Gravity beyond General Relativity

Shinji Mukohyama
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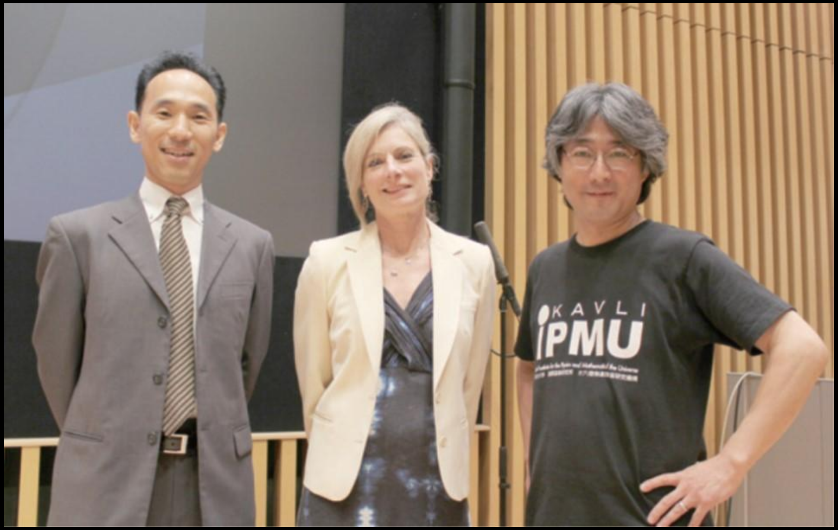
Thank you very much, Hitoshi!

- I was a member of IPMU from April 2008 to September 2014, when Hitoshi was the director.
- Hitoshi made IPMU a wonderful place for all members. I had a very good time.
- Hitoshi at that time was younger than I am now. This makes me think again of his greatness.
- I sincerely appreciate his efforts and kindness.

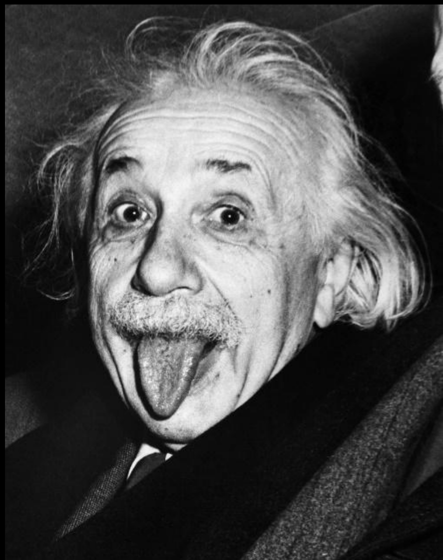


Happy 60th Birthday!

Why gravity beyond GR?

(GR : general relativity)

- Challenging **mysteries in the universe**
  Dark energy, dark matter, inflation, big-bang singularity, cosmic magnetic field and tensions
- Necessary for **quantum gravity**
  Superstring, Horava-Lifshitz, etc.
- **Testing GR**
  One of the best ways to test GR is to make predictions and to compare them with observations/experiments.
- …



Some examples (my personal experiences)

I. Effective field theory (EFT) approach
IR modification of gravity
motivation: dark energy/inflation, universality

II. Massive gravity
IR modification of gravity
motivation: "Can graviton have mass?" & dark energy

III. Minimally modified gravity
IR modification of gravity
motivation: tensions in cosmology, various constraints

IV. Horava-Lifshitz gravity
UV modification of gravity
motivation: quantum gravity

V. Superstring theory
UV modification of gravity
motivation: quantum gravity, unified theory

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Collaborators


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K.Takahashi


K.Tomikawa


K.Aoki


E.Seraille


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H.Kobayashi


N.Oshita

Ref.

arXiv: 2204.00228 w/ V.Yingcharoenrat
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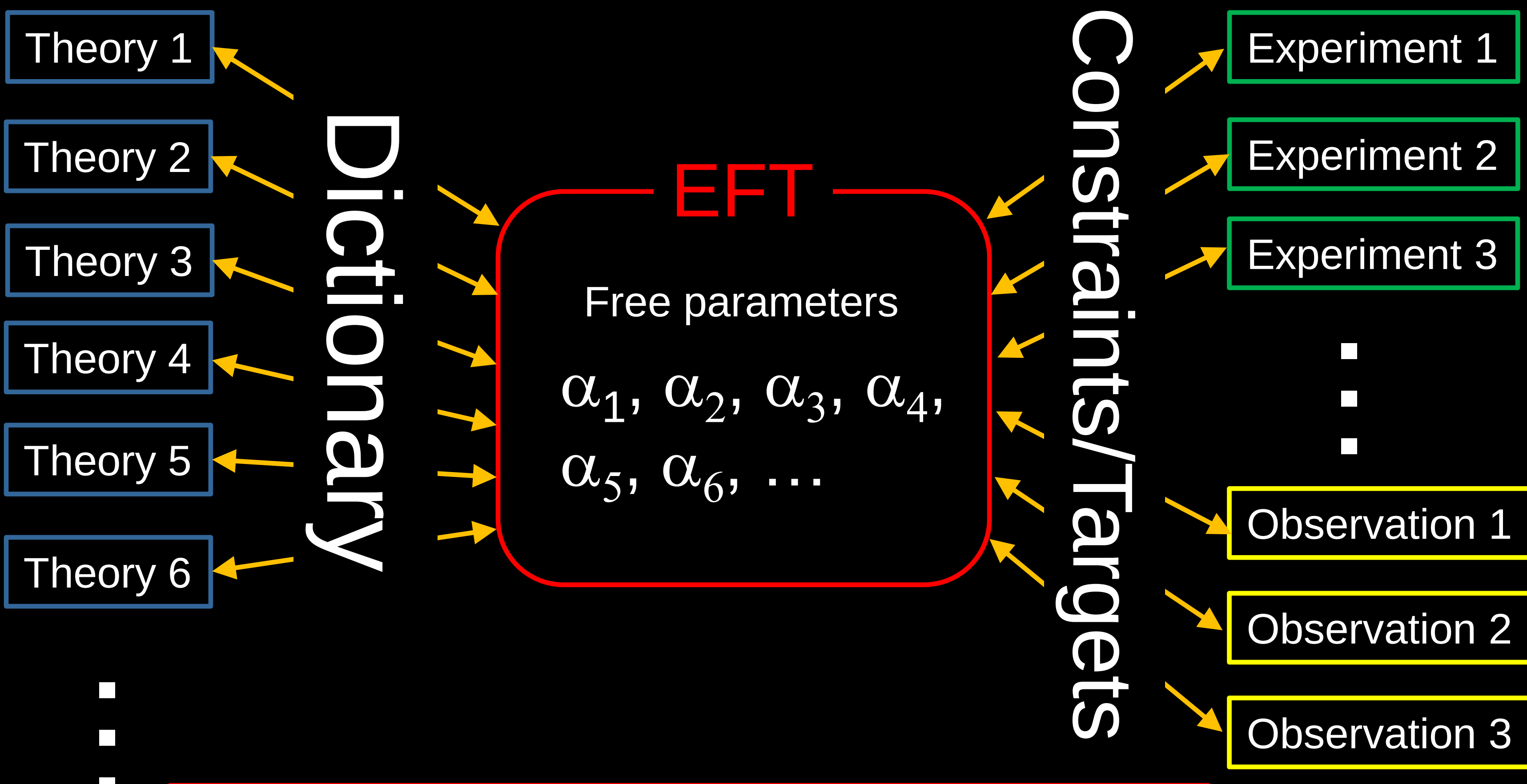
Also

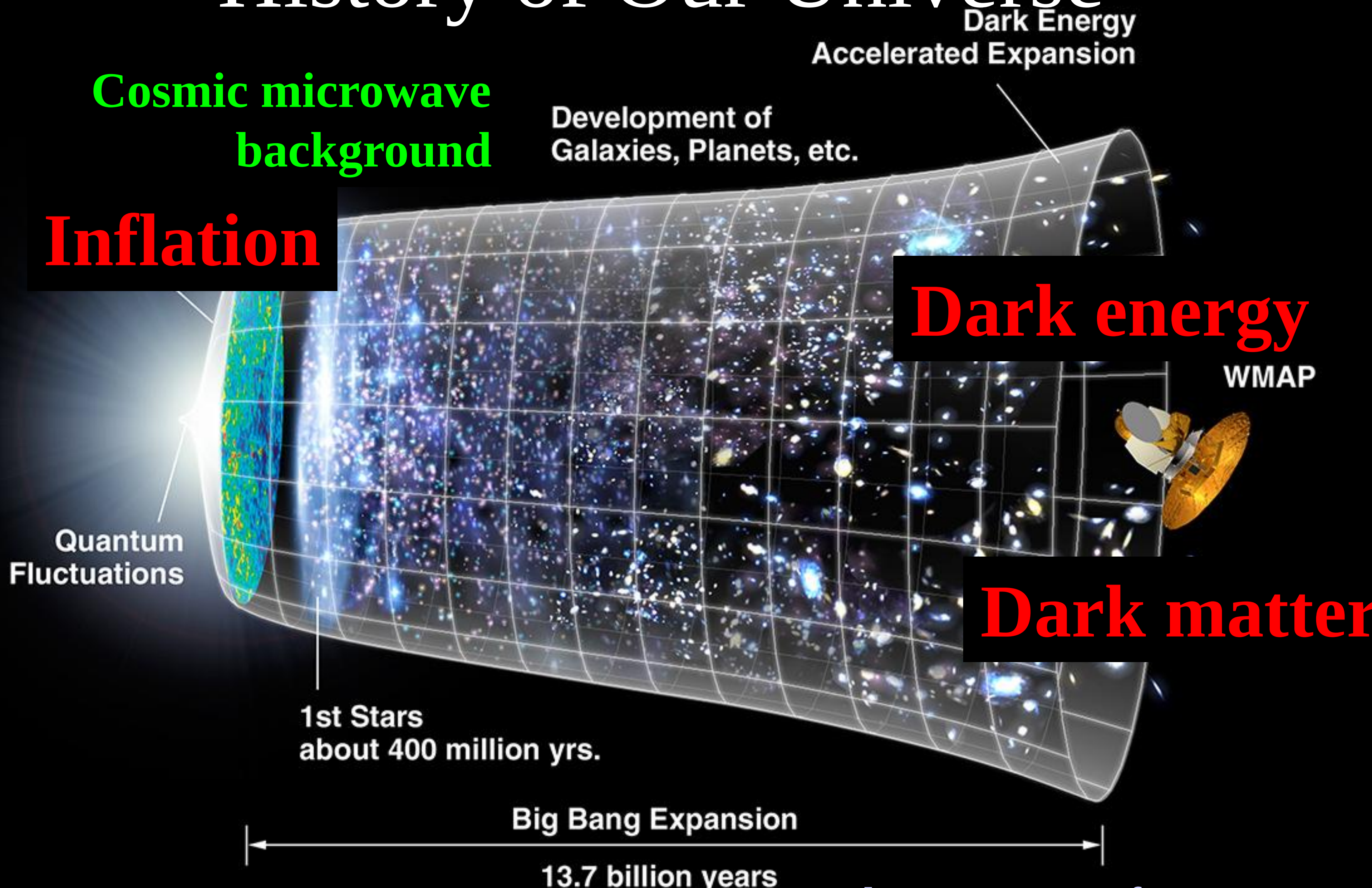
Arkani-Hamed, Cheng, Luty and Mukohyama 2004 (hep-th/0312099)
Mukohyama 2005 (hep-th/0502189)

Effective field theory (EFT) approach



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

History of Our Universe



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

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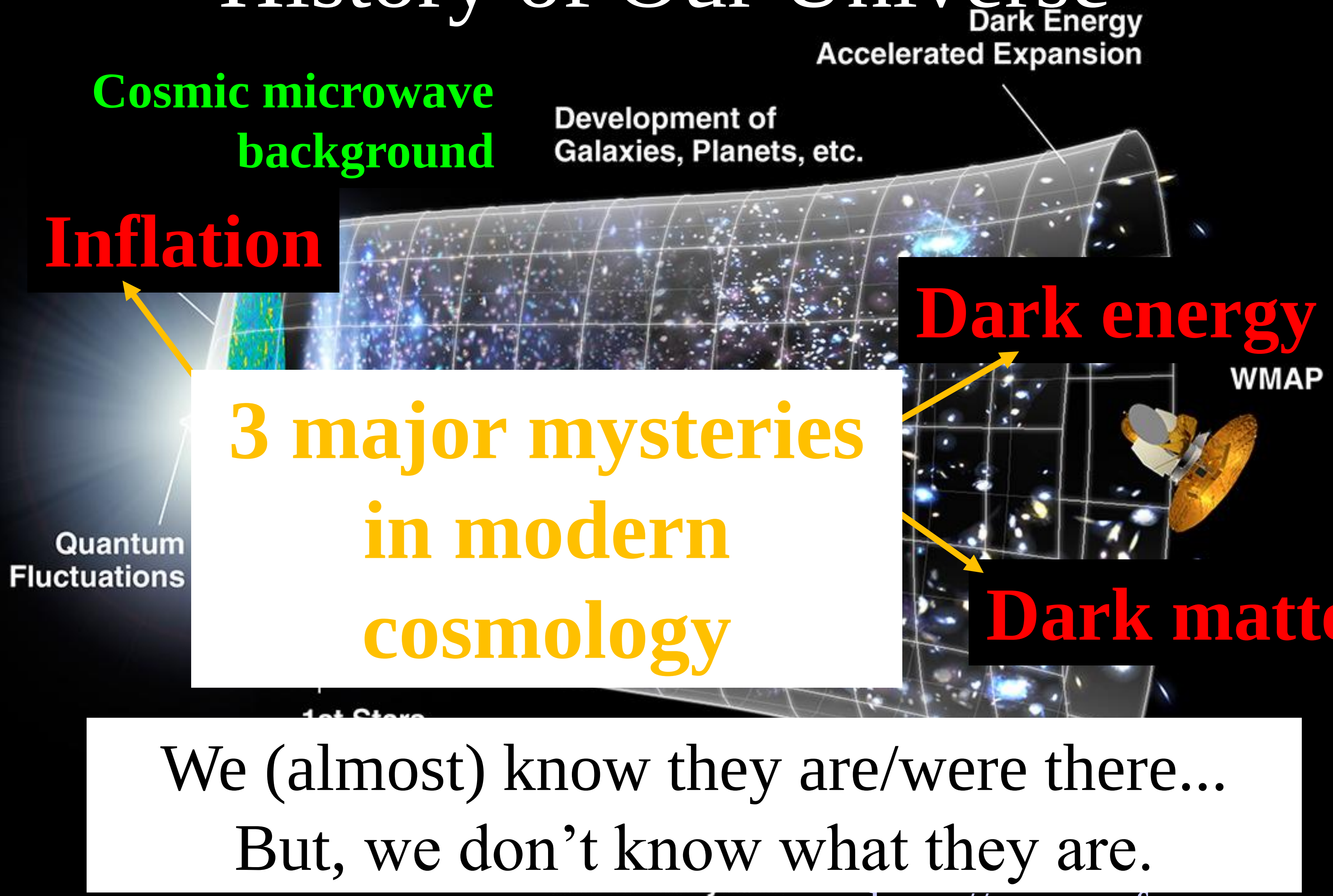


Cosmic microwave background

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.

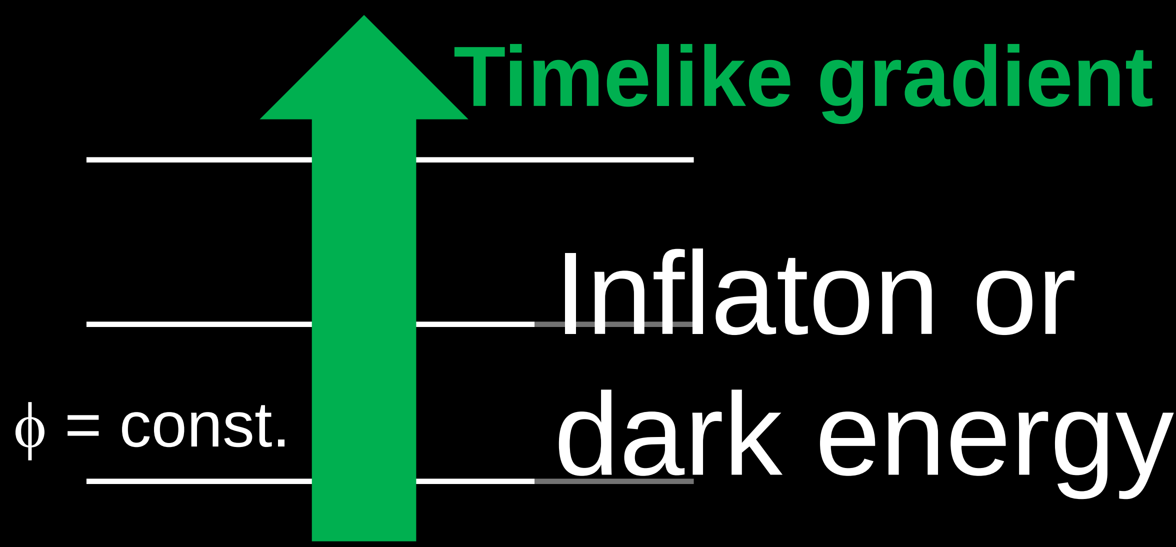
http://map.gsfc.nasa.gov/

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

EFT of scalar-tensor gravity with timelike scalar profile

- Scalar-tensor gravity contains majority of inflation & dark energy models
- Inflaton/dark energy has timelike derivative
- Time diffeo is broken by the scalar profile but spatial diffeo is preserved.



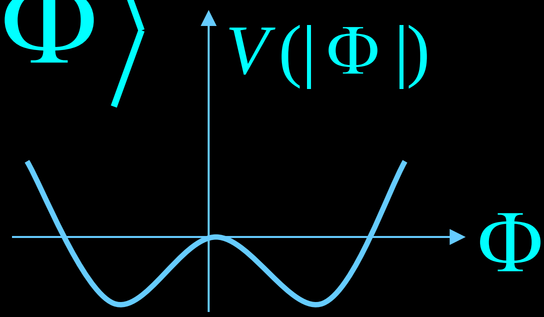
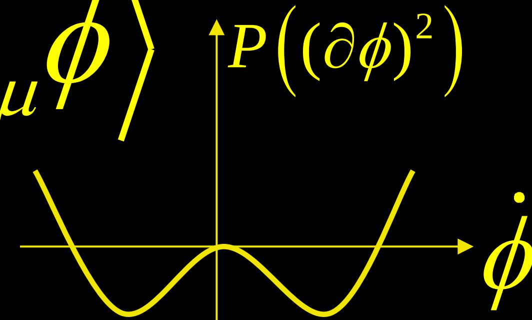
EFT of scalar-tensor gravity with timelike scalar profile

- **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

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

Gauge choice: $\phi(t,\vec{x}) = t.$ $\pi \equiv \delta\phi = 0$

(Unitary gauge)

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

➡ Write down most general action invariant under this residual symmetry.

(➡ Action for π: undo unitary gauge!)

Start with flat background $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$

$$\delta h_{\mu\nu} = \partial_\mu \xi_\nu + \partial_\nu \xi_\mu$$

Under residual ξ^i

$$\delta h_{00} = 0, \delta h_{0i} = \partial_0 \xi_i, \delta h_{ij} = \partial_i \xi_j + \partial_j \xi_i$$

Action invariant under ξ^i

$$\begin{cases} (h_{00})^2 & \textbf{OK} \\ (h_{0i})^2 & \\ K^2, K^{ij}K_{ij} & \textbf{OK} \end{cases}$$

Beginning at quadratic order, since we are assuming flat space is good background.

$$K_{ij} = \frac{1}{2}\left(\partial_0 h_{ij} - \partial_j h_{0i} - \partial_i h_{0j}\right)$$

$$\Rightarrow \quad L_{eff} = L_{EH} + M^4\left\{(h_{00})^2 - \frac{\alpha_1}{M^2}K^2 - \frac{\alpha_2}{M^2}K^{ij}K_{ij} + \cdots\right\}$$

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Action for π

$$\xi^0 = \pi \quad \begin{cases} h_{00} \to h_{00} - 2\partial_0 \pi \\ K_{ij} \to K_{ij} + \partial_i \partial_j \pi \end{cases}$$

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

$$E \to rE$$

$$dt \to r^{-1} dt$$

$$dx \to r^{-1/2} dx$$

$$\pi \to r^{1/4} \pi$$

Make invariant ⇒ $\int dt d^3x \left[\frac{1}{2} \dot{\pi}^2 - \frac{\alpha (\vec{\nabla}^2 \pi)^2}{M^2} + \cdots \right]$

Leading nonlinear operator in infrared $\int dt d^3x \frac{\dot{\pi} (\nabla \pi)^2}{\tilde{M}^2}$

has scaling dimension 1/4. **(Barely) irrelevant**

⇒ Good low-E effective theory
Robust prediction

e.g. Ghost inflation [Arkani-hamed, Creminelli, Mukohyama, Zaldarriaga 2004]

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

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

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

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

→ 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

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

2 types of 3-point interactions

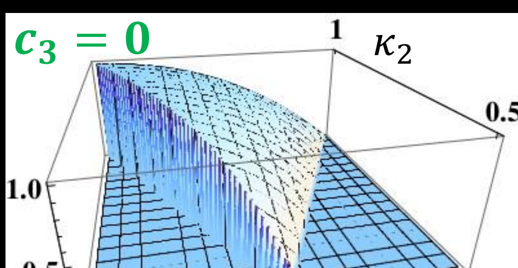
c_s^2 → size of non-Gaussianity

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

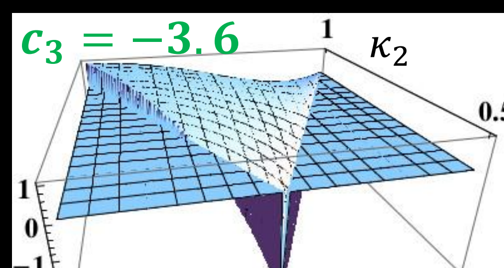
$$f_{NL}^{\dot{\pi}(\partial_i\pi)^2} = \frac{85}{324}\left(1 - \frac{1}{c_s^2}\right) \qquad f_{NL}^{\dot{\pi}^3} = \frac{5c_3}{81}\left(1 - \frac{1}{c_s^2}\right) \qquad \propto \frac{1}{c_s^2} \text{ for small } c_s^2$$

c_3 → shape of non-Gaussianity

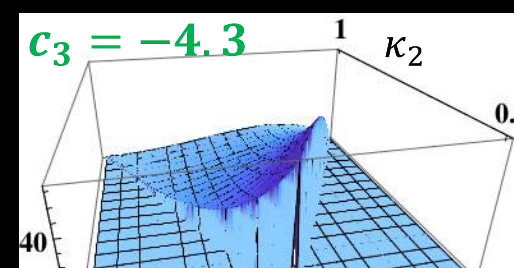
plots of $B_\zeta(k, \kappa_2 k, \kappa_3 k)/B_\zeta(k, k, k)$



Prototype of the equilateral shape



Prototype of the orthogonal shape



Linear combination of the two shapes

Parametrization tailored to 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. Otherwise, the basic construction is the same as EFT of inflation.
- Implemented in Boltzmann codes, e.g. EFTCAMB [Hu, Raveri, Frusciante, Silvestri 2014].
- Constraint on c_{GW} by GW170817 imposed [Creminelli and Vernizzi 2017, Ezquiaga and Zumalacárregui 2017] .
- Will be used to interpret data from future observations.

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- Majorities of inflation/DE models are described by scalar-tensor gravity with timelike scalar profile.
- Ghost condensation universally describes all scalar-tensor 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. They have been used to interpret observational data. Adopted by e.g. ESA's Planck team.

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Of course, this is not the end of the story!

- Extension of ghost condensation to FLRW backgrounds results in the EFT of inflation/DE. They have been used to interpret observational data. Adopted by e.g. ESA's Planck team.

Extension of EFT of inflation/DE to arbitrary background

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EFT on arbitrary background	= EFT of black hole perturbation with timelike scalar profile Mukohyama and Yingcharoenrat, JCAP 09 (2022) 010

- EFT of scalar-tensor gravity with timelike scalar profile on arbitrary background was developed.
- Can describe all scalar-tensor gravity with timelike scalar profile.
- Applied to black holes in the presence of dark energy.

It was not straightforward…

- General action in the unitary gauge ($\phi = \tau$)

$$S = \int d^4x \sqrt{-g}\, F(R_{\mu\nu\alpha\beta}, g^{\tau\tau}, K_{\mu\nu}, \nabla_\nu, \tau)$$

- Taylor expansion around the background

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

- The whole action is invariant under 3d diffeo but **each term is not…**
- Each coefficient is a function of (τ, x^i) but cannot be promoted to an arbitrary function.

Solution: consistency relations

- The chain rule

$$\begin{cases} \dfrac{d}{dx^i}\bar{F} = \bar{F}_{g^{\tau\tau}}\dfrac{\partial \bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_K \dfrac{\partial \bar{K}}{\partial x^i} + \dots \\ \dfrac{d}{dx^i}\bar{F}_{g^{\tau\tau}} = \bar{F}_{g^{\tau\tau}g^{\tau\tau}}\dfrac{\partial \bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_{g^{\tau\tau}K} \dfrac{\partial \bar{K}}{\partial x^i} + \dots \\ \dfrac{d}{dx^i}\bar{F}_K = \bar{F}_{g^{\tau\tau}K}\dfrac{\partial \bar{g}^{\tau\tau}}{\partial x^i} + \bar{F}_{KK} \dfrac{\partial \bar{K}}{\partial x^i} + \dots \end{cases}$$

  relates x^i-derivatives of an EFT coefficient to other EFT coefficients, and leads to consistency relations.

- **The consistency relations ensure the spatial diffeo invariance.**
- Taylor coefficients should satisfy the consistency relations but are otherwise arbitrary.
- (No consistency relation for τ-derivatives.)

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 modes deviate from GR
  [arXiv: 2304.14304 w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
  → Static Tidal Love numbers are non-vanishing
  [arXiv: 2405.10813 w/C.G.A.Barura, H.Kobayashi, N.Oshita, K.Takahashi, V.Yingcharoenrat]
  → (In)stability of greybody factors
  [arXiv: 2406.04525 w/N.Oshita and K.Takahashi]
- Even-parity perturbation around spherical BH
  [work in progress w/ K.Takahashi & K.Tomikawa & V.Yingcharoenrat]
- Rotating BH
  [work in progress w/ N.Oshita & K.Takahashi & Z.Wang & V.Yingcharoenrat]

Extension of EFT of inflation/DE to arbitrary background

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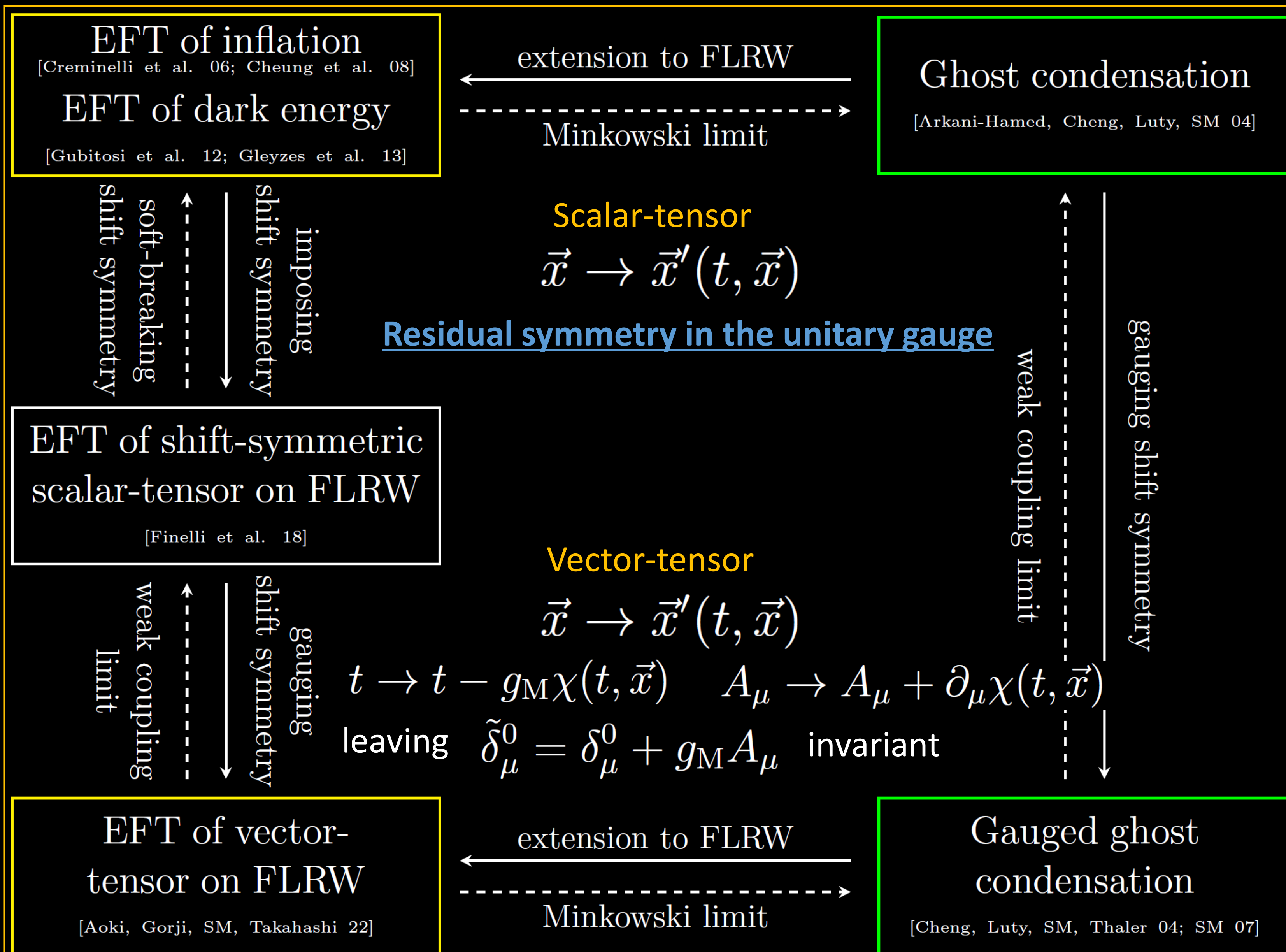
- EFT of scalar-tensor gravity with timelike scalar profile on arbitrary background was developed.
- Can describe all scalar-tensor gravity with timelike scalar profile.
- Applied to black holes in the presence of dark energy.
- Any other applications? Further extensions?

Further extension of the web of EFTs



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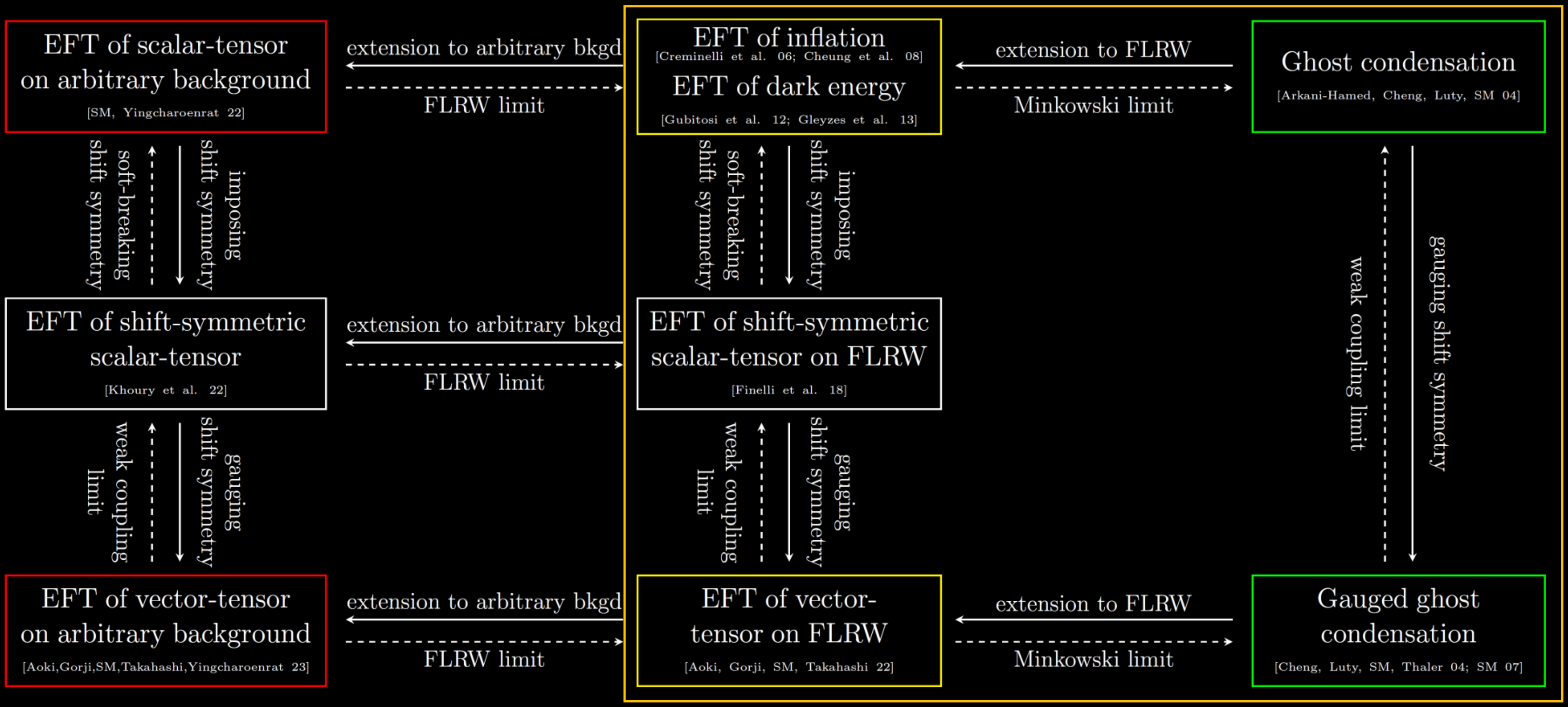


Residual symmetry in the unitary gauge

Scalar-tensor

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

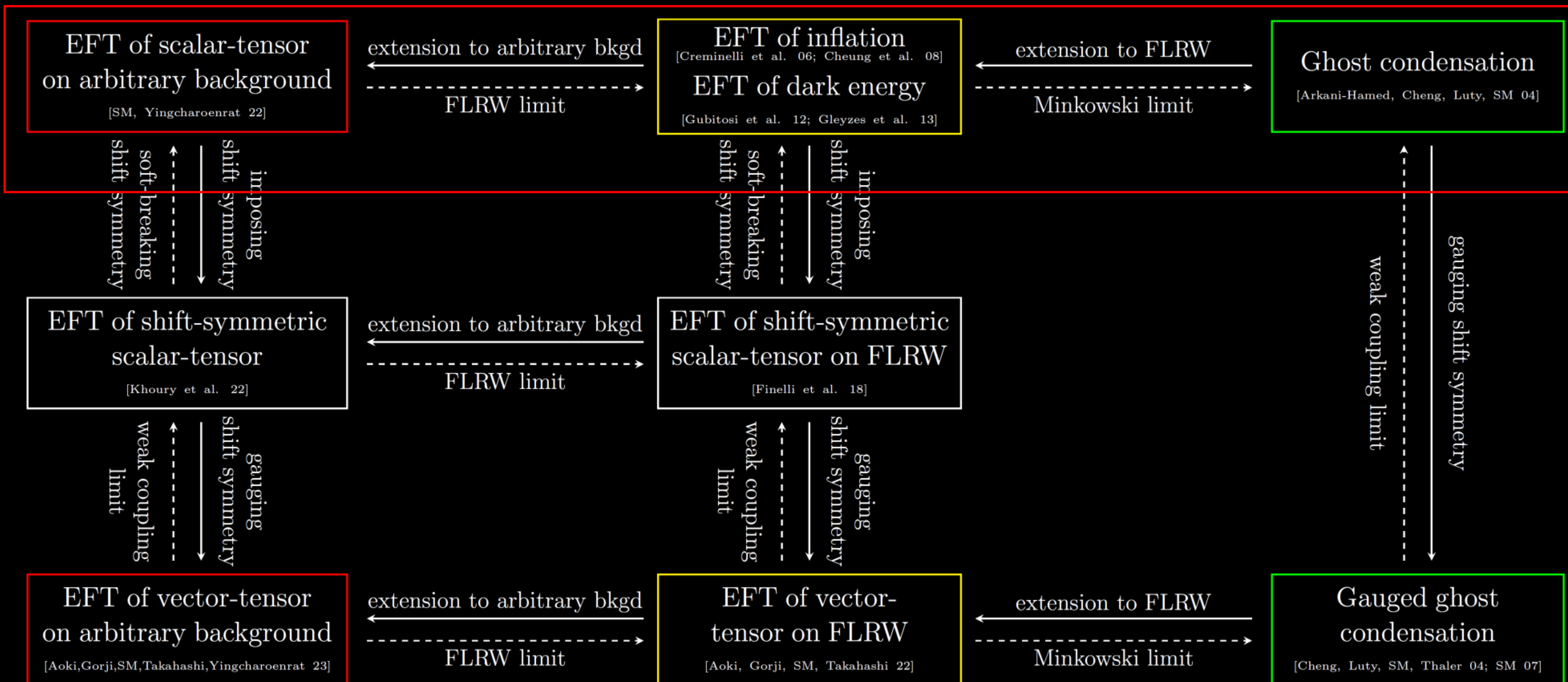
Vector-tensor

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

$$t \to t - g_{\rm M}\chi(t, \vec{x}) \quad A_\mu \to A_\mu + \partial_\mu \chi(t, \vec{x})$$

leaving $\tilde{\delta}^0_\mu = \delta^0_\mu + g_{\rm M} A_\mu$ invariant

Further extension of the web of EFTs



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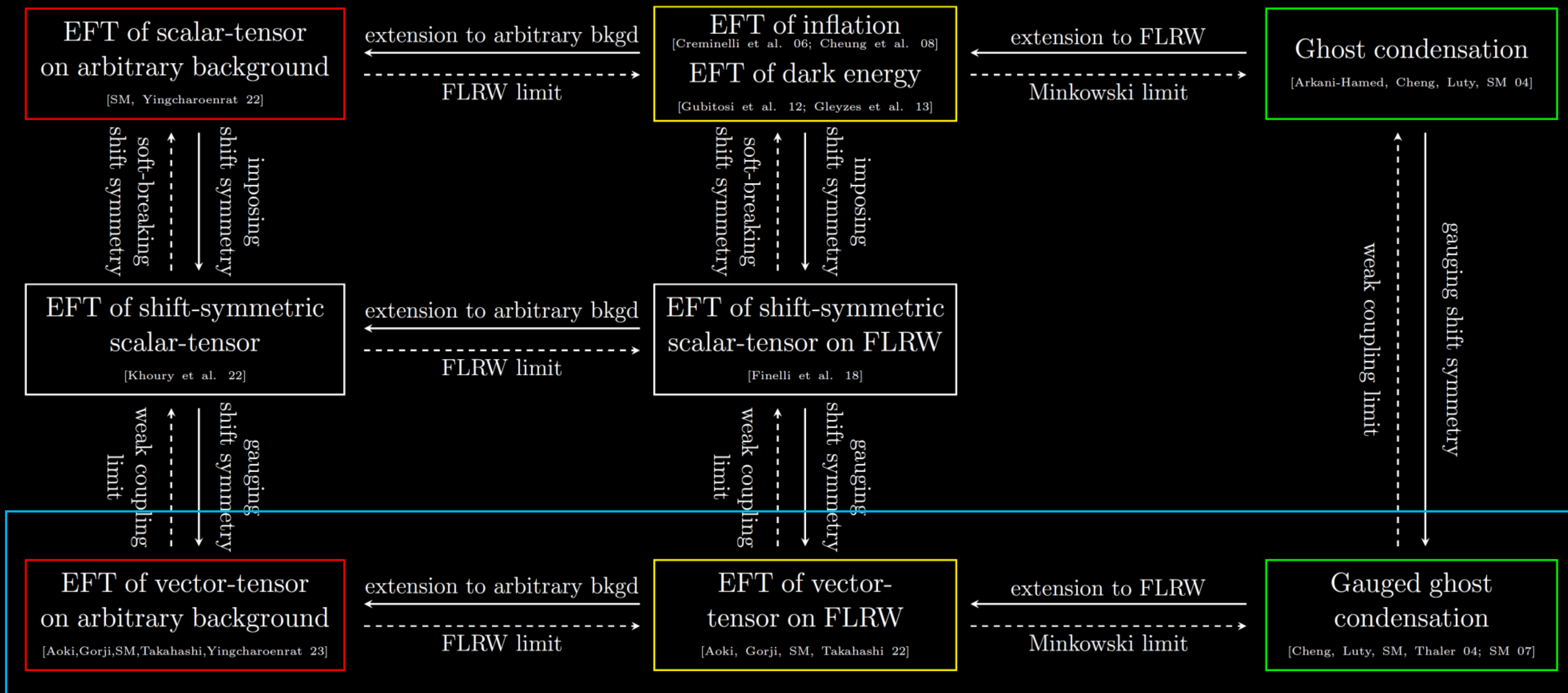

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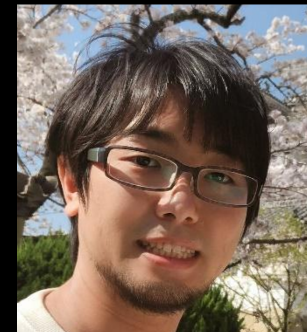
See also "CMB spectrum in unified EFT of dark energy: scalar-tensor and vector-tensor theories", arXiv: 2405.04265

Thank you!


V.Yingcharoenrat


K.Takahashi


K.Tomikawa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scalar-tensor:

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vector-tensor:

~~arXiv: 2111.08119 w/ K.Aoki, M.A.Gorji, K.Takahashi~~
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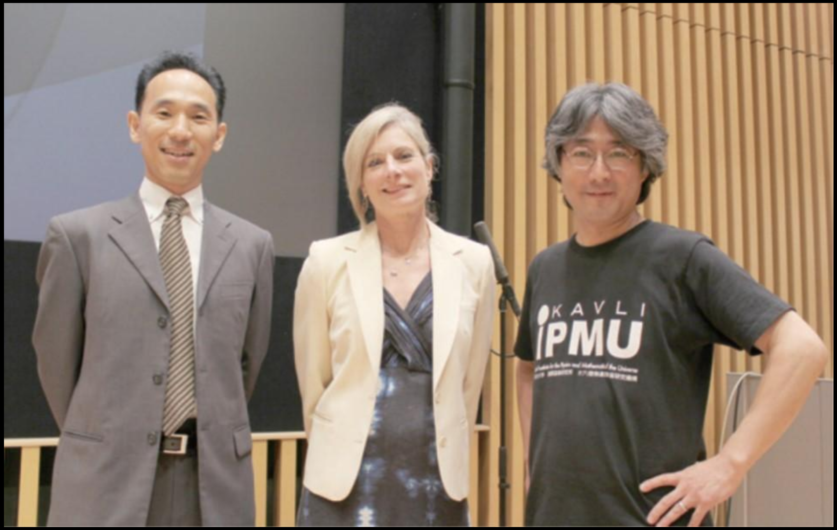
Thank you very much, Hitoshi!

- I was a member of IPMU from April 2008 to September 2014, when Hitoshi was the director.
- Hitoshi made IPMU a wonderful place for all members. I had a very good time.
- Hitoshi at that time was younger than I am now. This makes me think again of his greatness.
- I sincerely appreciate his efforts and kindness.



Happy 60th Birthday!