Two Lectures on

The Standard Cosmology

Rocky Kolb—University of Chicago

The Program

Rocky I

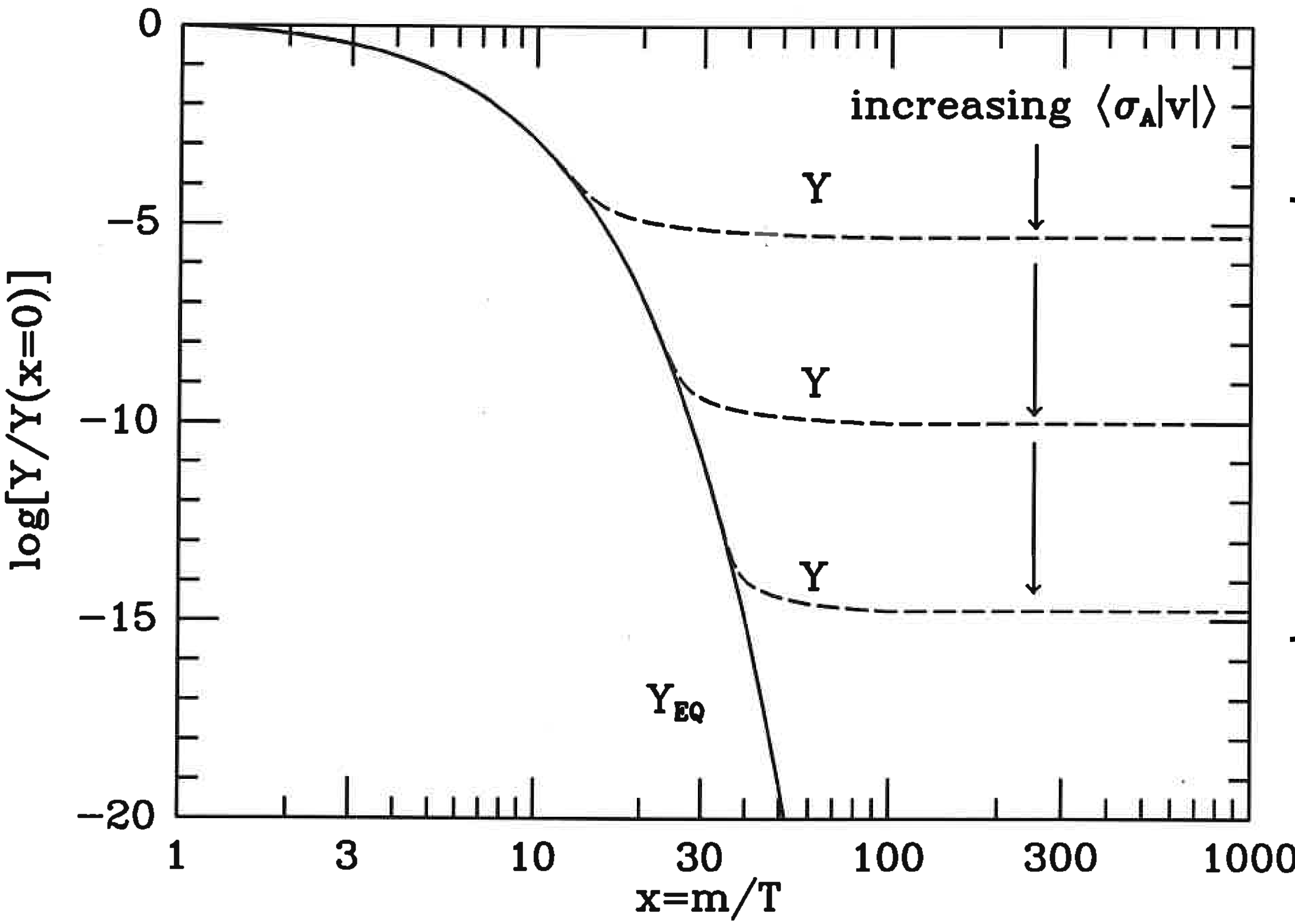
The Universe Observed
Energy and pressure
The Friedmann equation
<u>Primordial</u> origin of Dark Matter[#]

Rocky II

Finish Dark Matter
Primordial Inflation
Baryo/Leptogenesis
CMB[*] [†]
Dark Energy

[#] Matt Pyle
* Adrian Lee
[†] Dave Schlegel

Freeze Out of a Cold Thermal Relic

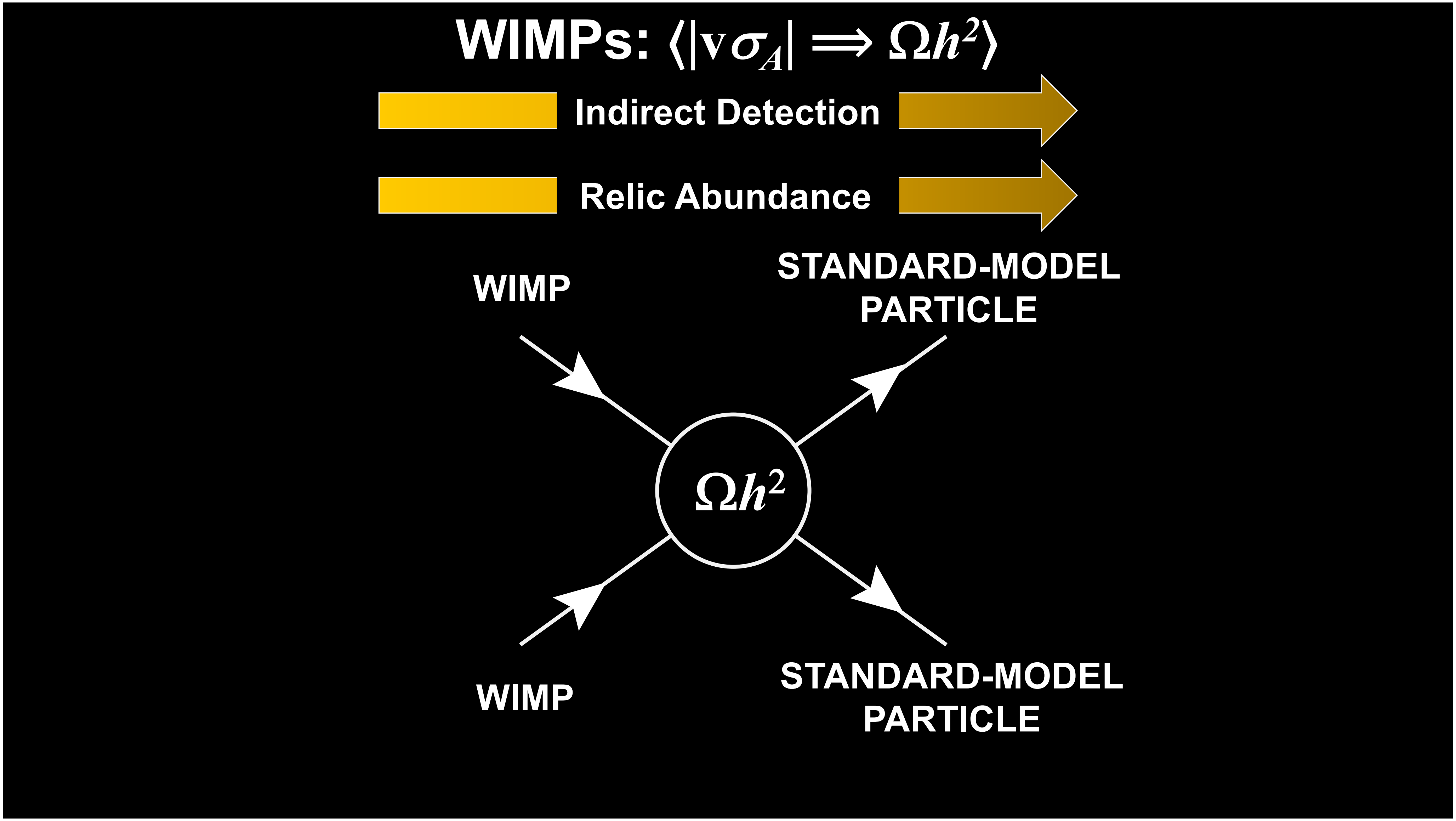


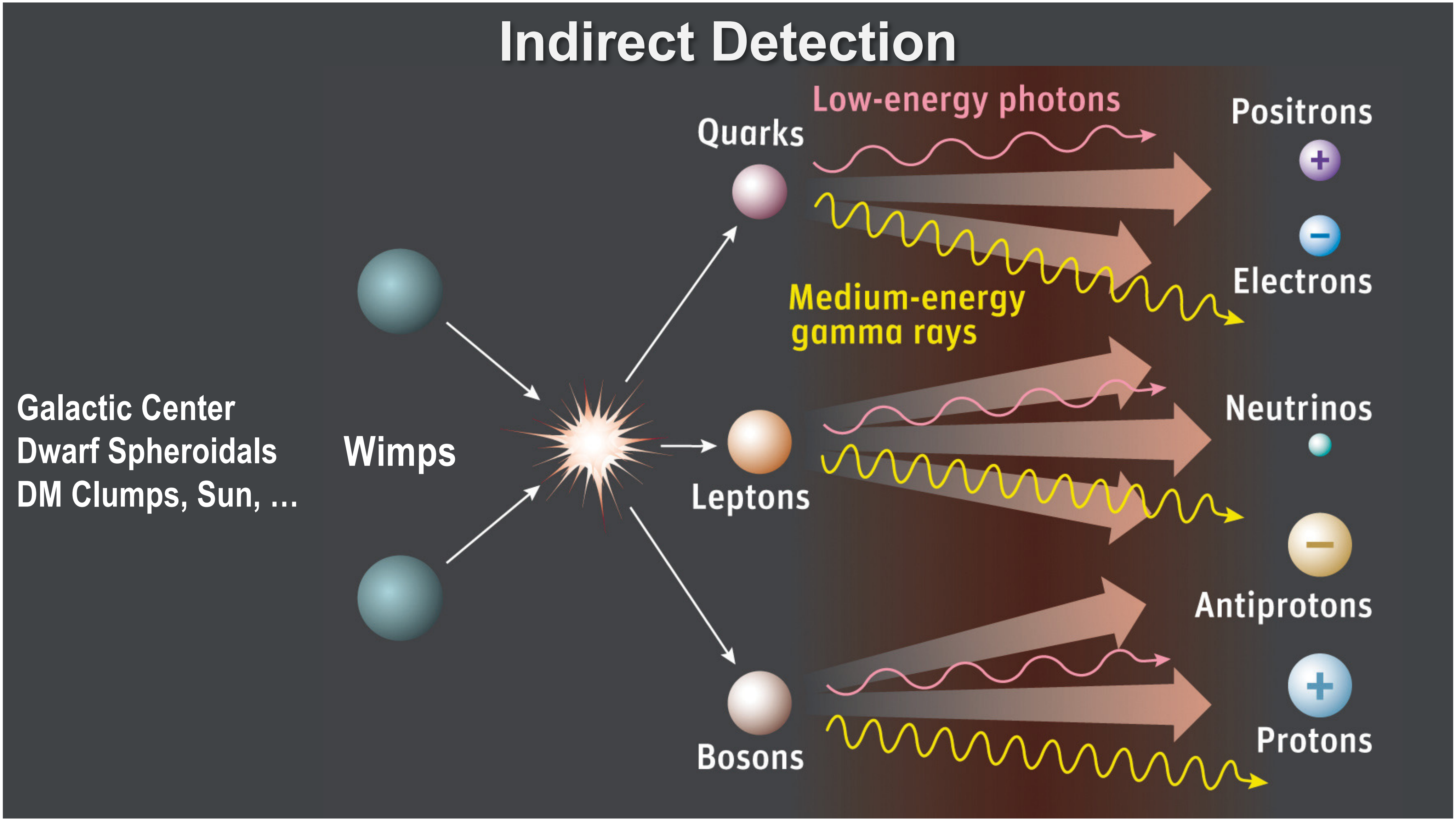
$$Y_\infty \propto \frac{1}{m m_{\rm Pl} \langle \sigma_A | v_{\rm Moller} | \rangle}$$

Freeze-out value of Y determines present mass density

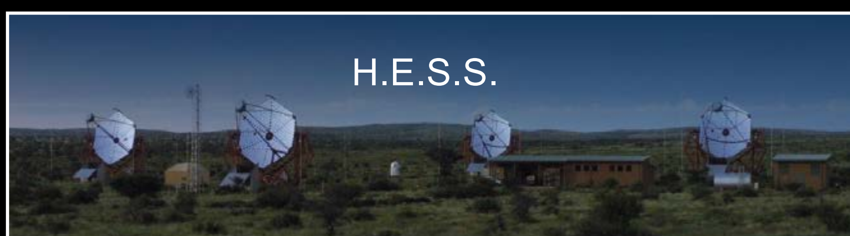
$$\Omega \propto m Y_\infty$$

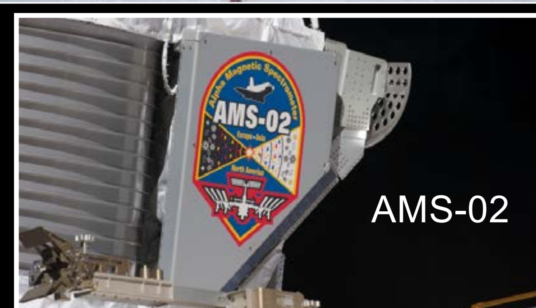
$$\propto \frac{1}{\langle \sigma_A | v_{\rm Moller} | \rangle}$$

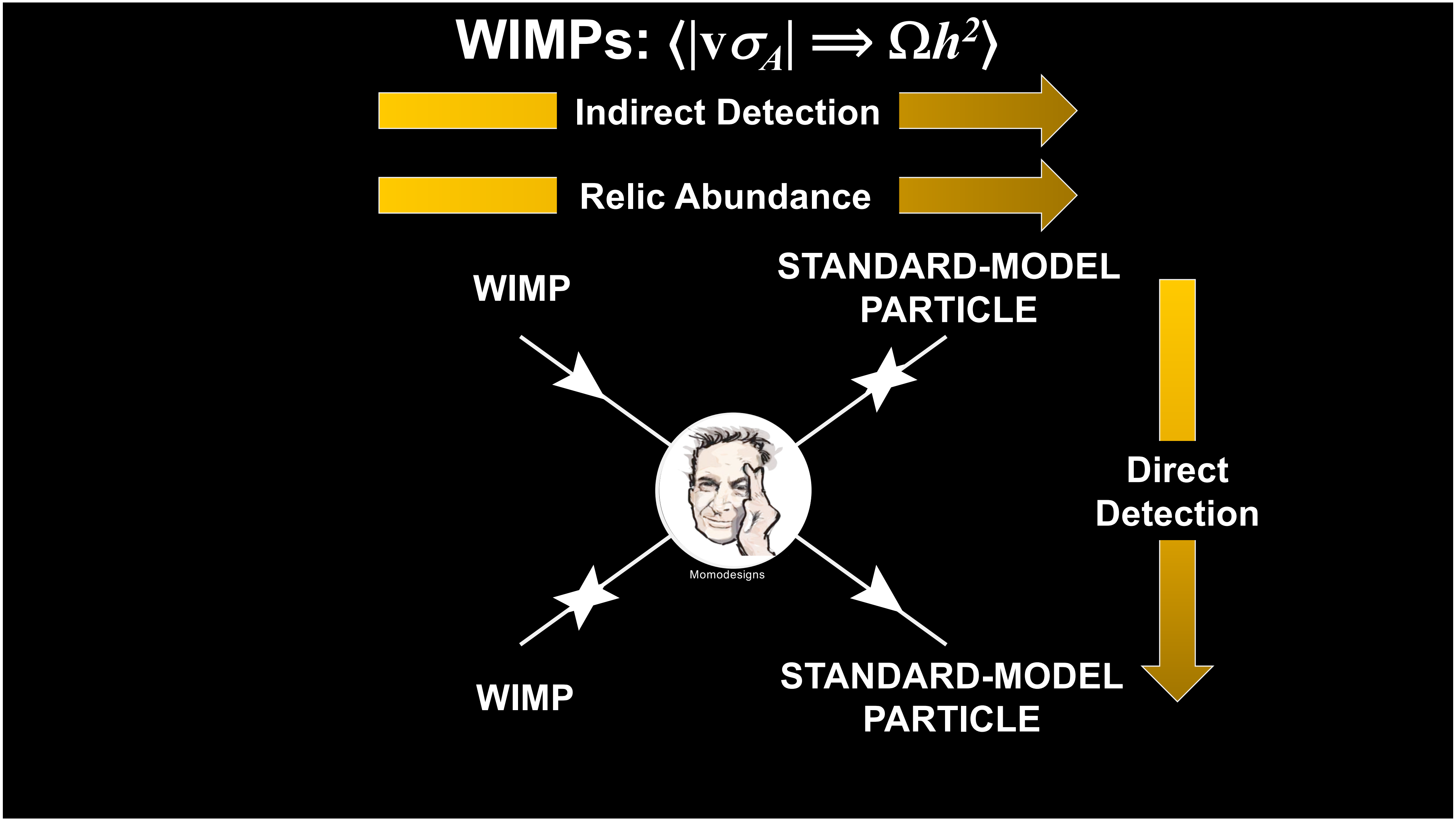

WIMPs: $\langle |v\sigma_A| \Longrightarrow \Omega h^2 \rangle$
Indirect Detection
Relic Abundance
WIMP
STANDARD-MODEL PARTICLE
Ωh^2
WIMP
STANDARD-MODEL PARTICLE


Indirect Detection
Galactic Center
Dwarf Spheroidals
DM Clumps, Sun, ...
Wimps
Quarks
Leptons
Bosons
Low-energy photons
Medium-energy gamma rays
Positrons
Electrons
Neutrinos
Antiprotons
Protons

Indirect Detection

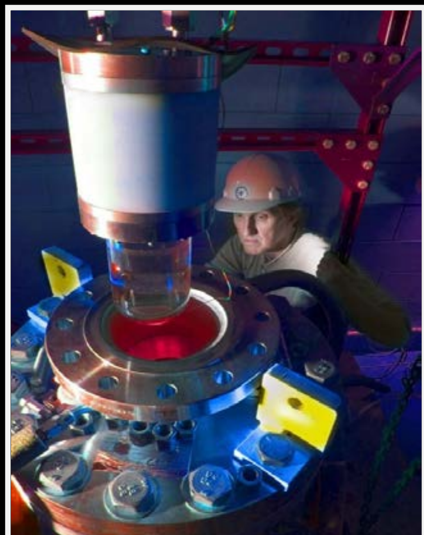




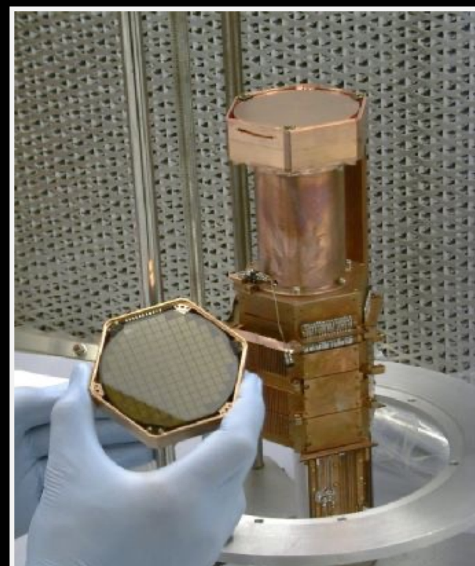

WIMPs: $\langle|v\sigma_A| \Longrightarrow \Omega h^2\rangle$
Indirect Detection
Relic Abundance
WIMP
STANDARD-MODEL PARTICLE
Direct Detection
Momodesigns
WIMP
STANDARD-MODEL PARTICLE

Direct Detection (Matt Pyle)

COUPP



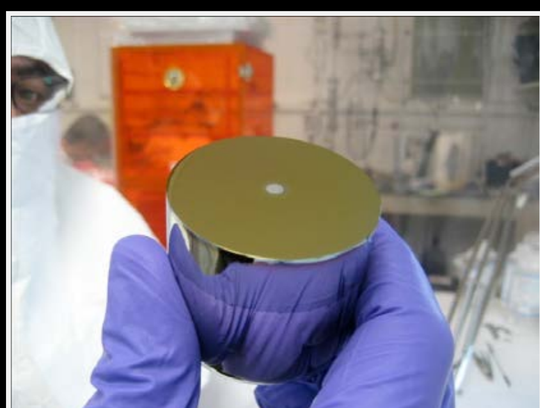
CDMS



CRESST

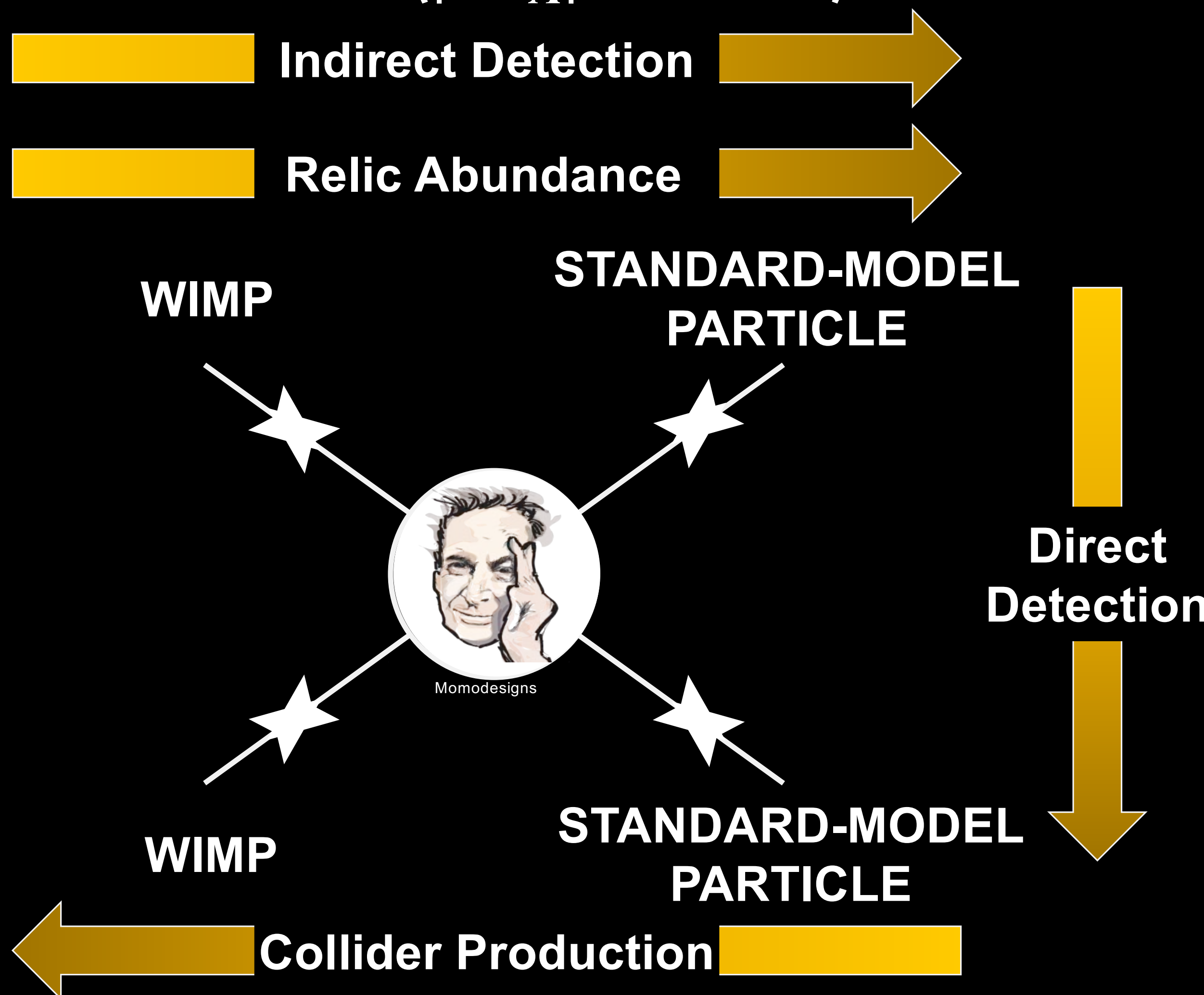
Xenon

CoGeNT

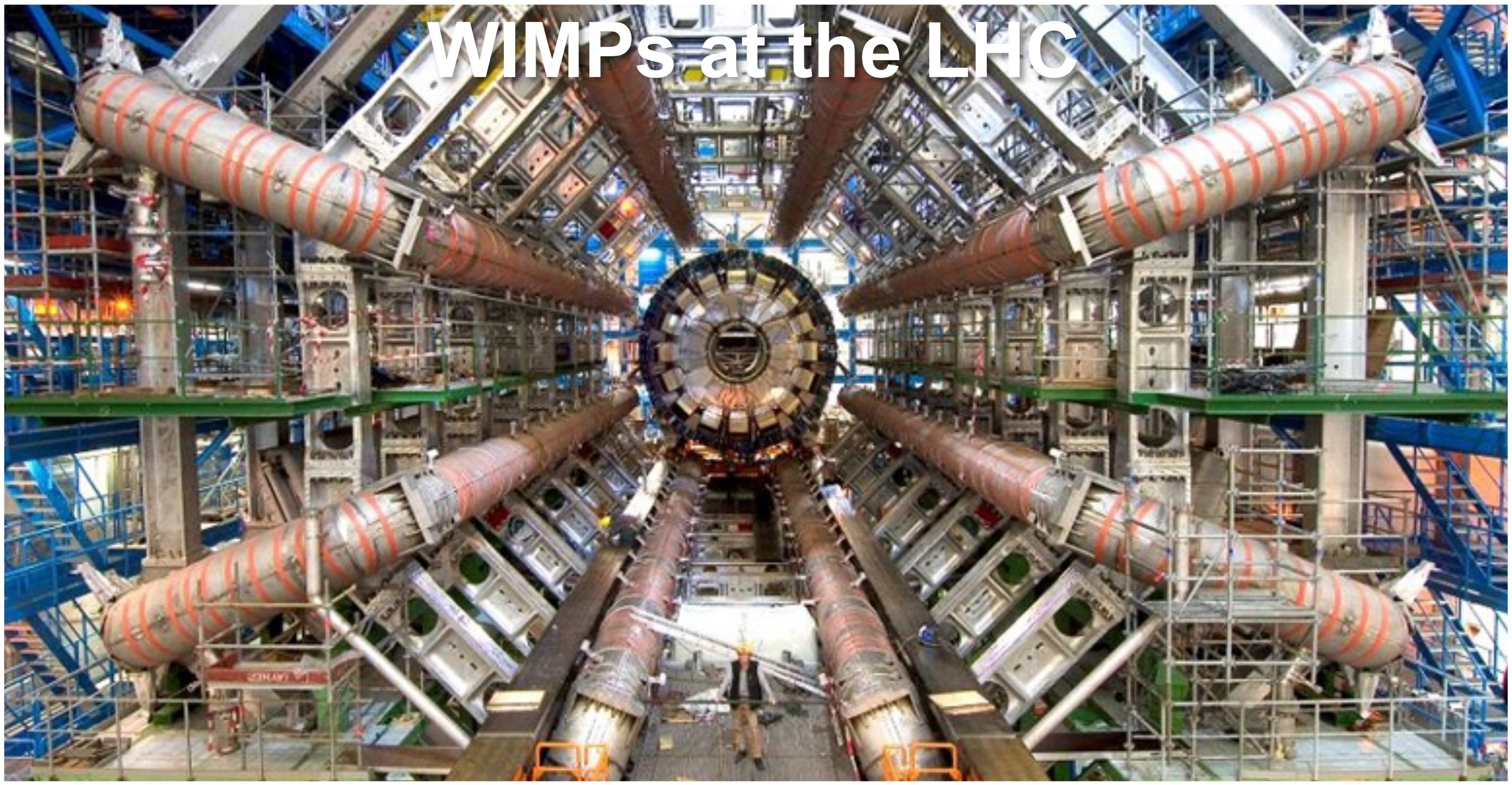


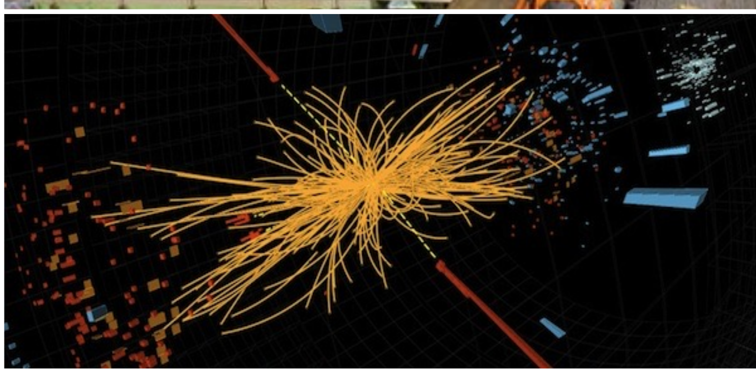
(+ CDMS, XENON,
LUX-ZEPLIN,
LED ZEPPELIN,
EDELWEISS,
DAMA/LIBRA,
EURECA,
DEAP, ArDM,
PICASSO, DMTPC,
WARP, SIMPLE, …)

WIMPs: $\langle|v\sigma_A| \Longrightarrow \Omega h^2\rangle$



WIMPs at the LHC

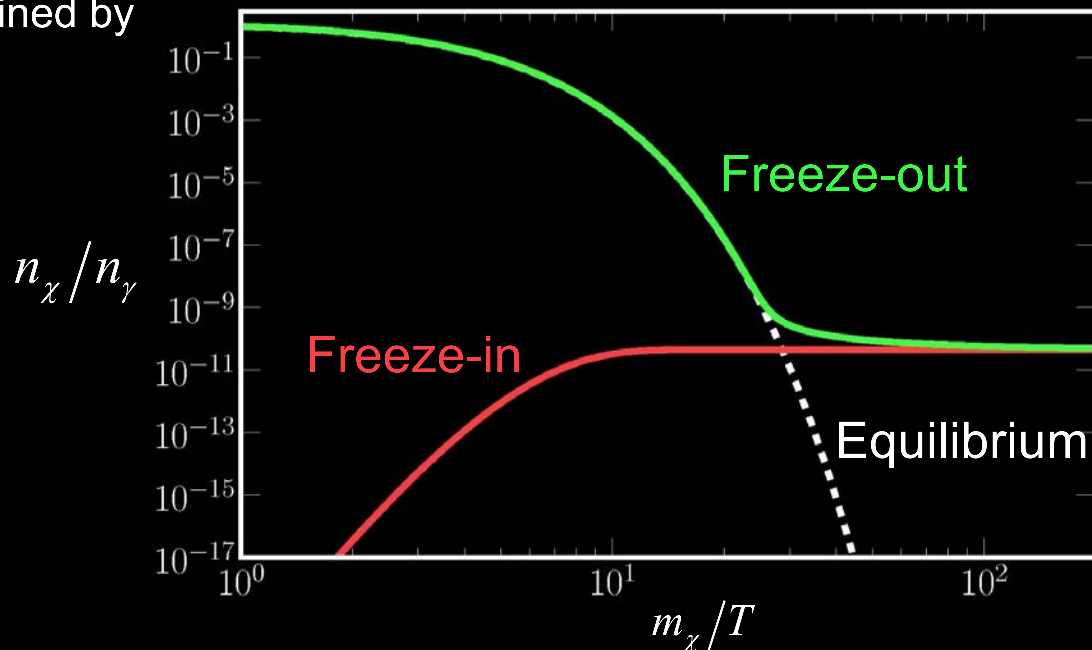




Looking for an
invisible
needle in a haystack

Most popular paradigm: cold thermal relic*

- DM abundance set by creation/annihilation with standard-model particles
- Equilibrium abundance of DM determined by m_χ / T (no asymmetry)
- DM species final abundance determined by
  "freeze-out" to final abundance, or
  "freeze-in" to final abundance



- Freeze-out/in: interplay between
  particle physics (DM—SM interactions) and cosmology (expansion rate)

* An object of particular veneration.

Direct, Indirect, Accelerator

Where is the WIMP?

No signal in direct (DAMA?), indirect (galactic center $\gamma -$ ray excess?), or accelerator searches.

Even more troubling, no sign of BSM physics at LHC.

This doesn't seem to be the decade of the WIMP!!!

(Perhaps) DM is NOT a WIMP (cold thermal relic), time to focus elsewhere

⬇ go lighter dark sector

⬇ go ultralight axion, dark photon

⬇ go ultraheavy WIMPzilla

⬇ boldly go where no one has gone before

Dark Matter particle mass range

<u>Mass Range for Particle Dark Matter</u>

$m \geq 10^{-22}$ eV: de Broglie wavelength smaller than dark-matter dominated objects

$m \leq 10^{19}$ GeV: mass less than Planck mass

$m \geq$ few eV: if fermion (exclusion principle)

<u>If thermal freeze-out</u>

$m \geq m_e$: annihilation to SM particles

$m \leq 100$ TeV: annihilation cross section too small for larger masses

<u>Is Dark Matter a Particle Or a Wave?</u>

$m \leq 1$ eV: occupation number in de Broglie-wavelength volume $\geq 1 \rightarrow$ WAVE

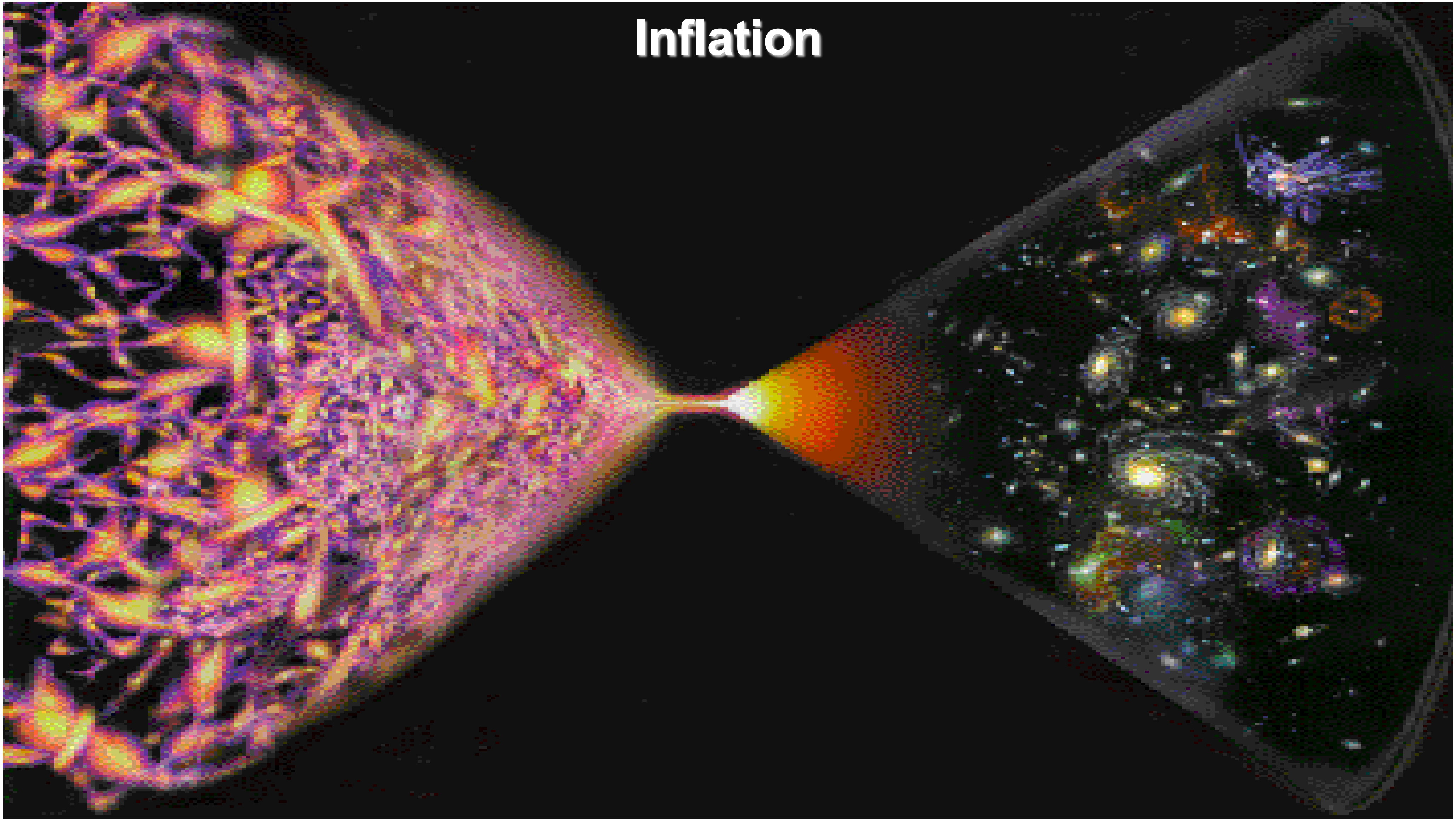
$m \geq 1$ eV: occupation number in de Broglie-wavelength volume $\leq 1 \rightarrow$ PARTICLE

Dark Matter particle mass range (mere 41 orders of magnitude)

Plancktons:	$m \sim m_{\text{Planck}} = 10^{19}$ GeV
WIMPzillas:	$m \sim m_{\text{inflaton}} = 10^{10} - 10^{13}$ GeV
Supermassive:	$m > 100$ TeV
WIMP range (e.g., neutralino):	$m_{\text{proton}} < m < 1$ TeV
Light dark matter (e.g., dark photon):	$m_{\text{electron}} < m < m_{\text{proton}}$
Ultralight dark matter (e.g., axion):	$m < 1$ eV
Fuzzy dark matter:	$m \sim 10^{-22}$ eV

Is Dark Matter Really a WIMP?

- Observation/experiment will tell!
- So far, after 30 years of effort nothing definite seen.
- KEEP
  CALM
  AND
  CARRY ON SEARCHING
  FOR
  DARK MATTER
- or, …
- Pursue other ideas.
- Hope for a disruptive discovery.


Inflation

Why is the Universe today so spatially flat?

- Start with Friedmann equation: $H^2(a) = \frac{8\pi G}{3}\rho(a) - \frac{k}{a^2}$. Hubble radius $R_H \equiv H^{-1}$
- Divide by H^2: $1 - \Omega(a) = -\frac{k}{a^2 H^2}$ with $\Omega(a) \equiv \frac{8\pi G\rho(a)}{3H^2(a)}$
- Comoving Hubble radius $[aH(a)]^{-1}$ grows with time

$\Longrightarrow$ $|\Omega(a) - 1|$ diverges with time $\frac{d|\Omega(a) - 1|}{d\ln a} = (1 + 3w)\,\Omega(a)\,|\Omega(a) - 1|$

- If today $|\Omega(a_0) - 1| \leq \mathcal{O}(1)$ then

$$|\Omega(a_{\rm BBN}) - 1| \leq \mathcal{O}(10^{-16})$$
$$|\Omega(a_{\rm GUT}) - 1| \leq \mathcal{O}(10^{-56})$$
$$|\Omega(a_{\rm Planck}) - 1| \leq \mathcal{O}(10^{-61})$$

- $\Omega = 1$ is an unstable fixed point. This demands an explanation.

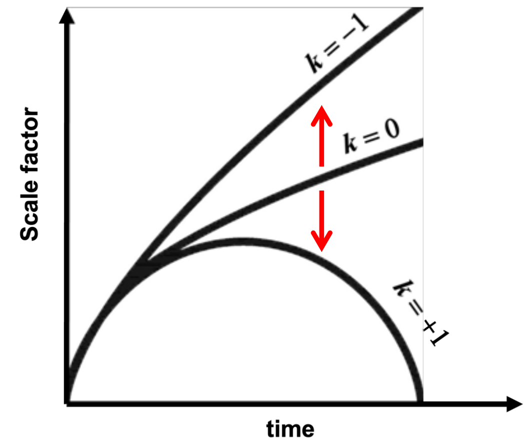
Why is the Universe so old?

- Start with Friedmann equation: $\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho(a) - \frac{k}{a^2}$

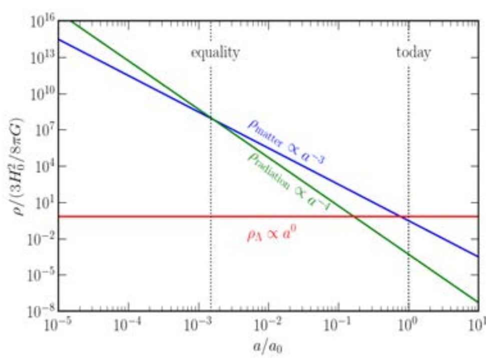
$\rho(a) \propto a^{-3}$ Matter

$\rho(a) \propto a^{-4}$ Radiation

- Evolution to collapse (if $k = +1$) or coast ($\dot{a} = \text{const.}$) (if $k = -1$)



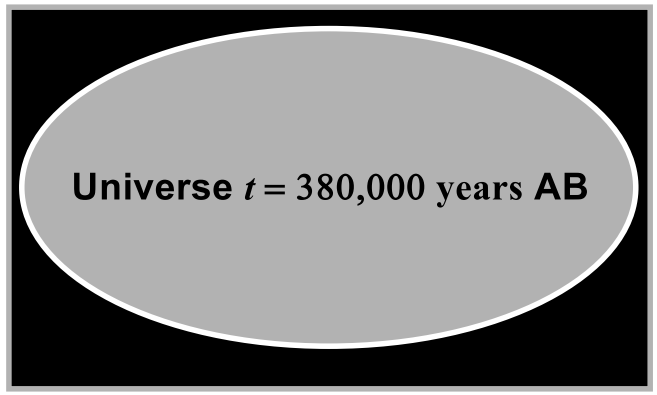
- At early times expect radiation to dominate



- $\rho_R \propto T^4$, no mass scale
- Only timescale is $G_N^{-1/2} = t_{\rm Pl} = 10^{-43}$ s

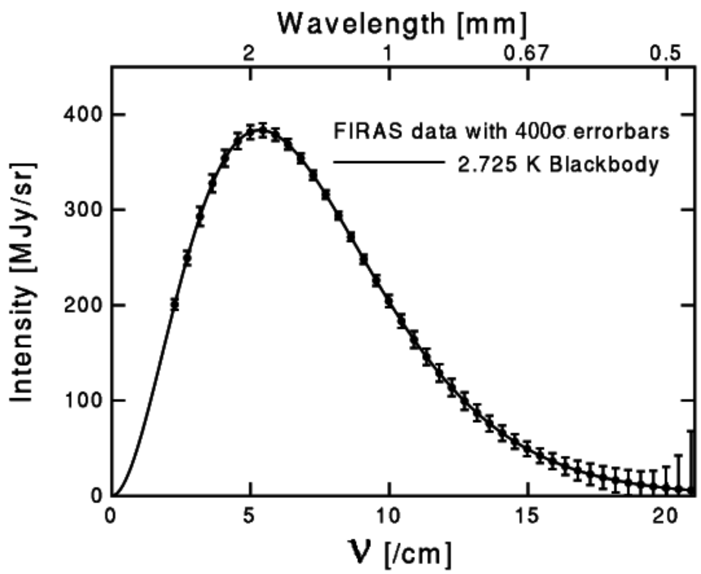
Why is the CMB today nearly homogeneous/isotropic?

Remember theorist's view of the Universe: $T \approx 3^{o}$ K everywhere. Why?

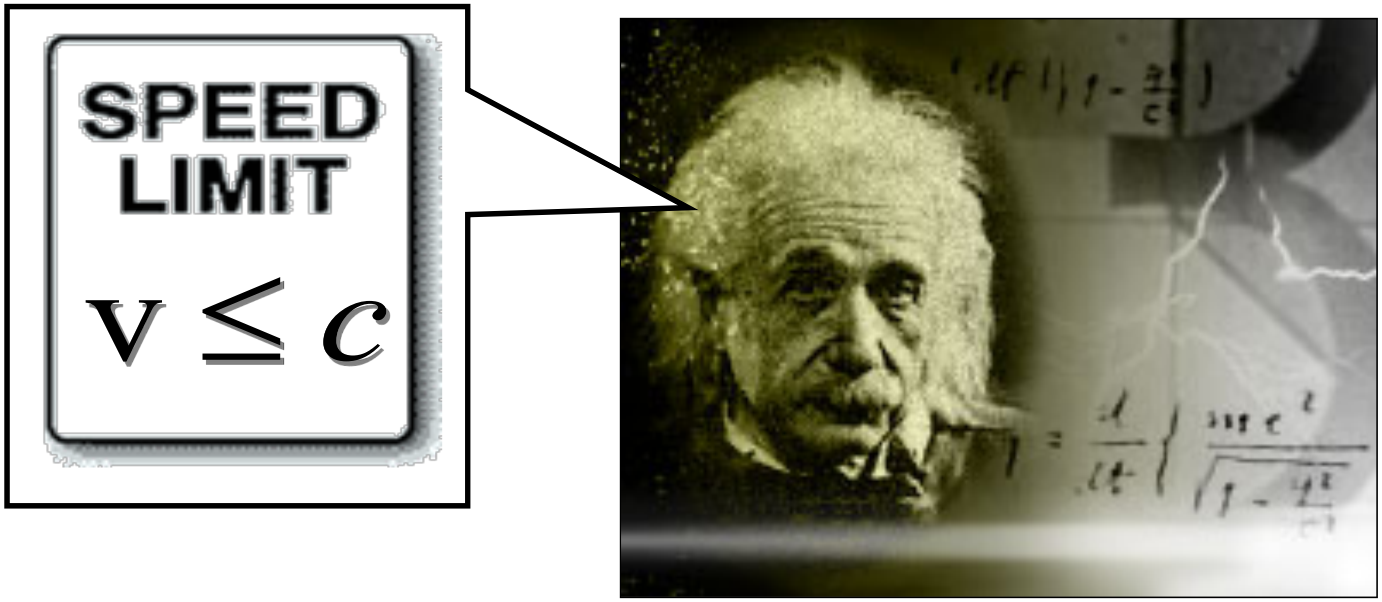


Temperature correlations on scales $\gg 380{,}000$ ly. How was thermal equilibrium established?

It's a blackbody spectrum!



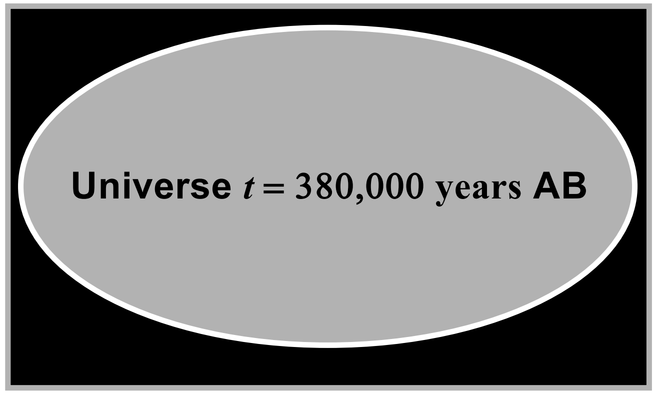
More than 380,000 light years in less than 380,000 years?



- $v \le c$ for velocity *through* space
- no limit on expansion velocity *of* space
- “acausal” requires “accelerated” expansion

Why is the CMB today nearly homogeneous/isotropic?

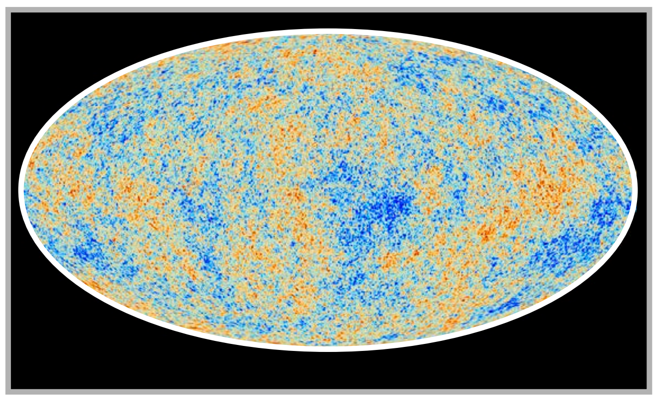
Remember theorist's view of the Universe: $T \approx 3^{\circ}\,\mathrm{K}$ everywhere.



Temperature correlations on scales $\gg 380{,}000$ ly. How was equilibrium established?

Remember observer's view of the Universe:

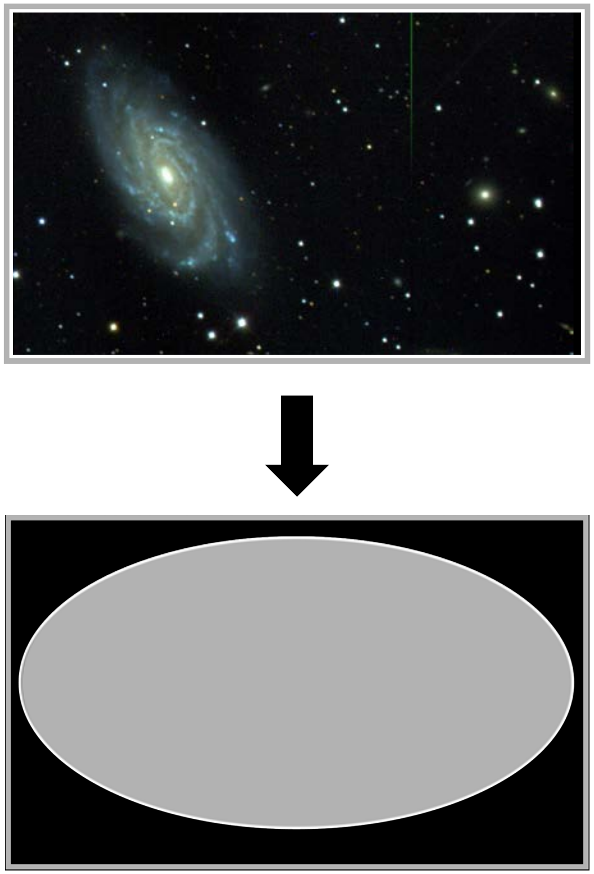
$\Delta T / T \approx \mathcal{O}(10^{-5})$.



Temperature almost, but not exactly, uniform

WHY?

Why is the matter distribution <u>nearly</u> homogeneous/isotropic?



- Autocorrelation function defines power spectrum
- Assume there is an average density $\bar{\rho}$
- Expand density contrast $\delta(\vec{x})$ in Fourier modes

$$\delta(\vec{x}) \equiv \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}} = \int \delta_{\vec{k}} \exp\left(-i\vec{k}\cdot\vec{x}\right) d^3k$$

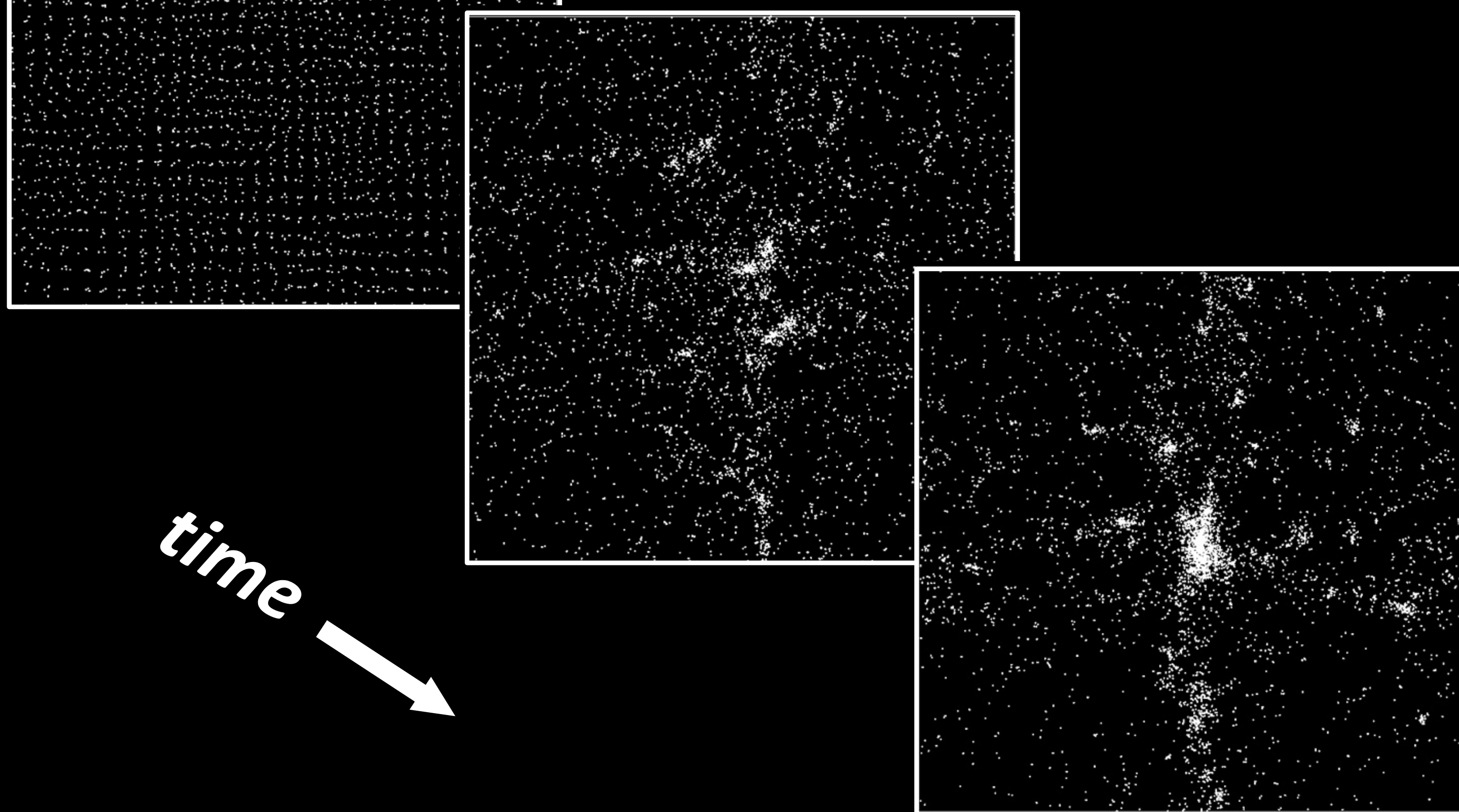
$$\left\langle \frac{\delta\rho(\vec{x})}{\rho} \right\rangle^2 = \langle \delta(\vec{x})\delta(\vec{x}) \rangle = \int_0^\infty \frac{dk}{k} \; \frac{k^3 \left|\delta_{\vec{k}}^2\right|}{2\pi^2}$$

$$\Delta^2(k) \equiv \frac{k^3 \left|\delta_{\vec{k}}^2\right|}{2\pi^2} \qquad P(k) \equiv \left|\delta_{\vec{k}}^2\right|$$

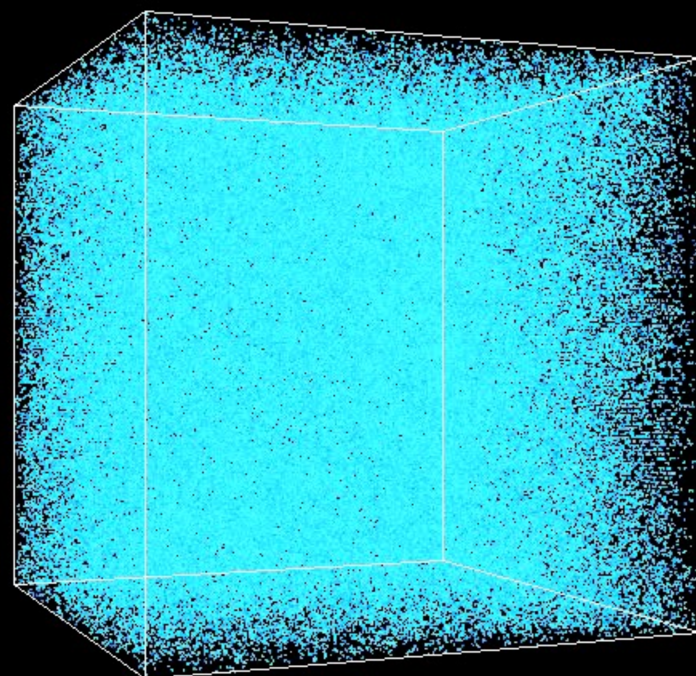
- Density contrast passes through unity around $8\ h^{-1}\,\mathrm{Mpc}$
- Universe becomes homogeneous on scales $\gtrsim 8\ h^{-1}\,\mathrm{Mpc}$

Gravitational Instability

Gravity is an Unregulated Free-Market Force:
The rich (gravity creators) get richer
at the expense of the poor

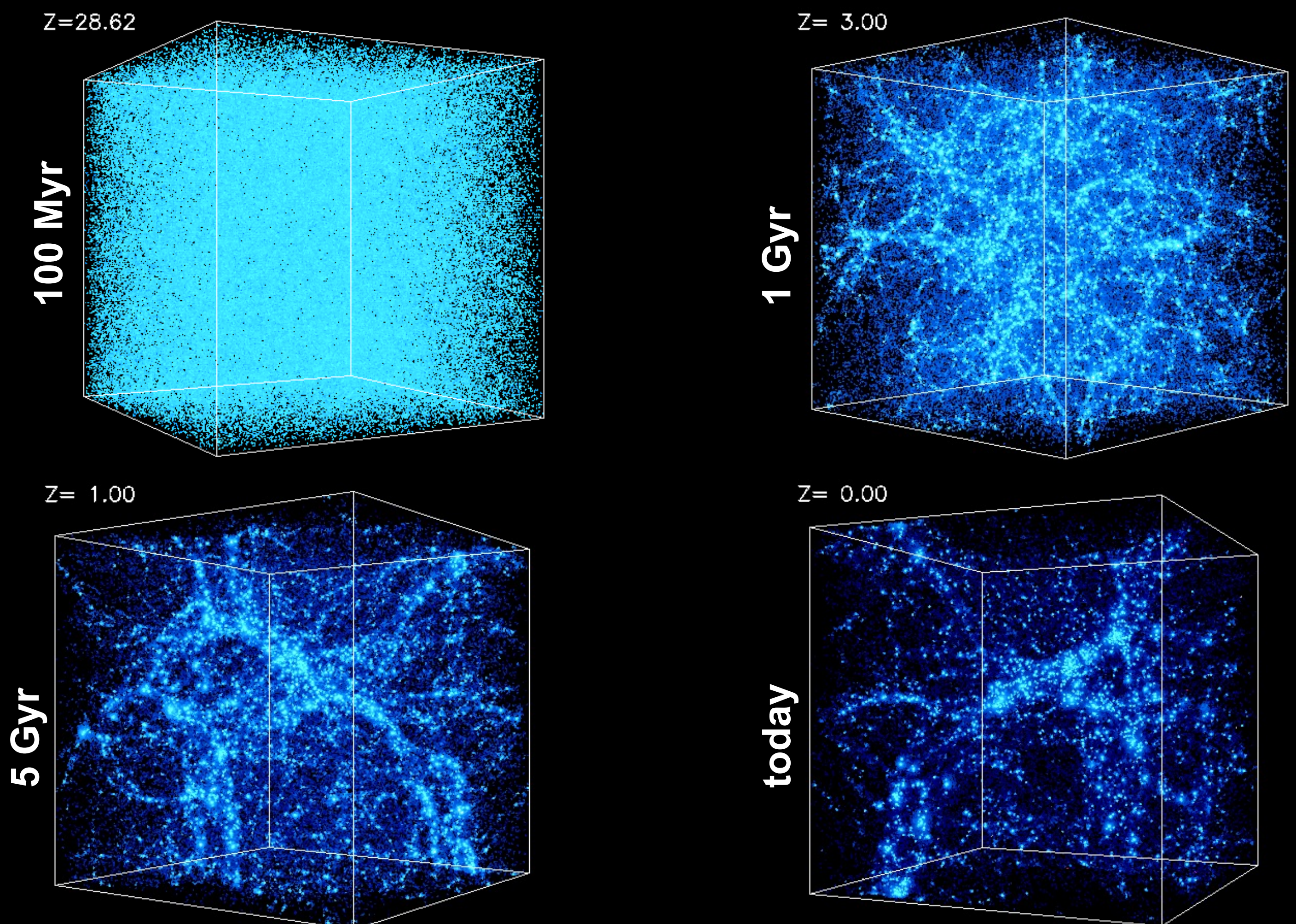


Gravitational Instability



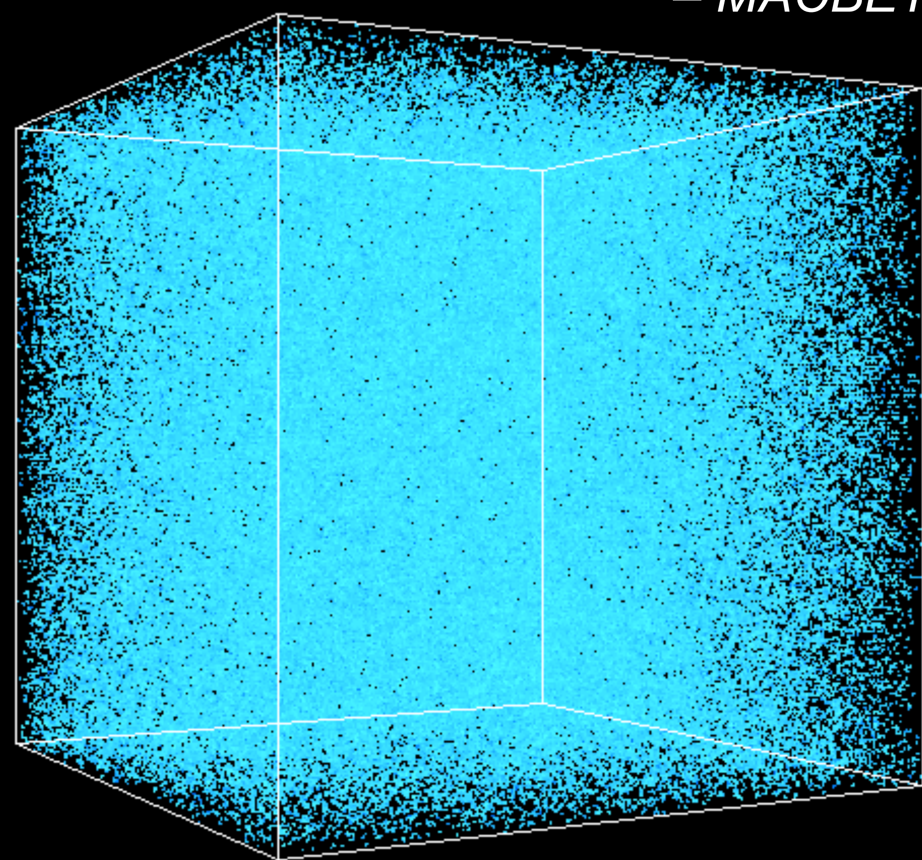
Andrey Kravtsov

The growth of cosmic seeds

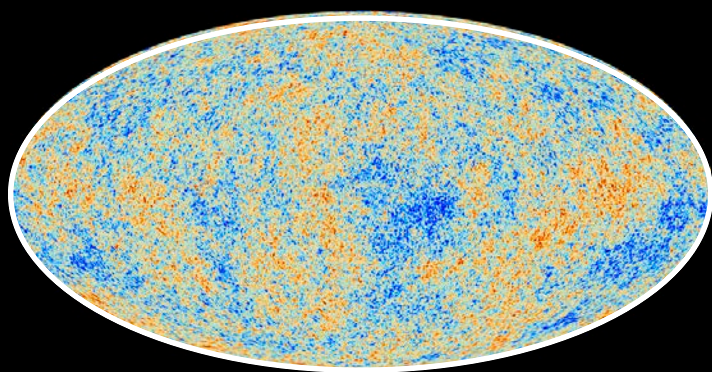


If you can look into the seeds of time
And say which grain will grow and which will not,
Speak then to me, who neither beg nor fear
Your favours nor your hate.

– *MACBETH (Banquo)*

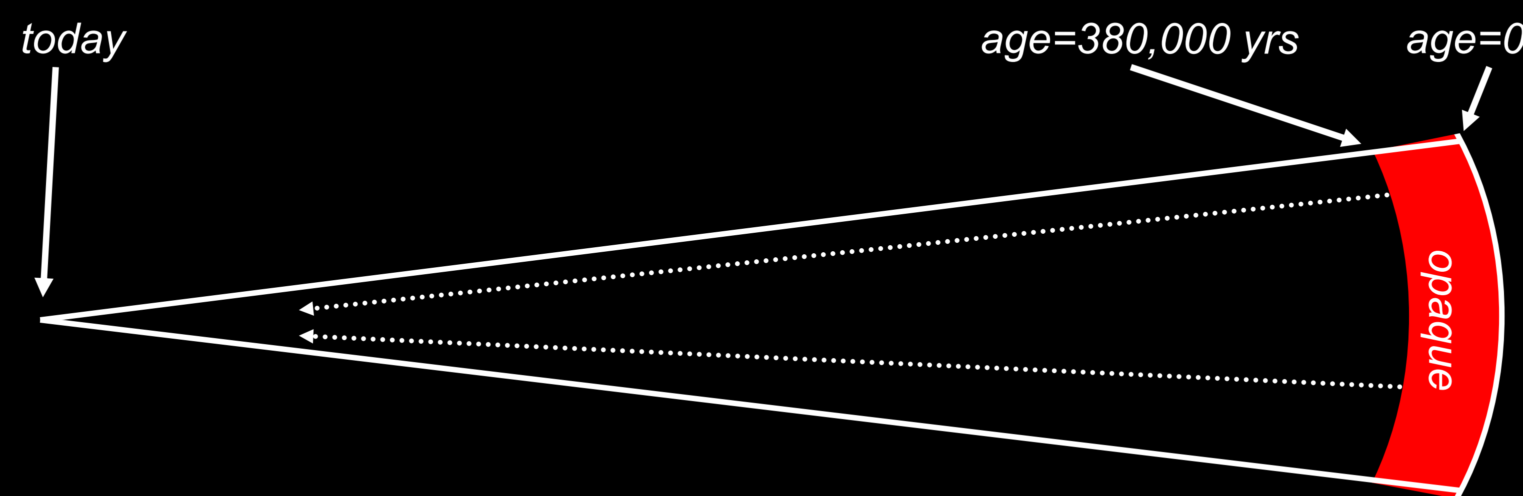


Primordial Seed Perturbations



$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

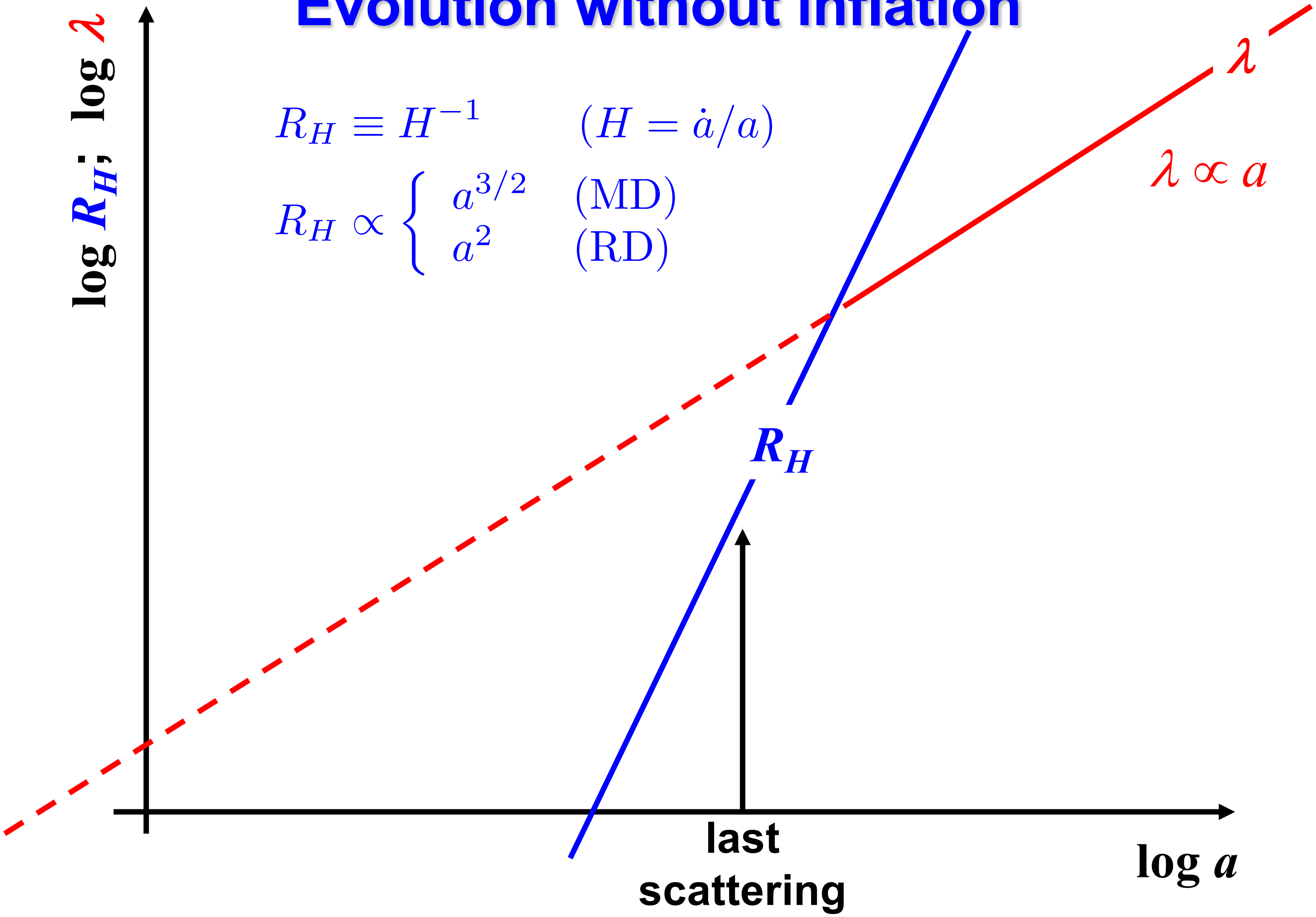
curvature perturbations $\leftrightarrow$ density perturbations



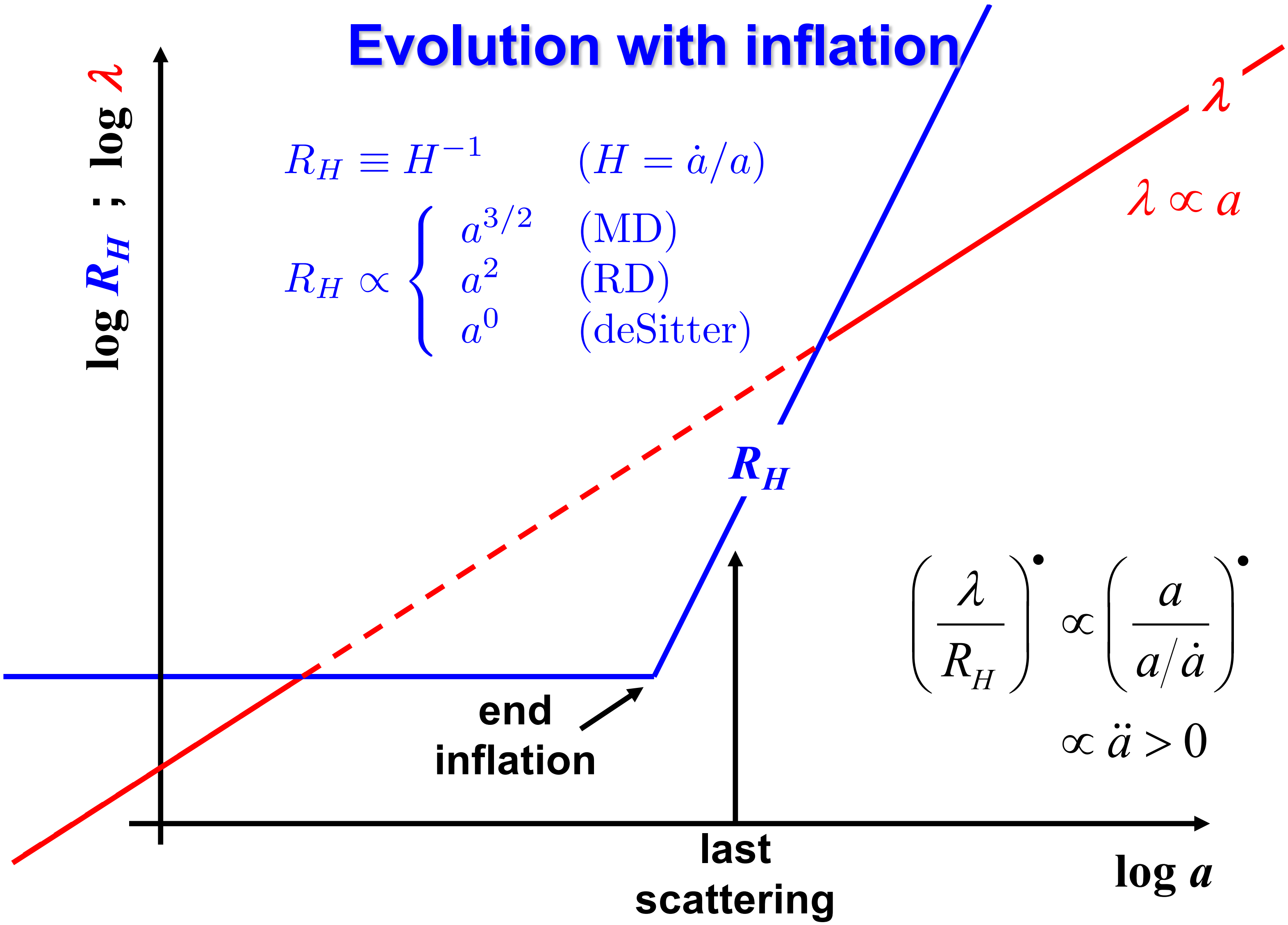
Unwanted relics

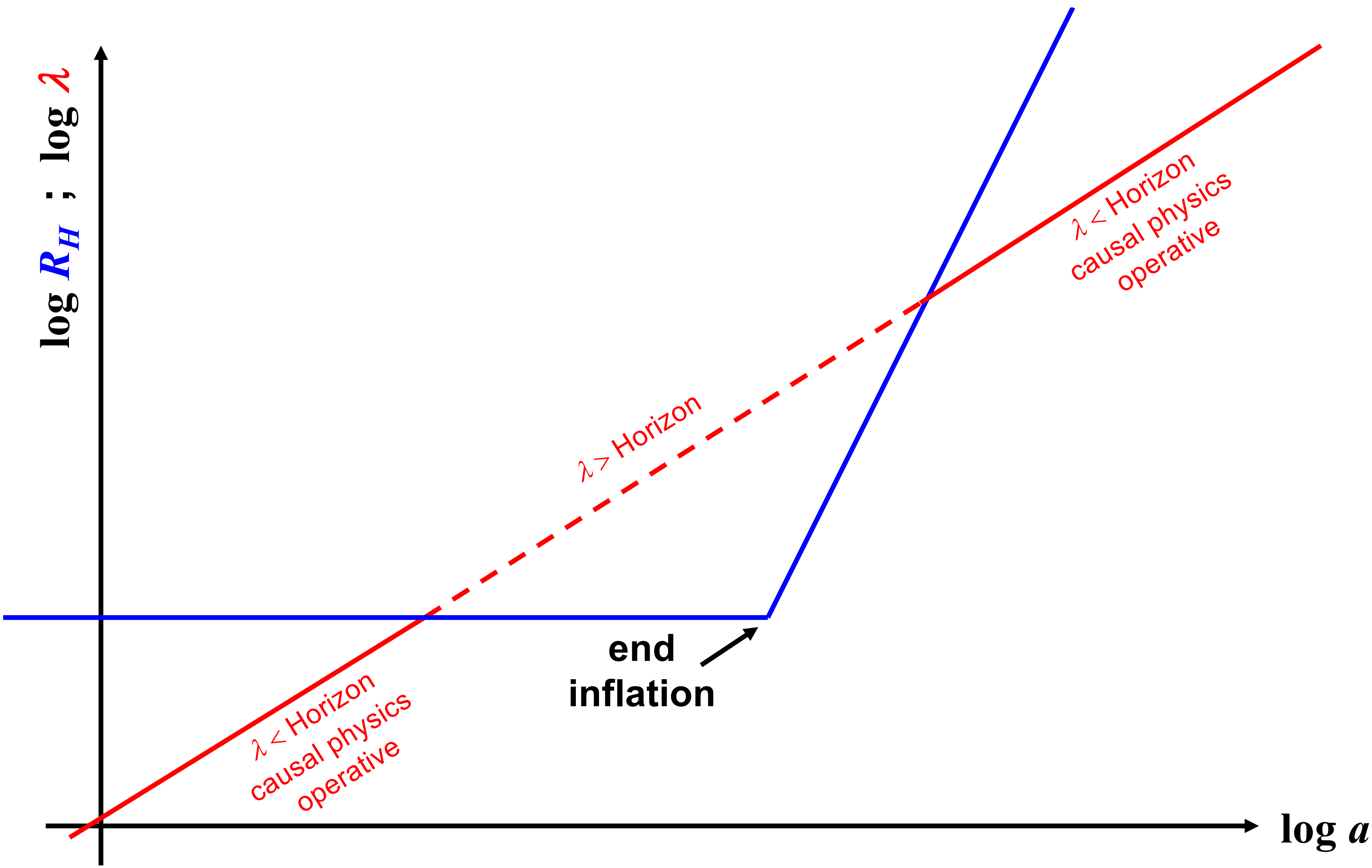
- High energies (temperatures) should have produced many things not seen today
    - Magnetic monopoles
    - String theorists say extra dimensions, strings, branes, walls, Kaluza-Klein modes, …
- How to get rid of them? Inflate them away!

Evolution without inflation



Evolution with inflation



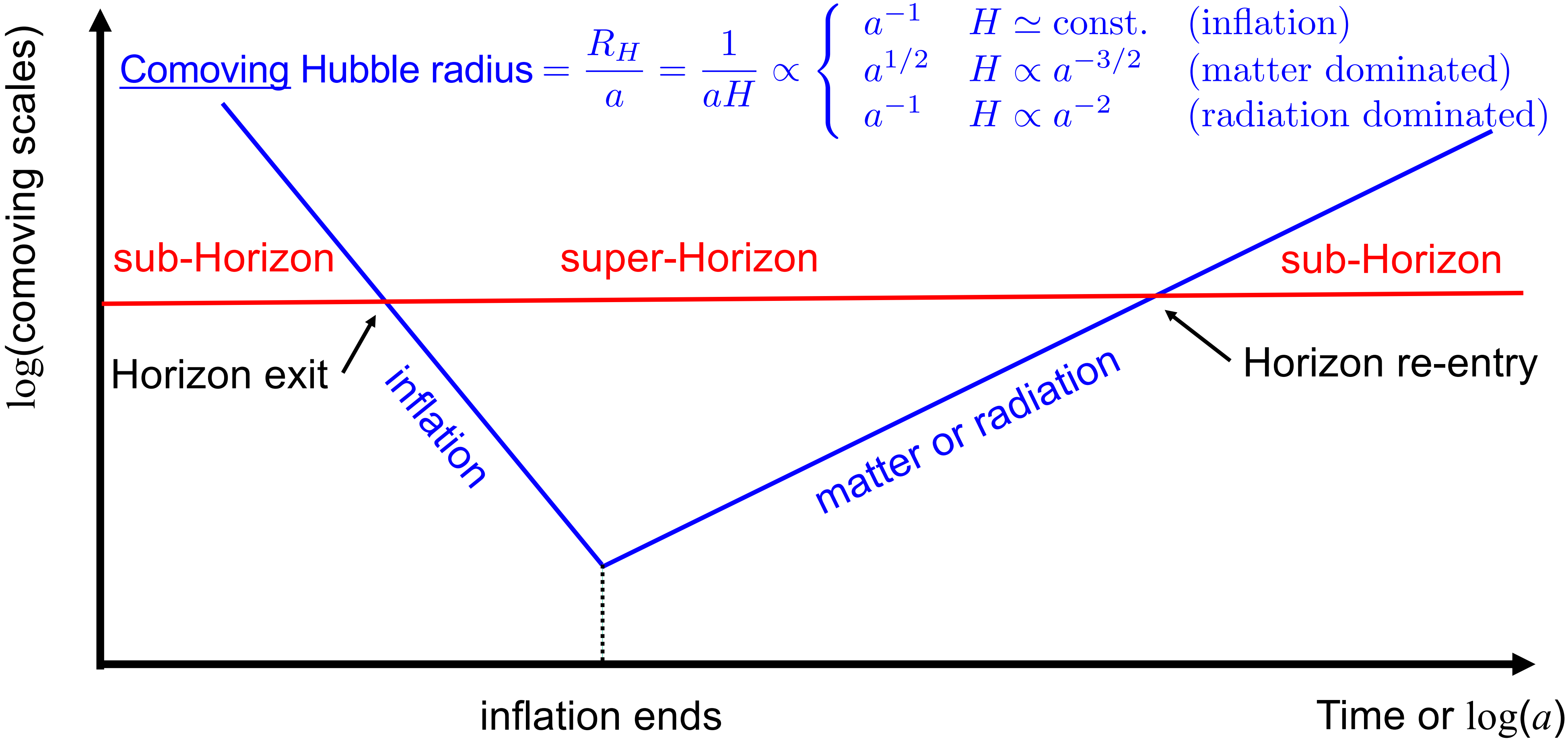


log R_H ; log λ
log a
λ < Horizon
causal physics
operative
λ > Horizon
λ < Horizon
causal physics
operative
end
inflation

Since it is important—another view

Comoving length scale $= \dfrac{\lambda}{a} = \text{const.}$

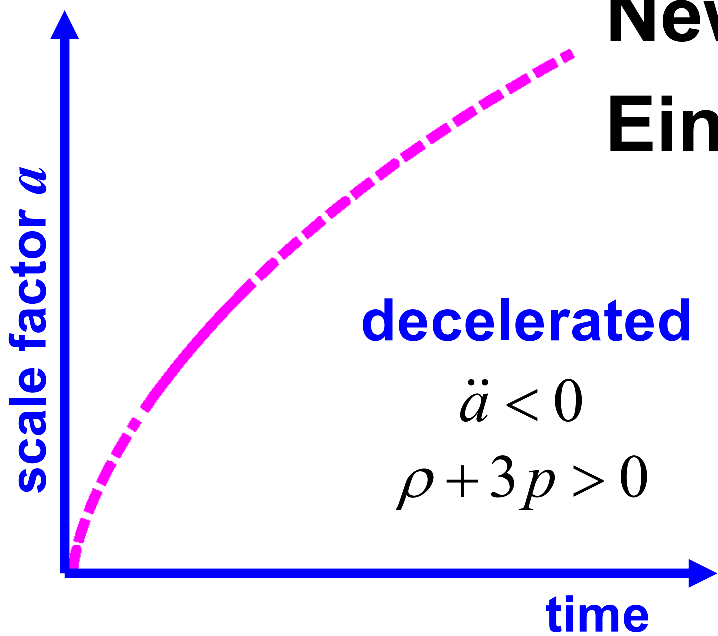
Comoving Hubble radius $= \dfrac{R_H}{a} = \dfrac{1}{aH} \propto \begin{cases} a^{-1} & H \simeq \text{const.} \quad \text{(inflation)} \\ a^{1/2} & H \propto a^{-3/2} \quad \text{(matter dominated)} \\ a^{-1} & H \propto a^{-2} \quad \text{(radiation dominated)} \end{cases}$

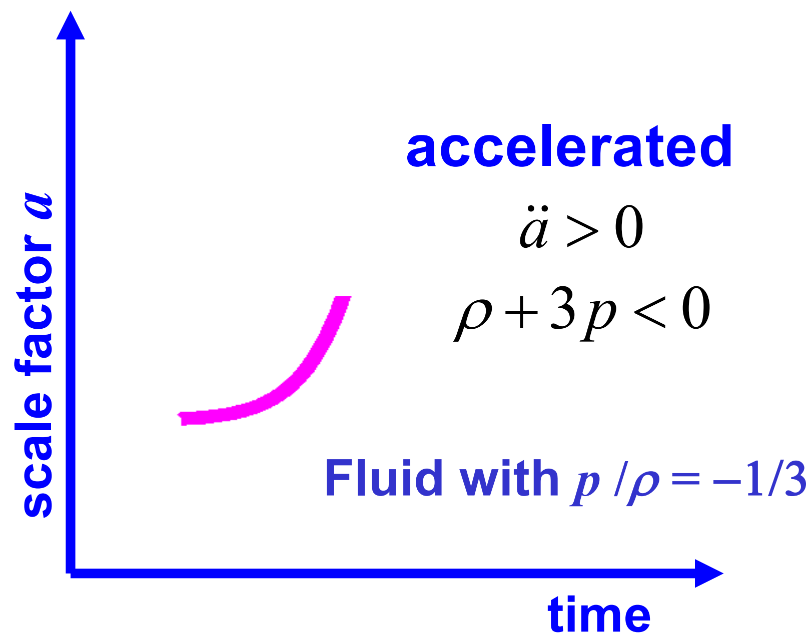


Newton

Einstein

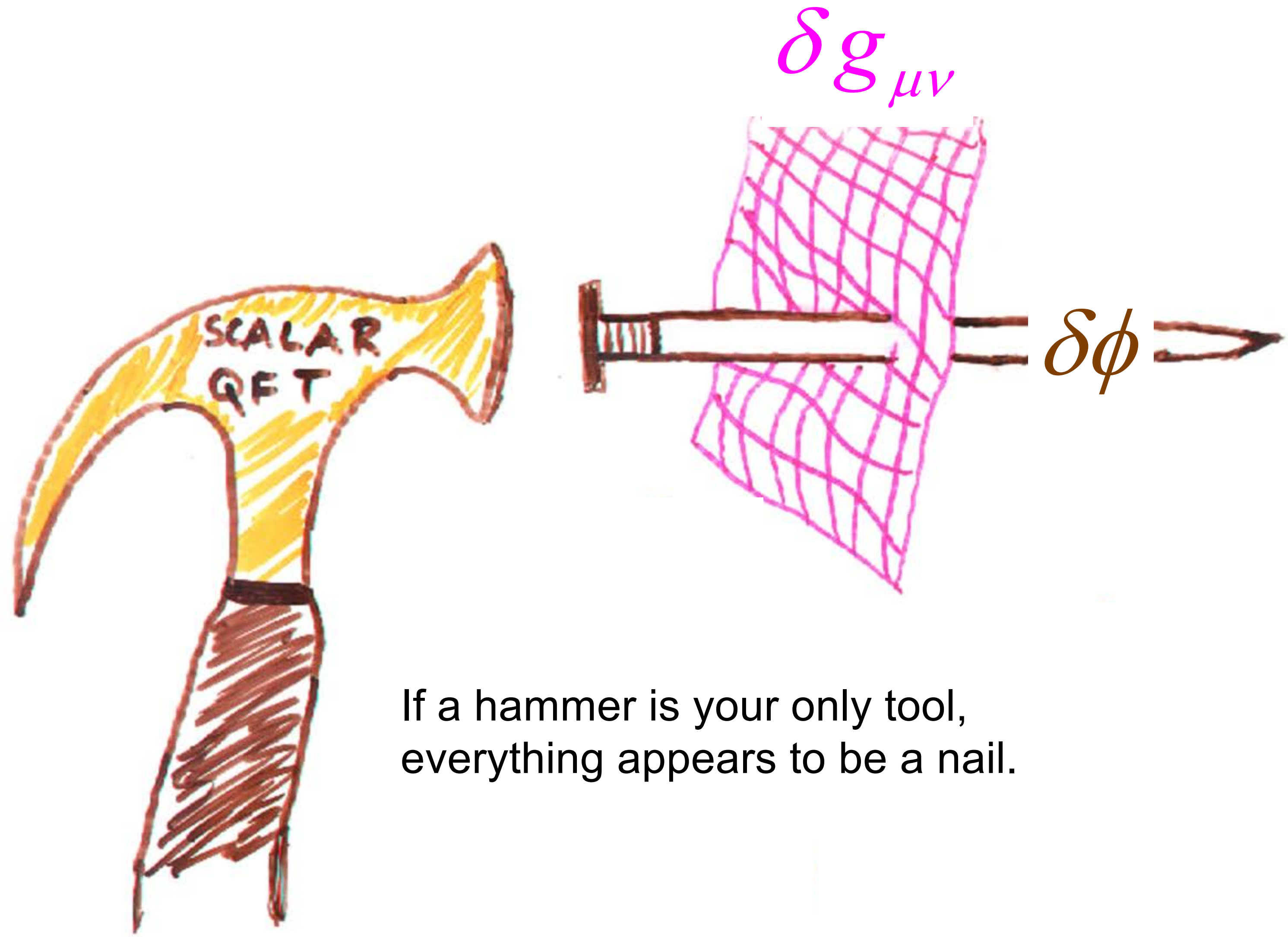
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3p\right)$$





Accelerated Expansion?

- From Friedmann equations: $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) = -\frac{4\pi G}{3}\rho(1+3w) \qquad (w \equiv p/\rho)$
- Accelerated expansion: $w < -1/3$
- Vacuum energy has $w = -1$
- Assume that at some (very) early time, the Universe was dominated by vacuum energy (quasi-) de Sitter phase.
- de Sitter space: Universe dominated by Λ: $\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3} \Longrightarrow a \propto e^{\sqrt{\Lambda}\ t}$
- How can one imagine starting with vacuum energy, then evolving to a radiation-dominated Universe?
- Scalar field to the rescue.



If a hammer is your only tool,
everything appears to be a nail.

Inflation

Usual picture of inflation:

Universe dominated by potential energy of a scalar field, the inflaton

- Scalar field has potential energy $V(\phi)$ and kinetic energy $\dot{\phi}^2$

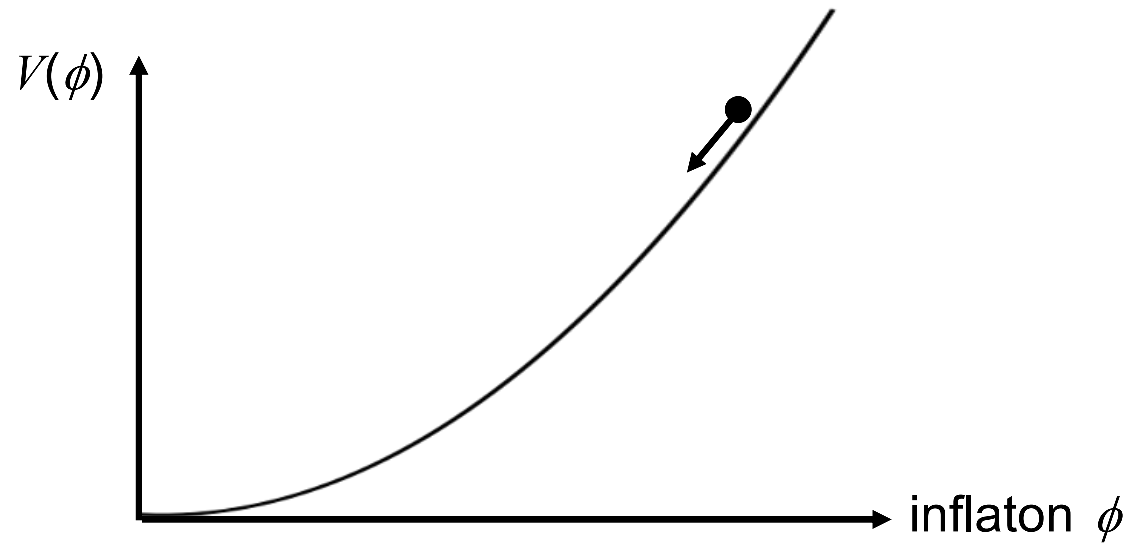
$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$\ddot{a} \propto -(\rho_\phi + 3p_\phi) = V(\phi) - \dot{\phi}^2$$

- Potential energy (zero-momentum mode of ϕ) dominates ⇒ acceleration

- As field evolves (rolls downhill) gains kinetic energy, eventually $\dot{\phi}^2$ dominates potential & inflation ends.

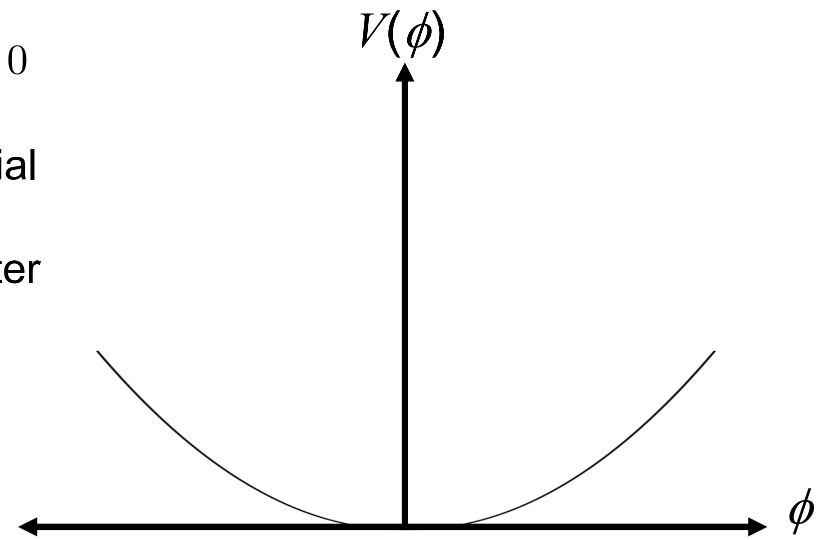


- Equation of motion: $\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$

- “Slow-roll”: $\ddot{\phi} < \left(3H\dot{\phi},\ \frac{dV}{d\phi}\right)$

Inflation must end!

- For illustration take quadratic potential $V(\phi) = \frac{1}{2}m^2\phi^2$
- Recall inflation ends when $\ddot{a} \propto 4V(\phi) - \dot{\phi}^2 = 2m_\phi^2\phi^2 - \dot{\phi}^2 = 0$
- After end of inflation field oscillates about minimum of potential
- During oscillations inflaton energy density decreases as matter
- Have to convert cold, low-entropy inflaton state to radiation (defrost the Universe)
- In simple models inflaton decays to SM particles
- Augment EOM with decay term $\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} + \Gamma_\phi\dot{\phi} = 0$
- The universe "reheats" to a temperature $T_{\rm RH} \sim (M_{\rm Pl}\Gamma_\phi)^{1/2}$
- This is the start of the hot early Universe



Who is the Inflation?

- Usual assumption
  - Single field
  - Minimally coupled (no $R\phi^2$ term)
  - Standard kinetic term
  - Potential $V(\phi)$ specifies model

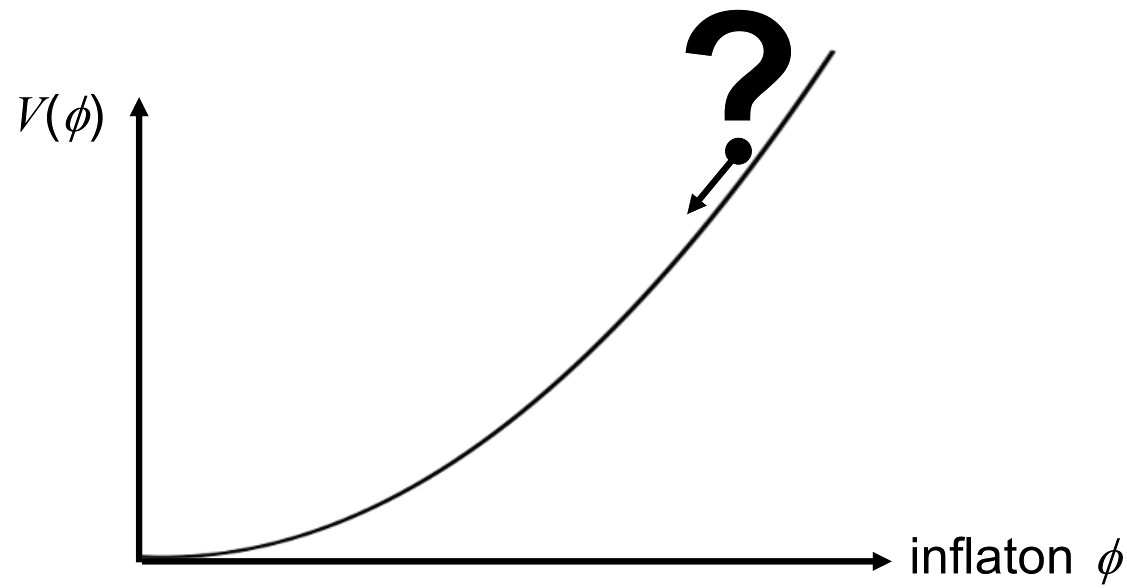
    $m^2\phi^2,\ \phi^4,\ \cos(\phi), \exp(\phi),\ \ldots$

- Beyond usual assumption

  Higgs inflation, k-inflation, warm inflation,
  DBI inflation, assisted inflation, D-brane, …

- Need very flat potential

- Hundreds of models



Models of Inflation

old, new, pre-owned,
chaotic, quixotic, ergodic,
ekpyrotic, autoerotic,
faith-based, free-based,
hilltop, hillflop,
strange attractor, α-attractor,
D-term, F-term, summer-term,
brane, braneless, brainless,
supersymmetric, supercilious,
natural, supernatural, *au natural,*
hybrid, low-bred, white-bread,
one-field, two-field, left-field,
eternal, internal, infernal,
self-reproducing, self-promoting,
dilaton, dilettante, …….

Encyclopædia Inflationaris

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Abstract. The current flow of high-accuracy astrophysical data, among which are the Cosmic Microwave Background (CMB) measurements by the Planck satellite, offers an unprecedented opportunity to constrain the inflationary theory. This is however a challenging project given the size of the inflationary landscape which contains hundreds of different scenarios. Given that there is currently no observational evidence for primordial non-Gaussianities, isocurvature perturbations or any other non-minimal extension of the inflationary paradigm, a reasonable approach is to consider the simplest models first, namely the slow-roll single-field models with minimal kinetic terms. This still leaves us with a very populated landscape, the exploration of which requires new and efficient strategies. It has been customary to tackle this problem by means of approximate model-independent methods while a more ambitious alternative is to study the inflationary scenarios one by one. We have developed the publicly available runtime library `ASPIC`[1] to implement this last approach. The `ASPIC` code provides all routines needed to quickly derive reheating-consistent observable predictions within this class of scenarios. `ASPIC` has been designed as an evolutive code which presently supports 118 different models. In this paper, for each of the `ASPIC` models, we present and collect new results in a systematic manner, thereby constituting the first *Encyclopædia Inflationaris*.

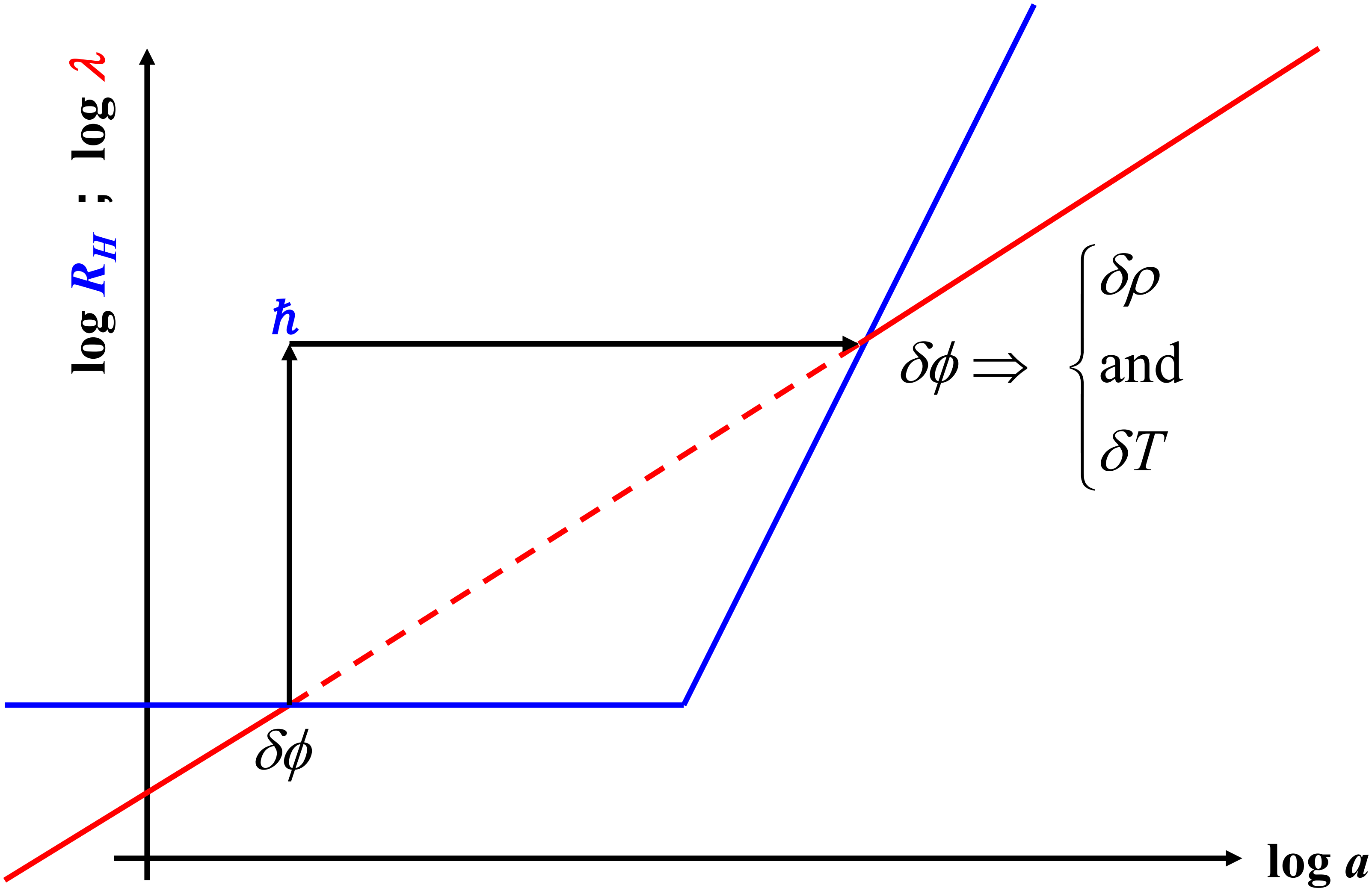
Keywords: Cosmic Inflation, Slow-Roll, Reheating, Cosmic Microwave Background, Aspic

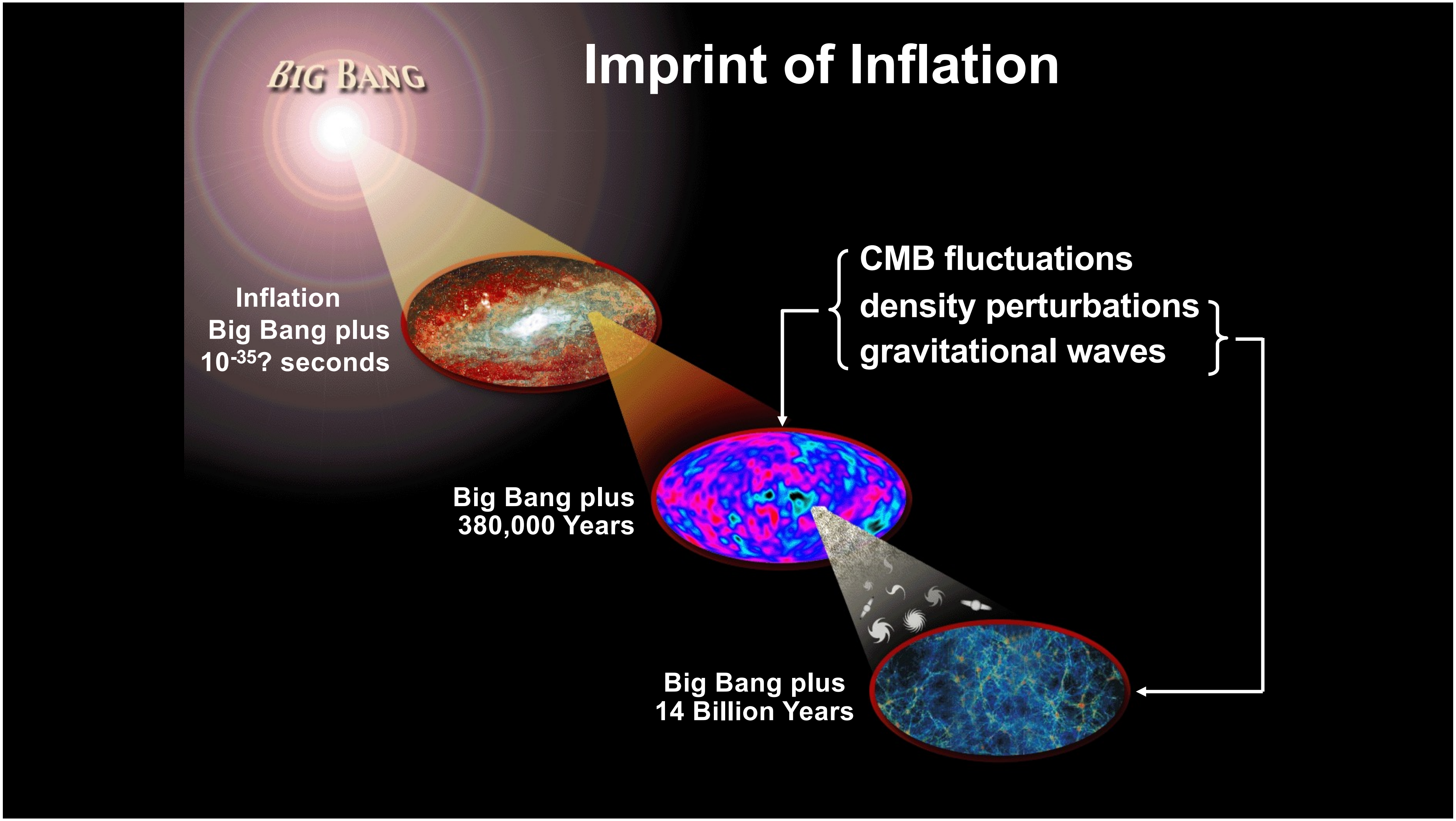
ArXiv ePrint: 1303.3787

Models of Inflation

- So far have considered classical evolution of inflaton.
- Inflaton should also have quantum fluctuations during evolution.
- During inflationary phase, background spacetime approximately de Sitter.
- In de Sitter, massless scalar field has fluctuations $|\delta\phi| = \dfrac{H}{2\pi}$.
- Fluctuations in ϕ are fluctuations in $V(\phi)$.
- After inflation, inflaton potential energy converted to radiation and eventually matter.
- $\delta\phi \longrightarrow \delta V \longrightarrow (\delta T,\ \delta\rho_M)$
- (Glossed over a lot of interesting details—complete treatment in Baumann's book).

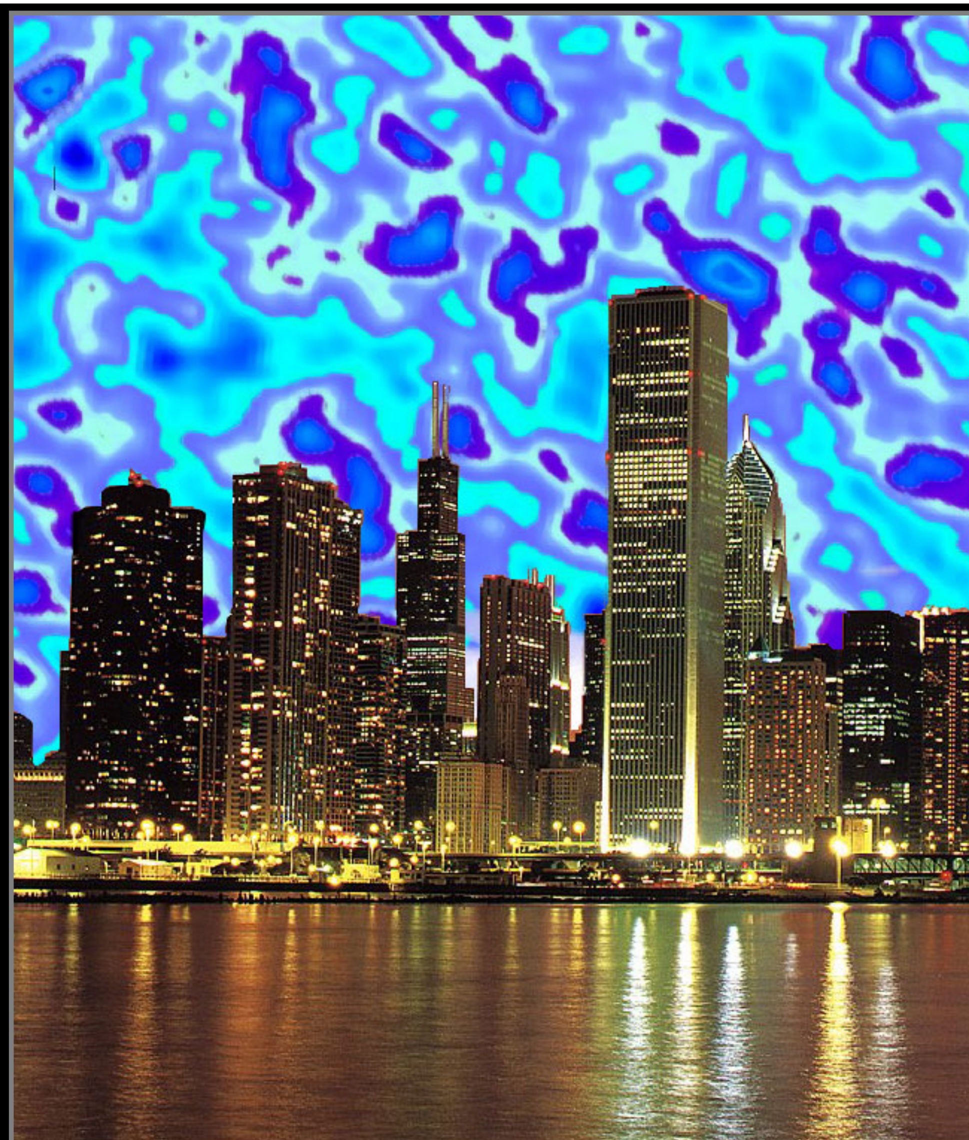
Quantum fluctuations during inflation seed $\delta\rho$ and δT



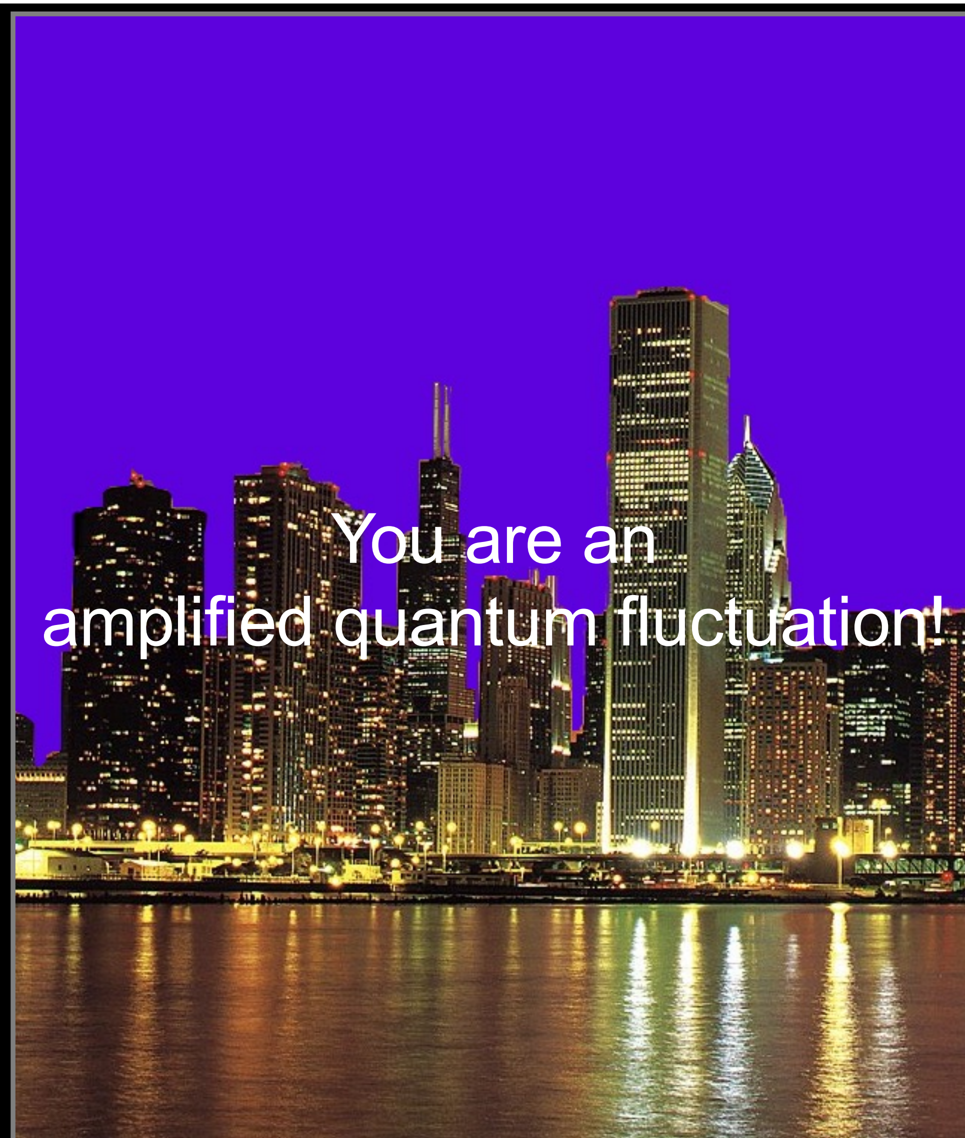


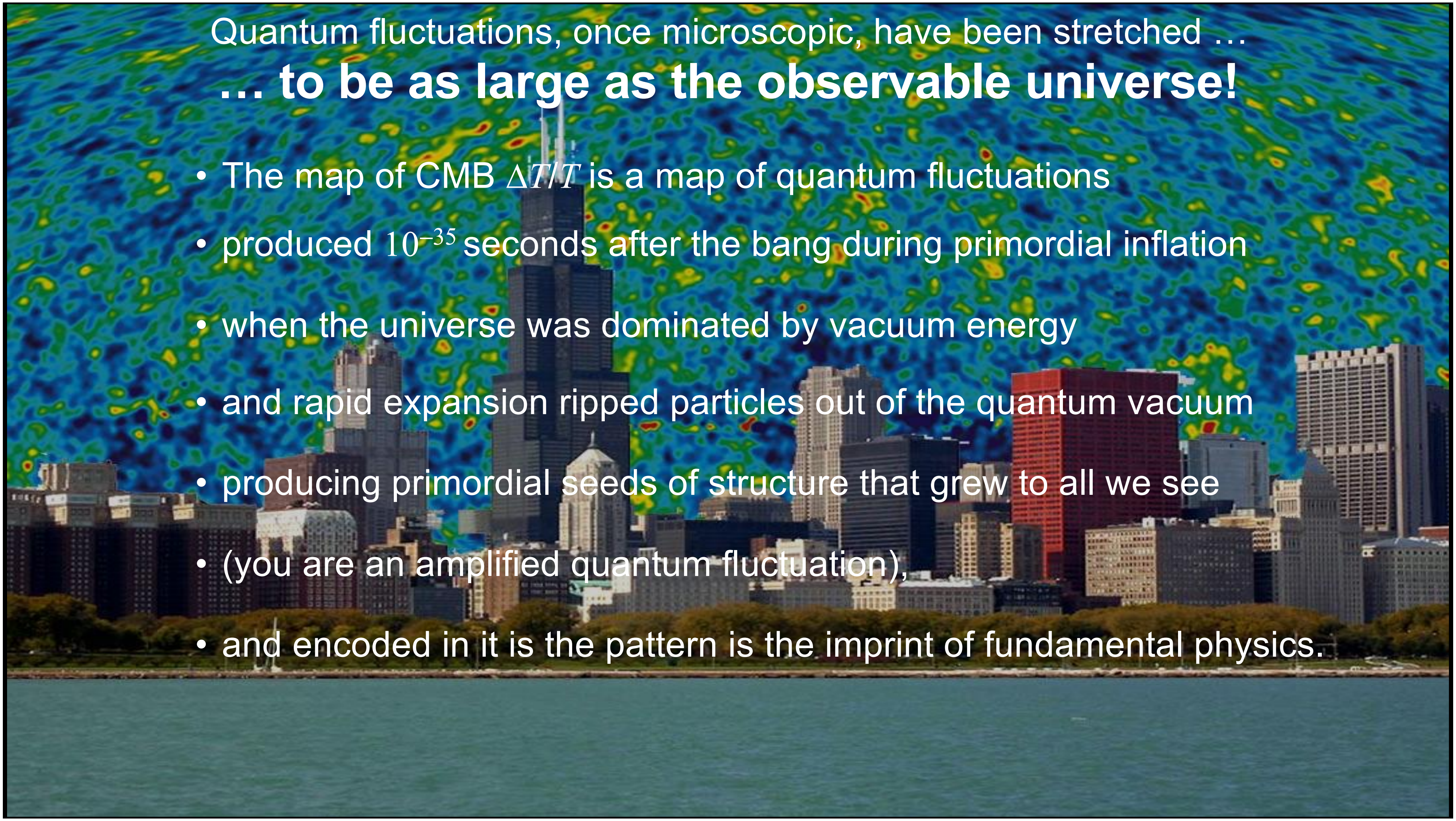
Imprint of Inflation
BIG BANG
Inflation
Big Bang plus
10^-35? seconds
CMB fluctuations
density perturbations
gravitational waves
Big Bang plus
380,000 Years
Big Bang plus
14 Billion Years

A pattern
of vacuum
quantum
fluctuations



$$\hbar \to \mathbf{0}$$





Quantum fluctuations, once microscopic, have been stretched …

… to be as large as the observable universe!

- The map of CMB $\Delta T/T$ is a map of quantum fluctuations
- produced 10^{-35} seconds after the bang during primordial inflation
- when the universe was dominated by vacuum energy
- and rapid expansion ripped particles out of the quantum vacuum
- producing primordial seeds of structure that grew to all we see
- (you are an amplified quantum fluctuation),
- and encoded in it is the pattern is the imprint of fundamental physics.

Quantum fluctuations $\delta\phi$ during inflation seed $\delta\rho$ and δT

- Regions which fluctuate "uphill" take longer to reach end of inflation.

- Fluctuations in $\delta\phi \rightarrow$ fluctuations in $\delta H \rightarrow$ fluctuations in $\delta N = \delta$ (# e-folds) $= \delta\,[\log$(scale factor)]

- Now for some algebra with use of a lot of ≈'s :
  - Slow-roll $3H\dot{\phi} = -dV/d\phi \equiv -V' \Longrightarrow \dot{\phi} \approx V'/H \Longrightarrow \delta t \approx H\,\delta\phi/V'$
  - Include $\hbar$: $\delta\phi \approx H \Longrightarrow \delta t \approx H^2/V'$
  - $\delta N = \delta\,[\log$(scale factor)] $\Longrightarrow \delta N \approx H\,\delta t \approx H^3/V'$
  - Friedmann equation: $3M_{\rm Pl}^2 H^2 = \rho \approx V \Longrightarrow H \approx V^{1/2}/M_{\rm Pl}$
  - Finally! $\delta N \approx \dfrac{V^{1/2}}{M_{\rm Pl}^3}\dfrac{V}{V'} \approx \dfrac{H}{M_{\rm Pl}}\dfrac{1}{M_{\rm Pl}}\dfrac{V}{V'}$

Quantum fluctuations $\delta\phi$ during inflation seed $\delta\rho$ and δT

- Define "slow-roll" parameters (V and V' change slowly during inflation)

$$\epsilon = \frac{M_{\rm Pl}^2}{16\pi}\left(\frac{V'}{V}\right)^2 \qquad\qquad \eta = \frac{M_{\rm Pl}^2}{8\pi}\,\frac{V''}{V}$$

- The power spectrum of perturbations related to (δN^2) :

$$\delta N \approx \frac{H}{M_{\rm Pl}}\frac{1}{M_{\rm Pl}}\frac{V}{V'} \approx \frac{H}{M_{\rm Pl}}\frac{1}{\sqrt{\epsilon}} \Longrightarrow P_S = \frac{H^2}{M_{\rm Pl}^2}\frac{1}{\epsilon}$$

- Different models with different potentials have different values of ϵ

- Graviton also receives quantum fluctuations during inflation: $P_T = 16\dfrac{H^2}{M_{\rm Pl}^2}$

- Tensor-to-scalar ratio: $r = \dfrac{P_T}{P_S} = 16\epsilon$

Quantum fluctuations $\delta\phi$ during inflation seed $\delta\rho$ and δT

- "Slow-roll" parameters (V and V') change (slowly) during inflation

- P_S and P_T change (slowly) during inflation, define spectral indices n_S and n_T

$$P_S = \frac{H^2}{M_{\rm Pl}^2}\frac{1}{\epsilon}\ k^{n_S-1}$$

$$n_S = 1 - 6\epsilon + 2\eta$$

$$n_T = -2\epsilon$$

$$P_T = 16\frac{H^2}{M_{\rm Pl}^2}\ k^{n_T}$$

- Scalar spectral index can be determined from CMB

ϵ

- Search is on for discovery of tensor mode from CMB

- Different models predict different values of (n_S, r)

- Can differentiate different inflation models

Instead of (say 118) different models, consider classes

Type I: single-field, slow-roll models (or models that can be expressed as such)

Type Ia: large-field models
Type Ib: small-field models
Type Ic: hybrid models

Type II: anything else (branes, pre-big-bang, etc.)

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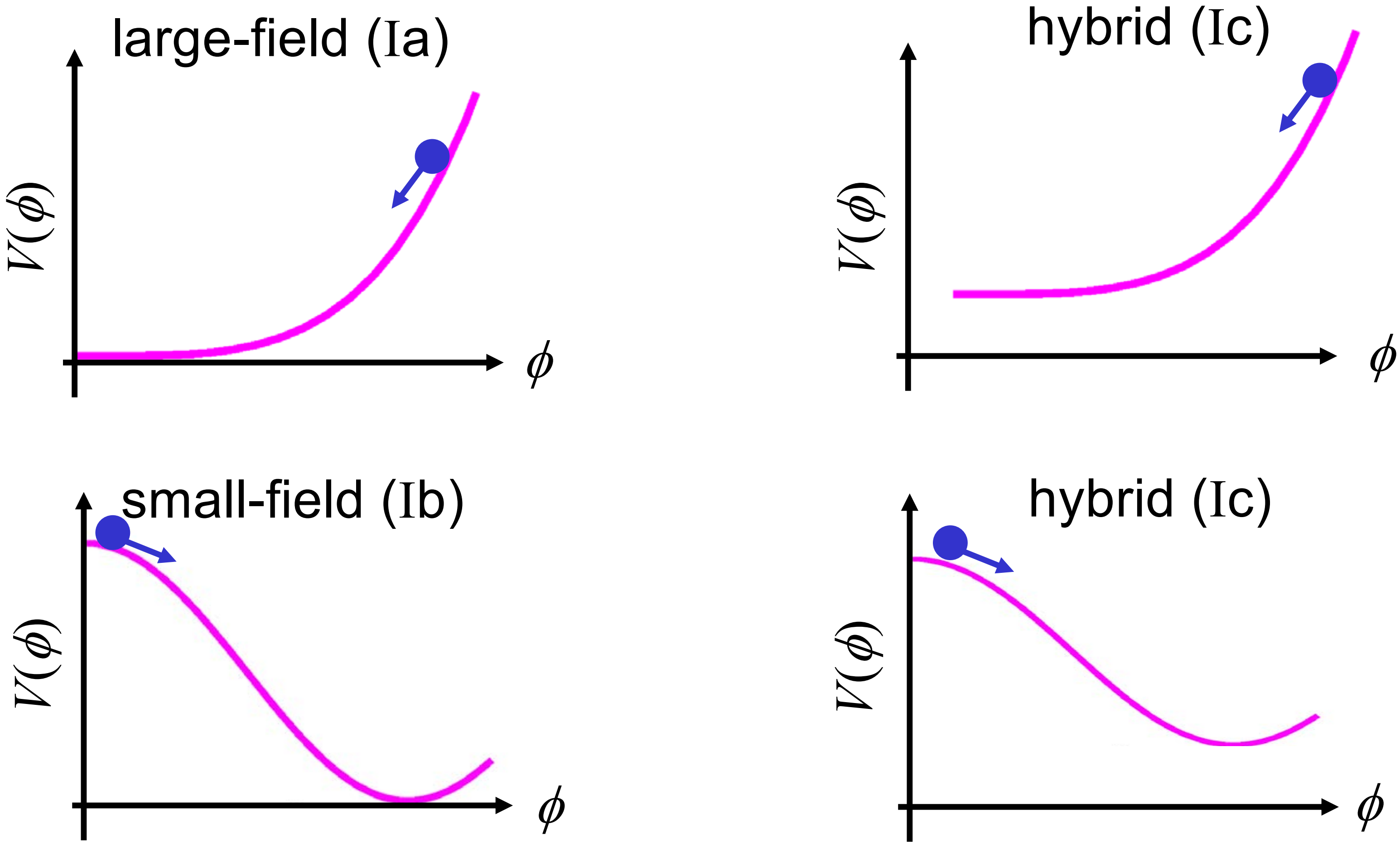
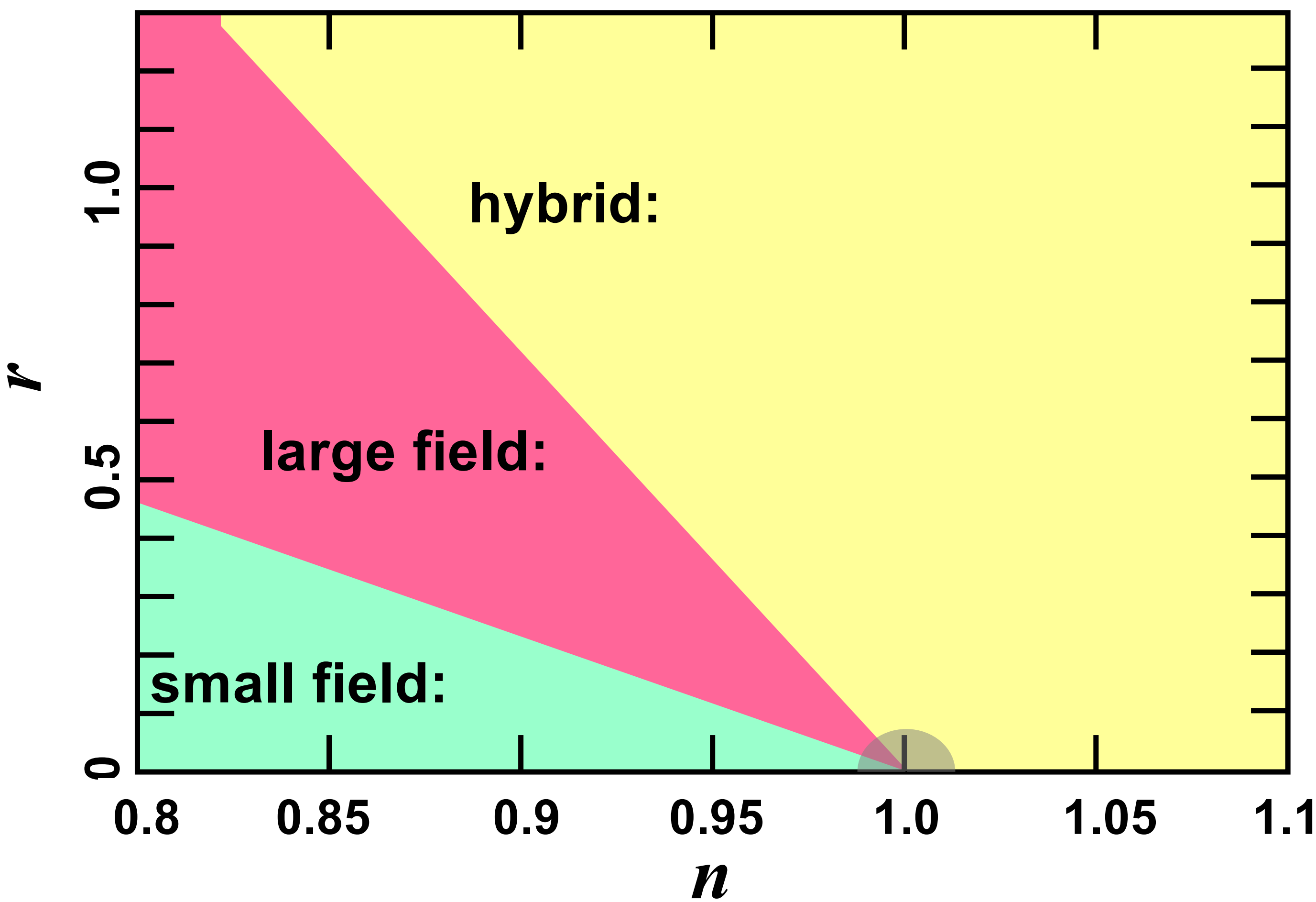
* Used for superstrings, supernovae, superconductors, …

Instead of (say 118) different models, consider classes

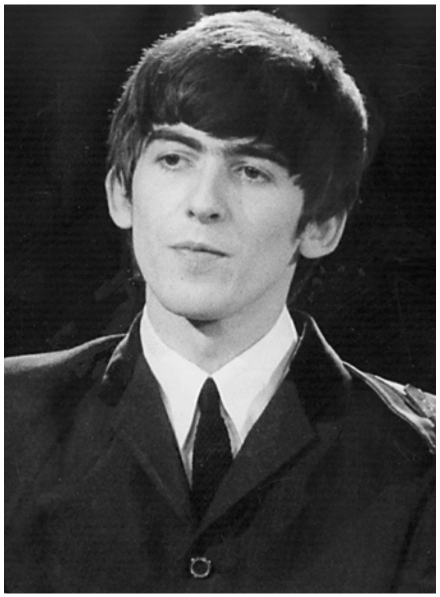


Dodelson, Kinney, Kolb 1997



$$r = \left(\text{tensor/scalar}\right)_{l=2} \qquad n = \text{scalar spectral index}$$

Harrison—Zel'dovich spectrum

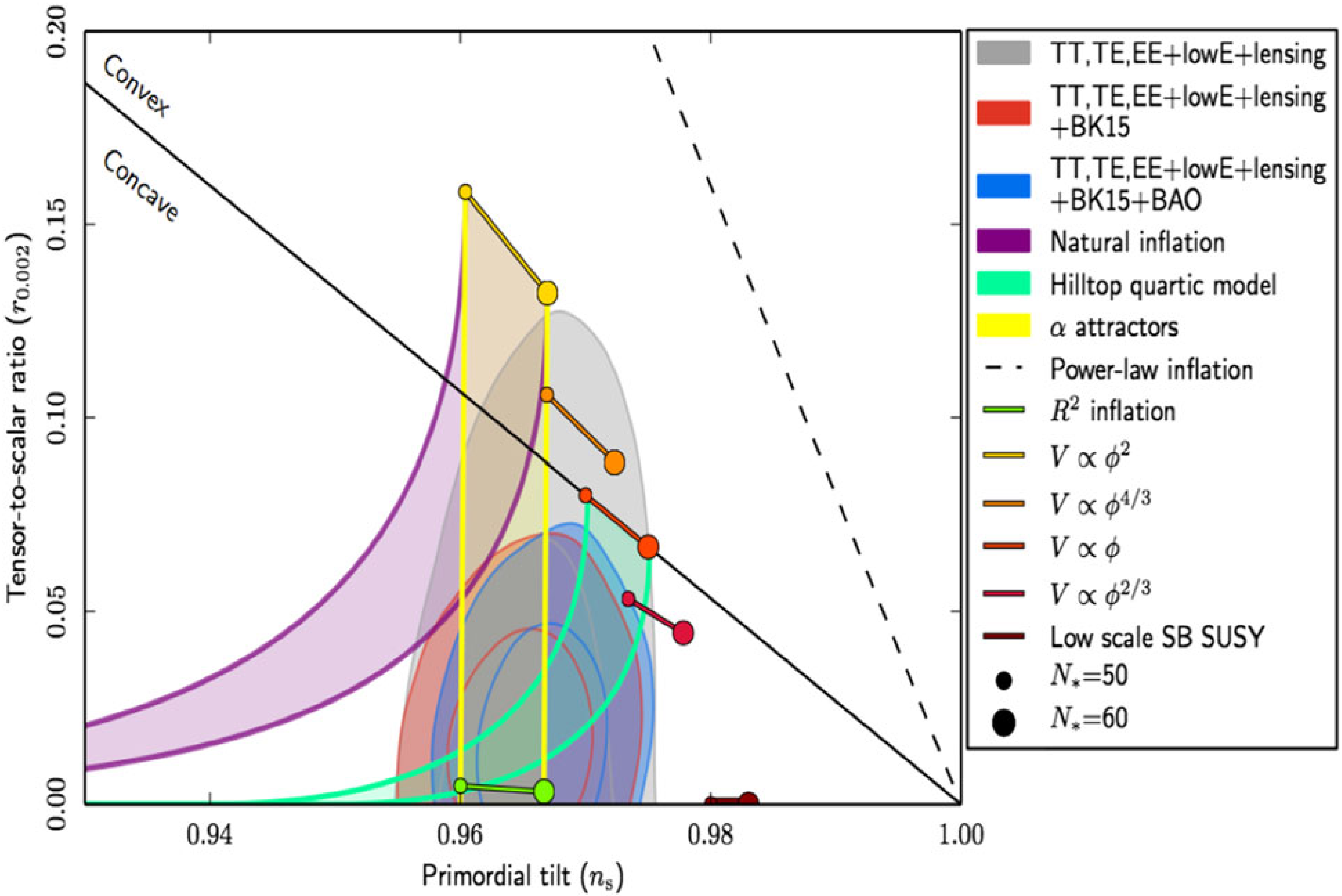


$$n \equiv 1$$

$$n' \equiv 0$$

$$r \equiv 0$$

Planck 2018



Convex
Concave
Tensor-to-scalar ratio ($r_{0.002}$)
Primordial tilt (n_s)
0.00
0.05
0.10
0.15
0.20
0.94
0.96
0.98
1.00
TT,TE,EE+lowE+lensing
TT,TE,EE+lowE+lensing +BK15
TT,TE,EE+lowE+lensing +BK15+BAO
Natural inflation
Hilltop quartic model
α attractors
Power-law inflation
R^2 inflation
$V \propto \phi^2$
$V \propto \phi^{4/3}$
$V \propto \phi$
$V \propto \phi^{2/3}$
Low scale SB SUSY
N_*=50
N_*=60

Comparison to observation:

1. a (nearly exact) *power-law*
2. spectrum of *gaussian*
3. *super-Hubble-radius*
4. *scalar* perturbations (seeds of structure) &
5. *tensor* perturbations (gravitational waves)
6. related by a *consistency relation*
7. in their *growing mode*
8. in a *spatially flat* universe.

Inflation, as a whole, can be divided into three parts

1. Beginning

   eternal inflation, wave function of the universe,
   did the universe have a beginning ????

2. Middle

   density perturbations, gravitational waves

3. End

   defrosting, heating, preheating, reheating,
   baryogenesis, phase transitions, dark matter,
   (particle production in the expanding universe)

Inflation solved some nagging problems

- Can explain homogeneity/isotropy: observable Universe once in causal contact.
- Diluted unwanted relics.
- Universe driven to flatness during inflation since $w < -1/3$.

$$\frac{d|\Omega(a)-1|}{d\ln a} = (1+3w)\,\Omega(a)\,|\Omega(a)-1|$$

- This also solves age problem.
- Universe *nearly* homogeneous/isotropic, but with small density and temperature fluctuations.

But questions remain

1. Was inflation "normal" (i.e., 3-D FRW)?
2. Can dynamics of inflation be described in terms of a single scalar field?
3. What was the expansion rate during inflation?
4. What was the general shape of the inflaton potential?
5. What was the more or less exact shape of the inflaton potential?
6. Did the perturbations arise from fluctuations in the inflaton?
7. Can inflation tell us anything about physics at very high energy scales (unification, string, Planck)?
8. Any indication of isocurvature fluctuations?
9. Any indications of non-Gaussian perturbations?

Issues

1. Transplanckian physics
    - probe of short-distance physics?
2. Defrosting
    - preheating, reheating, ….
3. Particle production
    - WIMPZILLAS, gravitons, ….
4. Why only one field?
    - isocurvature perturbations
5. Extra dimensions, brane, bulk, etc.?
    - new dynamics

The nature of inflation is a complex natural phenomenon.

Single-field, slow-roll inflation is a simple, elegant, compelling explanation.

“For every complex natural phenomenon there is a simple, elegant, compelling, but wrong explanation.”

- Tommy Gold

There is a Baryon Asymmetry in the Universe $n_{\text{baryons}} \gg n_{\text{antibaryons}}$

- The Universe is asymmetric (no antimatter, e.g., anti-planets, anti-stars, anti-galaxies, ...)

- Suppose at $T \gtrsim m_{\text{proton}}$ the Universe was baryon symmetric and baryon conserving

$b + \bar{b} \longleftrightarrow$ annihilation products with zero net baryon number

$$\dot{n}_b + 3Hn_b = \left[(n_b^{\text{EQ}})^2 - n_b^2\right] \langle |v_{\text{Moller}}| \; \sigma_A \rangle$$

- Annihilation cross section large $\Longrightarrow$

$$\Omega_b = \Omega_{\bar{b}} \propto mY_\infty \propto \frac{1}{\langle \sigma_A |v_{\text{Moller}}| \rangle} \quad \Rightarrow \Omega_b = \Omega_{\bar{b}} \sim 10^{-9}$$

CMB (Planck 2018): $\Omega_B h^2 = 0.02242 \pm 0.00014$

Changing baryon component in baryon-photon fluid:

- Changes sound speed.

$$c_S = \frac{c}{\sqrt{3}}\left(1+\frac{3}{4}\frac{\rho_B}{\rho_\gamma}\right)^{-1}$$

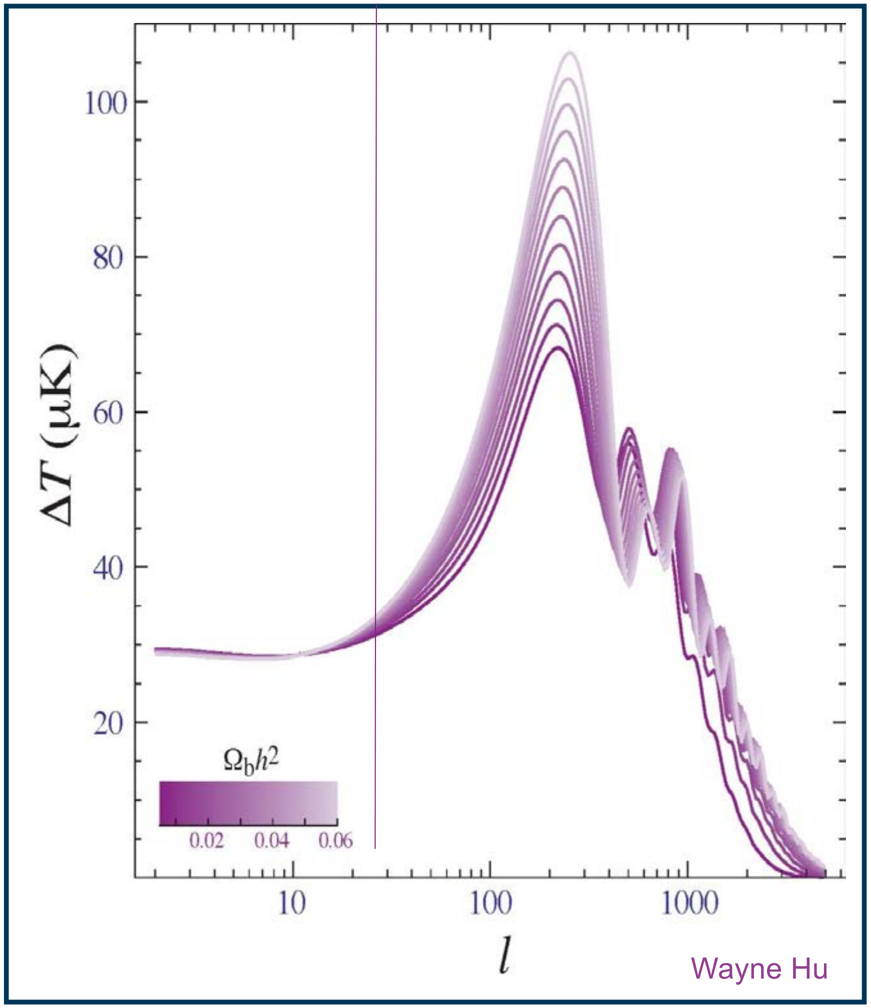
- Changes size of sound horizon.

$$r_S(\eta) = \int_0^\eta d\eta' \, c_S(\eta')$$

- Peaks moves to smaller angular scales (larger l).

$$k_{\text{PEAKS}} = n\pi / r_S$$

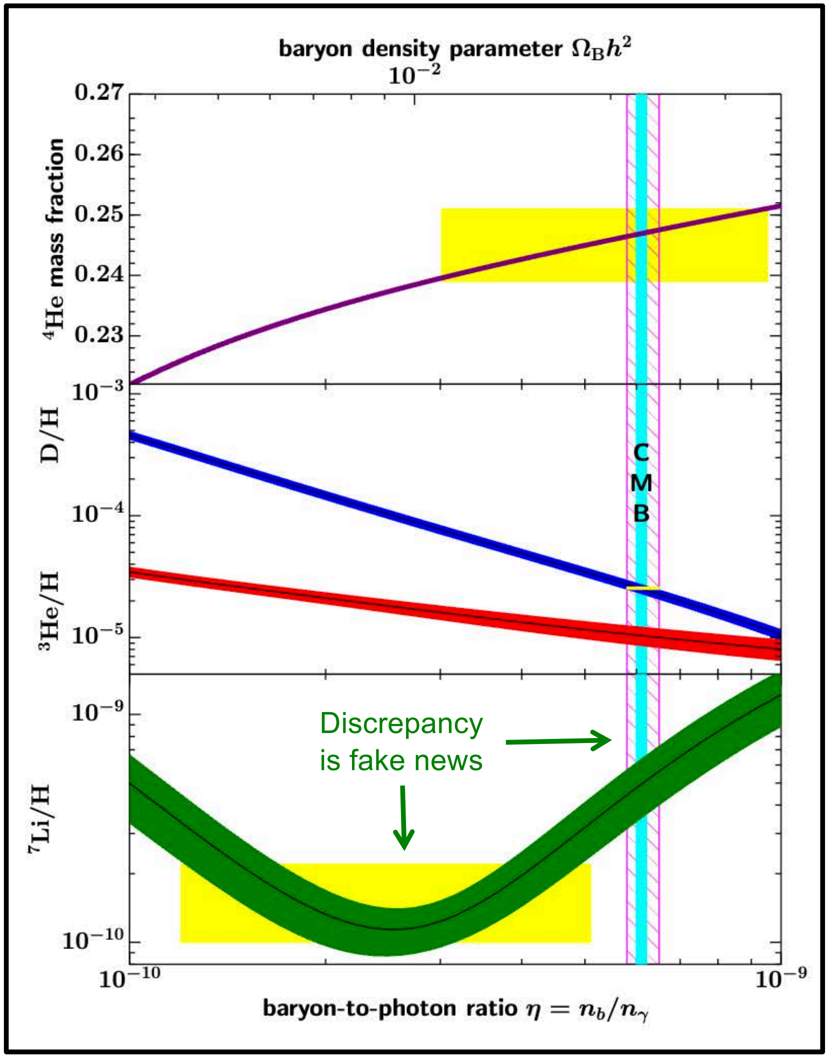
- Baryon loading increases compression peaks, lowers rarefaction peaks.



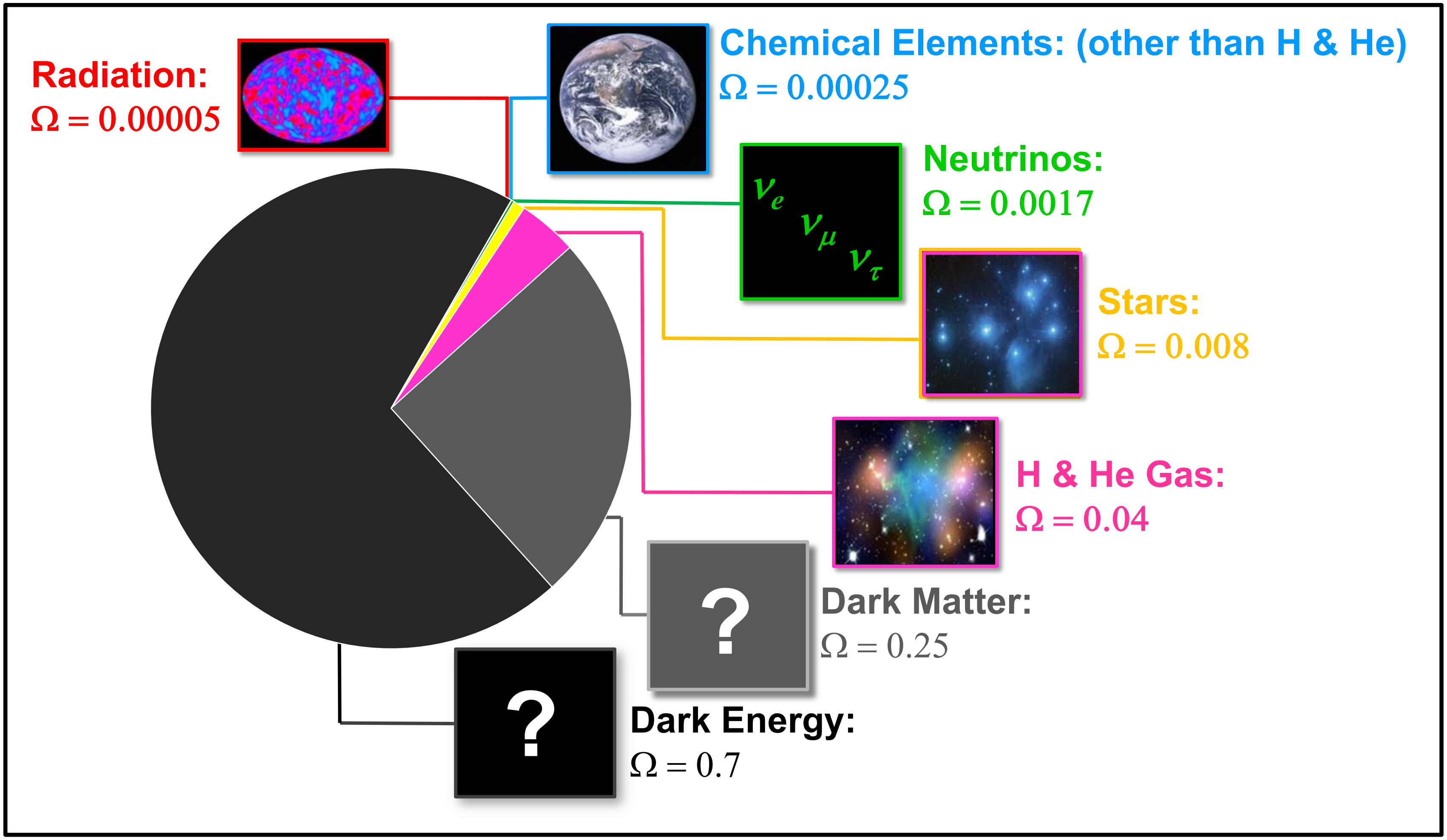
BBN (PDG 2024): $\Omega_B h^2 = 0.02205 \pm 0.00043$

Changing baryon component in baryon-photon fluid:

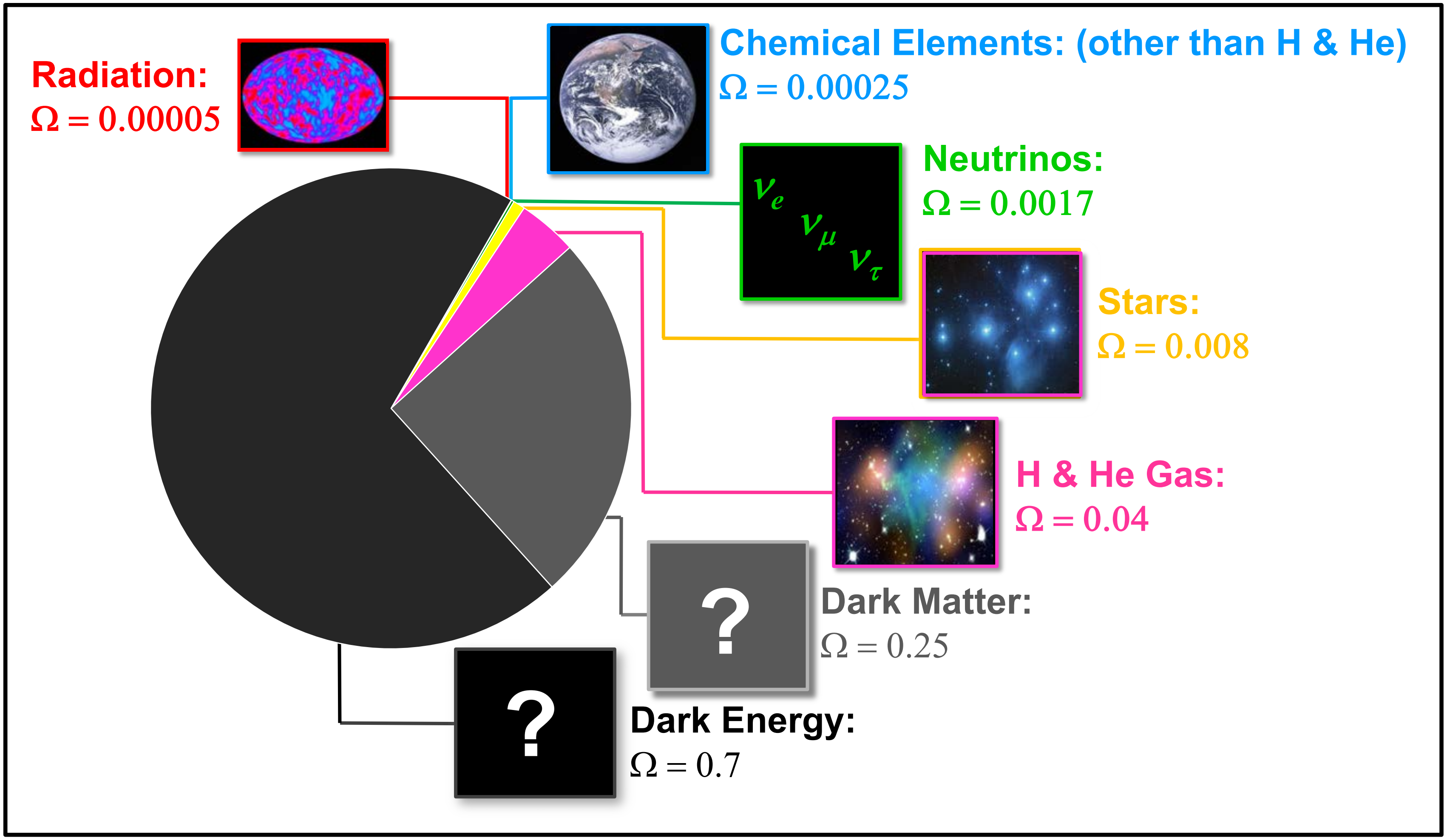
- Changes baryon-to-photon ratio η.
- In NSE, abundance of species $\propto$ to η^{A-1}.
- D, ^{3}He, ^{3}H build up changes, changing ^{4}He.
- Amount of D, ^{3}He, ^{3}H left changes.



95% of the Mass/Energy of the Universe is Mysterious



99.825% of the Mass/Energy of the Universe is Mysterious



Baryon Asymmetry

Baryon Asymmetry

Baryon Asymmetry

Baryon Asymmetry: $n_B/s = (0.861 \pm 0.005) \times 10^{-10}$

- Why is there an asymmetry between matter and antimatter?

  - Initial (anthropic?) conditions:
    - Requires "acausal" initial conditions.
    - Inflation, which seemingly evades acausal issue for density perturbations, dilutes pre-inflation baryon number by an exponential amount.

  - The modern perspective is that reheating after inflation produced a symmetric universe (equal abundances of matter & antimatter).

  - Asymmetry developed dynamically after inflation and reheating through a process known as "baryogenesis."

- Why is it about 10^{-10}?

Baryon Asymmetry: $n_B/s = (0.861 \pm 0.005) \times 10^{-10}$

- Can the standard model of particle physics explain a tiny number in the standard model of cosmology: $n_B/s = (0.861 \pm 0.005) \times 10^{-10}$?

  No, or at least, not yet!

- Can the standard model of particle physics explain an order-unity number in the standard model of cosmology: Dark Matter/Baryons $\approx$ 5.3?

  No, or at least, not yet!

- Starting after inflation/reheating with a symmetric universe, how must the SM be augmented to produce an asymmetric universe?

Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe

A. D. Sakharov

(Submitted 23 September 1966)
Pis'ma Zh. Eksp. Teor. Fiz. **5**, 32–35 (1967) [JETP Lett. **5**, 24–27 (1967).
Also S7, pp. 85–88]

Usp. Fiz. Nauk **161**, 61–64 (May 1991)

1967

Из эффекта С. Окубо
При большой температуре
Для Вселенной сшита шуба
По ее кривой фигуре

Literal translation: *Out of S. Okubo's effect*
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure.

The theory of the expanding universe, which presupposes a superdense initial state of matter, apparently excludes the possibility of macroscopic separation of matter from antimatter; it must therefore be assumed that there are no antimatter bodies in nature, i.e., the universe is asymmetrical with respect to the number of particles and antiparticles (C asymmetry). In particular, the absence of antibaryons and the proposed absence of baryonic neutrinos implies a nonzero baryon charge (baryonic asymmetry). We wish to point out a possible explanation of C asymmetry in the hot model of the expanding universe (see Ref. 1) by making use of effects of CP invariance violation (see Ref. 2). To explain baryon asymmetry, we propose in addition an approximate character for the baryon conservation law.

We assume that the baryon and muon conservation laws are not absolute and should be unified into a "combined" baryon-muon charge $n_c = 3n_B - n_\mu$. We put

for antimuons μ_+ and $\nu_\mu = \mu_0$: $n_\mu = -1$, $n_\kappa = +1$.

for muons μ_- and $\nu_\mu = \mu_0$: $n_\mu = +1$, $n_\kappa = -1$.

for baryons P and N: $n_B = +1$, $n_\kappa = +3$.

for antibaryons P and N: $n_B = -1$, $n_\kappa = -3$.

This form of notation is connected with the quark concept; we ascribe to the p, n, and λ quarks $n_c = +1$, and to antiquarks, $n_c = -1$. The theory proposes that under laboratory conditions processes involving violation of n_B and n_μ play a negligible role, but they were very important during the earlier stage of the expansion of the universe.

We assume that the universe is neutral with respect to the conserved charges (lepton, electric, and combined), but C asymmetrical during the given instant of its development (the positive lepton charge is concentrated in the electrons and the negative lepton charge in the excess of antineutrinos over the neutrinos; the positive electric charge is concentrated in the protons and the negative in the electrons; the positive combined charge is concentrated in the baryons, and the negative in the excess of μ neutrinos over μ antineutrinos).

According to our hypothesis, the occurrence of C asymmetry is the consequence of violation of CP invariance in the nonstationary expansion of the hot universe during the superdense stage, as manifest in the difference between the partial probabilities of the charge-conjugate reactions. This effect has not yet been observed experimentally, but its existence is theoretically undisputed (the first concrete example, Σ_+ and Σ_- decay, was pointed out by S. Okubo as early as 1958) and should, in our opinion, have much cosmological significance.

We assume that the asymmetry has occurred in an earlier stage of the expansion, in which the particle, energy, and entropy densities, the Hubble constant, and the temperatures were of the order of unity in gravitational units (in conventional units the particle and energy densities were $n \sim 10^{98}$ cm^{-3} and $\varepsilon \sim 10^{114}$ erg/cm^3).

M. A. Markov (see Ref. 3) proposed that during the early stages there existed particles with maximum mass of the order of one gravitational unit ($M_0 = 2 \times 10^{-5}$ g in ordinary units), and called them maximons. The presence of such particles leads unavoidably to strong violation of thermodynamic equilibrium. We can visualize that neutral spinless maximons (or photons) are produced at $t < 0$ from contracting matter having an excess of antiquarks, that they pass "one through the other" at the instant $t = 0$ when the density is infinite, and decay with an excess of quarks when $t > 0$, realizing total CPT symmetry of the universe. All the phenomena at $t < 0$ are assumed in this hypothesis to be CPT reflections of the phenomena at $t > 0$. We note that in the cold model CPT reflection is impossible and only T and TP reflections are kinematically possible. TP reflection was considered by Milne, and T reflection by the author; according to modern notions, such a reflection is dynamically impossible because of violation of TP and T invariance.

We regard maximons as particles whose energy per particle ε/n depends implicitly on the average particle density n. If we assume that $\varepsilon/n \sim n^{-1/3}$, then ε/n is proportional to the interaction energy of two "neighboring" maximons $(\varepsilon/n)^2 n^{1/3}$ (cf. the arguments in Ref. 4). Then $\varepsilon \sim n^{2/3}$ and

0038-5670/91/050392-02$01.00

For the universe to evolve from $B = 0$ to $B \neq 0$, requires:

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

Many, Many Models for Baryogenesis

<u>To be discussed:</u>

Electroweak Baryogenesis
Thermal Leptogenesis

<u>Other possibilities:</u>

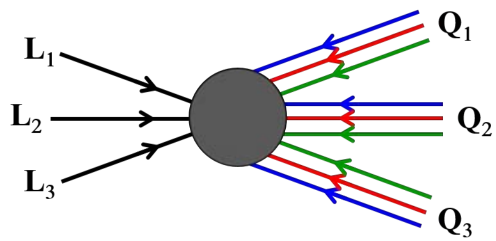
GUT Baryogenesis
Affleck-Dine Baryogenesis
Spontaneous Baryogenesis
Baryogenesis from
- Primordial Cosmic Strings
- Primordial Magnetic Fields
- Primordial Black Holes

Dissipative Baryogenesis
Warm Baryogenesis
Cloistered Baryogenesis
Cold Baryogenesis
Planck Baryogenesis
Post-Sphaleron Baryogenesis
WIMPy Baryogenesis
Dirac Leptogenesis
Resonant Leptogenesis
Non-Local Electroweak Baryogenesis
Magnetic-Assisted EW Baryogenesis
Singlet-Assisted EW Baryogenesis
Varying Constants Driven Baryogenesis

Sakharov Criteria in the Standard Model

1. Baryon number violating processes $\left[\hat{B},\hat{H}\right]\neq 0$:

Yes in SM
(nonperturbatively)
Conserves B – L



Zero temperature: 't Hooft

$\Gamma \propto e^{-16\pi^2/g^2} \approx 10^{-171}$

Non-zero temperature: Klinkhamer & Manton

$\Gamma \propto \left(M_W/\alpha_W T\right)^3 M_W^4\, e^{-E_{sph}(T)/T}$ $\quad \langle h\rangle \neq 0$

$\Gamma \propto \left(\alpha_W T\right)^4$ $\quad \langle h\rangle = 0$

2. C and CP violating processes:

Yes in SM
Direct CP violation
(CKM)

But Jarlskog invariant <u>very</u> small: Gavela, Hernandez, Orloff, & Pene

$\not{CP} \propto (m_t^2-m_c^2)\,(m_t^2-m_u^2)\,(m_c^2-m_u^2)\,(m_b^2-m_s^2)\,(m_b^2-m_d^2)\,(m_s^2-m_d^2)\times 2J$

$J = c_{12}\, c_{13}^2\, c_{23}\, s_{12}\, s_{13}\, s_{23}\, \sin\delta$

3. Nonequilibrium conditions: Dimopoulos & Susskind

No in SM and
standard cosmology

$$\langle\hat{\mathrm{B}}\rangle_T = \mathrm{Tr}\left[e^{-\beta\hat{H}}\hat{\mathrm{B}}\right] = \mathrm{Tr}\left[(\widehat{\mathrm{CPT}})(\widehat{\mathrm{CPT}})^{-1}e^{-\beta\hat{H}}\hat{\mathrm{B}}\right]$$
$$= \mathrm{Tr}\left[e^{-\beta\hat{H}}(\widehat{\mathrm{CPT}})^{-1}\hat{\mathrm{B}}\,(\widehat{\mathrm{CPT}})\right] = -\langle\hat{\mathrm{B}}\rangle_T$$

CPT conserved ⇒

$$\left[\widehat{\mathrm{CPT}},\hat{H}\right] = 0$$

Thermal Leptogenesis (Fukugita & Yanagida)

- Type-I see-saw model (Gell-Mann, Ramond & Slansky; Yanagida; Mohapatra & Senjanovic; Schecter & Valle) for neutrino masses and mixing enlarges the SM to include a Majorana neutrino N with a large mass which couples to SM leptons and Higgs via $\mathcal{L} = -\lambda\, L\, H\, N.$

- Large Majorana mass for N; small Dirac mass for ν (generated by EWK Higgs mechanism). The see-saw results in light neutrino mass of

  $$m_\nu \approx 0.3\ \text{eV}\ (\lambda\,/\,0.1)^2\ (10^{12}\ \text{GeV}\,/m_N)^2 \ \rightarrow\ \text{so want}\ \ m_N \approx 10^{12}\ \text{GeV}.$$

- N decays to SM leptons + Higgs, violating lepton number by ± 1:

  $N \rightarrow L\, H$ or $N \rightarrow \bar{L}\ \bar{H}$ Lepton-number violation.

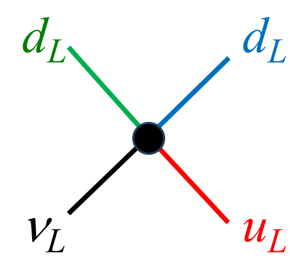
- Assume $\Gamma(N \rightarrow \bar{L}\,\bar{H}\,) > \Gamma(N \rightarrow L\,H\,)$ CP violation.

- If nonequilibrium conditions, can generate a lepton asymmetry with $B - L \neq 0$.

- Electroweak Sphalerons destroy $B + L$ at $T \gtrsim 100$ GeV, conserve $B - L$ always.

- $B = \frac{1}{2}(B + L) + \frac{1}{2}(B - L)$ If start with initial $L_i \neq 0$ & $B_i = 0$, end with $B_f = -L_i\,/\,2$.

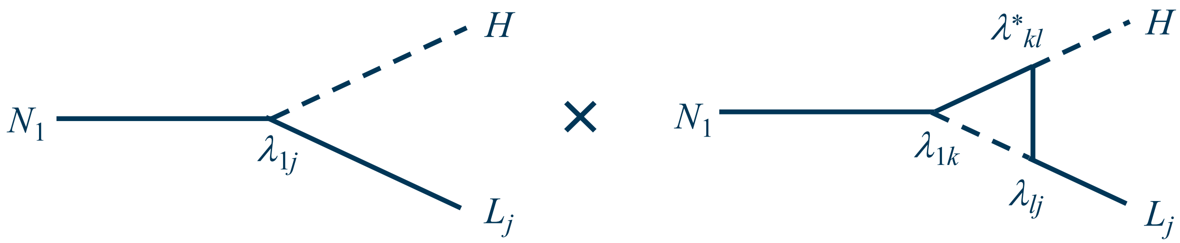
  ($B + L \rightarrow 0$) (Actually $B_f = -28\,L_i\,/\,79$ Harvey & Turner.)



Thermal Leptogenesis

CP violation

- Require interference between tree amplitude and loop corrections, e.g.,



- Lepton number generated in decay proportional to CP parameter $\boldsymbol{\varepsilon}_1$:

$$\epsilon_1 \equiv \frac{\left|\mathcal{M}_{N_1 \to \bar{l}\bar{H}}\right|^2 - \left|\mathcal{M}_{N_1 \to lH}\right|^2}{\left|\mathcal{M}_{\mathrm{TOTAL}}\right|^2} = \frac{3}{16\pi} \frac{1}{(\lambda^\dagger \lambda)_{11}} \sum_{i=1,2,3} \mathrm{Im}\left[(\lambda^\dagger \lambda)^2_{i1}\right] \frac{M_1}{M_i} < \frac{3}{16\pi} \frac{M_1 m_3}{\langle h \rangle^2}$$

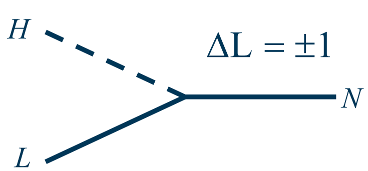
CP violation expressed in terms of microphysics

- If completely out of equilibrium (only drift and decay) $n_B/s \approx 10^{-2}\epsilon$

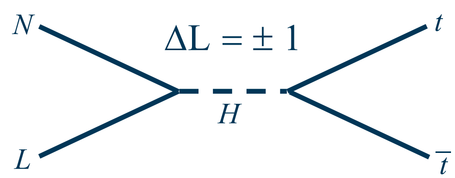
Thermal Leptogenesis

Nonequilibrium conditions

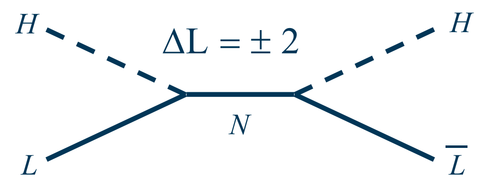
1. N decay products thermalize; if temperature large enough can washout lepton number through processes like:



Inverse decay, $H\,L \to N$



$2 \leftrightarrow 2$ scattering, $N\,L \leftrightarrow \bar{t}\,t$



$2 \leftrightarrow 2$ scattering, $H\,L \leftrightarrow H\,\bar{L}$

2. Efficiency of washout depends on competition between reaction rates (function of model parameters and T) and expansion rate $H \approx T^2 / M_{\rm Pl}$.

3. Interesting constraints on neutrino-sector parameters:
   - Condition for M_1 to decay out-of-equilibrium: $\tilde{m}_1 \equiv \dfrac{\left(m_D^\dagger m_D\right)_{11}}{M_1} \lesssim 10^{-3}\mathrm{eV} \qquad (m_1 < \tilde{m}_1 < m_3).$
   - Bound on r.m.s. neutrino mass to avoid $\Delta L = 2$ washout: $\sqrt{\sum_{i=e,\mu,\tau} m_{\nu_i}^2} \leq 0.3\ \mathrm{eV}.$

Thermal Leptogenesis

- Leptogenesis is BSM, but motivated by observation of neutrino oscillations (and masses). Also massive right-handed N fermions present in Grand Unified Theories beyond $\mathrm{SU}(5)$, e.g., $\mathrm{SO}(10)$.

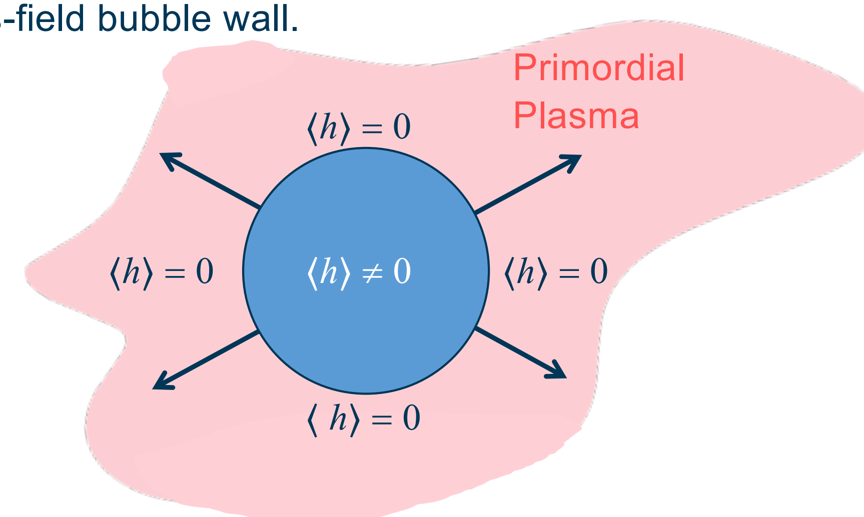
- Scenario has all the necessary ingredients: L violation from N decay followed by B violation from sphaleron conversion to B asymmetry; CP violation from complex Yukawa couplings; out-of-equilibrium decay for reasonable model parameters.

- Experimental proof of Majorana nature of neutrinos would give a boost to scenario.

- Inner-Space/Outer-Space connection between Baryon Asymmetry (one number) and the richness of the Type-I see-saw model.

Electroweak Baryogenesis

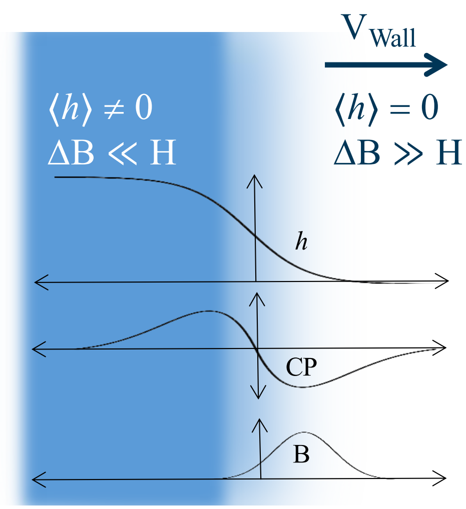
The baryon asymmetry is generated at the electroweak phase transition from the seed of CP-violating interactions of particles scattering at the Higgs-field bubble wall.



Assume 1st-order EWK phase transition: nucleate broken-phase bubble in symmetric phase background (phase coexistence → nonequilibrium conditions).

Broken phase expands into unbroken phase.

In broken phase sphalerons suppressed $\exp(-E_{sph}/T)$, while in symmetric phase sphalerons unsuppressed.



1. If ~~CP~~ in Higgs/fermion interactions, different transmission & reflection of left & right-handed quarks at the wall leads to CP asymmetry at wall.
2. Sphalerons violate B, they interact with q_L (not q_R) CP asymmetry converted to baryon asymmetry in front of wall.
3. Baryon asymmetry diffuses into broken phase across wall.

Electroweak Baryogenesis

Problems:

1. Phase transition not 1^{st}-order in the Standard Model (Higgs mass too large; need $m_h \lesssim 72$ GeV).

2. $\not{C}\mathrm{P}$ too small in the Standard Model (Jarlskog invariant small).

3. Wall velocity may be too large. As $\mathrm{V}_{\mathrm{wall}} \to 1$, wall moves too fast for baryon asymmetry to diffuse into broken-phase bubbles.

Bad News:	Electroweak baryogenesis doesn't work within the Standard Model.
Good News:	May point to directions BSM.