Evolution of the universe
and
physics beyond the SM

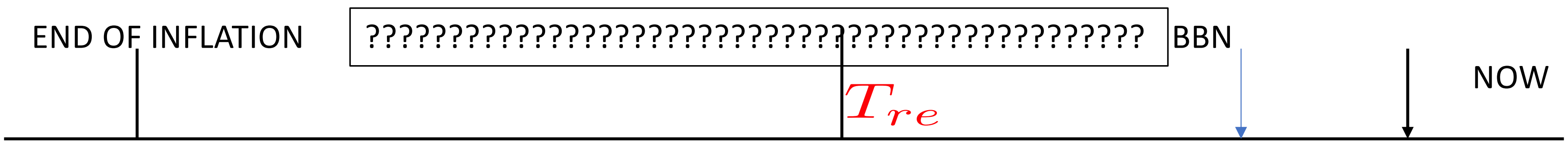
(CMB and reheating temperature linking inflation, reheating and BSM physics)

Based on: A. Ghoshal, P. Kozow, M.Olechowski, S.Pokorski;
M. Marciniak, M.Olechowski, S. Pokorski; Acta Physica Polonica

THE STANDARD PARADIGM: INFLATION, REHEATING, THERMAL HISTORY OF THE UNIVERSI

Beginning with BBN, under theoretical (thermal equilibrum + SM) and exp control; but the thermal equilibrum of the SM plasma could have been reached much earlier at T_{re}

BSM(DM, BA)



$a(t) = 10^{\mathcal{O}(-30)}$

$a(t) = 10^{-8}$ $a(t_0) = 1$

REHEATING TEMPERATURE--- TEMPERATURE OF THE RADIATION PLASMA ONCE ITS ENERGY DENSITY BEGINS TO DOMINATE OVER THE ENERGY DENSITY OF THE INFLATON FIELD

$$\rho_{rad} \sim T_{re}^4 \quad for \quad \rho_{rad} = \rho_{inf}$$

ONE CAN ANTICIPATE THAT REHEATING TEMPERATURE DEPENDS ON THE INFLATON DYNAMICS AND THE PROCESS OF DISSIPATION OF ITS ENERGY

MODEL INDEPENDENT BOUNDS ON THE REHEATING TEMPERATURE:

$$BBN \lessapprox T_{re} \lessapprox GUT$$

$\sim 10 MeV$ $\sim 10^{15} GeV$ **TO HAVE ENOUGH ROOM FOR INFLATION**

CONCERNING INFLATION: APART OF EXPLAINING FLATNESS AND HOMOGENITY,

QUANTUM PERTURBATIONS OF THE INFLATON FIELD (VIA EINSTEIN EQS- PERTURBATIONS

OF THE METRIC) ARE PREDICTED BY INFLATION AND THEY ARE CONFIRMED/

MEASURED BY THE CMB EXPERIMENTS.

THEY ARE MEASURED BY THE CMB EXPERIMENTS (PLANCK- SATELLITE, ATACAMA DESERT- TELESCOPE) AS TEMPERATURE ANGULAR FLUCTUATIONS IN THE SKY

CMB EXPERIMENTS MEASURE ANGULAR TEMPERATURE FLUCTUATIONS IN THE SKY.

IT IS A LONG WAY TO TRANSLATE IT TO THE OBSERVABLES PREDICTED BY INFLATION.

IT IS DETERMINED BY SO-CALLED TRANSFER FUNCTIONS:
VERY COMPLEX INDUSTRY;
COMPLEXITY SIMILAR TO GETTING THE HIGGS SIGNAL AT THE LHC

EXPERIMENT GIVES US THOSE OBERVABLES!

REFRESHING OUR MEMORY ABOUT THE EVOLUTION OF THE EARLY UNIVERSE

FRW METRIC FOR FLAT, ISOTROPIC, HOMOGENOUS UNIVERSE

$$ds^2 = g_{\alpha\beta}dx^\alpha dx^\beta = dt^2 - a^2(t)(dr^2 + r^2 d\Omega^2)$$

THE SPATIAL COMOVING COORDINATES ALWAYS USED: THAT IS, EVERY OBJECT HAS CONSTANT COORDINATES

$$r, \theta, \phi$$

ALSO CONFORMAL TIME SOMETIME USED $\eta \equiv \int \frac{dt}{a(t)}$

THE FRW METRIC THEN READS

$$ds^2 = a^2(\eta)(d\eta^2 - dr^2 - r^2 d\Omega^2)$$

EINSTEIN EQS (FRIEDMANN EQS) ARE REWRITTEN IN THIS METRIC

$$H^2 = \frac{8\pi G}{3}\rho \qquad \ddot{a} = -\frac{4\pi}{3}G(\rho + 3p)a$$

FIEDMANN EQS

$$H = \frac{\dot{a}}{a}$$

TAKE A HOMOGENOUS SCALAR FIELD IN THE FRW METRIC

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

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

$$H^2 = \frac{8\pi G}{3}(\frac{1}{2}\dot{\phi}^2 + V(\phi))$$

INFLATION

CHOOSE THE POTENTIAL SO THAT FOR THE SOLUTION OF THOSE EQUATIONS

$$\frac{1}{2}\dot{\phi}^2 << V(\phi)$$

$$\ddot{\phi} << 3H\dot{\phi}$$

OR EQUIVALENTLY

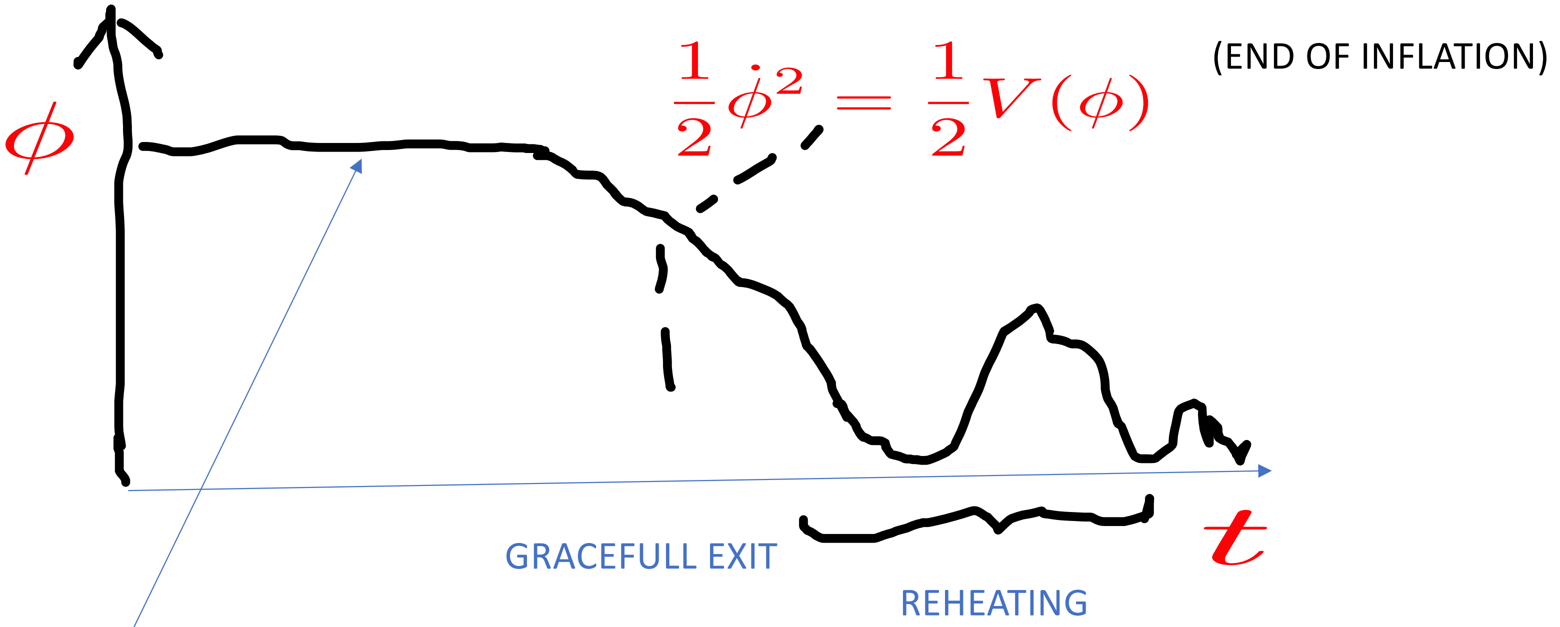
$$(\frac{V_{,\phi}}{V})^2 << 1$$

$$|\frac{V_{,\phi\phi}}{V}| << 1$$

FOR “SUFFICIENTLY” LONG TIME!

SLOW –ROLL CONDITIONS

THE SOLUTIONS OF THE TWO EQUATIONS LOOK THEN LIKE THIS



$$H \approx const$$

de SITTER UNIVERSE (BUT ONLY APPROXIMATELY !!!!)

$$H = \frac{\dot{a}}{a}$$

CRUCIAL FOR TESTS OF THE INFLATIONARY PICTURE (CMB)-
THE EFFECTS OF QUANTUM FLUCTUACTIONS
AROUND THE CLASSICAL EVOLUTION OF THE BACKGROUND
INFLATON FIELD

$$\phi(t,x) = \phi(t) + \delta\phi(t,x) \rightarrow$$
$$\rho(t,x) = \rho(t) + \delta\rho(t,x) \rightarrow \ \delta g_{\alpha\beta}$$

FOURIER DECOMPOSITION

$$X_k = \int dx X(t,x) e^{ikx} \qquad X \equiv \phi, \delta\rho, \delta g_{\mu\nu} \ldots$$

PERTURBATION WAVES $\lambda = 2\pi/k, \ \lambda_{phys} = a(t)\dfrac{2\pi}{k}$

FRIEDMANN EQS CAN BE REWRITTEN AS EQS FOR PERTURBATIONS AND THEIR FOURIER MODES

DENSITY PERTURBATIONS ARE THEN IN ONE TO ONE CORRESPONDENCE TO THE METRIC PERTURBATIONS

AND ONE CAN USE ANY OF THEM

USUALLY ONE USES METRIC PERTURBATIONS (SCALAR, TENSOR,VECTOR)

E.G. Scalar perturbations of the metric

$$ds^2 = a^2[(1+2\Phi)d\eta^2 + ...]$$

k, x ARE COMOVING

$$\Phi(x) = \int \Phi_k e^{ikx} d^3k/(2\pi)^3$$

$$\delta_\Phi^2(k) = \frac{|\Phi_k|^2 k^3}{2\pi^2}$$

Power spectrum

Parametrize (around a given value of k=k*)

$$\delta_\Phi^2(k) \propto A_s(k_*)(\frac{k}{k_*})^{n_s(k_*)-1}$$

$$n_s - 1 = \frac{d\ln\delta_\Phi^2}{d\ln k}$$

Spectral index of the scalar perturbation

PARAMETERS

$$A_s(k) \propto \delta_\Phi^2(k), \quad n_s(k), \quad r(k) = \frac{tensor}{scalar}(k)$$ ETC

ARE CALCULABLE FOR ANY CONCRETE INFLATON POTENTIAL

$n_s = 1$ FOR de SITTER,

DEVIATIONS MEASURE GRACEFUL EXIT; CMB

IT CAN BE PROVED:

$$\delta^2_\Phi(k) \sim (\frac{H^2}{M_{Pl}}\frac{H^2}{\dot{H}})_{k\sim aH}$$

$$\epsilon_k = \frac{1}{2}M_P^2(\frac{\partial_\phi V(\phi)}{V(\phi)})^2|k \sim aH$$

$$\eta_k = M_P^2\frac{\partial_\phi^{(2)}V(\phi)}{V(\phi)}|k \sim aH$$

THE CONDITION. $k \sim (aH)$ **MAKES THOSE RELATIONS FUNCTIONS OF THE COMOVING WAVE NUMBER**

$$n_s(k) = 1 - 6\epsilon_k + 2\eta_k$$

$$r(k) = 16\epsilon_k$$

$$A_s(k) = \frac{V(\phi_k)}{24\pi^2\epsilon_k M_P^2}$$

THE CMB EXPERIMENTS “MEASURE” OR PUT BOUNDS ON THOSE PARAMETERS FOR A PERTURBATION WITH SOME PHYSICAL WAVELENGTH “NOW”, (DEFINED BY THE ANGULAR RESOLUTION IN THE SKY)

$$\lambda_{phys} = a_0/k_* \approx 20Mpc \qquad k_* = a_0 \times 0.05Mpc^{-1}$$

COMOVING WAVE NUMBER

IT IS CONVENIENT AND CUSTOMARY TO PUT $a_0 = 1$

MEASURED:

$$A_s(k_*) \propto \delta_\Phi^2(k_*), \quad n_s(k_*), \quad r(k_*) = \frac{tensor}{scalar}(k_*)$$

CMB DATA GIVE BEAUTIFUL SUPPORT TO THE IDEA OF INFLATION AND INSIGHT INTO THE INFLATIONARY AND REHEATING PERIODS.

WE ADRRESS SIMILAR ISSUES BUT WITH STRONG EMPHASIS ON THE REHEATING TEMPERATURE AS A CRUCIAL PARAMETER FOR TESTING AND DISCRIMINATING BETWEEN DIFFERENT MODELS OF INFLATION (DUE TO MODEL INDEPENDENT BOUNDS ON REHEATING TEMPERATURE)

Secondly, the reheating temperature is a portal to constraining particle physics scenarios that are sensitive to it.
Examples: leptogenesis, freeze-in DM scenarios….

CMB as an additional (to colliders) tests of the DM models.

ILLUSTRATION OF THE METHOD FOR THE INFLATON POTENTALS:

$$V\left(\phi,\alpha,n,\Lambda_{\rm inf}\right) \;:=\; \Lambda_{\rm inf}^4(1-\exp[-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_{Pl}}])^{2n}$$

E-MODEL

$$\Lambda_{\rm inf}^4\frac{\phi^{2n}}{\phi^{2n}+\left(\sqrt{\frac{3\alpha}{2}}M_{Pl}\right)^{2n}}$$

P-MODEL

PARAMETERS OF THE POTENTIAL CAN BE FIXED IN TERMS OF THE MEASURED CMB OBERVABLES

$$\alpha=\alpha(n,n_s,r), \qquad \Lambda_{inf}=\Lambda_{inf}(n,n_s,r,A_s),$$

$$\phi=\phi(n,n_s,r)$$

FOR $k=k_*$

SOLVING A SET OF BOLTZMANN EQUATIONS :

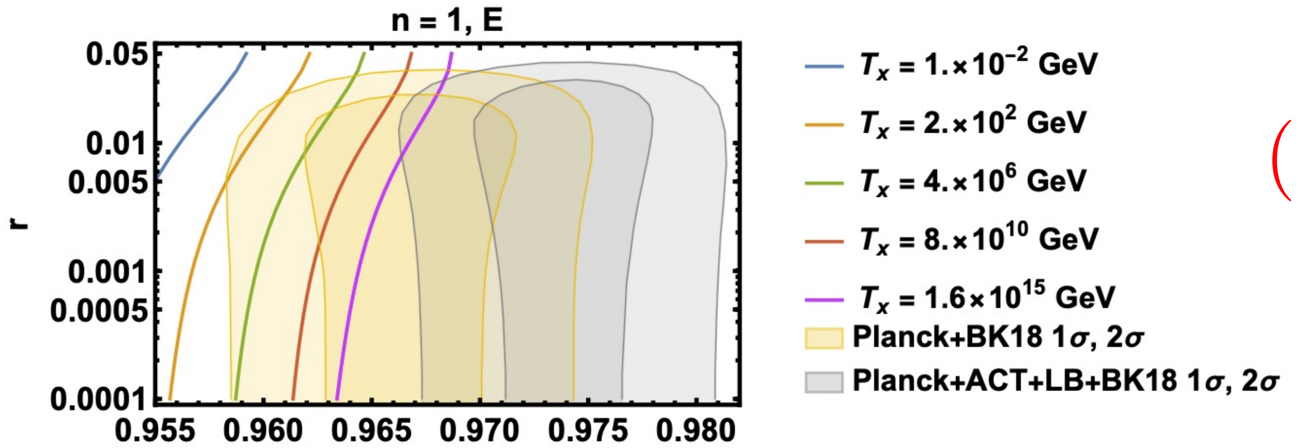
$$T_{re} = T_{re}(n, n_s(k_*), r(k_*), A_s(k_*))$$

OUR WORK:

1) $T_{re} = T_{re}(A_s, n_s, r)$

MODEL INDEPENDENT BOUNDS ON T_{re} PROVIDE VERY STRINGENT PREDICTIONS OF INFLATIONARY MODELS FOR CMB OBESRVABLES

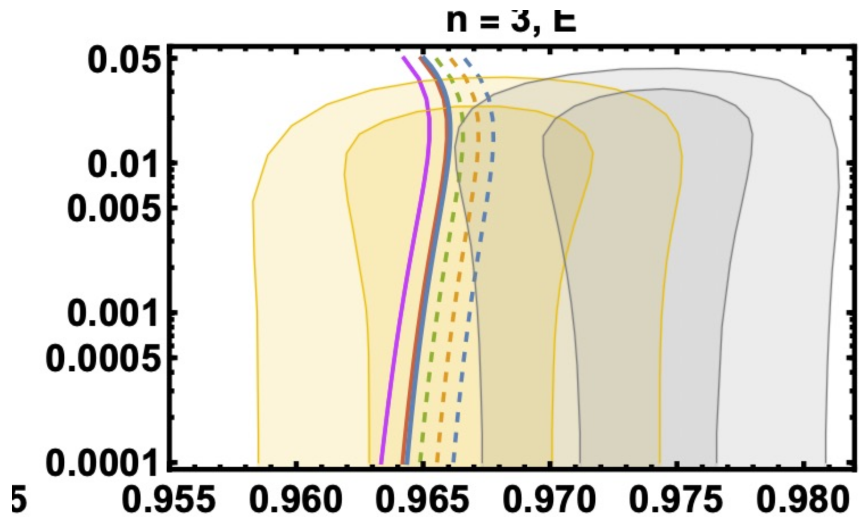
2) ONE OBTAINS A LINK BETWEEN CMB OBERVABLES AND T_{re} SENSITIVE PARTICLE PHYSICS (DM PRODUCTION…)

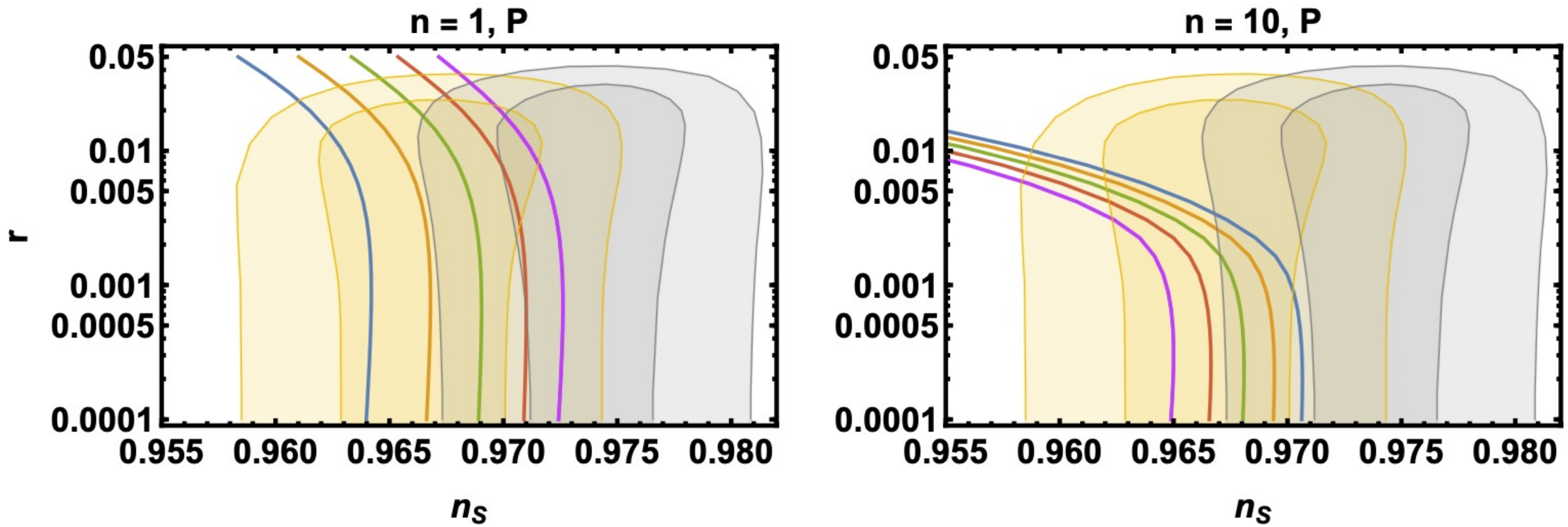


$$(T_{re} \equiv T_{\times})$$

MODEL INDEPENDENT BOUNDS ON T_{re}

------→STRONG TESTS OF INFLATIONARY MODELS BY CMB DATA





n = 1, P
n = 10, P
r
0.05
0.01
0.005
0.001
0.0005
0.0001
0.955
0.960
0.965
0.970
0.975
0.980
n_S

FREEZE-IN: SM PARTICLES IN THERMAL BATH ANNIHILATE INTO DM PARTICLES; IMAGINE THAT THE AMPLITUDE FOR THE PROCESS DEPENDS ON A PHYSICAL SCALE $\Lambda_{DM} > T_{re}$

THEN, BELOW. T_{re} , THE PROCESS CAN BE DESCRIBED IN EFT BY A HIGHER DIMENSION OPARATOR

$$\mathcal{L} = \mathcal{O}_{4+d}/\Lambda_{DM}^d$$

$$< \sigma v > \propto \frac{T_{re}^{2(d-1)}}{\Lambda_{DM}^{2d}}$$

BOLTZMANN EQUATION

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} =< \sigma v > (n_{EQ}^2 - n_{DM}^2)$$

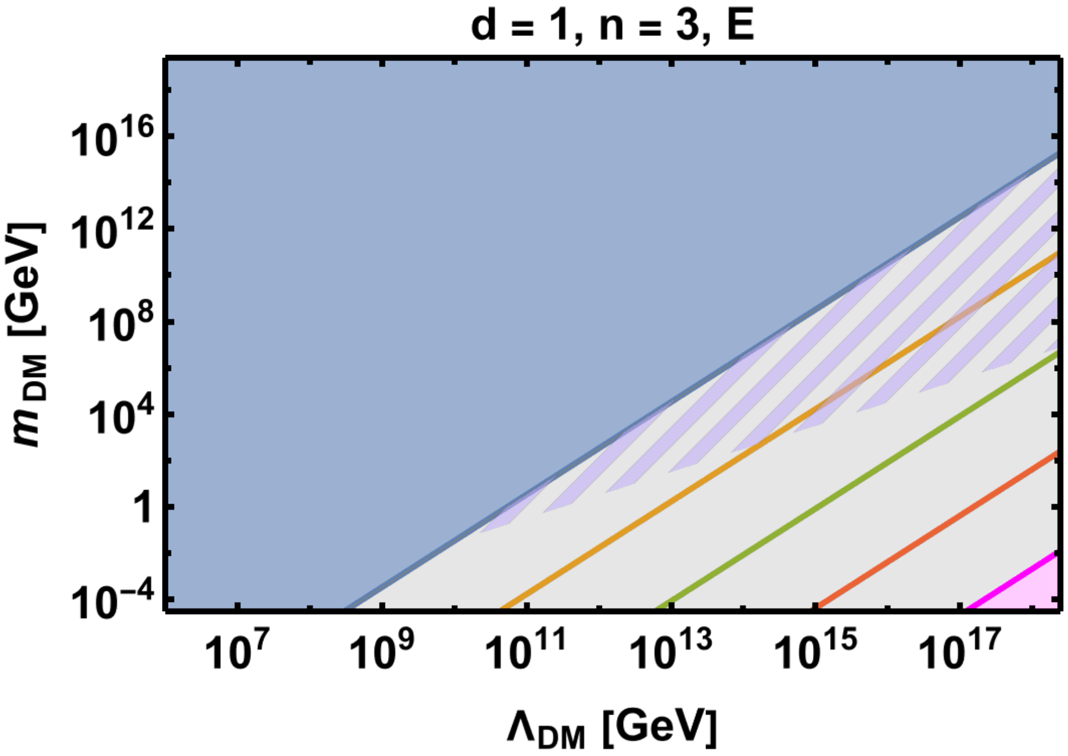
FOR COMOVING PARTICLE DENSITY $Y \equiv n_{DM}/s$ $\quad Y \propto M_{Pl} \frac{T_\times^{2d-1}}{\Lambda_{DM}^{2d}}$

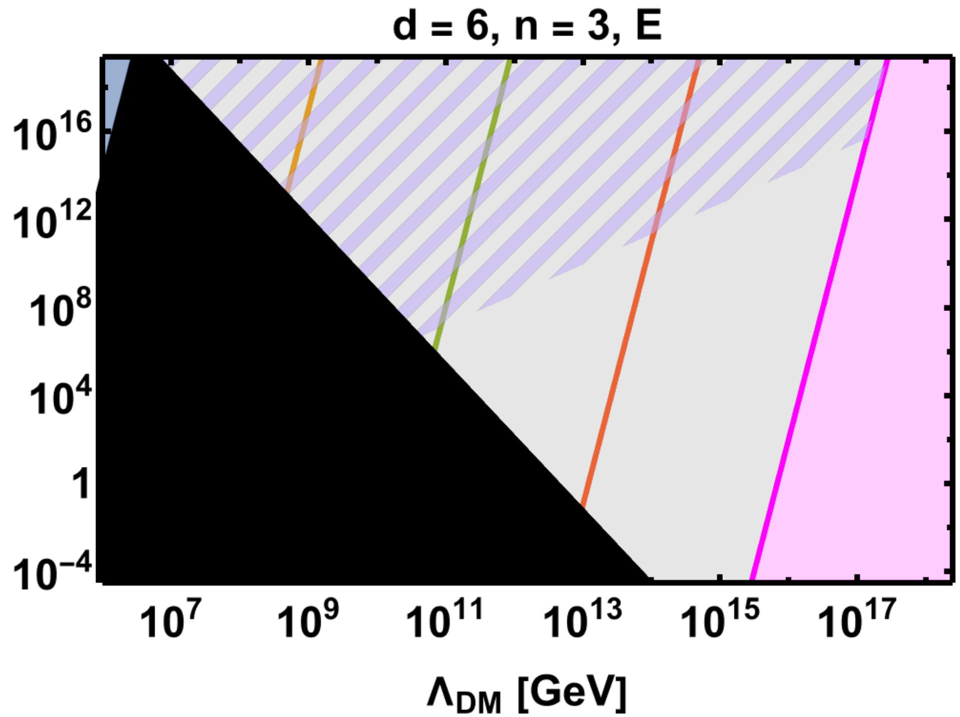
$$\Omega_{DM} = 0.2(\frac{m_{DM}}{1TeV})(\frac{Y_{DM}}{10^{-13}})$$

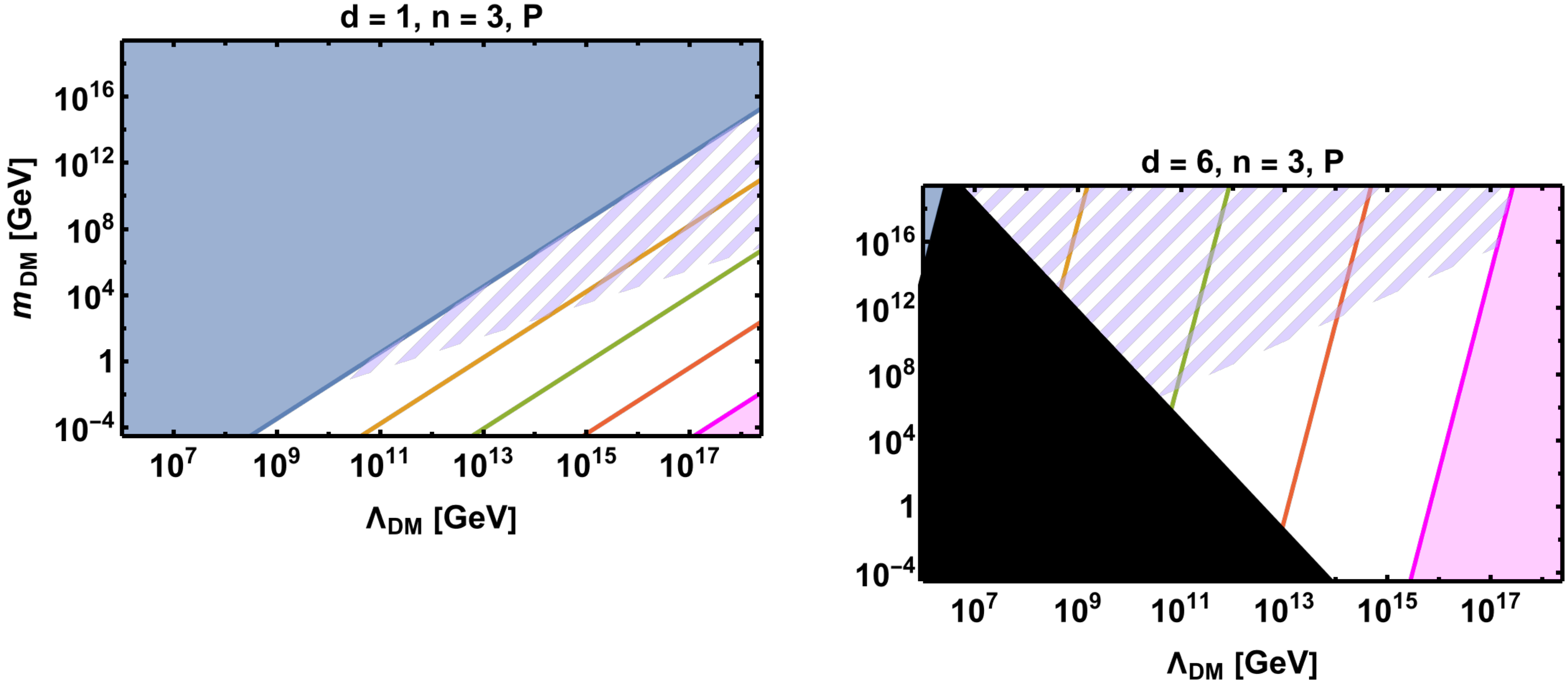
DEMANDING $\Omega_{DM} h^2 = 0.12$ ONE GETS m_{DM} $\quad versus \quad$ Λ_{DM}

AS A FUNCTION OF T_{re} FOR A CHOSEN MODEL OF INFLATION

(MODELS OF DM PRODUCTION ARE TESTED BY CMB OBSERVABLES)


d = 1, n = 3, E
m_{DM} [GeV]
Λ_{DM} [GeV]
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{7}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}


d = 6, n = 3, E
Λ_{DM} [GeV]
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{7}
10^{9}
10^{11}
10^{13}
10^{15}
10^{17}



d = 1, n = 3, P
m_{DM} [GeV]
Λ_{DM} [GeV]
d = 6, n = 3, P
Λ_{DM} [GeV]

SUMMARY

INFLATION NOT ONLY EXPLAINS BUT ALSO PREDICTS.

MODEL INDEPENDENT BOUNDS ON REHEATING TEMPERATURE STRONGLY ENHANCE PREDICTIVE POWER OF MODELS OF INFLATION
(A PROGRESS IS ALSO EXPECTED IN THE PRECISSION OF CMB EXPS)

CMB EXPS CAN BE RELEVANT FOR PARTICLE PHYSICS

HOMOGENITY PROBLEM

THE PRESENT HOMOGENOUS UNIVERSE-AT LEAST OF THE SIZE OF THE PRESENT HORIZON $ct_0 \sim 10^{28} \quad cm$

INITIALLY, THAT SIZE AT $t = t_i$

$$l_i \sim \frac{a_i}{a_0} ct_0$$

LET'S COMPARE IT WITH INITIAL CAUSAL REGION, $l_i^c = ct_i$ ASSUMING THE EVOLUTION AS IN THE RADATION ERA

$$\frac{l_i}{l_i^c} \sim \frac{t_0}{t_i}\frac{a_i}{a_0} \sim 10^{28}$$

HOW TO MAKE IT SMALLER THAN 1?

(We took $t_i = t_{Pl}, \quad T_{Pl} \sim 10^{32} \quad \frac{a_i}{a_0} \sim (T_0/T_{Pl} \sim 10^{-32}$)

AS $$a \sim \dot{a}t \quad for \quad a(t) \sim t^{\alpha}$$

WE CONCLUDE $$\frac{l_i}{l_i^c} \sim \frac{\dot{a}_i}{\dot{a}_0}$$

WE NEEED $$\frac{\dot{a}_i}{\dot{a}_0} < 1$$ (HENCE ACCELERATED EXPANSION!)

E.G. Scalar perturbations of the metric

$$ds^2 = a^2[(1+2\Phi)d\eta^2 + ...]$$

k, x ARE COMOVING

$$\Phi(x) = \int \Phi_k e^{ikx} d^3k/(2\pi)^3$$

THE SPACIAL TWO-POINT CORRELATION FUNCTION

$$<\Phi(x)\Phi(y)> = \int \frac{|\Phi_k|^2 k^3}{2\pi^2} \frac{\sin(kr)}{kr} \frac{d^3k}{k}$$

$$\delta^2_\Phi(k) = \frac{|\Phi_k|^2 k^3}{2\pi^2}$$ Power spectrum

Parametrize (around a given value of k)

$$\delta^2_\Phi(k) \propto k^{n_s(k)-1}$$

$$n_s - 1 = \frac{d \ln \delta^2_\Phi}{d \ln k}$$ Spectral index of the scalar perturbation

FOR "PERFECT FLUID" (MATTER, RADIATION, SCALAR FIELD) THE ENERGY-MOMENTUM TENSOR IS

$$T^{\mu}_{\nu} = diag(\rho, -p, -p, -p)$$

SIMPLE EQUATION OF STATE IS OFTEN USED

$$p = w\rho \qquad w = const$$

$w = 0$ MATTER

$w = 1/3$ RADIATION

FROM THE 1st LAW OF THERMODYNAMICS

$$dE = -pdV \quad (V = a^3, \; E = \rho a^3)$$

ONE GETS

$$\rho \sim a^{-3(1+w)}$$

EINSTEIN EQS (FRIEDMANN EQS) IN THIS METRIC, FOR "FLUID"
(MATTER, RADIATION, SCALAR FIELD)

$$H^2 = \frac{8\pi G}{3}\rho \qquad \ddot{a} = -\frac{4\pi}{3}G(\rho + 3p)a$$

$$G = 1/M_{Pl}^2$$

$$H = \frac{\dot{a}}{a}$$

$\ddot{a} < 0$ GRAVITY ATTRACTIVE (MATTER, RADIATION)

INFLATION

$\ddot{a} > 0 \quad for \quad p < -(1/3)\rho$ GRAVITY REPULSIVE

SOLUTIONS FOR $a(t)$ & H

$w = 0$ **MATTER** $a(t) \sim t^{2/3}$ $H \sim t^{-1}$

$w = 1/3$ **RADIATION** $a(t) \sim t^{1/2}$ $H \sim t^{-1}$

$w = -1$ **VEV OF A SCALAR FIELD (INFLATON)** $a(t) \sim e^{Ht} \leftarrow H = const$

(de SITTER UNIVERSE)

BOLTZMANN EQUATIONS

$$\dot{\rho}_\phi = -3(1+w)H\rho_\phi - \Gamma\rho_\phi$$

$$\dot{\rho}_r = -4H\rho_r + \Gamma\rho_\phi$$

$$H^2 = \frac{\rho_\phi + \rho_r}{3M_{Pl}^2}$$

HORIZONS (BECAUSE OF THE FINITE VELOCITY OF LIGHT)

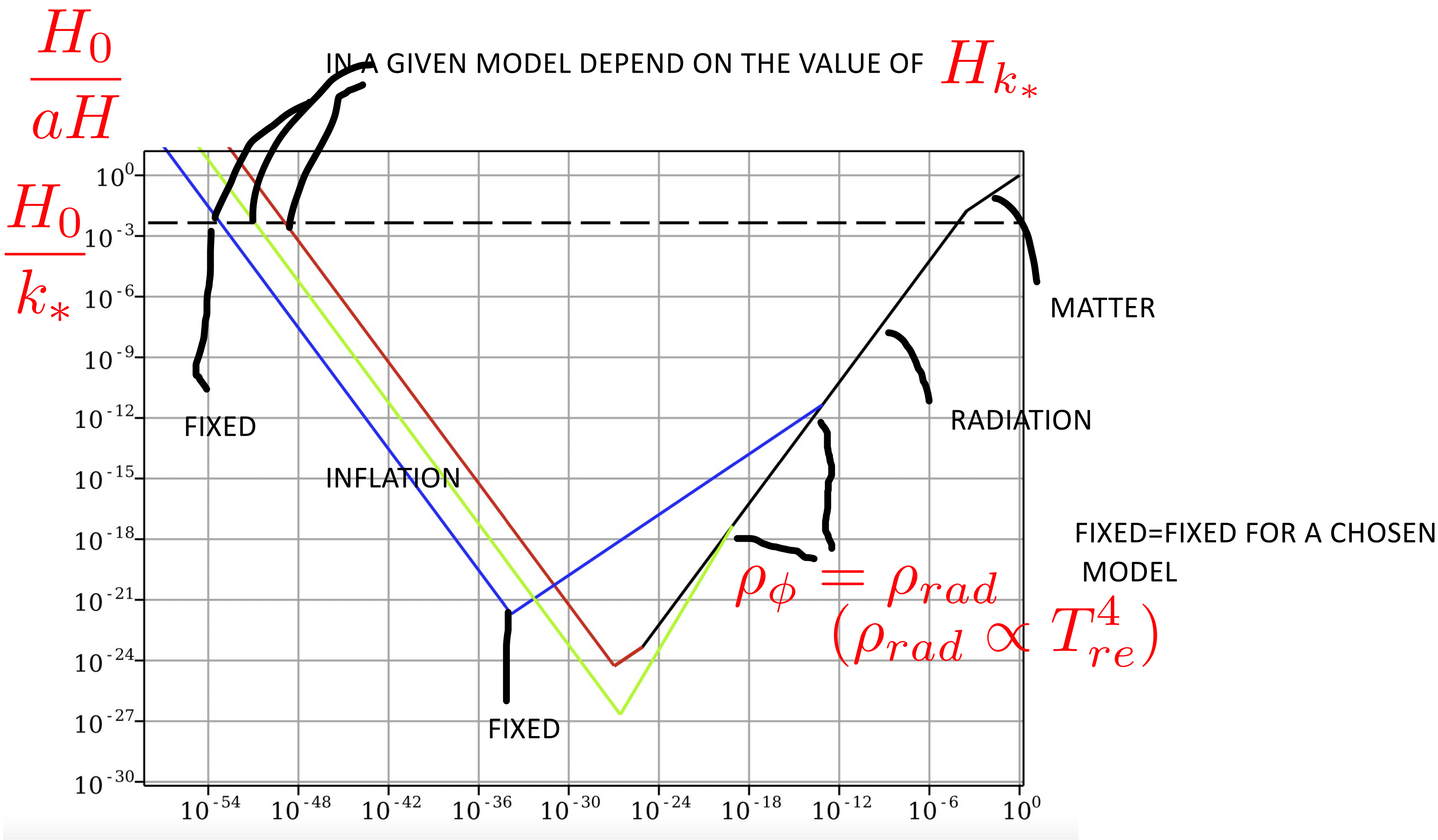
$$\frac{1}{H}$$

EVENT HORIZON DURING INFLATION, CAUSAL HORIZON AFTER INFLATION

COMOVING HORIZONS (DISTANCE SEEN BY AN OBERVED MOVING TOGETHER WITH AN EXPANDING UNIVERSE)

$$\frac{1}{aH}$$

SHRINKING EXPONENTIALLY DURING INFLATION;
INCREASING LIKE a(t) DURING RADIATION ERA



A SCHEMATIC EVOLUTION OF HORIZONS 1/aH

$a_0 = 1$

ONCE THE FROZEN PERTURBATIONS, DETERMINED BY THE INFLATON DYNAMICS, REENTER THE HORIZON THEY ARE UNDER CONTROL (OUR FRIENDLY UNIVERSE-RADIATION, MATTER)

THEY ARE MEASURED BY CMB EXPERIMENTS. STILL A LONG WAY TO CONTROL, TRANSFER FUNCTION, VERY COMPLEX INDUSTRY; COMPLEXITY SIMILAR TO GETTING THE HIGGS SIGNAL AT THE LHC

THIS IS THE CONSISTENCY RELATION THAT FIXES T_{re} FOR $\rho_\phi = \rho_R \equiv \rho_\times$

$$0 = \ln\left(\frac{k_*}{a_{k_*} H_{k_*}}\right) = \ln\left(\frac{a_{\rm end}}{a_{k_*}} \frac{a_\times}{a_{\rm end}} \frac{a_0}{a_\times} \frac{k_*}{a_0 H_{k_*}}\right),$$

T_{re} DEPENDENCE IN $\frac{a_\times}{a_{end}}$ and $\frac{a_0}{a_\times}$.

ONE HAS TO SOLVE THE BOLTZMANN EQ

FOR THE REHEATING TO FIND $\rho_\times \propto T_\times^4$

$$\frac{a_0}{a_\times} \propto T_0/T_\times$$

STEP 2: $T_\times = T_\times(n, n_s, r, A_s)$

REHEATING: A SIMPLEST DESCRIPTION-IN TERMS OF AN EFFECTIVE DISSIPATION RATE Γ THAT LEADS TO THE TRANSFER OF ENERGY FROM THE INFLATON FIELD TO RADIATION.

FOR ANY MODEL OF REHEATING, ONE IMPORTANT PARAMETER IS THE TEMPERATURE OF THE SM PLASMA CHARACTERIZING THE BEGINNING OF THE RADIATION ERA, T_{re}, DEFINED E.G. BY

$$\rho^{inf} = \rho_{rad} \qquad (\rho_{rad} \propto T_{re}^4)$$

Γ CAN BE TRADED FOR T_{re}

ILUSTRATION OF THE METHOD FOR THE INFLATON POTENTALS:

$$V\left(\phi,\alpha,n,\Lambda_{\rm inf}\right) \;\; := \;\; \Lambda_{\rm inf}^4(1-\exp[-\sqrt{\frac{2}{3\alpha}}\frac{\phi}{M_{Pl}}])^{2n}$$ E-MODEL

$$\Lambda_{\rm inf}^4\frac{\phi^{2n}}{\phi^{2n}+\left(\sqrt{\frac{3\alpha}{2}}M_{Pl}\right)^{2n}}$$ P-MODEL

STEP 1:

$$\alpha=\alpha(n,n_s,r), \qquad \Lambda_{inf}=\Lambda_{inf}(n,n_s,r,A_s),$$

$$\phi_{k_*}=\phi_{k_*}(n,n_s,r)$$

STEP 2: USE THE CONSISTENCY CONDITIONS –THE SAME PERTURBATION

WAS OBSERVED NOW WITH THE WAVELENGTH $\lambda_{phys} = 1/k_* = 20Mpc$

THAT LEFT THE HORIZON WITH WAVELENGTH $\lambda''_{phys} = a_{k_*}/k_* \propto H_{k_*}^{-1}$

PLOT $(\frac{1}{H})_{com} = \frac{1}{Ha}$ AS A FUNCTION OF a

$$\frac{1}{a_k H_k} = \frac{1}{k_*}$$

POINT 2 cont

$$\dot{\Phi}(k) = 0 \quad for \quad \lambda_k > 1/(aH)_k$$

PERTURBATIONS WHICH LEFT THE (EVENT) HORIZON DURING INFLATION ARE FROZEN UNTIL, UNCHANGED, REENTER (PARTICLE) HORIZON, , AFTER THE END OF INFLATION,

(after inflation 1/aH becomes comoving particle horizon, becoming larger and larger)

HORIZONS

PARTICLE HORIZON –THE BOUNDARY OF SPACE FROM WHICH WE CAN RECEIVE INFORMATION **AT A GIVEN MOMENT OF TIME**

$$H \sim \frac{1}{t} \to \frac{1}{H} \quad is \quad the \quad causal \quad horizon \quad (c = 1)$$

FOR RADIATION AND MATTER DOMINATED UNIVERSE

De SITTER: CAUSAL HORIZON

$$\frac{1}{H} e^{Ht}$$

MINIMAL TIME FOR INFLATION SHOULD GIVE LARGE ENOUGH UNIVERSE WHICH AFTER SUBSEQUENT EXPANSION IS AT LEAST AS LARGE AS OUR PRESENT O

DURING INFLATION THE CAUSALLY CONNECTED REGION GROWS EXPONENTIALLY

AFTER INFLATION , THE CAUSAL HORIZON BEGINS WITH VERY SMALL (1/H) AND IS RISING LINEARLY WITH TIME

EVENT HORIZON: A BOUNDARY OF THE REGION FROM WHICH SIGNALS SENT AT A GIVEN MOMENT OF TIME WILL NEVER BE SEEN BY AN OBSERVER IN THE FUTURE

De SITTER: 1/H WHAT HAPPENS BEYOND THAT DISTNCE CANNOT HAVE ANY EFFECT ON THE OBSEVER

de SITTER: PARTICLE + EVENT HORIZONS. -----→ A SMALL (1/H) HOMOGENOUS CAUSAL REGION AT THE BEGINNING OF INFLATION IS EXPANDING EXPONENTIALLY, UNAFFECTED BY EXTERNAL REGIONS, TOGETHER WITH PARTICLE HORIZON

COMOVING HORIZON (DISTANCE SEEN BY AN OBSERVER MOVING TOGETHER WITH AN EXPANDING UNIVERSE)

$$\frac{1}{aH}$$ (SHRINKING FOR de SITTER))

STRONG ASSUMPTION MADE ABOVE : IN THE INFLATON OSCILLATORY PERIOD,

THE (AVERAGED OVER AN OSCILLATION) EFFECTIVE EQUATION OF STATE PARAMETER

$$p = w\rho$$

IS DETERMINED BY THE INFLATON POTENTIAL

THE CMB EXPERIMENTS "MEASURE" OR PUT BOUNDS ON THOSE PARAMETERS FOR A PERTURBATION WITH SOME PHYSICAL WAVELENGHT NOW (DEFINED BY THE ANGULAR RESOLUTION OF THE SKY)

$$\lambda_{phys} = a_0/k_* \approx 20Mpc \qquad k_* = a_0 \times 0.05Mpc^{-1}$$

IT IS CONVENIENT AND CUSTOMARY TO PUT $a_0 = 1$

IT REENTERED THE (PARTICLE) HORIZON WITH THE WAVELENGTH λ'_{phys} AND AT THE FLRW SCALE FACTOR a

$$\lambda'_{phys} = \frac{a}{k_*} =\propto \frac{1}{H(a)} = a^2 \frac{1}{H_0}$$

FOR RADIATION

WE ARE INTERESTED IN $\Phi(x)$ GENERATED BY $\delta\phi(x)$ (inflaton field perturbations).

ONE CAN CALCULATE $\Phi(k)$ AND OTHER CMB OBSERVABLES IN TERMS OF THE INFLATON POTENTIAL, BY SOLVING EQ OF MOTION FOR $\delta\phi(x)$ IN THE CURVED SPACE.

FOR INSTANCE, E-MODEL, IN THE SLOW-ROLL APPROXIMATION: FIRST, EXPRESS THE OBSERVABLES IN TERMS OF THE POTENTIAL PARAMETERS, THEN INVERT THE RELATIONS

$$\xi = n(8\frac{(1-n_s)}{r} - 1)$$

$$\alpha = \frac{64n^2}{3r}\frac{1}{(\xi-1)^2}$$

$$\phi_k = \sqrt{(32/r)}\frac{n}{(n-1)}\ln(\xi)$$

$$\Lambda^4_{inf} = \frac{3n^2}{2} r A_s (\frac{\xi}{\xi - 1})^{2n}$$

ALSO, FIX ϕ_{end} IN TERMS OF THE OBERVABLES BY USING THE CONDITIONS

$$\epsilon, \eta = 1$$

$$\phi_{end} = M_P \frac{4\sqrt{2}n}{(\xi - 1)\sqrt{r}}$$

THE NUMBER OF e-FOLDS N_k

$$N_k = -\frac{1}{M_P^2} \int_{\phi_k}^{\phi_{end}} \frac{V(\phi)}{\partial_\phi V(\phi)} d\phi$$

STEP 2:

STEP 1 DOES NOT DEPEND ON THE REHEATING PERIOD. HOWEVER ,

THE CMB OBERVABLES MEASURE THE PRIMORDIAL PERTURBATION (WITHIN

THE INFLATION

PARADIGM), THAT LEFT THE (EVENT) HORIZON $H^{-1} \propto (\sqrt{V(\phi)})^{-1}$

(CAUSALY CONNECTED PART OF THE UNIVERSE) DURING INFLATION WITH THE WAVELENGTH

$$\lambda''_{phys} = a_{k_*}/k_* \propto H_{k_*}^{-1}$$

BOLTZMANN EQUATION

$$\frac{dn_{DM}}{dt} + 3Hn_{DM} =< \sigma v > (n_{EQ}^2 - n_{DM}^2)$$

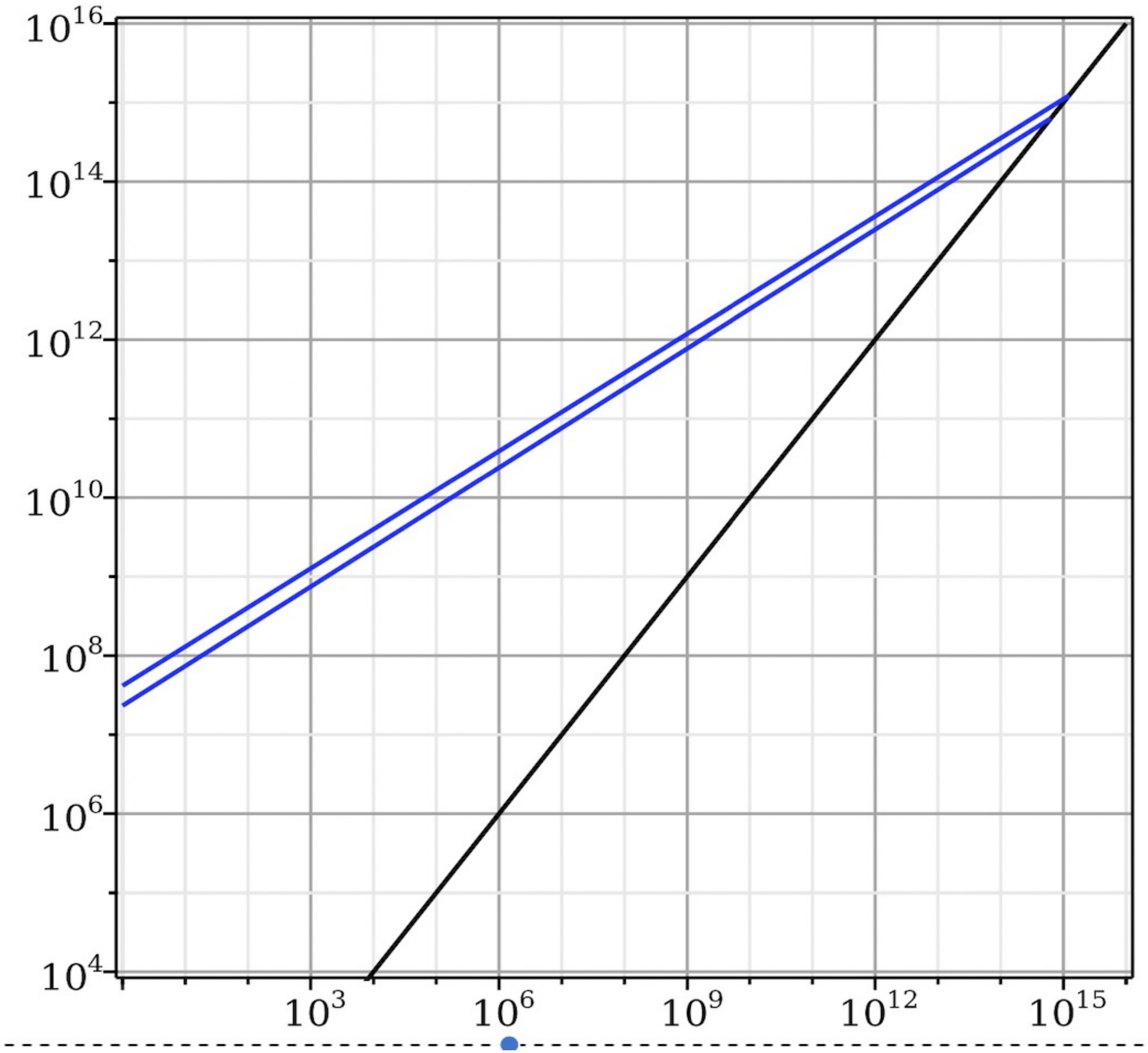
FOR COMOVING PARTICLE DENSITY $Y \equiv n_{DM}/s$ $\quad Y \propto \frac{T_\times^{2d-1}}{\Lambda_{DM}^{2d}}$

$$\Omega_{DM} = 0.2(\frac{m_{DM}}{1TeV})(\frac{Y_{DM}}{10^{-13}})$$

DEMANDING $\Omega_{DM}h^2 = 0.12$ ONE GETS $m_{DM} \quad versus \quad \Lambda_{DM}$

AS A FUNCTION OF $T_\times$ FOR A CHOSEN MODEL OF INFLATION

(MODELS OF DM PRODUCTION ARE TESTED BY CMB OBSERVABLES)



10^{16}
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