Probing the Early Universe with Baryogenesis & Inflation

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Outline

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  1. Electroweak baryogenesis
  2. Leptogenesis
  3. Other models

- **INFLATION**

  1. The basic picture
  2. Recent developments

II. Leptogenesis

Key references

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Reviews

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Thermal leptogenesis

Unification of gauge couplings suggests that Standard Model gauge group is part of larger simple group,

$$G_{SM} = U(1) \times SU(2) \times SU(3) \subset SU(5) \subset SO(10) \ldots$$

Quarks and leptons form GUT multiplets,

$$\mathbf{10} = (q_L, u_R^c, e_R^c)\ , \quad \mathbf{5}^* = (d_R^c, l_L)\ , \quad \mathbf{1} = \nu_R$$

Right-handed neutrinos are gauge singlets, can have Majorana masses not generated by electroweak symmetry breaking; Yukawa interactions couple fermions to Higgs fields $H_1(\mathbf{5})$ and $H_2(\mathbf{5}^*)$,

$$\mathcal{L} = h_{uij}\mathbf{10}_i\mathbf{10}_j H_1(\mathbf{5}) + h_{dij}\mathbf{5}_i^*\mathbf{10}_j H_2(\mathbf{5}^*) + h_{\nu ij}\mathbf{5}_i^*\mathbf{1}_j H_1(\mathbf{5}) + M_{ij}\mathbf{1}_i\mathbf{1}_j$$

Right-handed neutrinos can have large Majorana masses, $M \gg v_{EW}$

GUTs & seesaw

"Seesaw" mechanism and neutrino masses: Majorana masses and Dirac neutrino masses from electroweak symmetry breaking:

$$\mathcal{L}_\nu = h\bar{\nu}_R l_L H - \frac{1}{2} M \nu_R \nu_R + \text{h.c.} \; , \quad l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \; , \; \nu_R$$

after electroweak symmetry breaking, $\langle H \rangle = v_F$, generation of Dirac neutrino mass $m_D = h v_F$; Majorana mass of right-handed neutrinos not protected by electroweak symmetry breaking, hence much heavier, yields 3 light and 3 heavy neutrinos:

$$N \simeq \nu_R + \nu_R^c \; , \quad \nu \simeq \nu_L + \nu_L^c \; ,$$

$$m_N \simeq M \quad , \quad m_\nu \simeq -m_D^T \frac{1}{M} m_D$$

Successful phenomenology of neutrino masses and mixings, neutrino oscillations, ...

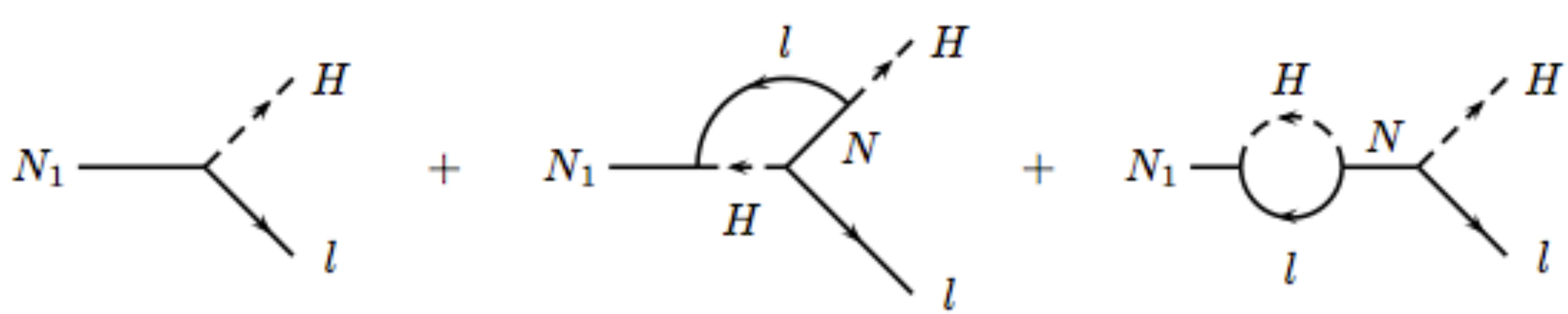
For hierarchical right-handed neutrinos, light neutrino masses naturally related to mass scale of grand unification:

$$M_3 \sim \Lambda_{\mathrm{GUT}} \sim 10^{15}\ \mathrm{GeV}\ , \quad m_3 \sim \frac{v^2}{M_3} \sim\ 0.01\ \mathrm{eV}$$

CP violating heavy neutrino decays (quantum interference!):

$$\varepsilon_1 = \frac{\Gamma\left(N_1 \to H + l_L\right) - \Gamma\left(N_1 \to H^\dagger + l_L^\dagger\right)}{\Gamma\left(N_1 \to H + l_L\right) + \Gamma\left(N_1 \to H^\dagger + l_L^\dagger\right)}$$

$$\simeq\ -\frac{3}{16\pi}\frac{M_1}{(hh^\dagger)_{11} v_F^2}\mathrm{Im}\left(h^* m_\nu h^\dagger\right)_{11}$$



Order-of-magnitude estimate

Rough estimate for ε_1 in terms of neutrino masses; assuming dominance largest eigenvalue m_3 and phases $\mathcal{O}(1)$,

$$\varepsilon_1 \sim \frac{3}{16\pi}\frac{M_1 m_3}{v^2} \sim 0.1\ \frac{M_1}{M_3}\ ,$$

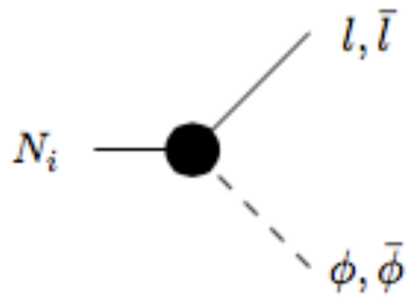
using seesaw relation; CP asymmetry determined by mass hierarchy of heavy Majorana neutrinos. Mass ratio like up-type quarks, $M_1/M_3 \sim 10^{-5}$, yields estimate $\varepsilon_1 \sim 10^{-6}$. Final estimate for baryon asymmetry,

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = -d c_s \varepsilon_1 \kappa_f \sim 10^{-10}\ ,$$

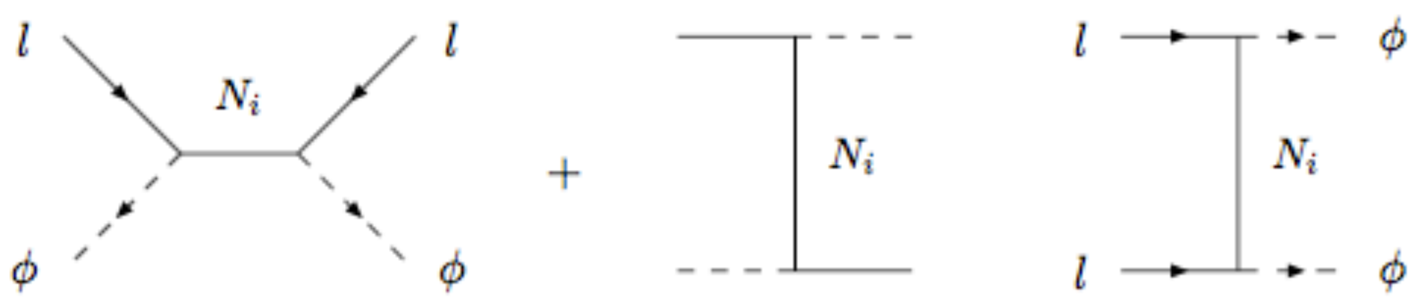
with dilution factor $d \sim 10^{-2}$; efficiency factor $\kappa_f \sim 10^{-2}$ for effect of washout processes. Correct value of baryon asymmetry is consequence of hierarchical heavy neutrinos masses and kinematical factors d and κ_f.

Decays (D) and inverse decays (ID)

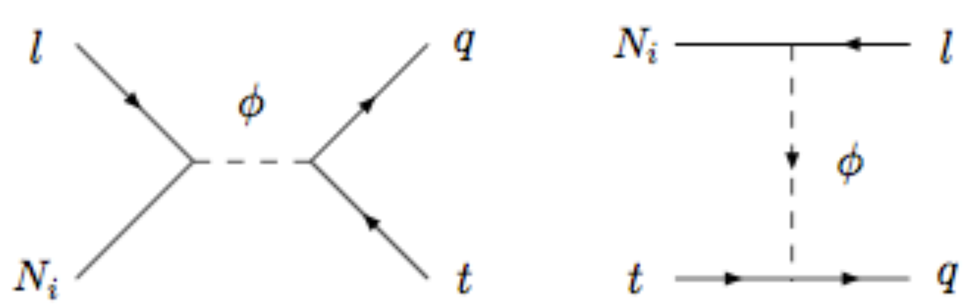
$N_i \leftrightarrow l\,\phi\,,\ \bar{l}\,\bar{\phi}$



$\Delta L = 2$ processes (N_i virtual)



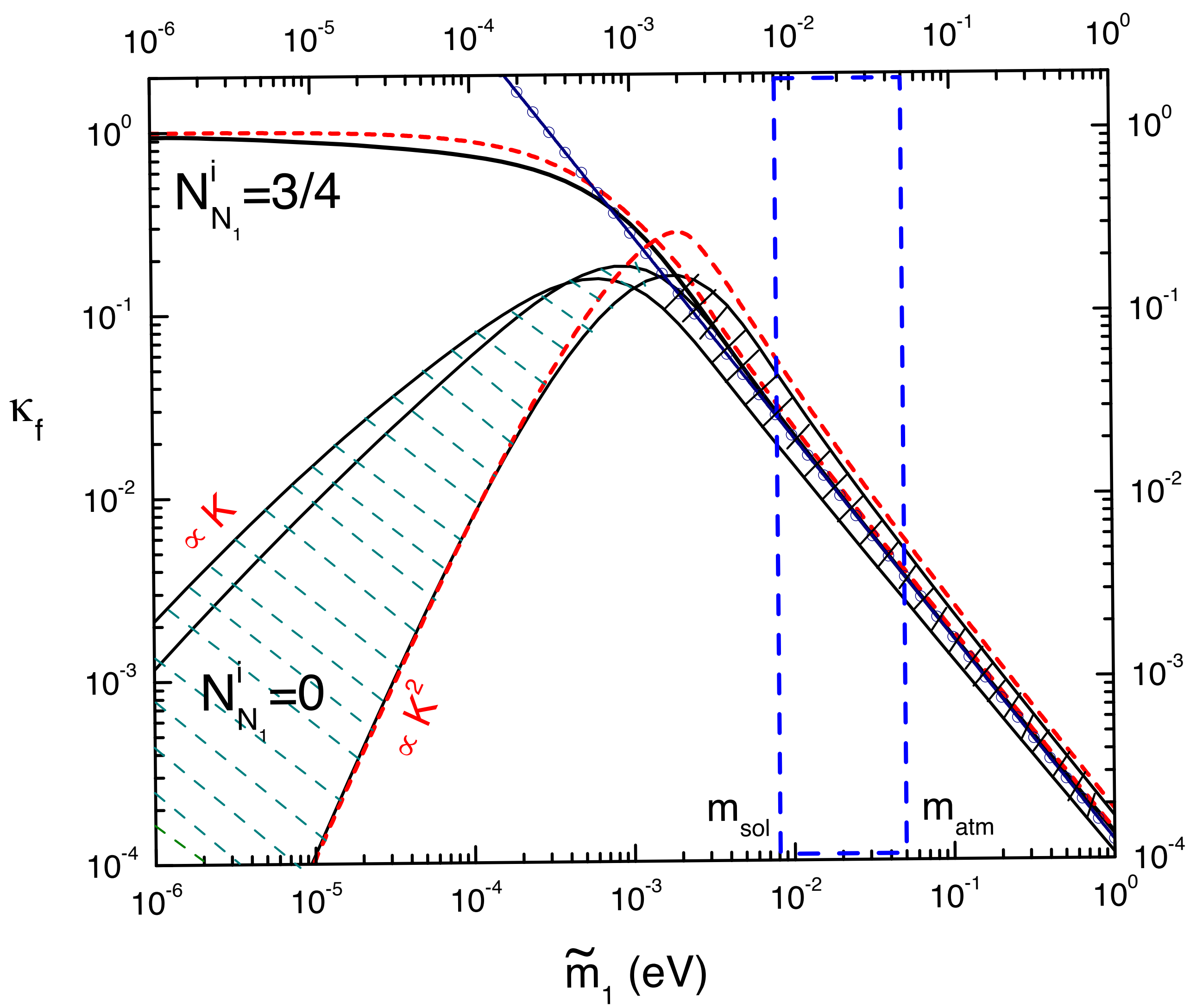
$\Delta L = 1$ processes (N_i real, ϕ virtual)



basic decay and scattering processes of heavy neutrinos in plasma

further important: interactions with gauge bosons!

$$\frac{dN_{N_1}}{dz} = -(D+S)\,(N_{N_1} - N_{N_1}^{\rm eq})\ ,$$
$$\frac{dN_{B-L}}{dz} = -\varepsilon_1\, D\,(N_{N_1} - N_{N_1}^{\rm eq}) - W\, N_{B-L}$$



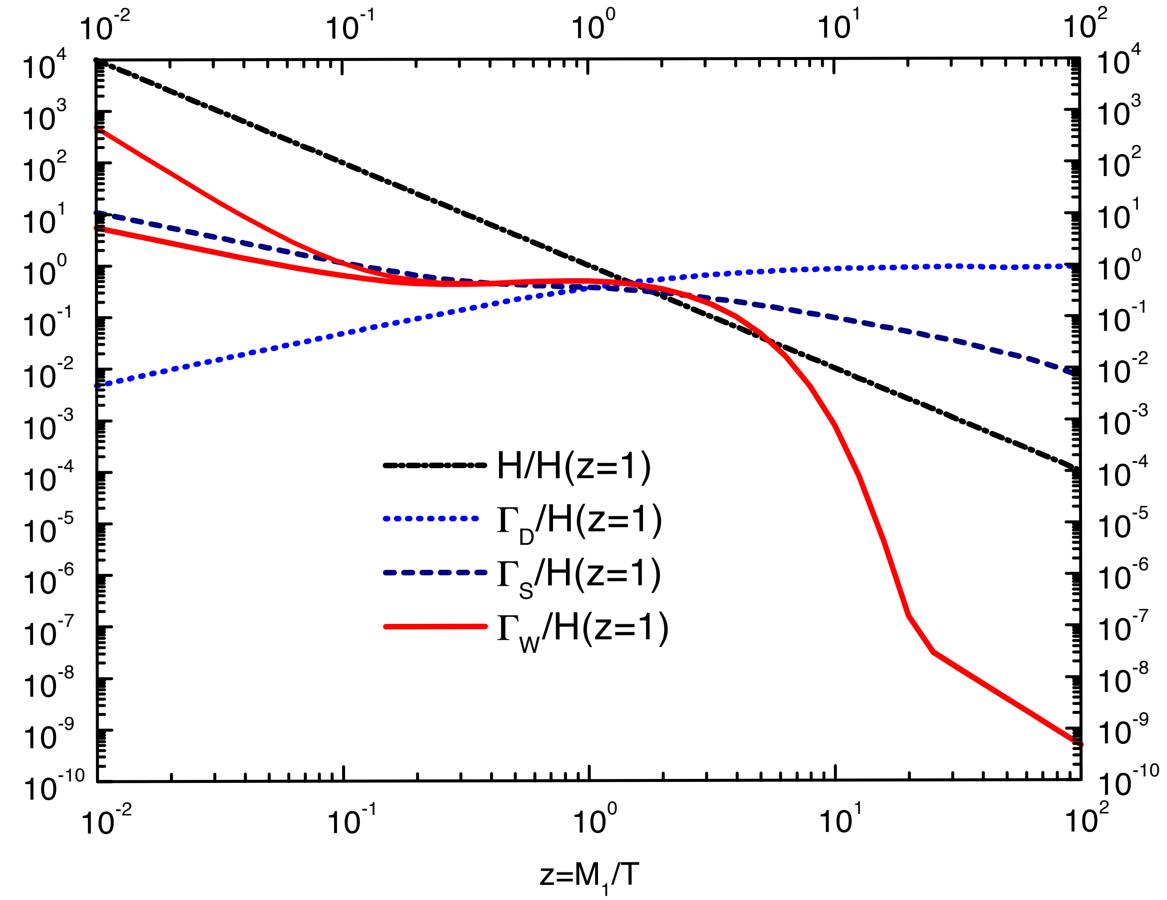
In "strong washout regime,"

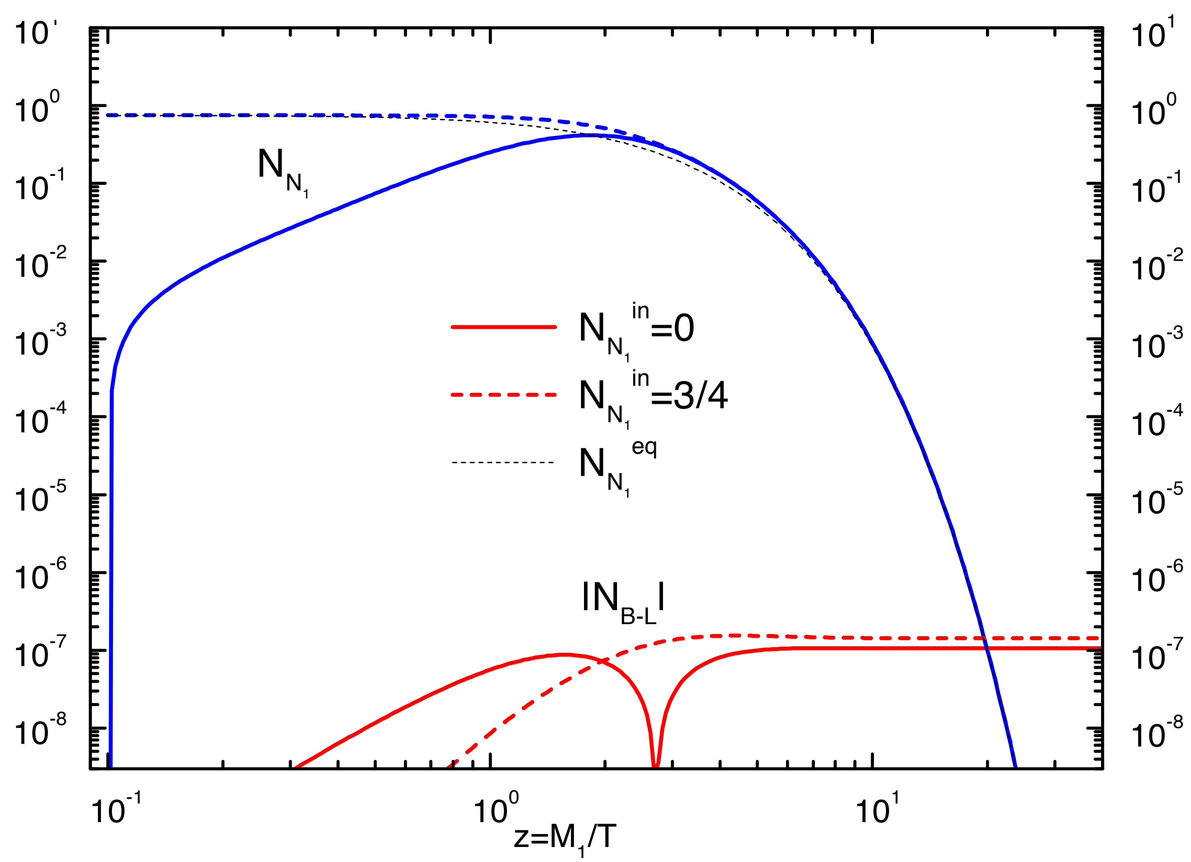
$$\widetilde{m} > m_* \sim 10^{-3}\ \mathrm{eV}$$

baryon asymmetry rather independent of initial conditions (but flavour effects!); efficiency factor:

$$\kappa_{\rm f} = (2 \pm 1)\, 10^{-2} \left(\frac{0.01\,\mathrm{eV}}{\widetilde{m}}\right)^{1.1\pm 0.1}$$

$$\widetilde{m} = \frac{(m_D m_D^\dagger)_{11}}{M_1}$$

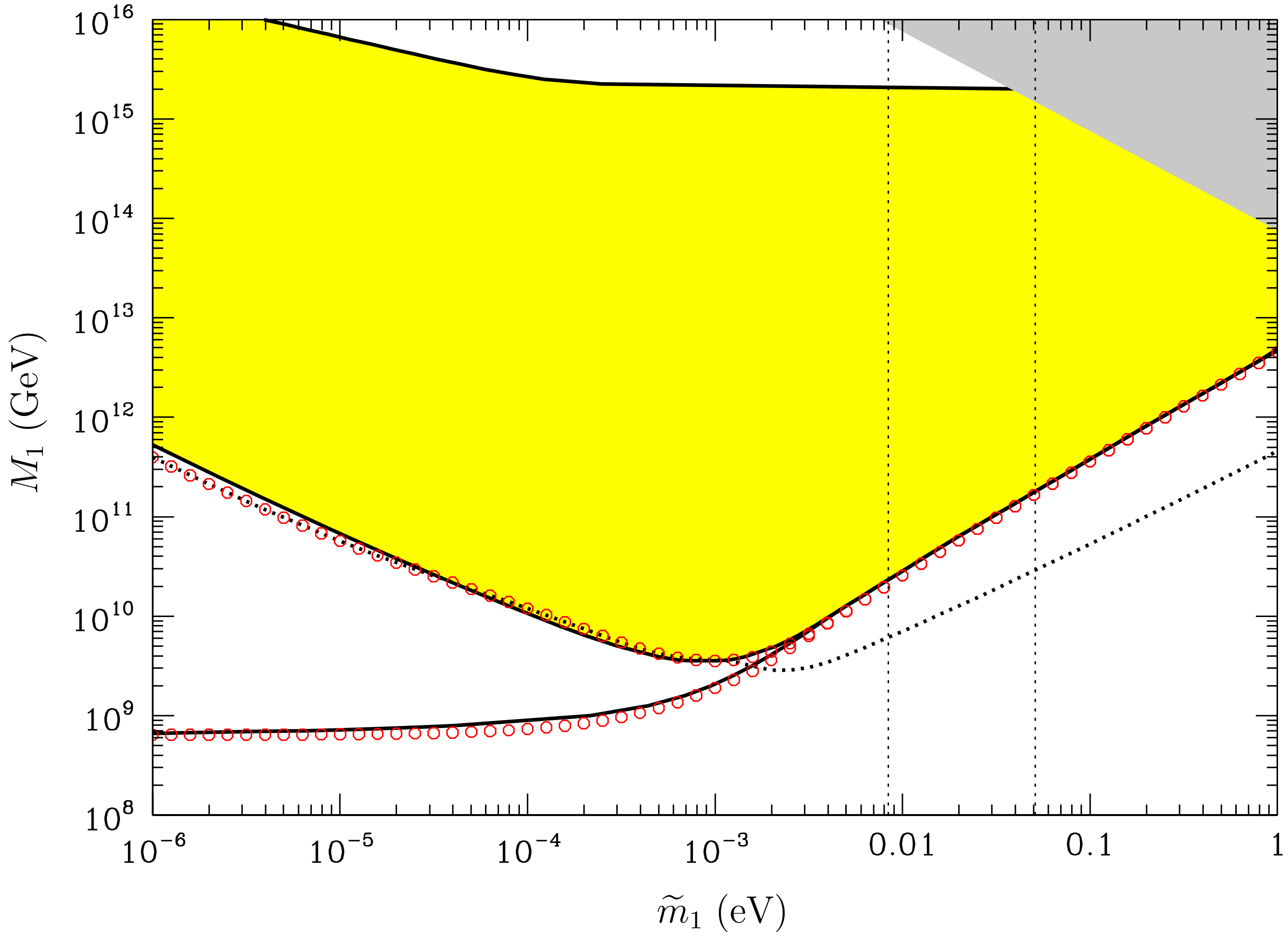




upper: comparison of decay/scattering/washout rates with Hubble parameter. It is amazing that leptogenesis works at all!

lower: heavy neutrino densities & baryon asymmetry; leptogenesis process close to equilibrium

Constraints on neutrino masses



Detailed study of Boltzmann equations leads to bound on light and heavy neutrino masses (and reheating temperature); in simplest approximation (sum over lepton flavours):

$$m_i < 0.1\,\text{eV}\ , \quad M_1 > 4 \times 10^8\ \text{GeV}$$

Preferred neutrino mass range ("strong washout regime", independence of initial conditions):

$$10^{-3}\ \text{eV} < m_i < 0.1\ \text{eV}$$

modifications: lepton flavour effects (bounds relaxed by about one order of magnitude ?!); furthermore effects from possible neutrino mass degeneracies

Resonant leptogenesis

Basic idea: enhance CP asymmetry by mass degeneracy of heavy neutrinos, lower scale of B-L breaking, look for signatures at the LHC

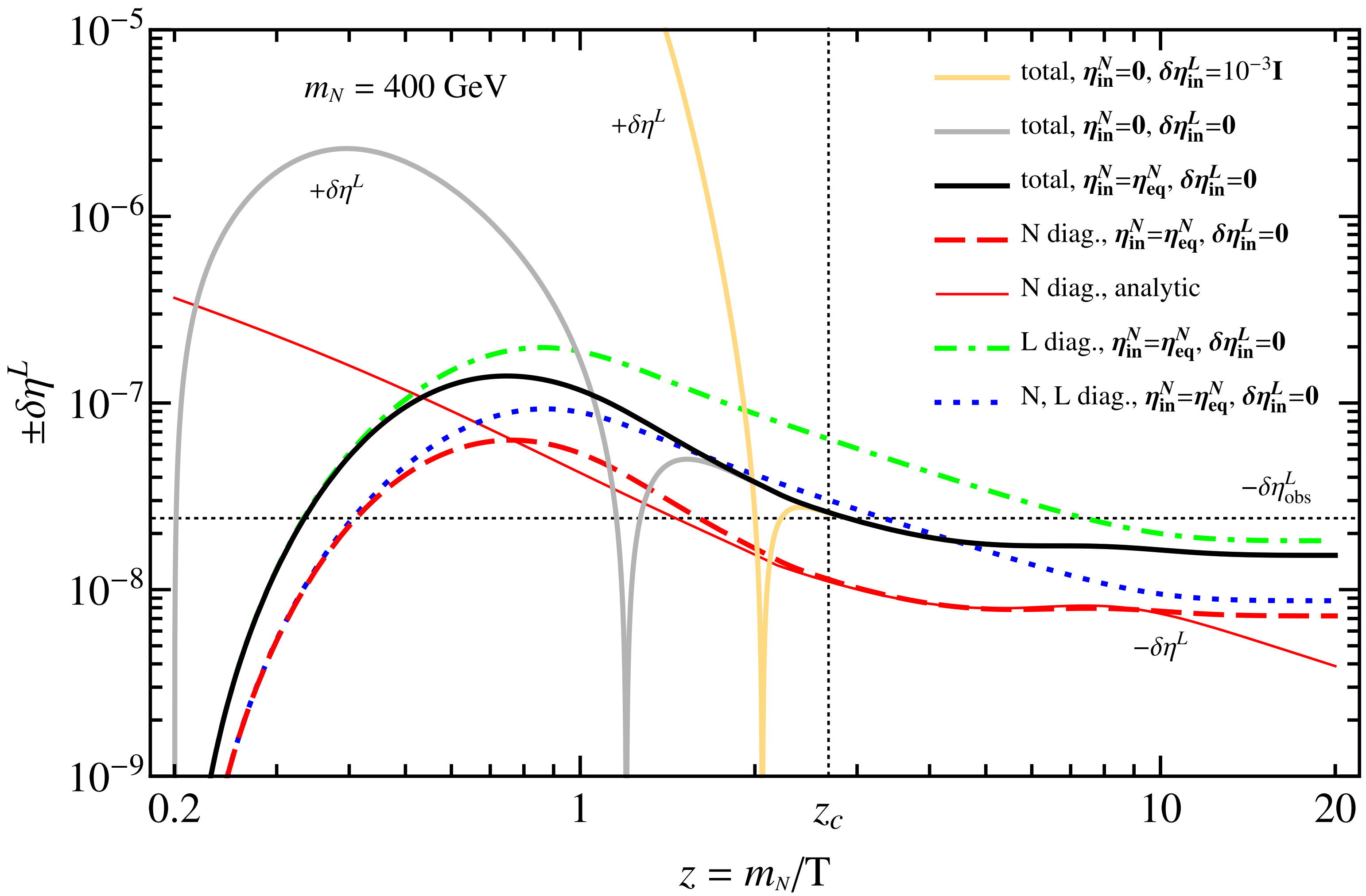
$$\Gamma_{\alpha l} \;=\; \Gamma(N_\alpha \to l_L^- + W^+) \;+\; \Gamma(N_\alpha \to \nu_{lL} + Z, H)$$

Leptonic asymmetries for individual lepton flavour in terms of the resummed neutrino Yukawa couplings:

$$\delta_{\alpha l} \;\equiv\; \frac{\Gamma_{\alpha l} \;-\; \Gamma^C_{\alpha l}}{\sum\limits_{l=e,\mu,\tau} \left(\Gamma_{\alpha l} \;+\; \Gamma^C_{\alpha l}\right)} \;=\; \frac{\left|\overline{\mathbf{h}}^{\nu}_{l\alpha}\right|^2 \;-\; \left|\overline{\mathbf{h}}^{\nu C}_{l\alpha}\right|^2}{\left(\overline{\mathbf{h}}^{\nu\dagger}\, \overline{\mathbf{h}}^{\nu}\right)_{\alpha\alpha} \;+\; \left(\overline{\mathbf{h}}^{\nu C\dagger}\, \overline{\mathbf{h}}^{\nu C}\right)_{\alpha\alpha}}$$

Leptonic asymmetries $\delta_{\alpha l}$ enhanced for degeneracy of heavy neutrinos (2-heavy neutrino mixing):

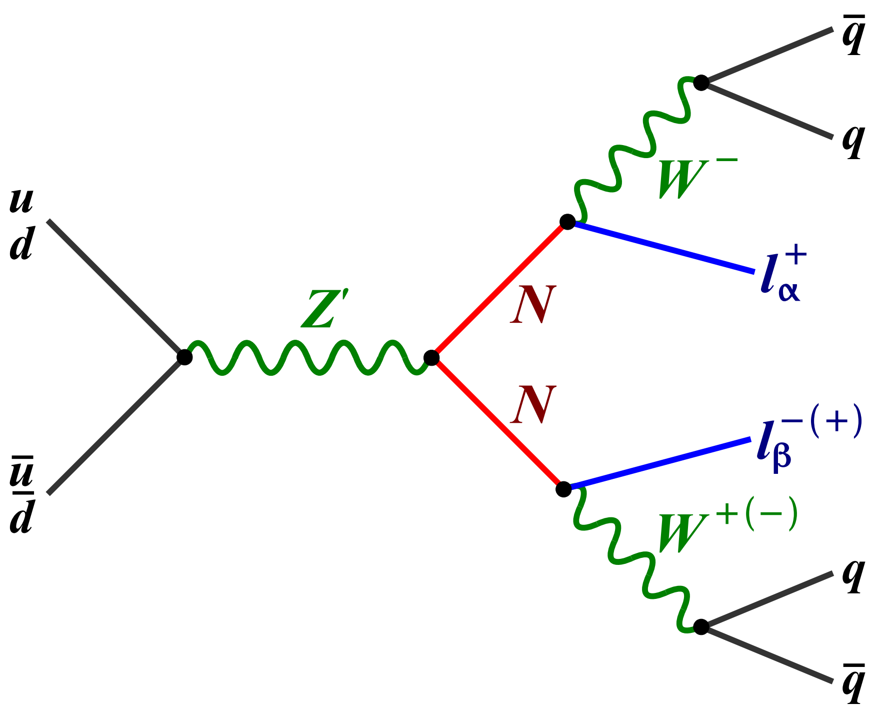
$$\delta_{\alpha l} \;\approx\; \frac{\mathrm{Im}\big[\, (\mathbf{h}^{\nu\dagger}_{\alpha l}\mathbf{h}^{\nu}_{l\beta})\,(\mathbf{h}^{\nu\dagger}\mathbf{h}^{\nu})_{\alpha\beta}\big]}{(\mathbf{h}^{\nu\dagger}\mathbf{h}^{\nu})_{\alpha\alpha}\,(\mathbf{h}^{\nu\dagger}\mathbf{h}^{\nu})_{\beta\beta}}\; \frac{(m^2_{N_\alpha} - m^2_{N_\beta})\, m_{N_\alpha}\, \Gamma^{(0)}_{N_\beta}}{(m^2_{N_\alpha} - m^2_{N_\beta})^2 \;+\; m^2_{N_\alpha}\, \Gamma^{(0)2}_{N_\beta}}$$



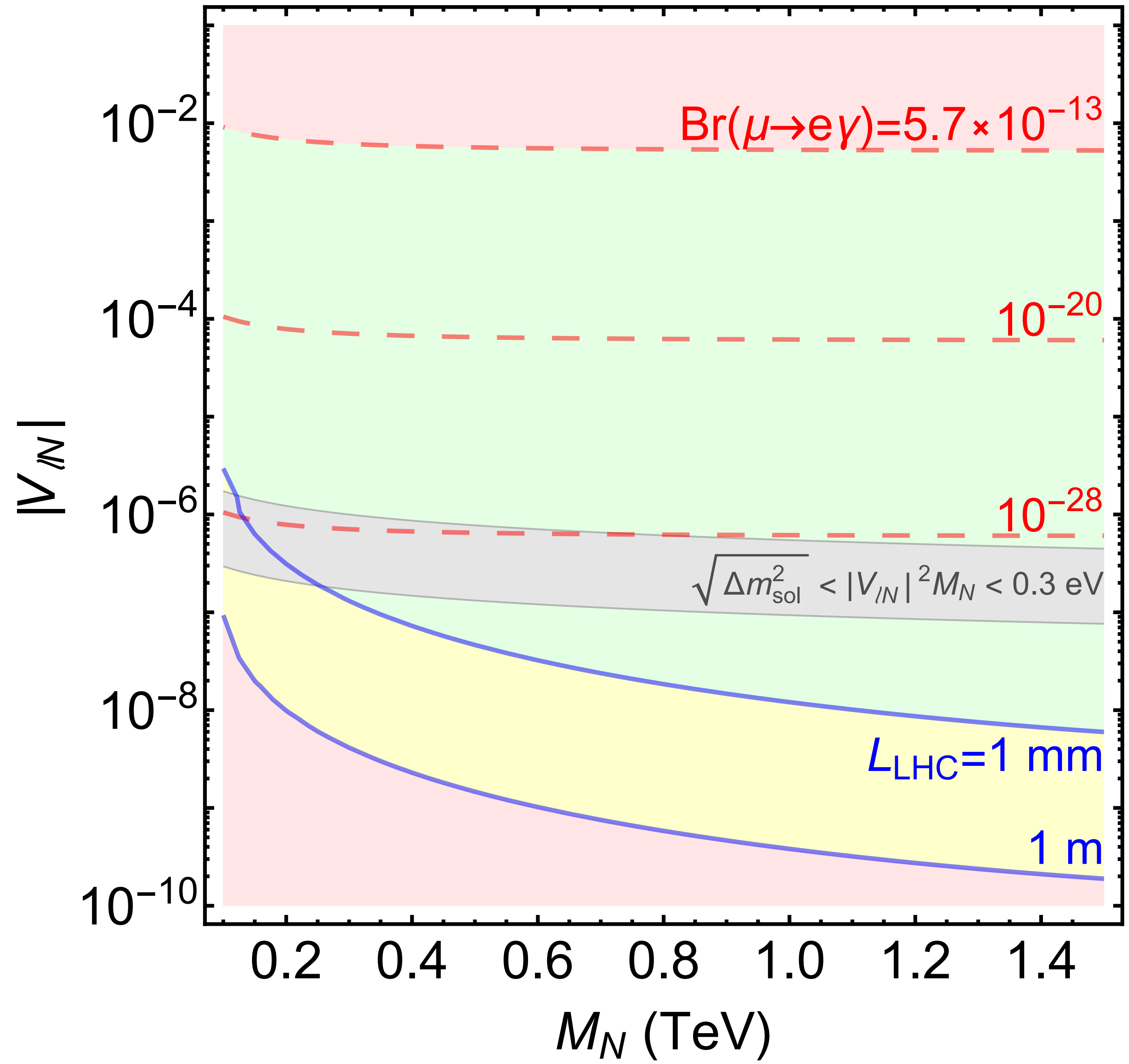
Parameter	Value
m_N	400 GeV
c	2×10^{-7}
$\frac{\Delta M_1}{m_N}$	-3×10^{-5}
$\frac{\Delta M_2}{m_N}$	$(-1.21 + 0.10\, i) \times 10^{-9}$
a	$(4.93 - 2.32\, i) \times 10^{-3}$
b	$(8.04 - 3.79\, i) \times 10^{-3}$
ϵ_e	$5.73\, i \times 10^{-8}$
ϵ_μ	$4.30\, i \times 10^{-7}$
ϵ_τ	$6.39\, i \times 10^{-7}$

[Dev, Millington, Pilaftsis, Teresi '15]

Resonant leptogenesis: strong enhancement due to close degeneracy of heavy neutrino masses; flavour effects included



[Depisch, Dev, Pilaftsis '15]



Heavy neutrino production at the LHC: consistent with leptogenesis, lepton-flavour violation; displaced vertices

Towards a theory of leptogenesis

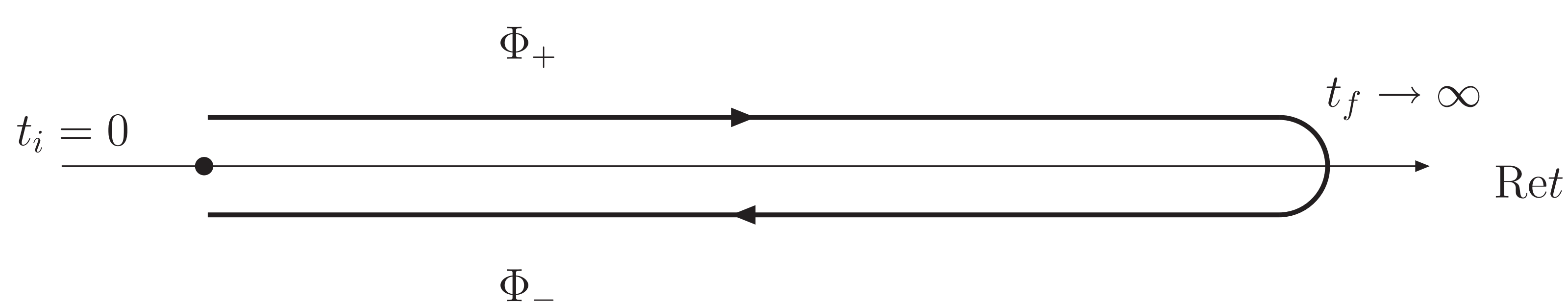
Basic idea: instead of Boltzmann equations, consider Green's functions interpotating between equilibrium states → rigorous QFT!

Green's functions Δ for heavy neutrino N_1, lepton and Higgs on complex time contour, (self energy Π_C),

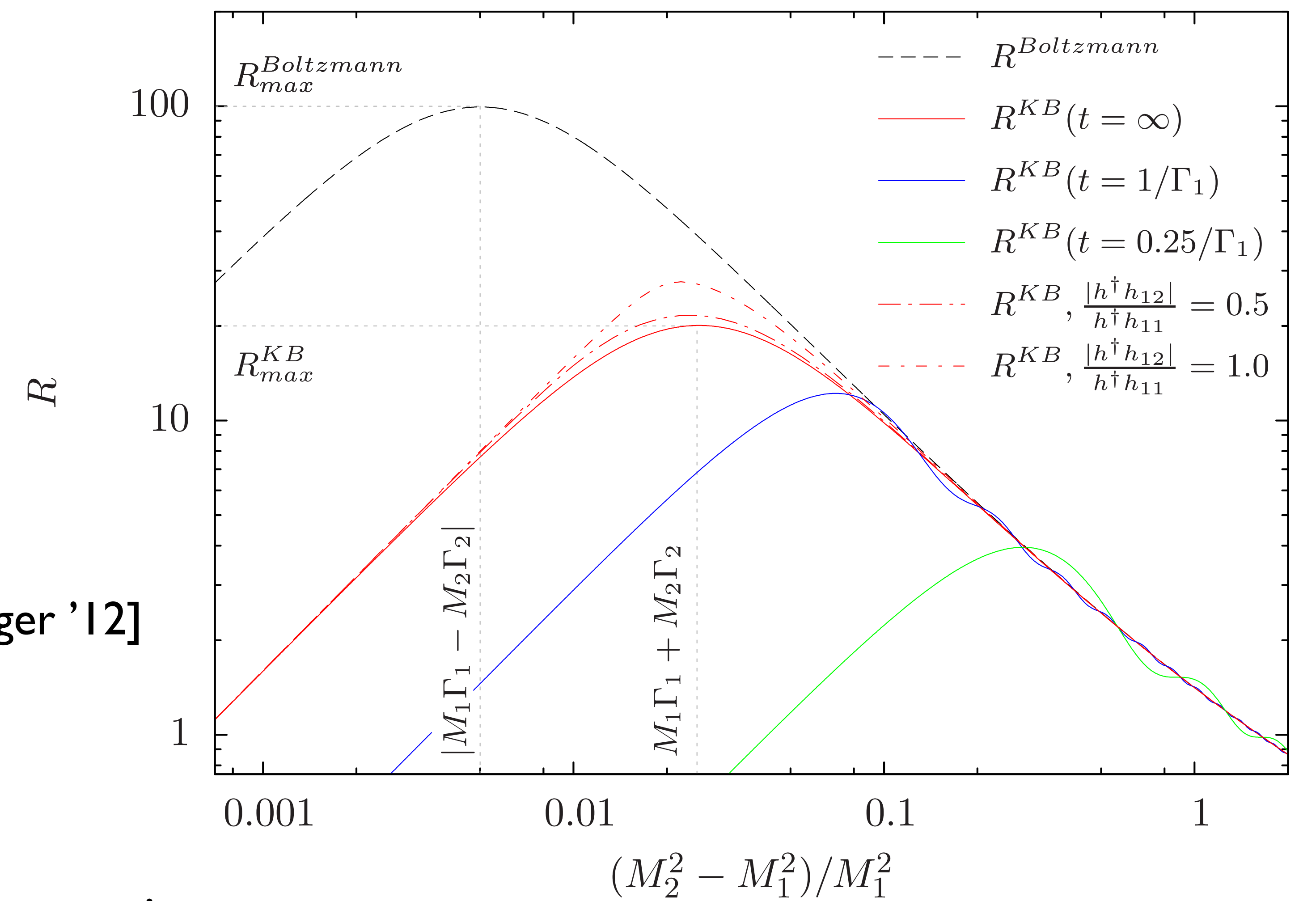
$$(\Box_1 + m^2)\Delta_C(x_1, x_2) + \int_C d^4x' \Pi_C(x_1, x')\Delta_C(x', x_2) = -i\delta_C(x_1 - x_2)$$

Consider particular correlation functions, spectral functions Δ^- with information about system, and statistical propagators Δ^+ depending on initial state,

$$\Delta^+(x_1, x_2) = \frac{1}{2}\langle\{\Phi(x_1), \Phi(x_2)\}\rangle \ ,$$
$$\Delta^-(x_1, x_2) = i\langle[\Phi(x_1), \Phi(x_2)]\rangle$$



[Garny, Kartavtsev, Hohenegger '12]



Solve Kadanoff-Baym equations,

$$\Box_{1,\mathbf{q}}\Delta^-_{\mathbf{q}}(t_1,t_2) = -\int_{t_2}^{t_1} dt'\Pi^-_{\mathbf{q}}(t_1,t')\Delta^-_{\mathbf{q}}(t',t_2)\ ,\ldots$$

Compare for *resonant leptognesis* enhancement predicted by Boltzmann eqs. and Kadanoff-Baym eqs.,

$$R^{Boltzmann}_{max} = \frac{M_1 M_2}{2|M_1\Gamma_1 - M_2\Gamma_2|}\ ,\quad R^{KB}_{max} = \frac{M_1 M_2}{2(M_1\Gamma_1 + M_2\Gamma_2)}\ ,$$

$\rightarrow$ enhancement suppressed!

Summary: leptogenesis

- Thermal leptogenesis simple and natural mechanism for explanation of baryon asymmetry, supported by small neutrino masses
- Important: determinaton of absolute neutrino mass scale (cosmology?) smallest neutrino mass ~ 0.01 eV ?
- Further work: flavour effects, corrections from interactions with gauge bosons in plasma
- Resonant leptogenesis can be tested at the LHC; consistency with GUTs?
- Nonthermal leptogenesis also possible, less predictive
- Significant progress towards full QFT treatment of leptogenesis

III. Other models

- Affleck-Dine mechanism: generic possibility (particularly attractive for flat directions in MSSM)
- Heavy moduli decay (can simultaneously predict dark matter, very model dependent)
- Cold baryogenesis
- Baryogenesis from strong CP violation and the QCD axion
- Baryogenesis from Hawking radiation
- ....
- important: motivation by extension of the Standard Model

INFLATION

What is the origin of the CMB anisotropies, and why

$$n_s = 0.968 \pm 0.006, \quad r = ?, \ \ldots$$

? ? ? ?

Key references

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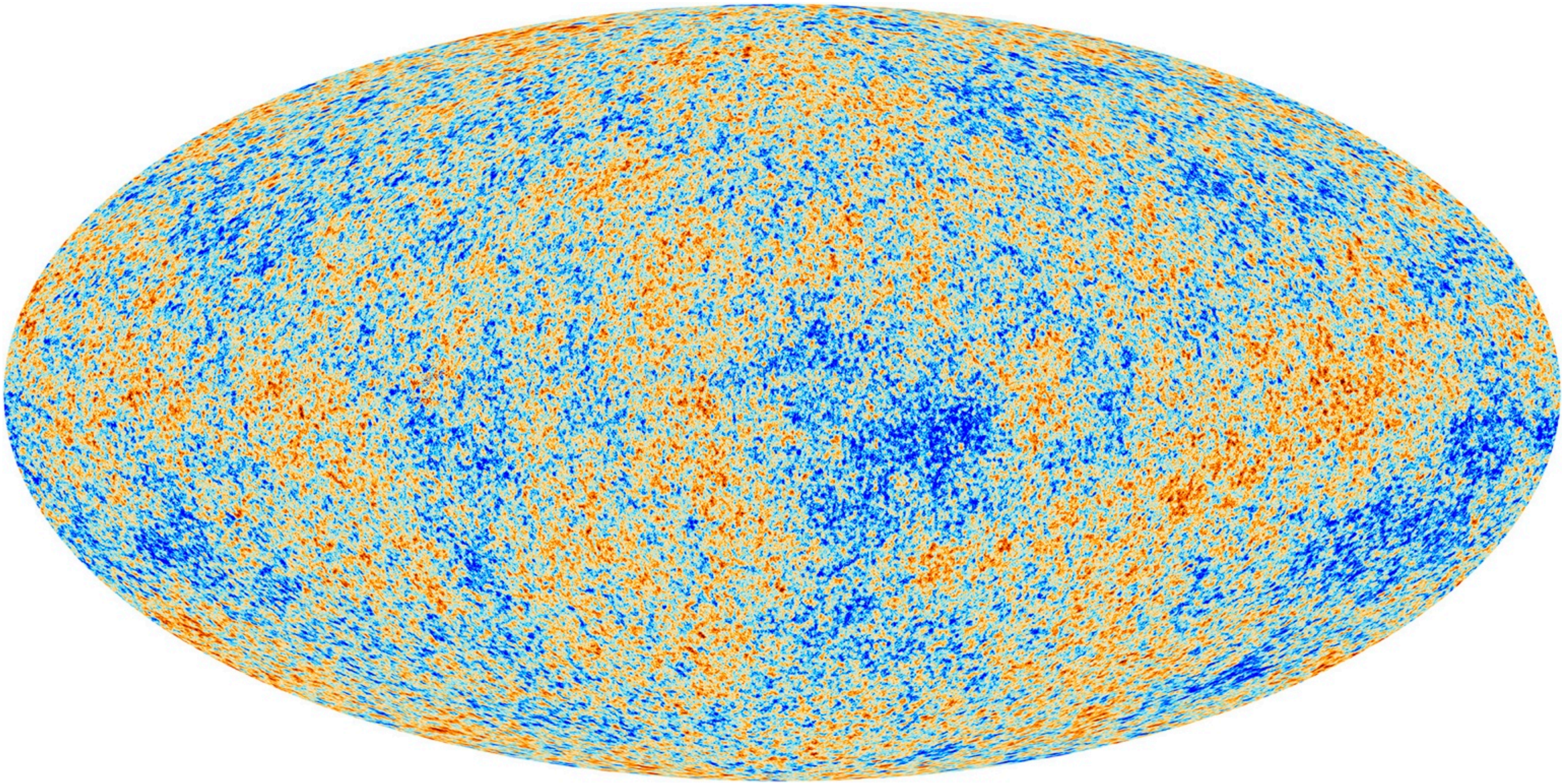


The microwave background sky as seen by Planck 2013: fluctuations one million times smaller than average; best evidence for hot early universe

Horizon problem

How can one understand the amazing isotropy of the CMB?

Expanding universe (Friedmann Robertson Walker metric), use conformal co-ordinates:

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)\,, \quad k = 0, \pm 1$$

change radial coordinate, and time to conformal time:

$$dr/\sqrt{1-kr^2} = d\chi\,, \quad dt/a(t) = d\tau$$

In new coordinates lightcone as in Minkowski space:

$$ds^2 = a^2(\tau)\left(d\tau^2 - d\chi^2 - \Phi^2(\chi) d\Omega^2\right)\,,$$

$$\Phi^2(\chi) = \begin{cases} \sinh^2\chi\,, & k=-1 \\ \chi^2\,, & k=0 \\ \sin^2\chi\,, & k=1 \end{cases}$$

Particle horizon (also *past horizon*, causally connected domain, i.e. "region from which information can have reached the observer until now"):

$$d_p(t) = a(t)\chi_p(t)\,, \quad \chi_p(t) = \int_{t_i}^{t} \frac{dt}{a(t)}\,, \qquad \chi_p : \textit{comoving particle horizon}$$

Time evolution of cosmic scale factor determined by Friedman equation:

$$H^2 + \frac{k}{a^2} = \frac{\rho}{3M_{\mathrm{P}}^2}\,, \quad H = \frac{\dot{a}}{a}\,,$$

with H: Hubble parameter, ρ: energy density, $M_{\mathrm{P}} = 2.4 \times 10^{18}$ GeV: Planck mass; time dependence of scale factor depends on equation of state $\omega = p/\rho$ ($\omega = (0, 1/3, -1)$ for (matter, radiation, constant vacuum energy):

$$\rho \propto a^{-3(1+\omega)}\,,$$

i.e. energy density constant for "vacuum". Useful quantity: *comoving Hubble radius*:

$$\frac{1}{aH} = \frac{1}{a_0 H_0}\left(\frac{a}{a_0}\right)^{\frac{1}{2}(1+3\omega)}$$

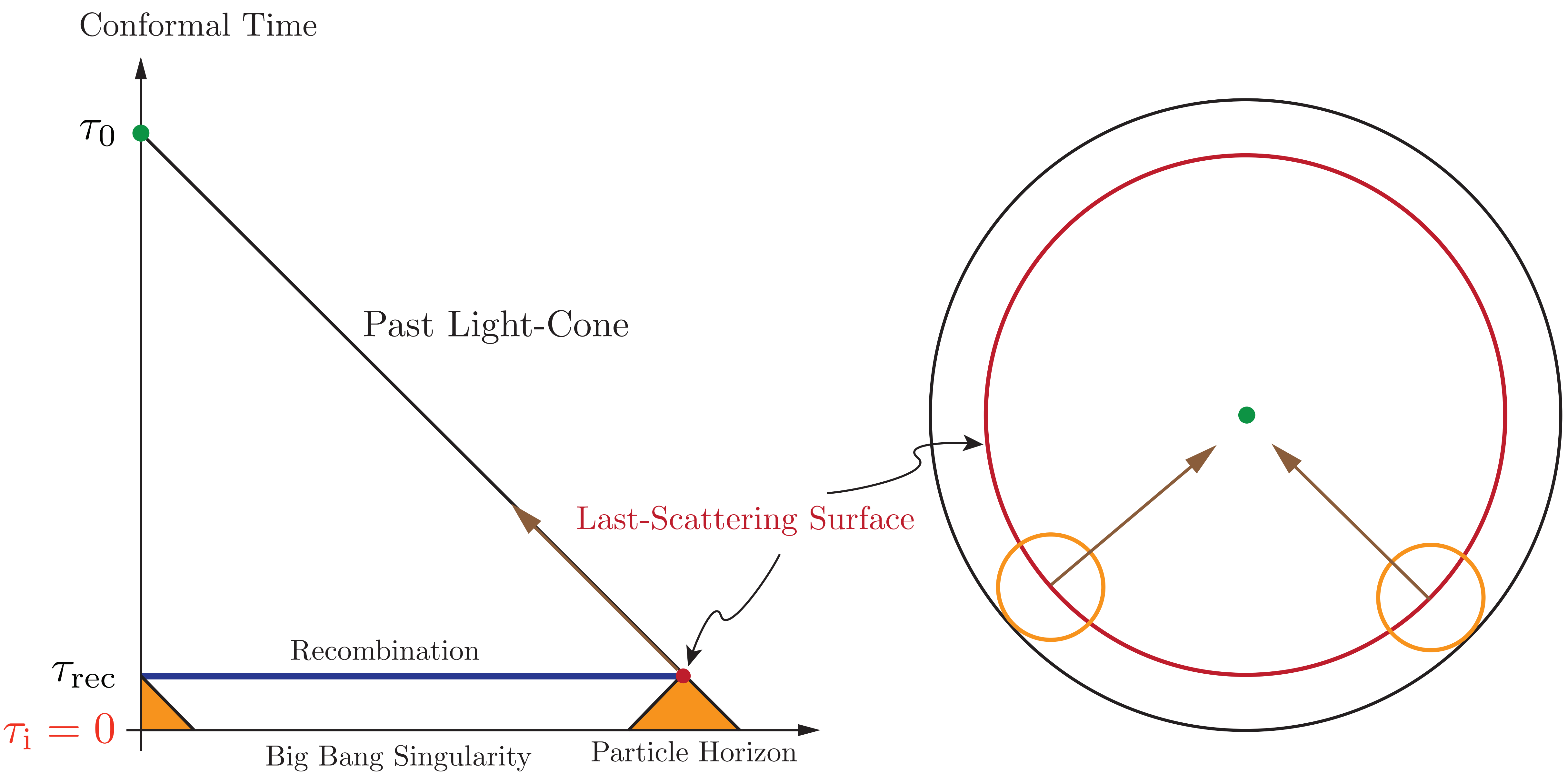
Comoving horizon as function of scale factor (use scale factor as "time"):

$$\chi_p(a) = \frac{1}{a_0 H_0} \begin{cases} 2(a/a_0)^{1/2}\,, & \text{matter} \\ a/a_0\,, & \text{radiation} \\ a_0/a_i - a_0/a\,, & \text{vacuum} \end{cases}$$

For matter/radiation, horizon grows with scale factor. *"Natural assumption"*: $\chi_p(t_0) \gg \chi_p(t_{\rm rec})$ (t_0: today, $t_{\rm rec}$: time of recombination). Then one has a problem. Equation of state between today and recombination: $\omega \approx 0$ (see Sarkar); compare comoving horizons today and at recombination:

$$\frac{\chi_p(t_0)}{\chi_p(t_{rec})} \approx \left(\frac{a_0}{a(t_{rec}}\right)^{1/2} = (1 + z_{rec})^{1/2} \approx (1100)^{1/2}$$

Therefore the CMB we see today comes from $(1100)^{3/2} \sim 10^5$ causally disconnected regions - **how can that be?**

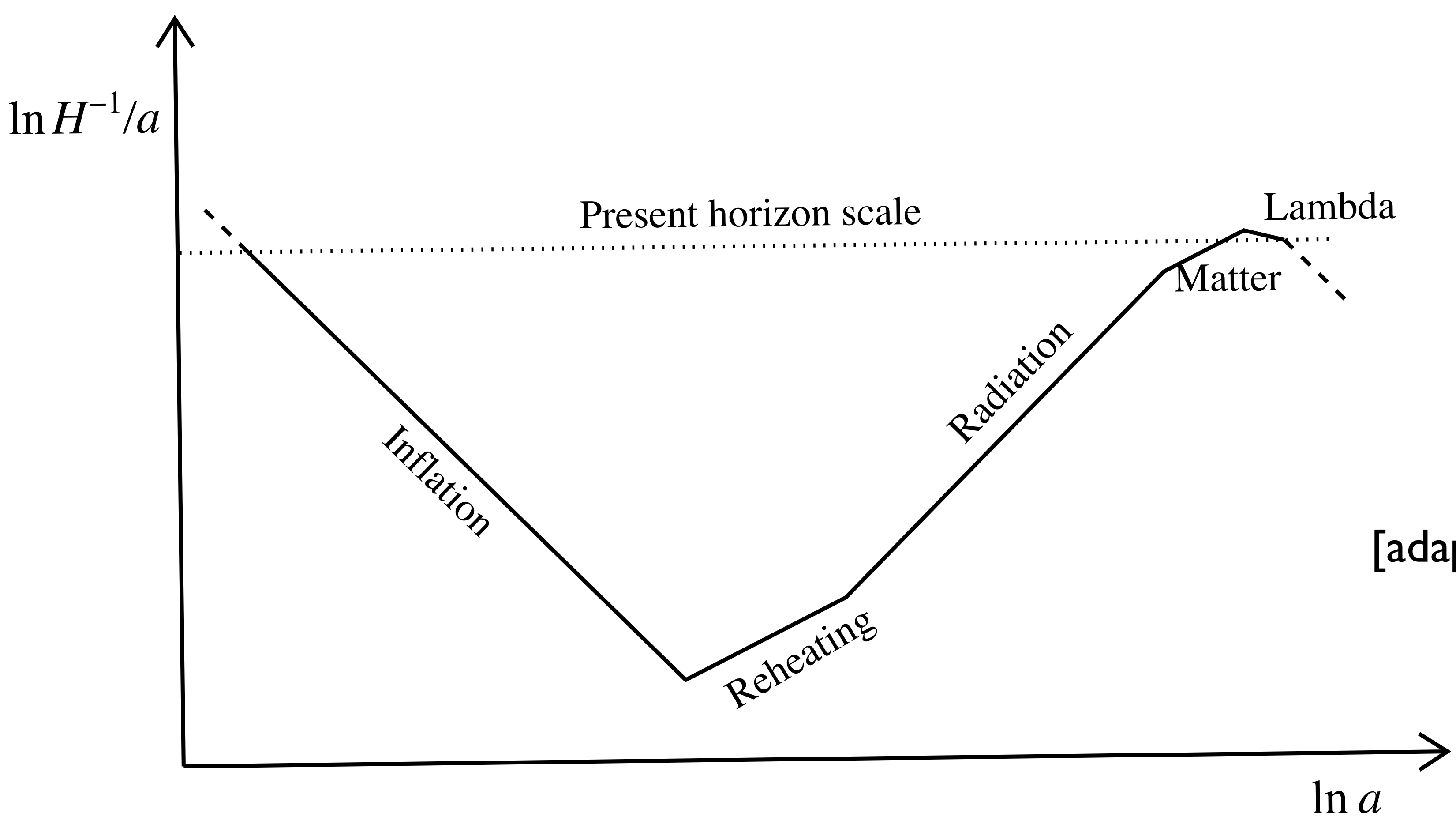


[adapted from Baumann '12]

Solution of the *horizon problem* proposed by inflation: *”shrinking Hubble sphere”*:

$$\chi_p(a) = \int_{a_i}^{a} \frac{da'}{a'} \frac{1}{a' H(a')}$$

add contribution to the integral which increases the comoving horizon at recombination:



[adapted from Liddle, Leach ’03]

shrinking Hubble sphere:

$$\frac{d}{dt}(aH)^{-1} = -\frac{\ddot{a}}{\dot{a}^2}\,, \quad \text{i.e.} \quad \ddot{a} > 0$$

Friedman equation:

$$\frac{\ddot{a}}{a} = -\frac{1}{6M_\mathrm{P}^2}(\rho + 3p)\,, \quad \text{i.e.} \quad p < -\frac{1}{3}\rho$$

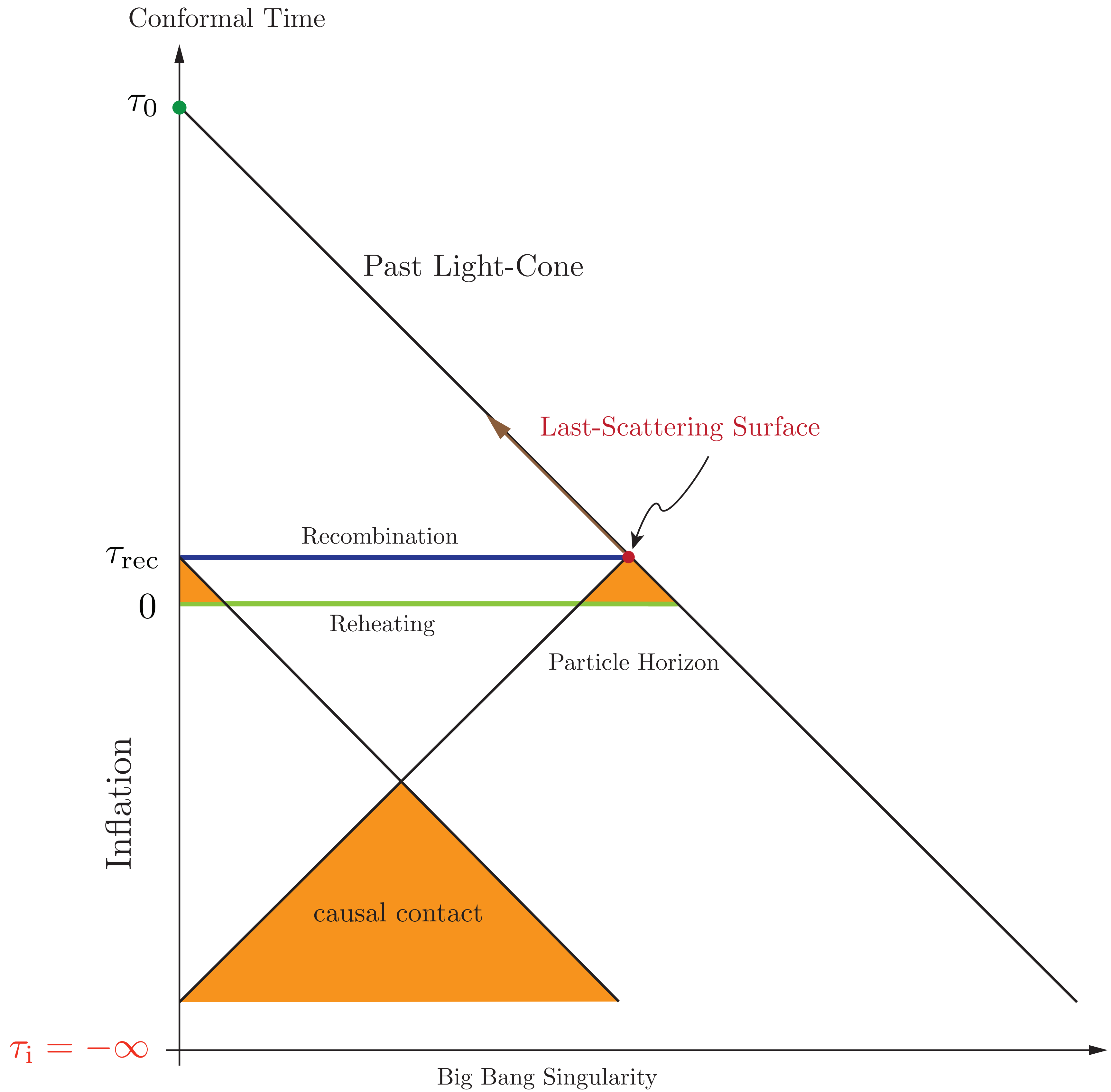
impossible for matter or radiation; vacuum dominance:

$$\rho \simeq \rho_\Lambda = \text{const}\,, \quad \text{i.e.} \quad H_\Lambda = \sqrt{\rho_\Lambda/3}/M_\mathrm{P} = \text{const}$$

consequence is "exponential" growth of scale factor:

$$a(t) = a_i e^{H_\Lambda(t-t_i)}$$

causally connected region is "arbitrarily" big



[adapted from Baumann '12]