Effective field theory of black hole perturbations with timelike scalar profile

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(YITP, Kyoto U)

Ref. arXiv: 2204.00228 w/ V.Yingcharoenrat
arXiv: 2208.02943 w/ K.Takahashi & V.Yingcharoenrat
arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat
arXiv: 2111.08119 w/ K.Aoki, M.A.Gorji & K.Takahashi
arXiv: 2311.06767 w/ K.Aoki, M.A.Gorji, K.Takahashi & V.Yingcharoenrat

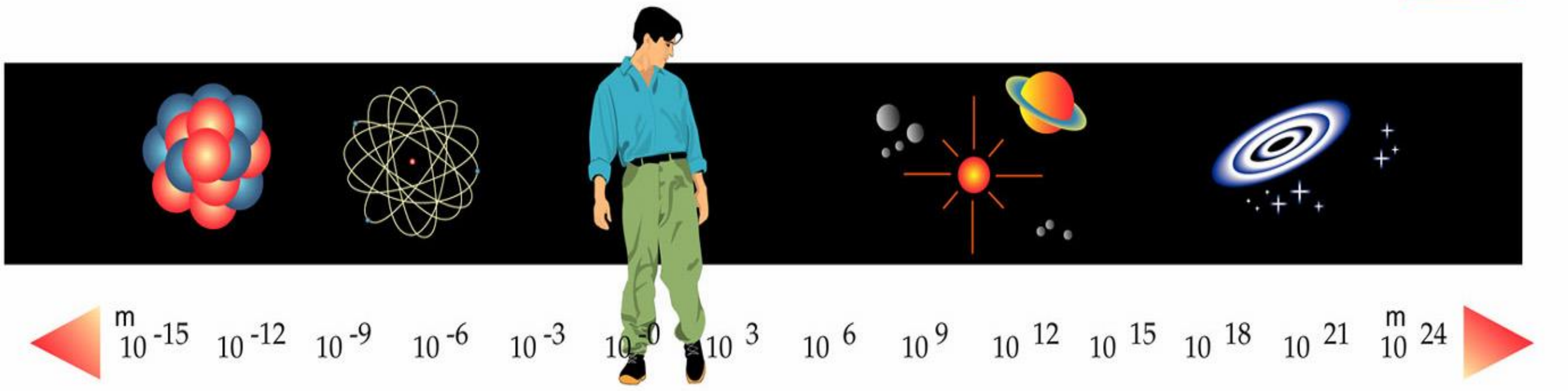
Also Arkani-Hamed, Cheng, Luty and Mukohyama 2004 (hep-th/0312099)
Mukohyama 2005 (hep-th/0502189)

Yukawa Institute for Theoretical Physics

YITP
YUKAWA INSTITUTE FOR
THEORETICAL PHYSICS

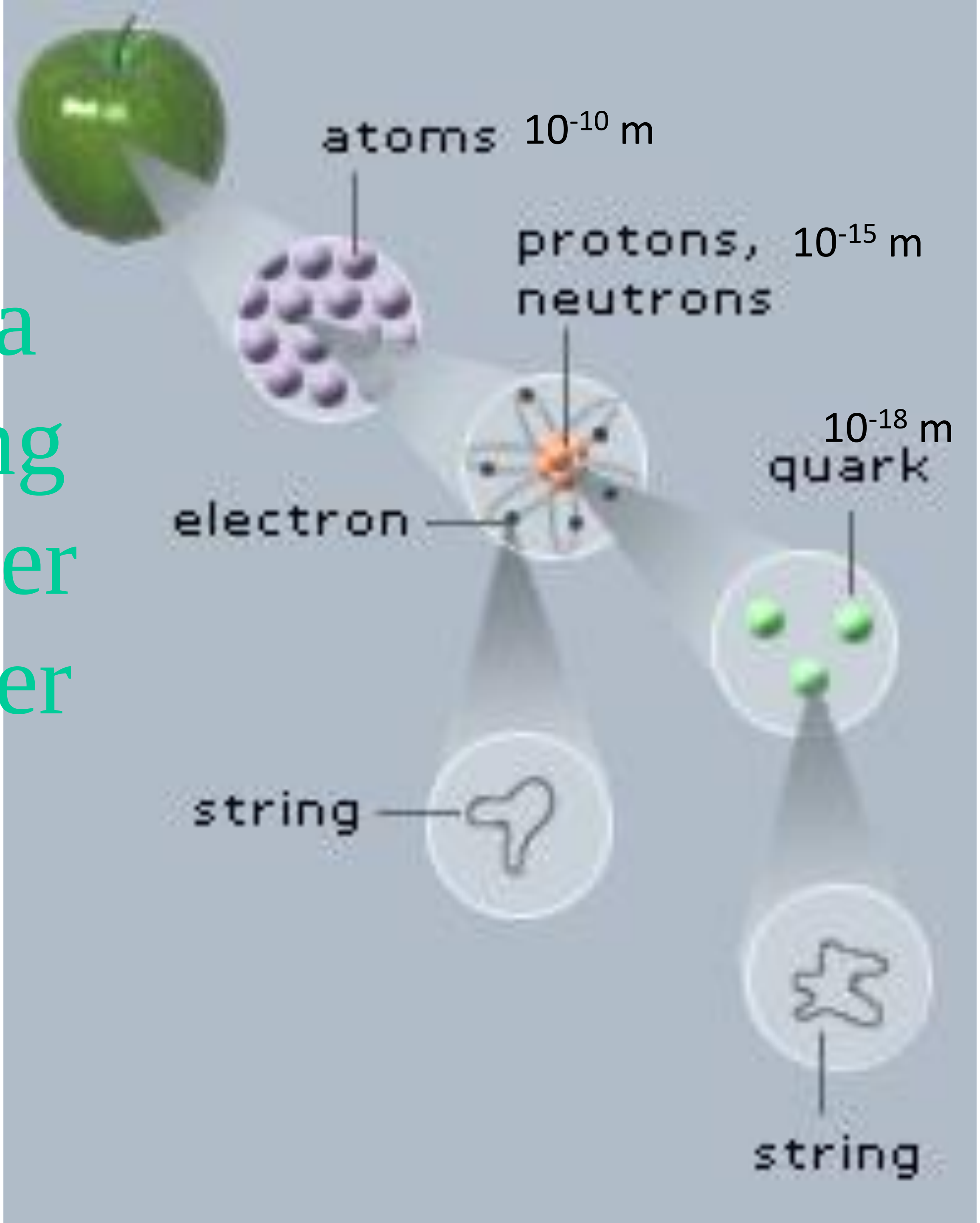
- Yukawa Memorial Hall was established at Kyoto University in 1952 to commemorate Dr. Hideki Yukawa, the first Japanese Nobel Prize winner in Physics in 1949 (the institute was established in 1953).
- Promoting research in theoretical physics (particle theory, theoretical astrophysics, nuclear theory, condensed matter theory, quantum information).
- Challenging the mysteries of the universe.

There are Frontiers in Physics:



at Short and Long Scales

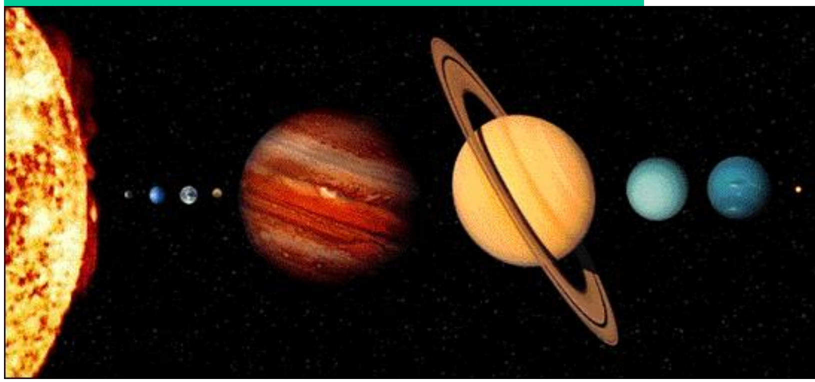
There is a story going into smaller and smaller scales.



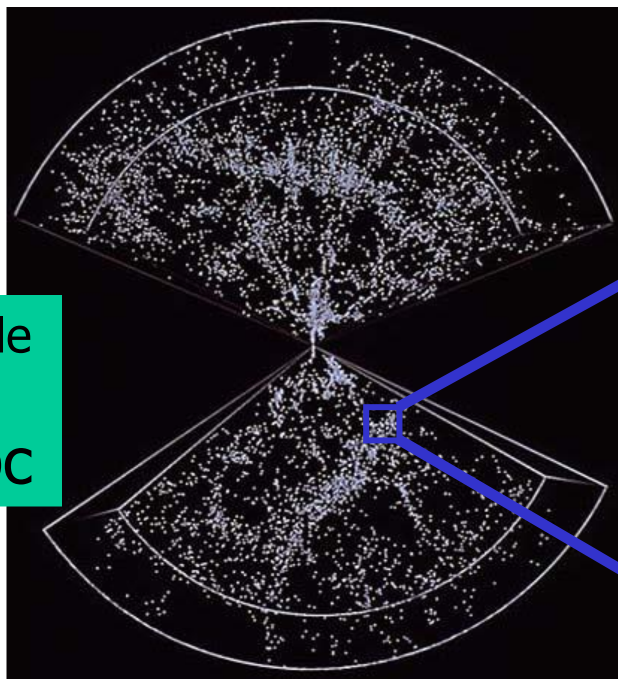
Also at Large scales

(pc = 3.3 light year=3.1 × 10^{18} cm)

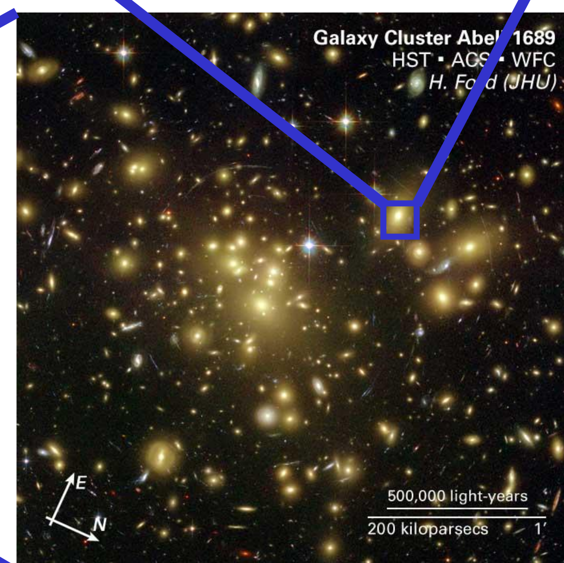
Solar system 10^{15}cm



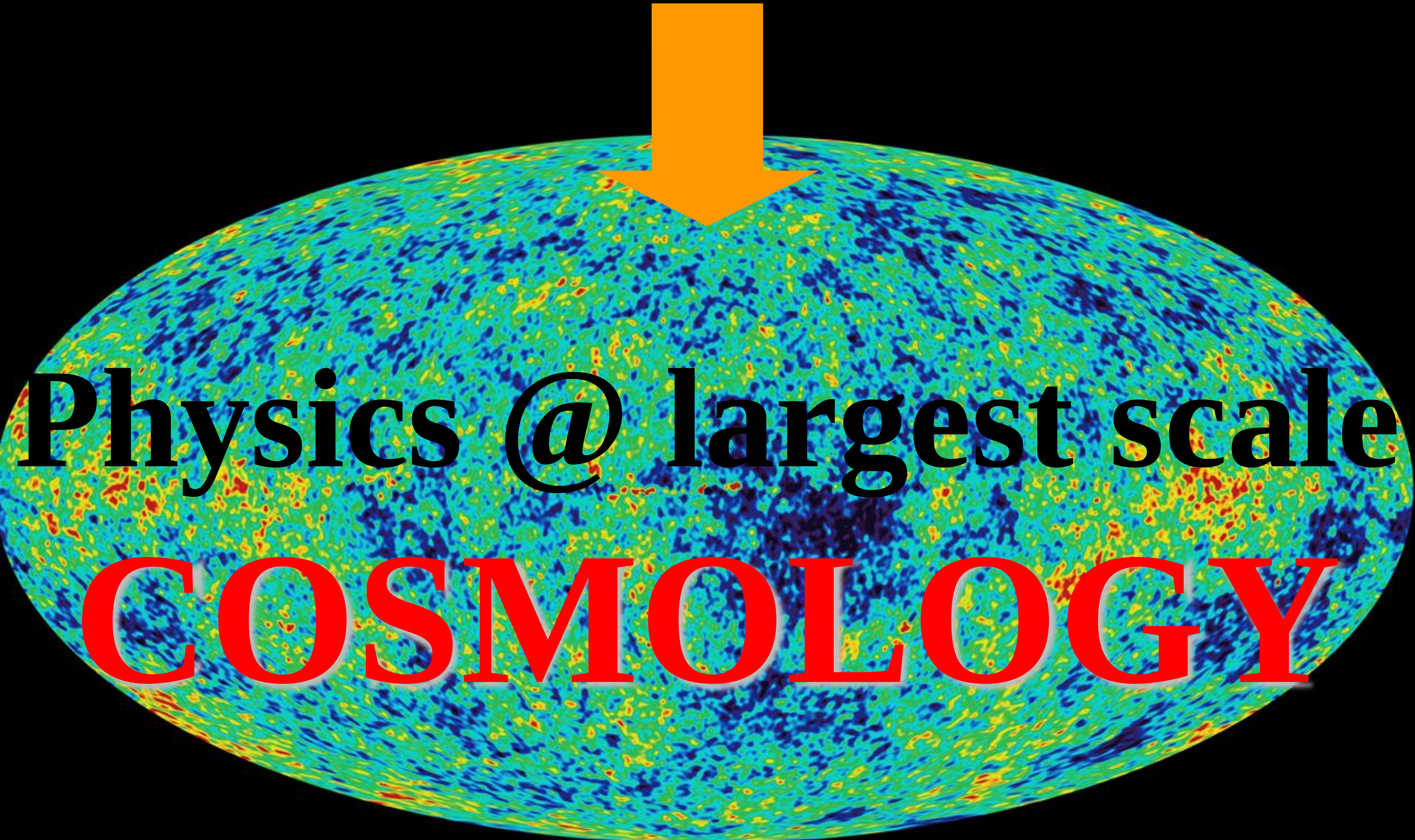
Galaxy
10 kpc



Large scale structure
100 Mpc



Cluster of galaxies
Mpc

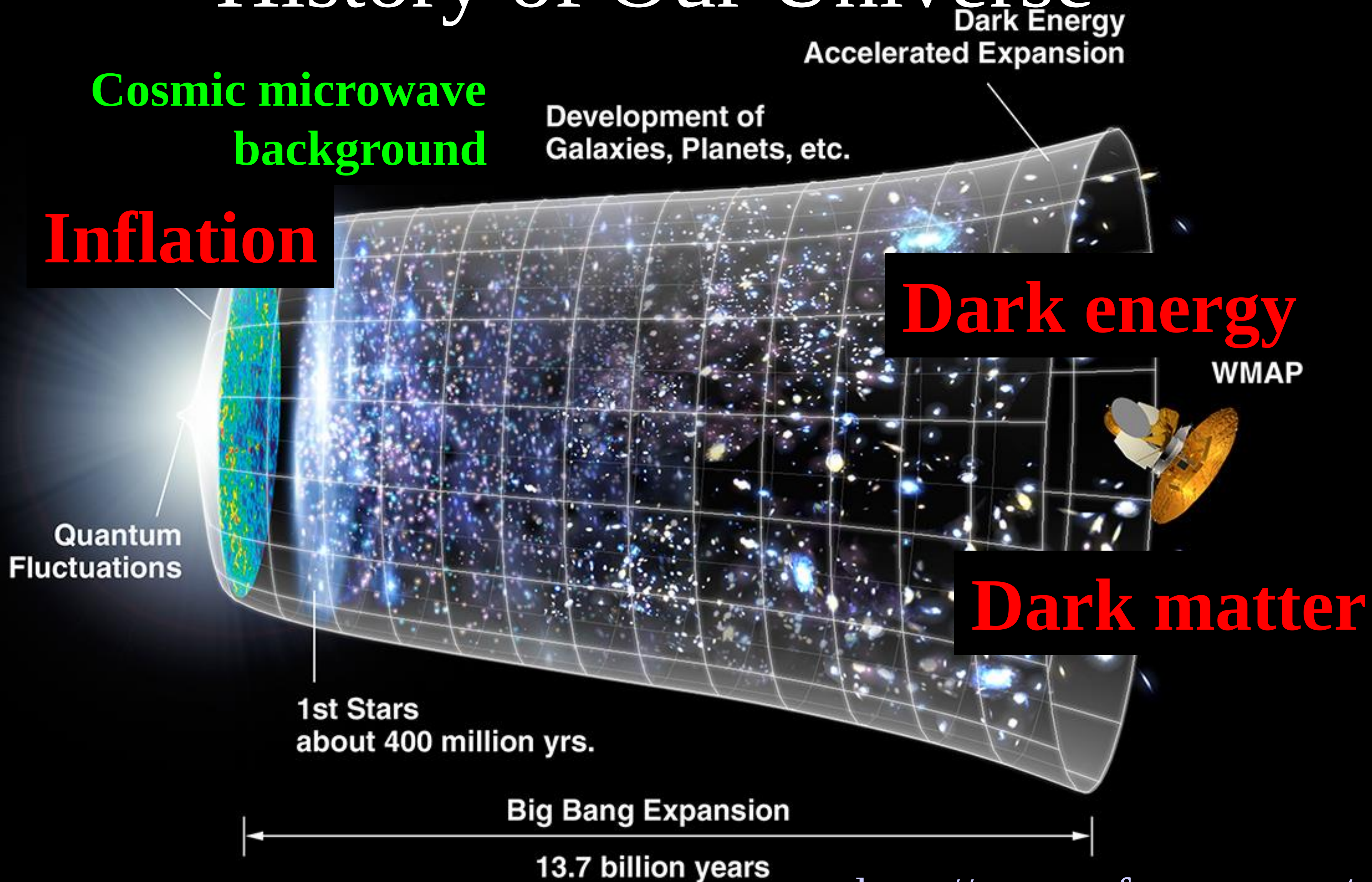

Physics @ largest scale
COSMOLOGY

Major successes of the standard big-bang cosmology

- Expanding universe: Hubble's law
- Cosmic Microwave background
- Nucleosynthesis

Unfortunately, or fortunately, the big-bang cosmology based on general relativity (GR) is NOT perfect.

History of Our Universe

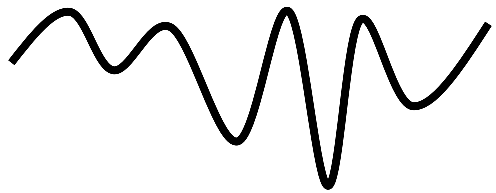


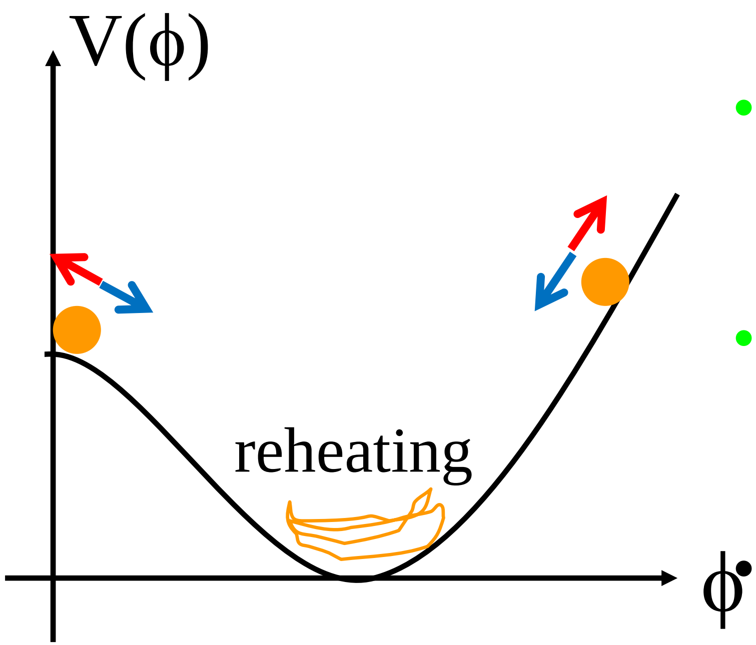
http://map.gsfc.nasa.gov/

Two phases of the accelerated expansion of the universe

- Inflation in the early universe
- Accelerated expansion of the late-time universe driven by dark energy

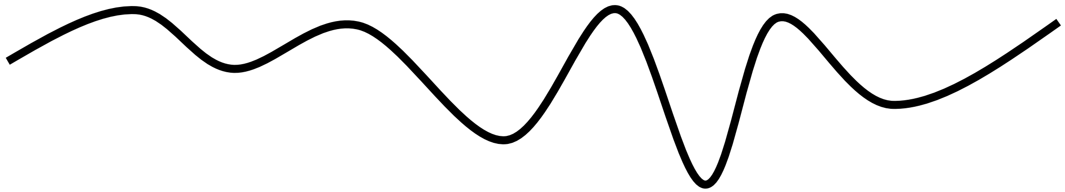
Inflation generates tiny inhomogeneities

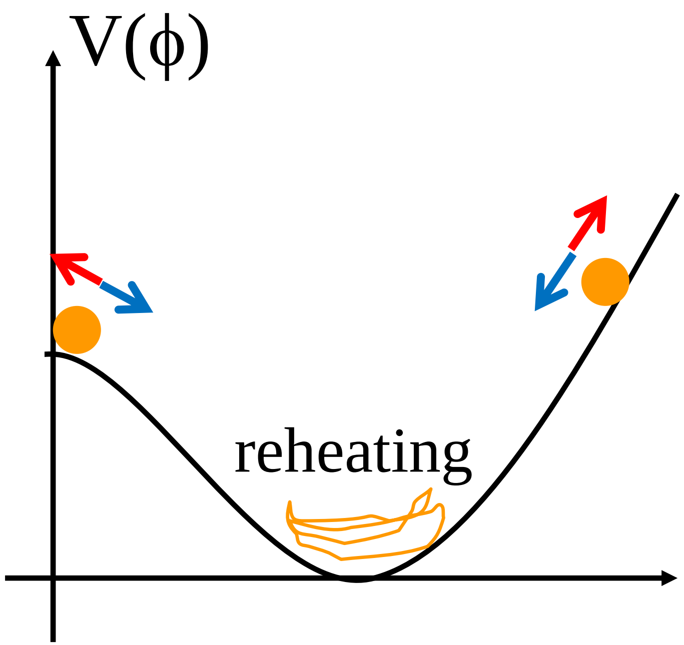




- Quantum effects become important in the early universe
- **Quantum mechanically,** the inflaton ϕ（alarm clock）moves forward or backward slightly due to fluctuations
- **Exponential expansion** stretches microscopic fluctuations to macroscopic lengthes
- If inflation ends a little earlier (or later) than the surrounding area, the energy density will be lower (higher) than the surrounding area.

Inflation generates tiny inhomogeneities





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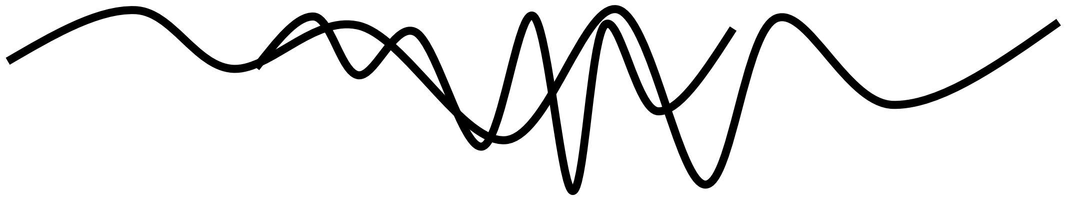

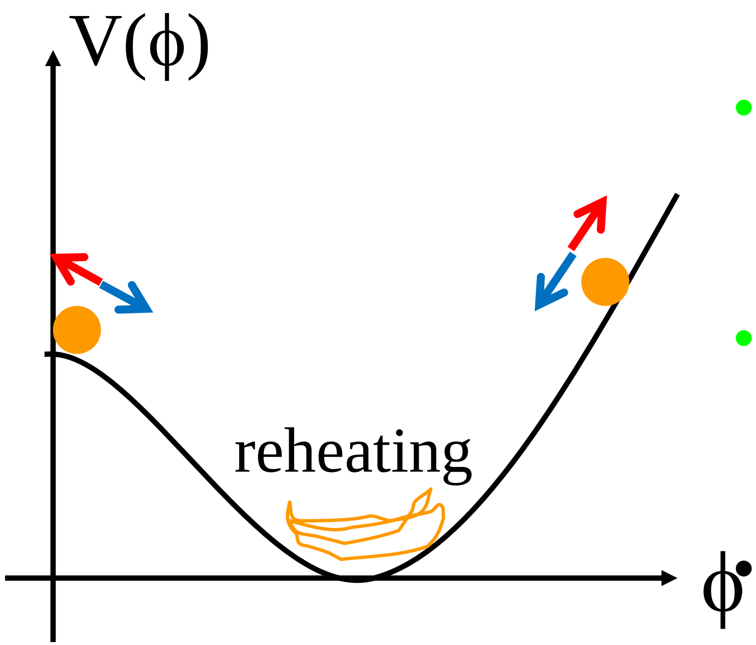

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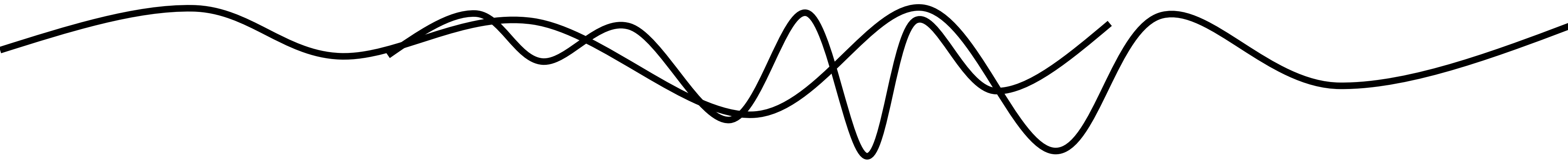

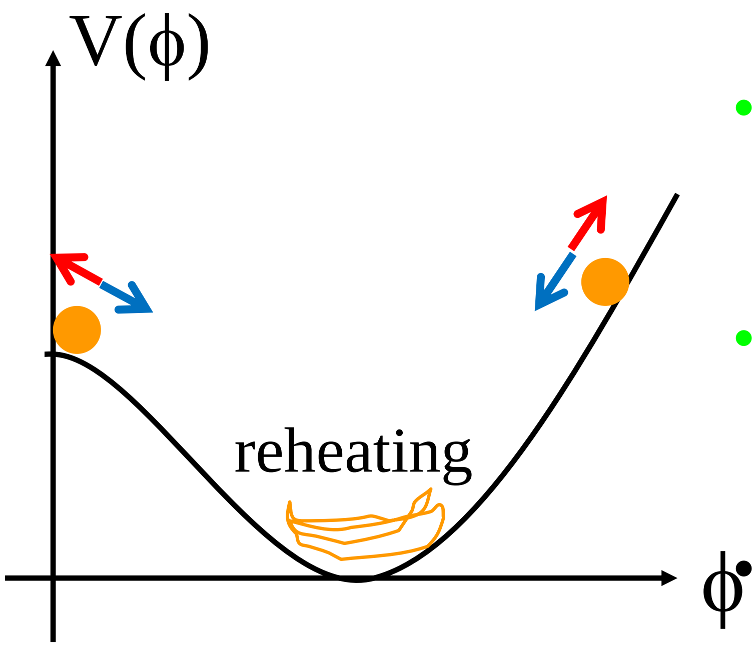

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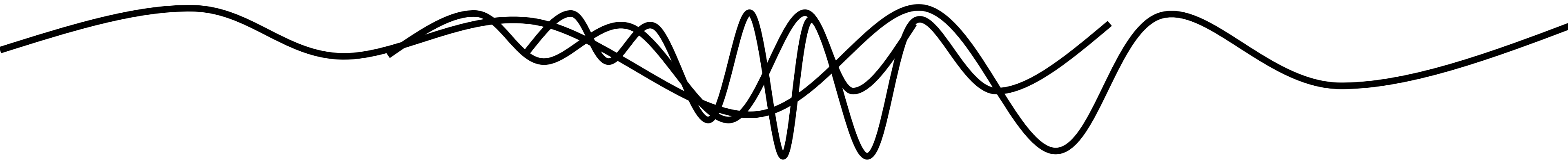

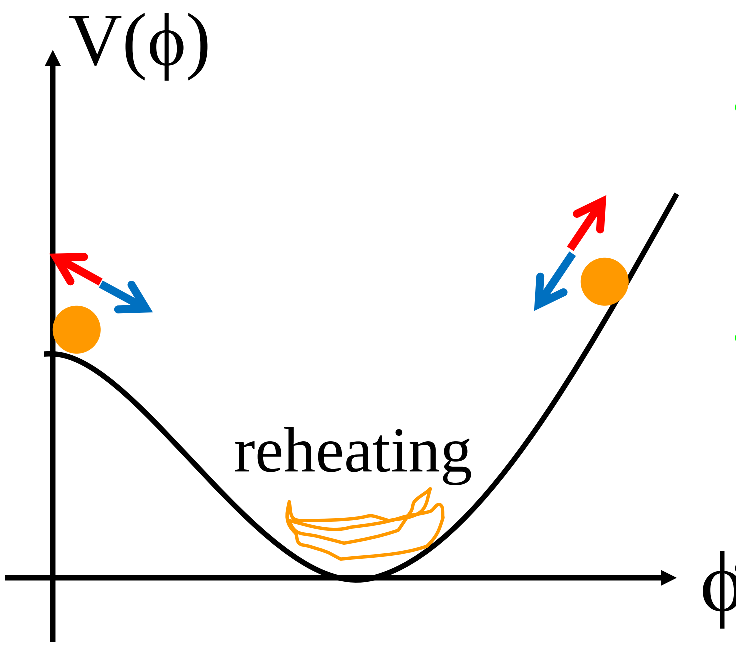

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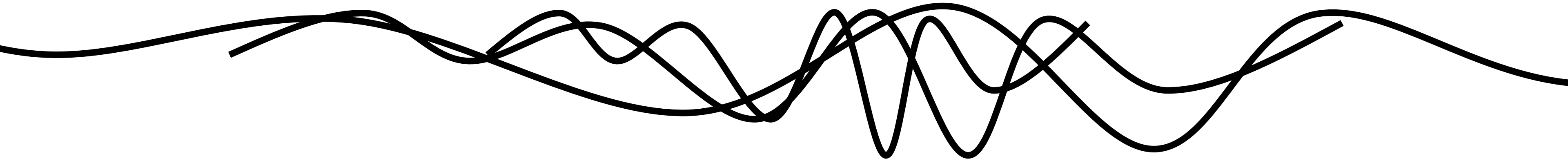

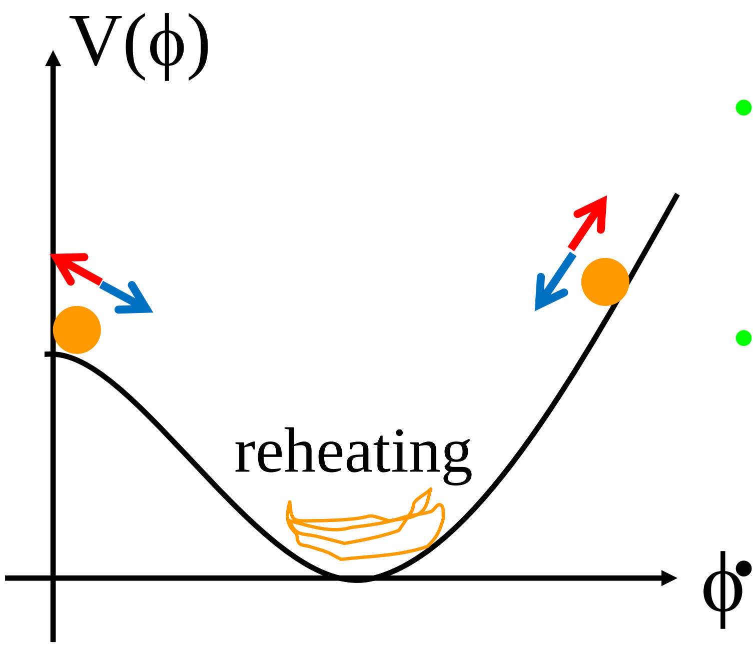

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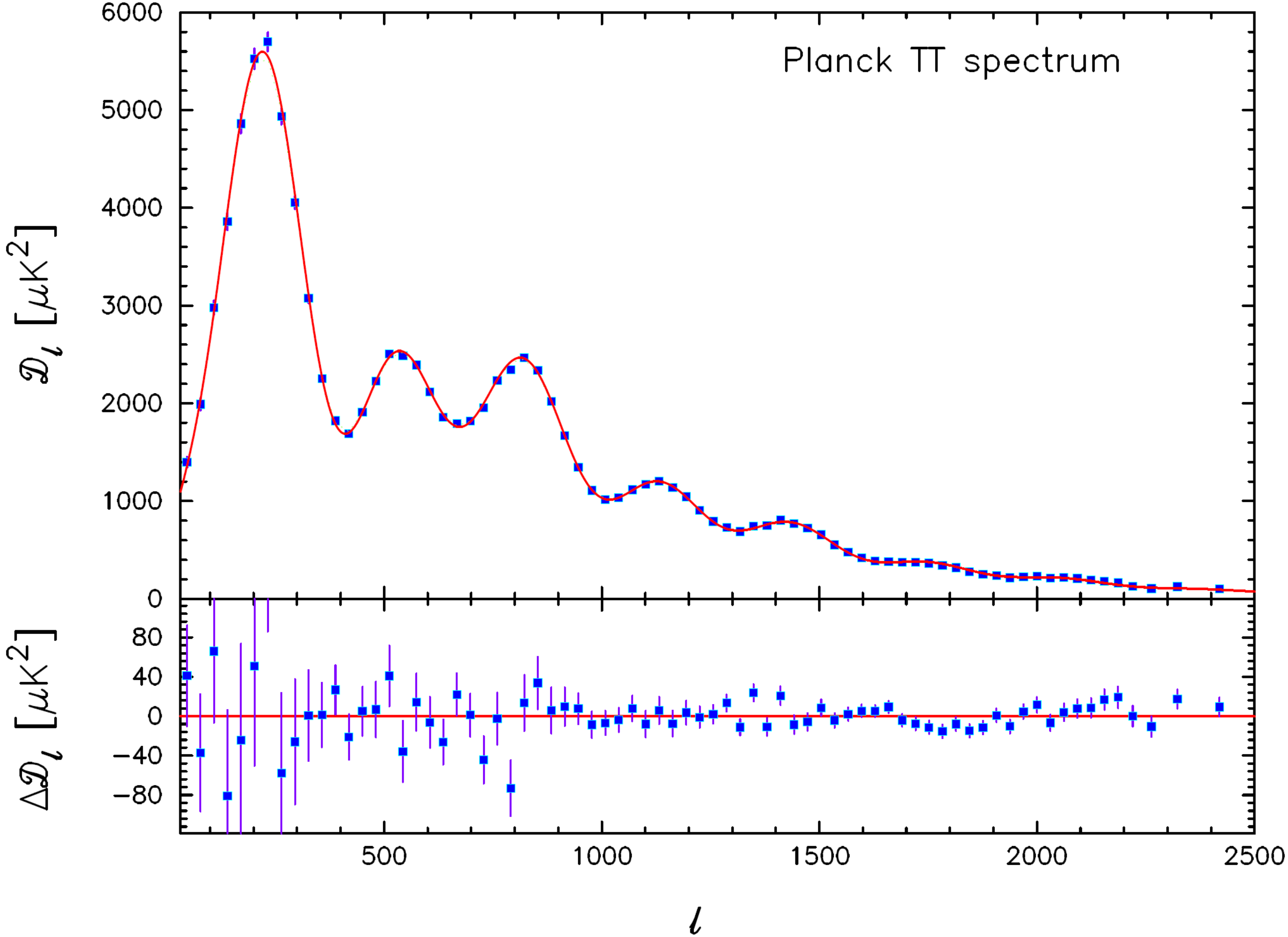
Perfect match with observation



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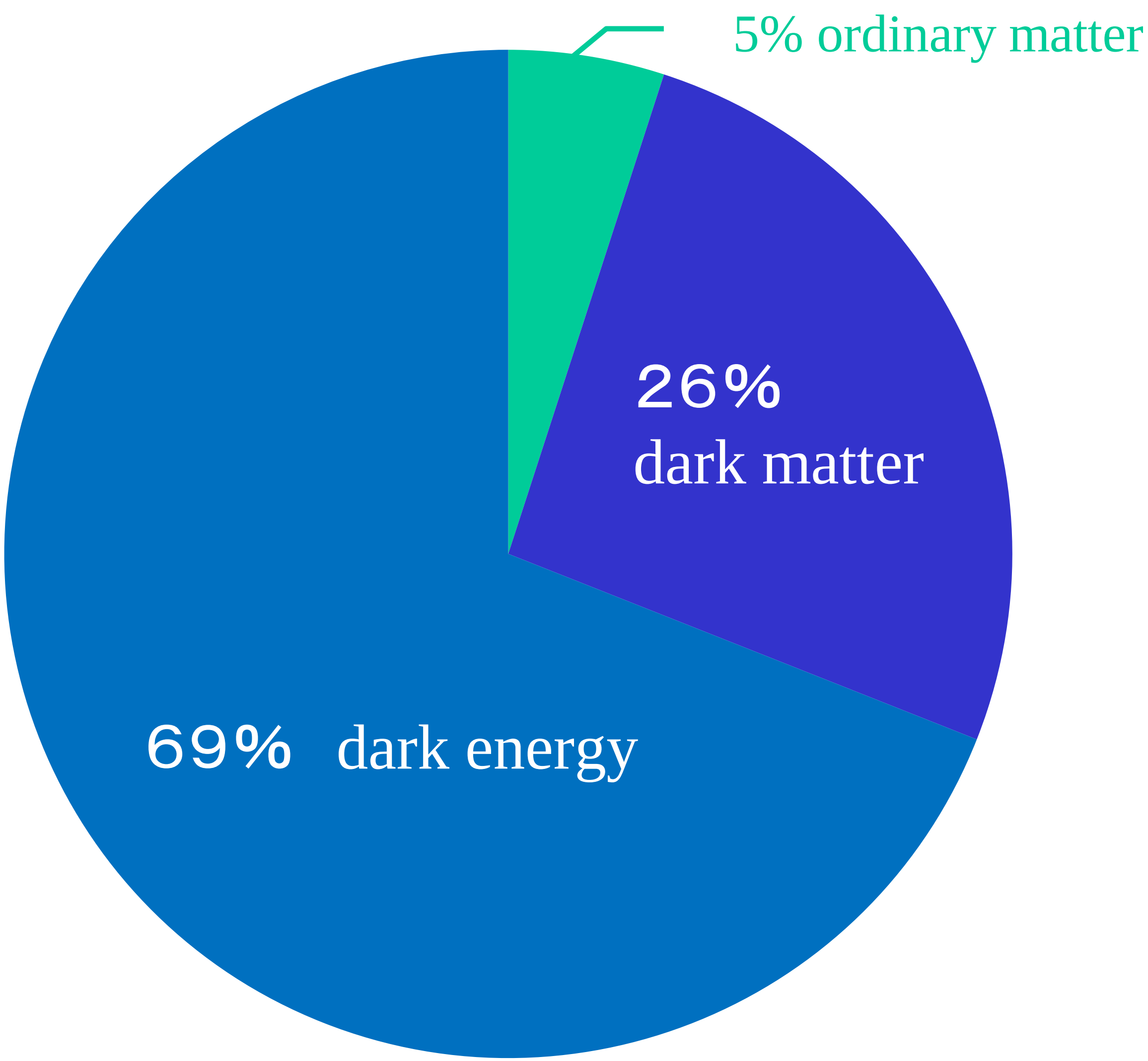
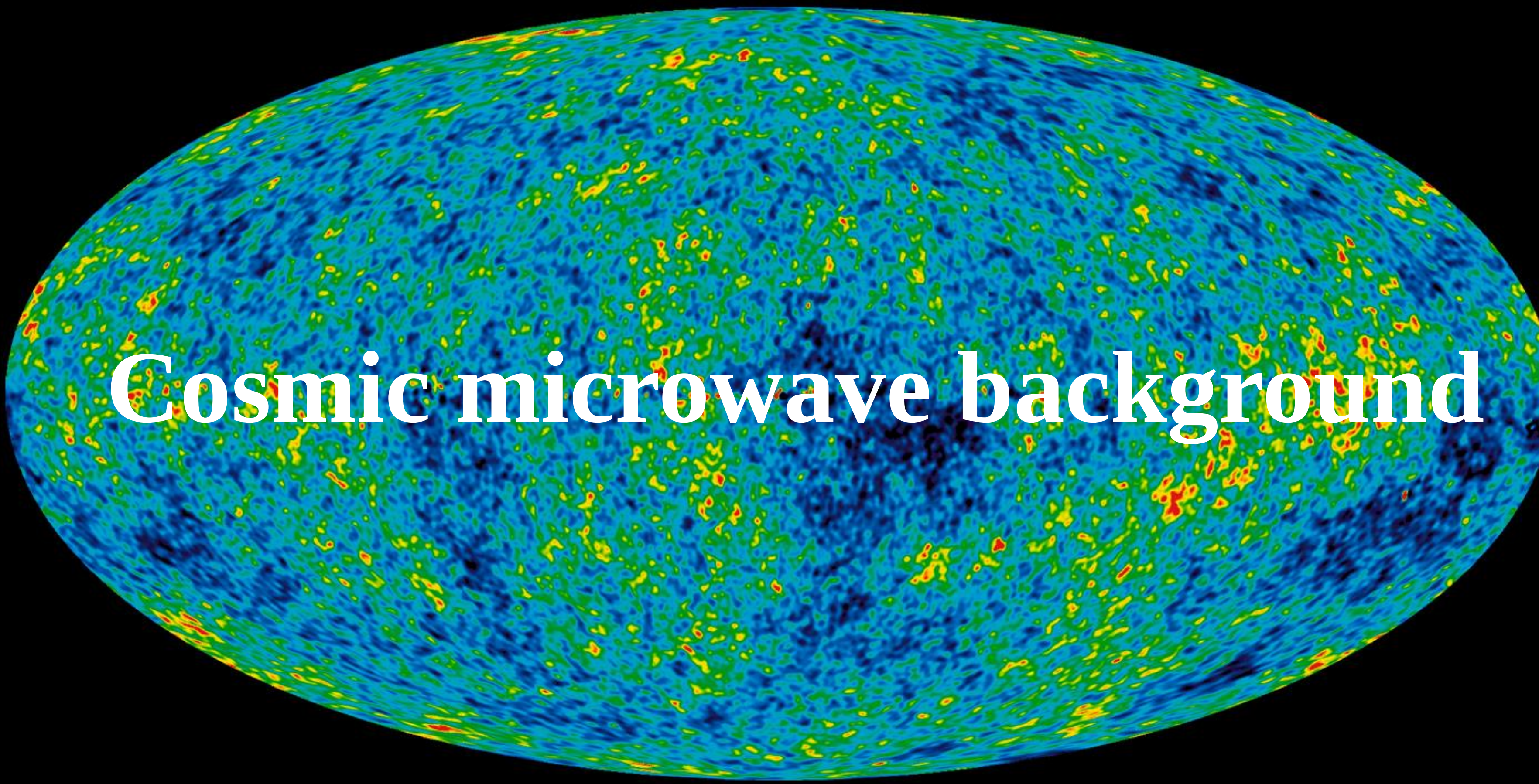
The composition of the universe:
95% unknown!

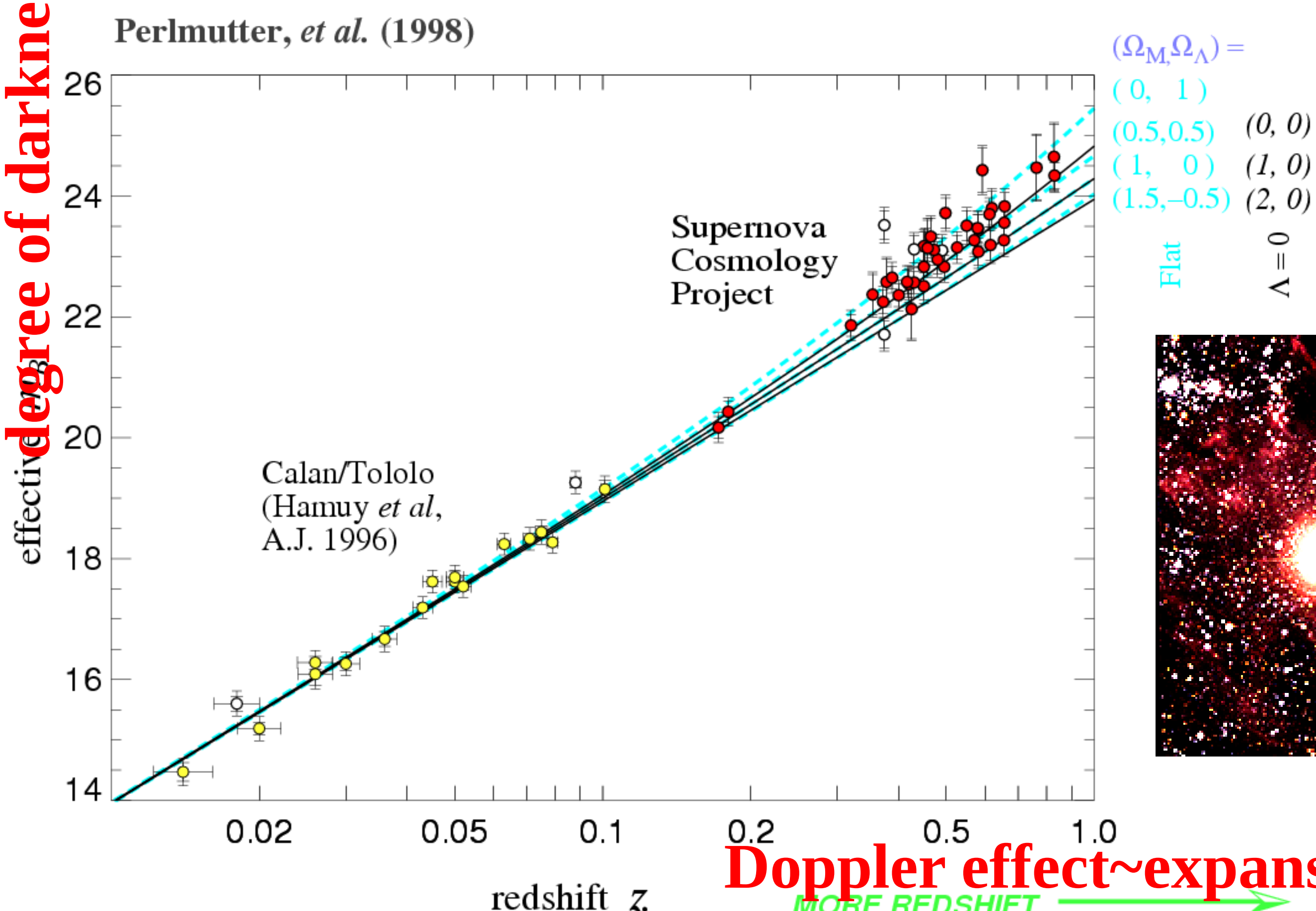


Inflation, dark energy & dark matter are (almost) confirmed by

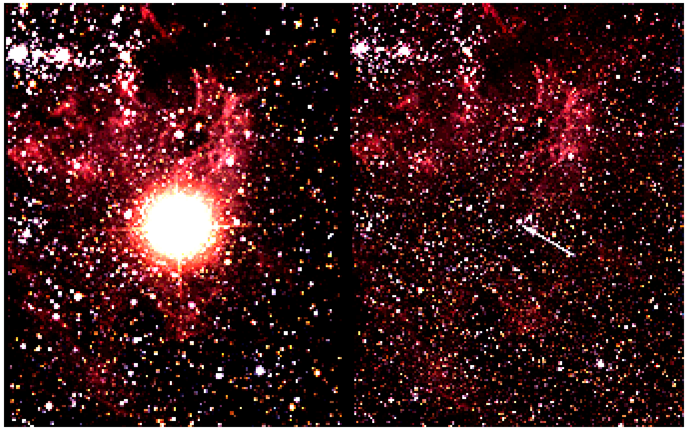


& Supernava observation

degree of darkness~distance



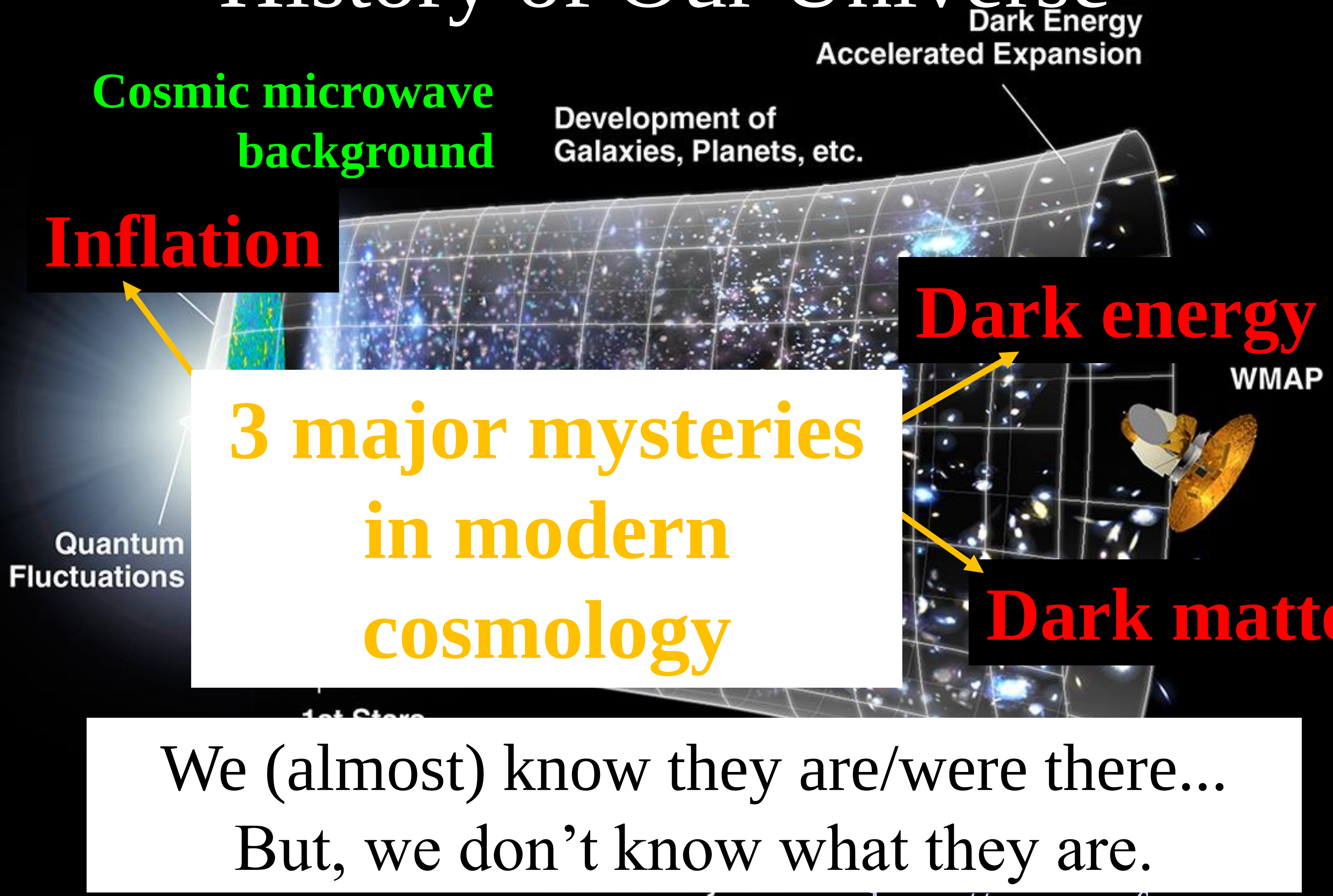
Explosion of a heavy star
10 billion times brighter than the sun



Doppler effect~expansion of universe

http://supernova.lbl.gov/

History of Our Universe



Cosmic microwave background

Inflation

Dark energy

Dark matter

3 major mysteries in modern cosmology

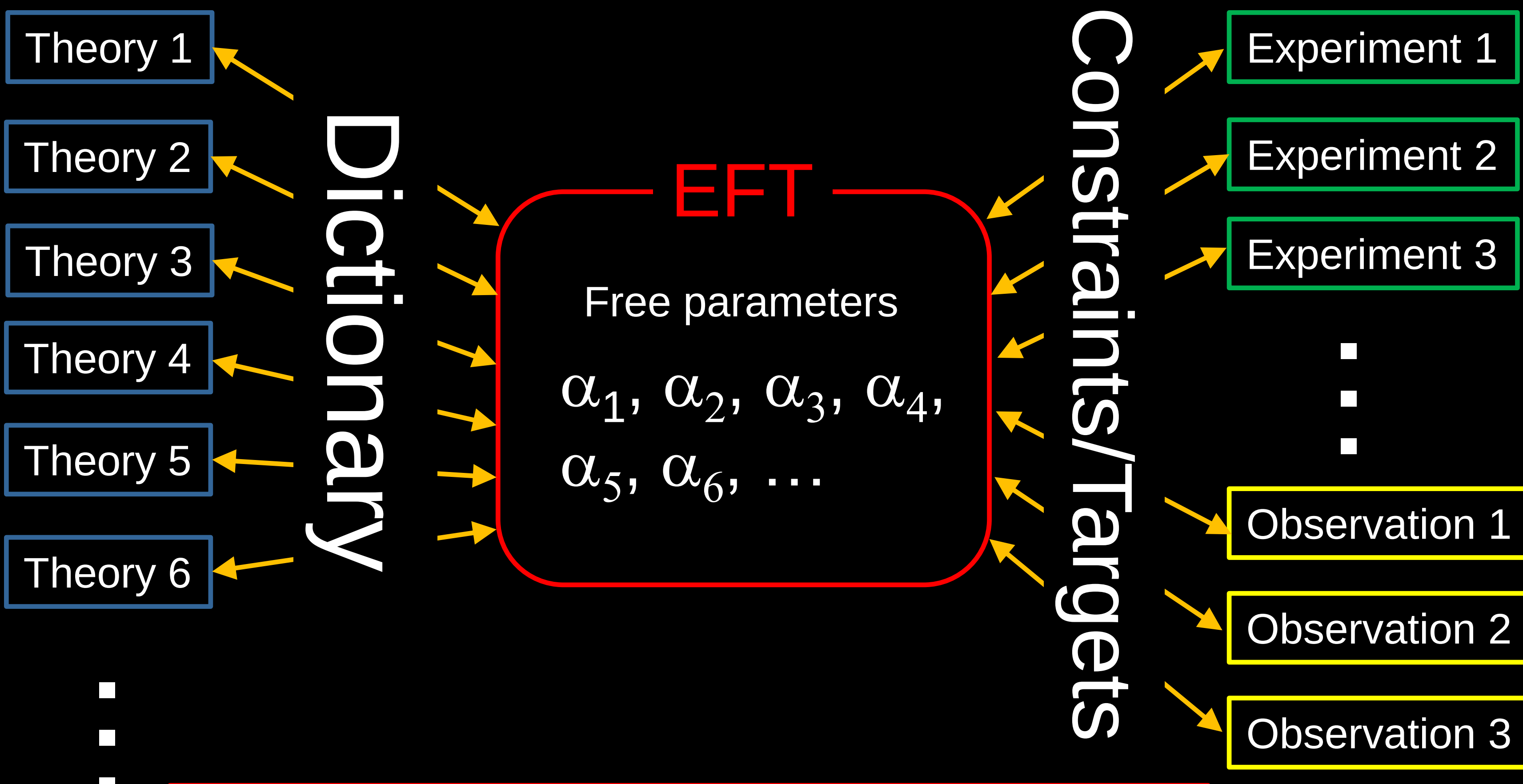
We (almost) know they are/were there...
But, we don’t know what they are.

http://map.gsfc.nasa.gov/

Scalar-tensor gravity

- Contains GR + a scalar field as a special case
- Contains majority of inflation & dark energy models
- Metric $g_{\mu\nu}$ + scalar field ϕ
- Jordan (1955), Brans & Dicke (1961), Bergmann (1968), Wagoner (1970), …
- Most general scalar-tensor theory of gravity with 2nd order covariant EOM: Horndeski (1974)
- DHOST theories beyond Horndeski: Langlois & Noui (2016)
- U-DHOST theories beyond DHOST: DeFelice, Langlois, Mukohyama, Noui & Wang (2018)
- All of them (and more) are universally described by an effective field theory (EFT)

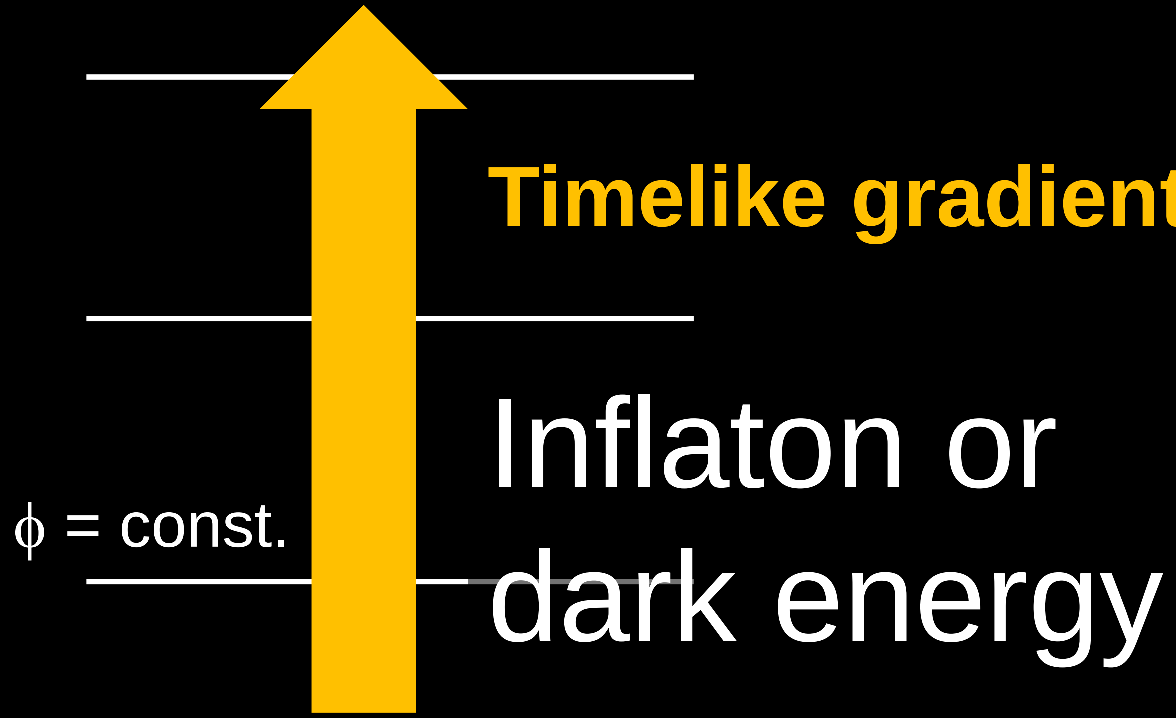
Effective field theory (EFT) approach



EFT plays the role of bridge between theories and experiments/observations!

EFT of scalar-tensor gravity with timelike scalar profile

- Inflaton/dark energy has timelike derivative
- Time diffeo is broken by the scalar profile but spatial diffeo is preserved.

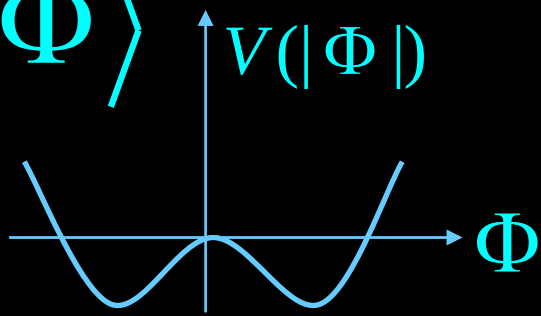
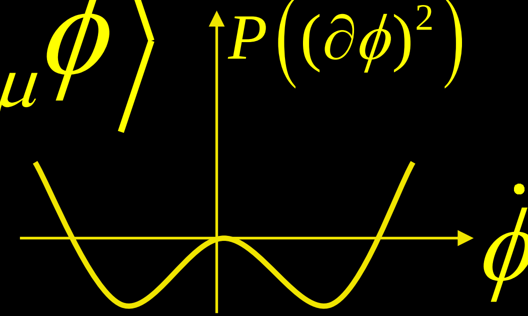


EFT of scalar-tensor gravity with timelike scalar profile

- **Time diffeo is broken by the scalar profile but spatial diffeo is preserved.**
- All terms that respect spatial diffeo must be included in the EFT action.
- Derivative & perturbative expansions
- Diffeo can be restored by introducing NG boson

EFT on Minkowski background	= ghost condensation

Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004

	Higgs mechanism	***Ghost condensate*** Arkani-Hamed, Cheng, Luty and Mukohyama 2004
Order parameter	$\langle \Phi \rangle$ 	$\langle \partial_\mu \phi \rangle$ 
Instability	Tachyon $-\mu^2\Phi^2$	Ghost $-\dot{\phi}^2$
Condensate	V'=0, V''>0	P'=0, P''>0
Broken symmetry	Gauge symmetry	Time diffeomorphism
Force to be modified	Gauge force	Gravity
New force law	Yukawa type	Newton+Oscillation

EFT of ghost condensation = EFT of scalar-tensor gravity with timelike scalar profile on Minkowski background

Arkani-Hamed, Cheng, Luty and Mukohyama 2004

Backgrounds characterized by

- ✧ $\langle \partial_\mu \phi \rangle = const \neq 0$ and timelike
- ✧ Minkowski metric

t → t + const & t → -t unbroken

up to ϕ → ϕ + const & ϕ → -ϕ

⇒

$$L_{eff} = L_{EH} + M^4 \left\{ \left(h_{00} - 2\dot{\pi} \right)^2 - \frac{\alpha_1}{M^2} \left(K + \vec{\nabla}^2 \pi \right)^2 - \frac{\alpha_2}{M^2} \left(K^{ij} + \vec{\nabla}^i \vec{\nabla}^j \pi \right) \left(K_{ij} + \vec{\nabla}_i \vec{\nabla}_j \pi \right) + \cdots \right\}$$

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- Derivative & perturbative expansions
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EFT on Minkowski background	= ghost condensation Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004
EFT on cosmological background	= EFT of inflation/dark energy Creminelli, Luty, Nicolis and Senatore 2006 Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore 2007

Application: non-Gaussinity of inflationary perturbation $\zeta = -H\pi$

$$I_\pi = M_{Pl}^2 \int dt d^3\vec{x}\, a^3 \left\{ -\frac{\dot{H}}{c_s^2}\left(\dot{\pi}^2 - c_s^2 \frac{(\partial_i \pi)^2}{a^2}\right) \right.$$

$$\left. -\dot{H}\left(\frac{1}{c_s^2} - 1\right)\left(\frac{c_3}{c_s^2}\dot{\pi}^3 - \dot{\pi}\frac{(\partial_i\pi)^2}{a^2}\right) + O(\pi^4, \tilde{\epsilon}^2) + L^{(2)}_{\tilde{\delta}K, \tilde{\delta}R} \right\}$$

2 types of 3-point interactions

→ power spectrum

$$P_\zeta(\vec{k}) = \frac{\Delta}{k^3}, \quad \Delta = \left.\frac{H^4}{-4M_{Pl}^2 \dot{H} c_s}\right|_{c_s k \simeq aH}$$

→ non-Gaussianity

$$\langle \zeta_{\vec{k}_1}(t)\, \zeta_{\vec{k}_2}(t)\, \zeta_{\vec{k}_3}(t) \rangle = (2\pi)^3 \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B_\zeta$$

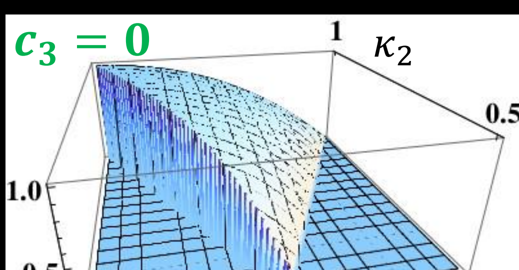
c_s^2 → size of non-Gaussianity

$$k^6 B_\zeta|_{k_1=k_2=k_3=k} = \frac{18}{5}\Delta^2\left(f_{NL}^{\dot{\pi}(\partial_i\pi)^2} + f_{NL}^{\dot{\pi}^3}\right)$$

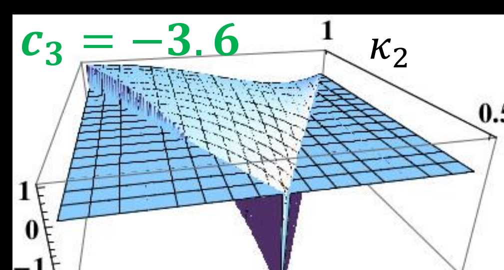
$$f_{NL}^{\dot{\pi}(\partial_i\pi)^2} = \frac{85}{324}\left(1 - \frac{1}{c_s^2}\right) \qquad f_{NL}^{\dot{\pi}^3} = \frac{5c_3}{81}\left(1 - \frac{1}{c_s^2}\right) \qquad \propto \frac{1}{c_s^2} \text{ for small } c_s^2$$

c_3 → shape of non-Gaussianity

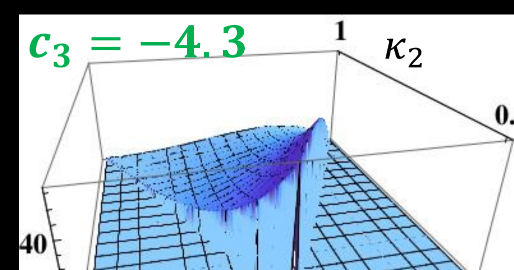
plots of $B_\zeta(k, \kappa_2 k, \kappa_3 k)/B_\zeta(k,k,k)$



Prototype of the equilateral shape



Prototype of the orthogonal shape



Linear combination of the two shapes

Parametrization suitable for DE → EFT of DE

Gubitosi, Piazza, Vernizzi 2012
Gleyzes, Langlois, Piazza, Vernizzi 2013

- Matter (in addition to DE) needs to be added → Jordan frame description is convenient
- In Jordan frame the coefficient of the 4d Ricci scalar is not constant.

$$S = \frac{1}{2}\int d^4x\sqrt{-g}\,\Big[\boxed{M_*^2 f R} - \rho_D + p_D - M_*^2(5H\dot{f} + \ddot{f}) - \Big(\rho_D + p_D + M_*^2(H\dot{f} - \ddot{f})\Big)\, g^{00}$$
$$+ M_2^4(\delta g^{00})^2 - \bar{m}_1^3\,\delta g^{00}\delta K - \bar{M}_2^2\,\delta K^2 - \bar{M}_3^2\,\delta K_\mu{}^\nu \delta K^\mu{}_\nu + m_2^2 h^{\mu\nu}\partial_\mu g^{00}\partial_\nu g^{00}$$
$$+ \lambda_1 \delta R^2 + \lambda_2 \delta R_{\mu\nu}\delta R^{\mu\nu} + \mu_1^2 \delta g^{00}\delta R + \gamma_1 C^{\mu\nu\rho\sigma}C_{\mu\nu\rho\sigma} + \gamma_2 \epsilon^{\mu\nu\rho\sigma}C_{\mu\nu}{}^{\kappa\lambda}C_{\rho\sigma\kappa\lambda}$$
$$+ \frac{M_3^4}{3}(\delta g^{00})^3 - \bar{m}_2^3\,(\delta g^{00})^2\delta K + \dots\Big]\,,$$

- Cosmology and black holes (BHs) play as important roles in gravitational physics as blackbody radiation and hydrogen atoms did in quantum mechanics.

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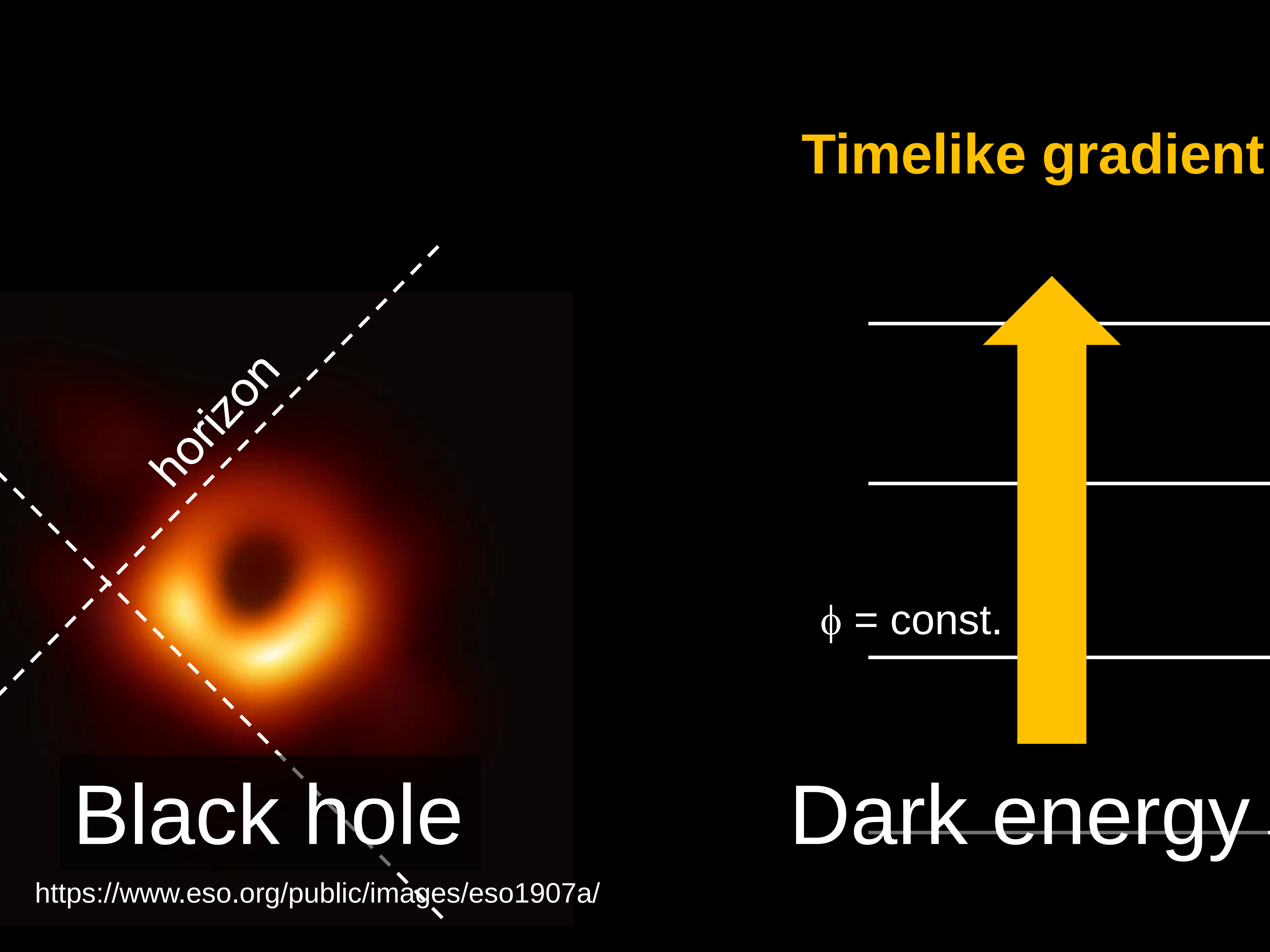
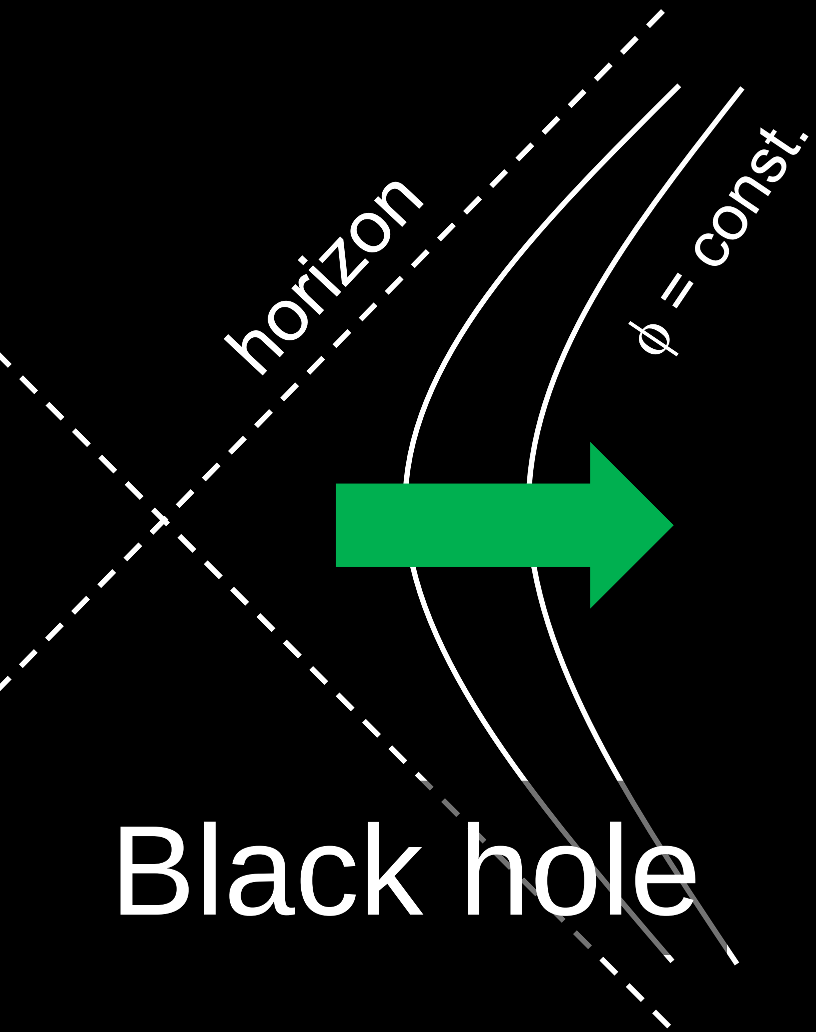
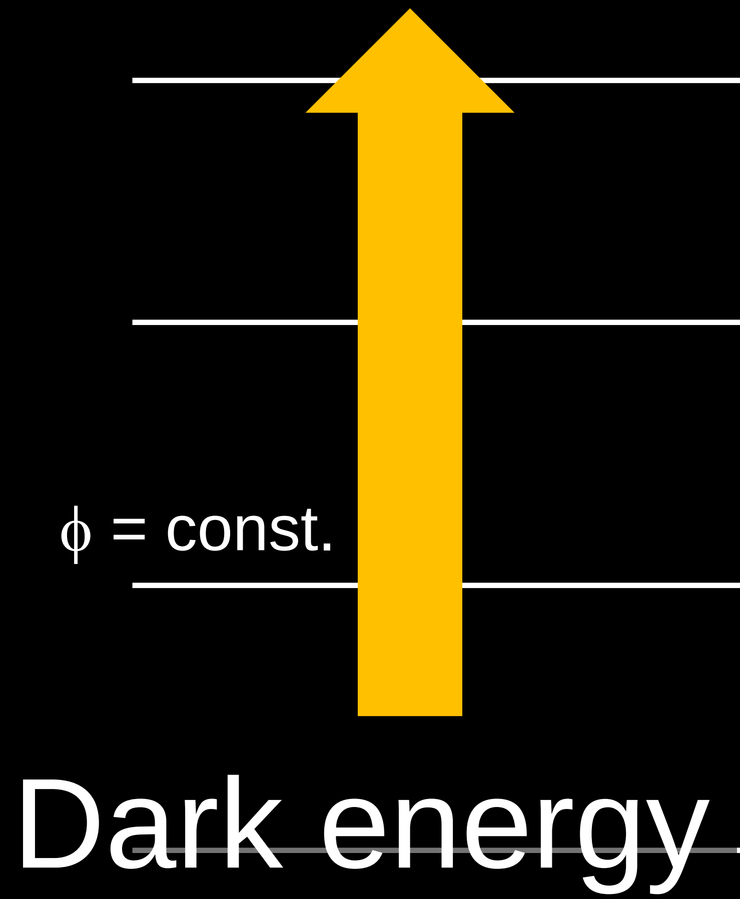
- This would require **the scalar field profile to be timelike near BH**. Otherwise, the two EFTs, one for DE and the other for BH, can be unrelated to each other (unless a UV completion is specified).


Timelike gradient
horizon
ϕ = const.
Black hole
Dark energy
https://www.eso.org/public/images/eso1907a/

Unlucky case

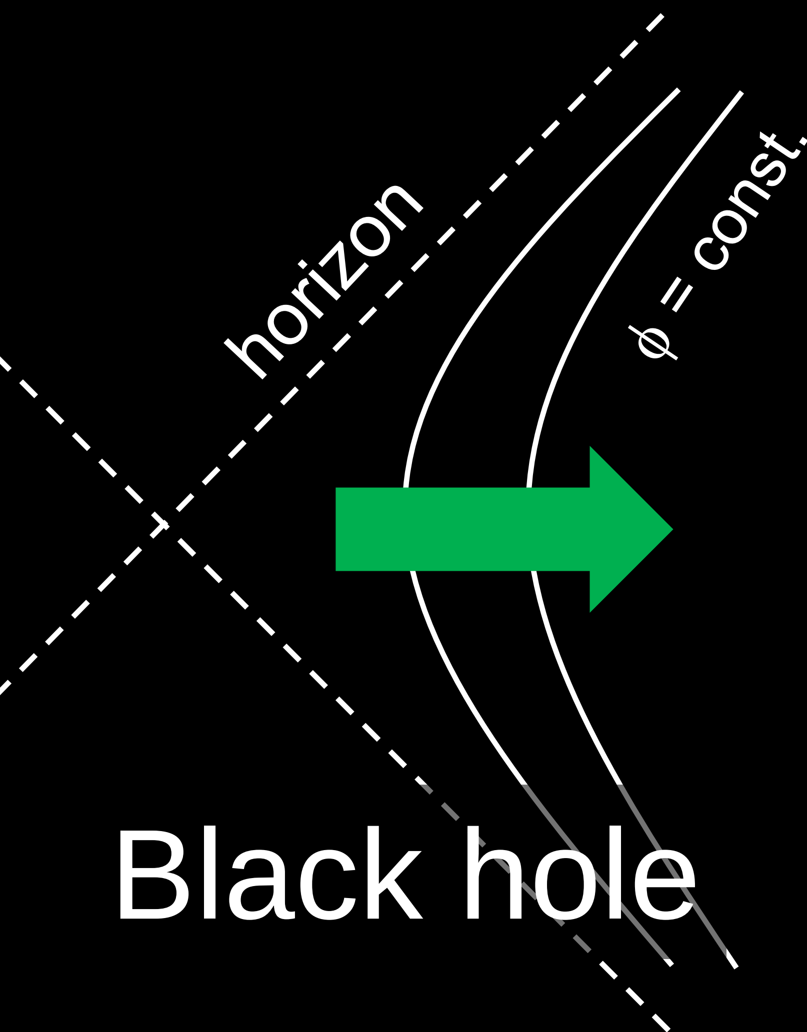
Spacelike gradient | **Timelike gradient**





Unlucky case

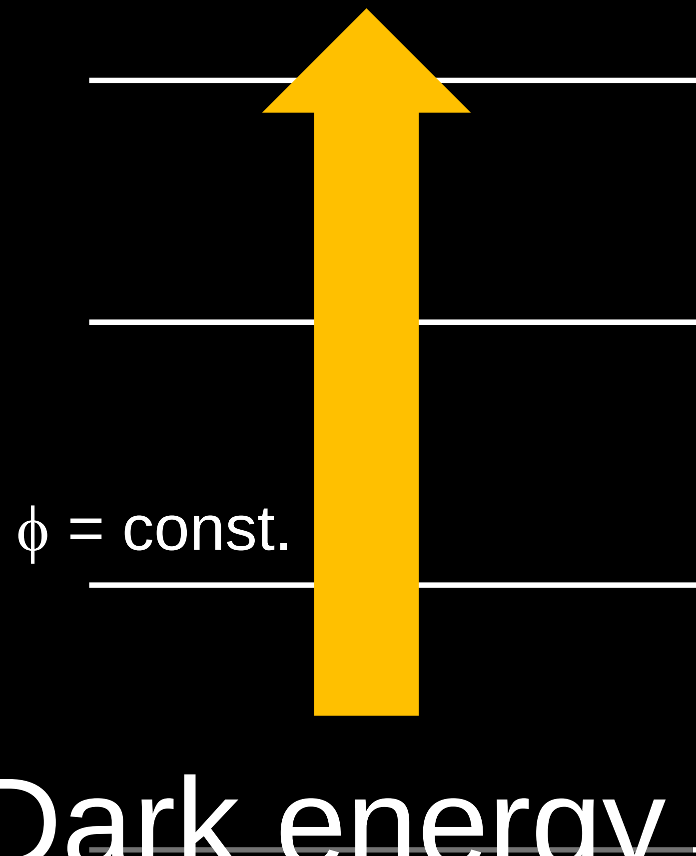
Spacelike gradient



Black hole

No smooth matching

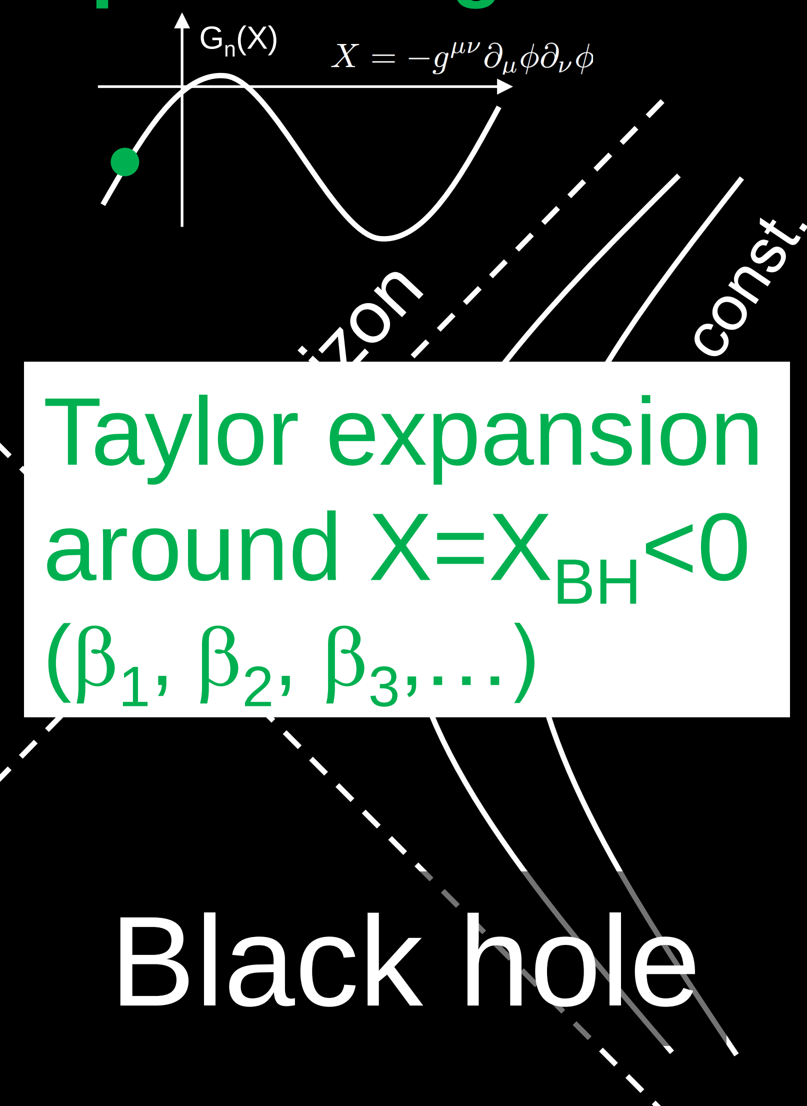
Timelike gradient



Dark energy

Unlucky case

Spacelike gradient

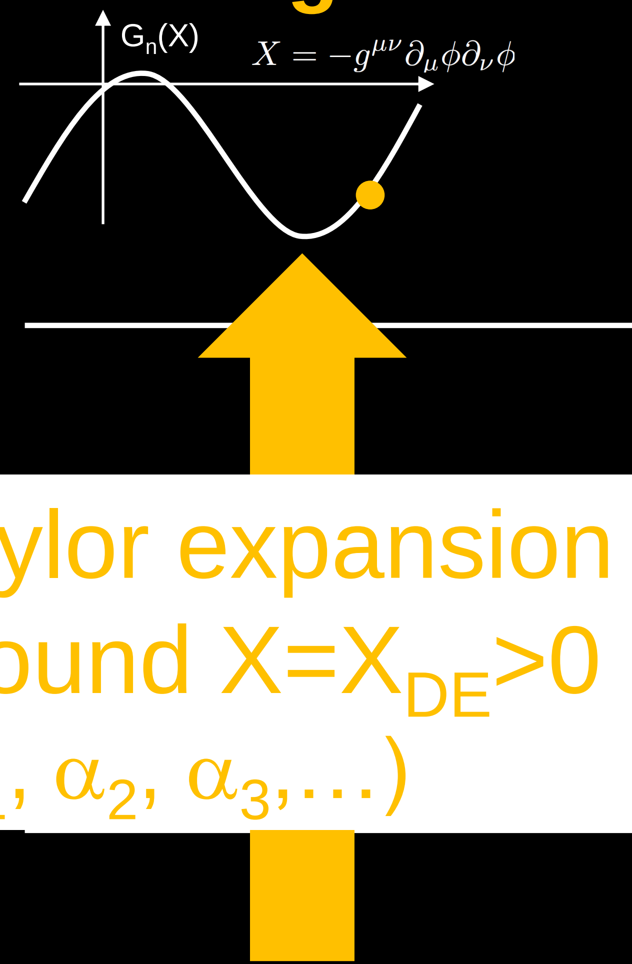


Taylor expansion around $X=X_{BH}<0$ $(\beta_1, \beta_2, \beta_3,\ldots)$

Black hole

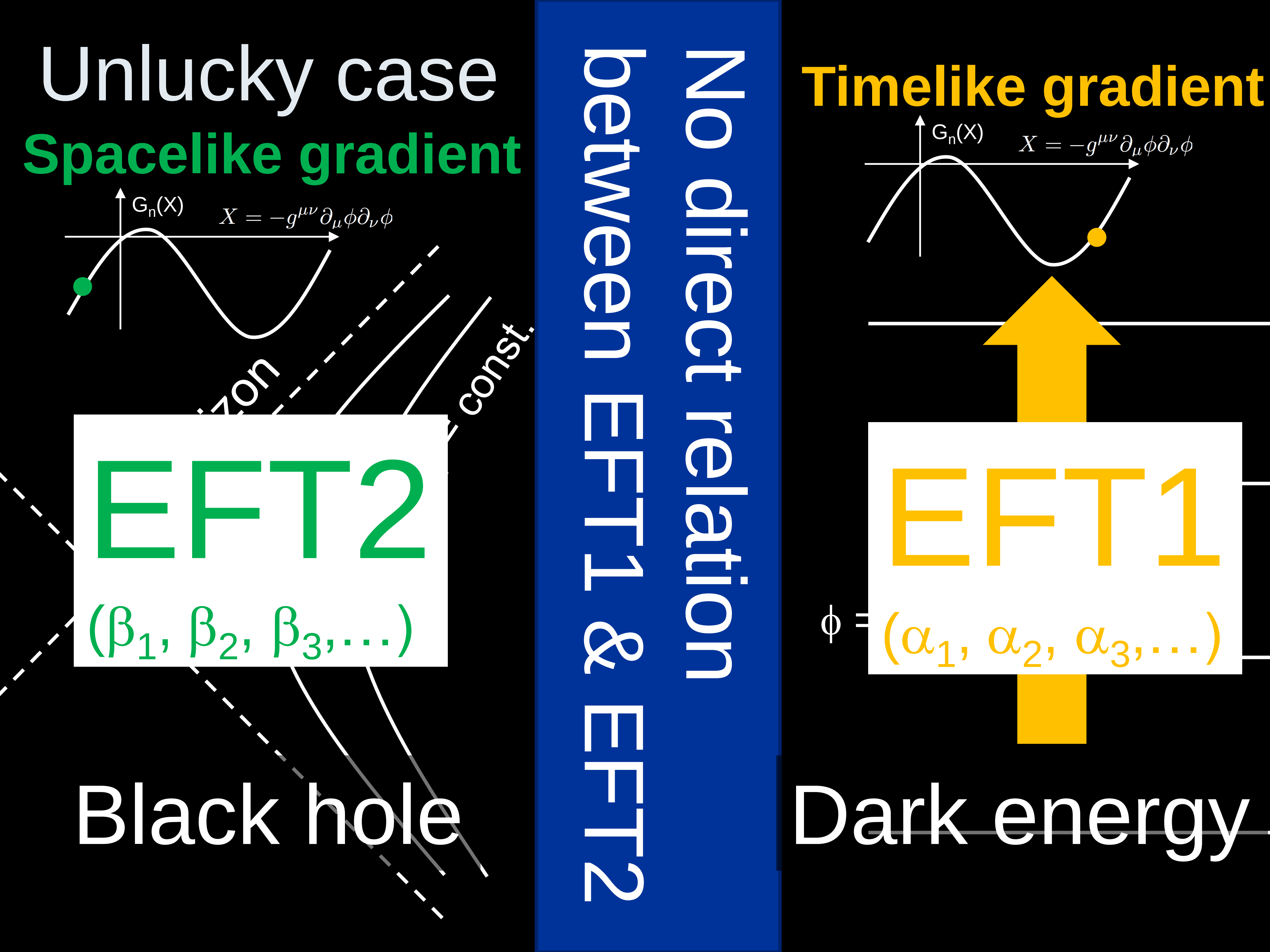
No direct relation between Taylor coefficients

Timelike gradient

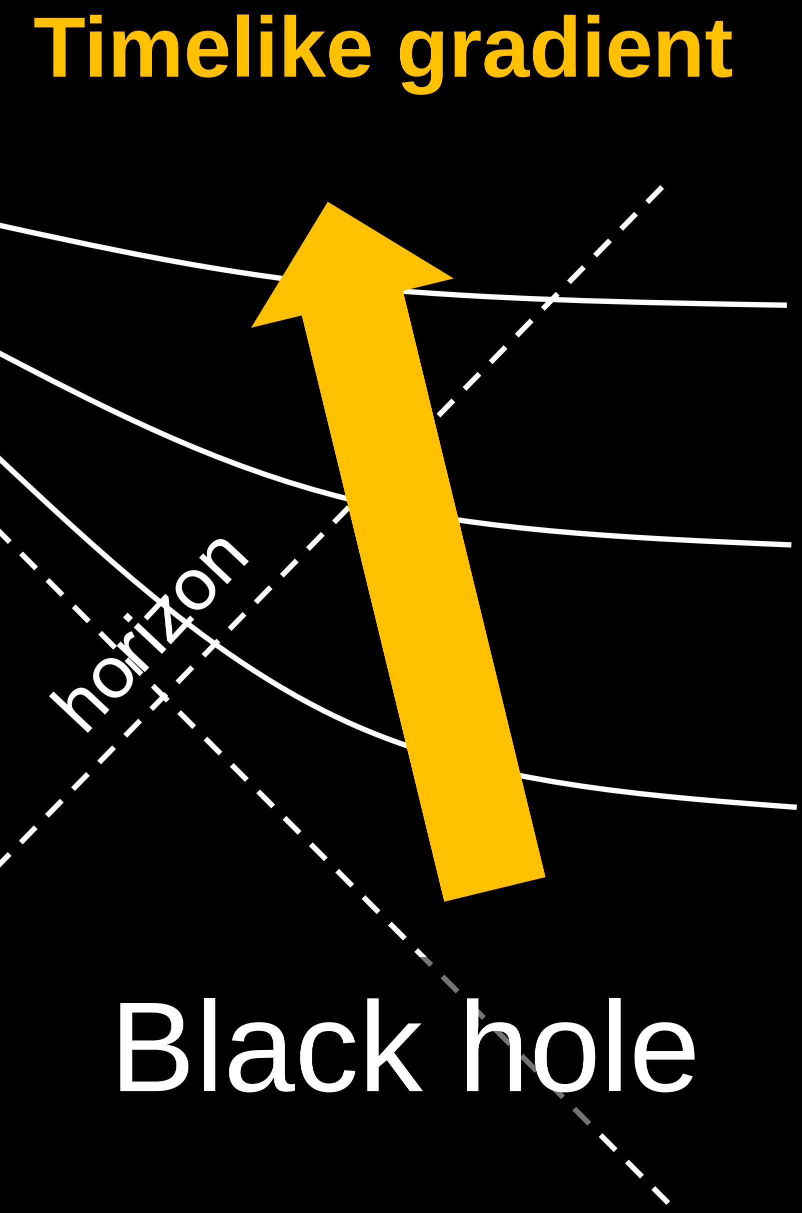


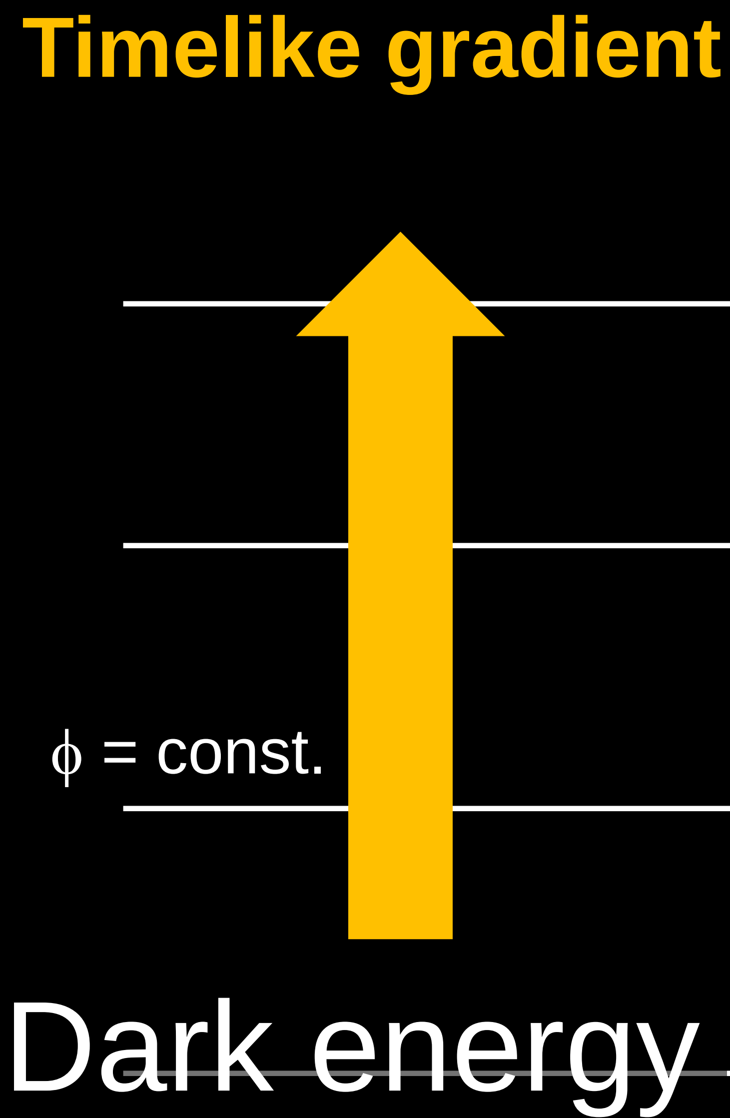
Taylor expansion around $X=X_{DE}>0$ $(\alpha_1, \alpha_2, \alpha_3,\ldots)$

Dark energy

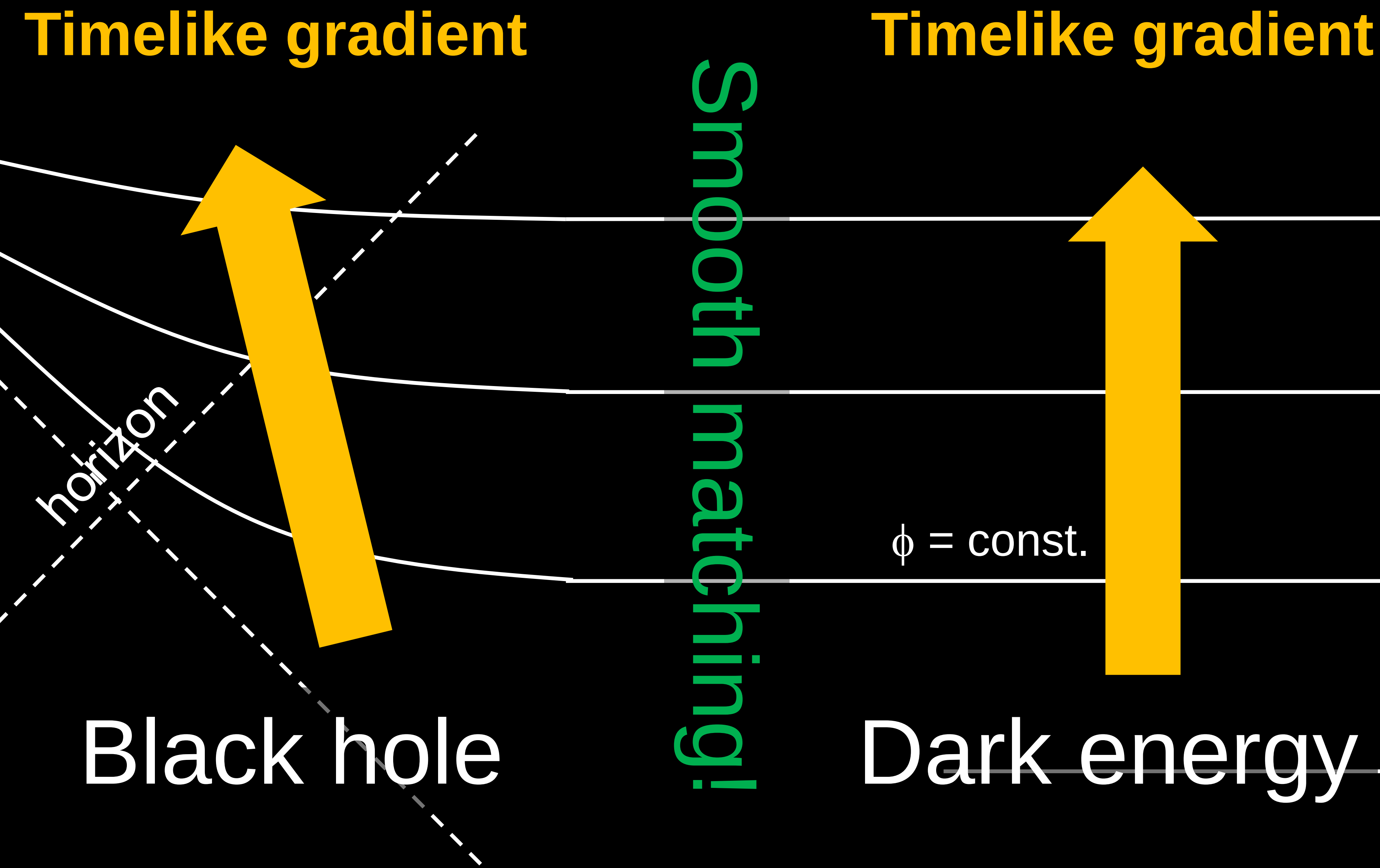

Unlucky case
Spacelike gradient
$G_n(X)$
$X = -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$
const.
EFT2
$(\beta_1, \beta_2, \beta_3, \ldots)$
Black hole
No direct relation
between EFT1 & EFT2
Timelike gradient
$G_n(X)$
$X = -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$
EFT1
$(\alpha_1, \alpha_2, \alpha_3, \ldots)$
Dark energy

Lucky case


Timelike gradient
horizon
Black hole


Timelike gradient
ϕ = const.
Dark energy

Lucky case



Timelike gradient
Timelike gradient
Smooth matching!
horizon
ϕ = const.
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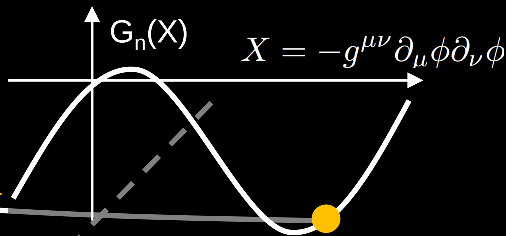
Lucky case

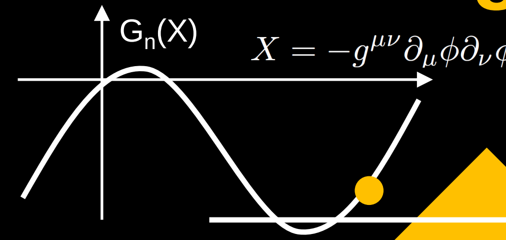
Timelike gradient



Taylor expansion around $X=X_{BH}>0$
$(\alpha'_1, \alpha'_2, \alpha'_3, \ldots)$

Black hole

Timelike gradient

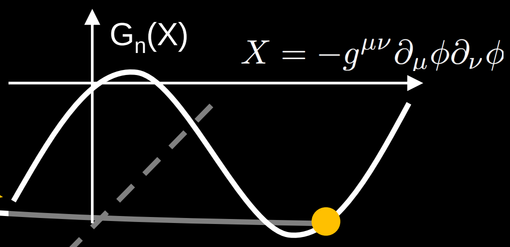


Taylor expansion around $X=X_{DE}>0$
$(\alpha_1, \alpha_2, \alpha_3, \ldots)$

Dark energy

Lucky case

Timelike gradient

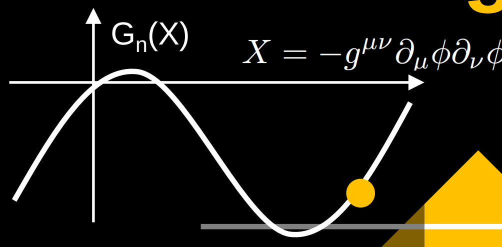


EFT

$(\alpha_1(t,\mathbf{x}^i),\ \alpha_2(t,\mathbf{x}^i),\ \alpha_3(t,\mathbf{x}^i),\ldots)$

Black hole

Timelike gradient



EFT

$(\alpha_1(t,\mathbf{x}^i),\ \alpha_2(t,\mathbf{x}^i),\ \alpha_3(t,\mathbf{x}^i),\ldots)$

~~Dark energy~~

Stealth solutions in k-essence

Mukohyama 2005

- Action in Einstein frame

$$I = \int d^4x\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + P(X)\right] \qquad X = -g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

- EOMs

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}P'(X)g^{\mu\nu}\partial_\nu\phi\right) = 0$$

$$M_{\rm Pl}^2 G_{\mu\nu} = 2P'(X)\partial_\mu\phi\partial_\nu\phi + P(X)g_{\mu\nu}$$

- Stealth sol with $X = X_0$, where $P'(X_0)=0$

$$G_{\mu\nu} = \Lambda_{\rm eff}\, g_{\mu\nu} \qquad \Lambda_{\rm eff} = P(X_0)/M_{\rm Pl}^2$$

- $X = X_0$ ($\neq 0$)

⟺ $u^\mu = g^{\mu\nu}\partial_\nu\phi$ defines geodesic congruence

$$(u^\nu\nabla_\nu u^\mu = -\nabla^\mu X/2 = 0)$$

⟺ $\phi/\sqrt{|X_0|}$ **defines Gaussian normal coord.**

Stealth solutions with $\phi = qt+\psi(r)$

- Schwarzschild in k-essence (Mukohyama 2005)
- Schwarzschild-dS in Horndeski theory (Babichev & Charmousis 2013, Kobayashi & Tanahashi 2014) Schwarzshild-dS in DHOST (Ben Achour & Liu 2019, Motohashi & Minamitsuji 2019)
- Kerr-dS in DHOST (Charmousis & Crisotomi & Gregory & Stergioulas 2019)
- However, perturbations around most of those stealth solutions are infinitely strongly coupled (de Rham & Zhang 2019) . This means the solutions cannot be trusted.
- Fortunately, Scordatura (= detuning of degeneracy condition) solves the strong coupling problem (Motohashi & Mukohyama 2019), if and only if the scalar profile is timelike.
- EFT of ghost condensation already includes scordatura (Arkani-Hamed & Cheng & Luty & Mukohyama 2004)
- Approximate Schwarzschild in ghost condensation (Mukohyama 2005). Also in quadratic HOST (DeFelice & Mukohyama & Takahashi, JCAP 03 (2023) 050).

- Cosmology and black holes (BHs) play as important roles in gravitational physics as blackbody radiation and hydrogen atoms did in quantum mechanics.
- In cosmology a time-dependent scalar field can act as dark energy (DE), while BHs serve as probes of strong gravity. We then hope to learn something about the EFT of DE by BHs.
- This would require **the scalar field profile to be timelike near BH**. Otherwise, the two EFTs, one for DE and the other for BH, can be unrelated to each other (unless a UV completion is specified).

EFT of scalar-tensor gravity on arbitrary background with timelike scalar profile

EFT of scalar-tensor gravity with timelike scalar profile

- **Time diffeo is broken by the scalar profile but spatial diffeo is preserved.**
- All terms that respect spatial diffeo must be included in the EFT action.
- Derivative & perturbative expansions
- Diffeo can be restored by introducing NG boson

EFT on Minkowski background = ghost condensation
Arkani-Hamed, Cheng, Luty and Mukohyama, JHEP 0405:074,2004

EFT on cosmological background = EFT of inflation/dark energy
Creminelli, Luty, Nicolis and Senatore 2006
Cheung, Creminelli, Fitzpatrick, Kaplan and Senatore 2007

EFT on arbitrary background = EFT of BH perturbations
Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

Taylor expansion of the general action
$$S = \int d^4x\sqrt{-g}\; F(R_{\mu\nu\alpha\beta}, g^{\tau\tau}, K_{\mu\nu}, \nabla_\nu, \tau)$$

$$S = \int d^4x\sqrt{-g}\left[\bar{F} + \bar{F}_{g^{\tau\tau}}\delta g^{\tau\tau} + \bar{F}_K\delta K + \quad \ldots\right]$$

Consistency relations ⬅ S is invariant under spatial diffeo but the background breaks it.

$$\frac{d}{dx^i}\bar{F} = \bar{F}_{g^{\tau\tau}}\frac{\partial \bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_K\frac{\partial \bar{K}}{\partial x^i} + \ldots$$

Applications to BHs with timelike scalar profile

- Background analysis for spherical BH
  [arXiv: 2204.00228 w/ V.Yingcharoenrat]
- Odd-parity perturbation around spherical BH
  → Generalized Regge-Wheeler equation
  [arXiv: 2208.02943 w/ K.Takahashi & V.Yingcharoenrat]
  [see also arXiv: 2208.02823 by Khoury, Noumi, Trodden, Wong]
  → Quasi-normal mode
  [arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
- Even-parity perturbation around spherical BH
  [work in progress w/ K.Takahashi & V.Yingcharoenrat]
- Tidal Love number of spherical BH
  [work in progress w/ C.GharibAliBarura & H.Kobayashi & N.Oshita & K.Takahashi & V.Yingcharoenrat]
- Future works include Rotating BH, BH with scalar accretion
  [c.f. arXiv:1304.6287 by Chadburn & Gregory; arXiv:1804.03462 by Gregory, Kastor & Traschen], BH formation, etc…

EFT of scalar-tensor gravity with timelike scalar profile

1. Introduction
2. EFT on Minkowski bkgd
3. EFT on cosmological bkgd
4. EFT on arbitrary bkgd
5. Applications
6. Summary

SUMMARY

- Ghost condensation universally describes all scalar-tensor theories of gravity with timelike scalar profile on Minkowski background respecting time translation / reflection symmetry (up to shift / reflection of the scalar).
- Extension of ghost condensation to FLRW backgrounds results in the EFT of inflation/DE.
- These EFTs provide universal descriptions of all scalar-tensor theories of gravity with timelike scalar profile on each background, including Horndeski theory, DHOST theory, U-DHOST theory, and more.

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- If we want to learn something about the EFT of DE from BH then we need to consider BH solutions with timelike scalar profile.
- EFT of scalar-tensor gravity with timelike scalar profile on arbitrary background was developed. Consistency relations among EFT coefficients ensure the spatial diffeo invariance. Applicable to BHs with scalar field DE.

EFT of scalar-tensor gravity with timelike scalar profile

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- All terms that respect spatial diffeo must be included in the EFT action.
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Taylor expansion of the general action $S = \int d^4x \sqrt{-g}\, F(R_{\mu\nu\alpha\beta}, g^{\tau\tau}, K_{\mu\nu}, \nabla_\nu, \tau)$

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- Other applications? Further extensions?

Further extension of the web of EFTs

"The Effective Field Theory of Vector-Tensor Theories"
Katsuki Aoki, Mohammad Ali Gorji, Shinji Mukohyama, Kazufumi Takahashi, , JCAP 01 (2022) 01, 059 [arXiv: 2111.08119].

Residual symmetry in the unitary gauge

$$\vec{x} \to \vec{x}'(t, \vec{x})$$

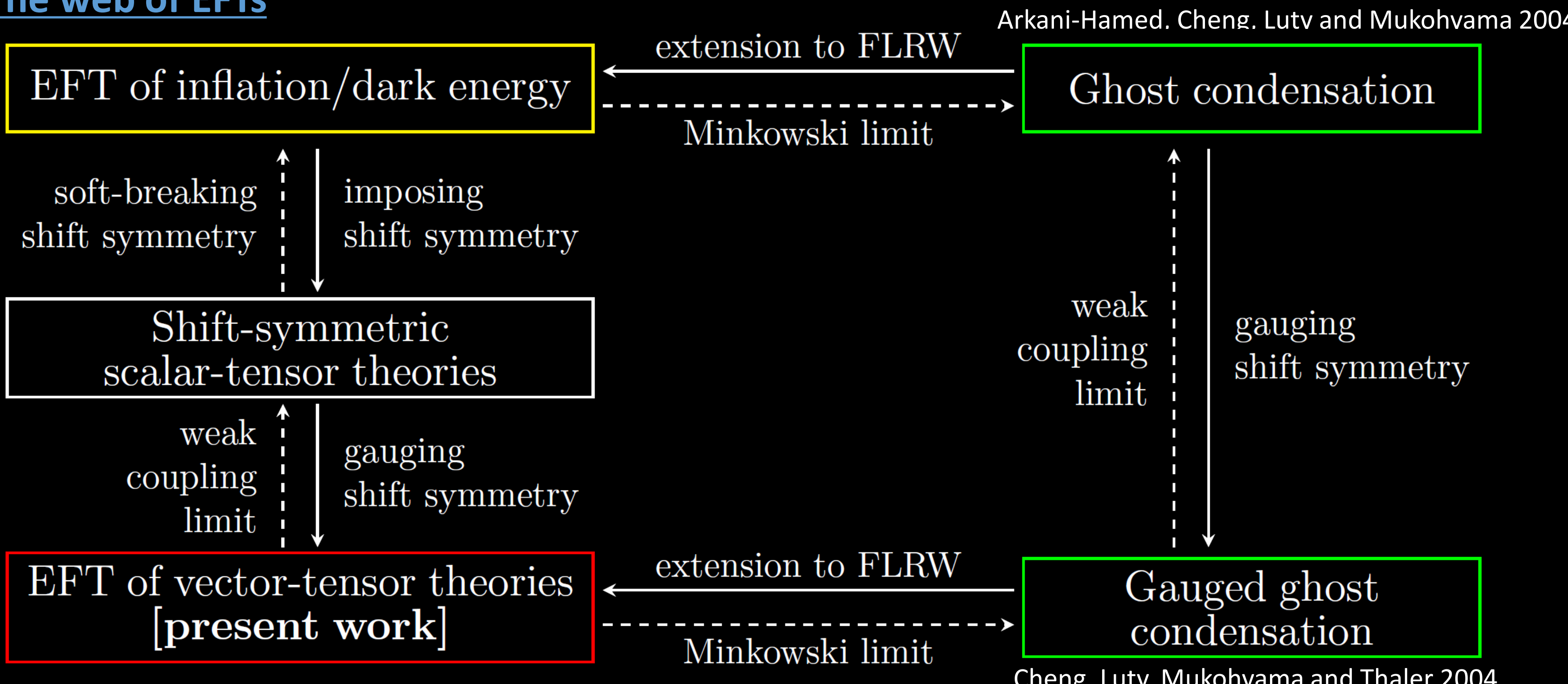
$$t \to t - g_M \chi(x)\,, \quad A_\mu \to A_\mu + \partial_\mu \chi(x)$$

leaving $\tilde{\delta}^0{}_\mu = \delta^0{}_\mu + g_M A_\mu$ invariant

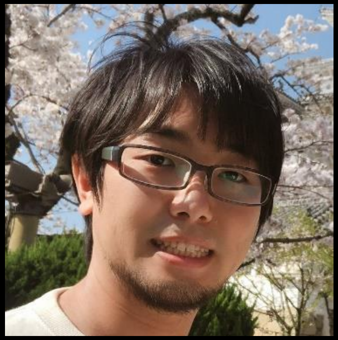
c.f. Residual symmetry in unitary gauge for scalar-tensor theories

$$\vec{x} \to \vec{x}'(t, \vec{x})$$

The web of EFTs



Thank you!



K.Aoki

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K.Tomikawa

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Also
Arkani-Hamed, Cheng, Luty and Mukohyama 2004 (hep-th/0312099)
Mukohyama 2005 (hep-th/0502189)

COSMO'24

Oct 21 - 25, 2024 | Kyoto University

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The clock tower in the main campus of Kyoto University, Japan.

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https://sites.google.com/view/cosmo2024/home