Matter antimatter asymmetry

The universe we live in is made of matter (fortunately for us)

Where has the antimatter gone?

Matter Anti-matter asymmetry: Observational evidence

At the scale of the solar system: no concentration of antimatter otherwise its interaction with the solar wind would produce important source of γ's visible radiation

At the galactic scale: There is antimatter in the form of antiprotons in cosmic rays with ratio $n_{\overline{p}}/n_p \sim 10^{-4}$ which can be explained with processes such as

$$p + p \rightarrow 3p + \overline{p}$$

At the scale of galaxy clusters: we have not detected radiation coming from annihilation of matter and antimatter due to $p + \overline{p} \rightarrow \pi^0 ... \rightarrow . \gamma\gamma$

The asymmetry between matter and antimatter is characterized in terms of the baryon to photon ratio

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

The number of photons is not constant over the universe evolution. At early times, it is better to compare the baryon density to the entropy density since the n_B/s ratio takes a constant value as long as B is conserved and no entropy production takes place. Today, the conversion factor is

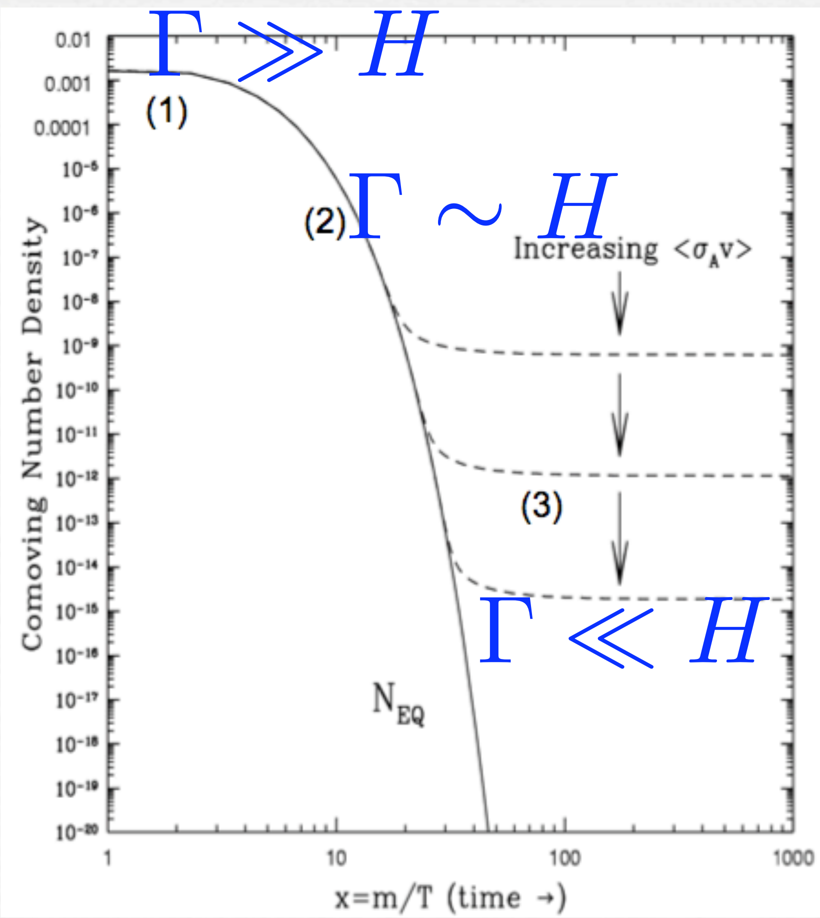
$$\frac{n_B - n_{\overline{B}}}{s} = \frac{\eta}{7.04}$$

How much baryons would there be in a symmetric universe?

nucleon and anti-nucleon densities are maintained by annihilation processes

$$n + \overline{n} \longleftrightarrow \pi + \pi \longleftrightarrow \gamma + \gamma + \ldots$$

which become ineffective when



$$\Gamma \sim (m_N T)^{3/2} e^{-m_N/T}/m_\pi^2 \sim H \sim \sqrt{g_*} T^2/m_{Pl}$$

leading to a freeze-out temperature

$$T_F \sim 20 \text{ MeV}$$

$$\frac{n_N}{s} \approx 7 \times 10^{-20}$$

10^9 times smaller than observed,
and there are no antibaryons
-> need to invoke an initial asymmetry

Matter Anti-matter asymmetry:

characterized in terms of the baryon to photon ratio

$$\eta \equiv \frac{n_B - n_{\overline{B}}}{n_\gamma}$$

~ $6. 10^{-10}$

The great annihilation

10 000 000 001 Matter	10 000 000 000 Anti-matter

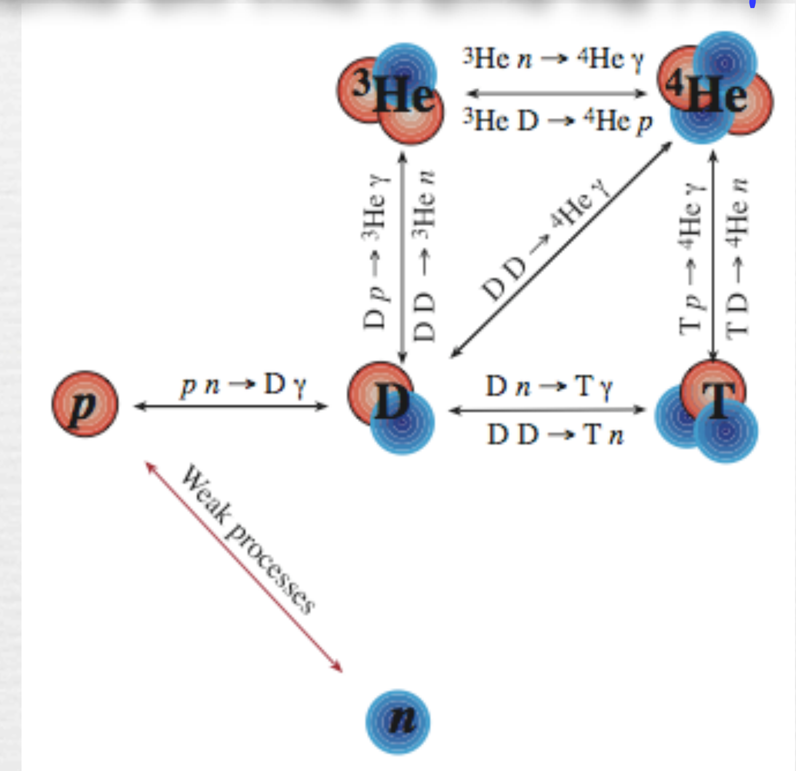
↓

1
(us)

How do we measure η ?

Counting baryons is difficult because only some fraction of them formed stars and luminous objects. However, there are two indirect probes:

1) Big Bang Nucleosynthesis predictions depend on the ratio n_B / n_γ



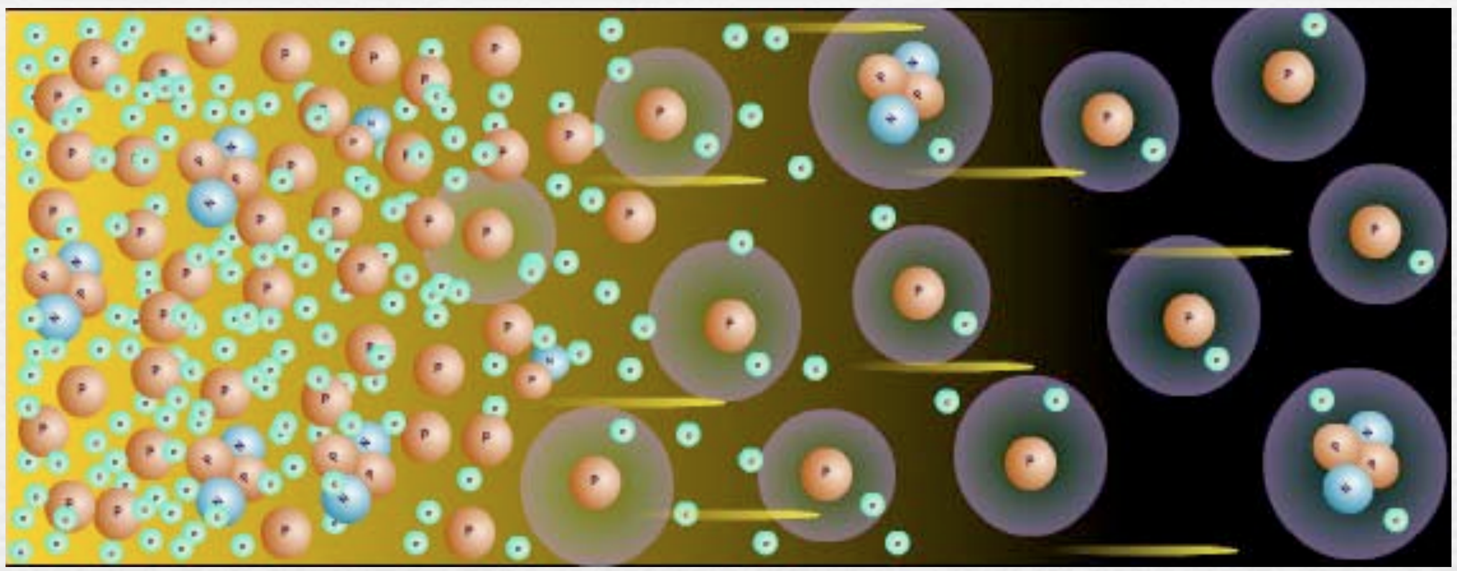
Many more photons than baryons delays BBN by enhancing the reaction D γ →pn

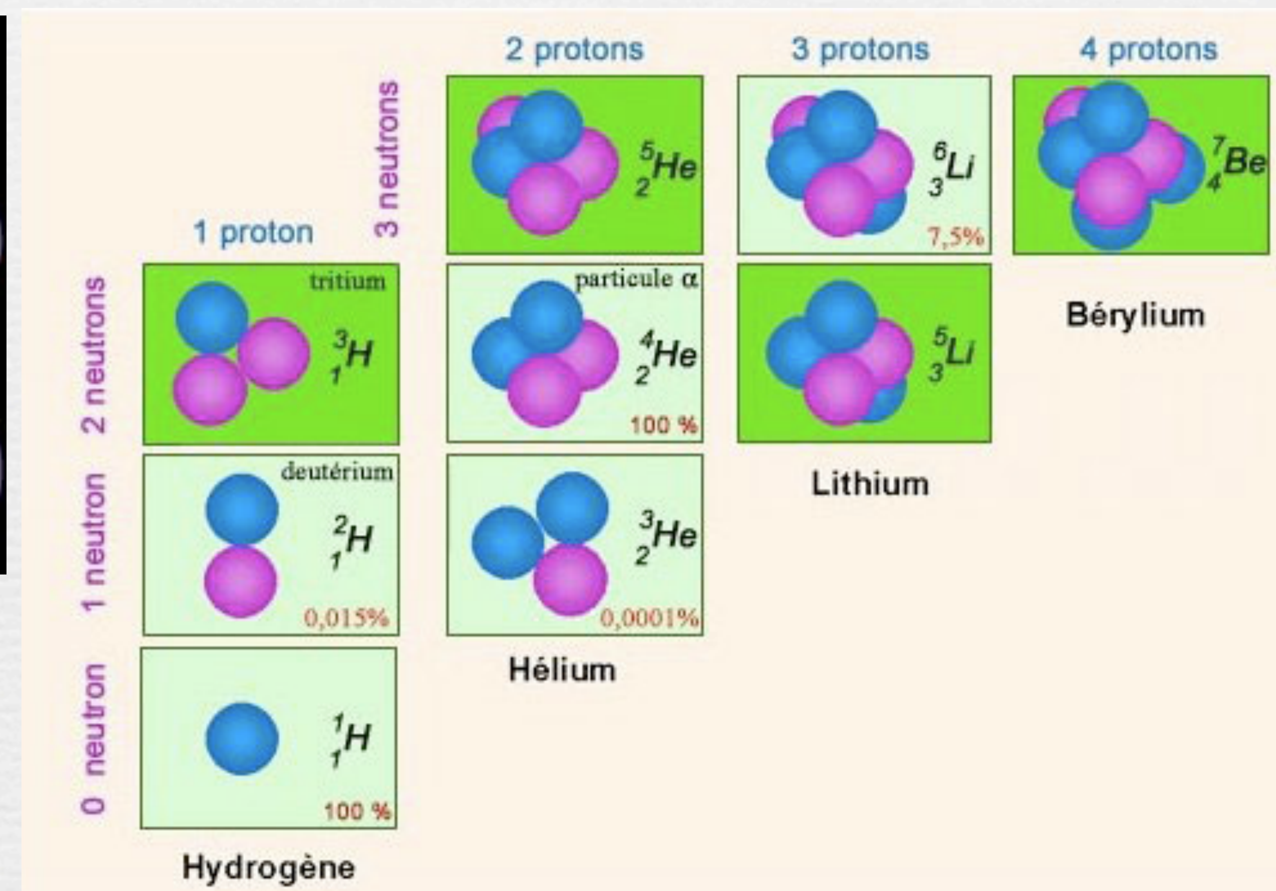
2) Measurements of CMB anisotropies

probe acoustic oscillations of the baryon/photon fluid

The amount of anisotropies depend on n_B / n_γ

The abundance of light elements (deuterium, helium, lithium) strongly depends on the amount of protons and neutrons in the primordial universe.

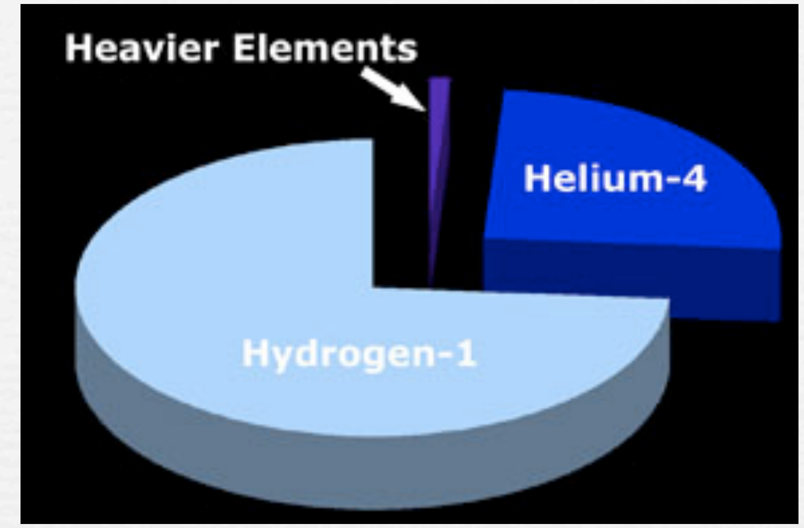


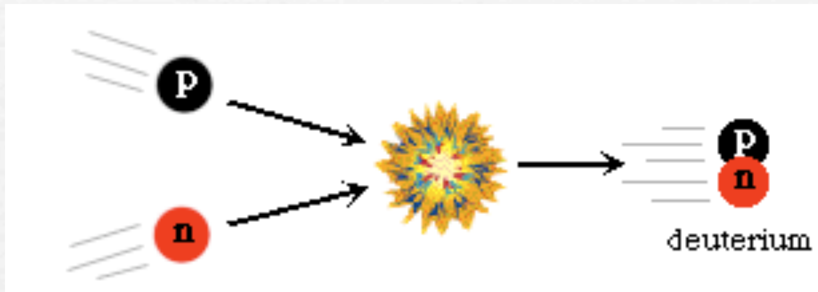


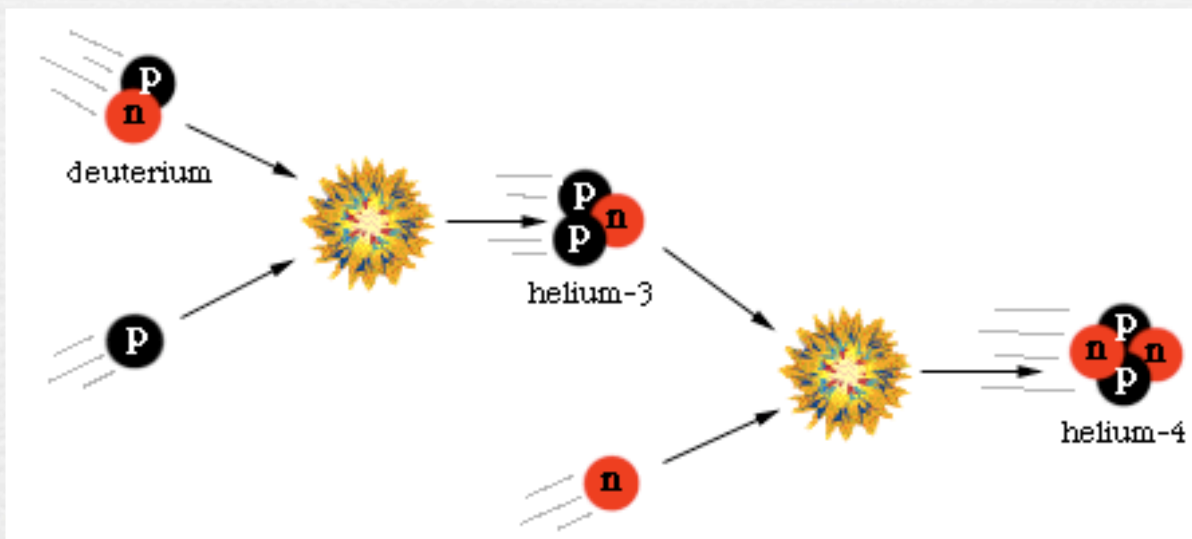
at t<1 s

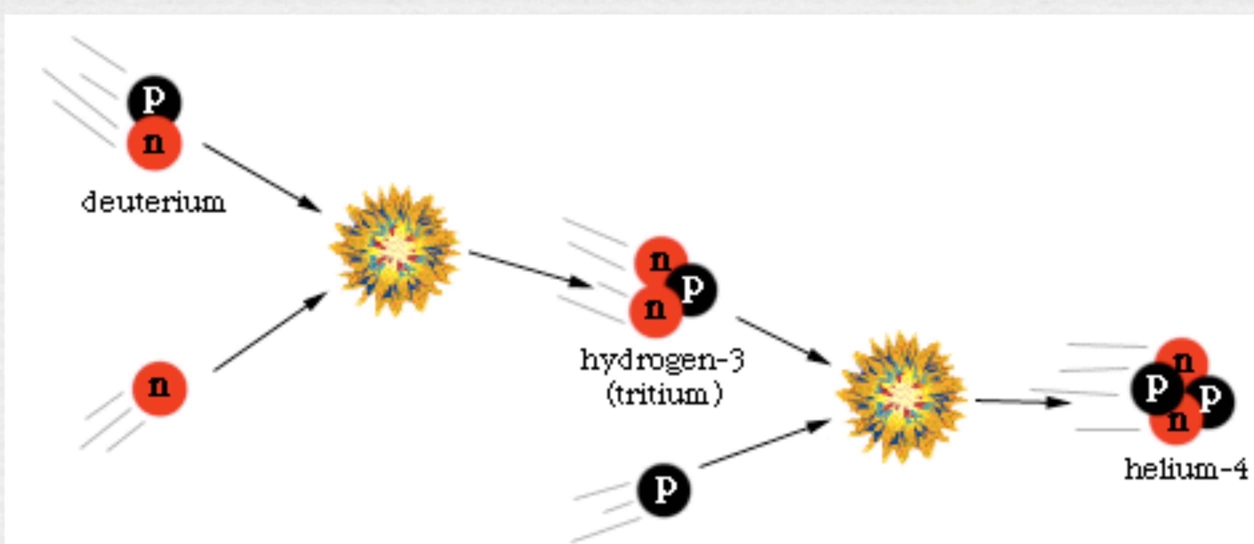
$$n + \nu_e \leftrightarrow p + e^-$$
$$n + e^+ \leftrightarrow p + \nu_e$$
$$n \leftrightarrow p + e^- + \overline{\nu_e}$$

Primordial nucleosynthesis



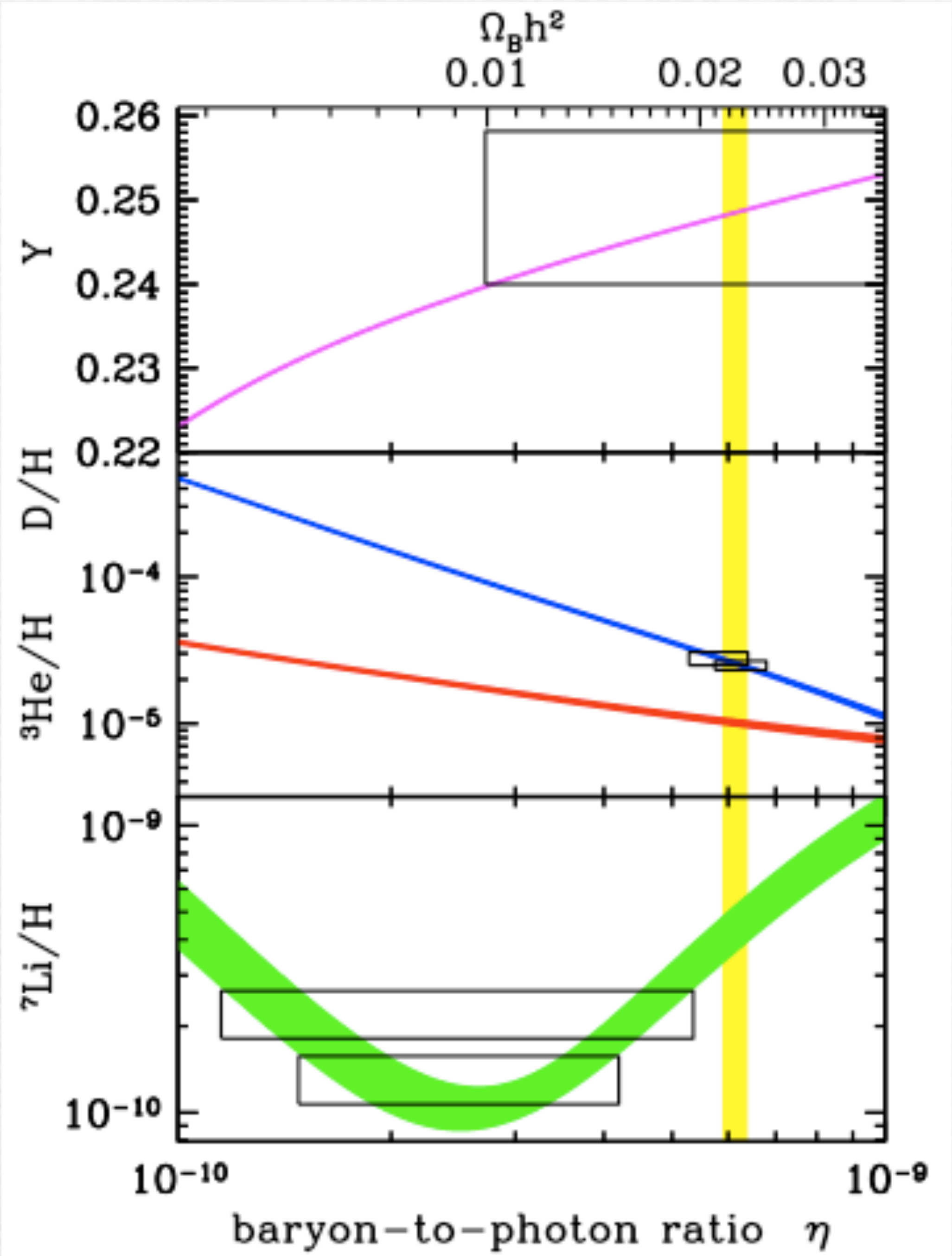






$p + n$	$\longrightarrow$	$D + \gamma$
$D + n$	$\longrightarrow$	$^3H + \gamma$
$D + p$	$\longrightarrow$	$^3He + \gamma$
$D + D$	$\longrightarrow$	$^3H + p$
$D + D$	$\longrightarrow$	$^3He + n$
$D + D$	$\longrightarrow$	$^4He + \gamma$
$^3H + p$	$\longrightarrow$	$^4He + \gamma$
$^3He + n$	$\longrightarrow$	$^3H + p$
$^3He + n$	$\longrightarrow$	$^4He + \gamma$
$^3H + D$	$\longrightarrow$	$^4He + n$
$^3He + D$	$\longrightarrow$	$^4He + p$
$^3He + ^3He$	$\longrightarrow$	$^4He + 2p$
$^4He + D$	$\longrightarrow$	$^6Li + \gamma$
$^4He + ^3H$	$\longrightarrow$	$^7Li + \gamma$
$^4He + ^3He$	$\longrightarrow$	$^7Be + \gamma$
$^6Li + n$	$\longrightarrow$	$^7Li + \gamma$
$^6Li + p$	$\longrightarrow$	$^7Be + \gamma$
$^7Li + p$	$\longrightarrow$	$^4He + \gamma$
$^7Be + n$	$\longrightarrow$	$^7Li + p$
$^7Be + e^-$	$\longrightarrow$	$^7Li + \gamma$

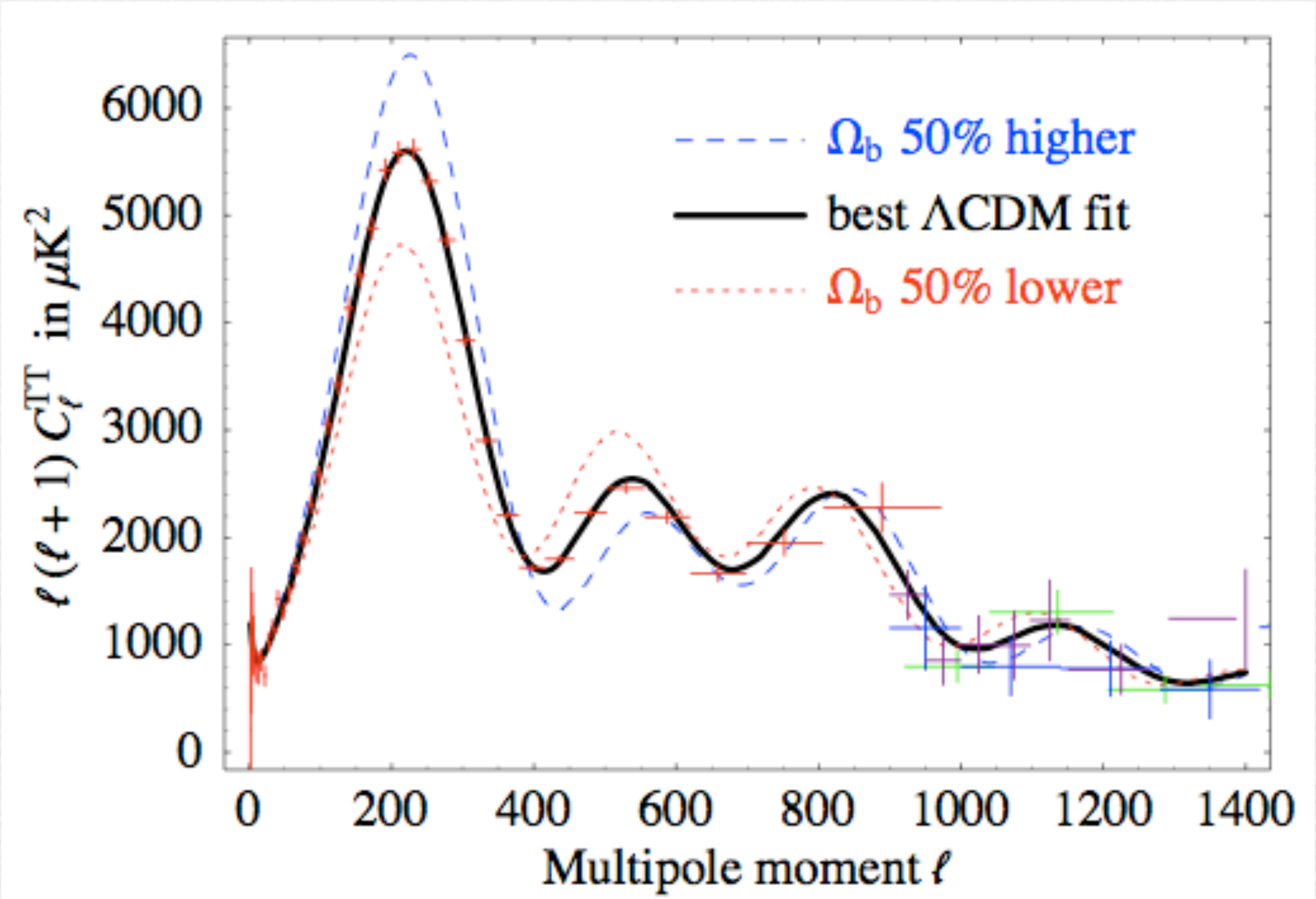
Primordial abundances versus η



$$\eta = 10^{-10} \times \begin{cases} 6.28 \pm 0.35 \\ 5.92 \pm 0.56 \end{cases}$$

Dependence of the CMB Doppler peaks on η

(CMB temperature fluctuations)



$$\eta = 10^{-10} \times (6.14 \pm 0.25)$$

$$\Omega_b h^2 = 0.0223^{+0.0007}_{-0.0009}$$

baryons: only a few percents of the total energy density of the universe

Sakharov's conditions for baryogenesis (1967)

1) Baryon number violation

(we need a process which can turn antimatter into matter)

2) C (charge conjugation) and CP (charge conjugation ×Parity) violation

(we need to prefer matter over antimatter)

3) Loss of thermal equilibrium

(we need an irreversible process since in thermal equilibrium, the particle density depends only on the mass of the particle and on temperature --particles & antiparticles have the same mass , so no asymmetry can develop)

$$\Gamma(\Delta B > 0) > \Gamma(\Delta B < 0)$$

Need to go out of equilibrium

In thermal equilibrium, any reaction which destroys baryon number will be exactly counterbalanced by the inverse reaction which creates it. Thus no asymmetry may develop, even if CP is violated. And any preexisting asymmetry will be erased by interactions

Need for

-> Long-lived particles decays out of equilibrium

-> first-order phase transitions

Why can't we achieve baryogenesis in the Standard Model?

B is violated

C and CP are violated

but which out-of-equilibrium condition?

no heavy particle which could decay out-of-equilibrium

no strong first-order phase transition

Electroweak phase transition is a smooth cross over

Also, CP violation is too small (suppressed by the small quark masses, remember there is no CP violation if quark masses vanish)

B violation

If B was conserved : ⇛ To explain η we would have to impose arbitrary and extremely fine-tuned initial value for B, while a plausible *guess* is rather : $B_i = L_i = 0$ (as the total electric charge appears to be)

Any baryon asymmetry existing before inflation is diluted away and we have to produce the baryon asymmetry between the time of reheating and the time of the electroweak phase transition

⇛ Some mechanism must exist to separate baryons and antibaryons on scales larger than galaxy clusters (otherwise we would have detected gamma rays resulting from annihilation of matter and antimatter)

$$p + \overline{p} \rightarrow \pi^0 ... \rightarrow \gamma\gamma$$

Baryon number violation in the Standard Model

B and L are accidental global symmetries of the Standard Model

$$B = \frac{N_c}{3} \int d^3x \sum_{i=1}^{N_f} (\overline{u}_i \gamma^0 u_i + \overline{d}_i \gamma^0 d_i)$$

$$L_i = \frac{N_c}{3} \int d^3x (\bar{l}_i \gamma^0 l_i + \overline{\nu}_i \gamma^0 (1 - \gamma_5) \nu_i) \qquad i = e, \mu, \tau$$

$$L = L_e + L_\mu + L_\tau$$

Non-perturbative (instanton) effects can lead to processes violating (B+L) while (B-L) is conserved. These effects result from:

1) chiral anomaly

2) non trivial topology of the vacuum of the electroweak theory

The B+L anomaly

The charge B+L is not conserved by quantum fluctuations of gauge fields while the orthogonal combination B-L remains a good symmetry of electroweak interactions.

$$\partial_\mu j^\mu_B = \partial_\mu j^\mu_L = -N_f \left(\frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a\mu\nu} - \frac{g'^2}{32\pi^2} f_{\mu\nu} \tilde{f}^{\mu\nu} \right)$$

The variation of the baryonic charge is given by $\Delta B = \int dt dx \partial_\mu j^\mu$

This integral is non-zero for certain gauge field configurations (instantons)

The topological charge of the instanton is defined by $N_{CS} = \int d^3x \; K^0$

the Chern Simons number

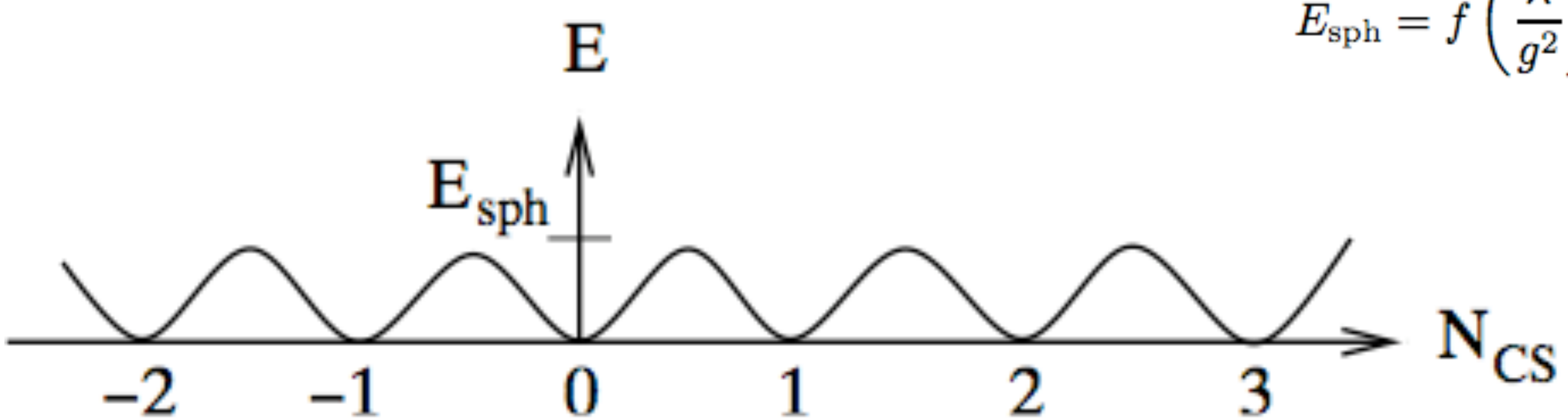
where $$\partial_\mu K^\mu = \frac{g^2}{32\pi^2} F^a_{\mu\nu} \tilde{F}^{a,\mu\nu}$$

$$K^\mu = \frac{g^2}{32\pi^2} \epsilon^{\mu\nu\alpha\beta} (F^a_{\nu\alpha} A^a_\beta - \frac{g}{3} \epsilon_{abc} A^a_\nu A^b_\alpha A^c_\beta)$$

Baryon number violation in the Standard Model

$$N_{CS}(t_1) - N_{CS}(t_0) = \int_{t_0}^{t_1} dt \int d^3x \; \partial_\mu K^\mu = \nu$$

$$E_{\rm sph} = f\left(\frac{\lambda}{g^2}\right)\frac{4\pi v}{g} \cong \frac{8\pi v}{g} = \frac{2M_W}{\alpha_W} f\left(\frac{\lambda}{g^2}\right)$$



Energy of gauge field configuration as a function of Chern Simons number

$$\Delta B = N_f \Delta N_{CS}$$

baryons are created by transitions between topologically distinct vacua of the $SU(2)_L$ gauge field

The sphaleron solution

Klinkhamer & Manton, PRD30, 2212, 1984

Static, unstable solution of the classical field equations of the Weinberg-Salam theory

with B=1/2

Start with the ansatz:

$$W_i^a \sigma^a dx^i = -\frac{2i}{g} f(\xi) dU\, U^{-1}, \quad \phi = \frac{v_0}{\sqrt{2}} h(\xi) U \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

where $\xi = g v_0 r$ and $U = \frac{1}{r}\begin{pmatrix} z & x+iy \\ -x+iy & z \end{pmatrix}$

The eq. of motion then read:

$$\xi^2 \frac{d^2 f}{d\xi^2} = 2f(1-f)(1-2f) - \frac{\xi^2}{4} h^2 (1-f),$$

$$\frac{d}{d\xi}\left[\xi^2 \frac{dh}{d\xi}\right] = 2h(1-f)^2 + \frac{\lambda}{g^2}\xi^2 (h^2-1) h$$

with boundary conditions:

$$f \xrightarrow[\xi \to 0]{} \alpha \xi^2 \qquad f \xrightarrow[\xi \to \infty]{} 1 - \gamma e^{-\xi/2}$$

$$h \xrightarrow[\xi \to 0]{} \beta \xi \qquad h \xrightarrow[\xi \to \infty]{} 1 - \frac{\delta}{\xi} e^{-\sqrt{\frac{2\lambda}{g^2}}\xi}$$

$$E = \frac{4\pi v}{g} \int_0^\infty \left[4\left[\frac{df}{d\xi}\right]^2 + \frac{8}{\xi^2}[f(1-f)]^2 + \frac{1}{2}\xi^2 \left[\frac{dh}{d\xi}\right]^2 + [h(1-f)]^2 + \frac{1}{4}\left[\frac{\lambda}{g^2}\right]\xi^2 (h^2-1)^2 \right] d\xi$$

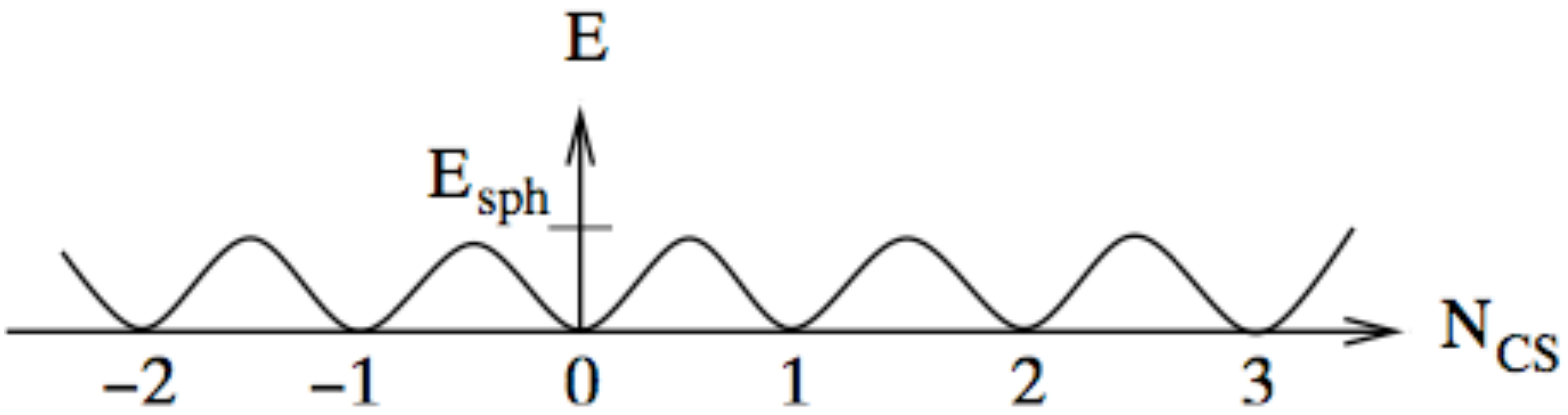
O(10 TeV)

The baryonic charge of the sphaleron is: $$Q_b = \int d^3x j_B^0$$

$$\frac{d}{dt} Q_B = \int d^3x \ \partial_t j_B^0 = \int d^3x \ \left(\overrightarrow{\nabla} \cdot \overrightarrow{j}_B + \frac{g^2}{64\pi^2} \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}^a F_{\rho\sigma}^a \right)$$

so

$$Q_B(\text{sphaleron}) = \frac{g^2}{32\pi^2} \int_{-\infty}^{0} dt \int d^3x \ \frac{1}{2} \epsilon^{\mu\nu\rho\sigma} F_{\mu\nu}^a F_{\rho\sigma}^a = \frac{1}{2}$$



Tunneling amplitude: $$\mathcal{A} \sim e^{-8\pi^2/g^2} \sim 10^{-173}$$

$\Rightarrow$ Baryon number violation is totally suppressed

in the SM at zero temperature

Rate of Baryon number violation in the Standard Model at finite temperature:

In the symmetric phase $\Gamma \sim \alpha_W^4 T^4$

out-of-equilibrium condition: $\alpha_W^4 T < T^2 / M_{Pl} \rightarrow T > 10^{12}$ GeV

In the broken phase $\Gamma \sim v^4 e^{-c \langle\varphi/T\rangle}$

(more precisely $\frac{\Gamma}{V} = \text{const}\left(\frac{E_{\text{sph}}}{T}\right)^3 \left(\frac{m_W(T)}{T}\right)^4 T^4 e^{-E_{\text{sph}}/T}$)

$$E_{\text{sph}} = f\left(\frac{\lambda}{g^2}\right)\frac{4\pi v}{g} \cong \frac{8\pi v}{g} = \frac{2M_W}{\alpha_W} f\left(\frac{\lambda}{g^2}\right)$$

out of equilibrium condition: $\langle\varphi\rangle/T > 1$

CP violation

Let M(i->j) be the amplitude for a transition from a state i to a state j, and let $\bar{i}$ be the state obtained by applying a CP transformation to i. Then the CPT theorem implies:

$$\mathcal{M}(i \to j) = \mathcal{M}(\bar{j} \to \bar{i})$$ (CPT invariance)

CP invariance (and hence, by CPT, T invariance) demands:

$$\mathcal{M}(i \to j) = \mathcal{M}(\bar{i} \to \bar{j}) = \mathcal{M}(j \to i)$$ (CP invariance)

The requirement of unitarity yields:

$$\sum_j |\mathcal{M}(i \to j)|^2 = \sum_j |\mathcal{M}(j \to i)|^2$$ (unitarity)

The sum over j includes states and antistates:

$$\sum_j |\mathcal{M}(i \to j)|^2 = \sum_j |\mathcal{M}(j \to \bar{i})|^2 = \sum_j |\mathcal{M}(j \to i)|^2$$ (CPT+unitarity)

In thermal equilibrium, interactions produce i and $\bar{i}$ in equal numbers. Thus no asymmetry may develop, even if CP is violated. And any preexisting asymmetry will be destroyed by interactions

CP violation continued

CPT + unitarity also leads to:

$$\sum_j |\mathcal{M}(i \to j)|^2 = \sum_j |\mathcal{M}(\bar{i} \to j)|^2$$

implying that the TOTAL decay rate of a particle and its antiparticle must be equal

However, if the decay of a particle (say X decays into b) violates CP, the decay of the system X + $\overline{X}$ can result in an asymmetry between b and $\bar{b}$

Note that for a system with 2 states:

$$|\mathcal{M}(1 \to 1)|^2 + |\mathcal{M}(1 \to 2)|^2 = |\mathcal{M}(1 \to 1)|^2 + |\mathcal{M}(2 \to 1)|^2$$

thus we always have CP invariance in this case

⇒ No asymmetry can be created in a system with only two states

CP violation

continued

Let T be the transition matrix for the process i->j.

Unitarity constrains possible violations of CP invariance.

One finds that deviations must obey:

$$|T_{ij}|^2 - |T_{ji}|^2 = -2\ \mathrm{Im}\left[\left(\sum_n TT^\dagger\right)_{ij} T^*_{ji}\right] + |(\sum_n TT^\dagger)_{ij}|^2$$

If the rates of transition i->j are governed by some small parameter, say α, so that $|\mathcal{M}(i \to j)|^2 = \mathcal{O}(\alpha^k)$ then any CP-violating difference $|\mathcal{M}(i \to j)|^2 - |\mathcal{M}(j \to i)|^2$ must be at least of order α^{k+1}

CP-violating effects must arise from loop diagram corrections to the process i->j

In addition, intermediate states in the loop, not only must have CP-violating complex couplings, but also must propagate on-shell .

Illustration on a simple example

Assume X (and $\overline{X}$) with two decay channels

(involving a coupling of order λ)

	Branching ratio	Baryon number
$X \to q_1 q_2$	r	2/3
$X \to \bar{q}_3 l$	$1-r$	-1/3
$\overline{X} \to \bar{q}_1 \bar{q}_2$	$\bar{r}$	-2/3
$\overline{X} \to q_3 l$	$1-\bar{r}$	1/3

$\Gamma \sim \lambda^2 M_X$

The baryon asymmetry produced by the decay of one pair (X- $\overline{X}$) is given by

$$\epsilon_X = [rB_1 + (1-r)B_2] - [\bar{r}B_1 + (1-\bar{r})B_2]$$
$$= (r-\bar{r})(B_1 - B_2)$$

⇒ no baryon asymmetry if $B_1 = B_2$

⇒ no baryon asymmetry if $r = \bar{r}$ (CP invariance)

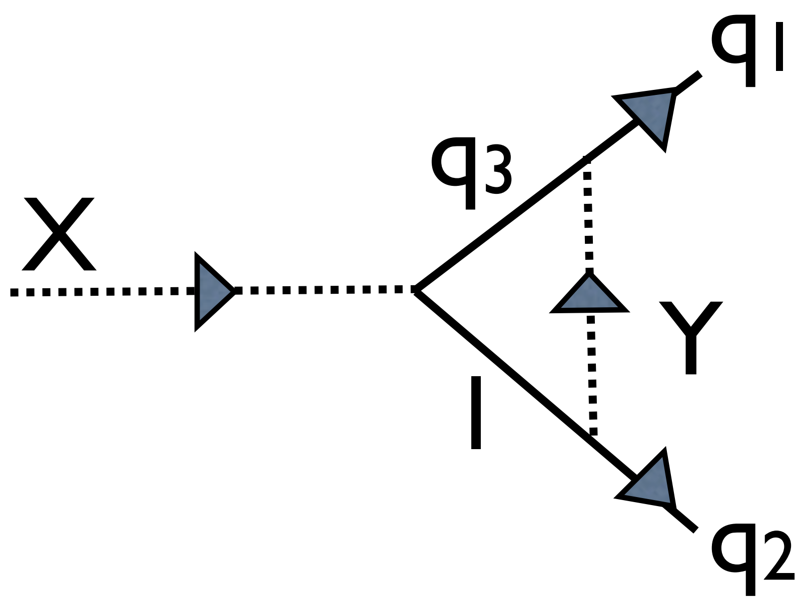
Out of equilibrium condition: $H > \Gamma \sim \lambda^2 M_X$ ⇒ $M_X > \lambda^2 M_{Pl}$

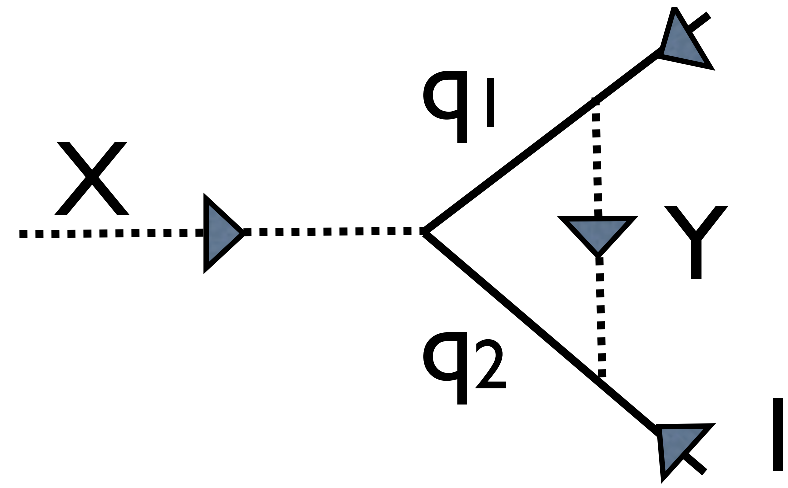
Assuming that initially $n_X = n_{\overline{X}} \sim n_\gamma$

$$\frac{n_B}{s} \sim \frac{\epsilon\, n_X}{g_* n_\gamma} \sim \frac{\epsilon}{g_*} \sim 10^{-2}\epsilon$$

Introduce additional particle Y

	Branching ratio	Baryon number
$Y \to q_1 q_3$	r'	2/3
$Y \to \bar{q}_2 \bar{l}$	$1 - r'$	-1/3
$\overline{Y} \to \bar{q}_1 \bar{q}_3$	$\overline{r'}$	-2/3
$\overline{Y} \to q_2 l$	$1 - \overline{r'}$	1/3

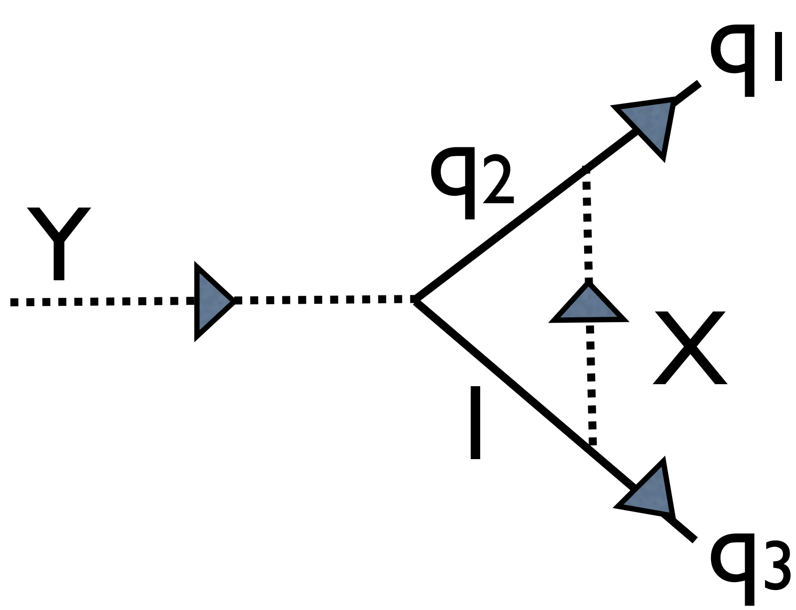


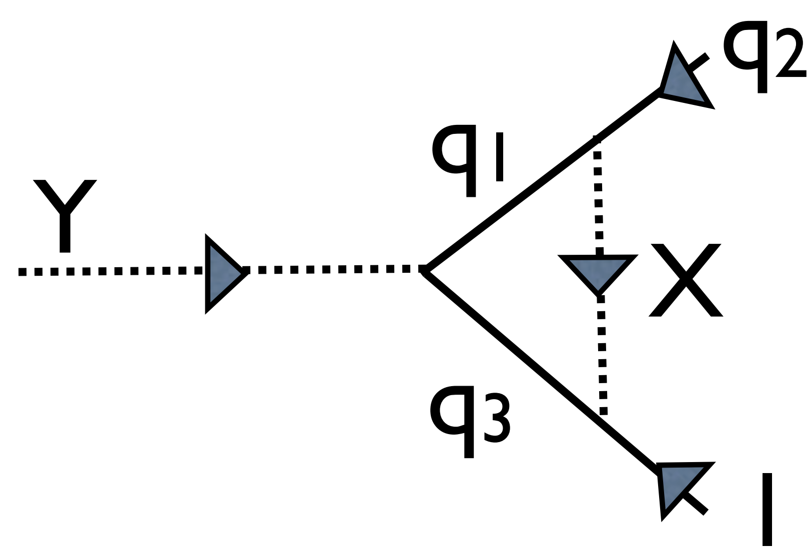


$$r - \bar{r} = \mathrm{Im}(\lambda_{12}\lambda_{3l}^*\lambda_{13}^*\lambda_{2l})\frac{\mathrm{Im}I_{XY}}{\Gamma_X} \approx \frac{\lambda^2}{4\pi}\frac{m_X^2}{m_Y^2}\sin\delta_{CP}$$

$$r' - \overline{r'} = \mathrm{Im}(\lambda_{12}^*\lambda_{3l}\lambda_{13}\lambda_{2l}^*)\frac{\mathrm{Im}I_{YX}}{\Gamma_Y} \approx -\frac{\lambda^2}{4\pi}\frac{m_Y^2}{m_X^2}\sin\delta_{CP}$$

I_{XY} : contains phase space integral





$\epsilon \neq 0$ requires: Im $I_{XY} \neq 0$ and $m_X \neq m_Y$

This is the original GUT baryogenesis

GUT necessarily breaks B

A GUT scale particle X decays out-of-equilibrium with direct CP violation

But minimal GUT models preserve B-L=0 $\Rightarrow$ “Anomaly washout” by sphalerons

Main reason why it is disfavored: requires too large a reheat temperature

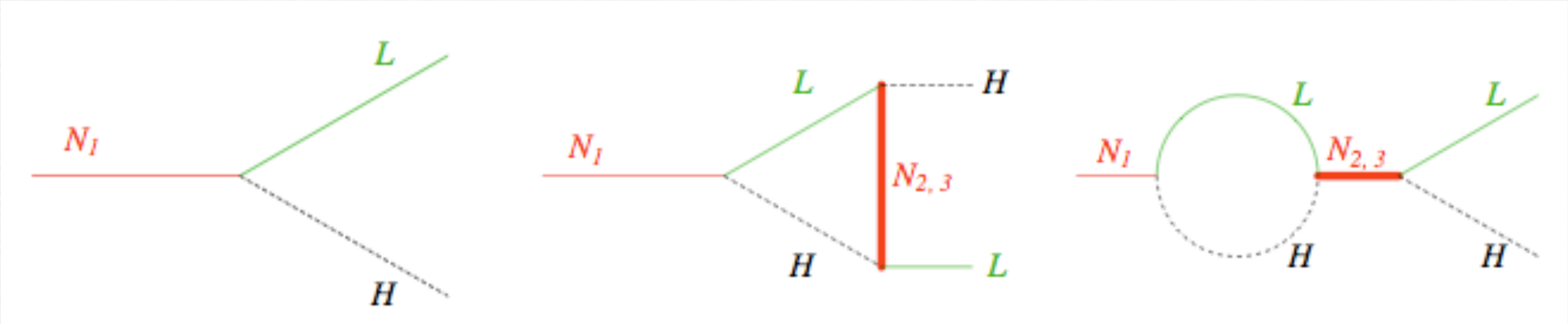
Leptogenesis

Fukugita, Yanagida

nicely connected to the explanation of neutrino masses

Majorana neutrino masses violate L and presumably CP

1) Generate L from the direct CP violation in RH neutrino decay



2) L gets converted to B by the electroweak anomaly

Out of equilibrium condition: $H > \Gamma \sim \lambda^2 M_1/(8\pi)$

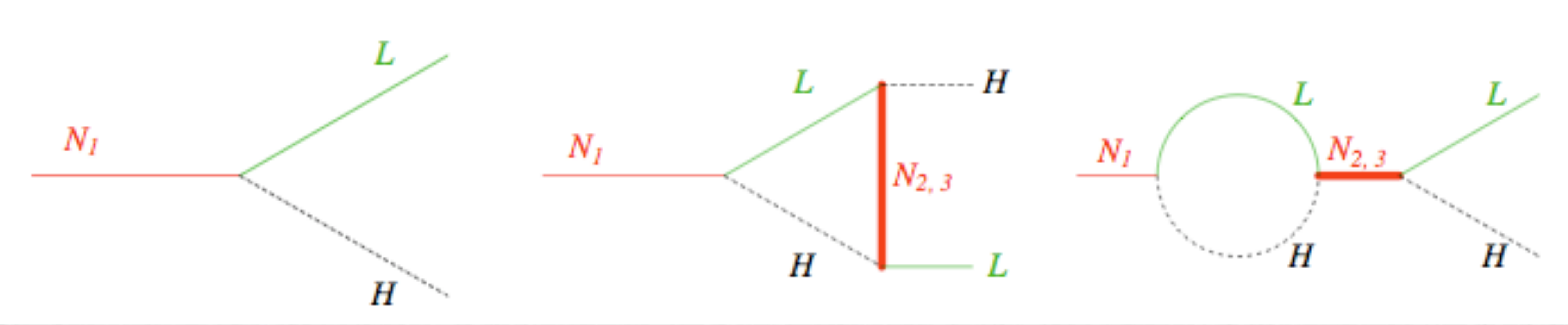
at $T \sim M_1$, this leads to $\lambda v^2/M_1 < (8\pi)\ v^2/M_{Pl} \sim$ meV

see-saw formula for m_ν

The basic physics

$$\mathscr{L} = \mathscr{L}_{SM} + \bar{N}_1 i\partial\!\!\!/ N_1 + \lambda_1 N_1 H L + \frac{M_1}{2} N_1^2 + $$
$$+\bar{N}_{2,3} i\partial\!\!\!/ N_{2,3} + \lambda_{2,3} N_{2,3} H L + \frac{M_{2,3}}{2} N_{2,3}^2 + \text{h.c.}$$

One can redefine fields in such a way that the ineliminable CP-violating phase is in $\lambda_{2,3}$



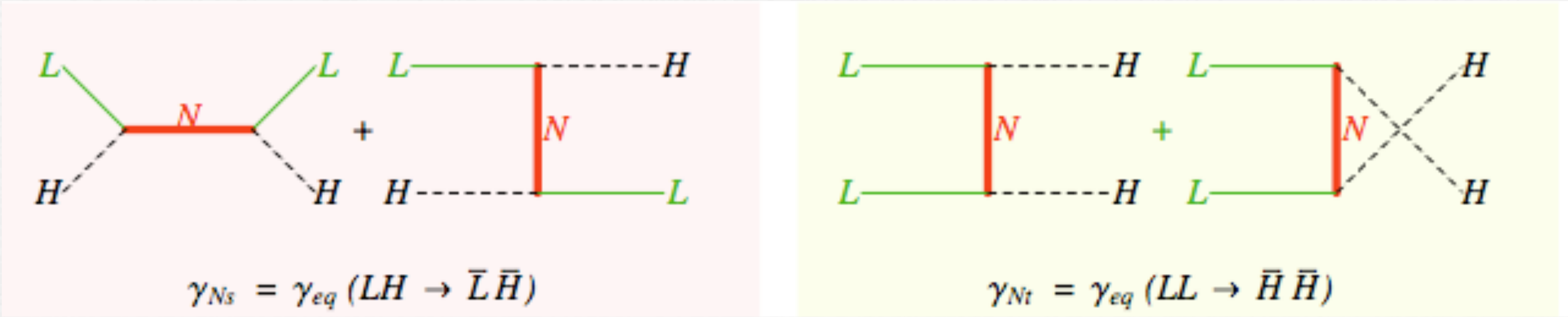
$$\epsilon_1 \equiv \frac{\Gamma(N_1 \to LH) - \Gamma(N_1 \to \overline{LH})}{\Gamma(N_1 \to LH) + \Gamma(N_1 \to \overline{LH})} \sim \frac{1}{4\pi} \frac{M_1}{M_{2,3}} \text{Im}\lambda_{2,3}^2$$

and $$\frac{n_B}{n_\gamma} \approx \frac{\epsilon_1 \eta}{g_{SM}}$$

efficiency

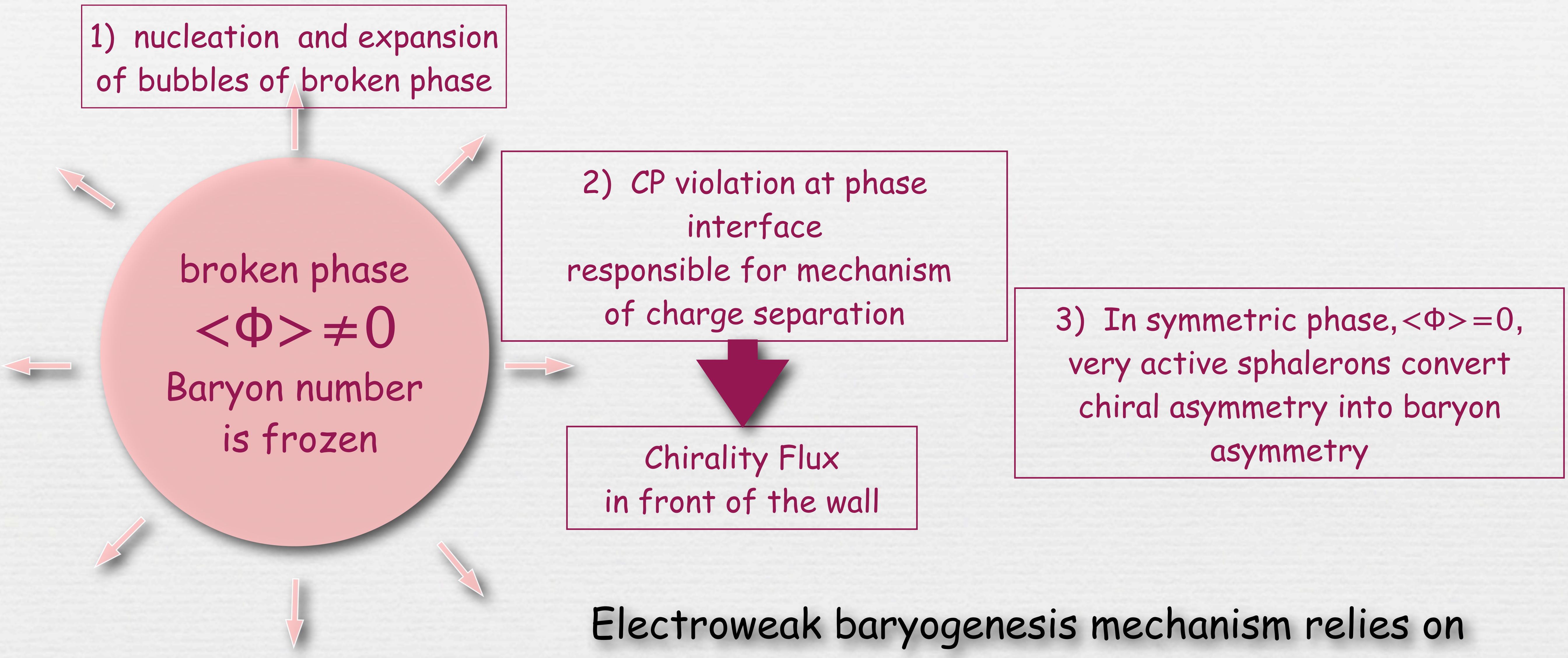
depends on how much decays are out-of-equilibrium and on washout of L by scatterings

Wash-out $LH \leftrightarrow \overline{LH}$ and $LL \leftrightarrow \overline{HH}$ ΔL=2 scatterings



relevant only if $M_1 > 10^{14}$ GeV

Baryon asymmetry and the EW scale



Electroweak baryogenesis mechanism relies on a first-order phase transition

What is the nature of the electroweak phase transition?

EW baryogenesis is natural ...

$$n_{\rm B} = \int_{-\infty}^{+\infty} \frac{dn_{\rm B}}{dt}\frac{dz}{v_z}$$

$$\frac{dn_{\rm B}}{dt} \sim n_{\rm B}\frac{\Gamma_{sph}}{T^3}$$

$$n_{\rm B} \propto \frac{\Gamma_{sph}}{T^3 v_z}\int_{-\infty}^{0} n_L\, dz$$

$$\Gamma_{sph} \sim 25\,\alpha_w^5 T^4 \sim \alpha_w^4 T^4 \;\longrightarrow\; \frac{n_{\rm B}}{s} \sim \frac{\alpha_w^4}{g_*}\epsilon_{\rm CP} \sim 10^{-10}$$

$$\longrightarrow \quad \boxed{\epsilon_{\rm CP} \gtrsim 10^{-2}}$$

If CP violating effects are large at weak energies, we obtain the right amount of baryon asymmetry

Rate of B violation in the EW broken phase

$$\Gamma = 2.8 \times 10^5 (\frac{\alpha_W}{4\pi})^4 \kappa C^{-7}\ T^4 \left(\frac{E_{sph}}{T}\right)^7 e^{-E_{sph}/T}$$

Arnold-McLerran'87
Khlebnikov-Shaposhnikov'88
Carson-McLerran'90
Carson-Li-McLerran-Wang'90

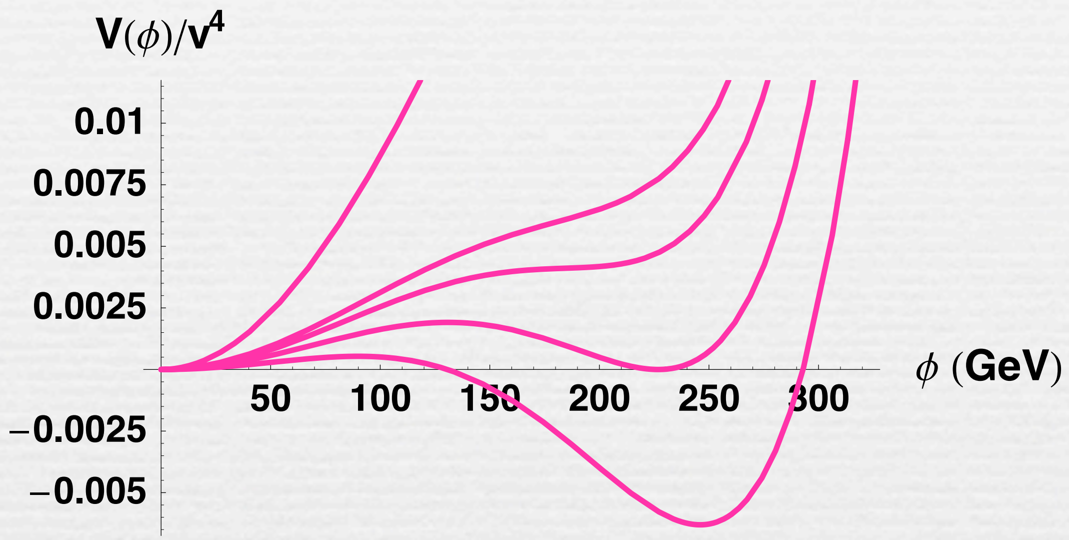
Out-of-equilibrium condition:

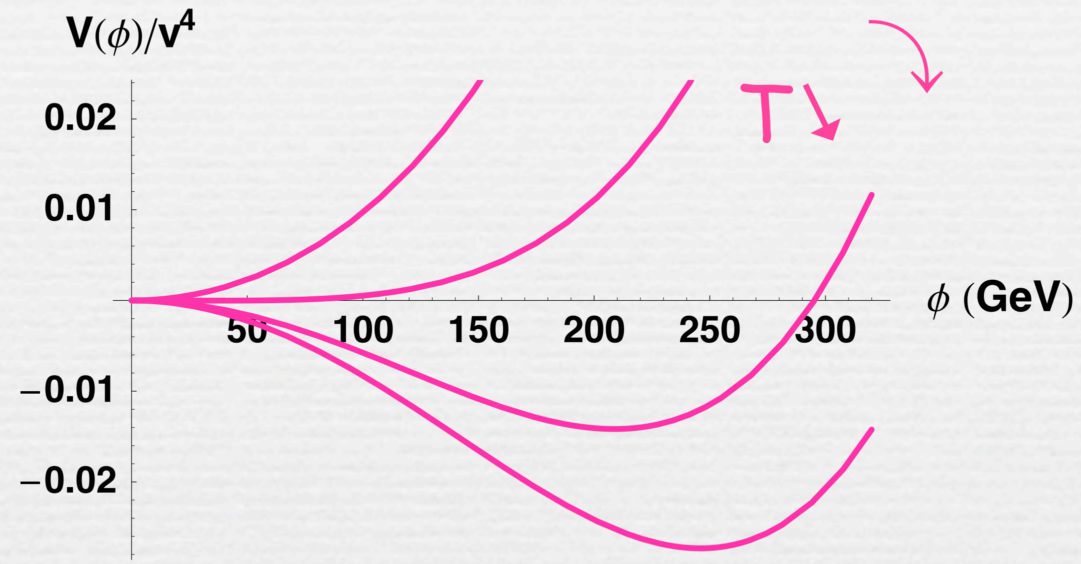
$$\frac{\Gamma}{T^3} < H \sim \frac{\sqrt{\rho}}{m_{Pl}} \quad \Rrightarrow \quad \left.\frac{\langle\phi\rangle}{T}\right|_{T_c} > 1$$

=`sphaleron bound'

Work out the nature of the electroweak phase transition

first-order or second-order?





indispensable for reliable computations of the baryon asymmetry

LHC will provide insight as it will shed light on the Higgs sector

Question intensively studied within the Minimal Supersymmetric Standard Model (MSSM). However, not so beyond the MSSM (gauge-higgs unification in extra dimensions, composite Higgs, Little Higgs, Higgsless...)

Beyond the beaten paths

Dirac Leptogenesis

Lindner et al '99; Murayama & Pierce '02

No need to violate Lepton number for leptogenesis ! and leptogenesis can be achieved with Dirac neutrinos

Disadvantage: no obvious relationship between the mechanism responsible for the generation of the lepton asymmetry and the smallness of neutrino masses

Like in traditional leptogenesis, assume the CP-violating decay of a heavy particle into leptons

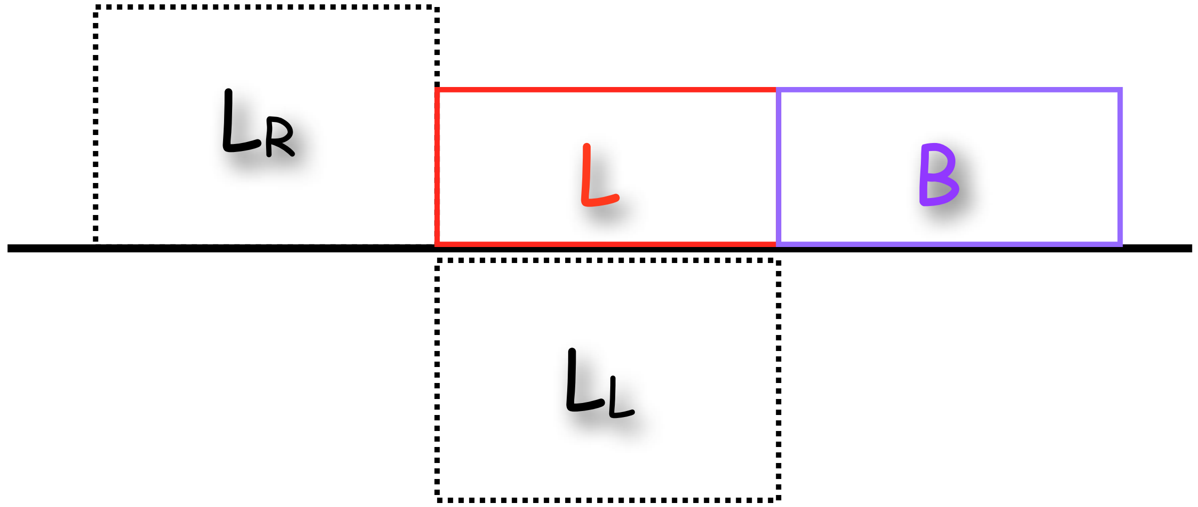
-> results in a non-zero lepton number for LH particles and an equal and opposite lepton number for RH particles :

$$n_R - n_{\overline{R}} = n_{\overline{L}} - n_L$$

For most SM species, Yukawa interactions between the LH and RH particles are sufficiently strong to cancel these two stores of lepton number rapidly

Only Lepton number in LH sector is processed into baryon number by sphalerons

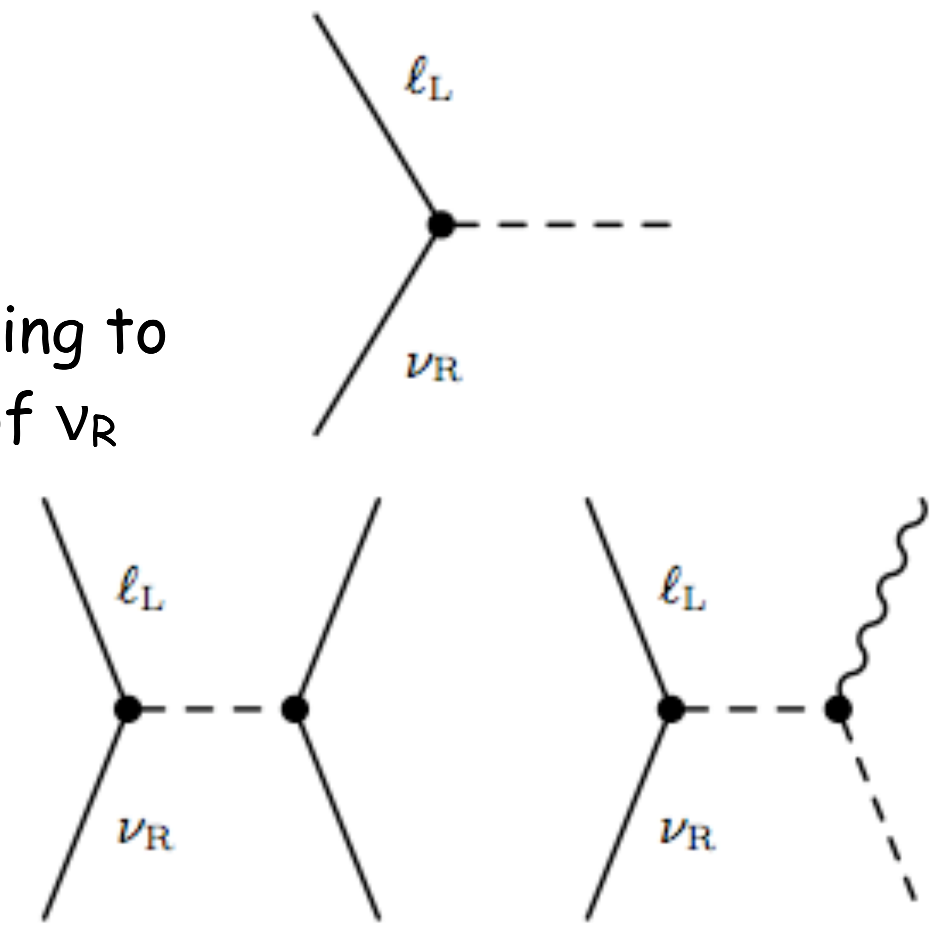
However, the interactions of ν_R are exceedingly weak and equilibrium between LH lepton number and RH lepton number will not be reached until T << weak scale



$$n_B = n_L = -\frac{28}{79} n_{\nu_R}$$

$$\begin{aligned} S &\leftrightarrow 3q + \ell \\ \phi &\leftrightarrow q + \bar{u} \\ \bar{\phi} &\leftrightarrow q + \bar{d} \\ \bar{\phi} &\leftrightarrow \ell + \bar{e} \end{aligned}$$

Processes contributing to the equilibration of ν_R



$$\Gamma \sim \lambda^2 g^2 T$$

Condition for non-equilibration

$\Gamma \lesssim H \sim T^2/M_{Pl}$

→ $\lambda \lesssim \sqrt{(T_c / M_{Pl})} \sim 10^{-8}$

T_c : T at electroweak phase transition

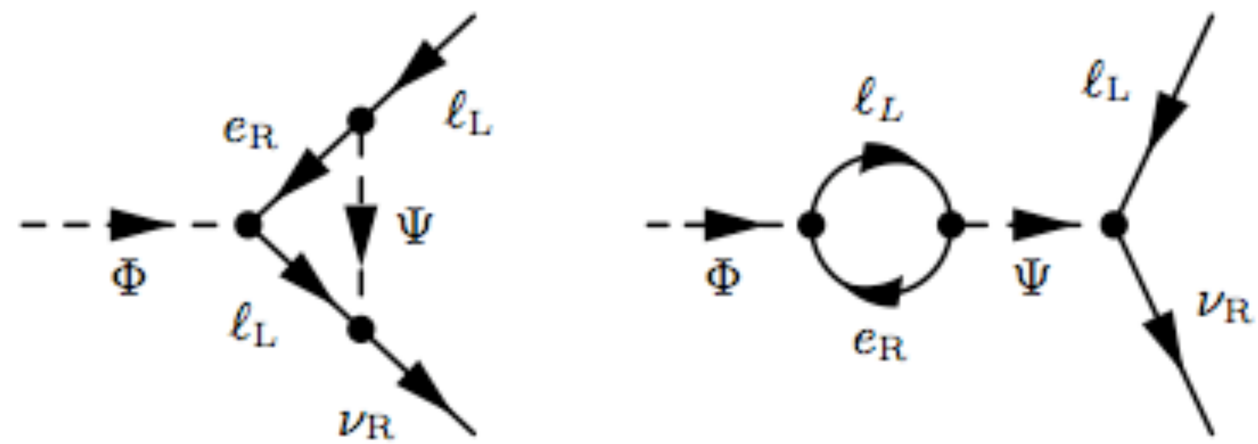
$m \sim \lambda\, T_c \lesssim 1$ keV

Toy model

Introduce 2 very heavy SU(2) doublet scalars
(with same quantum numbers as Higgs but with no vev)

$$\mathcal{L} = F(\ell_L \cdot \Phi)\nu_R^c + F'(\ell_L \cdot \Phi^c)e_R^c$$
$$G(\ell_L \cdot \Psi)\nu_R^c + G'(\ell_L \cdot \Psi^c)e_R^c + \text{h.c.}$$

$$\left.\begin{array}{c}\Phi \\ \Psi\end{array}\right\} \rightarrow \left\{\begin{array}{l}\bar{\ell}_L + \nu_R \\ \ell_L + \bar{e}_R\end{array}\right.$$



$$\epsilon_\Phi = \frac{\Gamma(\Phi \rightarrow \bar{\ell}\nu) - \Gamma(\bar{\Phi} \rightarrow \ell\bar{\nu})}{\Gamma(\Phi \rightarrow \bar{\ell}\nu) + \Gamma(\bar{\Phi} \rightarrow \ell\bar{\nu})}$$
$$= \frac{\text{Im}\,\text{tr}(F^* G F' G'^*)}{16\pi\ \text{tr}(F^* F)} \times$$
$$\left[1 - \frac{M_\Psi^2}{M_\Phi^2} \ln\left(1 + \frac{M_\Phi^2}{M_\Psi^2}\right) - \frac{M_\Phi^2}{M_\Phi^2 - M_\Psi^2}\right]$$

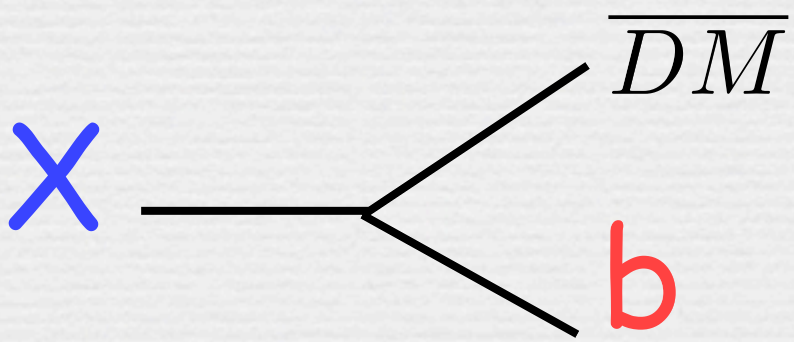
Baryogenesis without ~~B~~ nor ~~L~~ nor C~~P~~T

Possible if dark matter carries baryon number !

Farrar-Zaharijas hep-ph/0406281
Agashe-Servant hep-ph/0411254

In a universe where baryon number is a good symmetry
Dark matter would store the overall negative baryonic charge which is missing in the visible quark sector!

naturally arises in warped GUTs where
DM is a heavy RH neutrino carrying baryon number



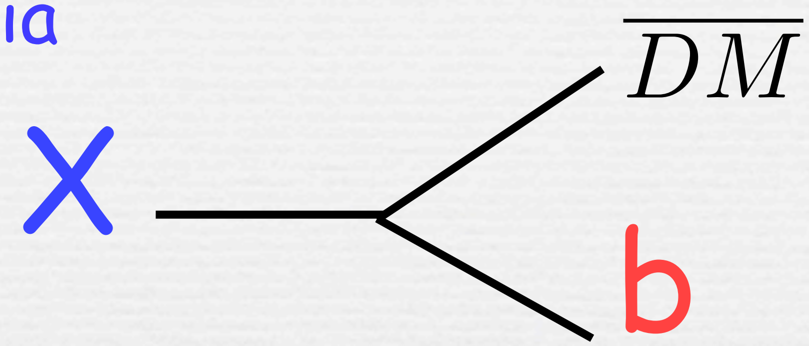
out-of equilibrium and CP violating decay of X sequesters the anti baryon number in the dark sector, thus leaving a baryon excess in the visible sector

A unified explanation for DM and baryogenesis !
can also explain the coincidence $\Omega_b \approx \frac{1}{6}\Omega_m$

Generalization: DM & baryon sectors share a quantum number (not necessarily B)

$$Q_{\text{universe}} = 0 = \underbrace{Q}_{\text{carried by baryons}} + \underbrace{(-Q)}_{\text{carried by antimatter}}$$

Assume an asymmetry between b and $\bar{b}$ is created via the out-of-equilibrium and CP-violating decay :



Charge conservation leads to

$$Q_{\text{DM}}(n_{\overline{\text{DM}}} - n_{\text{DM}}) = Q_b(n_b - n_{\bar{b}})$$

If efficient annihilation between DM and $\overline{DM}$, and b and $\bar{b}$:

$$\rho_{\text{DM}} = m_{\text{DM}} n_{\overline{\text{DM}}} \approx 6\rho_b \to m_{\text{DM}} \approx 6\frac{Q_{\text{DM}}}{Q_b}\ \text{GeV}$$

Farrar-Zaharijas hep-ph/0406281
Agashe-Servant hep-ph/0411254
Davoudiasl et al 1008.2399
} (DM carries B number)

Kitano & Low, hep-ph/0411133 (X and DM carry Z2 charge)
West, hep-ph/0610370

Back to electroweak baryogenesis

What to expect for the EW phase transition

Effective potential at finite temperature

$$V_{1-\text{loop}} = T \sum_i \pm \int \frac{d^3p}{(2\pi)^3} \ln\left(1 \mp e^{-\beta\sqrt{p^2+m_i^2(H)}}\right) \begin{cases} \text{bosons} \\ \text{fermions} \end{cases}$$

High-temperature expansion

$$\begin{aligned} V_{1-\text{loop}} &= \sum_{i\in B,F} \frac{m_i^2 T^2}{48} \times \begin{cases} 2, \text{ each real B} \\ 4, \text{ each Dirac F} \end{cases} - \frac{m_i^3 T}{12\pi} \begin{cases} 1, \text{ B} \\ 0, \text{ F} \end{cases} \\ &+ \frac{m_i^4}{64\pi^2}\left(\ln\frac{m_i^2}{T^2} - c_i\right) \times \begin{cases} -1, \text{ B} \\ +4, \text{ Dirac F} \end{cases} + O\left(\frac{m_i^5}{T}\right) \end{aligned}$$

$$c_i = \begin{cases} \frac{3}{2} + 2\ln 4\pi - 2\gamma_E \cong 5.408, \text{ B} \\ c_B - 2\ln 4 \cong 2.635, \text{ F} \end{cases}$$

In the SM, a 1rst-order phase transition can occurr due to thermally generated cubic Higgs interactions:

$$V(\phi,T) \approx \frac{1}{2}(-\mu_h^2 + cT^2)\phi^2 + \frac{\lambda}{4}\phi^4 - ET\phi^3$$

$$-ET\phi^3 \subset -\frac{T}{12\pi}\sum_i m_i^3(\phi)$$

Sum over all bosons which couple to the Higgs

In the SM: $\sum_i \simeq \sum_{W,Z}$ ⇒ not enough

mh<35 GeV would be needed to get Φ/T>1 and for mh >72 GeV, the phase transition is 2nd order

Strength of the transition in the SM:

$$\langle\phi(T_c)\rangle = \frac{2\ E\ T_c}{\lambda} \quad \Rrightarrow \quad \frac{\langle\phi(T_c)\rangle}{T_c} = \frac{2\ E\ v_0^2}{\lambda\ v_0^2} = \frac{4\ E\ v_0^2}{m_h^2}$$

$$v_0 \approx 246\ \mathrm{GeV} \quad \text{and} \quad E = \frac{2}{3}\frac{2m_W^3 + m_Z^3}{4\pi v_0^3} \sim 6.3 \times 10^{-3}$$

$$\frac{\langle\phi(T_c)\rangle}{T_c} \gtrsim 1 \quad \longrightarrow \quad m_h \lesssim 47\ \mathrm{GeV}$$

In the MSSM: new bosonic degrees of freedom with large coupling to the Higgs

Main effect due to the stop

$$-ET\phi^3 \subset -\frac{T}{12\pi}\sum_i m_i^3(\phi)$$

in MSSM, 'stop' contribution:

$$m_{\tilde{t}_R}^2(h,T) \approx m_U^2 + m_t(h)^2 + c_s T^2$$

we need $m_U^2 < 0$

i.e. the 'stop' should be lighter than the top quark.

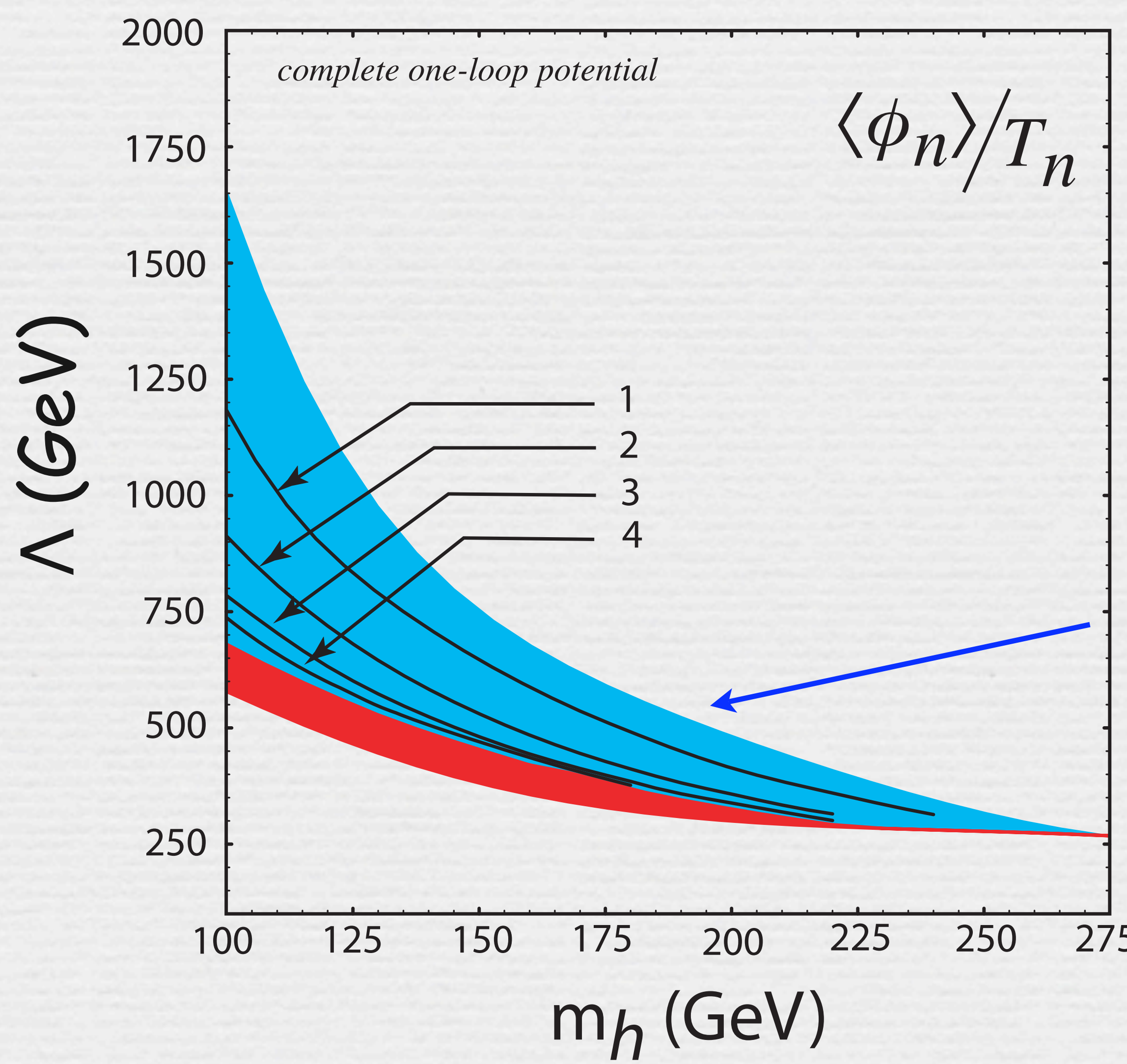
Effective field theory approach

add a non-renormalizable Φ^6 term to the SM Higgs potential and allow a negative quartic coupling

$$V(\Phi) = \mu_h^2 |\Phi|^2 - \lambda |\Phi|^4 + \frac{|\Phi|^6}{\Lambda^2}$$

"strength" of the transition does not rely on the one-loop thermally generated negative self cubic Higgs coupling

strong enough
for EW baryogenesis
if $\Lambda \lesssim 1.3$ TeV



region where EW phase transition is 1st order

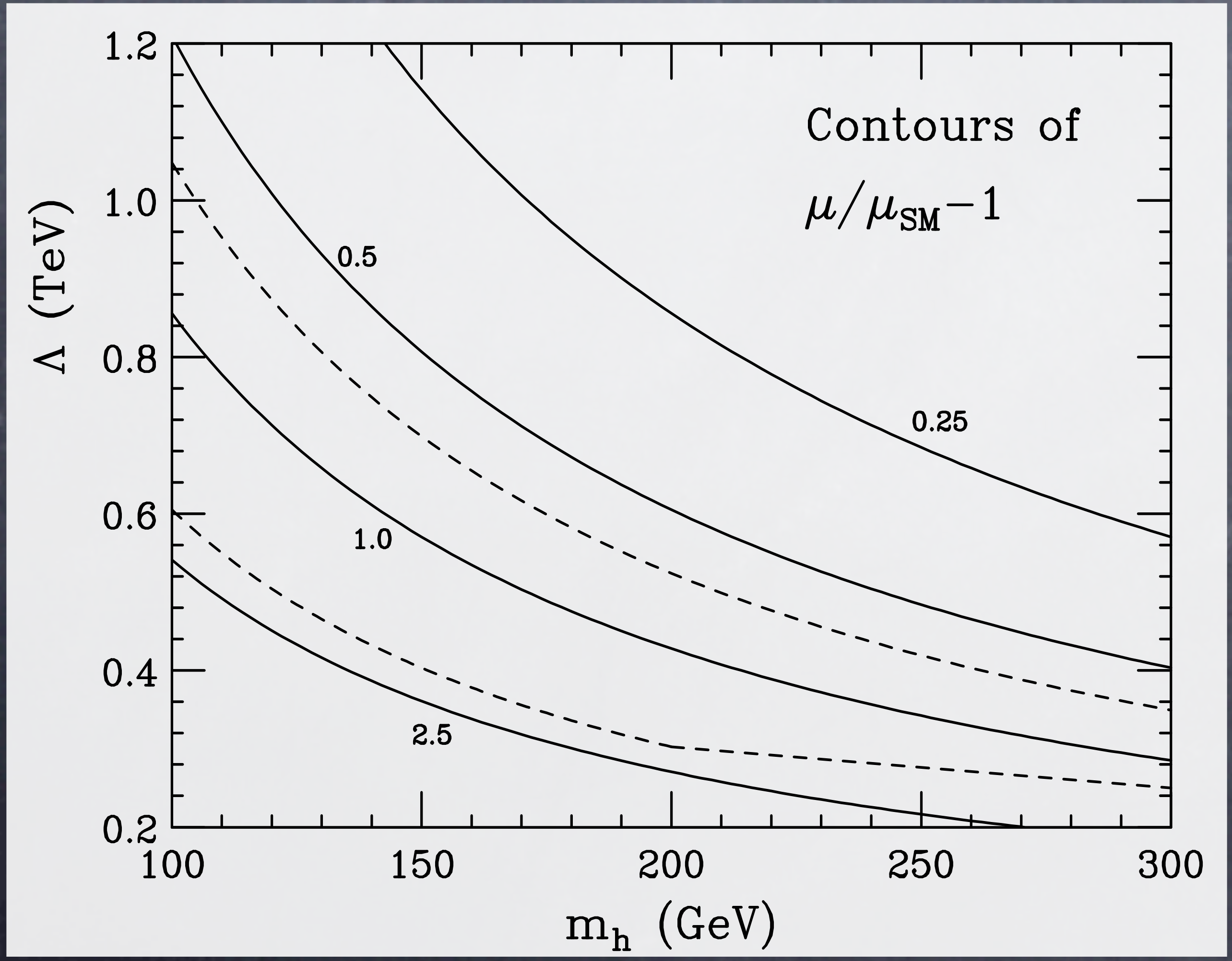
Grojean-Servant-Wells '04
Delaunay-Grojean-Wells '08

This scenario predicts large deviations to the Higgs self-couplings

$$\mathcal{L} = \frac{m_H^2}{2} H^2 + \frac{\mu}{3!} H^3 + \frac{\eta}{4!} H^4 + \ldots \quad where$$

$$\mu = 3\frac{m_H^2}{v_0} + 6\ \frac{v_0^3}{\Lambda^2}$$

$$\eta = 3\frac{m_H^2}{v_0^2} + 36\ \frac{v_0^2}{\Lambda^2}$$

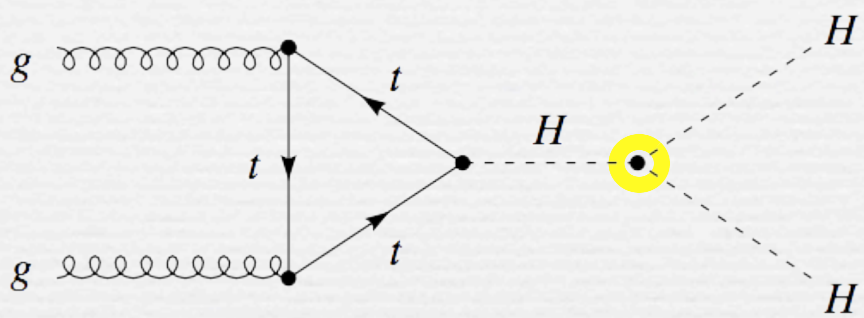


The dotted lines delimit the region for a strong 1rst order phase transition

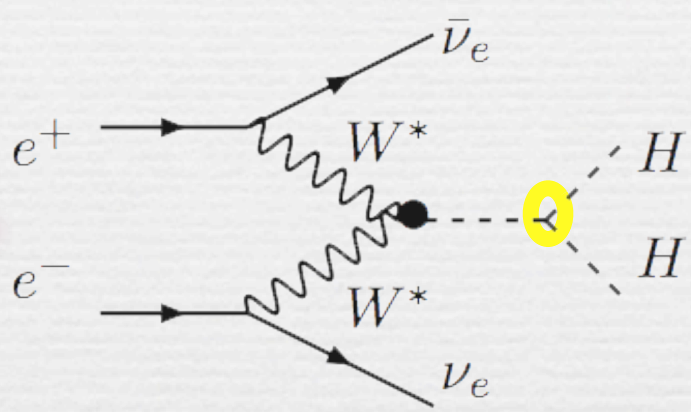
deviations between a factor 0.7 and 2

Experimental tests of the Higgs self-coupling

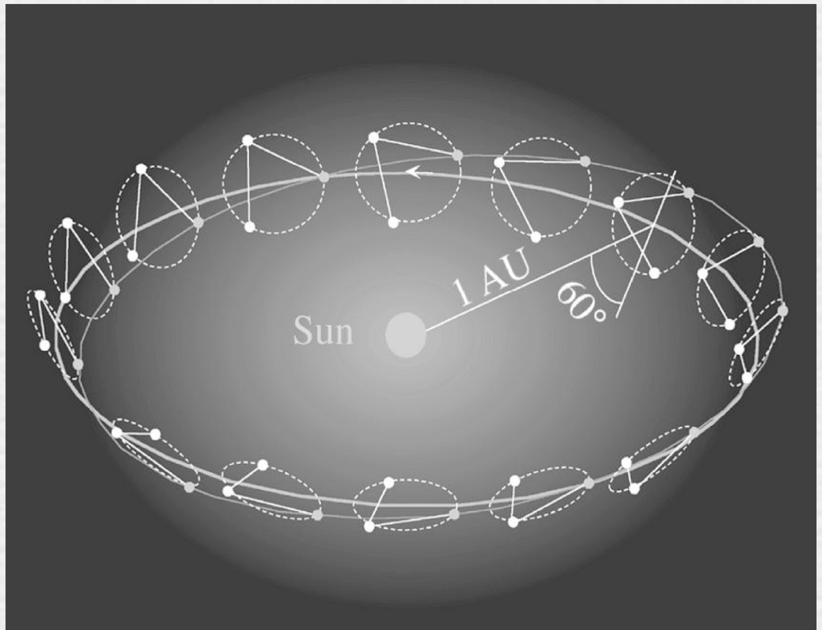
at a Hadron Collider

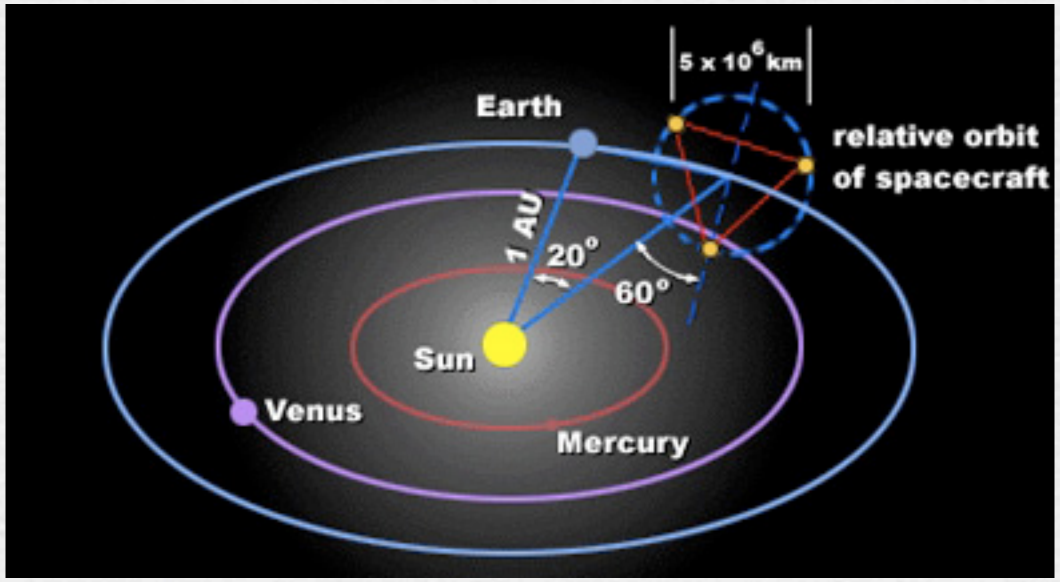


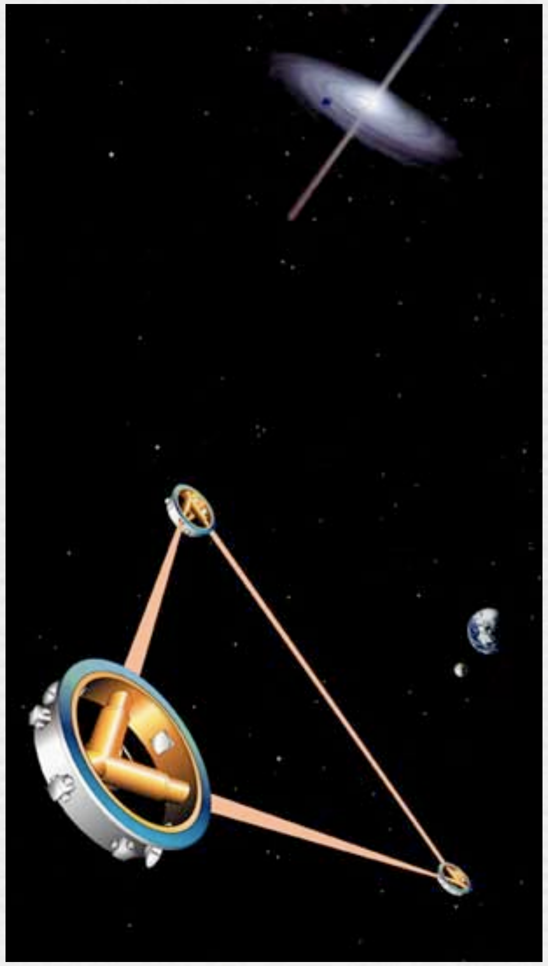
at an $e^+ e^-$ Linear Collider



... or at the gravitational wave detector LISA



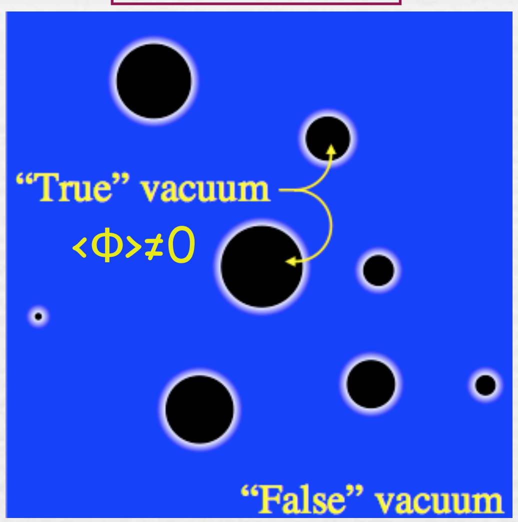




Gravitational Wave Spectrum of a strongly first order electroweak phase transition

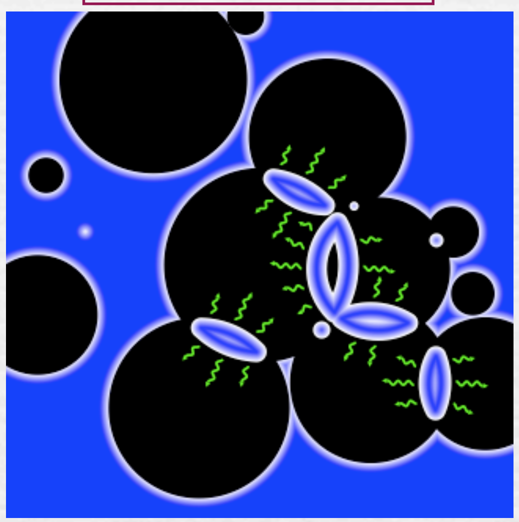
Stochastic background of gravitational radiation

Bubble nucleation



$\langle\Phi\rangle=0$

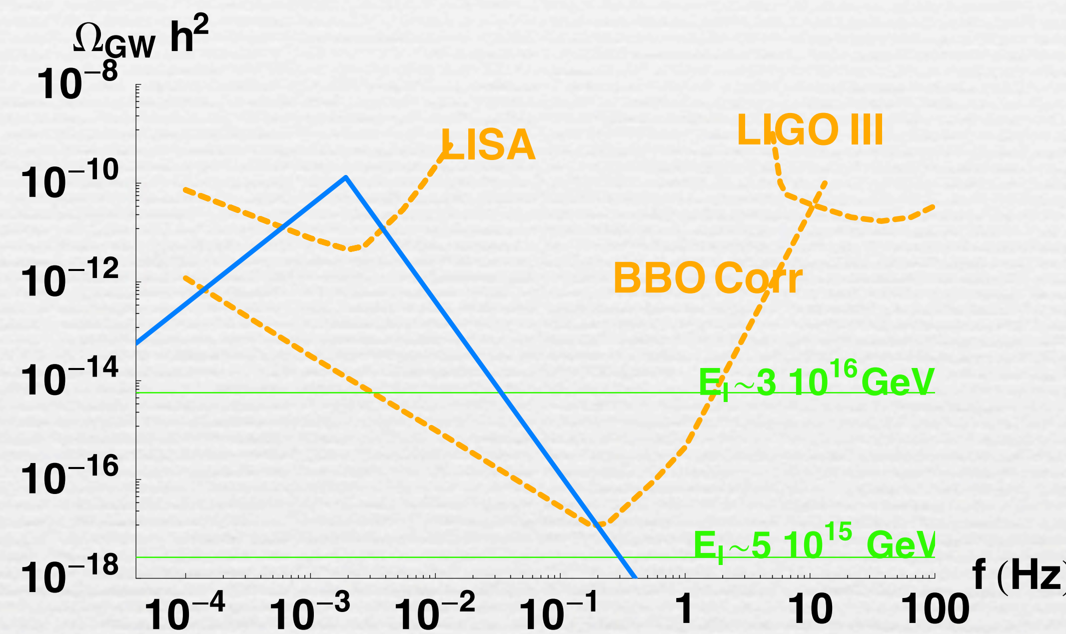
Bubble percolation



Fluid flows

turbulence

Magnetic fields



violent process if $v_b \sim O(1)$

- test of the dynamics of the phase transition
- relevant to models of EW baryogenesis
- reconstruction of the Higgs potential/study of new models of EW symmetry breaking (little higgs, gauge-higgs,composite higgs,higgsless...)

Gravitational Waves: A way to probe astrophysics
... and high energy particle physics.

Gravitational Waves interact very weakly and are not absorbed

direct probe of physical process of the very early universe

Small perturbations in FRW metric:

$$ds^2 = a^2(\eta)(d\eta^2 - (\delta_{ij} + 2h_{ij})dx^i dx^j) \qquad G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

$$\ddot{h}_{ij}(\mathbf{k},\eta) + \frac{2}{\eta}\dot{h}_{ij}(\mathbf{k},\eta) + k^2 h_{ij}(\mathbf{k},\eta) = 8\pi G a^2(\eta)\Pi_{ij}(\mathbf{k},\eta)$$

Source of GW: anisotropic stress

possible cosmological sources:

inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

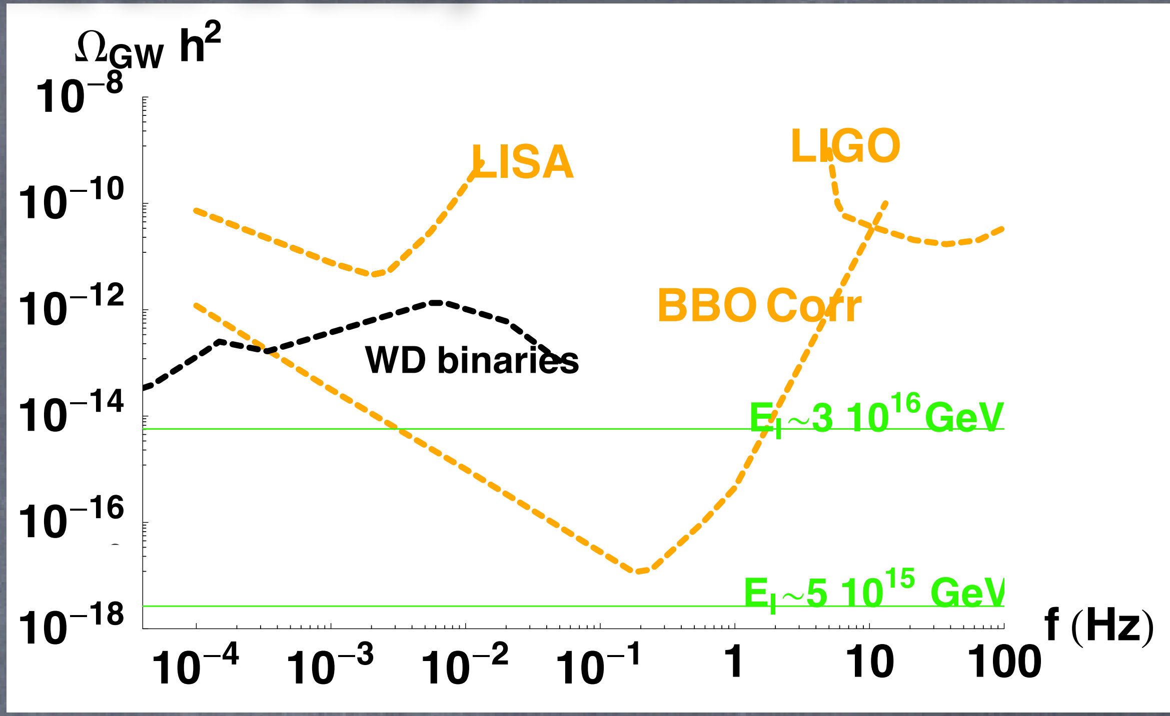
frequency observed today:

$$f = f_* \frac{a_*}{a_0} = f_* \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \approx 6 \times 10^{-3}\mathrm{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ \mathrm{GeV}} \frac{f_*}{H_*}$$

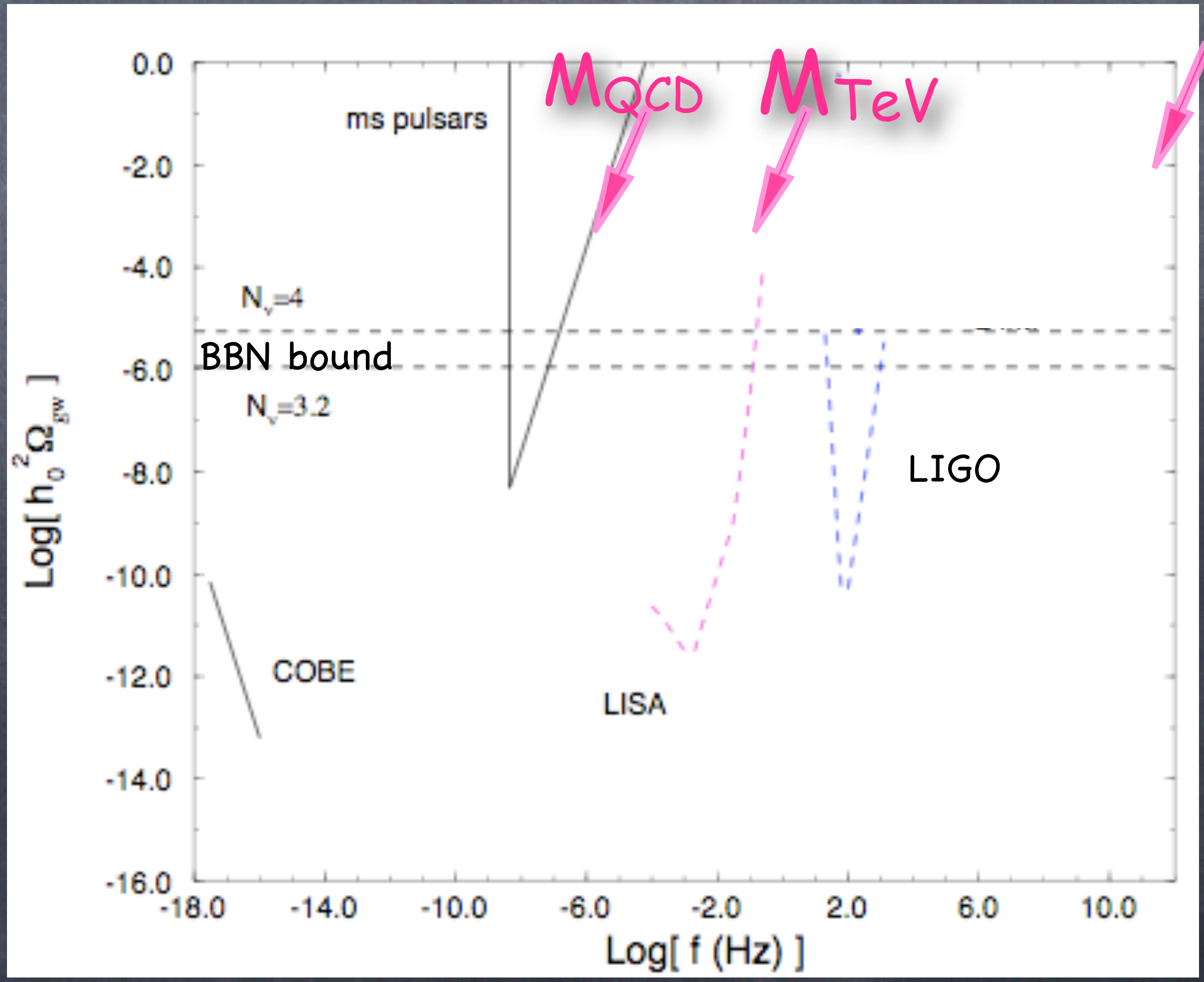
Beyond GW of astrophysical origin, another mission of GW astronomy will be to search for a stochastic background of gravitational waves of primordial origin (gravitational analog of the 2.7 K CMB)

Stochastic background: isotropic, unpolarized, stationary

GW energy density: $\Omega_G = \frac{\langle \dot{h}_{ij}\dot{h}^{ij}\rangle}{G\rho_c} = \int \frac{dk}{k}\frac{d\Omega_G(k)}{d\log(k)}$



A huge range of frequencies

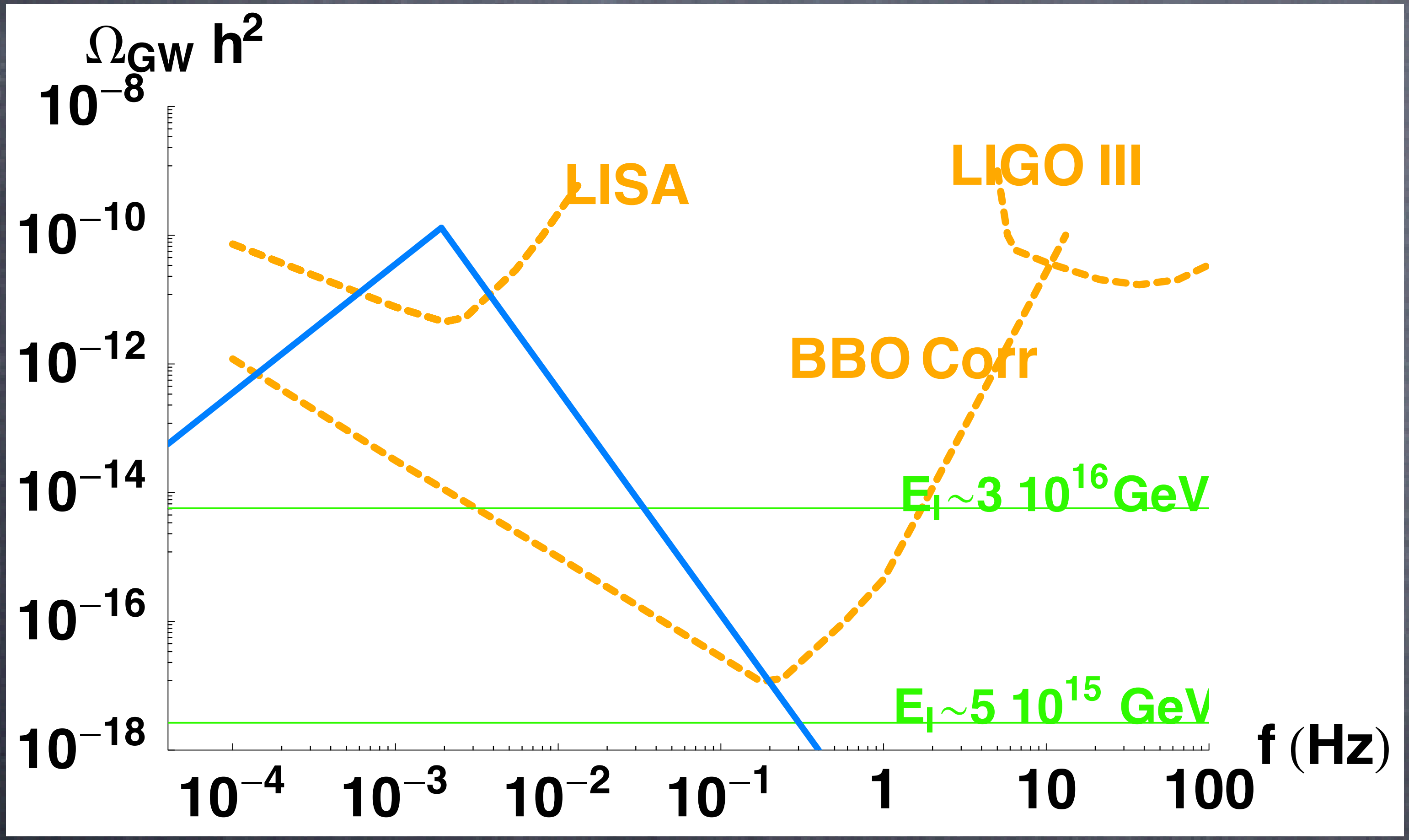


from Maggiore

Why should we be excited about mHZ freq.?

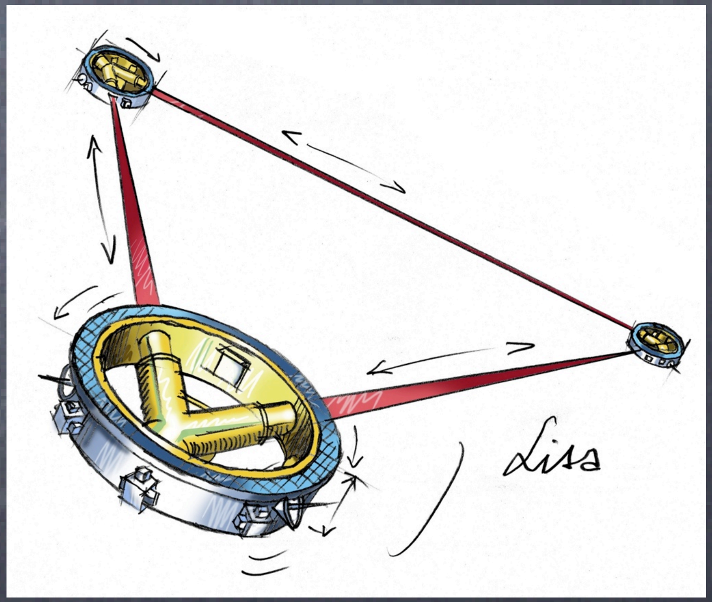
$$f = f_* \frac{a_*}{a_0} = f_* \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \approx 6\times 10^{-3}\mathrm{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100\ \mathrm{GeV}} \frac{f_*}{H_*}$$

LISA: Could be a new window on the Weak Scale



LISA band:

$10^{-4} - 10^{-2}$ Hz



complementary to collider informations

A not so new subject...

first suggestion: Witten'84

- Early 90's, M. Turner & al studied the production of GW produced by bubble collisions. Not much attention since the LEP data excluded a 1st order phase transition within the SM.

Kosowsky, Turner, Watkins'92
Kamionkowski, Kosowsky, Turner '94

- '01-'02: Kosowsky et al. and Dolgov et al. computed the production of GW from turbulence. Application to the (N)MSSM where a 1st order phase transition is still plausible.

Kosowsky, Mack, Kahniashvili'02
Dolgov, Grasso, Nicolis'02
Caprini, Durrer '06

Revival in 2006:

⇛ Model-independent analysis for detectability of GW from 1st order phase transitions

Grojean, Servant '06

⇛ Apply to Randall-Sundrum phase transition

Randall, Servant'06

⇛ Revisit the Turner et al original calculation

Caprini, Durrer, Servant'07'
Huber, Konstandin'08'

key quantities controlling the GW spectrum

$$\ddot{h}_{ij} + 2\mathcal{H}\dot{h}_{ij} + k^2 h_{ij} = 8\pi G a^2 T_{ij}^{(TT)}(k,t)$$

$$T_{ab}(\mathbf{x}) = (\rho + p)\frac{v_a(\mathbf{x})v_b(\mathbf{x})}{1 - v^2(\mathbf{x})}$$

Source of GW: anisotropic stress

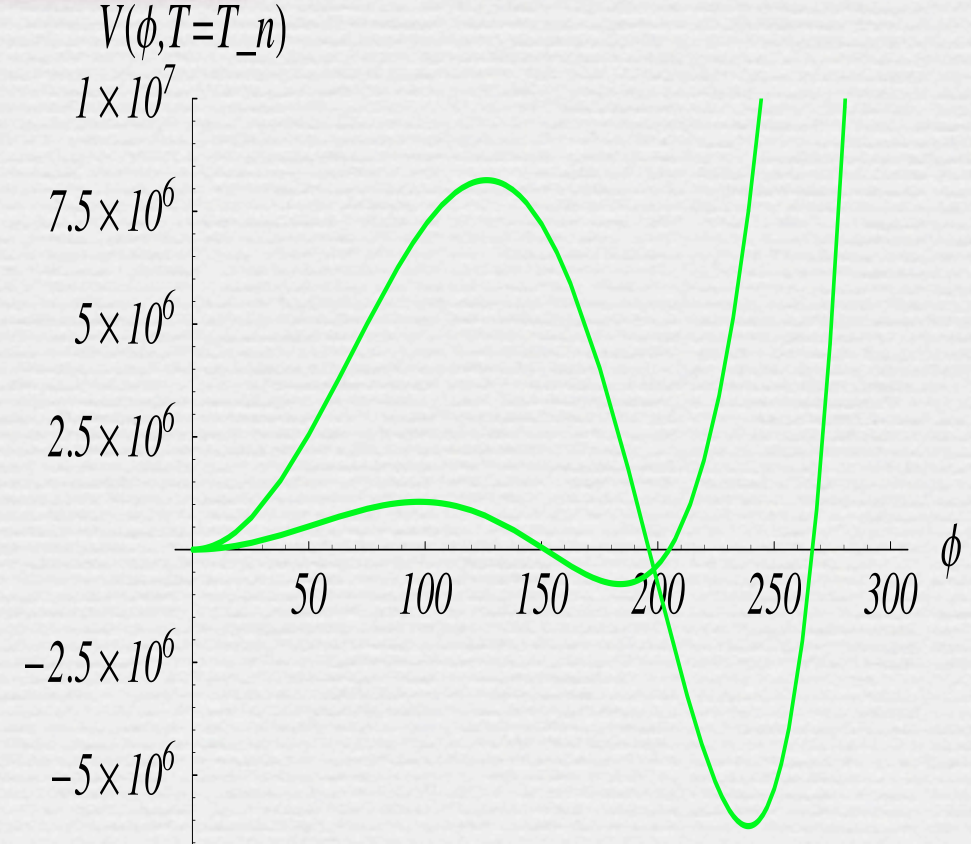
β : (duration of the phase transition)$^{-1}$

set by the tunneling probability $P \propto e^{\beta t} \propto \frac{T^4}{H^4} e^{-S_3/T} \sim 1$ ➔ $\frac{S_3}{T}$ ~ 140

and typically $\frac{\beta}{H} \sim \mathcal{O}(10^2 - 10^3)$

α : vacuum energy density/radiation energy density

α and β : entirely determined by the effective scalar potential at high temperature



Estimate of the GW energy density at the emission time

$$\rho_{GW} \sim \dot{h}^2 / 16\pi G$$

$$\delta G_{\mu\nu} = 8\pi G T_{\mu\nu} \longrightarrow \beta^2 h \sim 8\pi G T \longrightarrow \dot{h} \sim 8\pi G T/\beta$$

where $T \sim \rho_{kin} \sim \rho_{rad}\, v^2$

$$\Omega_{GW_*} = \frac{H_*^2}{\beta^2} \frac{\rho_{kin}{}^2}{\rho_{tot}{}^2}$$

$\rho_{kin}{}^2 \rightarrow \kappa^2 \alpha^2 v^4$

$$\Omega_{GW_*} \propto \frac{H_*^2}{\beta^2} \kappa^2 \frac{\alpha^2}{(\alpha+1)^2} v^4$$

κ : fraction of vacuum energy transformed into bulk fluid motions

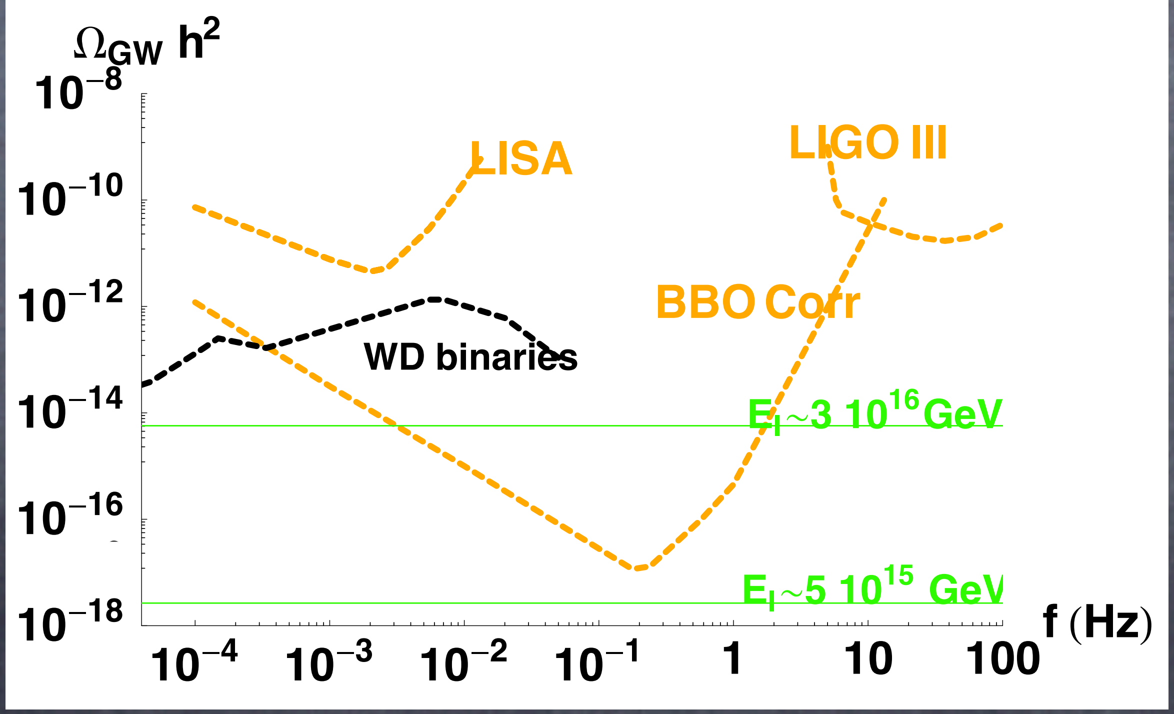
3 parameters:
α, β, v

Fraction of the critical energy density in GW today

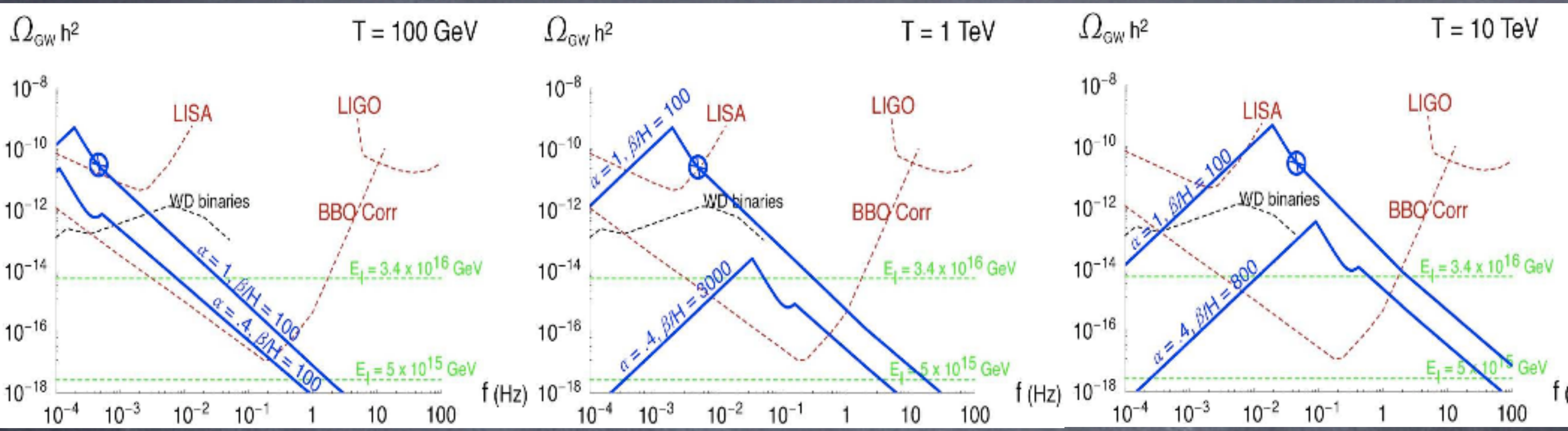
$$\Omega_{GW} = \frac{\rho_{GW}}{\rho_c} = \Omega_{GW*}\left(\frac{a_*}{a_0}\right)^4\left(\frac{H_*}{H_0}\right)^2 \simeq 1.67\times 10^{-5}h^{-2}\left(\frac{100}{g_*}\right)^{1/3}\Omega_{GW*}$$

has to be big ($\gtrsim 10^{-6}$ for LIGO/LISA and $\gtrsim 10^{-12} - 10^{-9}$ for BBO)

where we used: $\rho_{GW} = \rho_{GW*}\left(\frac{a_*}{a_0}\right)^4 \quad , \quad \rho_c = \rho_{c*}\frac{H_0^2}{H_*^2}$ and $H_0 = 2.1332\times h\times 10^{-42}\text{GeV}$

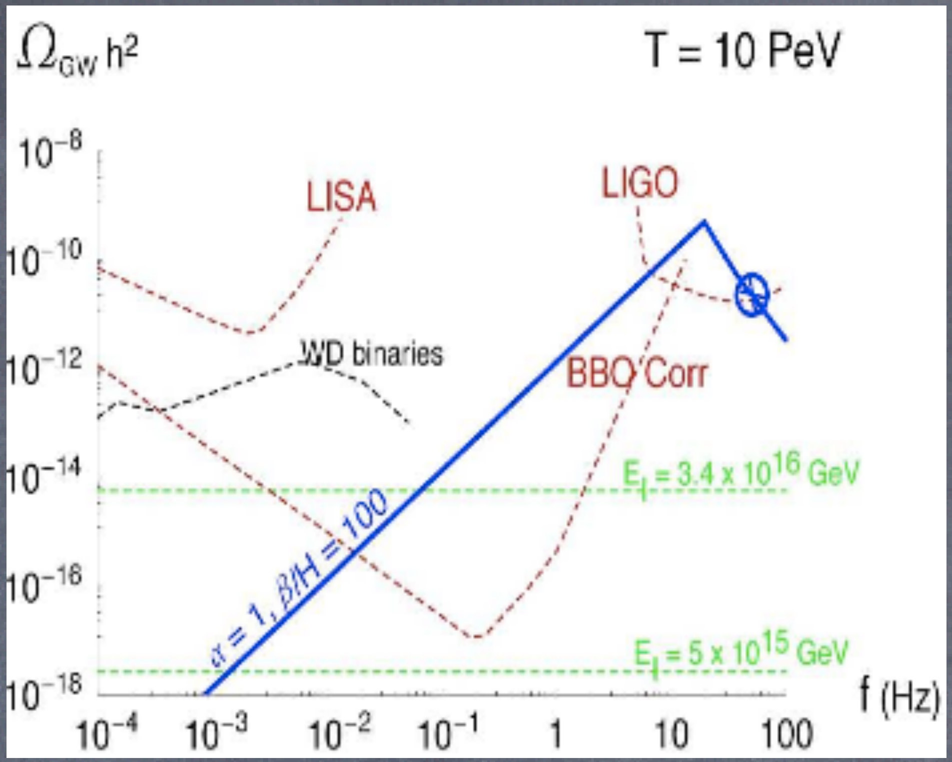


Spectrum of gravitational waves produced at 1rst order phase transitions

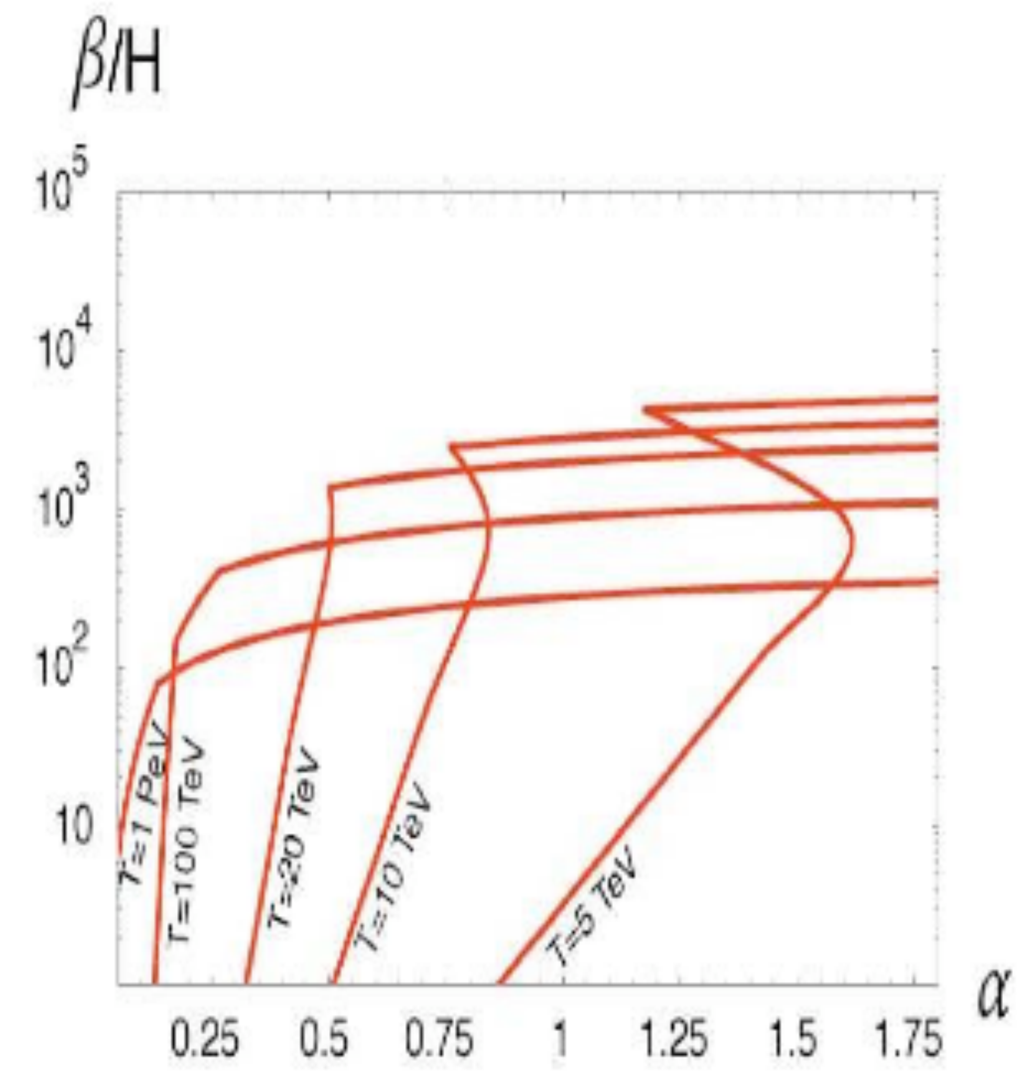


$$f_{\text{peak}} \sim 10^{-2}\,\text{mHz}\left(\frac{g_*}{100}\right)^{1/6}\frac{T_*}{100\ \text{GeV}}\ \frac{\beta}{H_*}\ \frac{1}{v}$$

A phase transition at $T \sim 10^7$ GeV could be observed both at LIGO and BBO:



GW from phase transitions could entirely mask the GW signal expected from inflation:

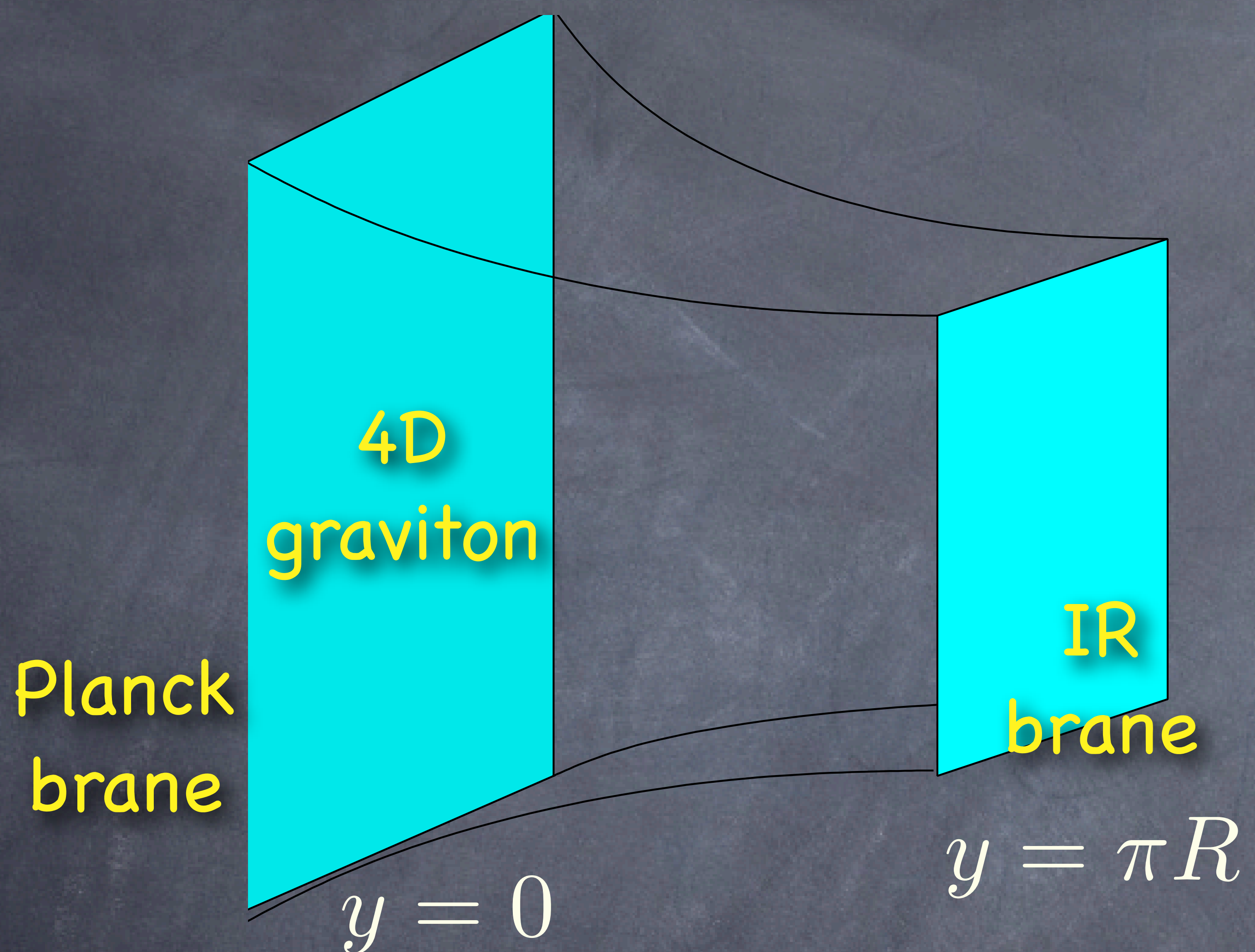


Gravitational Waves from Warped Extra-Dimensional Geometry

Randall-Servant '07

Space-time is a slice of AdS_5

[Randall, Sundrum '99]



$$ds^2 = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

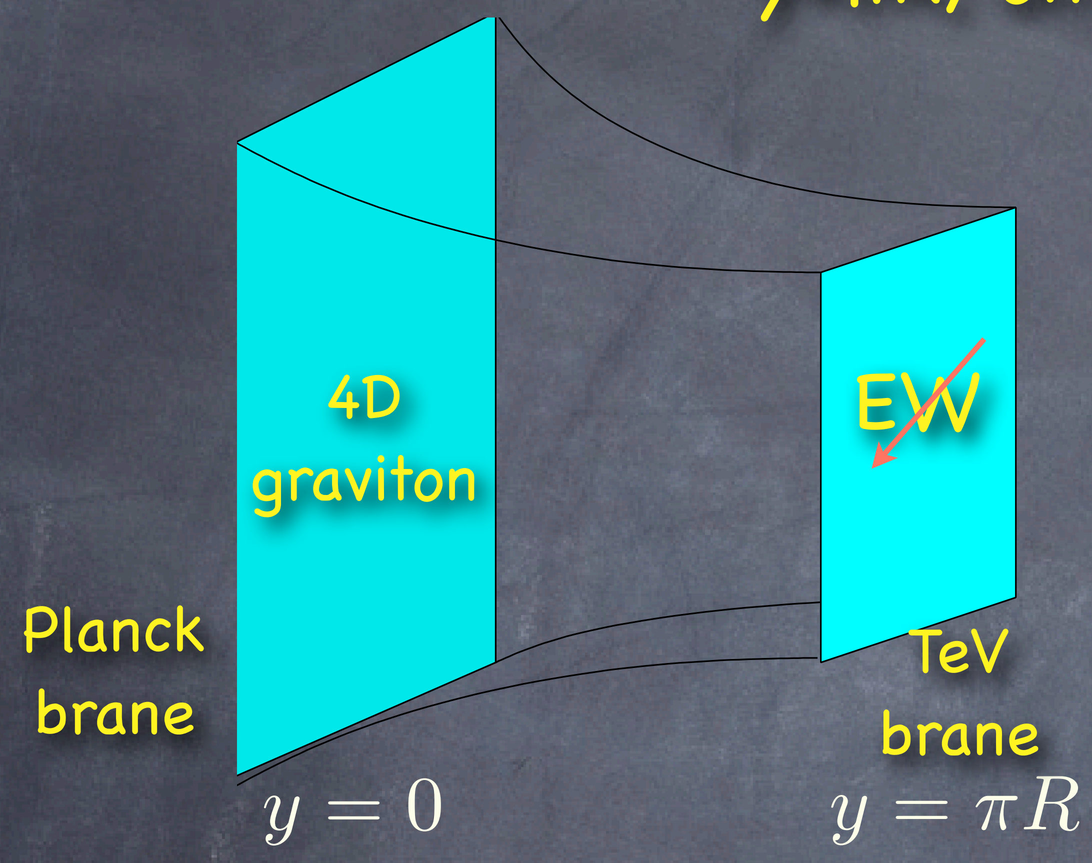
$$M_{Pl}^2 \sim \frac{M_5^3}{k}$$

The effective 4D energy scale varies with position along 5th dimension

RS1 (has two branes) versus RS2 (only Planck brane)

Solution to the Planck/Weak scale hierarchy

The Higgs (or any alternative EW breaking) is localized at $y=\pi R$, on the TeV (IR) brane



After canonical normalization of the Higgs:

$$v_{\rm eff} = v_0 e^{-k\pi R}$$

parameter in the 5D lagrangian

$$k\pi R \sim \log(\frac{M_{Pl}}{\rm TeV})$$

Exponential hierarchy from O(10) hierarchy in the 5D theory

One Fondamental scale : $M_5 \sim M_{Pl} \sim k \sim \Lambda_5/k \sim r^{-1}$

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

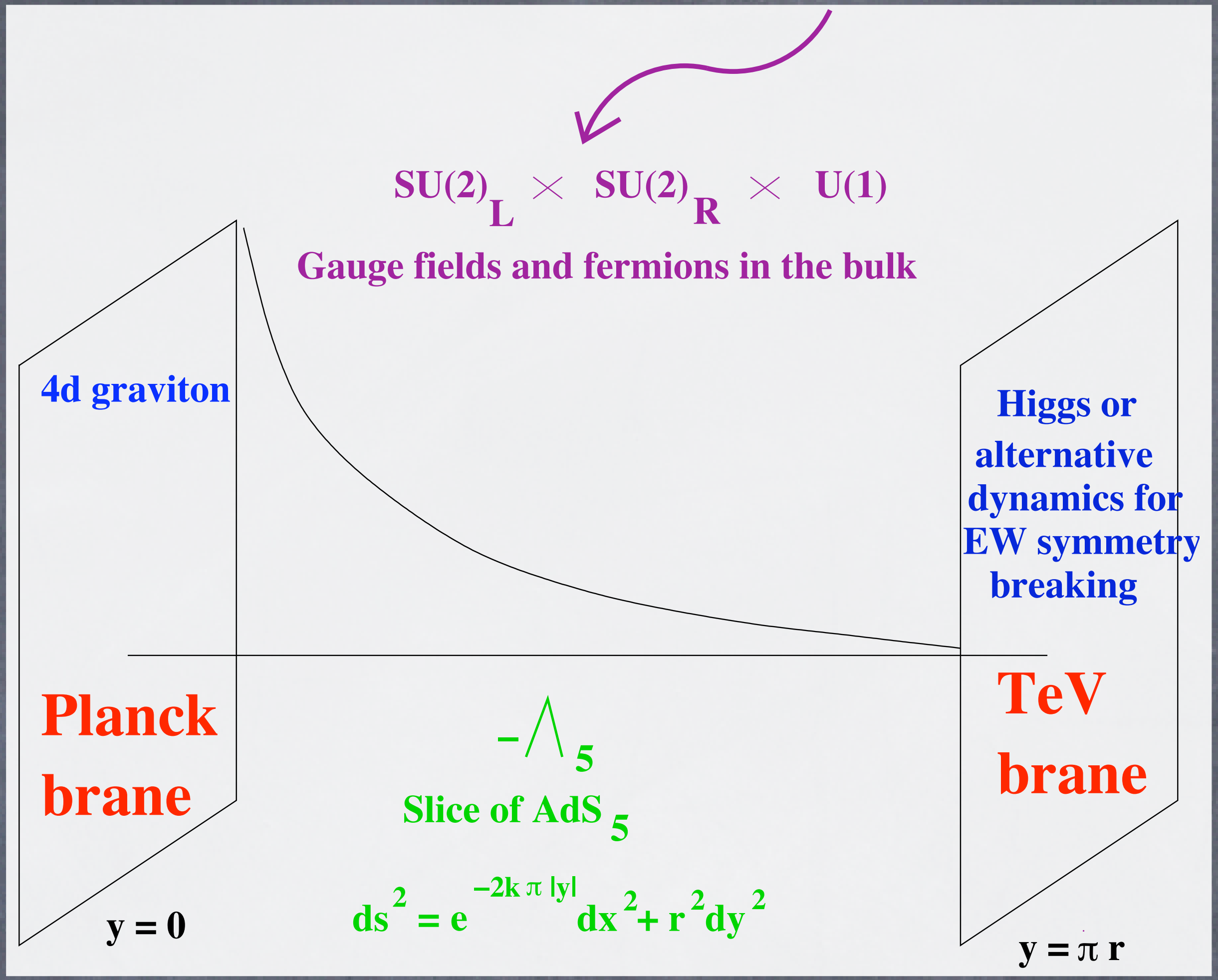
Warped hierarchies are radiatively stable as cutoff scales get warped down near the IR brane

Particle physics model building in warped space

favourite set-up:

- ✔ hierarchy pb
- ✔ fermion masses
- ✔ High scale unification
- ✔ FRW cosmology

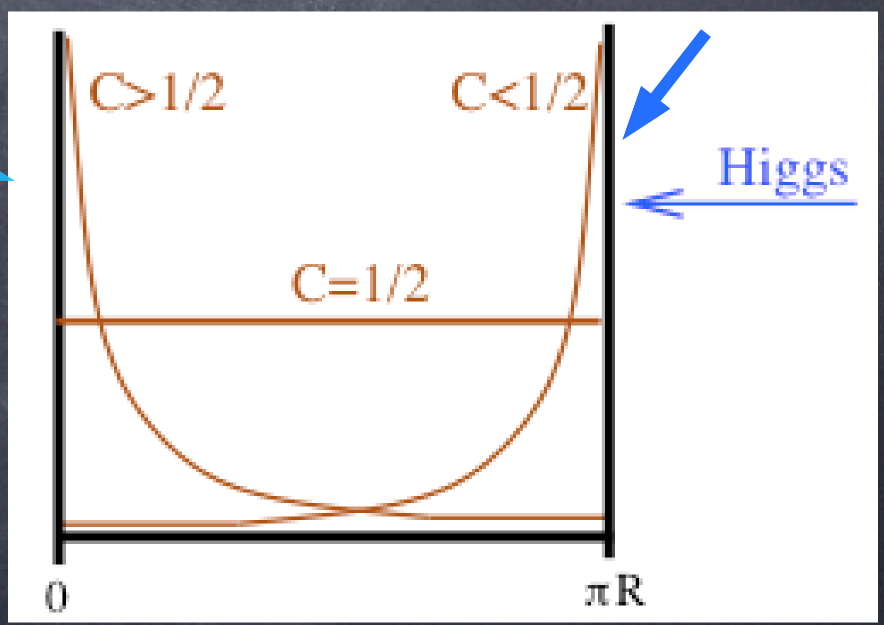
✔ Still active research on consistency with EW precision tests & little hierarchy pb



Note: No susy here

and many different realizations

M_{KK}~few TeV



[Grossman, Neubert '99]
[Gherghetta, Pomarol '00]

AdS/CFT dictionnary

[Maldacena '97]
[Arkani-Hamed, Porrati, Randall '01]
[Rattazzi, Zaffaroni '01]

Warped extra dim (RSI) ⟷ An almost CFT that very slowly runs but suddenly becomes strongly interacting at the TeV scale, spontaneously breaks the conformal invariance and confines, thus producing the Higgs

The hierarchy problem is solved due to the compositeness of the Higgs

KK modes localized on TeV brane ⟷ bound state resonances

A gauge symmetry in the bulk ⟷ A global symmetry of the CFT

$SU(2)_R$ will protect the rho parameter

[Agashe, Delgado, May, Sundrum '03]
[Csaki, Grojean, Pilo, Terning '03]

UV matter ⟷ Fundamental particles coupled to the CFT

IR matter ⟷ Composite particles of the CFT

RSI: A calculable model of technicolor

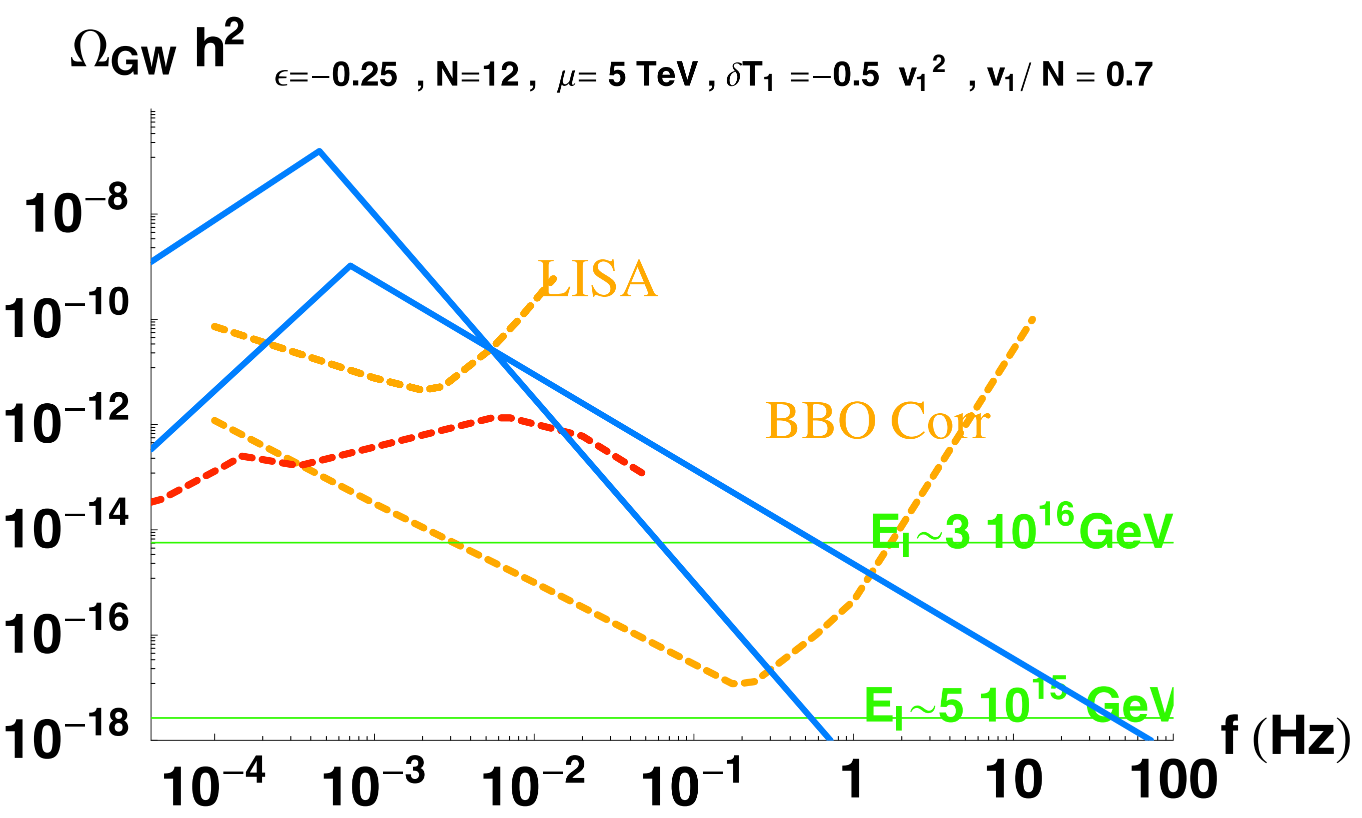
Cosmological phase transition associated with radion stabilisation (appearance of TeV brane)

↔

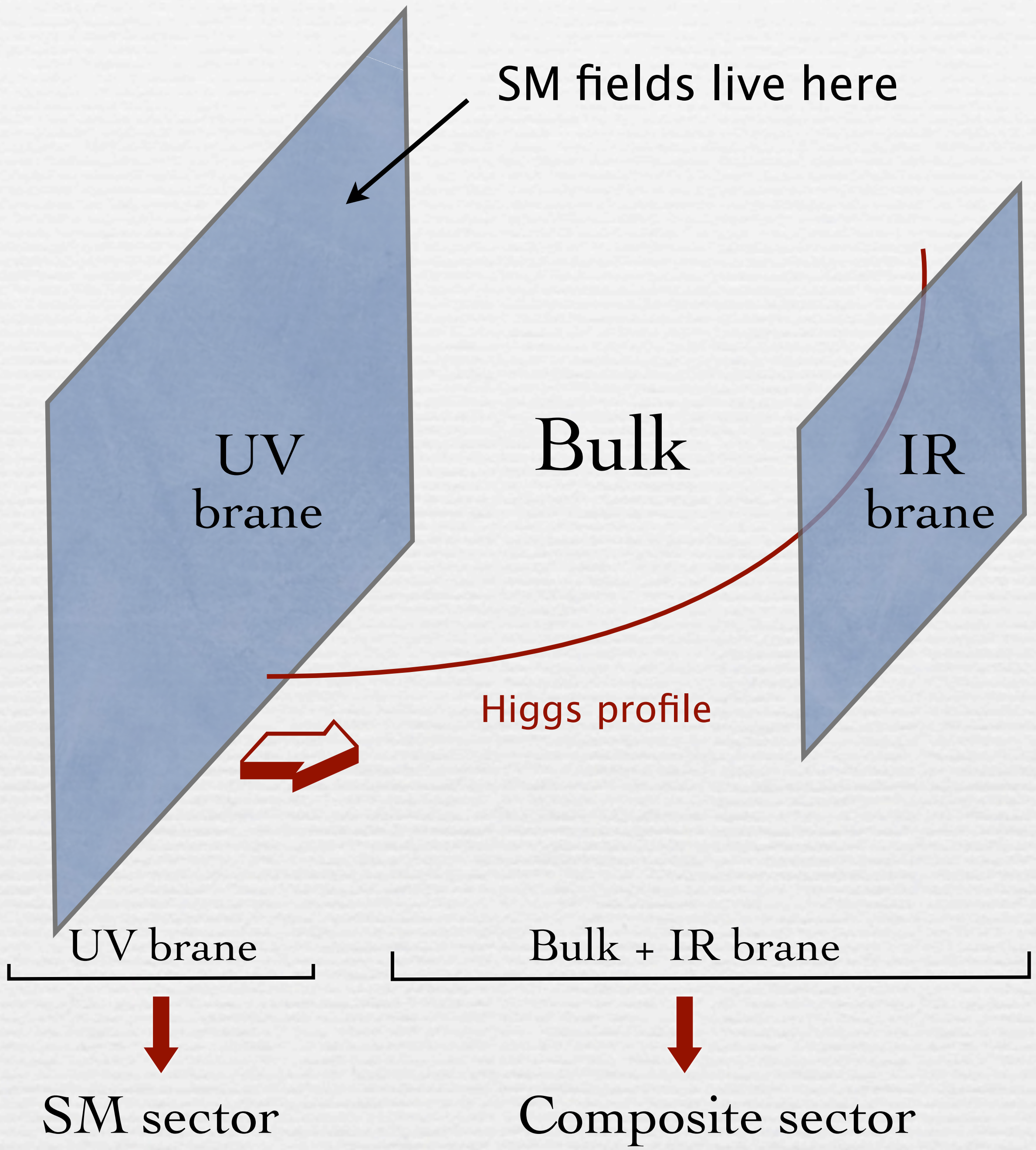
strongly 1st order confining phase transition of SU(N) gauge theory (N>3)

leads to stochastic background of gravity waves observable by LISA

[Randall-Servant, '06]



Using a warped extra dimension as a tool to study strong dynamics

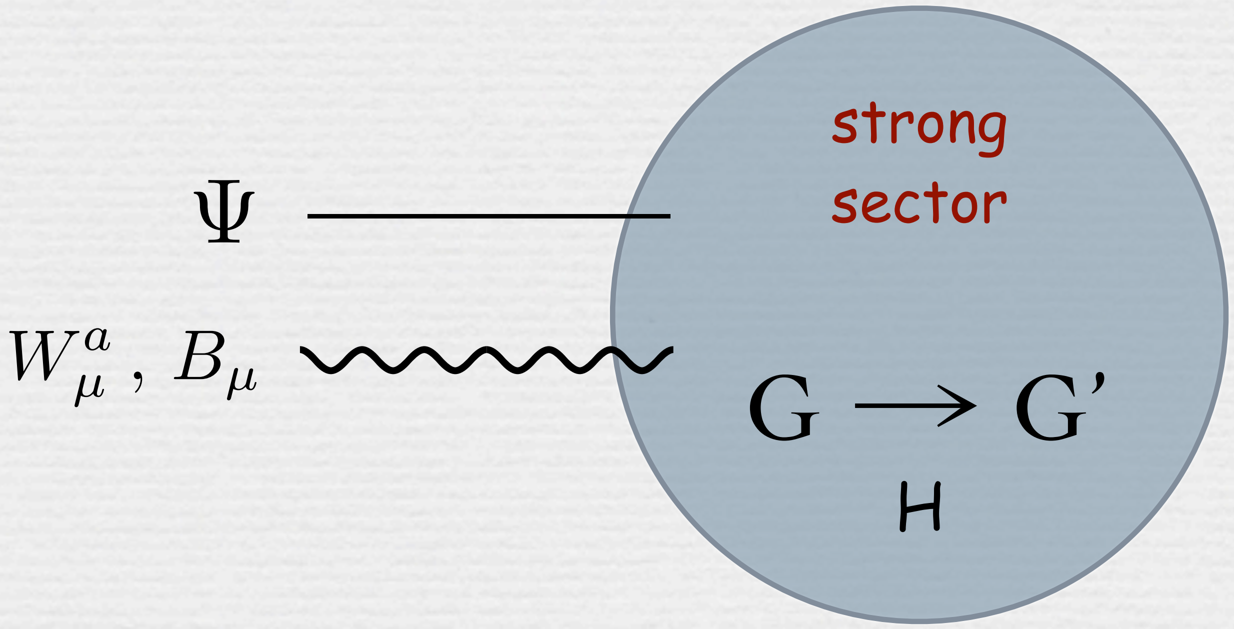


$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} - dy^2$$

Advantages of the 5D theories :

- ☑ The 5D field theory is weakly coupled (the strong dynamics is “solved” in 5D)
- ☑ Model Building is simple (especially in the fermionic sector)

In the 4D description of the 5D models the SM fields are linearly coupled to the strong sector:



$$\mathcal{L}_{int} = A_\mu J^\mu + \bar{\Psi} O + h.c.$$

Partial compositeness: Dual picture

Higgs is part of composite sector: it couples only to composite fermions

SM sector ⟷ strong sector EWSB

linear mixing

$-\Delta \overline{\chi}_L \psi_R$

elementary fermions: χ

Higgs

heavy fermions: ψ

vector resonances: ρ

zero mode mass eigen state is mixture of elementary and composite

- massless

$$|light>_L = \cos\phi|\chi_L> + \sin\phi|\psi_L>$$

amount of compositeness in the light dof ($\sin\phi$)

- massive

$$|heavy>_L = -\sin\phi|\chi_L> + \cos\phi|\psi_L>$$

$$|heavy>_R = |\psi_R>$$

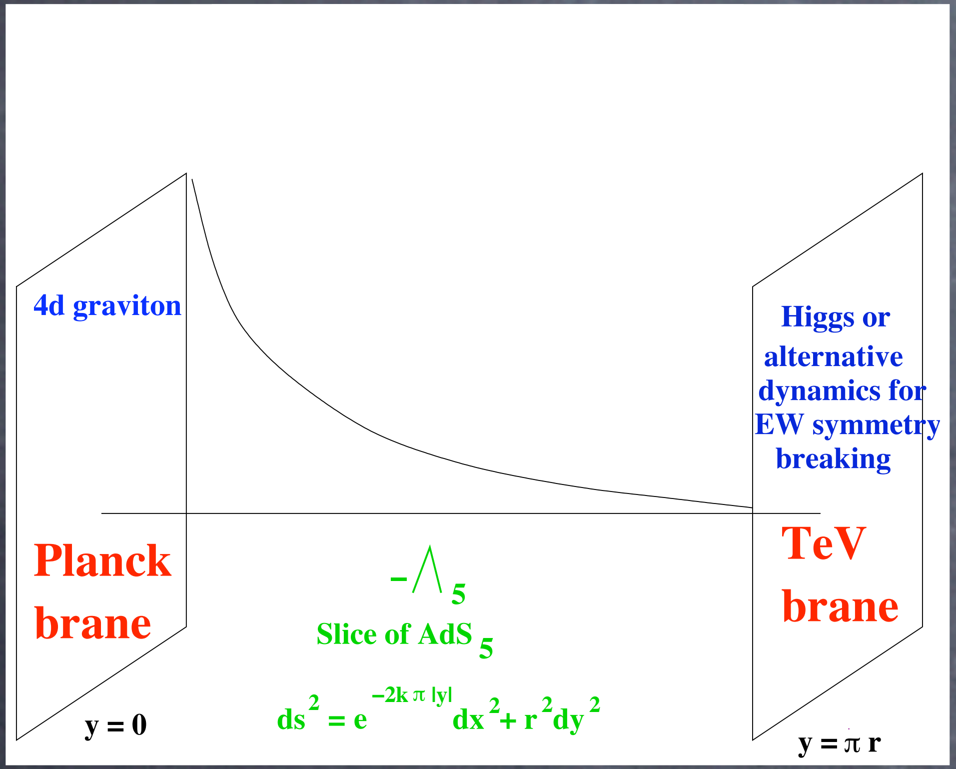
$$\tan\phi = \frac{\Delta}{M_*}$$

Yukawa hierarchy comes from the hierarchy of compositeness

Cosmology of the Randall-Sundrum model

At high T: AdS-Schwarzchild BH solution with event horizon shielding the TeV brane

At low T: usual RS solution with stabilized radion and TeV brane



Natural stabilisation of radius à la Goldberger-Wise :

$$kr = \frac{4}{\pi}\frac{k^2}{m^2}\ln\left[\frac{v_h}{v_v}\right] \sim 10$$

Randall-Sundrum phase transition

Creminelli-Nicolis-Rattazzi '01

Assuming the universe started at T>> Tc, the PT has to take place if we want a RS set-up at low T.

Start with a black brane, nucleate "gaps" in the horizon which then grow until they take over the entire horizon.

Completion of the phase transition

a five-dimensional set-up
but we can treat this as bubble nucleation in four dimensions

Low energies: radion dominates potential

High energies: holography

$$(M/k)^3 \sim N^2/16\pi^2$$

Need N large

Goldberger-Wise mechanism

Start with the bulk 5d theory $\mathcal{L} = \int dx^4 dz \sqrt{-g}[2M^3\mathcal{R} - \Lambda_5]$ $\qquad \Lambda_5 = -24M^3k^2$

The metric for RS1 is
$$ds^2 = (kz)^{-2}(\eta_{\mu\nu}dx^\mu dx^\nu + dz^2) = e^{-2ky}\eta_{\mu\nu}dx^\mu dx^\nu + dy^2$$
where $k = L^{-1}$ is the AdS curvature, $z = k^{-1}e^{ky}$

and the orbifold extends from $z=z_0=L$ (Planck brane) to $z=z_1$ (TeV brane)

Which mechanism naturally selects $z_1 \gg z_0$? simply a bulk scalar field φ can do the job:

$$\int d^4x dz \left(\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2] + \delta(z-z_0)\sqrt{g_0}L_0(\phi(z)) + \delta(z-z_1)\sqrt{g_1}L_1(\phi(z))\right)$$

φ has a bulk profile satisfying the 5d Klein-Gordon equation

$$\phi = Az^{4+\epsilon} + Bz^{-\epsilon}$$ where $$\epsilon = \sqrt{4+m^2L^2} - 2 \approx m^2L^2/4$$

Plug this solution into $$V_{eff} = \int_{z_0}^{z_1} dz\sqrt{g}[-(\partial\phi)^2 - m^2\phi^2]$$

$$V_{\rm GW} = z_1^{-4}\left[(4+2\epsilon)\left(v_1 - v_0\left(\frac{z_0}{z_1}\right)^\epsilon\right)^2 - \epsilon v_1^2\right] + \mathcal{O}(z_0^4/z_1^8) = z_1^{-4}P(z_1^{-\epsilon})$$

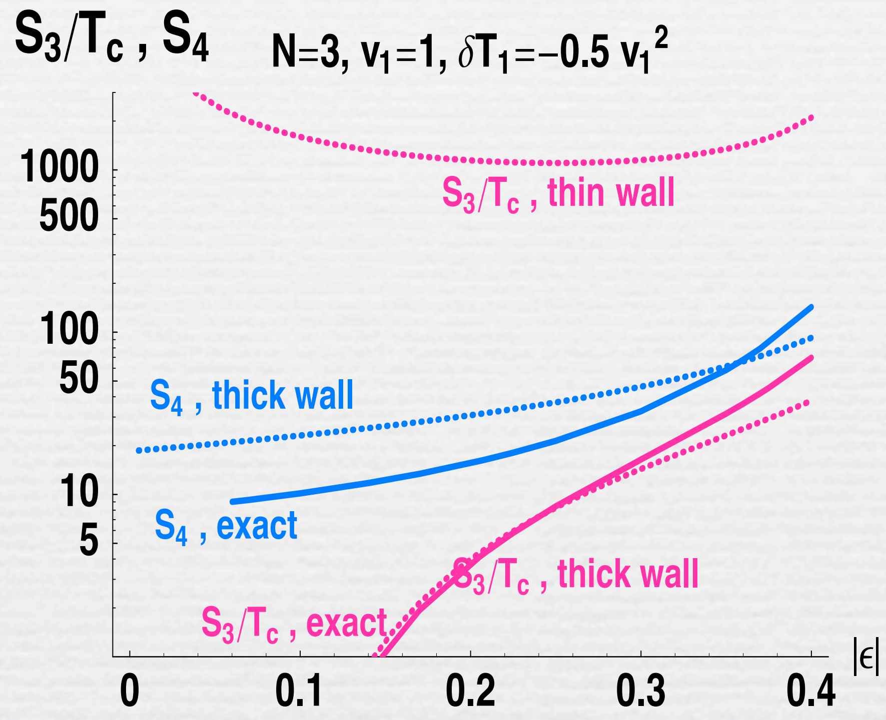
$$z_1 \approx z_0\left(\frac{v_0}{v_1}\right)^{1/\epsilon}$$

~ scale invariant fn modulated by a slow evolution through the $z^{-\epsilon}$ term

similar to Coleman-Weinberg mechanism

typically strong first-order PT, large supercooling

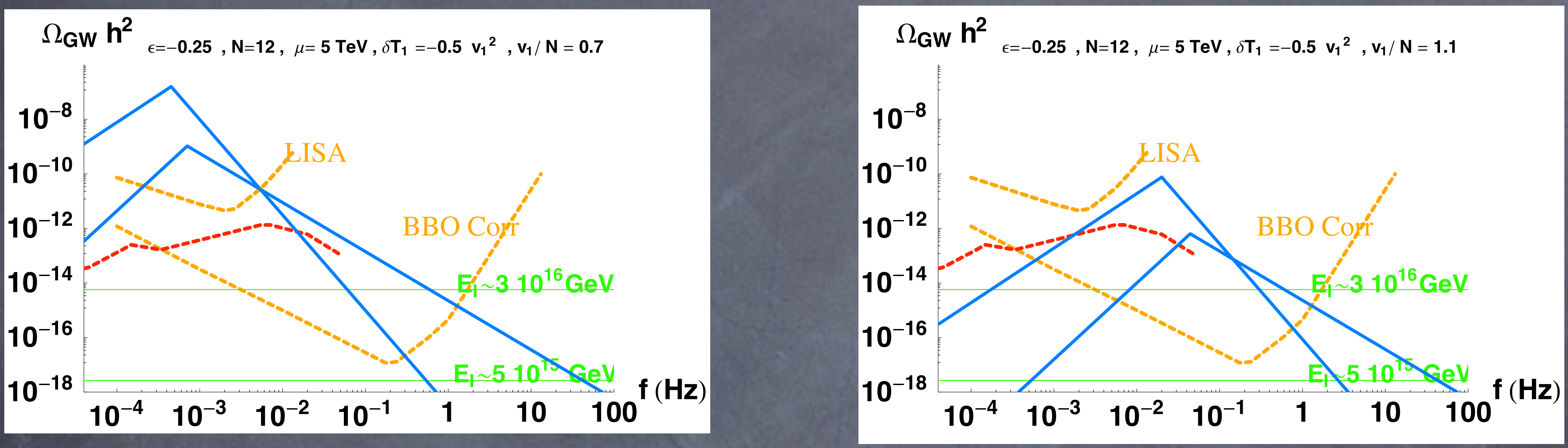
near conformal dynamics -> $T_n \ll \mu_{TeV}$, large α, small β/H



Randall-Servant'06

Gravitational Waves from "3-brane" nucleation:

Signal versus LISA's sensitivity



Randall-Servant'06

Signature in GW is generic,

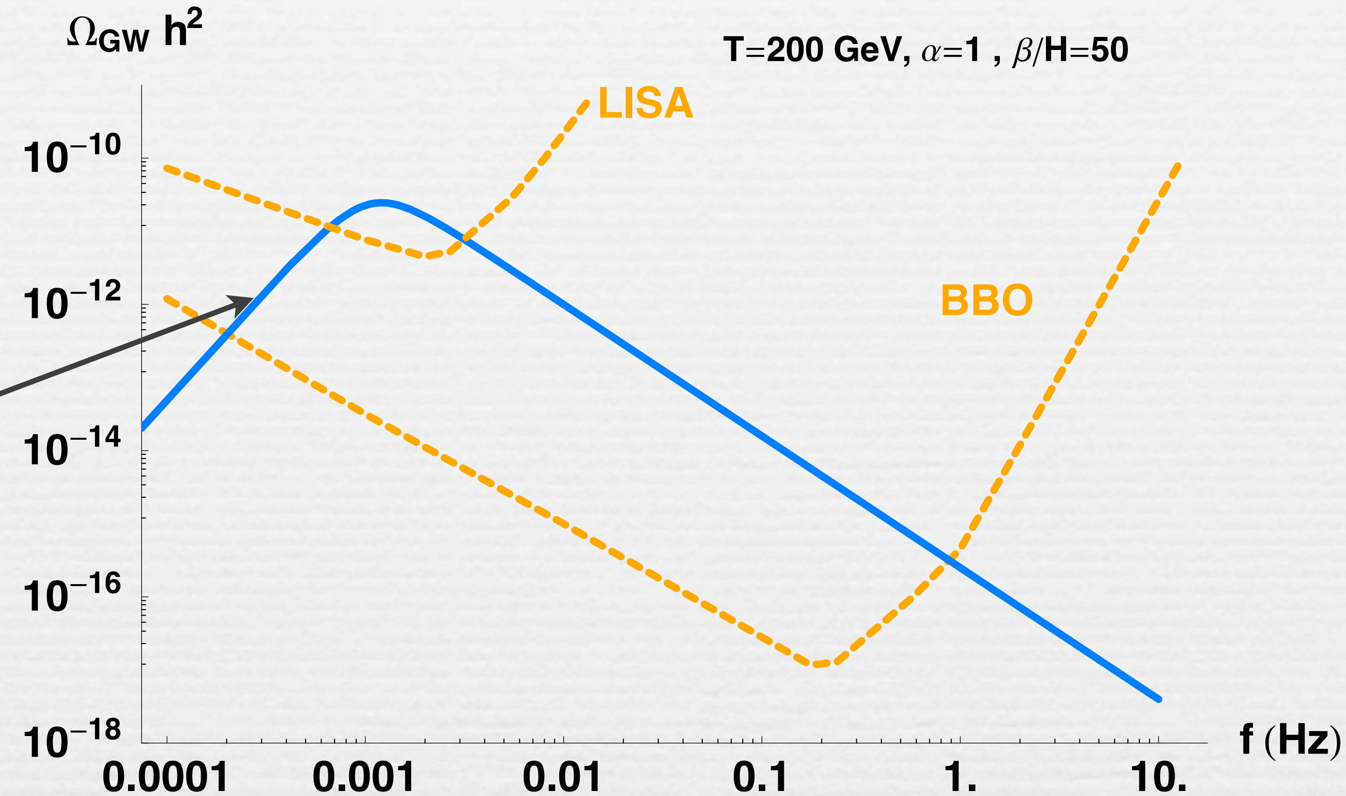
i.e. does not depend whether Standard Model is in bulk or on TeV brane

but crucially depends on the radion properties

Conclusion

We might be learning something about the Higgs/radion by looking at the sky

Expected shape of the GW spectrum



large scale part of the GW spectrum

~ f^3

$$\frac{d\Omega_G}{d\ln k} = \frac{k^3|\dot{h}|^2}{G\rho_c}$$

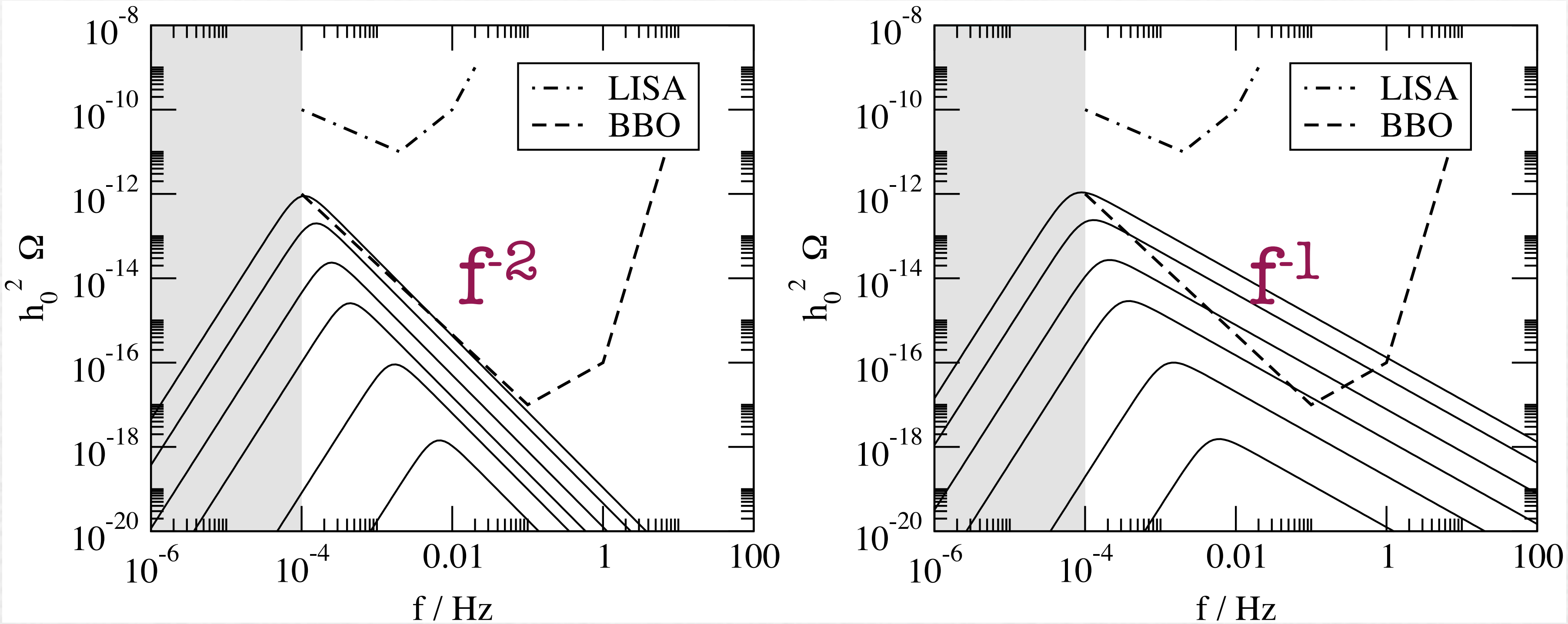
$$h_{ij}(\mathbf{k},\eta) = \int_{\eta_{\rm in}}^{\eta} d\tau \mathcal{G}(\tau,\eta)\Pi_{ij}(\mathbf{k},\tau)$$

white noise for the anisotropic stress -> k^3 for the energy density

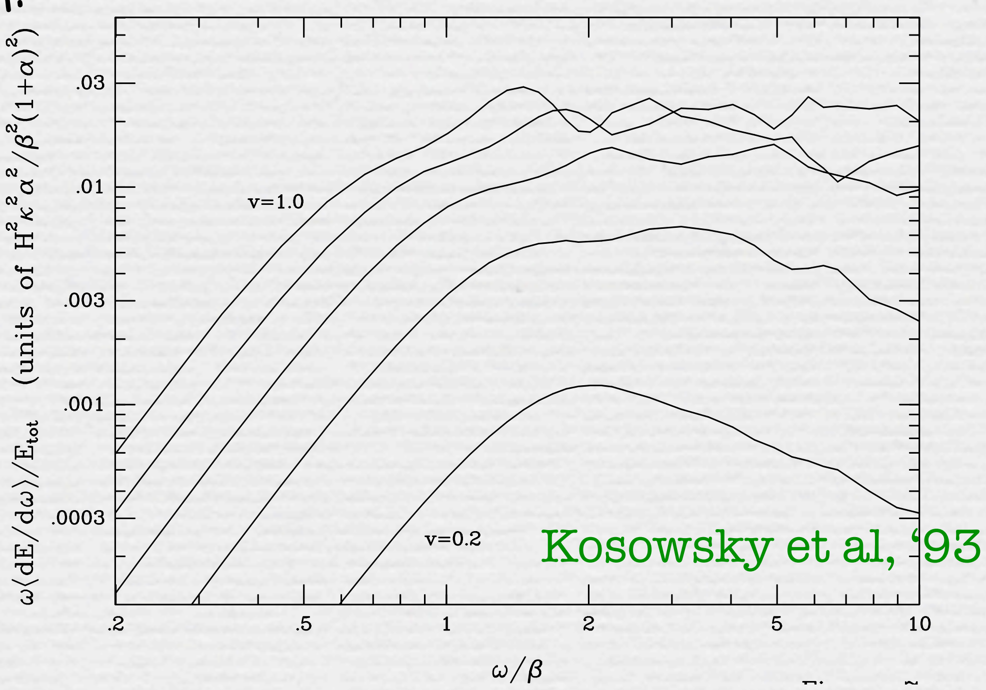
CAUSAL PROCESS: source is uncorrelated at scales larger than the peak scale

GW spectrum due to bubble collisions from numerical simulations: high frequency slope

Kosowsky et al, '93 $f^{-2} \rightarrow f^{-1}$ Huber-Konstandin,'08



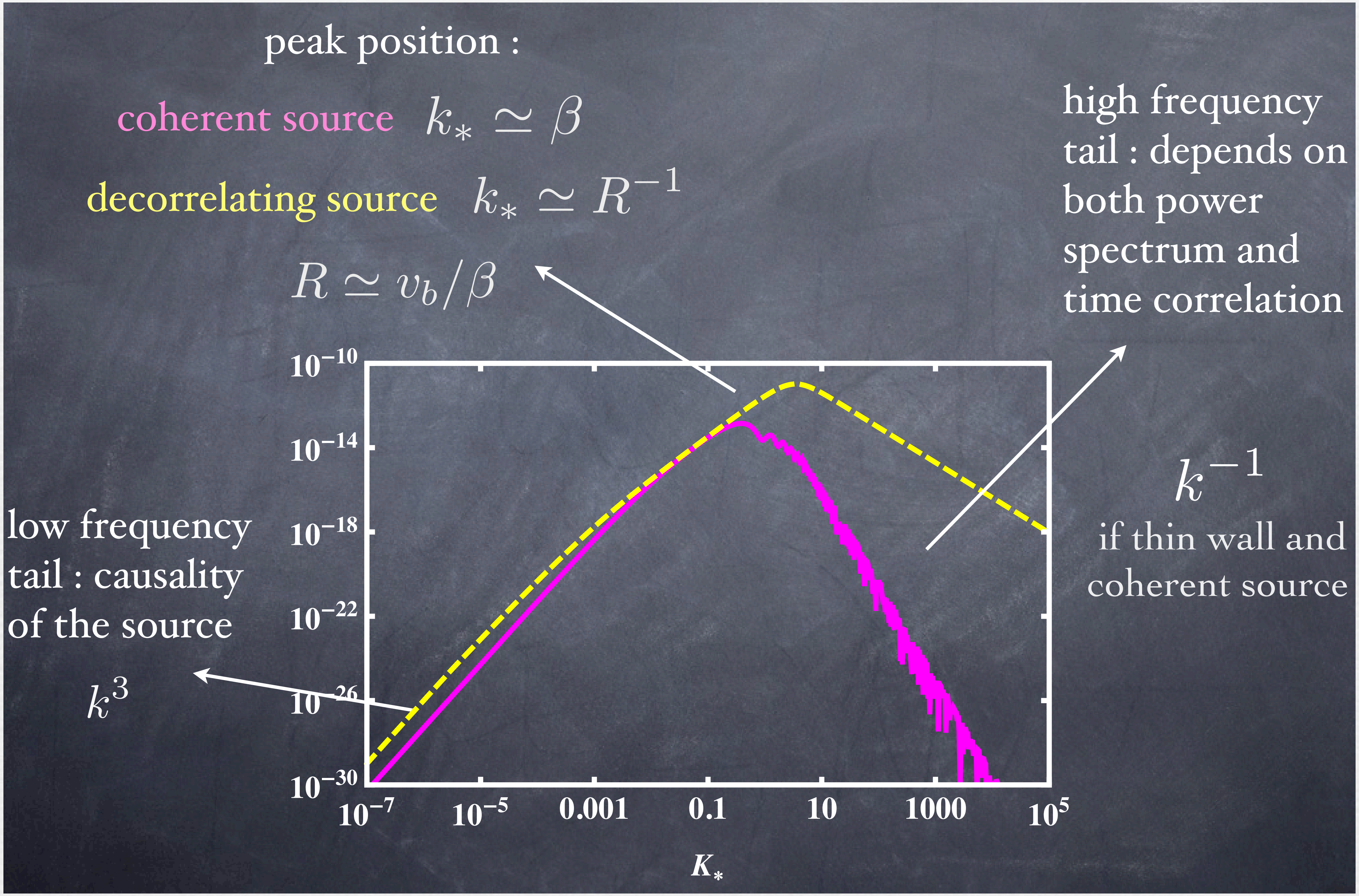
derived from:



simulations with many bubbles and high accuracy too demanding in the 90ies

Expected shape of the GW spectrum from bubble collisions

Caprini-Durrer-Konstandin-Servant'09



Comparison between analytic results of Caprini-Durrer-Servant'07 and numerical simulations of Huber-Konstandin'08 discussed in Caprini-Durrer-Konstandin-Servant'09

Note: Slope of high-frequency tail is different for GW from **turbulence** (see Caprini-Durrer-Servant'09)

Bulk flow & hydrodynamics

higgs vaccuum energy is converted into :
- -kinetic energy of the higgs,
- -bulk motion
- - heating

$$\Omega_{GW} \sim \kappa^2(\alpha, v_b) \left(\frac{H}{\beta}\right)^2 \left(\frac{\alpha}{\alpha+1}\right)^2$$

fraction that goes into kinetic energy

$$\alpha = \frac{\epsilon}{\rho_{rad}}$$

$$\frac{\beta}{H} = \frac{1}{T}\frac{dS}{dT}$$

fraction κ of vacuum energy density ϵ converted into kinetic energy

$$\kappa = \frac{3}{\epsilon \xi_w^3} \int w(\xi) v^2 \gamma^2 \xi^2 \, d\xi$$

wall velocity

fluid velocity

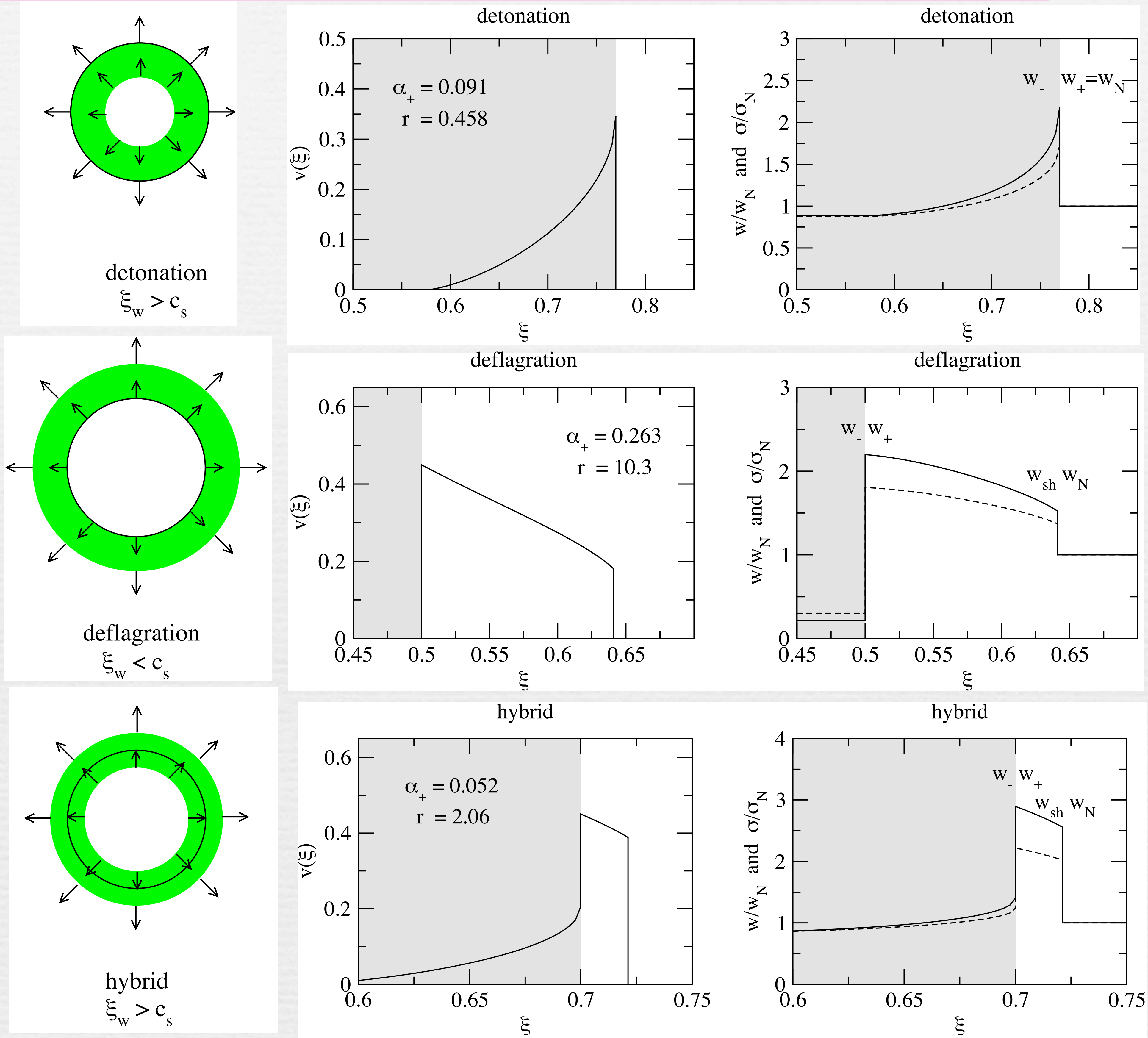
-> all boils down to calculating the fluid velocity profile in the vicinity of the bubble wall

Depending on the boundary conditions at the bubble front, there are three possible solutions:

detonations -rarefaction wave

deflagrations -shock front

hybrids -both



Espinosa, Konstandin, No, Servant'10

fraction κ of vacuum energy density ϵ converted into kinetic energy

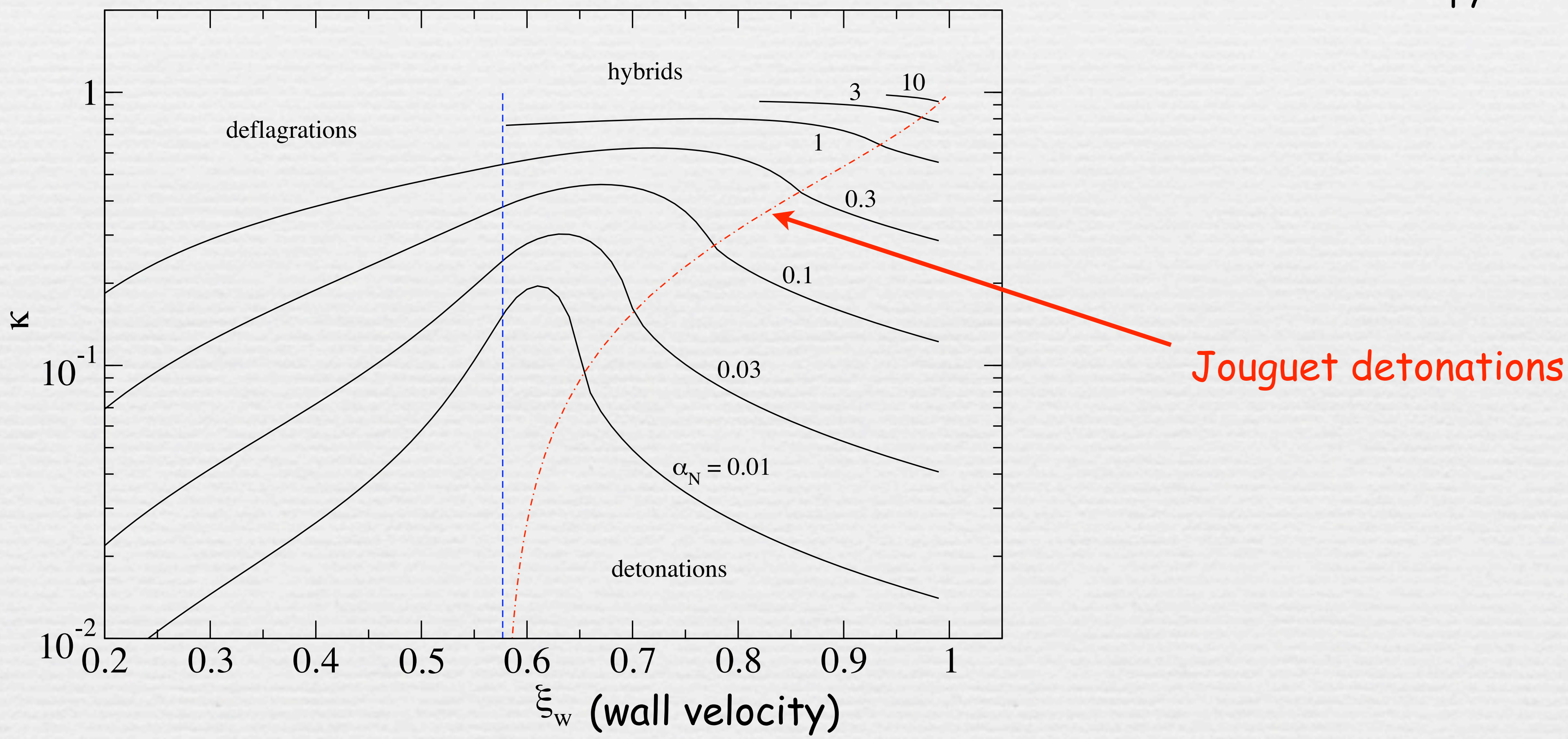
$$\kappa = \frac{3}{\epsilon \xi_w^3} \int w(\xi) v^2 \gamma^2 \, \xi^2 \, d\xi$$

ξ_w=wall velocity

v:fluid velocity

ξ =r/t where r is distance from the bubble center and t is time since nucleation

ω=enthalpy



Efficiency can be quite different than from the Jouguet detonations which were usually assumed

Espinosa, Konstandin, No, Servant'10

The velocity of the bubble wall can be determined by solving:

friction coefficient

$$\Box\phi + \frac{\partial \mathcal{F}}{\partial \phi} - \underbrace{T_N\ \tilde{\eta}\ u^\mu \partial_\mu}_{=}\phi = 0$$

$$-\sum_i \frac{dm_i^2}{d\phi}\int \frac{d^3p}{(2\pi)^3 2E_i}\delta f_i(p)$$

the wall velocity grows until the friction force equilibrates and a steady state is reached

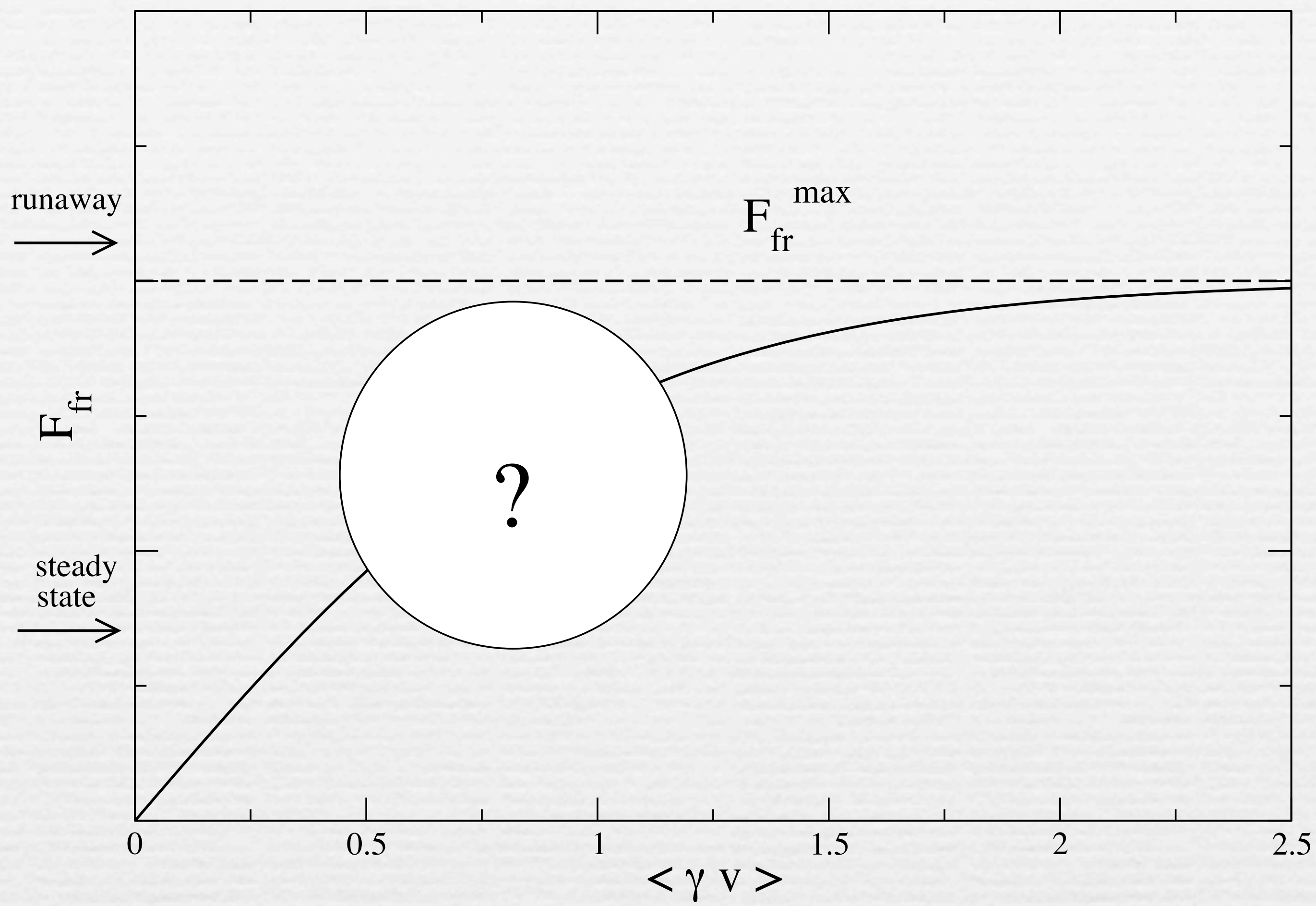
driving force: $F_{dr} \equiv \int dz\, \partial_z\phi\, \frac{\partial \mathcal{F}}{\partial \phi}$

$$F_{tot} = F_{dr} - F_{fr} = \Delta V_0 + \sum_i |N_i| \int dz \frac{dm_i^2}{dz}\int \frac{d^3p}{(2\pi)^3}\frac{f_i}{2E_i}$$

$\mathcal{F}_{tot} > 0$: runaway

[Bodecker-Moore '09]

Runaway regime



the friction force saturates at a finite value for v->1

runaway criterium

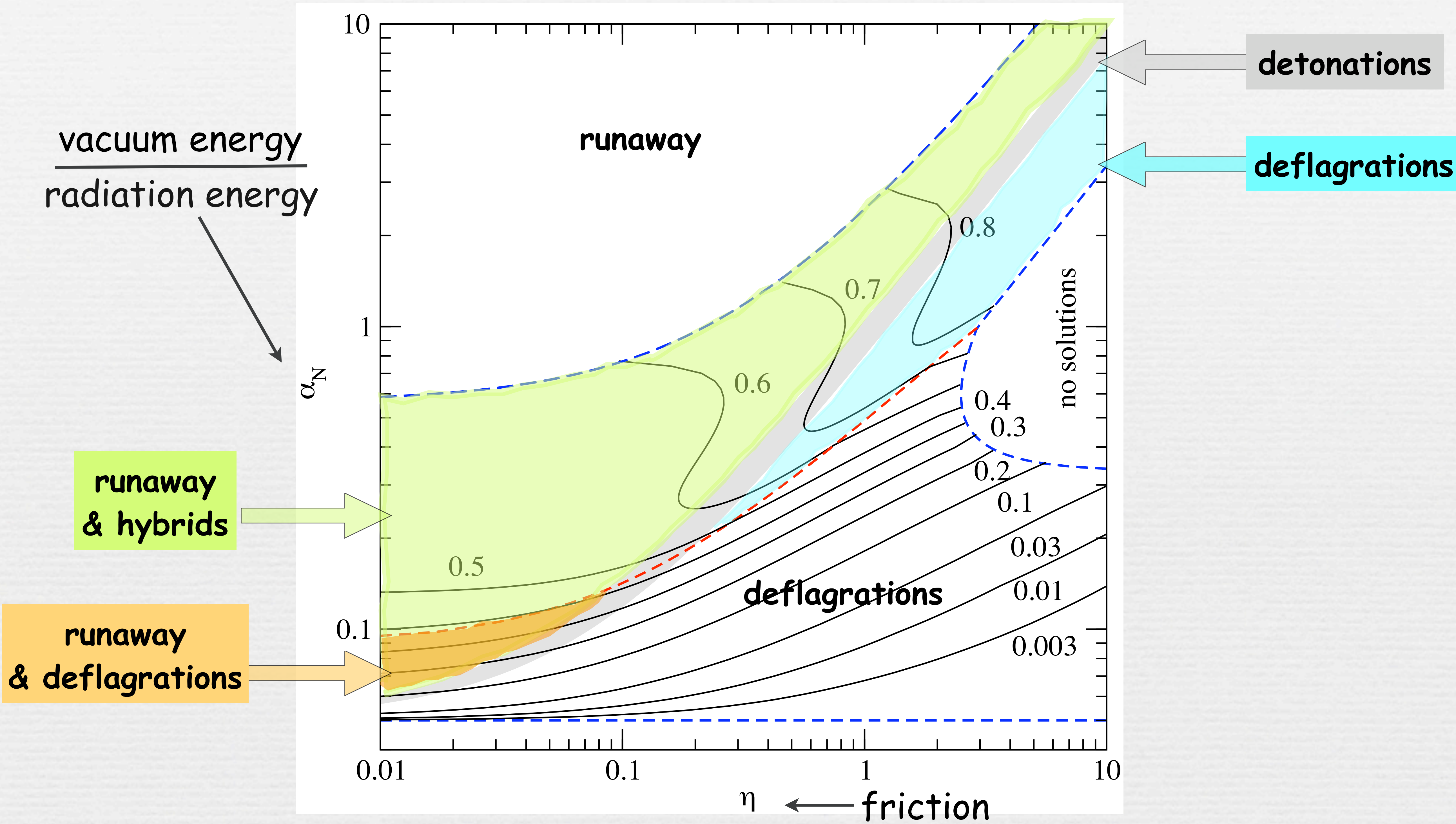
$$\alpha_N > \alpha_\infty \equiv \frac{30}{\pi^2}\left(\frac{\langle\phi\rangle}{T_N}\right)^2 \frac{\sum_{light\to heavy} c_i\,|N_i|\,y_i^2}{\sum_{light} c_i'\,|N_i|}$$

$$\alpha_N > 1.5\times 10^{-2}\left(\frac{\langle\phi\rangle}{T_N}\right)^2$$

For strong 1st order PT, the wall keeps accelerating

Model-independent κ contours

Espinosa, Konstandin, No, Servant'10

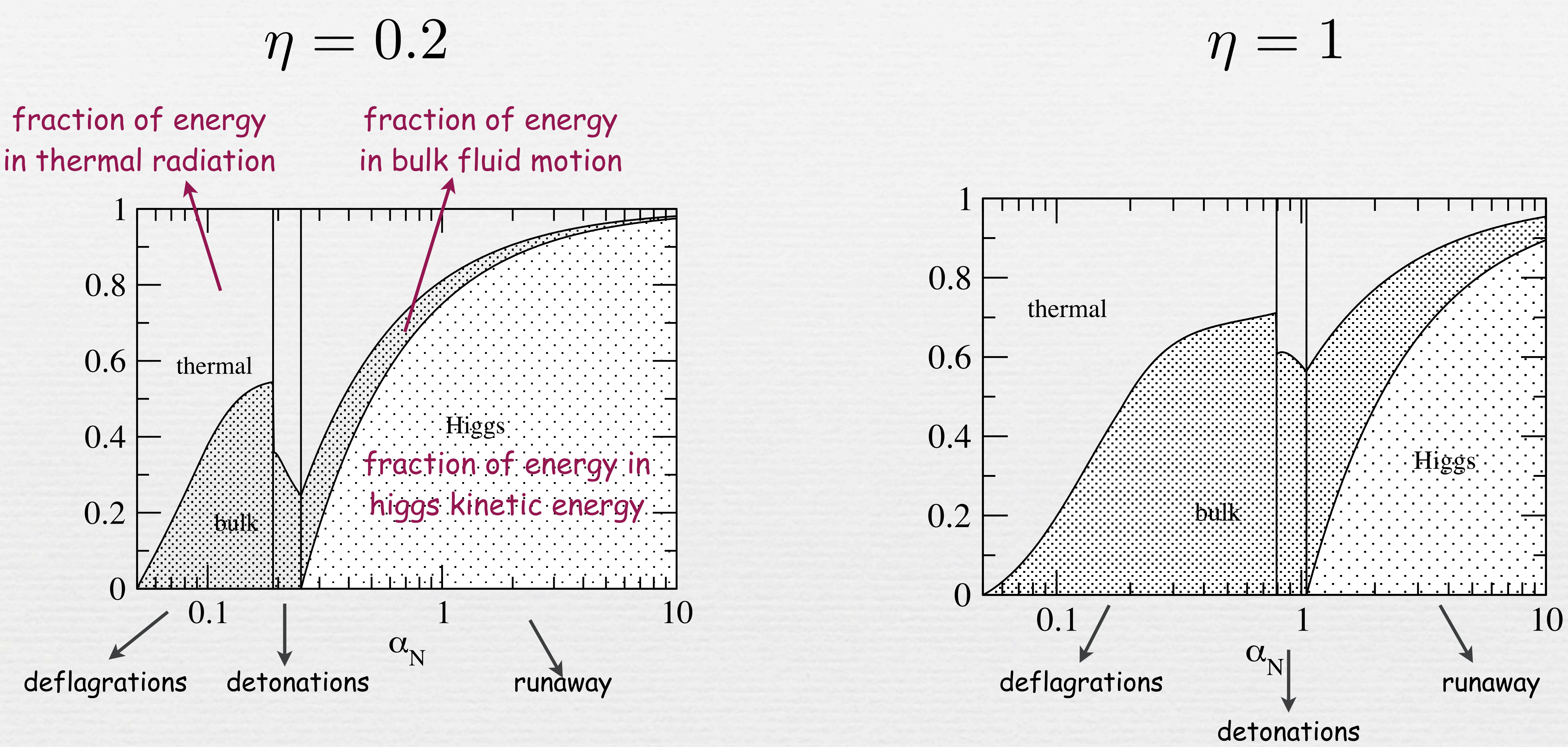


$$\eta_{\rm SM} \sim 10^{-3}$$

$$\eta_{\rm MSSM} \sim 10^{-2} \qquad v \sim 0.05 - 0.1$$

Energy budget of the phase transition

Espinosa, Konstandin, No, Servant'10



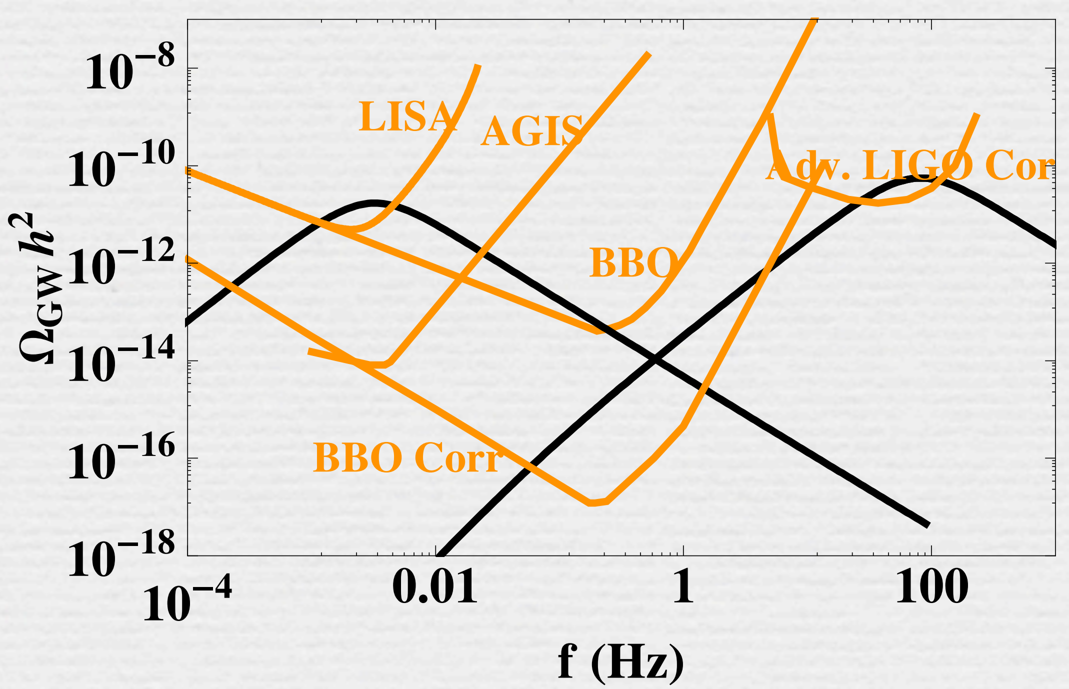
Determination of energy budget is important since gravity wave spectra from bubble collisions and turbulence are different

Summary

The nature of the EW phase transition is unknown & it will take time before we can determine whether EW symmetry breaking is purely SM-like or there are large deviations in the Higgs sector which could have led to a first-order PT

It is an interesting prospect that some TeV scale physics could potentially be probed by LISA

Discussion applies trivially to any other 1st order phase transition (only shift peak frequency, amplitude and shape of signal do not depend on the absolute energy scale of the transition)



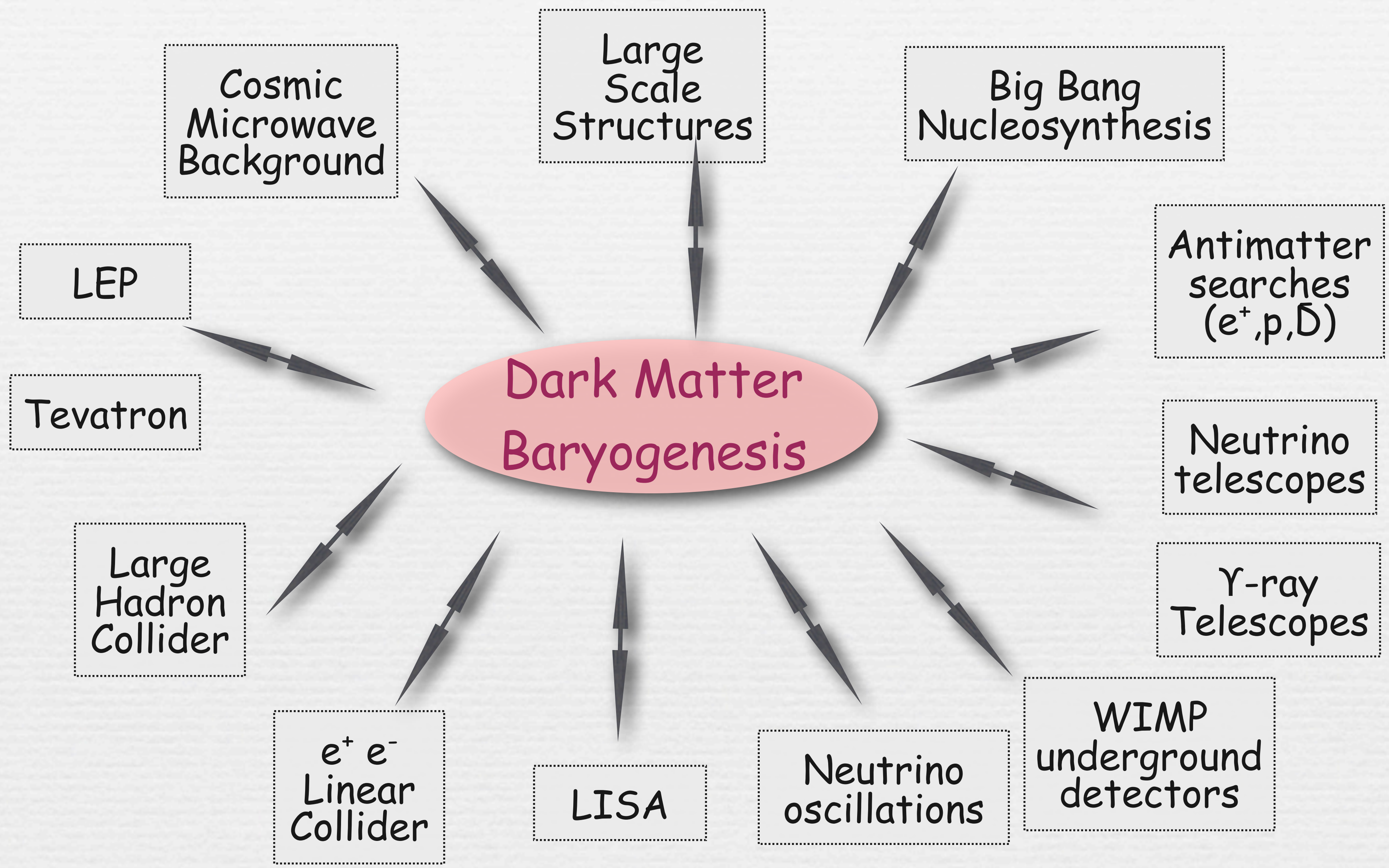
To conclude

As the LHC will unveil the mysteries of the electroweak symmetry breaking, it could also have far-reaching implications for cosmology, such as the nature of the Dark Matter or the origin of the matter- antimatter asymmetry of the Universe.

The LHC program has a strong overlap with astrophysics and getting a complete understanding of the matter/energy budget requires to complement LHC results with data from particle astrophysics experiments such as neutrino telescopes, gamma ray telescopes, antimatter searches, cosmic microwave background missions, galaxy surveys or gravity wave interferometers.

The next 10 years: an exciting era for particle physics

Cosmic connections of electroweak symmetry breaking: A multi-form and integrated approach



Besides:

a strong link between
cosmic ray and accelerator physics

LHC forward (LHCf) experiment

smallest one of the six official LHC experiments

Goal: understand the development of atmospheric showers induced by very high energy cosmic rays hitting the Earth atmosphere.

by studying the energy distribution of particles (neutral pions, gammas and neutrons) emitted in the very forward region in proton-proton interactions at an equivalent energy of 10^{17} eV in the laboratory frame.

Run is over! (ended on july 23rd!) Low luminosity needed

Measurements at LHCf will give an important clue to judging the validity of nuclear interaction models used in Monte Carlo simulations of air showers induced by ultra-high energy cosmic-rays, and thus give a milestone for understanding cosmic ray phenomena up to the GZK region

NA61

simulations are based on extrapolations of hadronic interaction properties to phase space regions presently no covered by particle physics experiments.

NA61/SHINE is a fixed-target experiment to study hadron production in hadron-nucleus and nucleus-nucleus collisions at the CERN Super Proton Synchrotron.

NA61 results will measure properties of interactions needed for a reconstruction of the AUGER events and will therefore improve resolution of the cosmic-ray experiments needed to establish elemental composition at high energies...

As a last slide:

A blooming field

Abundance of experimental activity related to dark matter searches

still much activity in model building

many viable alternatives to LSPs LKPs, LZPs, LTPs, IDM ...

with a large variety of signatures