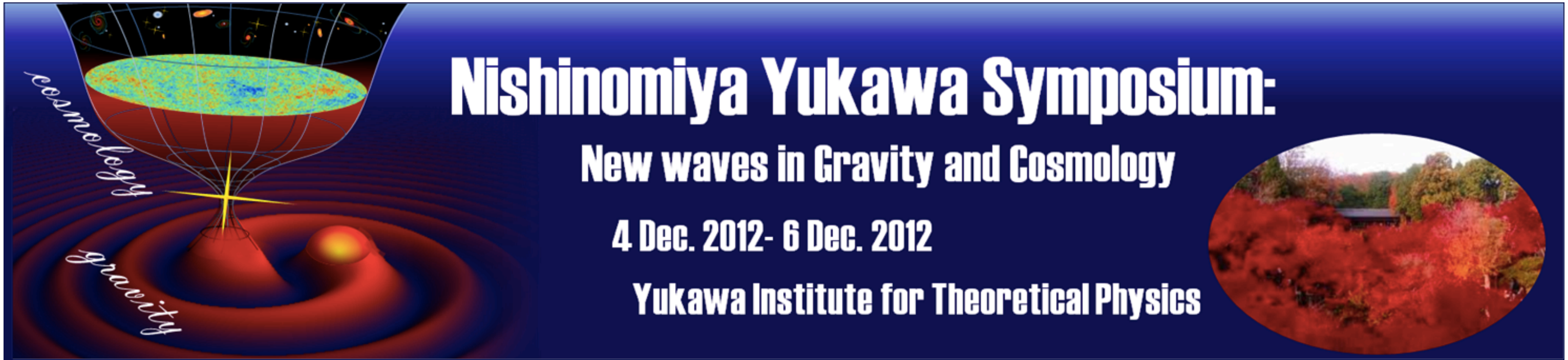


Can we detect the Gravitational Wave Background from preheating after inflation?

Juan García-Bellido

Instituto de Física Teórica - UAM

December 5th 2012

Zel’dovich Conference, IUCAA, Pune (1995)

Kanreki Omedetou gozaimasu

Misao-san!

Outline

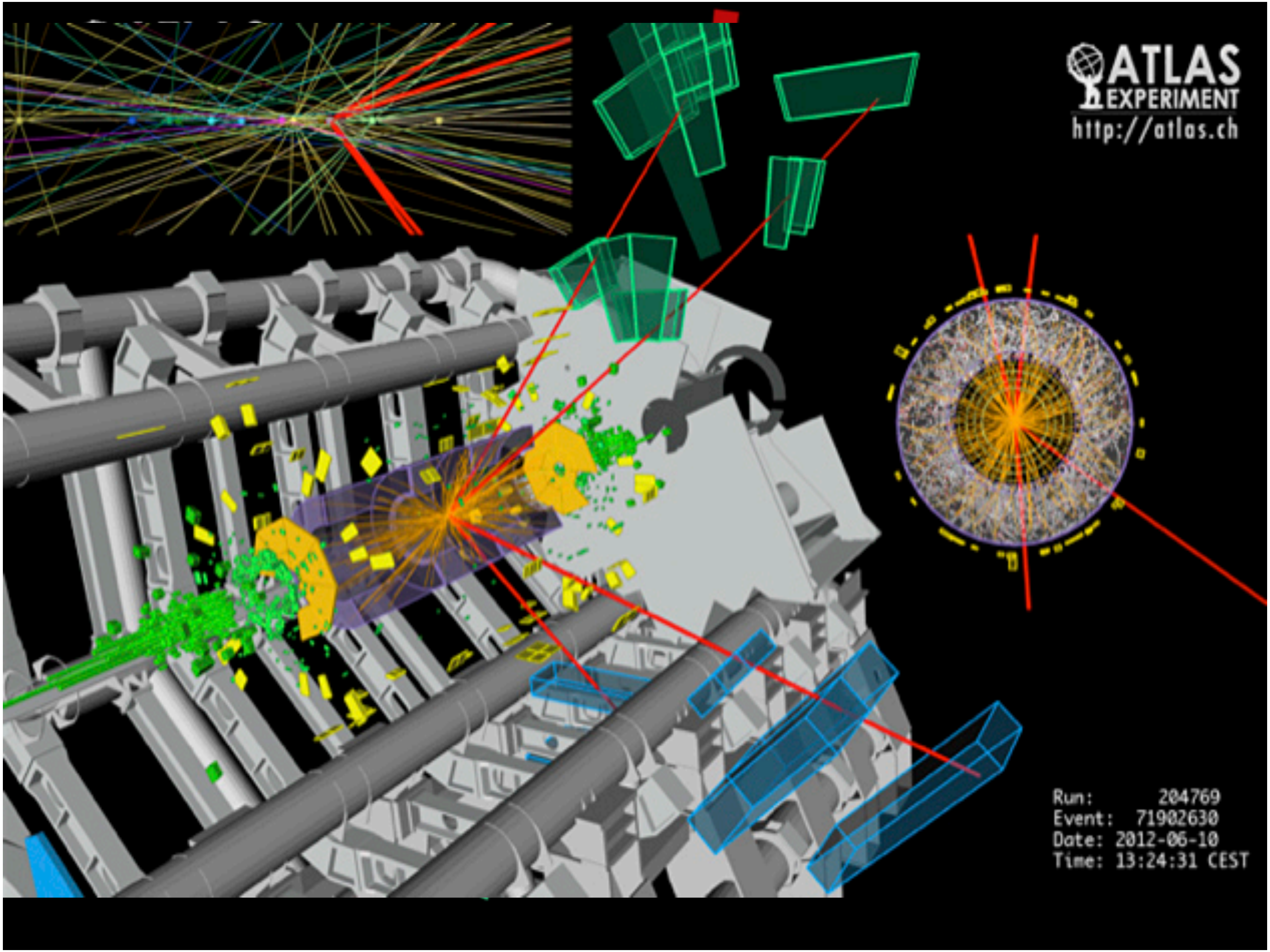
Most fields I have worked on are **also** fields in which Misao-san has worked:

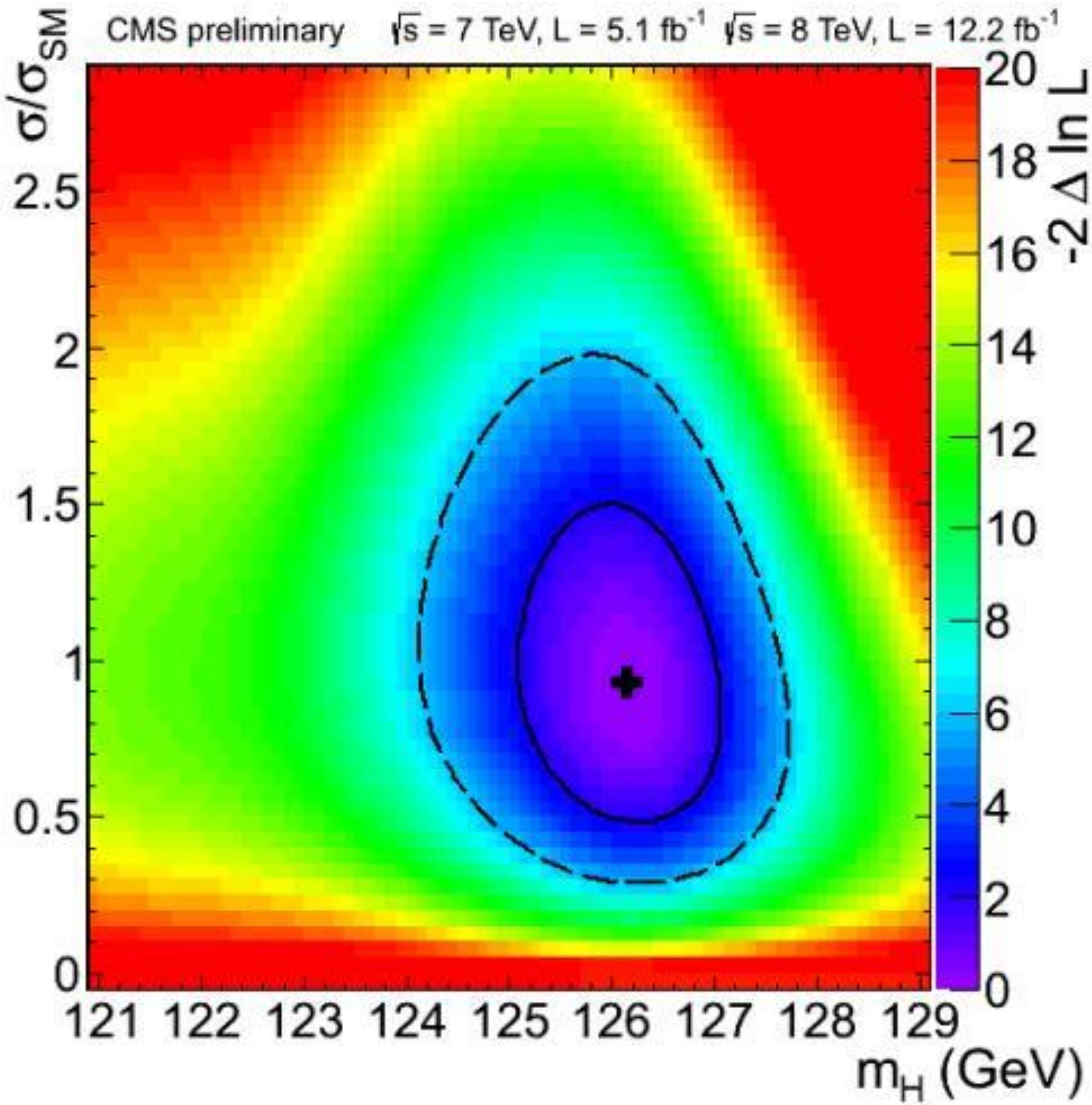
- Stochastic inflation
- Multiple-field inflation (isocurvature modes)
- Open inflation
- Brane worlds
- CMB polarization anisotropies
- Large void LTB models

It is **difficult** to find fields in which Misao-san has **not** worked on:

- Higgs (-Dilaton) Inflation
- Deep Galaxy Surveys (e.g. DES, Euclid, …)
- Gravitational Waves from preheating

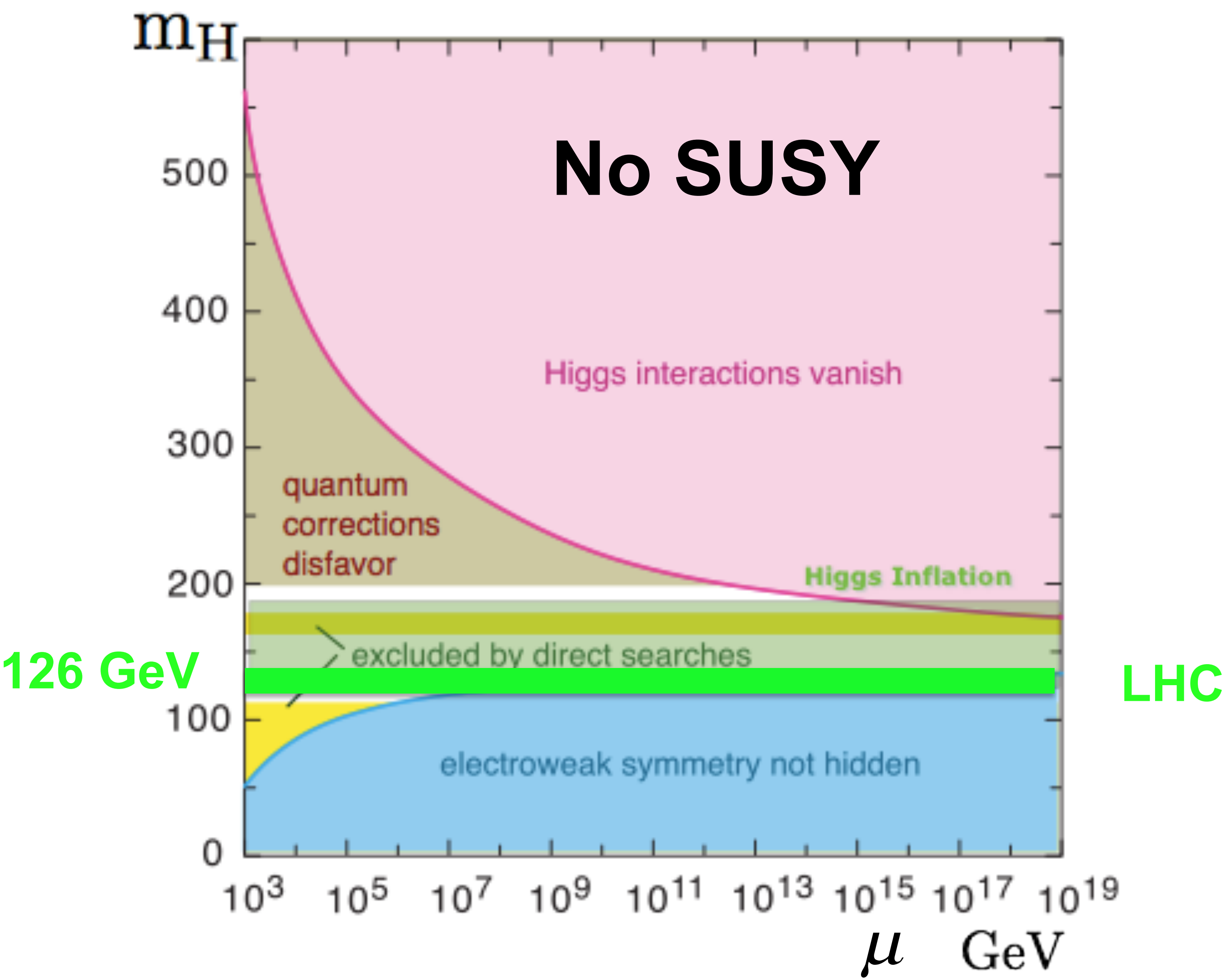

4th July 2012
LHC @ CERN
The Higgs is found!


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST



CMS preliminary
√s = 7 TeV, L = 5.1 fb⁻¹ √s = 8 TeV, L = 12.2 fb⁻¹
σ/σSM
-2 Δ ln L
mH (GeV)
0
0.5
1
1.5
2
2.5
121
122
123
124
125
126
127
128
129
20
18
16
14
12
10
8
6
4
2
0

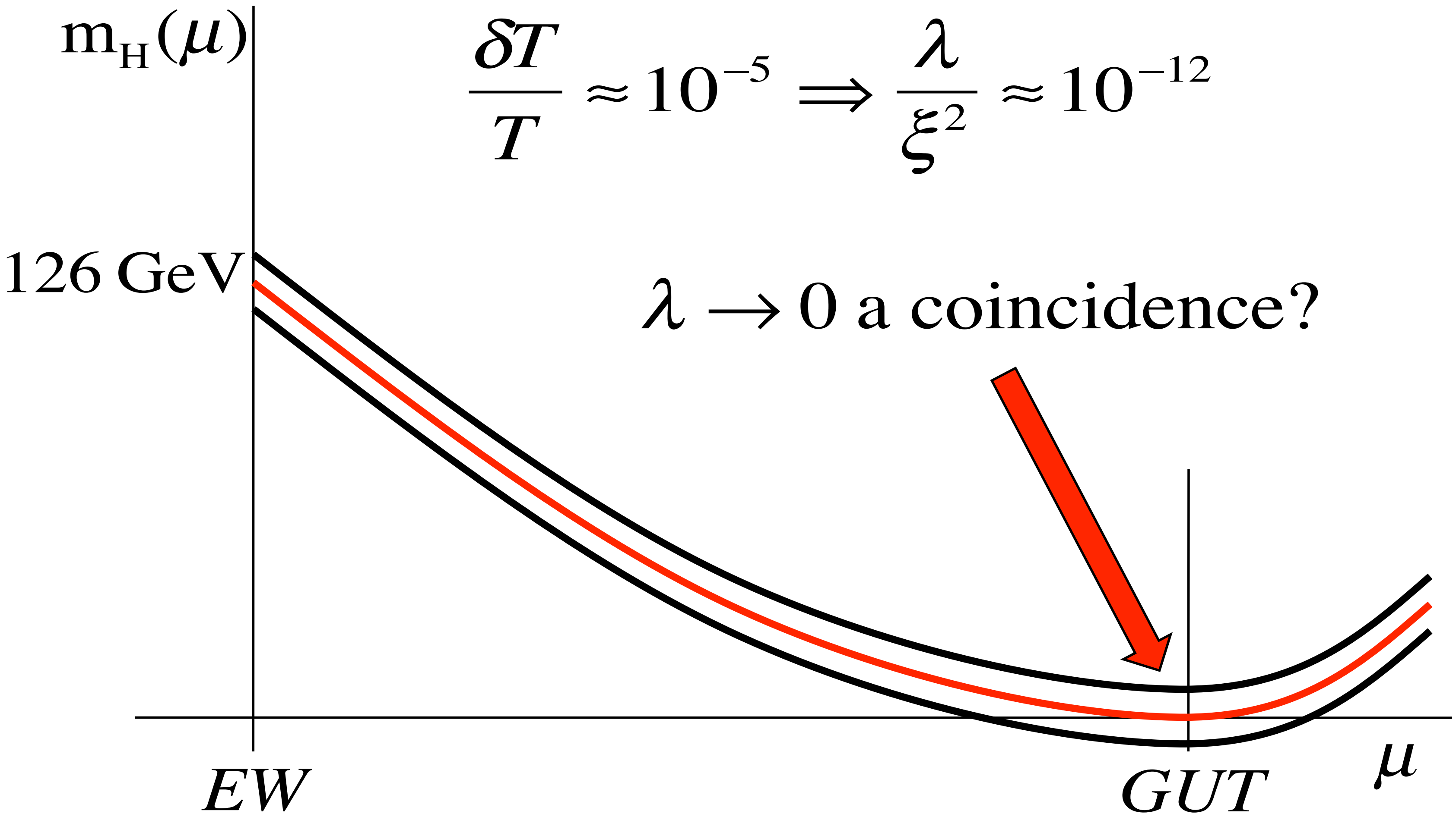
Higgs Landau Pole



RGE running

Bezrukov-Shaposhnikov (2008)

$$\frac{\delta T}{T} \approx 10^{-5} \Rightarrow \frac{\lambda}{\xi^2} \approx 10^{-12}$$



$$S_{HG} \equiv \int d^4x \sqrt{-g} \left\{ \frac{M_P^2}{2} R + \xi H^\dagger H R \right\}$$

Non-minimal grav. coupling

Higgs-dilaton inflation

JGB, Rubio, Shaposhnikov, Zenhausern (2011)

Spontaneous breaking of scale invariance ➔ massless dilaton

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{1}{2}\left(\xi_\chi \chi^2 + \xi_h h^2\right) R - \frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{2}(\partial_\mu h)^2 - V(h,\chi) - \Lambda_0 \;,$$

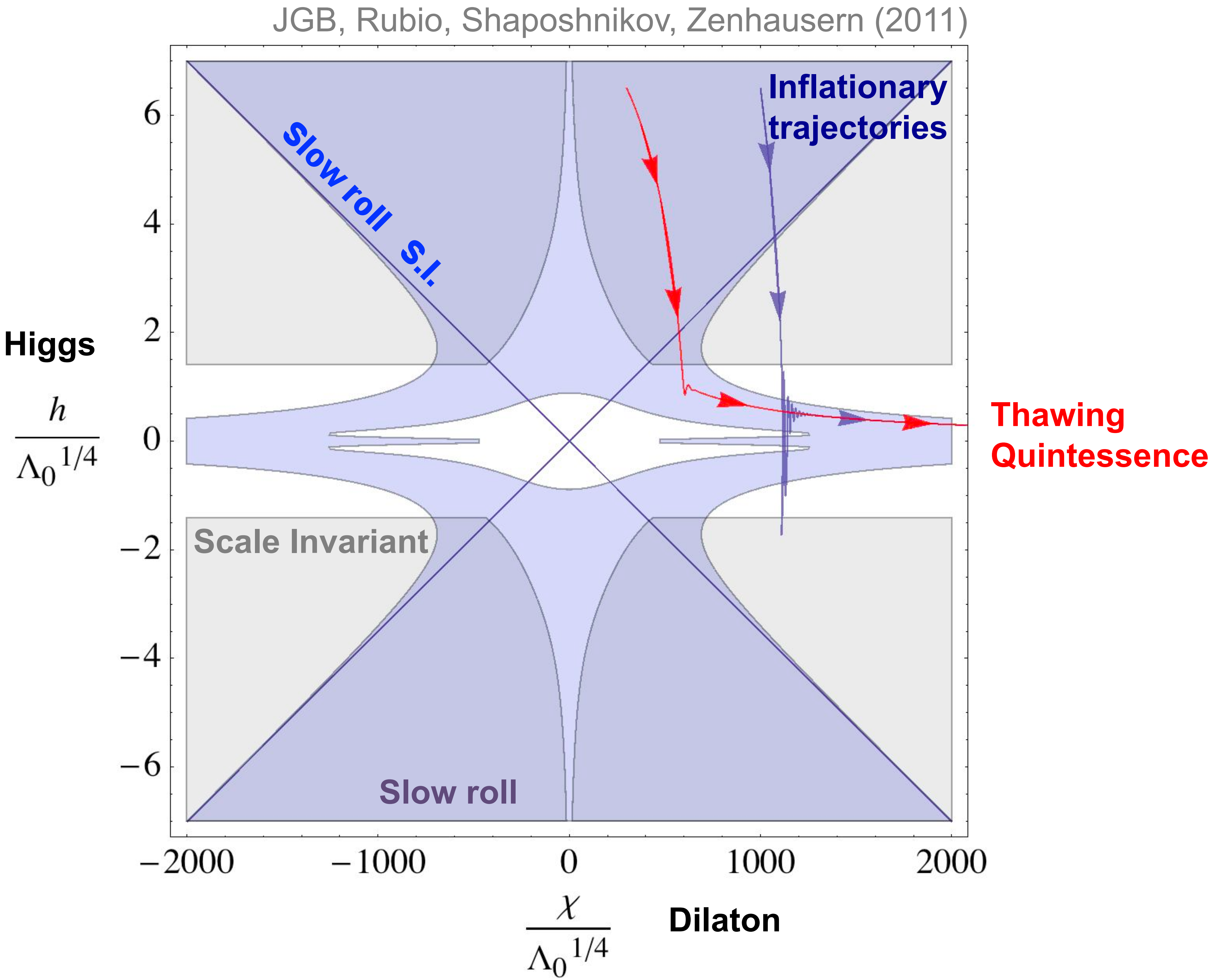
$$\tilde{g}_{\mu\nu} = M_P^{-2}\left(\xi_\chi \chi^2 + \xi_h h^2\right) g_{\mu\nu}$$ Einstein frame metric

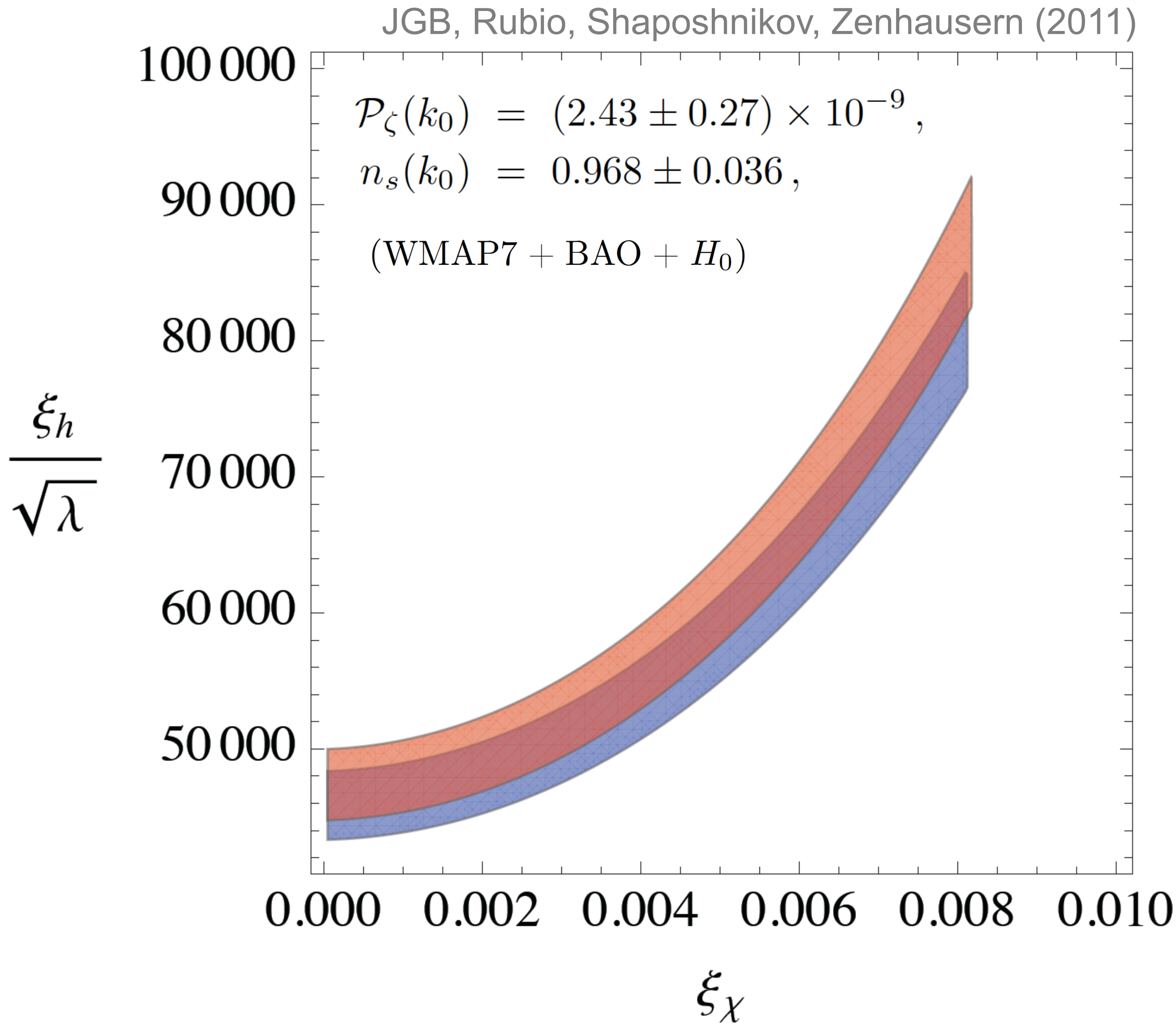
$$\frac{\mathcal{L}}{\sqrt{-\tilde{g}}} = M_P^2 \frac{\tilde{R}}{2} - \frac{1}{2}\tilde{K} - \tilde{U}(h,\chi)$$

$$\tilde{U}(h,\chi) = \frac{M_P^4}{\left(\xi_\chi \chi^2 + \xi_h h^2\right)^2}\left(\frac{\lambda}{4}\left(h^2 - \frac{\alpha}{\lambda}\chi^2\right)^2 + \Lambda_0\right)$$

$$\tilde{D}_\mu \tilde{J}^\mu = -\frac{\partial \tilde{V}_{\Lambda_0}}{\partial \phi^i}\Delta\phi^i = \frac{4\Lambda_0}{\Omega^4}$$ Noether current of scale invariance in E-frame

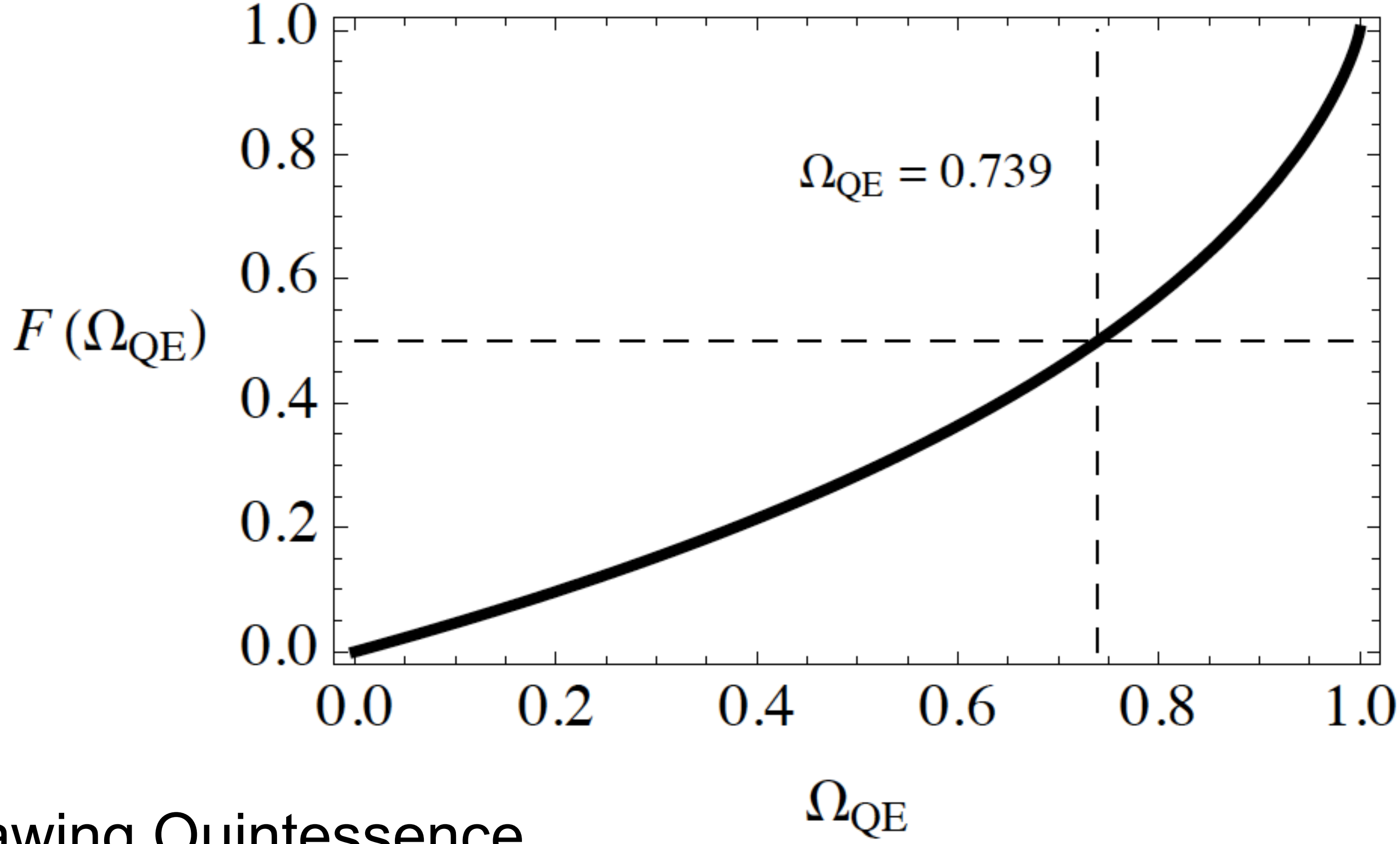
$$\tilde{J}^\mu = \tilde{g}^{\mu\nu}\frac{M_P^2}{2(\xi_\chi \chi^2 + \xi_h h^2)}\partial_\nu\left((1+6\xi_\chi)\chi^2 + (1+6\xi_h)h^2\right)$$


JGB, Rubio, Shaposhnikov, Zenhausern (2011)
Inflationary trajectories
Slow roll S.I.
Higgs
$\frac{h}{\Lambda_0^{1/4}}$
Thawing Quintessence
Scale Invariant
Slow roll
$\frac{\chi}{\Lambda_0^{1/4}}$
Dilaton
6
4
2
0
−2
−4
−6
−2000
−1000
0
1000
2000



JGB, Rubio, Shaposhnikov, Zenhausern (2011)
$\mathcal{P}_\zeta(k_0) = (2.43 \pm 0.27) \times 10^{-9}$,
$n_s(k_0) = 0.968 \pm 0.036$,
(WMAP7 + BAO + H_0)
100 000
90 000
80 000
70 000
60 000
50 000
$\frac{\xi_h}{\sqrt{\lambda}}$
0.000
0.002
0.004
0.006
0.008
0.010
ξ_χ

Early Universe – Late Universe connection



Thawing Quintessence

$$F(\Omega_{QE}) = \left[\frac{1}{\sqrt{\Omega_{QE}}} - \frac{1}{2}\left(\frac{1}{\Omega_{QE}} - 1\right)\ln\frac{1+\sqrt{\Omega_{QE}}}{1-\sqrt{\Omega_{QE}}}\right]^2 \qquad 1 + w_{QE} \simeq \frac{16\gamma^2}{3}F(\Omega_{QE})$$

Early Universe – Late Universe connection

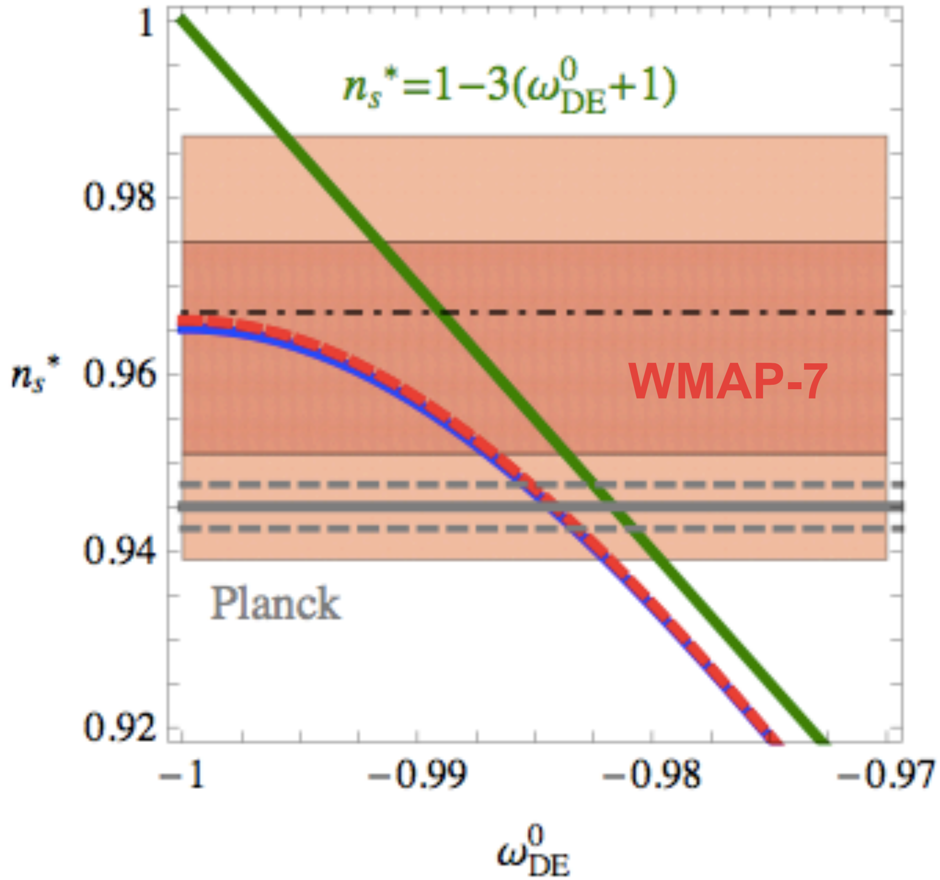
Consistency conditions

1st order ⟷ 0th order

$$n_s^* - 1 \simeq -3(w_{DE}^0 + 1)$$

2nd order ⟷ 1st order

$$\alpha_\zeta(k^*) \simeq 3w_{DE}^a$$



$$w_{DE}(a) = w_{DE}^0 + w_{DE}^a \ln(a/a_0)\,.$$

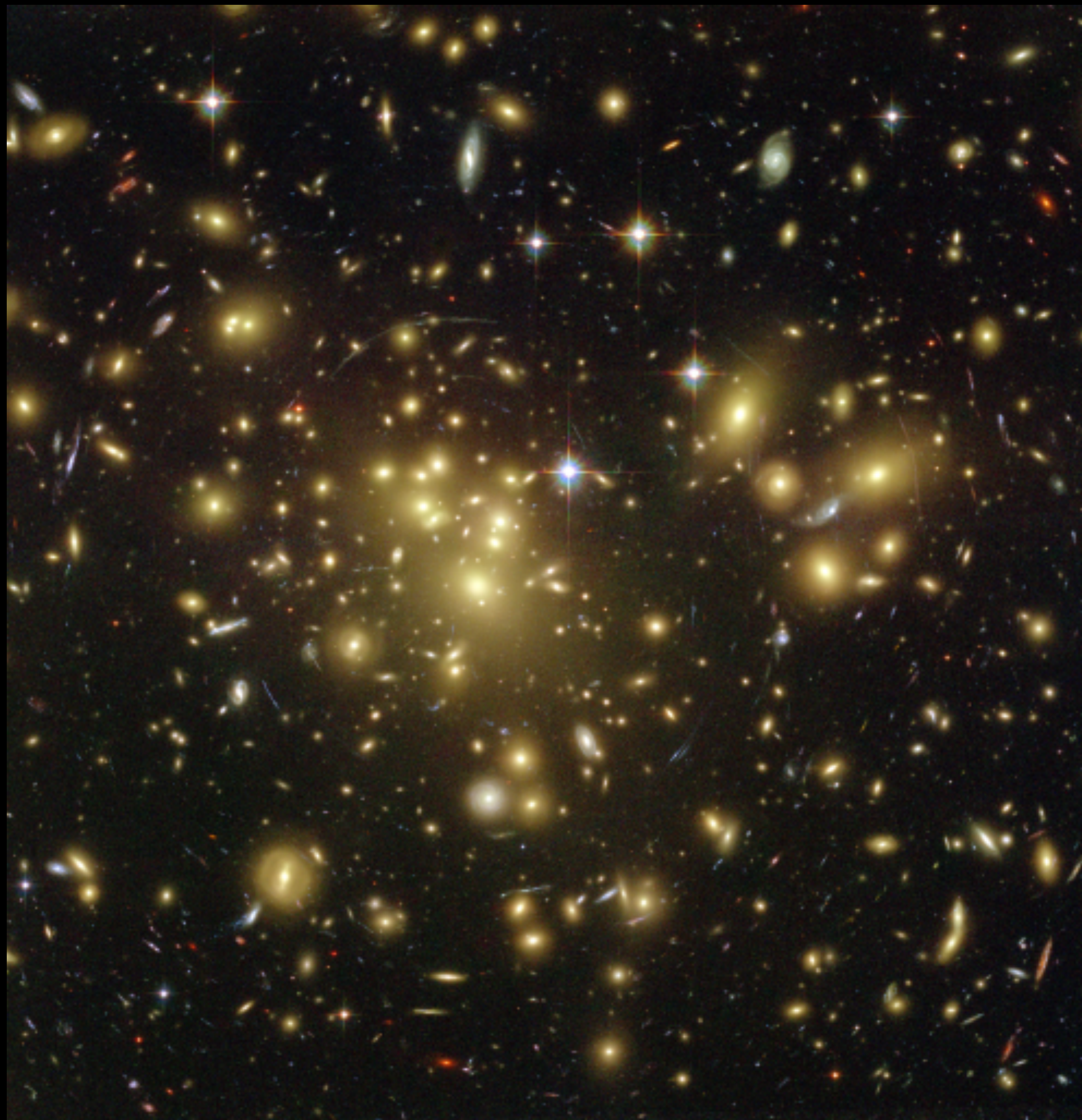
Can we test this?
We need deep and wide galaxy surveys

Four main probes

- Gravitational lensing
- Supernovae luminosities
- Galaxy cluster mass function & no. counts
- Baryon Acoustic Oscillations

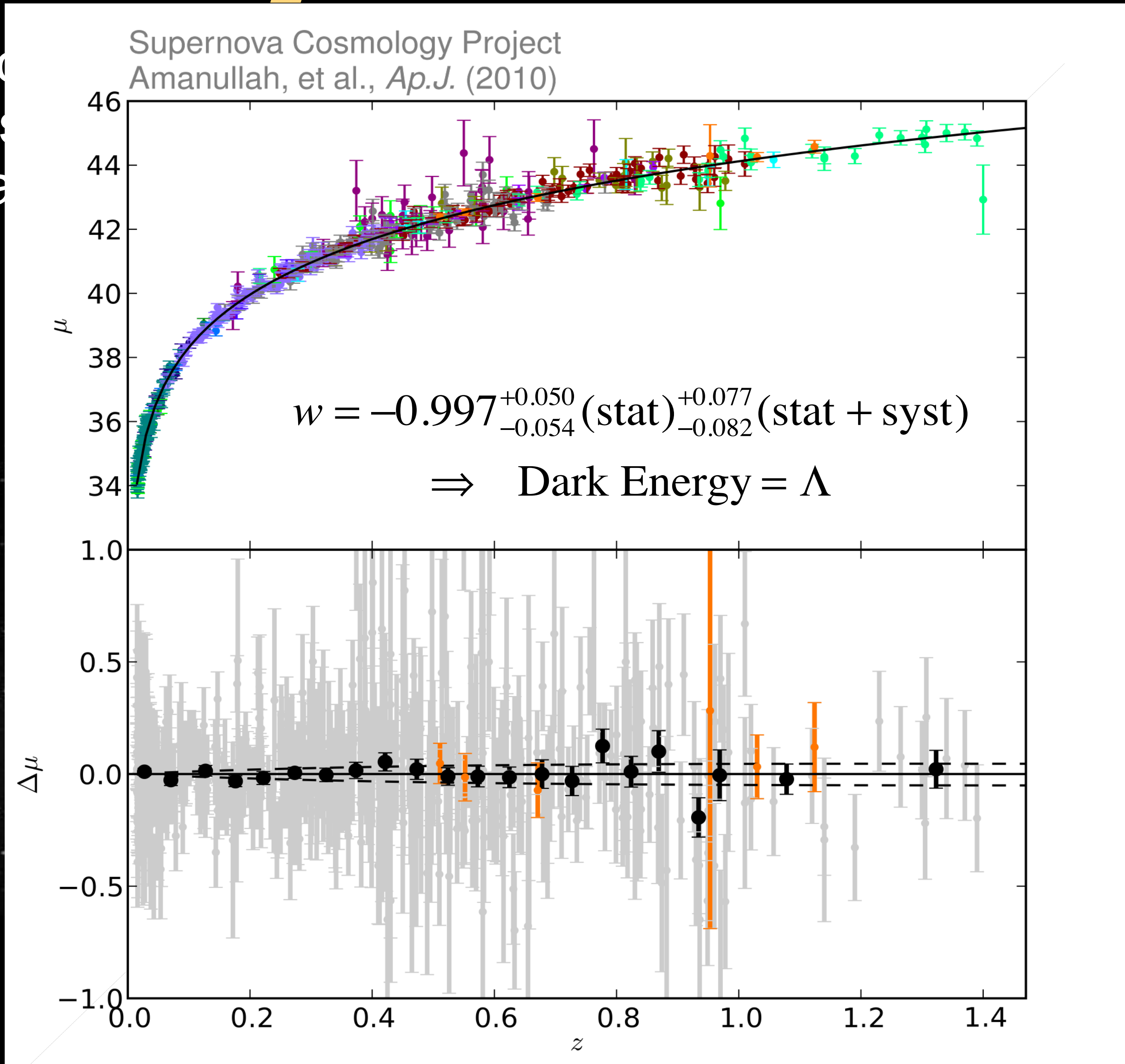
Gravitational lensing

Purely geometric effect, only depends on the matter distribution between the source & us. Allow us to model the matter distributions and measure its content. Clean & reliable probe.



Supernovae

Superno... ...ose light
can be ...
They ca... ...ls.



Galaxy clusters

They are the largest virializaed structures in the Universe.

Their X-ray emission allow us to estimate their total mass and thus determine their mass function.

Their number density in the Universe is specially sensitive to cosmological parameters like Λ.

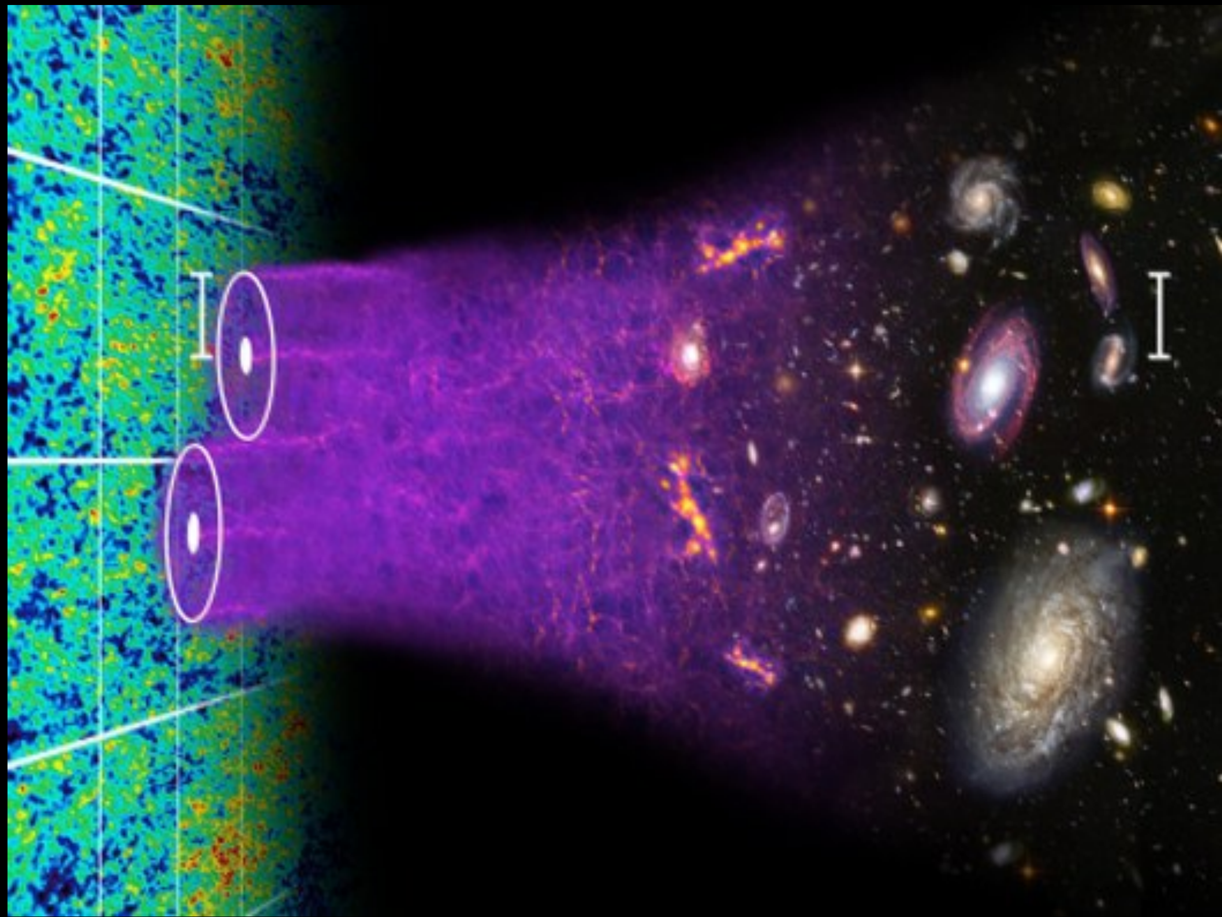
Baryon Acoustic Oscillations

The plasma before photon decoupling has fluctuations that propagate as sound waves.

At decoupling a characteristic scale is fixed, the sonic horizon, which acts as a standard ruler.

Its evolution with redshift since then allows us to use it as a comic probe.

Seen both at the CMB and in the galaxy distribution today.



DARK ENERGY SURVEY

4m Blanco Telescope
Cerro Tololo
Chile

Dark Energy Survey

500 million galaxies
5000 deg sq.
$\Delta z_{photo} = 0.05\ (1+z)$
20 bins z range [0.2,1.5]

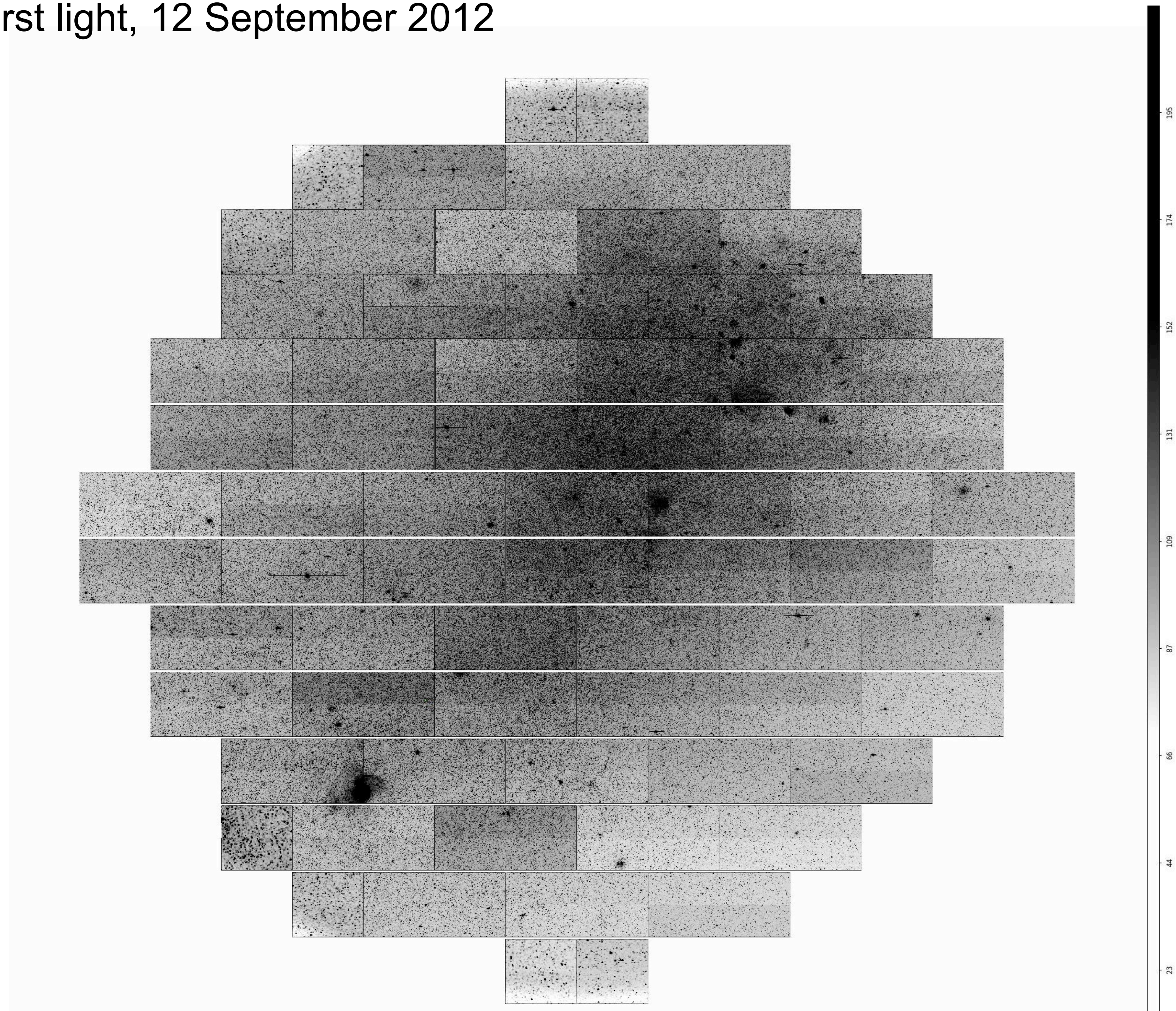
Cost: 100M$


Blanco Telescope at Cerro Tololo International Observatory, Chile
First light, 12 September 2012
DARK ENERGY SURVEY

DARK ENERGY SURVEY

Large Magellanic Cloud, which lies about 2 million light years from Earth.

First light, 12 September 2012

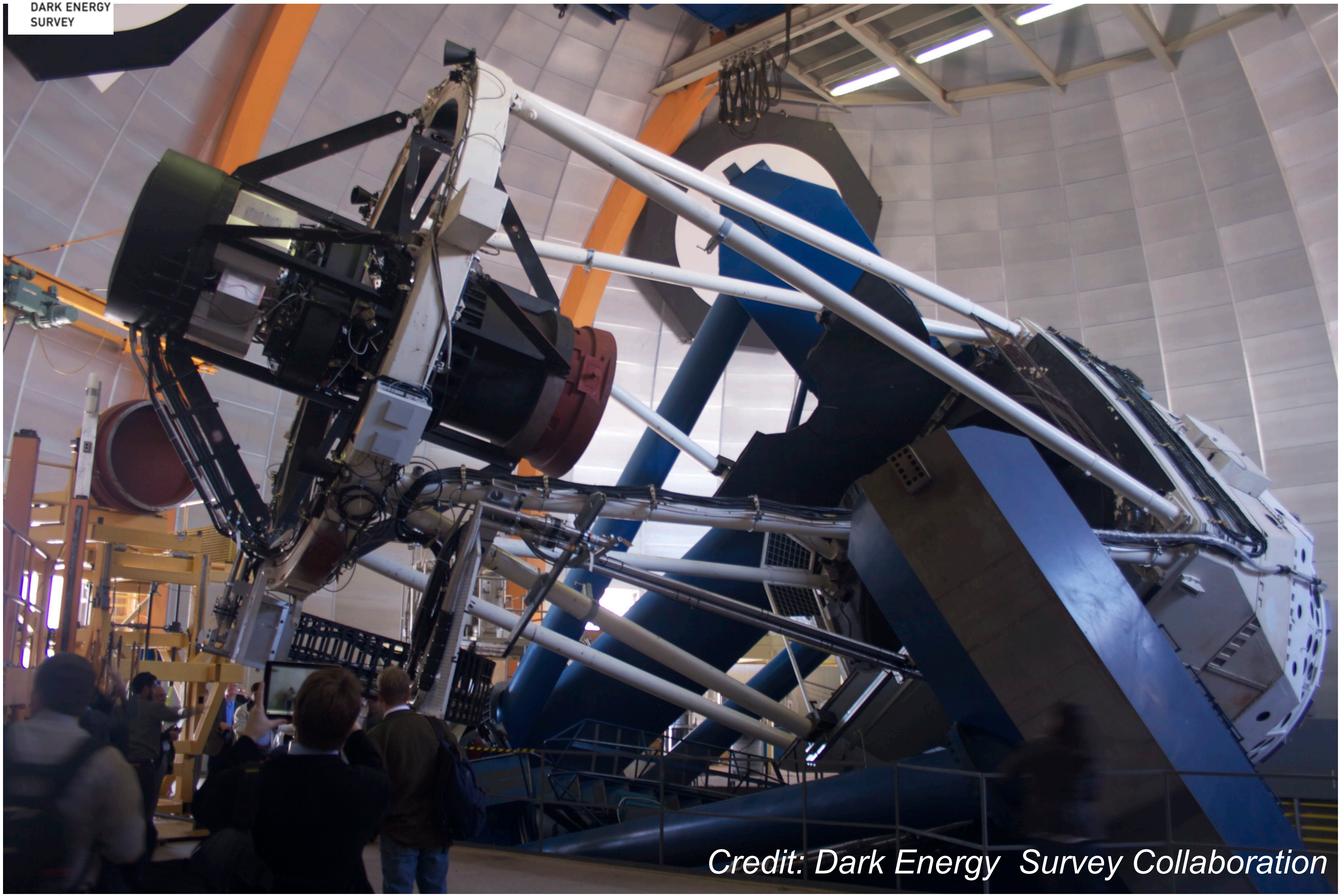


Credit: Dark Energy Survey Collaboration

DARK ENERGY SURVEY

DES inauguration – 8 November 2012, Cerro Tololo, Chile

DES inauguration – 8 November 2012, Cerro Tololo, Chile



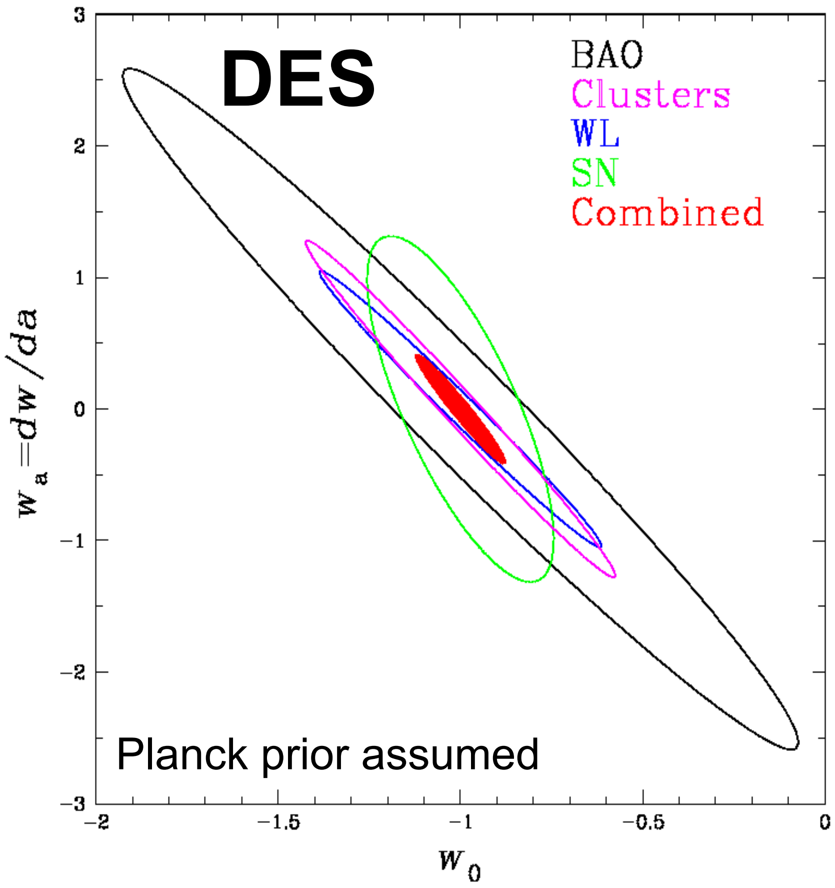
Credit: Dark Energy Survey Collaboration

DES Science Reach

DARK ENERGY SURVEY

Four Probes of Dark Energy

- **Galaxy Clusters**
  - ~100,000 clusters to z>1
  - Synergy with SPT, VHS
  - Sensitive to growth of structure and geometry
- **Weak Lensing**
  - Shape measurements of 200 million galaxies
  - Sensitive to growth of structure and geometry
- **Baryon Acoustic Oscillations**
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- **Supernovae**
  - 30 sq deg time-domain survey
  - ~4000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

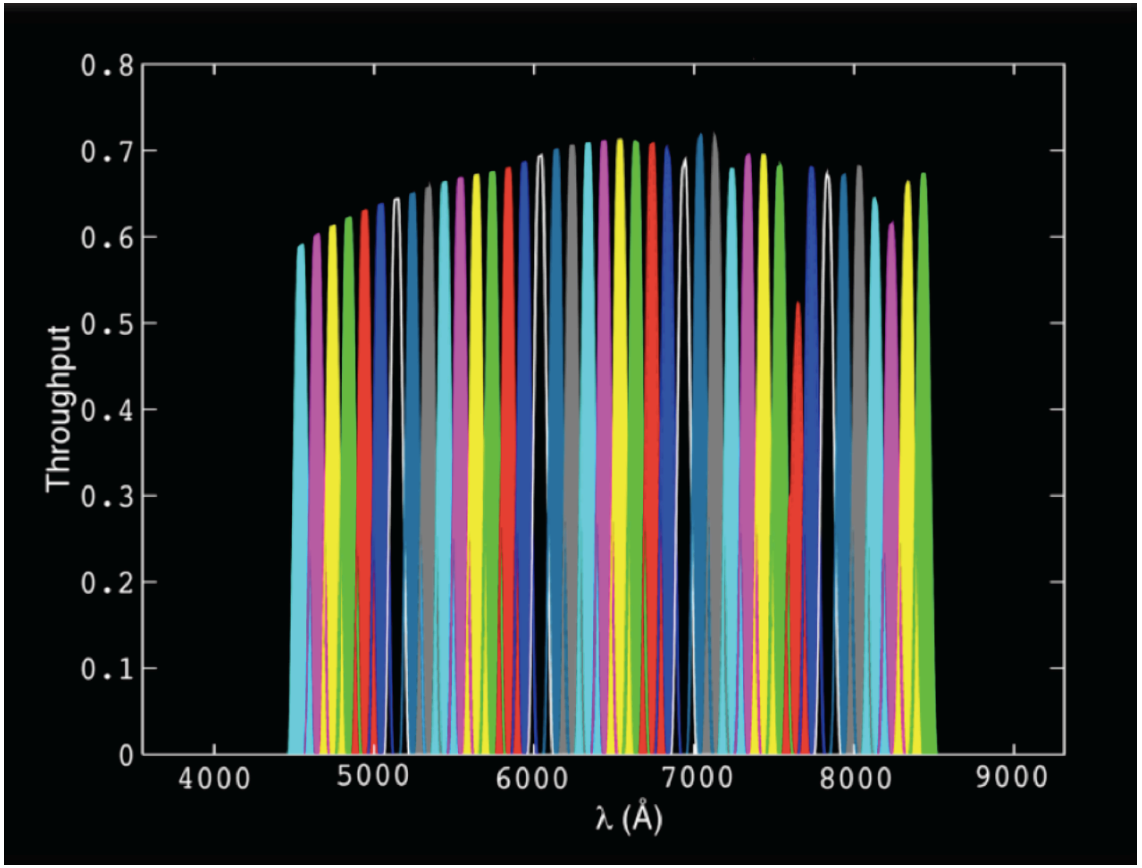


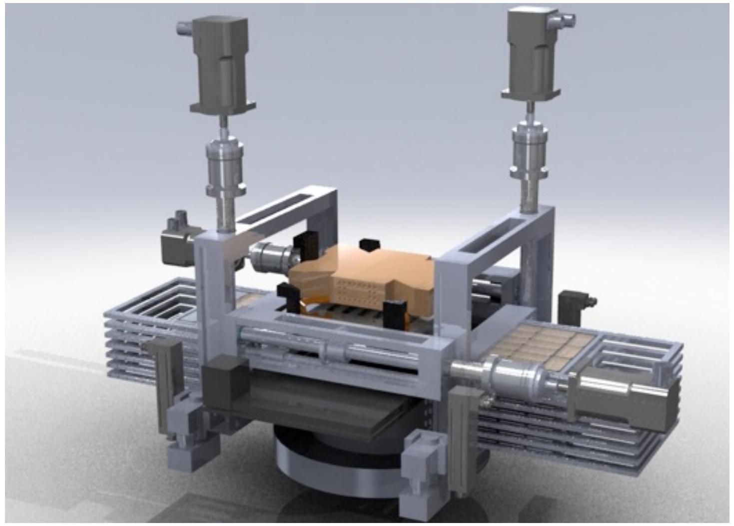
Factor 3-5 improvement over Stage II DETF Figure of Merit

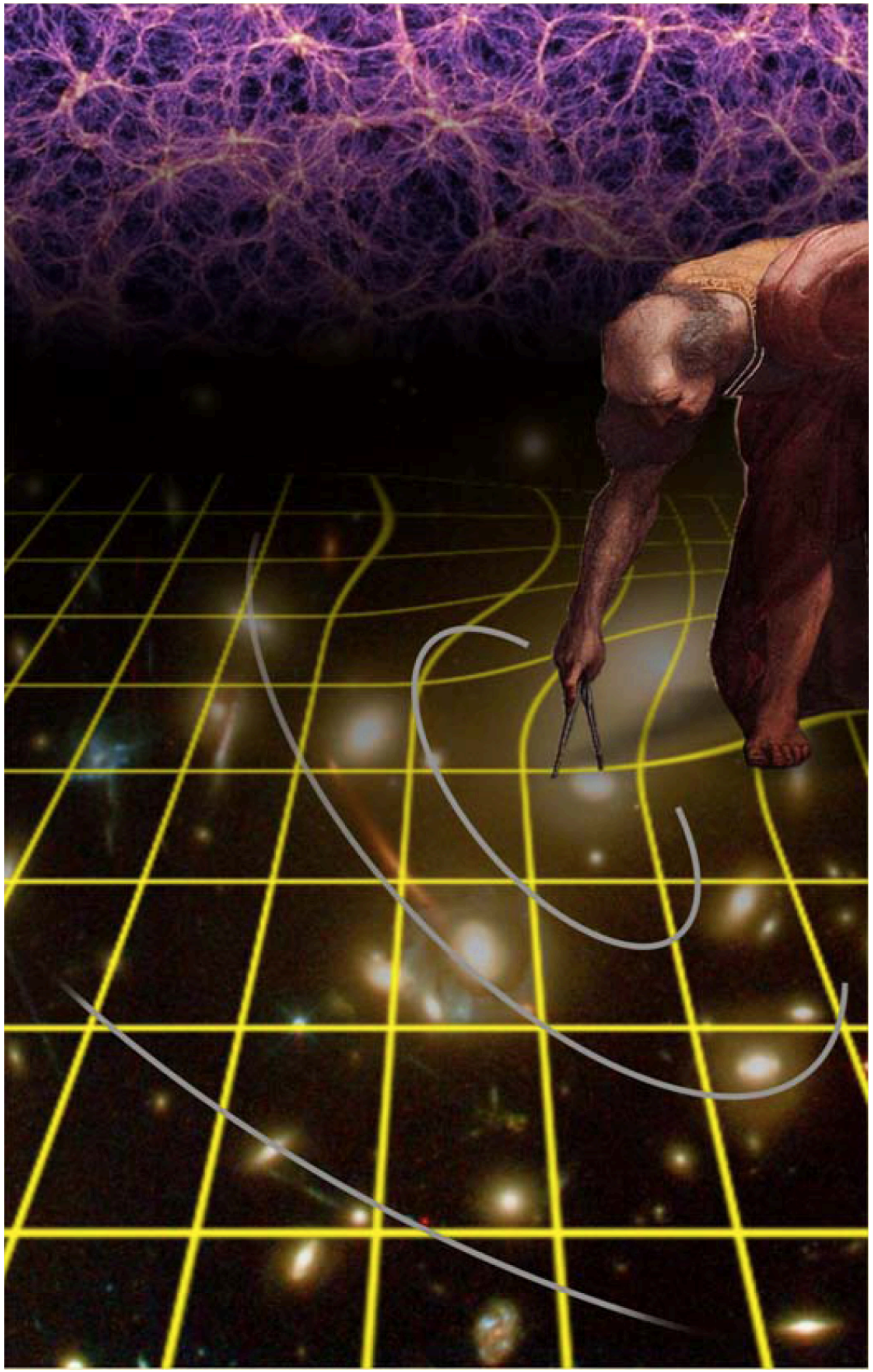
PAU photometric survey

100 million galaxies
200 – 1000 deg sq.
Δz_{photo} = 0.0035 (1+z)
100 bins z range [0.2,1.5]
"Tomography"

Cost: 10M$







esa

EUCLID

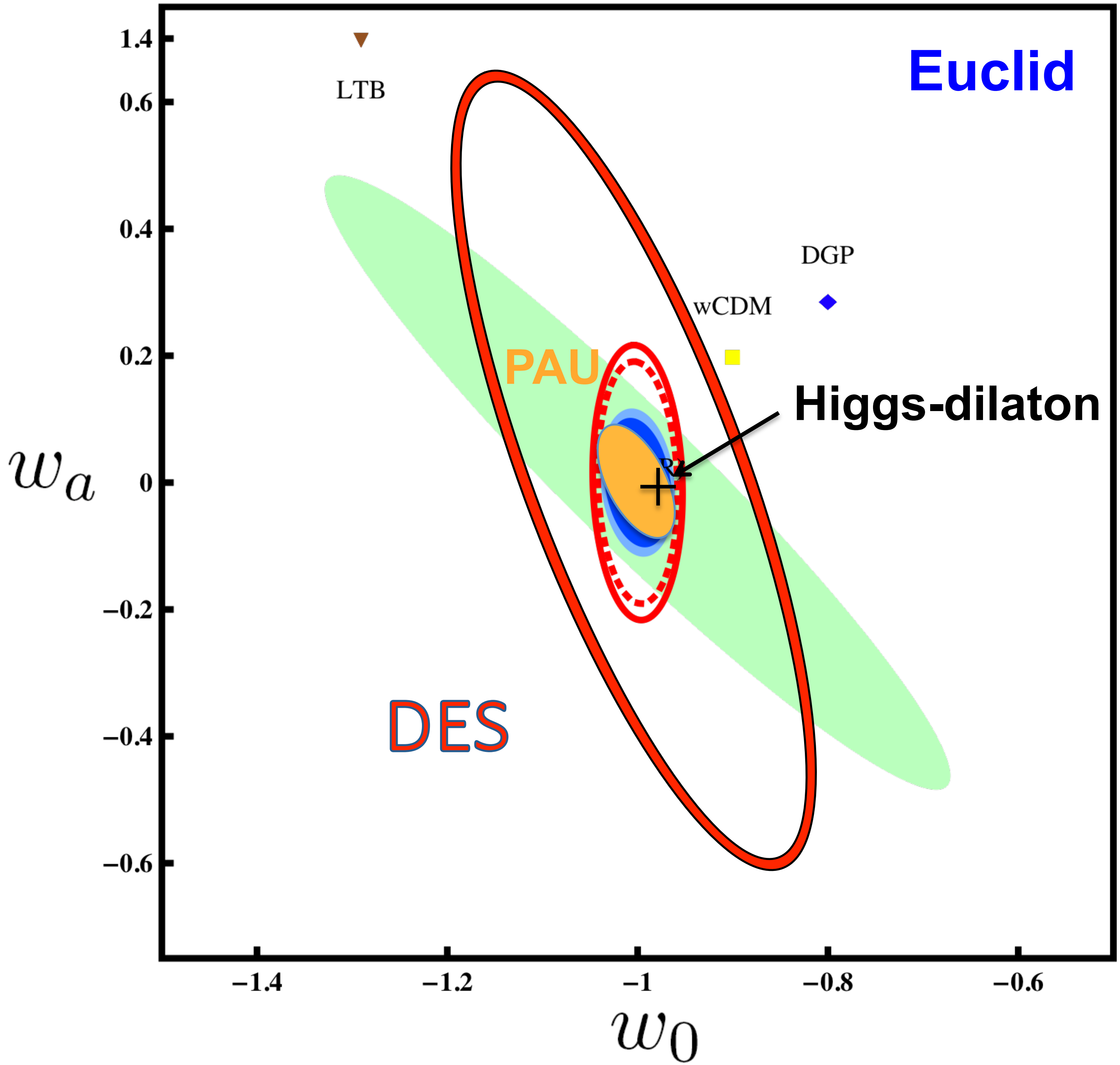
Spectroscopic survey

100 million galaxies
15,000 sq. deg
$\Delta z_{spec} = 0.001\ (1+z)$
8 bins z range [0.5,2.1]

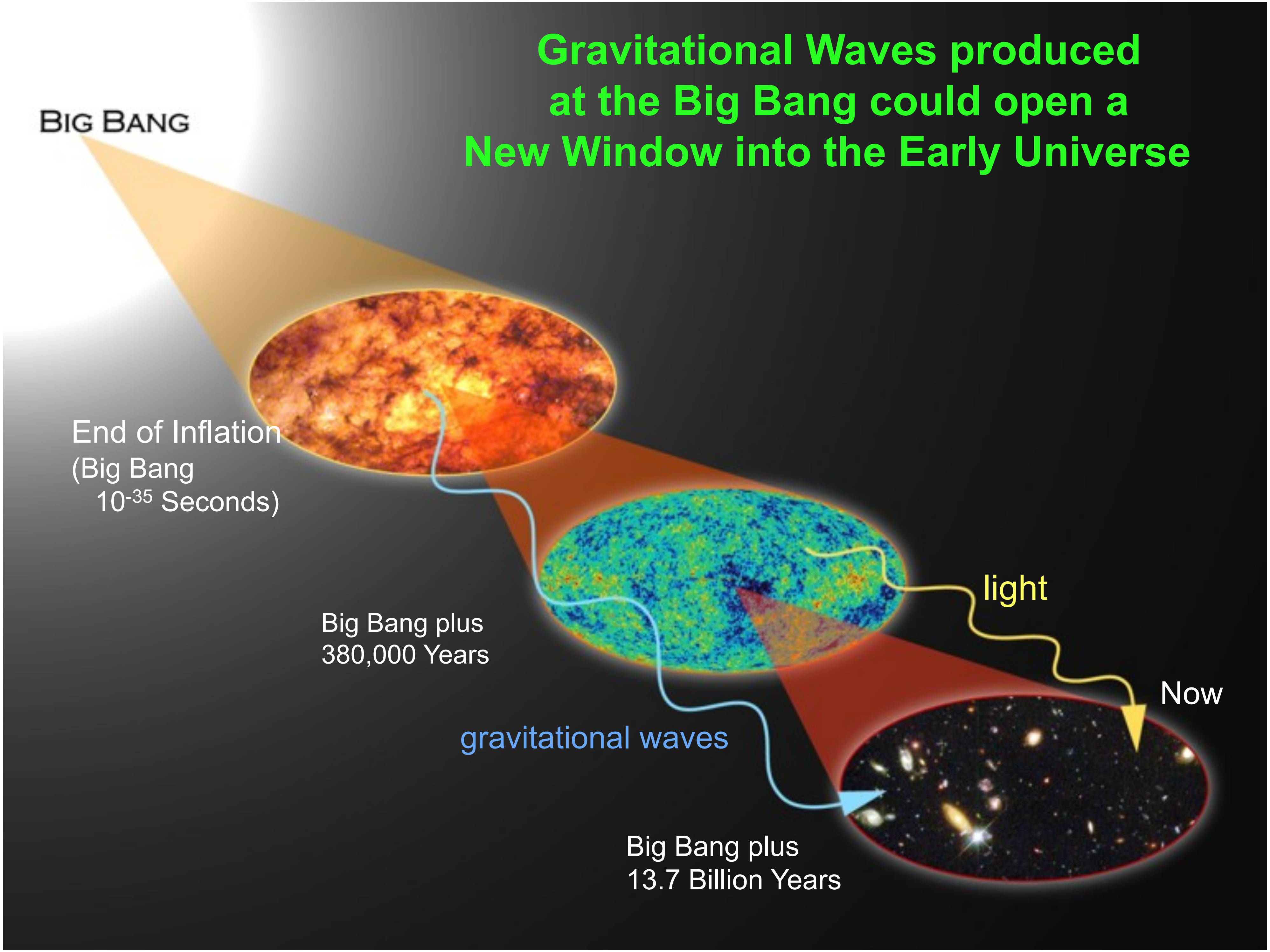
Cost: 1B$

Imaging survey

1000 million galaxies
15,000 deg sq.
$\Delta z_{photo} = 0.05\ (1+z)$
5 bins z range [0.5,3.0]



Euclid
LTB
DGP
wCDM
PAU
Higgs-dilaton
DES
1.4
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−1.4
−1.2
−1
−0.8
−0.6
w_a
w_0


Gravitational Waves produced
at the Big Bang could open a
New Window into the Early Universe
BIG BANG
End of Inflation
(Big Bang
10-35 Seconds)
Big Bang plus
380,000 Years
light
Now
gravitational waves
Big Bang plus
13.7 Billion Years

Grav.Wave Background from preheating

Khlebnikov+Tkachev	PRD 56, 653 (1997)
JGB	arXiv:hep-ph/9804205
+Daniel G. Figueroa	PRL 98, 061302 (2007)
+Alfonso Sastre	PRD 77, 043517 (2008)
+Dufaux	PRD 82,083518 (2010)
Easther et al.	PRL 99, 221301 (2007)
Price et al.	PRD 78, 063541 (2008)
Dufaux et al.	JCAP 0903, 001 (2009)

The Higgs-Inflaton model + GWs

JGB, Figueroa (2007)

$$L = Tr[(\partial_\mu \Phi)^+ \partial^\mu \Phi] + \frac{1}{2}(\partial_\mu \chi)^2 - V(\Phi, \chi)$$

$$Tr[\Phi^+ \Phi] = \frac{1}{2}\sum_a \phi^a \phi_a \equiv \frac{1}{2}\phi^2$$

$$V(\phi, \chi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \frac{g^2}{2}\phi^2\chi^2 + \frac{1}{2}m^2\chi^2$$

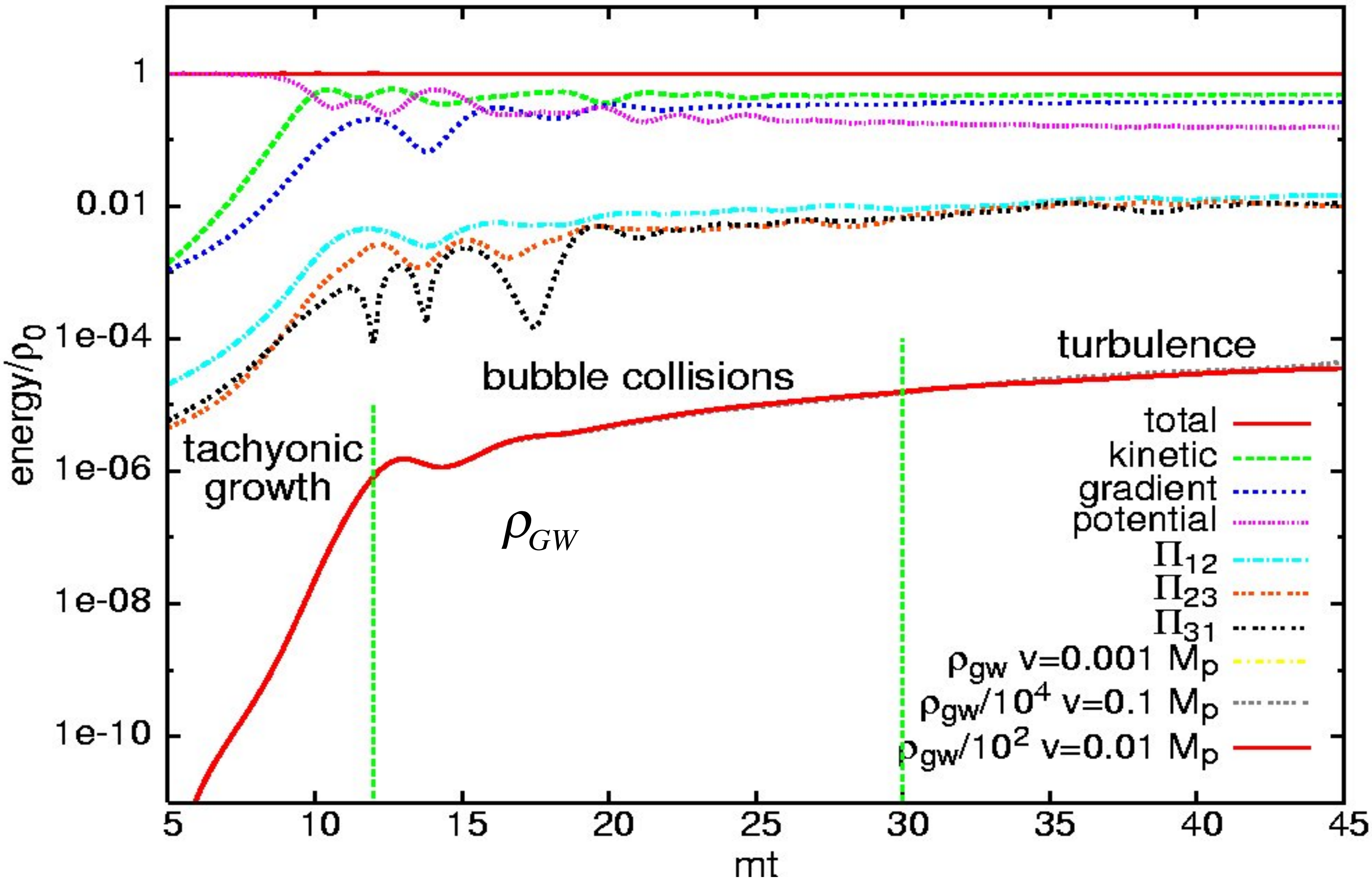
TT gauge

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad h_{\mu 0} = 0, \quad \nabla^i h_{ij} = 0, \quad h_i^i = 0$$

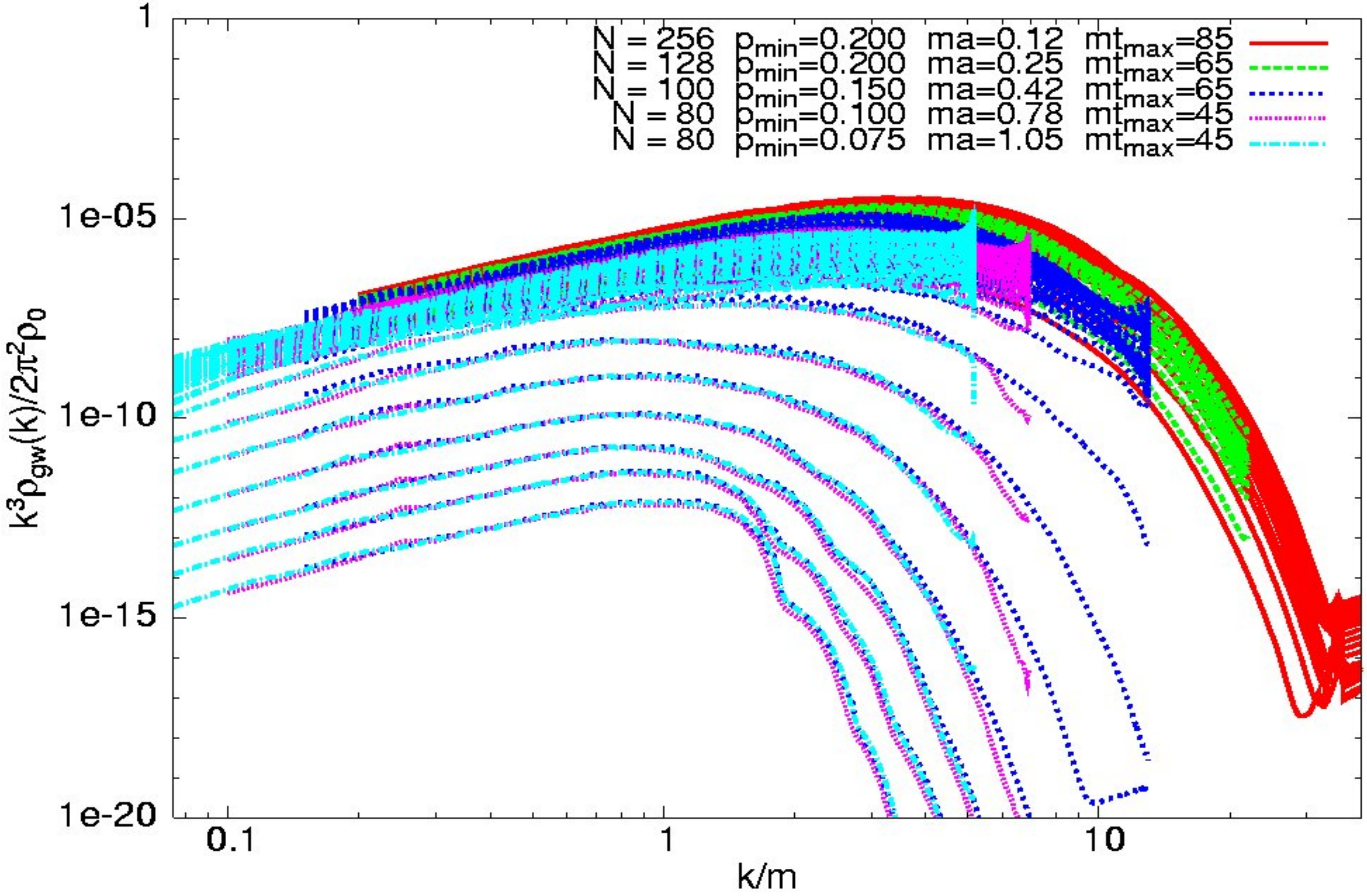
$$g^{\mu\nu}\partial_\mu \phi\, \partial_\nu \phi = (\partial_0 \phi)^2 - (\nabla \phi)^2 - \underline{h^{ij}\nabla_i \phi\, \nabla_j \phi}$$

including backreaction

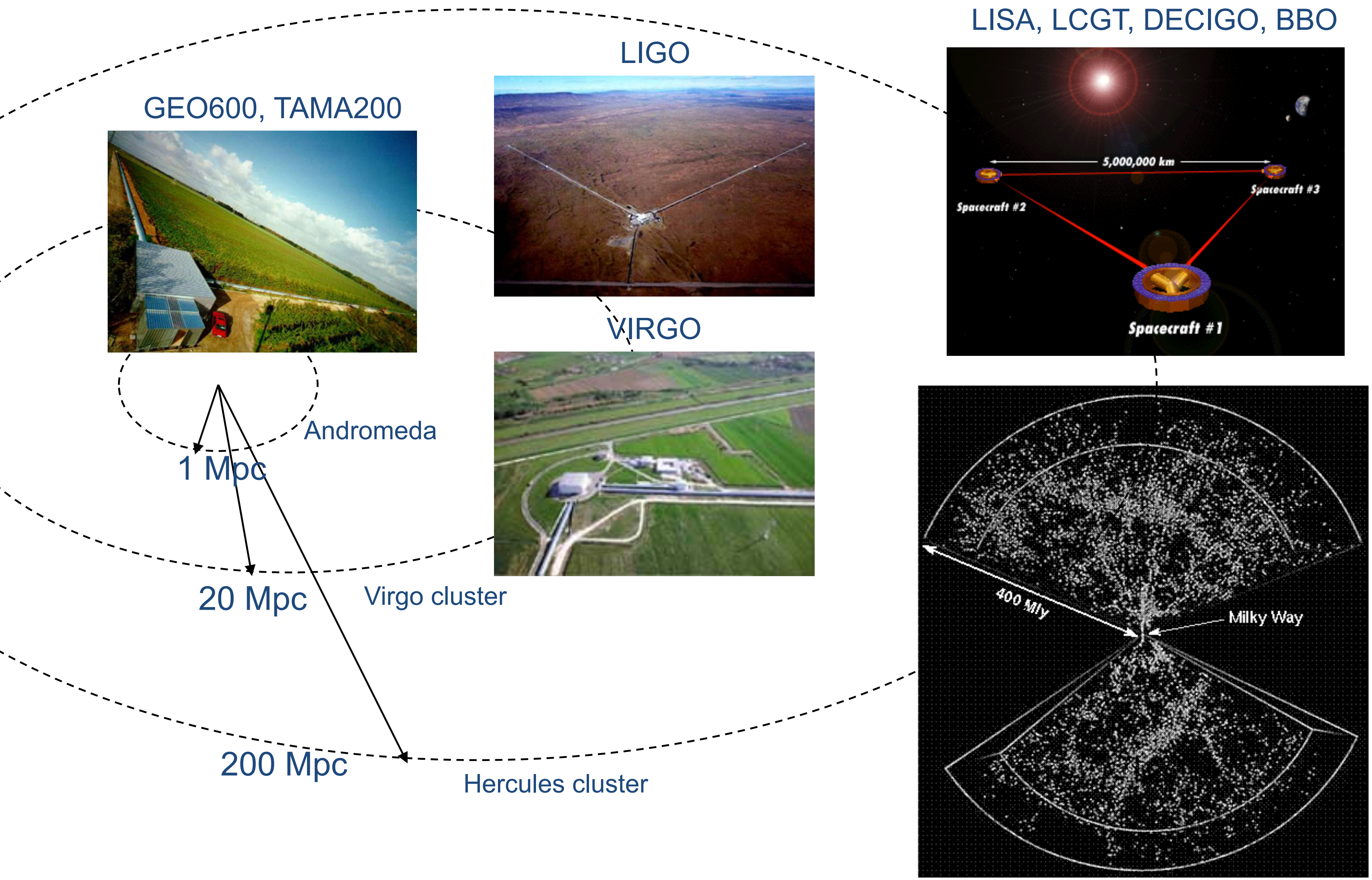
Time evolution after inflation



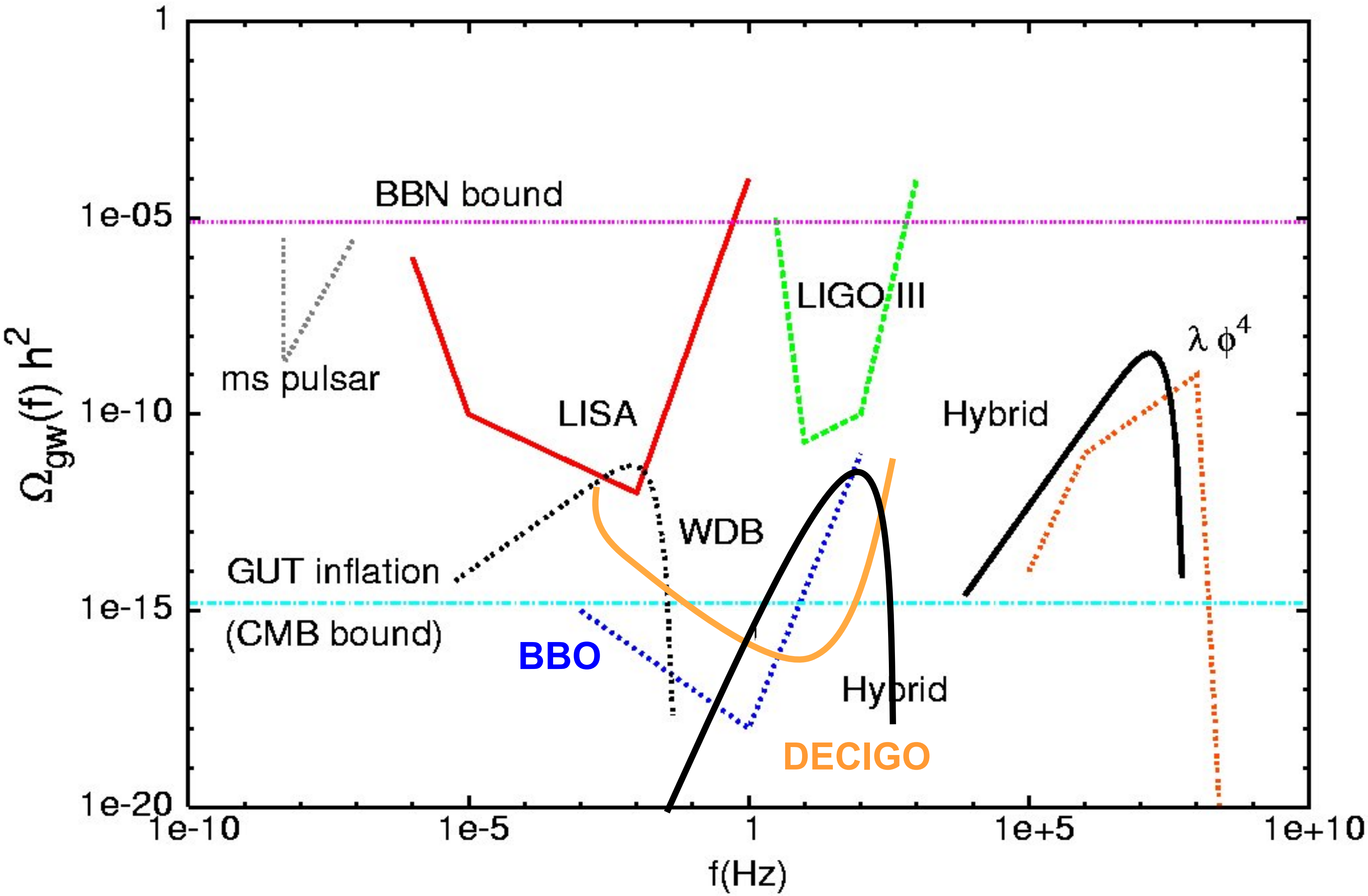
Gravitational wave spectrum



Gravitational Wave detectors in the world



Backgrounds, Bounds & Sensitivity



Gravitational waves in Abelian-Higgs model

J. G.-B.
Daniel G. Figueroa
Jeff Dufaux

Phys.Rev.D82, 083518 (2010)
ArXiv:1006.0217

The Abelian Higgs-Inflaton model

$$L = -\frac{1}{4} F_{\mu\nu}^{a} F_{a}^{\mu\nu} + Tr[(D_\mu \Phi)^+ D^\mu \Phi] + \frac{1}{2}(\partial_\mu \chi)^2 - V(\Phi, \chi)$$

$$D_\mu = \partial_\mu - ieA_\mu \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$Tr[\Phi^+ \Phi] = \frac{1}{2}(\phi^a \phi_a) \equiv \frac{1}{2}\phi^2$$

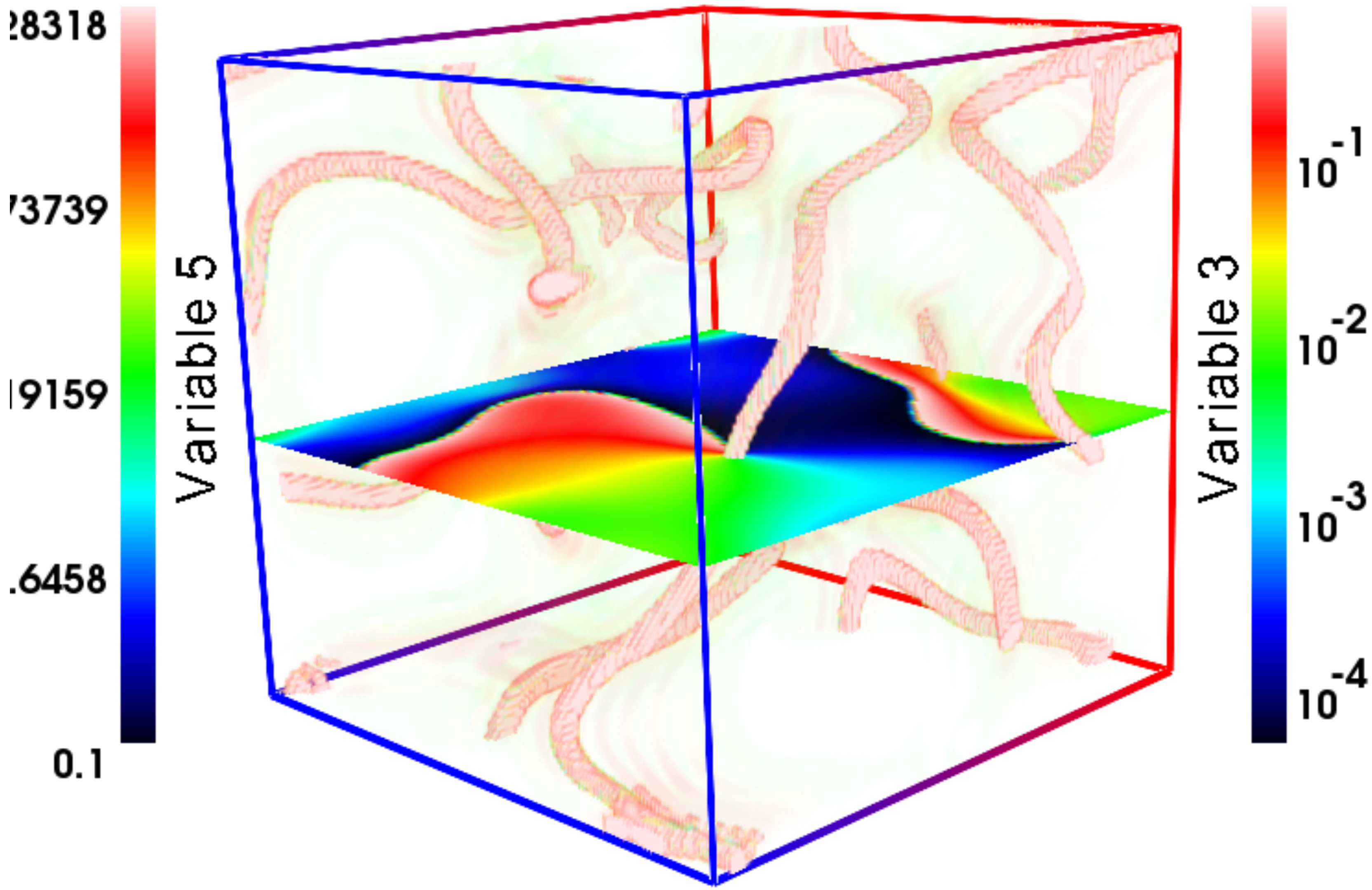
Dufaux, Figueroa, JGB (2007)

$$V(\phi, \chi) = \frac{\lambda}{4}(\phi^2 - v^2)^2 + \frac{g^2}{2}\phi^2 \chi^2 + \frac{1}{2} m^2 \chi^2$$

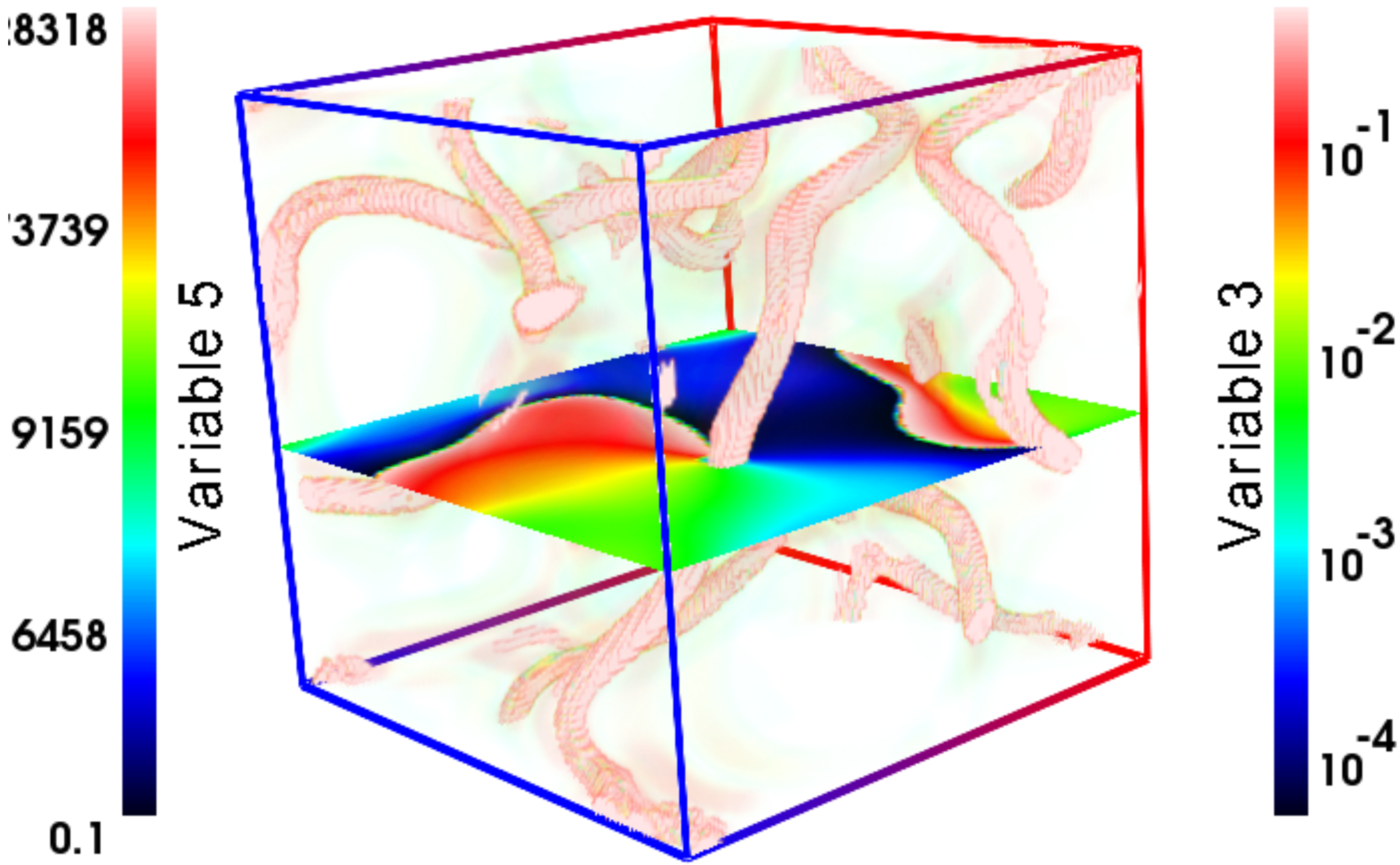
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad h_{\mu 0} = 0, \quad \nabla^i h_{ij} = 0, \quad h_i^i = 0$$

$$g^{\mu\nu}\partial_\mu \phi \, \partial_\nu \phi = (\partial_0 \phi)^2 - (\nabla \phi)^2 - h^{ij} \nabla_i \phi \, \nabla_j \phi$$

including backreaction

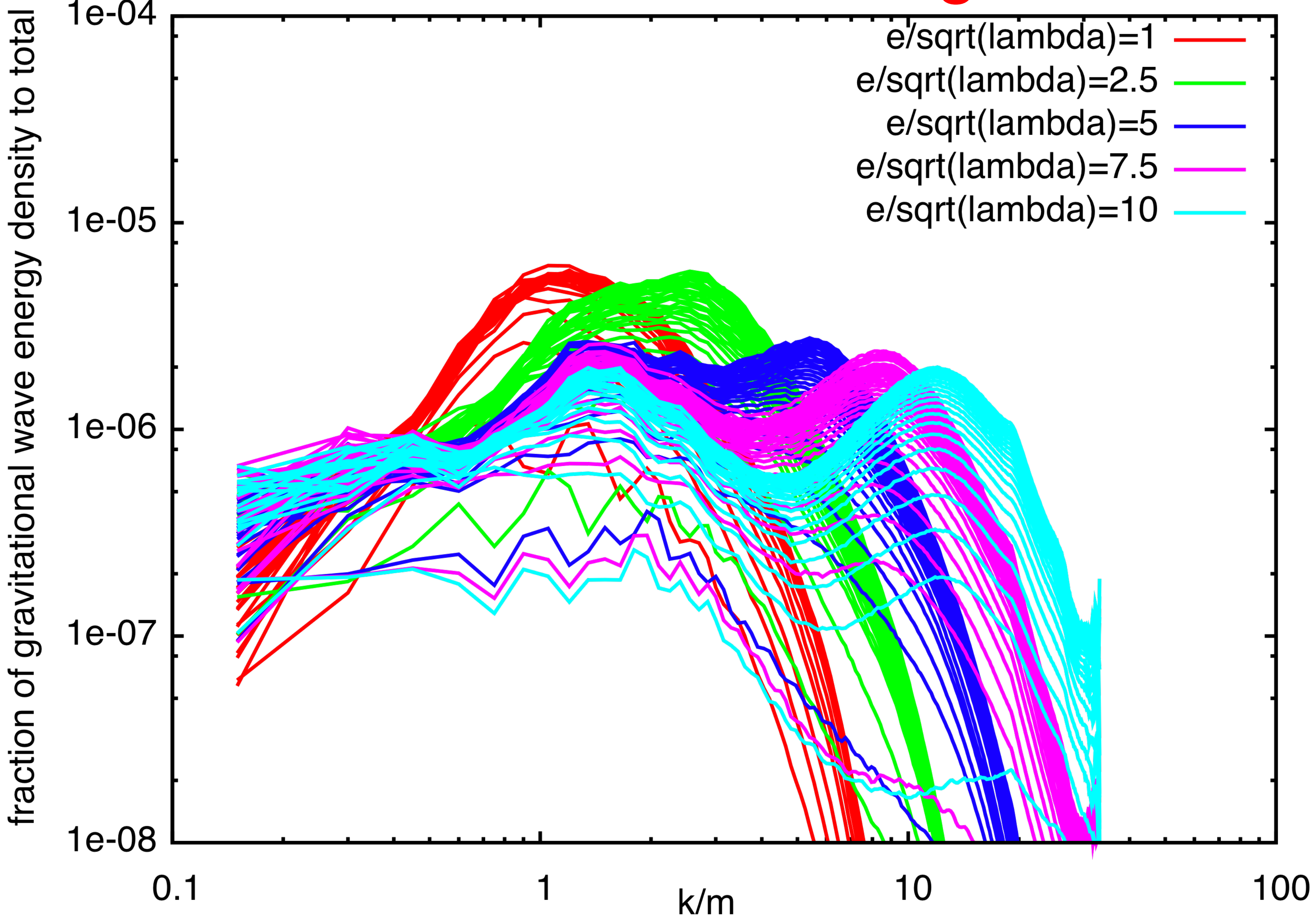


28318
73739
19159
.6458
0.1
Variable 5
Variable 3
10^{-1}
10^{-2}
10^{-3}
10^{-4}

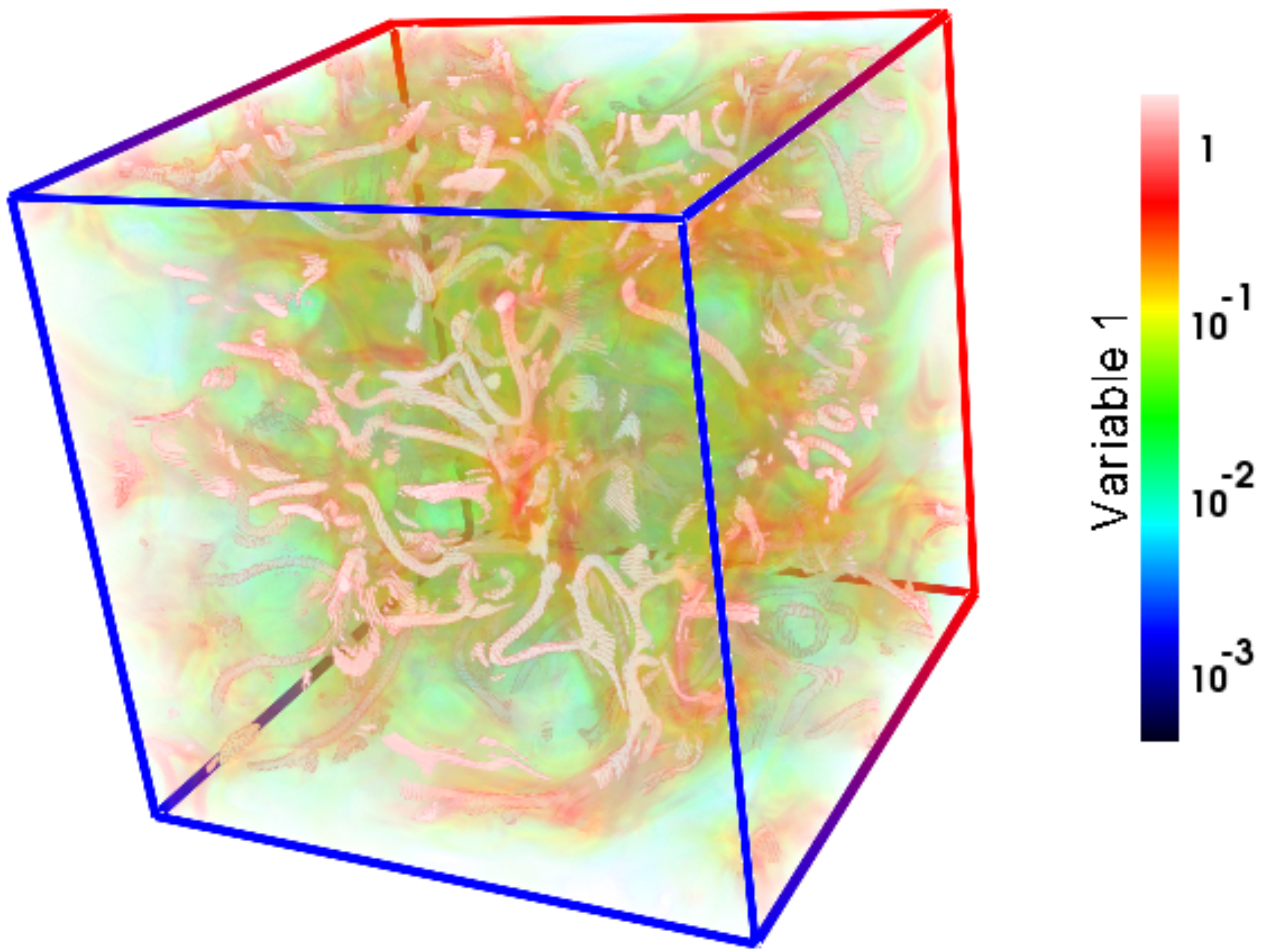


28318
3739
9159
6458
0.1
Variable 5
Variable 3
10^{-1}
10^{-2}
10^{-3}
10^{-4}

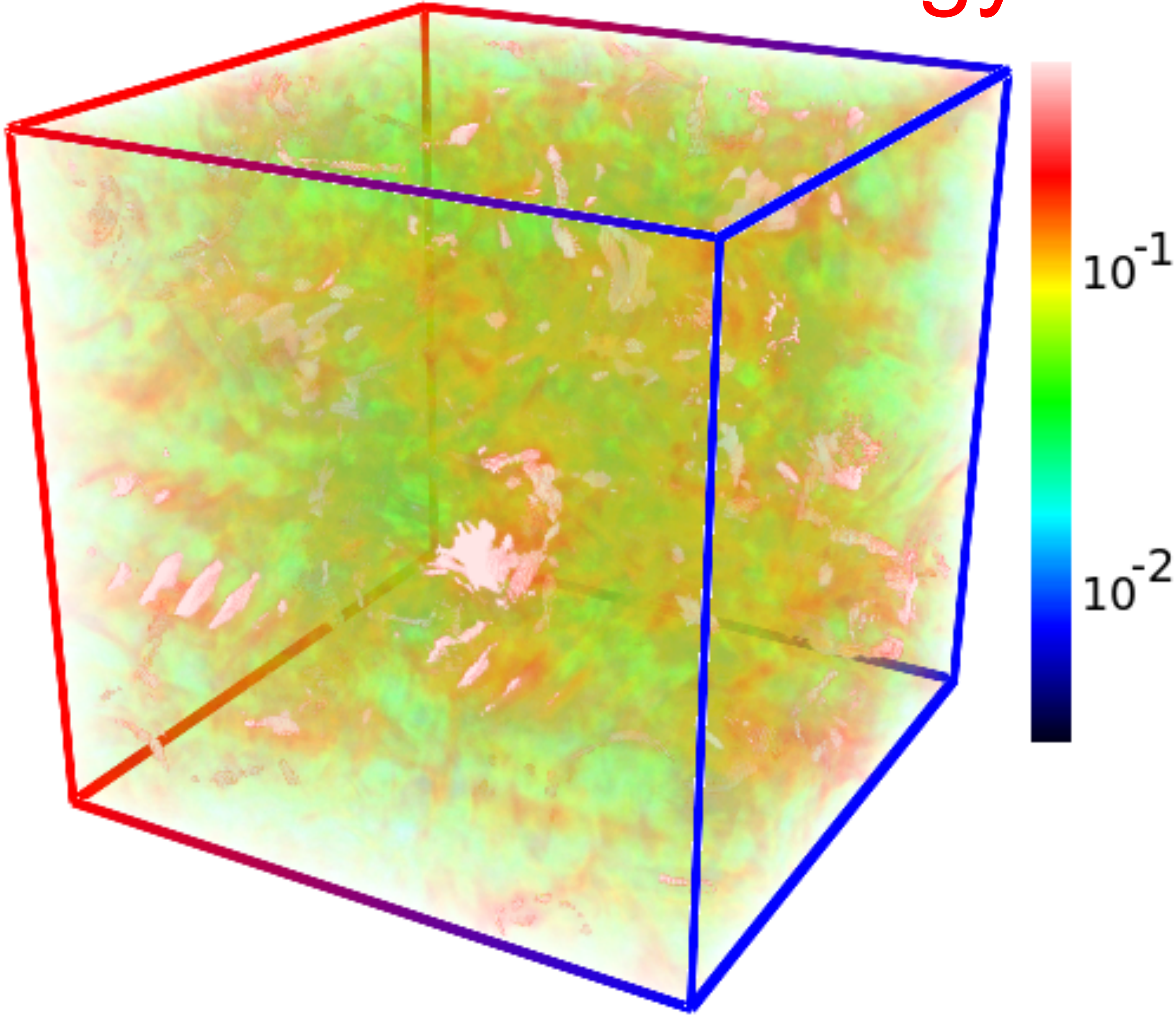
Evolution of GW background



Higgs covariant gradient energy

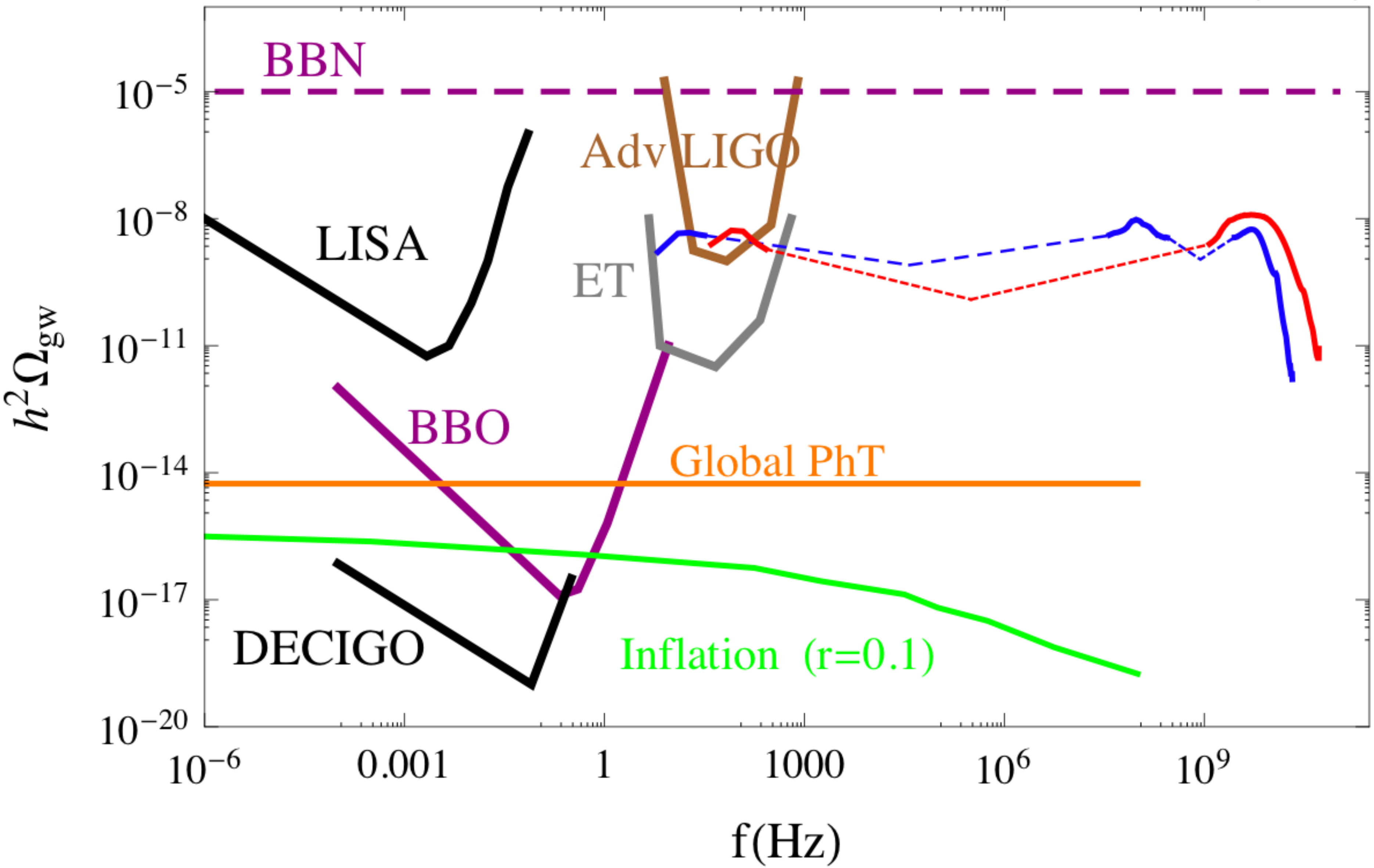


Gravitational waves energy density



Gravitational waves energy density

Dufaux, Figueroa, JGB (2010)



Combined Preheating in Higgs-Dilaton model

J. G.-B., D. G. Figueroa, J. Rubio

Phys.Rev.D79,063531(2009)

J. G.-B., J. Rubio, D. Zenhausern, M. Shaposhnikov

Phys.Rev.D84,123504(2011)

J. G.-B., J. Rubio, M. Shaposhnikov

Phys.Lett.B718,507(2012)

The SU(2)xU(1) Higgs-Dilaton model

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} + Tr[(D_\mu\Phi)^+ D^\mu\Phi] + \frac{1}{2}\xi\Phi^+\Phi R$$

$$+\frac{1}{2}(\partial_\mu\chi)^2 - V(\Phi,\chi)$$

$$-h\Phi\overline{\Psi}\Psi$$

$$D_\mu = \partial_\mu - \frac{i}{2}g_w A^a_\mu \tau_a - \frac{i}{2}g_Y B_\mu \tau_3$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_w \varepsilon^{abc} A^b_\mu A^c_\nu$$

$$F_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

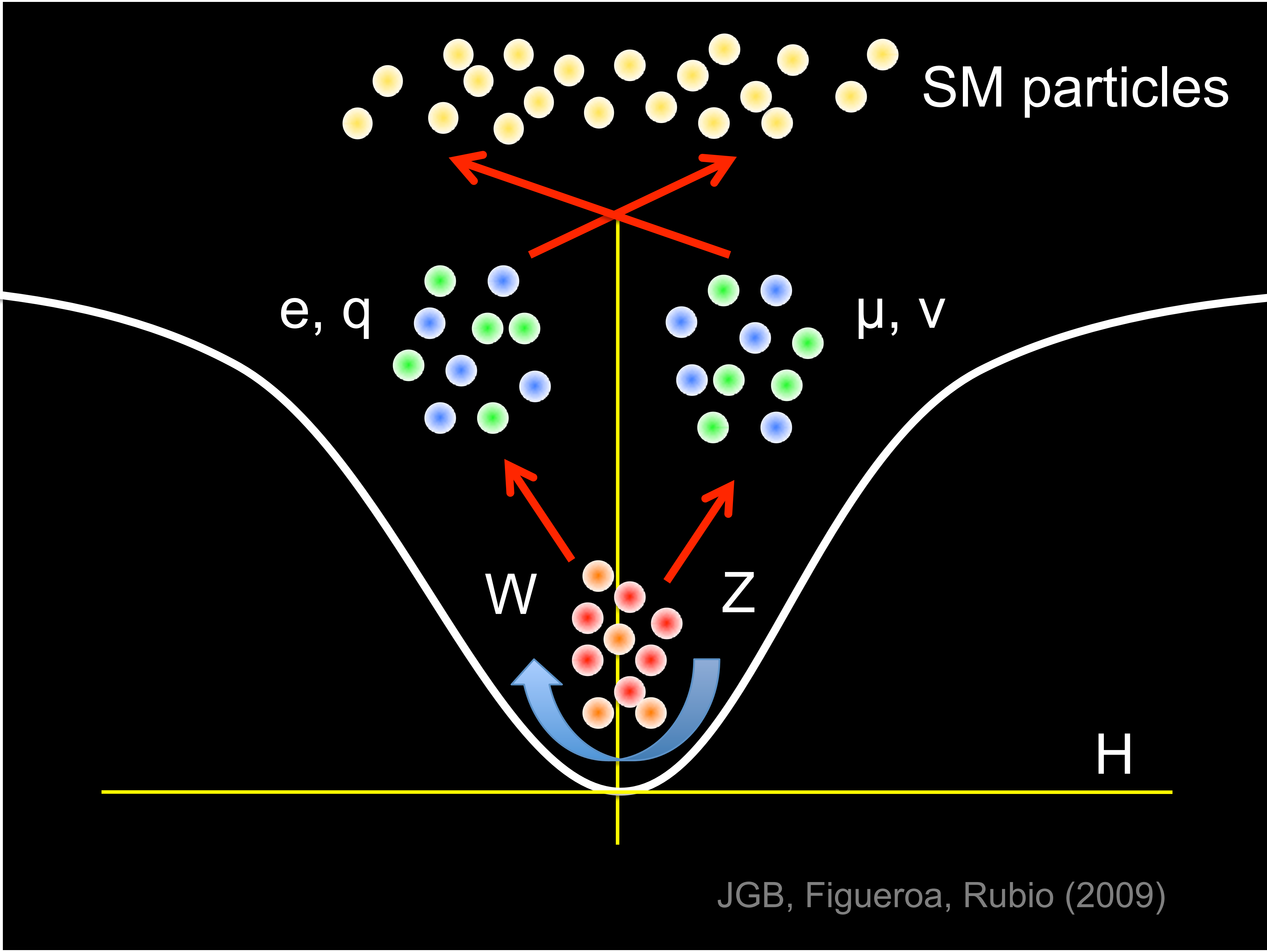
Bezrukov, Shaposhnikov (2008)
Shaposhnikov, Zenhausern (2009)

$$Tr[\Phi^+\Phi] = \frac{1}{2}(\phi_0^2 + \phi^a\phi_a) \equiv \frac{1}{2}\phi^2$$

$$V(\phi,\chi) = \frac{\lambda}{4}(\phi^2 - \alpha\chi^2)^2 + \frac{\beta}{4}\chi^4$$

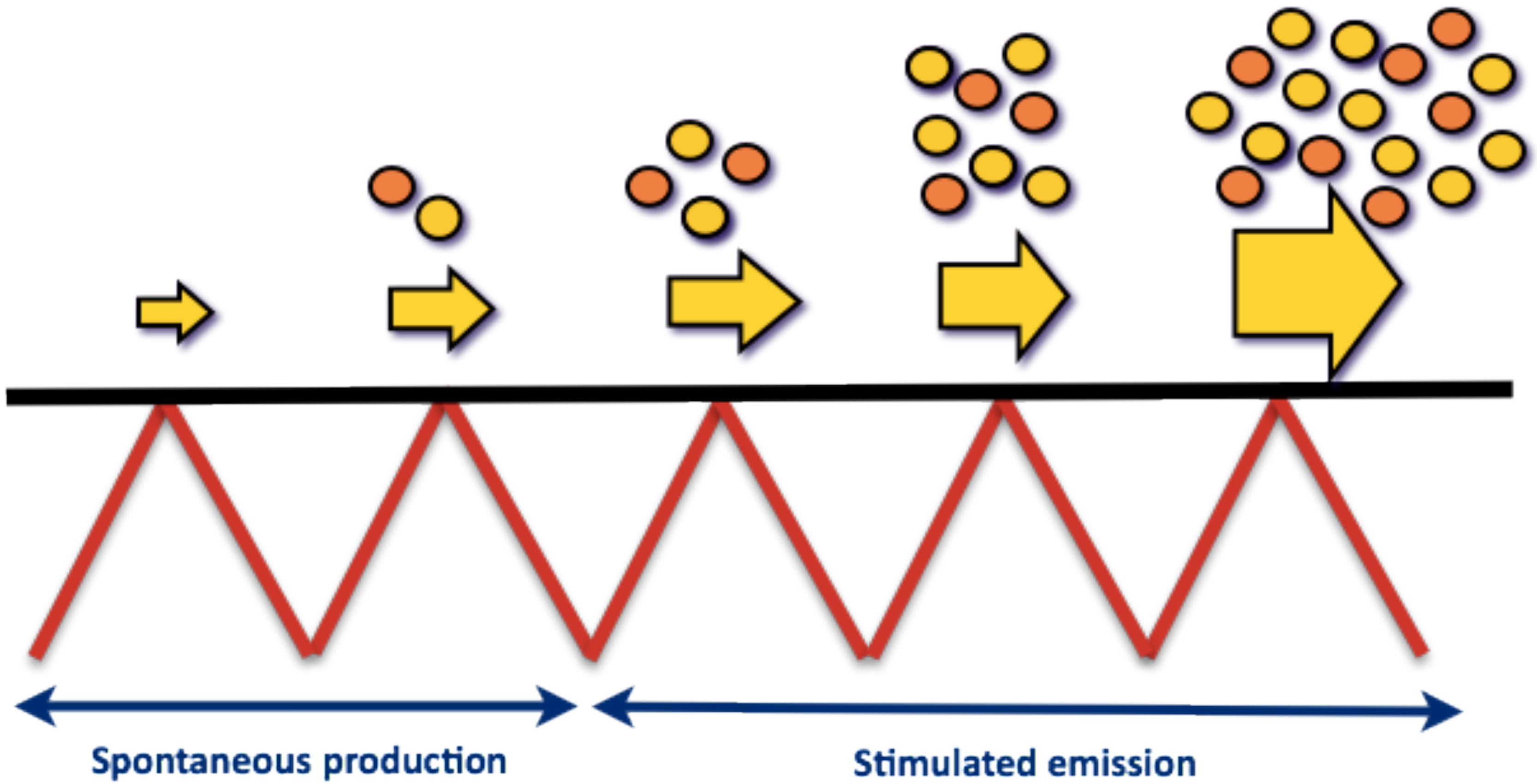
+SM couplings

JGB, Rubio, Shaposhnikov, Zenhausern (2011)


SM particles
e, q
μ, ν
W
Z
H
JGB, Figueroa, Rubio (2009)

Parametric resonance

$$n_k(j^+) = \mathcal{C}(x_j) + (2\mathcal{C}(x_j)+1)n_k(j^-) + 2\cos\theta_j\sqrt{\mathcal{C}(x_j)\,(\mathcal{C}(x_j)+1)}\sqrt{n_k(j^-)\,(n_k(j^-)+1)}$$

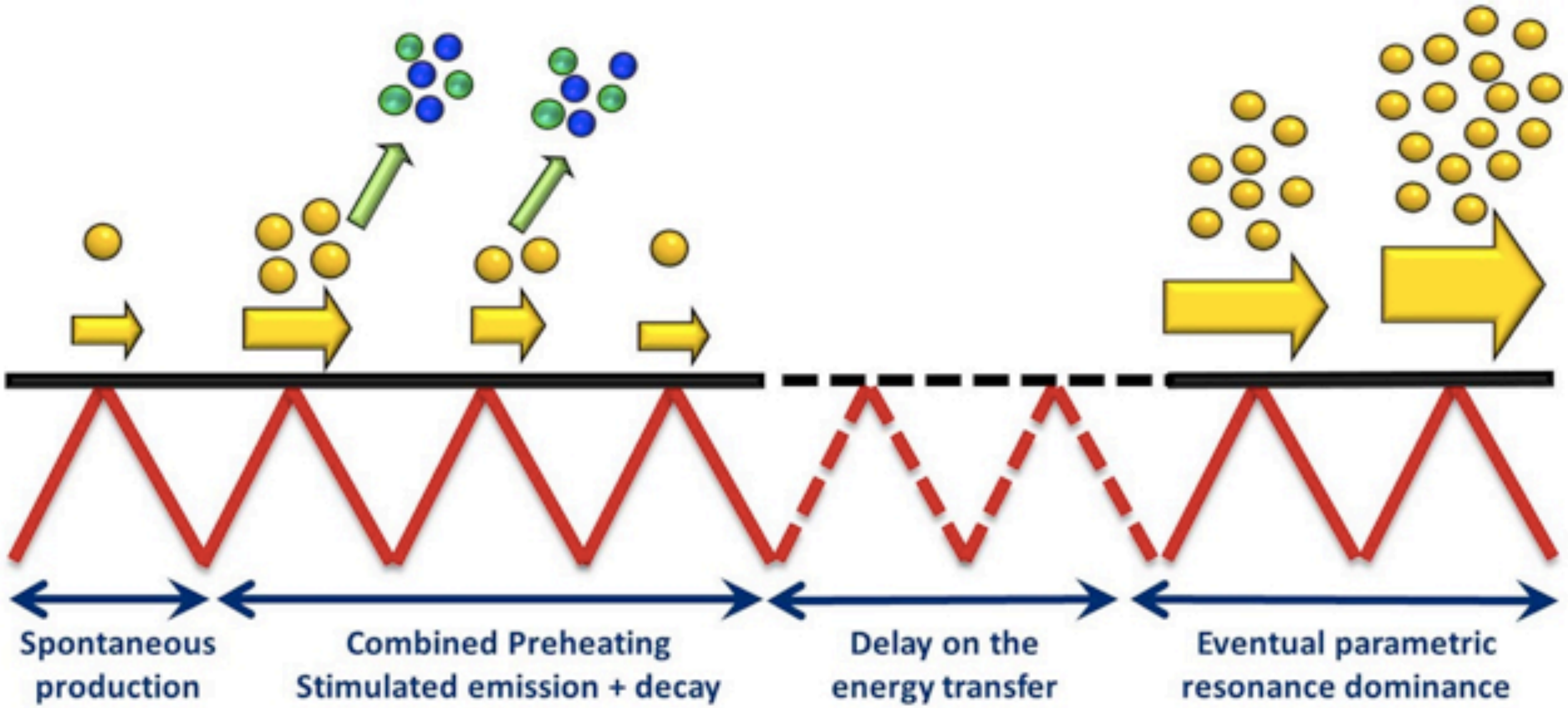


$$n_k(j^+) = n_k(j^-)e^{2\pi\mu_k(j)}$$

JGB, Figueroa, Rubio (2009)

Combined Preheating

$$n_k((j+1)^+) = n_k(1^+)\, e^{-\gamma F_\Sigma(j)}\, e^{2\pi \sum_{i=1}^{j} \mu_k(i+1)}$$



General Formalism to be incorporated in any realistic theory of (p)reheating

JGB, Figueroa, Rubio (2009)

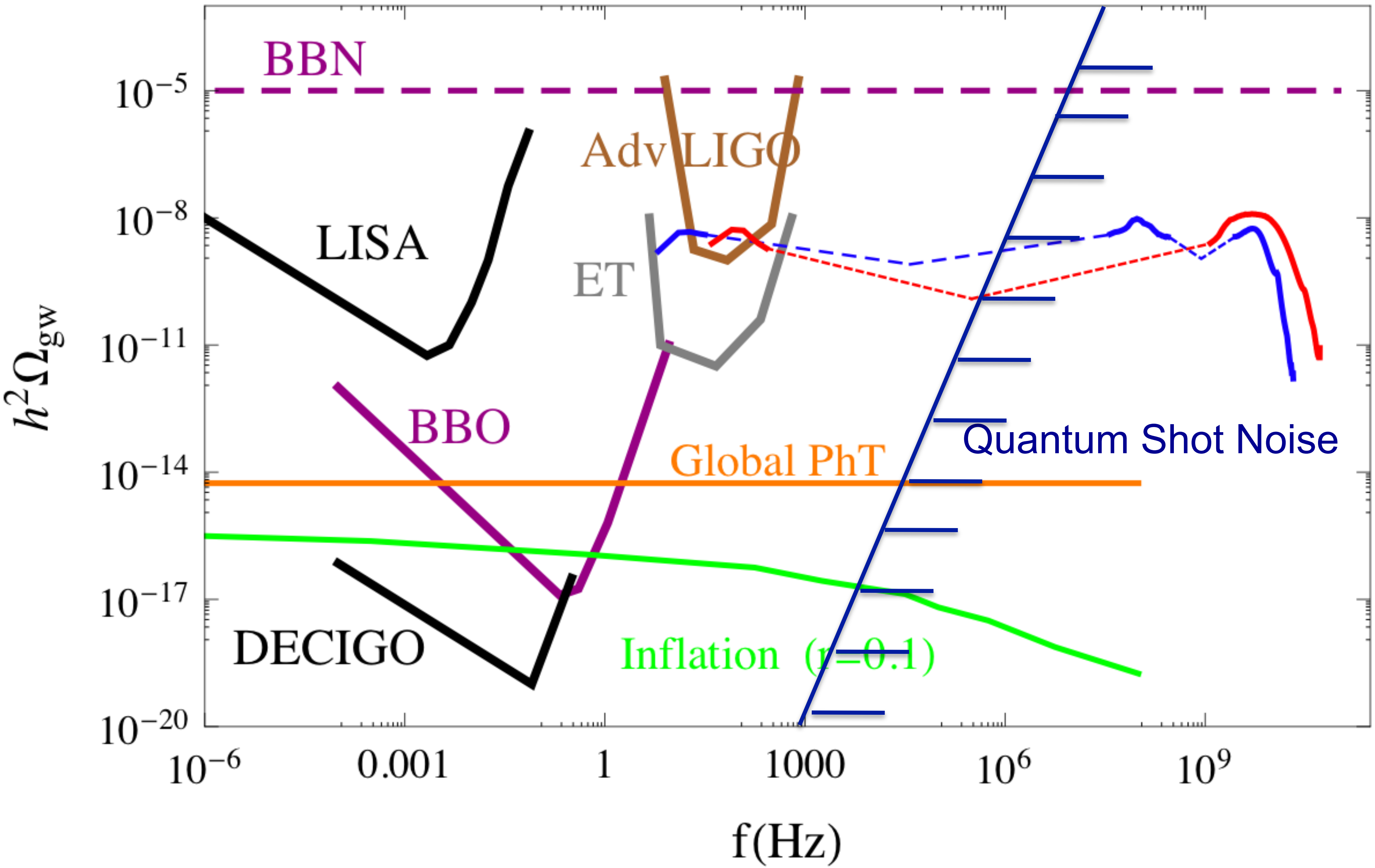
Can we test this model?

Search for its gravitational wave backg.

- Peaked at GHz frequencies
- Amplitude much larger than GW from inflation
- Several featured due to gauge fields
- Possibly defect structures seen in the GW Background as anisotropies

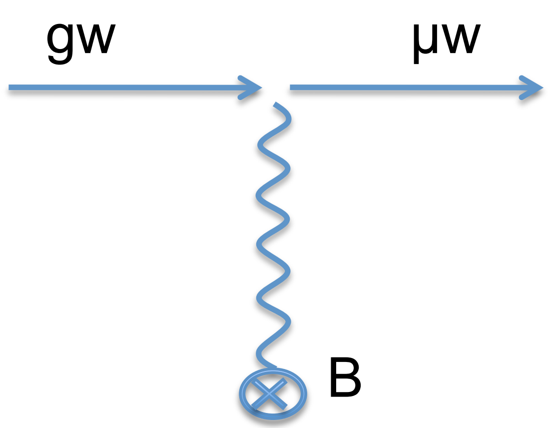
Gravitational waves energy density

Dufaux, Figueroa, JGB (2010)



Inverse Gertsenshtein effect

@ GHz frequencies

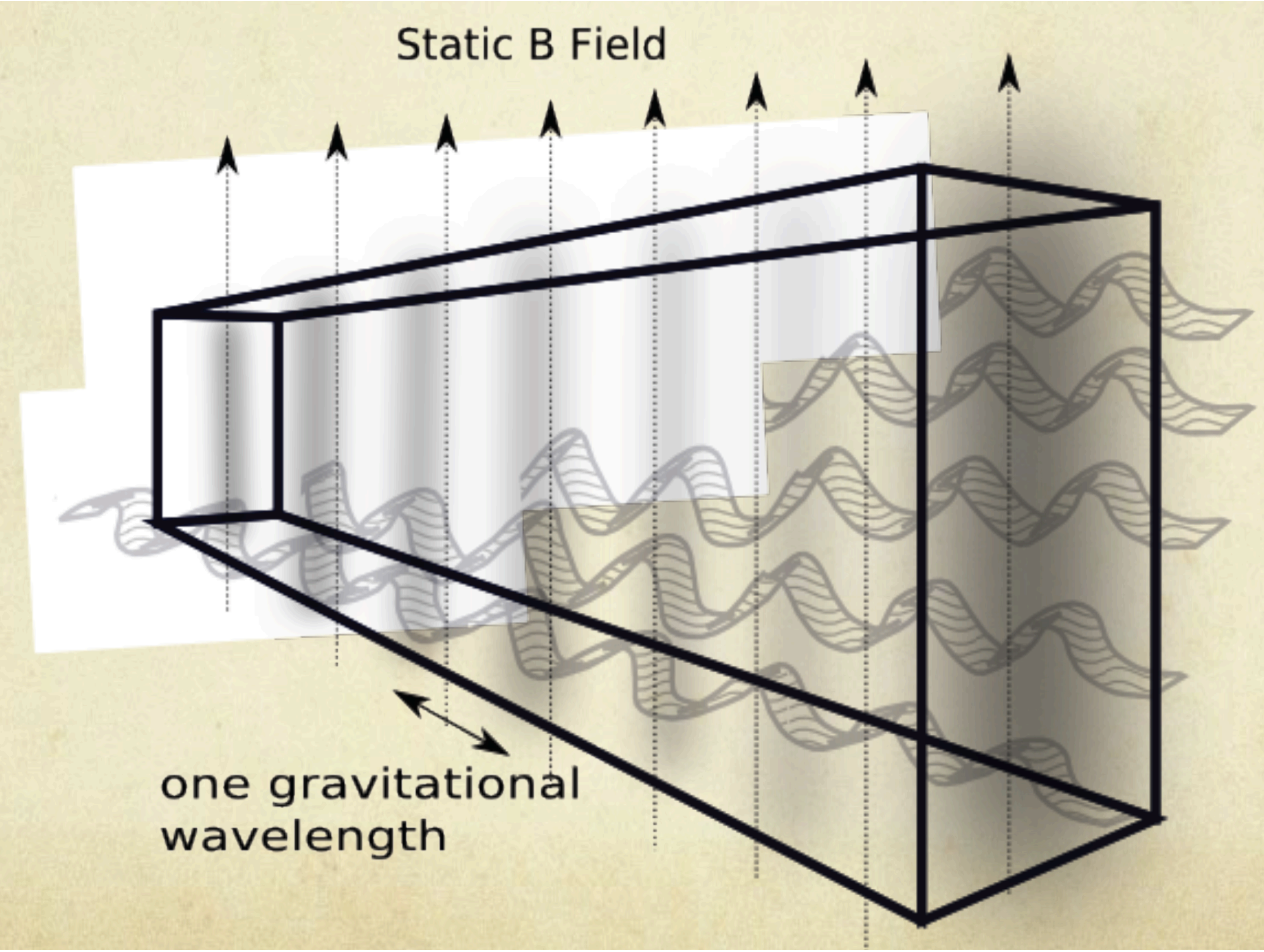


Gertsenshtein (1961)

$$\Gamma = \frac{8\pi G B^2 L^2}{c^3} \sum \text{Spin states}$$

De Logi, Michelson (1977)

$$\text{Photon Flux} = \Gamma \frac{c^2}{16\pi G} \omega_{gw}^2 h^2 \frac{1}{\hbar \omega_{gw}}$$



Static B Field
one gravitational
wavelength

Conclusions

We live through a fascinating era in which theoretical ideas in Cosmology can be tested with next generation experiments.

- Higgs-dilaton inflation connection between Early and Late Universe: $1-n_s = 3(w+1)$

- Wide galaxy surveys: DES, PAU, Euclid

- The violent process of reheating after inflation produces a background of gravitational waves

Old Japanese Proverb

年寄りの冷や水

(toshiyori no hiyamizu)

Translation: An old person’s cold water.

Meaning: An old person acting like a child.

Mísao-san, may you drink cold water for many years to come!