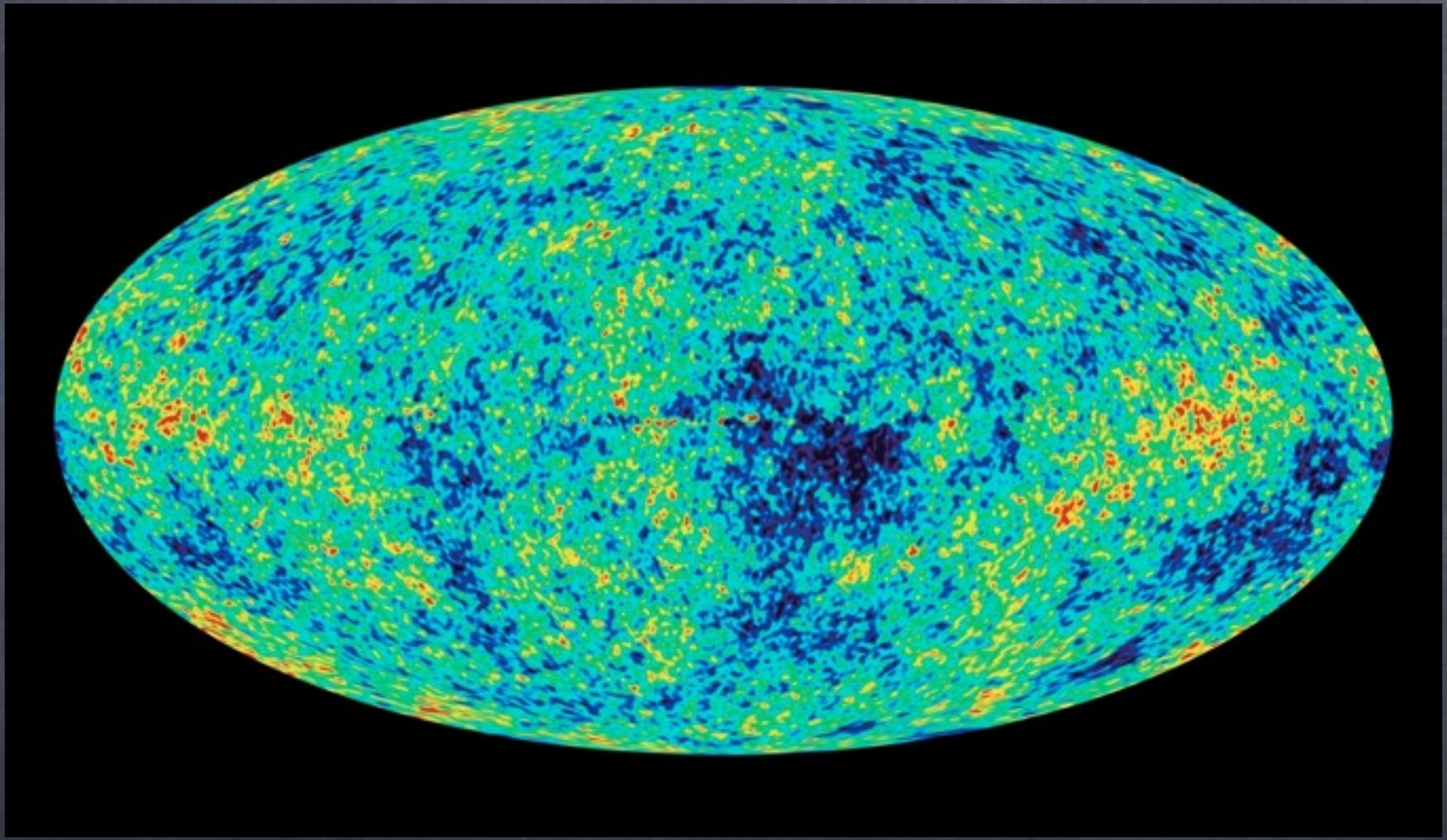
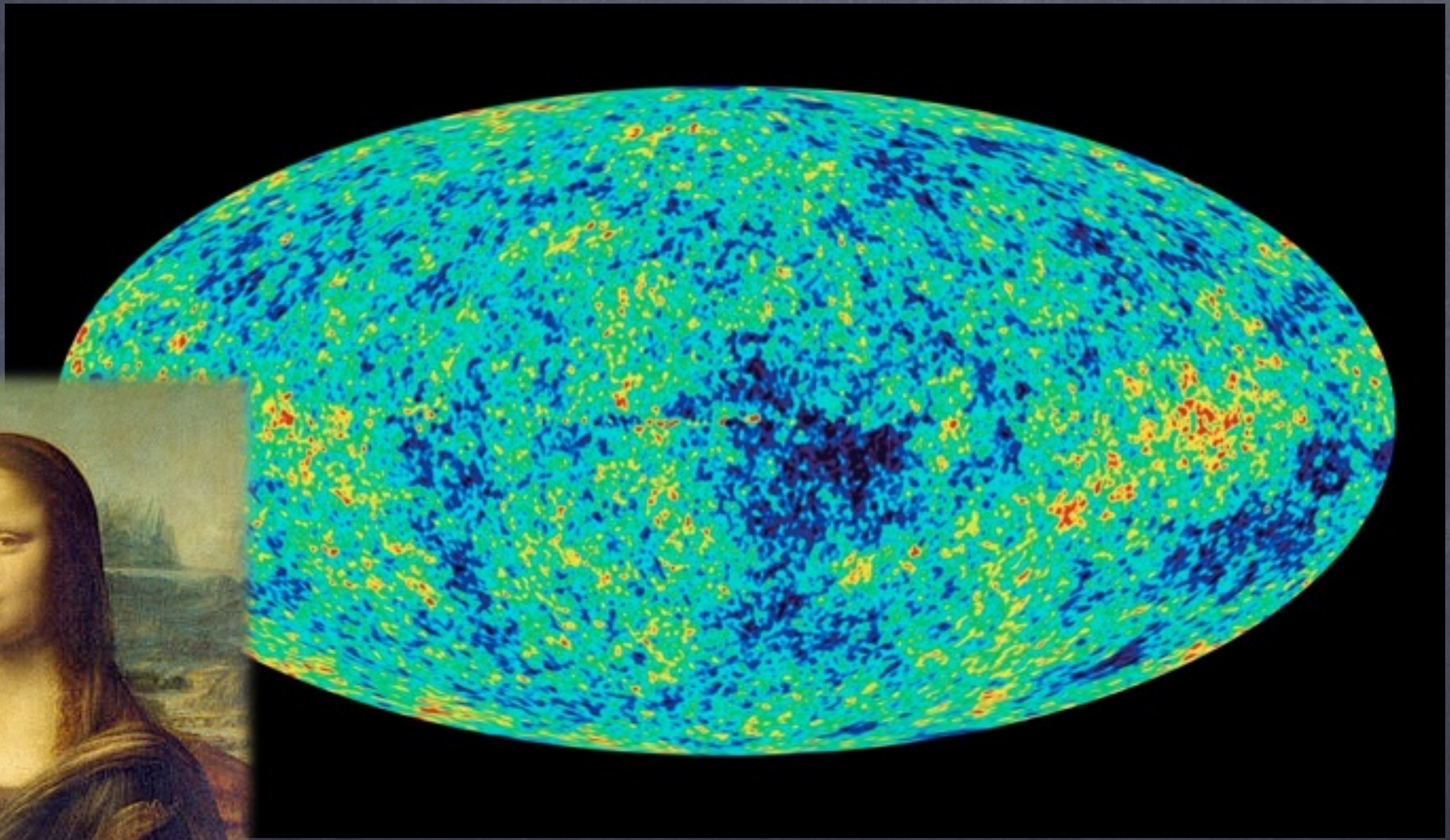
SCUOLA NORMALE SUPERIORE PISA

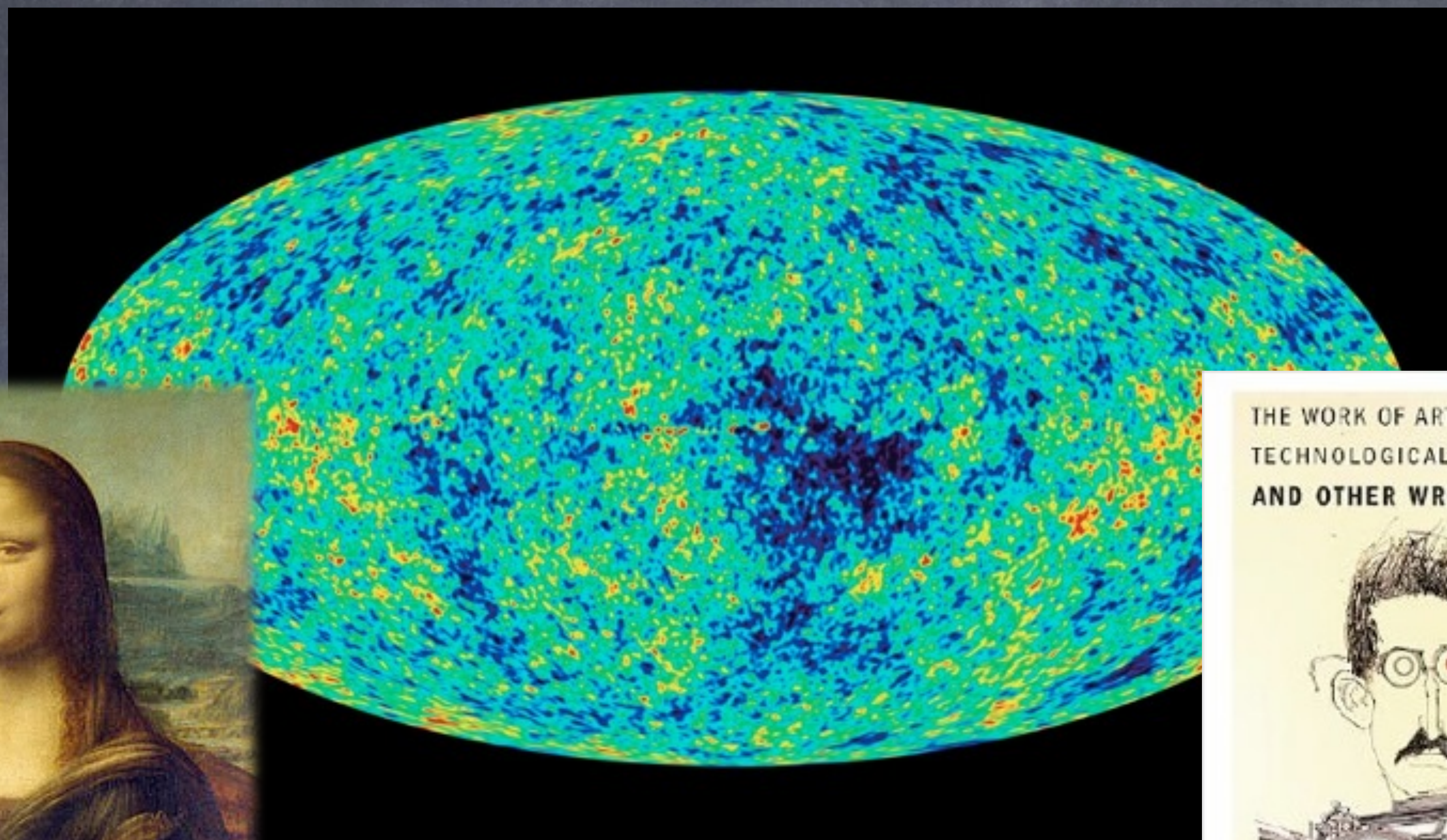
INFN Istituto Nazionale di Fisica Nucleare

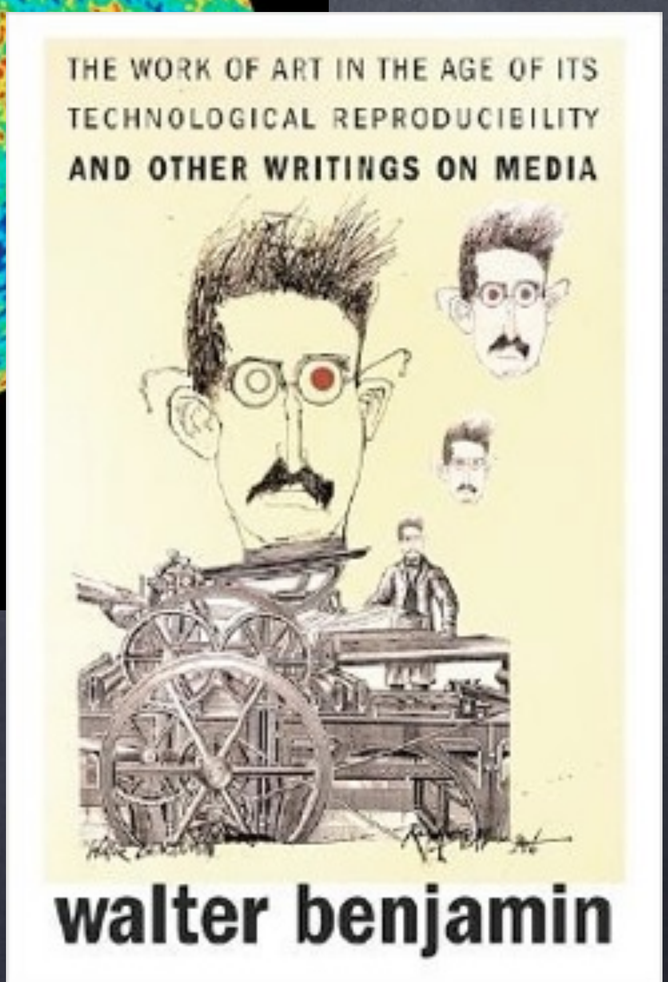
The Universe in the Age of Its Technical Reproducibility

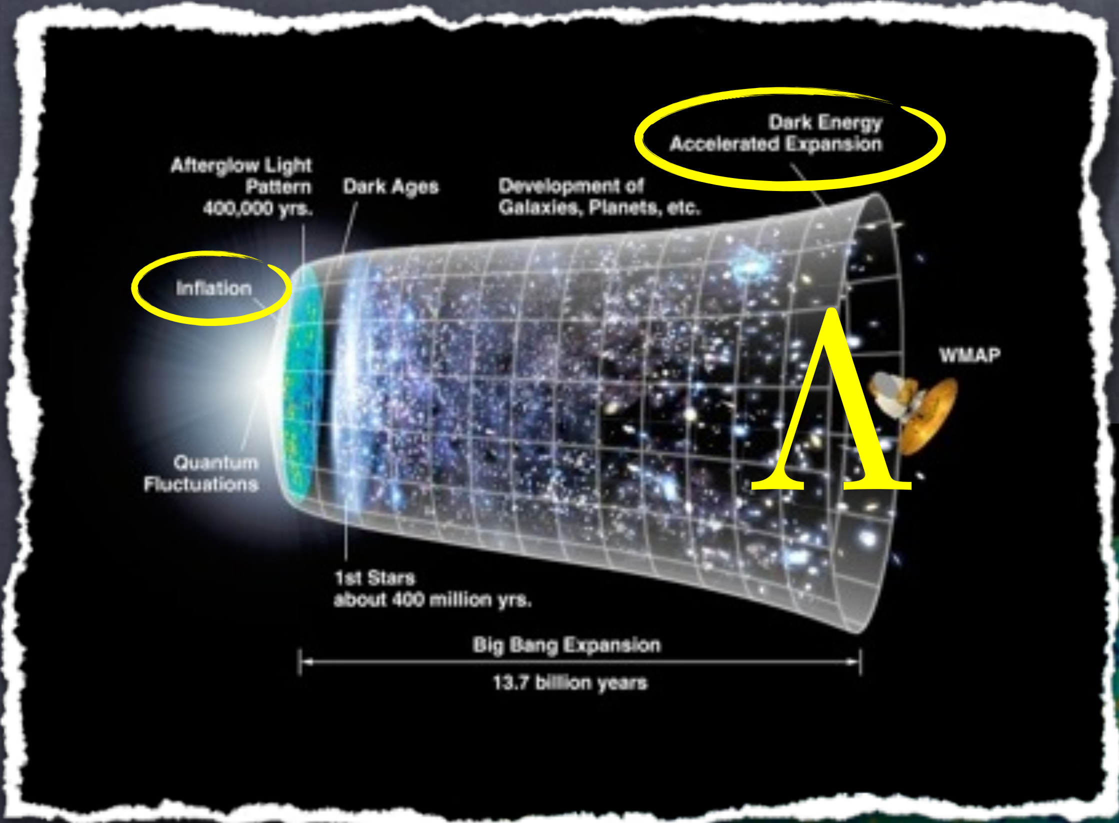
Enrico Trincherini (SNS)

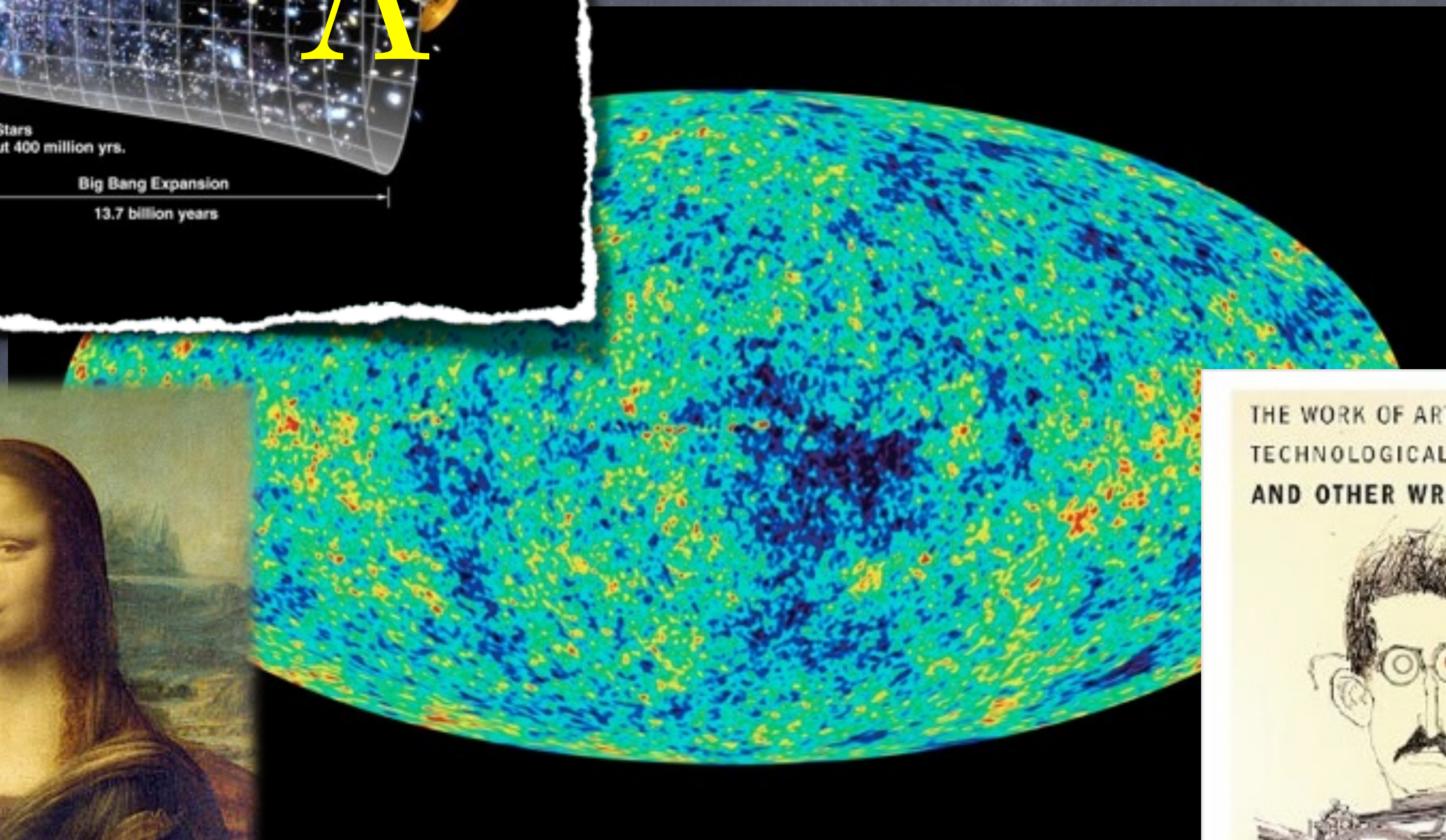


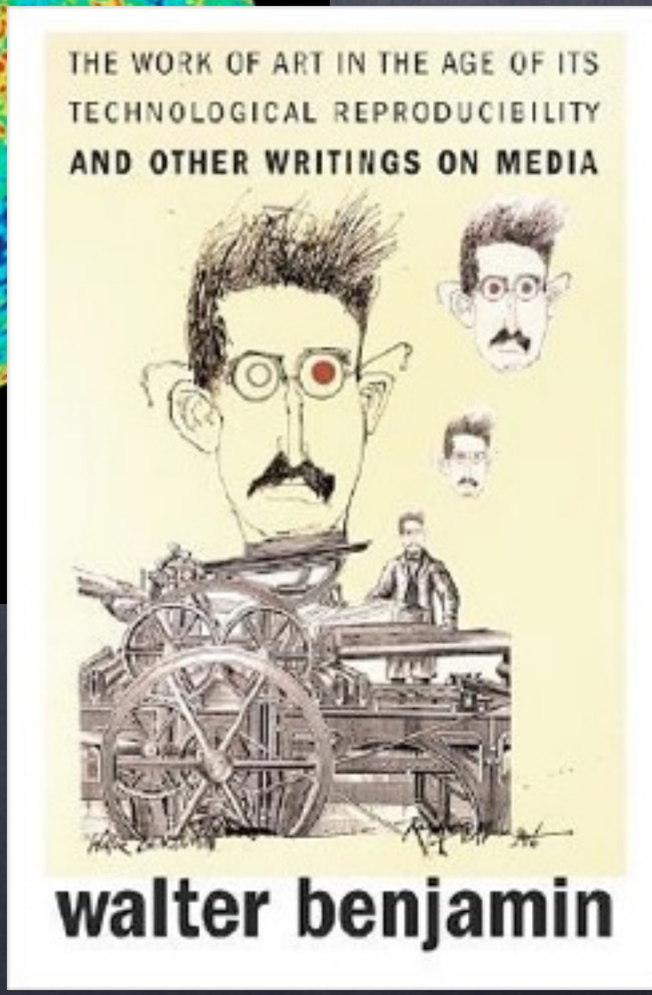



THE WORK OF ART IN THE AGE OF ITS
TECHNOLOGICAL REPRODUCIBILITY
AND OTHER WRITINGS ON MEDIA
walter benjamin


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Λ
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

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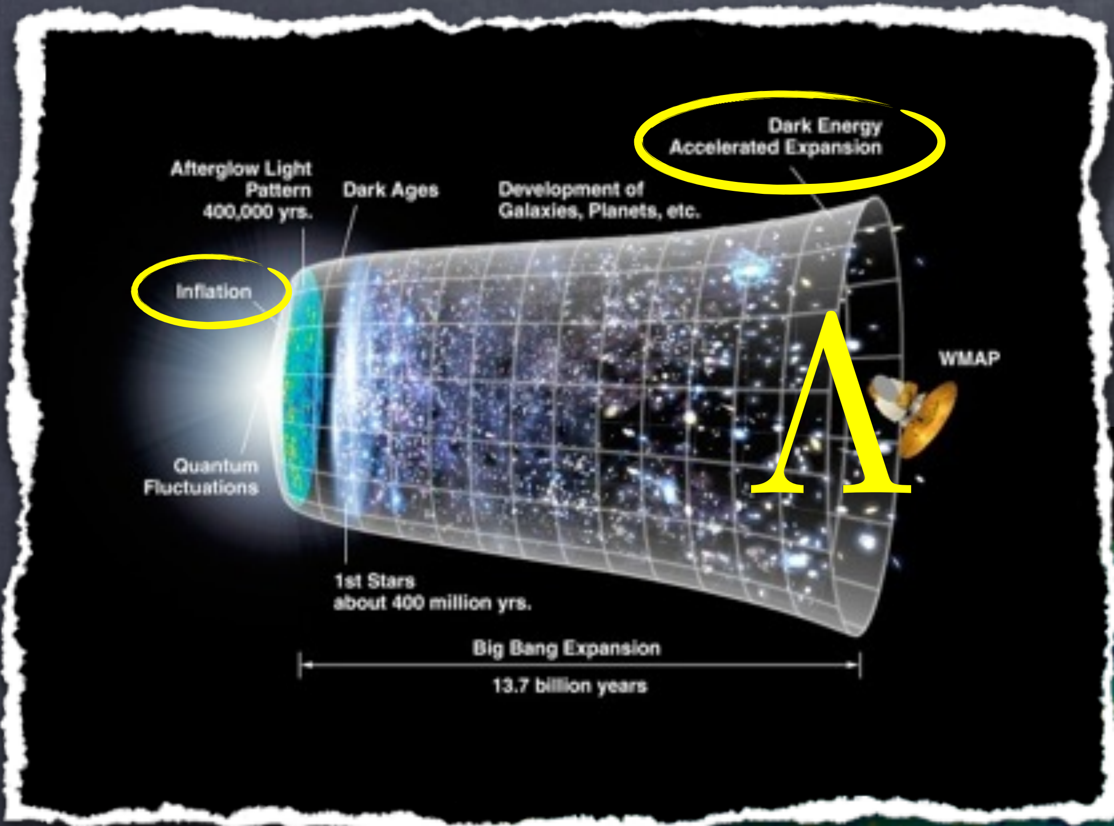
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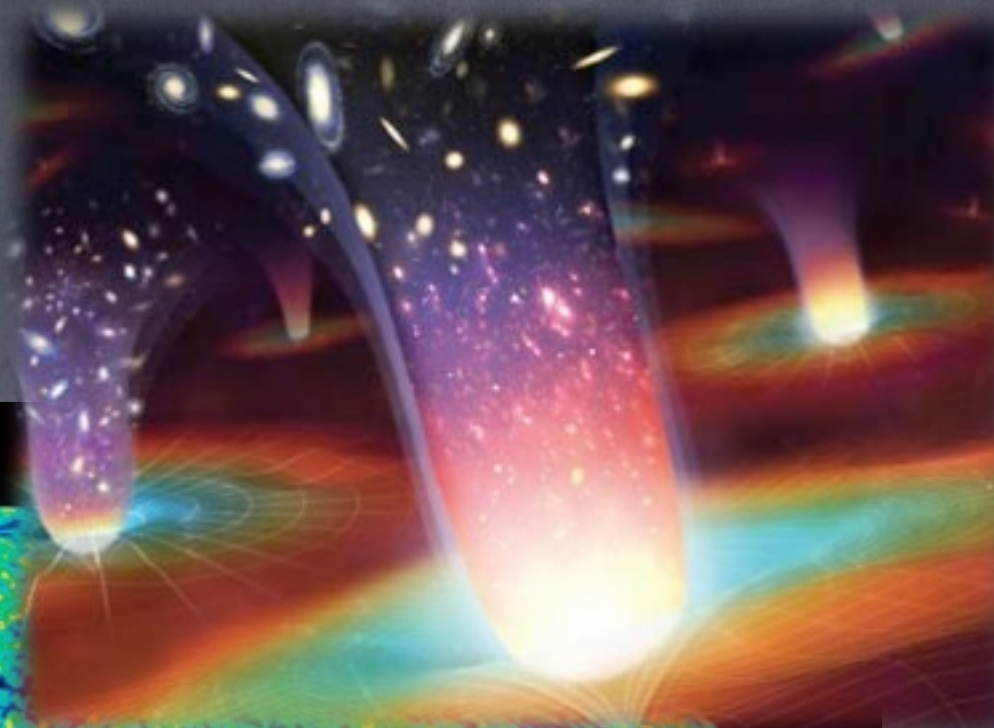

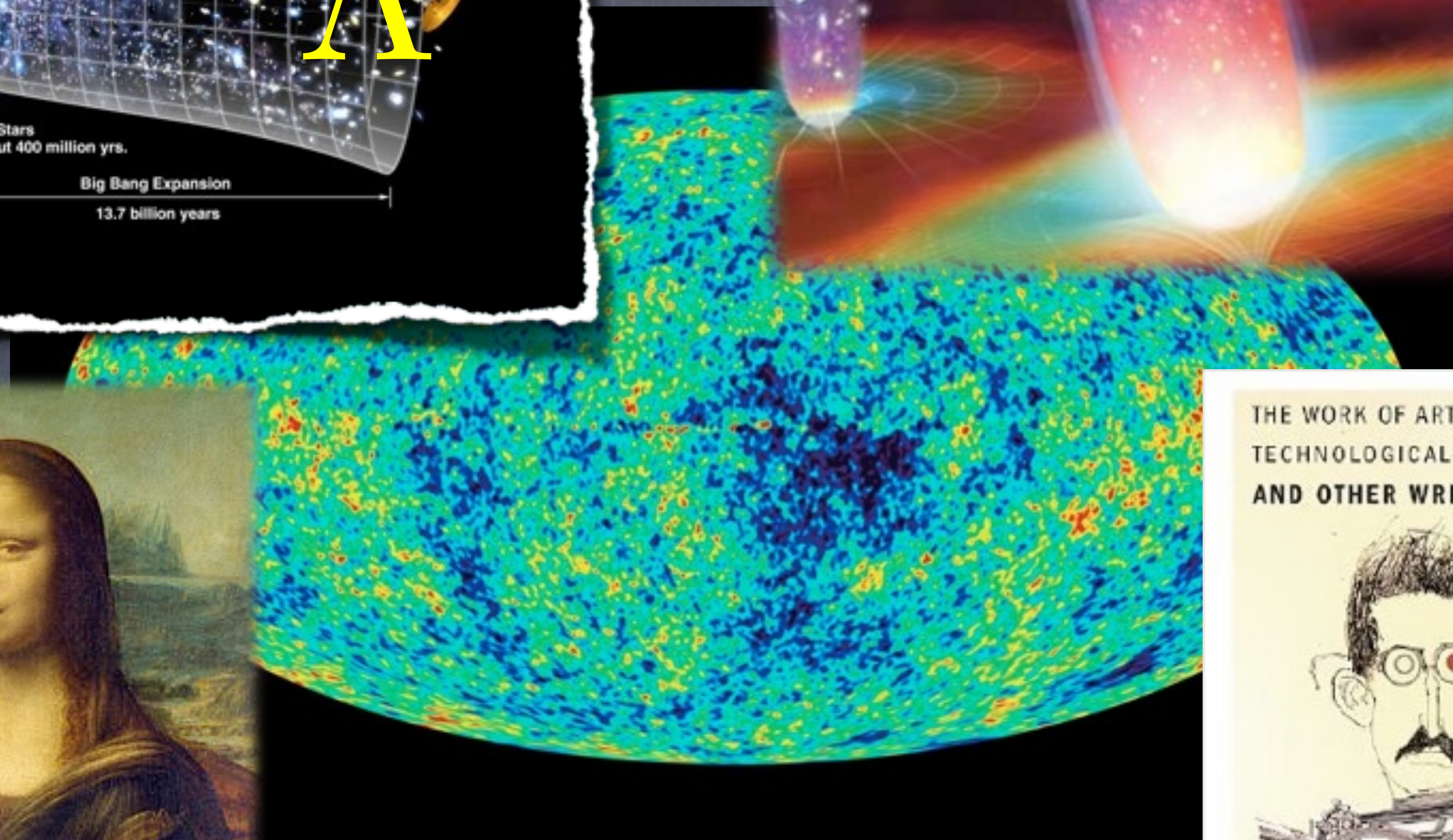

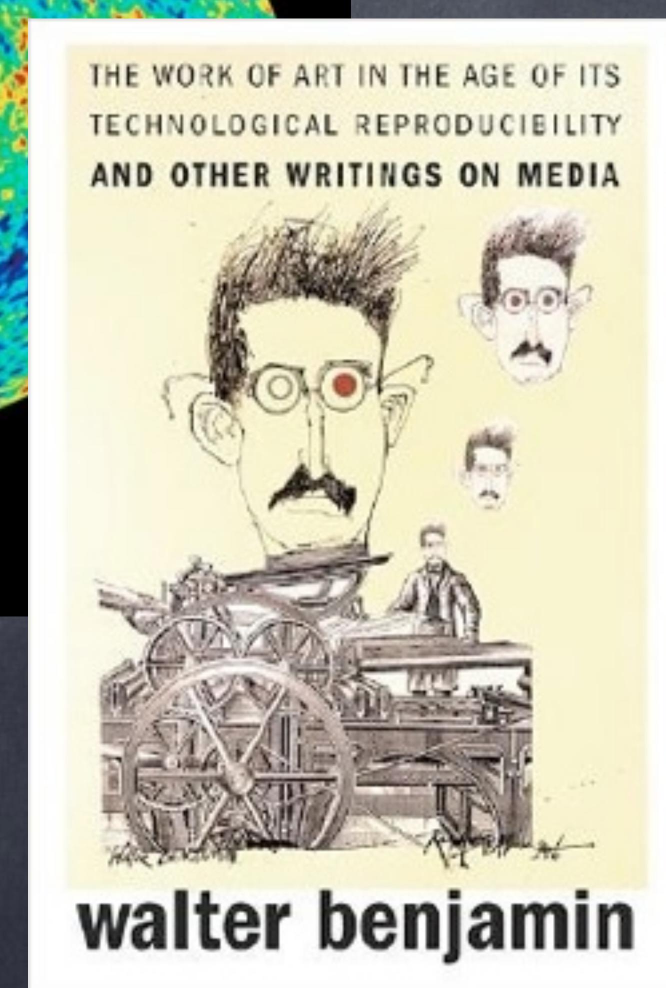
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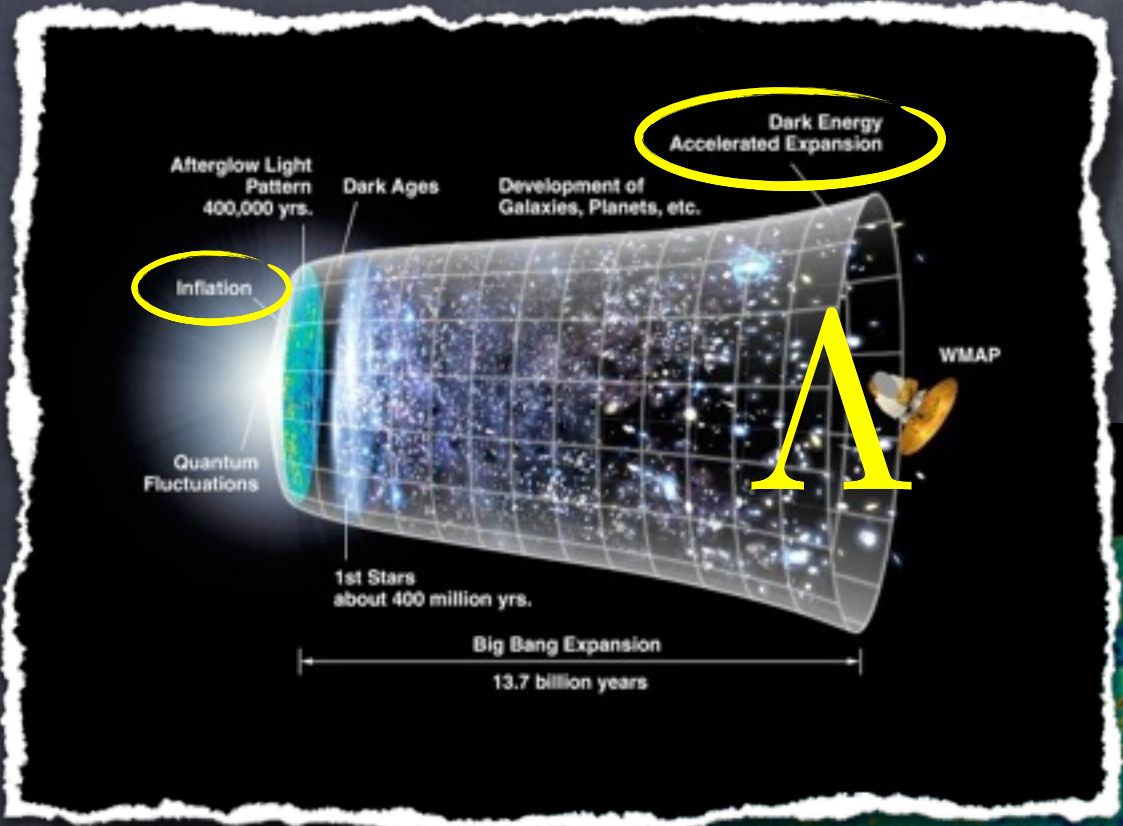
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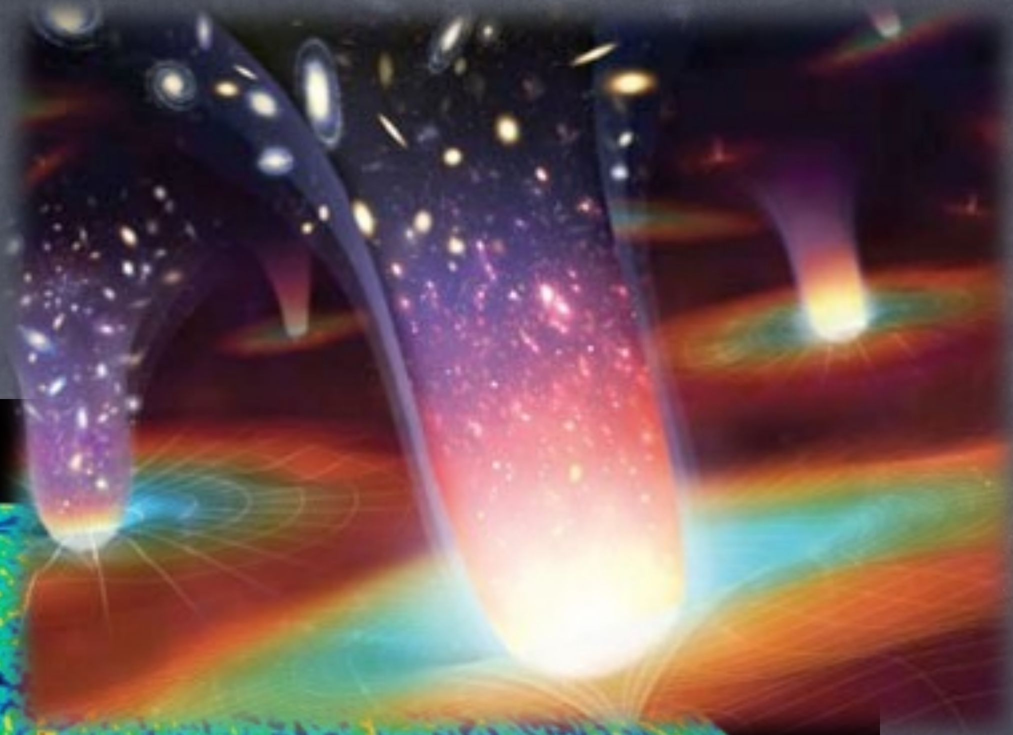
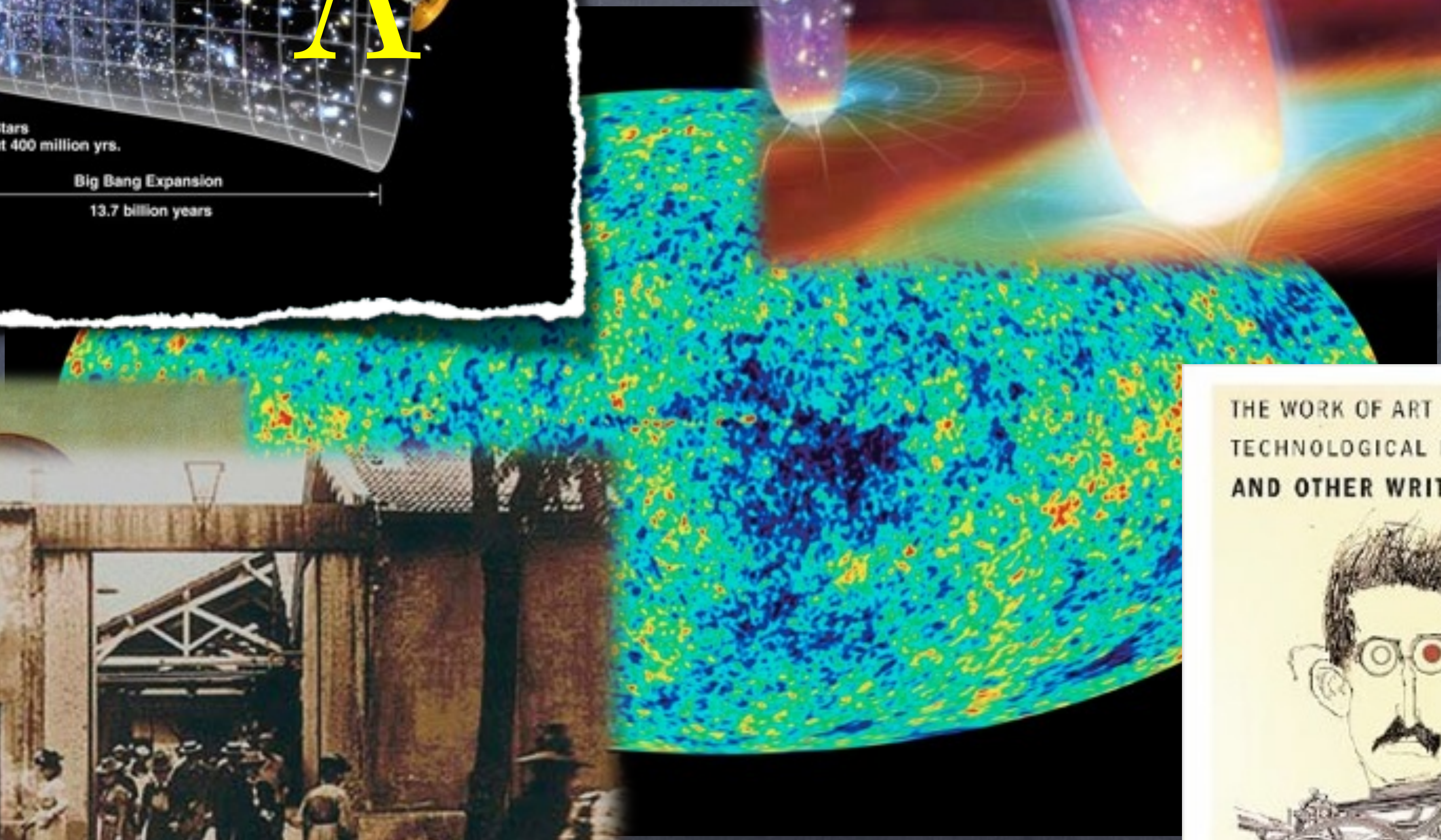

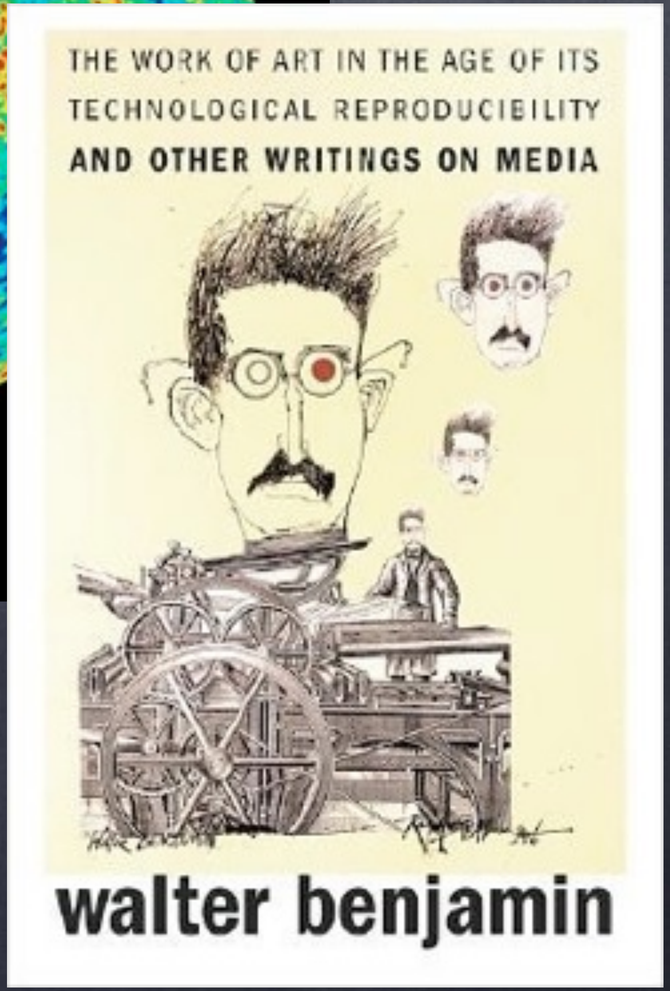
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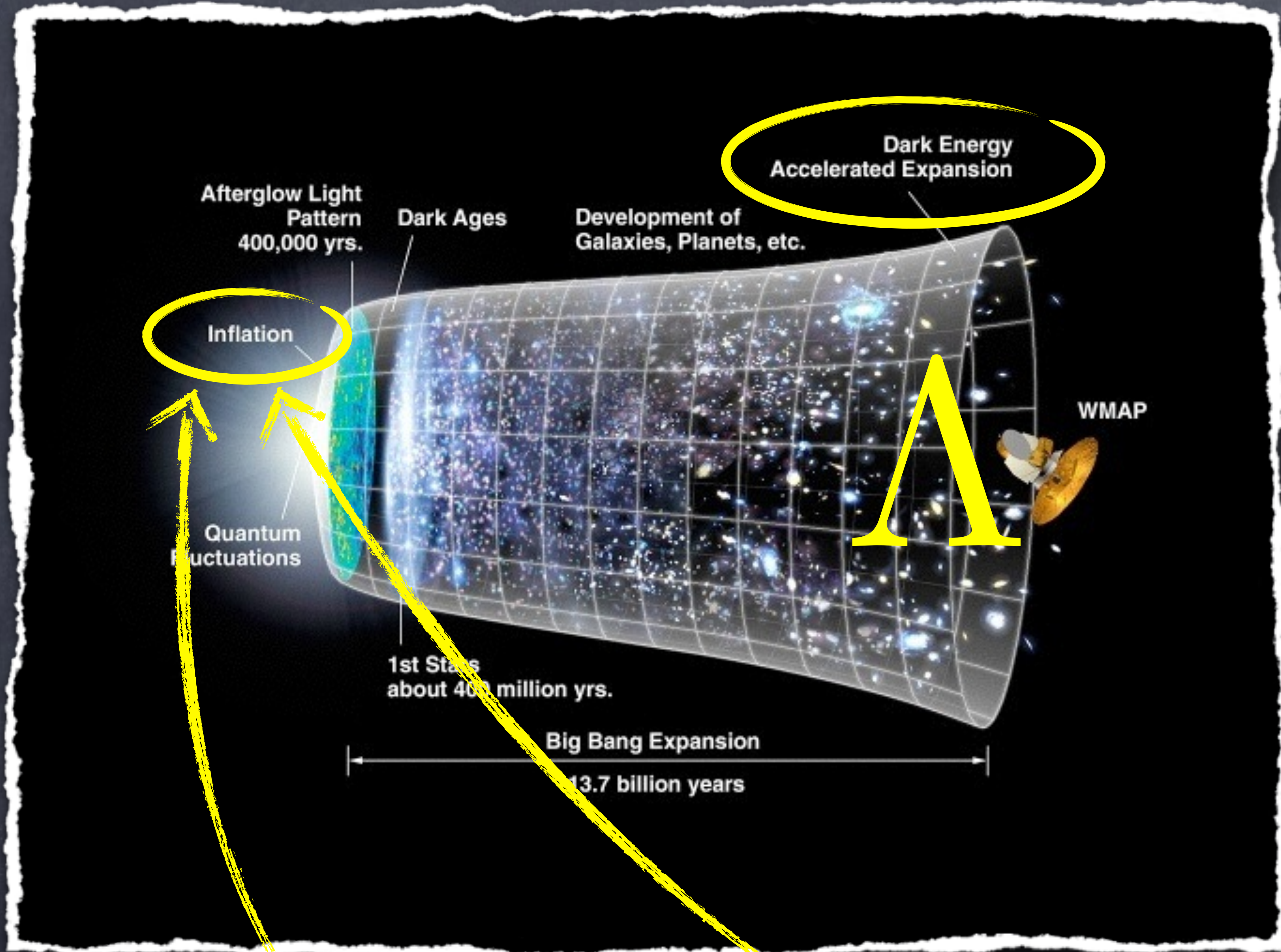
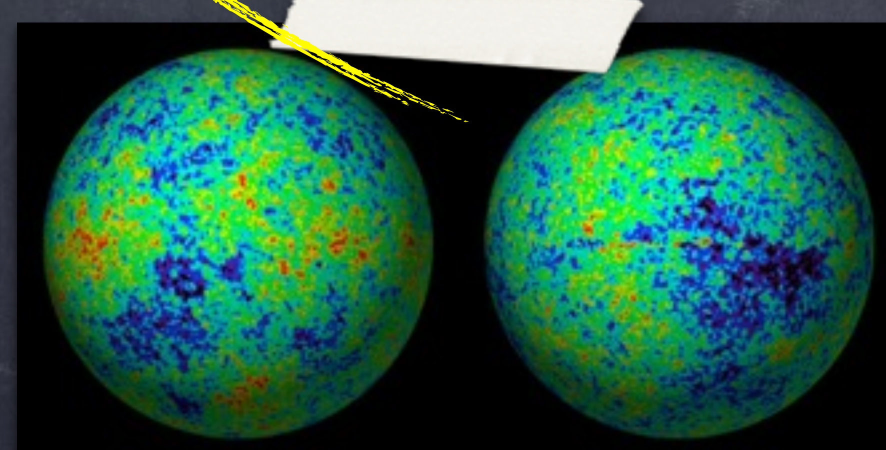
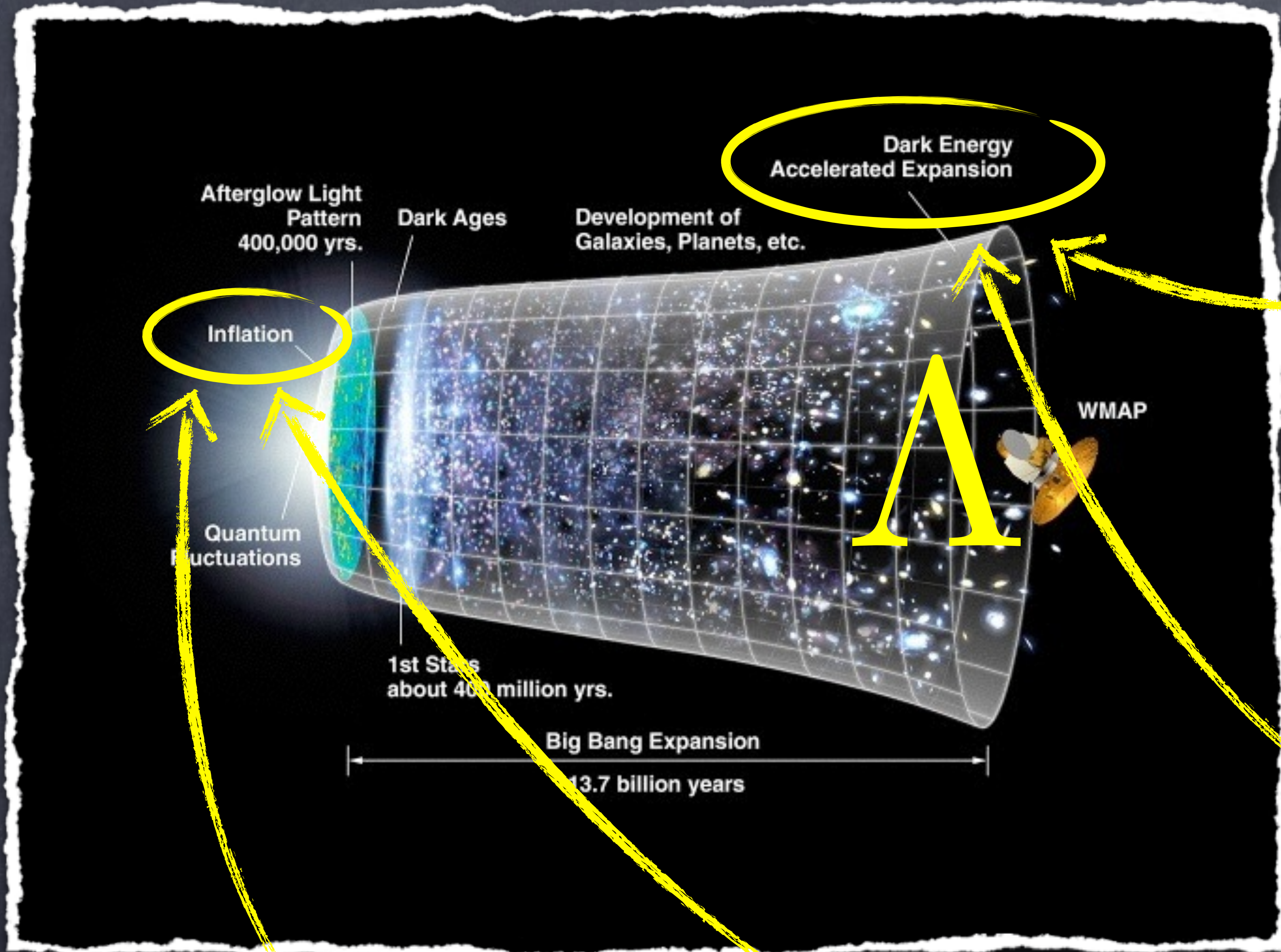
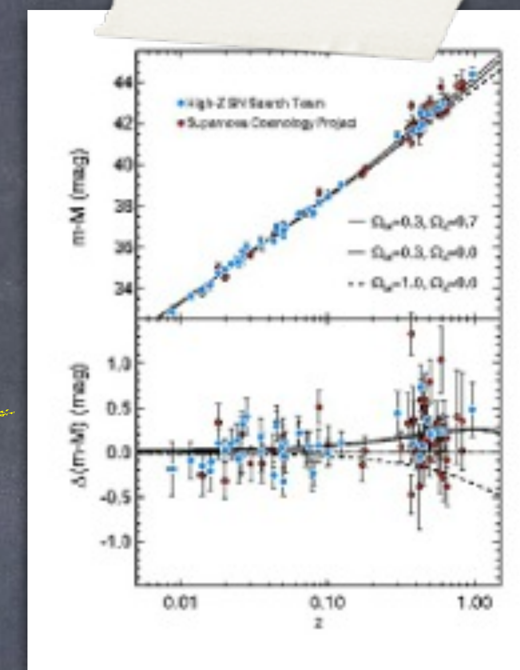


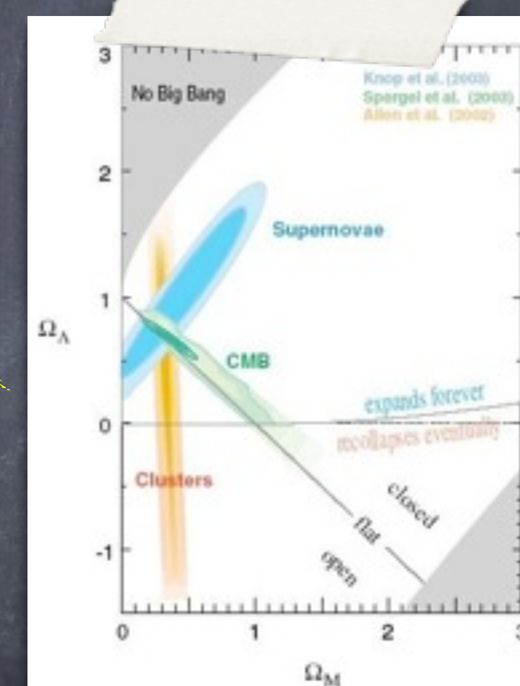
Horizon problem

Flatness problem









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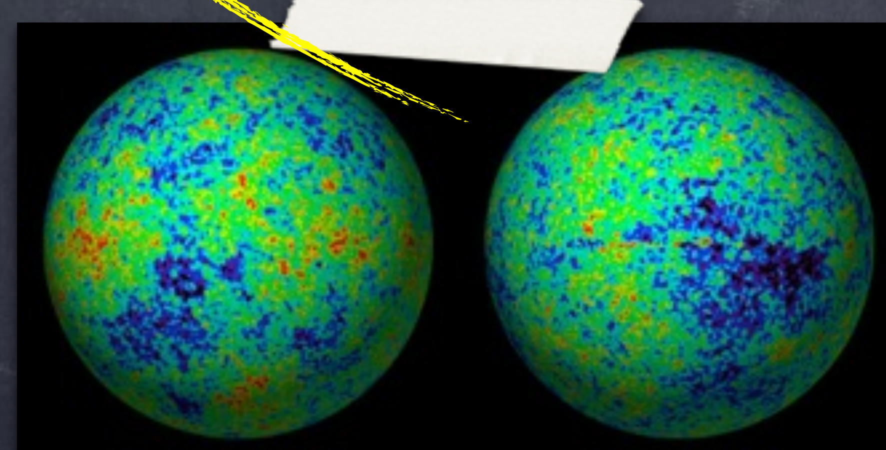
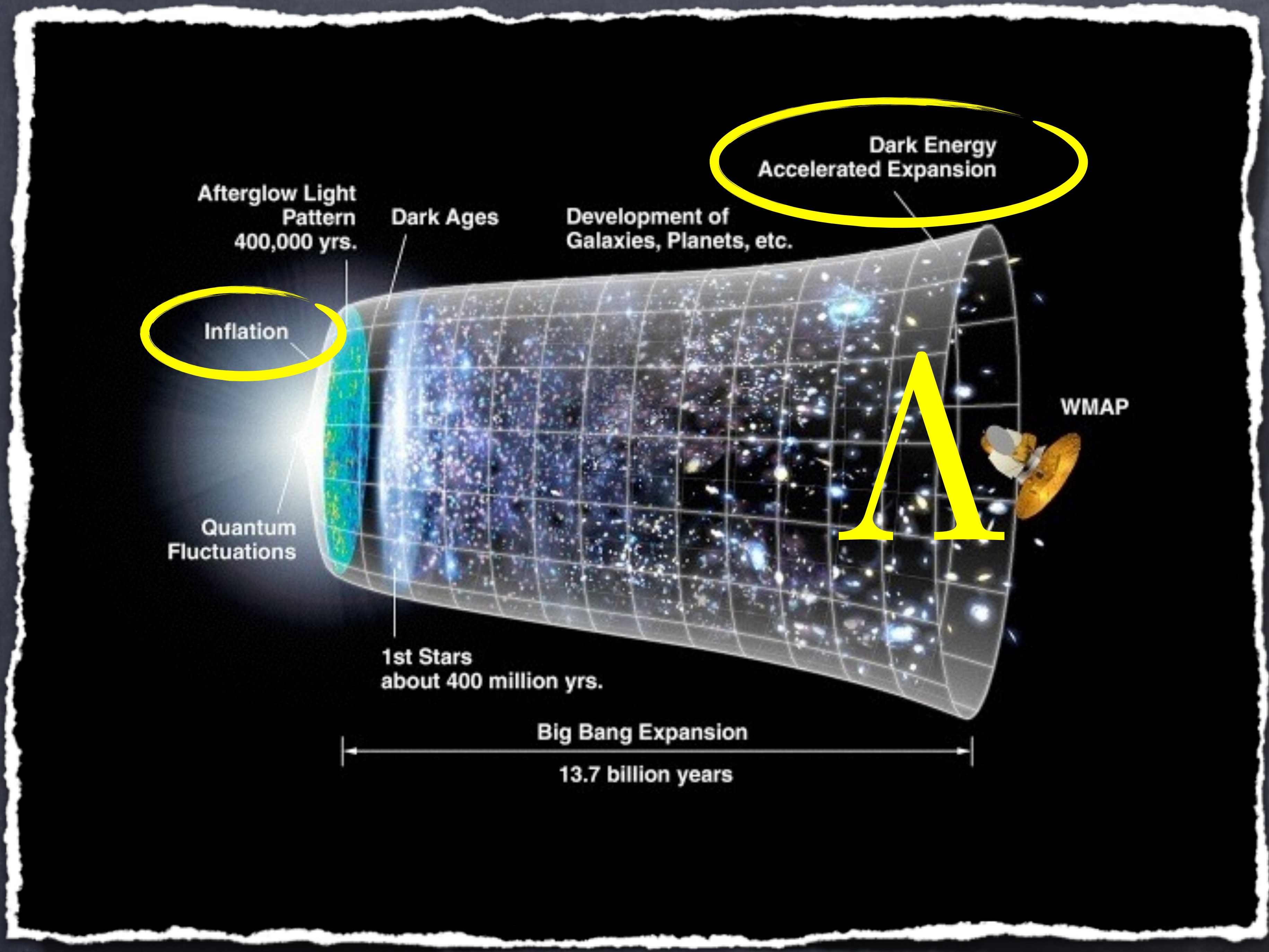
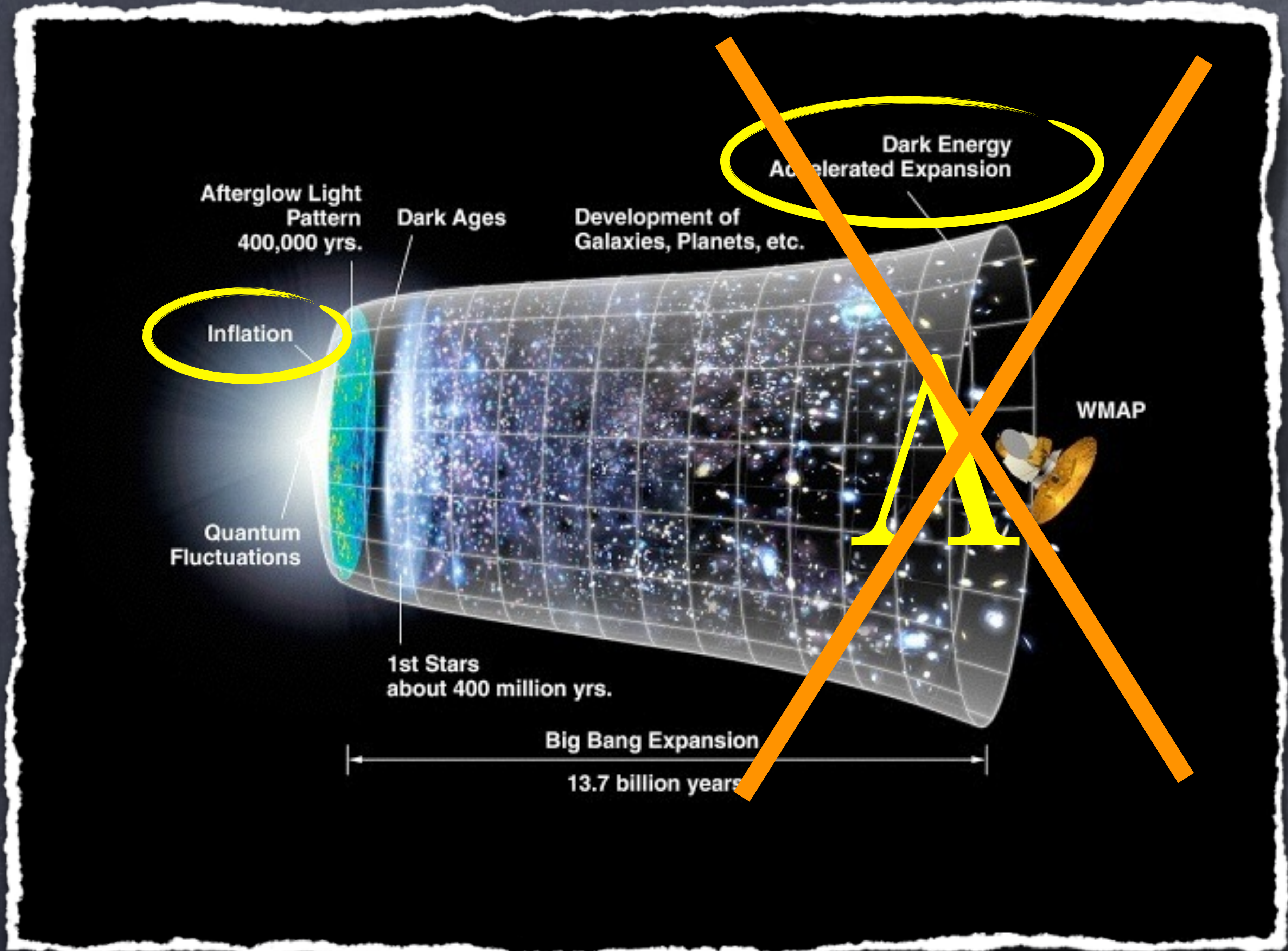


Cosmology
as a precision
science



How different the Universe can be?



NO CC or
Dark Energy

No acceleration in the Einstein frame

Observed acceleration is a genuine modified gravity effect

What is GR?

It is the only consistent Lorentz invariant theory of a massless spin 2 field at low energies

Weinberg '65

What is GR?

It is the only consistent Lorentz invariant theory of a massless spin 2 field at low energies

Weinberg '65

Modify GR in the infrared

There must be extra light degrees of freedom

(Brans-Dicke, f(R), Pauli-Fierz massive gravity, DGP, ...)

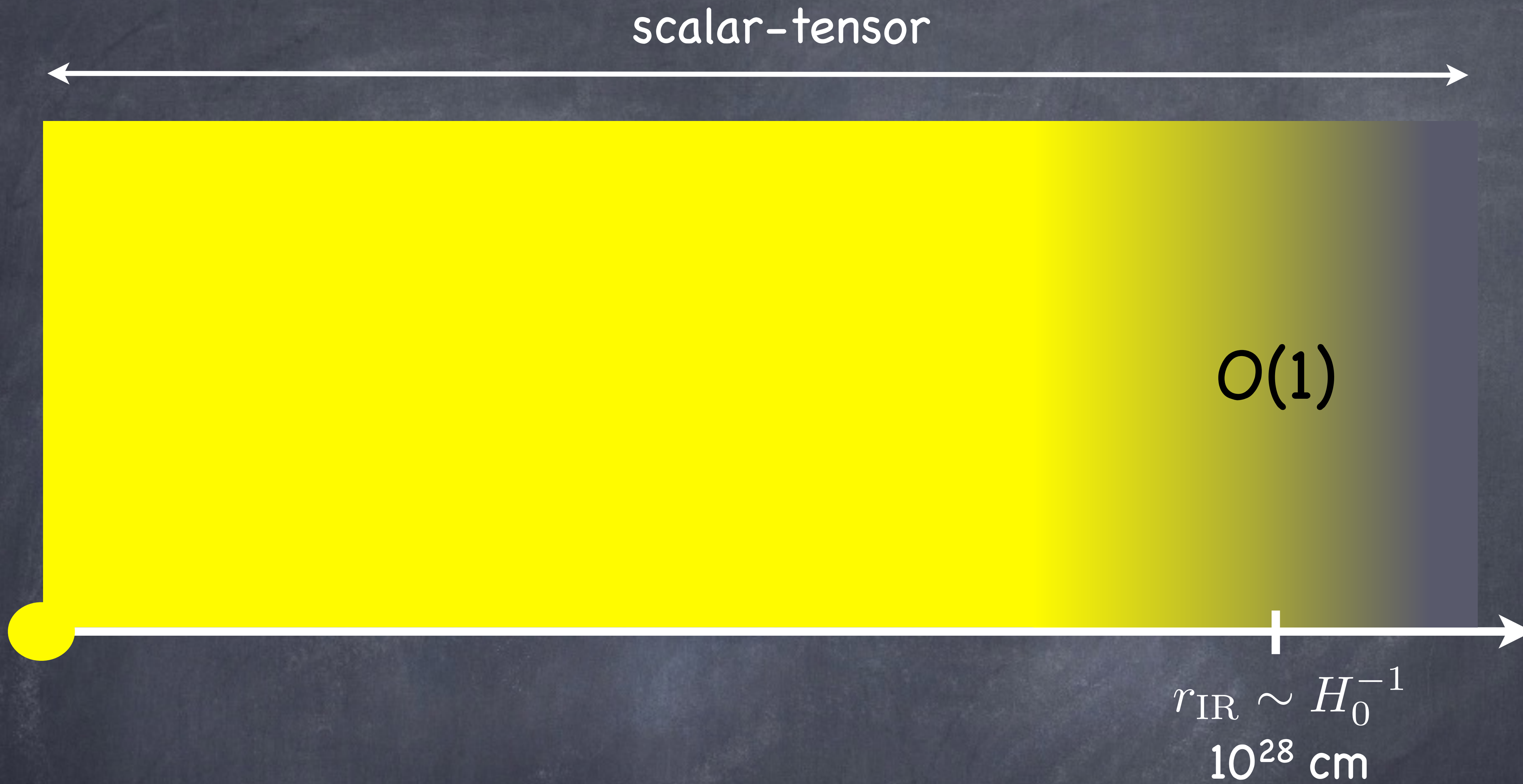
one extra scalar ϕ

$$M_{\rm Pl}^2 R - (\partial\varphi)^2 + \frac{1}{M_{\rm Pl}} h_{\mu\nu} T^{\mu\nu} + \frac{1}{M_{\rm Pl}} \varphi T$$

universal coupling

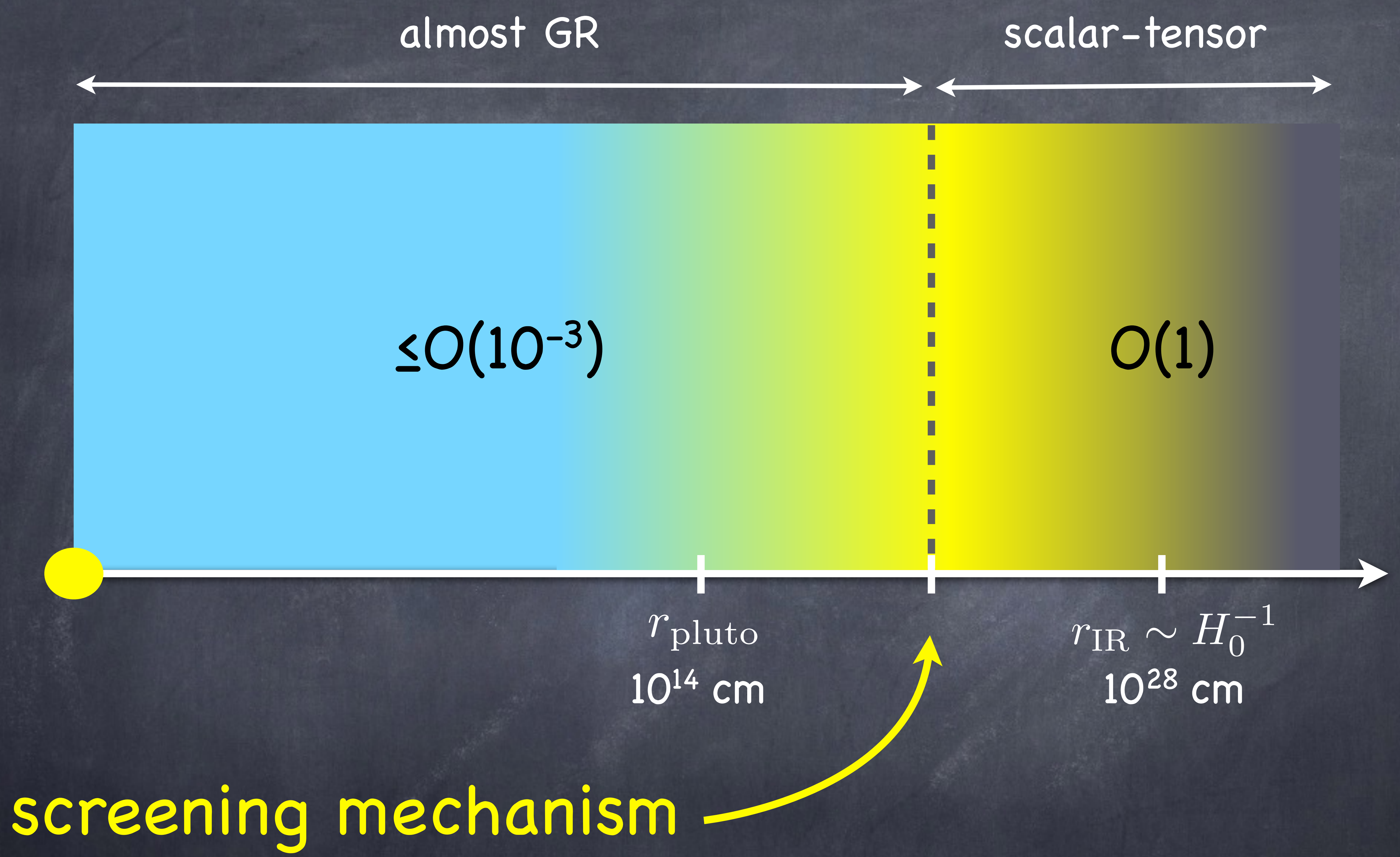
No microscopic violation of EP

"Physical" metric $\hat{h}_{\mu\nu} = h_{\mu\nu} + \pi \eta_{\mu\nu}$



$$M_{\rm Pl}^2 R - (\partial\varphi)^2 + \frac{1}{M_{\rm Pl}} h_{\mu\nu} T^{\mu\nu} + \frac{1}{M_{\rm Pl}} \varphi T$$


almost GR
scalar-tensor
≤O(10^-3)
O(1)
$r_{\rm pluto}$
10^{14} cm
$r_{\rm IR} \sim H_0^{-1}$
10^{28} cm



almost GR
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≤O(10⁻³)
O(1)
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10^{14} cm
$r_{\rm IR} \sim H_0^{-1}$
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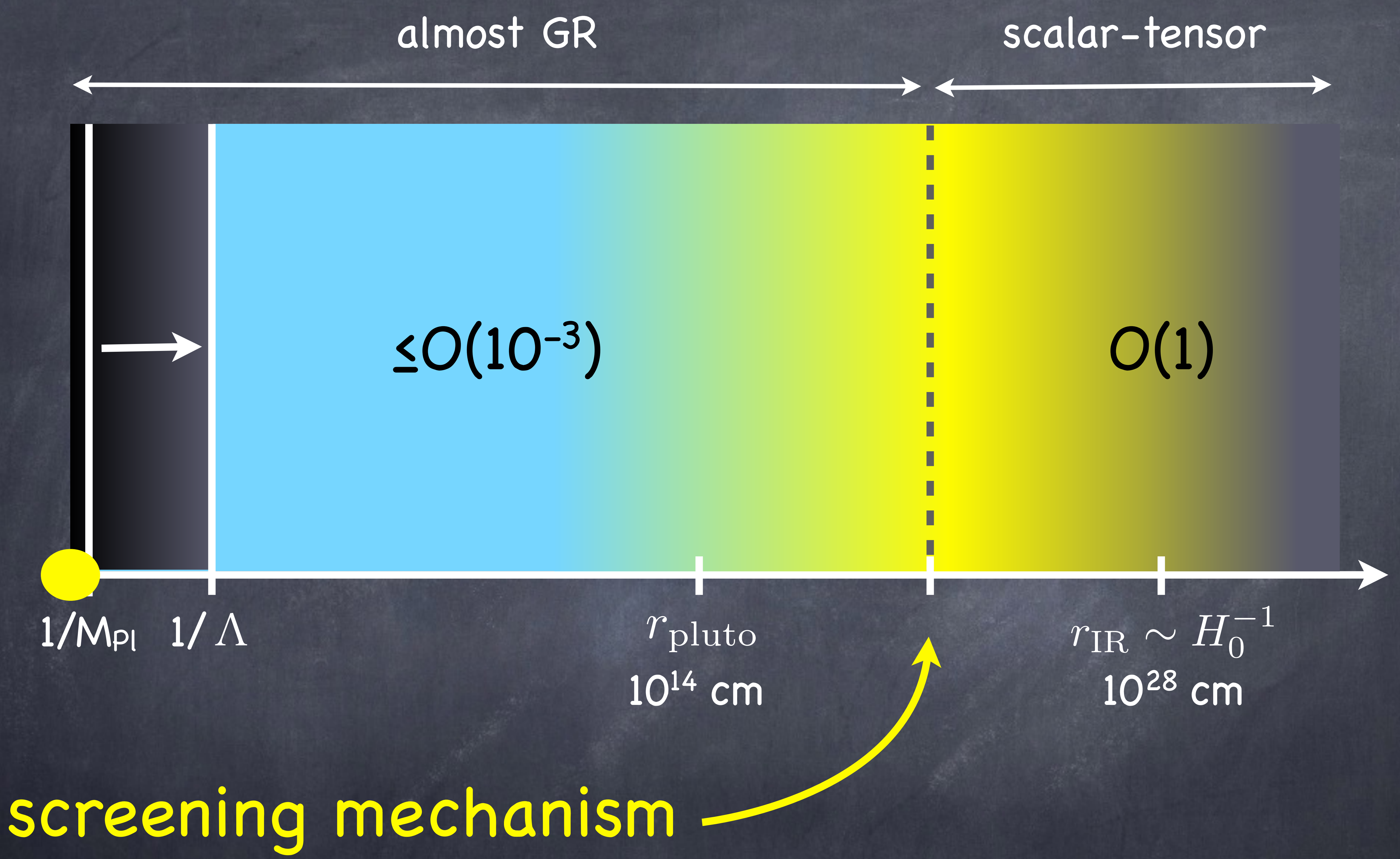
screening mechanism


almost GR
scalar-tensor
$\lesssim O(10^{-3})$
O(1)
1/Mpl
$1/\Lambda$
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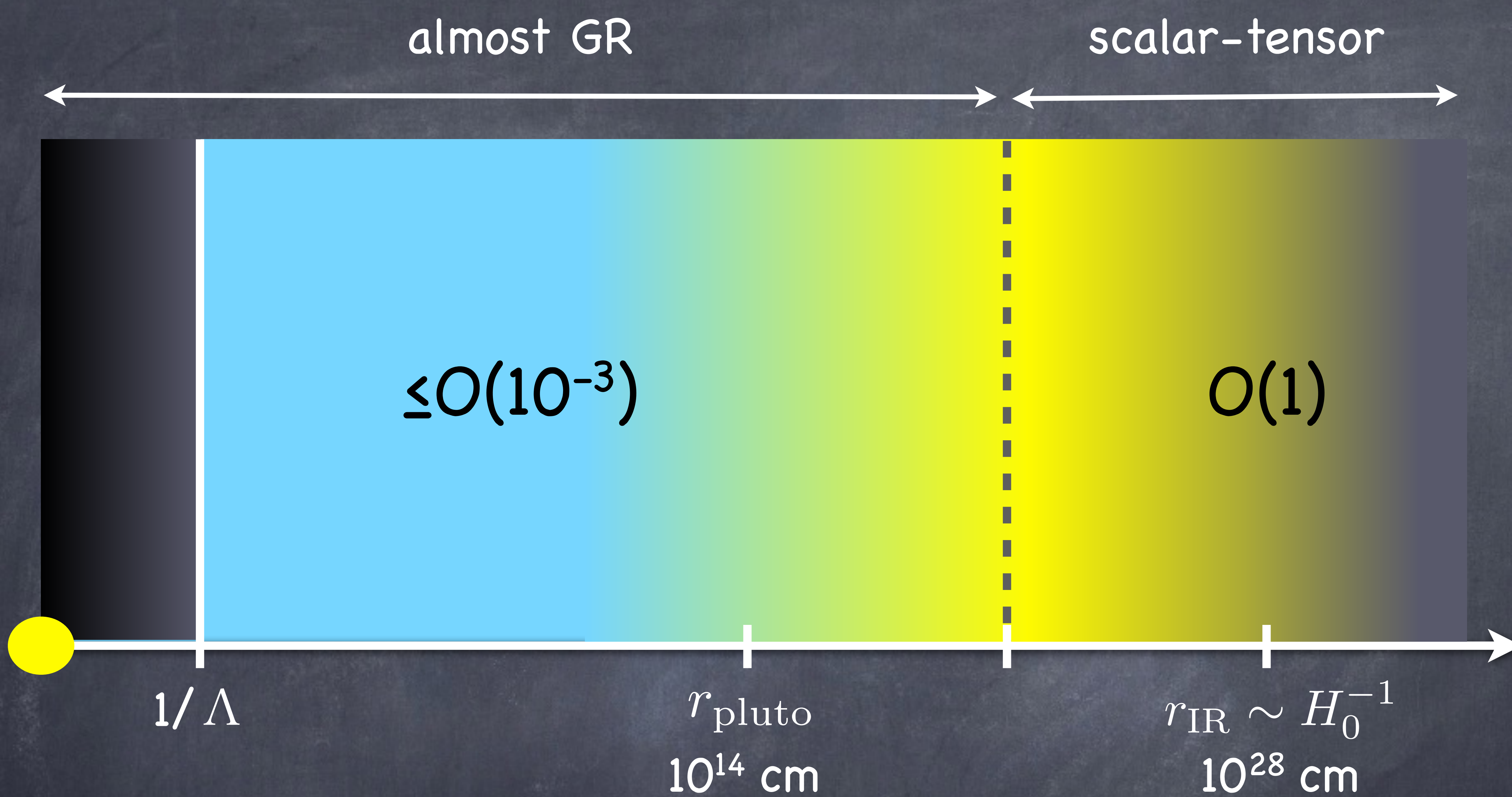
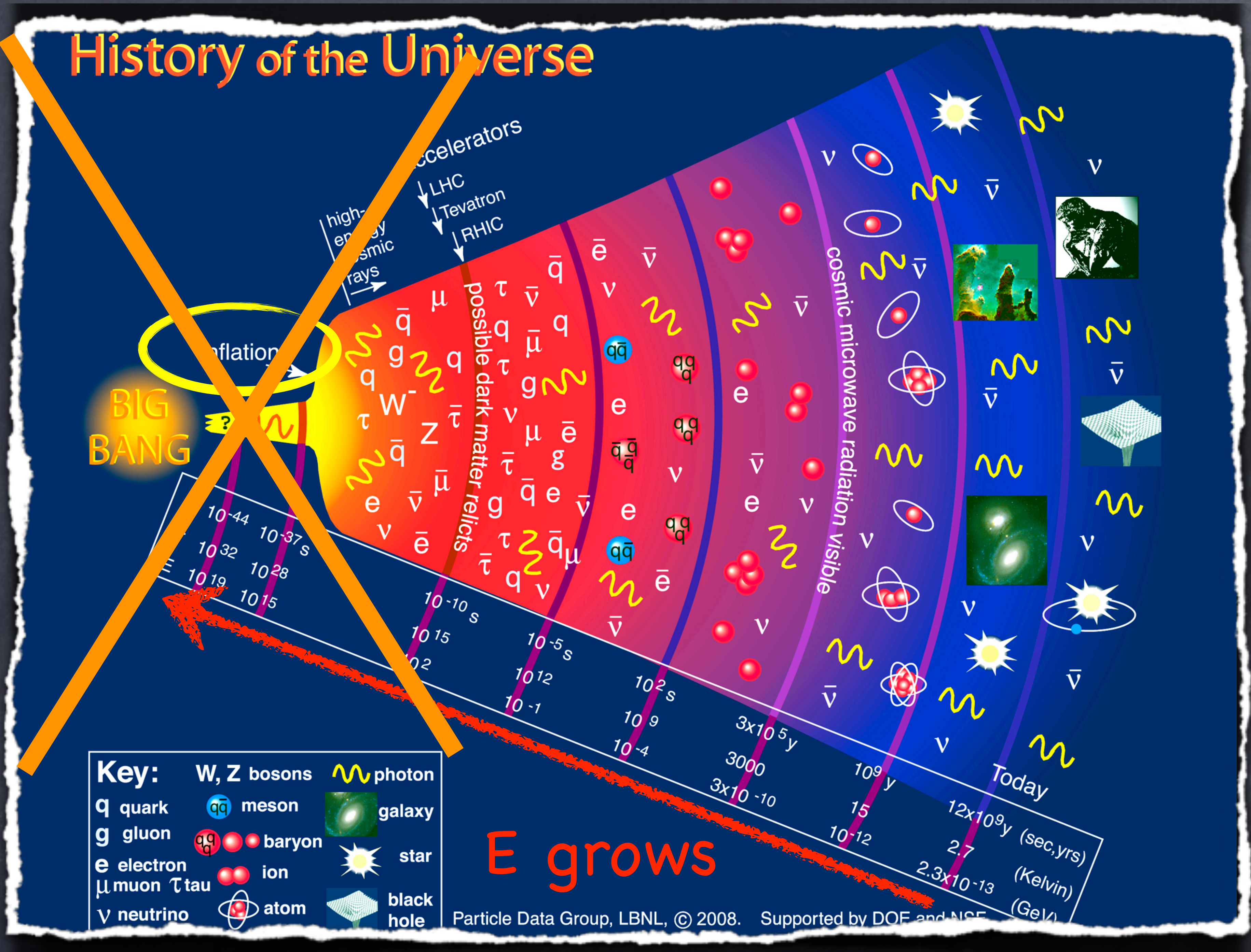


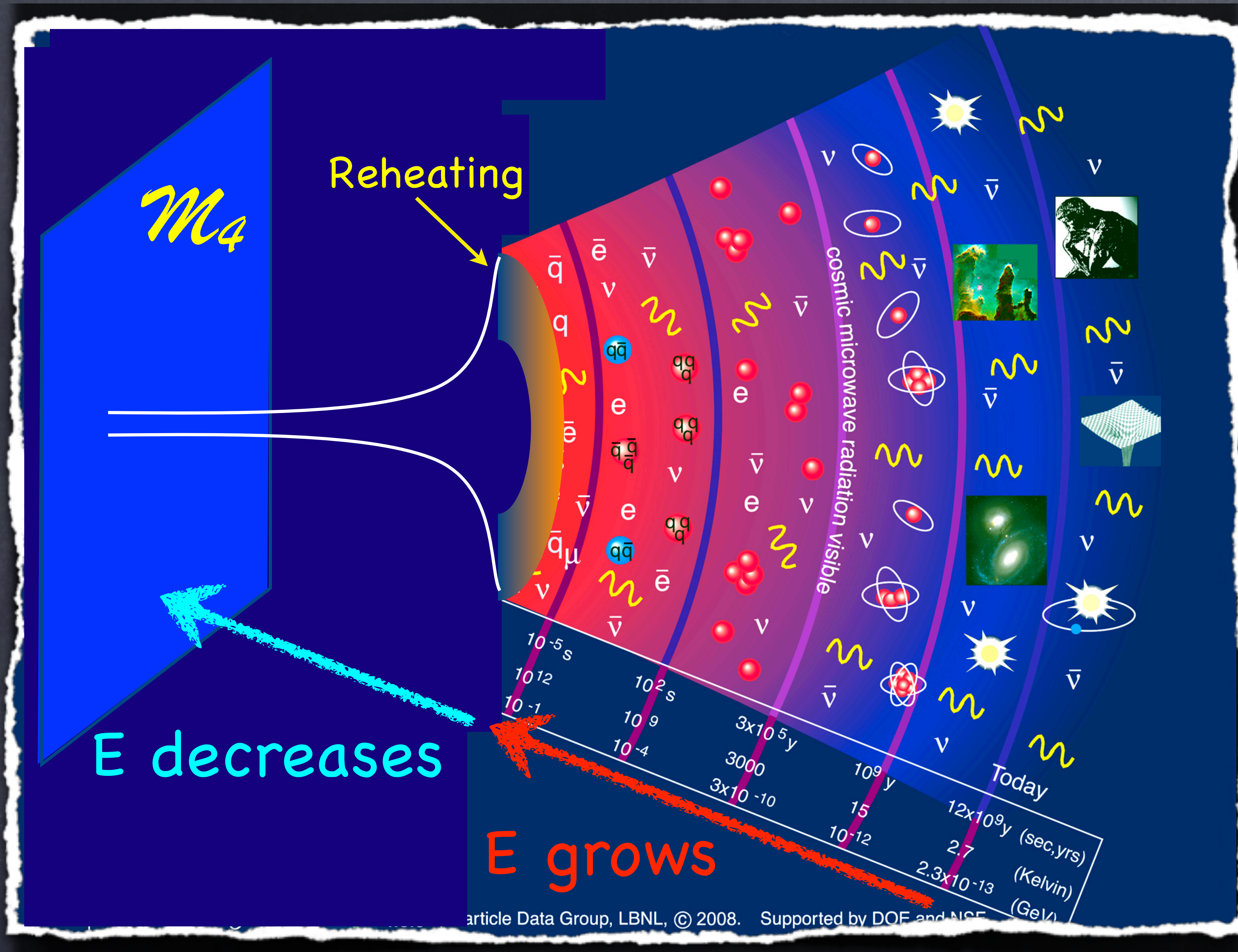
Vainshtein screening

Vainshtein '72

self-interactions suppress the scalar at short scales



No Big bang
No inflation



$\mathcal{M}_4$
Reheating
cosmic microwave radiation visible
10⁻⁵ s
10¹²
10⁻¹
10² s
10⁹
10⁻⁴
3x10⁵ y
3000
3x10⁻¹⁰
10⁹ y
15
10⁻¹²
Today
12x10⁹ y
2.7
2.3x10⁻¹³
(sec,yrs)
(Kelvin)
(GeV)
E decreases
E grows
article Data Group, LBNL, © 2008. Supported by DOE and NSF

How can it be possible?

The Big Bang paradigm assumes (at least) the null energy condition (NEC)

$T_{\mu\nu} n^\mu n^\nu \geq 0$ in FRW spacetime reduces to $\rho + p \geq 0$

$$\dot{H} = -4\pi G(\rho + p)$$
$$\dot{\rho} = -3H(\rho + p)$$

NEC $\Rightarrow \dot{H}, \dot{\rho} \leq 0$

NEC satisfied by matter, radiation
NEC saturated by a cosmological constant

Is there a form of matter that violates it?

Can we violate the NEC?

Usually ~~NEC~~ are unstable:

$$\mathcal{L} = \pm\frac{1}{2}(\partial\phi)^2 - V(\phi) \qquad\qquad \phi = \phi(t) \Rightarrow (\rho + p) = \mp\dot{\phi}^2$$

Can we violate the NEC?

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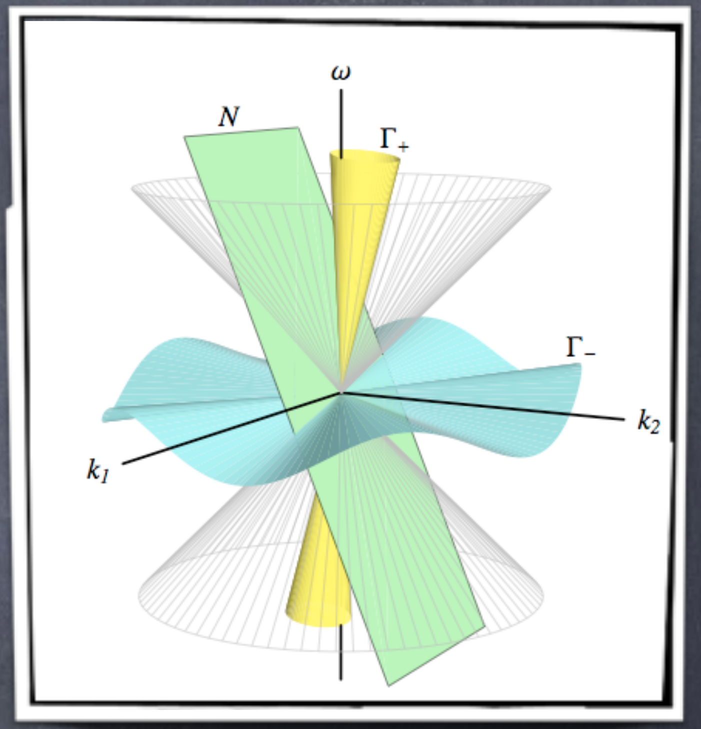
$$\mathcal{L} = \pm\frac{1}{2}(\partial\phi)^2 - V(\phi) \qquad \phi = \phi(t) \Rightarrow (\rho + p) = \mp\dot{\phi}^2$$

No-go theorem

$$\mathcal{L} = F(\phi_I, \partial\phi_I, \partial^2\phi_I, \ldots) \qquad I = 1, \ldots, N$$

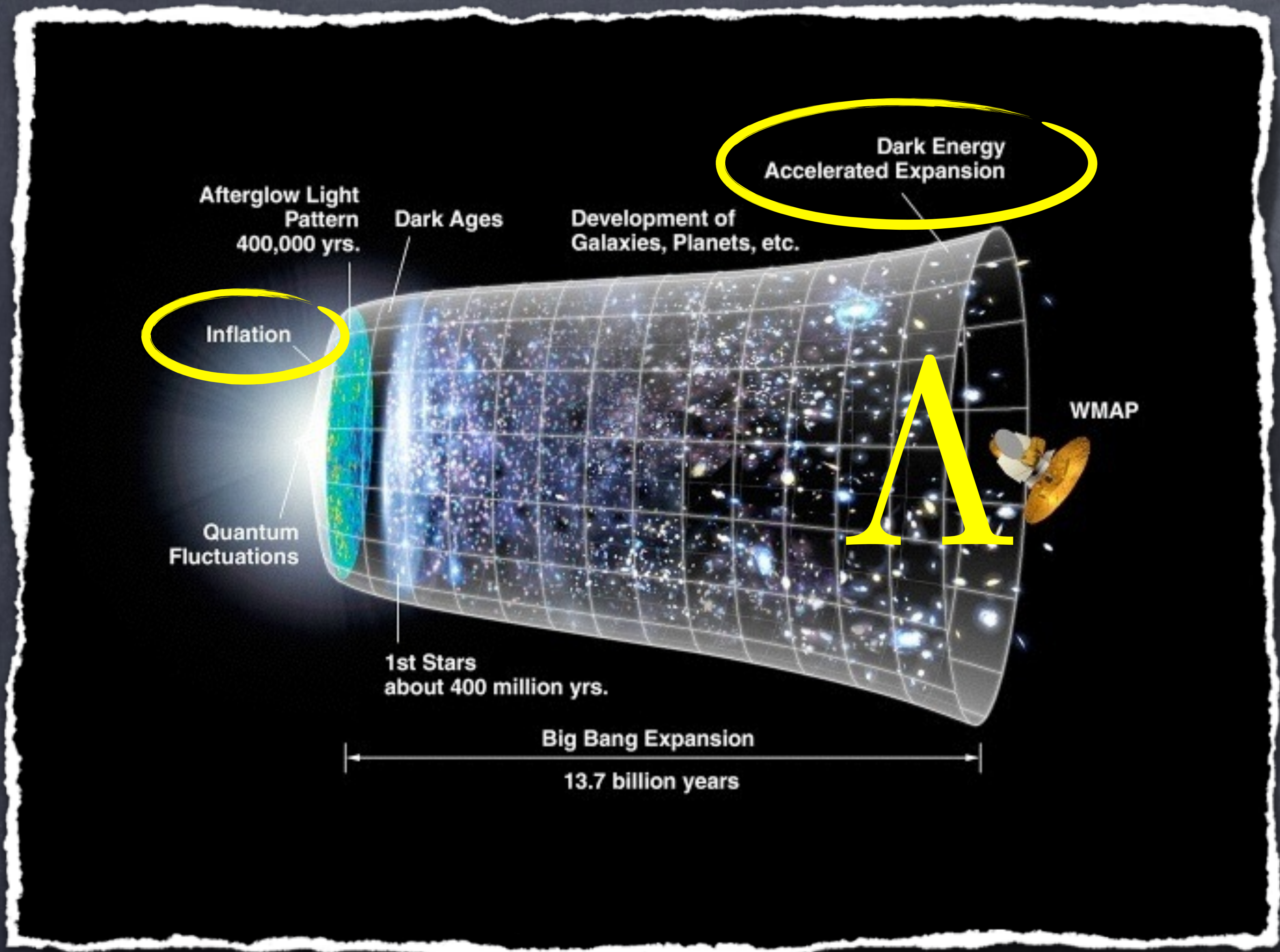


There are no stable NEC-violating EFT
if we can neglect HD terms

Dubovsky, Gregoire, Nicolis, Rattazzi '06

- They are irrelevant at low energies. When they are important ~~EFT~~
- They describe new pathological ghost-like degrees of freedom

But...



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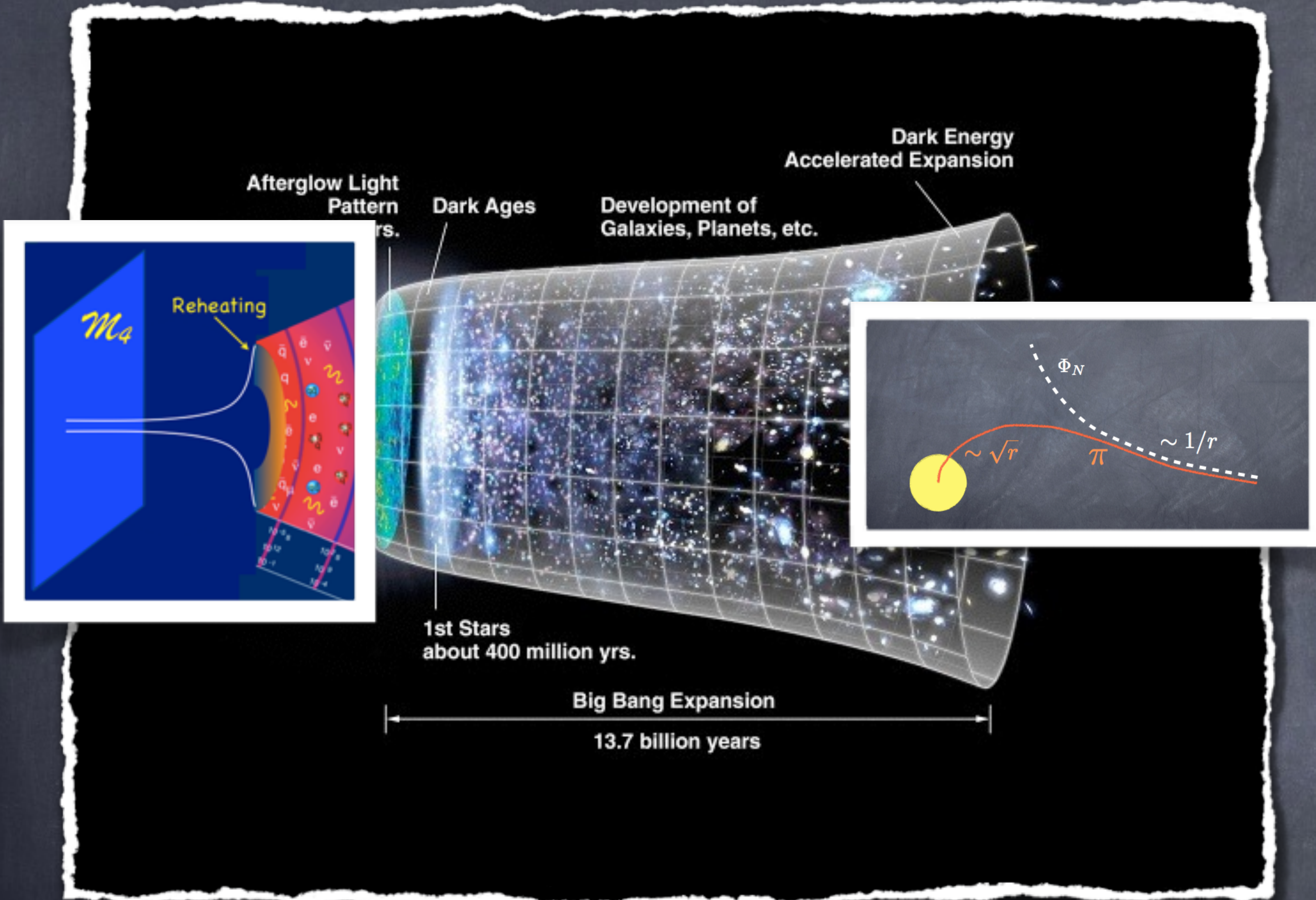
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$\mathcal{M}_4$
Reheating
Φ_N
$\sim \sqrt{r}$
π
$\sim 1/r$

Spirit of the talk

Emphasis not on radicalness instead on consistency as a quantum EFT

understand what is possible and what is not in cosmological evolution

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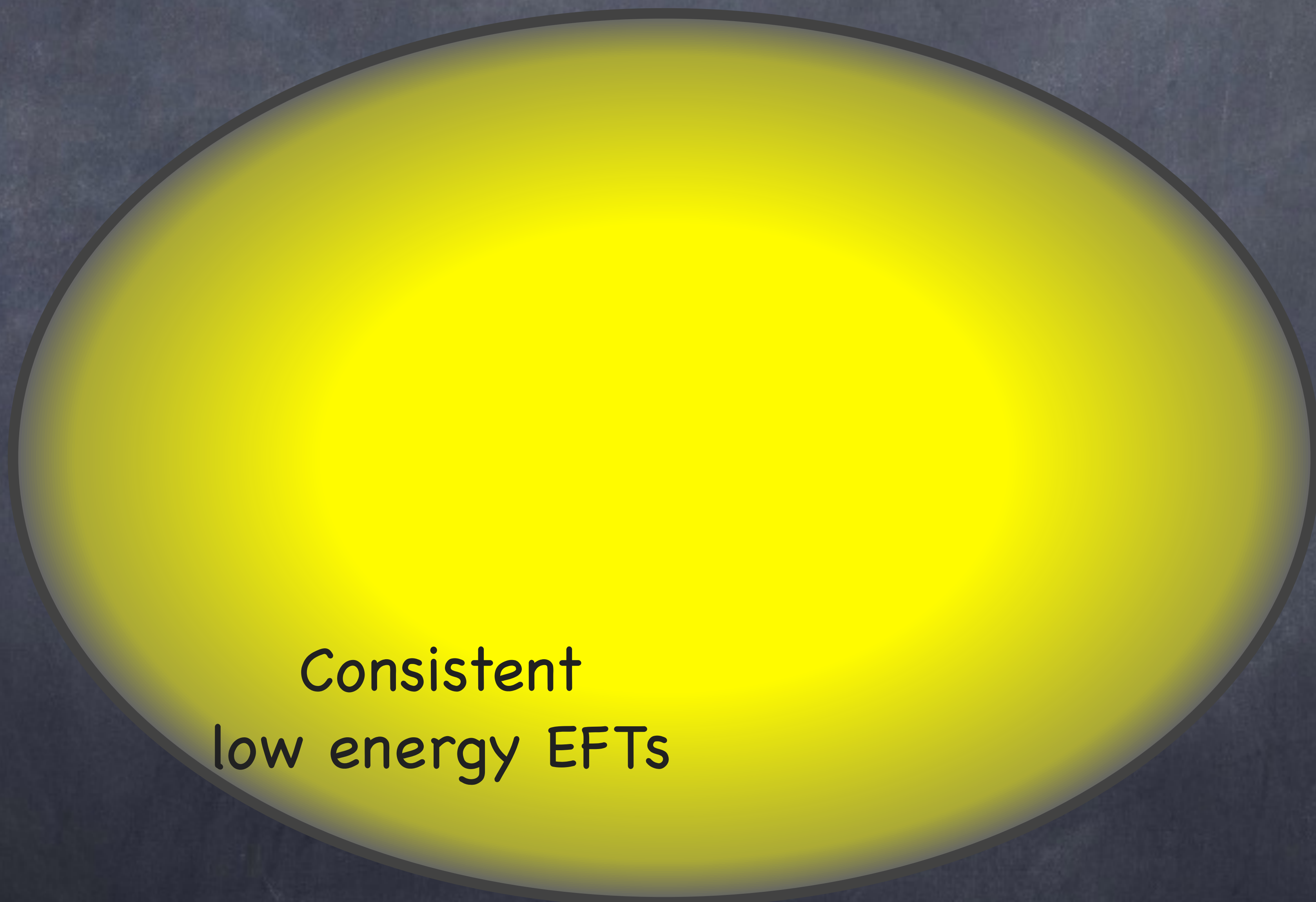
Emphasis not on radicalness instead on consistency as a quantum EFT

understand what is possible and what is not in cosmological evolution

Include all
Ops compatible
with symmetries

Local,
Lorentz-invariant
Lagrangian



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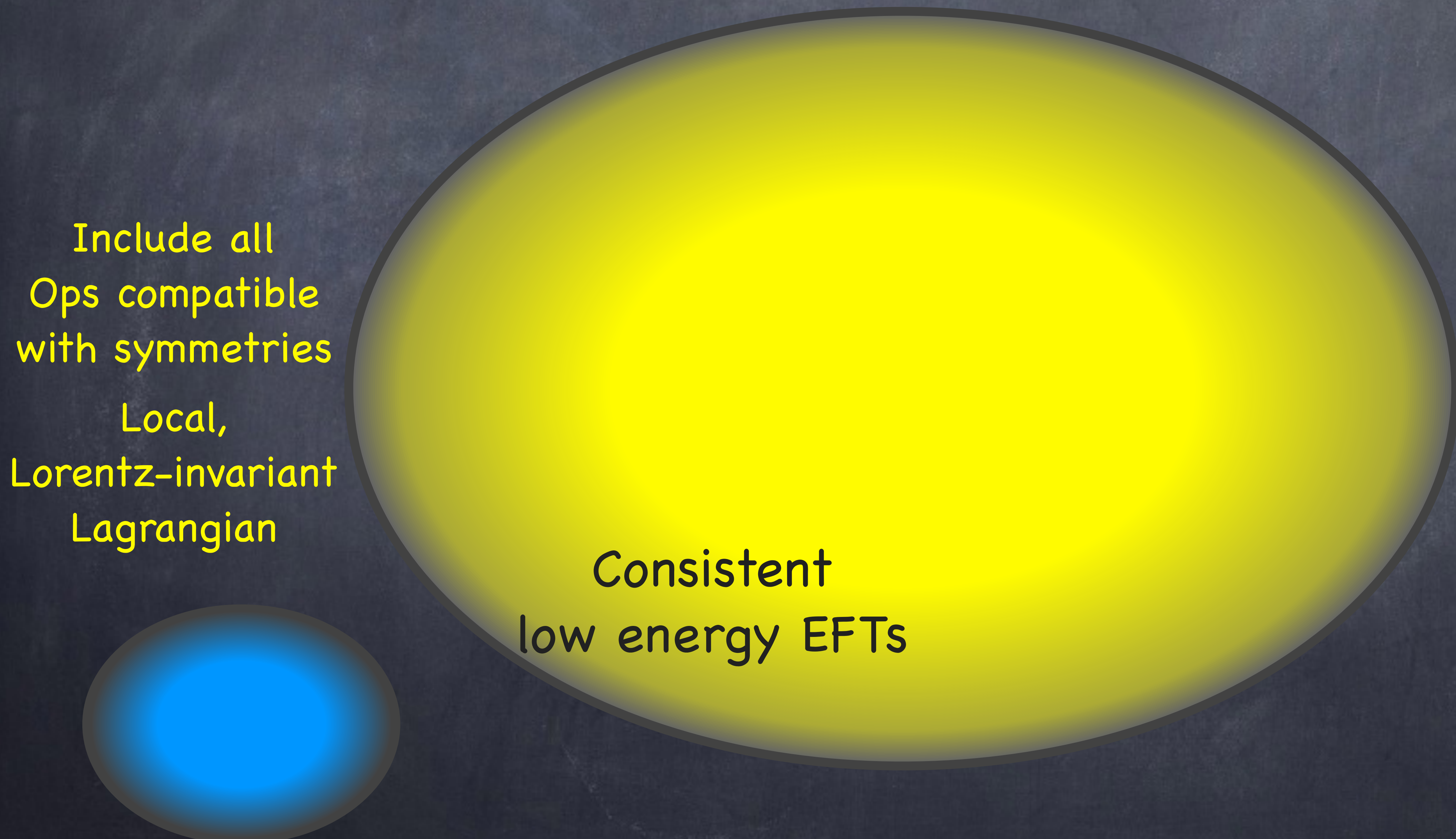

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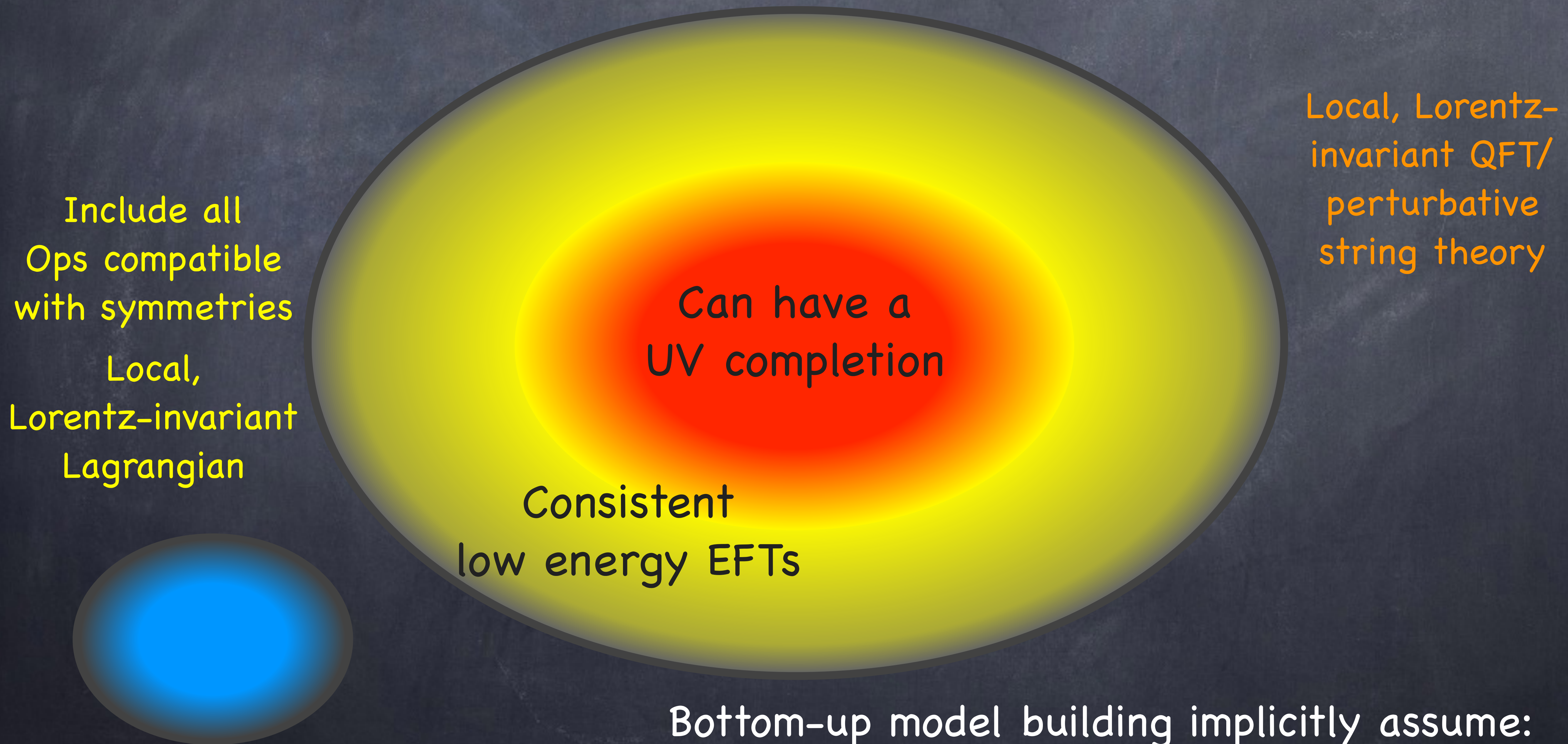

Bottom-up model building implicitly assume:
every EFT can be UV completed

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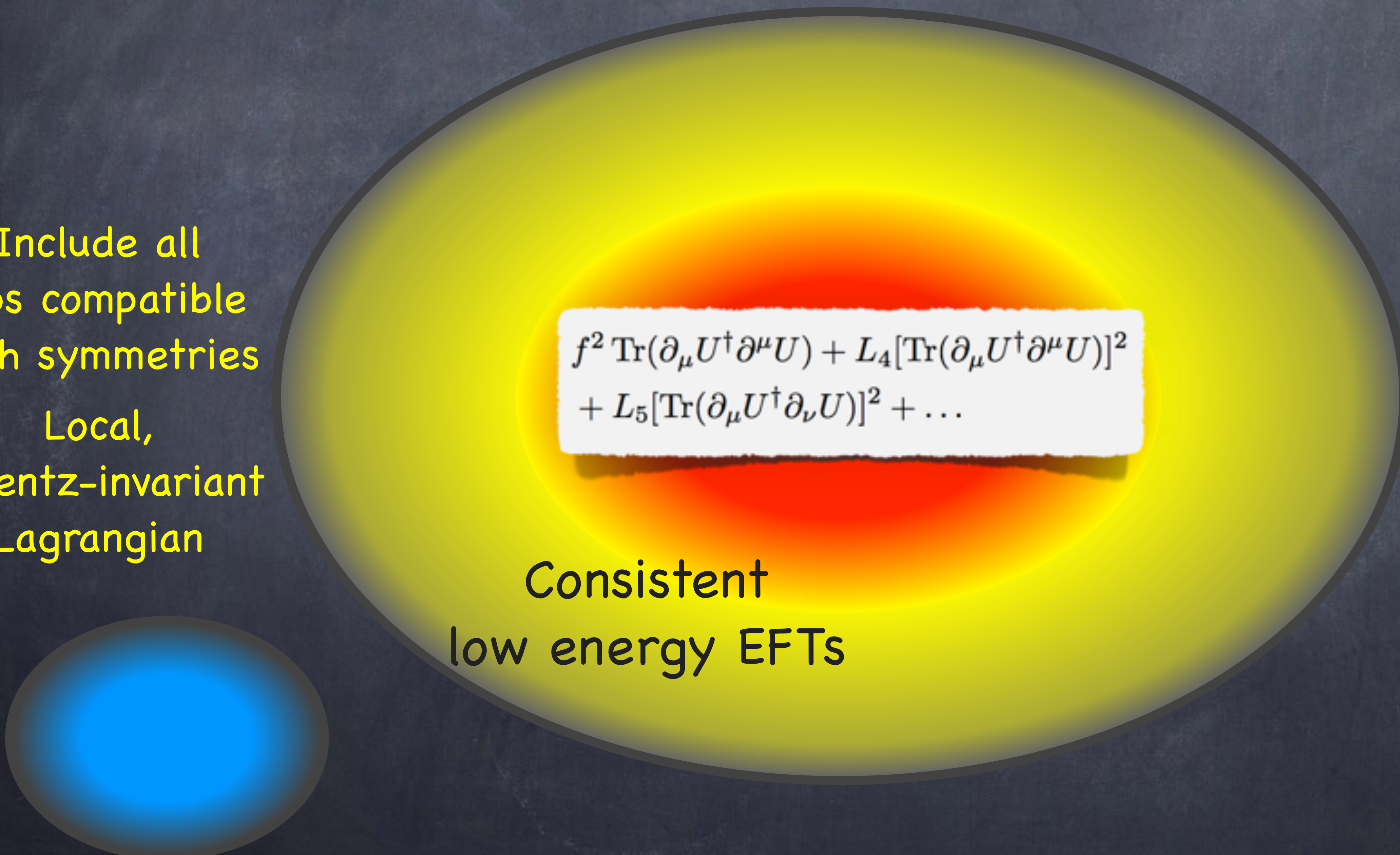

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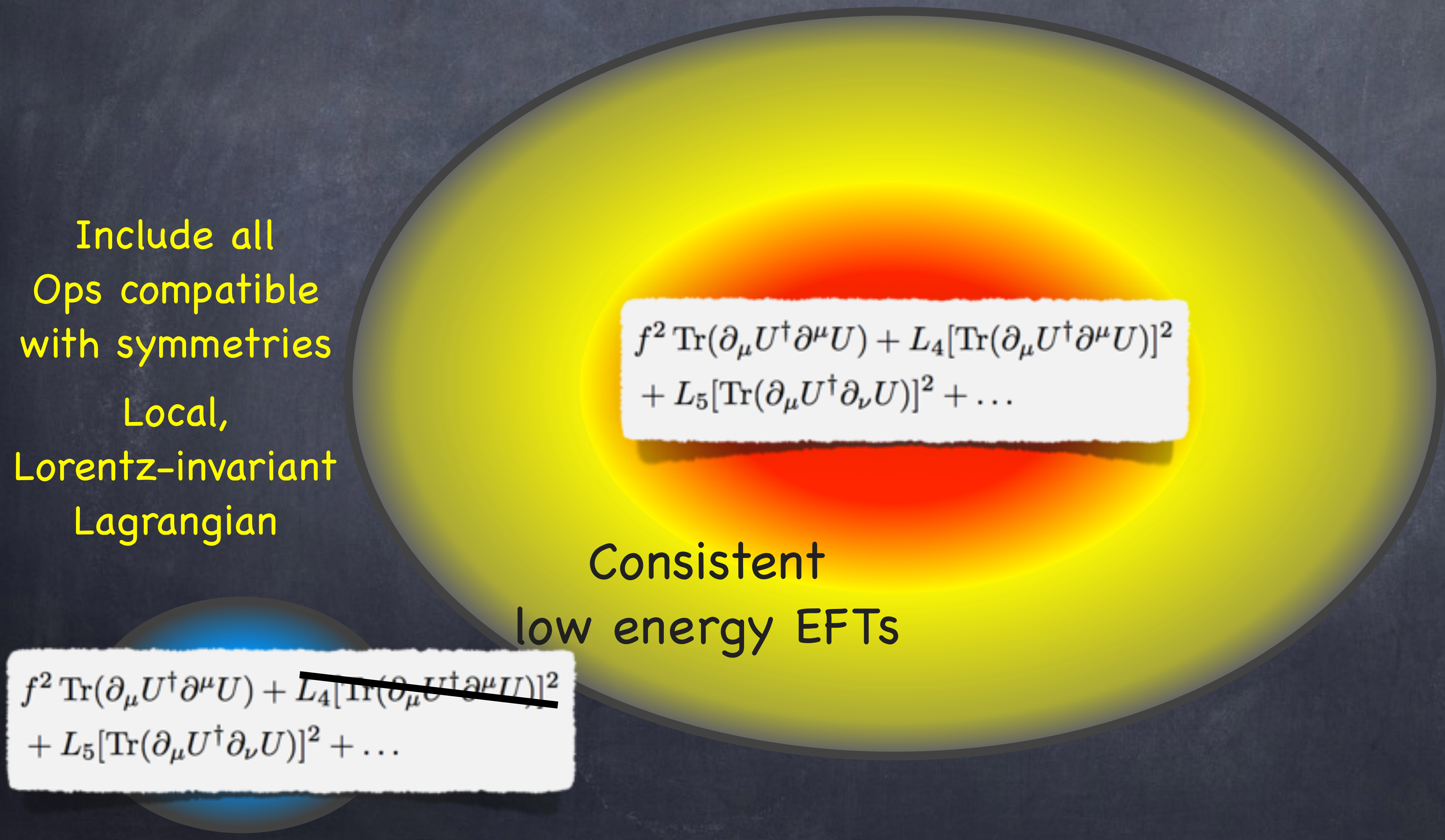
Include all Ops compatible with symmetries

Local, Lorentz-invariant Lagrangian



Local, Lorentz-invariant QFT/ perturbative string theory

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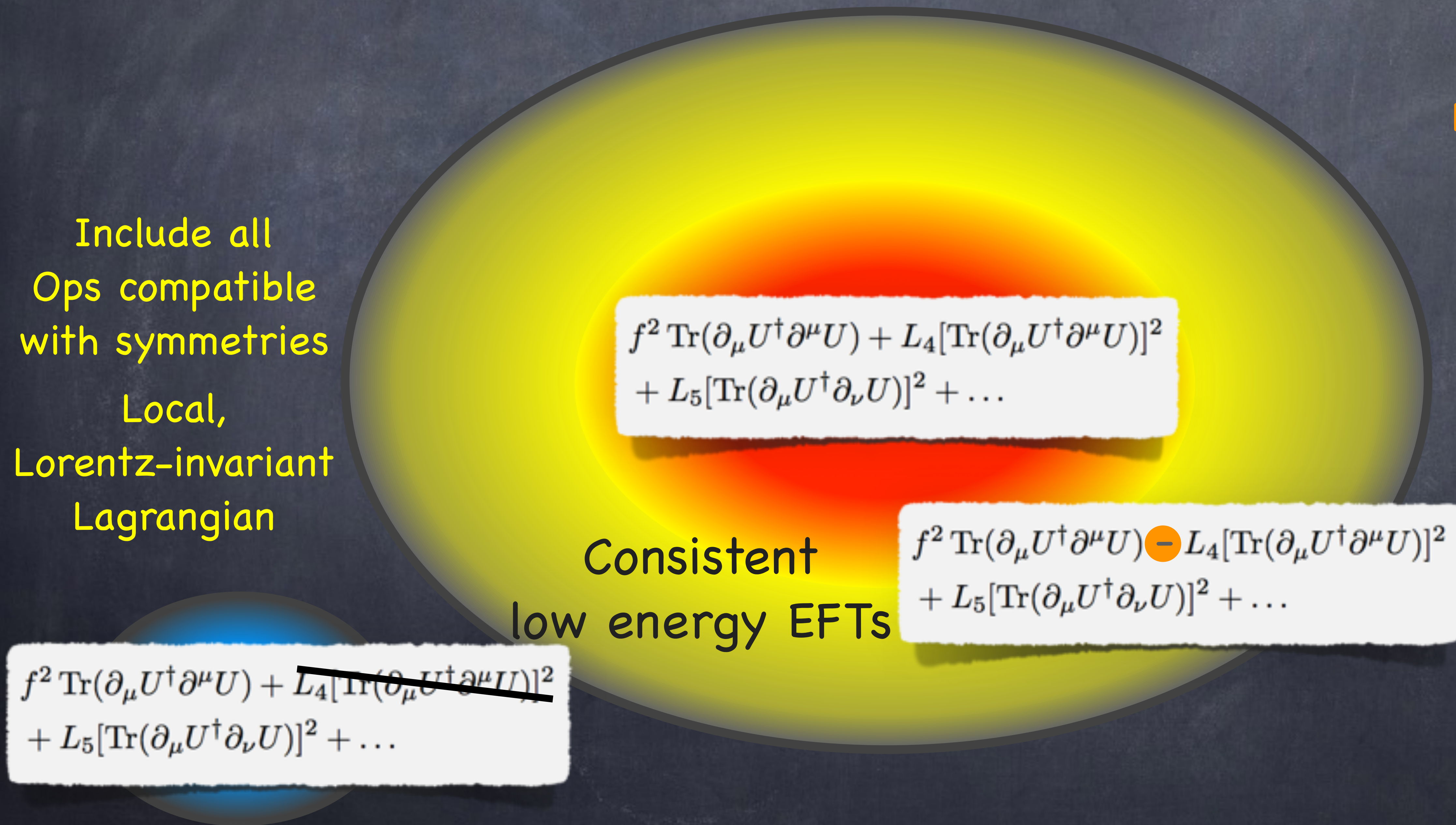

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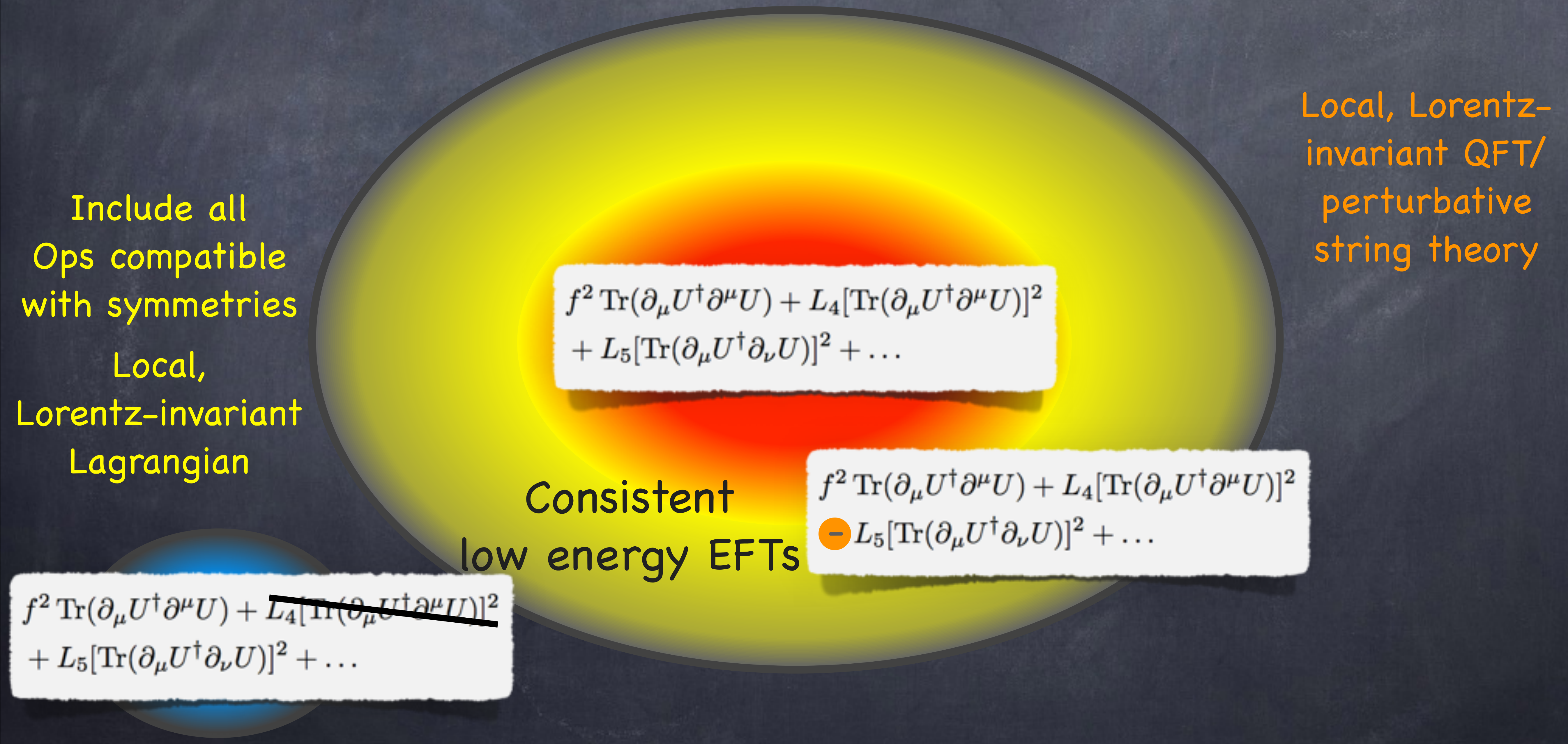

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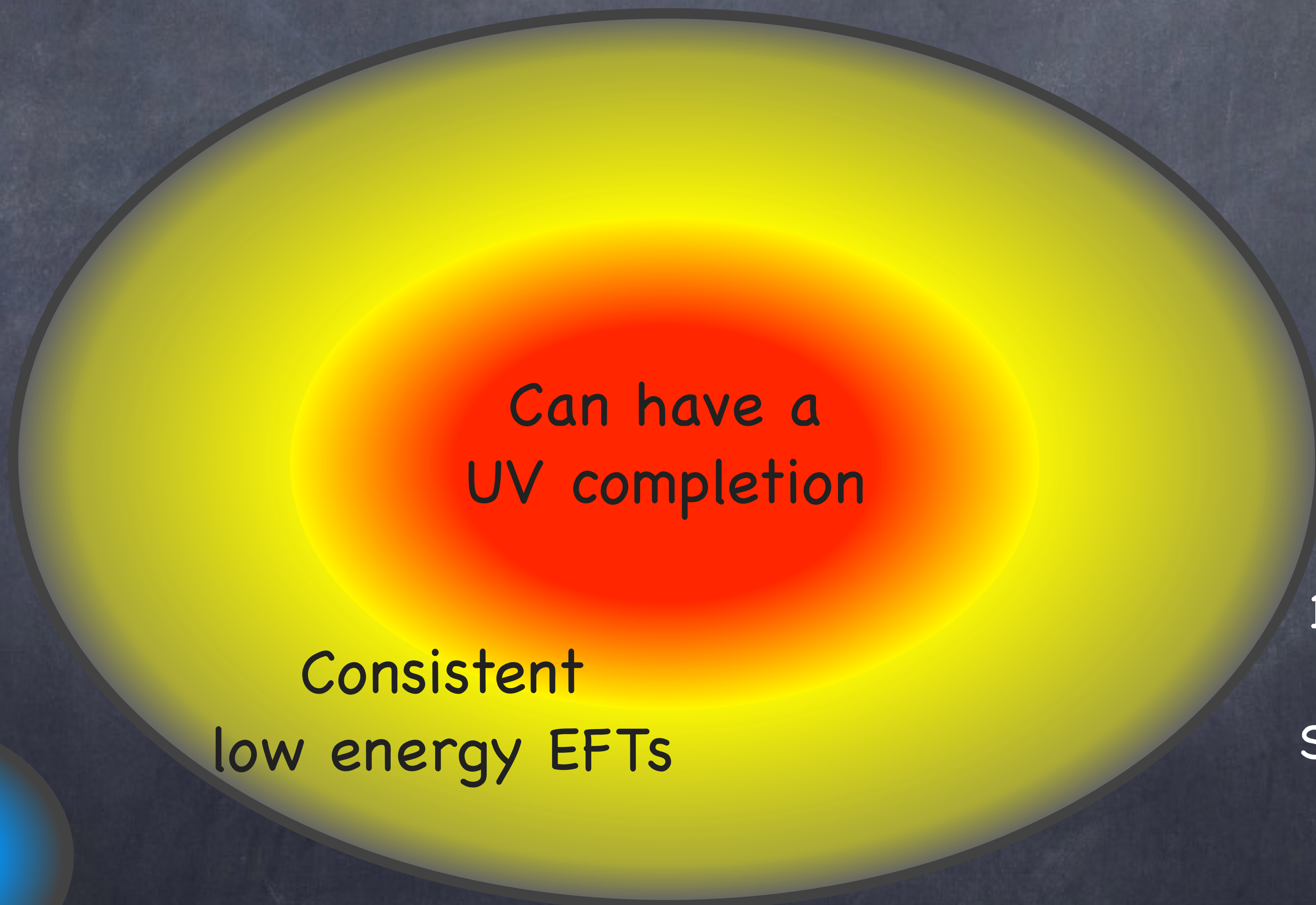

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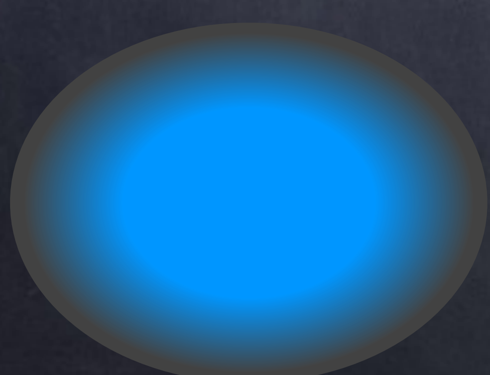

1) Compatible with a microscopic S-matrix satisfying usual analyticity conditions

2) No superluminal propagation

Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi '06

If EFT is the low energy limit of a theory with standard S-matrix properties (unitarity, analiticity, Froissart bound) then

$2 \longrightarrow 2$ forward scattering amplitude cannot go to zero faster than cs^2 with $c>0$

$$\mathcal{L} = \partial_\mu \pi \partial^\mu \pi + \frac{c}{\Lambda^4}(\partial_\mu \pi \partial^\mu \pi)^2 + \dots$$

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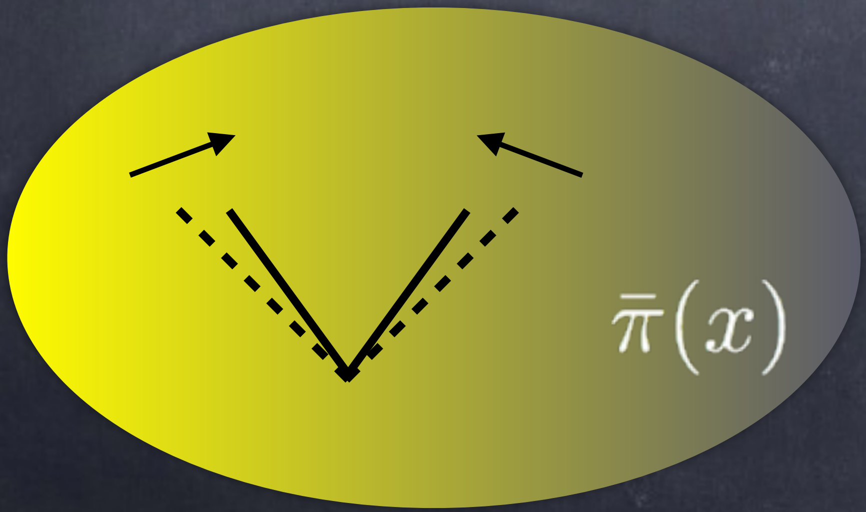
2 ⟶ 2 forward scattering amplitude cannot go to zero faster than cs^2 with $c>0$

If EFT is the low energy limit of a local, Lorentz invariant theory then

$$\mathcal{L} = \partial_\mu \pi \partial^\mu \pi + \frac{c}{\Lambda^4}(\partial_\mu \bar{\pi} \partial^\mu \pi)^2 + \ldots$$

The correction to the light cone around non-trivial backgrounds must always go in the subluminal direction



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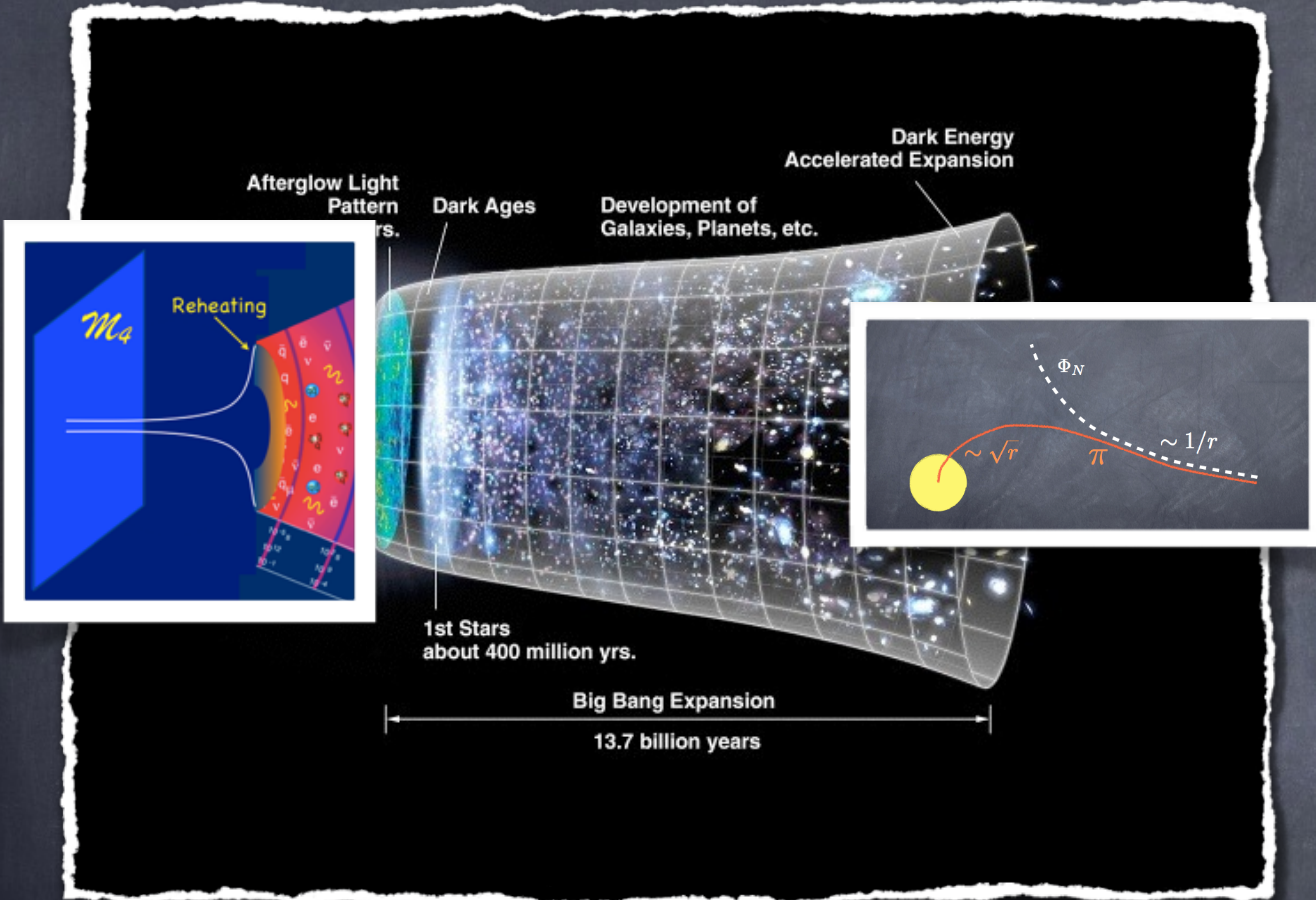
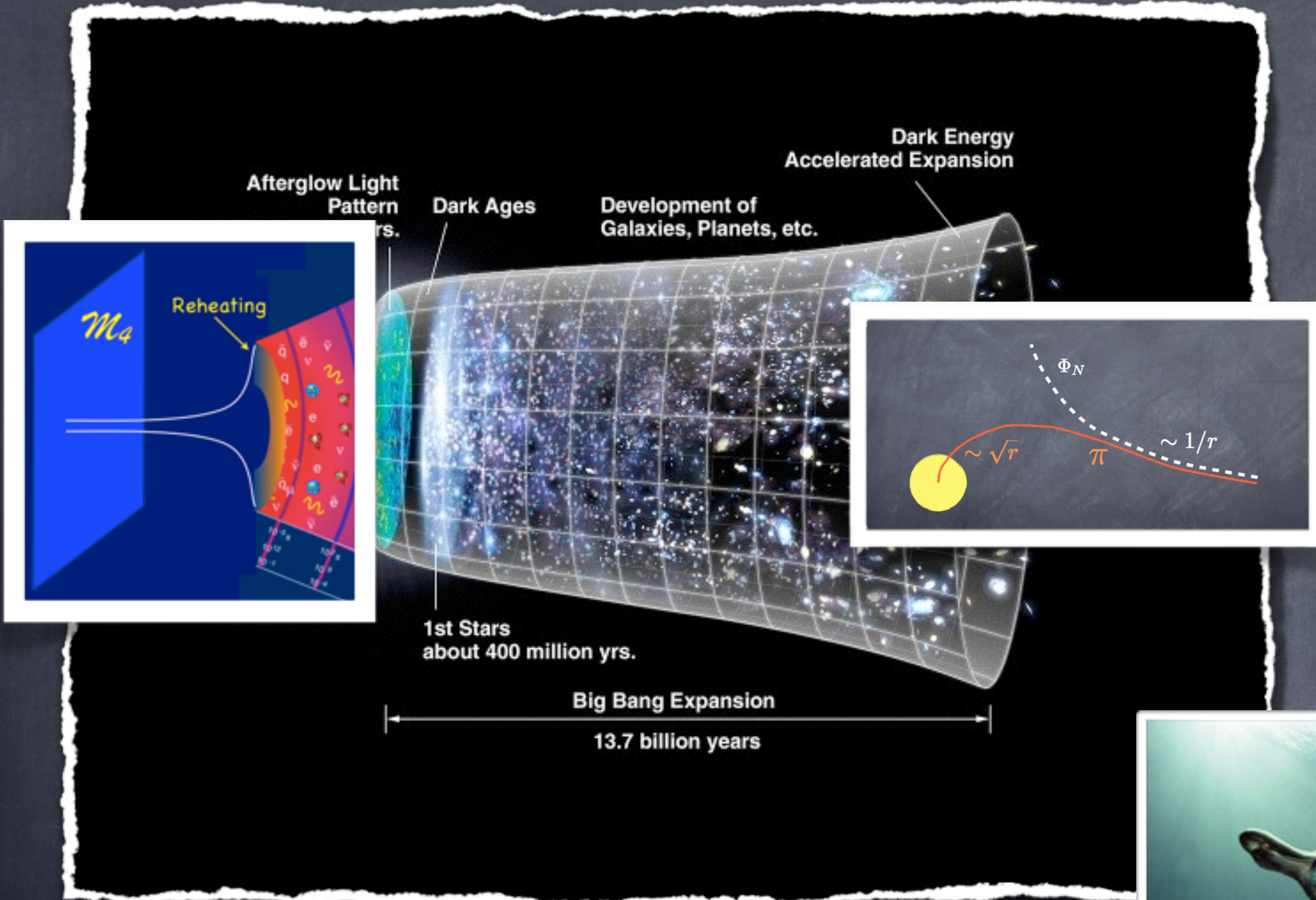


The Galileon



The Galileon

"The ornithorhynchus of EFT"

A weird animal: a HD theory with only 2nd order e.o.m.

As its four legged analogue, it evades the standard preconceptions...

Scalar theories with higher derivatives

Usually they describe new pathological ghost-like degrees of freedom

$$-(\partial\phi)^2 + \frac{1}{M^2}(\Box\phi)^2 \to -(\partial\phi)^2 + (\partial\chi)^2 + M^2\chi^2$$

Is there a HD lagrangian that gives 2 derivatives EOM?

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Is there a HD lagrangian that gives 2 derivatives EOM?

$$\frac{\delta \mathcal{L}_\pi}{\delta\pi} = F(\partial_\mu\partial_\nu\pi)$$ Avoids new ghost-like d.o.f. $\mathcal{L}^{(n)} \sim \partial^{2n-2}\pi^n$

$$\boxed{\pi(x) \to \pi(x) + c + b_\mu x^\mu}$$

The Galileon

Nicolis, Rattazzi, ET '08

$$\mathcal{L}^{(2)} = (\partial\pi)^2$$

$$\mathcal{L}^{(3)} = (\partial\pi)^2\Box\pi$$

There are D operators in D dimensions

$$\mathcal{L}^{(4)} = (\partial\pi)^2[(\Box\pi)^2 - \partial_\mu\partial_\nu\partial^\mu\partial^\nu\pi]$$

$$\mathcal{L}^{(5)} = (\partial\pi)^2[(\Box\pi)^3 - 3\Box\partial_\mu\partial_\nu\pi\partial^\mu\partial^\nu\pi + 2\partial_\mu\partial_\nu\pi\partial^\nu\partial^\alpha\pi\partial^\mu\partial_\alpha\pi]$$

Scalar theories with higher derivatives

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The Galileon

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$$\partial^m(\partial^2\pi)^n$$

$$\mathcal{L}^{(2)} = (\partial\pi)^2$$

$$\mathcal{L}^{(3)} = (\partial\pi)^2\Box\pi$$

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Interesting regime

When classical non-linearities are large. Is it within EFT?

General Relativity

$M_{\rm Pl}^2 \mathcal{R}$

$\mathcal{R}^2, \mathcal{R}_{\mu\nu}\mathcal{R}^{\mu\nu}, \ldots$

$$(\partial h_c)^2 + \frac{h_c}{M_{\rm Pl}}(\partial h_c)^2 + \frac{h_c^2}{M_{\rm Pl}^2}(\partial h_c)^2 + \ldots + \frac{1}{M_{\rm Pl}^2}(\partial^2 h_c)^2 + \frac{h_c}{M_{\rm Pl}^3}(\partial^2 h_c)^2 + \ldots + \frac{1}{M_{\rm Pl}} h_c T$$

$$g_{\mu\nu} = \eta_{\mu\nu} + \frac{h^c_{\mu\nu}}{M_{\rm Pl}}$$

General Relativity

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$$\rho = M\delta^3(r) \qquad h_c \sim \frac{M}{M_{\rm Pl}}\frac{1}{r}$$

Non-linearities become important at a scale rs where $\frac{h_c}{M_{\rm Pl}} \sim 1 \Rightarrow r_s \sim \frac{M}{M_{\rm Pl}^2}$

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All the other terms are suppressed by extra-powers of $\dfrac{\partial}{\Lambda} \sim \dfrac{1}{r\, M_{\rm Pl}} \ll 1$

We can compute classical non-linearities without knowing the UV compl

The Galileon

Non renormalization theorem Luty, Porrati, Rattazzi '03

Loops of quantum fields with interactions $\mathcal{L}^{(3)}, \mathcal{L}^{(4)}, \mathcal{L}^{(5)}$ generate terms involving at least 2 derivatives on the external legs.

In particular galilean terms are not renormalized

$$(\partial\pi)^2 + \frac{c_3}{\Lambda^3}(\partial\pi)^2\Box\pi + \frac{c_4}{\Lambda^6}(\partial\pi)^2(\partial^2\pi)^2 + \frac{c_5}{\Lambda^9}(\partial\pi)^2(\partial^2\pi)^3$$

$$+\frac{d_2}{\Lambda^2}(\partial^2\pi)^2 + \frac{d_3}{\Lambda^5}(\partial^2\pi)^3 + \ldots + \frac{1}{M_{\rm Pl}}\pi T$$

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$$\pi \sim \frac{M}{M_{\rm Pl}}\frac{1}{r}$$

Classical non-linearities important $\frac{\partial^2\pi}{\Lambda^3} \sim 1 \Rightarrow r_V \sim \left(\frac{M}{M_{\rm Pl}\Lambda^3}\right)^{\frac{1}{3}}$

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Interesting regime

When classical non-linearities are large. Is it within EFT?

Galilean invariance protects the structure of the Lagrangian

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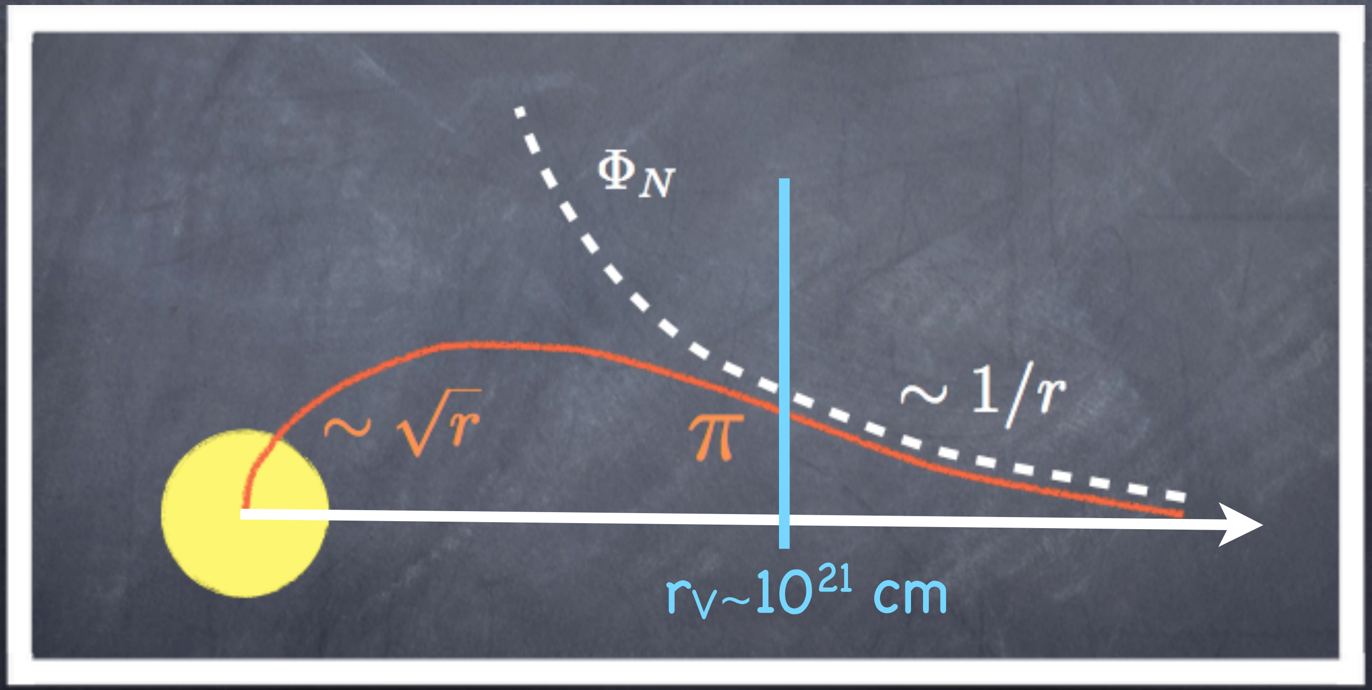
Stable spherically symmetric Vainshtein-like solutions around compact objects

Nicolis, Rattazzi, ET '08



Stable self-accelerating dS solutions $\Lambda = (H_0^2 M_{\rm Pl})^{1/3}$

Superluminality

Fluctuations are exactly luminal about the "de Sitter" background because of SO(4,1)

About a generic deformation, perturbations will propagate on the light cone of the effective metric

$$G_{\mu\nu} \simeq \eta_{\mu\nu} + \frac{2}{\Lambda^3}\partial_\mu\partial_\nu\pi_0 \qquad\qquad \nabla^2\pi_0 \simeq 0$$

the Galileon cubic interaction increases the velocity in some directions while decreases it in others

Any small deformation will have superluminal perturbations (measurable within the EFT)

Nicolis, Rattazzi, ET '09

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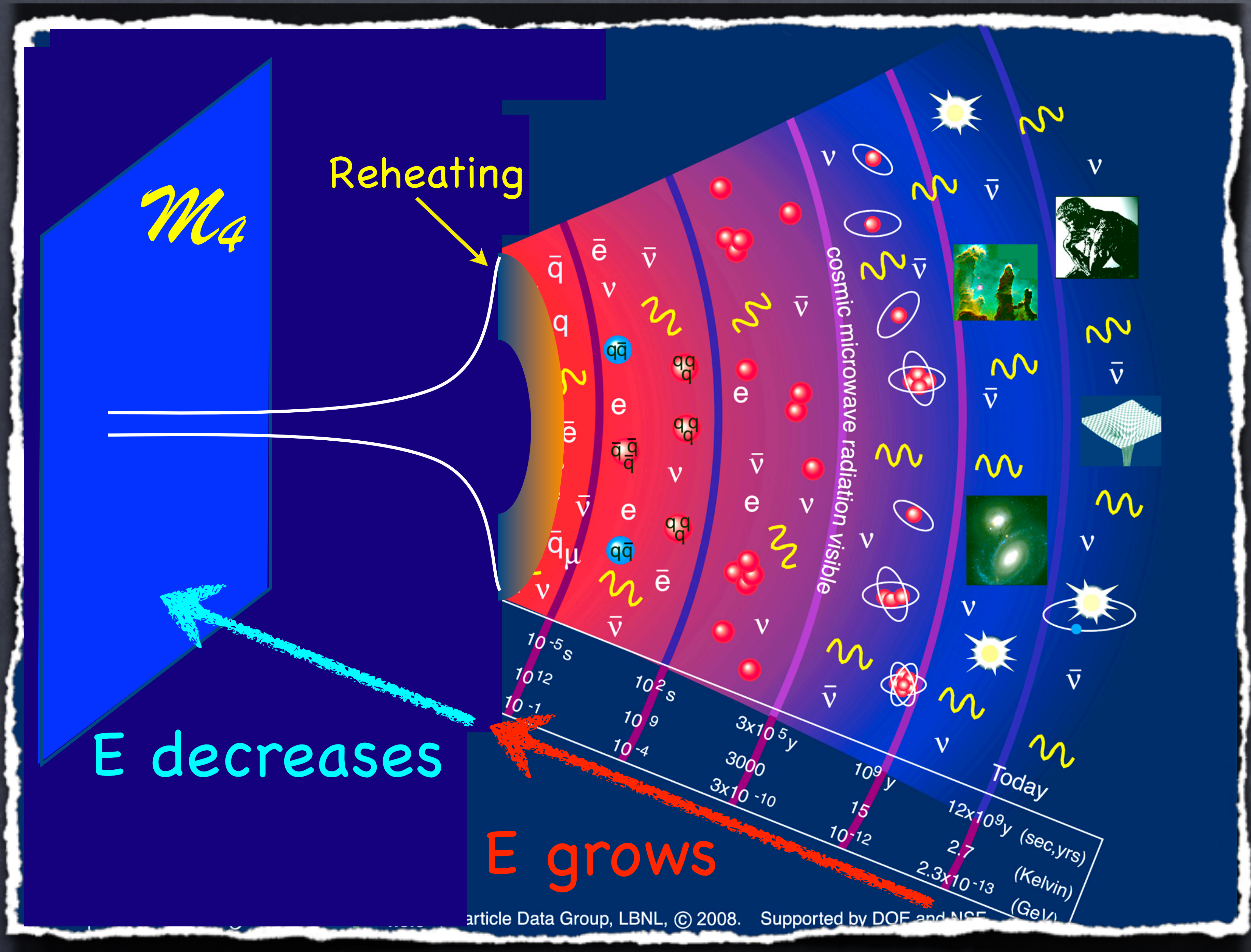
Nicolis, Rattazzi, ET '09

The UV completion cannot be a Lorentz-invariant local QFT

Adams, Arkani-Hamed, Dubovsky, Nicolis, Rattazzi '06



$\mathcal{M}_4$
Reheating
E decreases
E grows
cosmic microwave radiation visible
10^{-5} s
10^{12}
10^{-1}
10^{2} s
10^{9}
10^{-4}
3×10^{5} y
3000
3×10^{-10}
10^{9} y
15
10^{-12}
Today
12×10^{9} y (sec,yrs)
2.7 (Kelvin)
2.3×10^{-13} (GeV)
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The conformal Galileon

Nicolis, Rattazzi, ET '08

Promote galilean transformation + Poincaré to conformal group SO(4,2)

$$\pi(x) \to \pi(\lambda x) + \log \lambda$$

$$\pi(x) \to \pi(cx^2 - 2(c\dot{x})x) - 2c_\mu x^\mu$$

π plays the role of the dilaton $\quad g_{\mu\nu} = e^{2\pi}\eta_{\mu\nu}$

$$\mathcal{L}_\pi = f^2 e^{2\pi}(\partial\pi)^2 + \frac{f^3}{\Lambda^3}\Box\pi(\partial\pi)^2 + \frac{f^3}{2\Lambda^3}(\partial\pi)^4$$

$$e^{\pi_{\rm dS}} = -\frac{1}{H_0 t} \qquad -\infty < t < 0 \qquad H_0^2 = \frac{2\Lambda^3}{3f}$$

Spontaneously breaks SO(4,2) SO(4,1) de Sitter group

Conservation+ scale invariance

$$\begin{cases} \rho = 0 \\ p \propto -\frac{1}{t^4} \end{cases}$$

~~NEC~~

$$\pi(x) = \pi_{\rm dS}(t) + \phi(x)$$

Stable luminal fluctuations

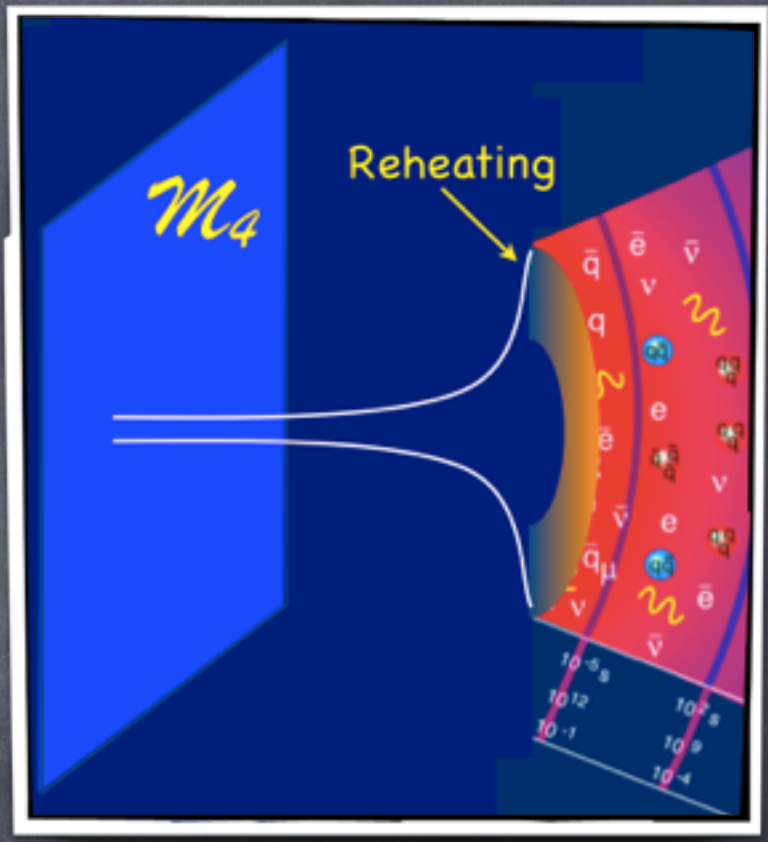
Nicolis, Rattazzi, ET '09

Galilean Genesis

Creminelli, Nicolis, ET '10

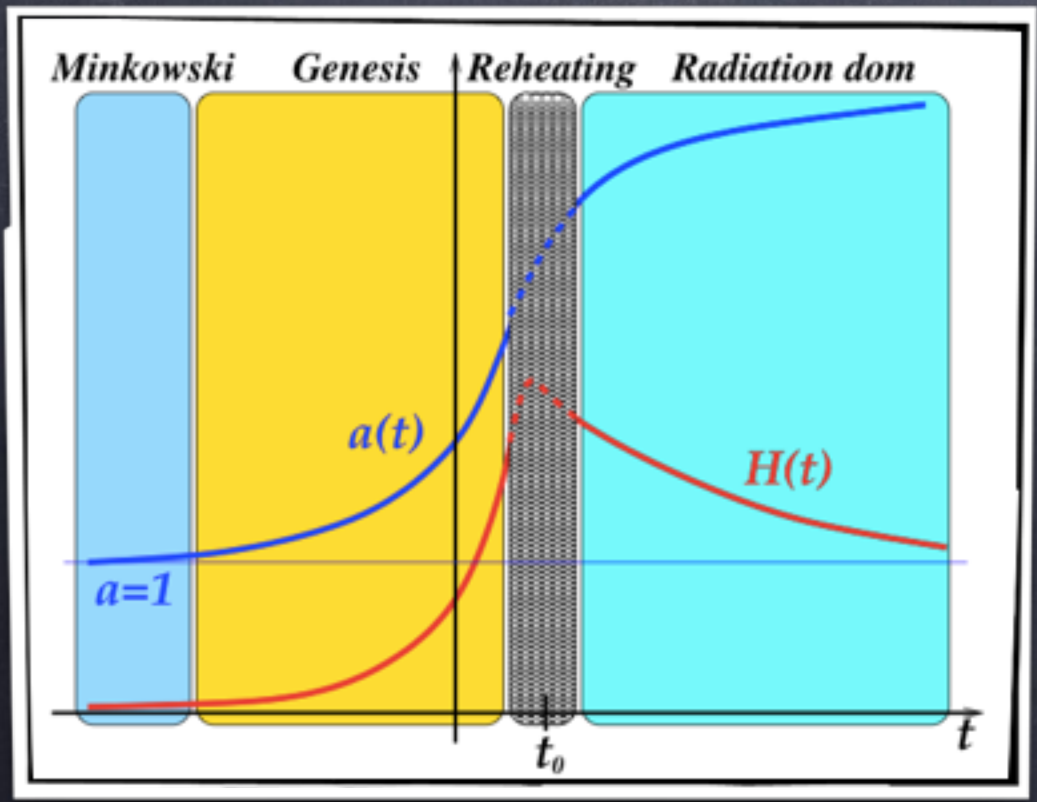
$$\int d^4x\,\sqrt{-g}\Big[f^2e^{2\pi}(\partial\pi)^2+\frac{f^3}{\Lambda^3}\Box\pi(\partial\pi)^2+\frac{f^3}{2\Lambda^3}(\partial\pi)^4\Big]+S_{EH}$$

Conformal Galileon minimally coupled to gravity



$$ds^2=-dt^2+a^2(t)d\vec{x}^2 \qquad \pi=\pi(t)$$

Solve Friedmann's equations for H perturbatively



$$H\simeq-\frac{1}{3}\frac{f^2}{M_{\rm Pl}^2}\frac{1}{H_0^2t^3}$$

$$\pi=\pi_{\rm dS}-\frac{1}{2}\frac{f^2}{M_{\rm Pl}^2}\frac{1}{H_0^2t^2}$$

Galilean Genesis

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$$\int d^4x \sqrt{-g}\Big[f^2 e^{2\pi}(\partial\pi)^2 + \frac{f^3}{\Lambda^3}\Box\pi(\partial\pi)^2 + \frac{f^3}{2\Lambda^3}(\partial\pi)^4\Big] + S_{EH}$$

Conformal Galileon minimally coupled to gravity

$$ds^2 = -dt^2 + a^2(t)d\vec{x}^2 \qquad \pi = \pi(t)$$

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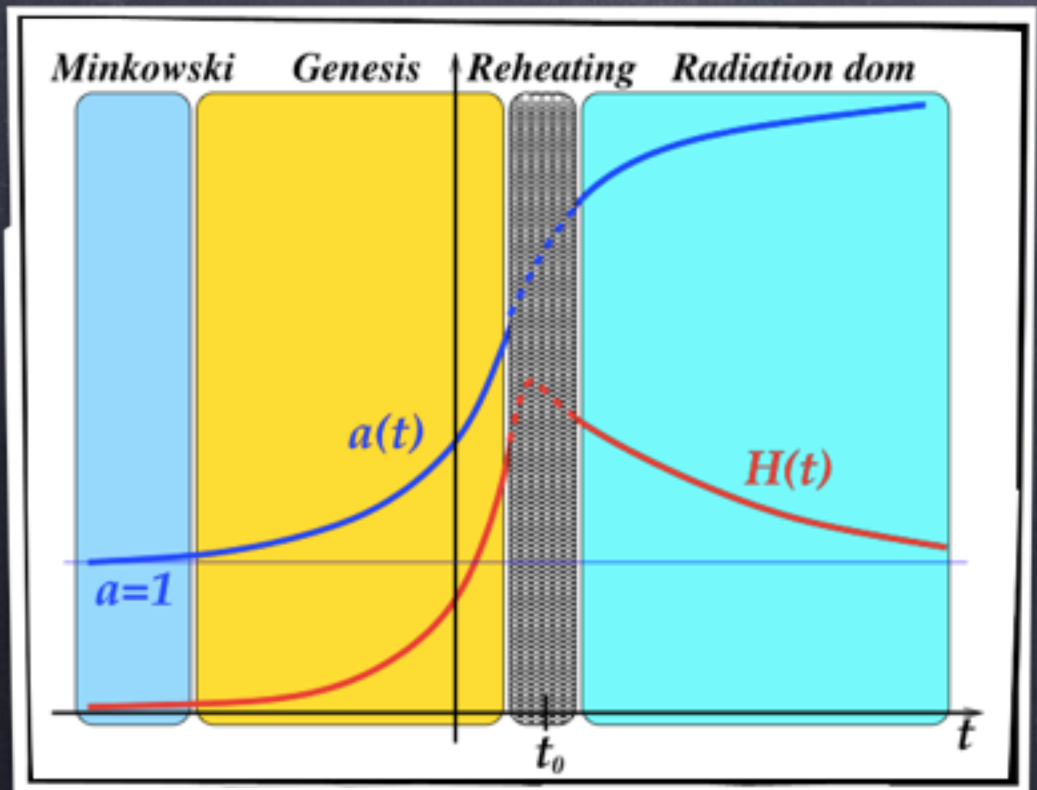
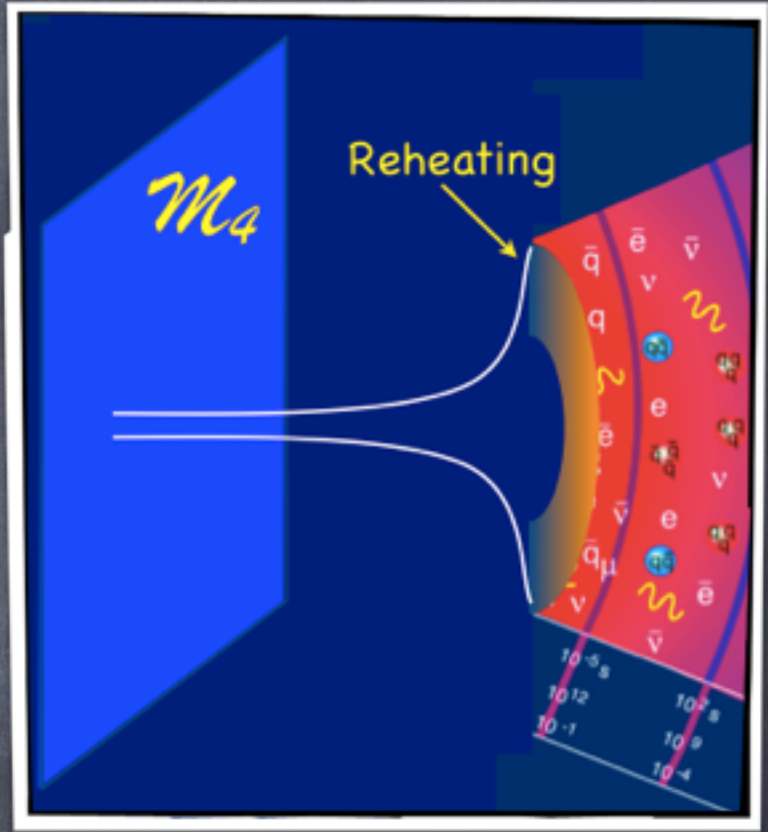
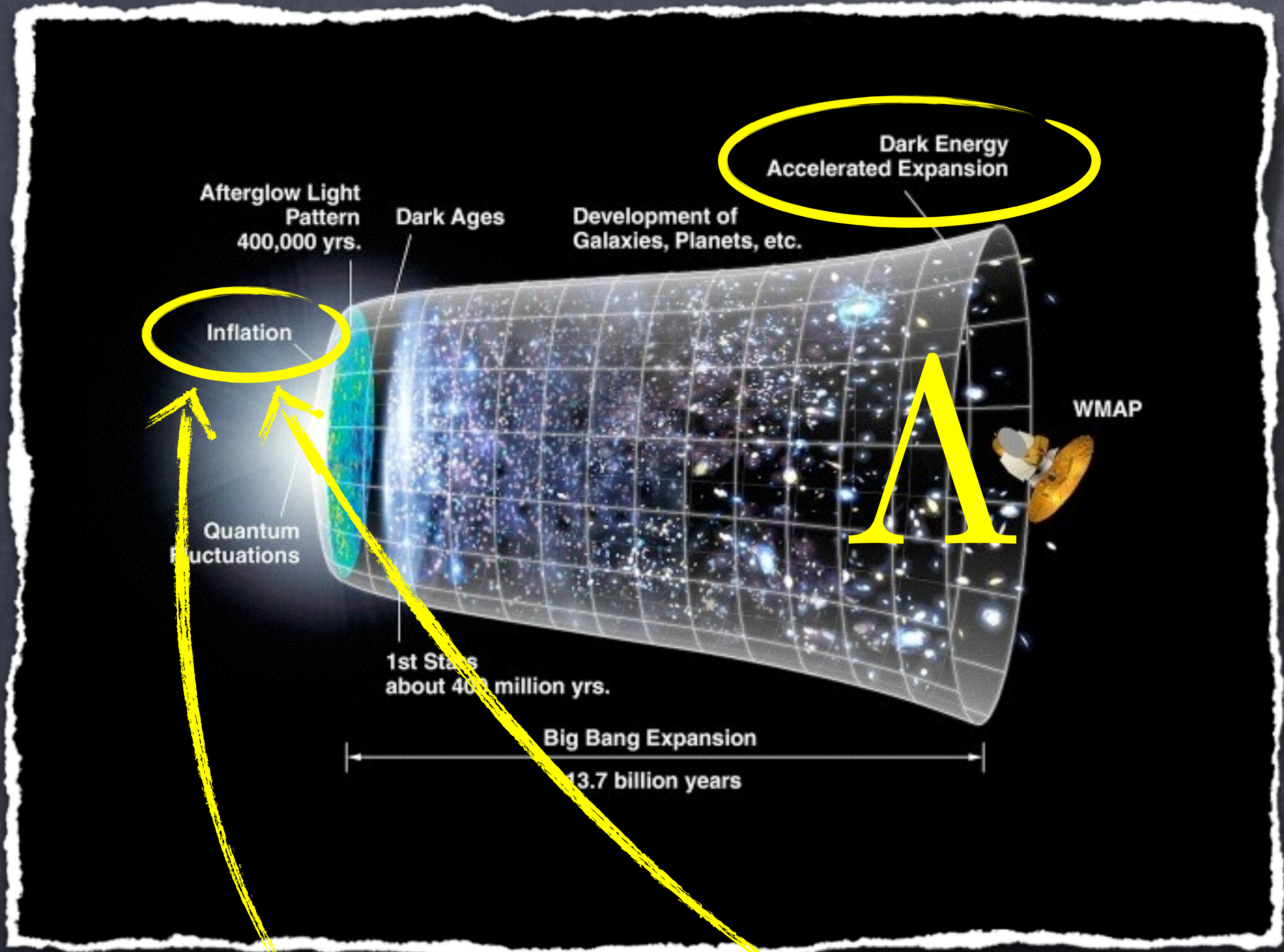


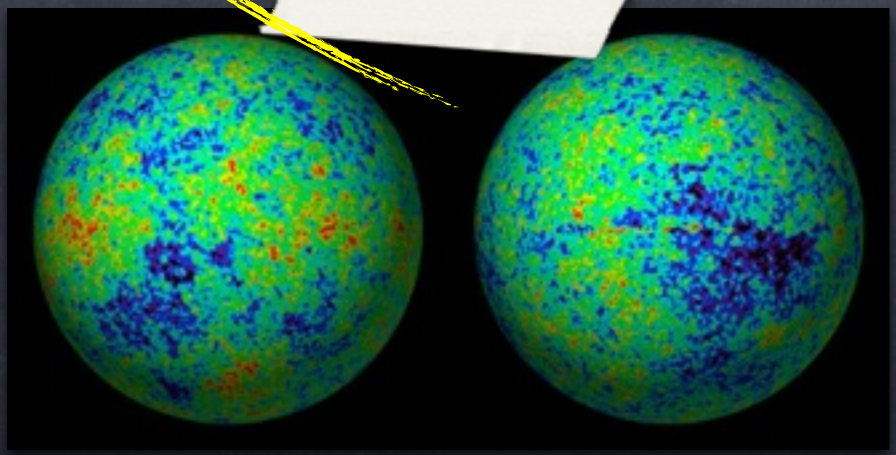


It solves
Horizon & Flatness problems

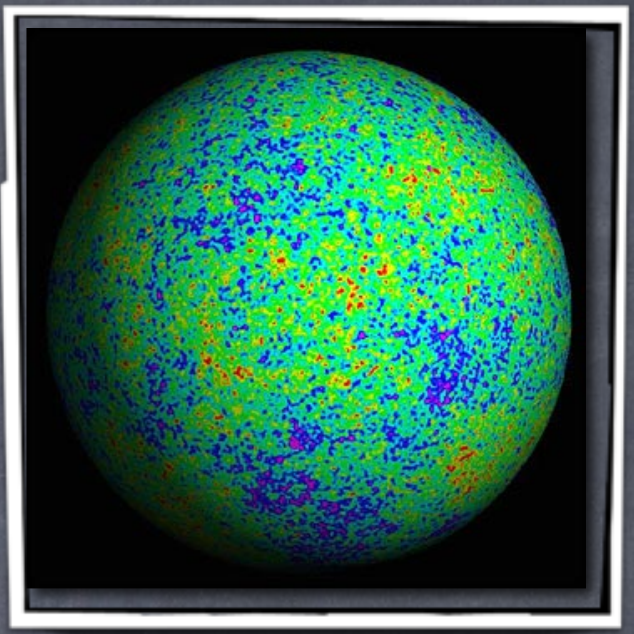


Horizon problem

Flatness problem



Scalar perturbations



π perturbations are not scale invariant
always irrelevant at cosmological scales

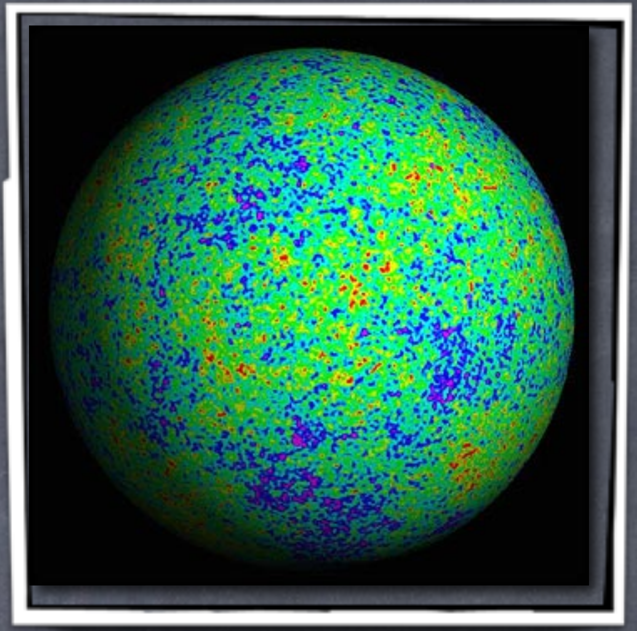
Any coupling to π has to go
through the fictitious metric

$$g^{(\pi)}_{\mu\nu} = e^{2\pi(x)}\eta_{\mu\nu}$$

A spectator massless scalar field σ behave as in de Sitter

Its spectrum is scale invariant because of the dS symmetry

Scalar perturbations



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A spectator massless scalar field σ behave as in de Sitter

Its spectrum is scale invariant because of the dS symmetry

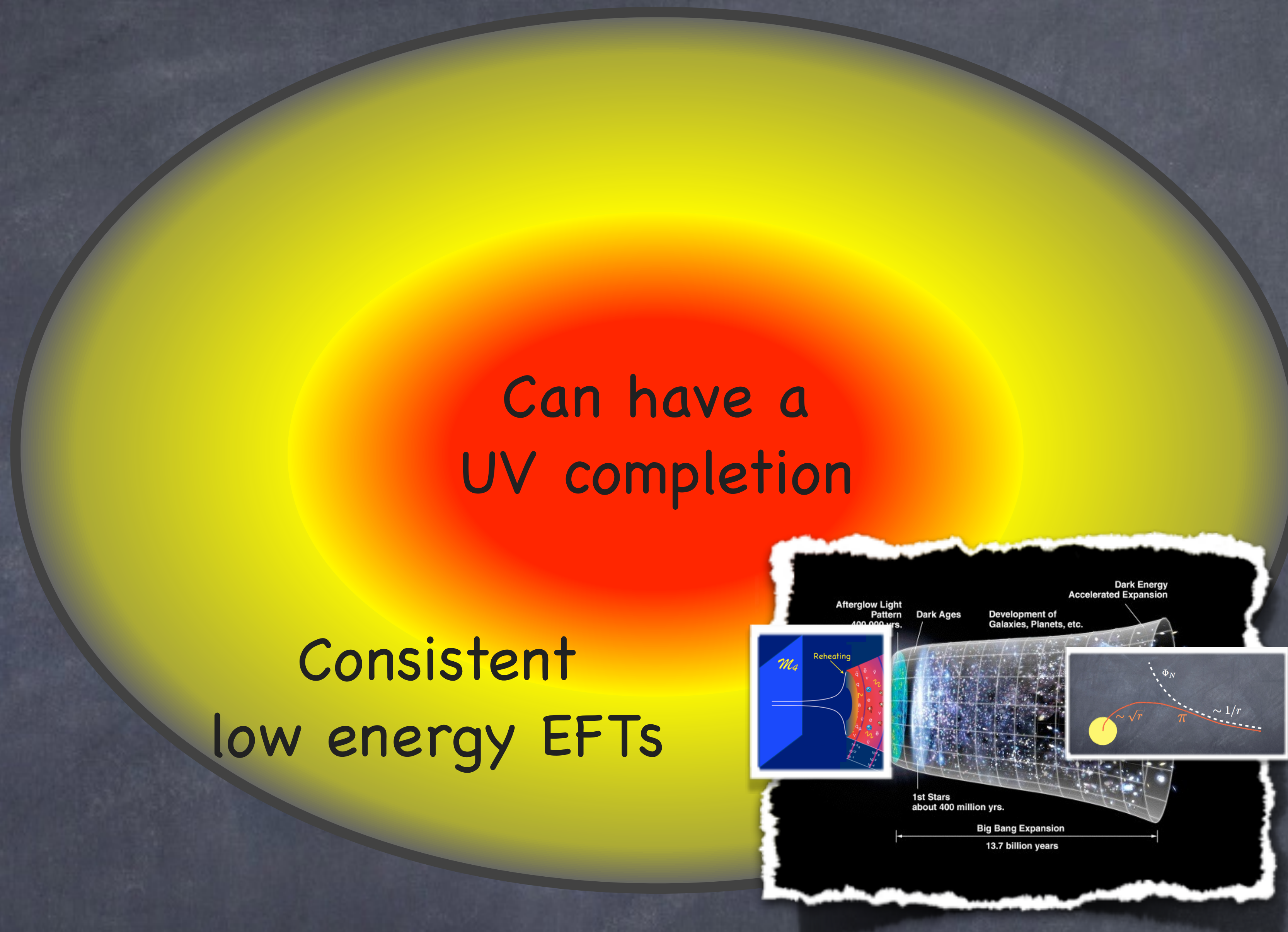
Conversion of σ fluctuations analogous to "second field" mechanism in inflation

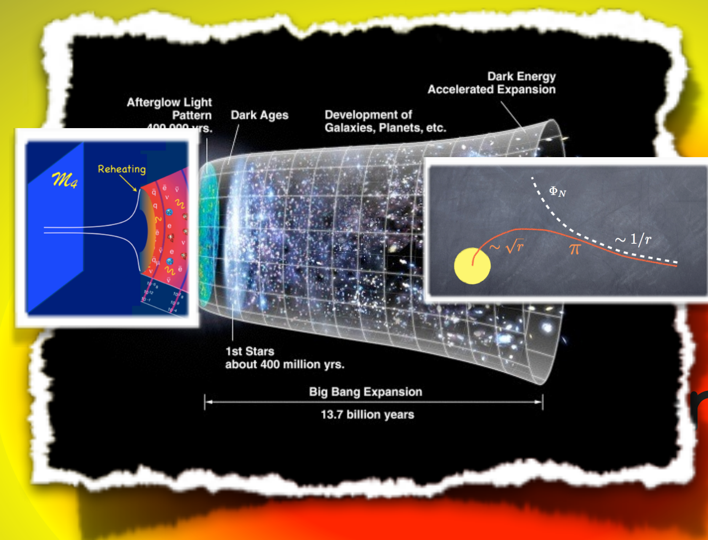
Typical signatures

Low GWs: perturbations produced at low energy

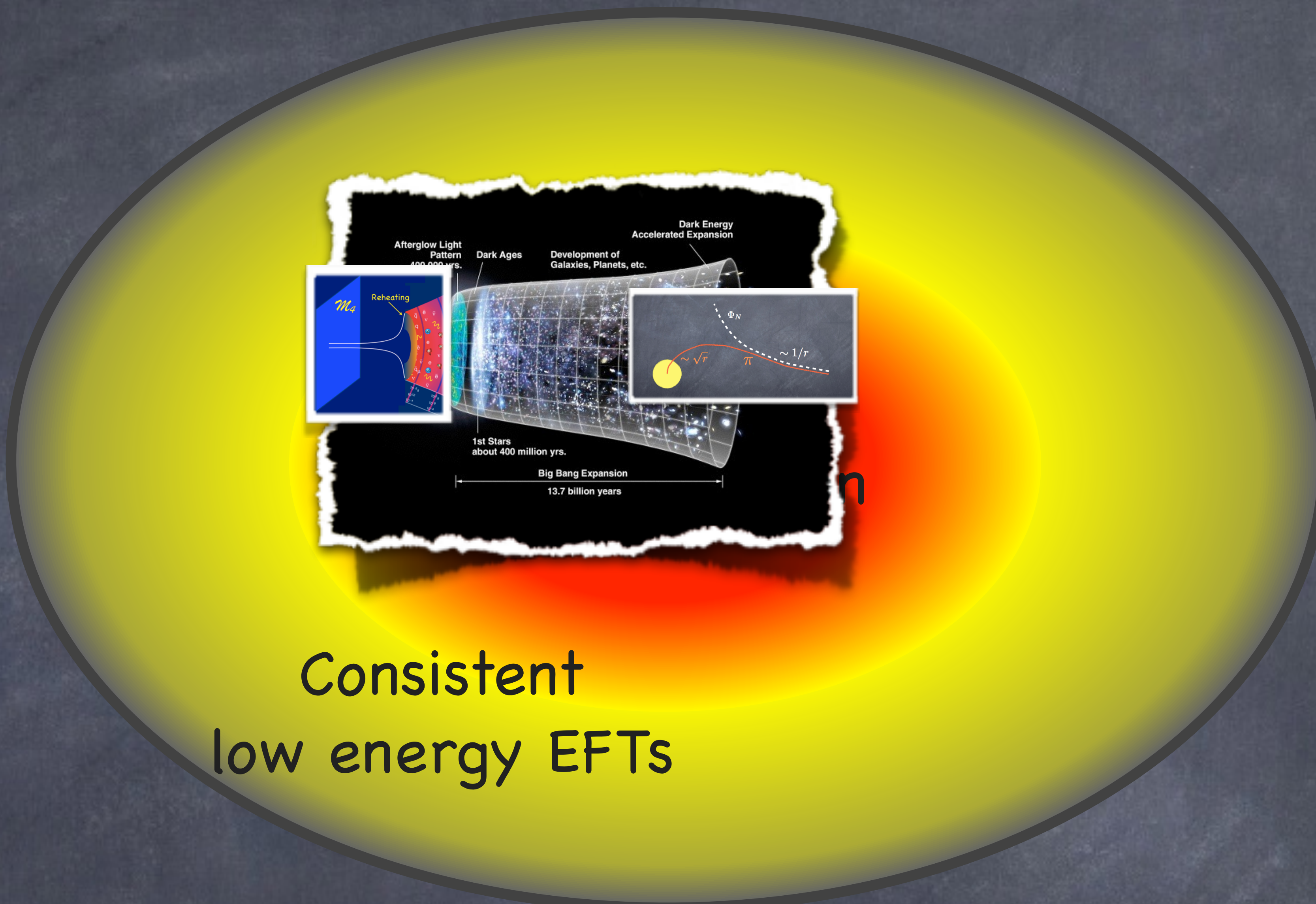
Large local non-Gaussianities

Blue GWs: contraction or ~~NEC~~


Can have a
UV completion
Consistent
low energy EFTs
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
Dark Ages
Development of
Galaxies, Planets, etc.
Reheating
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years



Consistent
low energy EFTs



- Effective Field Theory in cosmological evolution (large non-linear backgrounds)
- Goldstone bosons for spacetime symmetries
- Quantum effects and non-renormalization theorems
- Consistency conditions for a UV completion (superluminality, analiticity, ….)