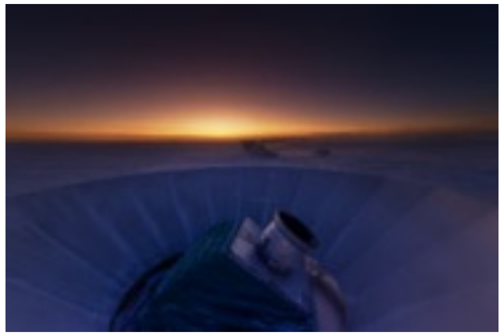
Bモード偏光から探る
初期宇宙と素粒子理論

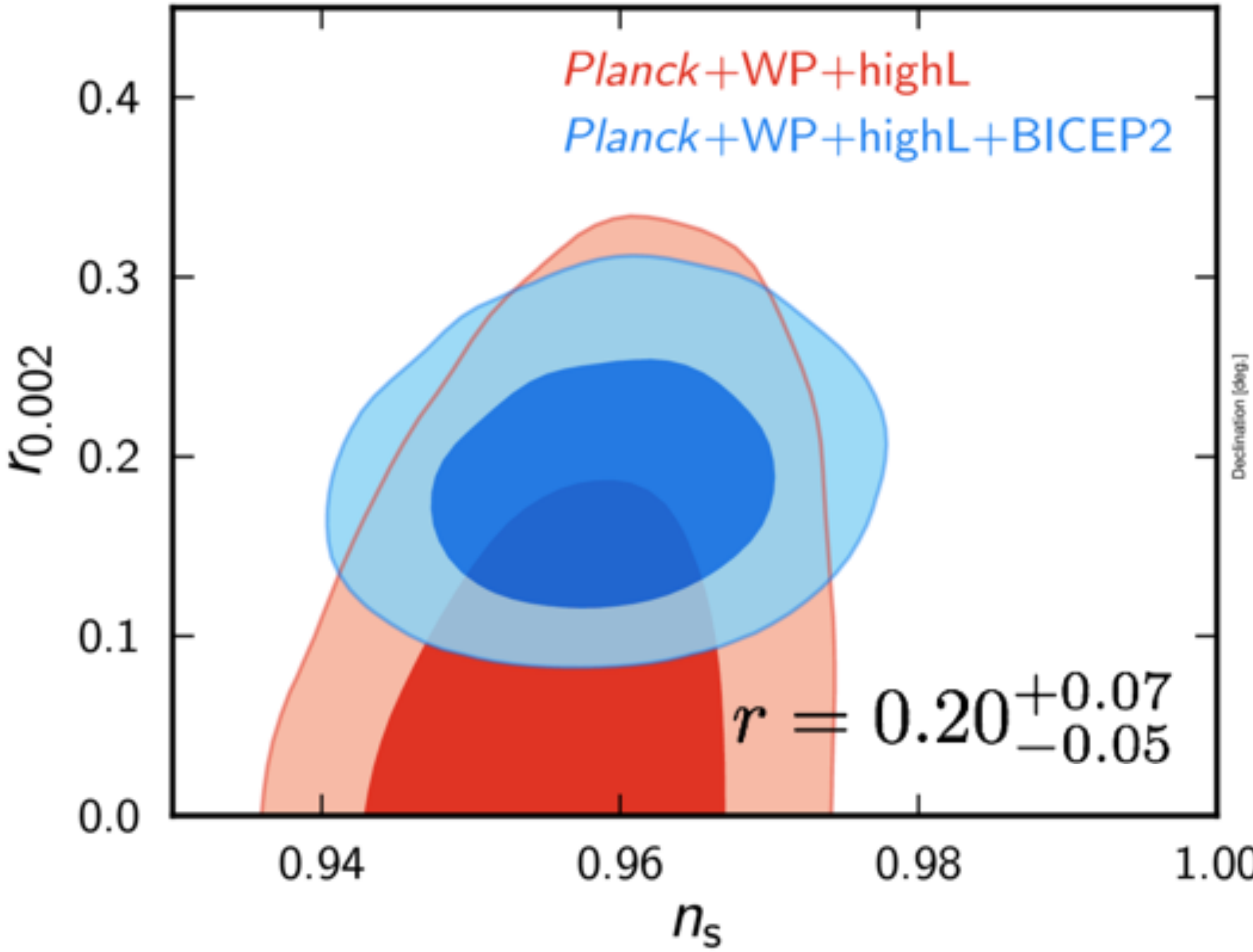
2014年９月19日
日本物理学会@佐賀大学

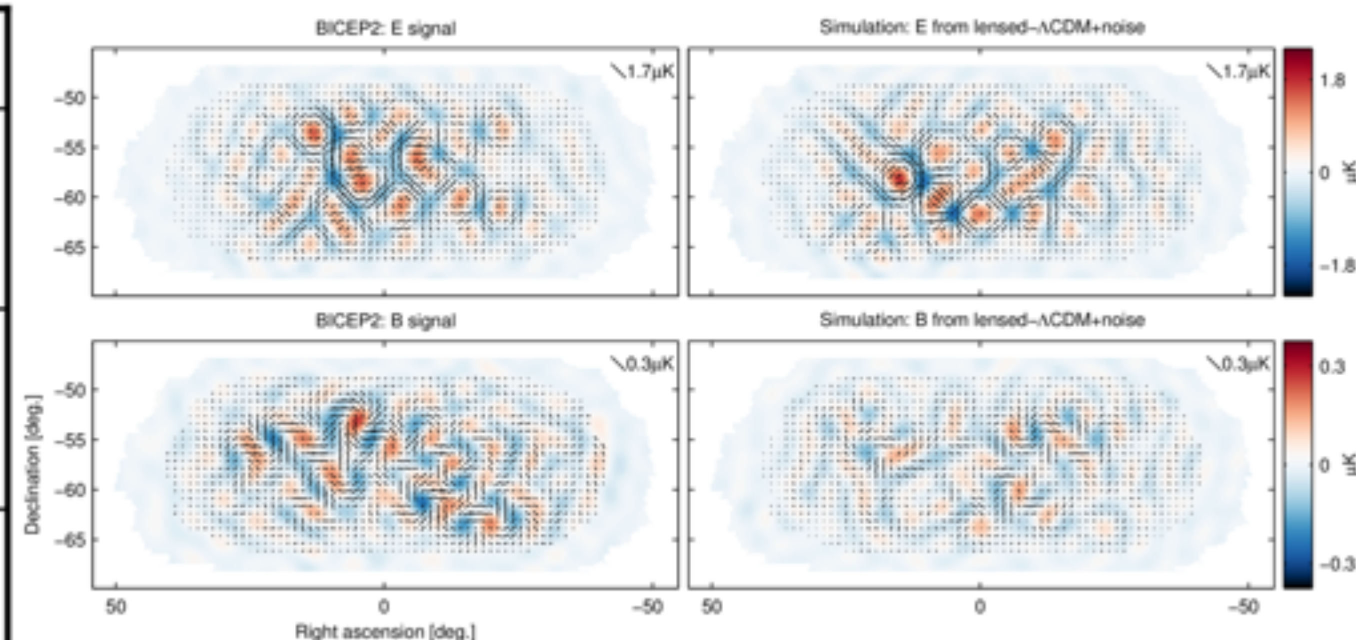
高橋　史宜
（東北大学）

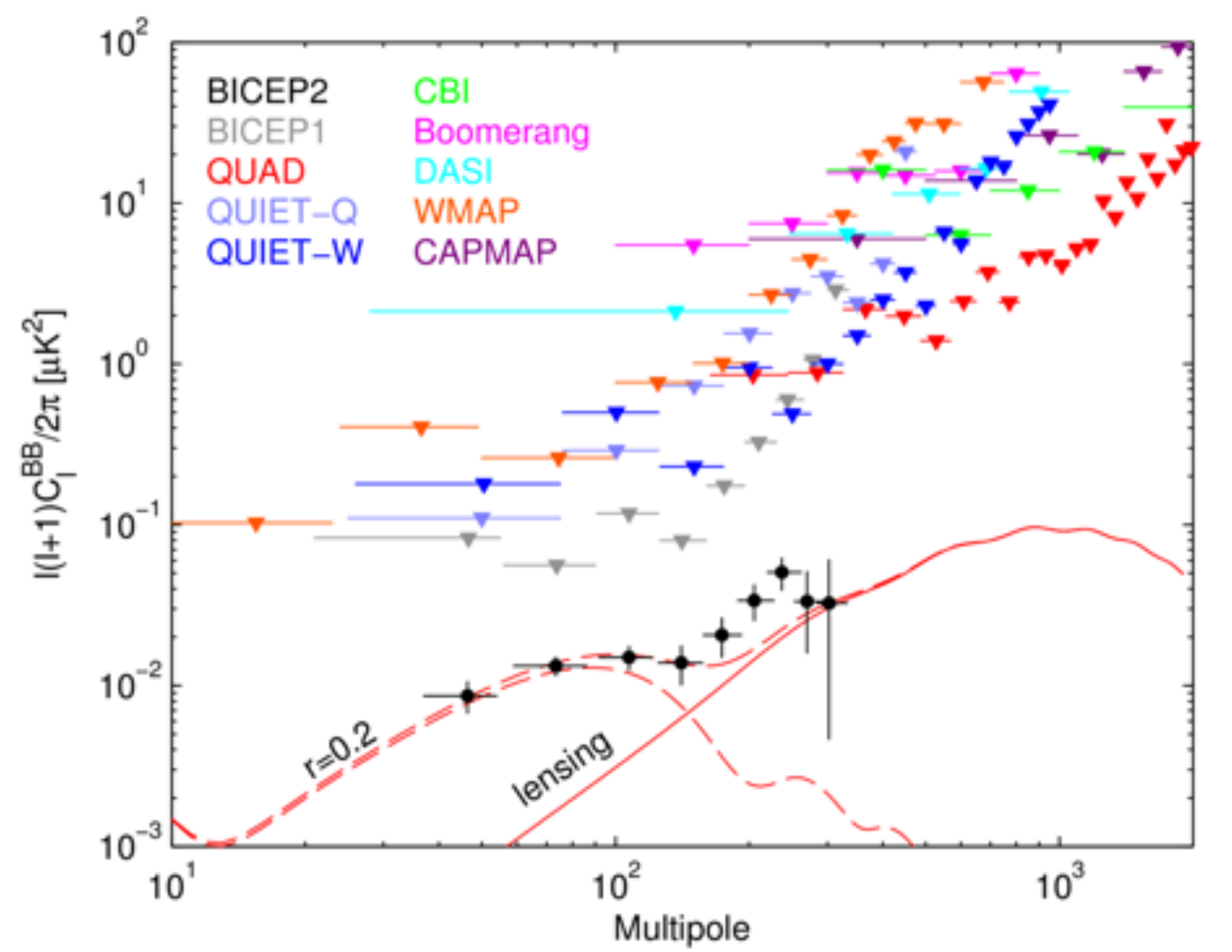


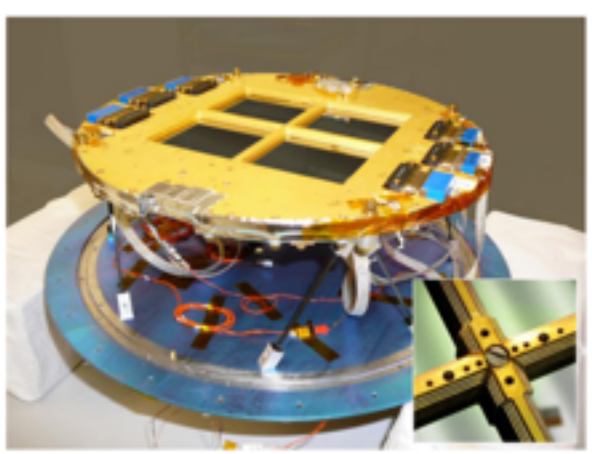
BICEP2

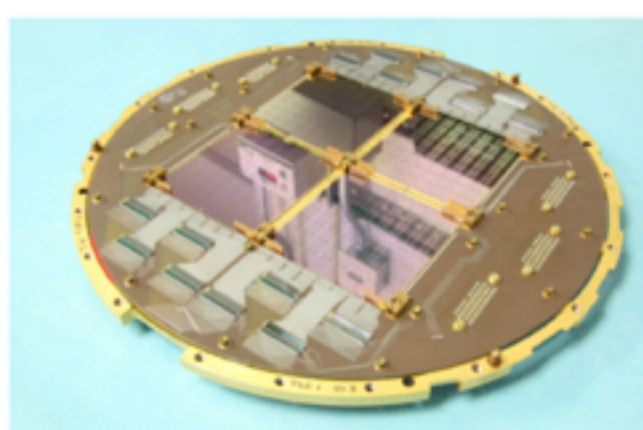
1403.3985

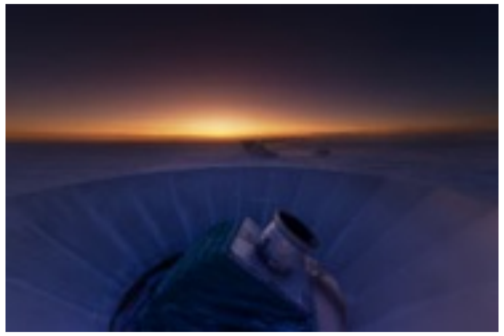












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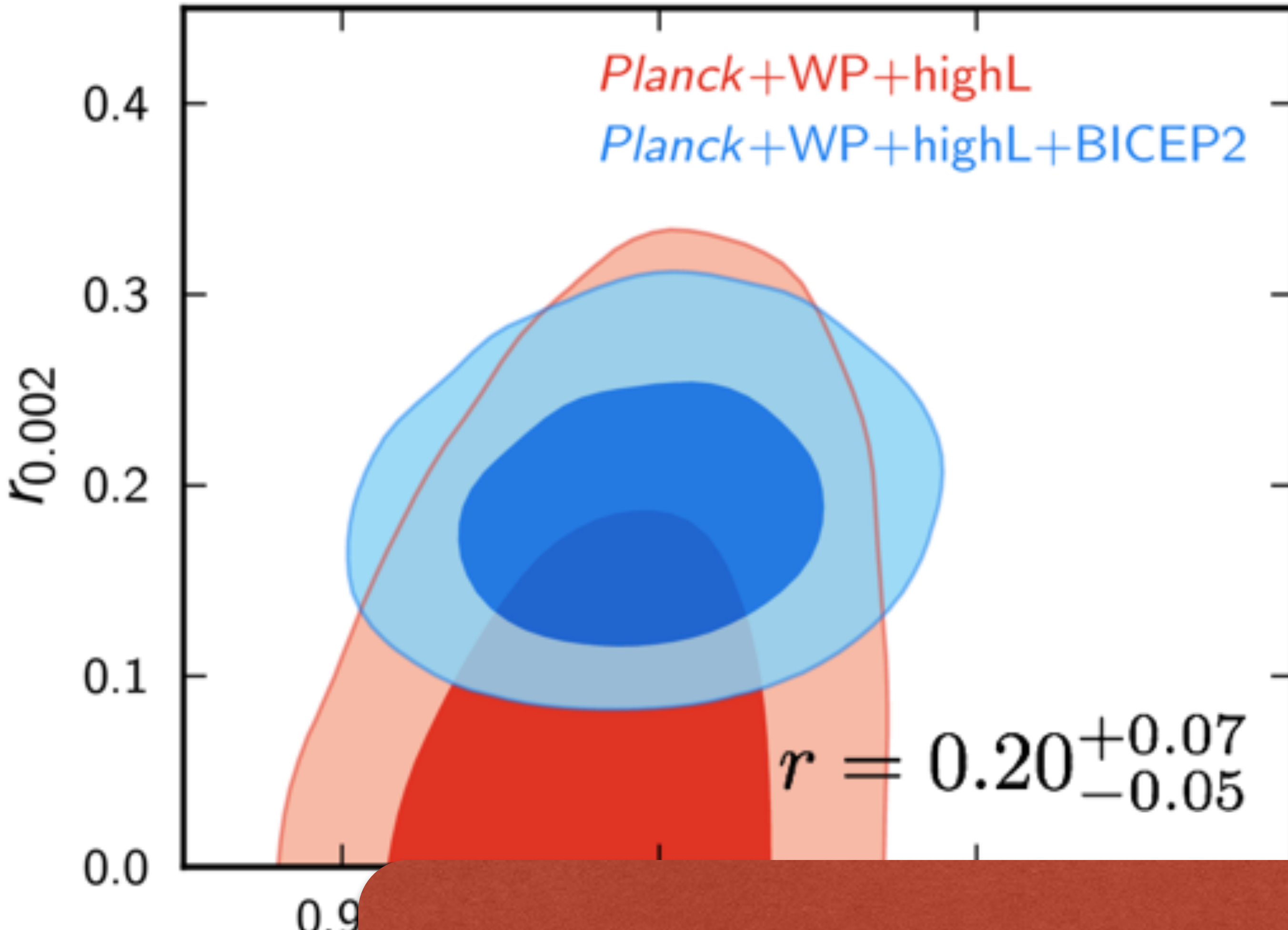
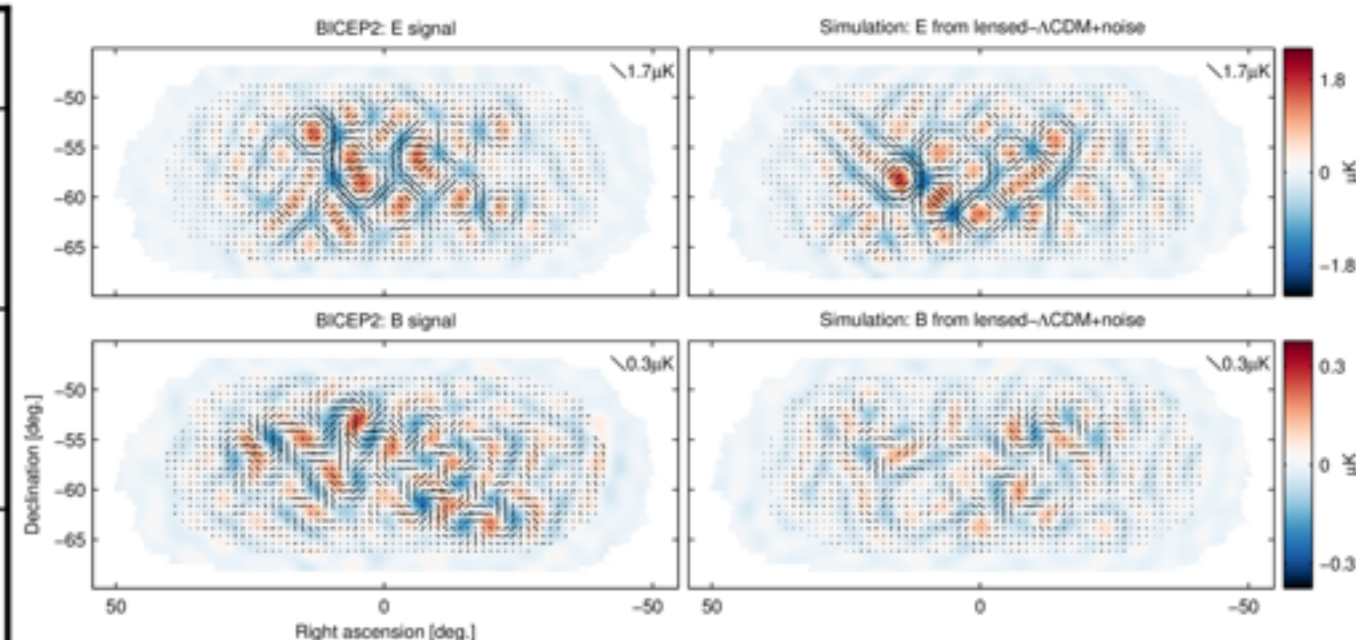
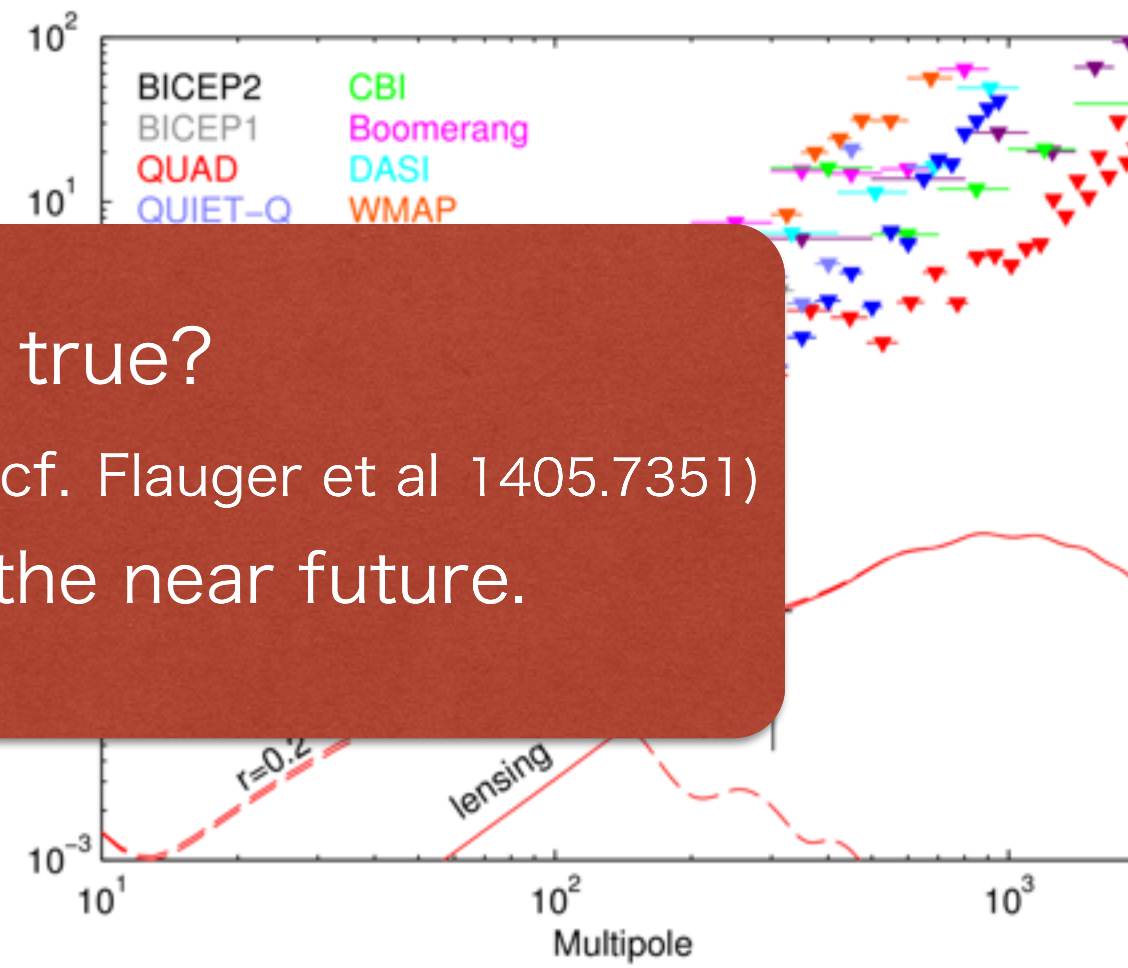
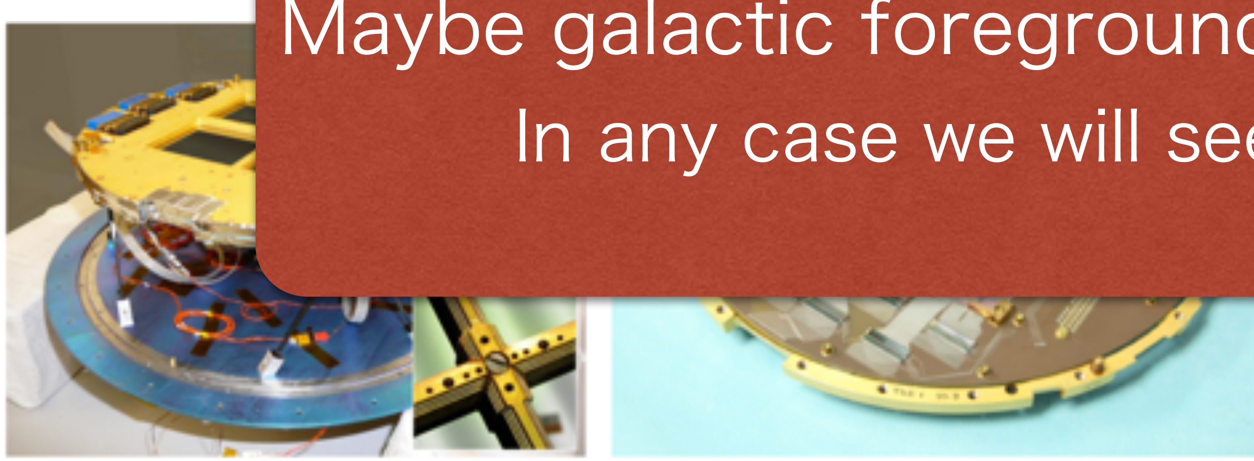








Too good to be true?

Maybe galactic foreground? (cf. Flauger et al 1405.7351)

In any case we will see in the near future.

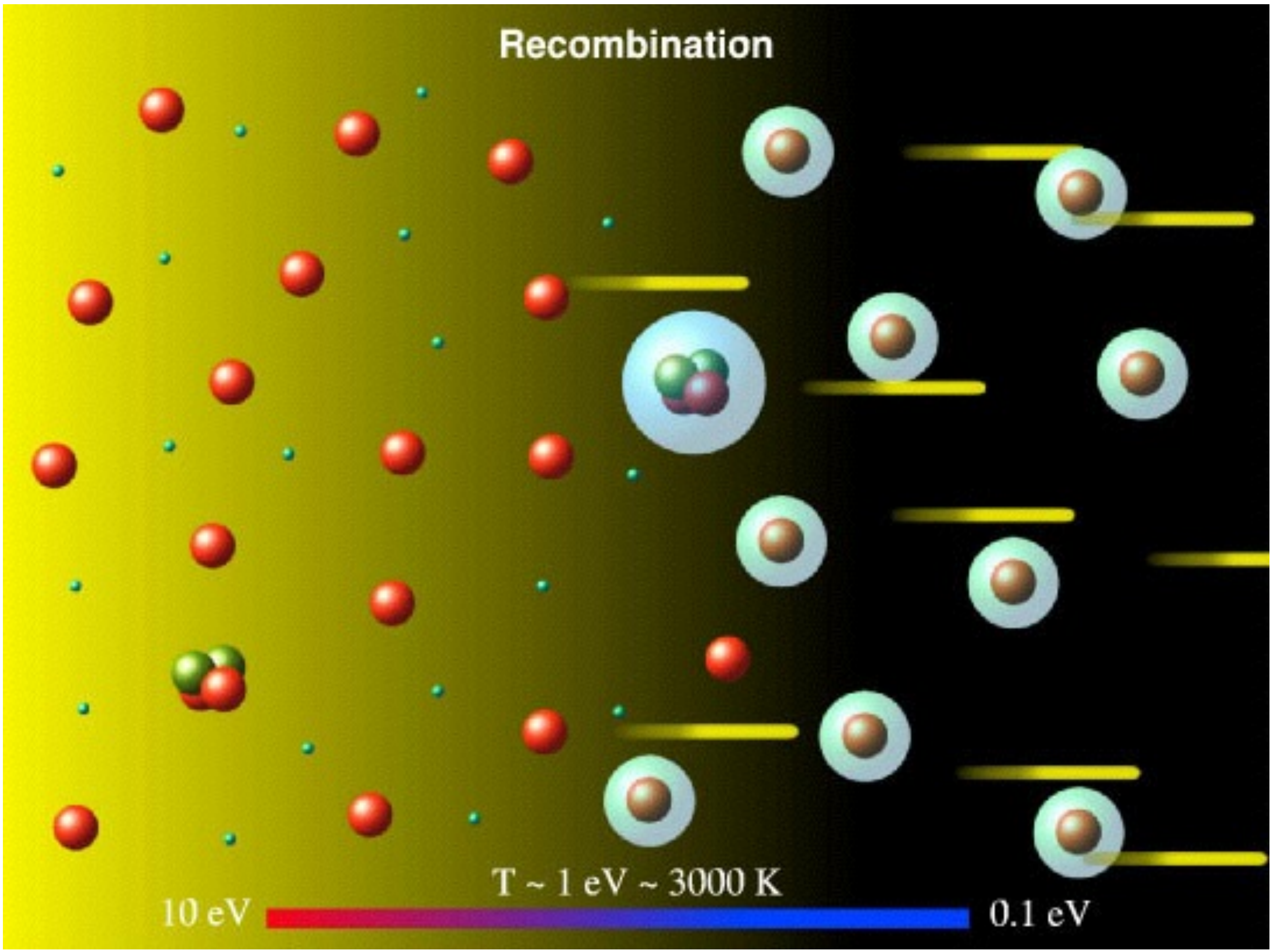
もしr = O(10^{-3}–10^{-1})だったら
いったい何がわかるのか？

Talk plan

1. CMB Bモードと計量揺らぎ
2. インフレーションとその示唆
3. インフレーション模型
    1. RH sneutrino inflation
    2. Axion landscape
4. まとめ

1. CMB Bモードと計量揺らぎ

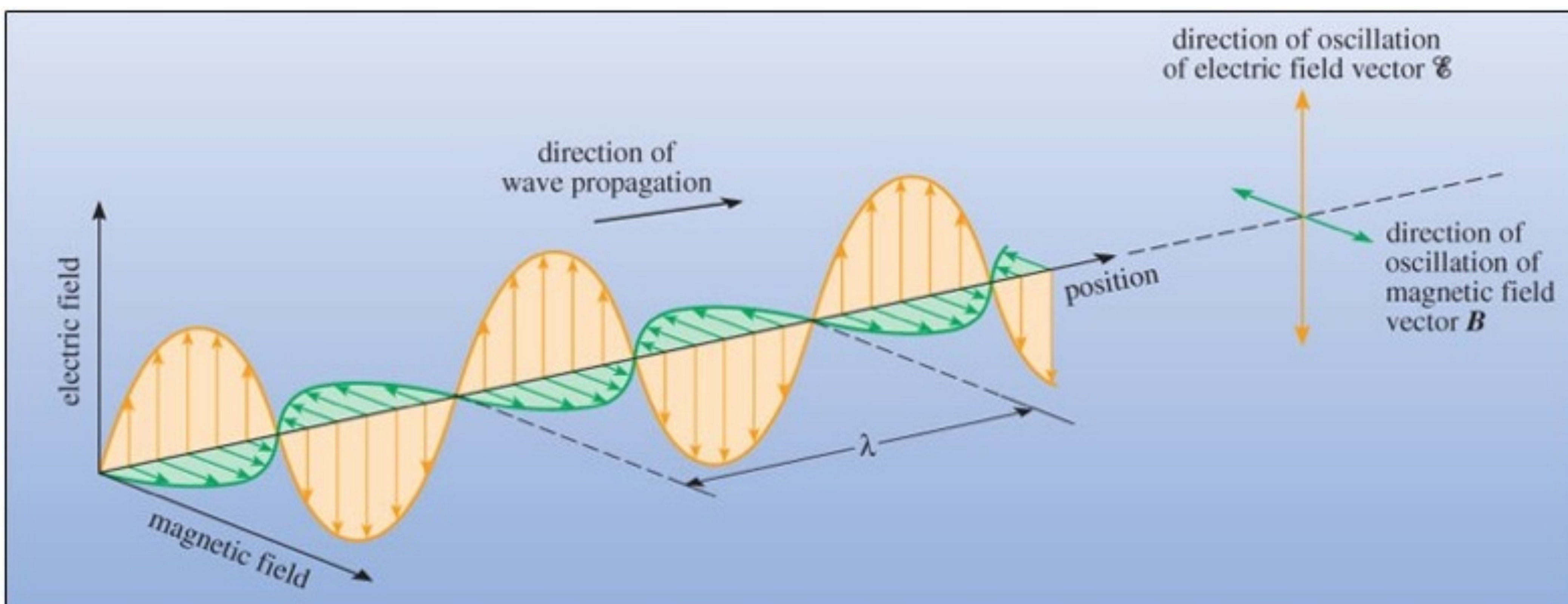
Cosmic Microwave Background
(宇宙背景輻射)



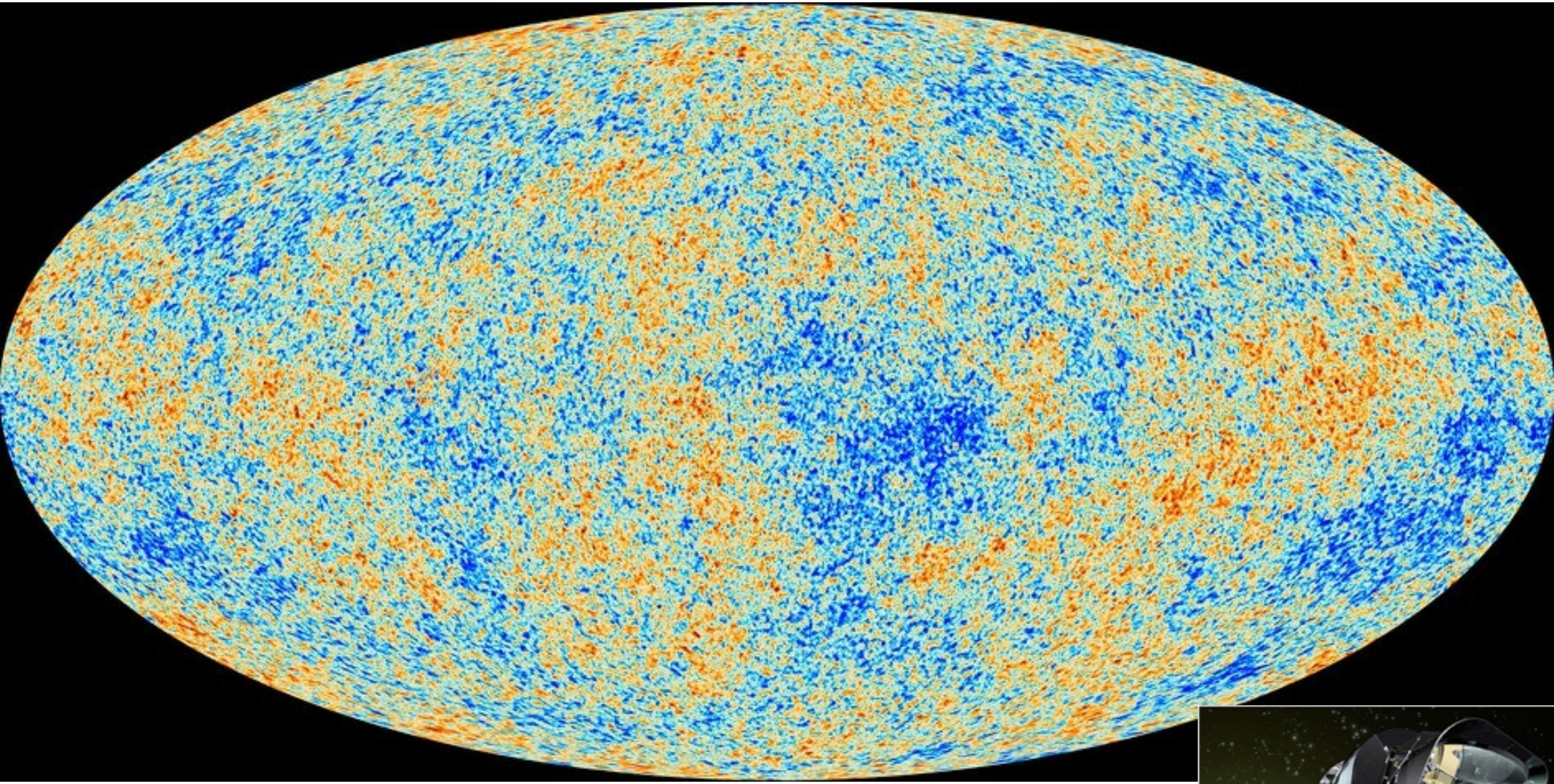
CMB光子は

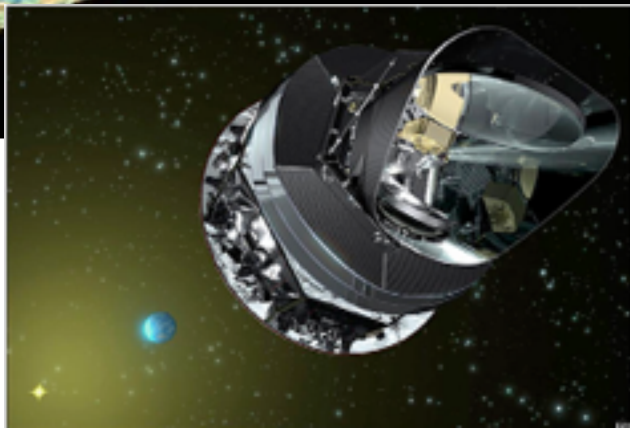
1. **エネルギー (あるいは 温度)**
2. **偏光**

で特徴付けられる。CMB温度および偏光の到来方向異方性はすでに検出。

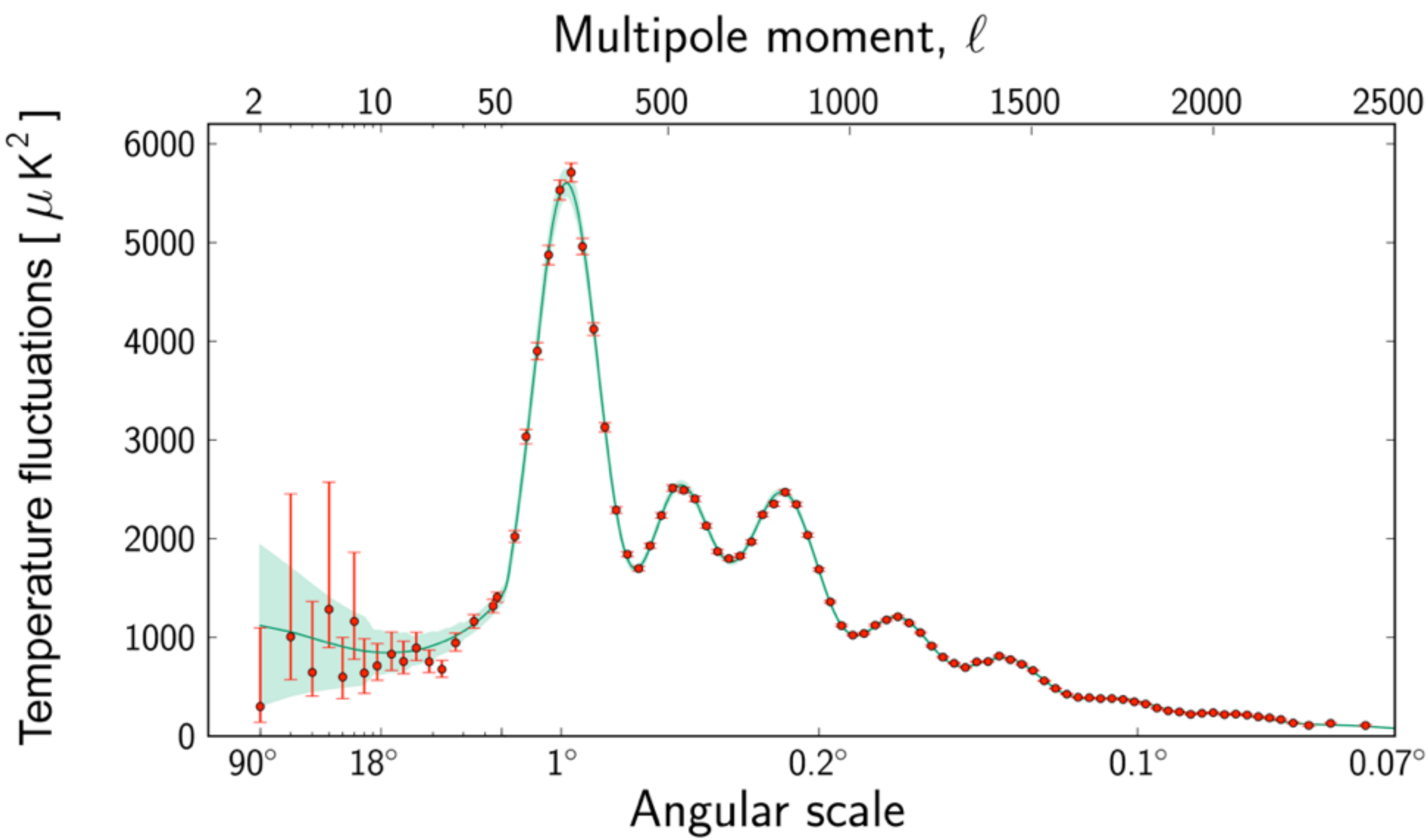


CMB temperature sky map





CMB anisotropy angular power spectrum



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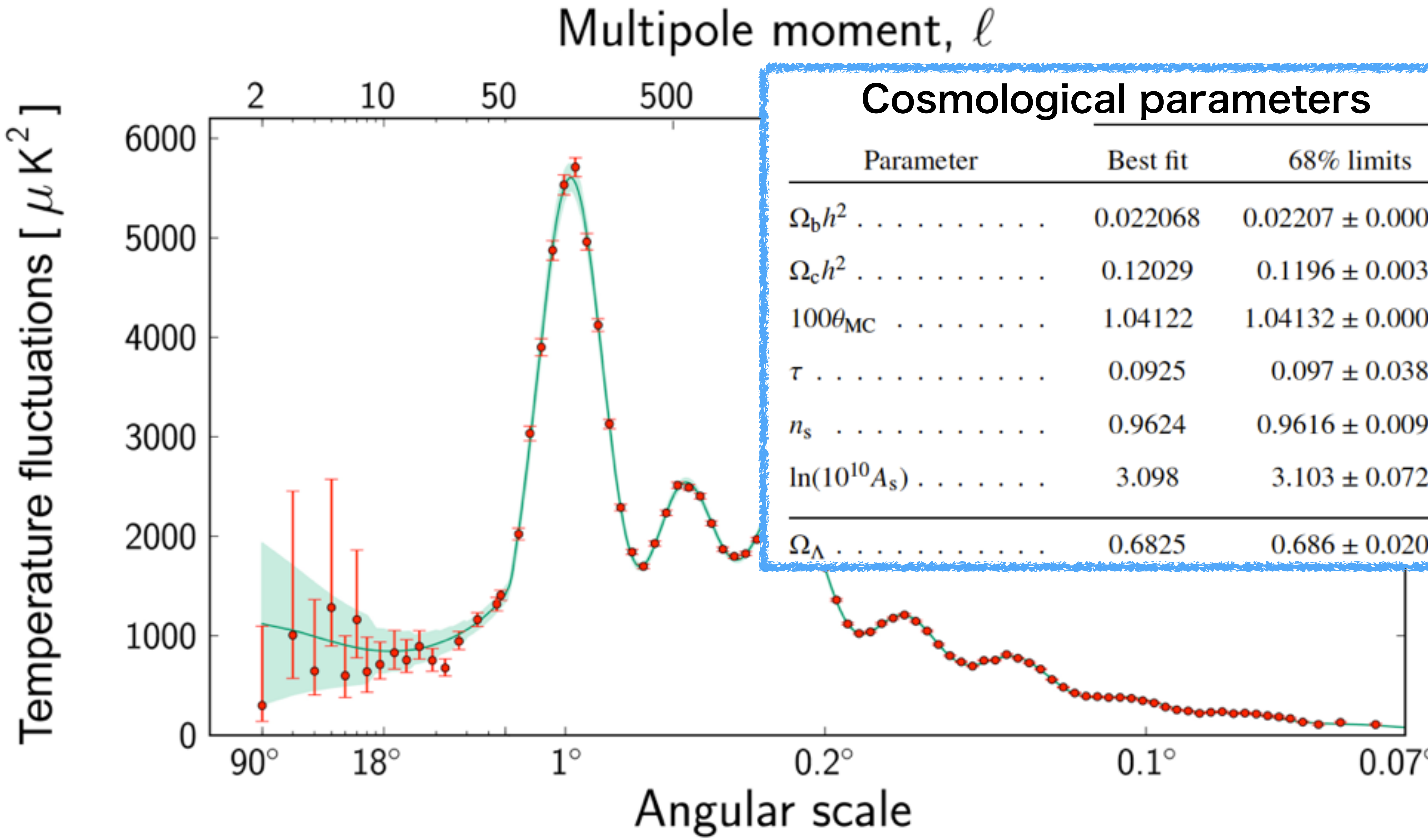
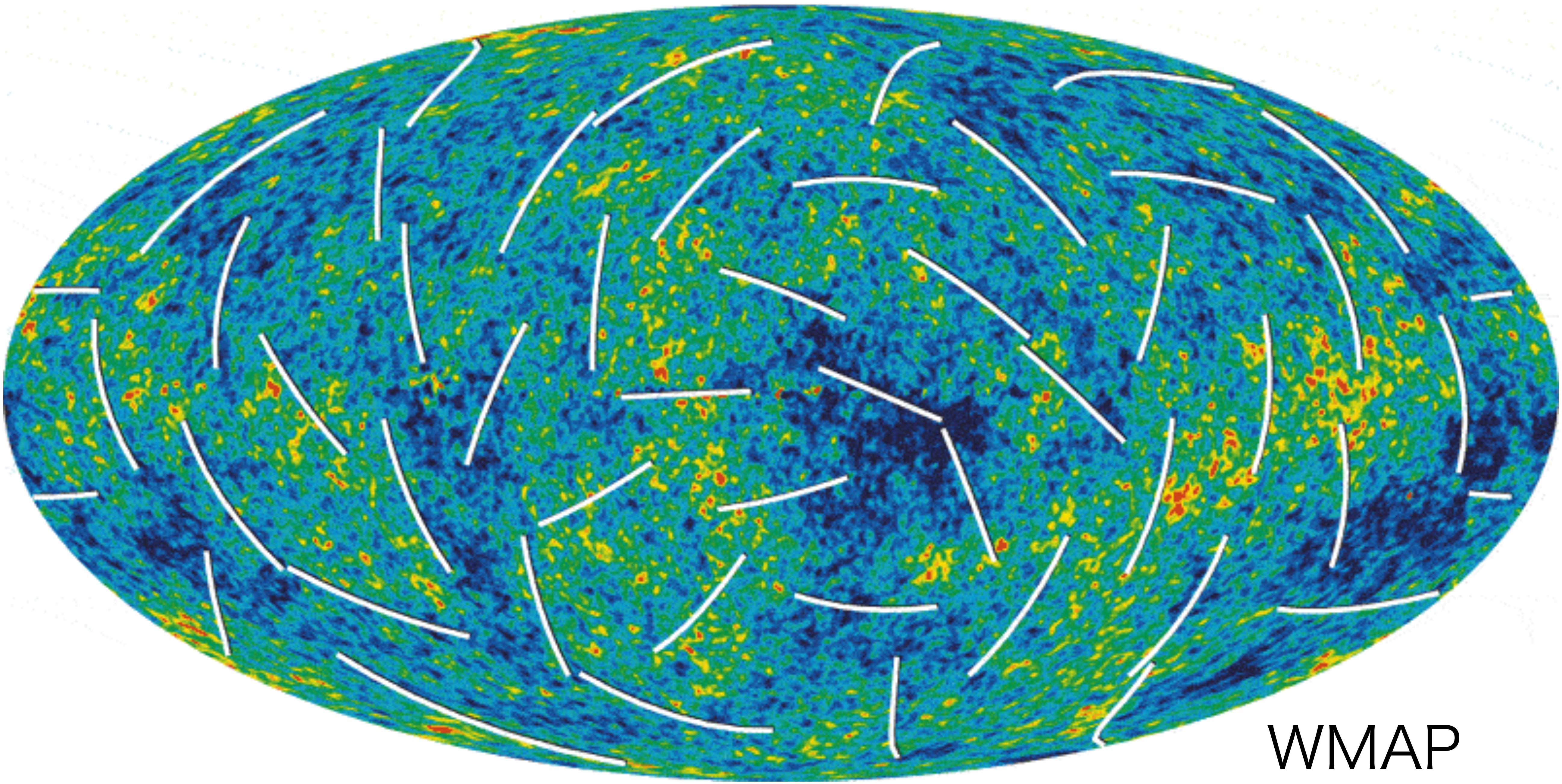


Cosmological parameters

Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072
Ω_Λ	0.6825	0.686 ± 0.020

CMB polarization

CMB photons are polarized!!



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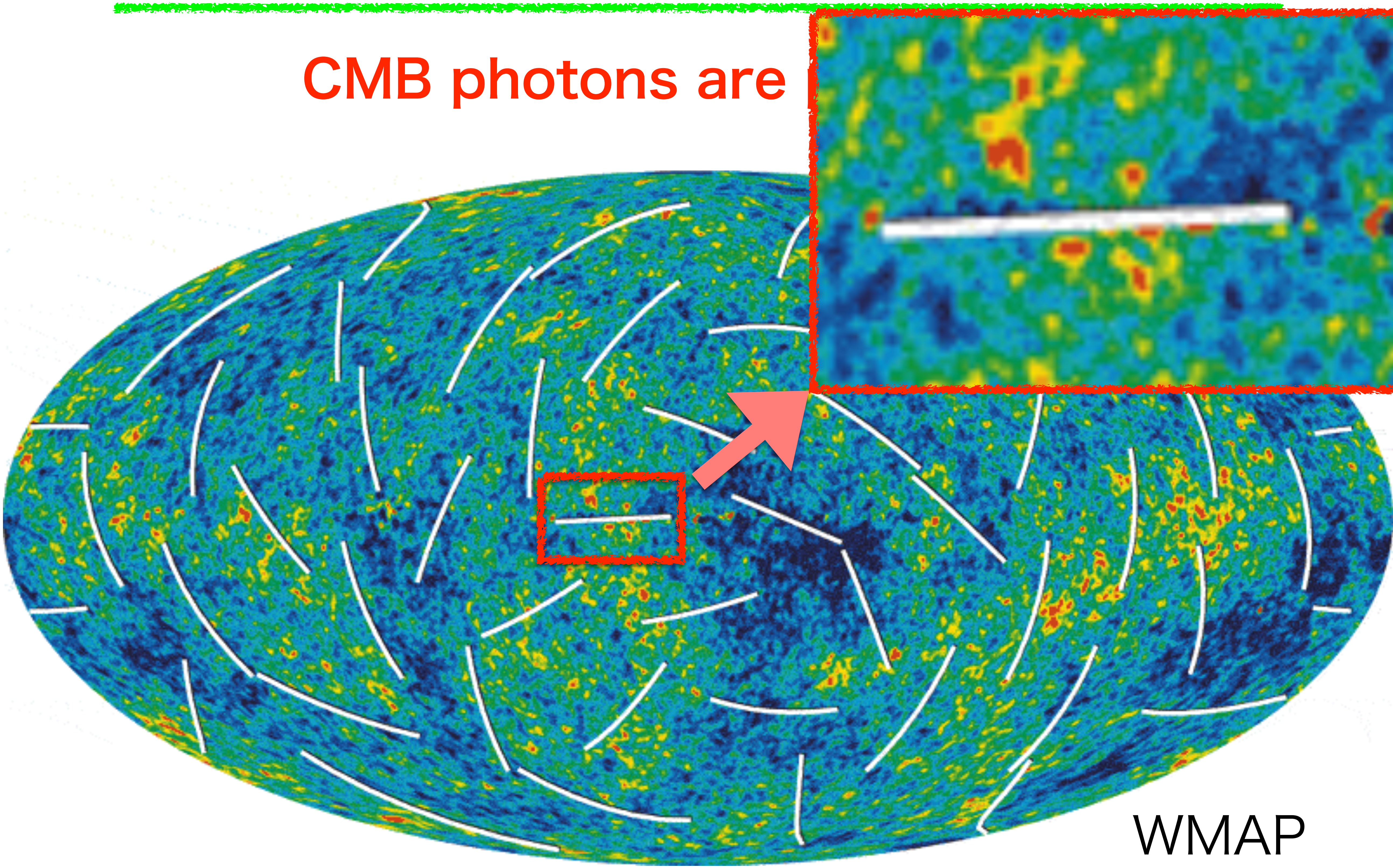
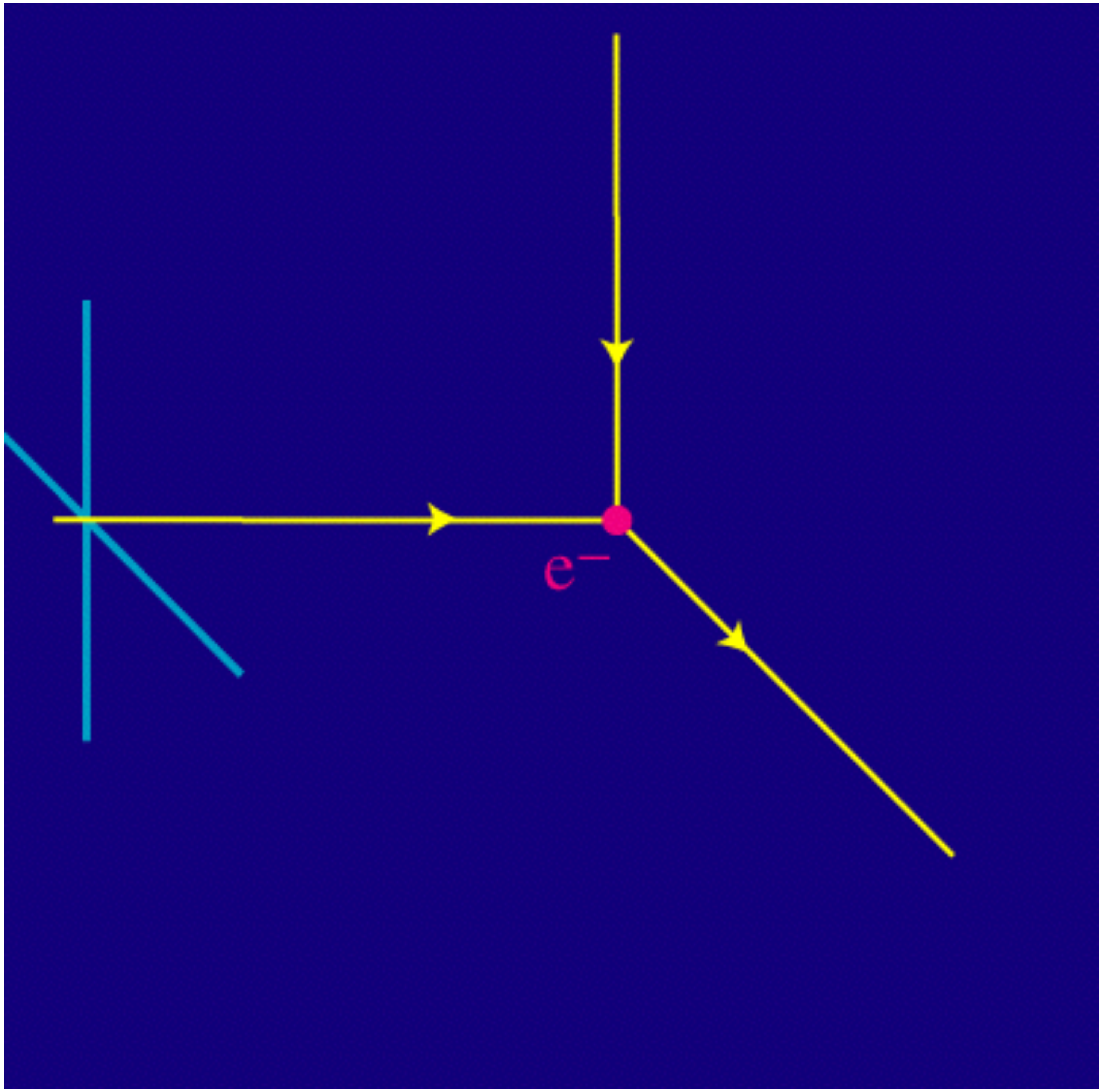


トムソン散乱によって直線偏光は
容易に作られるが、



(Taken from W. Hu’s webpage)

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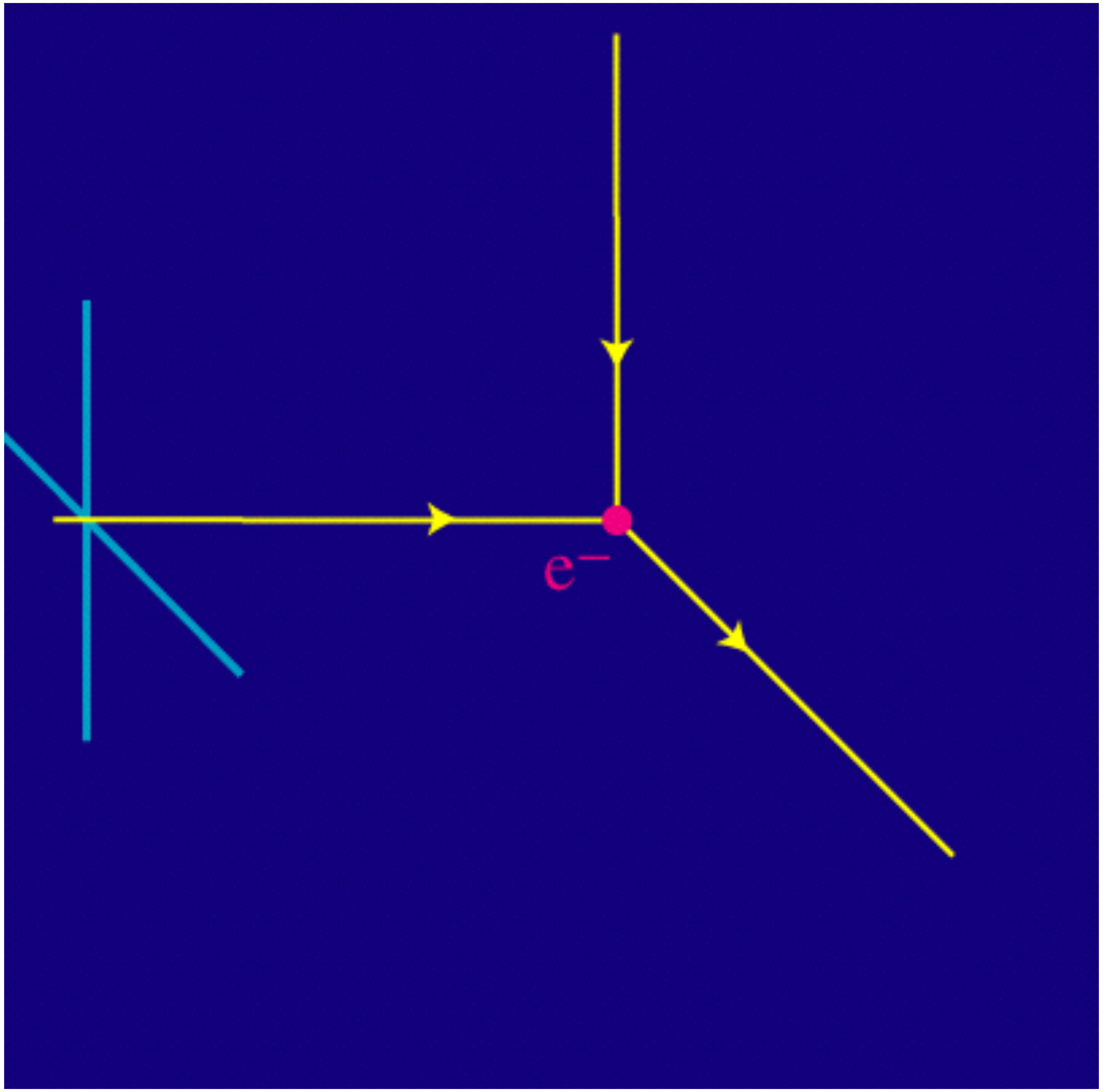

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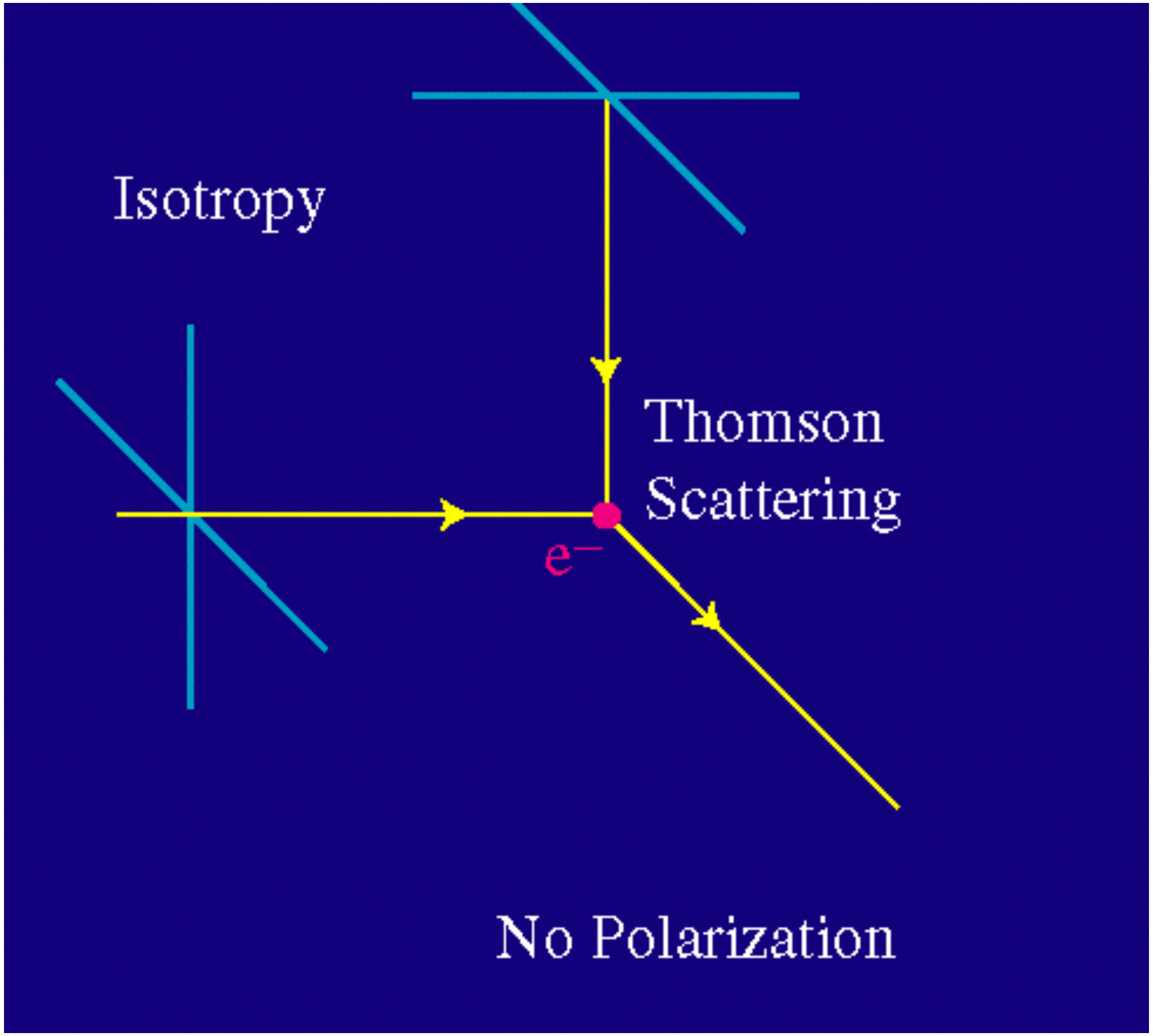
宇宙が等方だったら偏光は生じない。
双極子揺らぎでも互いにキャンセルしてダメ。



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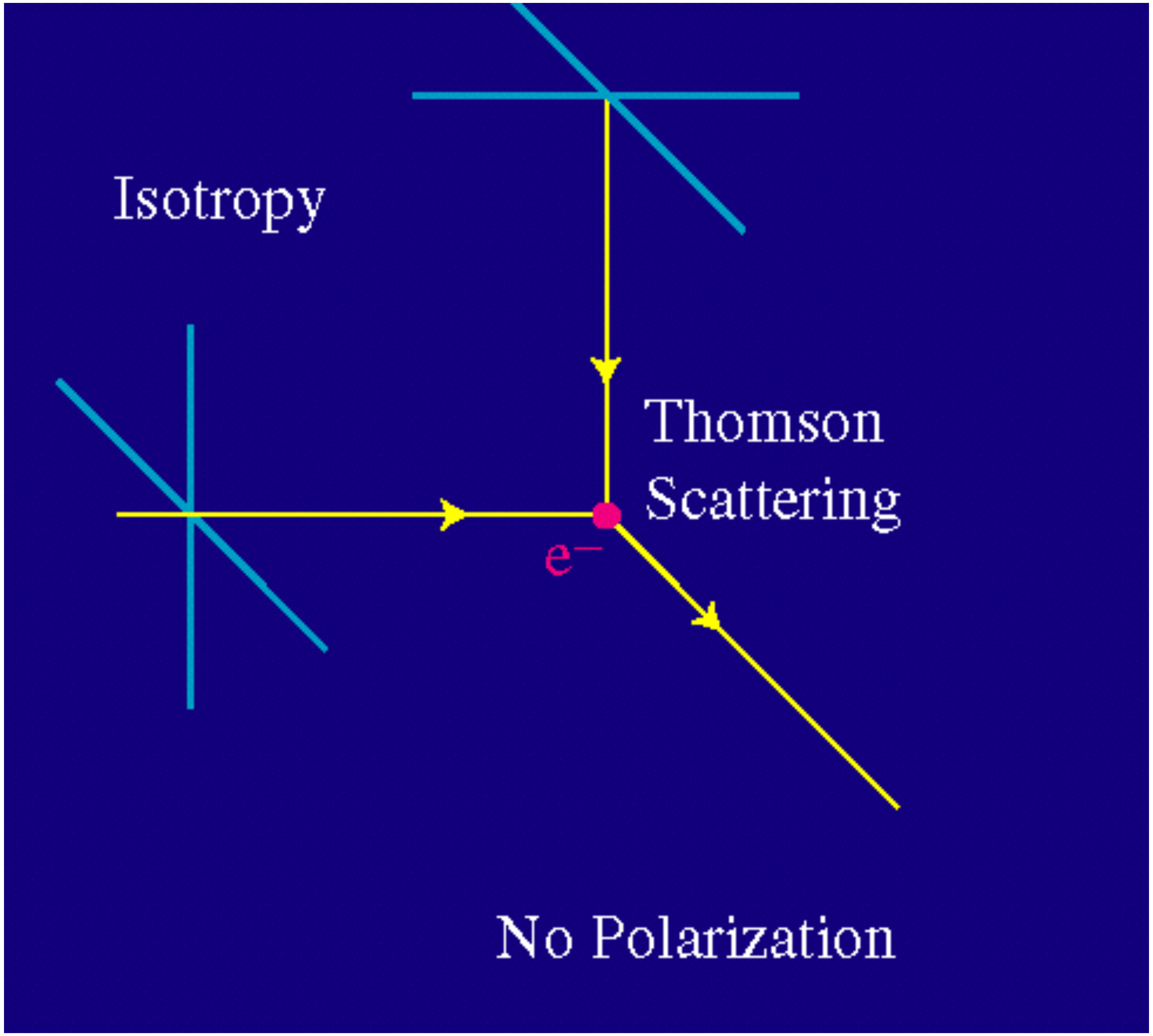

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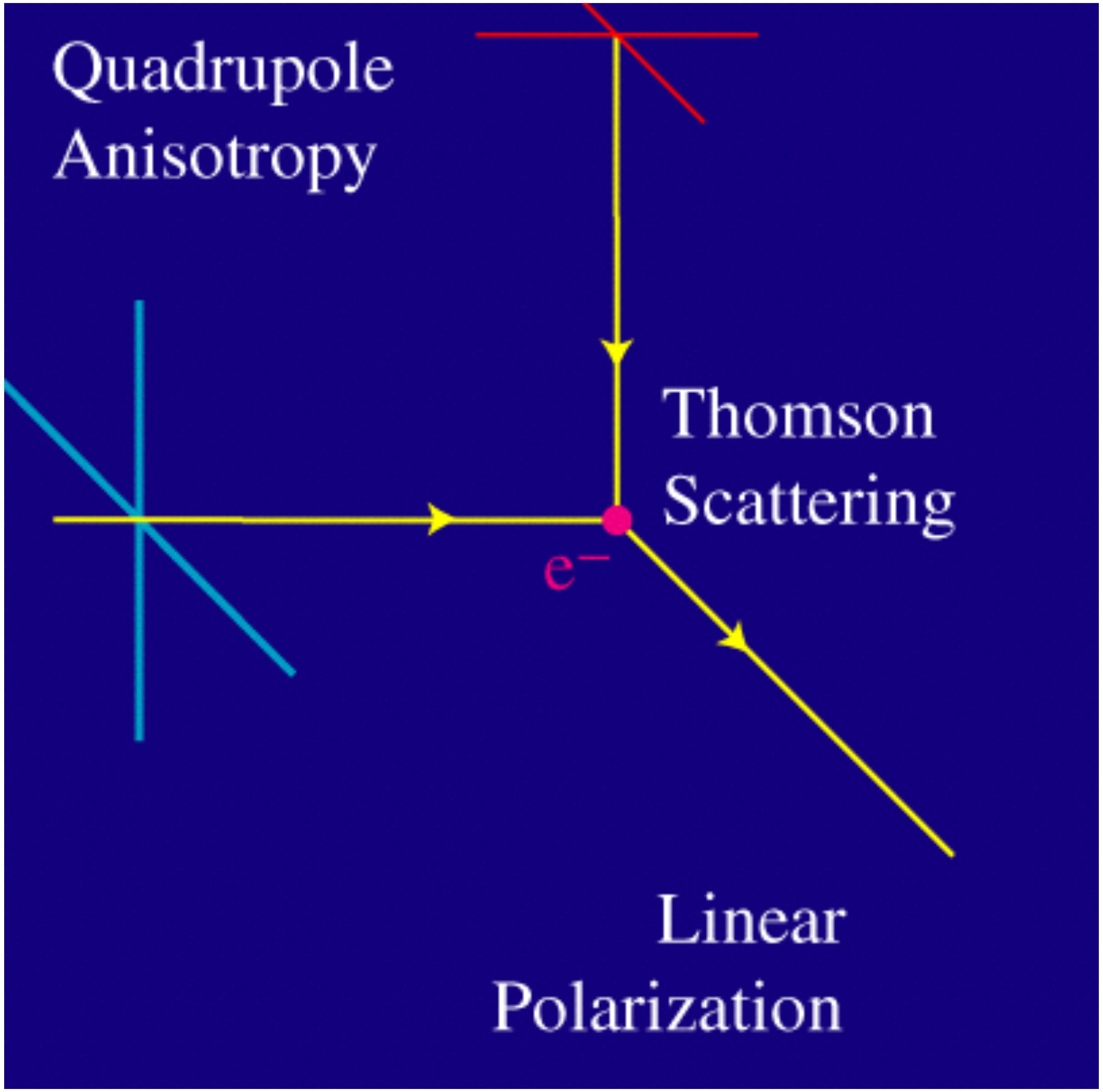
結局、四重極揺らぎによって偏光が生じる。

偏光ベクトルは冷たい方向を結ぶ。（下の例では上下方向）



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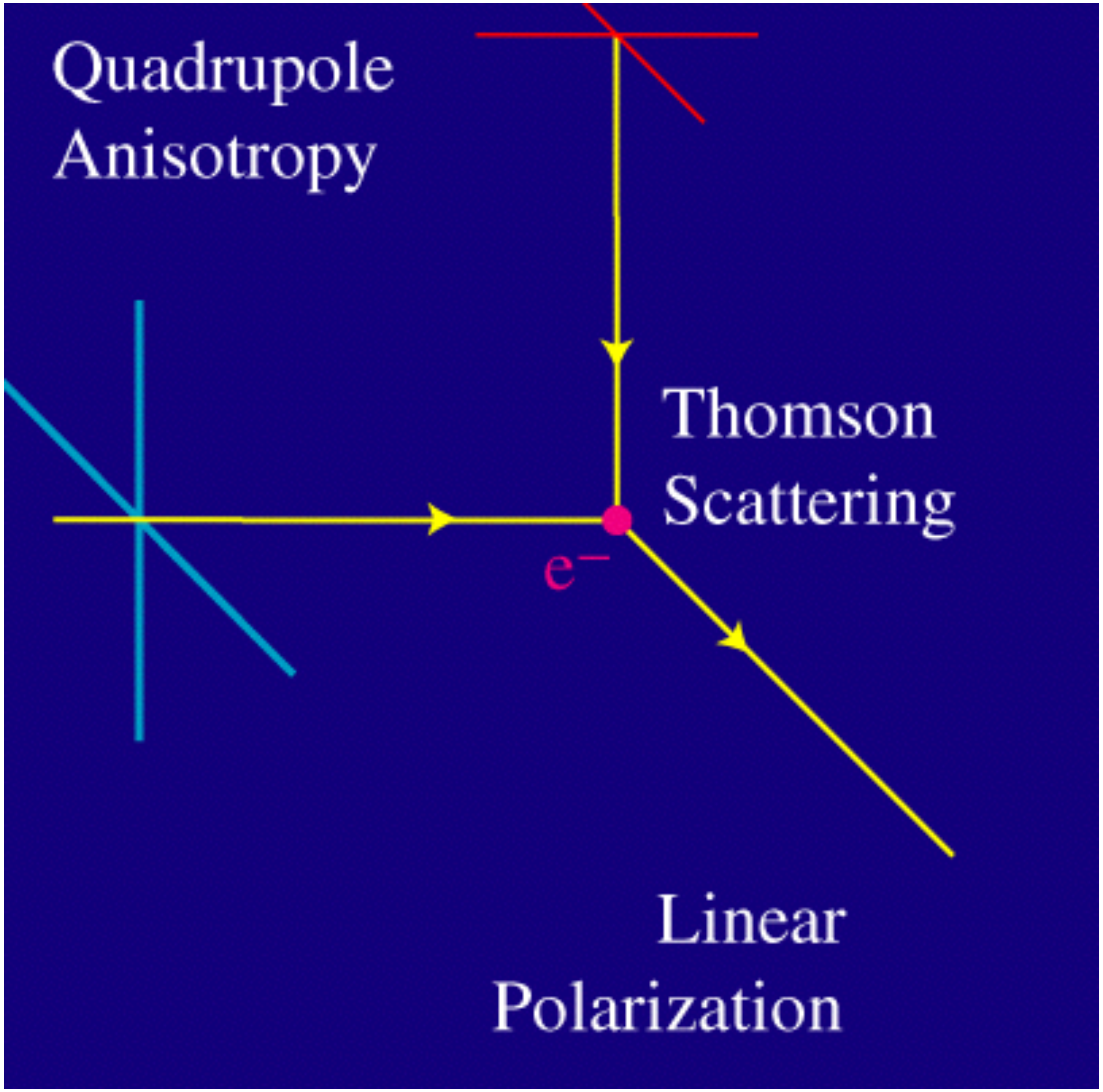

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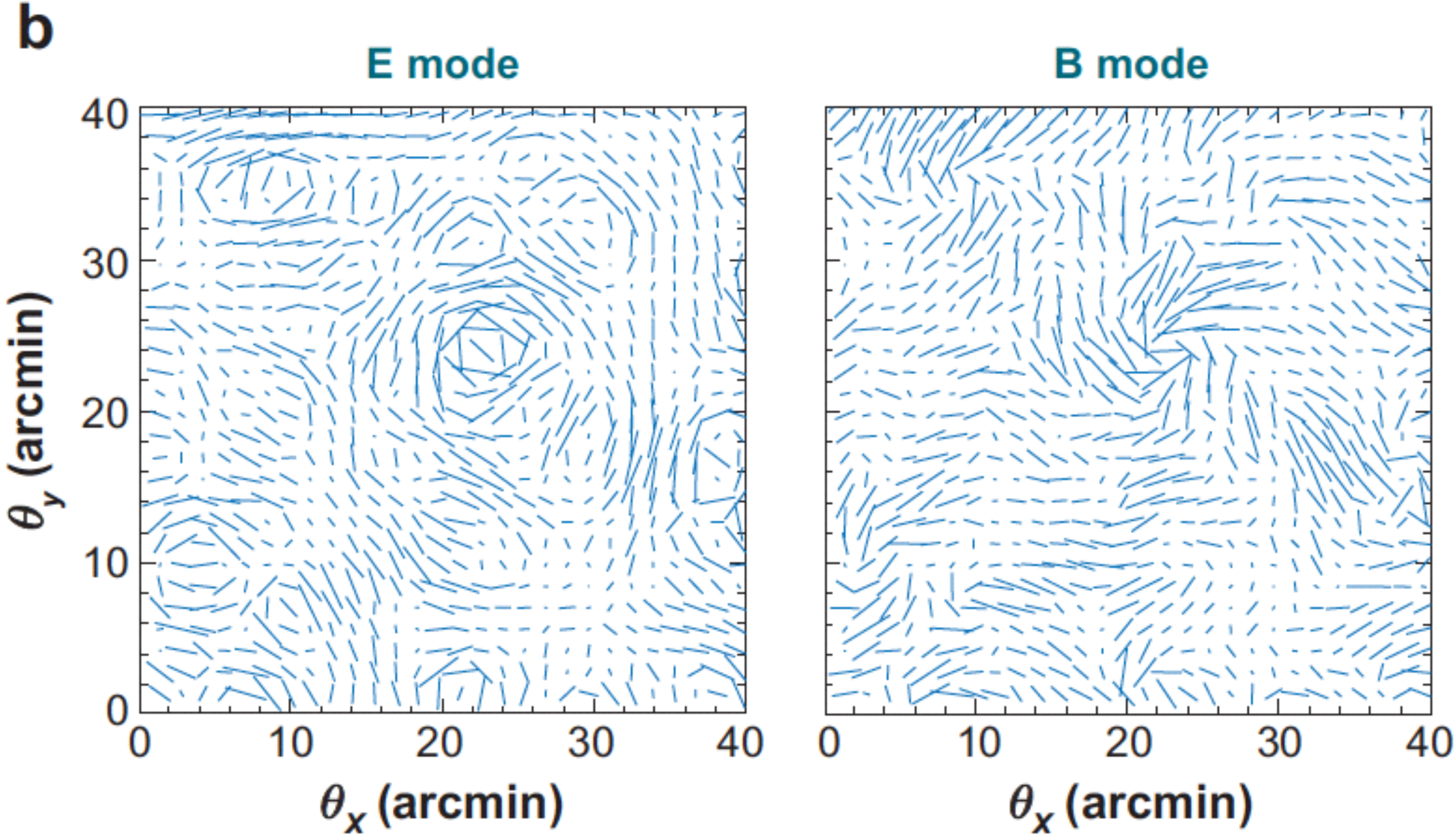
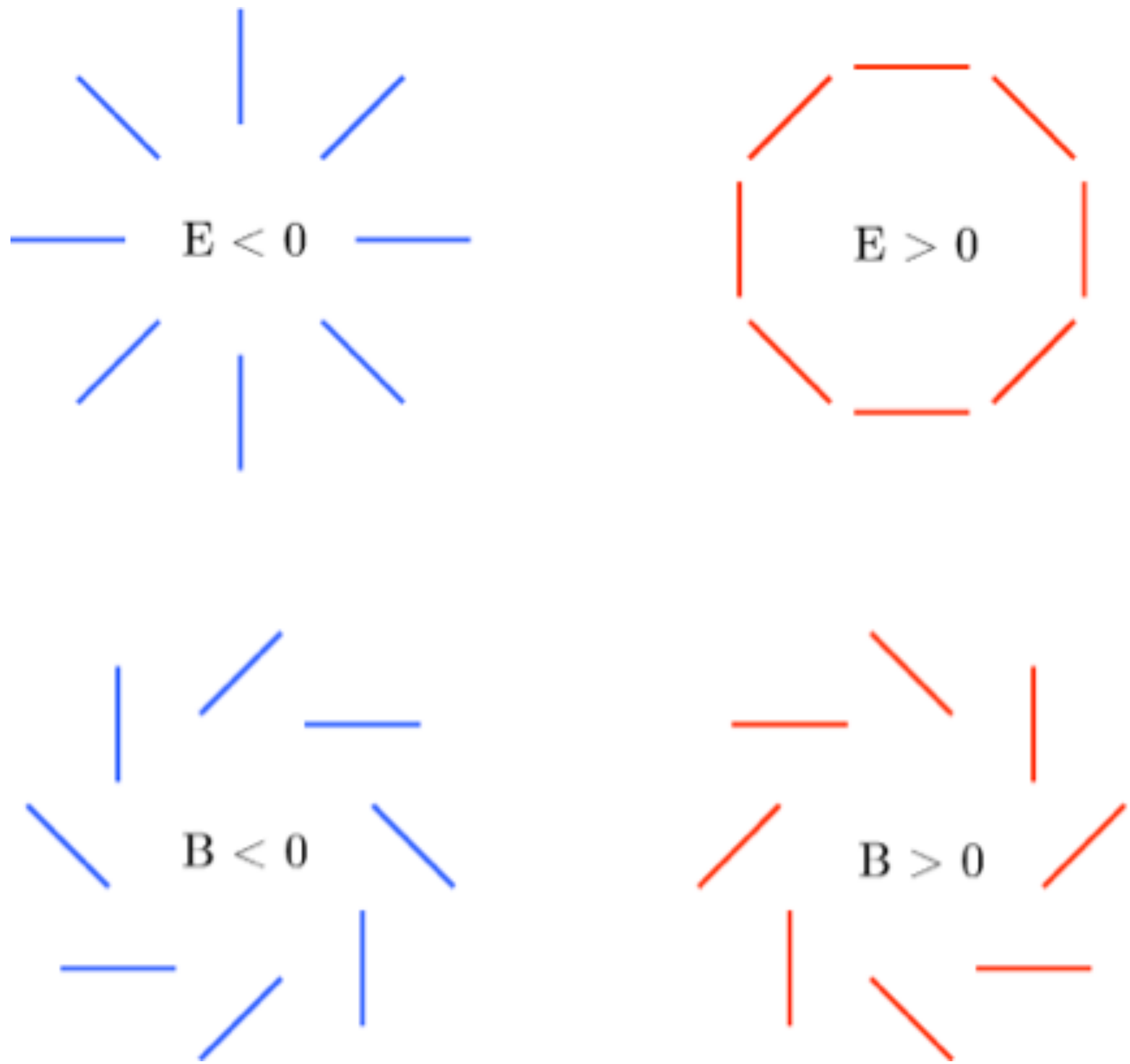


(Taken from Samtleben et al, `07)



EモードとBモードは偏光ベクトルを
４５度回転すると互いに移り合う。

計量揺らぎ

平坦な一様等方宇宙

$$ds^2 = -dt^2 + a(t)^2 \delta_{ij} dx^i dx^j$$

計量揺らぎ

平坦な一様等方宇宙

$$ds^2 = -dt^2 + a(t)^2 \delta_{ij} dx^i dx^j$$

に小さな摂動を加える：

$$ds^2 = -(1+2A)dt^2 - 2aB_i dt dx^i + a^2 \left(\delta_{ij} + 2H_L \delta_{ij} + 2H_{Tij}\right) dx^i dx^j$$

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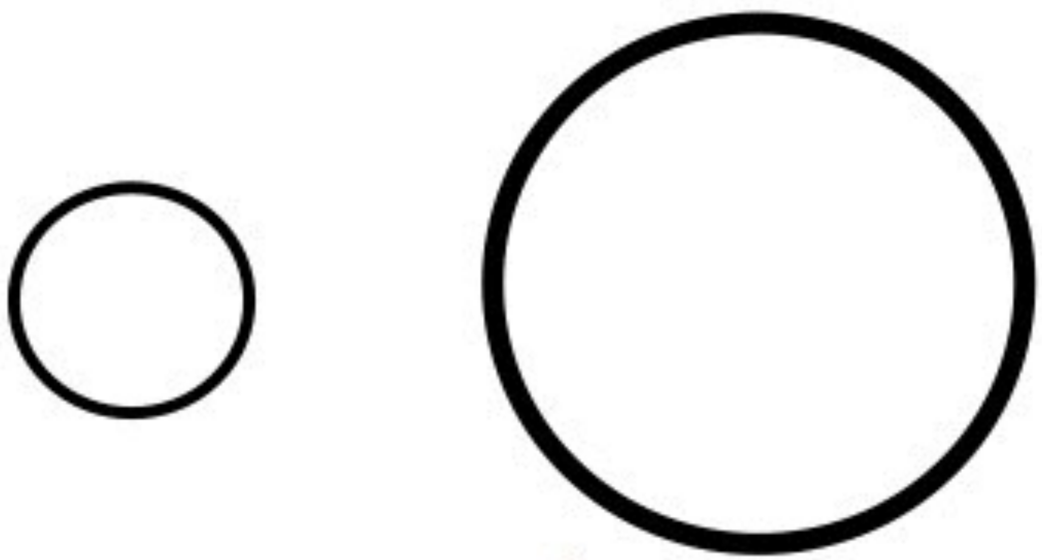
線形揺らぎの範囲では以下の３つに分解できる。

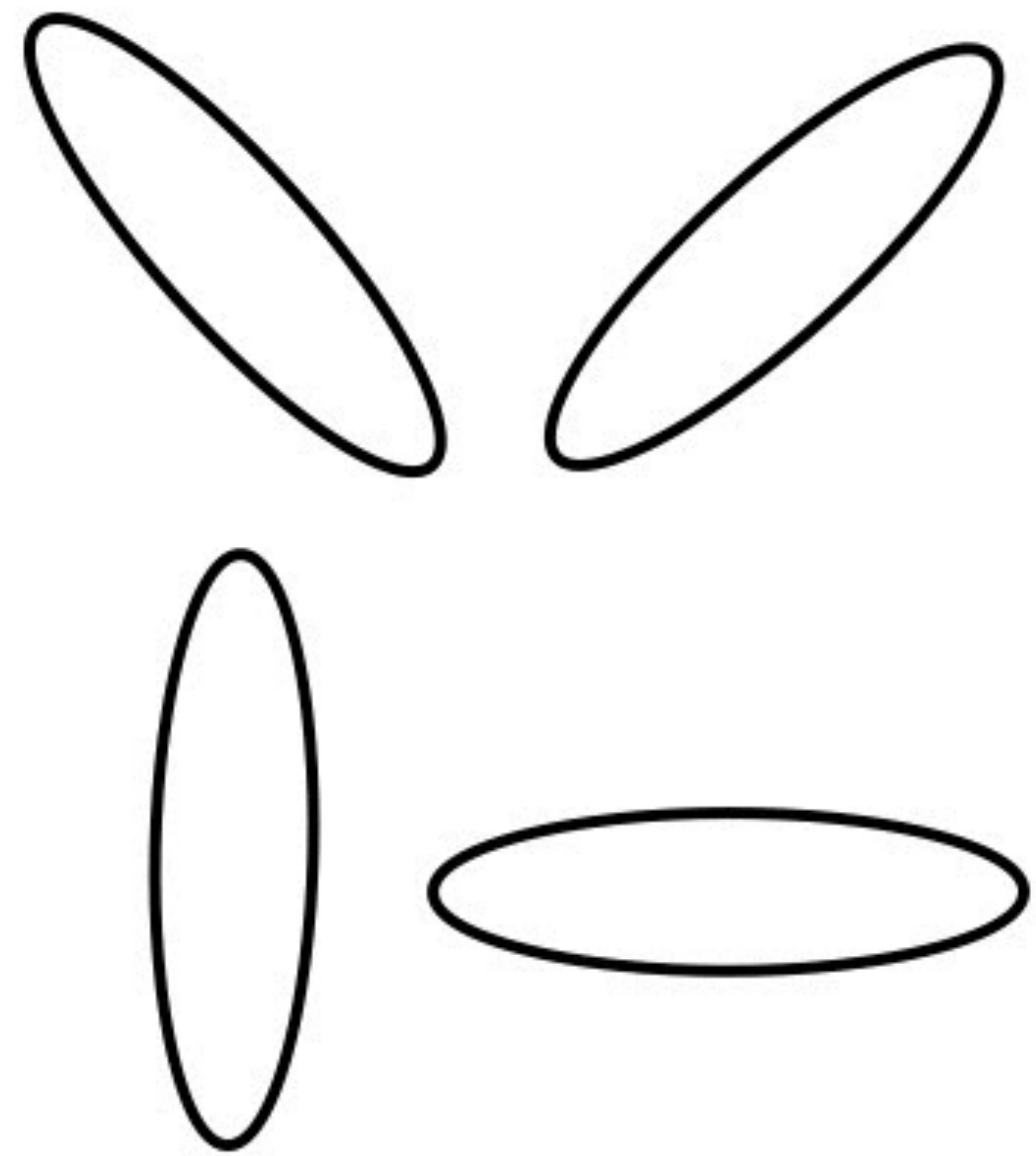
1. Scalar $ds^2 = -(1+2\Phi)dt^2 + a^2(1+2\Psi)d\mathbf{x}^2$ inflaton
2. Vector
3. Tensor $ds^2 = -dt^2 + a^2\left(\delta_{ij} + h_{ij}\right)dx^i dx^j$ graviton

Scalar perturbations



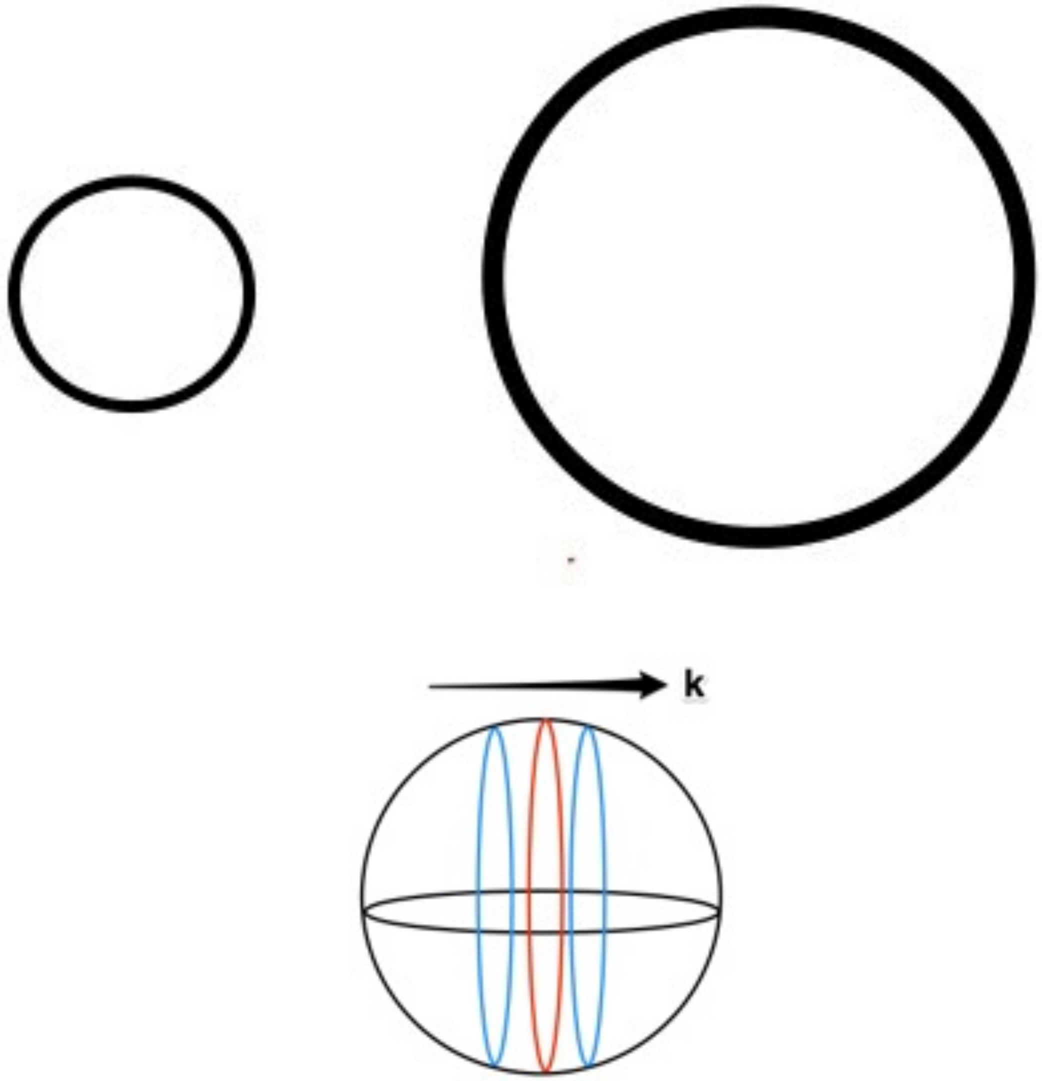
E-mode ONLY

Tensor perturbations



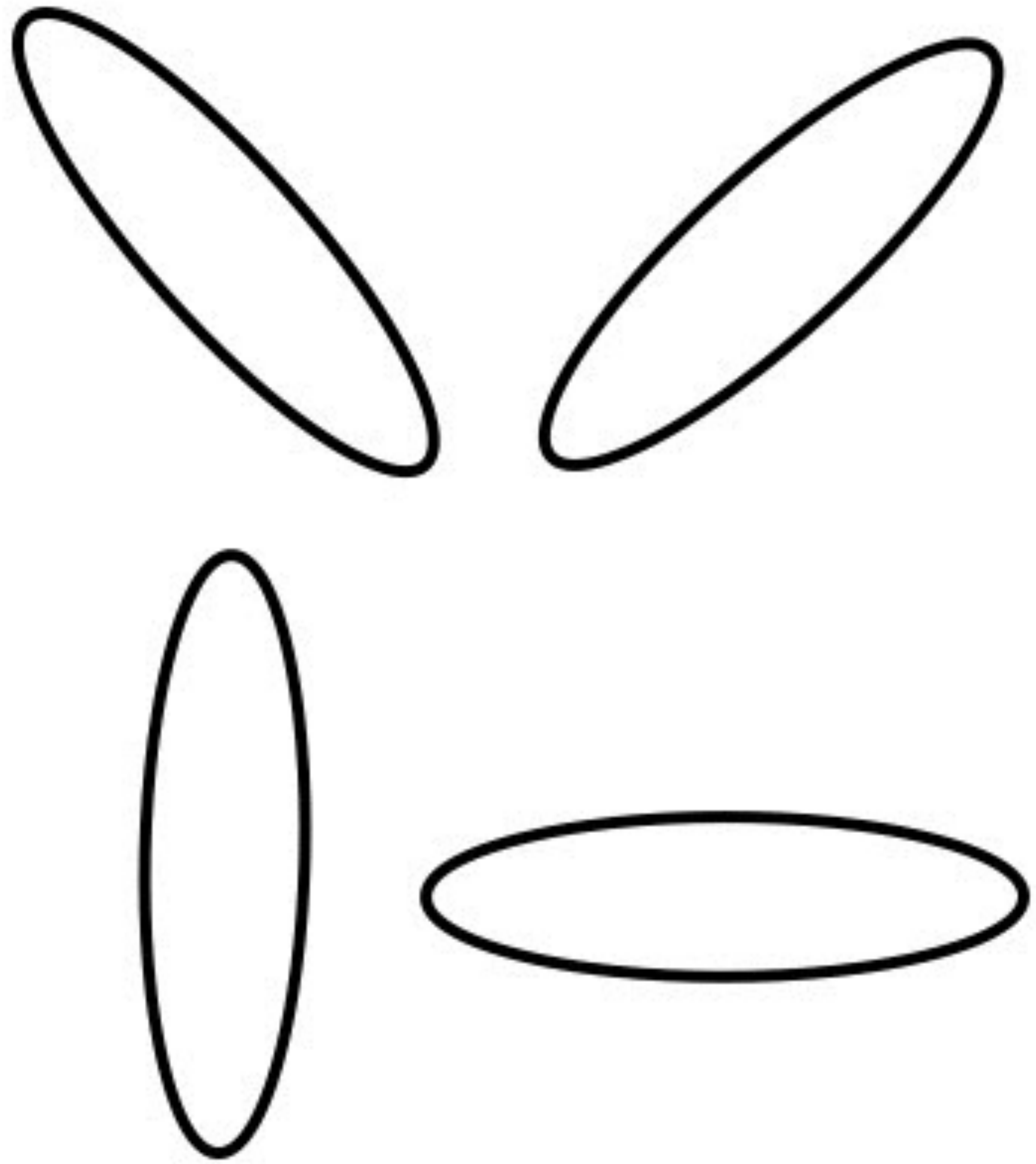
BOTH E-mode
and B-mode

Scalar perturbations



E-mode ONLY

Tensor perturbations



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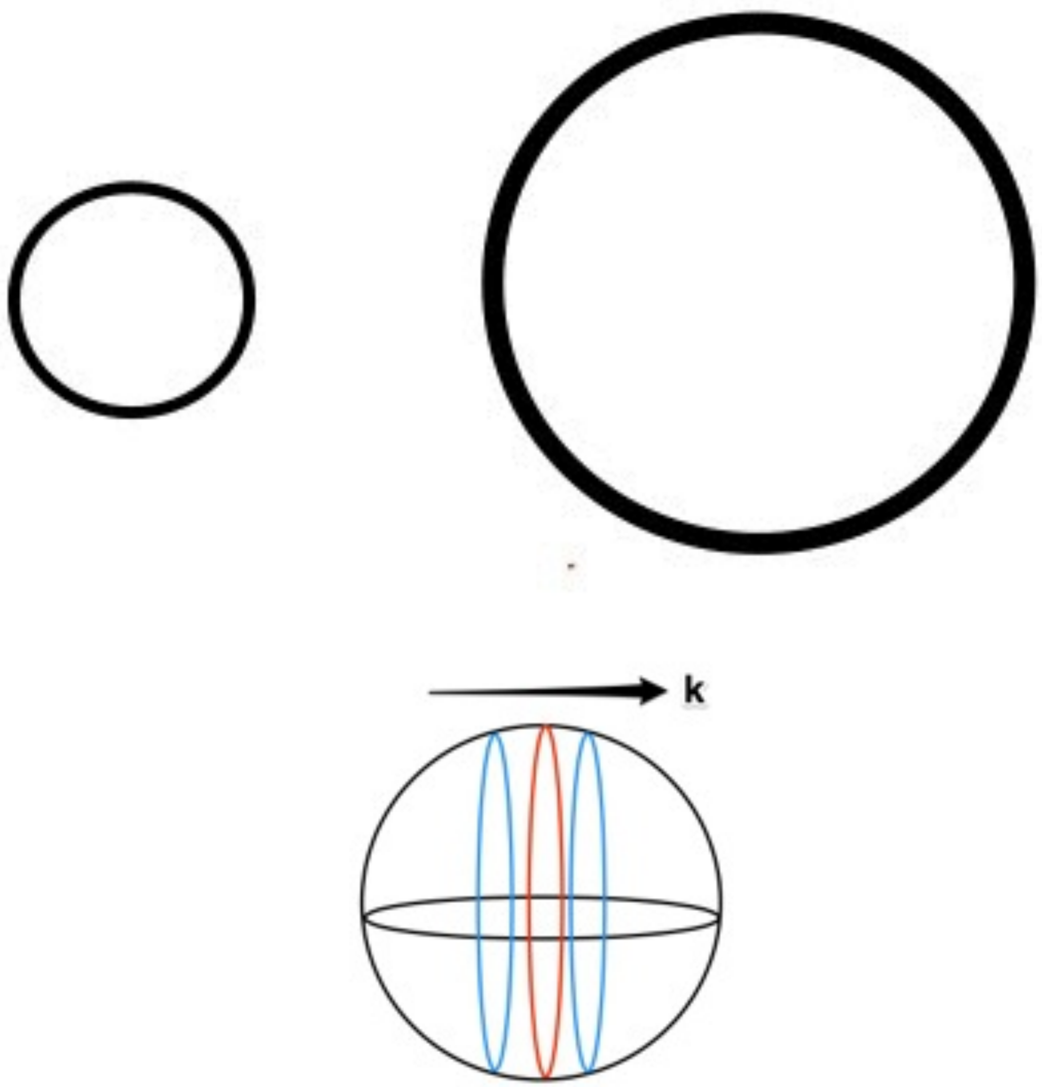

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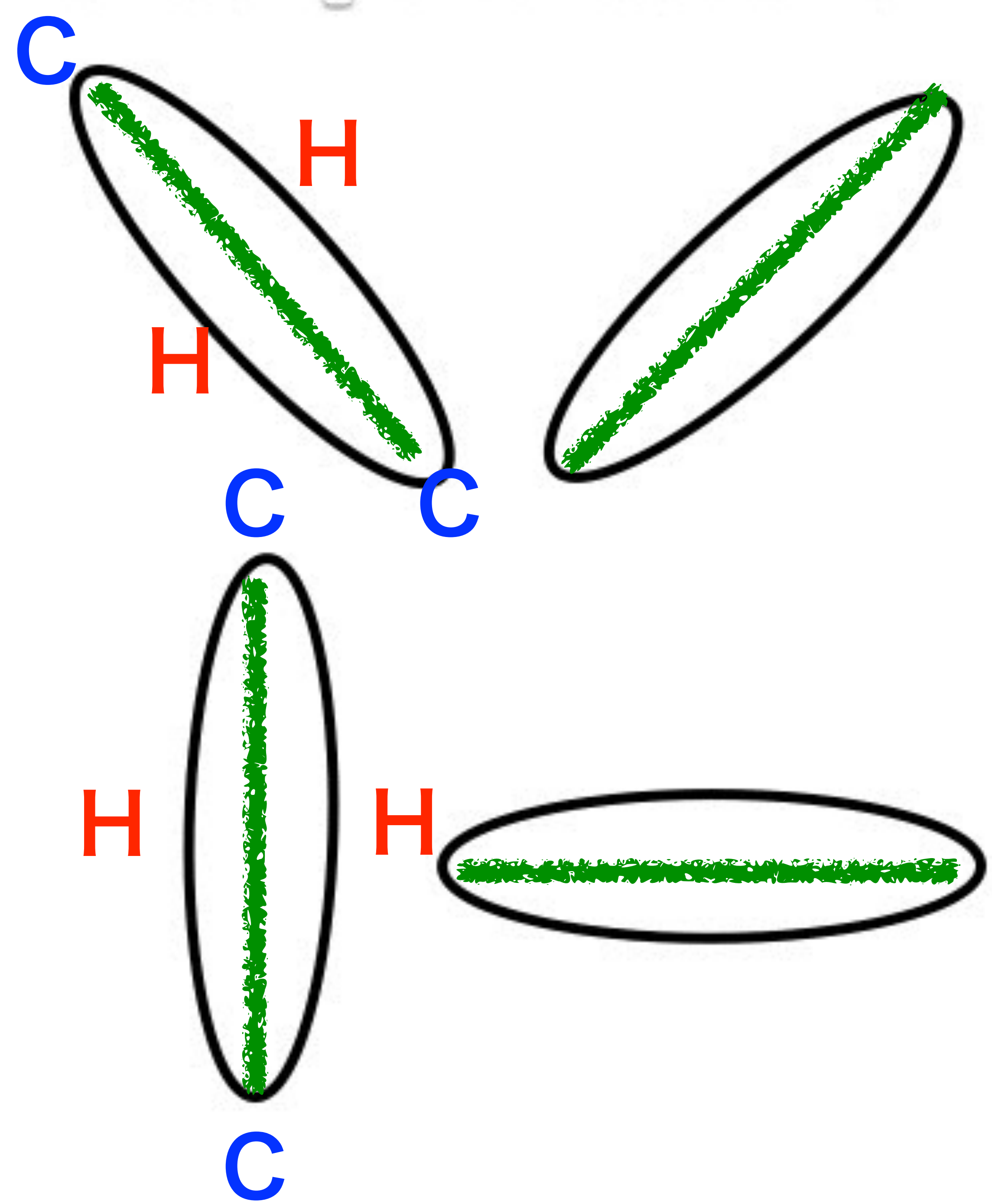

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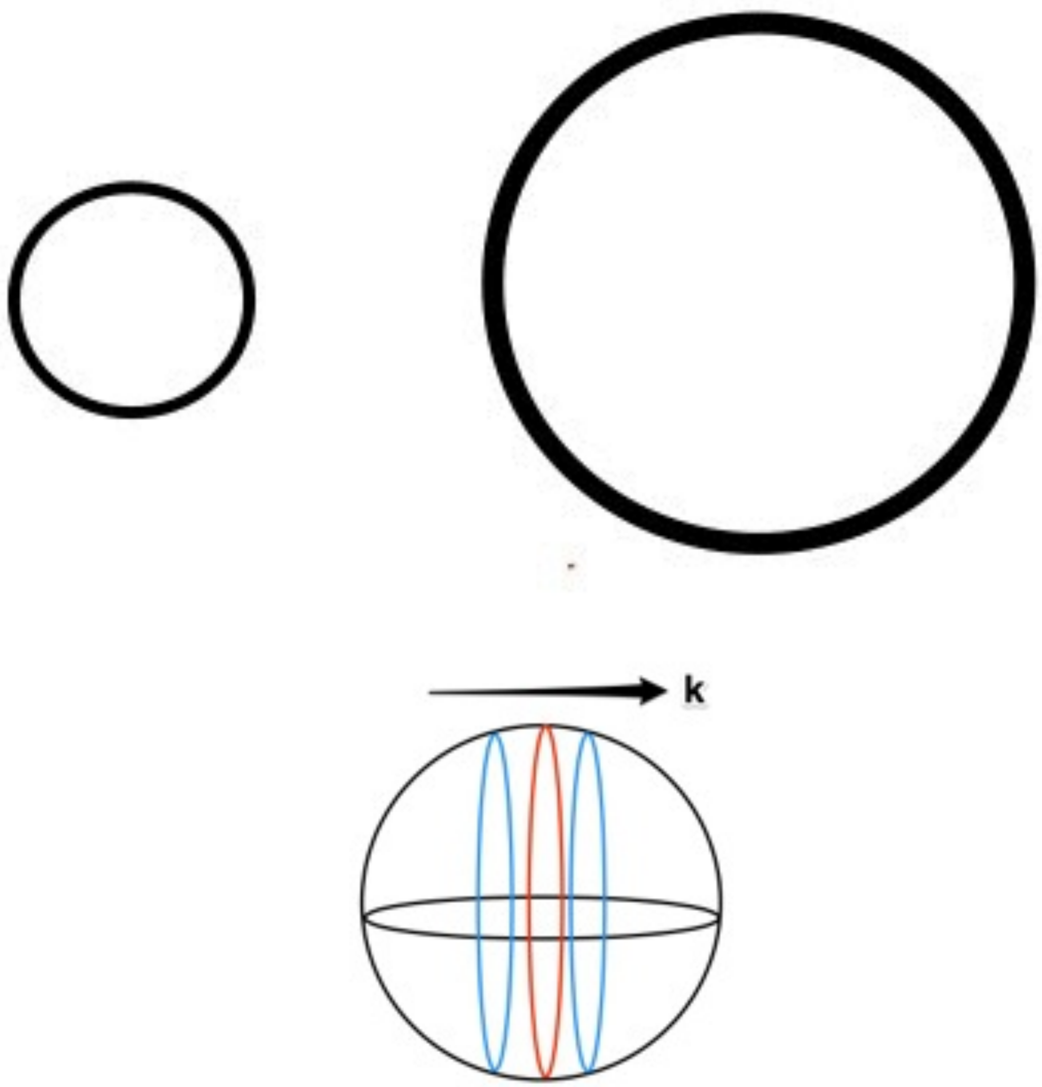

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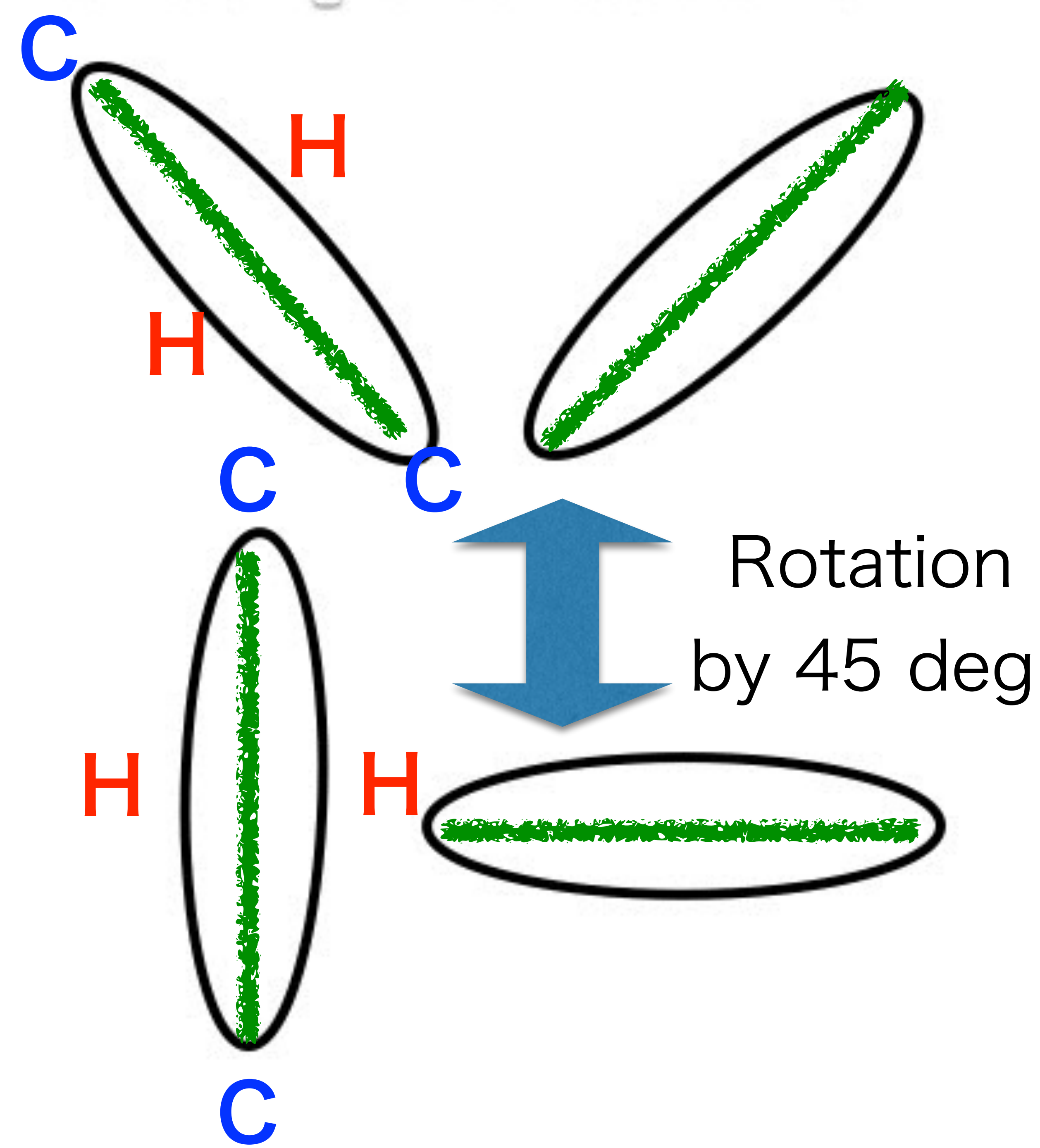
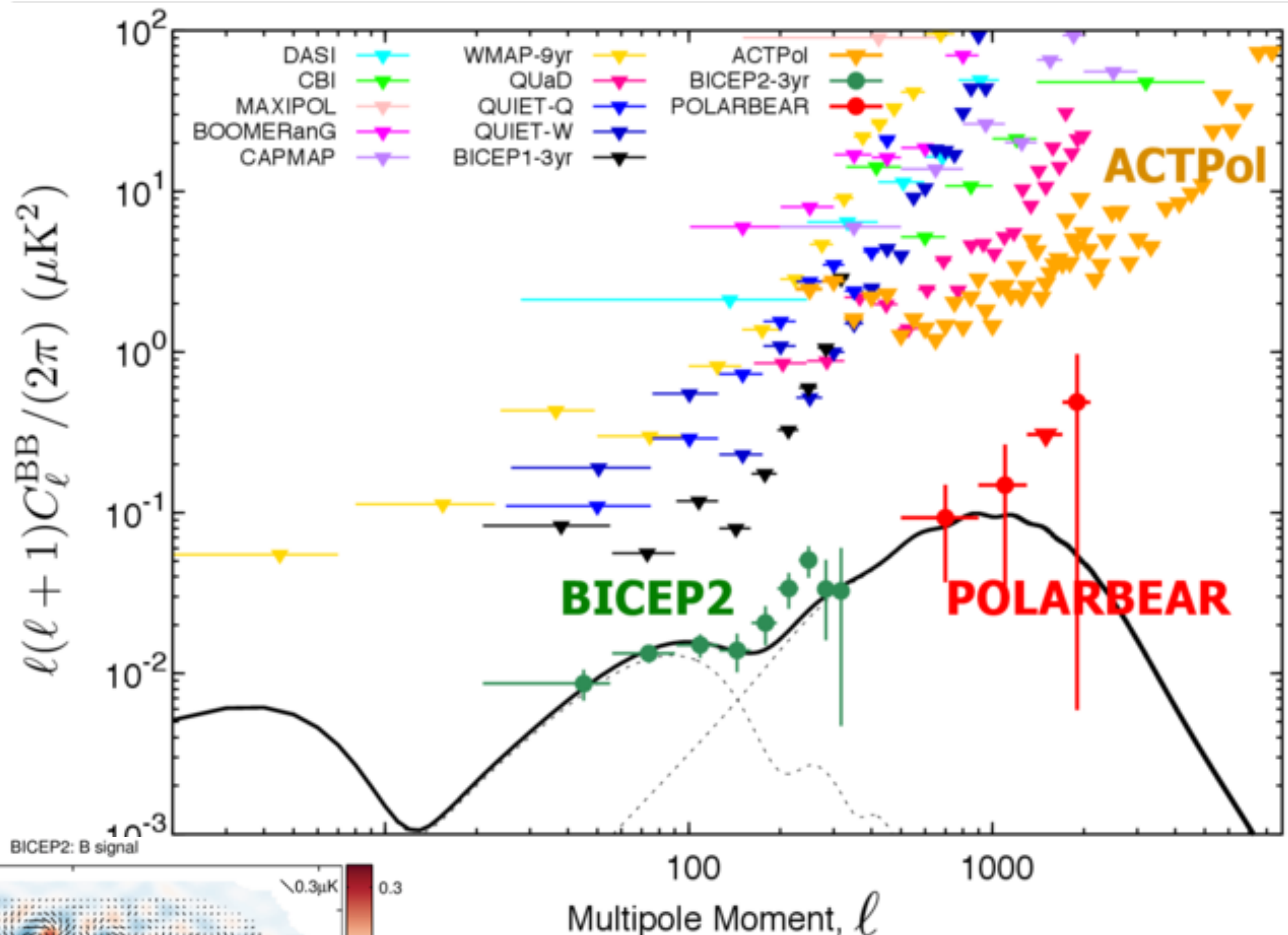
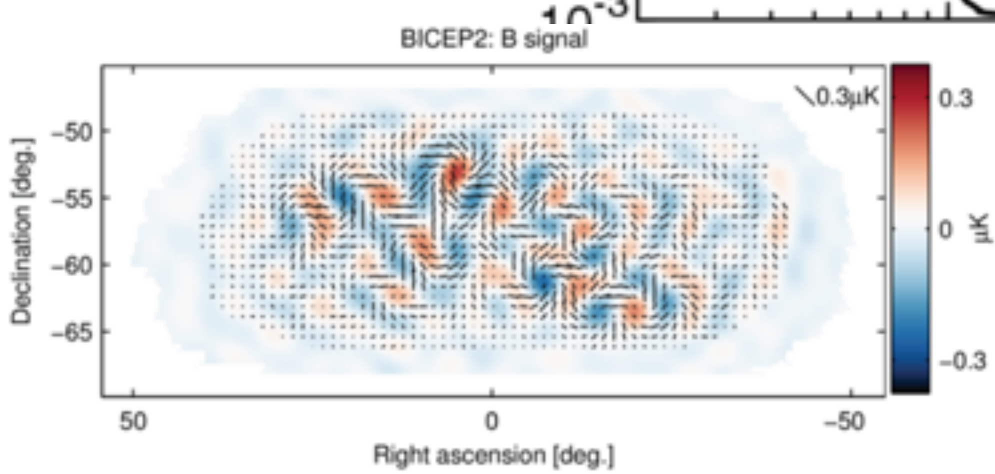


BOTH E-mode
and B-mode

BICEP2 found B-mode





Taken from
Chinone's webpage

2.インフレーションとその示唆

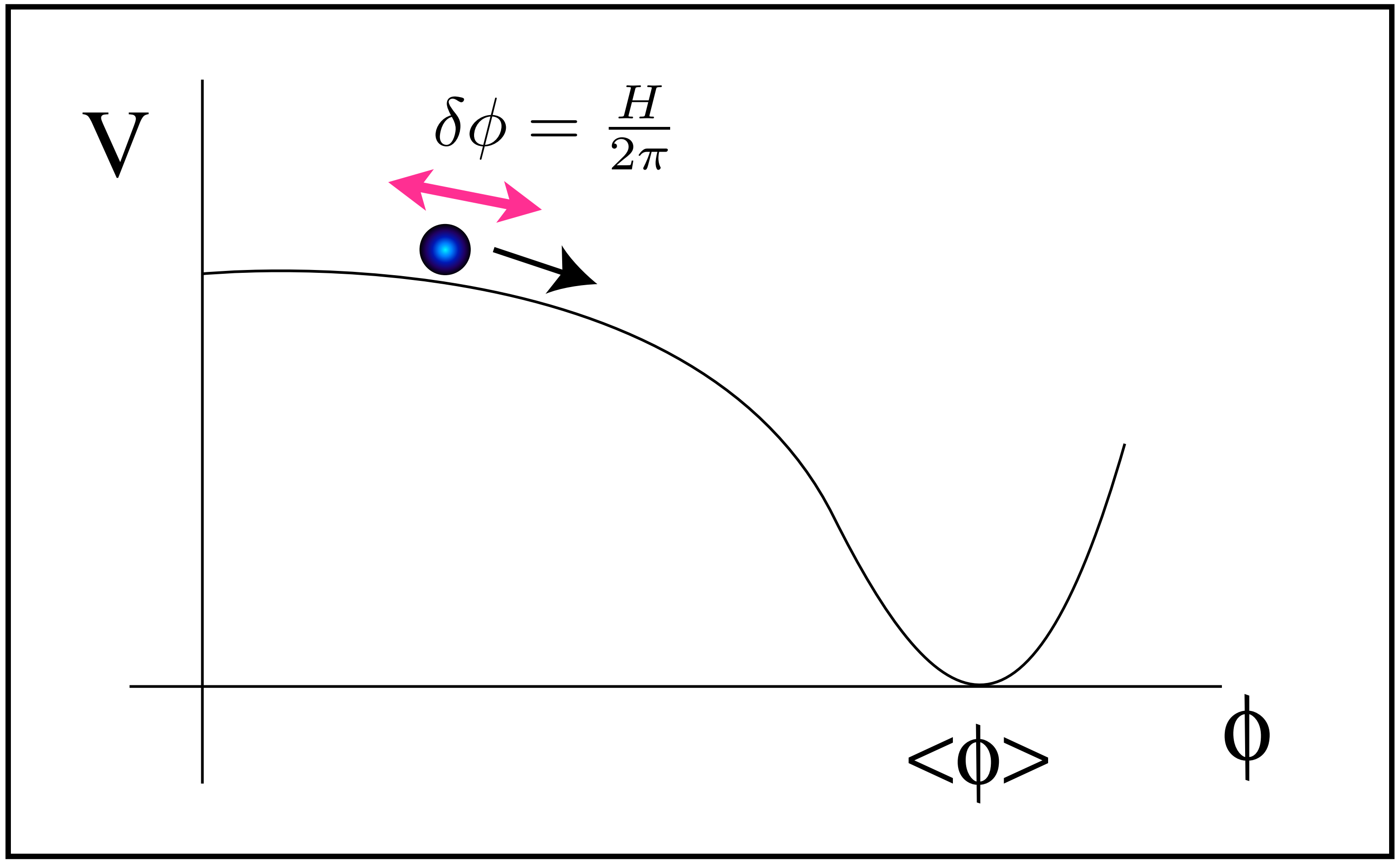
Inflation

宇宙初期における加速膨張

Guth `81, Sato `80, Starobinsky `80, Kazanas `80, Brout, Englert, Gunzig, `79

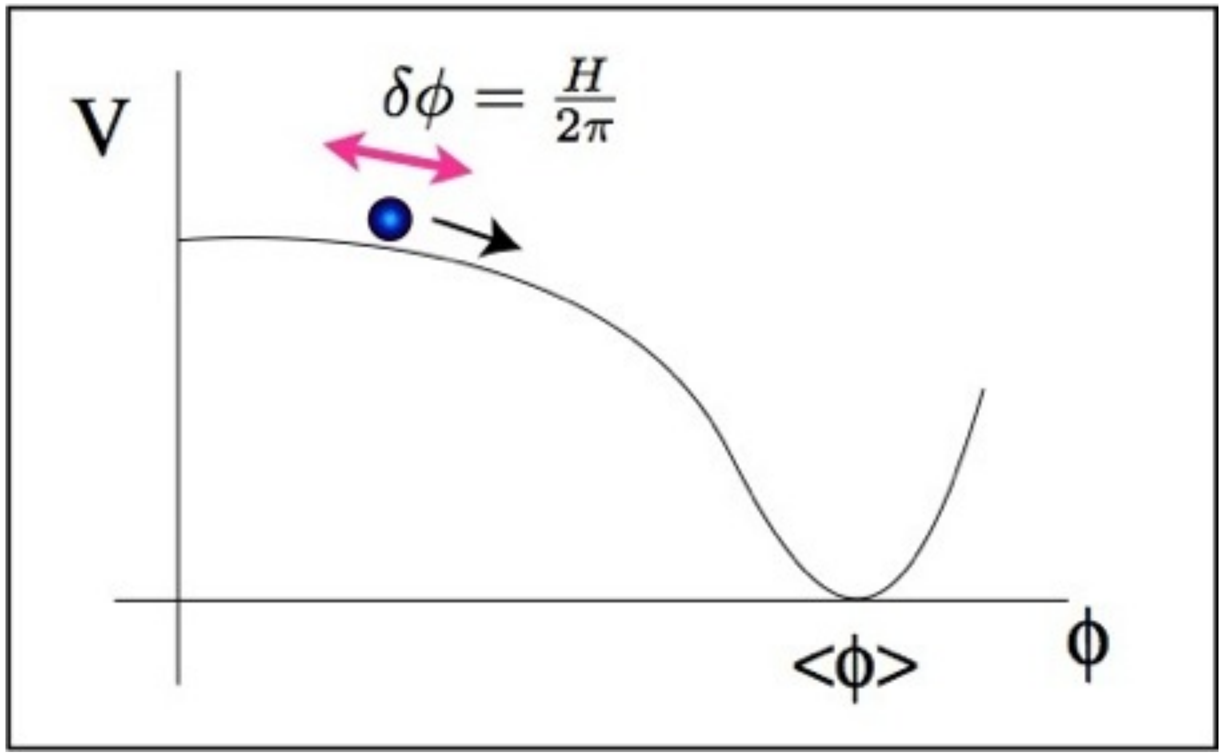
ゆっくり転がるスカラー場 によってインフレーション (Slow-roll inflation)を実現。終了後、軽い自由度に崩壊し、熱い宇宙をつくる（再加熱）。

Linde `82, Albrecht and Steinhardt `82



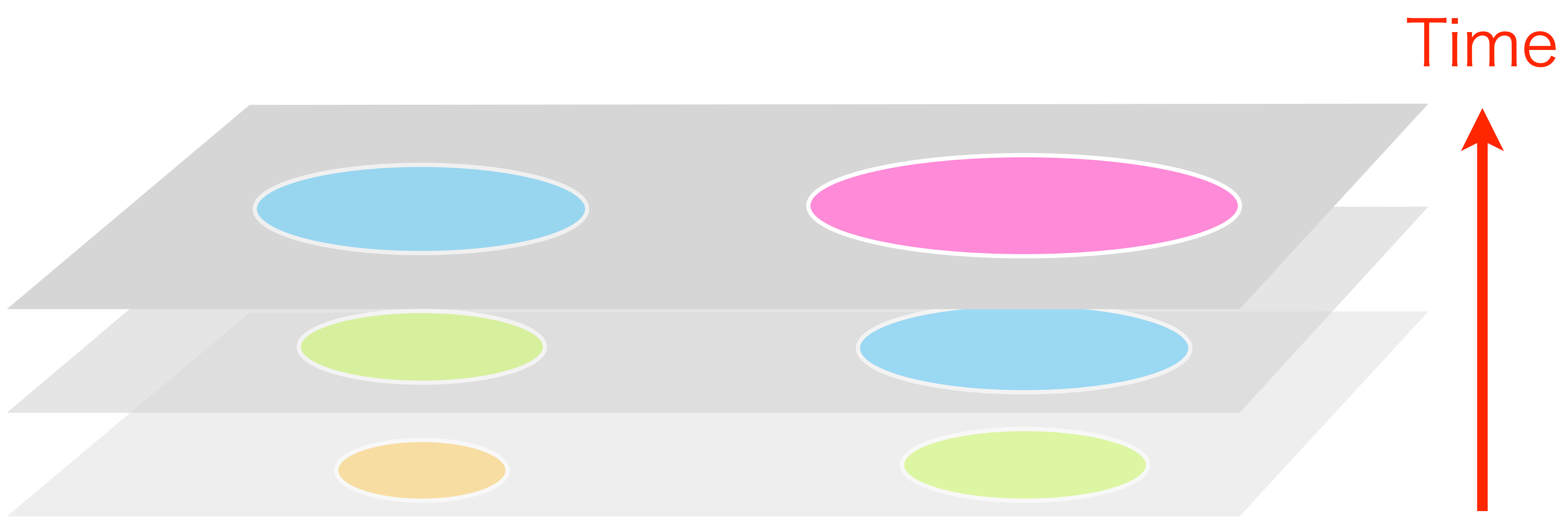
Scalar mode

$$ds^2 = -(1+2\Phi)dt^2 + a^2(1+2\Psi)d\mathbf{x}^2$$



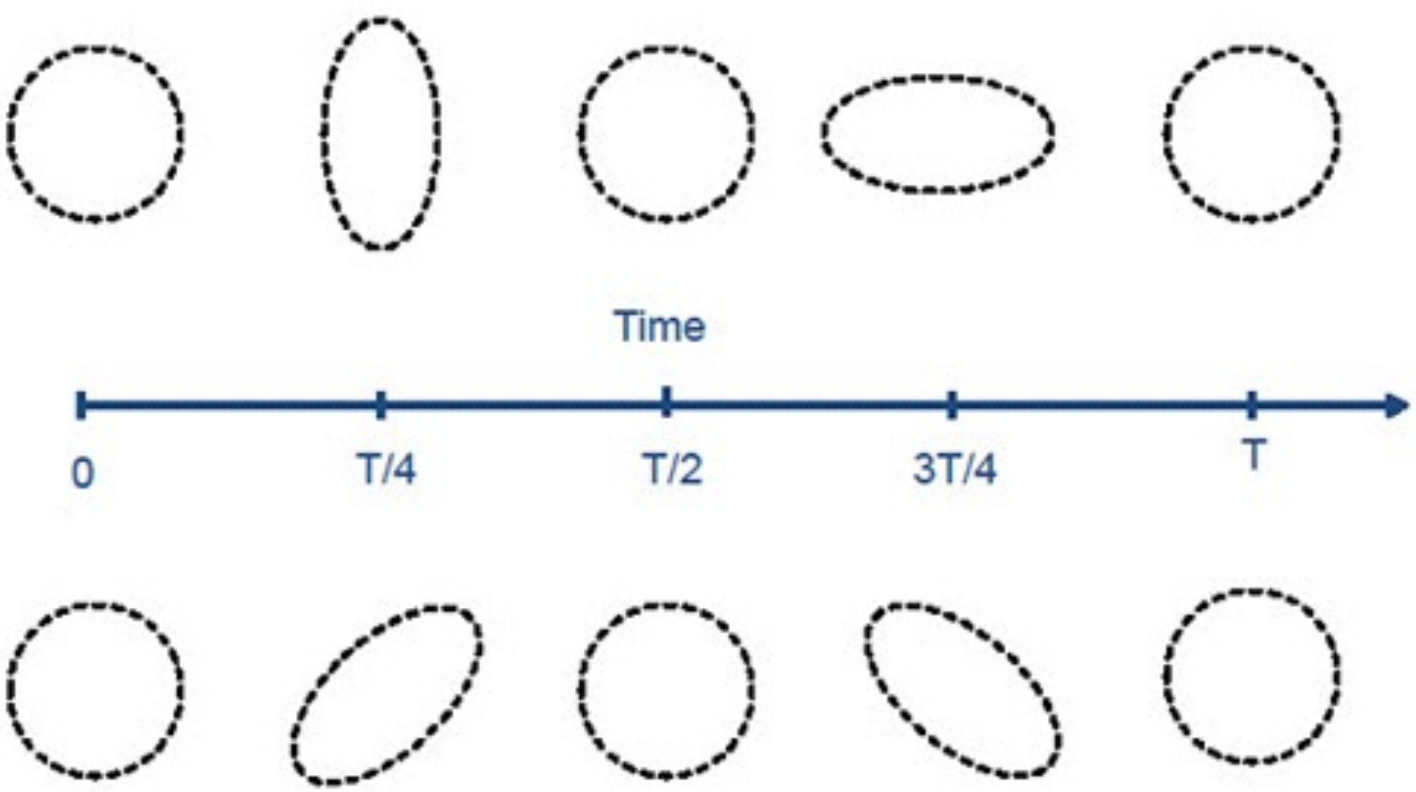
インフラトンの揺らぎが**時間進化**に揺らぎを与える。宇宙は膨張しているので、**体積の揺らぎ**。

$$\Phi \sim \frac{\delta\rho}{\rho} \sim H\delta t \sim H_{\rm inf}\frac{\delta\phi}{\dot\phi} \sim \left|\frac{V^{3/2}}{V' M_P^3}\right|$$



Tensor mode

$$ds^2 = -dt^2 + a^2 \left(\delta_{ij} + h_{ij}\right) dx^i dx^j$$



It is due to **fluctuations of graviton itself.**

$$h_{ij} \sim \frac{H_{\rm inf}}{M_P}$$

Observation vs Theory

Scalar mode

$$P_{\mathcal{R}} = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Tensor mode

$$P_t = A_t \left(\frac{k}{k_0}\right)^{n_t}$$

$$A_s = \frac{V^3}{2\sqrt{3}V'^2},$$

$$n_s = 1 + 2\frac{V''}{V} - 3\left(\frac{V'}{V}\right)^2,$$

$$r = 8\left(\frac{V'}{V}\right)^2$$

$$A_s,\ n_s,\ r \equiv \frac{A_t}{A_s} \quad \Longleftrightarrow \quad V,\ V', V''$$

V : the inflaton potential

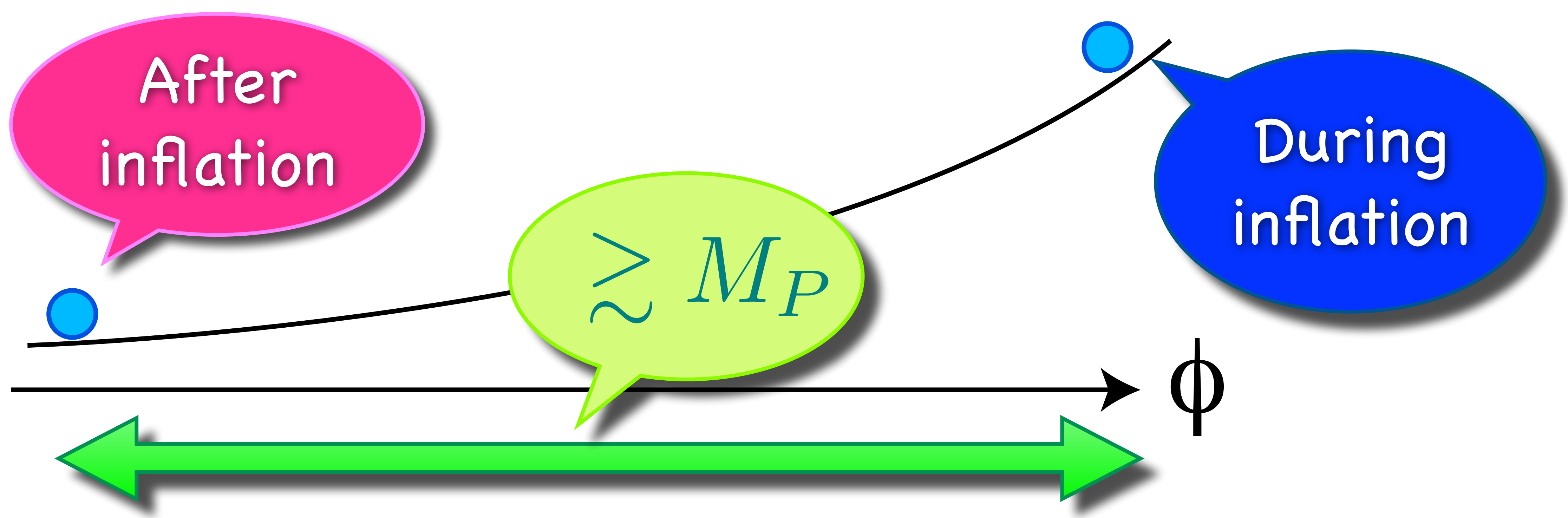
It's GUT-scale inflation!

$$V_{\rm inf} \simeq (2.1 \times 10^{16}\,{\rm GeV})^4 \left(\frac{r}{0.16}\right)$$

$$H_{\rm inf} \simeq 1.0 \times 10^{14}\,{\rm GeV} \left(\frac{r}{0.16}\right)^{\frac{1}{2}},$$

Large-field inflation

The inflaton excursion exceeds the Planck scale.



Lyth bound: $\Delta\phi \gtrsim 8M_P \left(\frac{r}{0.2}\right)^{\frac{1}{2}} \left(\frac{N}{50}\right)$

Lyth 1997

GUT-scale, large-field inflation

- **Inflation model building in sugra/string**
  - Shift symmetry is likely.
- **High reheating temperature:** $T_R \gtrsim 10^{8-9}\,\mathrm{GeV}$
  - Thermal leptogenesis is likely.
  - Baryogenesis, dark matter, unwanted relics.
  - Symmetry restoration is possible.
- **The inflaton mass is about** $m_{\rm inf} \sim 10^{12-13}\,\mathrm{GeV}$.
  - Related to SUSY breaking scale or RH neutrino mass?
- **Too large isocurvature perturbations.**
  - The QCD axion less likely? PQ symmetry restoration?

3.インフレーション模型

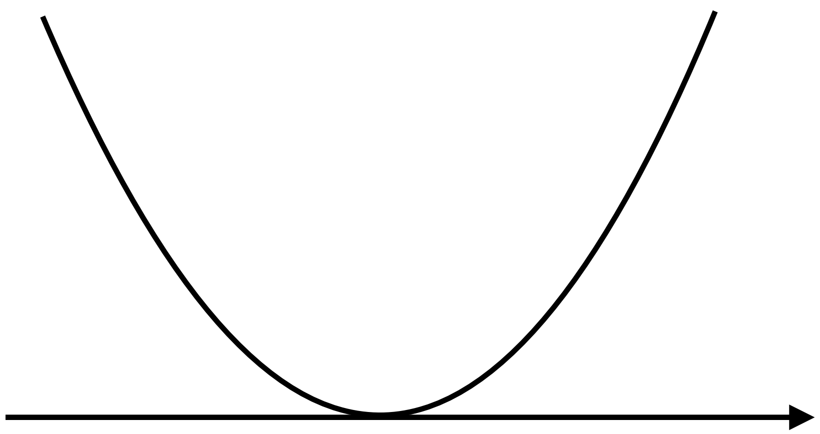
Various large-field inflation models

Quadratic chaotic inflation

Linde `83

$$V = \frac{1}{2}m^2\phi^2$$

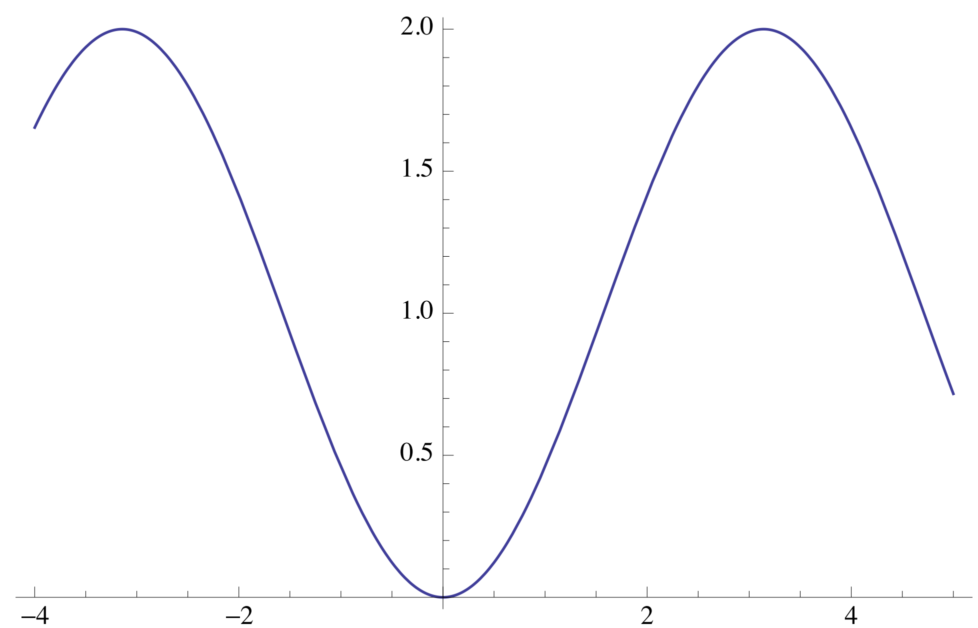
$$m \simeq 2 \times 10^{13}\,\text{GeV} \qquad \phi_{60} \sim 16 M_P$$



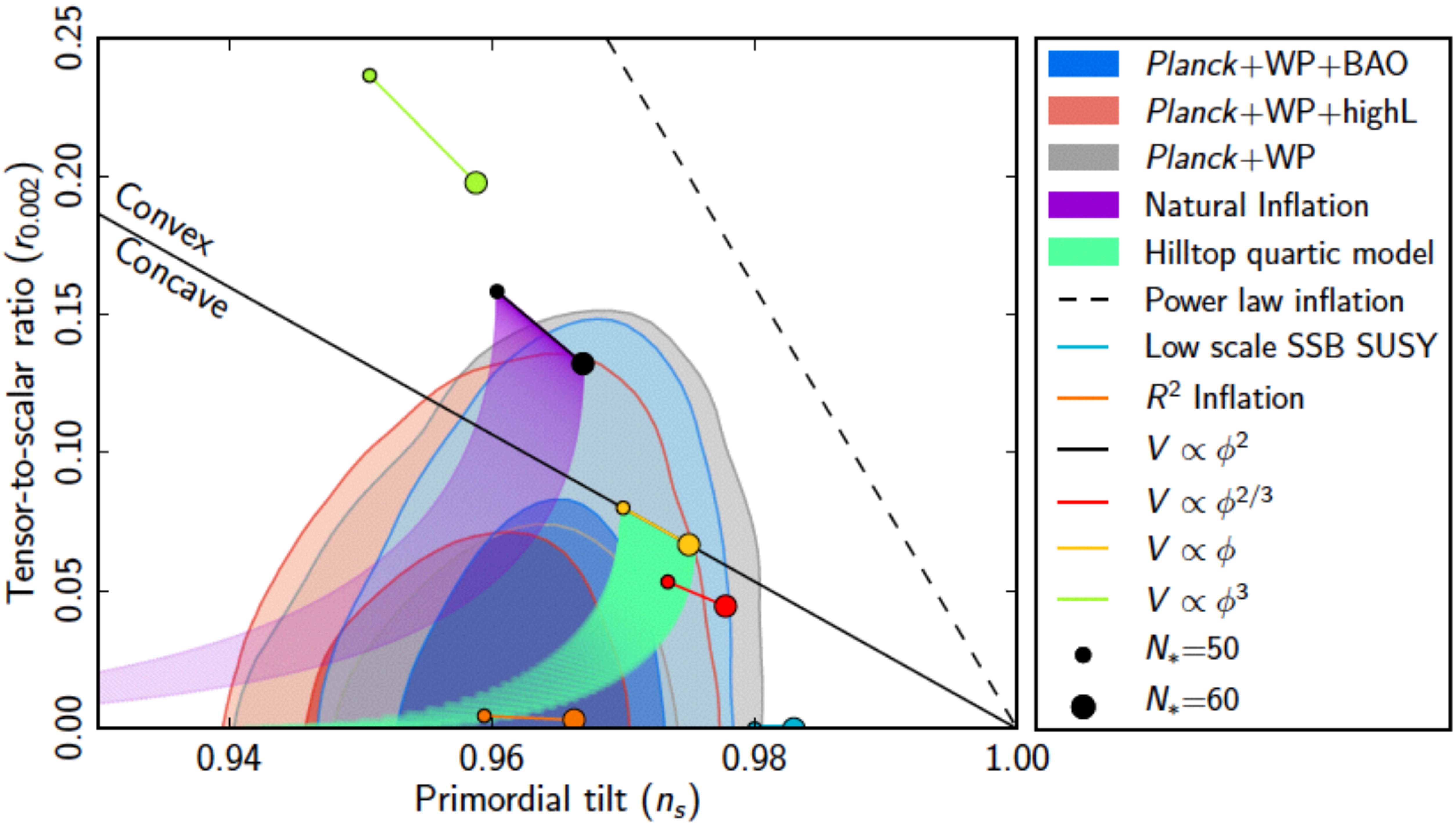
Natural inflation

Freese et al, `90

$$V = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$$

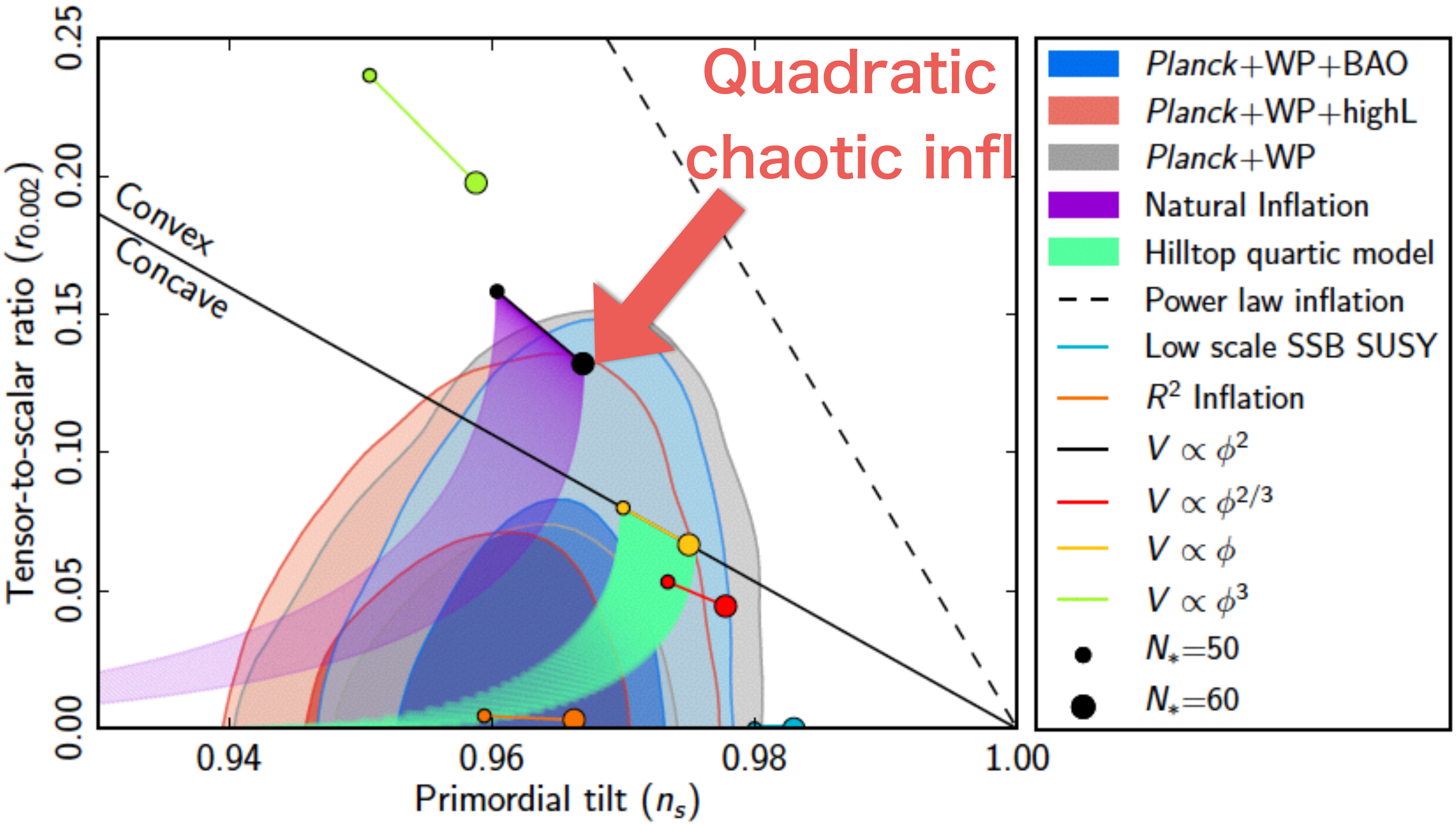


Predicted values of (n_s, r)



Planck, 1303.5802

Predicted values of (n_s, r)



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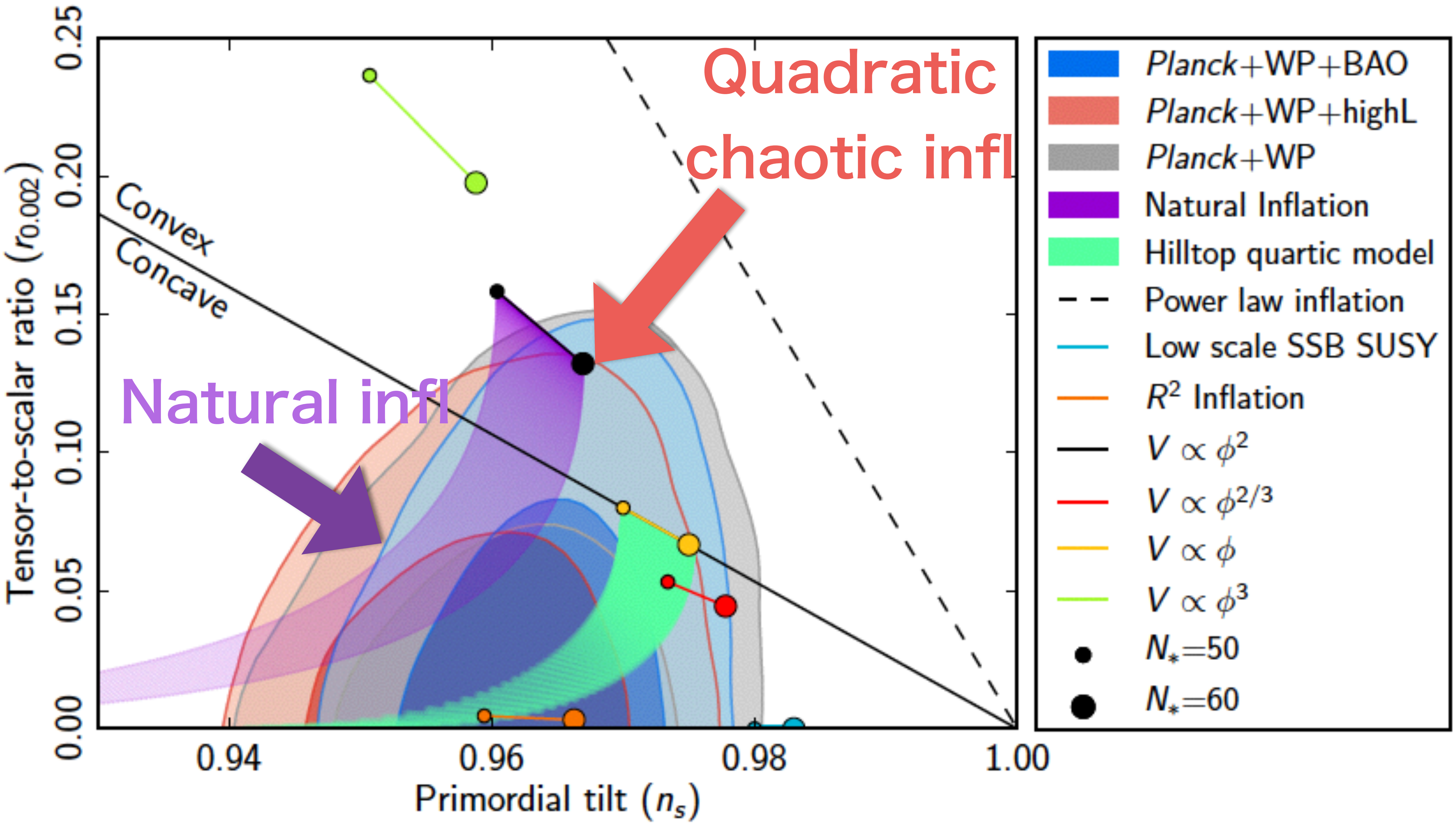


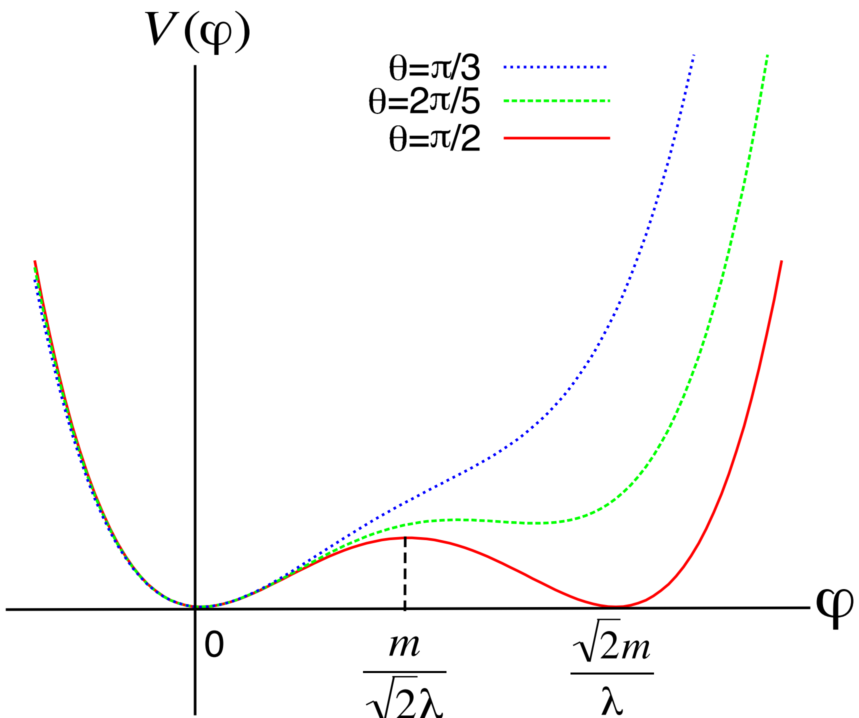
Planck, 1303.5802

Various large-field inflation models

Polynomial chaotic inflation

Destri, de Vega, Sanchez [astro-ph/0703417]
Nakayama, FT, Yanagida 1303.7315
(see also Kobayashi, Seto 1403.5055
Kallosh, Linde, Wesphal 1405.0270)

$$V = \frac{1}{2}m^2\phi^2 + \frac{\kappa}{3}\phi^3 + \frac{\lambda}{4}\phi^4 + \cdots$$



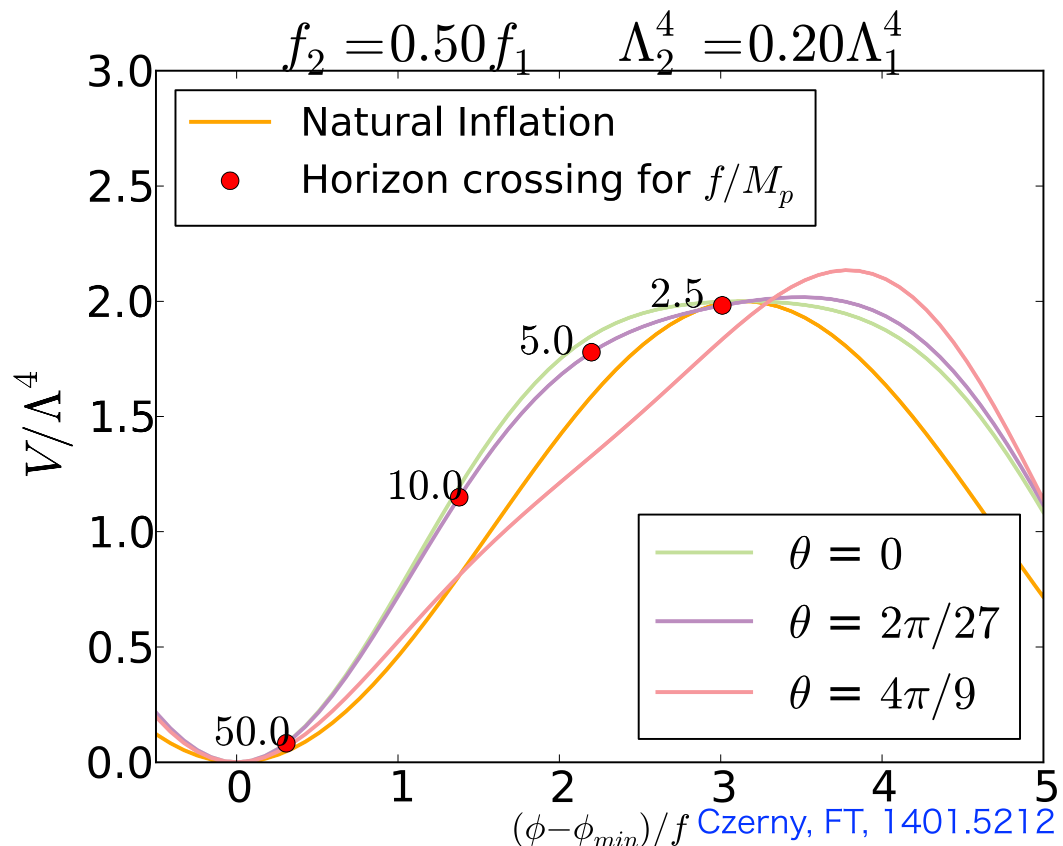
Nakayama, FT, Yanagida, 1303.7315

Multi-Natural inflation (MNI)

Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410, 1403.5883

$$V(\phi) = C - \Lambda_1^4 \cos(\phi/f_1) - \Lambda_2^4 \cos(\phi/f_2 + \theta),$$

Sub-Planckian decay constants are allowed as hilltop inflation can be realized.



Czerny, FT, 1401.5212

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(see also Kobayashi, Seto 1403.5055
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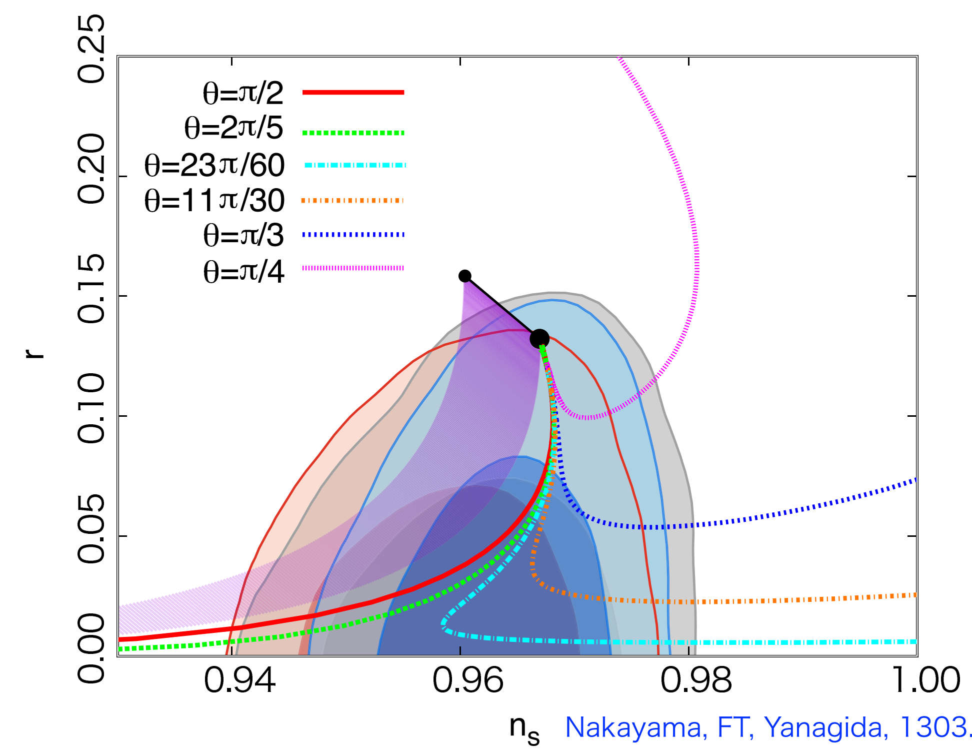
$$V = \frac{1}{2}m^2\phi^2 + \frac{\kappa}{3}\phi^3 + \frac{\lambda}{4}\phi^4 + \cdots$$

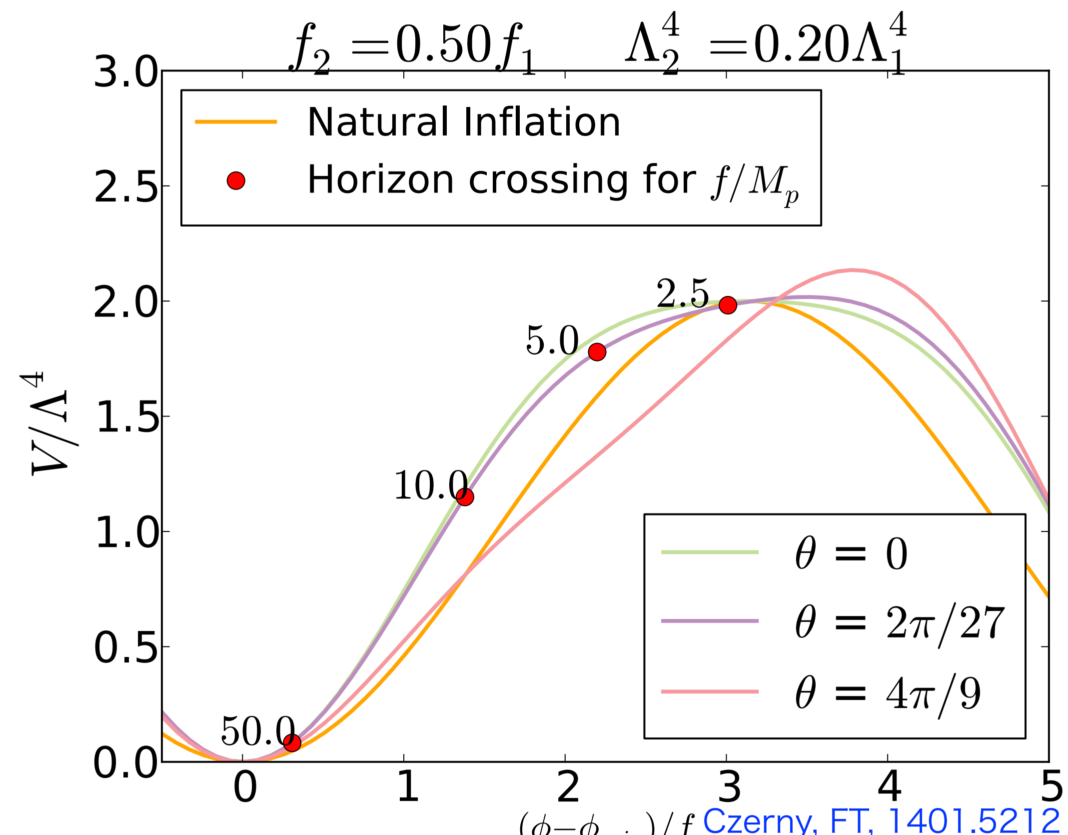


Nakayama, FT, Yanagida, 1303.7315

Multi-Natural inflation (MNI)

Czerny, FT 1401.5212
Czerny, Higaki FT 1403.0410, 1403.5883

$$V(\phi) = C - \Lambda_1^4 \cos(\phi/f_1) - \Lambda_2^4 \cos(\phi/f_2 + \theta),$$



Czerny, FT, 1401.5212

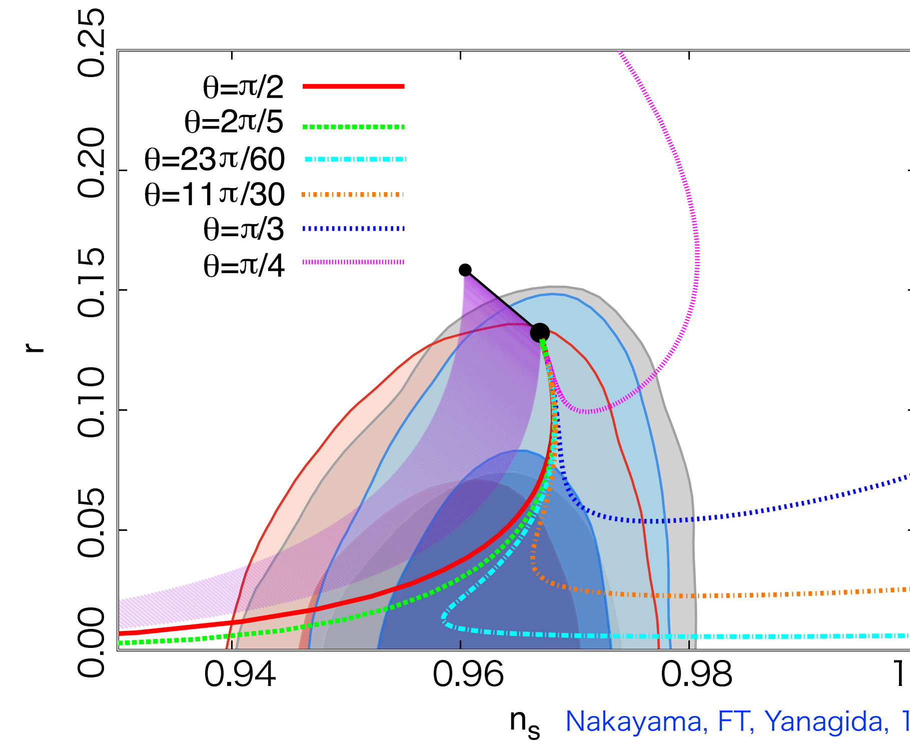
Sub-Planckian decay constants are allowed as hilltop inflation can be realized.

Various large-field inflation models

Polynomial chaotic inflation

Destri, de Vega, Sanchez [astro-ph/0703417]
Nakayama, FT, Yanagida 1303.7315
(see also Kobayashi, Seto 1403.5055
Kallosh, Linde, Wesphal 1405.0270)

$$V = \frac{1}{2}m^2\phi^2 + \frac{\kappa}{3}\phi^3 + \frac{\lambda}{4}\phi^4 + \cdots$$



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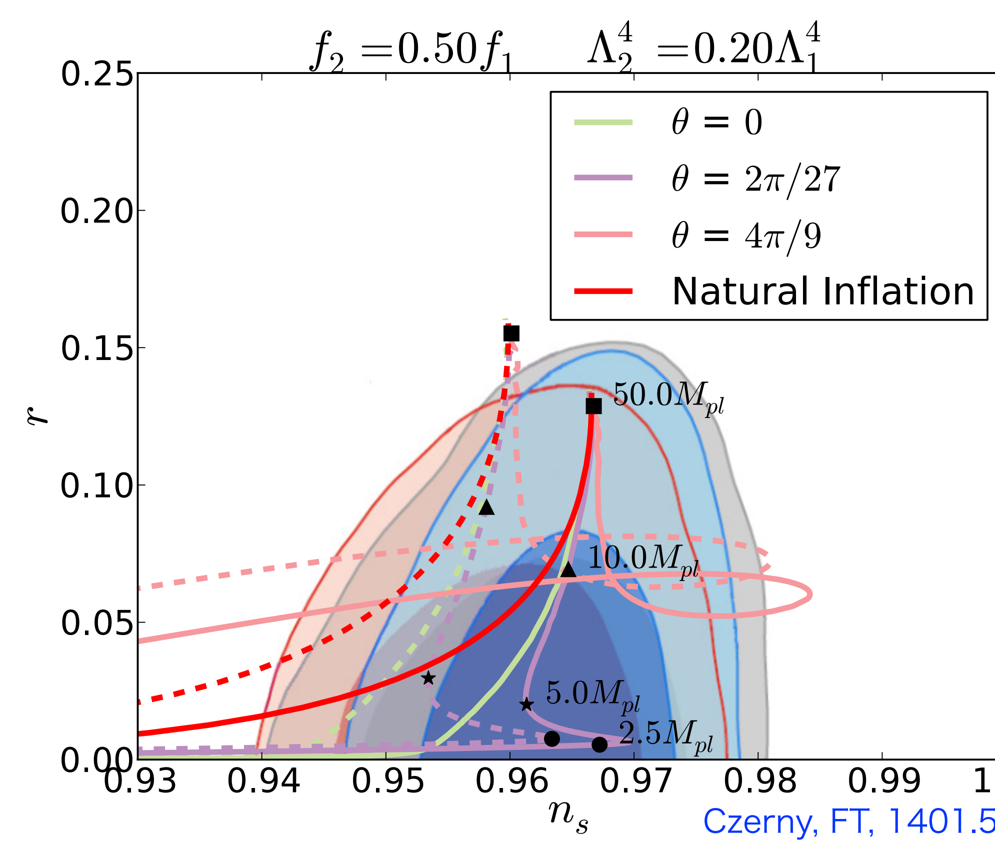

Czerny, FT, 1401.5212

Chaotic inflation in SUGRA

Kawasaki, Yamaguchi, Yanagida, hep-ph/0004243 ,hep-ph/0011104

To have a good control over the inflaton field values greater than the Planck scale, we impose a shift symmetry;

$$\phi \to \phi + iC,$$

which is explicitly broken by the superpotential.

$$K_{\rm inf} = c(\phi+\phi^\dagger) + \frac{1}{2}(\phi+\phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

$$W_{\rm inf} = mX\phi,$$

$$V_{\rm sugra} = e^K \left((D_i W) K^{i\bar{j}} (D_j W)^* - 3|W|^2 \right).$$

$$V \simeq \frac{1}{2} m^2 \varphi^2$$

$\varphi \equiv \sqrt{2}{\rm Im}[\phi]$

even for $\varphi \gg M_p$

Z_2 or not Z_2?

- One can impose a Z_2 symmetry on the inflaton and X.

$$Z_2: \quad \phi \to -\phi \qquad X \to -X$$

$$K_{\rm inf} = c(\phi + \phi^\dagger) + \frac{1}{2}(\phi + \phi^\dagger)^2 + |X|^2 - k|X|^4 + \cdots$$

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The visible sector particles must be also charged under Z_2 for successful reheating.

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The Z_2 might be the matter parity! $\quad W_{\not R} = \cancel{udd}, \cancel{LLe}, \cancel{QdL}$

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The Z_2 might be the matter parity! $W_{\not R} = \cancel{udd}, \cancel{LLe}, \cancel{QdL}$

The inflaton might be right-handed sneutrino.

Murayama, Nakayama, FT, Yanagida,1404.3857

$$W = \phi L H_u$$
(-) (-)

$$\Rightarrow \quad \mathcal{L} \sim \frac{(LH_u)^2}{M}$$

Neutrino mass is a low-E consequence of the inflaton!

Sneutrino Chaotic inflation

Murayama, Nakayama, FT, Yanagida,1404.3857

We impose an approximate shift symmetry on one of N_i

$$K = |N_1|^2 + |N_2|^2 + \frac{1}{2}(N_3 + N_3^\dagger)^2 + \cdots$$

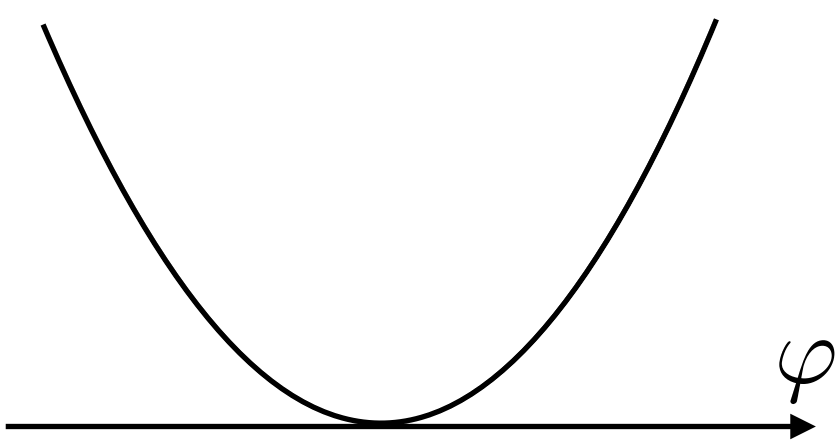
$$W = \frac{1}{2}M_{ij}N_iN_j + h_{i\alpha}N_iL_\alpha H_u$$

with

$$M_{ij} = \begin{pmatrix} m & 0 & 0 \\ 0 & 0 & M \\ 0 & M & 0 \end{pmatrix}$$

The inflaton is $\varphi = \sqrt{2}\mathrm{Im}N_3$

$$V = \frac{1}{2}M^2\varphi^2$$



All the other directions can be stabilized during inflation.

Natural and Multi-Natural Inflation

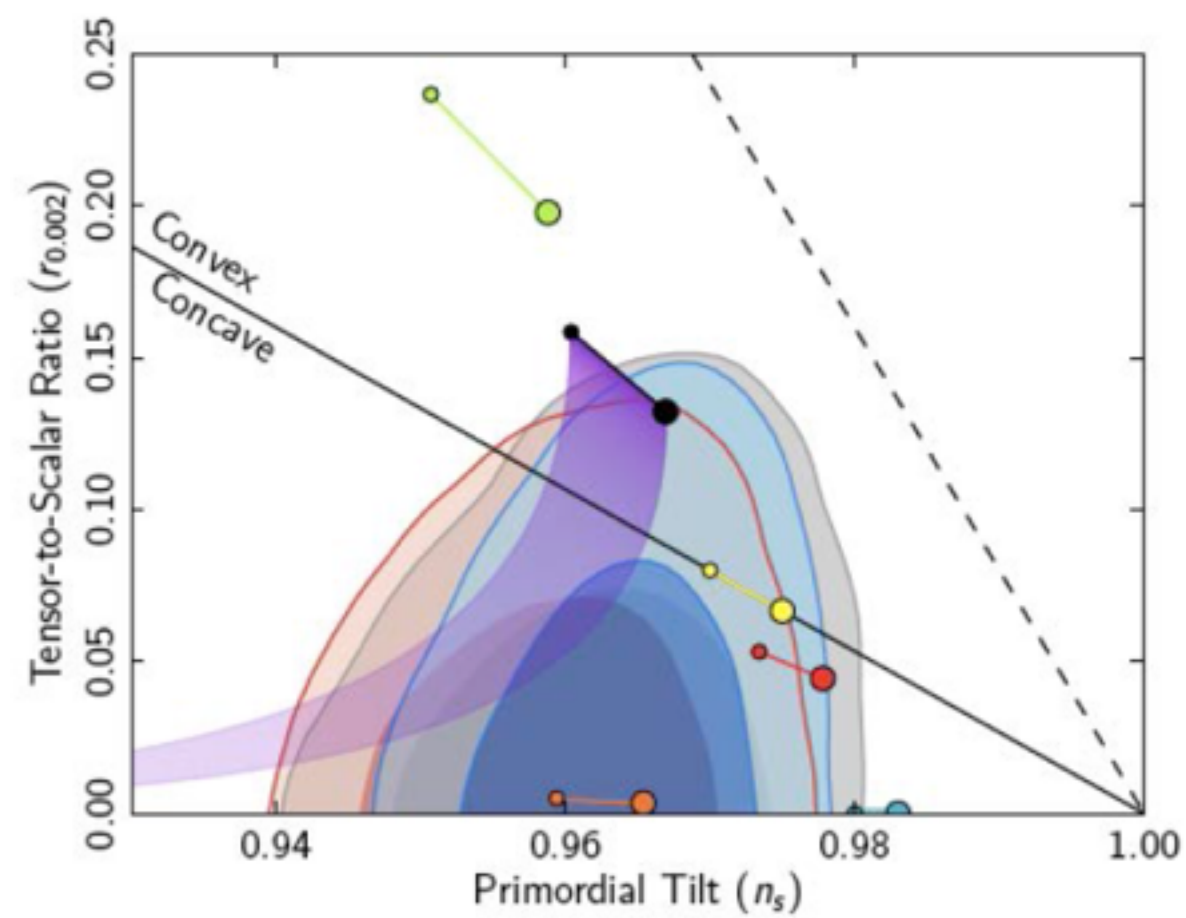
-Natural inflation

Freese, Frieman, Olinto `90

$$V = \Lambda^4 \left(1 - \cos\left(\frac{\phi}{f}\right)\right)$$

Only large-field inflation is possible, and f is bounded below:

$$f \gtrsim 5 M_P$$



Aligned Natural Inflation

Kim, Nilles, Peloso, hep-ph/0409138
Czerny, Higaki, FT 1403.5883, Harigaya and Ibe 1404.3511, Choi, Kim, Yun, 1404.6209, Higaki, FT, 1404.6923, Tye, Won, 1404.6988, Kappl, Krippendorf, Nilles, 1404.7127, Bachlechner et al, 1404.7496, Ben-Dayan, Pedro, Westphal,1404.7773 ,Long, McAllister, McGuirk 1404.7852

The effectively large decay constant can be realized by the alignment of two (or more) axion potentials.

- Two axions: $\phi_1 \to \phi_1 + 2\pi f_1 \quad \phi_2 \to \phi_2 + 2\pi f_2$

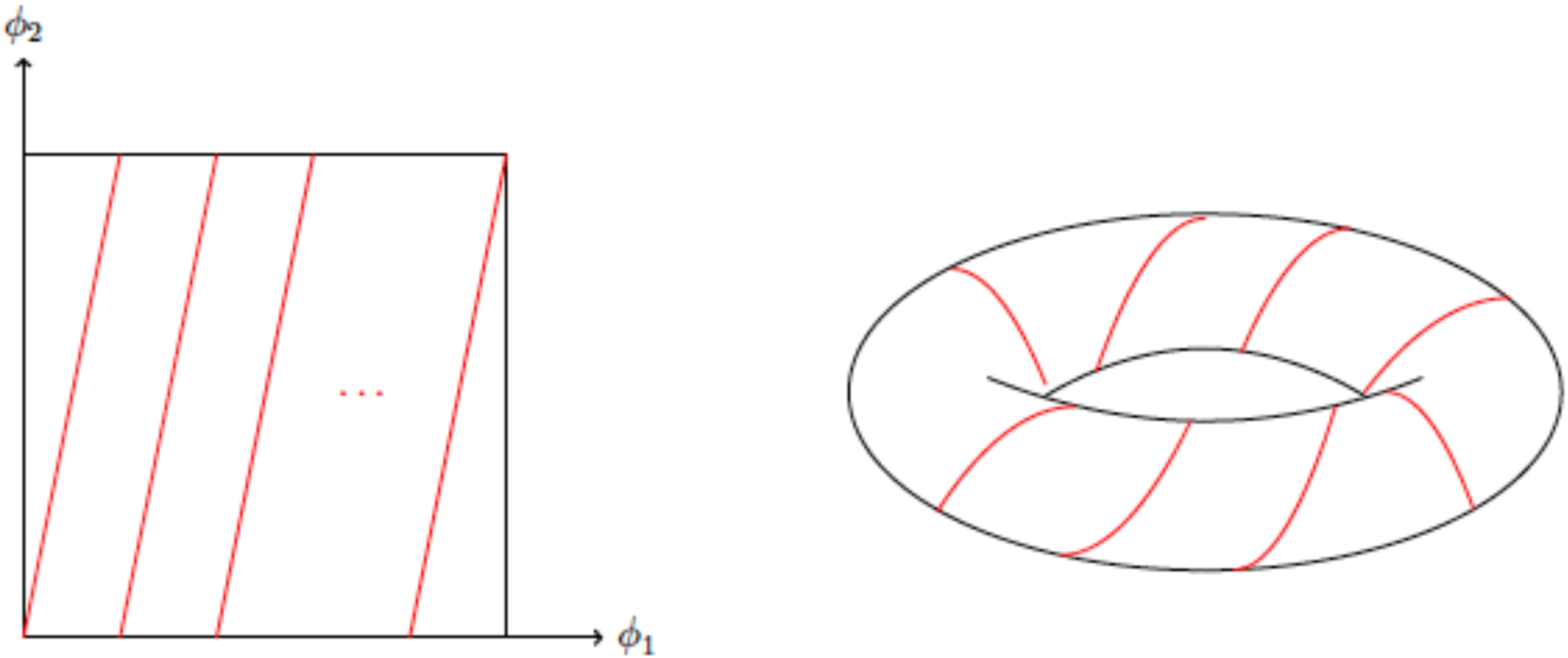
$$V(\phi_i) = \Lambda_1^4 \left[1 - \cos\left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2}\right)\right] + \Lambda_2^4 \left[1 - \cos\left(m_1 \frac{\phi_1}{f_1} + m_2 \frac{\phi_2}{f_2}\right)\right]$$

If $n_1/n_2 = m_1/m_2$, there is a flat direction; the corresponding decay constant would be infinite.

If $n_1/n_2 \approx m_1/m_2$, there is a relatively light direction; the corresponding decay constant can be larger than f_1 or f_2.

Aligned Natural Inflation

Kim, Nilles, Peloso, hep-ph/0409138



Taken from 1404.6209 by Choi, Kim, Yun

Aligned Natural Inflation

- Multiple axions: $\phi_i \equiv \phi_i + 2\pi f_i \quad (i = 1, \cdots, N)$

$$V(\phi_i) = \sum_{i=1}^{N} \Lambda_i^4 \left[1 - \cos\left(\sum_{j=1}^{N} \frac{n_{ij}\phi_j}{f_j} \right) \right]$$

For a moderately large N (> 5 or so), the effective decay constant can be enhanced w/o hierarchy among the anomaly coefficients.

Choi, Kim, Yun, 1404.6209

Prob. dist. was studied in detail for various cases incl. $N_{\rm source} \neq N_{\rm axion}$

Higaki, FT, 1404.6923

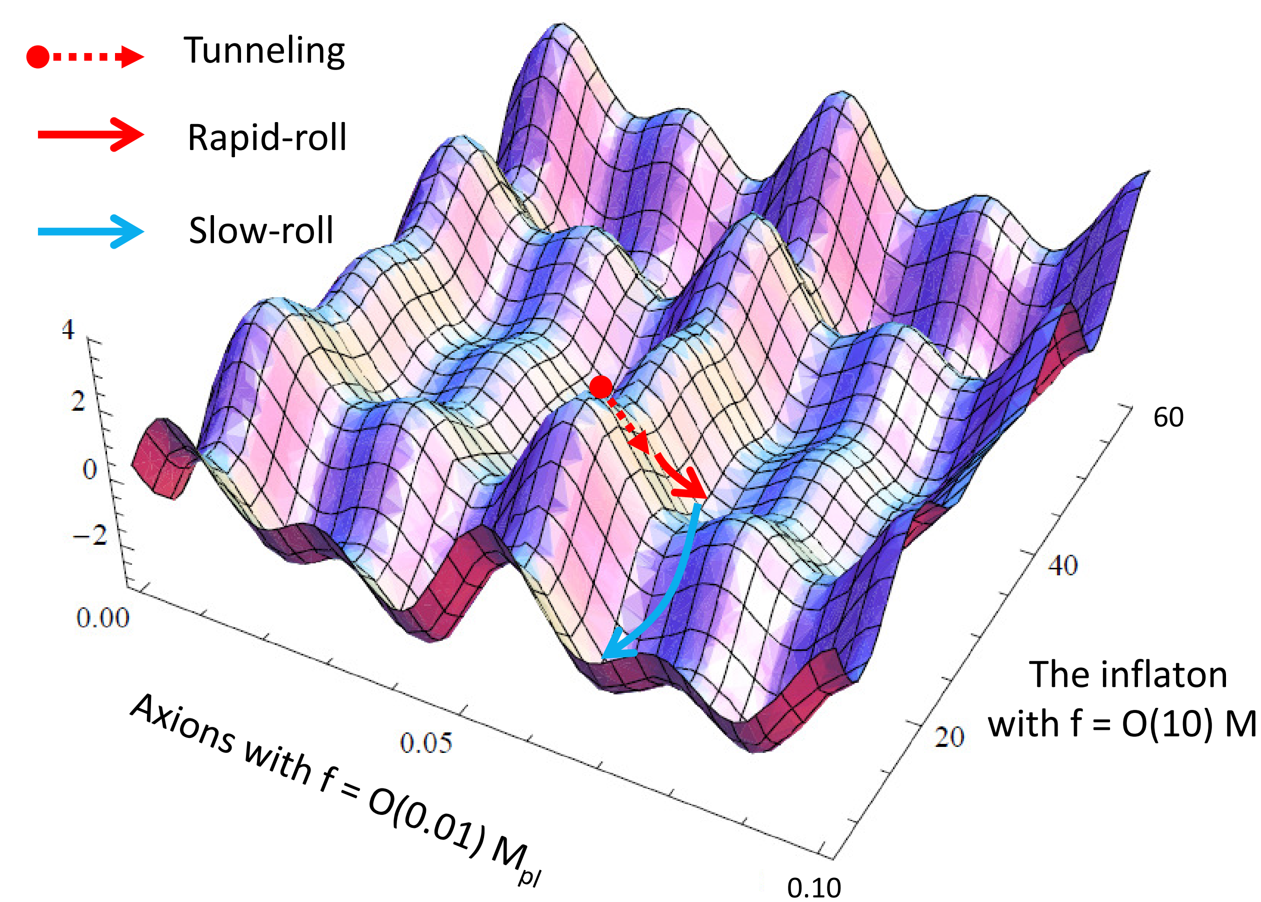
Axion Landscape

Higaki, FT 1404.6923

For $N_{\rm source} > N_{\rm axion}$, many axions may form a mini-landscape.

$$V(\phi_i) = \sum_{i=1}^{N_{\rm source}} \Lambda_i^4 \cos\left(\sum_{j=1}^{N_{\rm axion}} a_{ij}\frac{\phi_j}{f_j} + \theta_i\right) + V_0$$

- **Eternal inflation** takes place in a local minimum.
- A flat direction arises by the alignment mechanism.
- Slow-roll inflation begins after the **tunneling** event.
- **Negative curvature**/suppression at large scales if the total e-folding is just 50-60.



Linde `95, Freivogel et al `05, Yamauchi et al `11, Bousso et al `13

4. まとめ

- ✓ 宇宙初期にインフレーション（加速膨張期）があり、CMB温度及び偏光揺らぎにその情報が残っている。
- ✓ もし **r=O(0.001-0.1)** であれば１０年(?)以内に分かる。その場合、
  See talks by 長谷川さん、松村さん
  - ✓ **GUTスケール**かつ**Large-field (super-Planckian) inflation**
    - ✓ 原始重力波直接検出に期待。 See talks by 横山さん、安東さん
    - ✓ どうやってinflaton potentialを制御するのか？
    - ✓ インフラトンは何か？**右巻きスニュートリノ**？**アクシオン**？
- ✓ 一方、もしrが10^{-3}より小さかったらsmall-field inflationである。非常に平らなポテンシャルの頂上近くから始まった。
  - ✓ 初期値問題？　対称性の破れと関連？(e.g. B-L Higgs etc.)