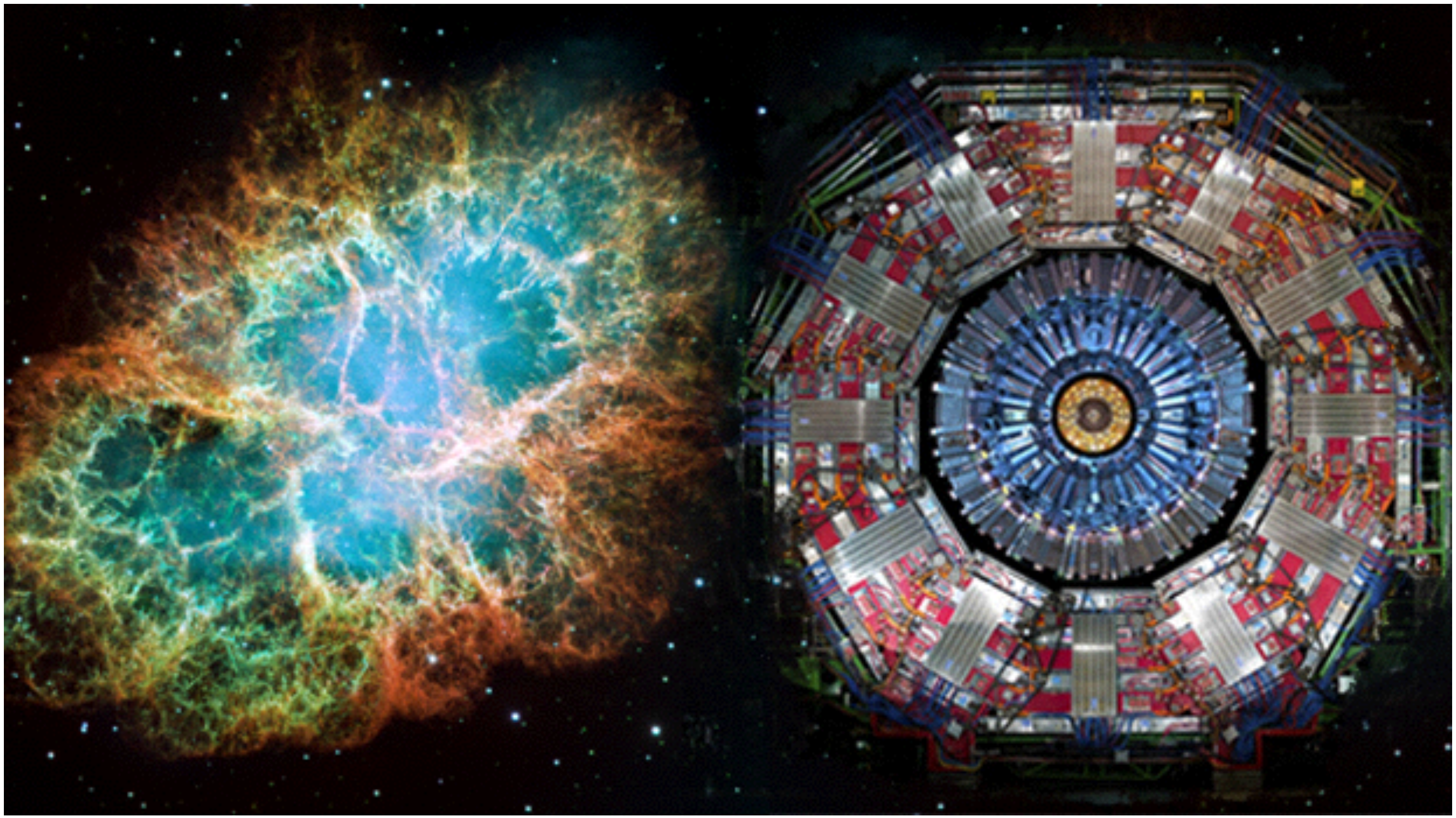
State of the Universe Address

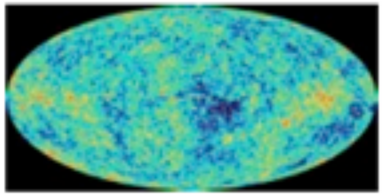
Prof. Scott Watson (Syracuse University)

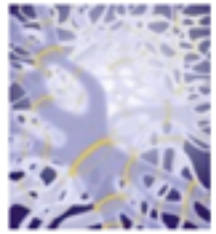


This talk is available online at: https://gswatson.expressions.syr.edu

This research was supported in part by: NASA U.S. DEPARTMENT OF ENERGY

Theoretical Cosmology @ Syracuse





https://gswatson.expressions.syr.edu

Scott Watson
Ph.D. Brown University (2005)
Particle theory, String theory, and Cosmology

HAPPY BIRTHDAY CRISTIAN!

Cristian Armendariz-Picon
Ph.D. Munich (2001)
Dark Matter and Observational Cosmology

Research Associate:

Kuver Sinha
Ph.D. Rutgers University (2008)
Particle theory, String theory, and Cosmology

Graduate Students:


Ogan Ozsoy


Gizem Sengor

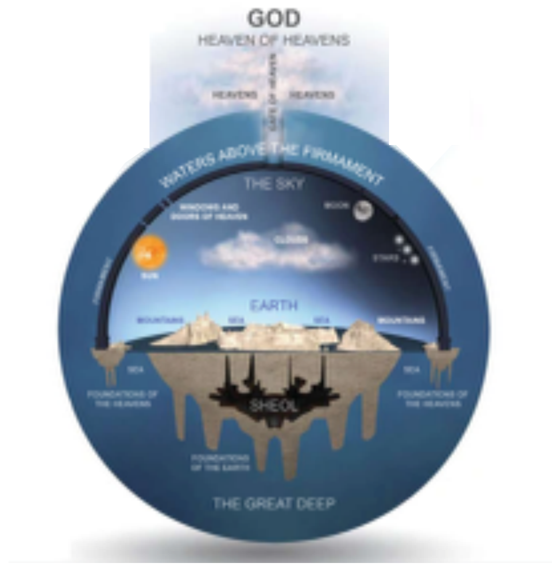

Julian Georg

Group Meetings Every Wednesday

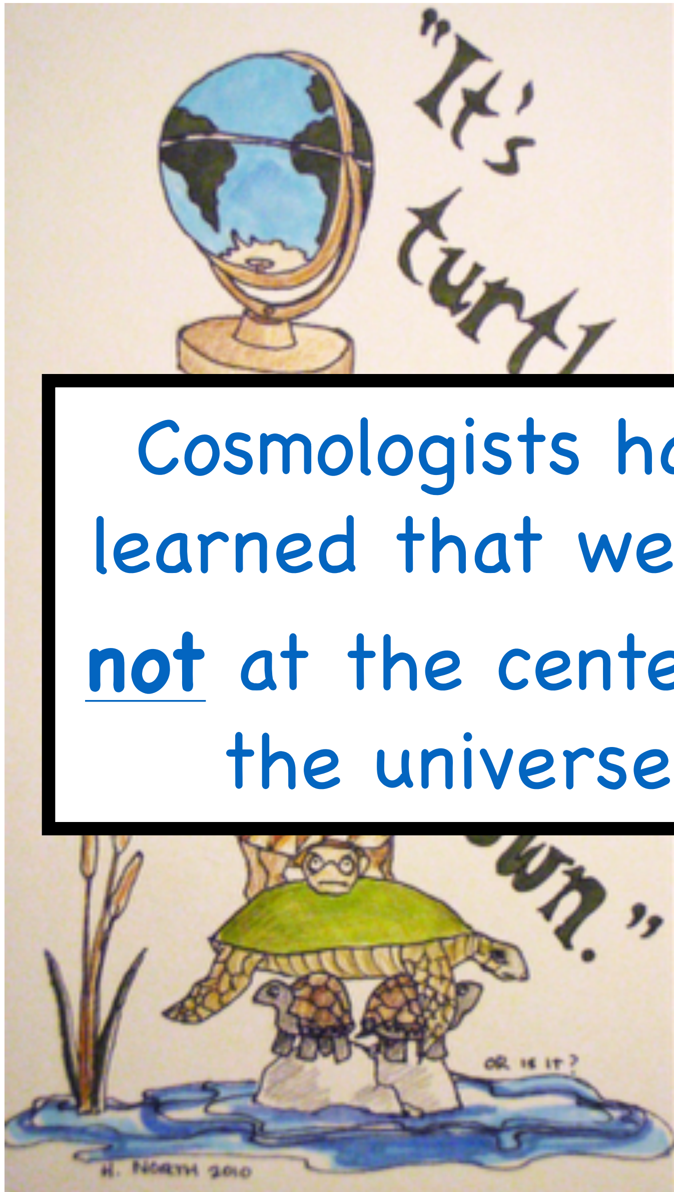
11am, room 203 (next to the physics office)

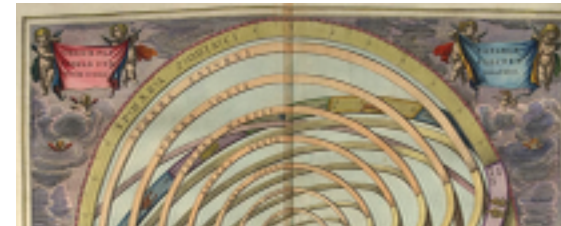
You are invited!

Early Days of Cosmology



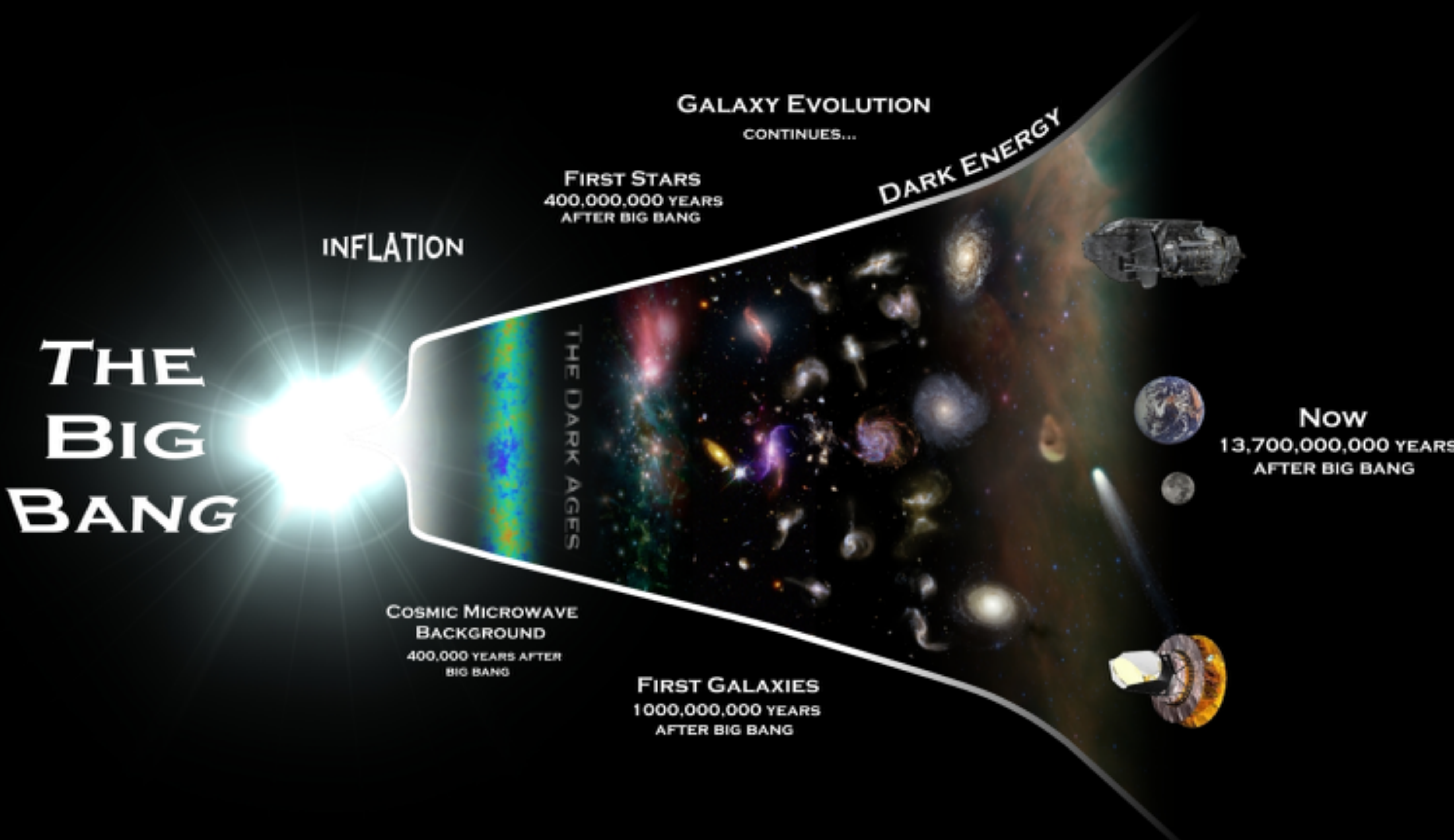
Early Days of Cosmology



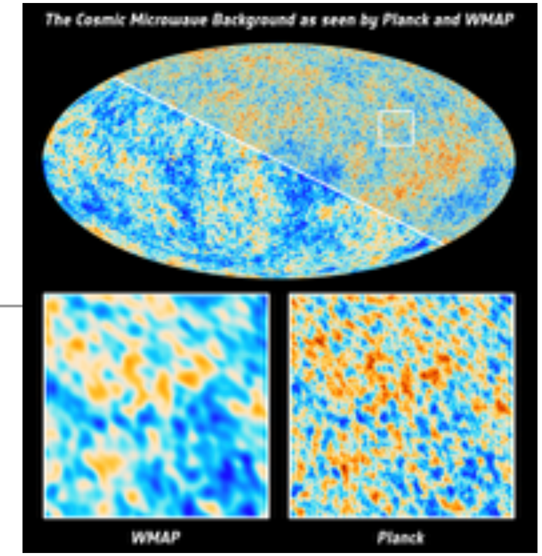


Cosmologists have learned that we are **<u>not</u>** at the center of the universe.

Today's Cosmological Standard Model



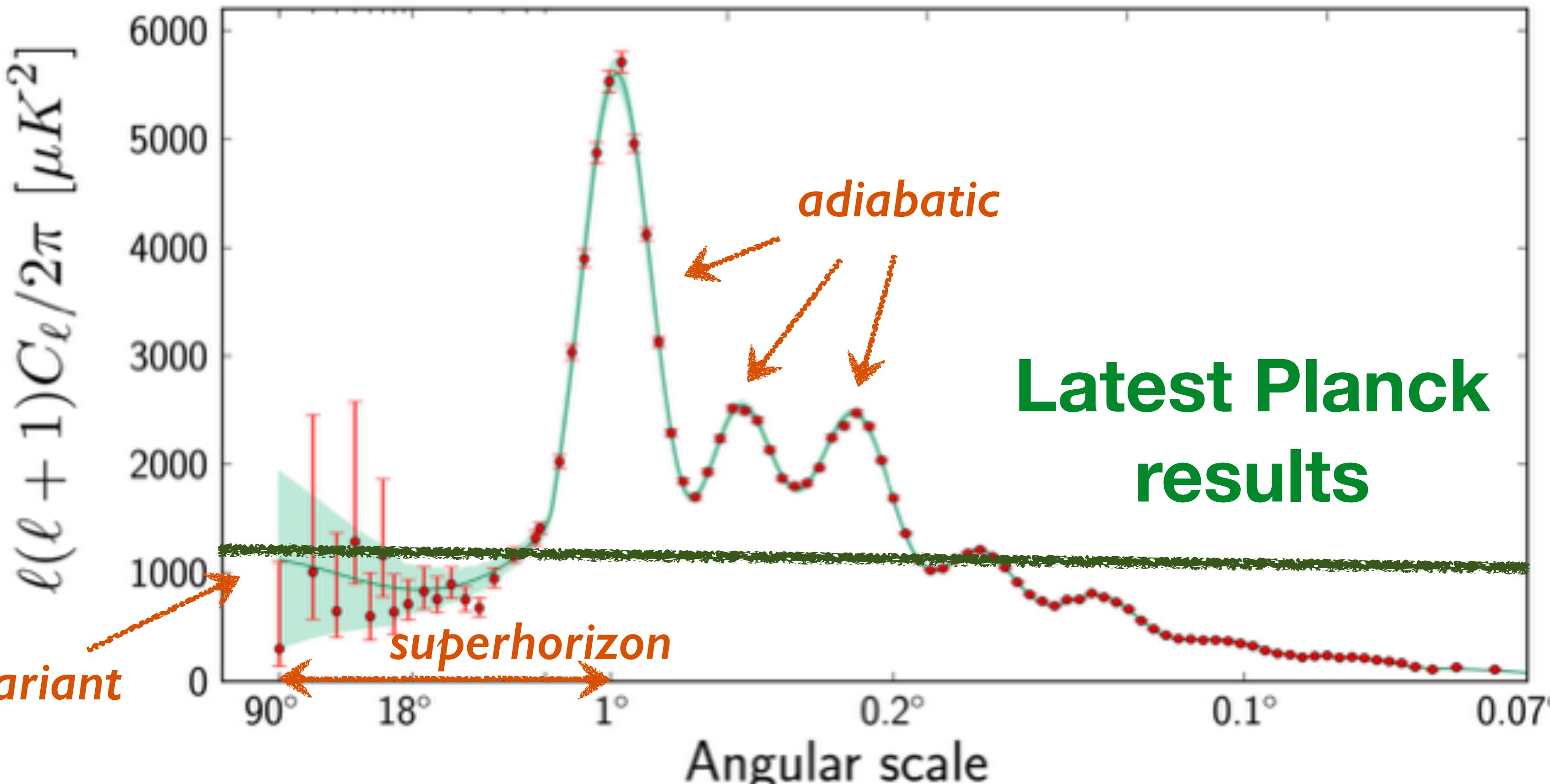
Observations Agree with Theory



flat

homogeneous

Gaussian

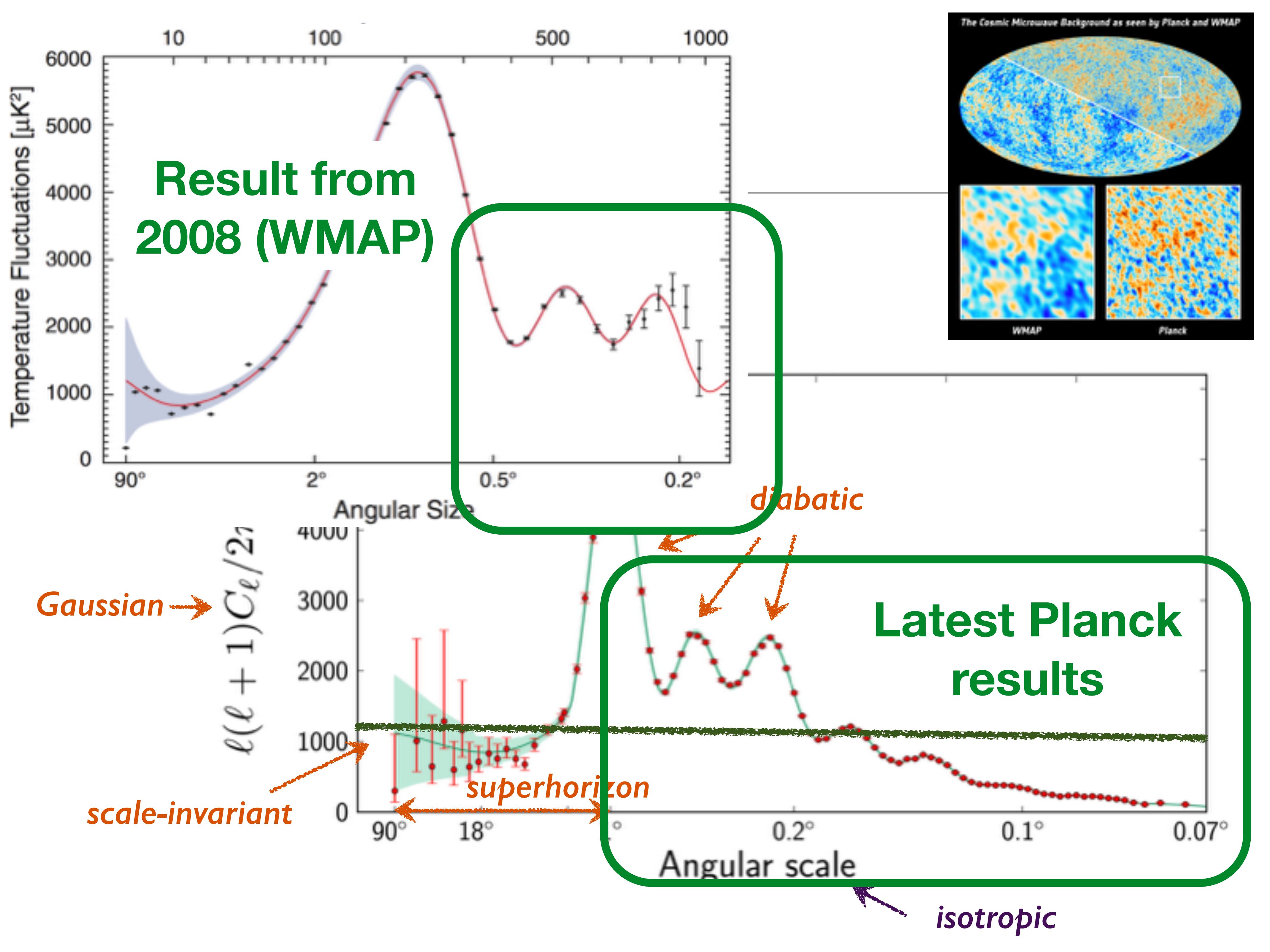


adiabatic

Latest Planck results

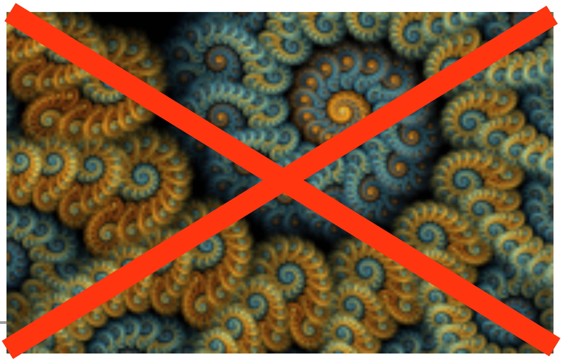
scale-invariant

isotropic

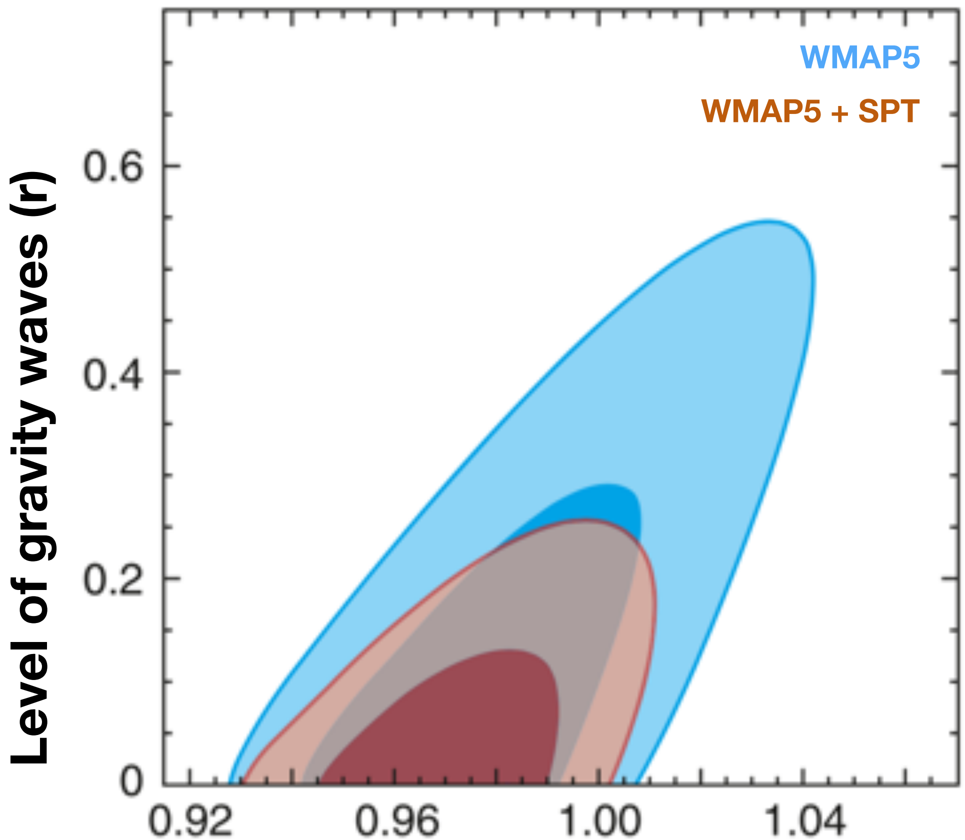


Result from 2008 (WMAP)
Latest Planck results
Temperature Fluctuations [μK²]
Angular Size
10
100
500
1000
90°
2°
0.5°
0.2°
The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck
$\ell(\ell+1)C_\ell/2\pi$
Angular scale
90°
18°
0.2°
0.1°
0.07°
Gaussian
scale-invariant
superhorizon
diabatic
isotropic

Improved understanding of Inflation

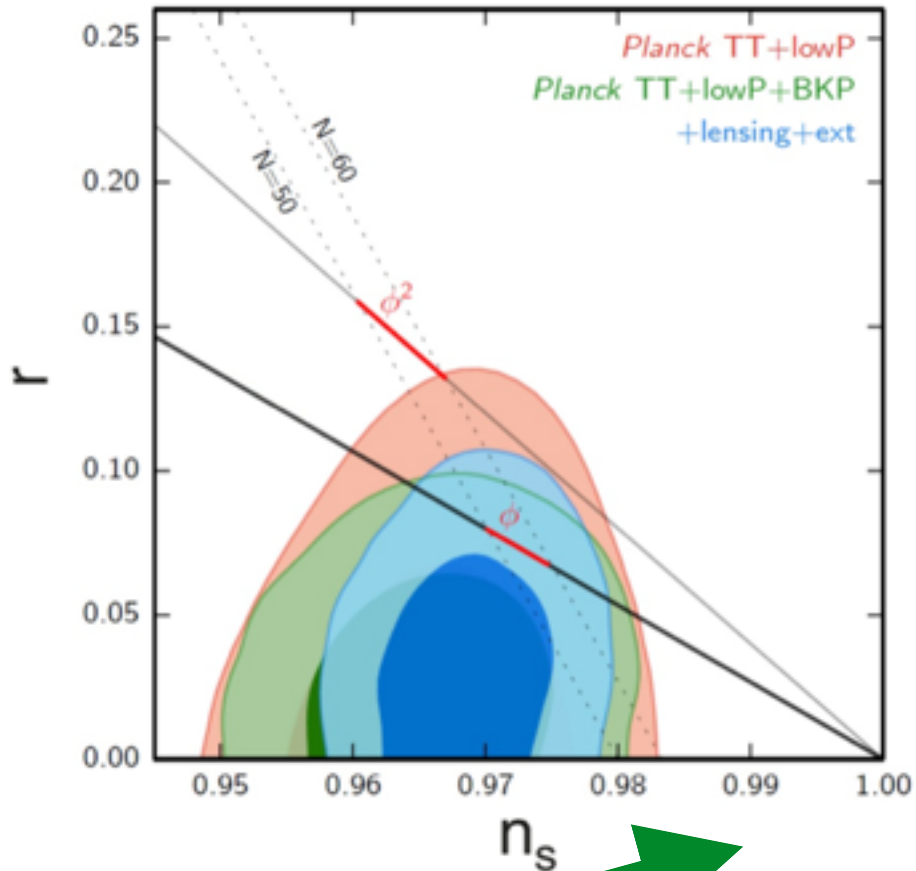


Data as of 2009



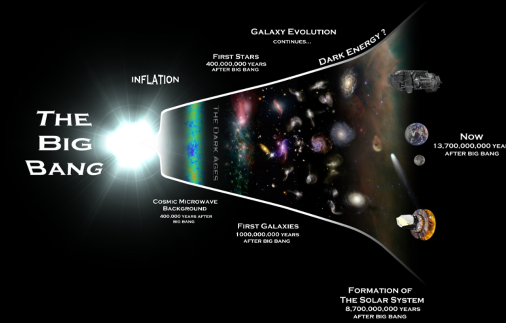
Departure from scale invariance (n_s)

Data today

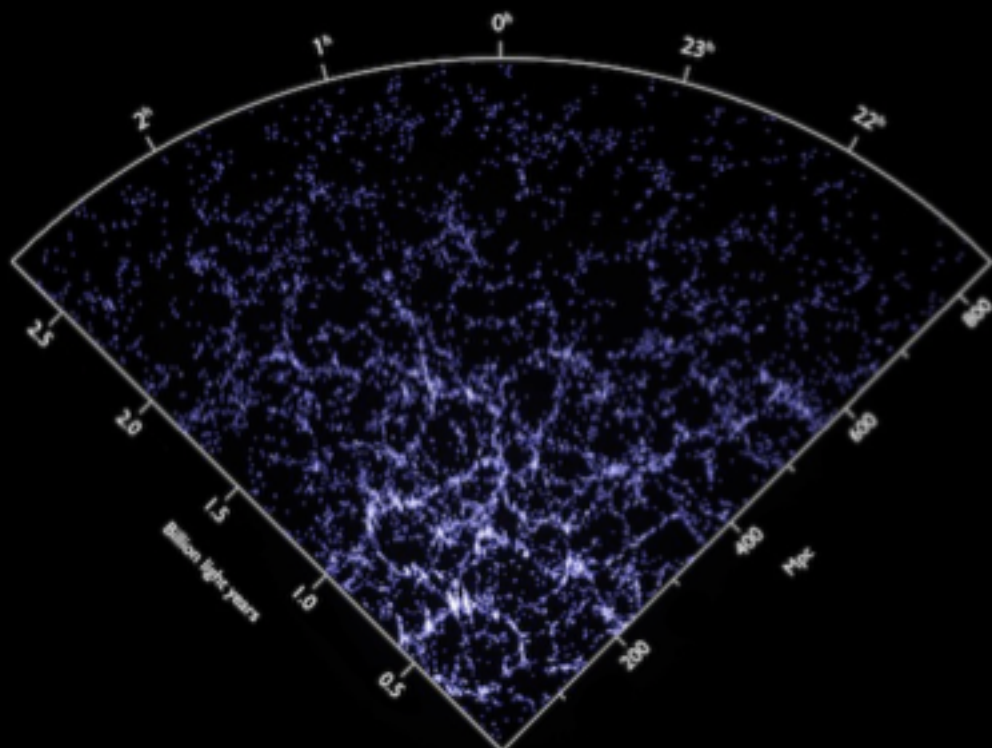


The **new result** $n_s < 1$ is **very important** theoretically.

Observations Agree with Theory

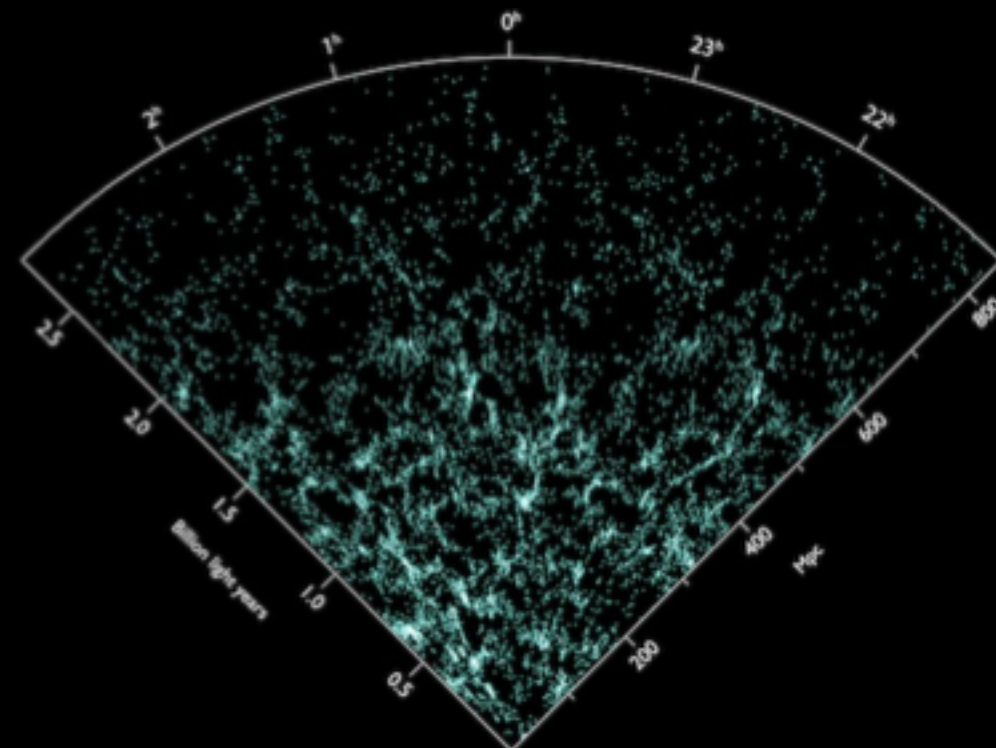


Observation



Data from SDSS Collaboration

Theory



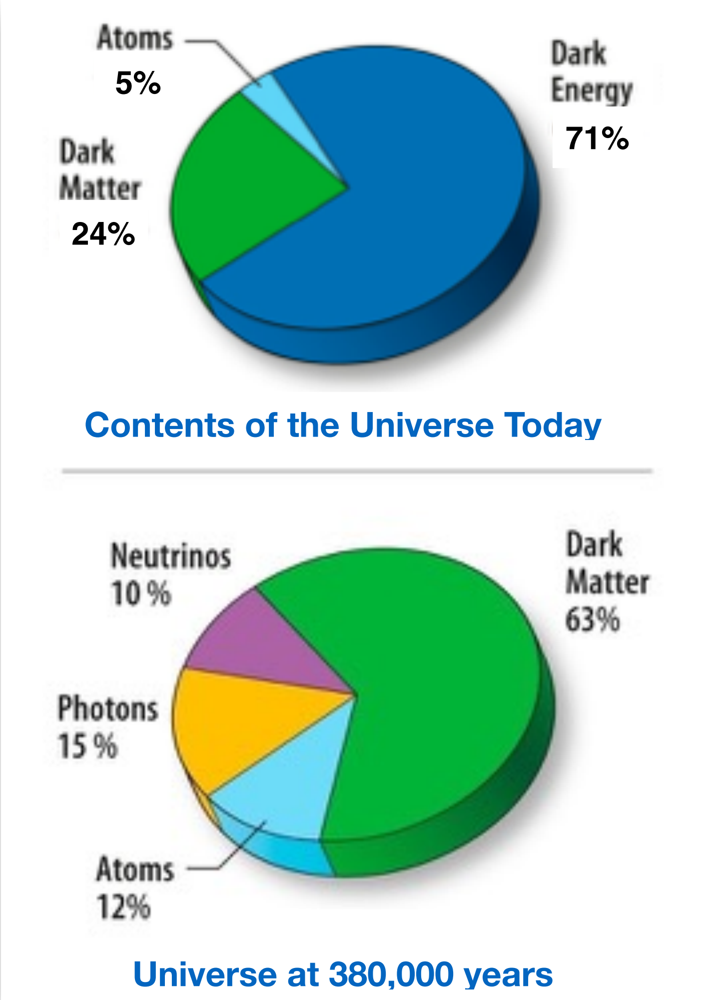
Bolshoi Simulation

High precision observations help us determine the composition and evolution of the universe.

Precision Cosmology

Cosmic Energy Budget Today

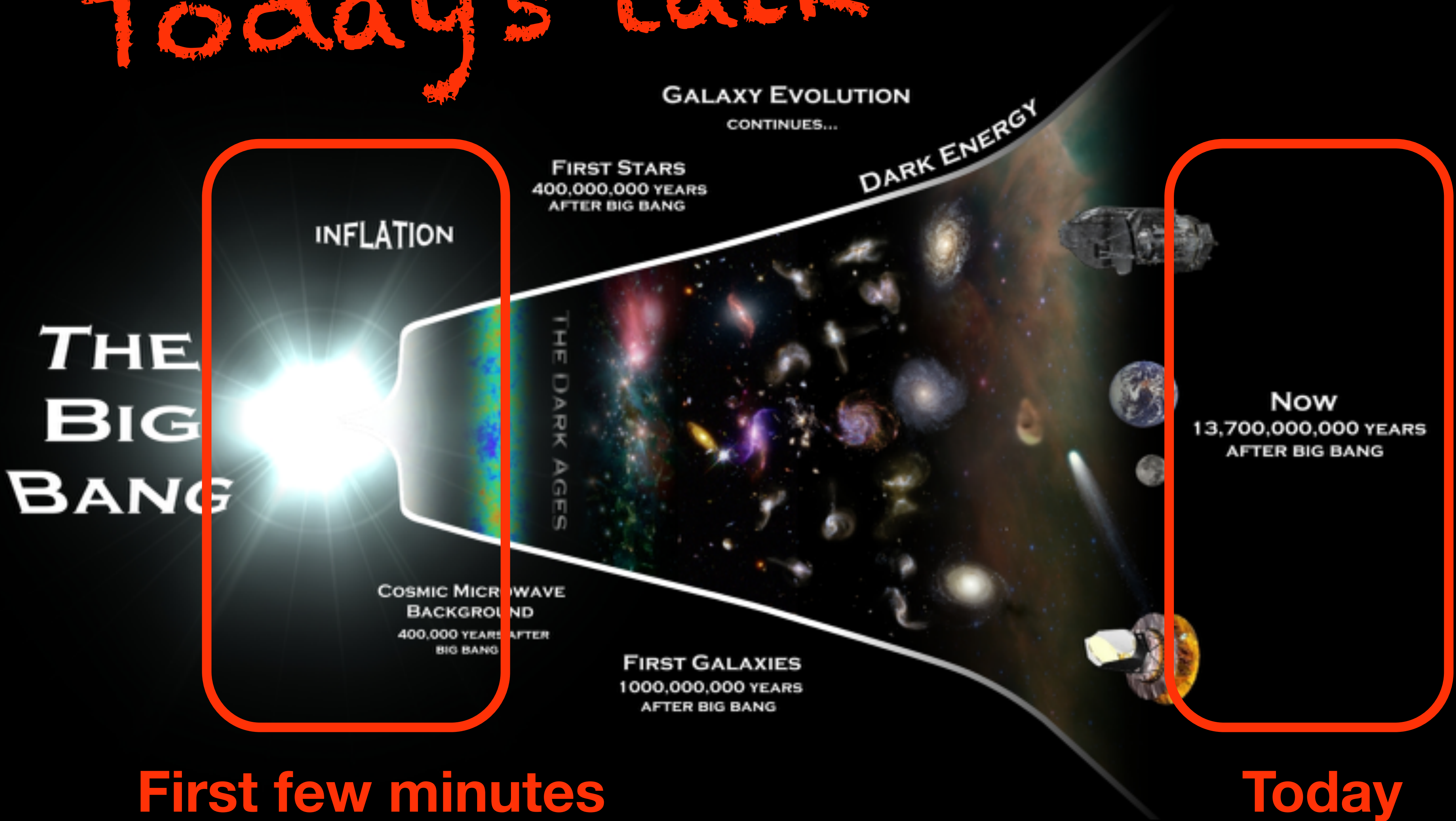
- Dark Energy 71.35%
- Dark Matter 24.02%
- Baryons 4.63%
- Early universe remarkably homogeneous
- Very small density contrast (1 / 100,000) at time of CMB decoupling



All suggest physics beyond the standard model.

The Cosmological Standard Model

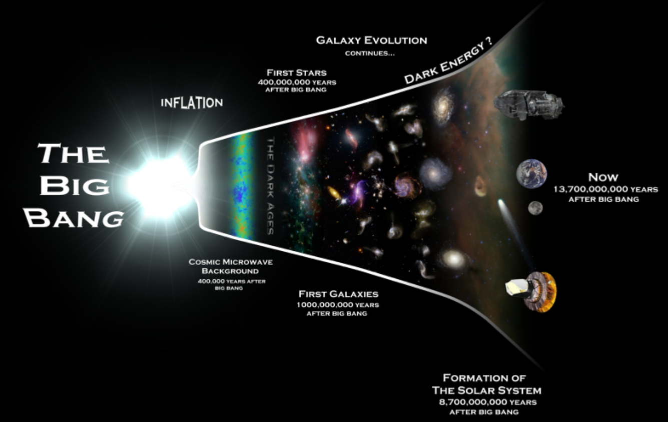
Today's talk

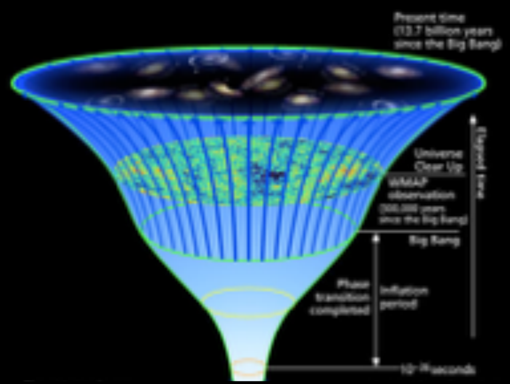


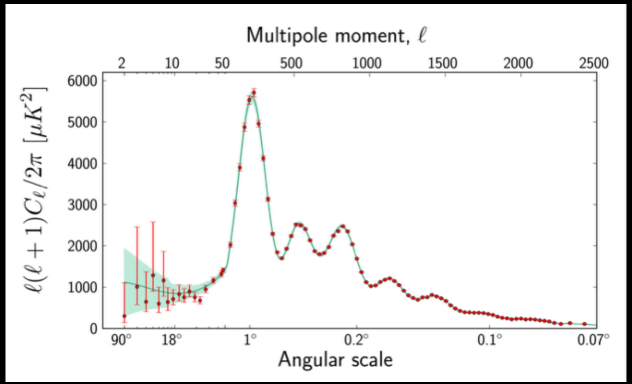
First few minutes

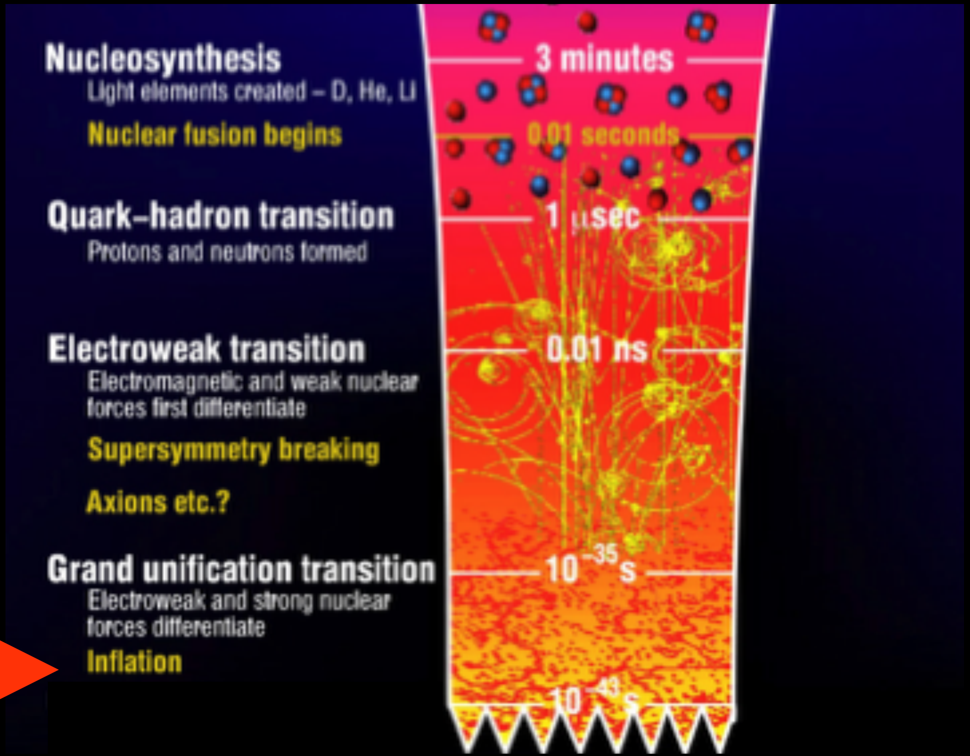
Today

The First Three Minutes





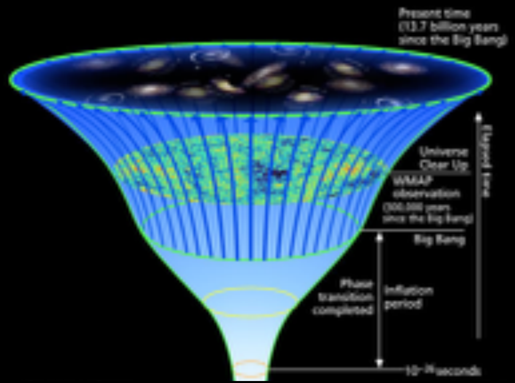




Inflation

Is there smoking gun evidence for inflation?

Gravity Waves from Inflation



A positive detection of primordial GWs would:

- Confirm Einstein was correct and gravity waves exist.
- Demonstrate that gravity is quantized
(Further motivating the need for a quantum theory of gravity — i.e. string theory)
- Provide "smoking gun" evidence that inflation occurred.
- Teach us the energy scale at which inflation took place.
- Allow us to directly probe physics beyond the standard model.


THE POST-STANDARD

syracuse.com

Syracuse University physicist explains the Big Bang breakthrough

Inflation, its signatures, and possible alternatives have been significant focus of my group's research program:

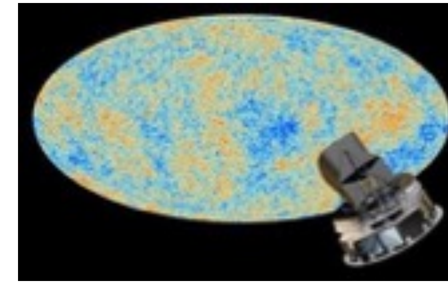
"How Well Can We Really Determine the Scale of Inflation? "
with O. Ozsoy and K. Sinha, Phys. Rev. D91 (2015)

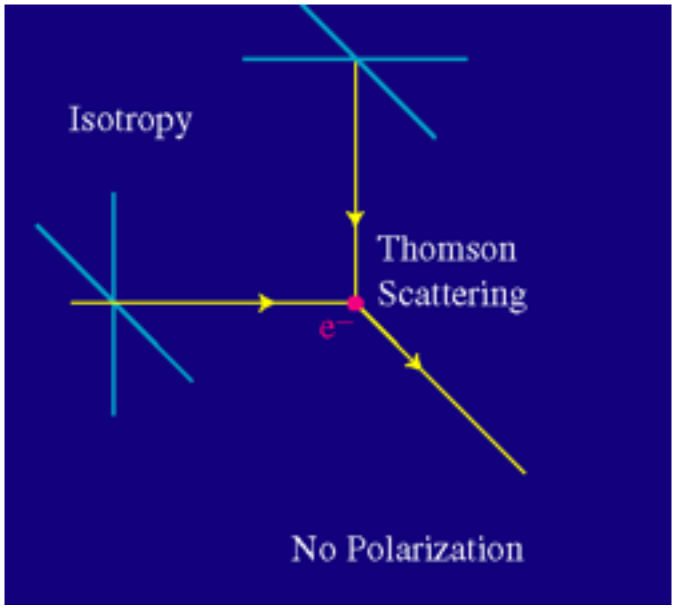
"Decoupling Survives Inflation "
with A. Avgoustidis, et. al., JCAP 1206 (2012)

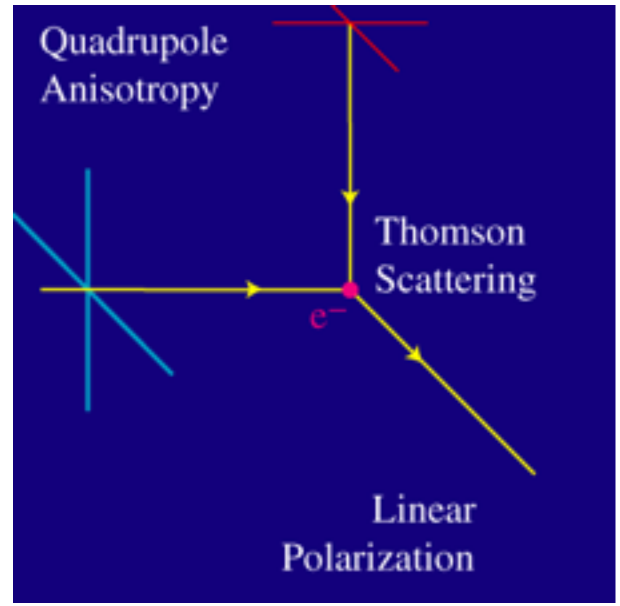
"The Importance of Slow-roll Corrections During Multi-field Inflation "
with A. Avgoustidis, et. al., JCAP 1202 (2012)

NASA Panelist (IPSAG and PCOS) for future CMB Polarization experiments

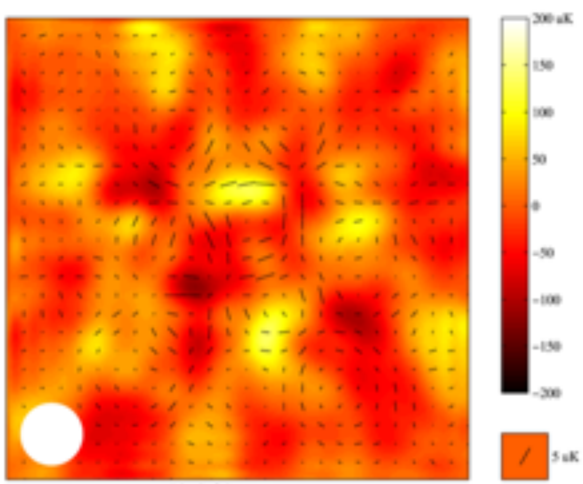
CMB Polarization and Primordial Gravity Waves

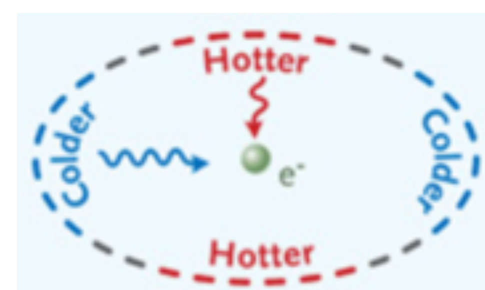




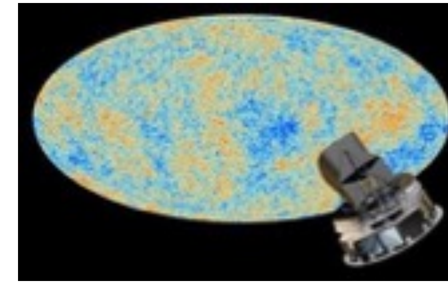


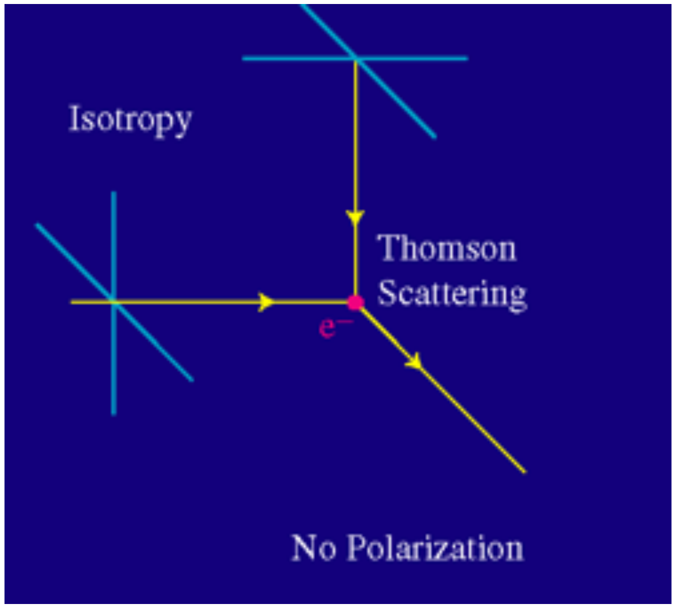
E-mode Polarization (DASI — 2002)

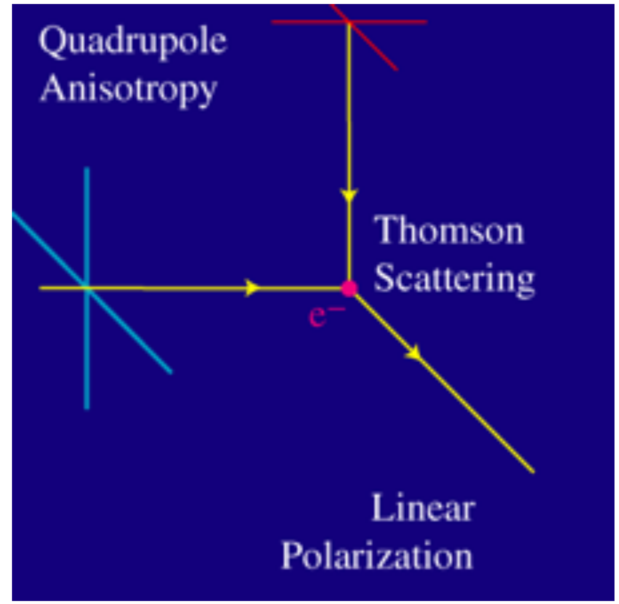




CMB Polarization and Primordial Gravity Waves







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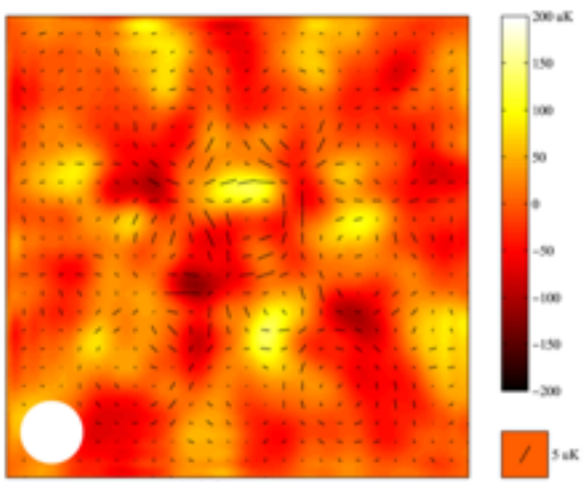

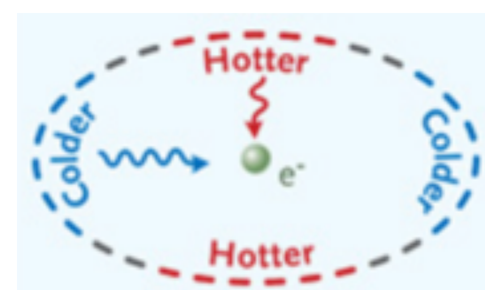

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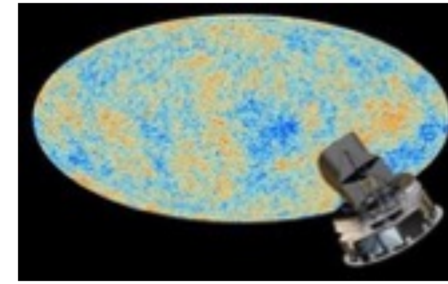

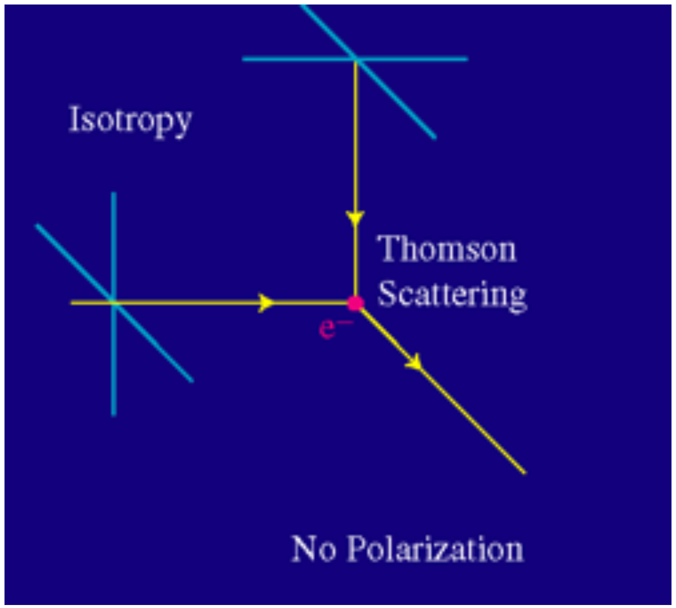

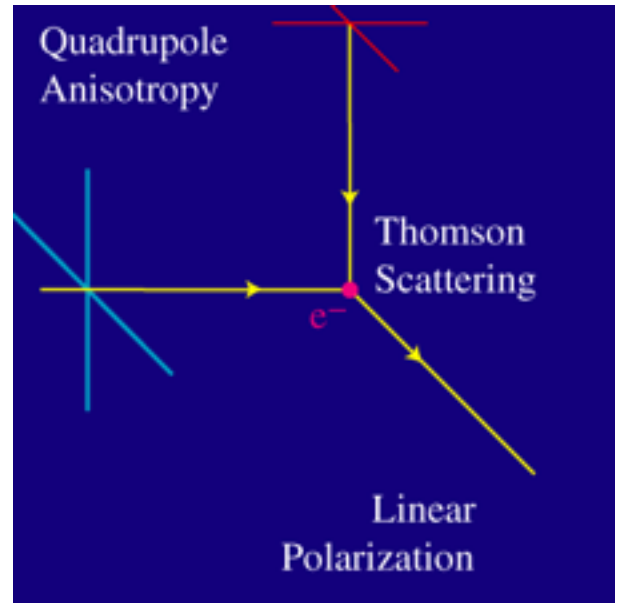

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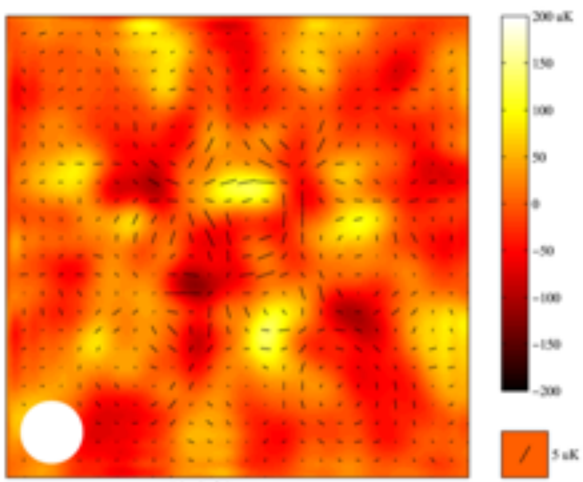
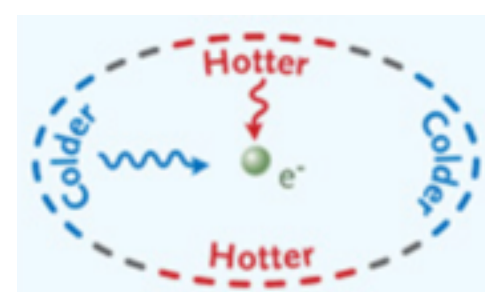
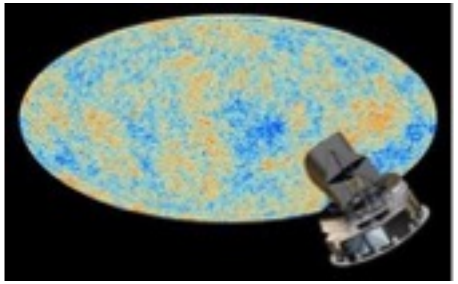
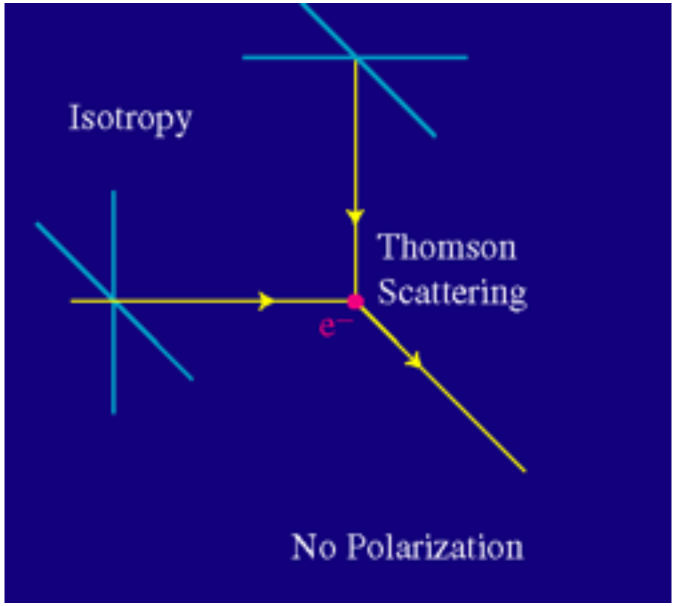
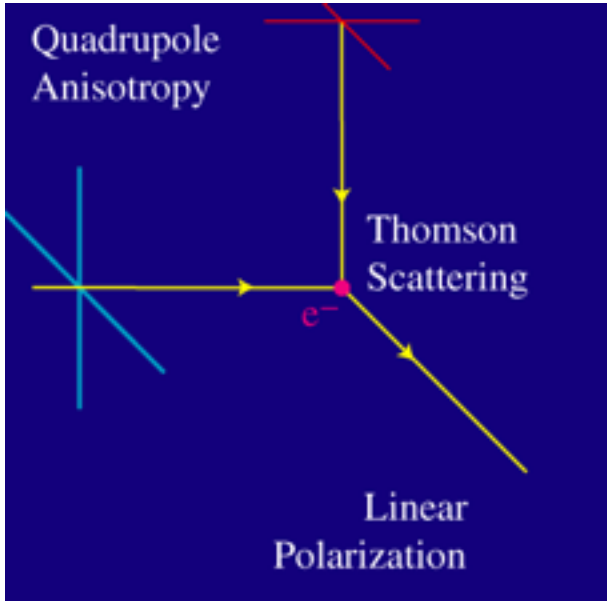




CMB Polarization and Primordial Gravity Waves







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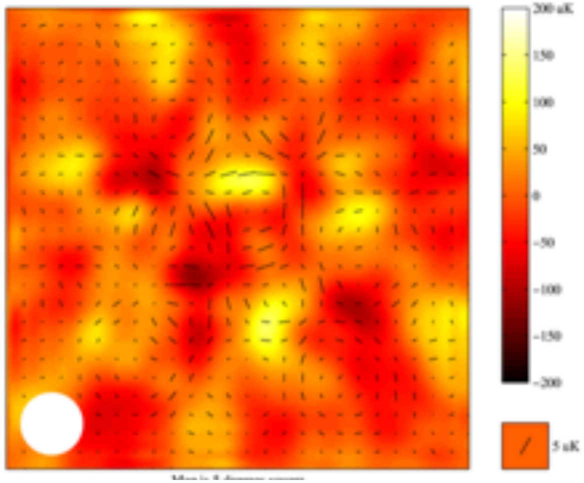

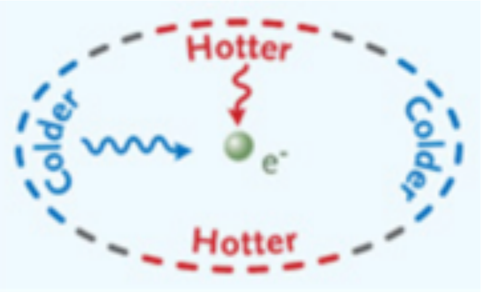

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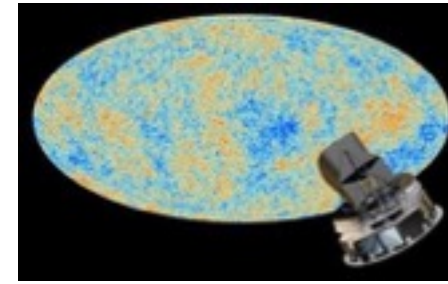

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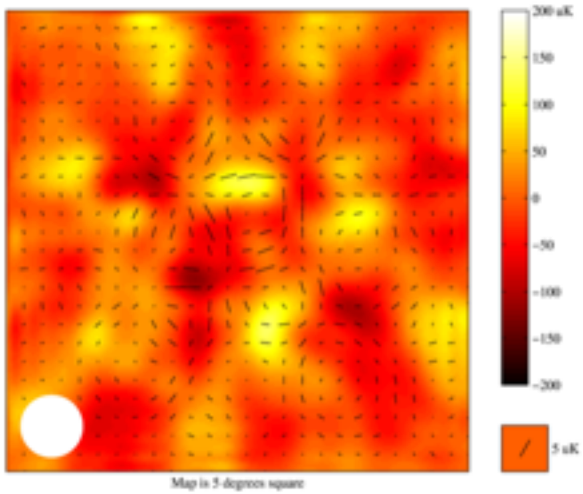
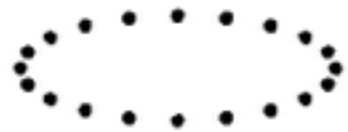
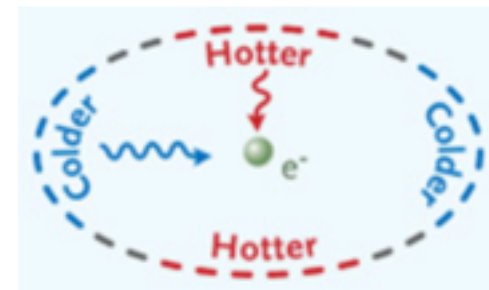
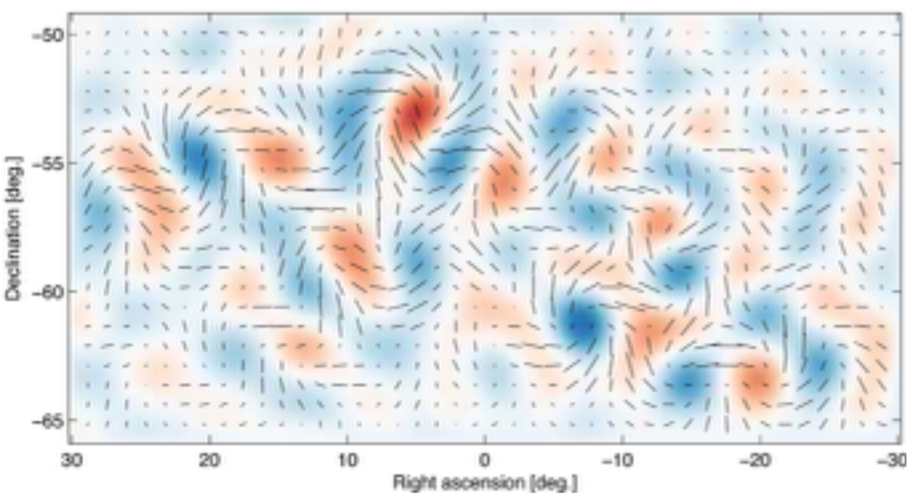


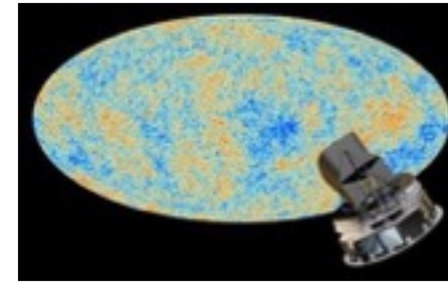




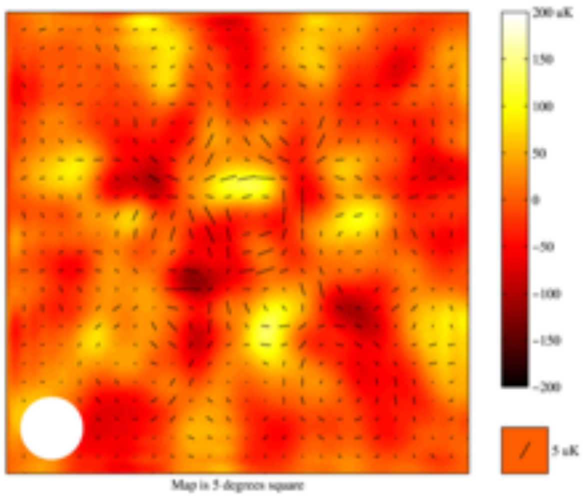
Gravity Waves can also produce B-mode Polarization

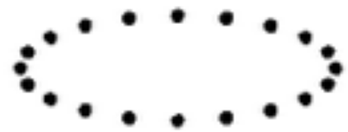


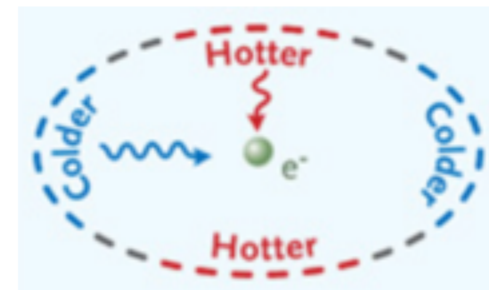
CMB Polarization and Primordial Gravity Waves



E-mode Polarization (DASI — 2002)







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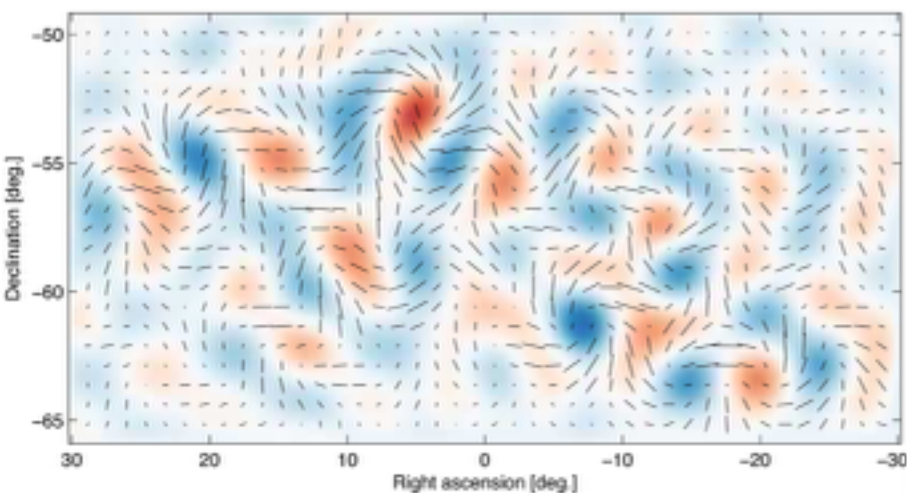


The Inflaton Hierarchy Problem

with O. Ozsoy and K. Sinha, Phys. Rev. D91 (2015)

Scale of inflation

Amount of gravity waves

$$\frac{H_I}{m_p} \simeq 10^{-5} \left(\frac{r}{0.1}\right)^{1/2}$$

Scale of gravity

Proximity to scale of quantum gravity makes this problem challenging.

There can be additional sources of primordial gravity waves.

$$\mathcal{L}^{\theta}_{\rm QCD} = \theta_{\rm QCD}\, \epsilon_{\mu\nu\alpha\beta}\, G^{\mu\nu}_a G^{\alpha\beta}_a$$

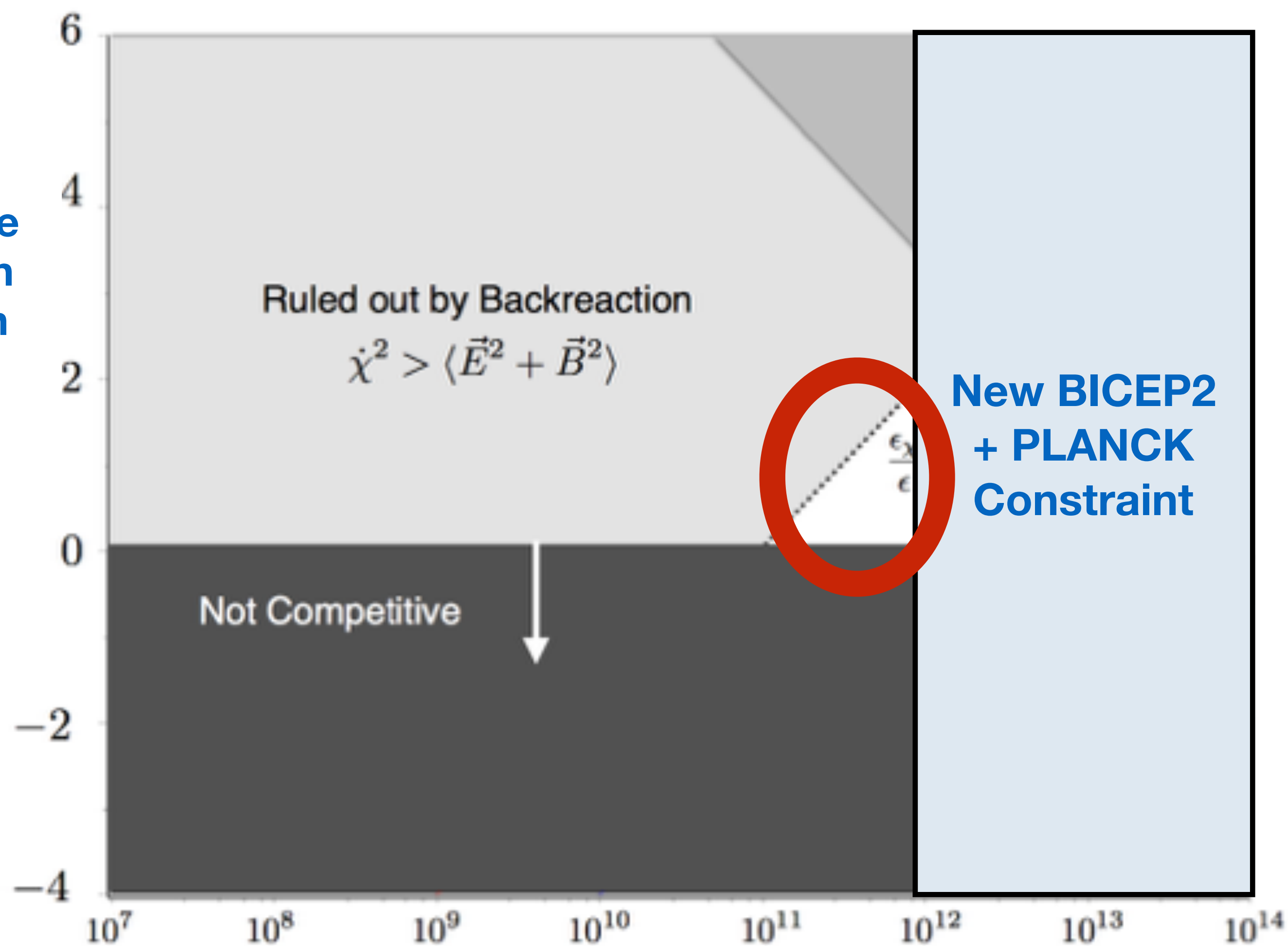
Other fields can produce gravity waves during inflation

Is there smoking gun evidence for inflation?

Can we really determine the scale of inflation?

with K. Sinha and O. Ozsoy, arXiv:1410.0016, Phys. Rev. D91 (2015)

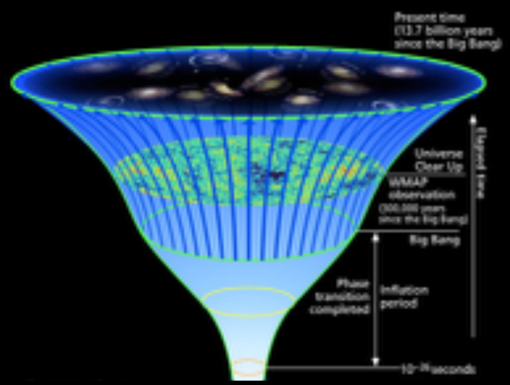
Gravity Wave Contribution v.s. Inflation (log scale)

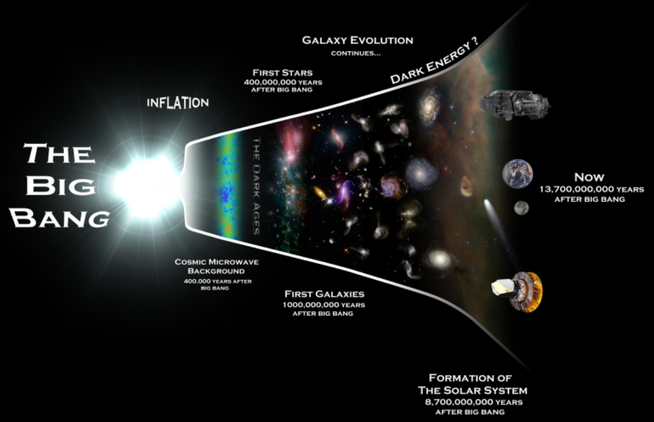


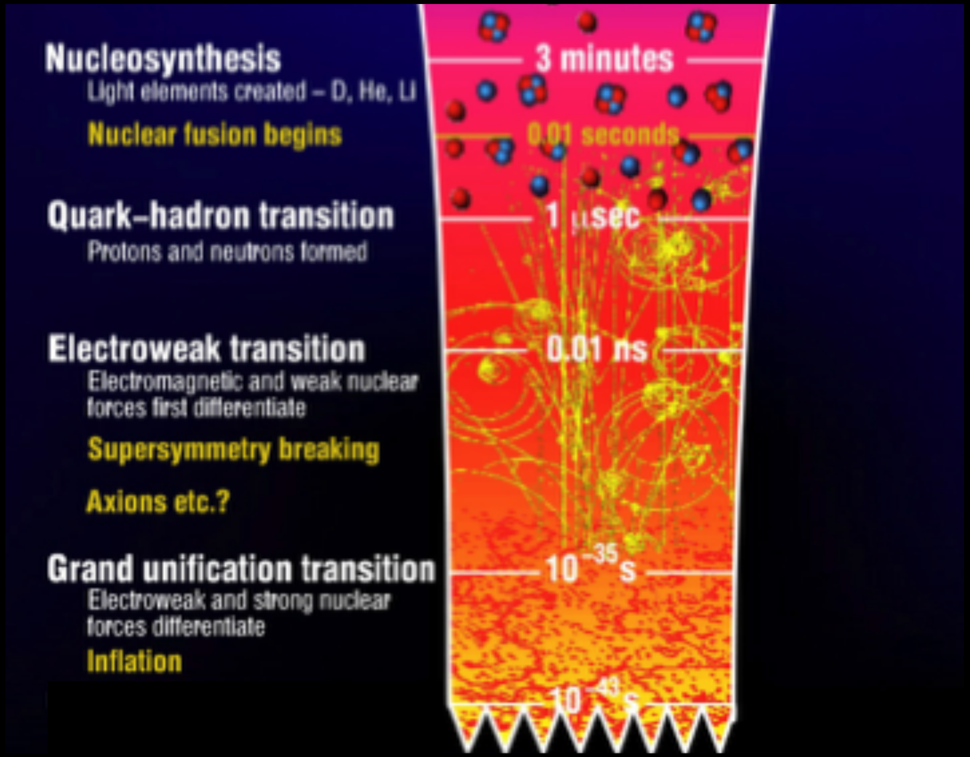
Energy Scale of Inflation (GeV)

Yes, measurement of gravity waves will tell us the scale of inflation

The First Three Minutes







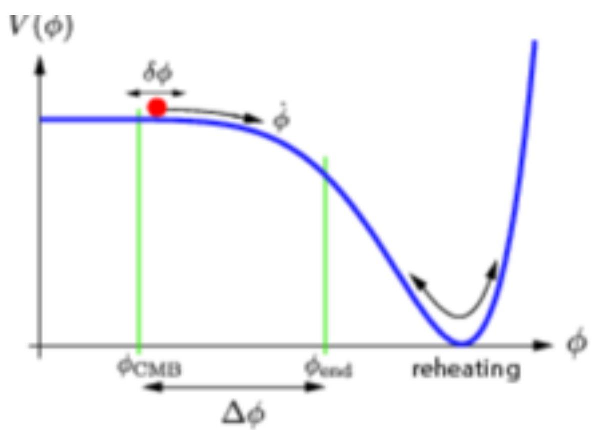
How does Inflation End?

How does the hot Big Bang proceed?

Much less is known about this important process!

Two pioneers of inflationary reheating

From Inflation to the Hot Big Bang

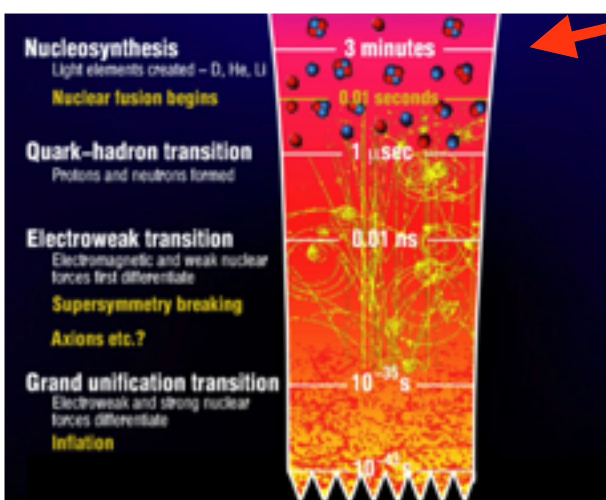


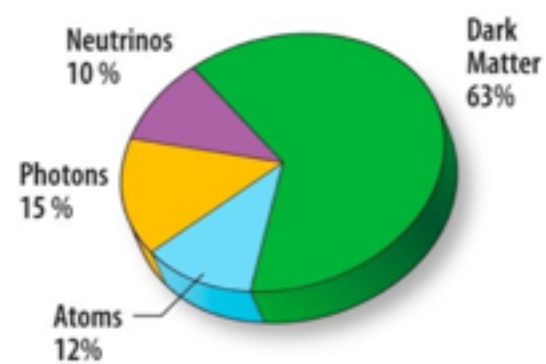
Robert Brandenberger
(McGill University)

Lev Kofman
1957 — 2009

Observational requirements

$T \gtrsim 5\ \mathrm{MeV}$ (Billion degrees)

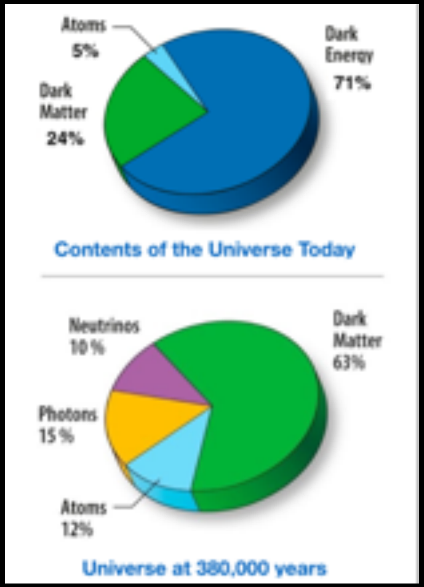


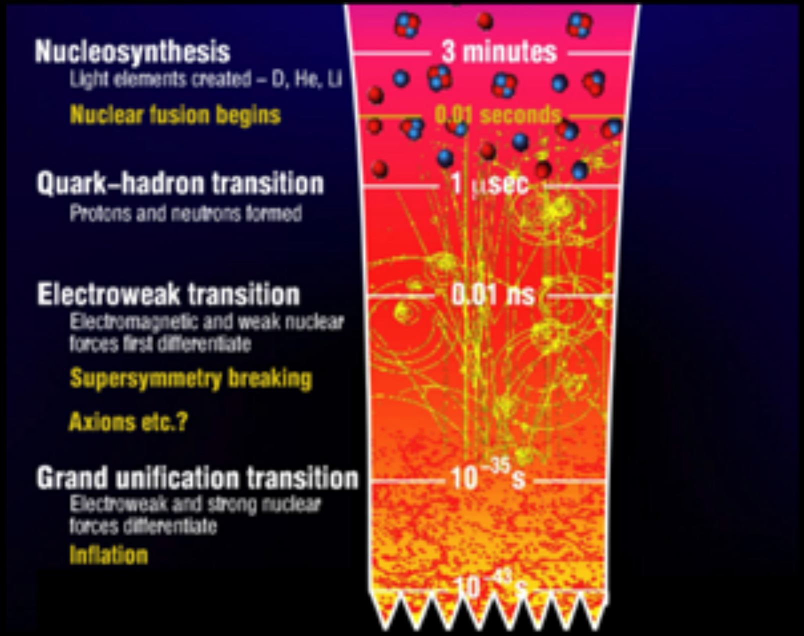


Universe at 380,000 years

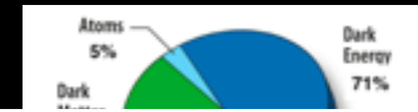
The Bullet Cluster

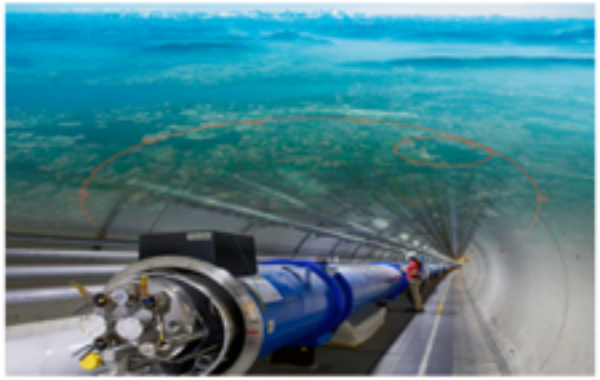
There is compelling evidence for particle dark matter.

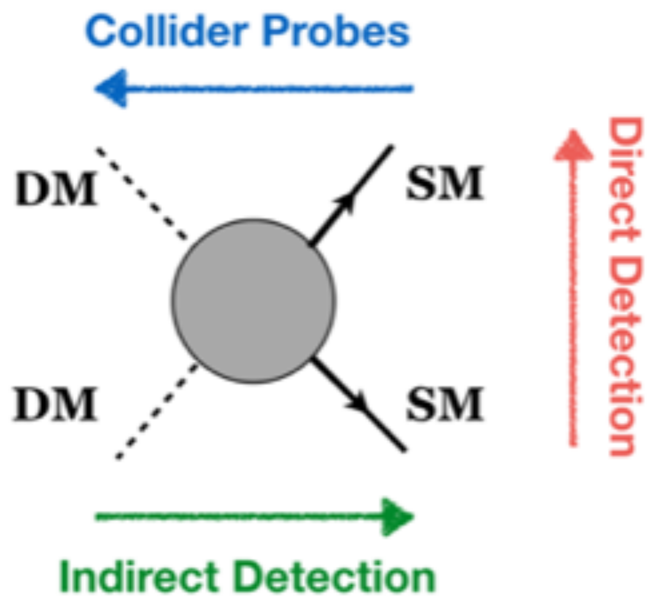


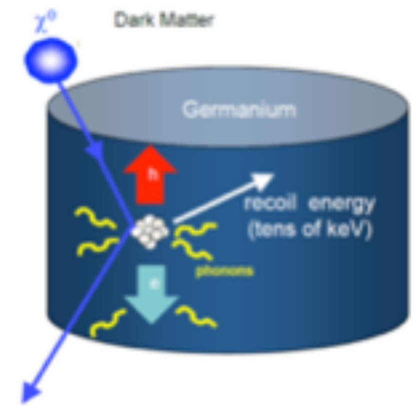


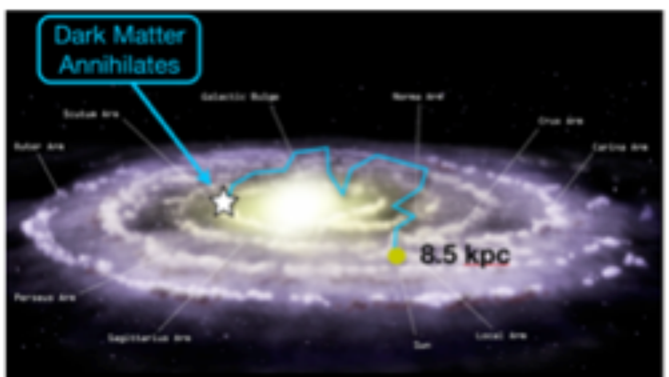
To reveal its particle properties we need to understand its primordial creation.









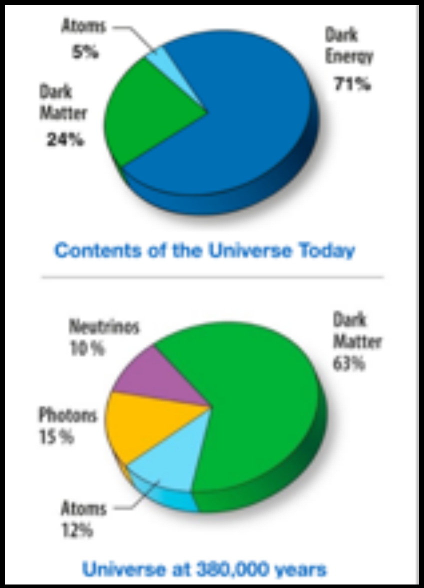


“WIMP Miracle”

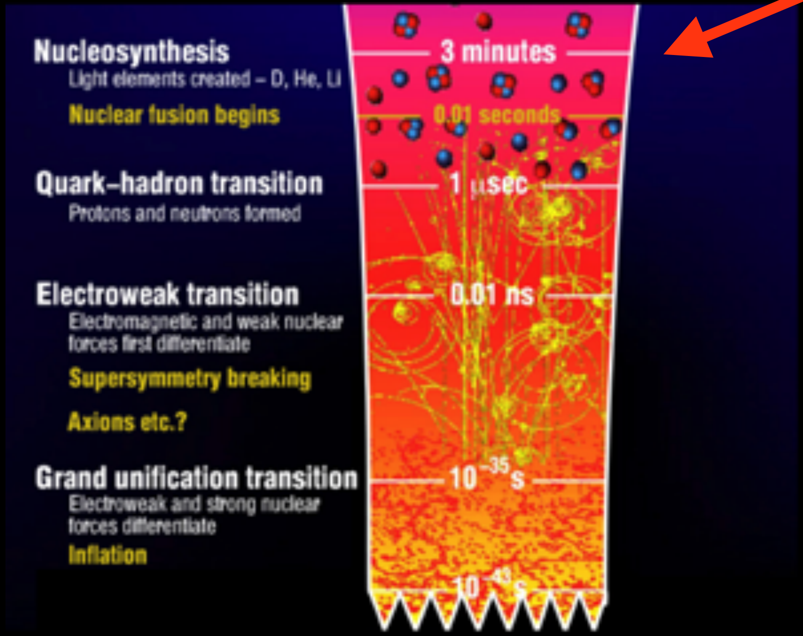
$$\sigma_{\mathrm{DM\,DM}\to\mathrm{SM\,SM}} \simeq 1\,\mathrm{pb}$$

The Bullet Cluster

There is compelling evidence for dark matter.



What is the temperature of the Hot Big Bang?



What if the Big Bang occurred after dark matter was created?

(In fact, we demonstrated this is a robust possibility motivated by fundamental theory)

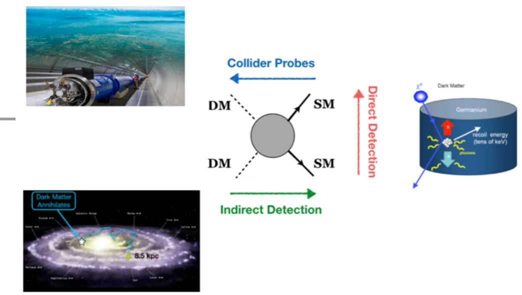
"Cosmological Moduli and the Post-Inflationary Universe: A Critical Review"

**Invited review with Gordy Kane and Kuver Sinha

Dark Matter and the Temperature of the Hot-Big Bang

R. Easther, R. Galvez, O. Ozsoy, **S.W.** [arXiv:1307.2453, Phys.Rev. D89 (2014)]

JiJi Fan and M. Reece. [arXiv:1307.4400, JHEP 1310 (2013)]



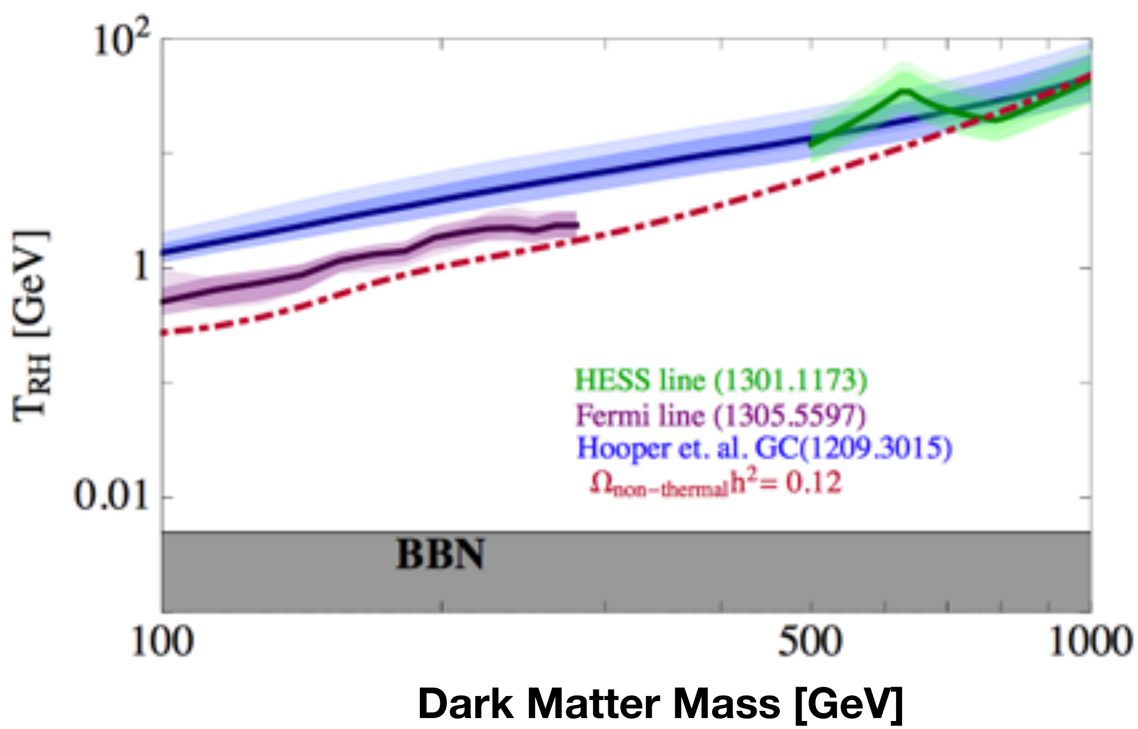
$$\Omega_{\rm DM} \sim \frac{1}{\langle \sigma v \rangle T} = 0.24$$

Fixed by Planck Observations

Relative amount of Dark Matter Today

Dark Matter annihilation rate

Temperature of the Hot Big Bang



$$\boxed{T \gtrsim 1 \text{ GeV}}$$

Toward Establishing the post-Inflationary Universe

"Cosmological Moduli and the Post-Inflationary Universe: A Critical Review"
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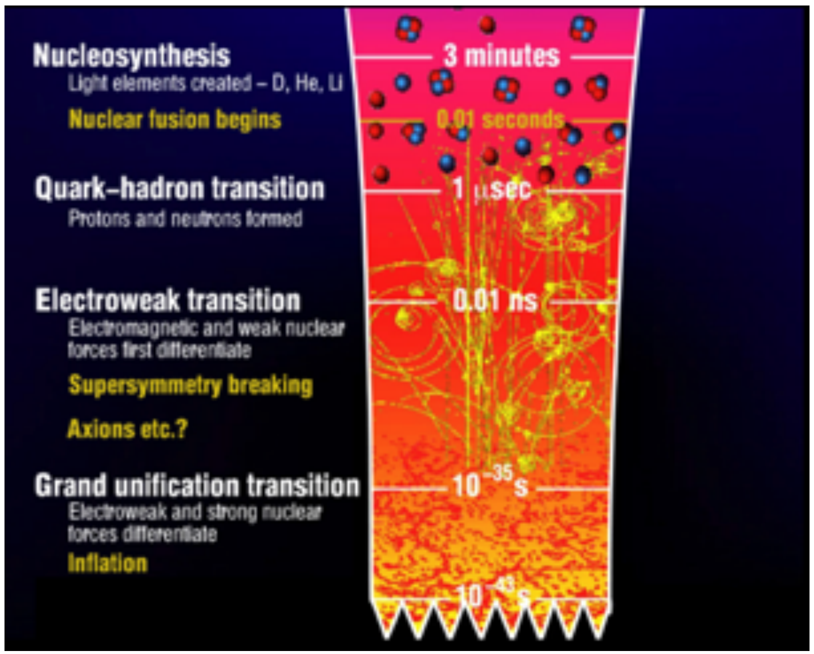


CMB Physics

Extra matter phase changes the way CMB observations are used to constrain inflationary models.

R. Easther, R. Galvez, O. Ozsoy, **S.W**. [Phys.Rev. D89 (2014)]

Additional relativistic energy from enhanced annihilations of dark matter changes physics of recombination.

Slatyer, Padmanabhan and Finkbeiner [Phys.Rev. D80]

Bounds on isocurvature contribution to CMB anisotropies lead to constraints.

L. Iliesiu, D. Marsh, K. Moodley, **S.W**. [Phys.Rev. D89]

Dark Radiation

Decays to non-Standard Model (hidden sector) radiation can lead to constraints from bounds on new light species (N_{eff}).

L. Iliesiu, D. Marsh, K. Moodley, **S.W**. [Phys.Rev. D89]

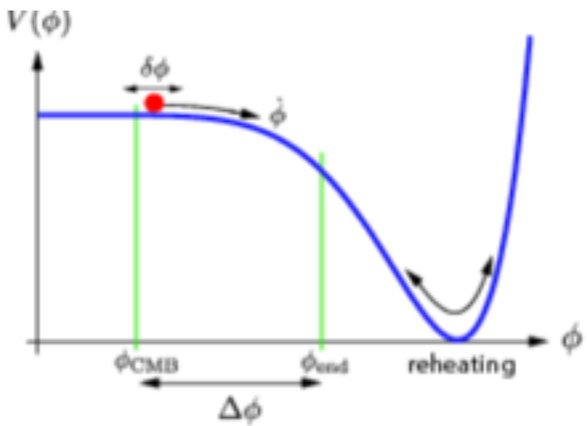
Enhanced Structure on Small Scales

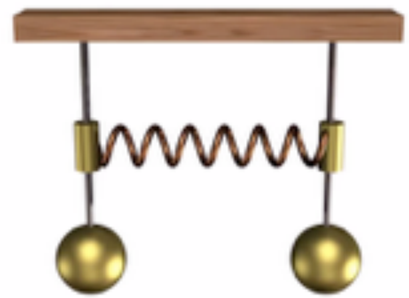
Extra matter phase leads to additional growth of dark matter on small scales, sometime enhancing the predicted number of compact mini-halos

J. Fan, O. Özsoy, **S.W**. [Phys. Rev. D90 (2014)]

A. Erickcek, K. Sinha, **S.W.** [To appear soon]

From Inflation to the Hot Big Bang





Two pioneers of inflationary reheating

Robert Brandenberger
(McGill University)

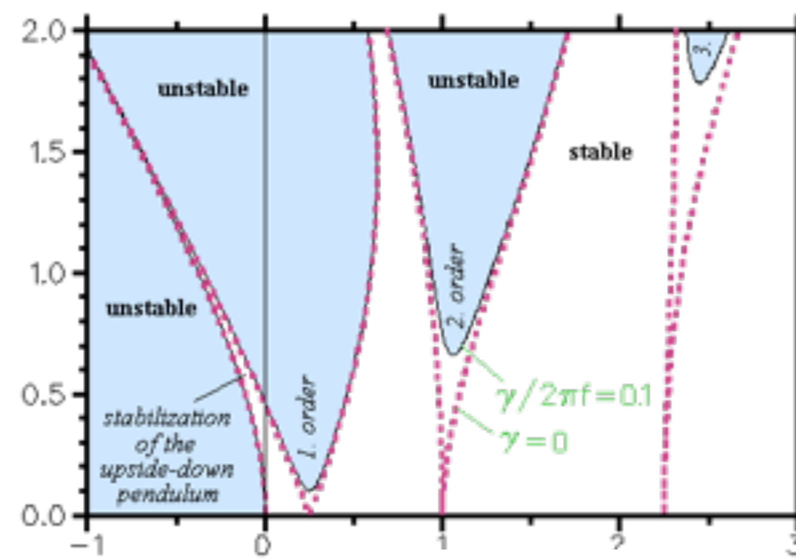
Lev Kofman
1957 — 2009

The transition from inflation to “reheating” can be complicated.

Stages of Reheating:

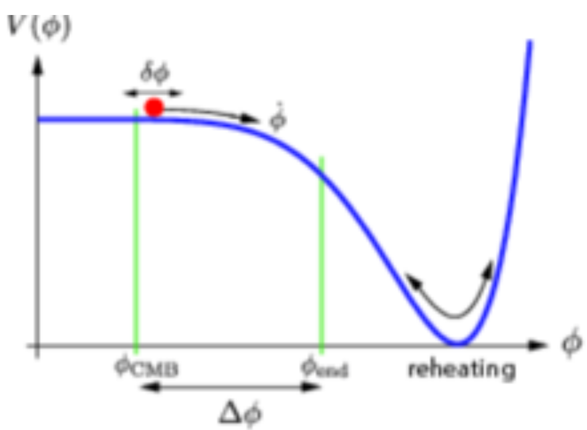
1. Non-perturbative (parametric resonance)
2. Non-linear Dynamics and Chaos
3. Turbulence
4. Thermalization

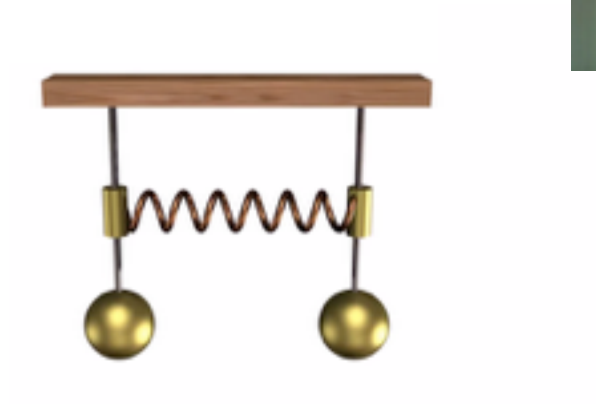
Coupling Strength



Relative Frequency

From Inflation to the Hot Big Bang





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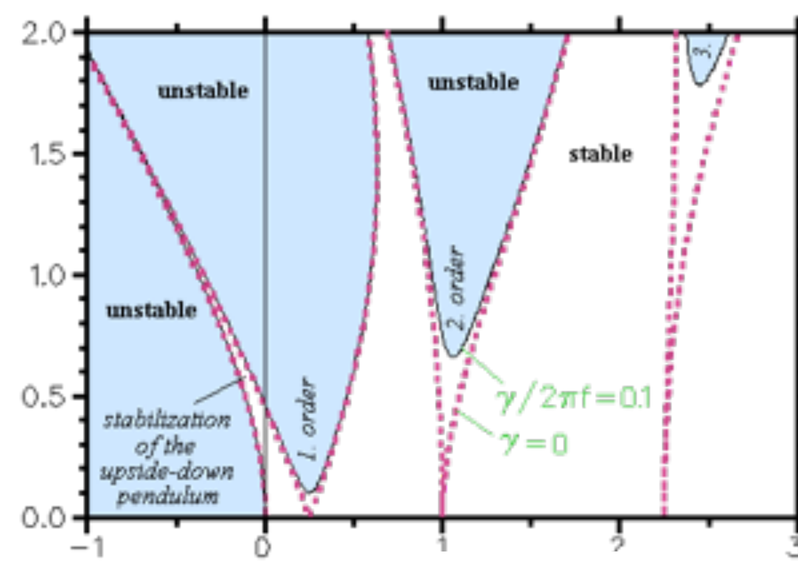
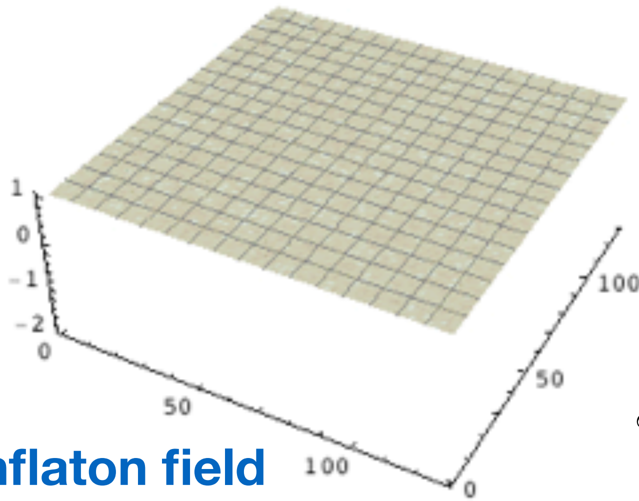
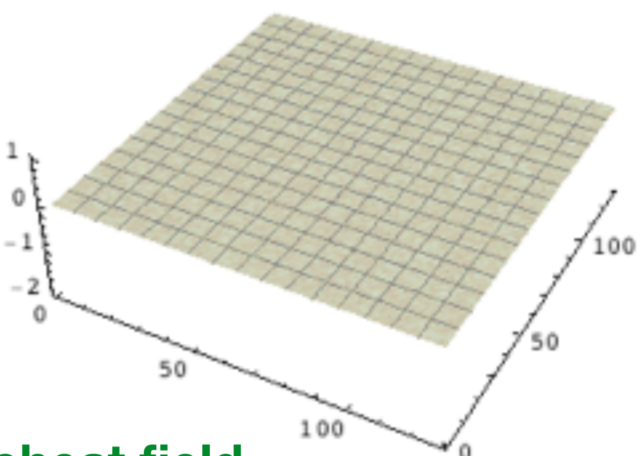


Relative Frequency

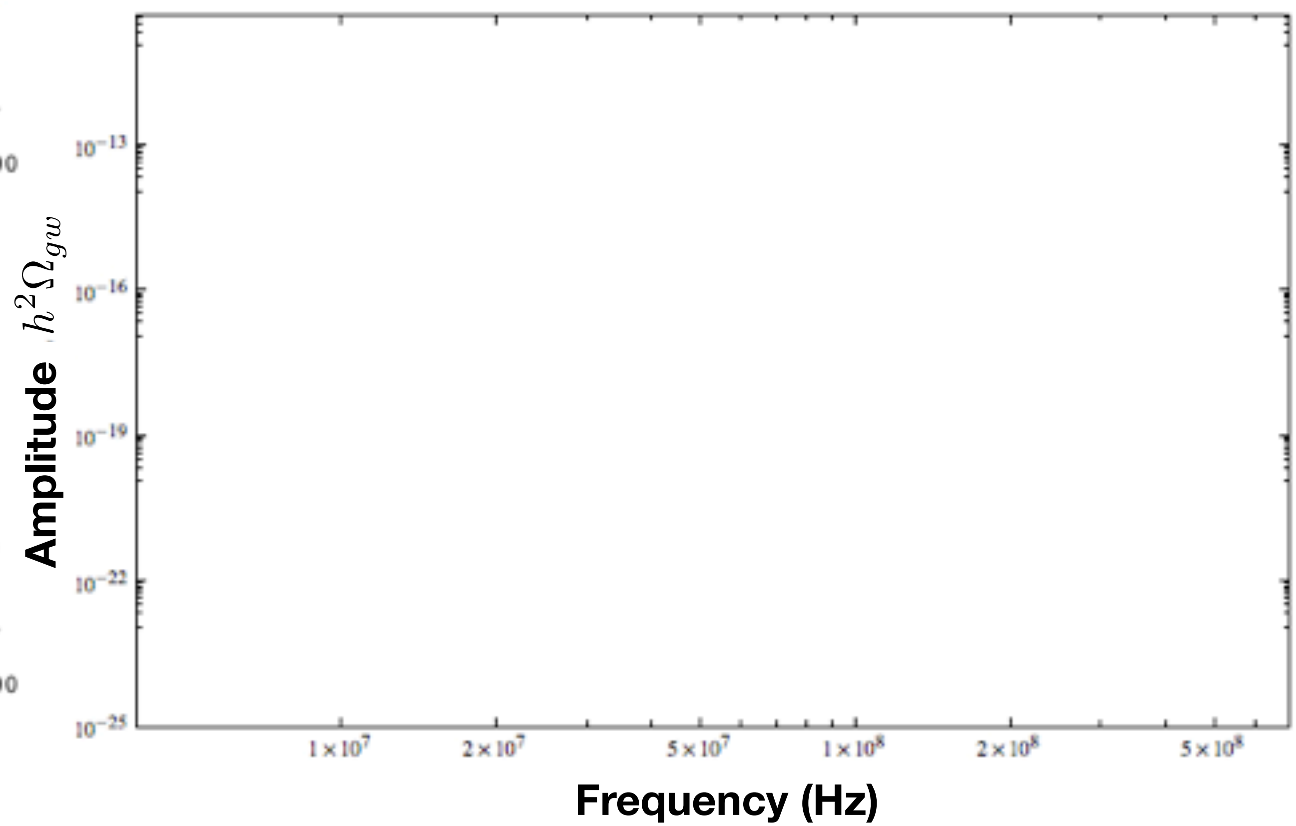


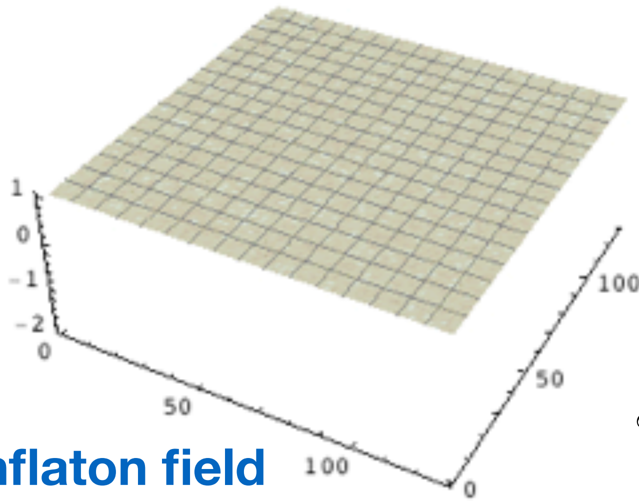
Inflaton field



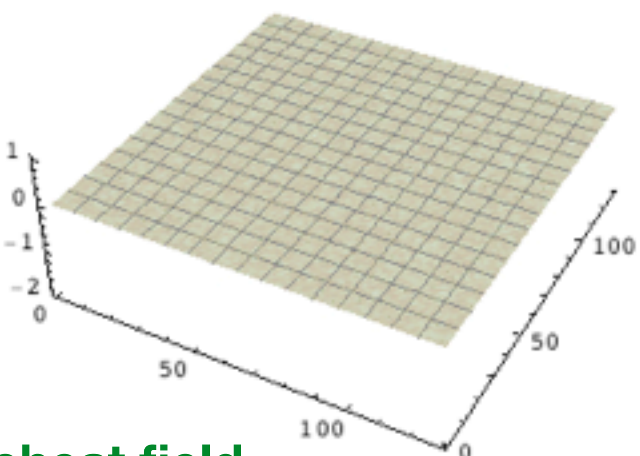
Reheat field

Gravity wave spectrum



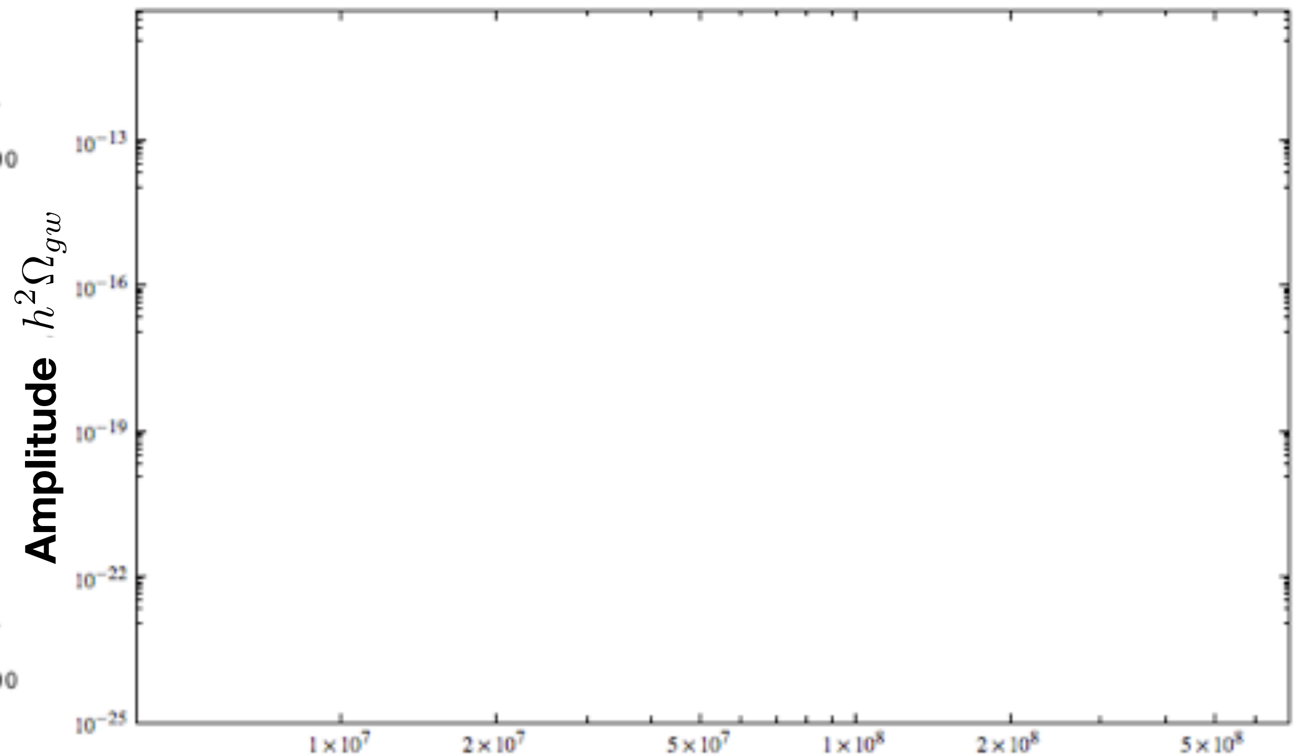


Inflaton field

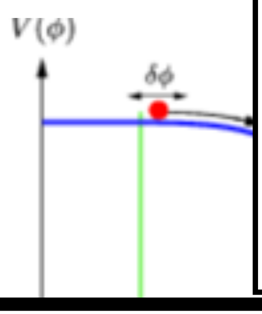


Reheat field

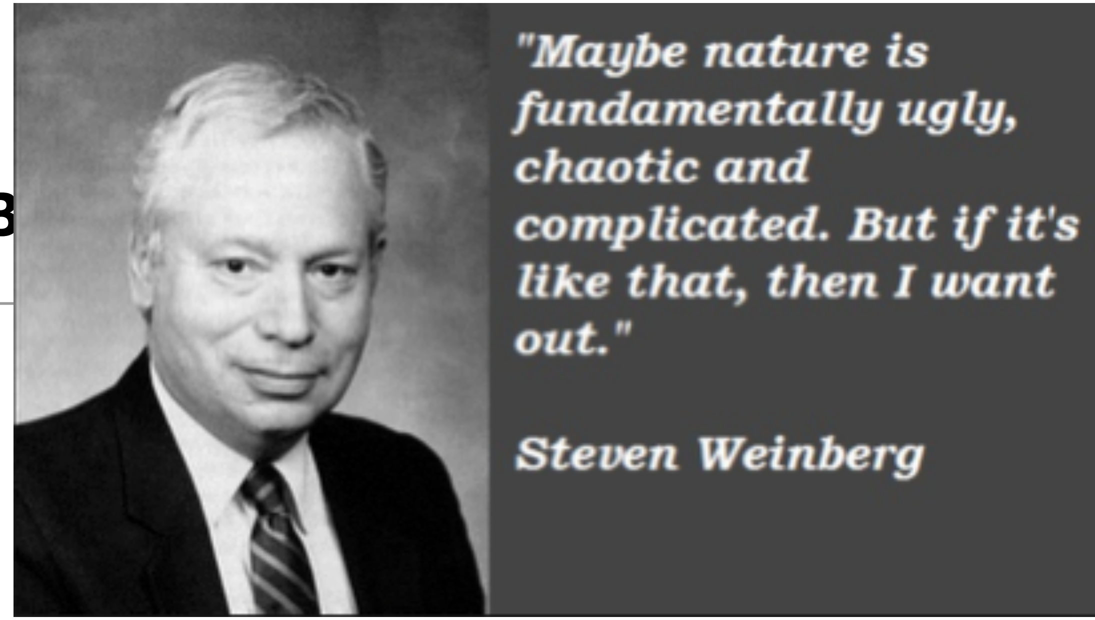
Gravity wave spectrum



From Inf ot Big B



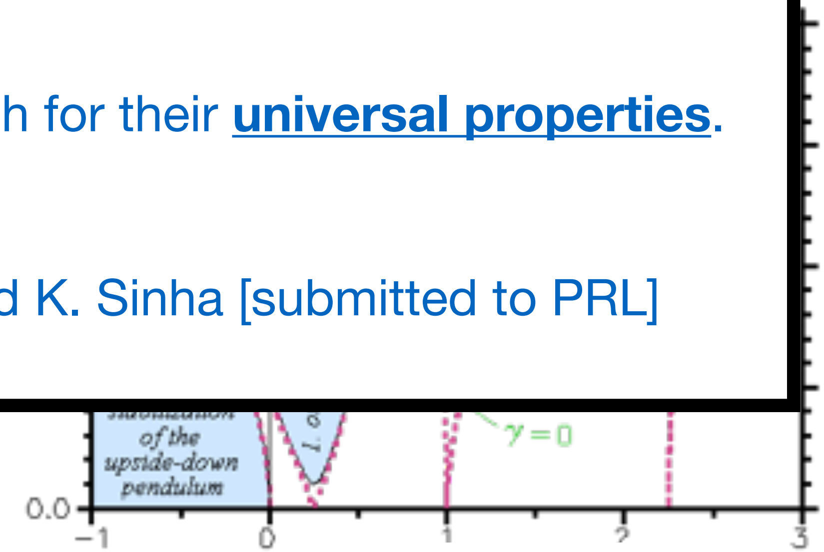
Lev Kofman
1957 — 2009



Establishing a more systematic approach to the reheating processes is an important open challenge.

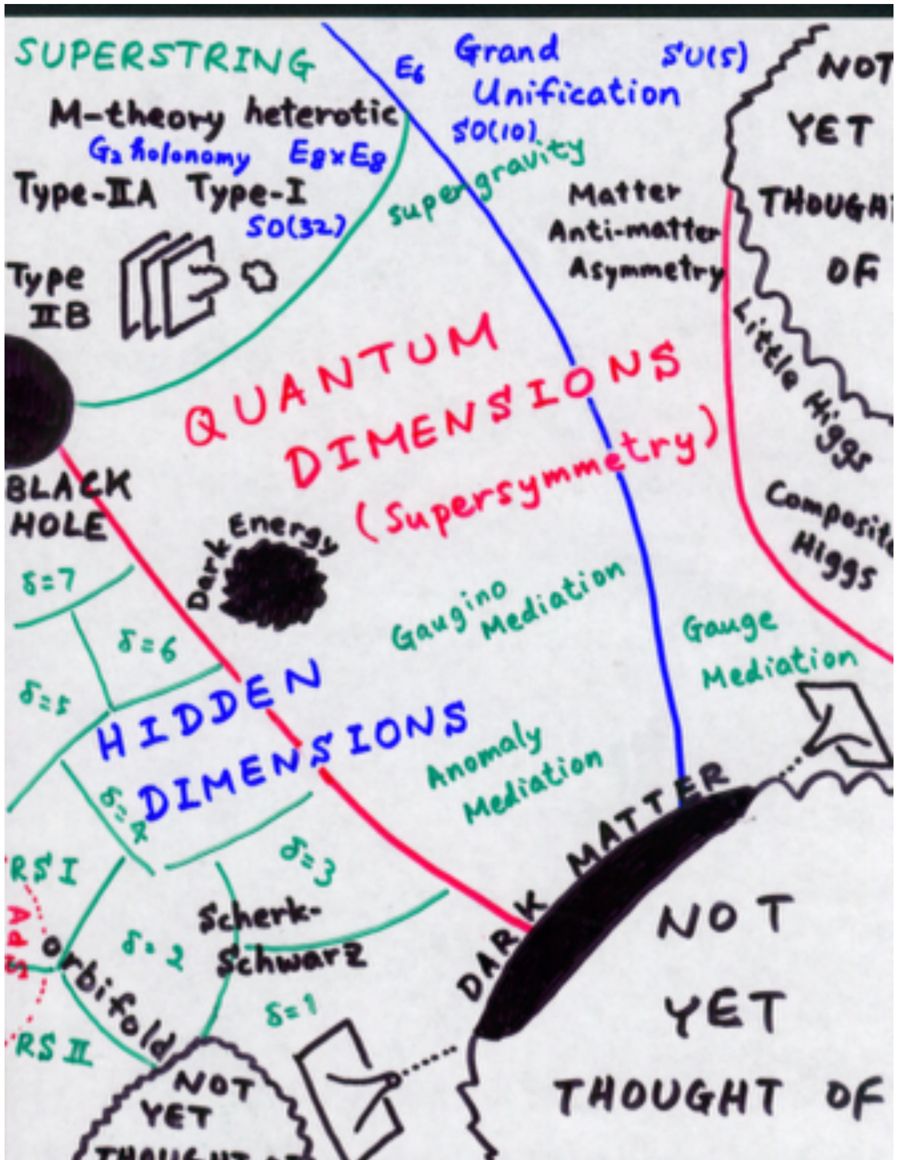
We would like a way to **classify models** and search for their **universal properties**.

Recent progress: with O. Ozsoy, G. Sengor, and K. Sinha [submitted to PRL]



4. Thermalization

A similar challenge existed in the search for the Higgs and Beyond the Standard Model physics

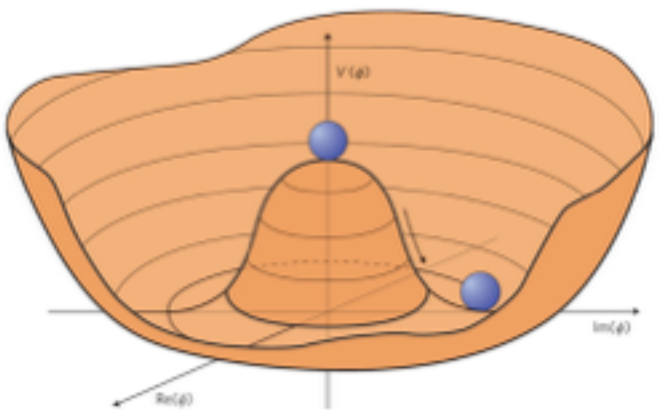


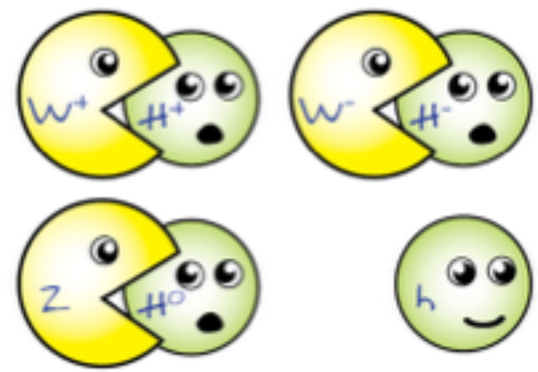
The possible extensions of the Standard Model are many and also contain unknown, unknowns.

Symmetry Breaking and Goldstone Bosons

(or, how to get over $1000K and a gold medal to wear around your neck)

Spontaneous Symmetry Breaking





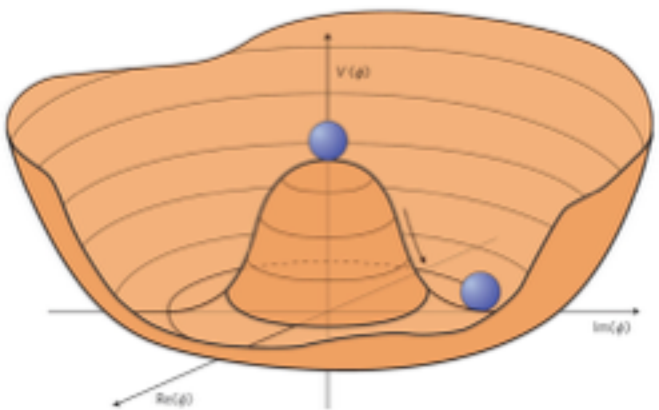
In the broken phase, Goldstone bosons are eaten by Gauge Fields

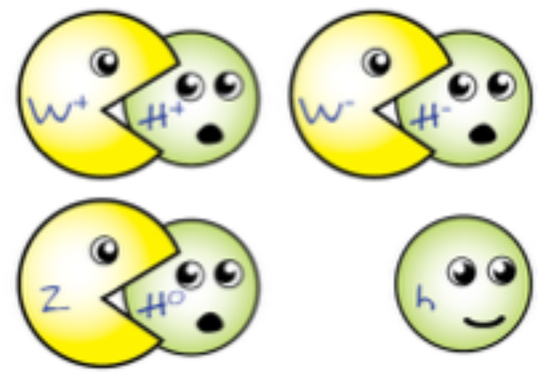
(assuming gauge fields are present).

Symmetry Breaking and Goldstone Bosons

(or, how to get over $1000K and a gold medal to wear around your neck)

Spontaneous Symmetry Breaking





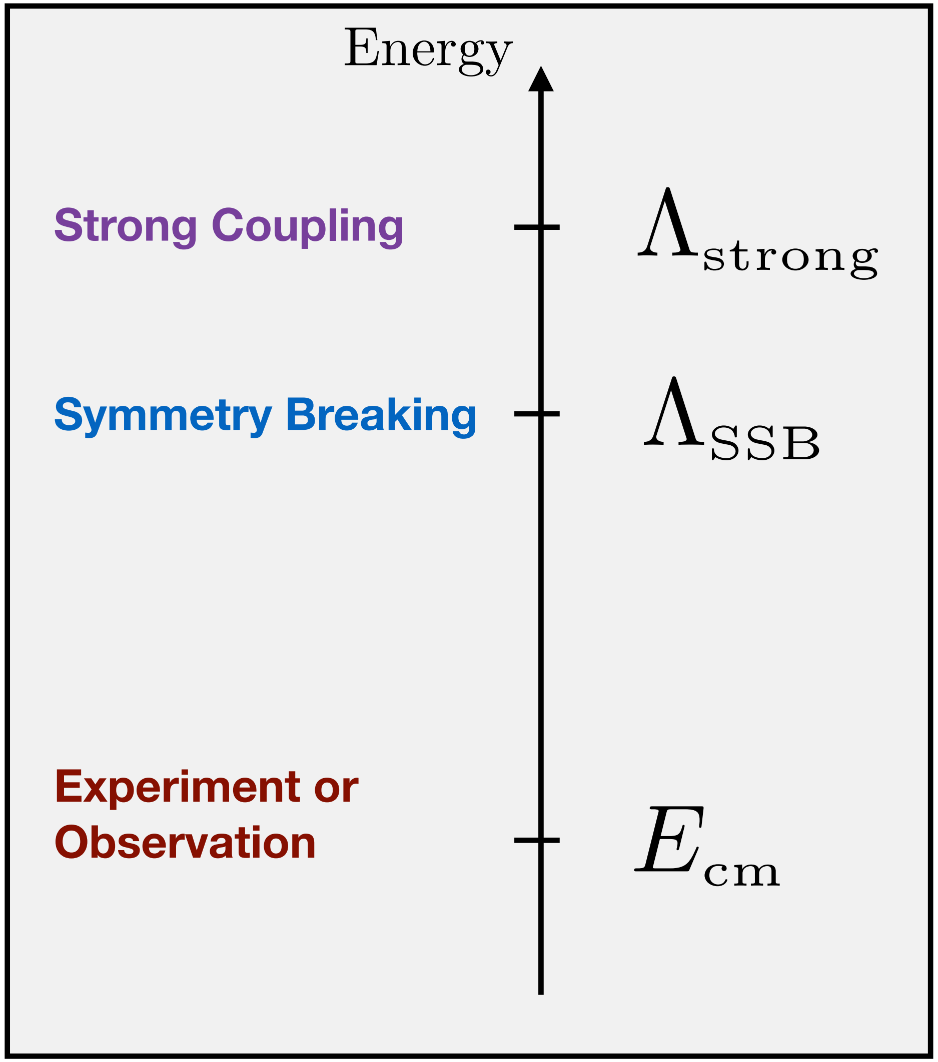
In the broken phase, Goldstone bosons are eaten by Gauge Fields

(assuming gauge fields are present).

<u>The key</u>: The Goldstone approach provides a method for studying the consequences of symmetry breaking at low energies without a detailed knowledge of the higher energy theory.

All we need to know is the symmetry breaking pattern!

Goldstone Bosons and Spontaneous Symmetry Breaking



Electroweak Symmetry Breaking

$$SU(2) \times U(1)_Y \to U(1)_{\rm EM}$$

$$\Lambda_{\rm strong} \simeq 800 \text{ GeV}$$

$$\Lambda_{\rm SSB} = \langle h \rangle \simeq 247 \text{ GeV}$$

Longitudinal components of
W and Z gauge bosons are the Goldstones

QCD Symmetry Breaking

$$SU(2) \times SU(2) \to SU(2)_{\rm isospin}$$

$$\Lambda_{\rm SSB} \simeq f_\pi \simeq 300 \text{ MeV}$$

$$\Lambda_{\rm strong} \simeq 4\pi f_\pi$$

Pions are the Goldstones

Decoupling Limit (Electroweak Symmetry Case)

$$\Lambda_{\rm Strong} > E_{\rm cm} \gg M_w$$ **(Equivalence Theorem)**

Essential physics captured by Goldstones — Massless theory of scalars (much easier)

Goldstone Bosons and Spontaneous Symmetry Breaking

Electroweak Physics

$$
\begin{aligned}
L[\pi,\vec{W},B,h] = & -\frac{1}{2}\pi_a\Box\pi_a - \frac{1}{2}h(\Box + m_h^2)h - \lambda(\pi_a^2 + h^2)^2 \\
& - 4\lambda v h(\pi_a^2 + h^2) - \frac{g}{2}\partial^\mu\pi_1(W_\mu^3\pi_2 - W_\mu^2\pi_3) \\
& - \frac{g}{2}\partial^\mu\pi_2(W_\mu^1\pi_3 - W_\mu^3\pi_1) - \frac{g}{2}\partial^\mu\pi_3(W_\mu^2\pi_1 - W_\mu^1\pi_2) \\
& + g\partial^\mu h(\vec{W}_\mu\cdot\vec{\pi}) - \frac{g'}{2}(\pi_1\partial_\mu\pi_2 - \pi_2\partial_\mu\pi_1)B^\mu - g\partial_\mu h\pi_3 B^\mu \\
& + \frac{1}{2}m_W^2\vec{W}_\mu\cdot\vec{W}^\mu + \frac{1}{2}m_B^2 B_\mu B^\mu - m_W m_B W_\mu^3 B^\mu \\
& + \frac{g^2}{8}(\vec{W}_\mu\cdot\vec{\pi})(\vec{W}^\mu\cdot\vec{\pi}) + \frac{g'^2 v}{4}hB_\mu B^\mu \\
& + \frac{g'^2}{8}H^2 B_\mu B^\mu - \frac{gg'}{4}h^2 W_\mu^3 B^\mu - \frac{gg'v}{2}hW_\mu^3 B^\mu \\
& + \frac{g^2}{8}h^2\vec{W}_\mu\cdot\vec{W}^\mu + \frac{g^2 v}{4}h\vec{W}_\mu\cdot\vec{W}^\mu + \frac{g'^2}{8}B_\mu B^\mu\vec{\pi}\cdot\vec{\pi} \\
& + \frac{gg'}{4}W_\mu^3 B^\mu\vec{\pi}\cdot\vec{\pi} - \frac{gg'}{2}\pi_3 B_\mu(W_1^\mu\pi_1 + W_2^\mu\pi_2) \\
& + g' m_W B_\mu(W_1^\mu\pi_2 - W_2^\mu\pi_1) + \frac{gg'}{2}B_\mu(W_1^\mu\pi_2 - W_2^\mu\pi_1)h
\end{aligned}
$$

$$\longrightarrow \quad \mathcal{L}_{\text{eff}} = -\frac{f_\pi}{2}\partial_\mu U\cdot\partial^\mu U^\dagger + c_1\left(\partial_\mu U\cdot\partial^\mu U^\dagger\right)^2 + \ldots$$

Decoupling Limit (Electroweak Symmetry Case)

$$\Lambda_{\text{Strong}} > E_{\text{cm}} \gg M_w$$

Essential physics captured by Goldstones — Massless theory of scalars (much easier)

Symmetry Breaking and Goldstone Effective Theory

Spontaneously Broken
non-abelian Symmetry

$G \longrightarrow H$

Introduce
Goldstone Bosons

$$U = e^{i\,\pi(x)/f_\pi}$$

Generators of G / H

$$\pi^a T^a \equiv \pi$$

Low Energy Effective Action

$$\mathcal{L}_{\text{eff}} = -\frac{f_\pi}{2}\partial_\mu U \cdot \partial^\mu U^\dagger + c_1 \left(\partial_\mu U \cdot \partial^\mu U^\dagger\right)^2 + \dots$$

Universal **non-Universal**

Symmetry Breaking and Goldstone Effective Theory

Spontaneously Broken non-abelian Symmetry $\longrightarrow$ Introduce Goldstone Bosons

$$G \to H$$

$$U = e^{i\pi(x)/f_\pi} \qquad \pi^a T^a \equiv \pi$$

Generators of G / H

Low Energy Effective Action

$$\mathcal{L}_{\text{eff}} = -\frac{f_\pi}{2}\partial_\mu U \cdot \partial^\mu U^\dagger + c_1 \left(\partial_\mu U \cdot \partial^\mu U^\dagger\right)^2 + \ldots$$

Universal **non-Universal**

$$\mathcal{L}_{\text{eff}} = -\frac{1}{2}(\partial_\mu \pi)^2 + \frac{1}{6f_\pi^2}\left[(\pi\cdot\partial_\mu\pi)^2 - \pi^2(\partial_\mu\pi)^2\right] + \cdots$$

MUCH SIMPLER!

Symmetry is "non-linearly realized"

Goldstones and Cosmology?

The cosmic expansion breaks time translation invariance.

No longer a symmetry

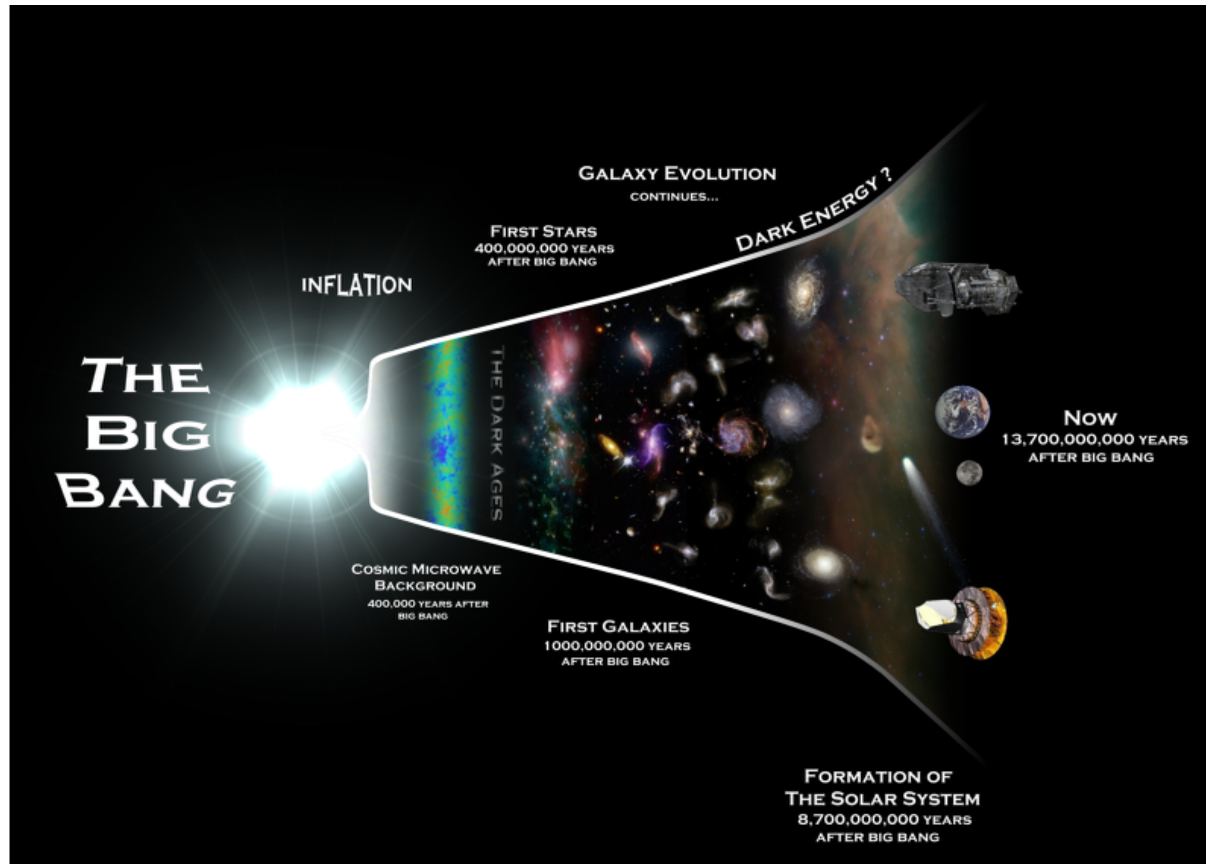
$$t \to t + \xi$$

Inflaton breaks the symmetry

$$\Lambda_{\mathrm{SSB}} \sim \dot{\varphi}(t)^{1/2}$$

Radiation or matter evolving breaks the symmetry

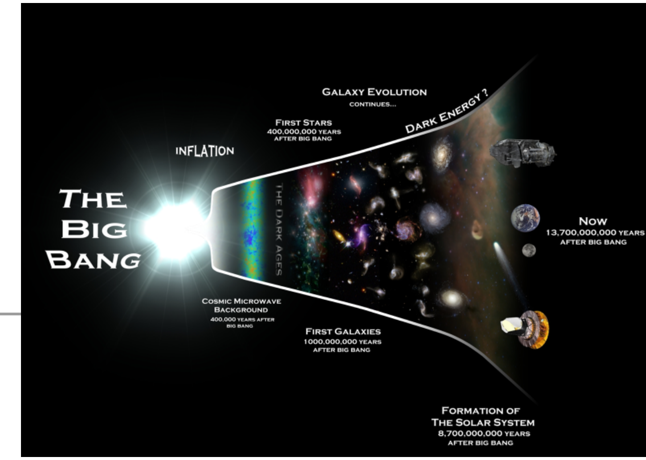
$$\Lambda_{\mathrm{SSB}} \sim \rho(t)^{1/4}$$



At high energy (small length scales) symmetry is realized.

This is spontaneous symmetry breaking!

Example: Slow-roll Inflation



The cosmic expansion implies that time translation invariance is spontaneously broken!

Energy

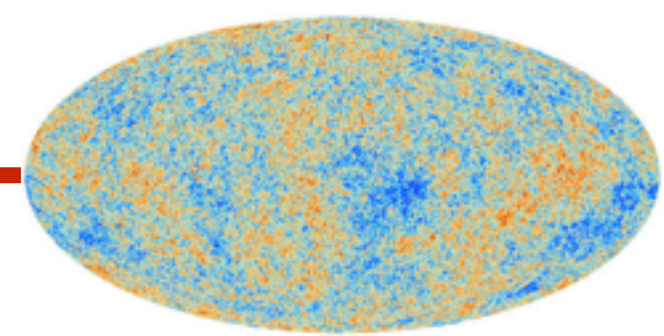
Strong Coupling $\Lambda_{\mathrm{Strong}} \simeq m_p$

Symmetry Breaking $\Lambda_{\mathrm{SSB}} \simeq \dot{\varphi}(t)^{1/2}$

Experiment or Observation $E_{\mathrm{cm}} \sim H(t)$

No longer a symmetry

$$t \to t + \xi$$



Symmetry Breaking from Cosmic Expansion

Introduce Goldstone Bosons to non-linearly realize time translations

$$U = e^{i\pi(x)/f_\pi} \qquad f_\pi^2 = \dot\varphi \simeq \dot H^{1/2} m_p$$

Low Energy Effective Action

$$\mathcal{L}_{\rm eff} = -\frac{f_\pi}{2}\partial_\mu U \cdot \partial^\mu U^\dagger + c_1\left(\partial_\mu U \cdot \partial^\mu U^\dagger\right)^2 + \dots$$

Universal **non-Universal**

$$\mathcal{L}_{\rm eff} = -\frac{1}{2}(\partial_\mu\pi)^2 + \frac{1}{6f_\pi^2}\left[(\pi\cdot\partial_\mu\pi)^2 - \pi^2(\partial_\mu\pi)^2\right] + \cdots$$

Symmetry is “non-linearly realized”

Decoupling Limit

$$\Lambda_{\rm Strong} > E_{\rm cm} \gg M_w \longrightarrow m_p > E_{\rm cm} \gg \dot H^{1/2}$$

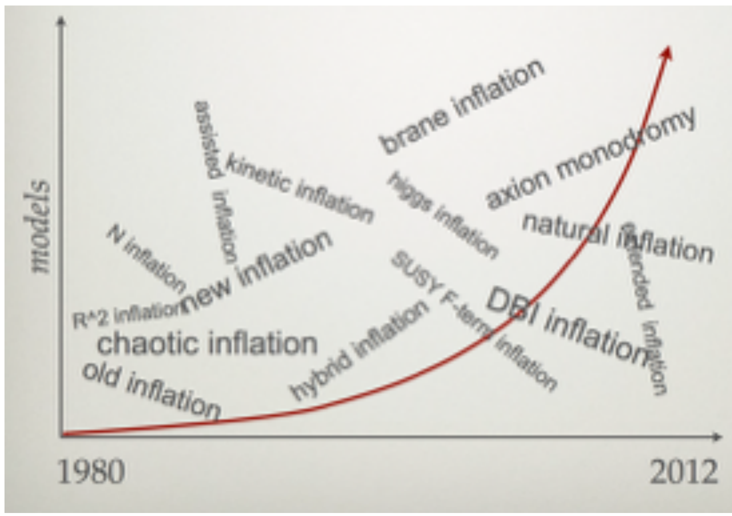
Gravity decouples!

Essential physics captured by Goldstones — Massless theory of scalars (much easier)

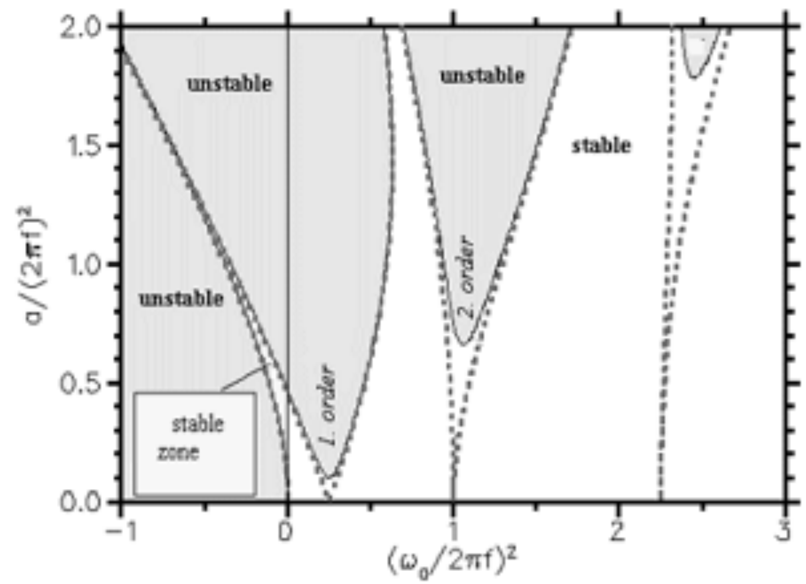
Effective Field Theory and Reheating the Universe

with O. Ozsoy, G. Sengor, and K. Sinha [submitted to PRL]

All models are captured by their symmetry breaking pattern.



Inflational Zoo of models



Reheating Zoo of models

Correction to sound speed of fluctuations

$$S_\pi = \int d^4x\,\sqrt{-g}\left[M_{\rm Pl}^2\dot{H}\,(\partial_\mu\pi)^2 + 2M_2^4\left(\dot{\pi}^2 + \dot{\pi}^3 - \dot{\pi}\frac{1}{a^2}(\partial_i\pi)^2\right) - \frac{4}{3}M_3^4\dot{\pi}^3 - \frac{\bar{M}^2}{2}\,\frac{1}{a^4}(\partial_i^2\pi)^2 + \dots\right]$$

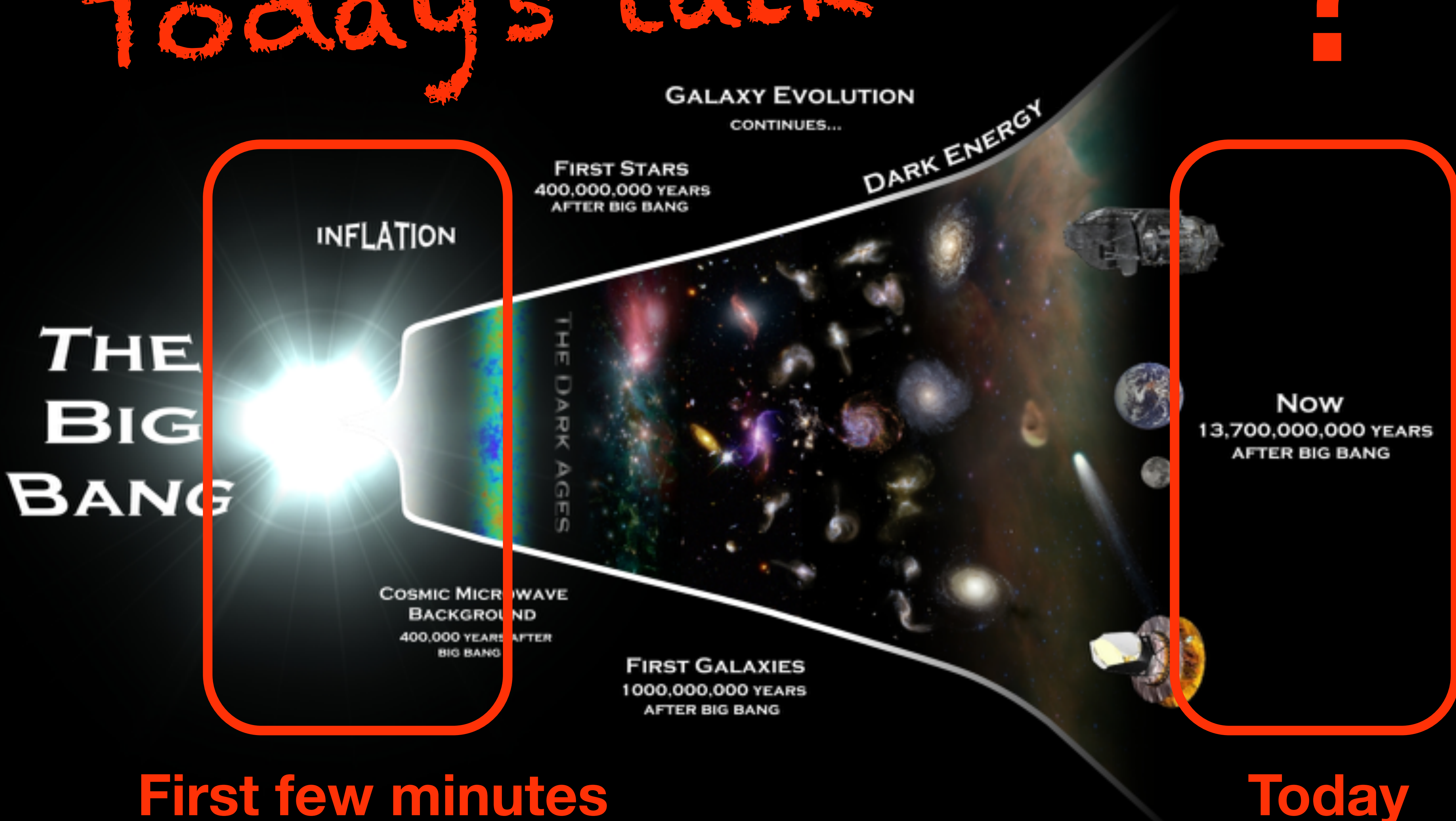
Same coefficient for both because of symmetry breaking pattern

Cubic interaction (CMB non-gaussianity)

The Cosmological Standard Model

Today's talk

?



First few minutes

Today

Thank you for coming.

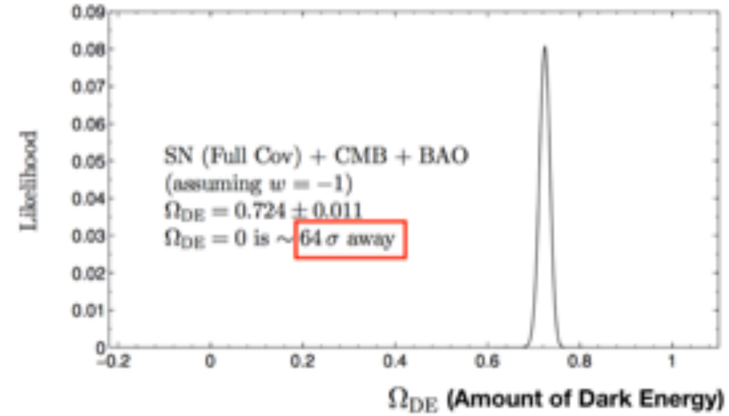
2011 Nobel Prize

Photo: Roy Kaltschmidt. Courtesy: Lawrence Berkeley National Laboratory — **Saul Perlmutter**

Photo: Belinda Pratten, Australian National University — **Brian P. Schmidt**

Photo: Homewood Photography — **Adam G. Riess**

Current evidence for dark energy is impressively strong



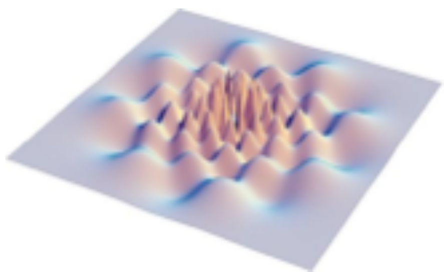
Slide provided by Dragan Huterer and Dan Shafer

The Universe is accelerating today!

Today

Is the Dark Energy a Cosmological Constant?

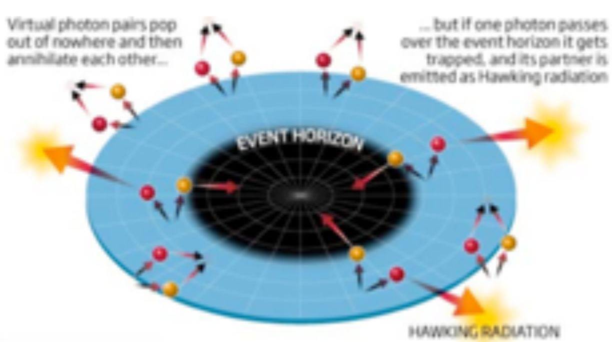
We expect space-time to contain quantum fluctuations



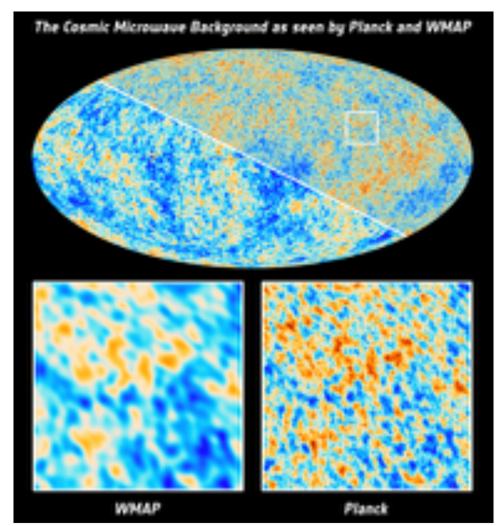
Stephen is still at work!

Our “Lab”

Hawking radiation from Black Holes



Inflationary Fluctuations

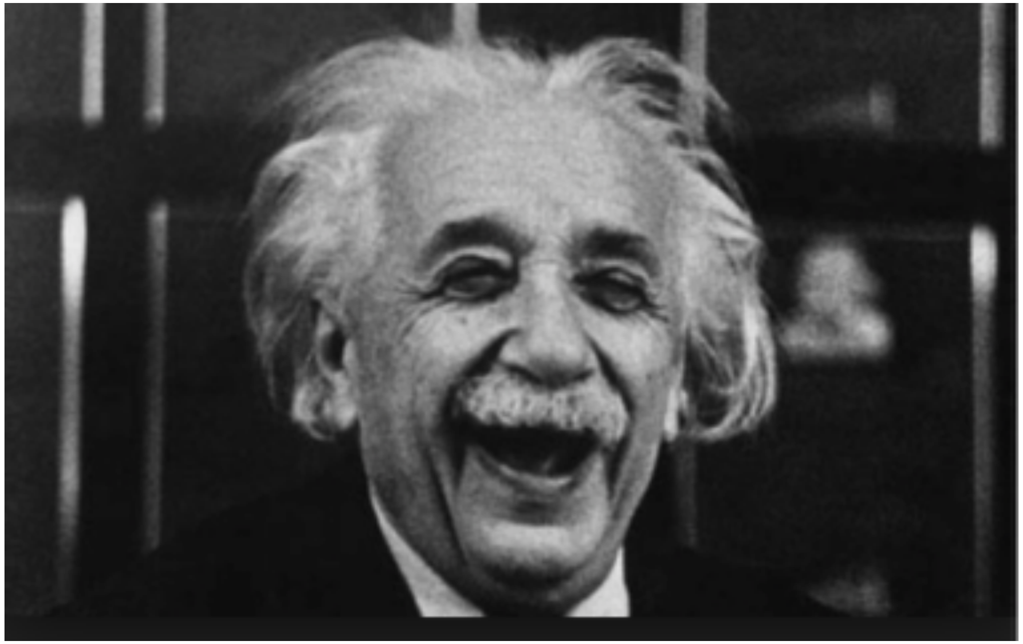


Could vacuum fluctuations be causing the acceleration?

The Cosmological Constant Problem

$$\left(\frac{\Lambda_{\text{observed}}}{m_p}\right)^4 \simeq 10^{-120}$$

Could vacuum fluctuations be causing the acceleration?



If Dark Energy is not a Cosmological Constant then what is it?

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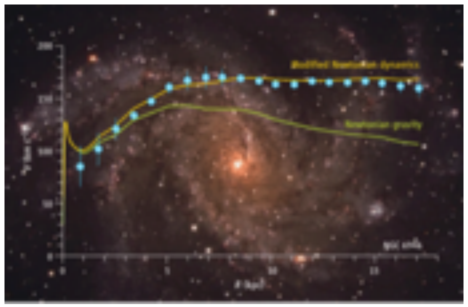


Modified Gravity?

Time varying constants?

New forms of matter or energy?

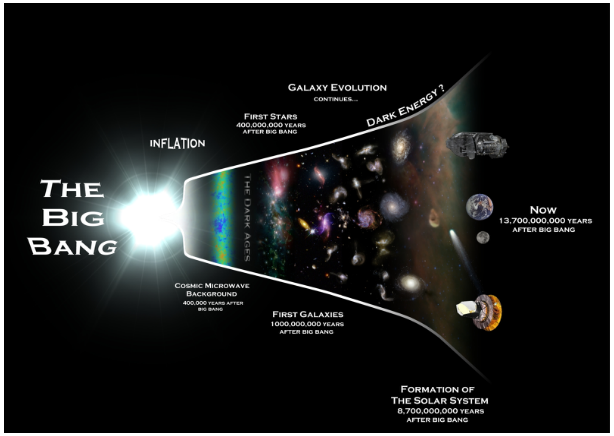
$$\color{green}{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R} = \color{blue}{8\pi G_{\rm N}\, T_{\mu\nu}}$$

Space-time evolution **Matter and Energy**

Λ ?

The Effective Field Theory of Cosmic Acceleration

with J. Bloomfield, E. Flanagan, and M. Park [JCAP 1308 (2013)]
with R. Bean and E. Mueller [Phys. Rev. D87 (2013)]
with M. Park and K. Zurek [Phys. Rev. D81 (2010)]



The cosmic expansion implies that time translation invariance is spontaneously broken

An effective theory approach to cosmic acceleration
(dark energy or modified gravity)

Low Energy Effective Action

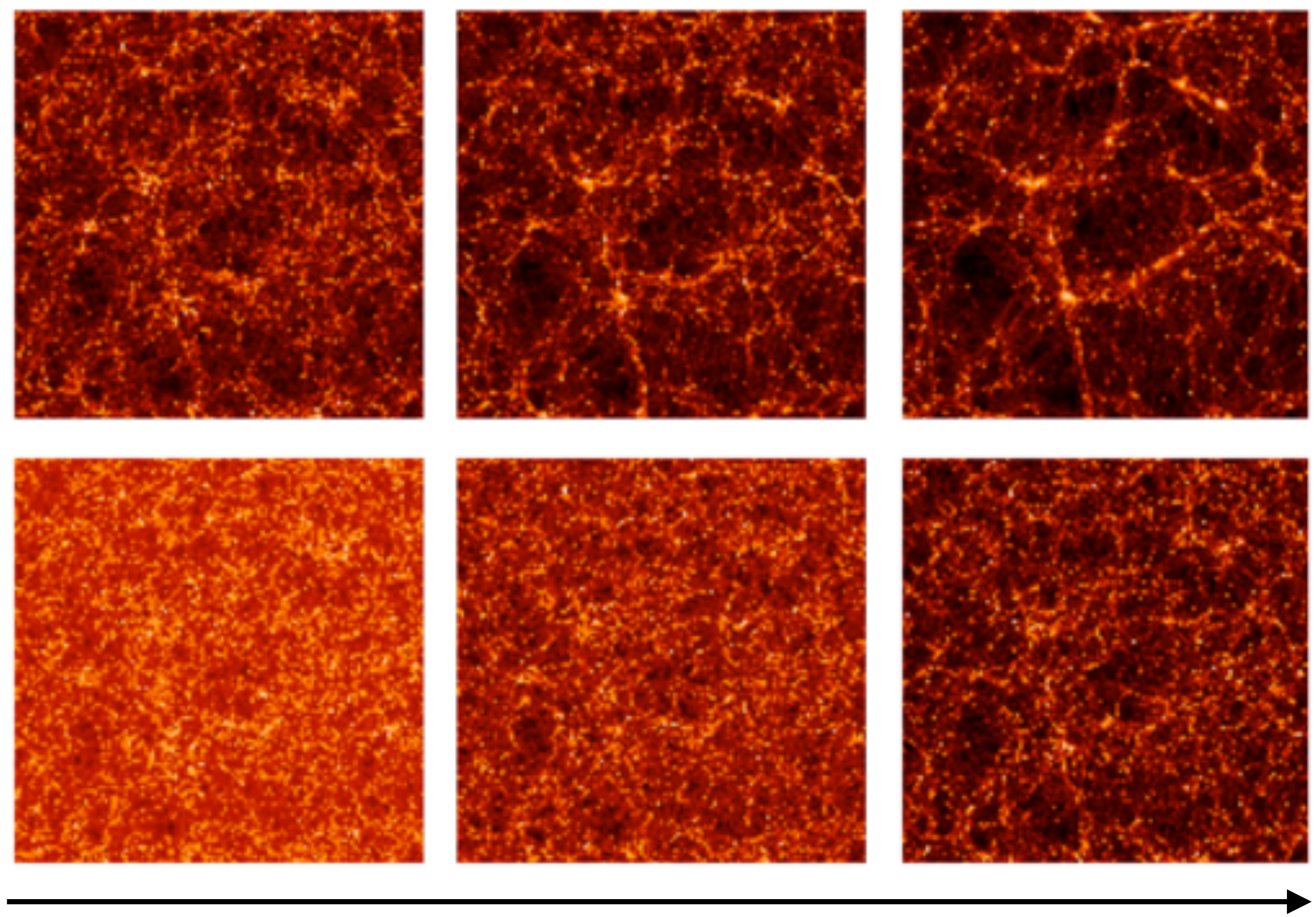
$$\mathcal{L}_{\text{eff}} = -\frac{f_\pi}{2}\partial_\mu U \cdot \partial^\mu U^\dagger + c_1 \left(\partial_\mu U \cdot \partial^\mu U^\dagger\right)^2 + \ldots$$

Universal non-Universal

Symmetries and **observations** can be used together to restrict free parameters.
(like in Electroweak Precision studies)

What observations?

Dark Energy suppresses the growth of density fluctuations



Huterer et al, Snowmass report, 1309.5385

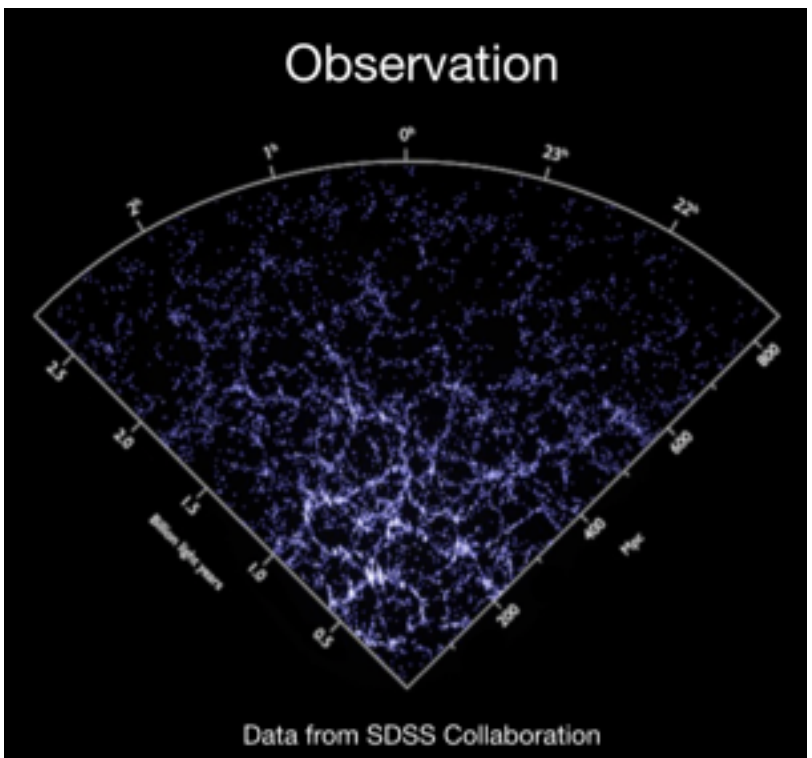
The Virgo Consortium (1996)

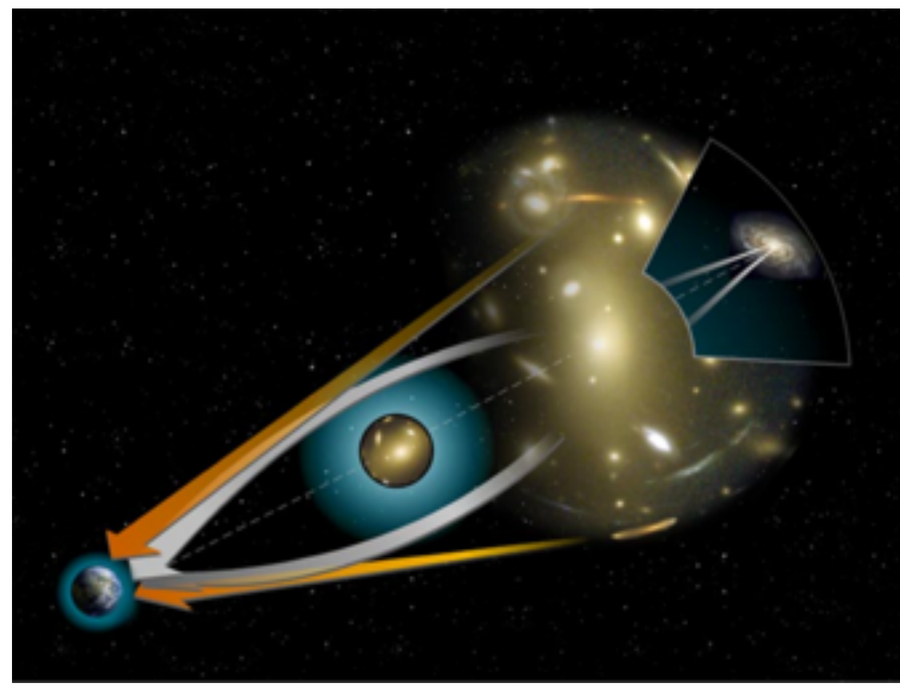
Constraints on the EFT of Cosmic Acceleration

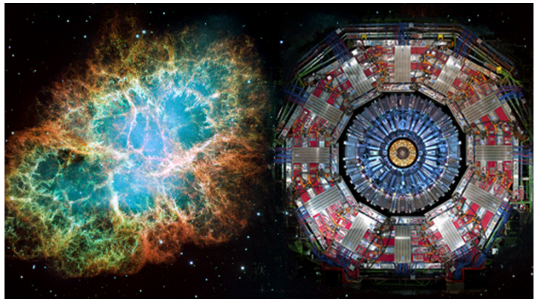
$$ds^2 = -\left(1+2\Phi\right)dt^2 + a^2\left(1-2\Psi\right)d\vec{x}^2$$

Φ Growth of Structure

$\Phi + \Psi$ Gravitational Lensing







A Unified Approach to Cosmic Acceleration

with J. Bloomfield, E. Flanagan, and M. Park [JCAP 1308 (2013)]
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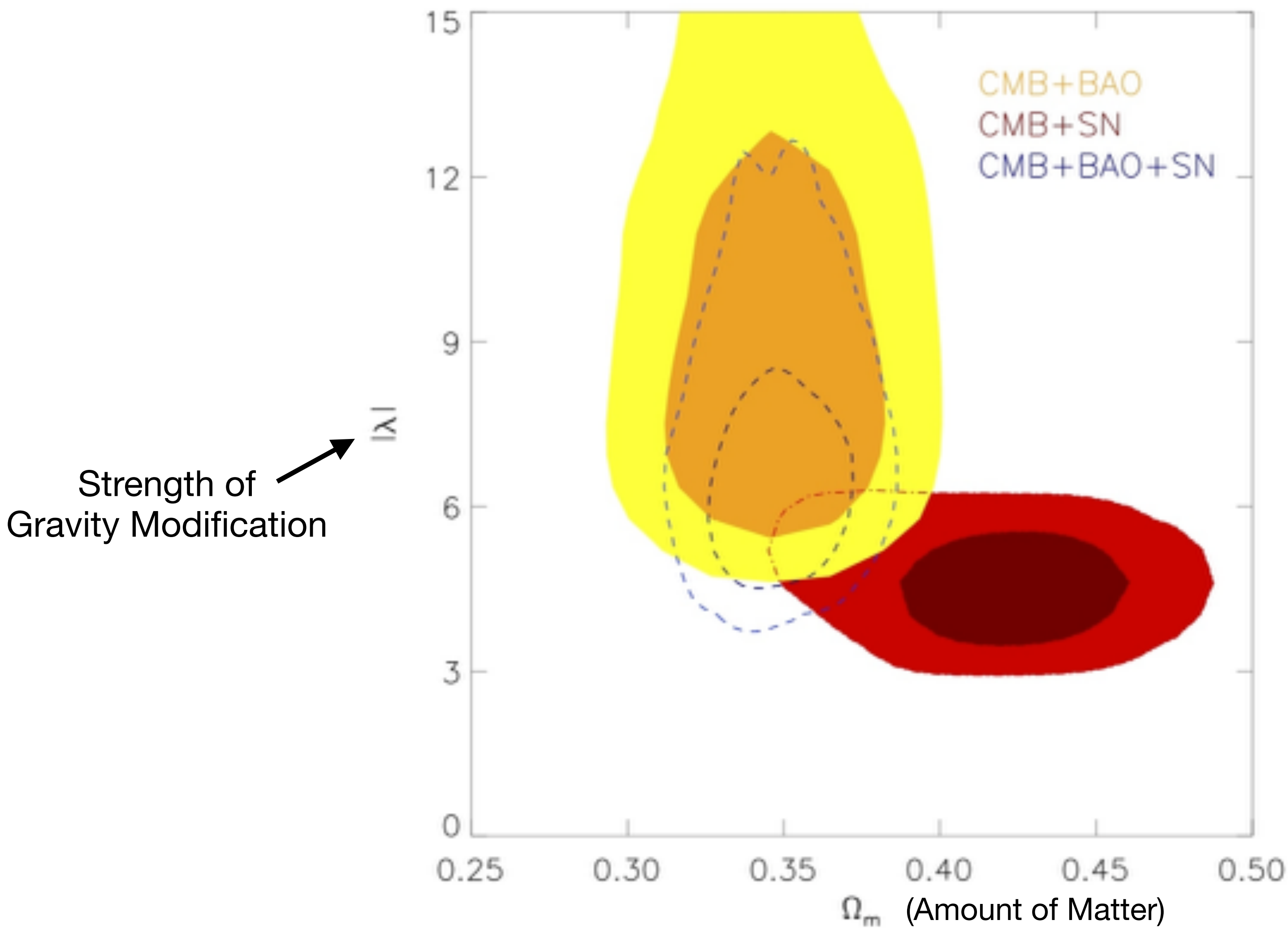

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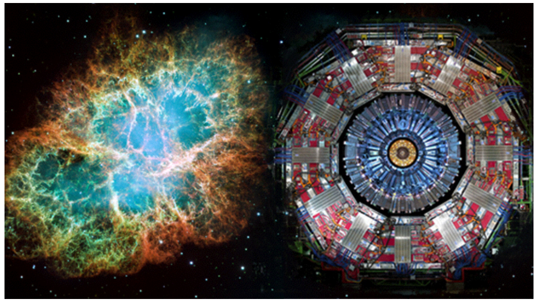

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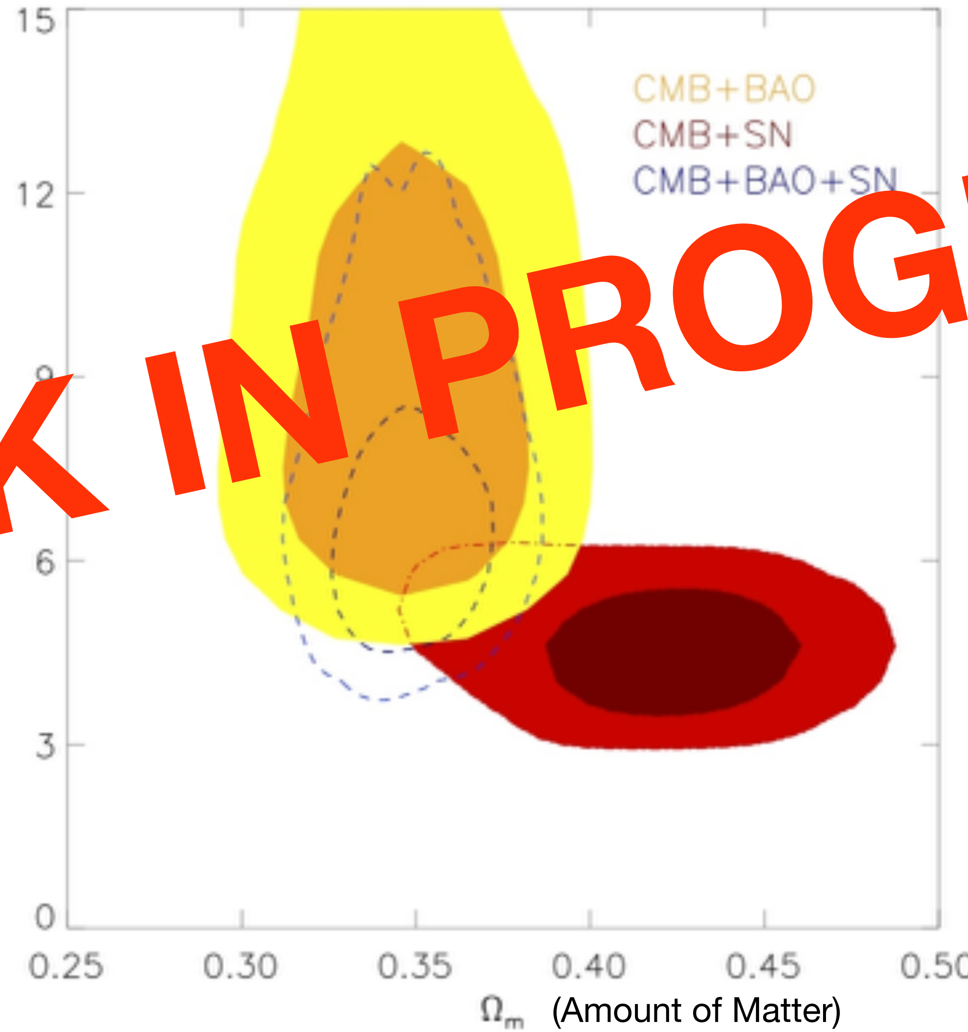
WORK IN PROGRESS

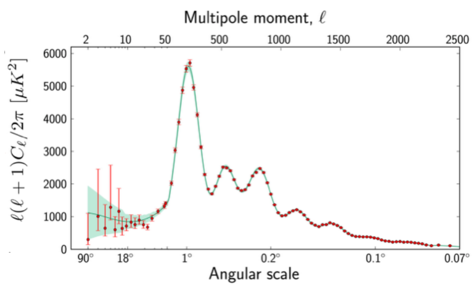


with R. Bean and E. Mueller [Phys. Rev. D87 (2013)]

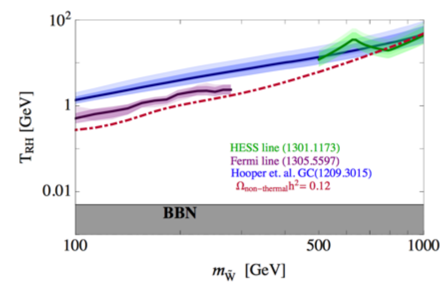
Summary: State of the Universe

What has changed since I took (my) office in 2010?

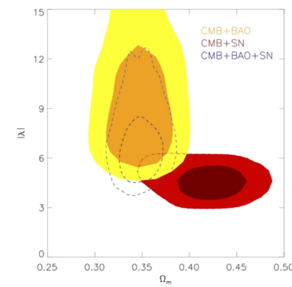
Data has dramatically improved helping to focus model building.



Inflation

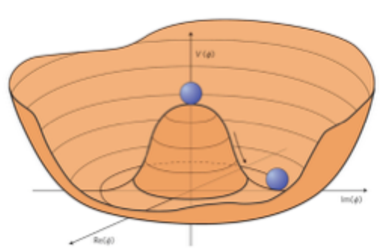


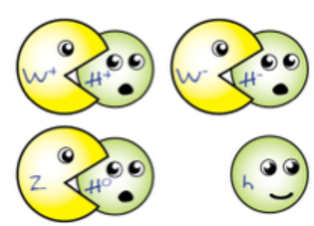
Dark Matter



Dark Energy

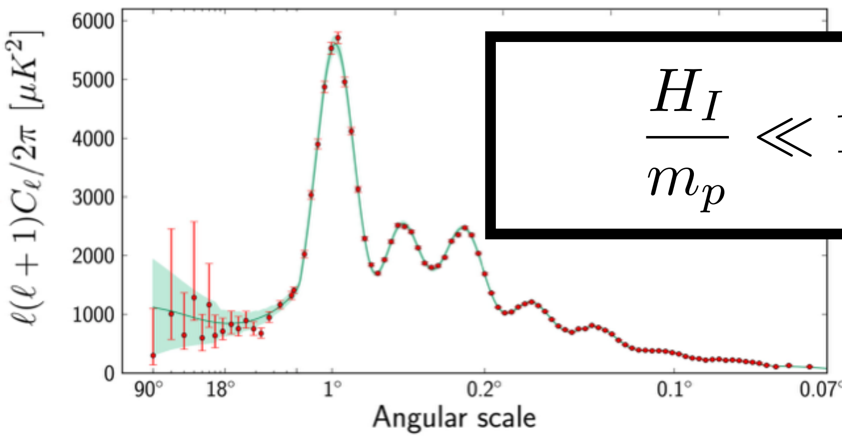
We have developed powerful techniques that utilize symmetries to establish <u>universal</u> properties of models.
This approach isolates model dependent parameters, which can be determined through a combination of theoretical and observational efforts.





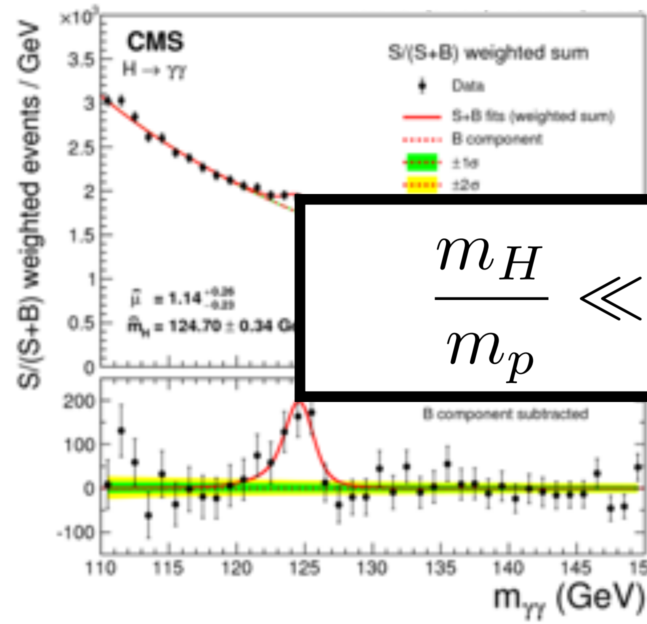
Challenges *Moving Forward*

Why is the inflaton light?
(Can we determine the scale of inflation?)



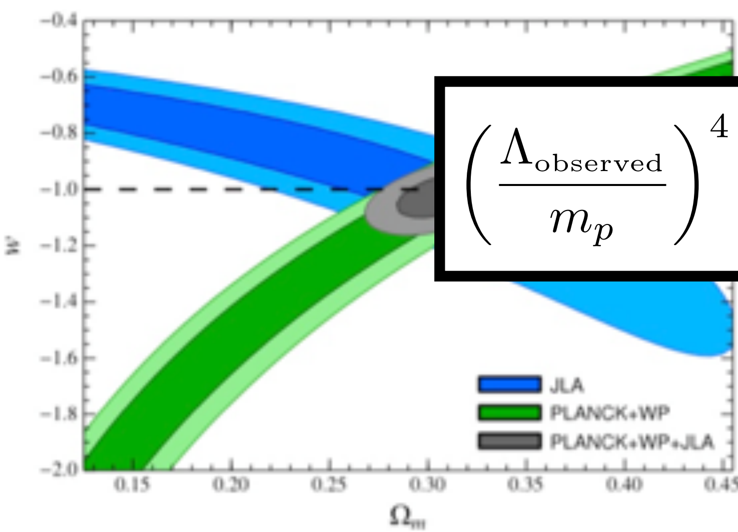
$$\frac{H_I}{m_p} \ll 1$$

Why is the Higgs light?



$$\frac{m_H}{m_p} \ll 1$$

Why is the Cosmological Constant small?



$$\left(\frac{\Lambda_{\text{observed}}}{m_p}\right)^4 \simeq 10^{-120}$$

Exciting time for cosmology beyond the standard model!

Thank you for your time.