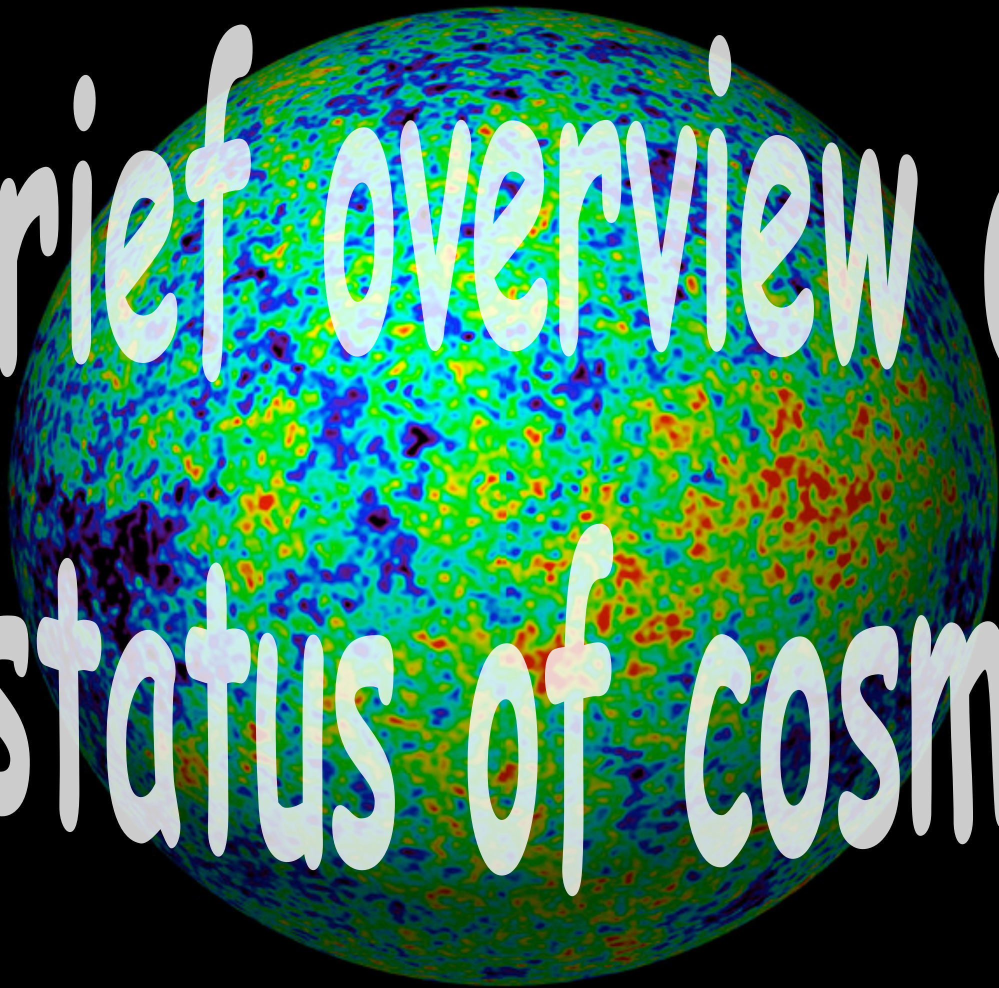
brief overview of the status of cosmology



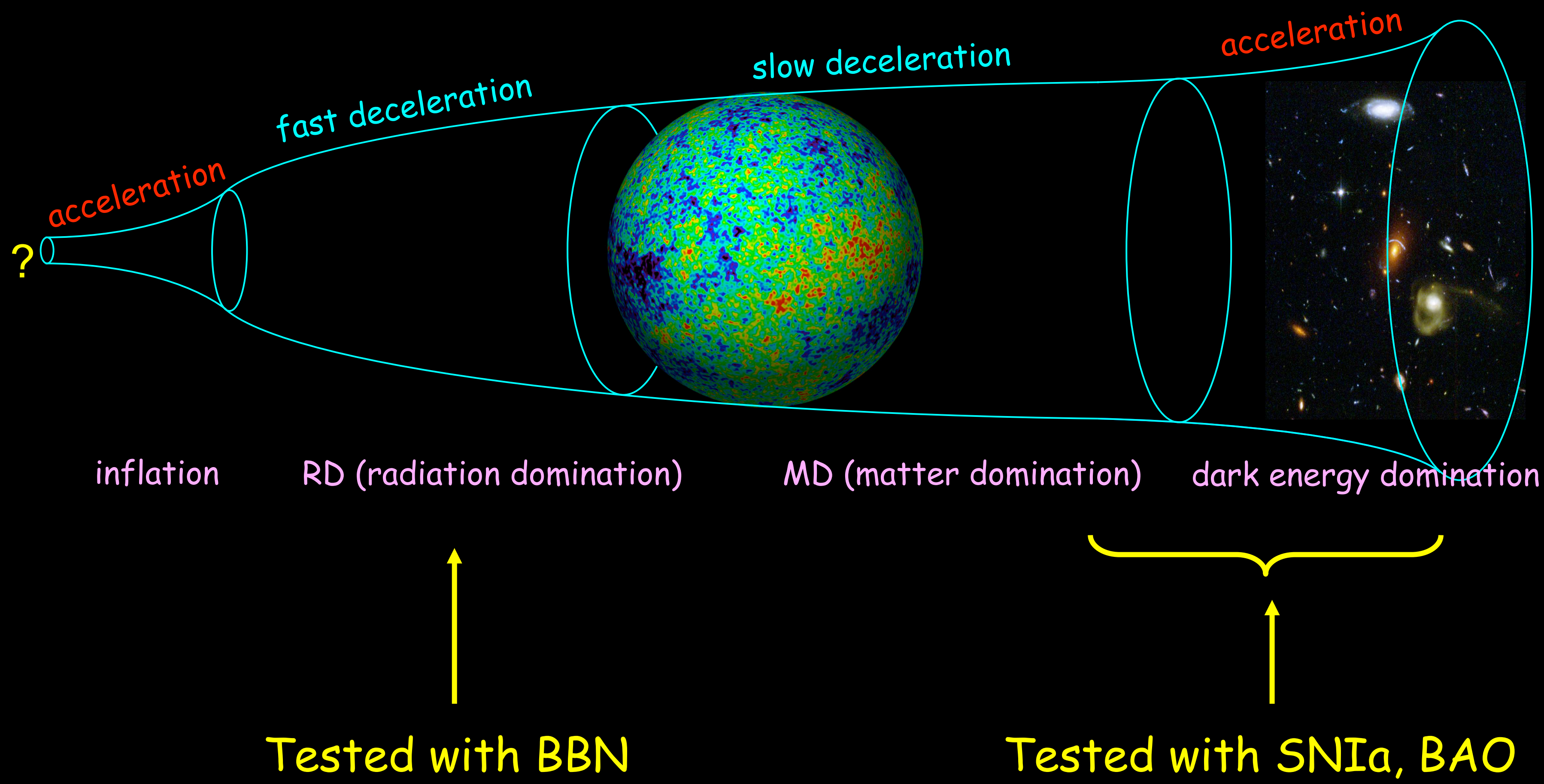
CHIPP Astroparticle meeting, EPFL, 03.06.06

Julien Lesgourgues (CERN/TH & EPFL/LPPC)

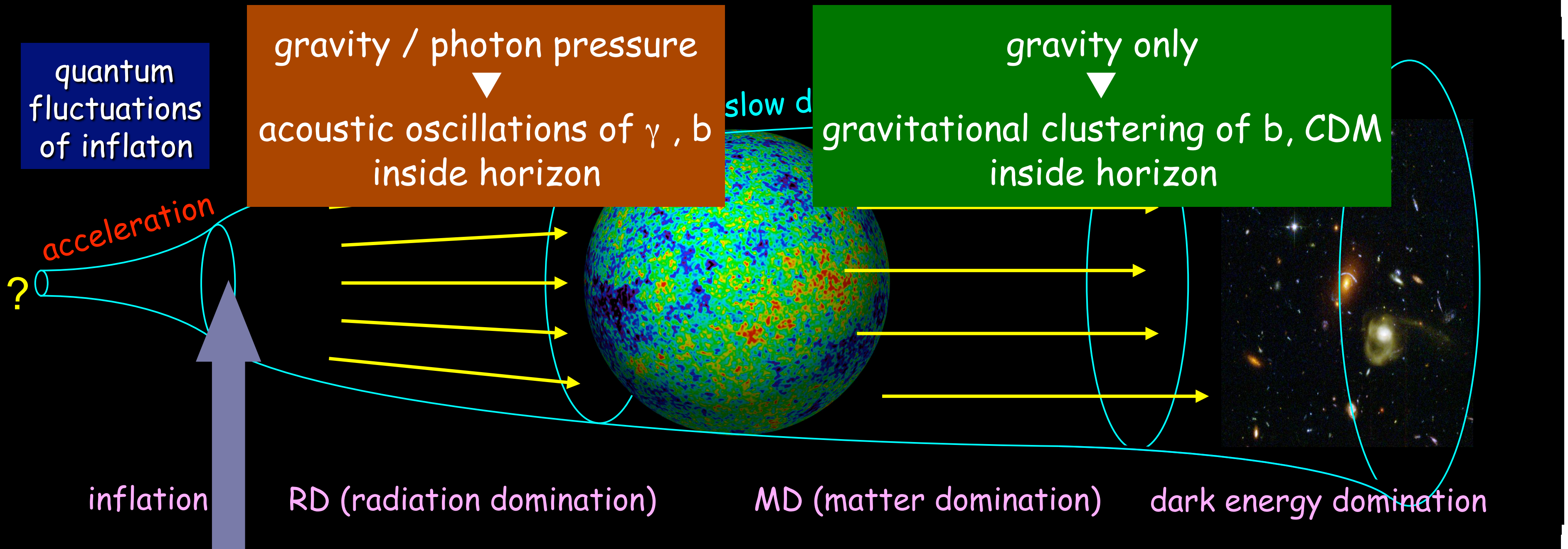
Plan

- Introduction: theory and observations
- Early universe: status of inflation
- Dark matter and neutrinos
- Universe acceleration
- Predictions for non-linear scales

Cosmological background

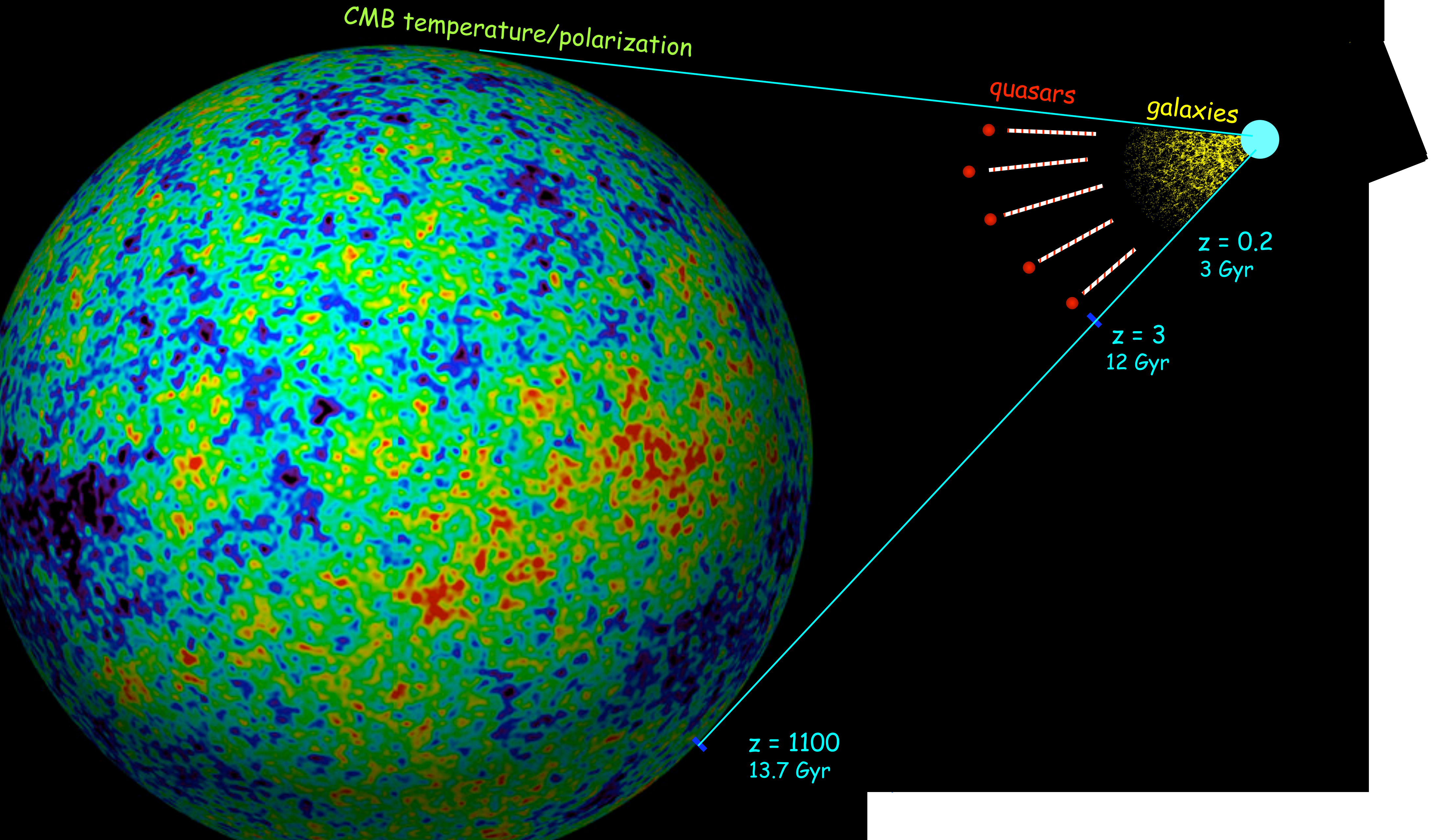


Cosmological perturbations

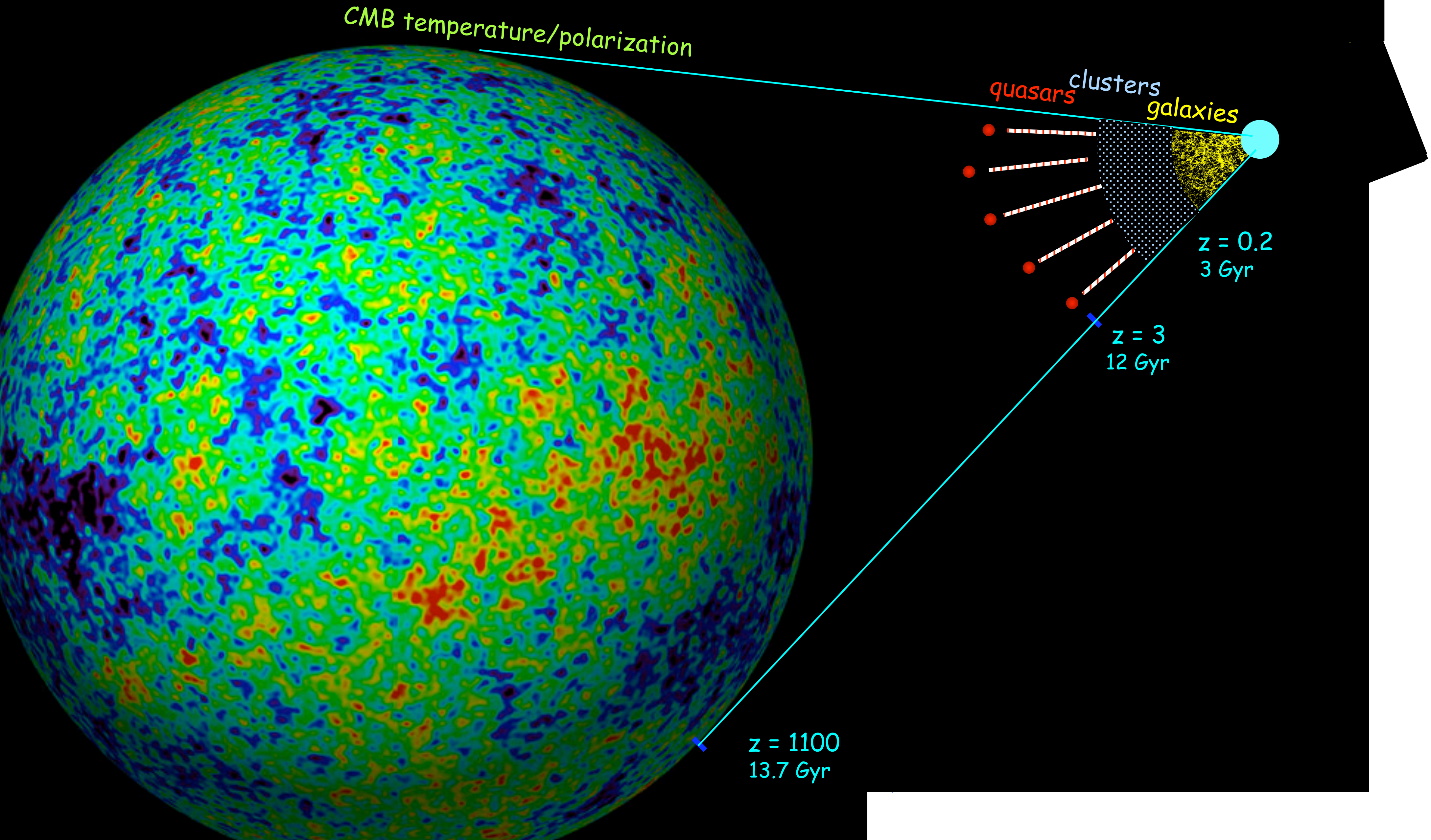


- curvature perturbations for $\lambda > R_H$
- time-independent (no entropy perturbations)
- nearly gaussian and scale-invariant

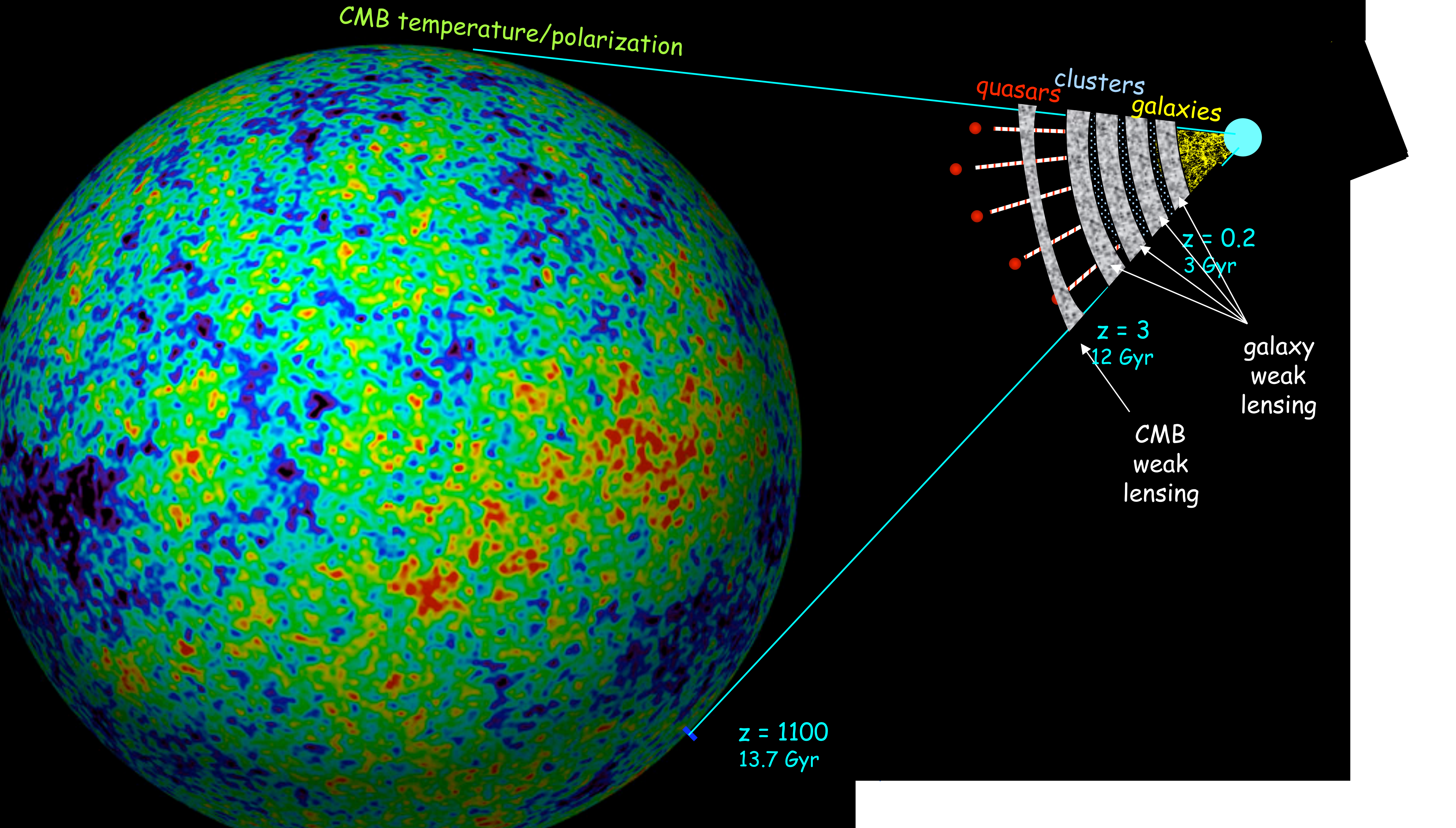
Observing perturbations



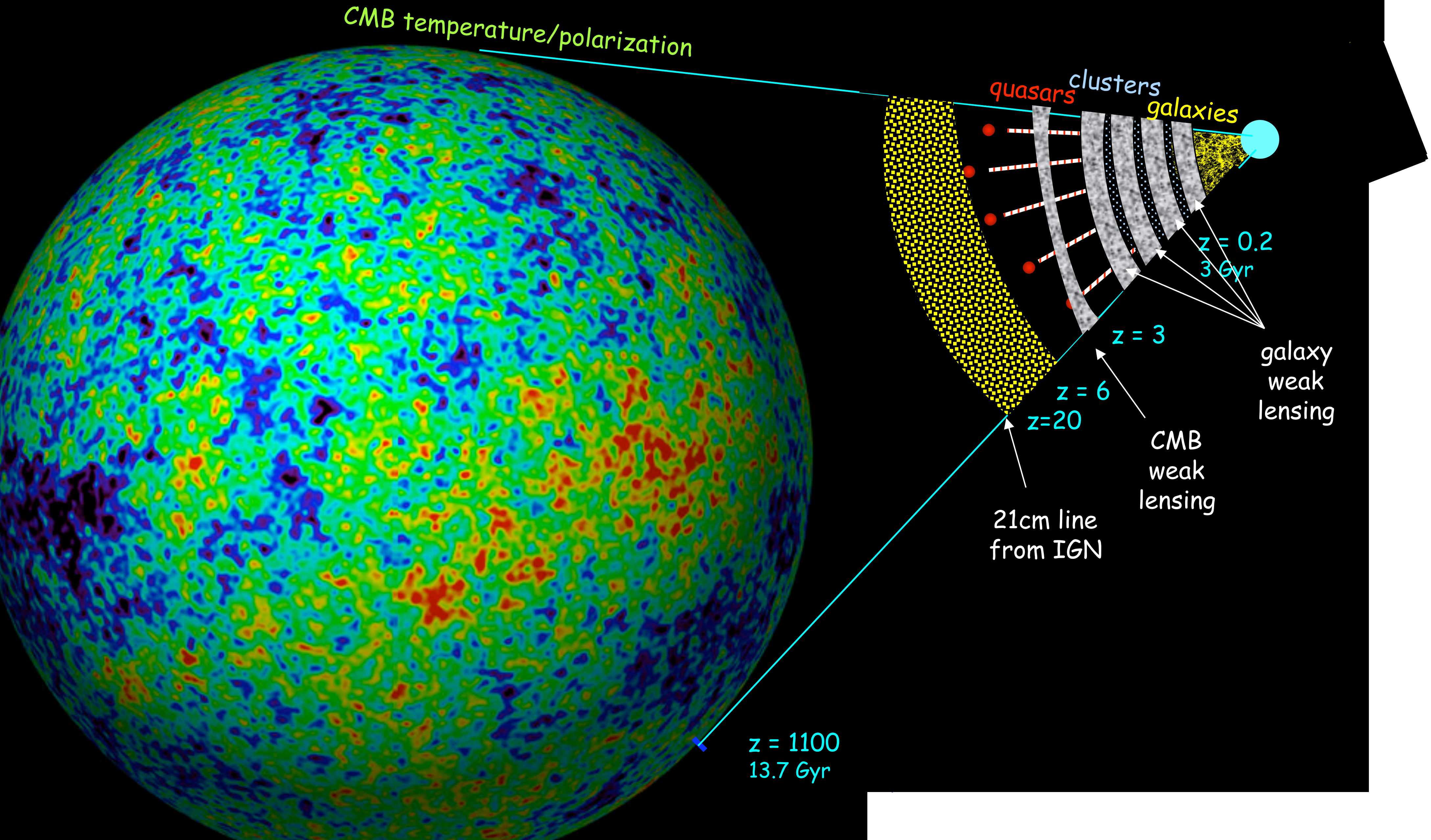
Observing perturbations

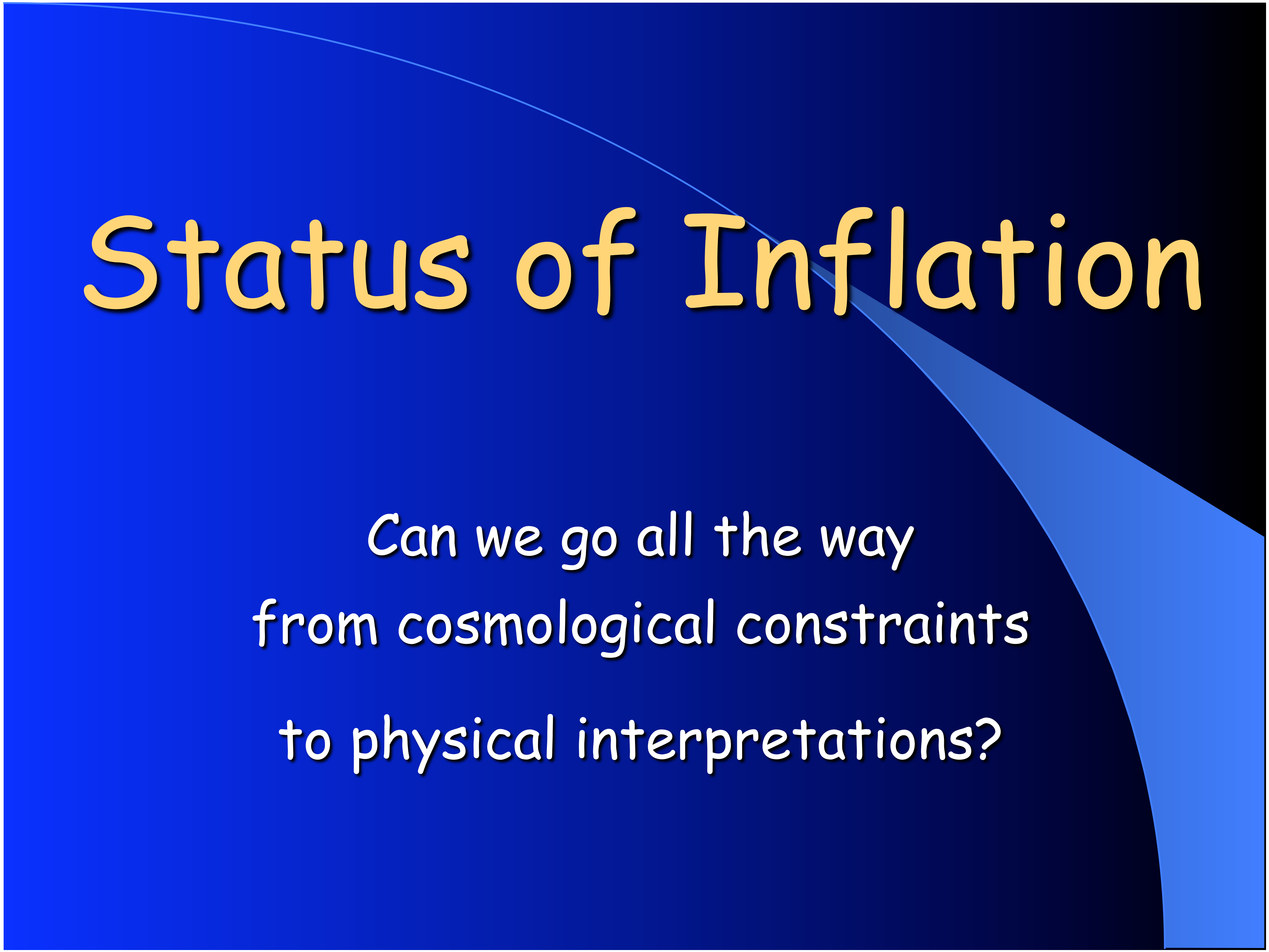


Observing perturbations



Observing perturbations

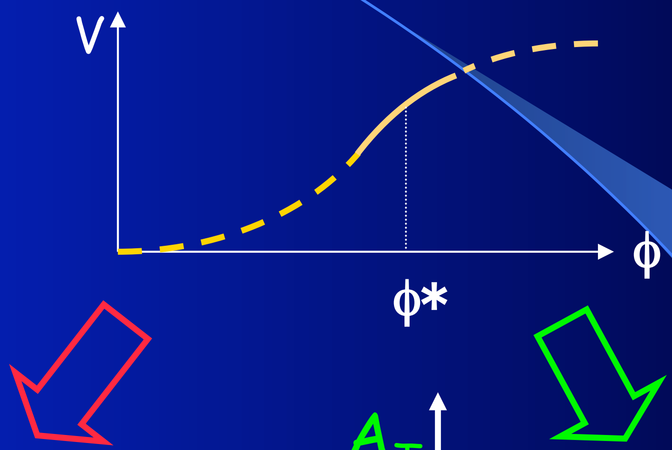


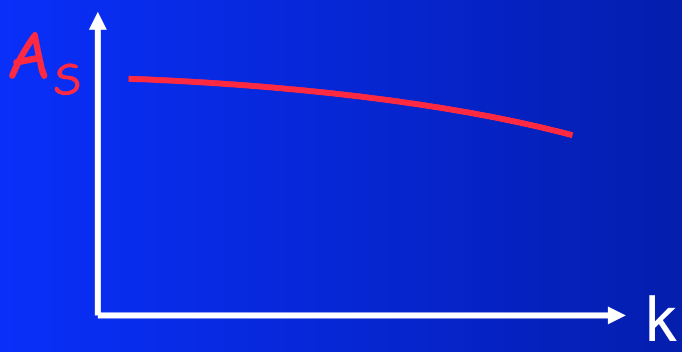

Status of Inflation
Can we go all the way
from cosmological constraints
to physical interpretations?

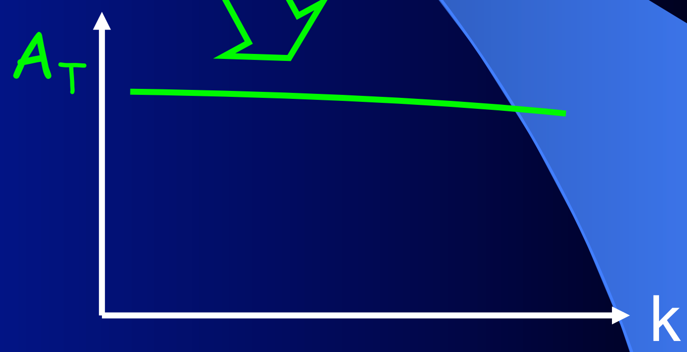
What can be measured ???

single field

slow-roll inflation :







amplitude $\leftrightarrow V^{3/2}/V'$

tilt $(1-n_S) \leftrightarrow (V'/V)^2\ ,\ V''/V$

+ next-order corrections

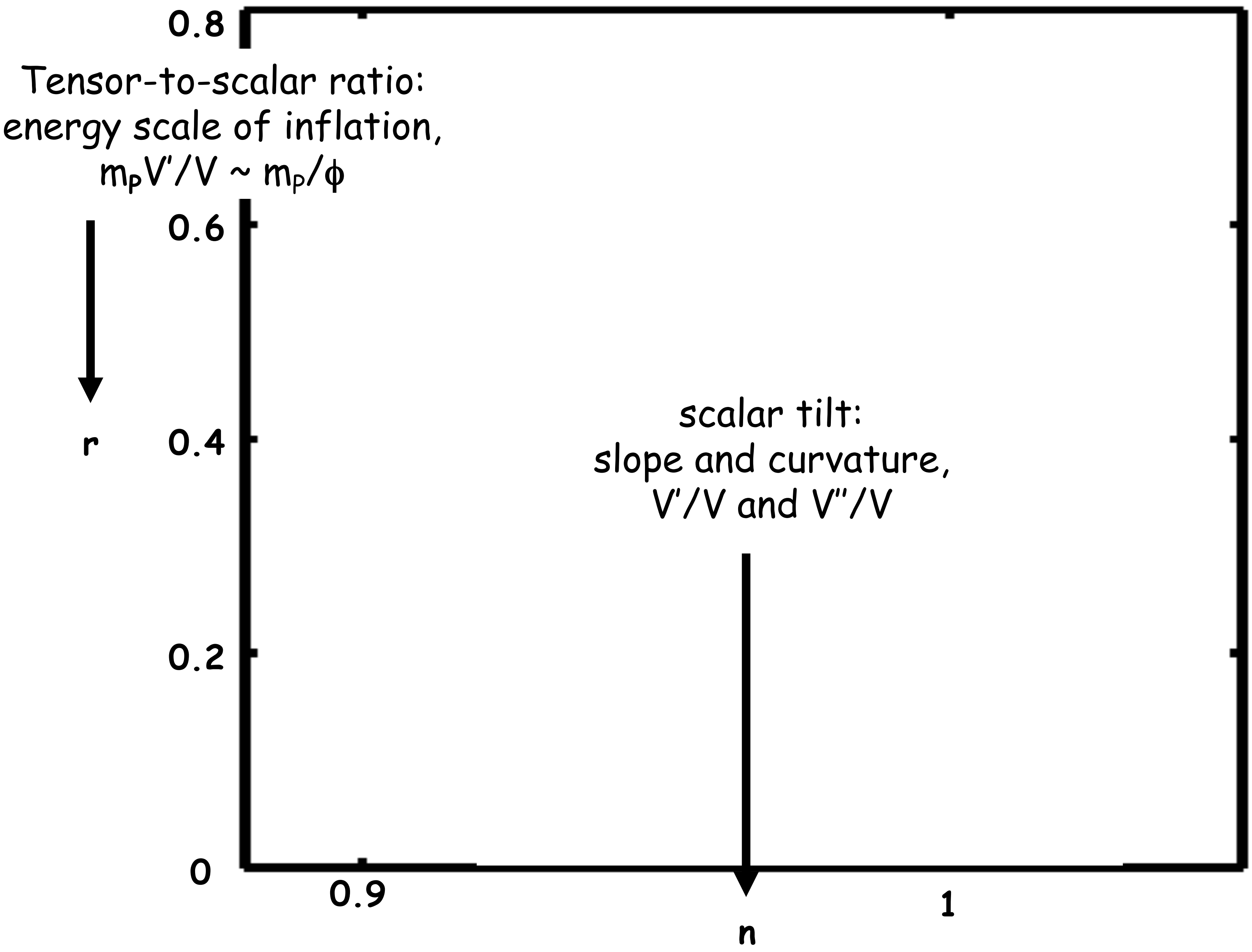
(running of the tilt, …)

amplitude $\leftrightarrow V^{1/2}$

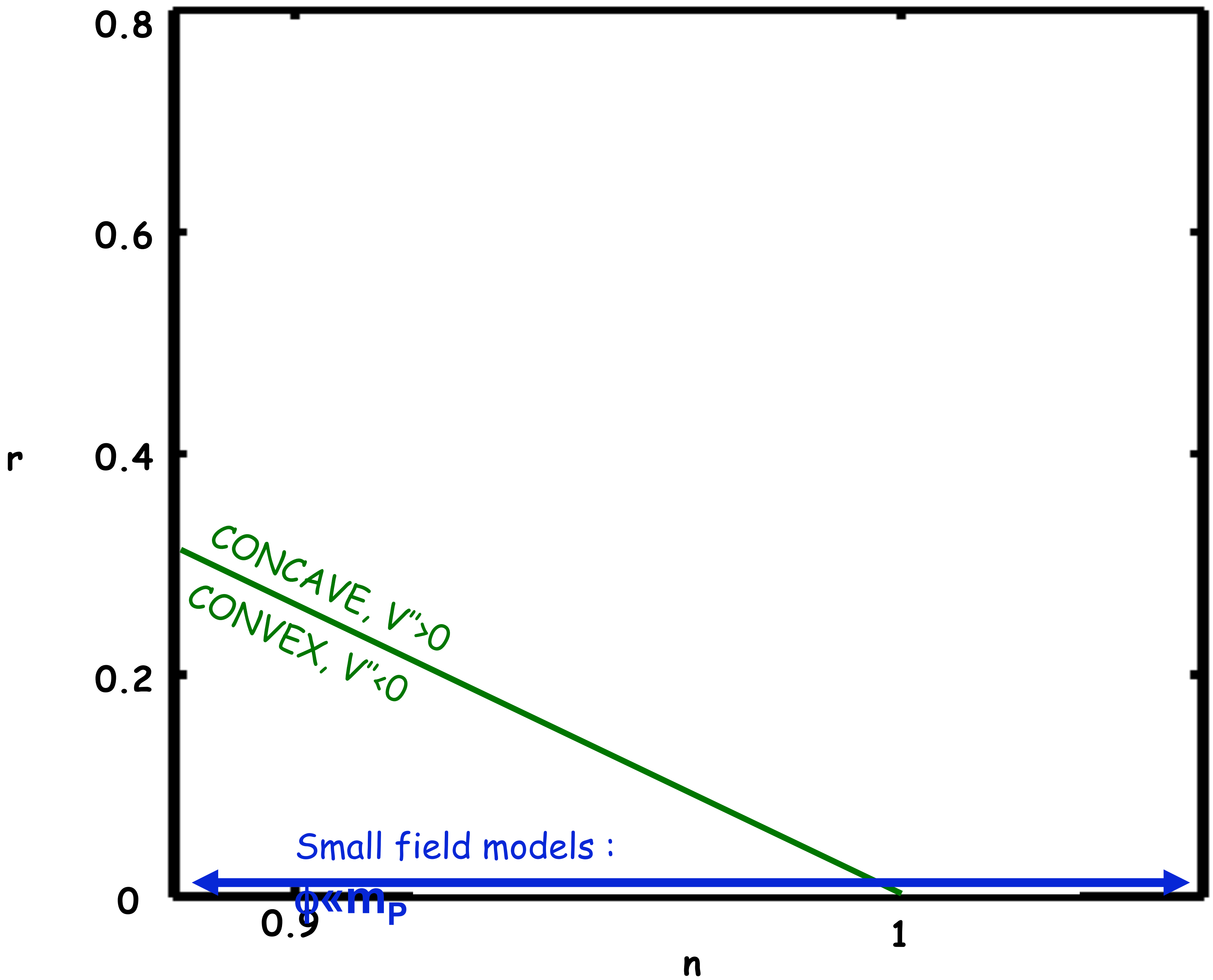
tilt $n_T \leftrightarrow (V'/V)^2$

+ next-order corrections

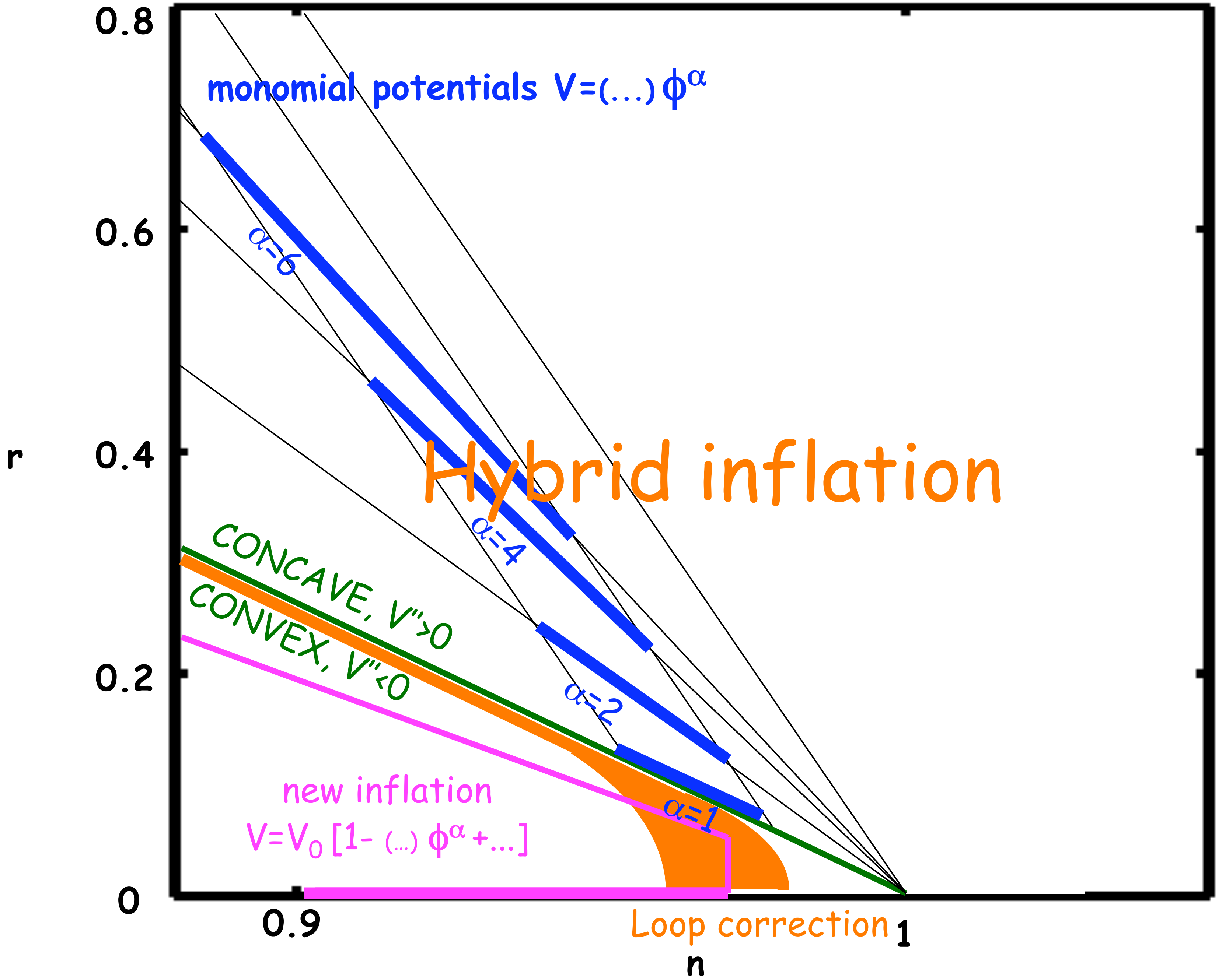
(running of the tilt, …)



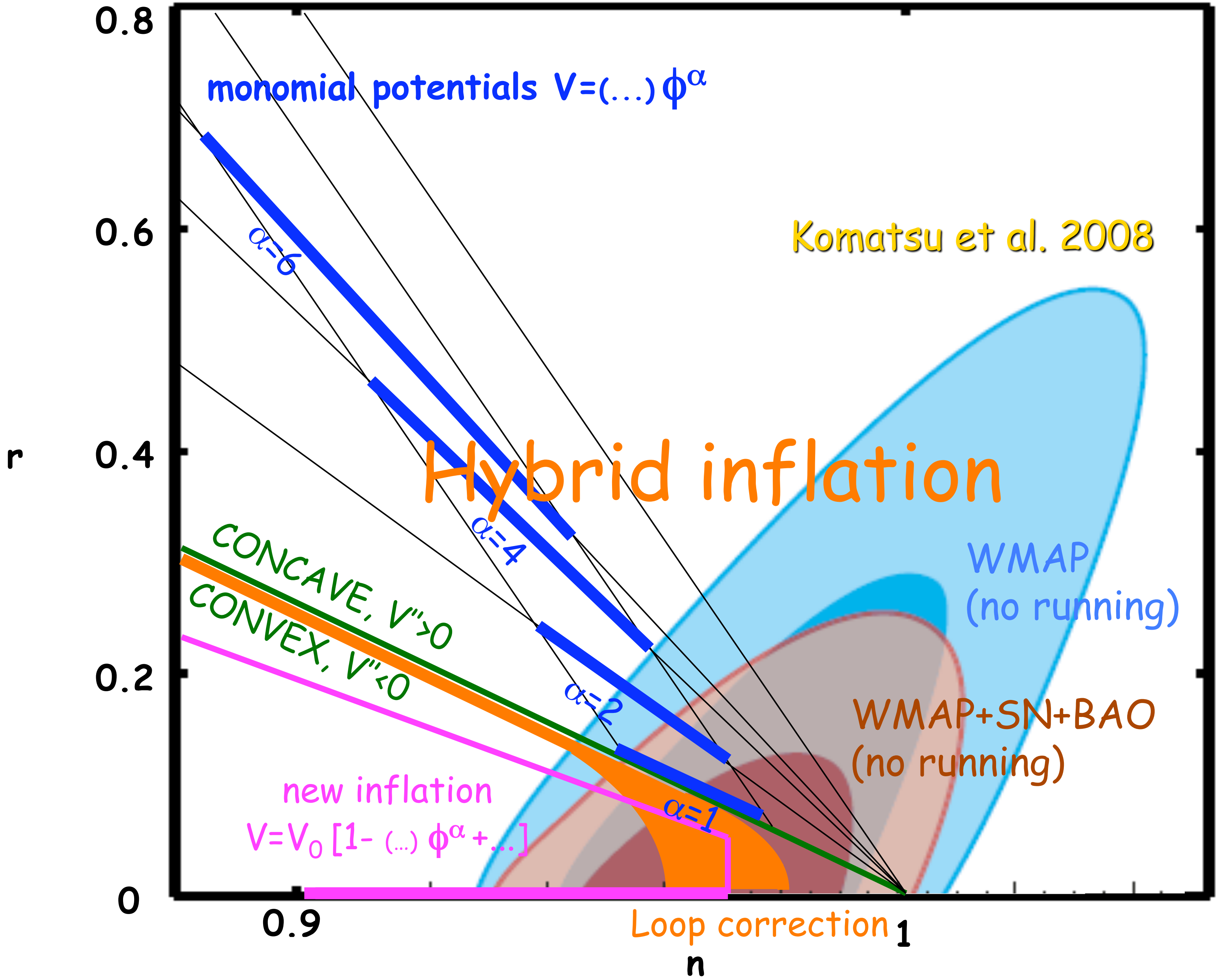
Tensor-to-scalar ratio:
energy scale of inflation,
$m_P V'/V \sim m_P/\phi$
r
0.8
0.6
0.4
0.2
0
scalar tilt:
slope and curvature,
V'/V and V''/V
0.9
1
n



0.8
0.6
r
0.4
0.2
0
0.9
1
n
CONCAVE, V''>0
CONVEX, V''<0
Small field models :
ϕ«mP



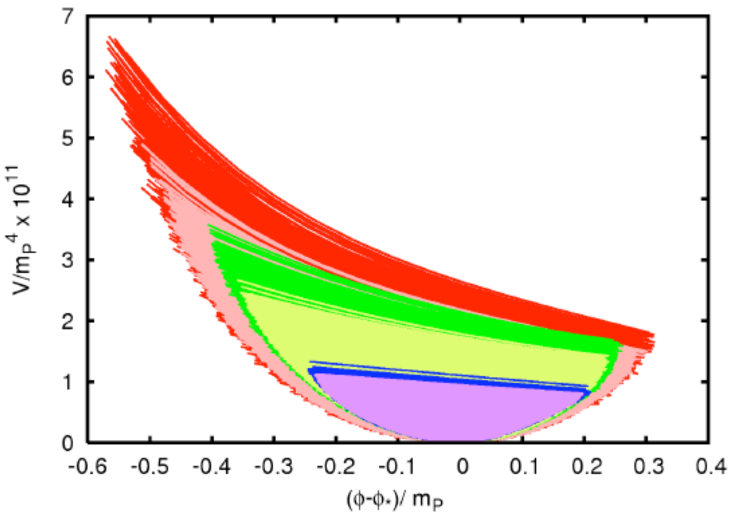
0.8
0.6
0.4
0.2
0
r
0.9
1
n
monomial potentials V=(...) φ^α
α=6
α=4
α=2
α=1
Hybrid inflation
CONCAVE, V''>0
CONVEX, V''<0
new inflation
V=V0 [1- (...) φ^α +...]
Loop correction



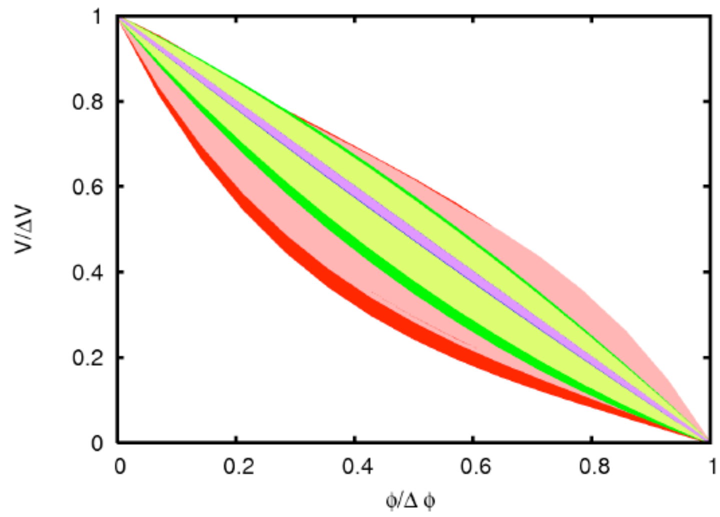
monomial potentials V=(…) ϕ^α
Komatsu et al. 2008
α=6
α=4
α=2
α=1
Hybrid inflation
WMAP
(no running)
WMAP+SN+BAO
(no running)
CONCAVE, V''>0
CONVEX, V''<0
new inflation
$V=V_0\,[1-(\dots)\,\phi^\alpha+\dots]$
Loop correction
r
n
0.8
0.6
0.4
0.2
0
0.9
1

Compatible with most potential shapes…

Observable window of inflaton potential allowed by WMAP+SDSS



rescaled to common ϕ_*



rescaled to common extremities

Valkenburg, JL & Starobinsky 2007

…frustration of the model builder…

Attempts to fit inflation within:

- most sophisticated HEP framework: SUSY, string theory, large extra-D Lyth et al., Quevedo et al., Linde et al., …

  Latest trends: brane dynamics along throat of Calabbi-Yau, inflation in landscape…

- minimal HEP framework: MSSM with non-minimal coupling of Higgs with gravity Shaposhnikov & Bezrukov 08, 09

… any model fitting observation

is degenerate with many others …

...need more smoking guns...

- Tensor amplitude/tilt (CMB, direct detection?)
  - Energy scale, self-consistency, blue tilt?

Smith et al. 2006

- Primordial non-gaussianity (CMB)
  - Predictions of 2nd order perturbation, non-perturbative approaches, ...

Matarrese et al., Vernizzi et al., Lyth et al.

  - Non-trivial issues with detection — Creminelli et al., Komatsu et al.

- entropy perturbations (CMB+LSS)
- features in the primordial spectrum (CMB+LSS)
- contribution of topological defects (CMB)

Dark Matter

Is this a question for cosmology,
or only for astroparticle physics
(cosmic rays, direct detection...) ?

Dark Matter

- CMB, LSS, SN, BAO point to $\Omega_{dm}h^2 \sim 0.1$
- Compatible with standard CDM (dust: negligible <v>, no electromagnetic interactions, no entropy perturbations)
- CDM structure formation in N-body can be accomodated with astrophysical data
- If DM=CDM, cosmology can say nothing more…

(apart from observation of caustics due to single-flow in phase space ? Sikivie et al., Bertschinger et al. 08, etc…)

Beyond standard CDM

- Non-cold : sizeable velocity dispersion:
  - affects stucture formation on scales ≤ $(\langle p\rangle/m)\, R_H$
  - Visible in (CMB), LSS, non-linear structures
- Non-dark : tiny electromagnetic coupling
- Non-adiabatic : fraction of entropy perturbations
  - Non-thermal, multiple dof's in early universe
- Non-matter : just modified gravity

Beyond standard CDM

- Non-cold : sizeable velocity dispersion:
  - affects stucture formation on scales ≤ (<p>/m) R_H
  - Visible in (CMB), LSS, non-linear structures

  active neutrinos
  WDM candidates

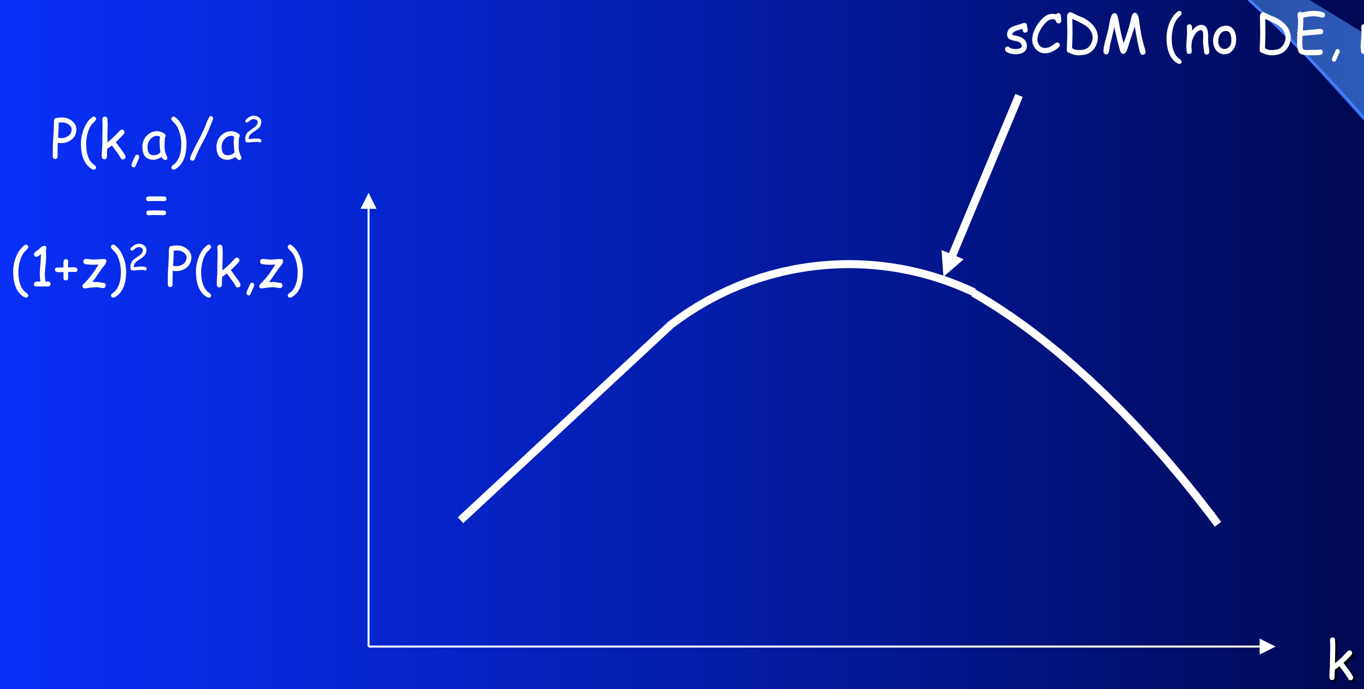
- Non-dark : tiny electromagnetic coupling

- Non-adiabatic : fraction of entropy perturbations — PQ axion
  - Non-thermal, multiple dof's in early universe — Hamann et al. 09

- Non-matter : just modified gravity — MOND

Signature of massive neutrinos on P(k)

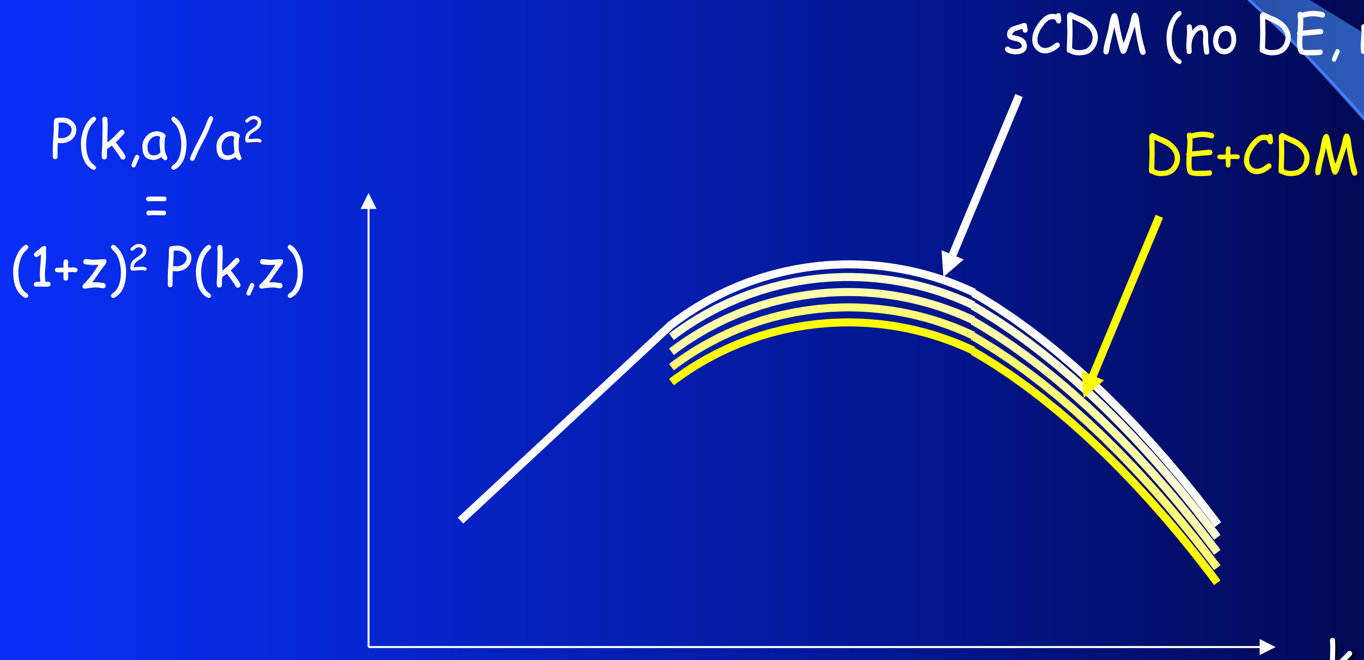
linear growth factor set by density of total matter/clustering matter



sCDM ⟶ $(\delta\rho/\rho)_m$ increases like a

Signature of massive neutrinos on P(k)

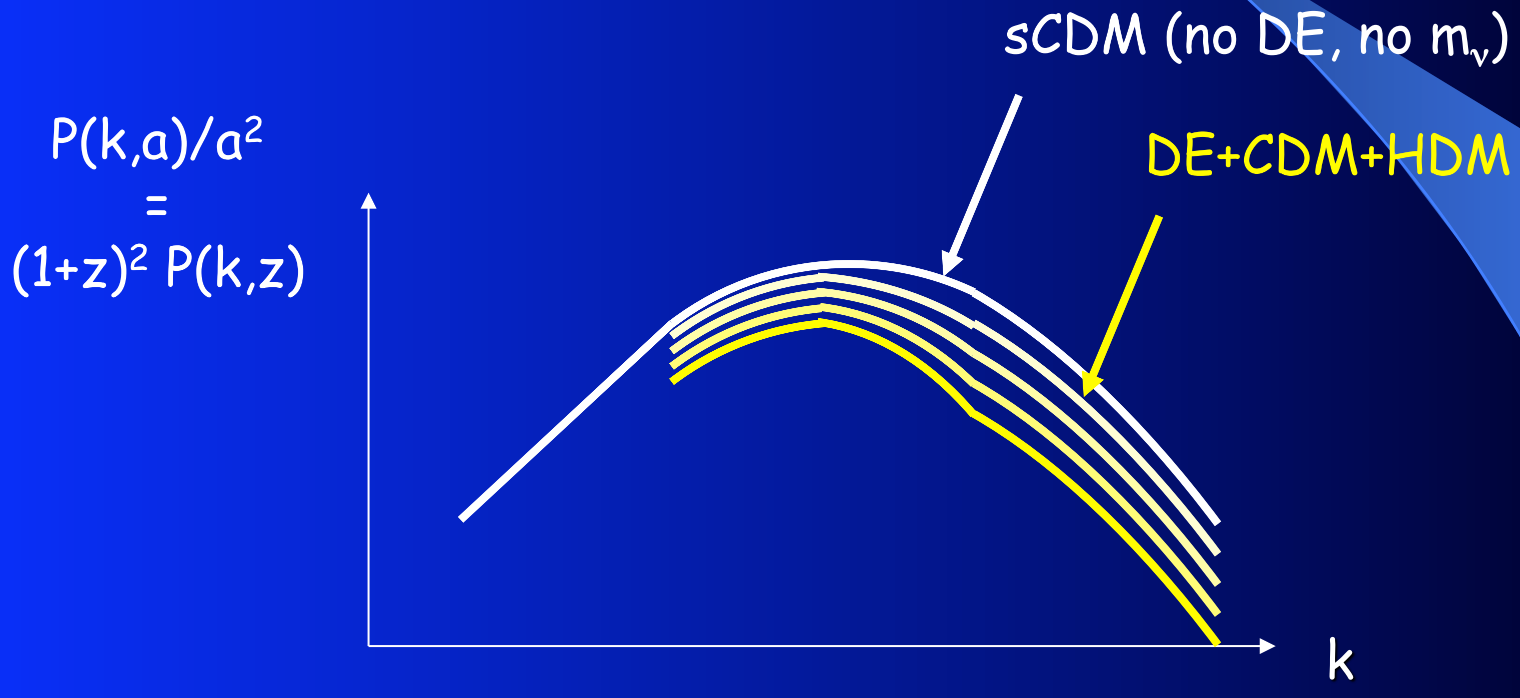
linear growth factor set by density of total matter/clustering matter



DE+CDM → scale-independent linear growth factor

Signature of massive neutrinos on P(k)

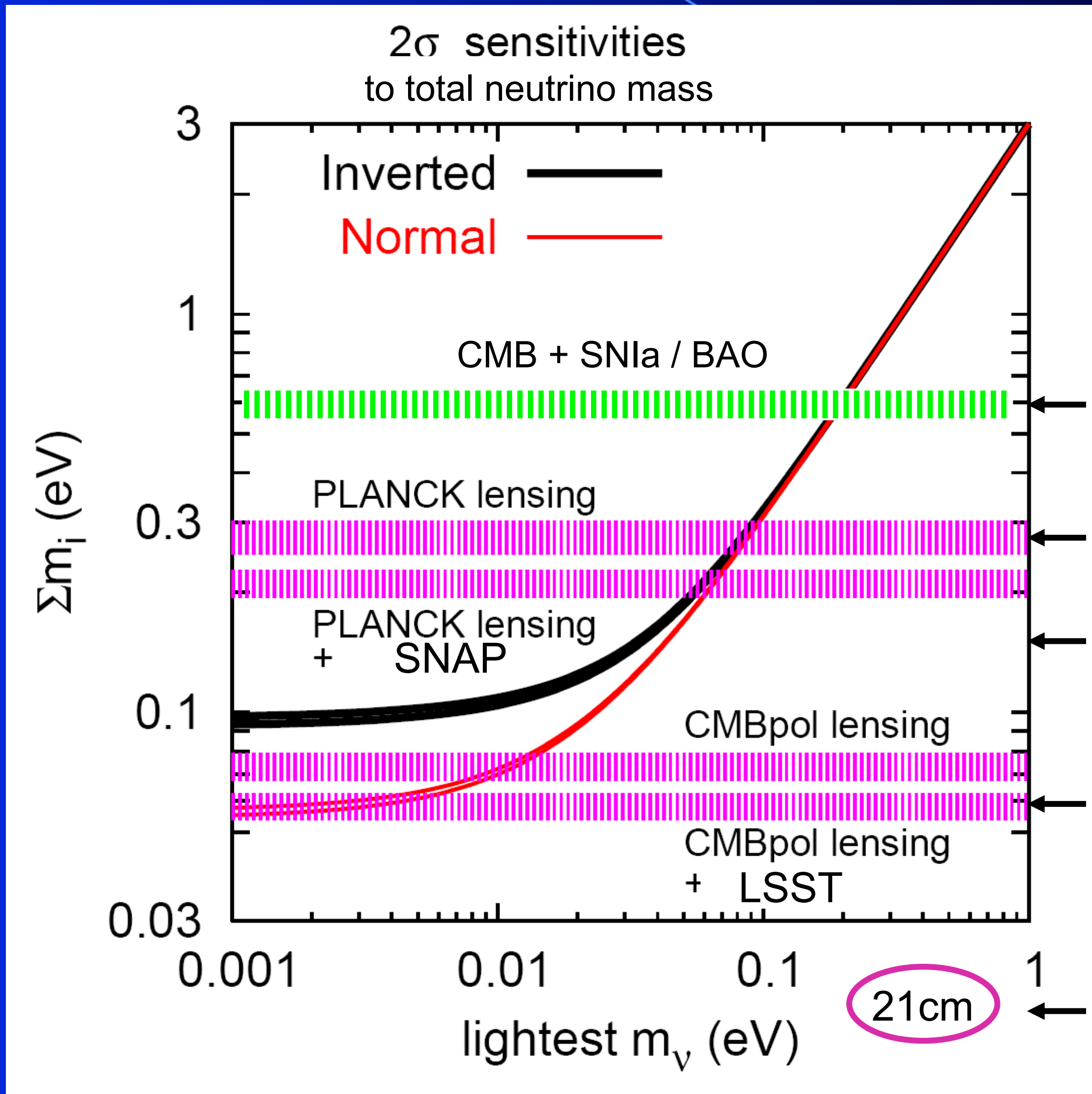
linear growth factor set by density of total matter/clustering matter



DE+CDM+m_ν ⟶ scale-dependent linear growth factor

Bounds on neutrino mass

J.L. & S. Pastor, Physics Reports [astro-ph/0603494]



Komatsu et al. 08

Perotto et al. 06
Lesgourgues et al. 05

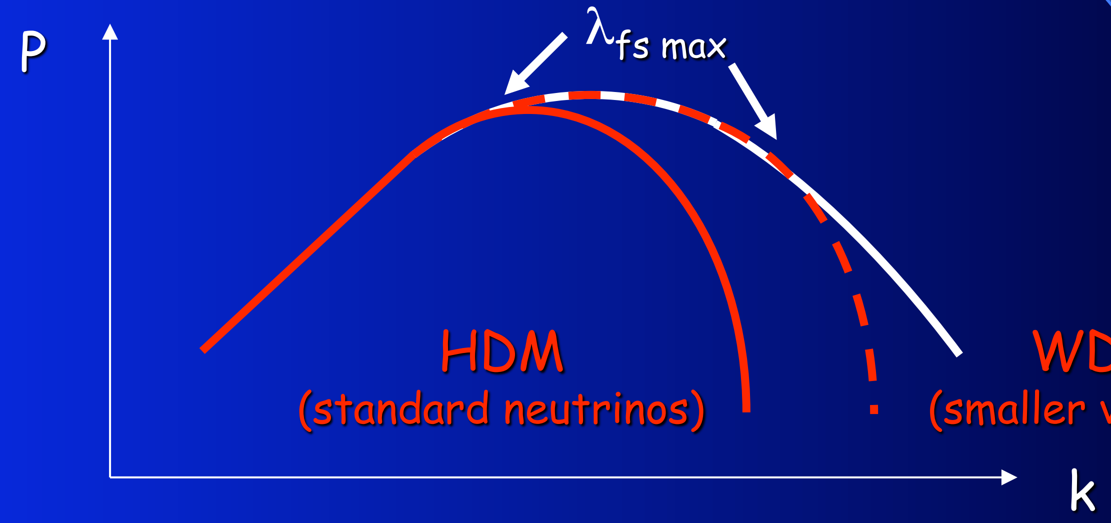
Planck+DUNE
Kitching et al 08

Song & Knox 2003

Pritchard & Pierpaoli 2008

WDM and structure formation

1) <u>pure HDM or WDM</u> (e.g.: light gravitino, keV sterile neutrino)



Constraints are always model-dependent: any f(p), must be tested;

- thermal relic : m > 2 keV
- renormalized neutrino distribution : m > 10 keV Viel et al. 06

sterile neutrinos produced non-resonantly are excluded!

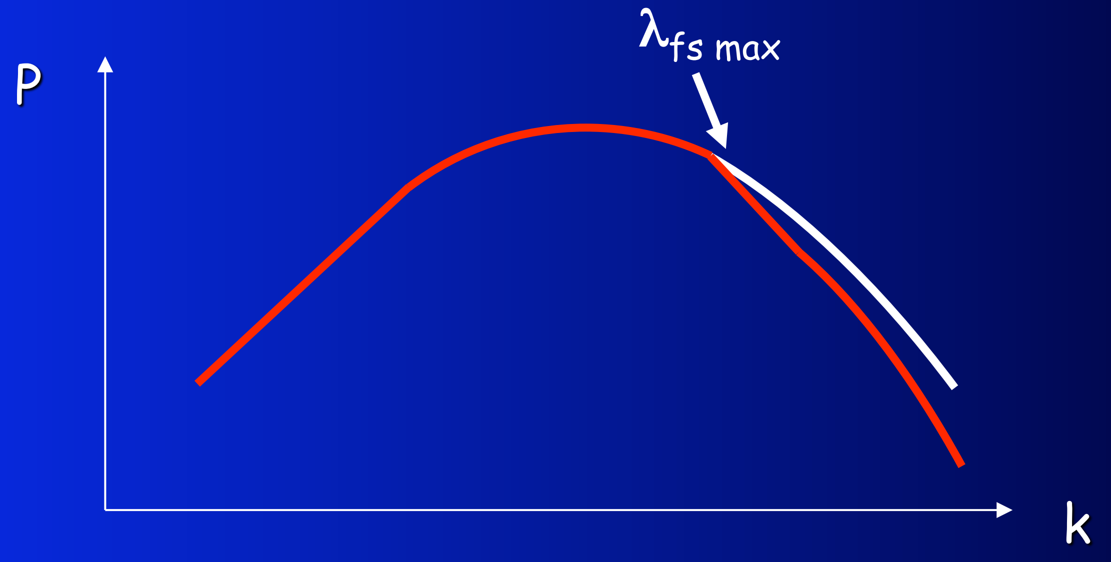
WDM and structure formation

2) mixed CDM+WDM (same particle? gravitino, axino: thermal + LSP,

Covi et al., Rozkowski et al.

resonantly produced sterile neutrino)

Shi & Fuller 99, Laine & Shaposhnikov 08

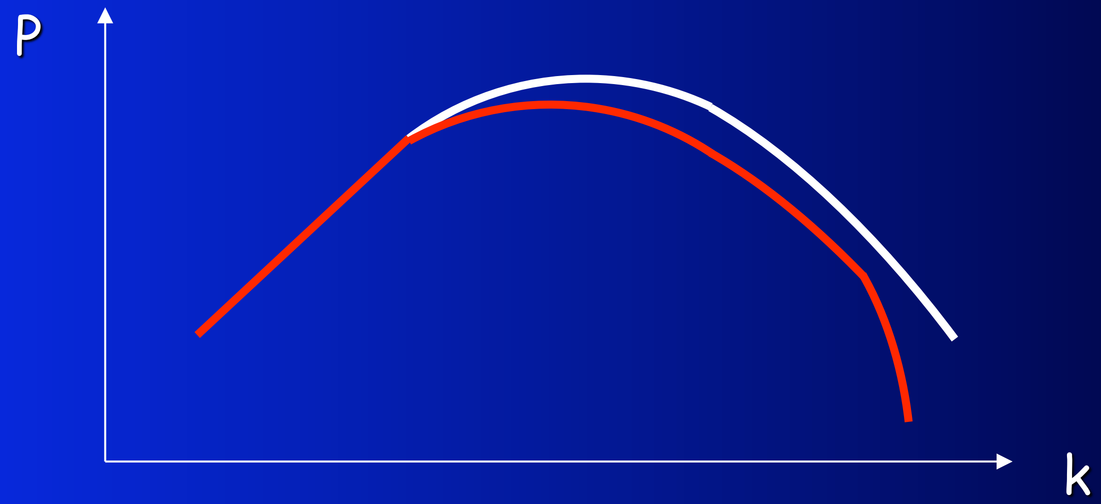


sterile neutrinos produced resonantly :
models with mass as low as 2 keV allowed!

Boyarski et al. 08

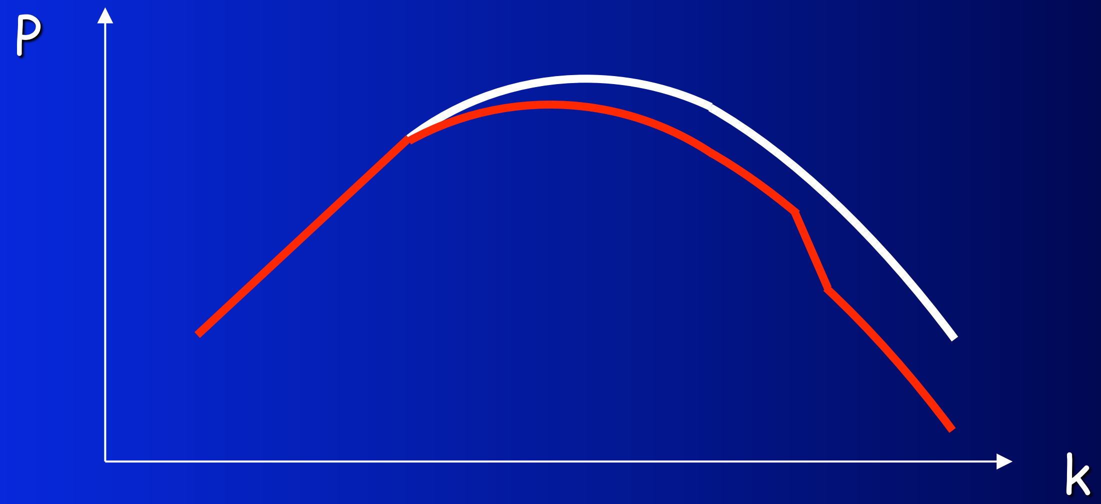
WDM and structure formation

3) <u>mixed WDM+HDM</u> (non-resonantly produced keV sterile neutrino + ordinary neutrinos)



WDM and structure formation

4) mixed CDM+WDM+HDM (resonantly produced keV sterile neutrino + ordinary neutrinos)



Universe acceleration

Can we avoid simultaneously
fine-tuning issues
& anthropic considerations?

Universe acceleration

- Modified gravity, e.g. massive gravity: Dvali et al., …

  (still far from phenomenology) see however Blas et al. 09

- Dark energy:
  - scalar field (fine-tuned)
  - scalar field coupled with dark matter/neutrinos (fifth force -> nuggets) Mota et al.
  - exotic fluids/species: Chaplygin gas, network of defects… (perturbations wrong)
- beyond FLRW:
  - Tolman-Bondi, local voids, swiss cheese (distorsions of CMB) Valkenburg 09
  - backreaction of non-linear stuctures (no GR simulations of structure formation)

    Buchert; Rasanen

Beyond luminosity distance…

- Linear growth factor depends on

  background evolution + DE perturbations

  background: $w(t)=p/\rho$

  perturbations: $c_s^2(t,x)=\delta p/\delta\rho$ (+ maybe shear)

  different from each other (e.g. for scalar field)

- Observable with weak lensing tomography, Lyman-alpha, cluster mass function…

Predictions on non-linear scales

At which point will precision cosmology reach its limits?

Non-linear gravitational clustering

… is crucial to understand, in order to constrain

- models of Dark Matter (incl. neutrino mass)
- models for universe acceleration

through:

- Extended analysis of galaxy / cluster/ cosmic shear surveys to larger k
- proper analysis of Ly-α / BAO / 21cm data
- Proper extraction / interpretation of CMB foregrounds (thermal SZ)
- Addressing small-scale CDM distribution problem (satellites)

Improvement in simulations…

- Challenge for astrophysicists: higher resolution (race for large-k, low-z), more realistic implementation of baryons/gas
- Cosmologists whish to implement: free-streaming dark matter matter (neutrinos, WDM), other exotic types of DM, perturbed DE, etc.

- Brute force (CPU time and algorithmic)

  Zürich, Durham, Munchen…

- New ideas: e.g.: mixed simulations with CDM particles + smooth neutrino grid evolved with linear theory Brandbyge et al. 09

…and (semi)-analytic approaches

- Inspired from QFT: Feynman diagrams, renormalization group equations…

  Scoccimarro et al., Pietroni et al., Shoji & Komatsu 09

- Equations heavy, computational time very small w.r.t. N-body…
- Possible implementation of neutrinos and others

  Wong 08, JL et al. 09

- Work only in limited range of (k,z)

  Carlson et al. 09

End