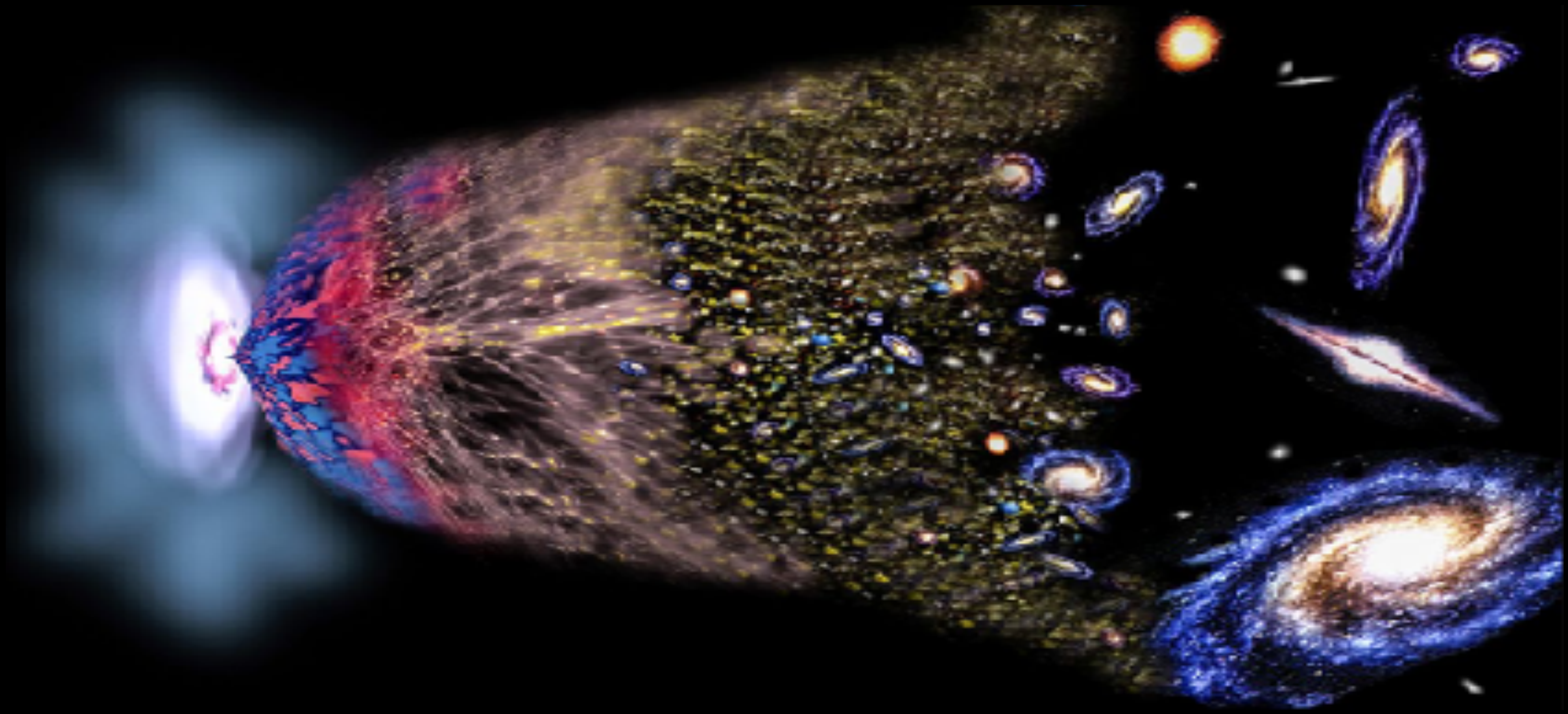
Cosmology as a Probe of Physics Beyond the Standard Model

Scott Watson (Syracuse University)

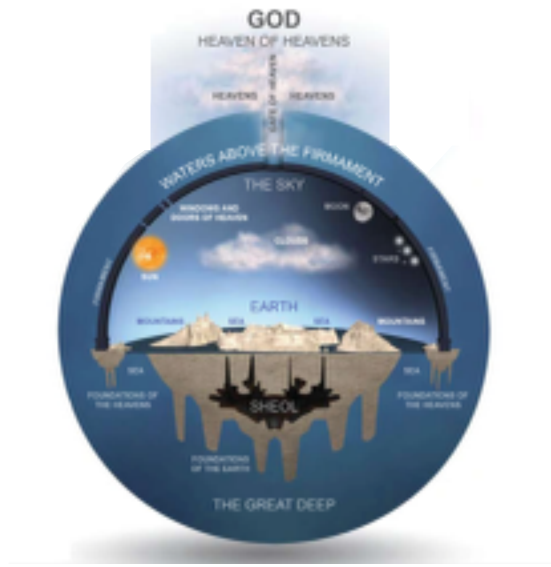


University of Utah — February 2018

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

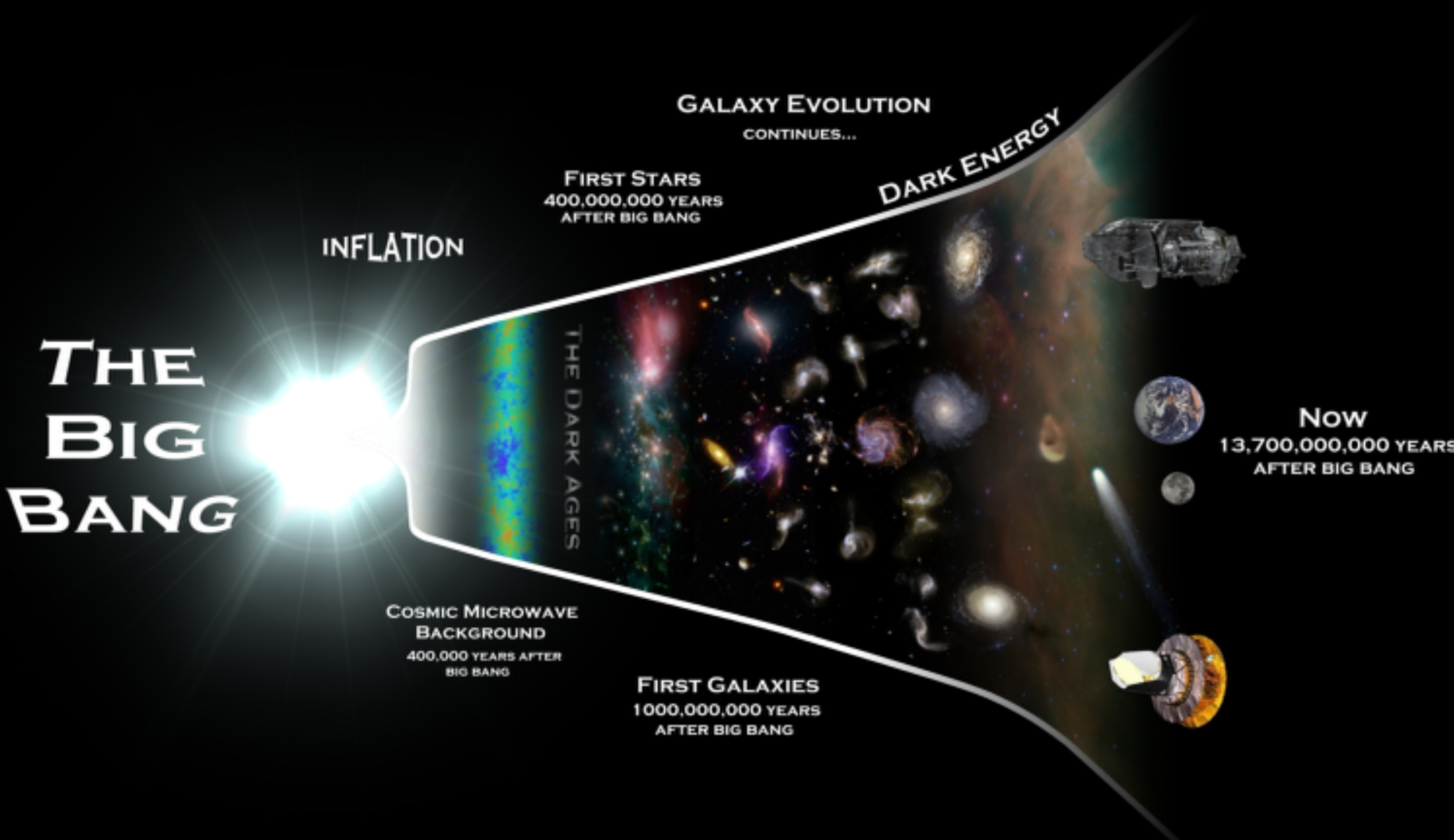
This talk is available online at: https://gswatson.expressions.syr.edu

Early Days of Cosmology

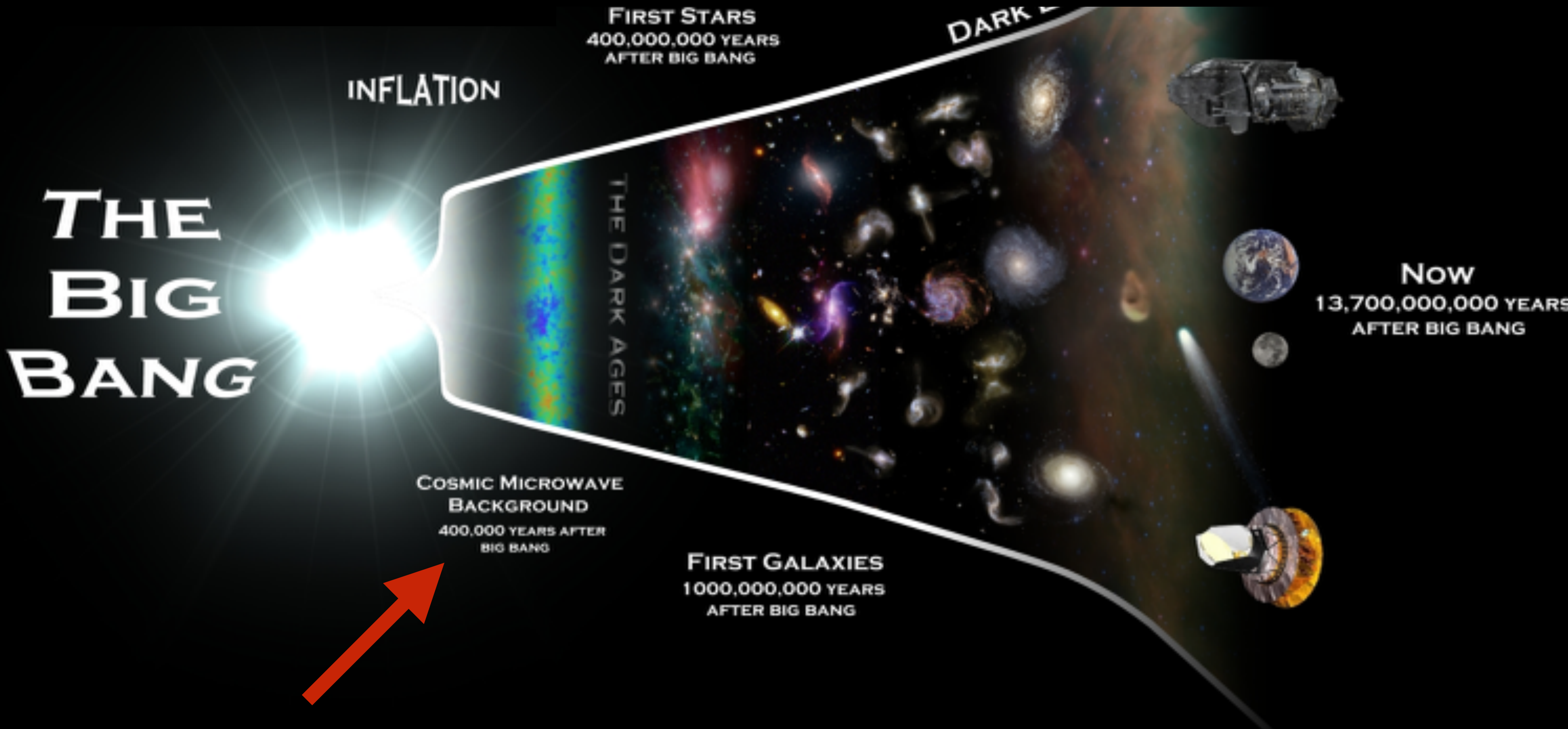


"SINCE YOU CONDUCT ONLY THOUGHT-EXPERIMENTS, WE WERE HOPING YOU WOULD, FROM TIME TO TIME, COME UP WITH SOME THOUGHT-RESULTS."

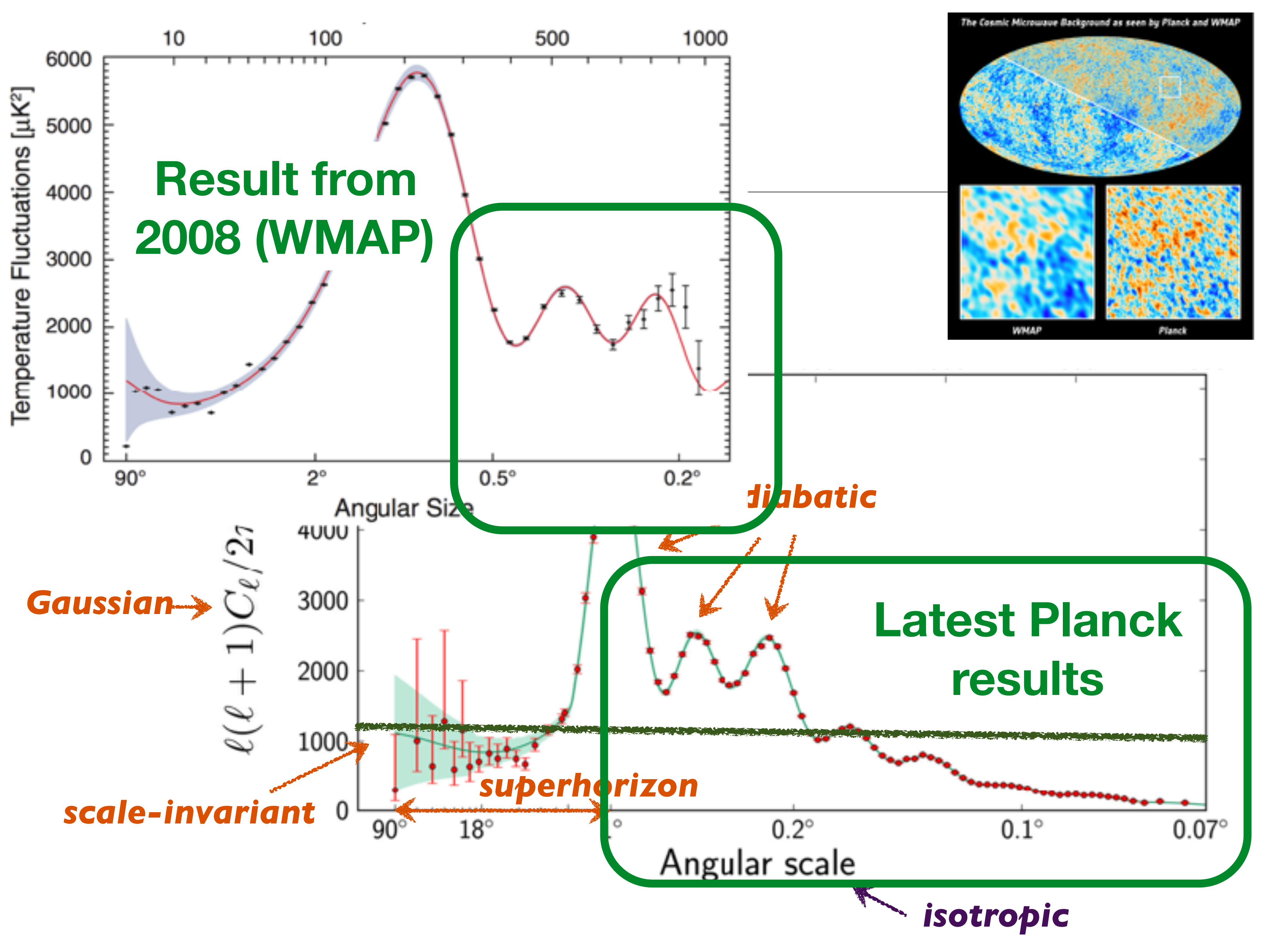
Today's Cosmological Standard Model



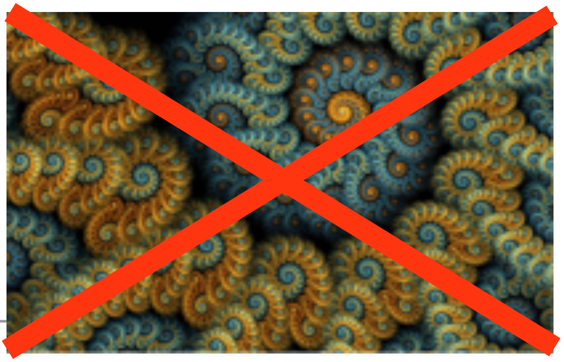
The Universe is expanding.
As it expanded it cooled.
This results in observational implications that allow us to verify the Big Bang Theory



Relic light from the Big Bang

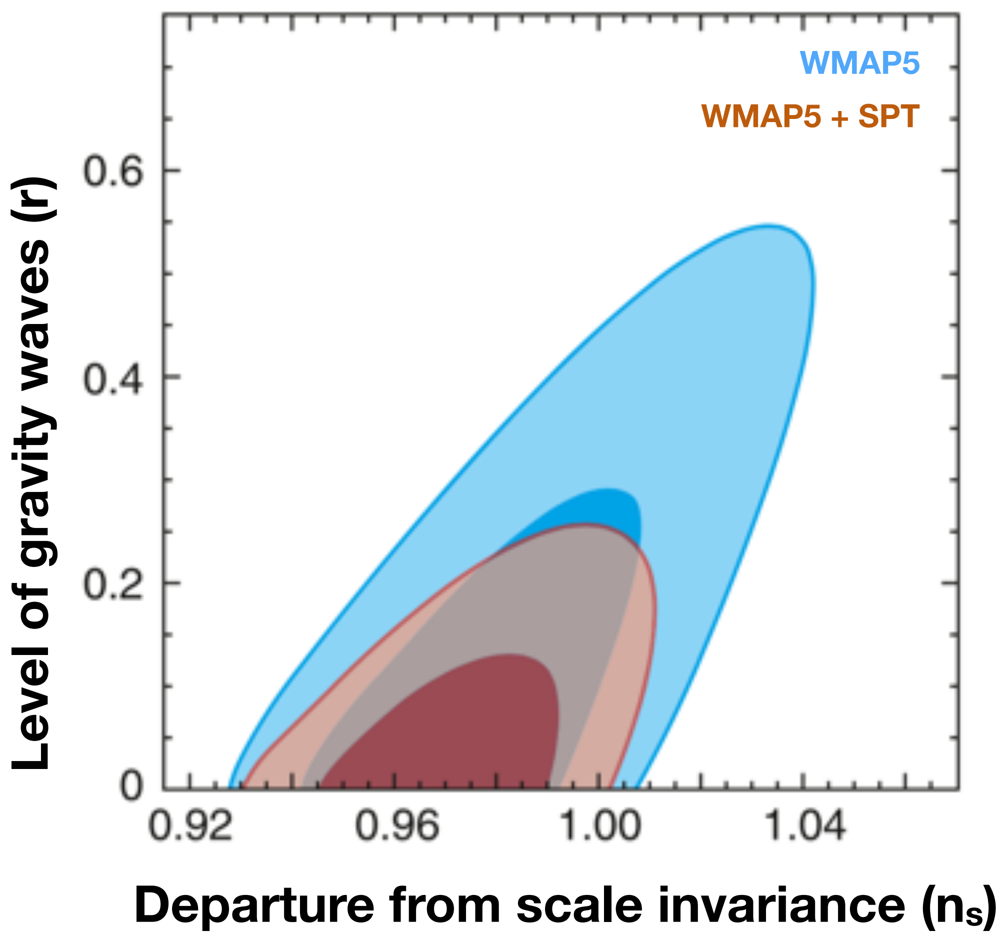


Result from 2008 (WMAP)
Temperature Fluctuations [μK²]
Angular Size
10
100
500
1000
6000
5000
4000
3000
2000
1000
0
90°
2°
0.5°
0.2°
The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck
Latest Planck results
$\ell(\ell+1)C_\ell/2\pi$
Gaussian
scale-invariant
superhorizon
adiabatic
isotropic
Angular scale
90°
18°
0.2°
0.1°
0.07°

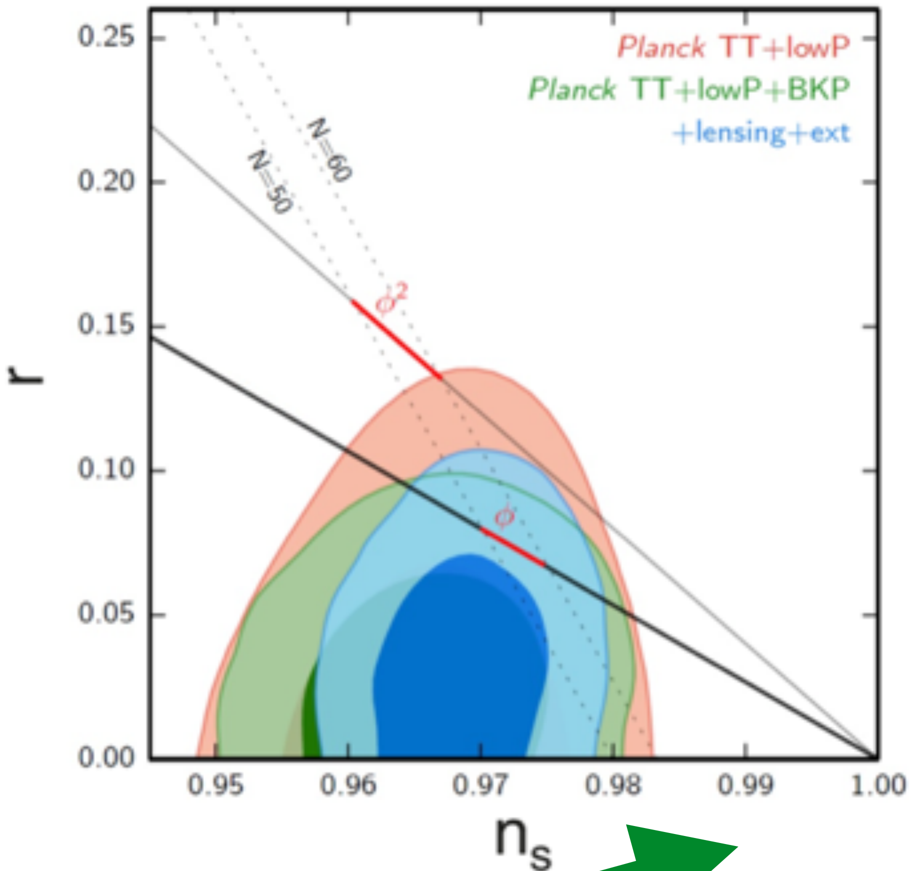


Improved understanding of Inflation

Data as of 2009

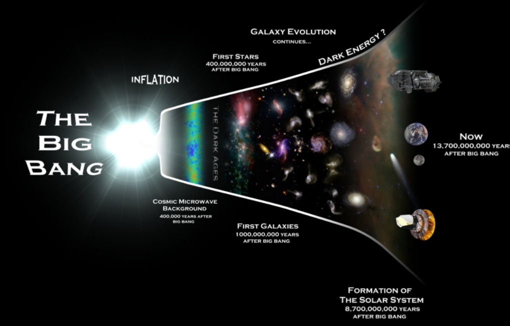


Data today

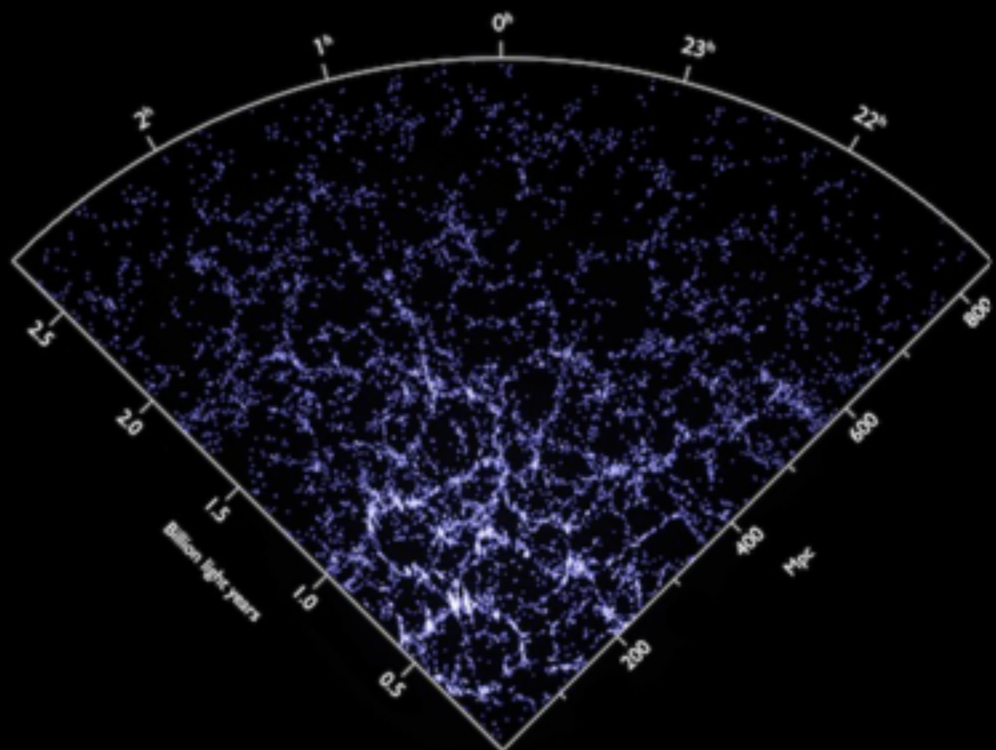


The **new result** $n_s < 1$ is **very important** theoretically.

Observations Agree with Theory

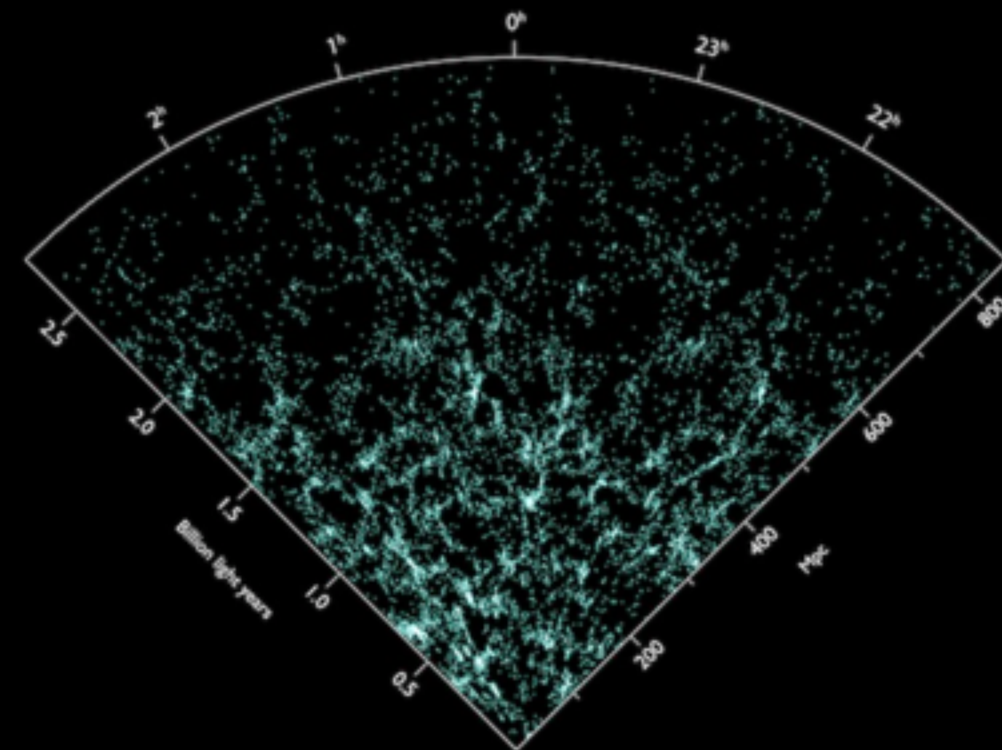


Observation



Data from SDSS Collaboration

Theory



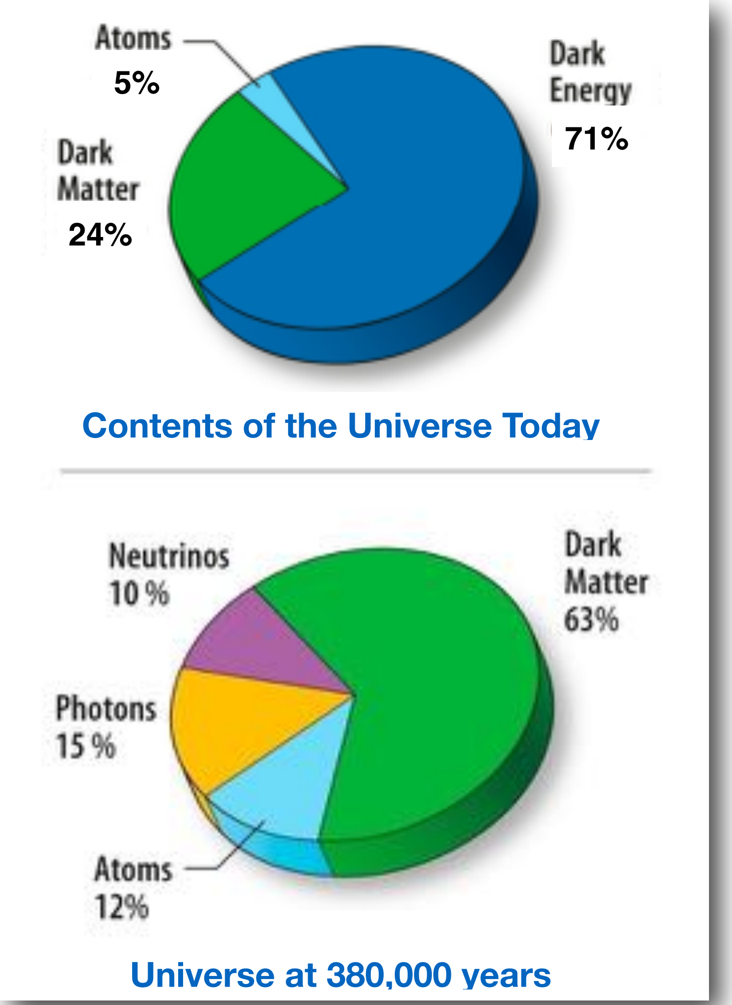
Bolshoi Simulation

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

Precision Cosmology

Cosmic Energy Budget Today

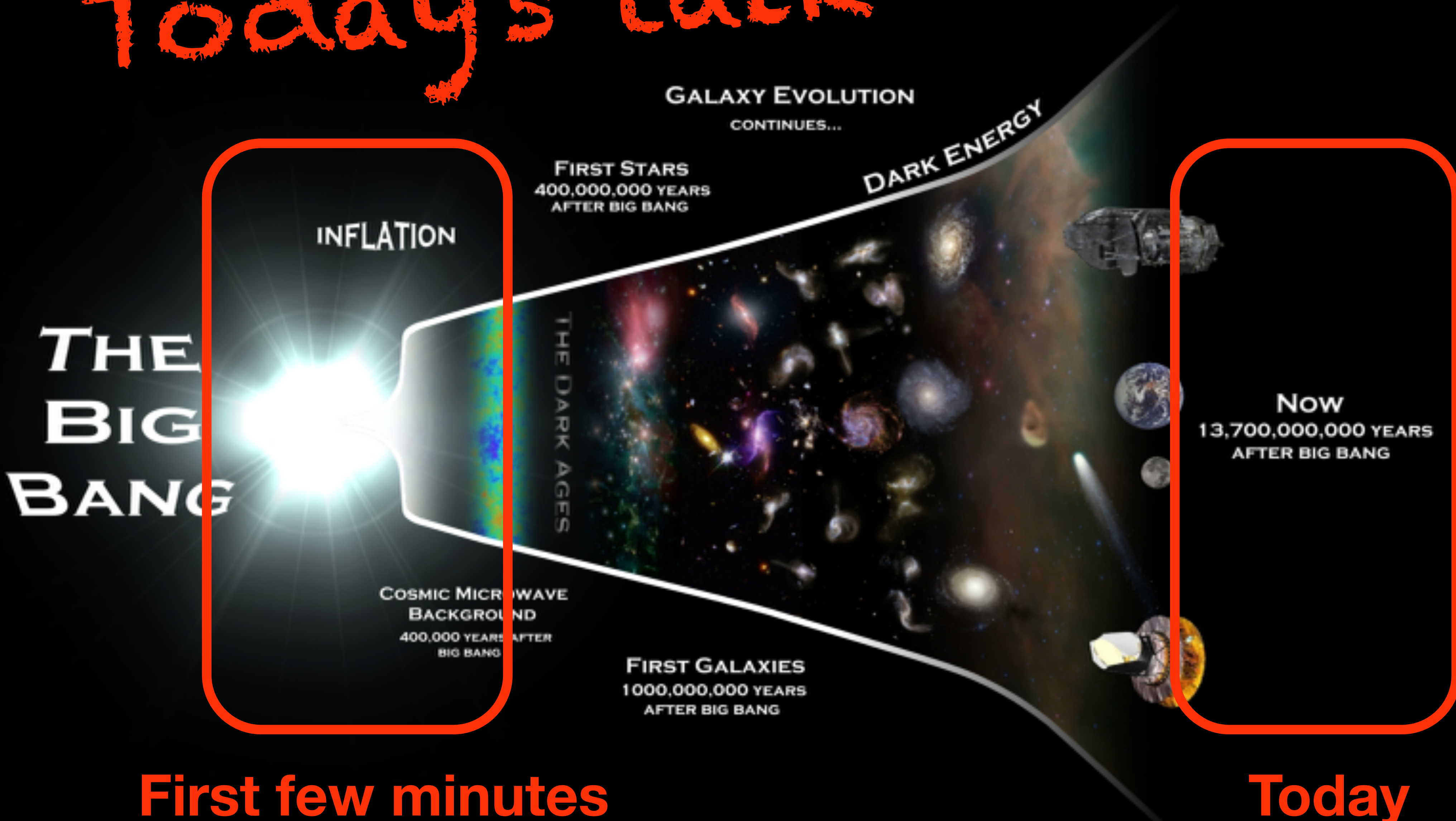
- Dark Energy 71.35%
- Dark Matter 24.02%
- Baryons 4.63%
- Early universe remarkably homogeneous
- Very small density contrast (1 / 100,000) at time of CMB decoupling



All suggest physics beyond the standard model.

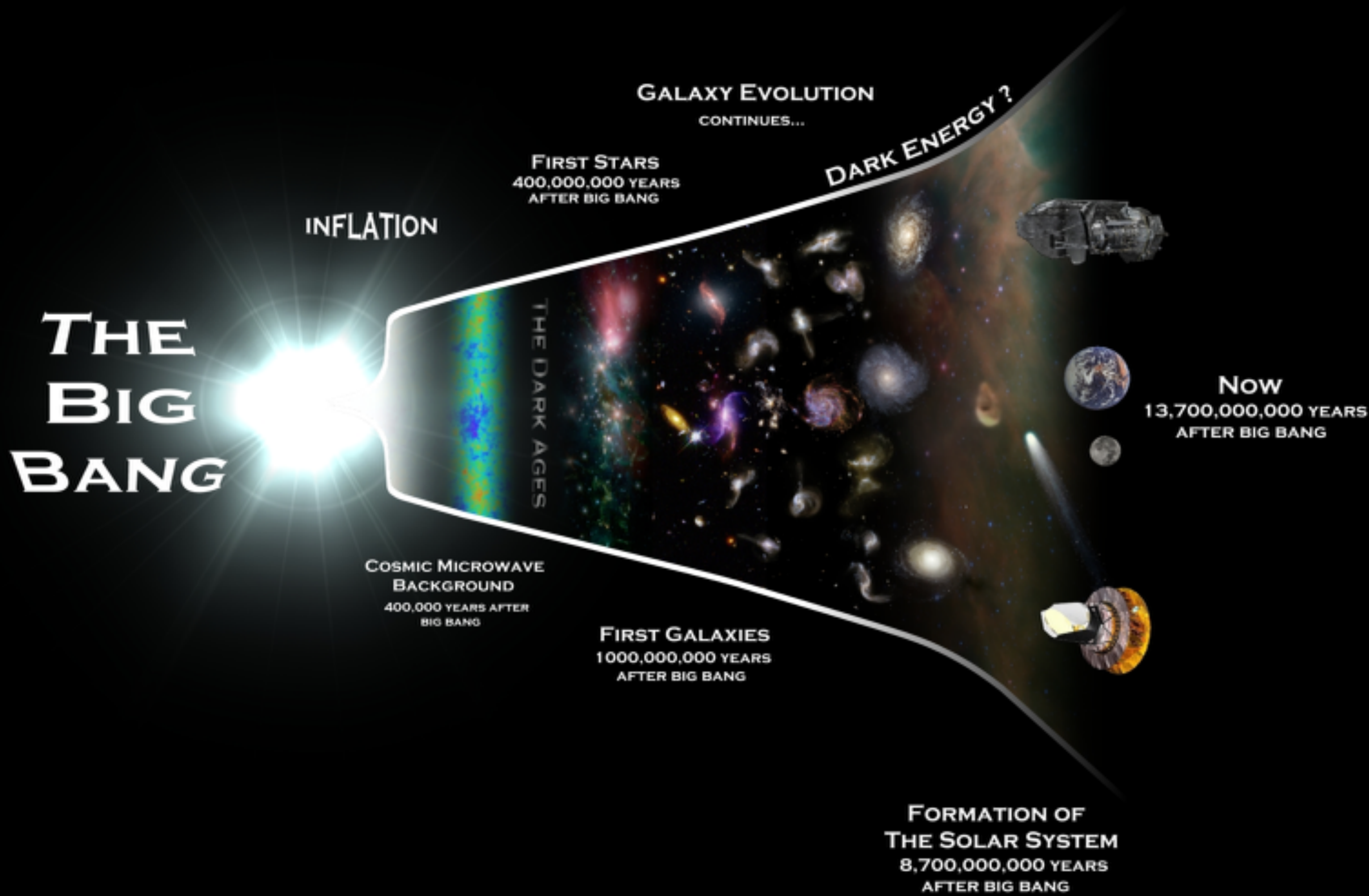
The Cosmological Standard Model

Today's talk



First few minutes

Today



Is there smoking gun evidence for inflation?


THE POST-STANDARD
syracuse.com
Syracuse University physicist explains the Big Bang breakthrough

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

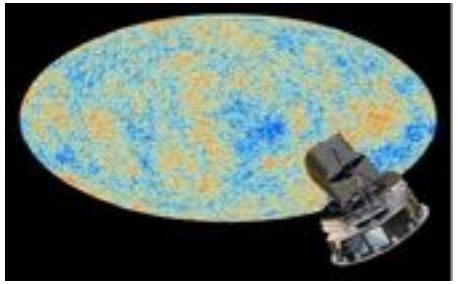
"How Well Can We Really Determine the Scale of Inflation? "
with O. Ozsoy and K. Sinha, Phys. Rev. D91 (2015)

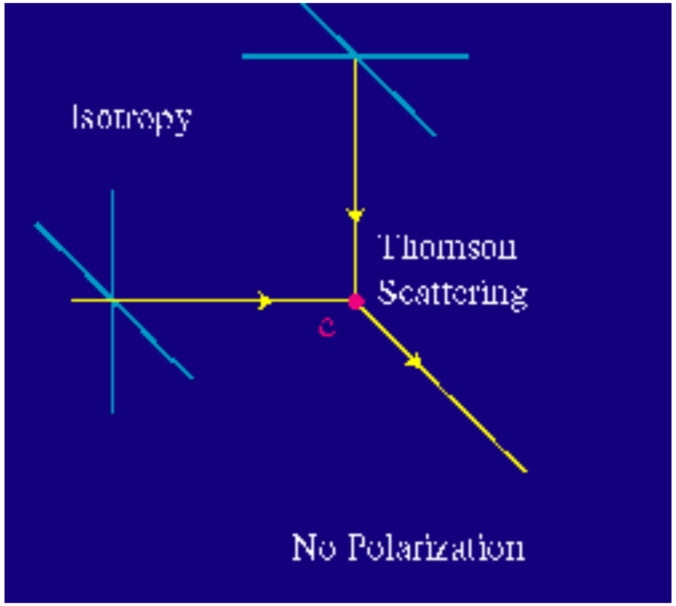
"Decoupling Survives Inflation "
with A. Avgoustidis, et. al., JCAP 1206 (2012)

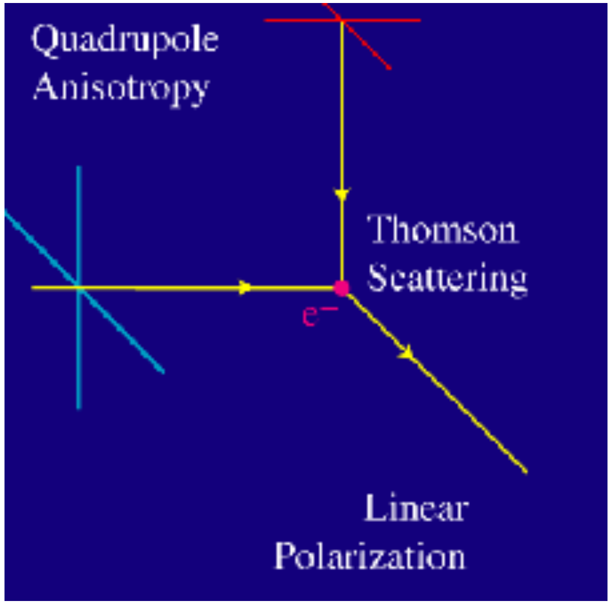
"The Importance of Slow-roll Corrections During Multi-field Inflation "
with A. Avgoustidis, et. al., JCAP 1202 (2012)

CMB-S4 Collaboration, selected by NASA 2016 (DOE / NSF support as well)

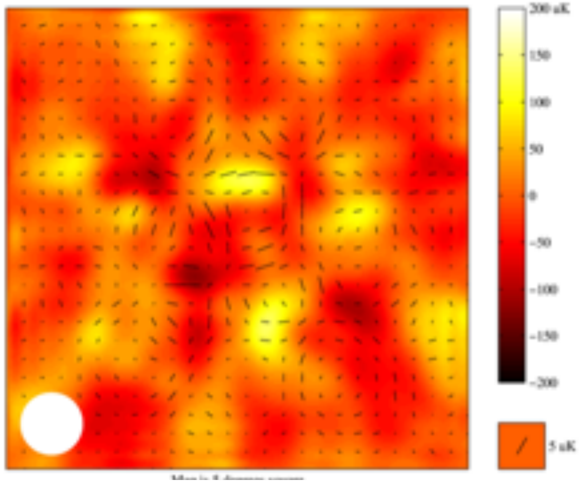
CMB Polarization and Primordial Gravity Waves

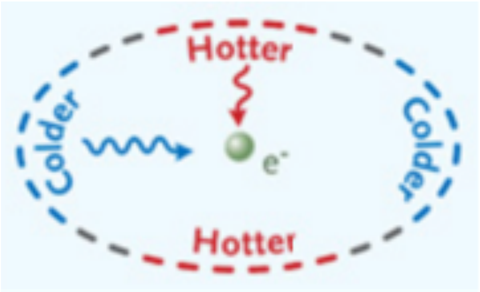




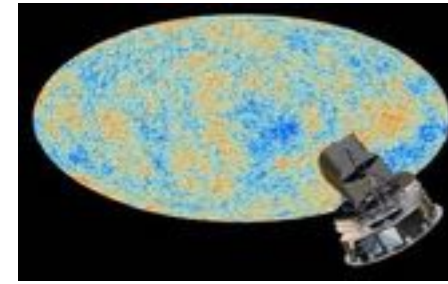


E-mode Polarization (DASI — 2002)





CMB Polarization and Primordial Gravity Waves



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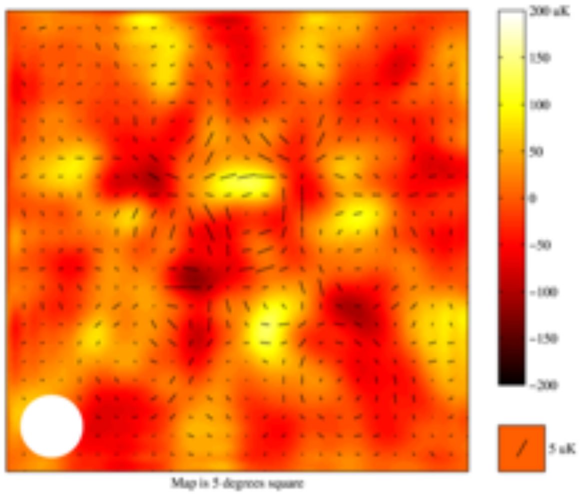
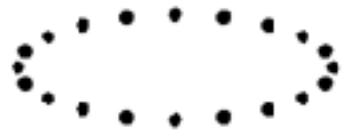
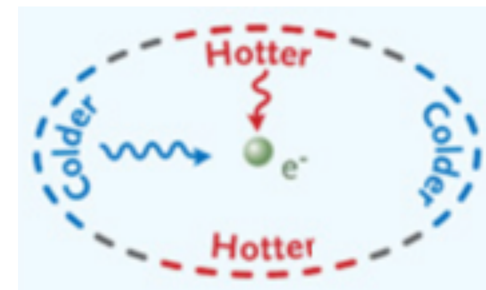
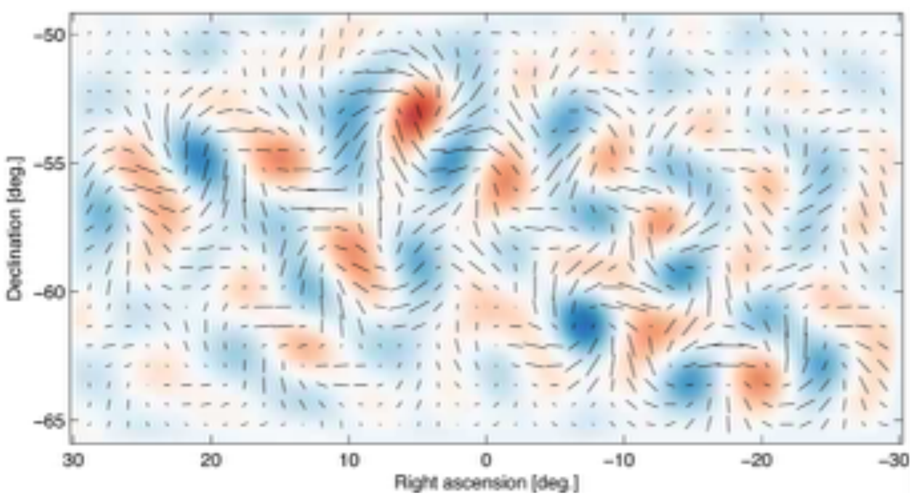






Gravity Waves can also produce B-mode Polarization



Measuring the Energy Scale of Inflation

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.

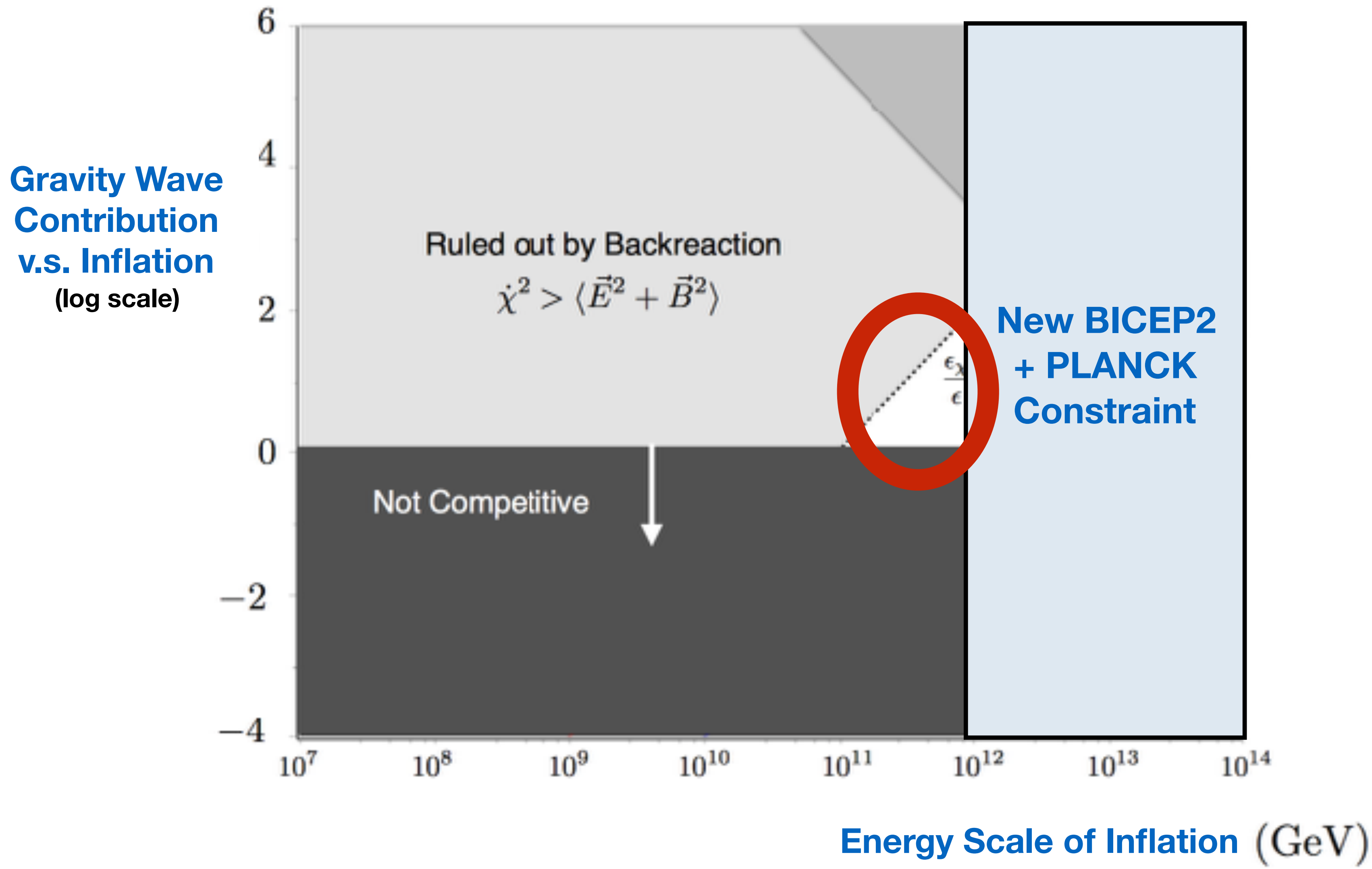
There can be additional sources of primordial gravity waves.

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

Other fields can produce gravity waves during inflation

Can we really determine the scale of inflation?

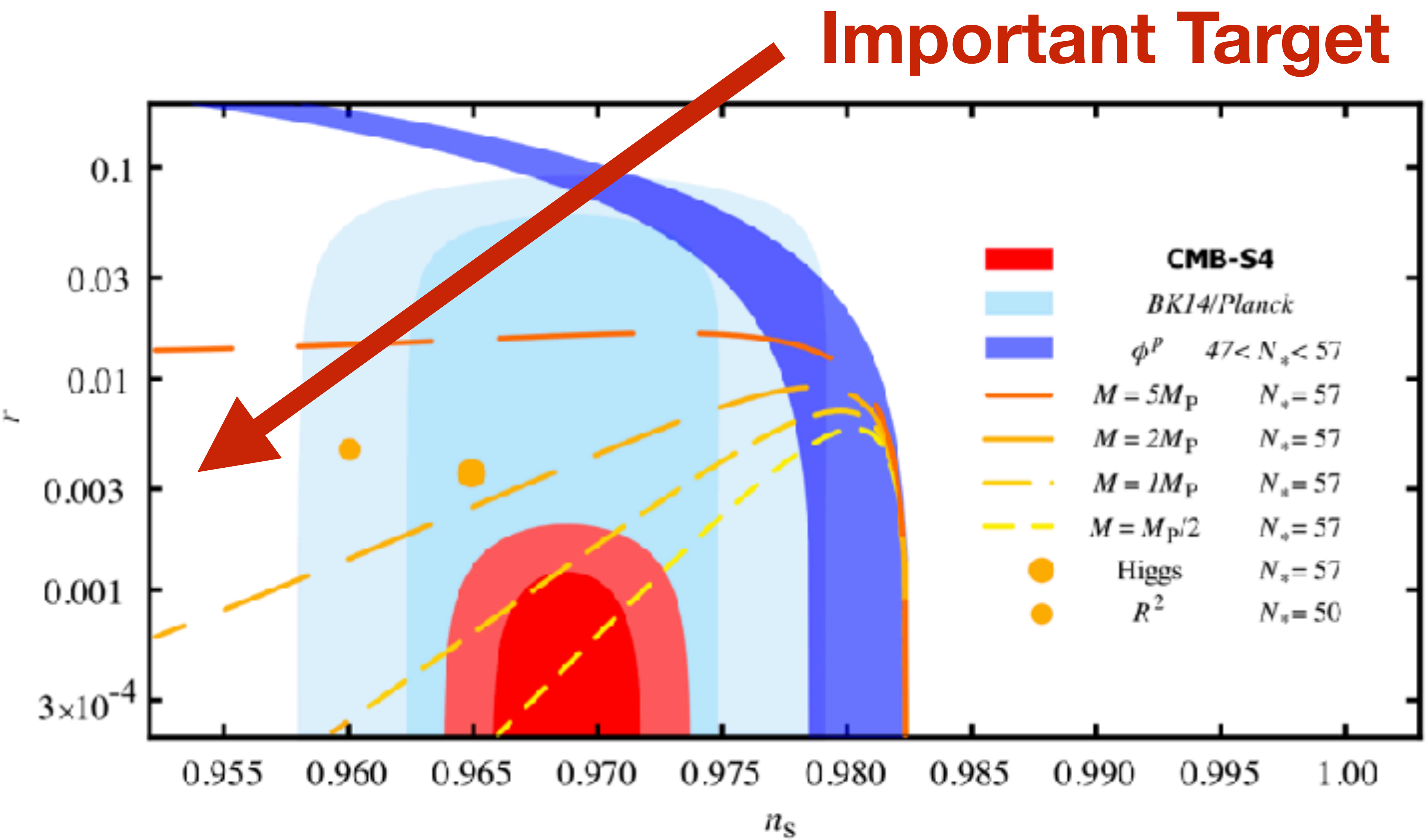
with K. Sinha and O. Ozsoy, PRD 91 (2015)



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

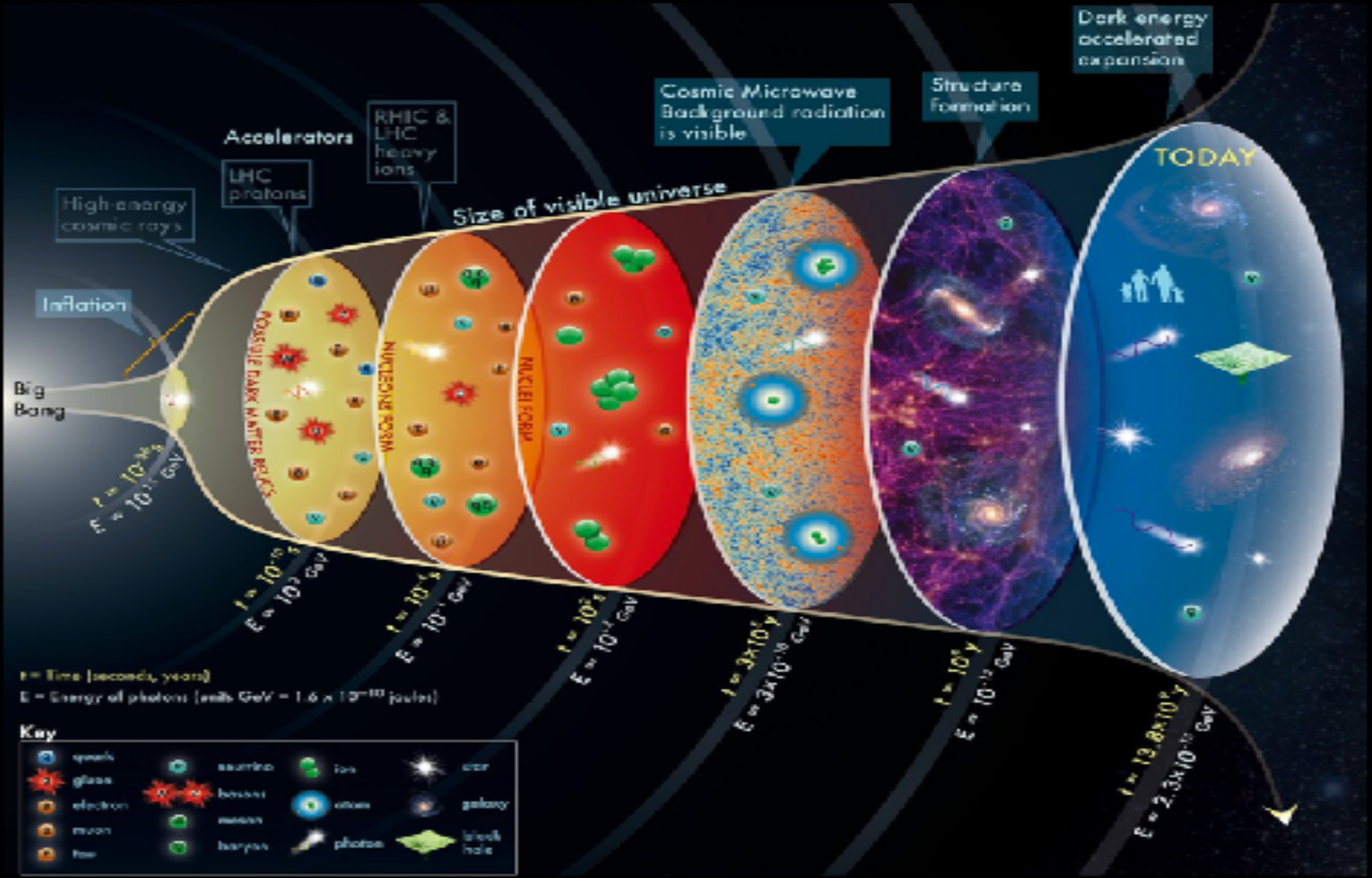
Measuring the Energy Scale of Inflation

with CMB S4 Collaboration, arXiv:1610.02743



The First Three Minutes

How does Inflation End?

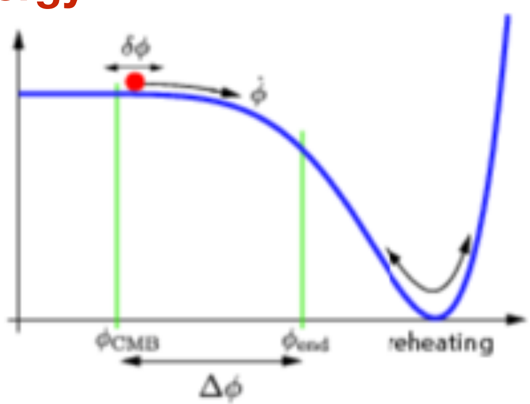


When did the universe thermalize?

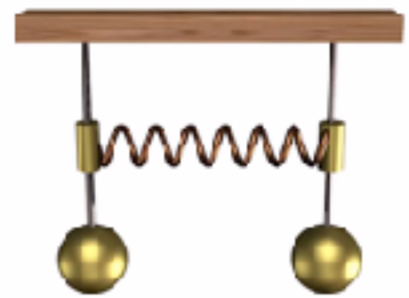
Two pioneers of inflationary reheating

From Inflation to the Hot Big Bang

Energy



Time



Robert Brandenberger
(McGill University)

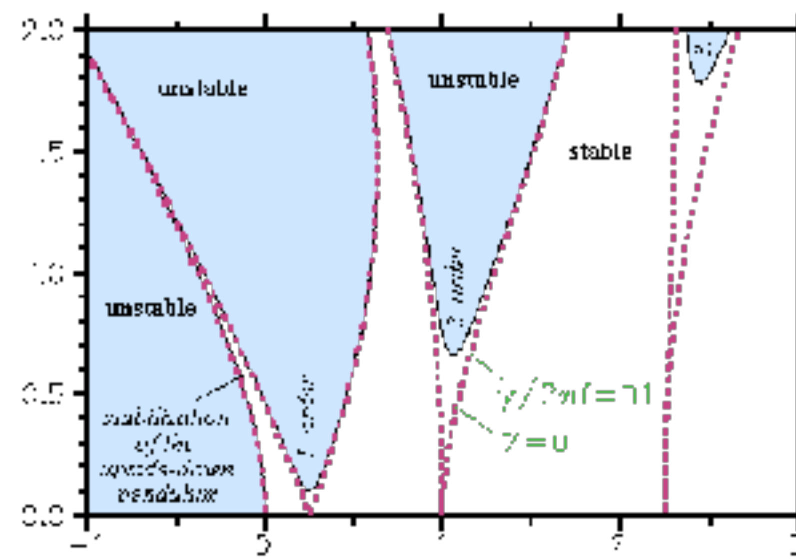
Lev Kofman
1957 — 2009

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

Stages of Reheating:

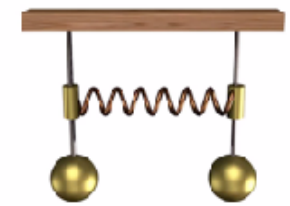
1. Non-perturbative (parametric resonance)
2. Non-linear Dynamics and Chaos
3. Turbulence
4. Thermalization

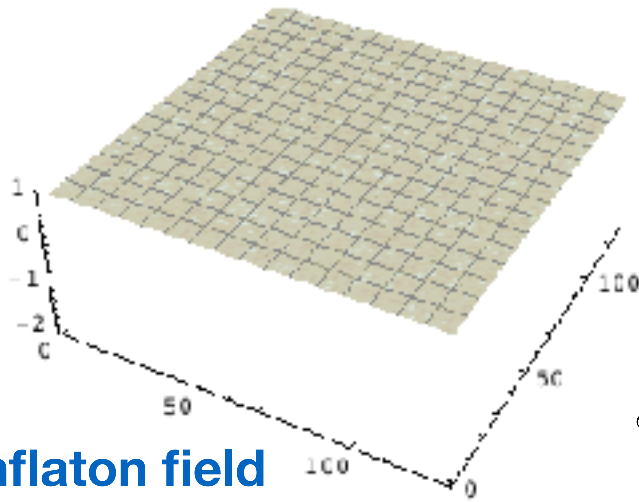
Coupling Strength



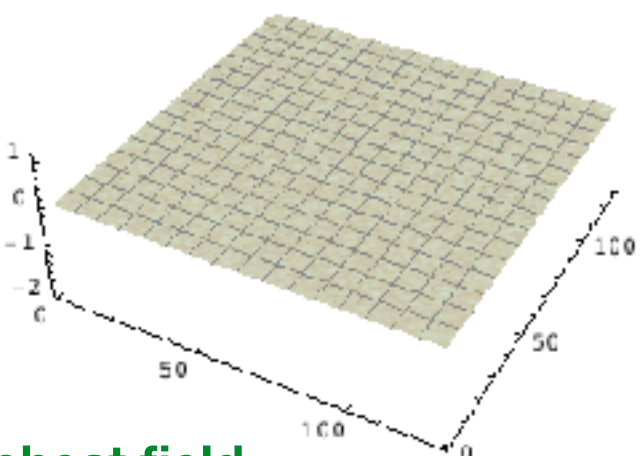
Relative Frequency

Observables from Inflationary reheating



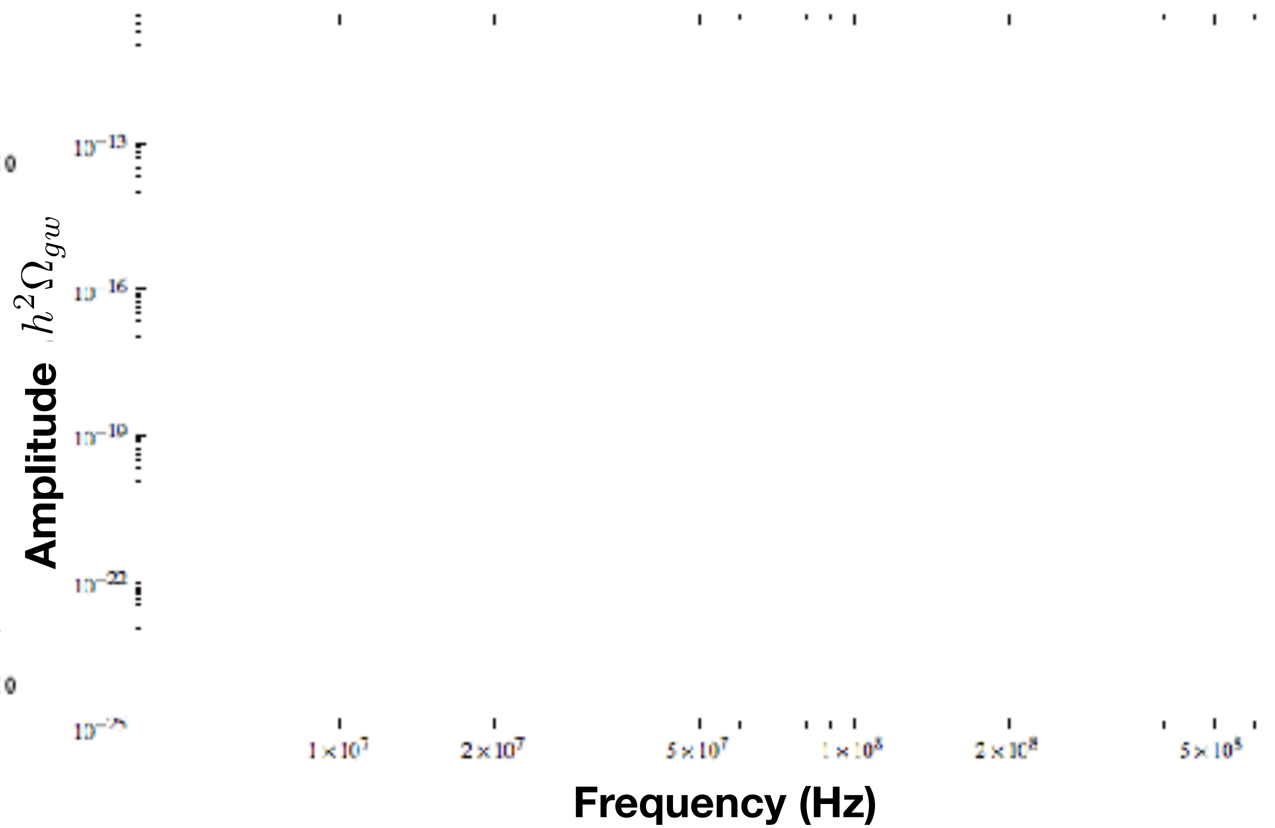


Inflaton field



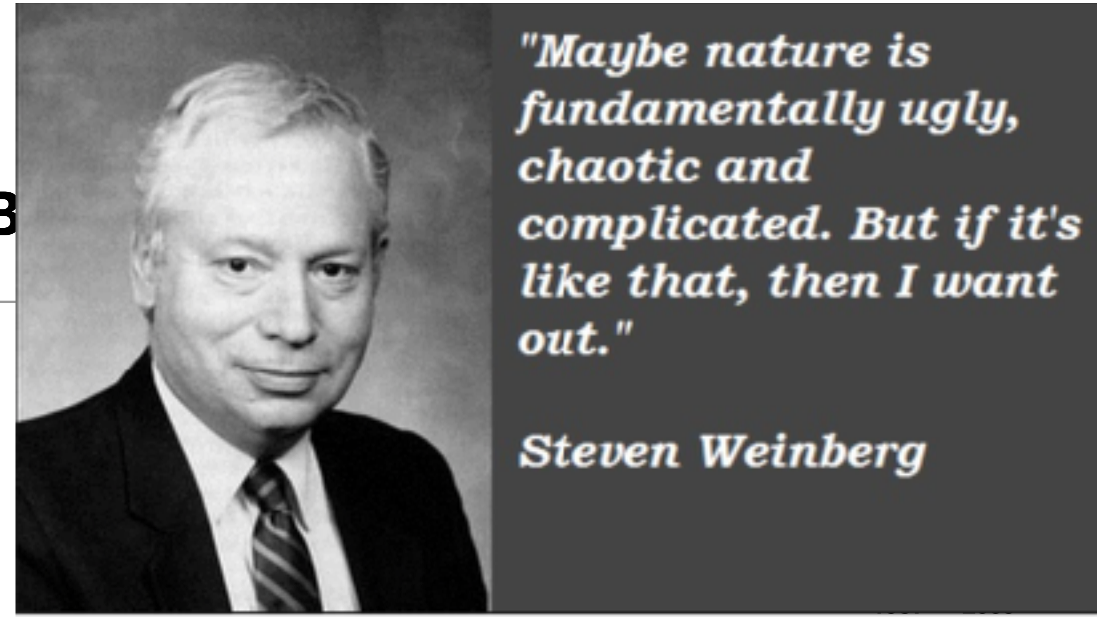
Reheat field

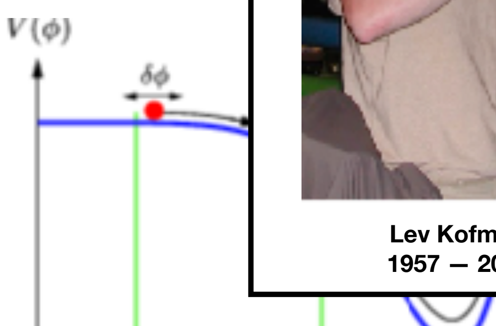
Gravity wave spectrum



From Inf… ot Big B

Lev Kofman
1957 — 2009





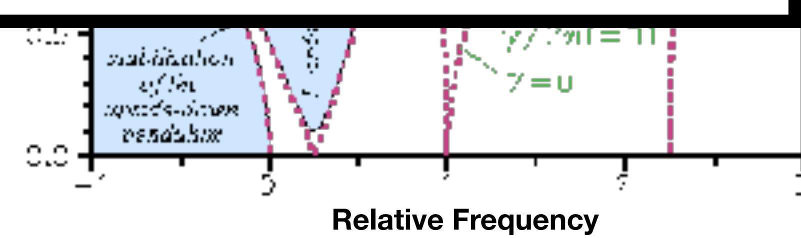
Establishing a more systematic approach to the reheating processes is an important open challenge.

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

Recent Summer workshop at Aspen Center for Physics.
Future (2019) workshop at KITP — Santa Barbara (with Adshead, Cui, and Flauger)

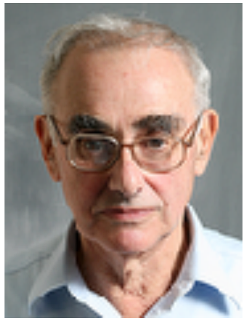
3. Turbulence

4. Thermalization



Symmetry Breaking and Goldstone Bosons

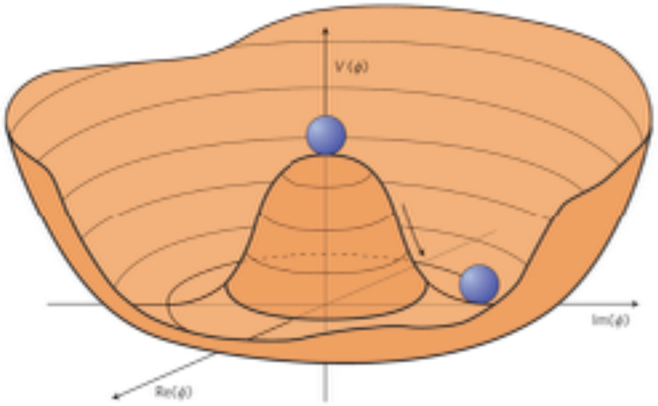
Emmy Noether

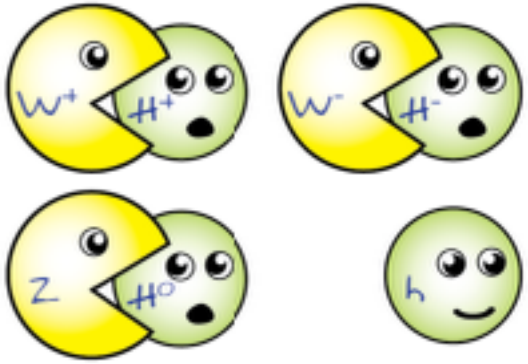


Jeffrey Goldstone

Stephen Weinberg

Spontaneous Symmetry Breaking

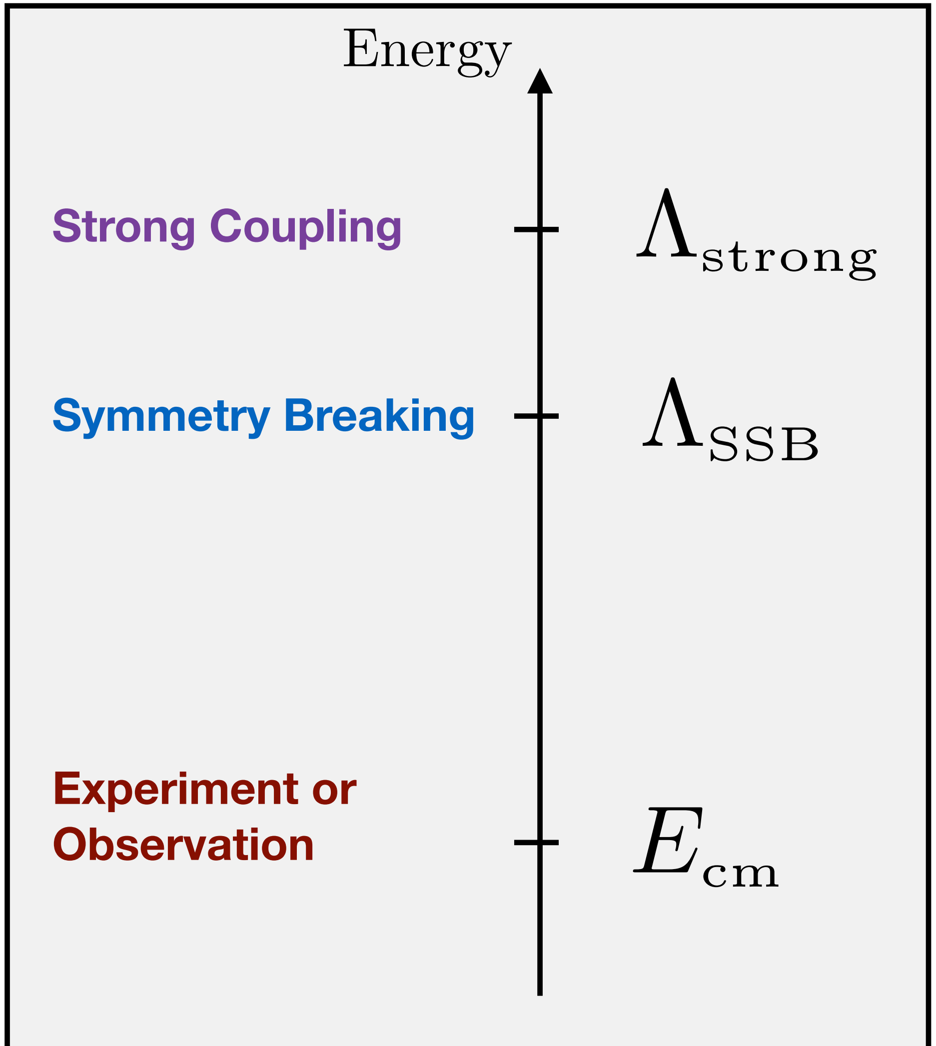




In the broken phase, Goldstone bosons are eaten by Gauge Fields

(assuming gauge fields are present).

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

Goldstone Bosons and Spontaneous Symmetry Breaking

Electroweak Physics

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

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

Goldstones and Cosmology?

The cosmic expansion breaks time translation invariance.

No longer a symmetry

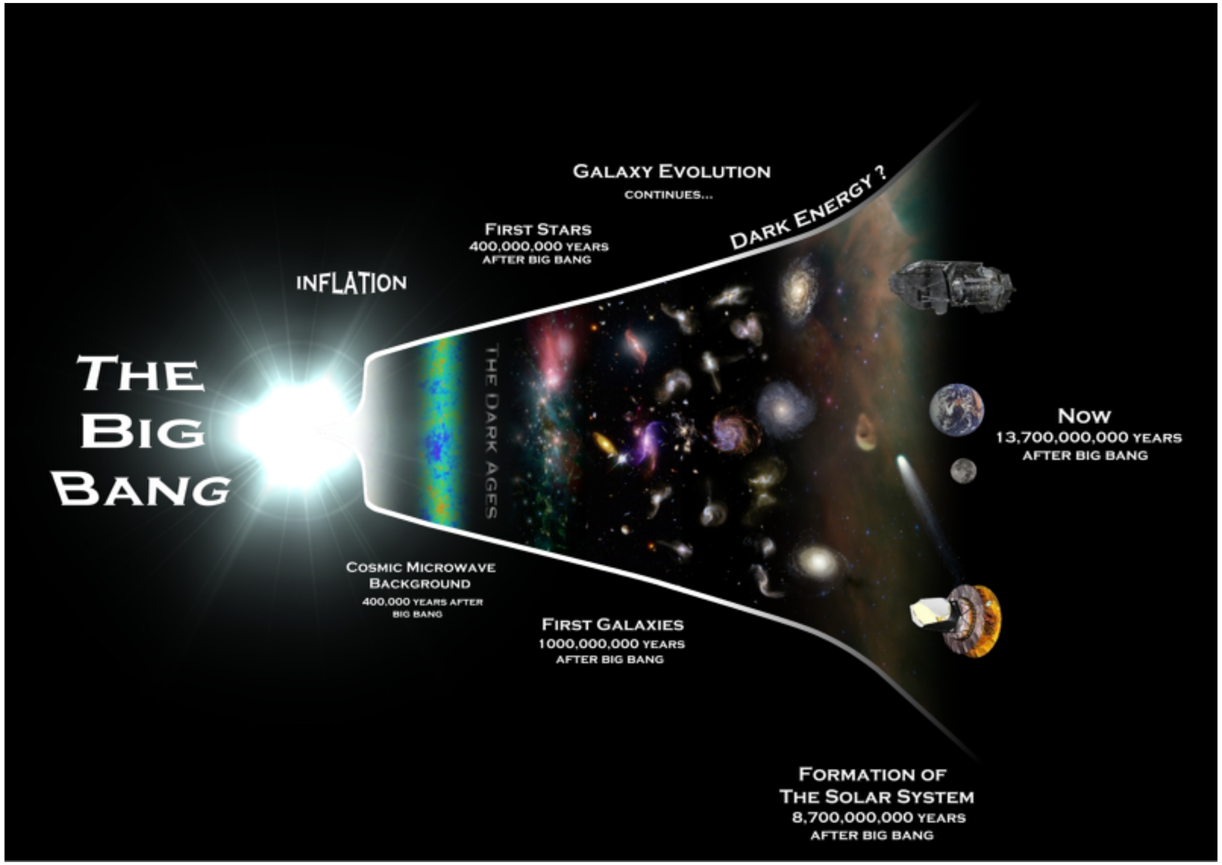
$$t \to t + \xi$$

Inflaton breaks the symmetry

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

Radiation or matter evolving breaks the symmetry

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



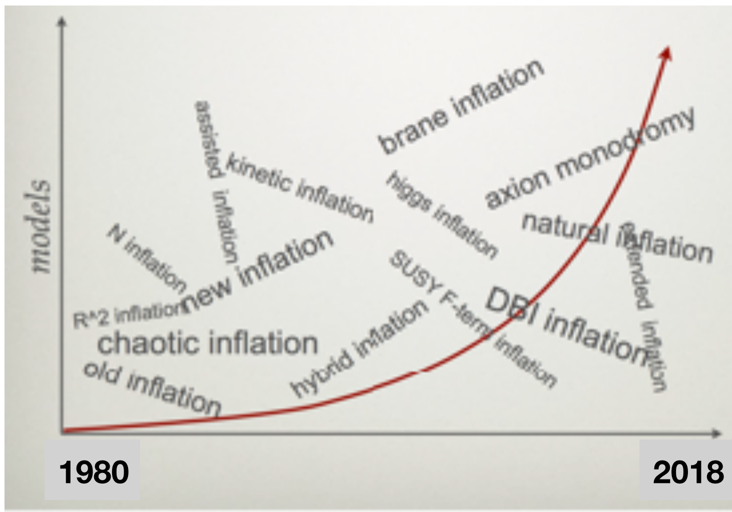
At high energy (small length scales) symmetry is realized.

This is spontaneous symmetry breaking!

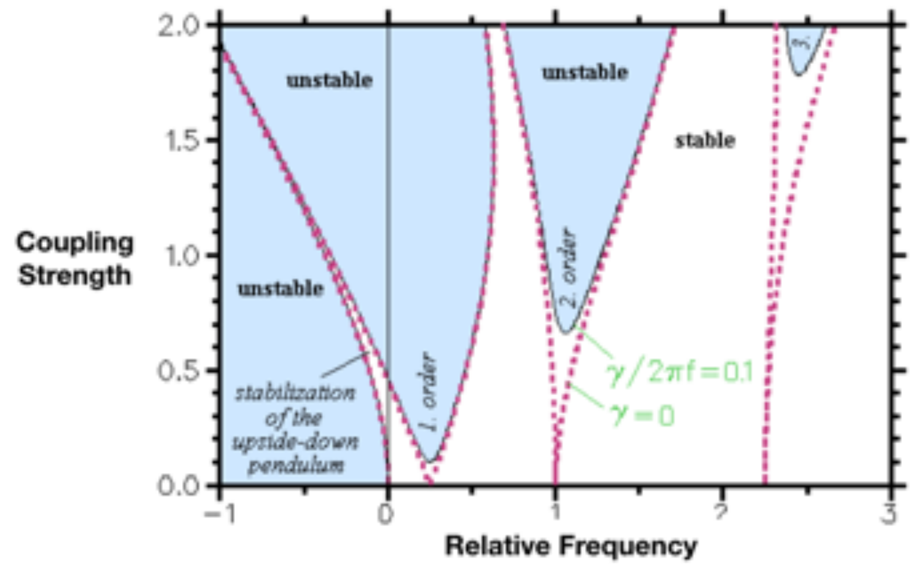
Effective Field Theory and Reheating the Universe

with T. Giblin, E. Nesbit, O. Ozsoy, and G. Sengor **[Phys.Rev. D96 (2017)]**

All models are captured by their symmetry breaking pattern.



Inflationary Zoo of models



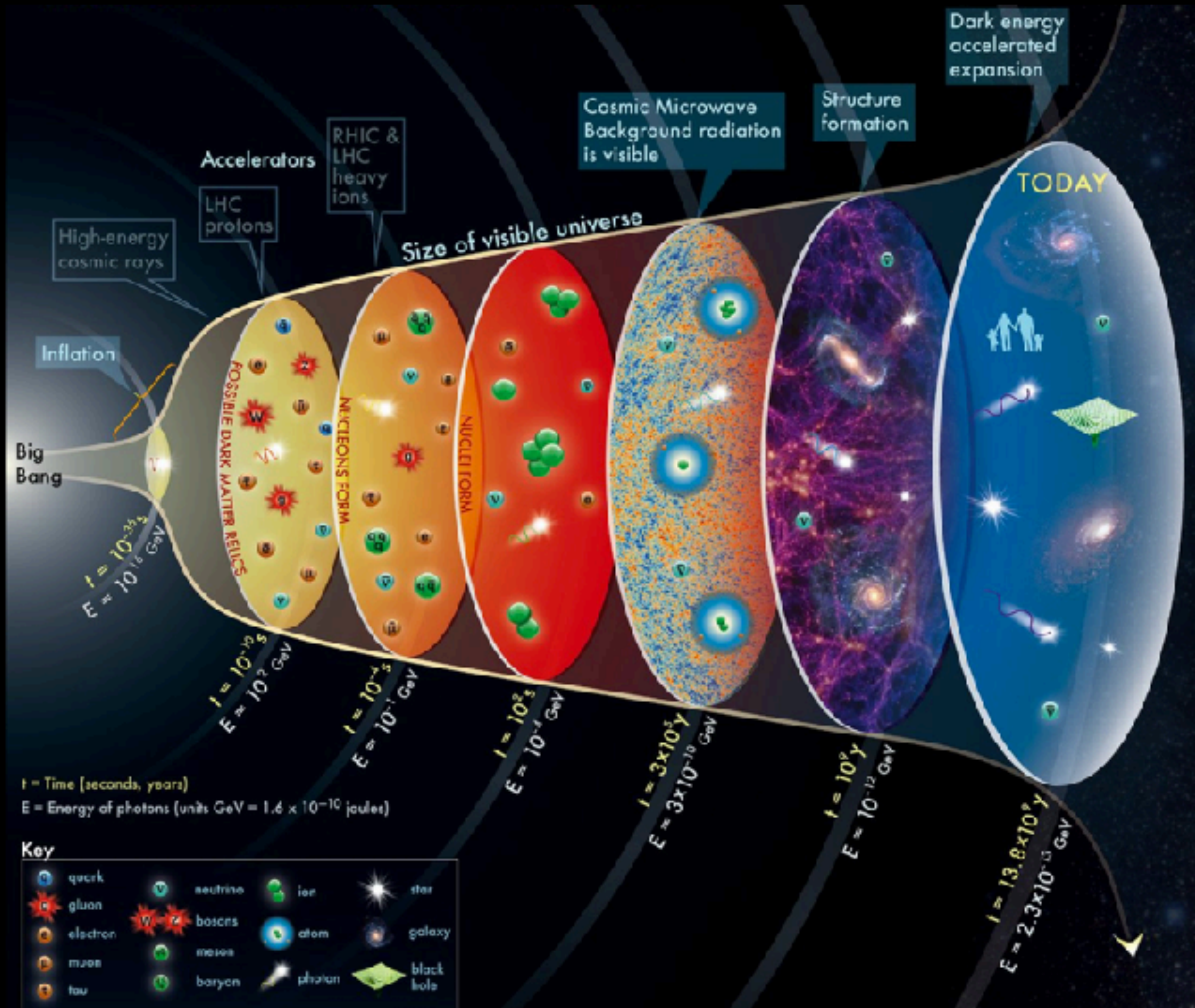
Correction to sound speed of fluctuations

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

Same coefficient for both because of symmetry breaking pattern

Cubic interaction (CMB non-gaussianity)

How can we determine when the universe thermalized?



The growth of structure depends on the cosmic history.

Early Matter Phase and Growth of Structure

with J. Georg JHEP 1709 (2017)
with J. Georg and G. Sengor and O. Ozsoy PRD D93 (2016)
with J. Fan and O. Ozsoy PRD D90 (2015)

Evolution of Density Perturbations

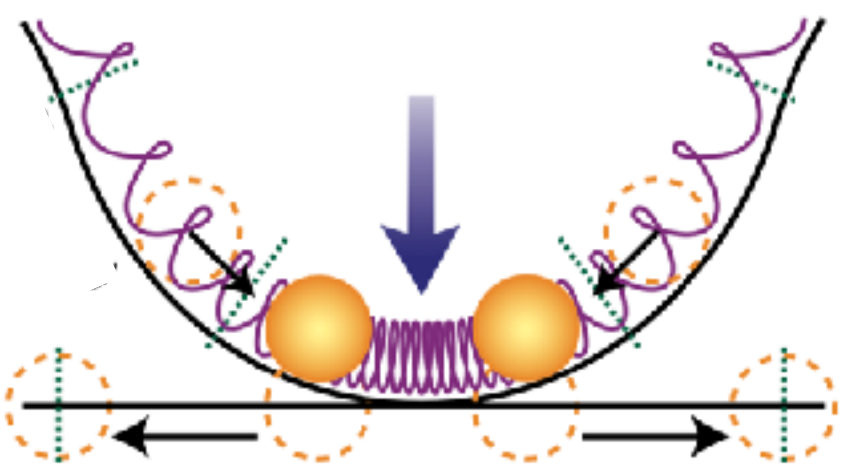
$$\delta_k \equiv \frac{\delta\rho(t,\vec{k})}{\bar{\rho}}$$

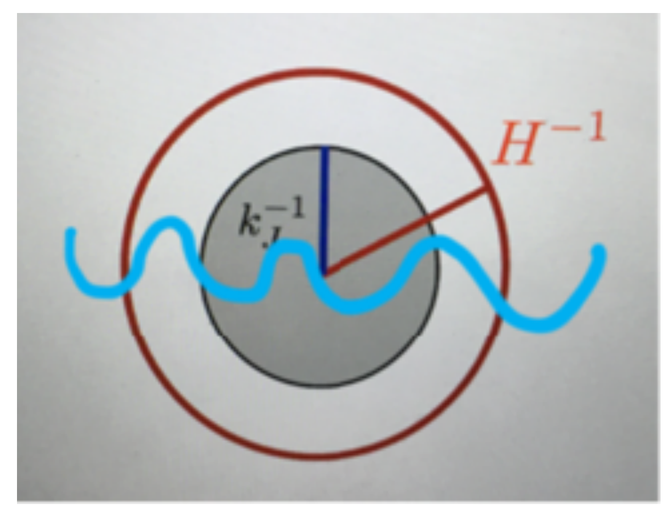
$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(c_s^2 k_p^2 - \frac{3}{2}H^2\right)\delta_k = 0$$

Hubble "friction" slows the instability

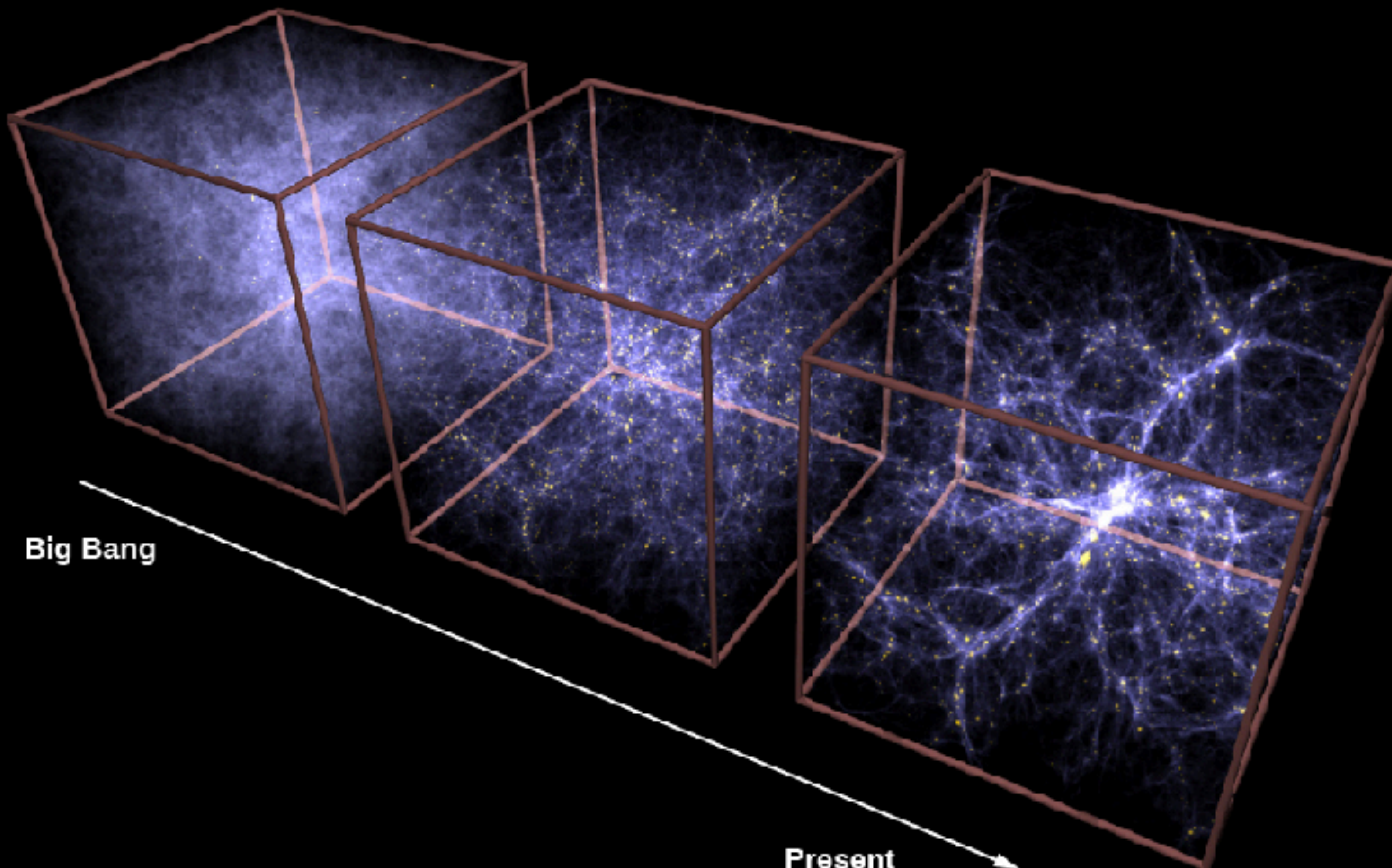
Pressure prevents collapse

Gravity drives collapse





Growth of Structure During a Matter Phase



Over-dense regions grow in a matter dominated universe

New ways to create (and detect) dark matter

with J. Georg JHEP 1709 (2017)
with J. Georg and G. Sengor and O. Ozsoy PRD D93 (2016)

Evolution of Density Perturbations

$$\delta_k \equiv \frac{\delta\rho(t,\vec{k})}{\bar{\rho}}$$

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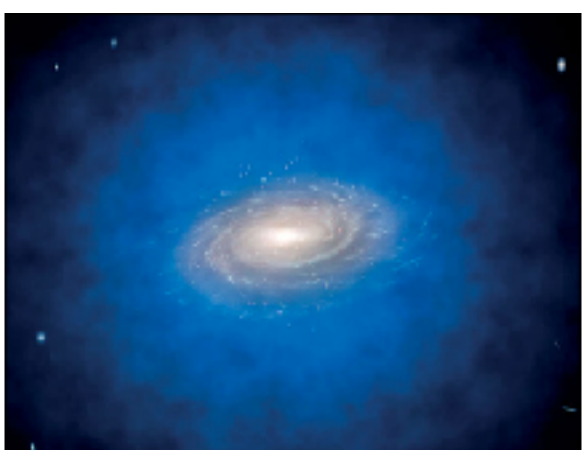
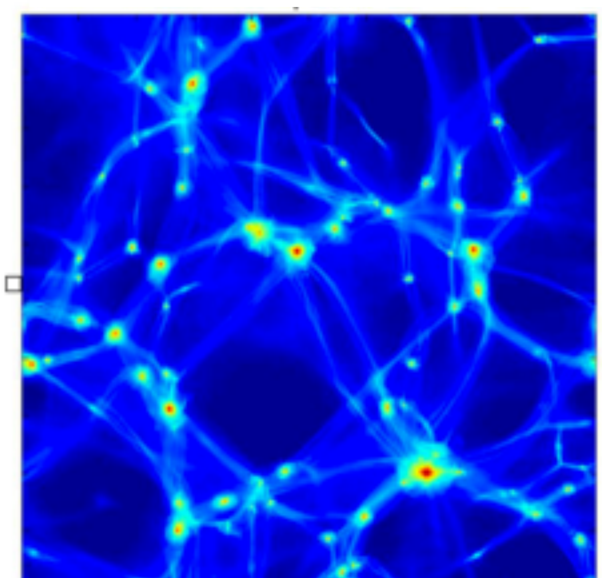
Pressure prevents collapse

Gravity drives collapse



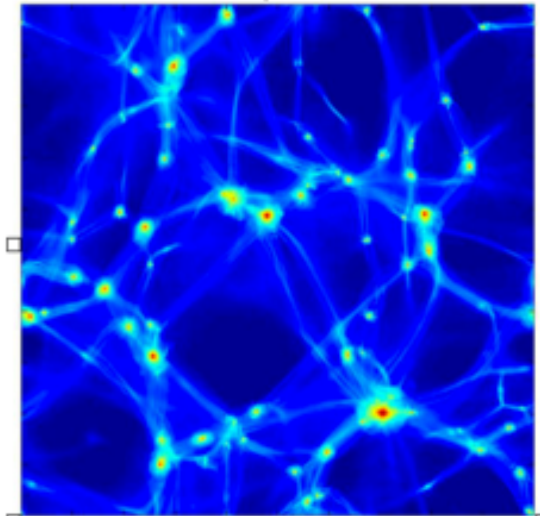
Primordial substructure in dark matter

Enhanced signals for indirect detection



Concentrated Dark Matter

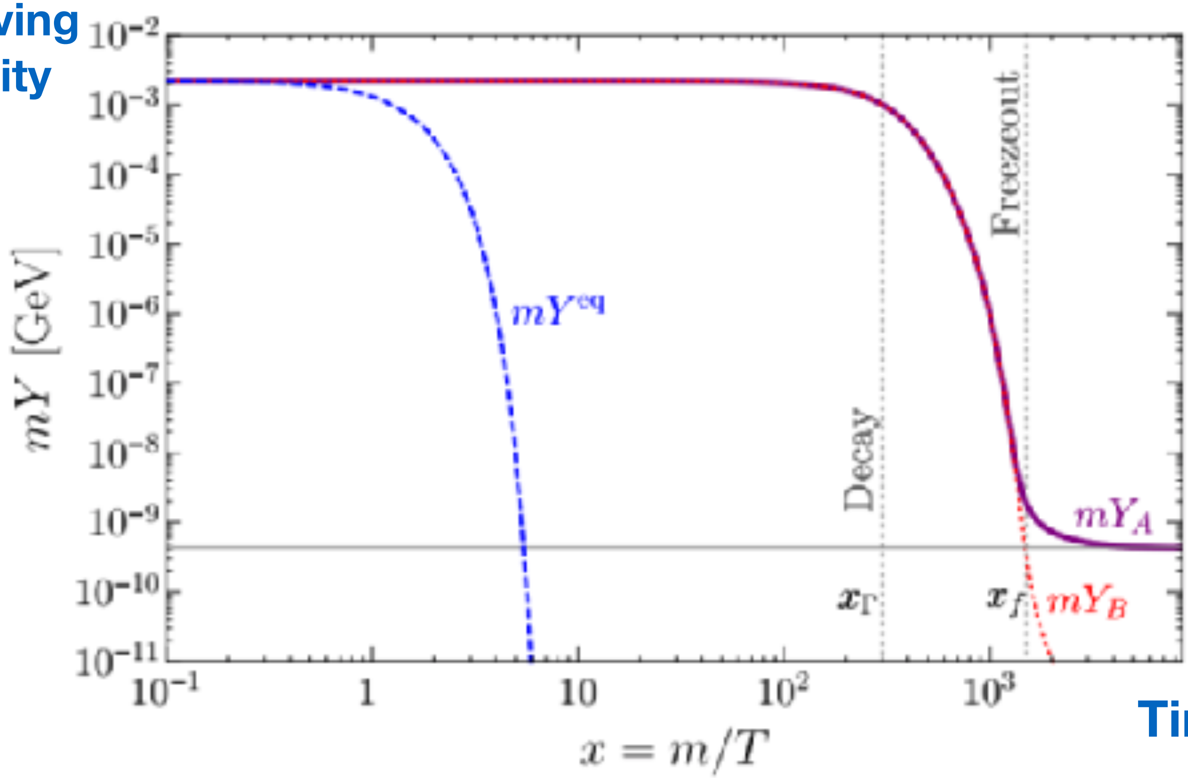
with J. Dror, E. Kuflik, and B. Melcher (submitted to PRL) arXiv:1711.04773



Dark matter decouples from Standard Model early in the universe.

Hidden sector particles lead to a matter phase.

Comoving Density



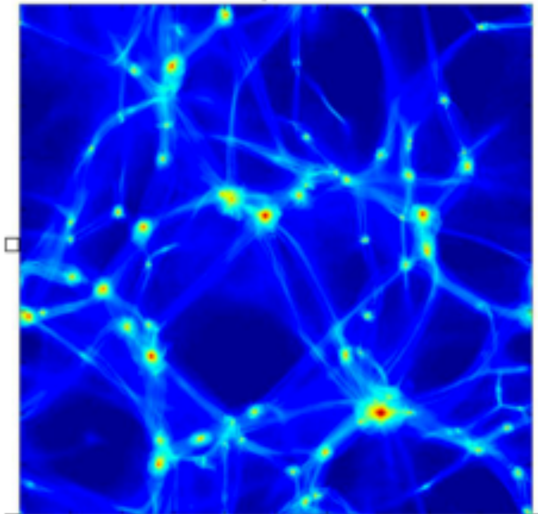
Time

Cosmological Dark matter results from decay of hidden sector particles.

Growth of substructure can lead to enhanced signals for indirect detection.

Concentrated Dark Matter

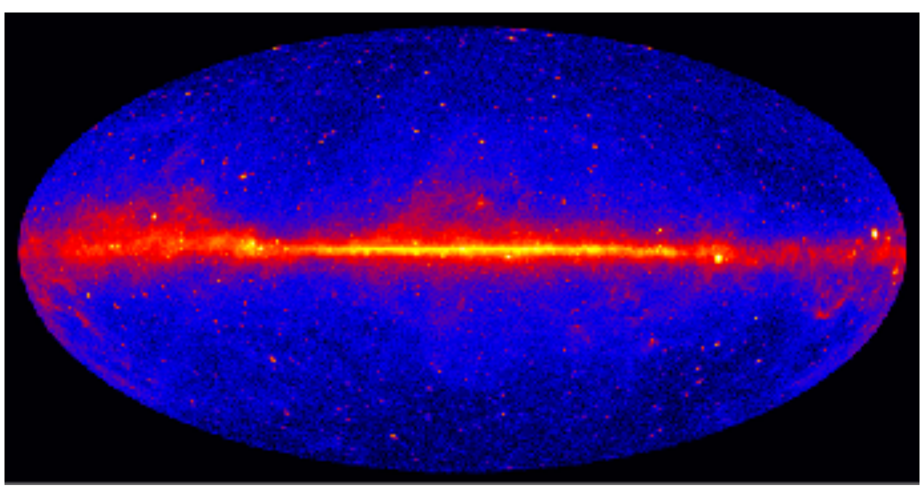
with J. Dror, E. Kuflik, and B. Melcher (submitted to PRL) arXiv:1711.04773

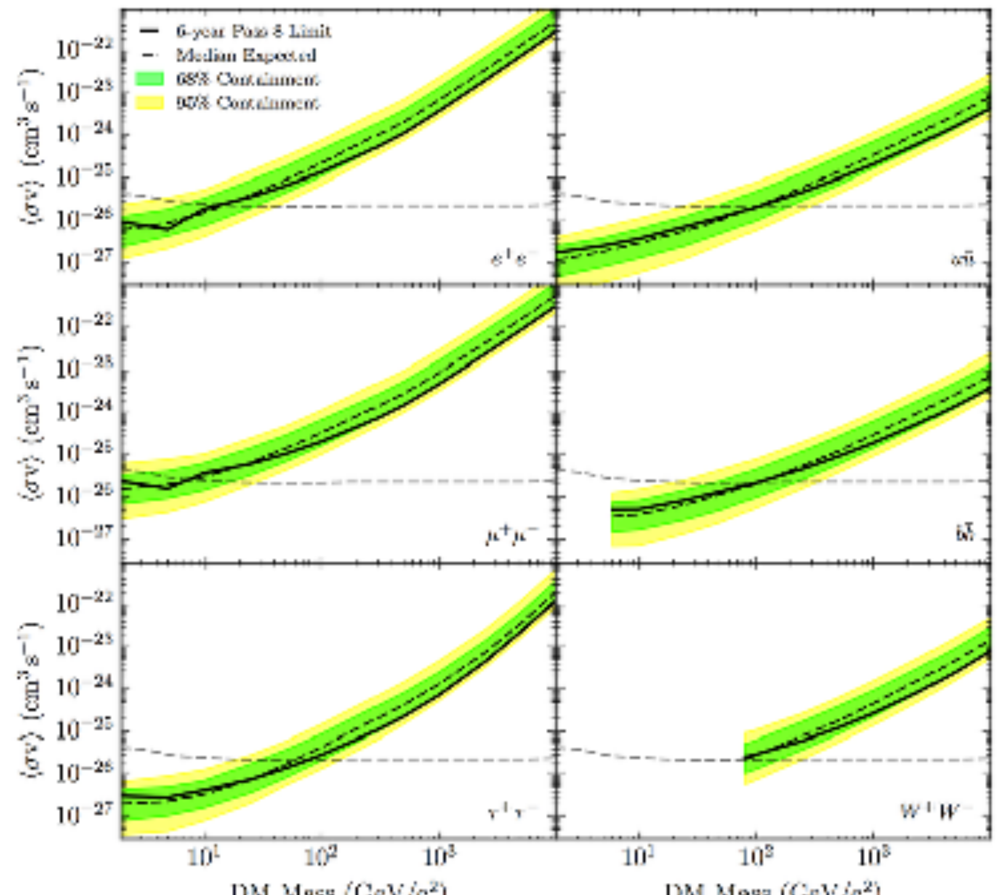


Expected Signal (flux)

$$\Phi \sim \frac{\langle \sigma v \rangle}{m_X^2} \times \rho^2(r)$$

Microphysics   Astrophysics





Could primordial Black Holes be the dark matter?

with J. Georg JHEP 1709 (2017)

If structures can form in a matter phase, why can't black holes?

Mass Fraction in PBHs (Thermal History)

Equation of State ($w > 0$)

$$\beta_0(M) \simeq \delta_M(t_H) \exp\left(-\frac{w^2}{2\delta_M^2(t_H)}\right)$$

$$\delta_M \equiv \frac{\delta M}{M}$$

Mass Fraction in PBHs (Non-thermal History)

$$\delta_k(t_H) \sim 10^{-4} \longrightarrow \delta_k(t > t_H) \sim \mathcal{O}(1)$$

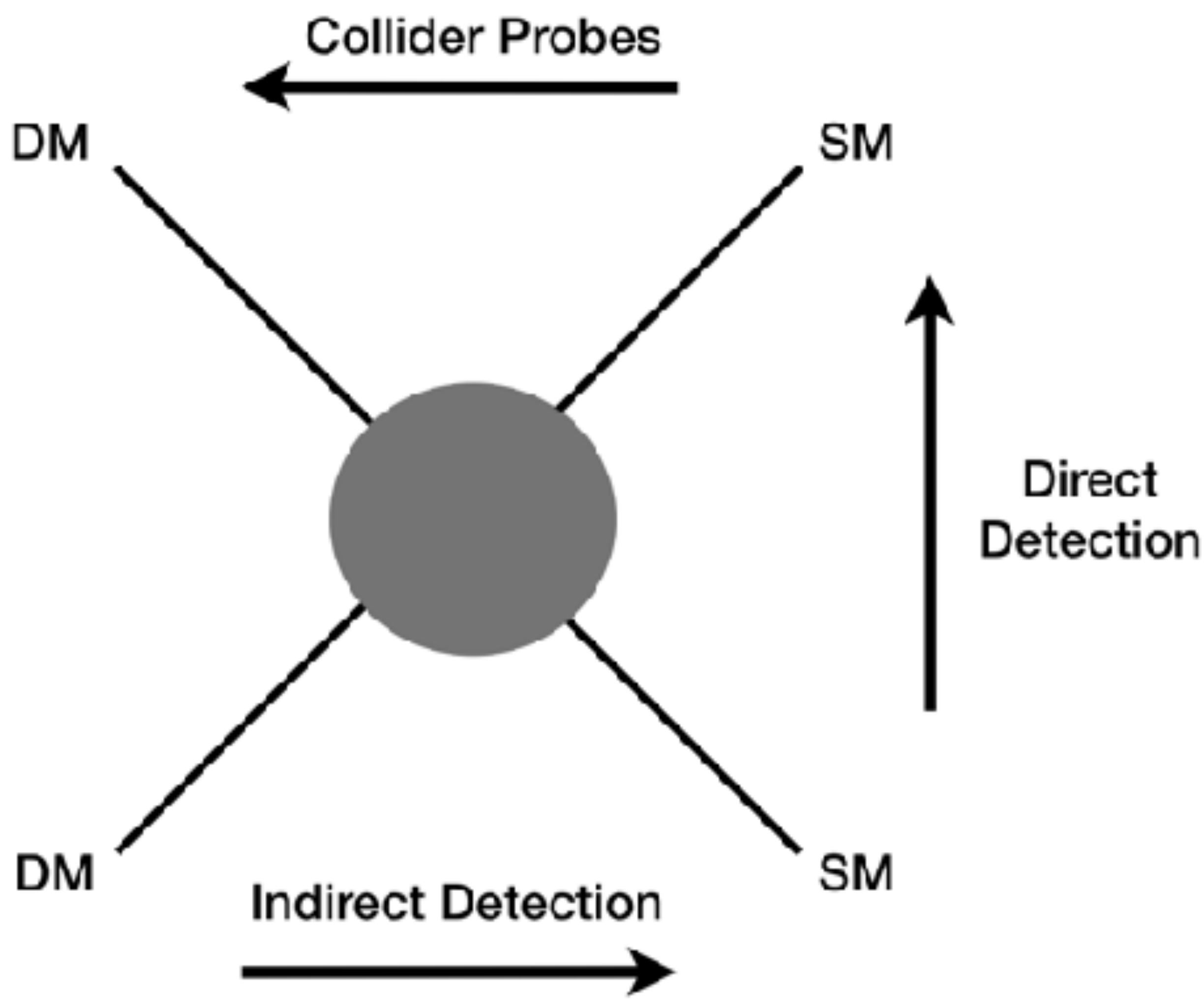
(unlike PBH formation in a thermal universe)

Non-linearity does not guarantee PBH formation!

$$\beta(M) \simeq 2 \times 10^{-2}\, \delta_M^{13/2}$$

(Fraction of density in black holes at Mass scale M)

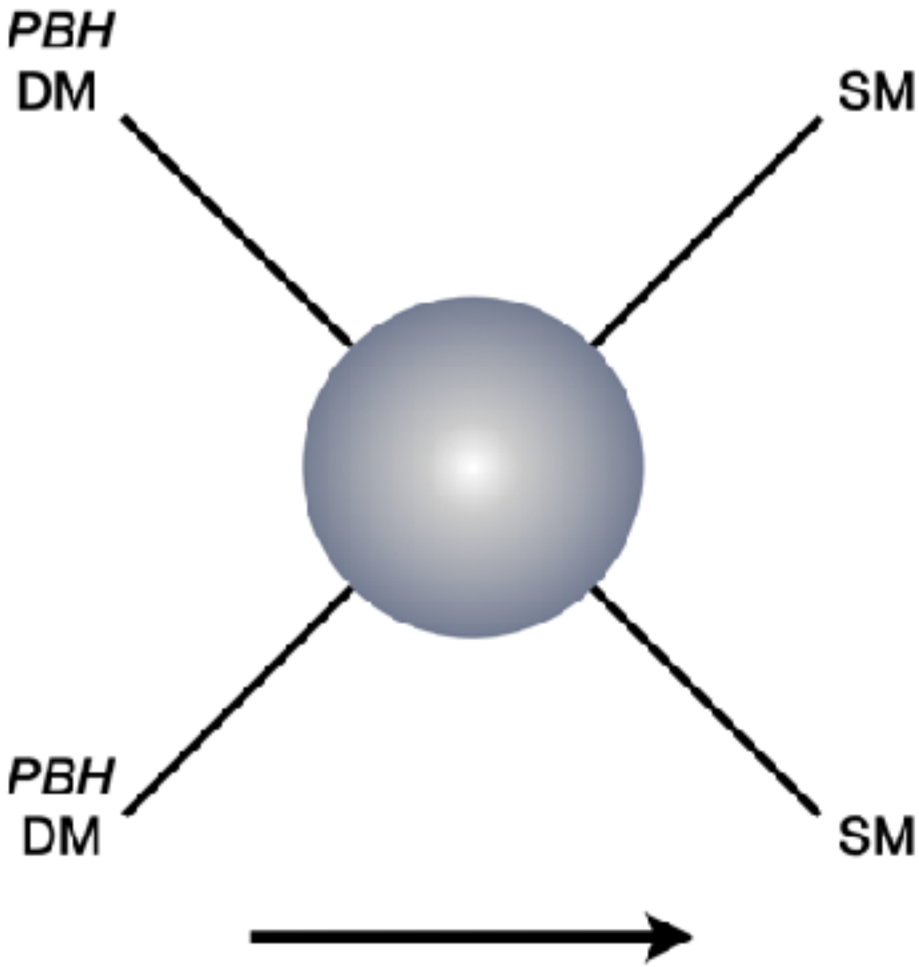
No sign of WIMPs yet



What if dark matter only interacts gravitationally?

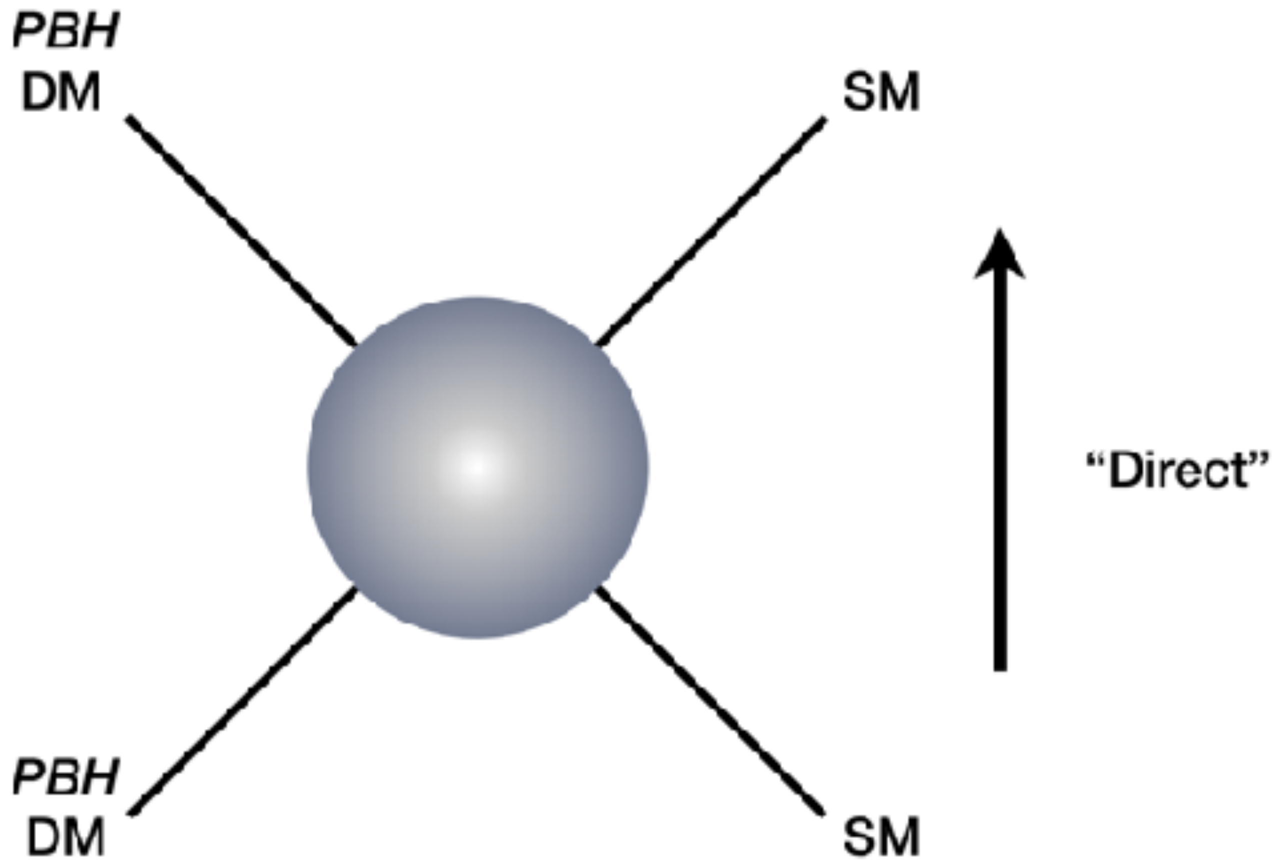
(Ex: Lots of "hidden sectors" in beyond the Standard Model physics)

What if dark matter only interacts gravitationally?
Ex: Primordial Black Holes (PBHs)



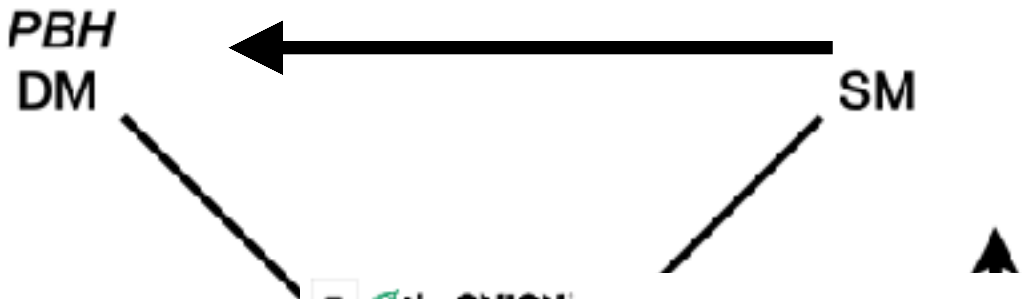
"Indirect": **Gravity Waves**

What if dark matter only interacts gravitationally?
Ex: Primordial Black Holes (PBHs)

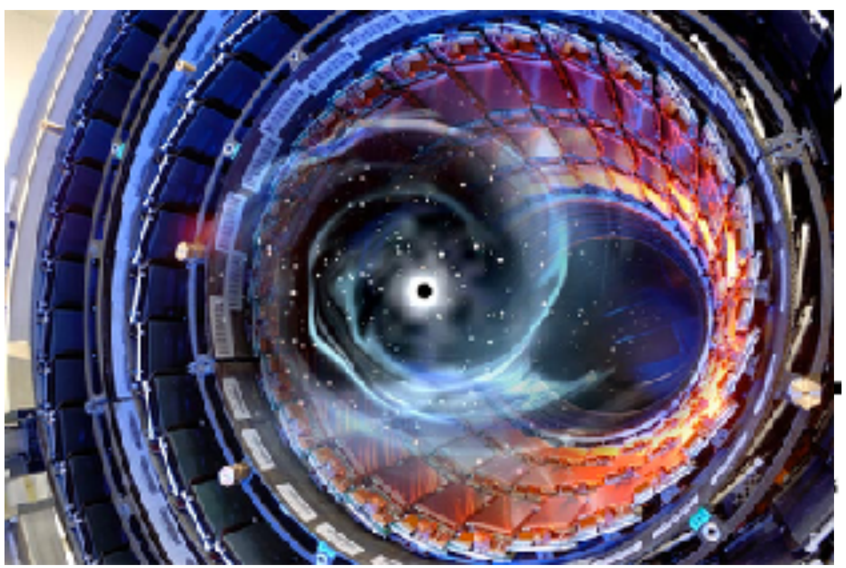


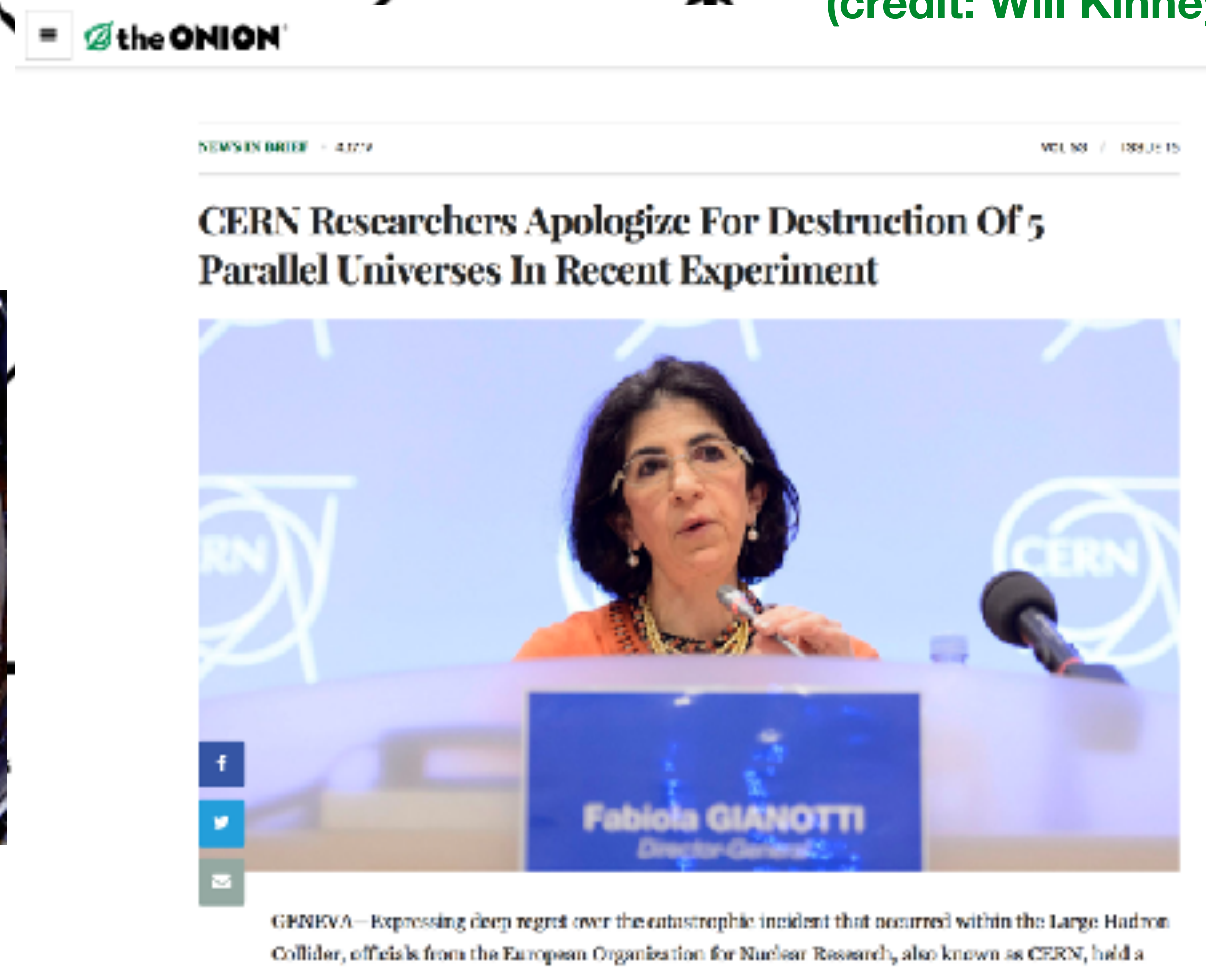
What if dark matter only interacts gravitationally?
Ex: Primordial Black Holes (PBHs)

Collider probes?!



(credit: Will Kinney)



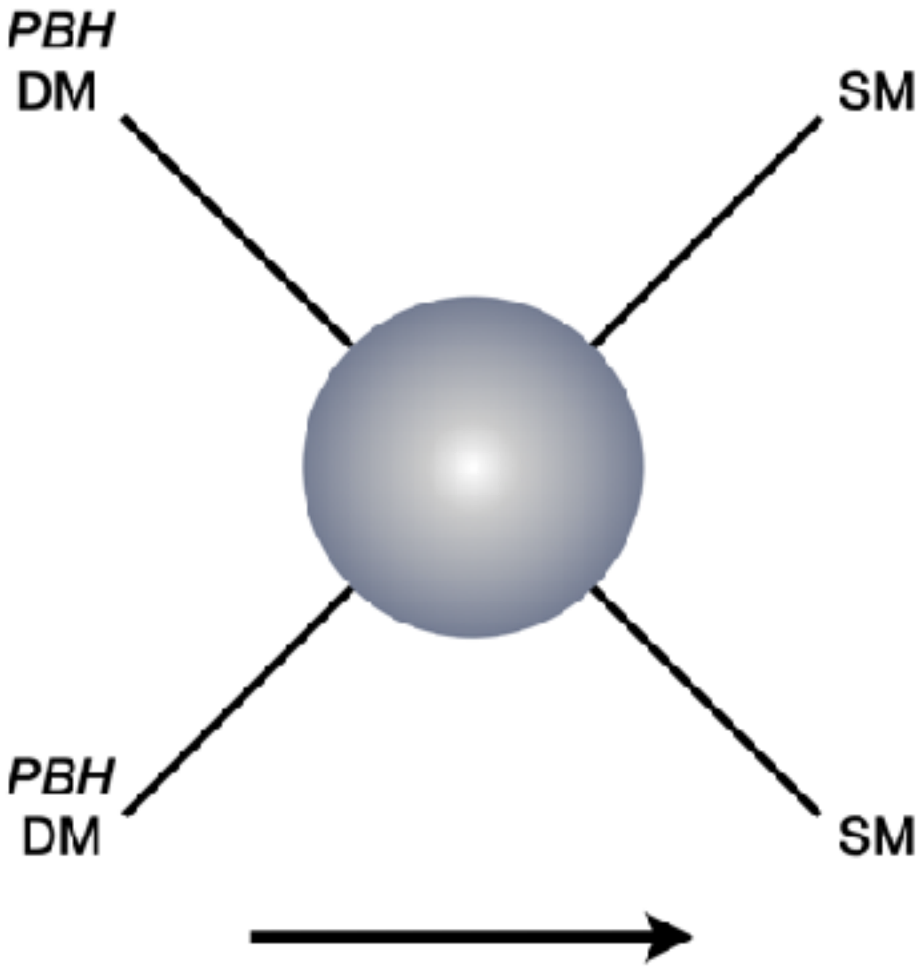

the ONION

NEWS IN BRIEF

CERN Researchers Apologize For Destruction Of 5 Parallel Universes In Recent Experiment

GENEVA—Expressing deep regret over the catastrophic incident that occurred within the Large Hadron Collider, officials from the European Organization for Nuclear Research, also known as CERN, held a

What if dark matter only interacts gravitationally?
Ex: Primordial Black Holes (PBHs)



"Indirect": **Gravity Waves**

5 years of advanced LIGO data (No PBH DM)

(Kovetz et al., arXiv:1611.01157)

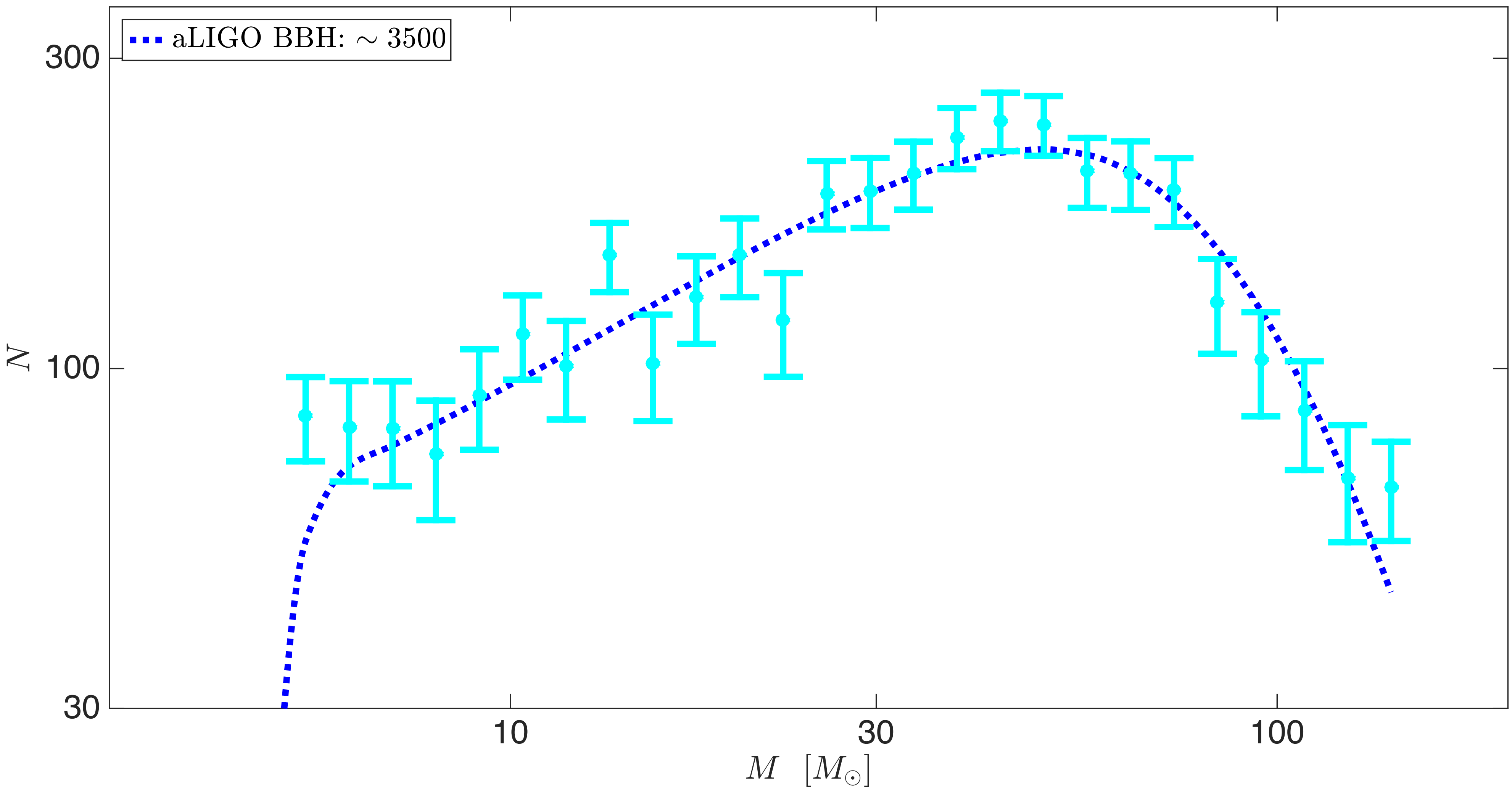


Figure Credit: Ely Kovetz

5 years of advanced LIGO data (with PBH DM)

(Kovetz et al., arXiv:1611.01157)

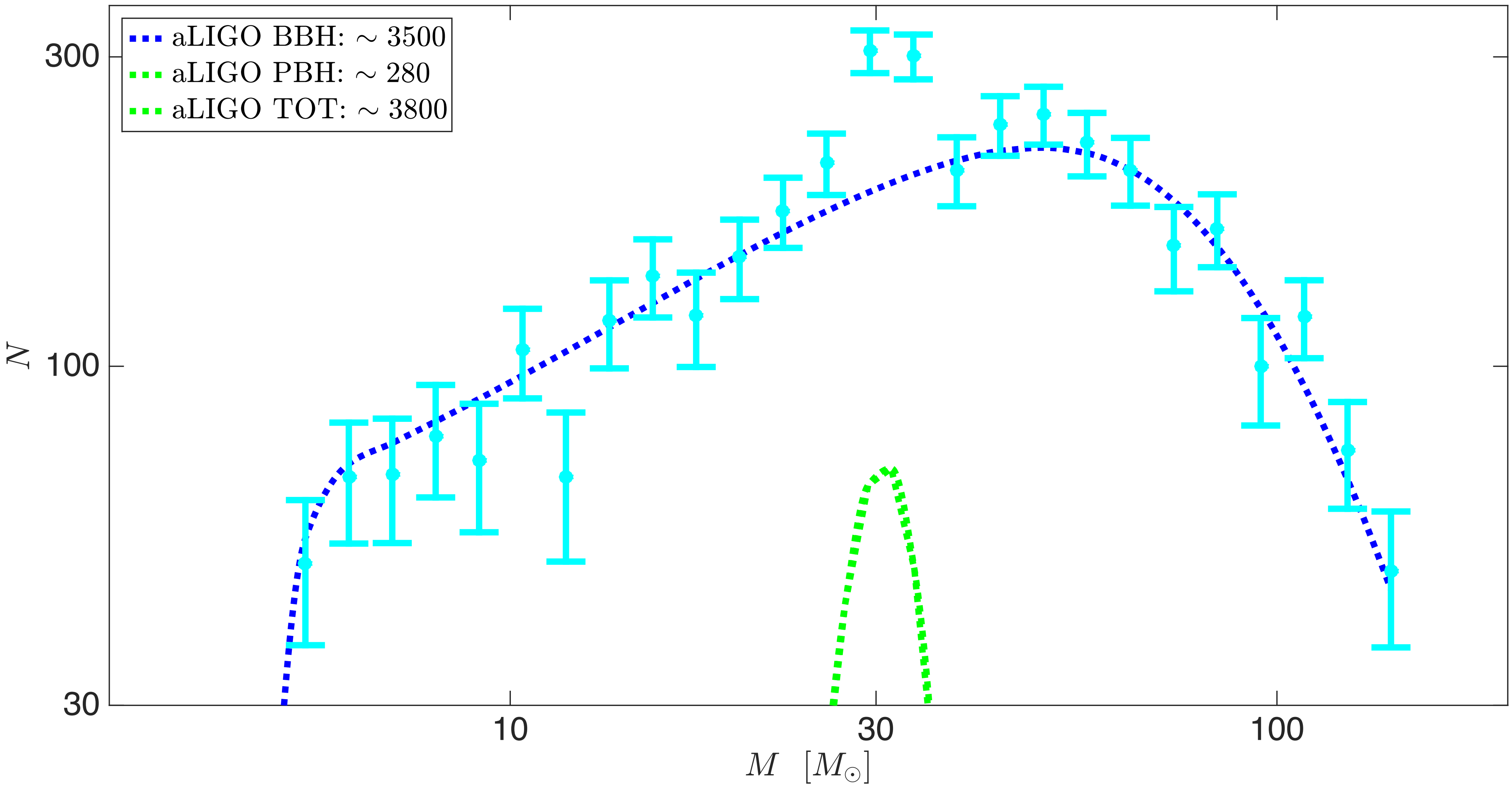
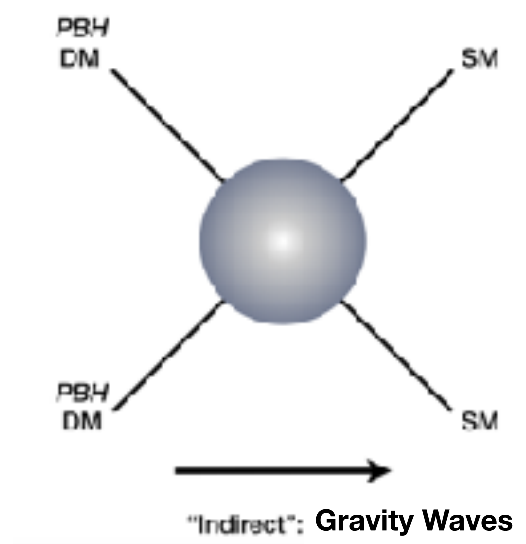


Figure Credit: Ely Kovetz

Indirect Detection of PBH dark matter



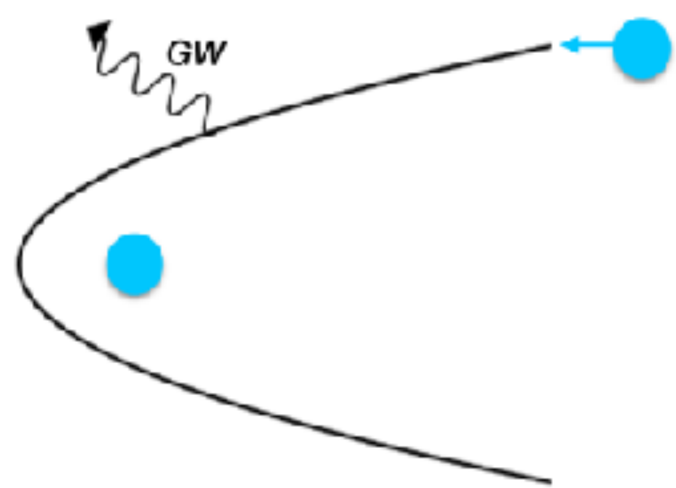
- **No EM or neutrino counterparts**
  Difficult for stars to form in low mass halos
  None have been found so far
  (~70 follow-ups to date)

- **A Stochastic GW background**
  Mundic, Bird & Cholis arXiv:1608.06699

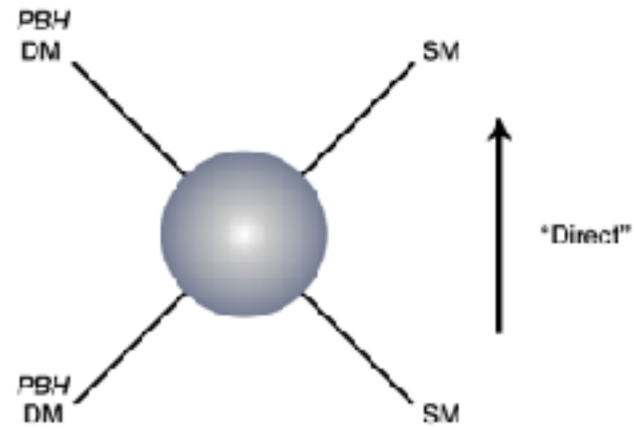
- **Originate in low mass halos**
  Cross-correlate with galaxy surveys

- **Traces of High Eccentricities**
  Cholis et al., Phys. Rev. D94 (2016)

$$Rate = \frac{1}{2} n_{pbh}^2 \langle \sigma v_{pbh} \rangle$$



Direct Detection of PBH dark matter



Fast Radio Bursts (FRBs)
(Muñoz, Kovetz, Dai, Kamionkowski, PRL 117 (2016))

Extra-galactic origin

milli-second bursts

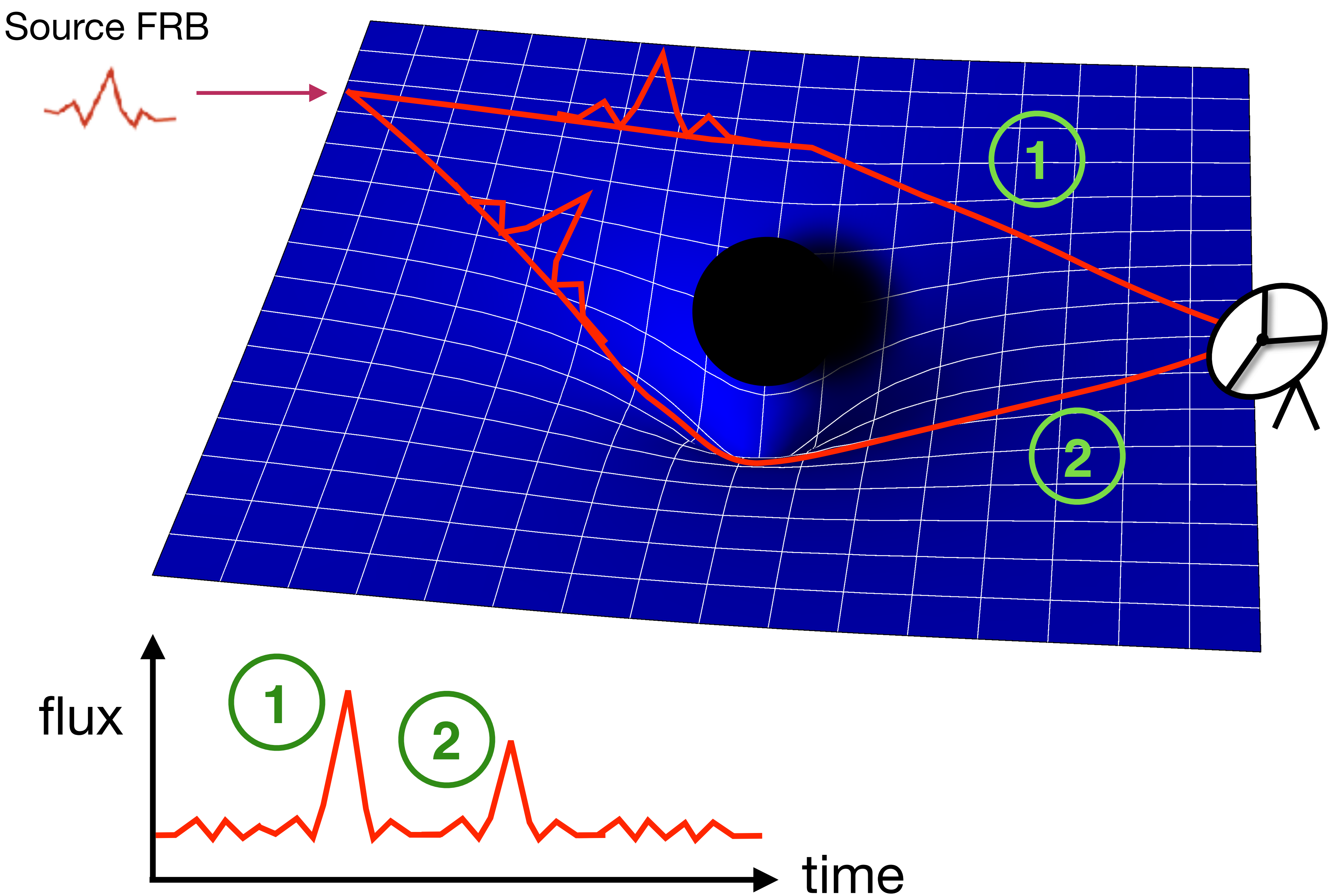
Ghz frequencies

CHIME expected to observe 10,000 events per year (10 - 100 lensed by PHBs)

"First light" this past September

Constraining PHB Dark Matter: FRB Lensing

(Muñoz, Kovetz, Dai, Kamionkowski, PRL 117 (2016))

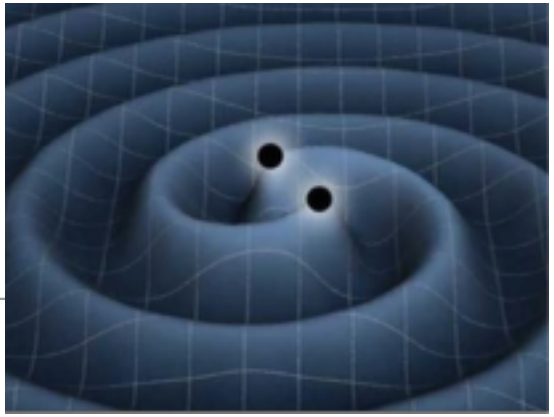


Credit: Ely Kovetz

Dark matter interpretation will be tested in near-term experiments

Did LIGO see PBH Dark Matter?

1603.00464 Bird, et. al.



"GW150914"

LIGO detected a gravity wave signal consistent with the merger of two $\sim 30\ M_\odot$ Black holes at around a 1.3 billion Lyr away

How did this mass become favored?

Dark Matter Interpretation

$$20\ M_\odot \lesssim M \lesssim 100\ M_\odot$$

Lensing (improved)

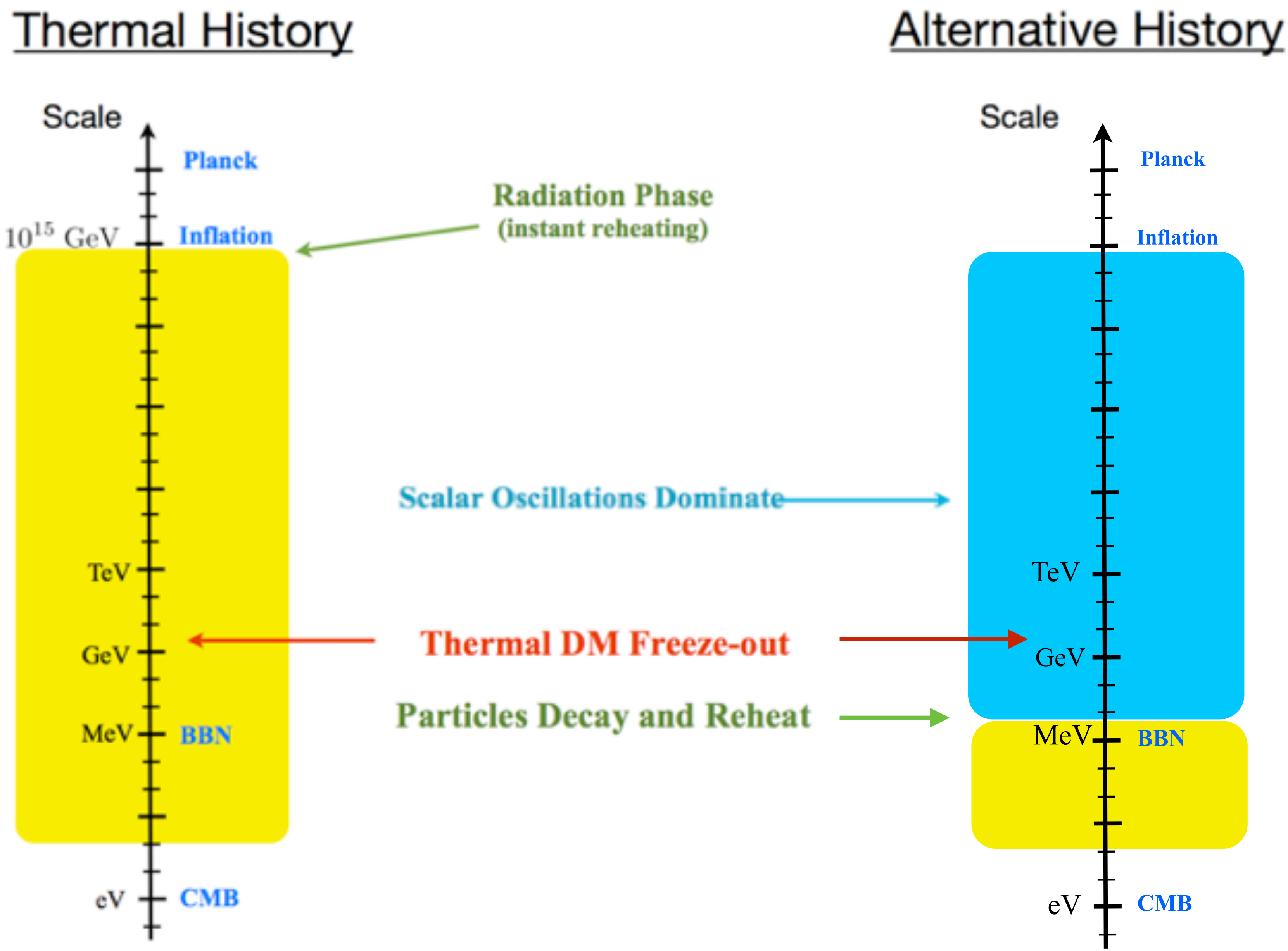
Disrupt Wide Binaries (perhaps CMB as well)

LIGO observation lies in the window where MACHOs are still viable to be all of the dark matter.

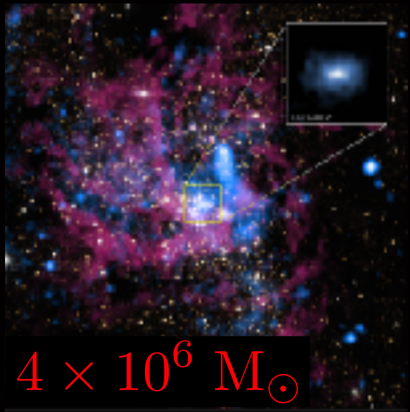
Constraints weaken if PBHs are not all of the dark matter.

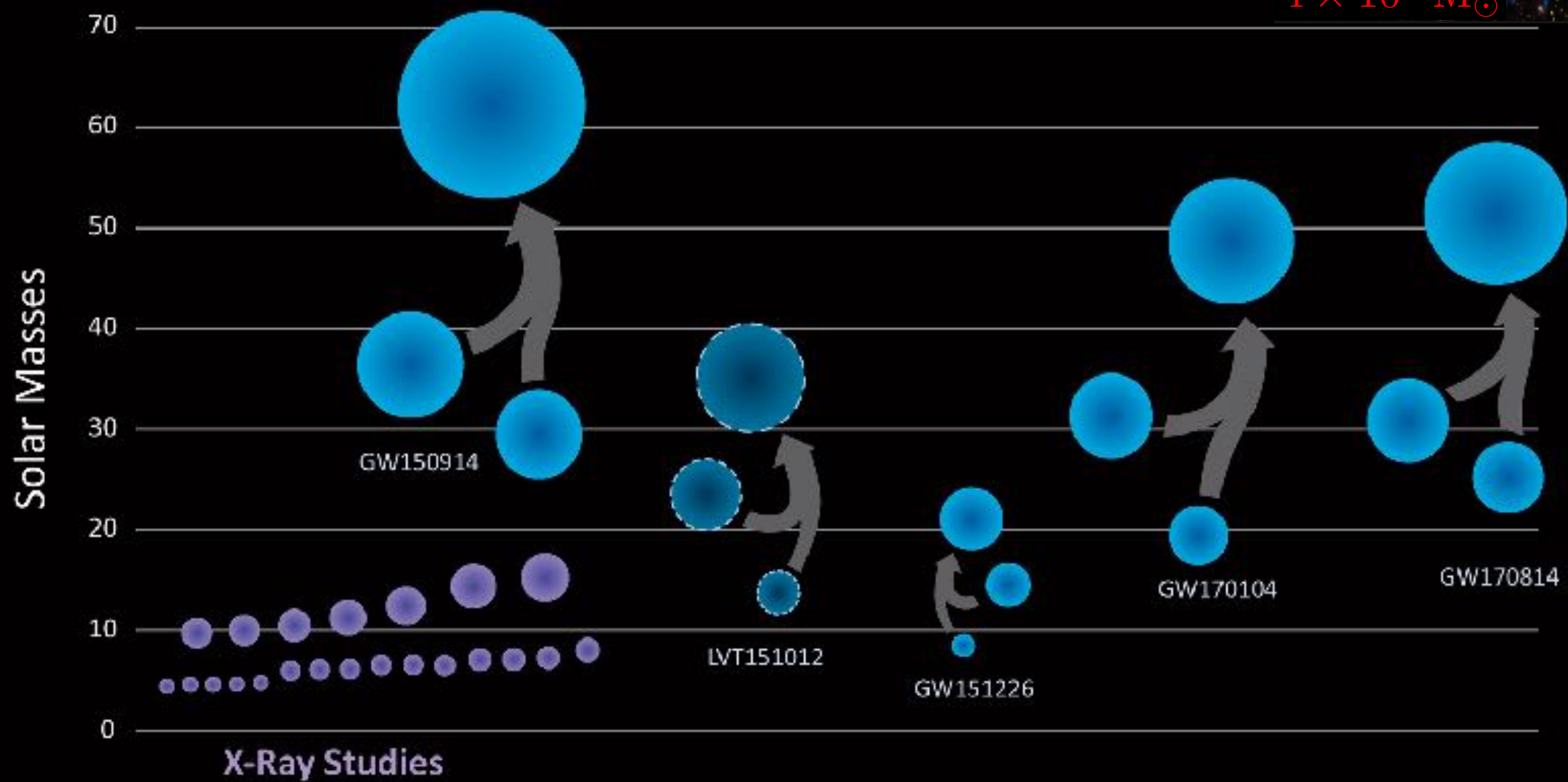
1603.08338 Sasaki, et. al.;

When / how did the universe thermalize?



Black Holes of Known Mass





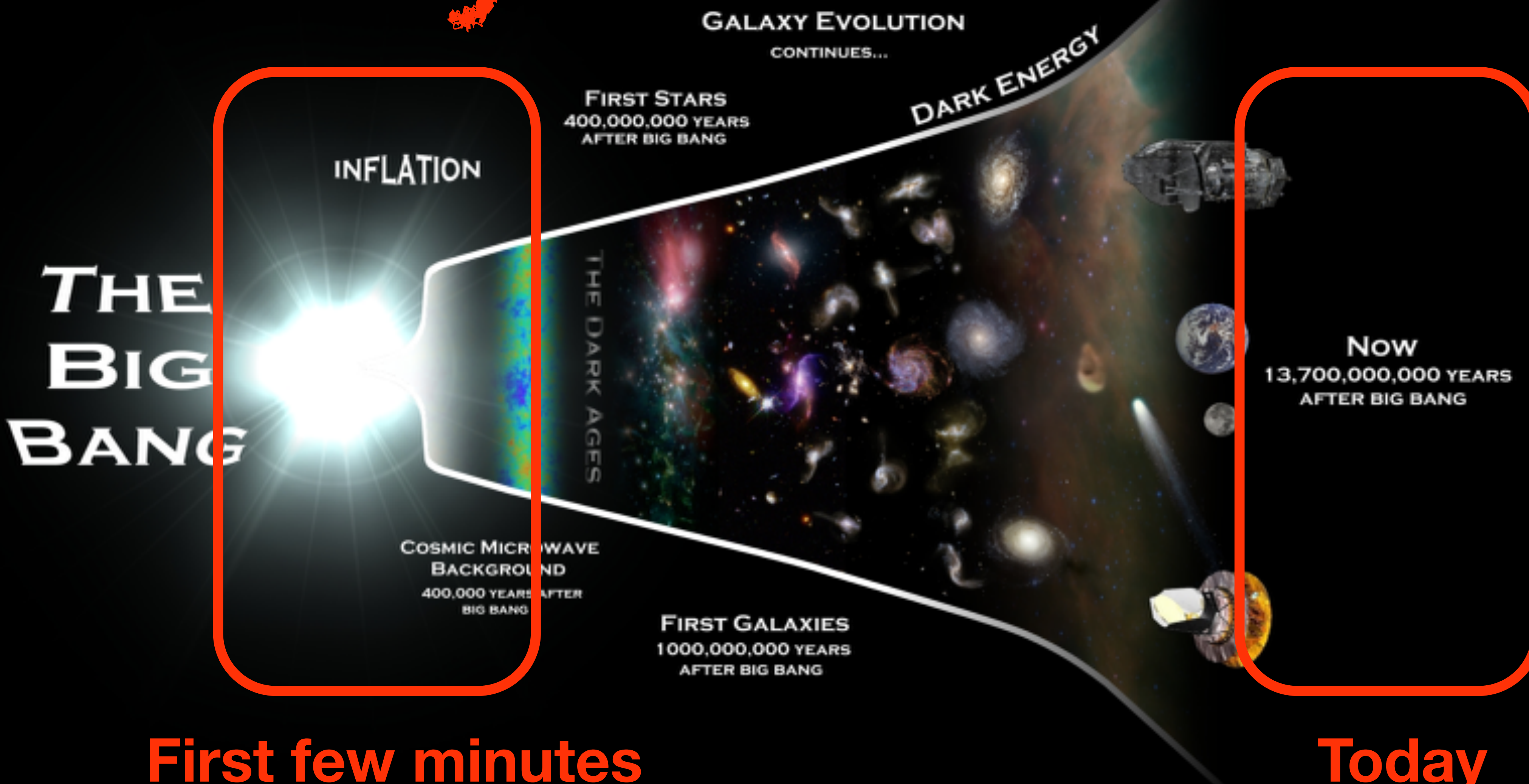
LIGO/VIRGO

Perhaps it is time to rethink about dark matter and its detection!

The Cosmological Standard Model

Today's talk

?



First few minutes

Today

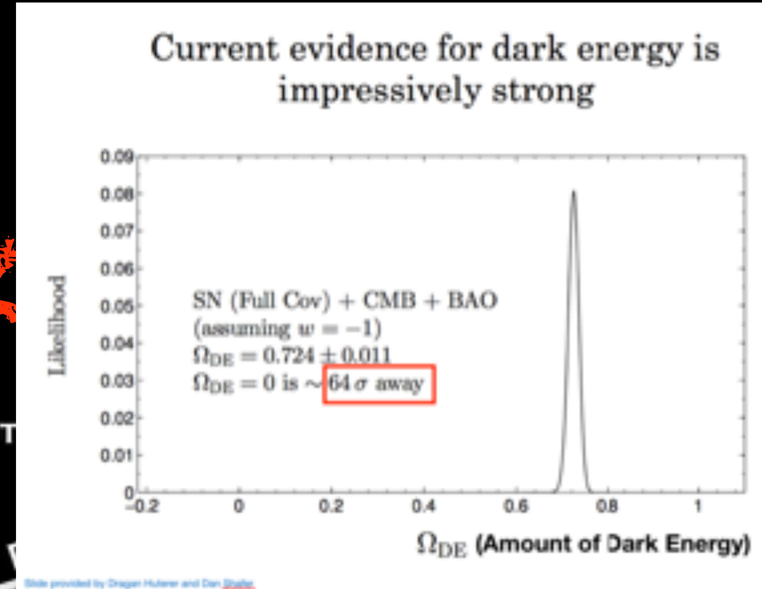
Thank you for coming.

Thank you for coming.

(joke)

2011 Nobel Prize

andard

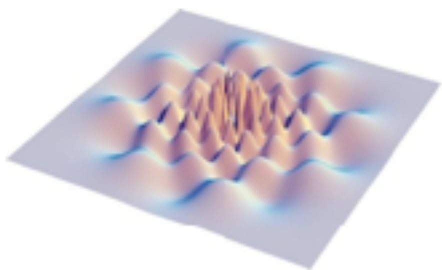


Today

The Universe is accelerating today!

Is the Dark Energy a Cosmological Constant?

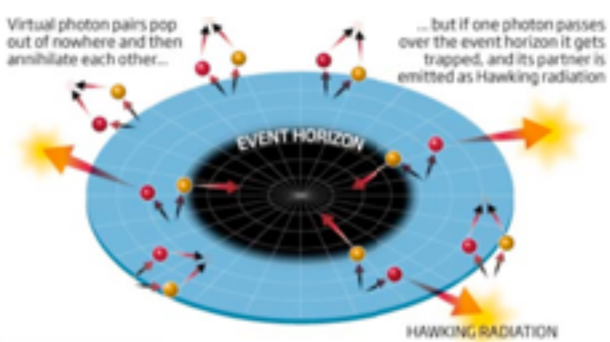
We expect space-time to contain quantum fluctuations



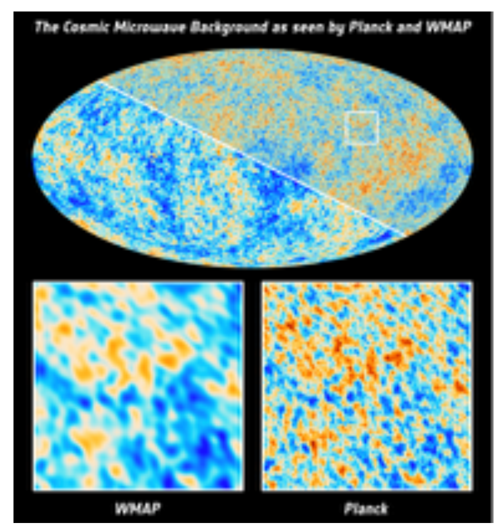
Our “Lab”

Stephen is still at work!

Hawking radiation from Black Holes



Inflationary Fluctuations

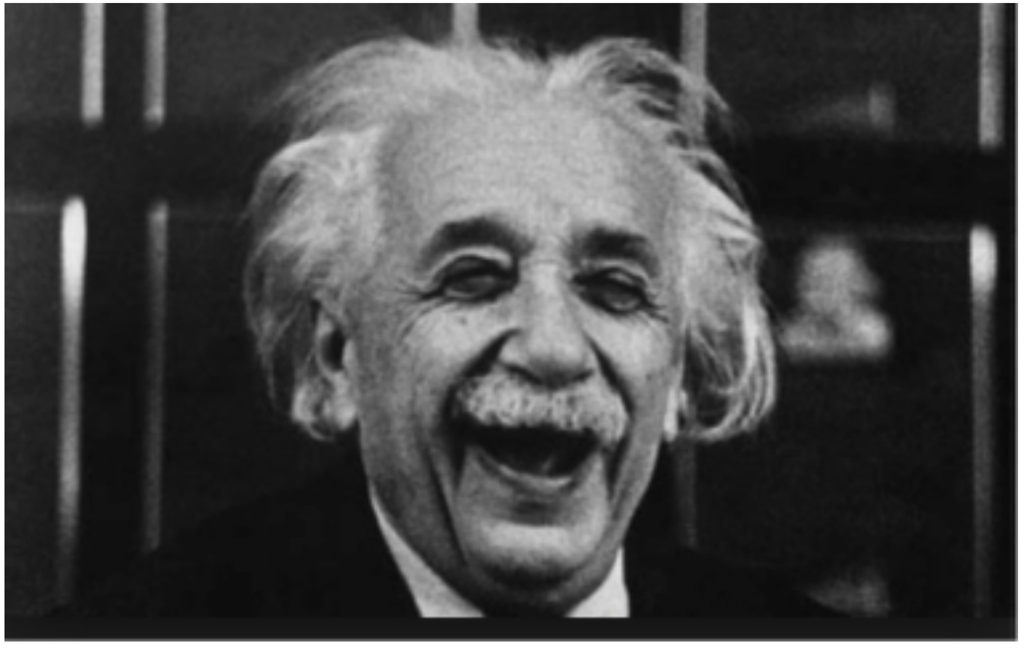


Could vacuum fluctuations be causing the acceleration?

The Cosmological Constant Problem

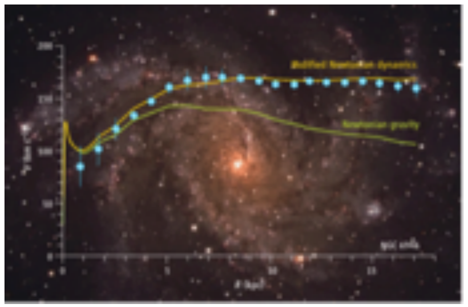
$$\left(\frac{\Lambda_{\mathrm{observed}}}{m_p}\right)^4 \simeq 10^{-120}$$

Could vacuum fluctuations be causing the acceleration?



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

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



Modified Gravity?

Time varying constants?

New forms of matter or energy?

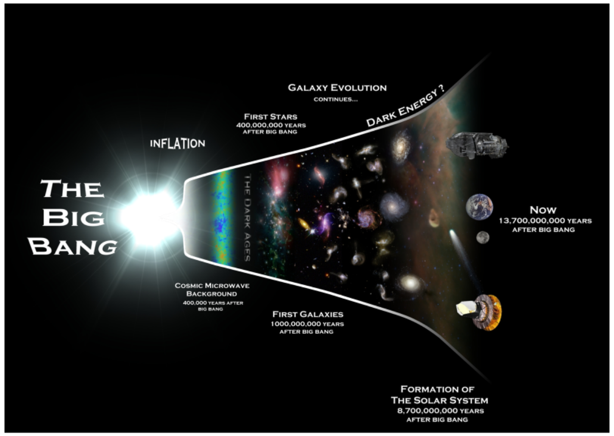
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_{\mathrm{N}} T_{\mu\nu}$$

Space-time evolution **Matter and Energy**

Λ ?

The Effective Field Theory of Cosmic Acceleration

with E. Linder and G. Sengor [JCAP 1605 (2016)]
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

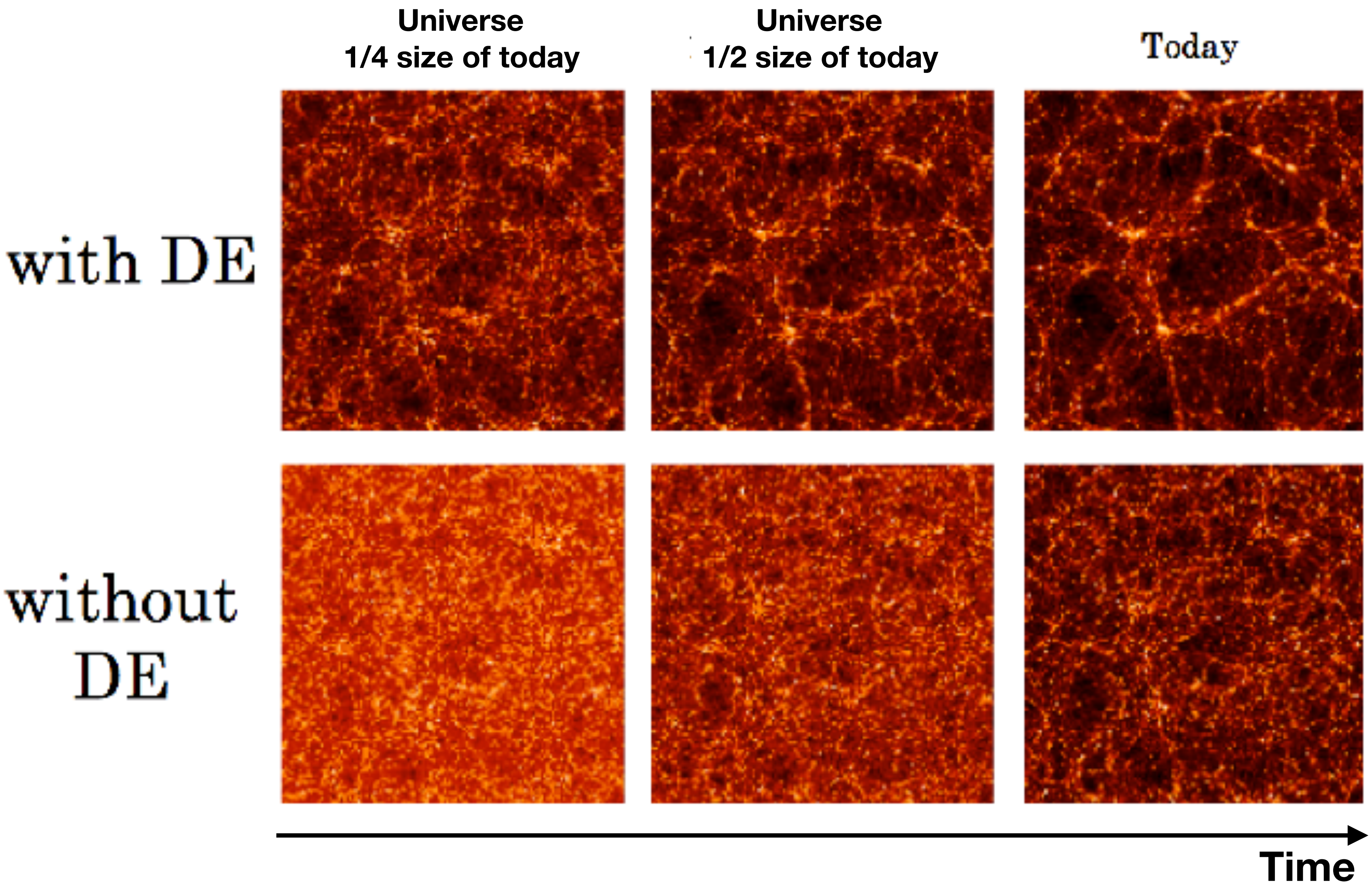
$$\mathcal{L}_{\rm eff} = -\frac{f_\pi}{2}\partial_\mu U \cdot \partial^\mu U^\dagger + c_1 \left(\partial_\mu U \cdot \partial^\mu U^\dagger\right)^2 + \ldots$$

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

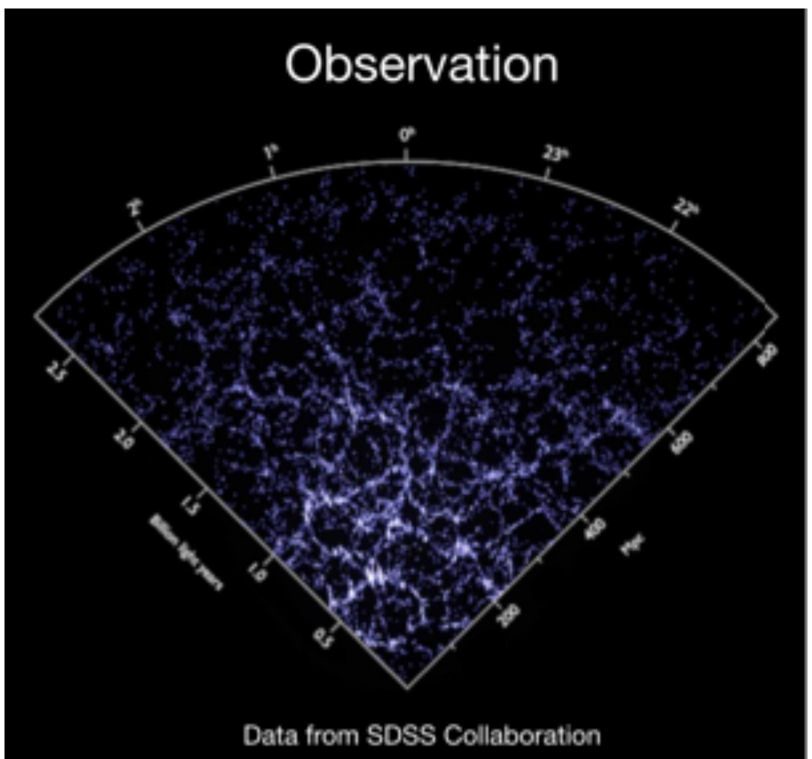
The Virgo Consortium (1996)

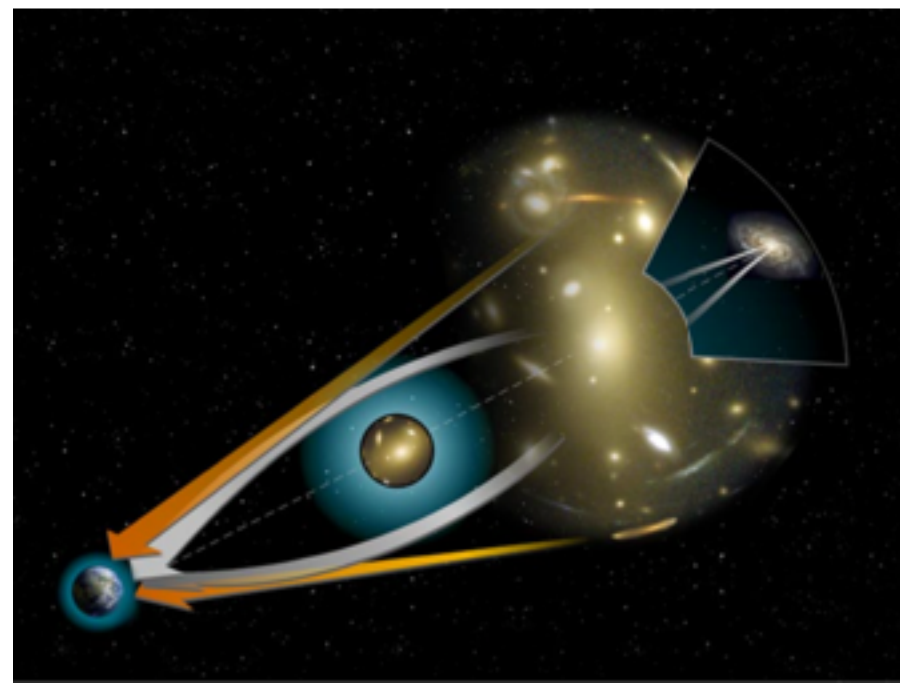
Constraints on the EFT of Cosmic Acceleration

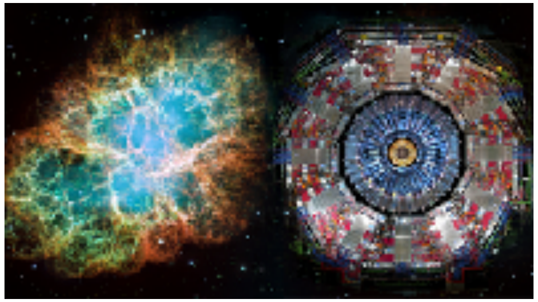
$$ds^2 = -\left(1 + 2\Phi\right) dt^2 + a^2 \left(1 - 2\Psi\right) d\vec{x}^2$$

Φ Growth of Structure

$\Phi + \Psi$ Gravitational Lensing



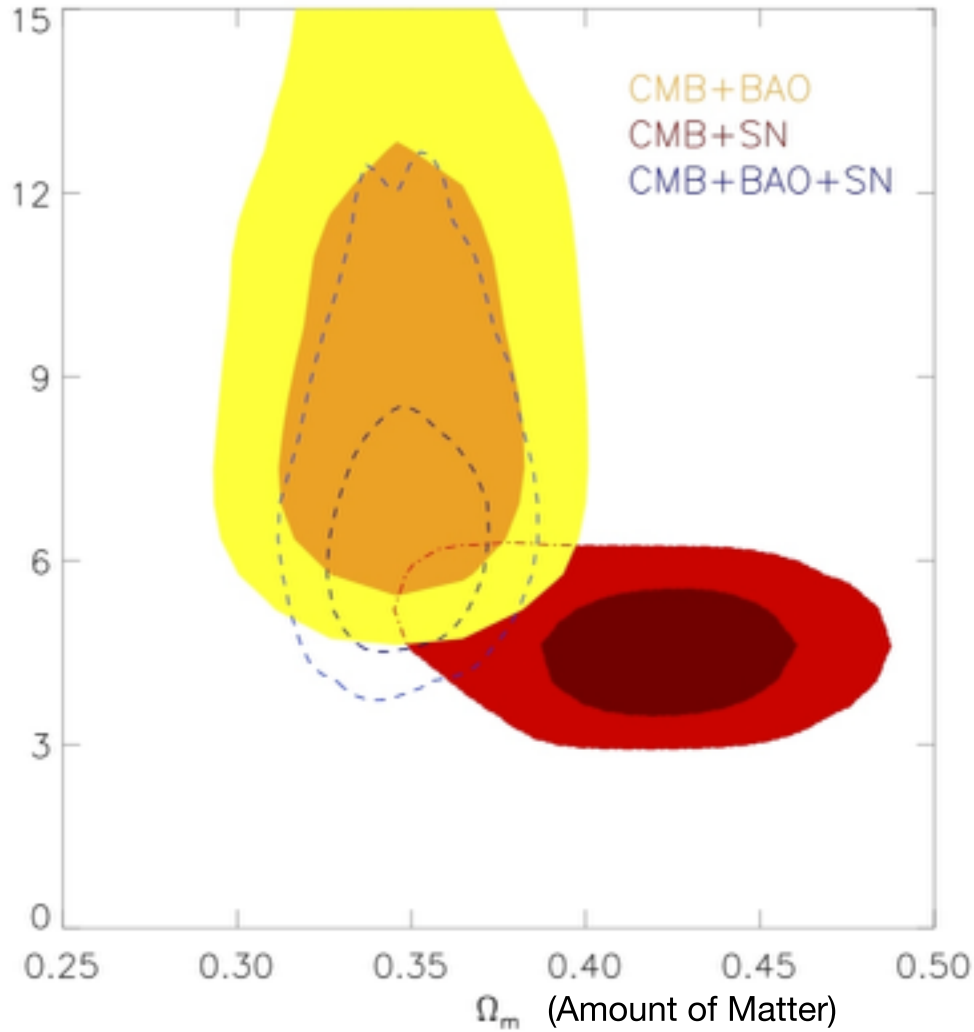




A Unified Approach to Cosmic Acceleration

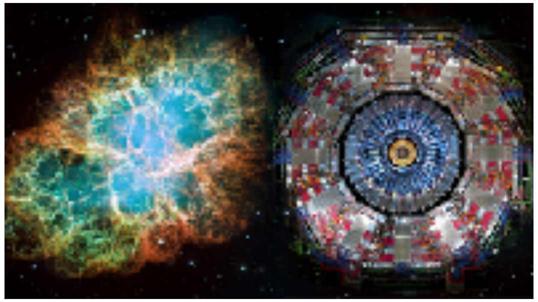
with E. Linder and G. Sengor [JCAP 1605 (2016)]
with J. Bloomfield, E. Flanagan, and M. Park [JCAP 1308 (2013)]
with R. Bean and E. Mueller [Phys. Rev. D87 (2013)]
with M. Park and K. Zurek [Phys. Rev. D81 (2010)]

Strength of Gravity Modification



R. Bean, E. Mueller, and S. Watson [Phys. Rev. D87 (2013)]

A Unified Approach to Cosmic Acceleration



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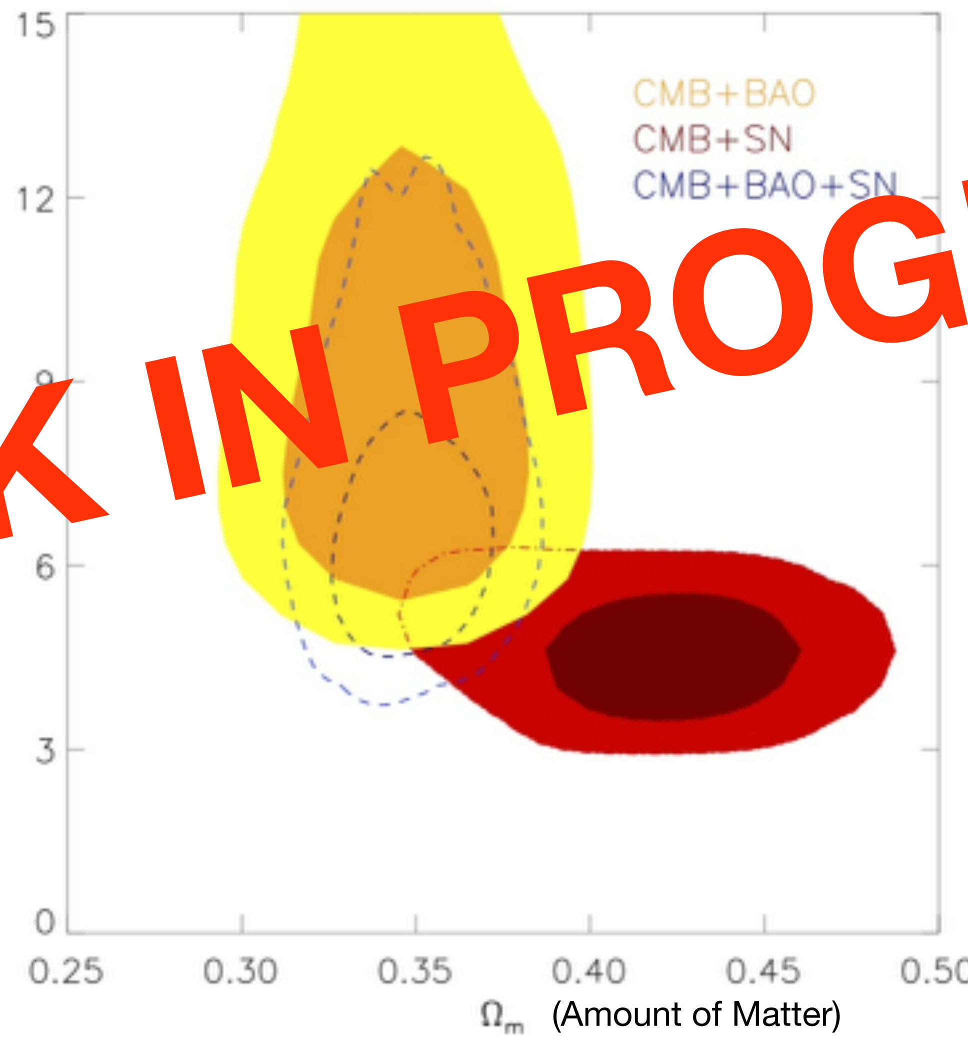


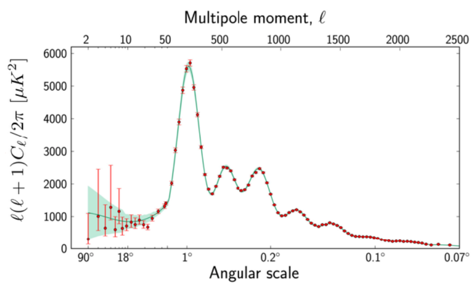
WORK IN PROGRESS

R. Bean, E. Mueller, and S. Watson [Phys. Rev. D87 (2013)]

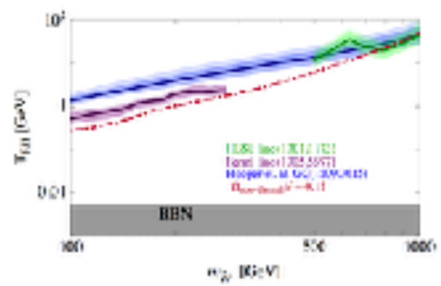
Summary: State of the Universe

What has changed since my last visit?

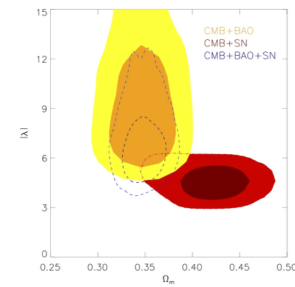
Data has dramatically improved helping to focus model building.



Inflation

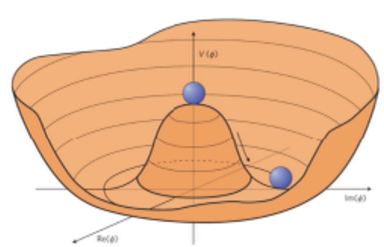


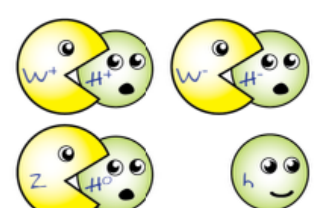
Dark Matter



Dark Energy

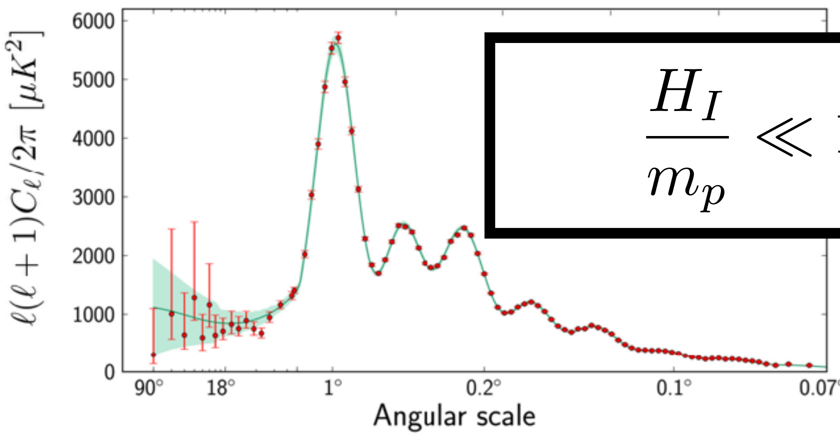
We have developed powerful techniques that utilize symmetries to establish <u>universal</u> properties of models.
This approach isolates model dependent parameters, which can be determined through a combination of theoretical and observational efforts.





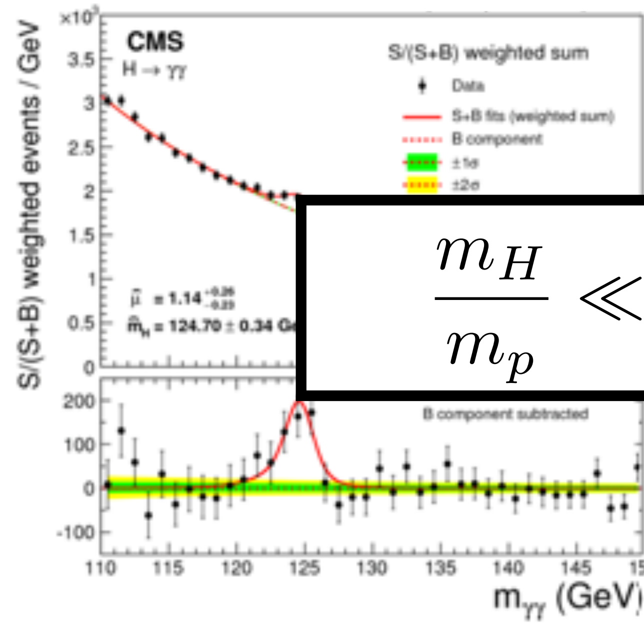
Big questions remain… the hierarchy problem has many faces.

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



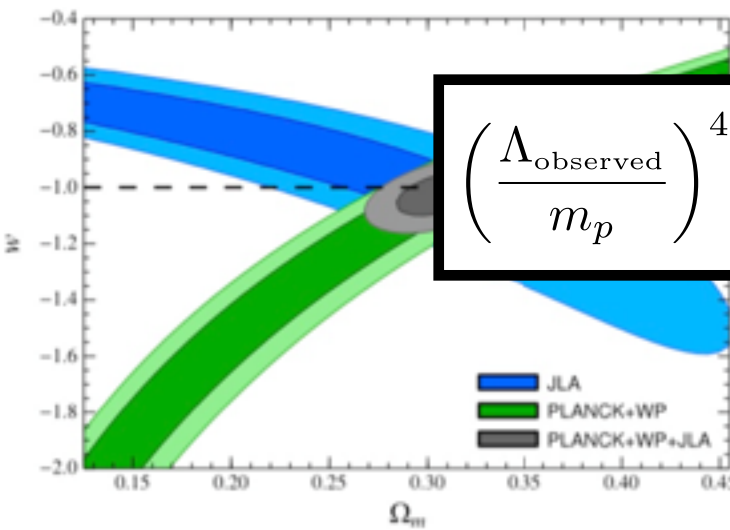
$$\frac{H_I}{m_p} \ll 1$$

Why is the Higgs light?



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

Why is the Cosmological Constant small?



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

Exciting time for cosmology and physics beyond the standard model!

Thank you for your time.

And thanks to these people…

Cosmology group at Syracuse


Julian Georg


Brandon Melcher


Eva Nesbit


Kenneth Ratliff


Gizem Sengor

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