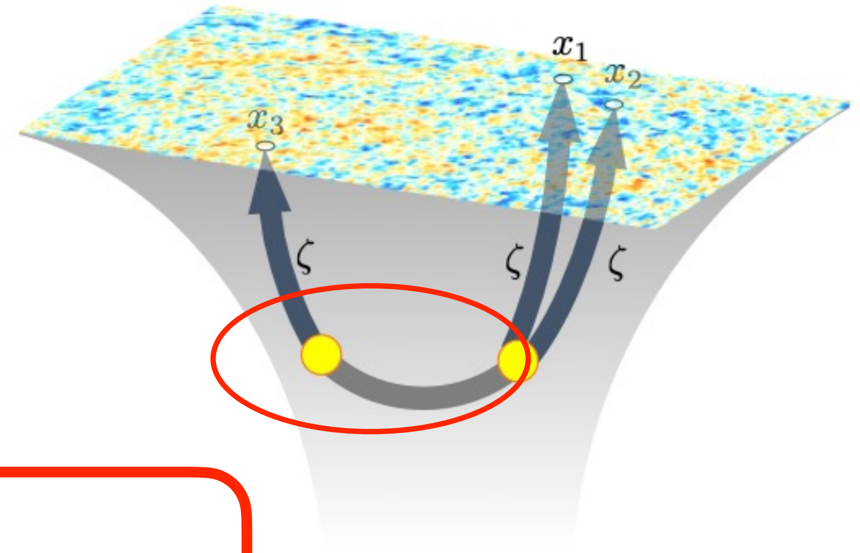

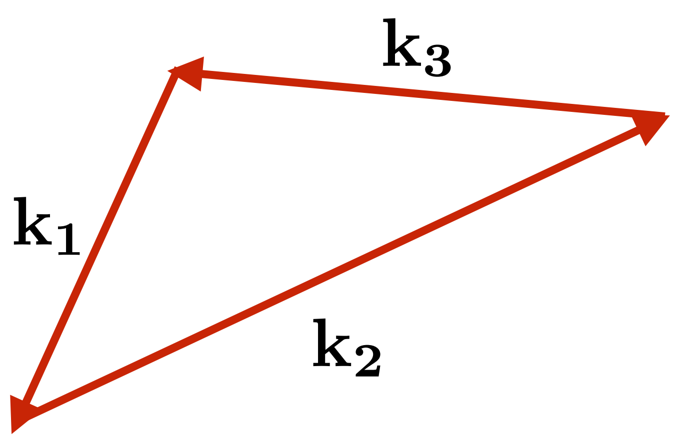

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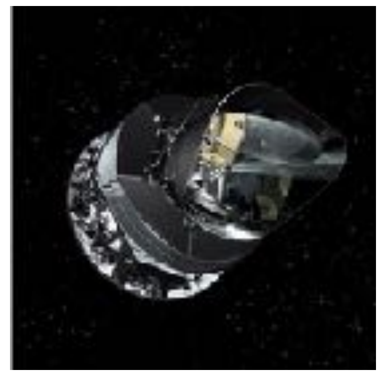

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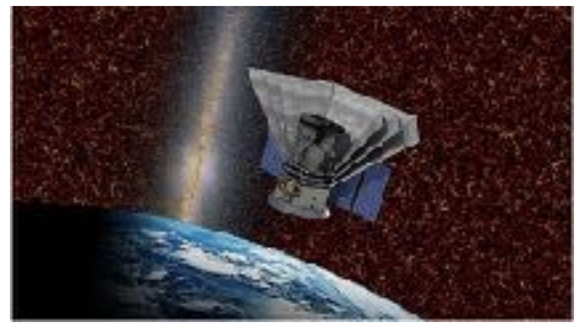

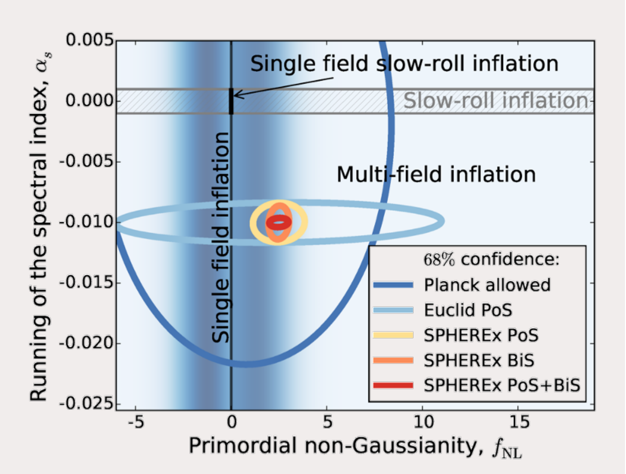

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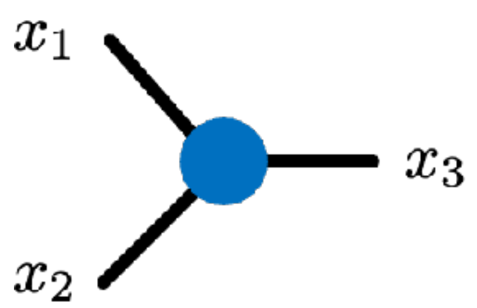
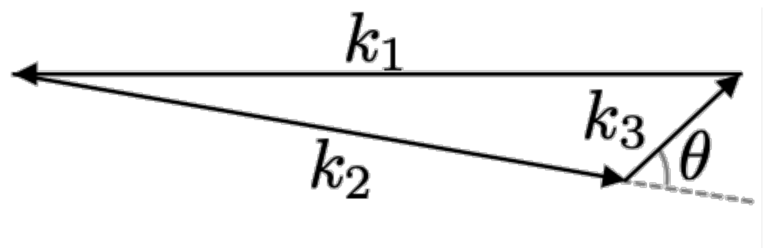


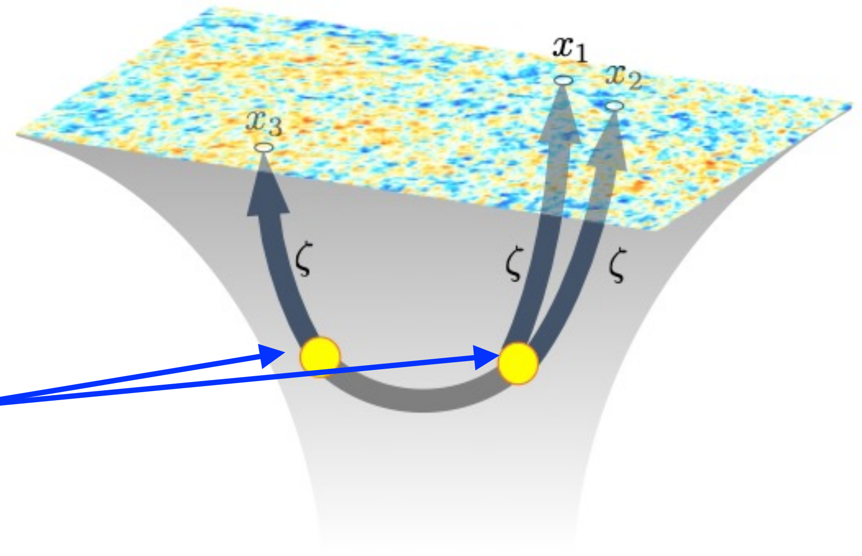
Squeezed limit of bispectrum: $k_1 \simeq k_2 \gg k_3$

☞ key for revealing new heavy particles

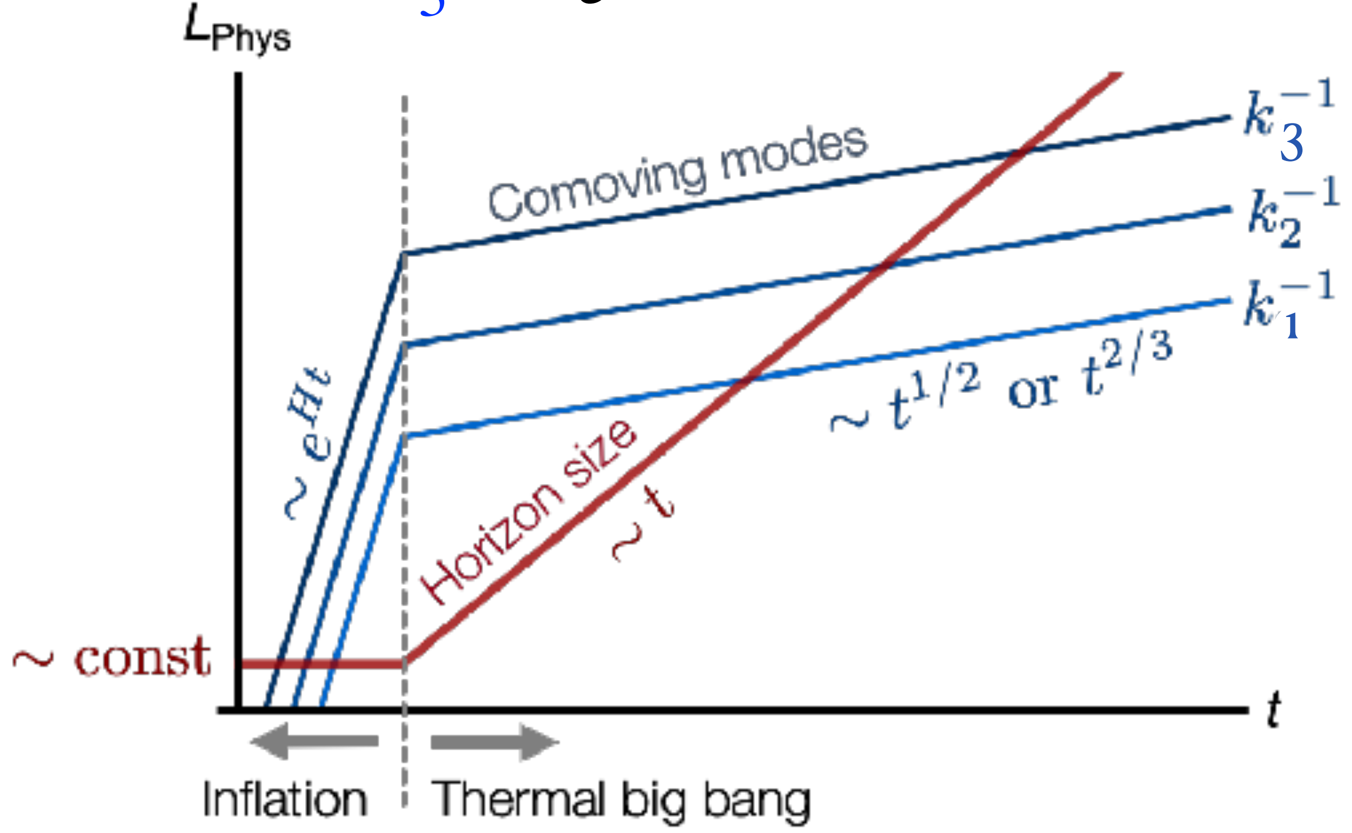


Small-momentum mode exits horizon earlier during inflation

☞ k_1/k_3: measures time difference



$$\frac{k_1}{k_3} = \frac{e^{Ht_{\rm late}}}{e^{Ht_{\rm early}}} = e^{H\Delta t}$$



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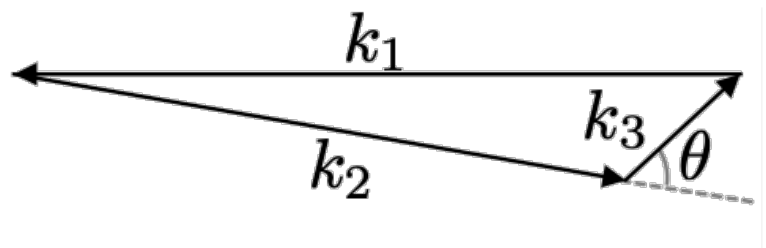

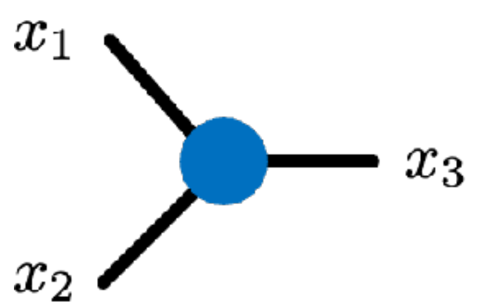

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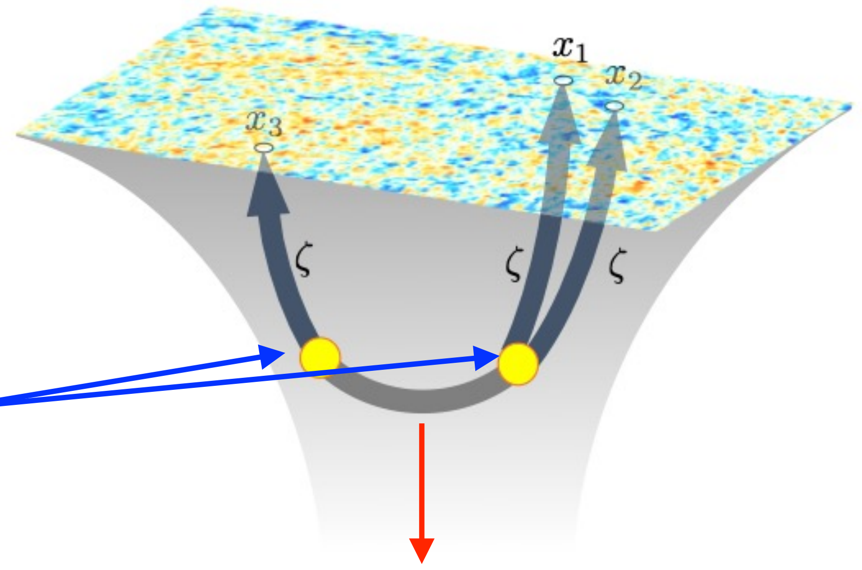

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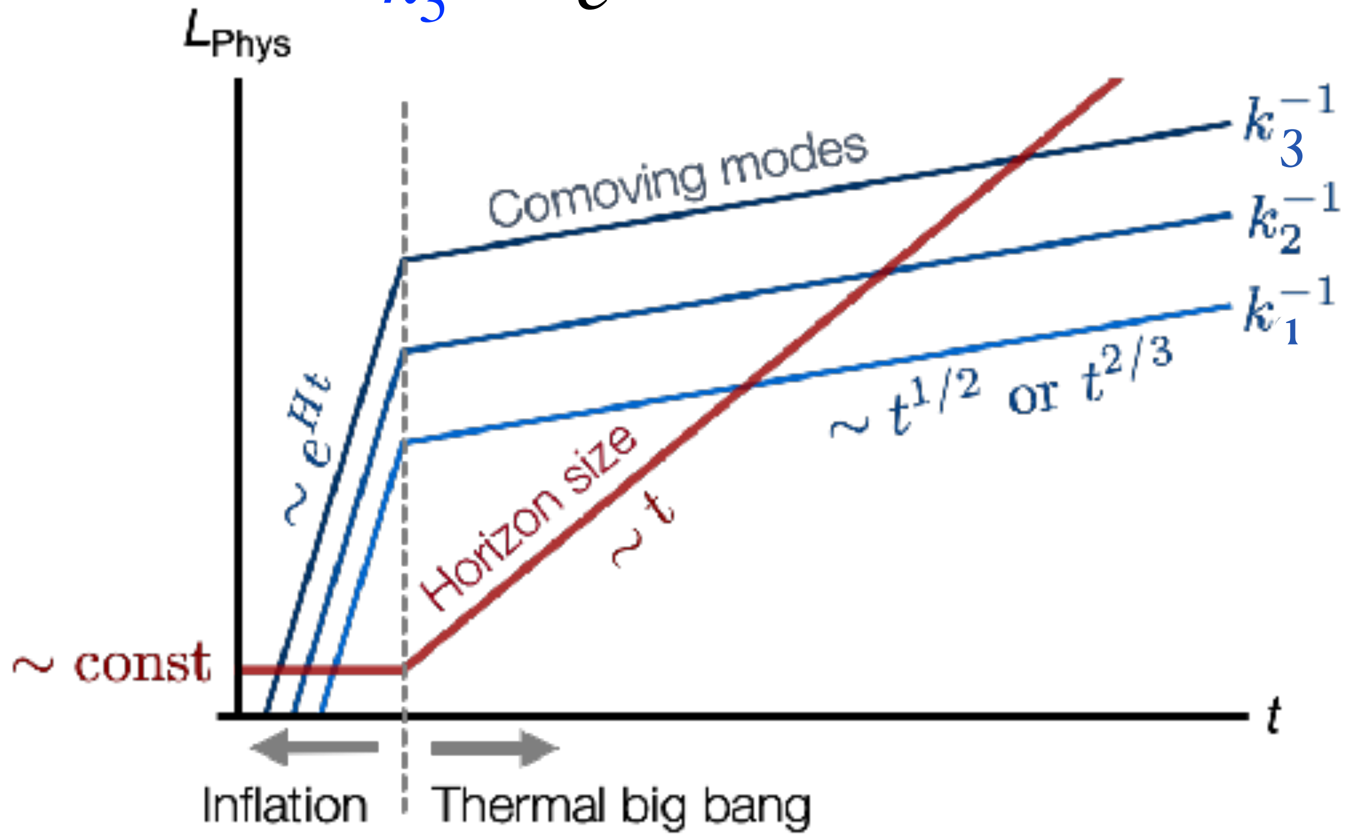


Propagating, real intermediate particle!

$$S(k_1, k_3) \propto e^{-\pi m/H} e^{im\Delta t}$$

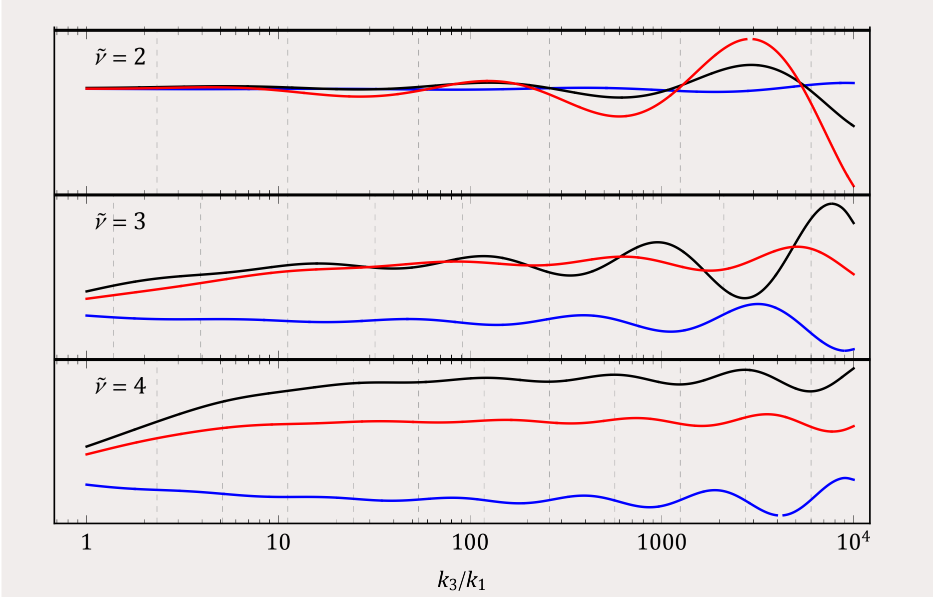
Boltmann factor ($T_{\rm dS} \sim H$)   Oscillation (QM)

$$= e^{-\pi m/H} (k_1/k_3)^{im/H}$$

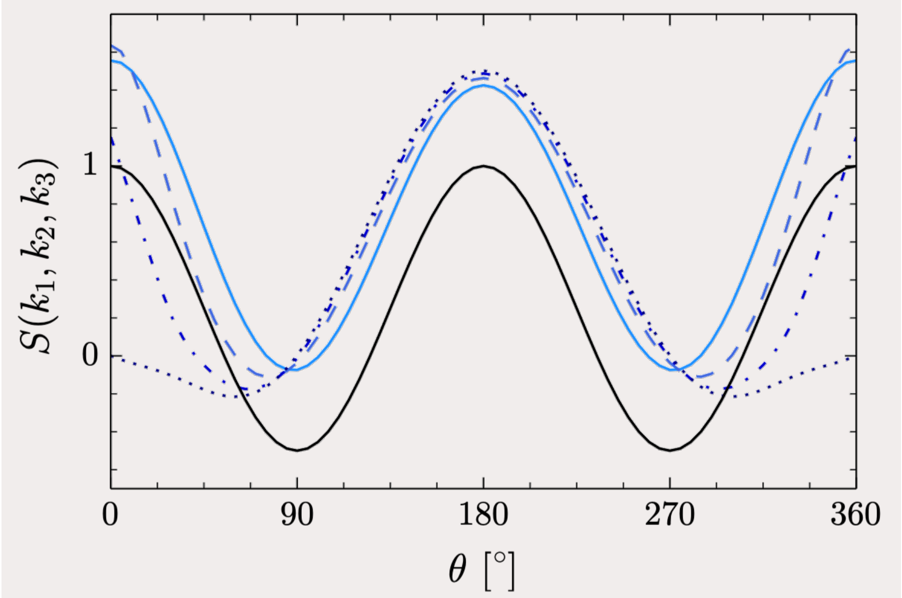
— **Mass measurement!**

(C.f. bump hunting at the LHC)

Examples of $S(k_1, k_3)$:



Chen, Chua, Guo, Wang, ZZX, Xie, 1803.04412



Lee, Baumann, Pimentel, 1607.03735