Cosmological probes of Electroweak symmetry breaking

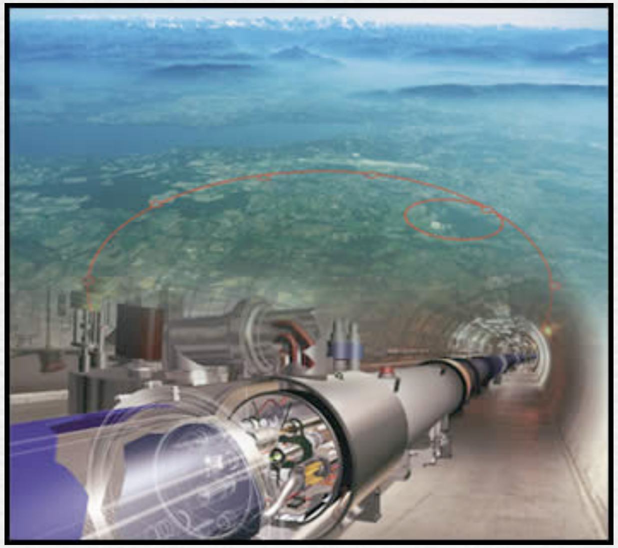
Géraldine SERVANT
CERN, Theory Unit & IPhT CEA Saclay

2010: First collisions at the LHC

Direct exploration of the TeV scale has started

main physics goal:

What is the mechanism of Electroweak Symmetry breaking ?



Searching for complementary probes of the EW symmetry breaking mechanism in cosmological observables

New TeV scale physics ⇄ **Cosmological signatures**

mainly from

- dark matter
- baryogenesis

(see also recent interest in higgs inflation, not covered in this talk)

1) Dark Matter

very hot topic + talk by N. Fornengo, so I will mainly skip

New symmetries at the TeV scale and Dark Matter

to cut-off quadratically divergent quantum corrections to the Higgs mass

→ New TeV scale physics needed

↓

tension with precision tests of the SM in EW & flavor sector (post-LEP "little hierarchy pb")

↓

introduce new discrete symmetry P

R-parity in SUSY, KK parity in extra dim, T parity in Little Higgs ...

↓

Lightest P-odd particle is stable

↓

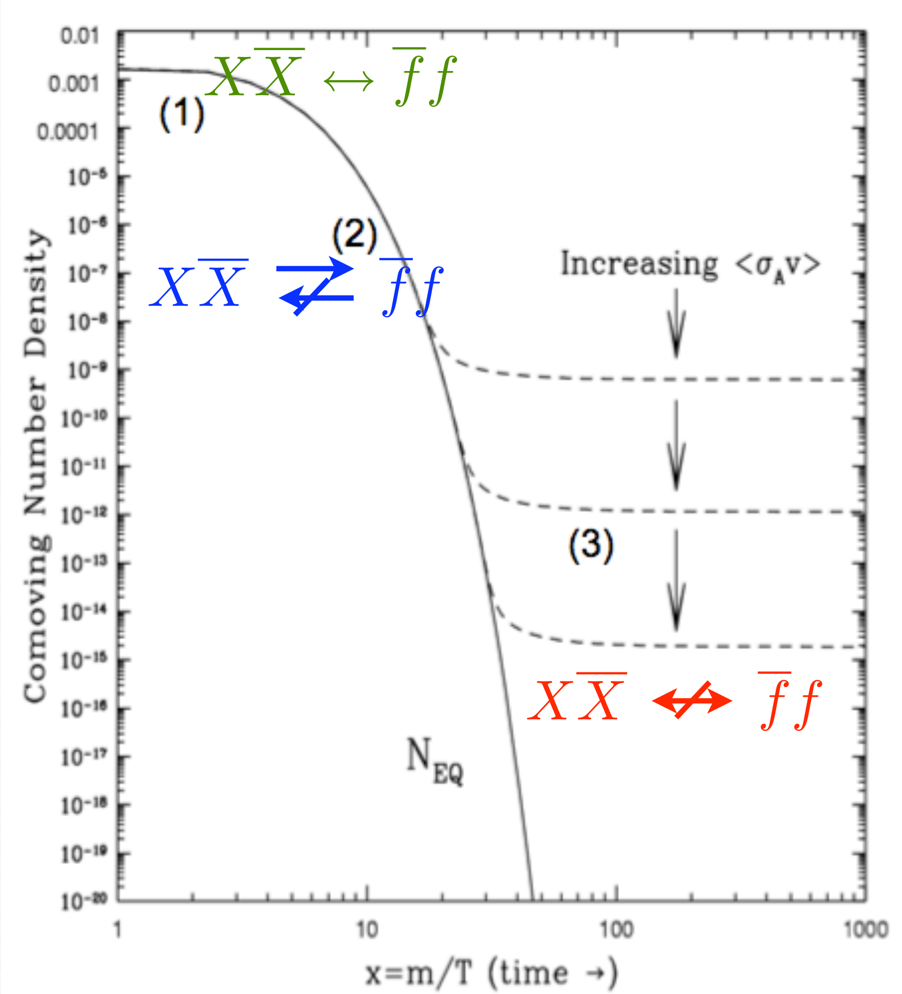
DM candidate

The "WIMP miracle"

$$\dot{n} + 3Hn = -\langle \sigma v \rangle (n^2 - n_{\rm T}^2)$$

freese-out :

$$H \sim \frac{\sqrt{g}T^2}{M_{\rm P}} \sim \Gamma = n\sigma v$$



Thermal relic: $\Omega\, h^2 \propto 1/\langle\sigma_{anni}\, v\rangle$

$\Rightarrow \langle\sigma_{anni}\, v\rangle = 0.3$ pb

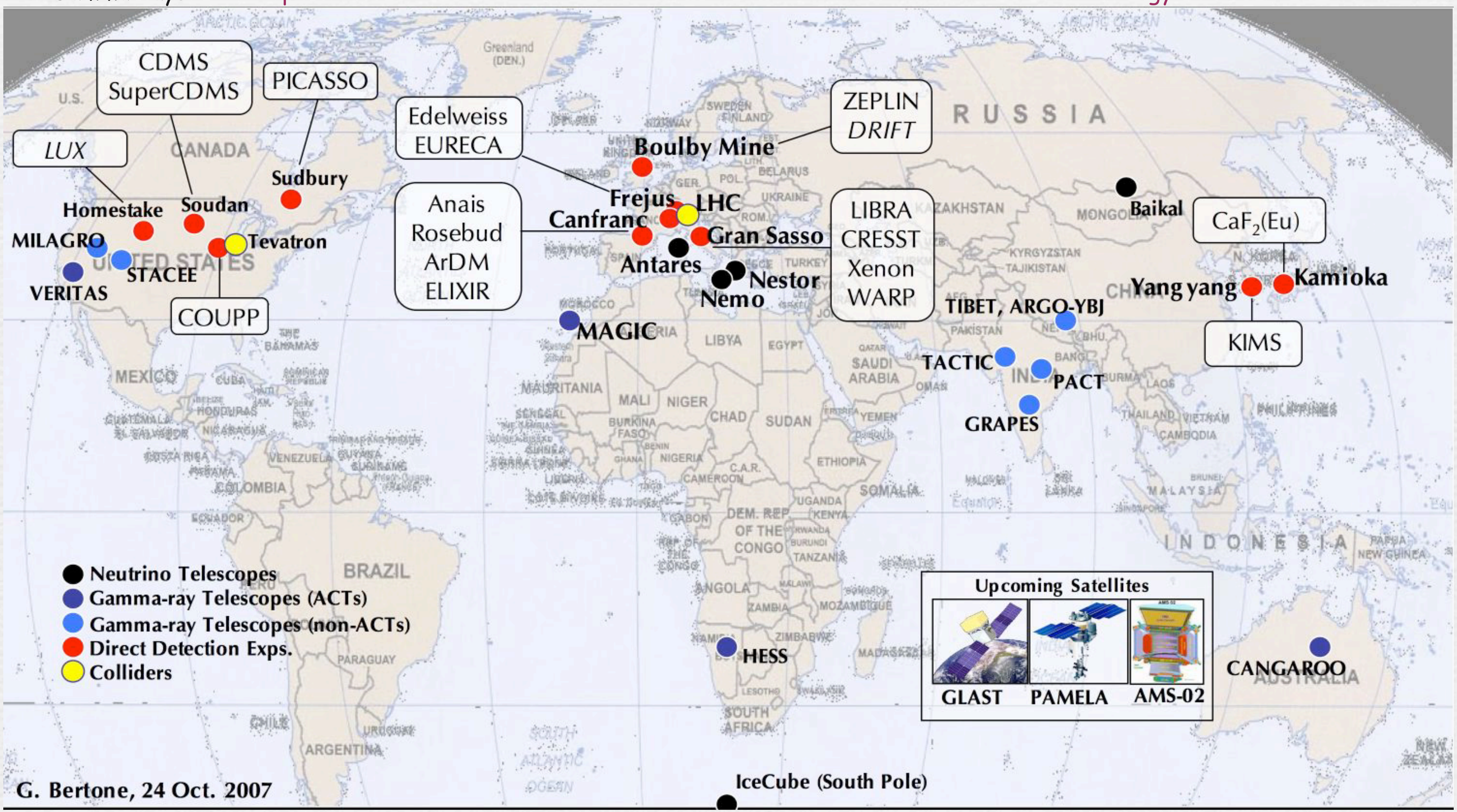
$\sigma \sim \alpha^2/m^2$

$\Rightarrow m \sim 100$ GeV

The Dark Matter Decade

Major experimental effort towards the identification of Dark Matter

Indirect		Direct	Collider experiments
Antimatter Neutrinos Gamma Rays	Signature of Annihilation in space	Elastic Scattering signature in underground labs	Missing Energy signature in high energy accelerators

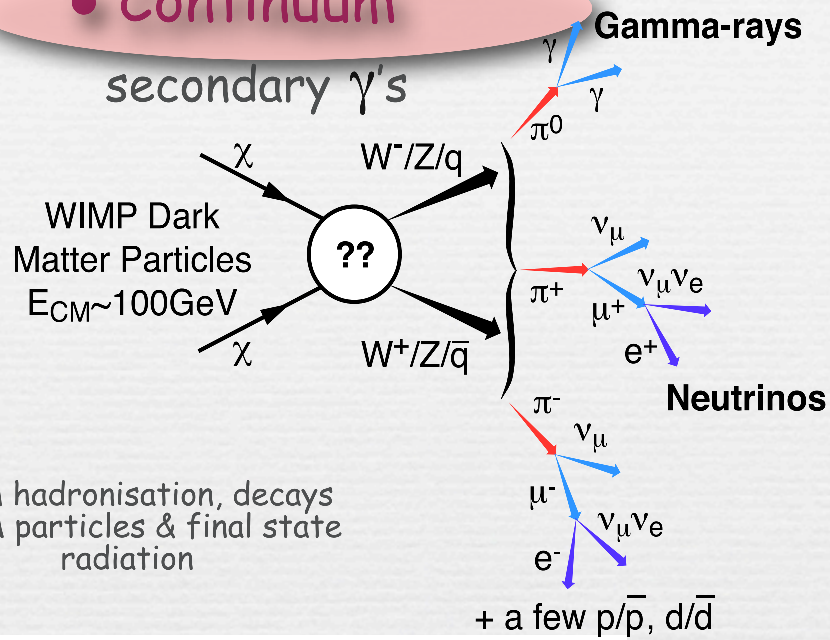


Seeing the light from Dark Matter

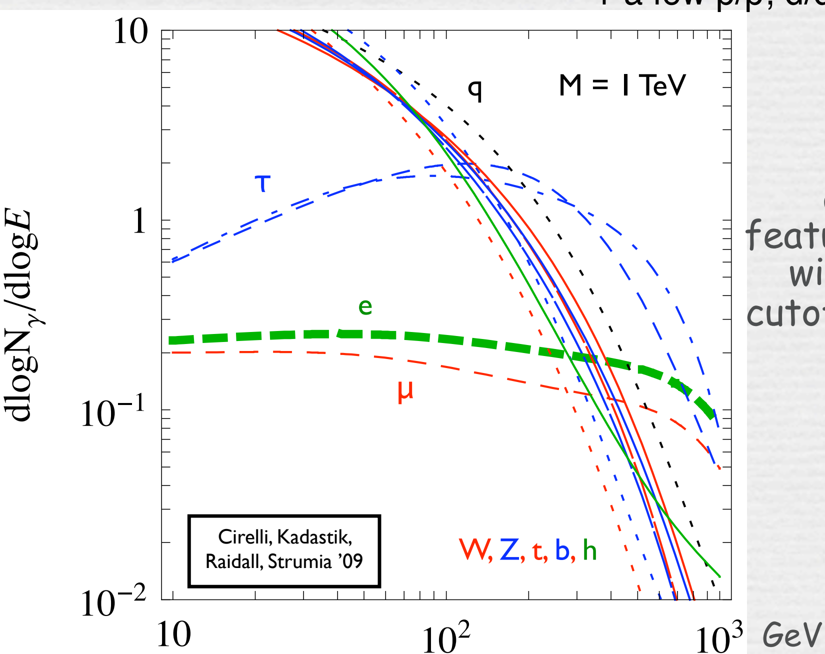
γ's from DM annihilations consist of 2 components

• Continuum

secondary γ's



from hadronisation, decays of SM particles & final state radiation

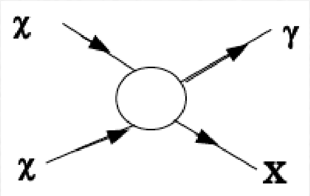


almost featureless but with sharp cutoff at Wimp mass

• Lines

primary γ's

loop-level annihilation into γ+X



-> mono energetic lines superimposed onto continuum at

$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

☺ -> striking spectral feature, SMOKING GUN signature of Dark Matter

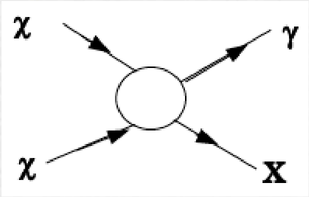
☹ lines are usually small (loop-suppressed) compared to continuum

Bergstrom, Ullio, Buckley '98

Seeing the light from Dark Matter

- detected from the ground (ACTs) and from above (FERMI)

- The position and strength of lines can provide a wealth of information about DM:



$$E_\gamma = M_{DM}\left(1 - \frac{M_X^2}{4M_{DM}^2}\right)$$

→ γγ line measures mass of DM

→ relative strengths between lines provides info on WIMP couplings

→ observation of γH would indicate WIMP is not scalar or Majorana fermion

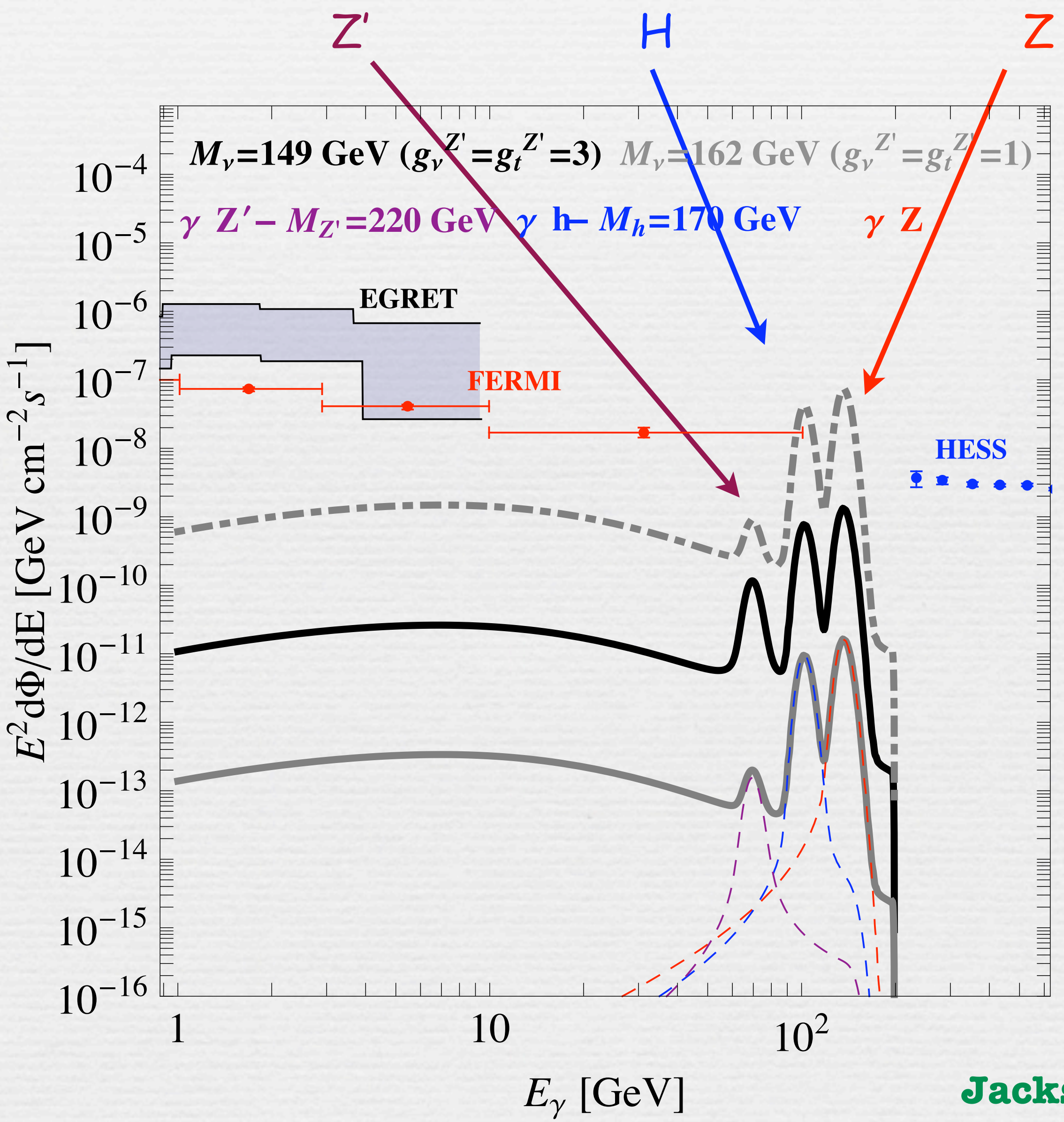
Jackson et al. '09

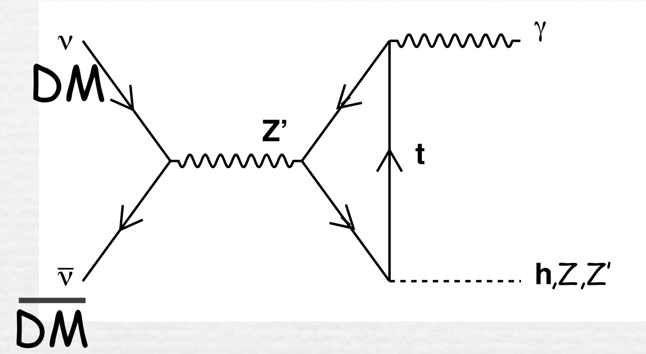
→ if other particles in the dark sector, we could possibly observe a series of lines

[the "WIMP forest", Bertone et al. '09]

Higgs in Space!

γ-ray lines from the Galactic Center ΔΩ= 10^{-5} sr





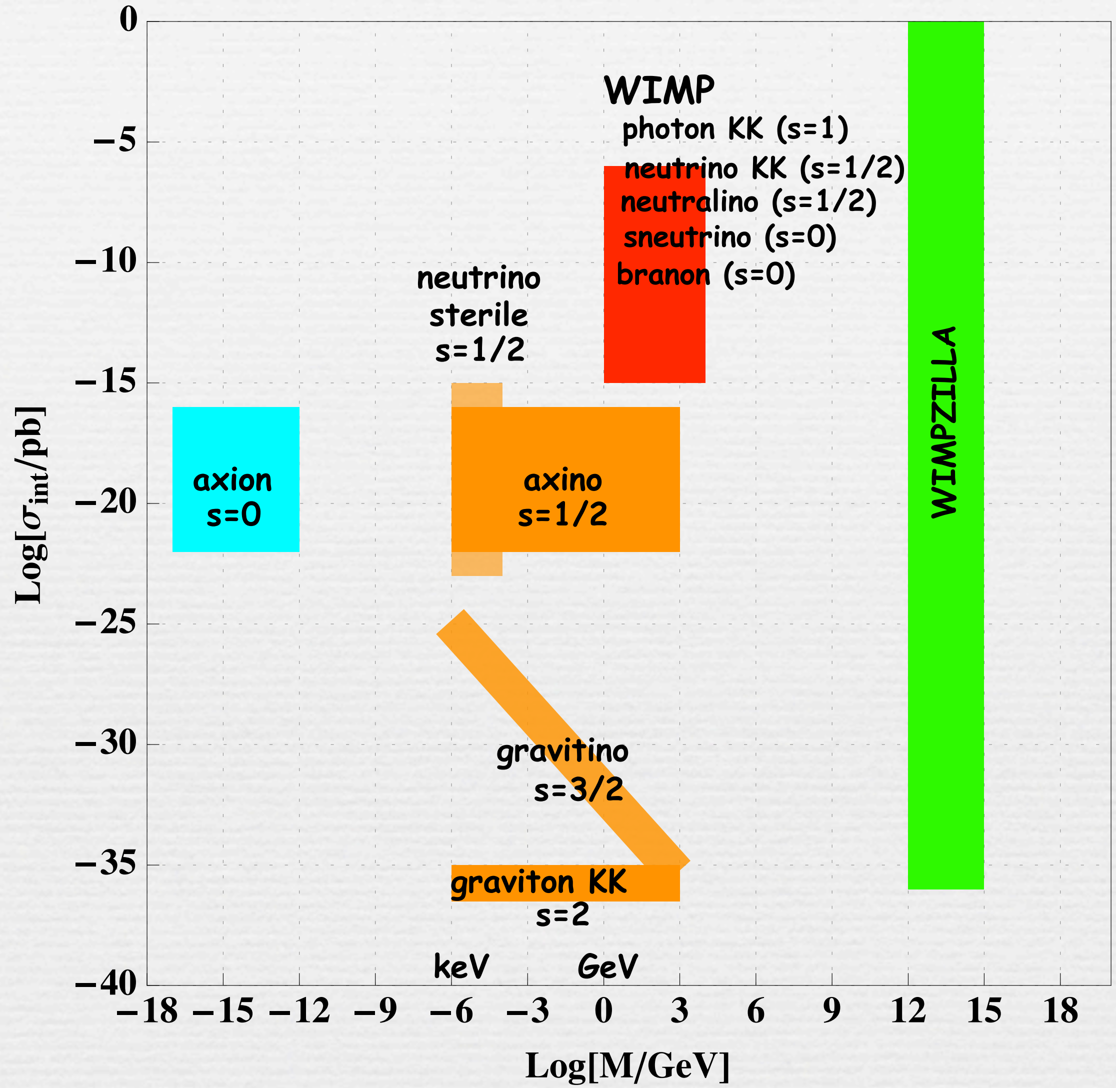
Spectra for parameters leading to correct relic density and satisfying direct detection constraints

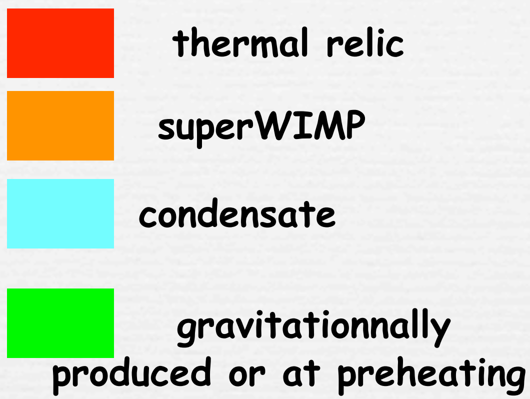
NFW profile

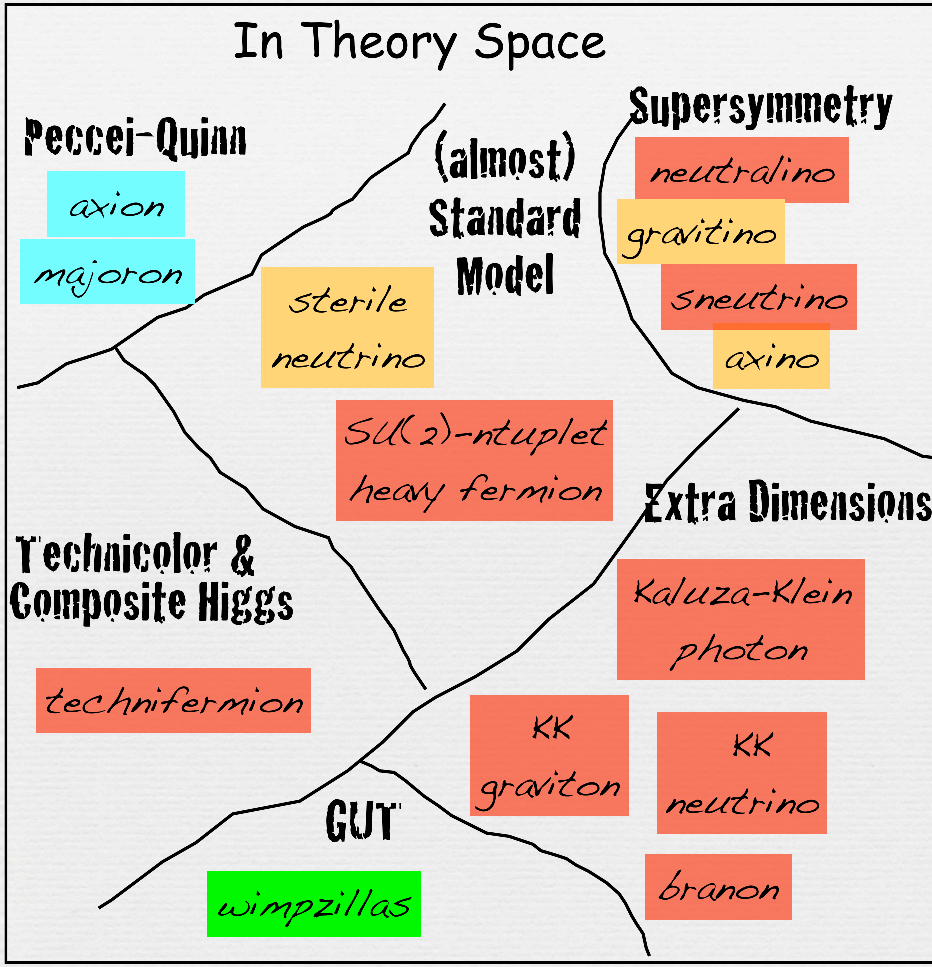
adiabatically contracted

Jackson, Servant, Shaughnessy, Tait, Taoso,'09

Dark Matter Candidates with $\Omega_{DM} \sim 1$





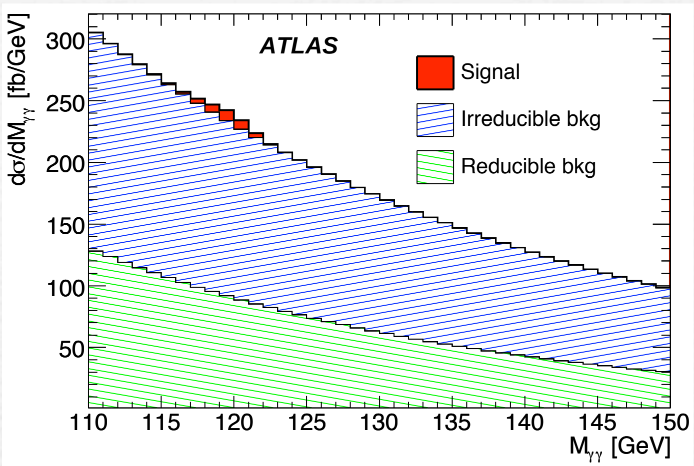


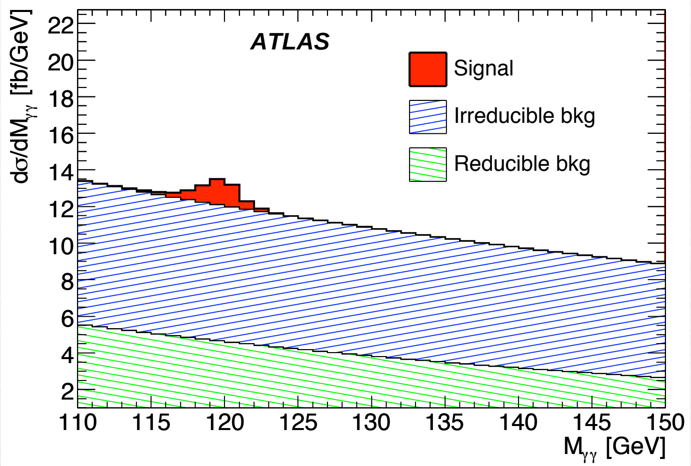
good to keep in mind if no sign of wimp detection within the next decade ...

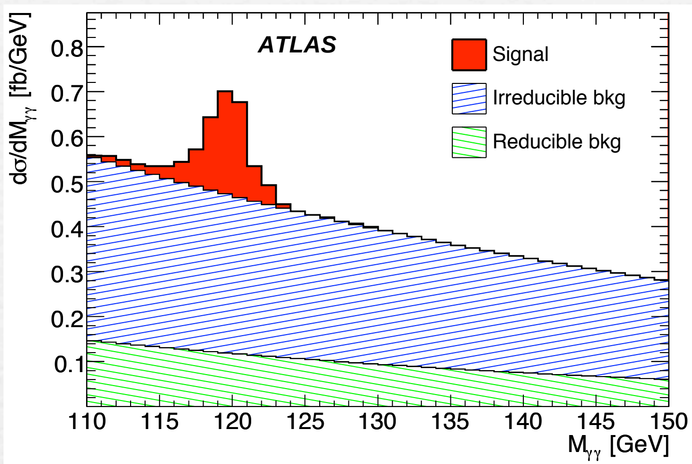
2) The Electroweak phase transition

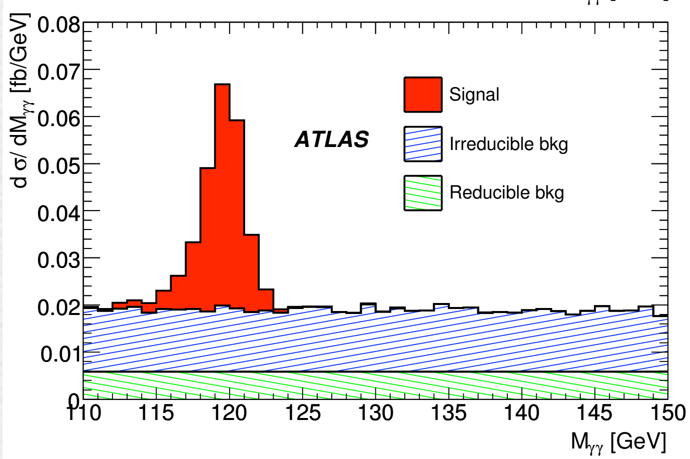
What questions the LHC experiments will try to answer :

Does a Higgs boson exist ?









If yes :

- is there only one ?
- what are its mass, width, quantum numbers ?
- does it generate EW symmetry breaking and give mass to fermions too as in the Standard Model or is something else needed ?
- what are its couplings to itself and other particles
- Spin determination
- CP properties

If no :

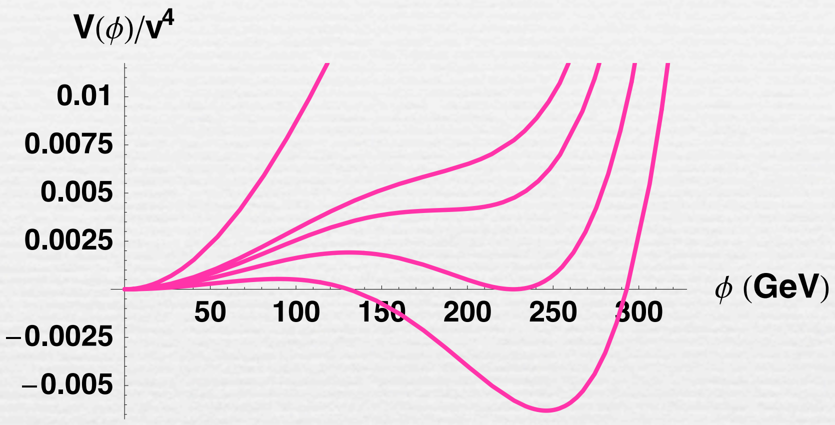
be ready for

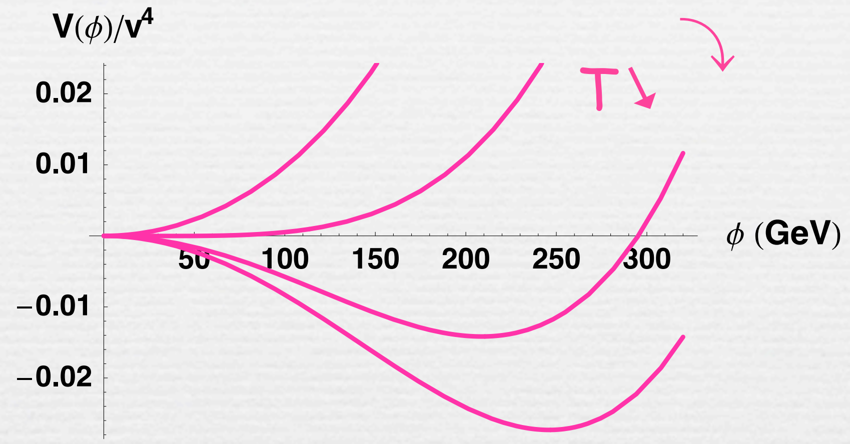
- very tough searches at the (S)LHC (VLVL scattering, ...) or
- more spectacular phenomena such as W', Z' (KK) resonances, technicolor, etc...

+ searches for new particles -> do they play any role in EW symmetry breaking?

What is the nature of the electroweak phase transition ?

first-order or second-order?





indispensable for reliable computations of electroweak baryogenesis

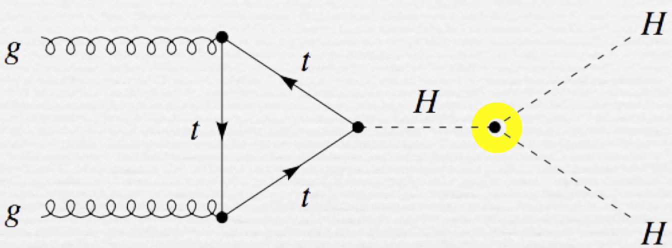
LHC will provide insight as it will shed light on the Higgs sector

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...)

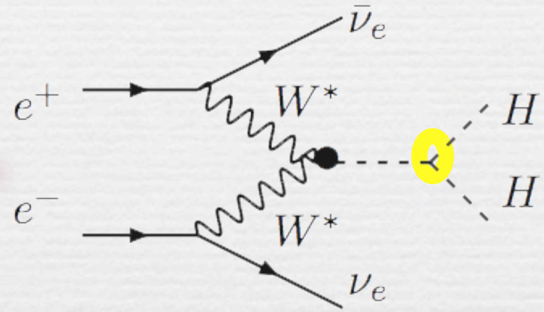
LHC will most likely not provide the final answer

Experimental tests of the Higgs self-coupling

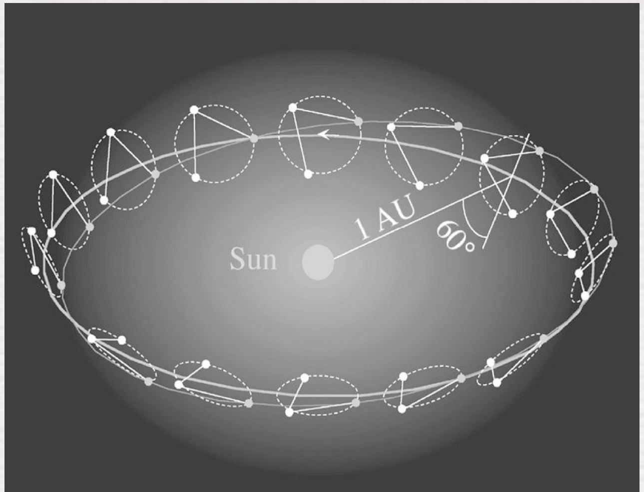
at a Hadron Collider

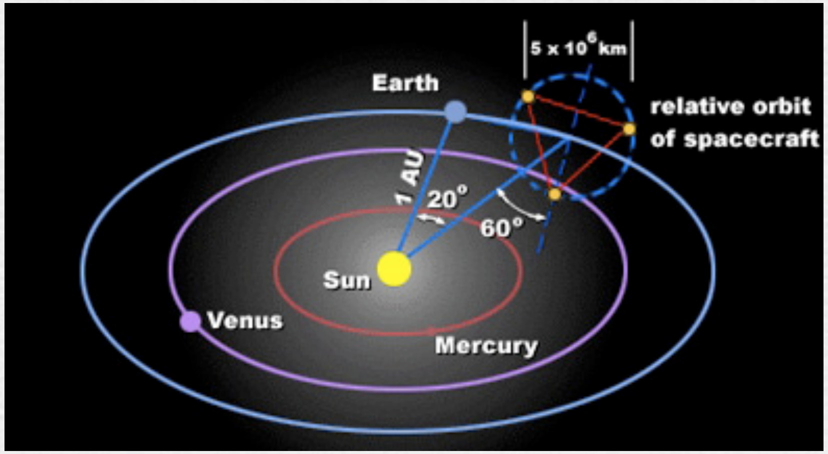


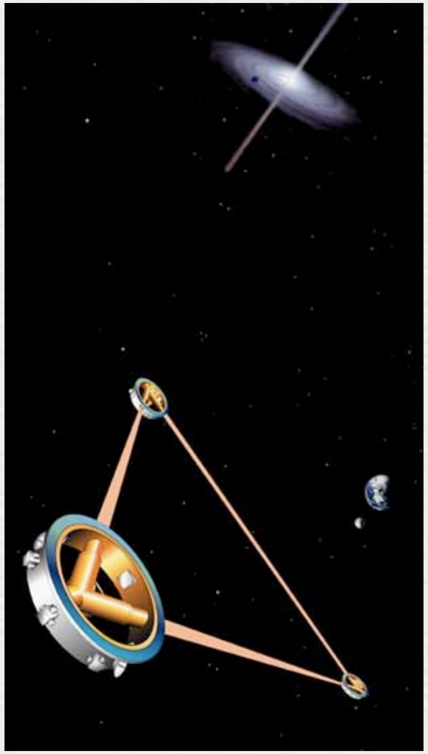
at an $e^+ e^-$ Linear Collider



... or at the gravitational wave detector LISA



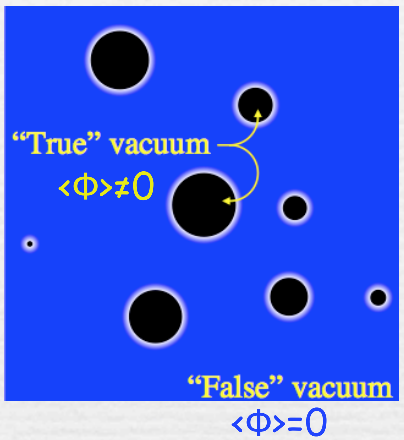




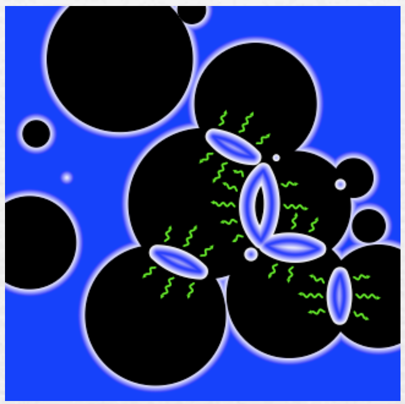
Gravitational Wave Spectrum of a strongly first order electroweak phase transition

Stochastic background of gravitational radiation

Bubble nucleation



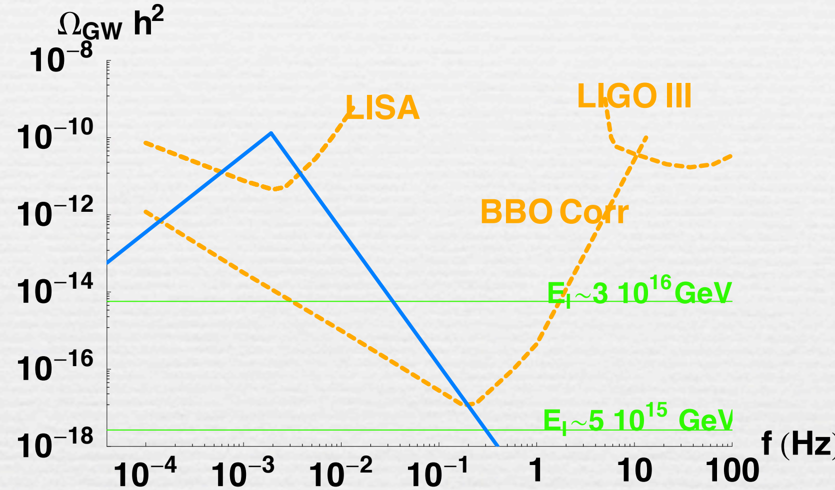
Bubble percolation



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:

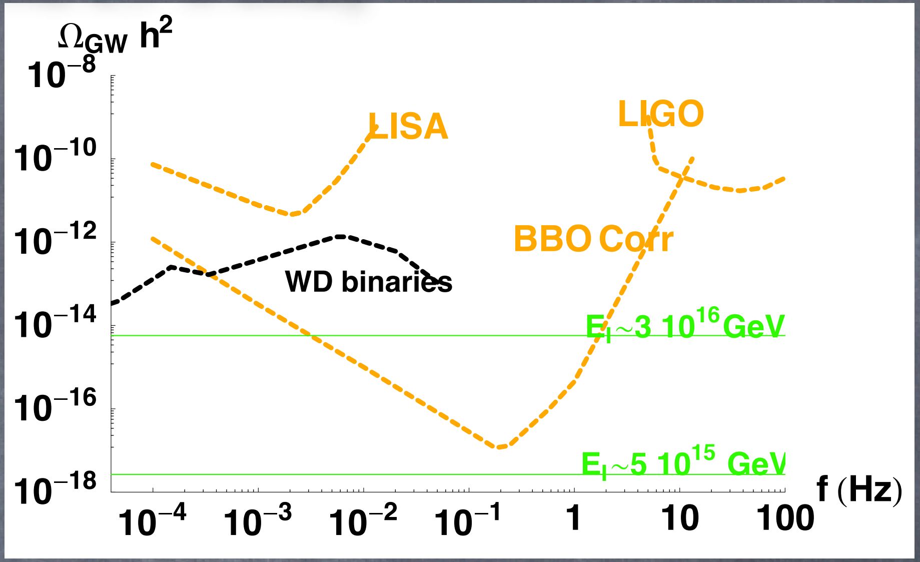
inflation, vibrations of topological defects, excitations of xdim modes, 1st order phase transitions...

frequency observed today:

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

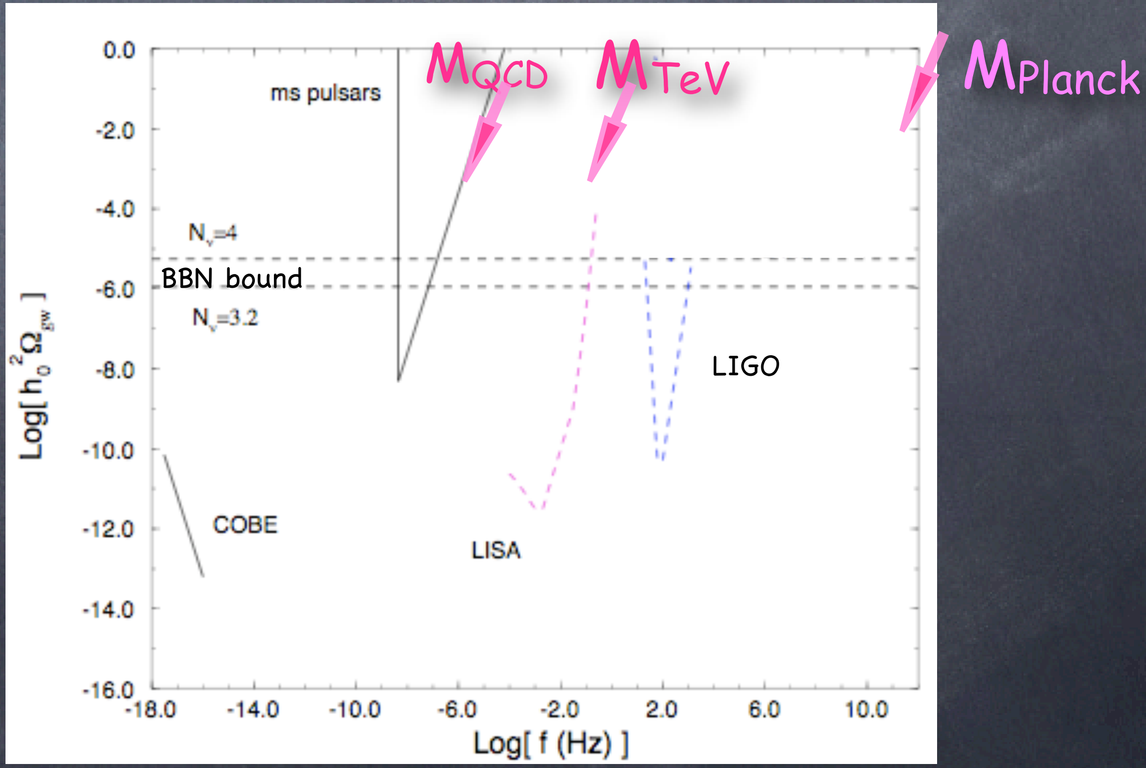
Beyond GW of astrophysical origin, another mission of GW astronomy will be to search for a stochastic background of gravitational waves of primordial origin (gravitational analog of the 2.7 K CMB)

Stochastic background:
isotropic, unpolarized, stationary



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

A huge range of frequencies

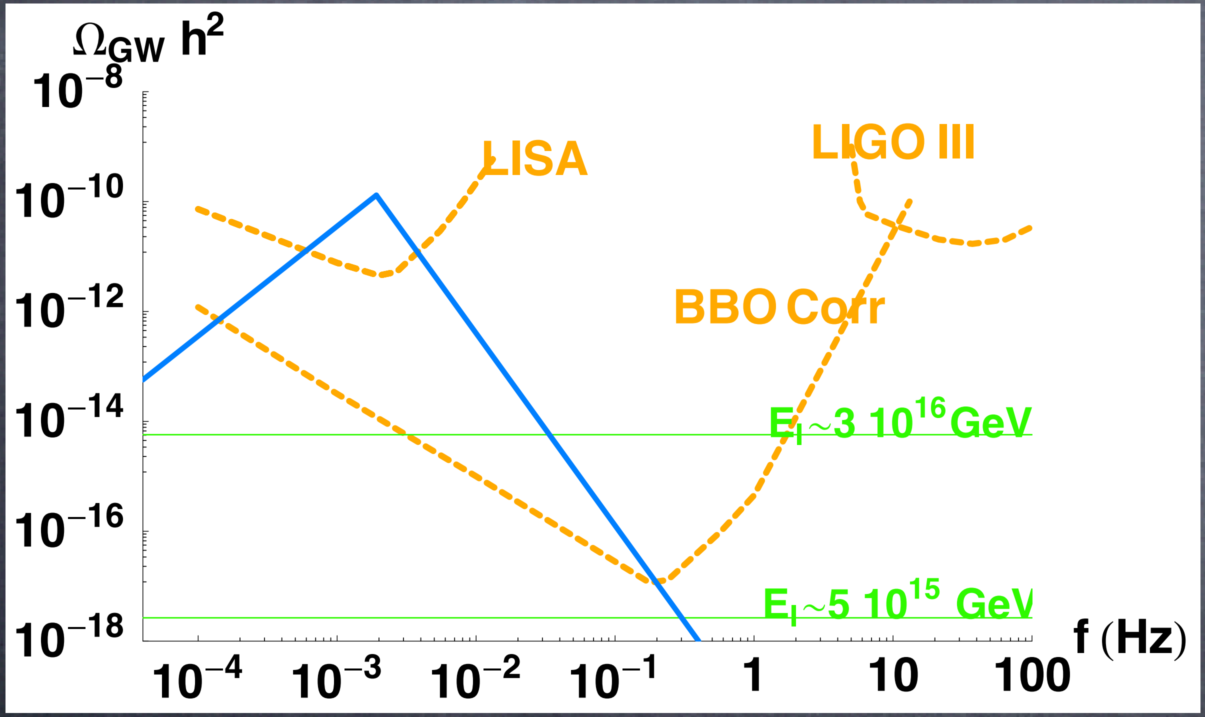


from Maggiore

Why should we be excited about mHZ freq.?

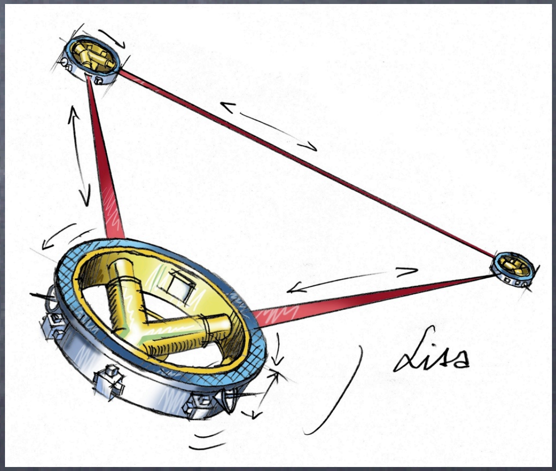
$$f = f_* \frac{a_*}{a_0} = f_* \left(\frac{g_{s0}}{g_{s*}}\right)^{1/3} \frac{T_0}{T_*} \approx 6 \times 10^{-3} \mathrm{mHz} \left(\frac{g_*}{100}\right)^{1/6} \frac{T_*}{100 \ \mathrm{GeV}} \frac{f_*}{H_*}$$

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 1^{st} 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 1^{st} 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 1^{st} 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

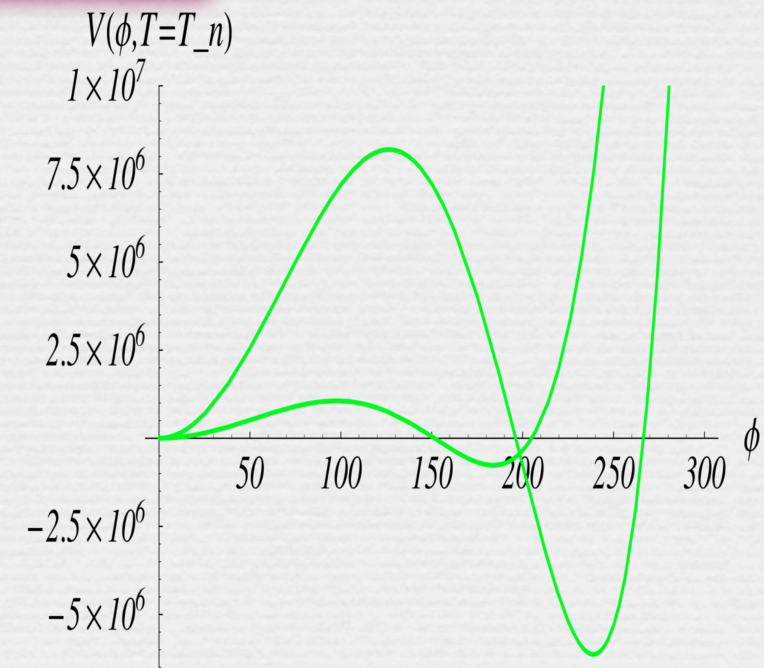
β : (duration of the phase transition)$^{-1}$

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

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

$$\Omega_{GW_*} = \frac{H_*^2}{\beta^2} \frac{\rho_{kin}^2}{\rho_{tot}^2} \qquad \rho_{kin}^2 \rightarrow \kappa^2 \alpha^2 v^4$$

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

κ : fraction of vacuum energy transformed into bulk fluid motions

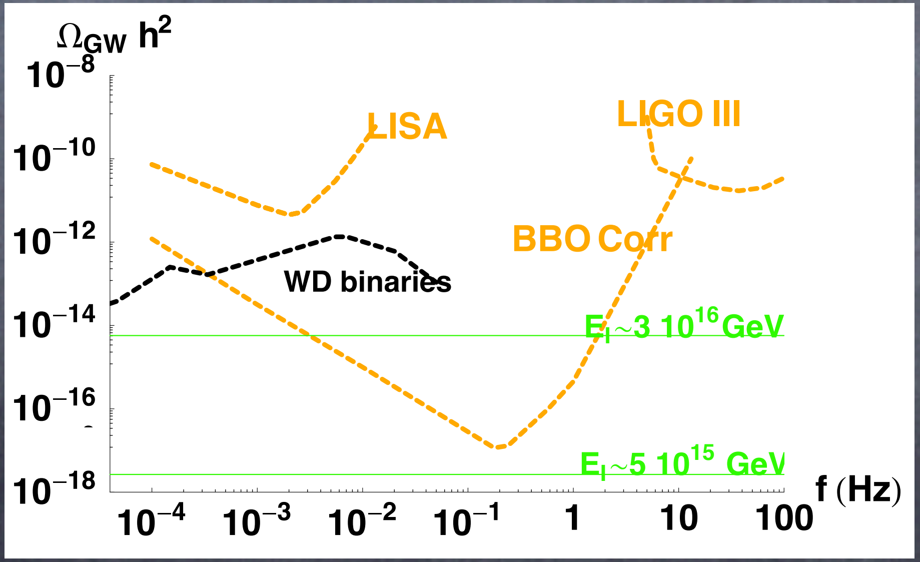
3 parameters: α, β, v

Fraction of the critical energy density in GW today

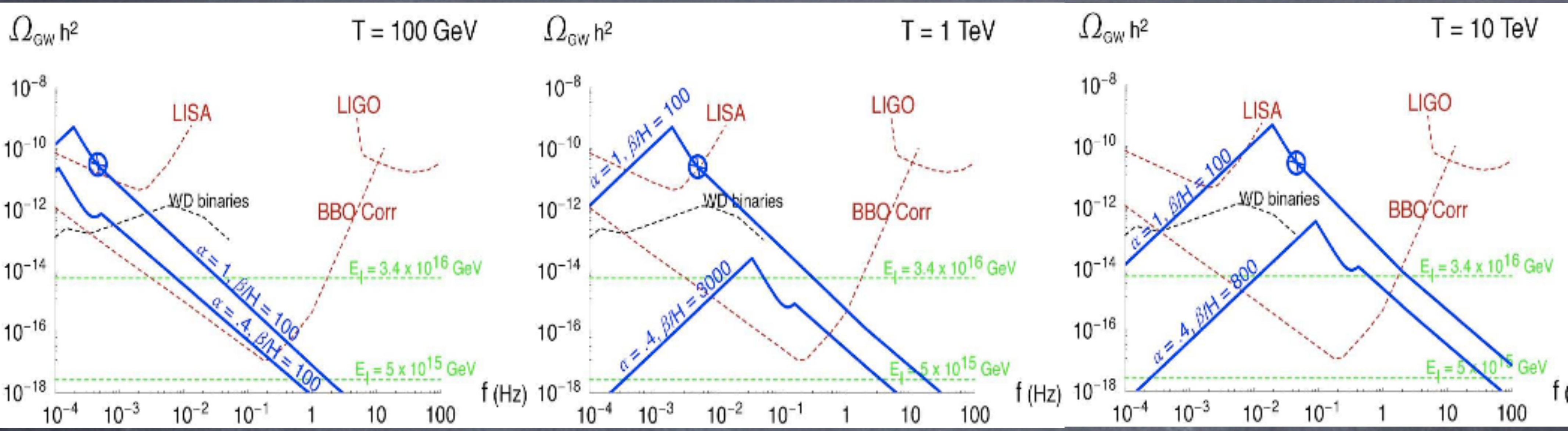
$$\Omega_{GW} = \frac{\rho_{GW}}{\rho_c} = \Omega_{GW*}\left(\frac{a_*}{a_0}\right)^4\left(\frac{H_*}{H_0}\right)^2 \simeq 1.67\times 10^{-5}h^{-2}\left(\frac{100}{g_*}\right)^{1/3}\Omega_{GW*}$$

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

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

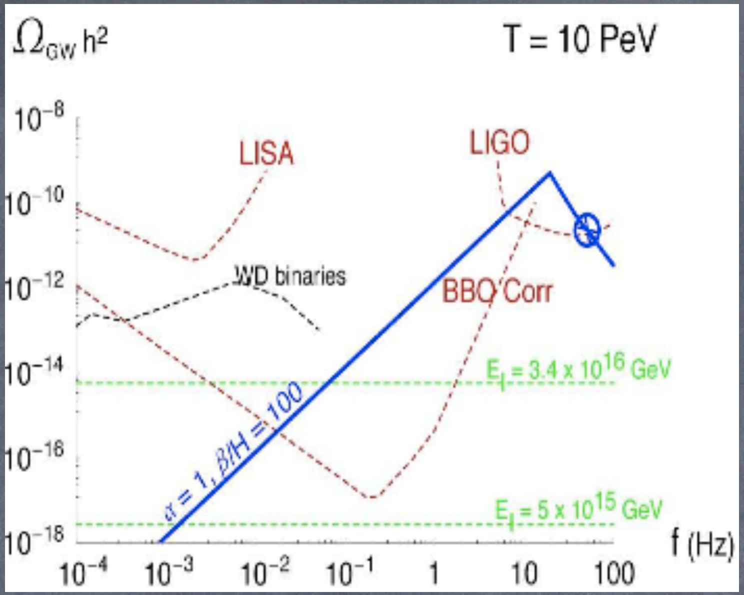


Spectrum of gravitational waves produced at 1rst order phase transitions



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

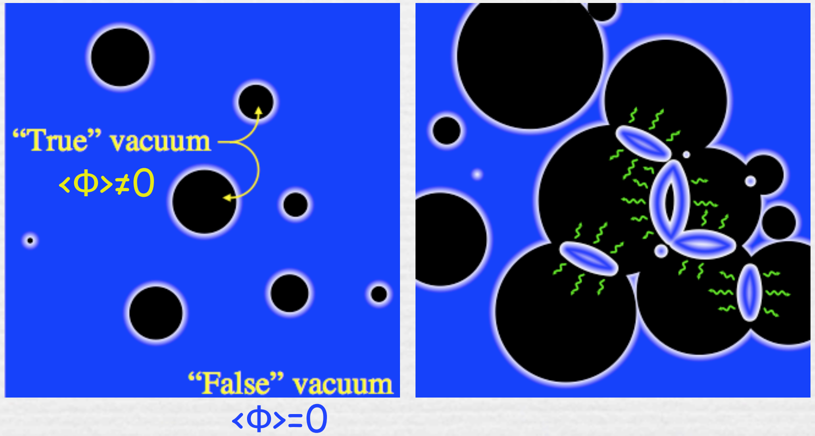
A phase transition at $T \sim 10^7$ GeV could be observed both at LIGO and BBO:

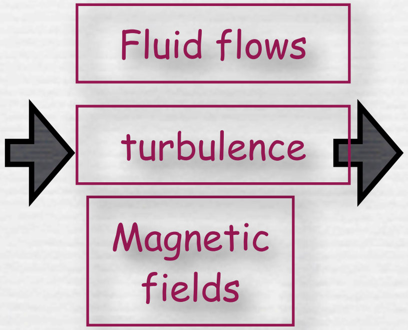


Summary

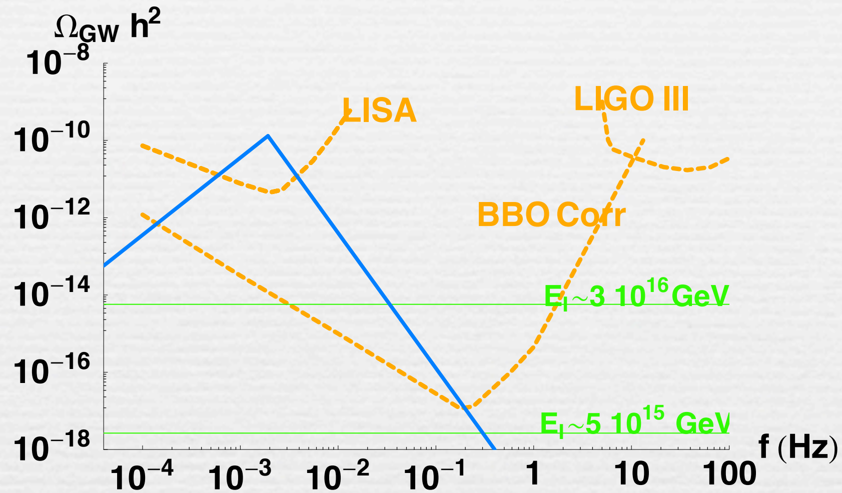
Bubble nucleation

Bubble percolation





Stochastic background of gravitational radiation



$$\Omega_{GW} \sim \kappa^2$$

fraction κ of vacuum energy density ϵ converted into kinetic energy

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

fluid velocity

wall velocity

$$\rightarrow \Omega_{GW} \sim v^4$$

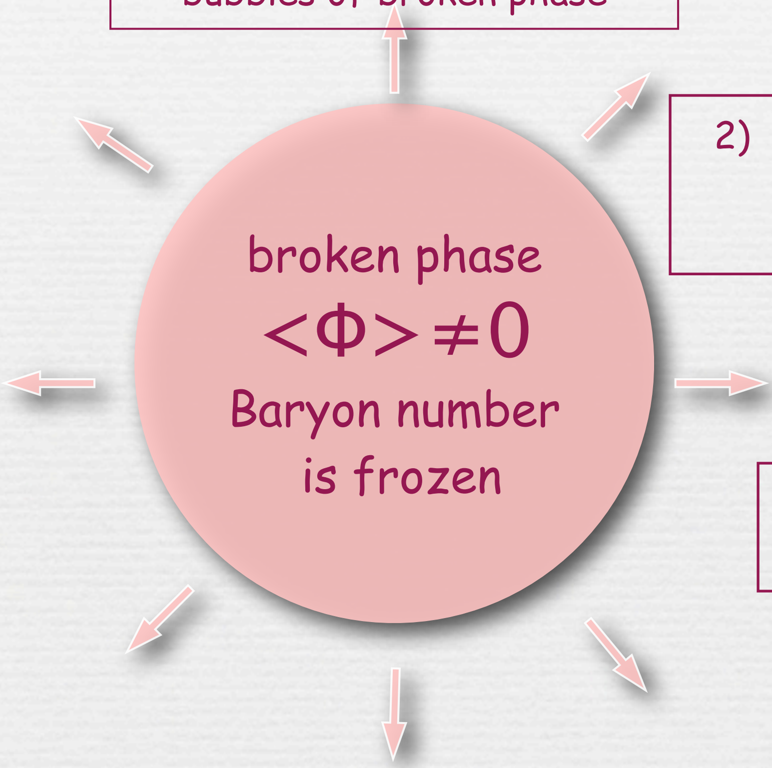
Why do we care?

1) Nature and properties of the EW phase transition reflect information on the dynamics behind EW symmetry breaking (e.g weakly or strongly interacting)

2) Crucial for EW baryogenesis

Baryon asymmetry and the EW scale

1) nucleation and expansion of bubbles of broken phase



2) CP violation at phase interface responsible for mechanism of charge separation

3) In symmetric phase, $<\Phi>=0$, very active sphalerons convert chiral asymmetry into baryon asymmetry

Chirality Flux in front of the wall

Electroweak baryogenesis mechanism relies on a first-order phase transition

wall velocity is a crucial quantity,
we need strong 1st order phase transition, however if too strong->
bubble expand too fast -> no time to build up the baryon asymmetry

What to expect for the EW phase transition

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:

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

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

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

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:

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

we need $m_U^2 < 0$

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

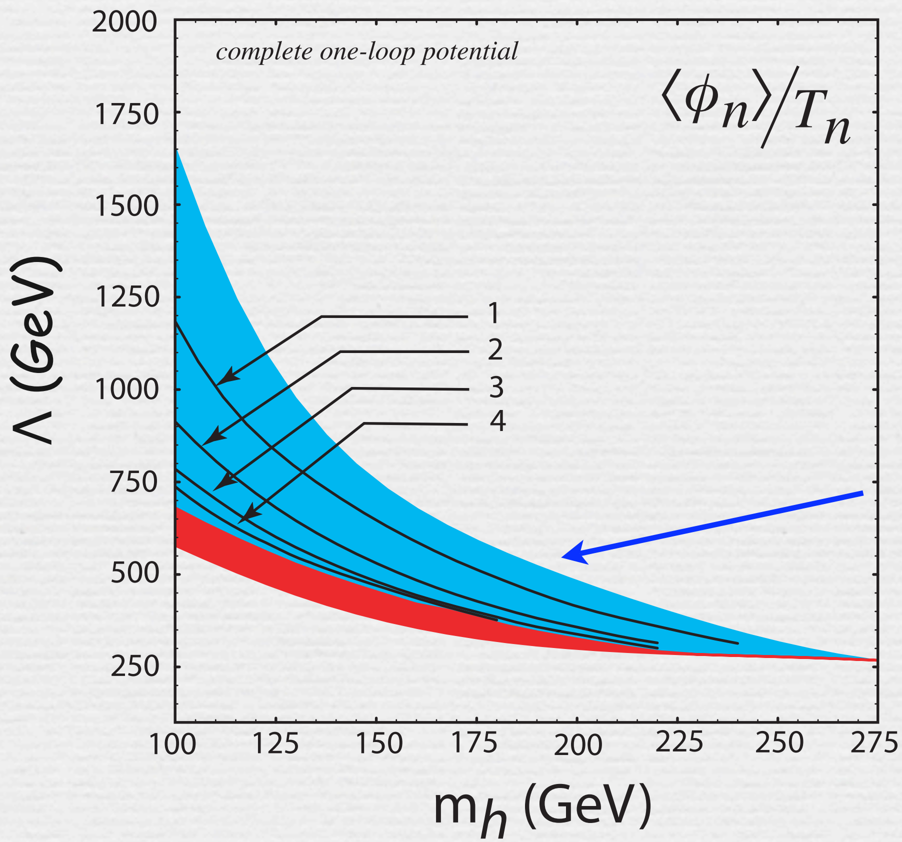
Effective field theory approach

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

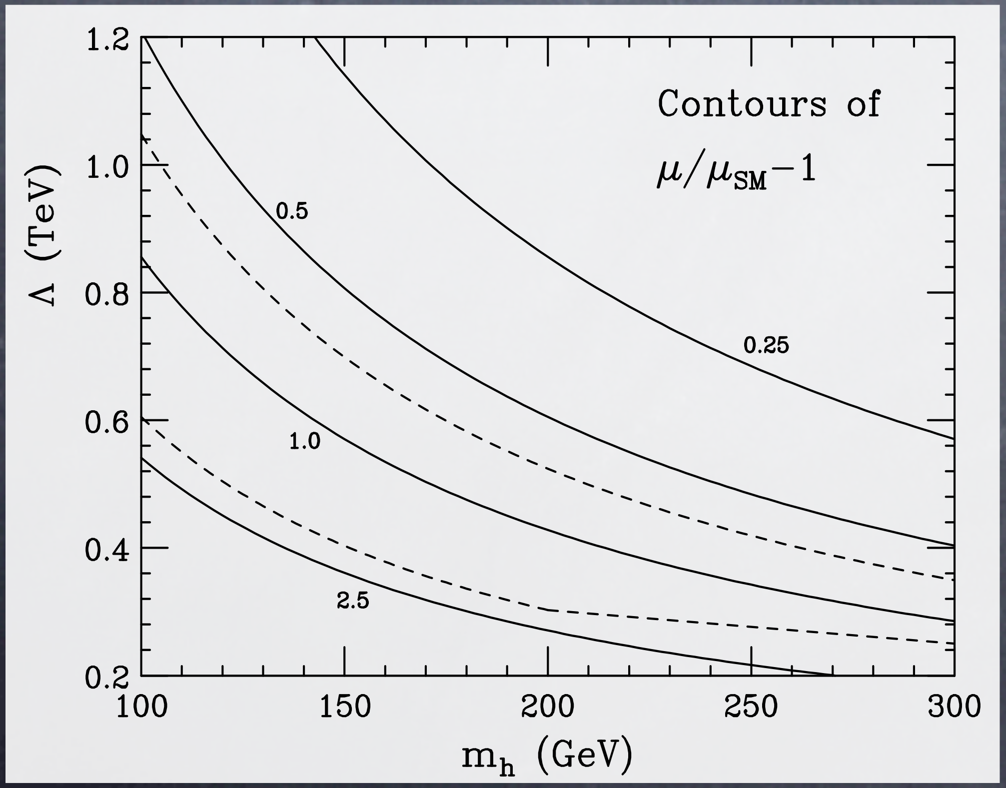
Grojean-Servant-Wells '04
Delaunay-Grojean-Wells '08

This scenario predicts large deviations to the Higgs self-couplings

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

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

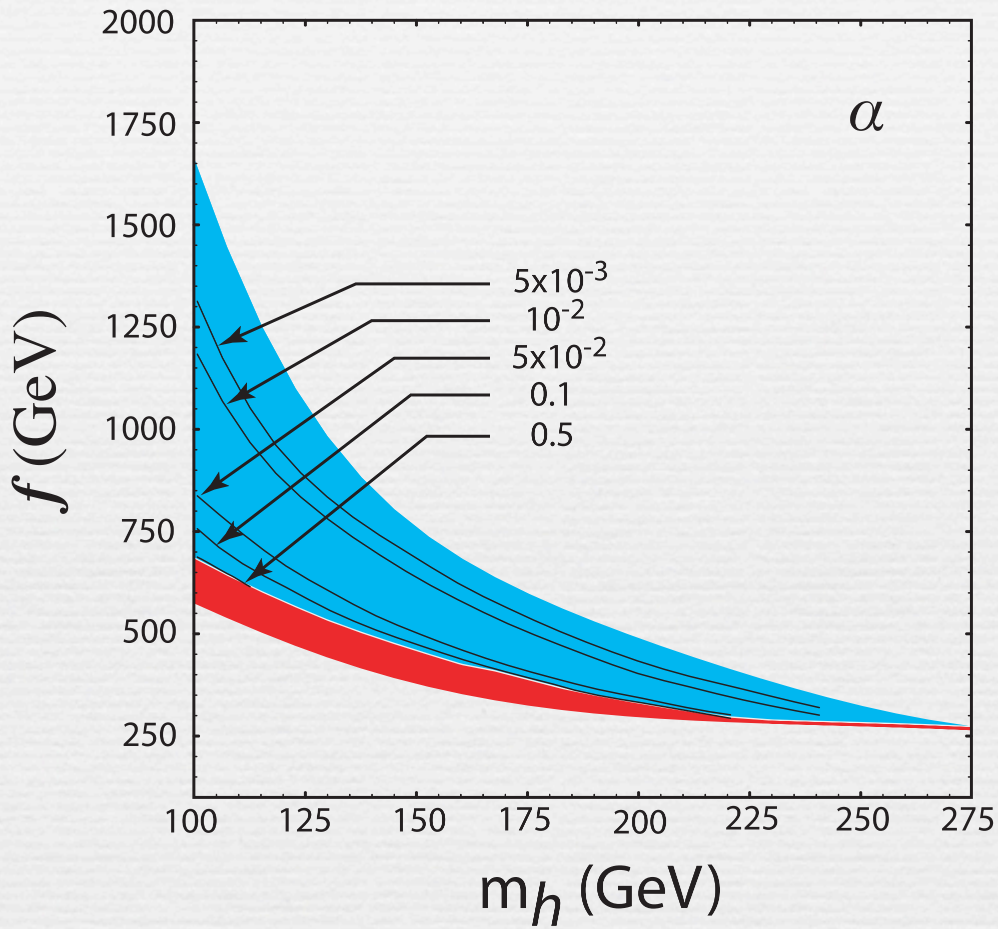
$$\eta = 3\frac{m_H^2}{v_0^2} + 36\,\frac{v_0^2}{\Lambda^2}$$



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

deviations between a factor 0.7 and 2

However, with typical polynomial potential, getting a detectable signal of gravity waves is very fine-tuned



different conclusion if near-conformal dynamics →

How likely is the possibility that we ever detect a GW signal from a 1st order phase transition?

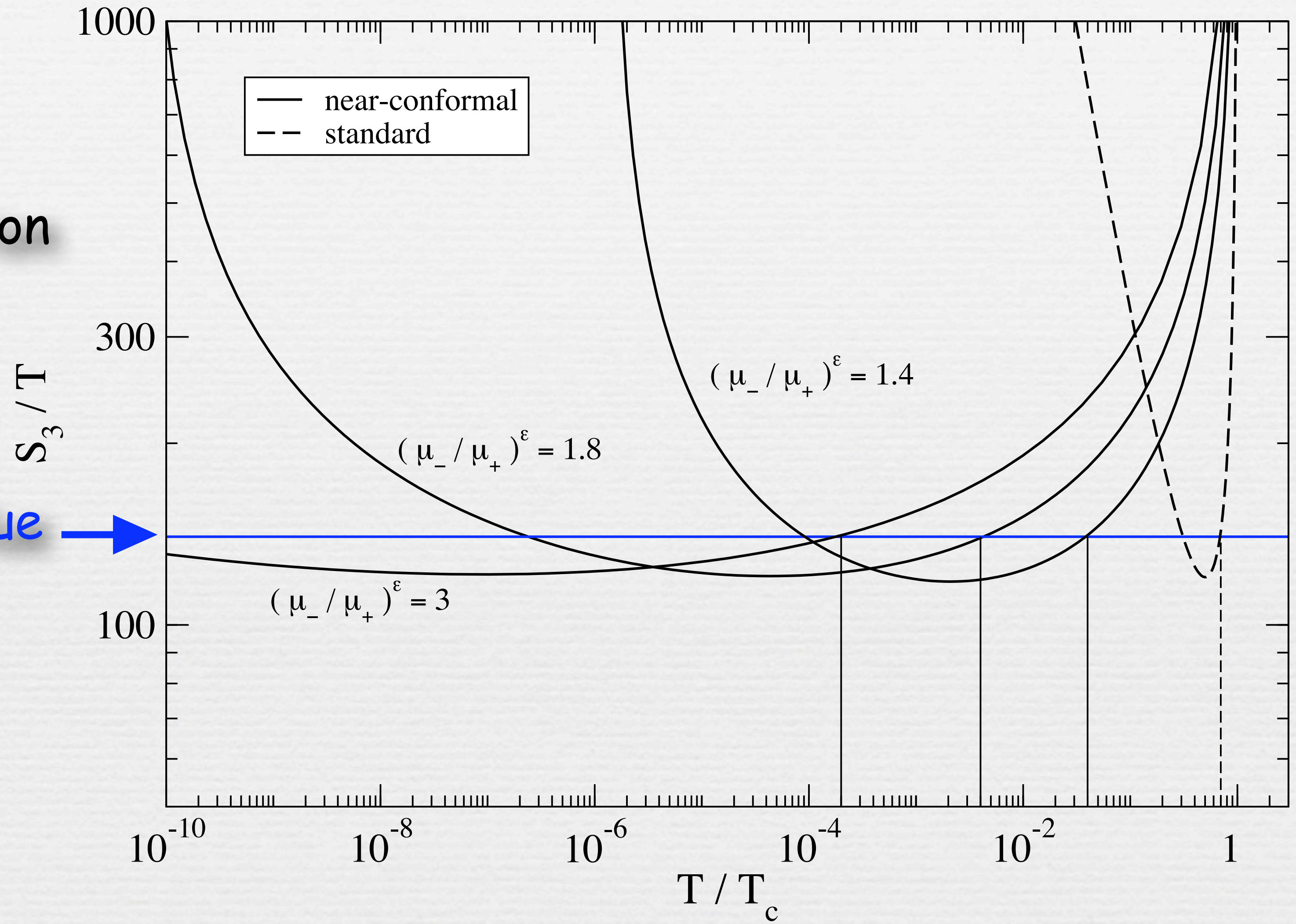
High if potential is of the form

$$V(\mu) = \mu^4 P((\mu/\mu_0)^\epsilon).$$

a scale invariant function modulated by a slow evolution through the μ^ϵ term

similar to Coleman-Weinberg mechanism where a slow RG evolution of potential parameters can generate widely separated scales bubble action

critical value



Konstandin-Servant, in progress

key point: value of the field at tunneling is much smaller than value at the minimum of the potential

nucleation temperature very small

⇒

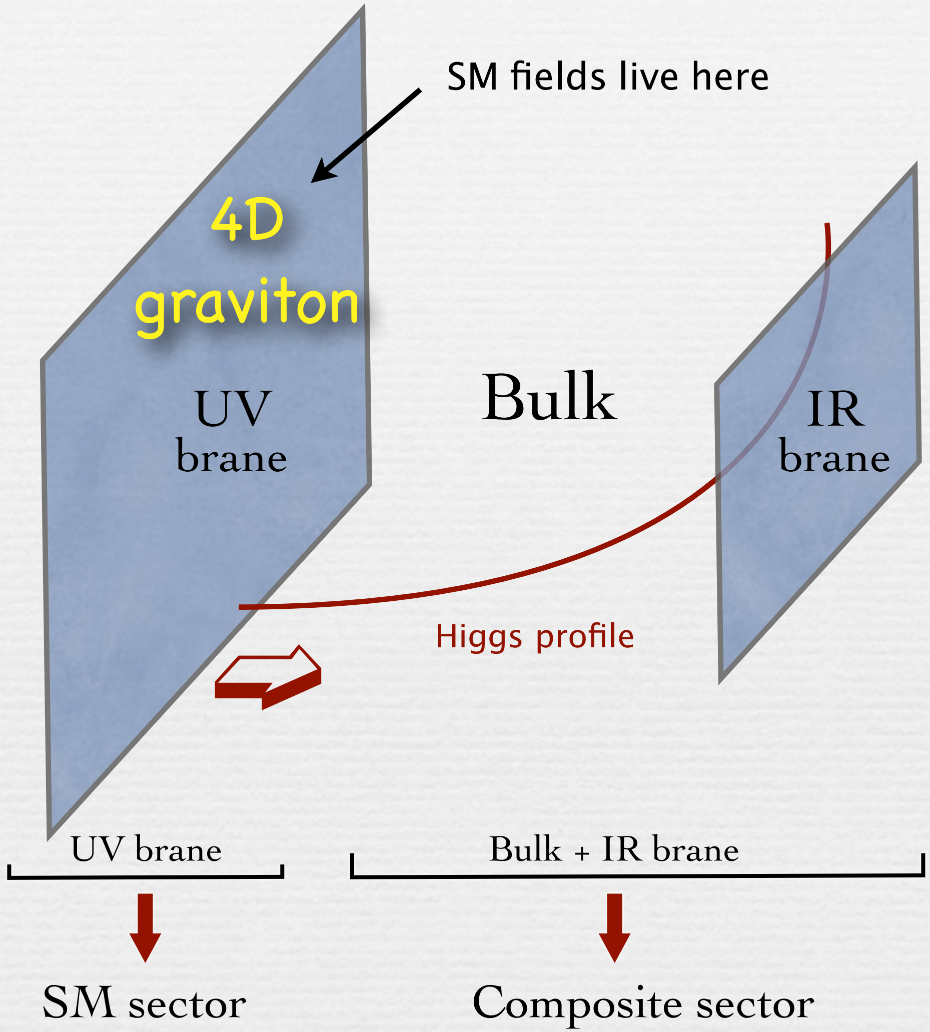
Detection of a GW stochastic background peaked in the milliHertz:

a signature of near conformal dynamics et the TeV scale

Gravitational Waves from Warped Extra-Dimensional Geometry

Randall-Servant '07

Space-time is a slice of AdS_5



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

Radius stabilisation using bulk scalar (Goldberger-Wise mechanism)

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

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)

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

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

[Creminelli, Nicolis, Rattazzi'01]

High-T Phase: AdS-S Black hole

$$ds^2 = \left(\frac{\rho^2}{L^2} - \frac{\rho_h^4/L^2}{\rho^2}\right) dt^2 + \frac{d\rho^2}{\frac{\rho^2}{L^2} - \frac{\rho_h^4/L^2}{\rho^2}} + \frac{\rho^2}{L^2}\sum_i dx_i^2$$

reduces to pure AdS metric for $\rho_h = 0$

$$T_h \equiv \frac{\rho_h}{\pi L^2}$$

$$F_{\text{AdS-S}} = -2\pi^4 (ML)^3 T^4$$

both local minima of free energy

by holography:
$(ML)^3 = N^2/16\pi^2$

Low-T Phase : RS1 geometry

Radion field determines spacing between branes

Require that radion is stabilized around TeV

$$\mu = e^{-k\pi r} M_{Pl}$$

$$F_{RS} = (4+2\epsilon)\mu^4 (v_1 - v_0(\mu/\mu_0)^\epsilon)^2 - \epsilon v_1^2 \mu^4 + \delta T_1 \mu^4 + \mathcal{O}(\mu^8/\mu_0^4)$$

$$V_{min} \approx -\epsilon^{3/2} v_1^2 \mu_{\text{TeV}}^4$$

Second brane emerges at T~TeV

i.e. radion starts at $\mu = 0$
and evolves to $\mu = \mu_{\text{TeV}}$

Key is stabilising mechanism

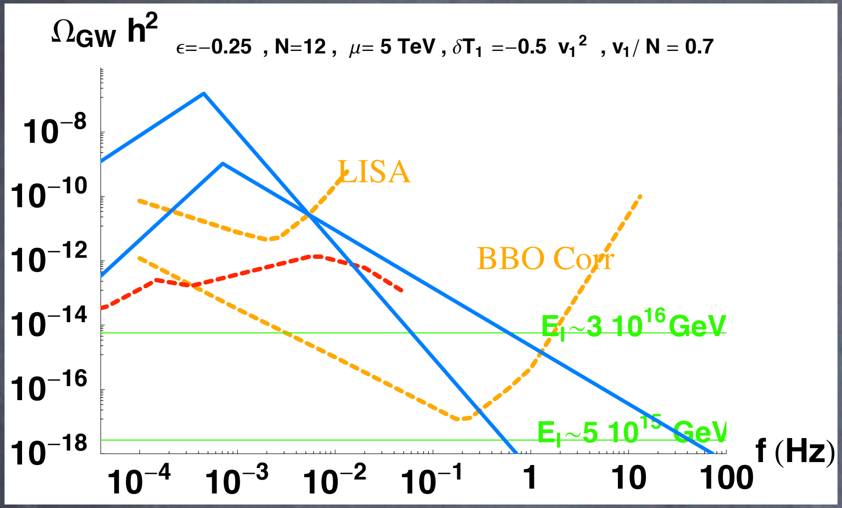
$$T_c = \left(\frac{-8V_{min}}{\pi^2 N^2}\right)^{1/4}$$

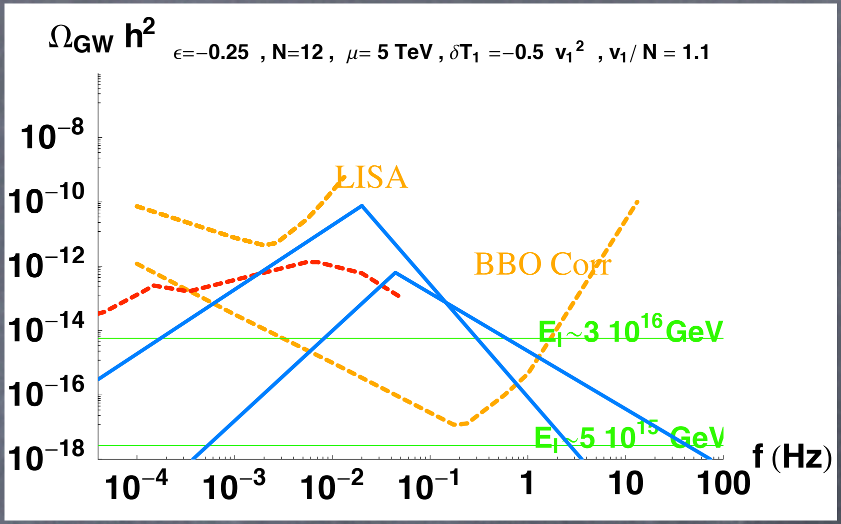
Below T_c , expect first-order phase transition

From 4D perspective , expect transition through bubble nucleation
From 5D perspective , spherical brane patches on horizon

Gravitational Waves from "3-brane" nucleation:

Signal versus LISA's sensitivity





Randall-Servant'06

Signature in GW is generic,

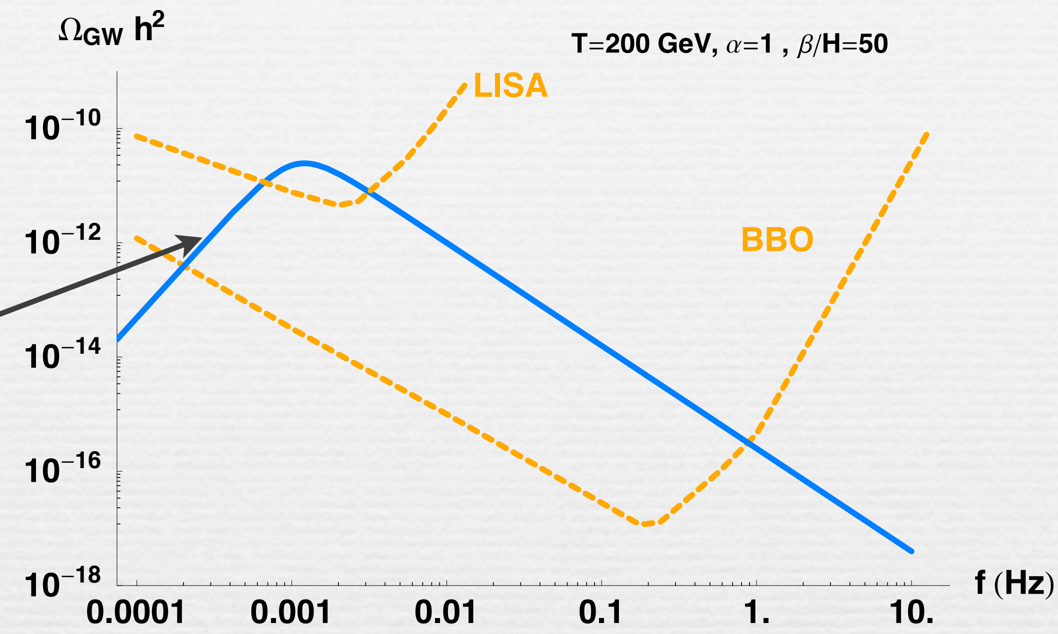
i.e. does not depend whether Standard Model is in bulk or on TeV brane

but crucially depends on the radion properties

Conclusion

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

Expected shape of the GW spectrum



large scale part of the GW spectrum

~ f^3

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

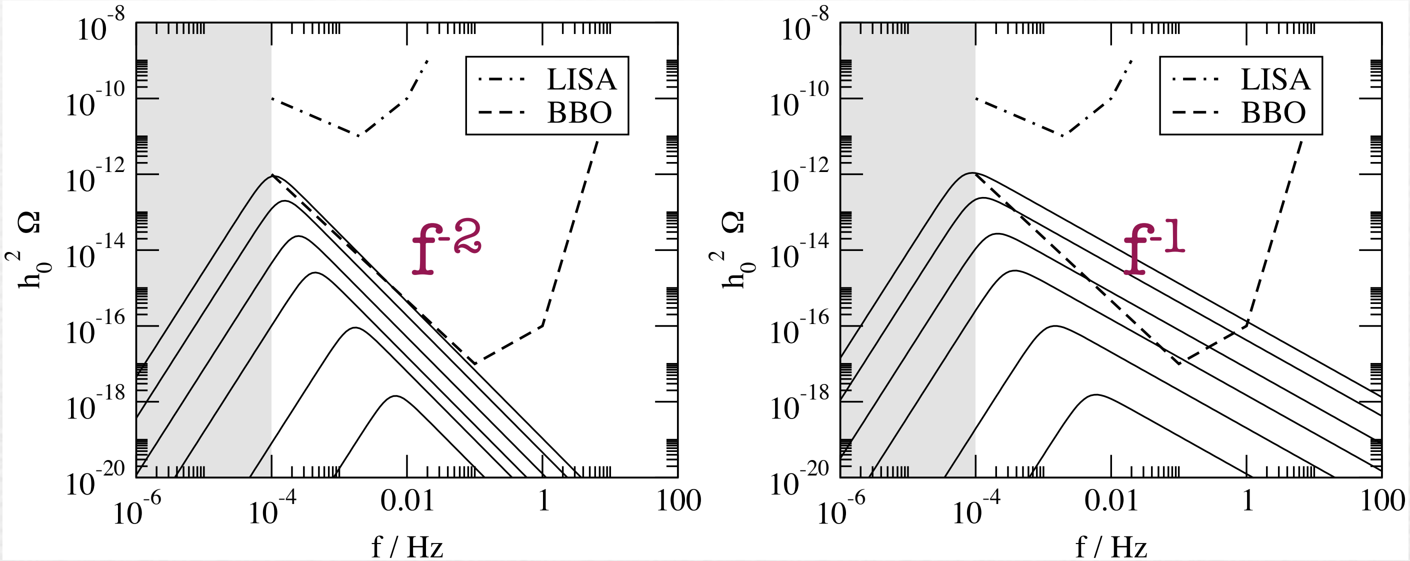
$$h_{ij}(\mathbf{k},\eta) = \int_{\eta_{\rm in}}^{\eta} d\tau \mathcal{G}(\tau,\eta)\Pi_{ij}(\mathbf{k},\tau)$$

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

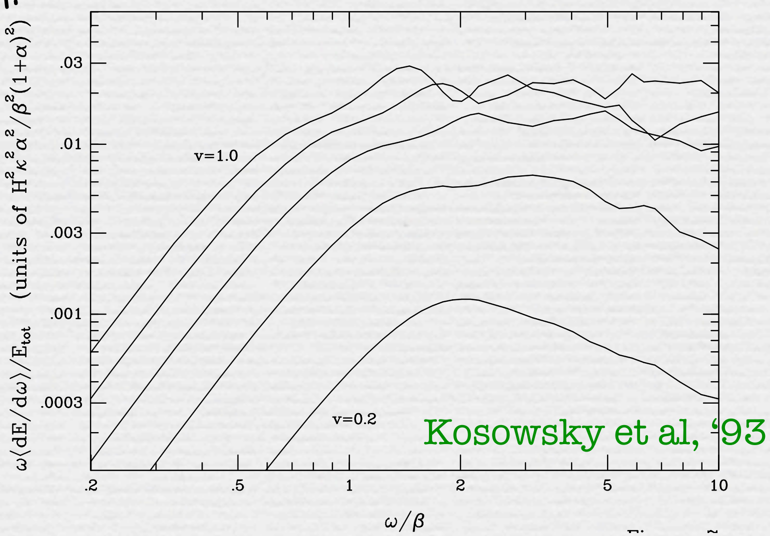
CAUSAL PROCESS: source is uncorrelated at scales larger than the peak scale

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

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



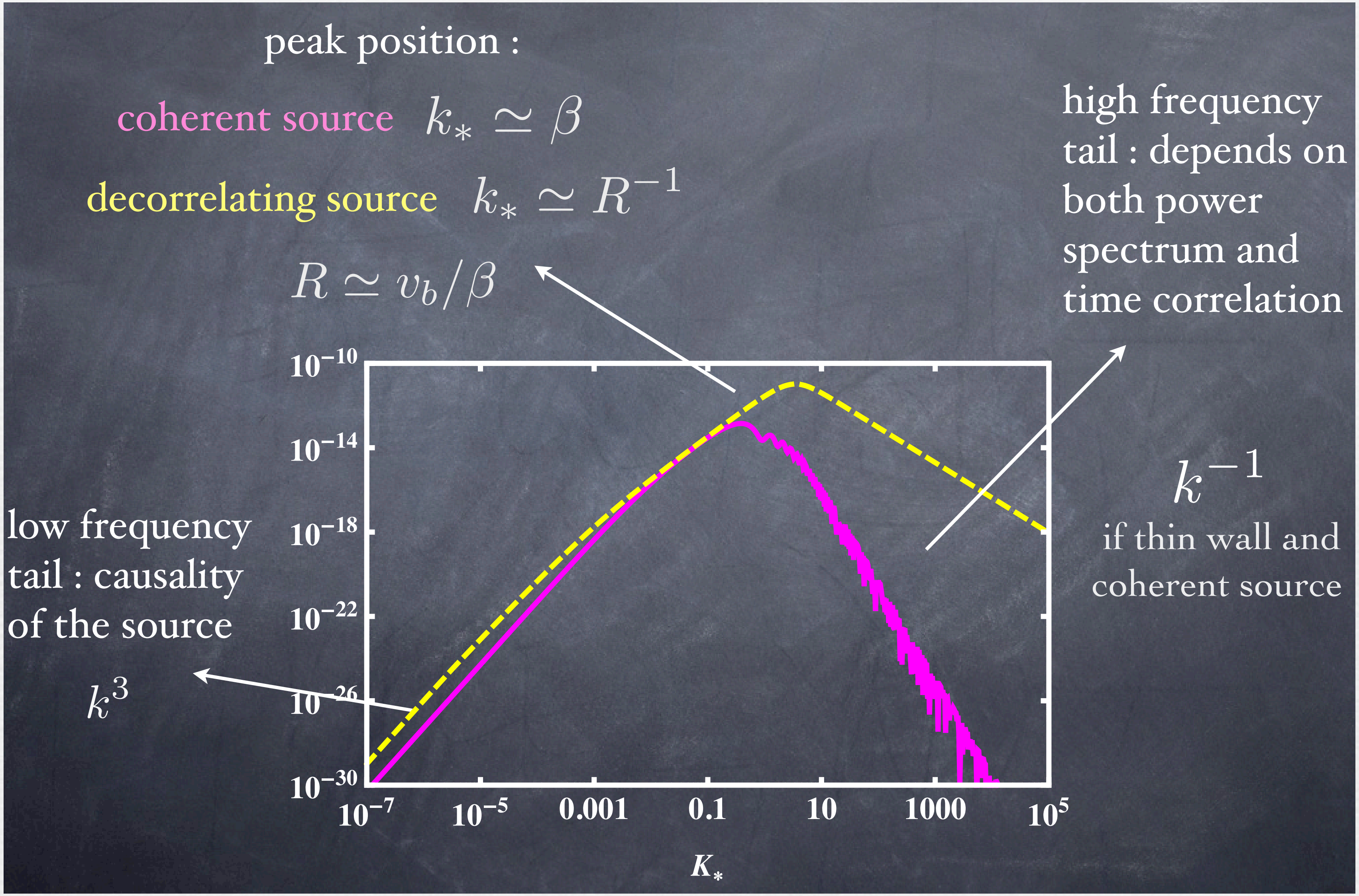
derived from:



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)

1st order EW phase transition

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

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

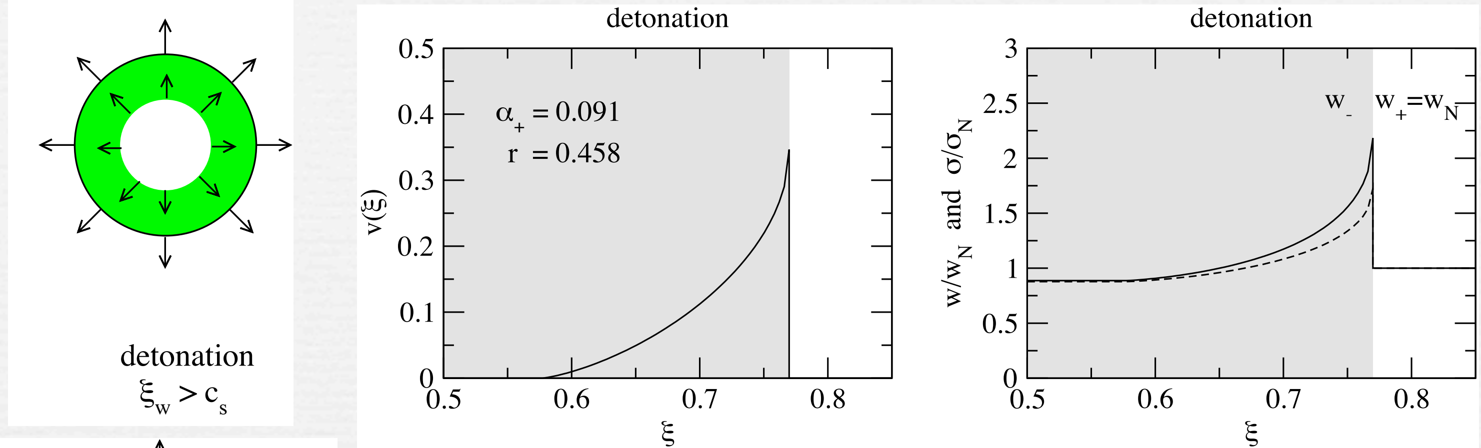
wall velocity (ξ_w)

fluid velocity (v)

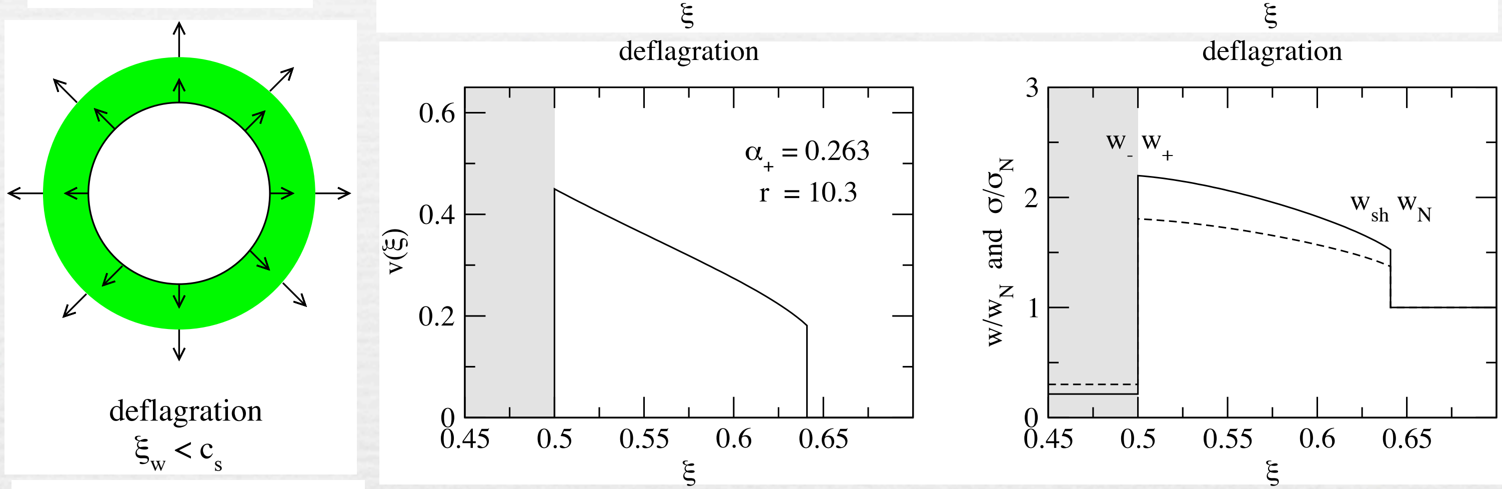
-> all boils down to calculating the fluid velocity profile in the vicinity of the bubble wall

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

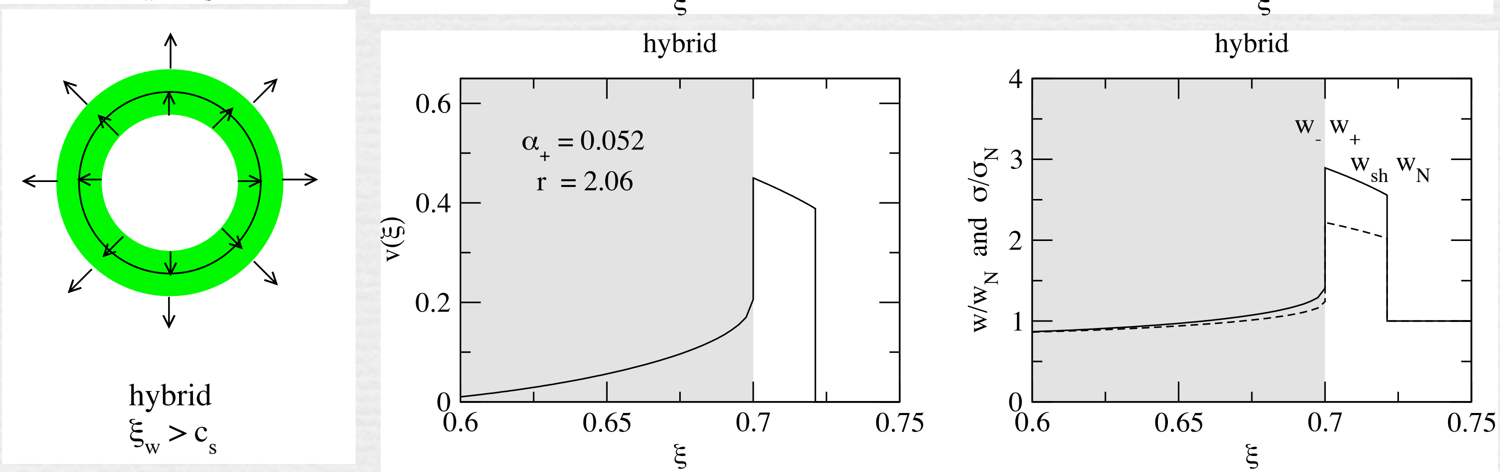
detonations -rarefaction wave



deflagrations -shock front



hybrids -both



Espinosa, Konstandin, No, Servant'10

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

friction coefficient

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

$$T_N\ \tilde{\eta}\ u^\mu \partial_\mu \phi = -\sum_i \frac{dm_i^2}{d\phi} \int \frac{d^3p}{(2\pi)^3 2E_i} \delta f_i(p)$$

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

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

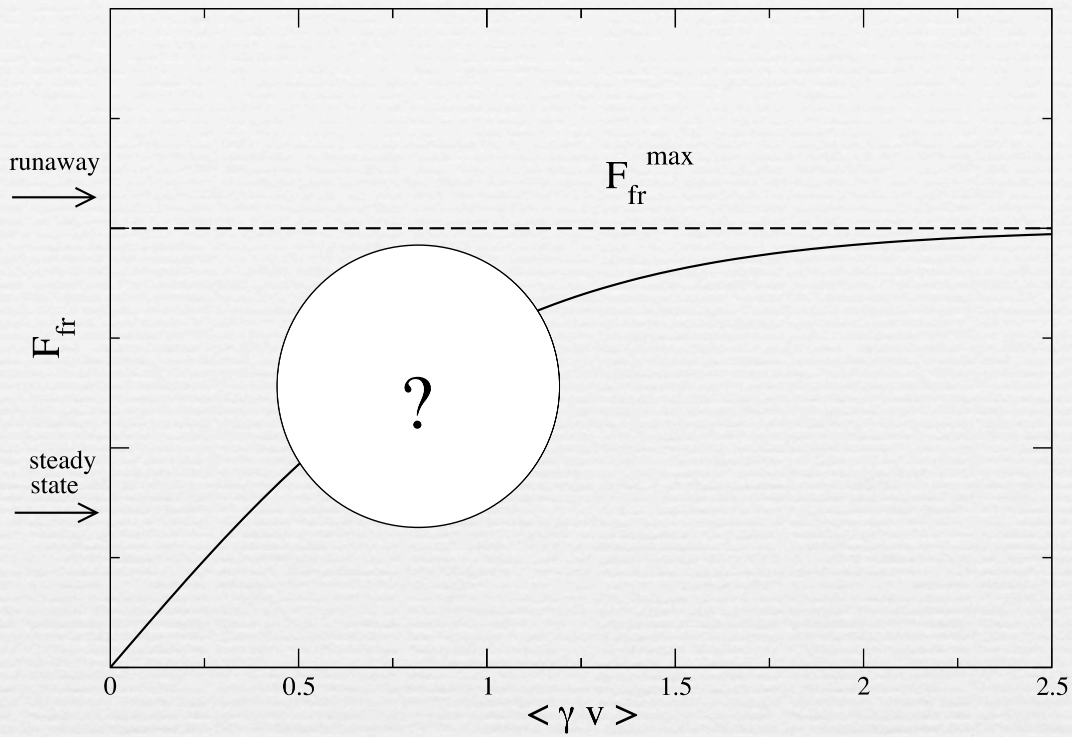
$$F_{tot} = F_{dr} - F_{fr} = \Delta V_0 + \sum_i |N_i| \int dz \frac{dm_i^2}{dz} \int \frac{d^3p}{(2\pi)^3} \frac{f_i}{2E_i}$$

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

[Bodecker-Moore '09]

Runaway regime

Espinosa, Konstandin, No, Servant'10



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

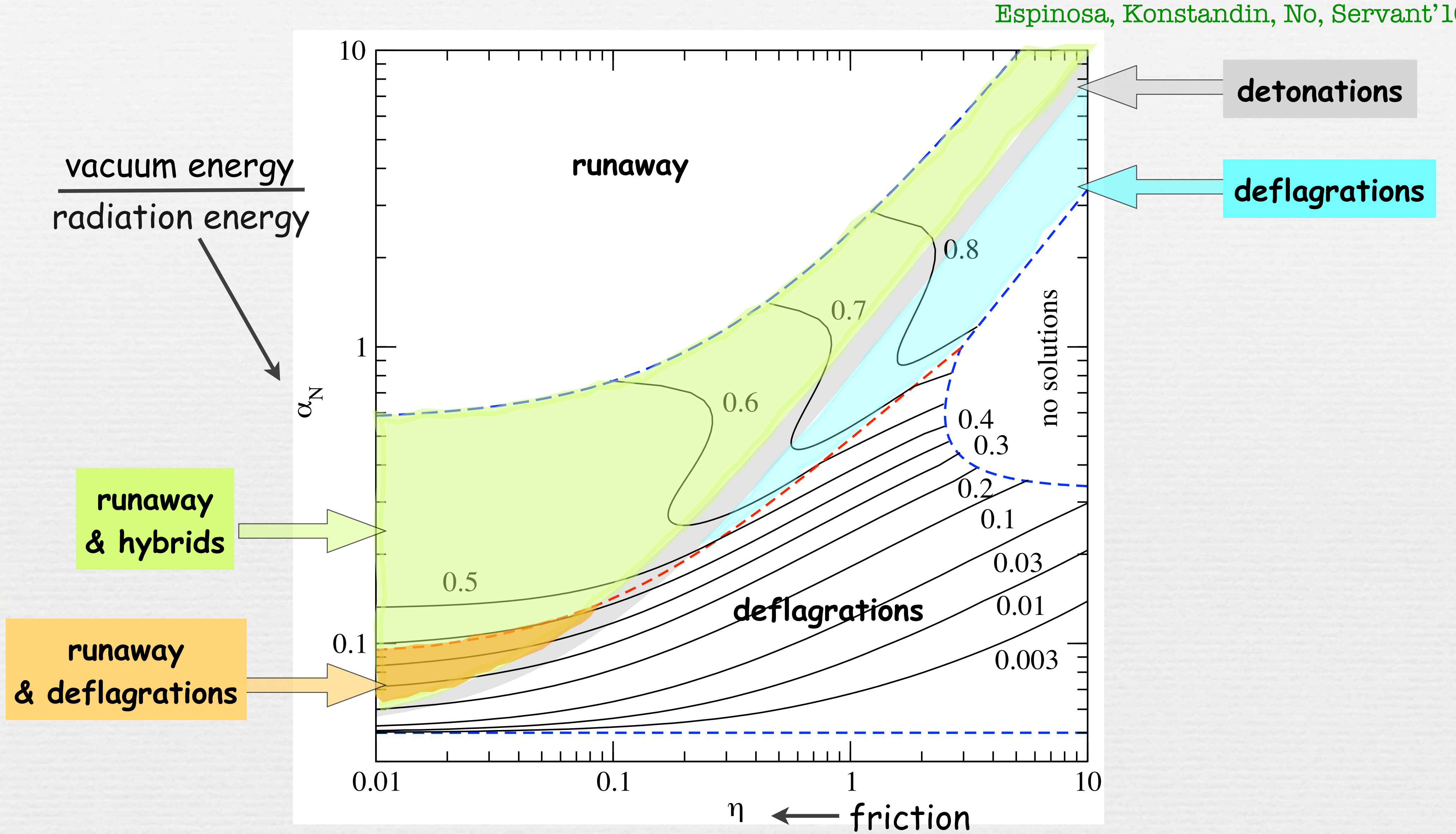
runaway criterium

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

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

For strong 1st order PT, the wall keeps accelerating

Model-independent κ contours

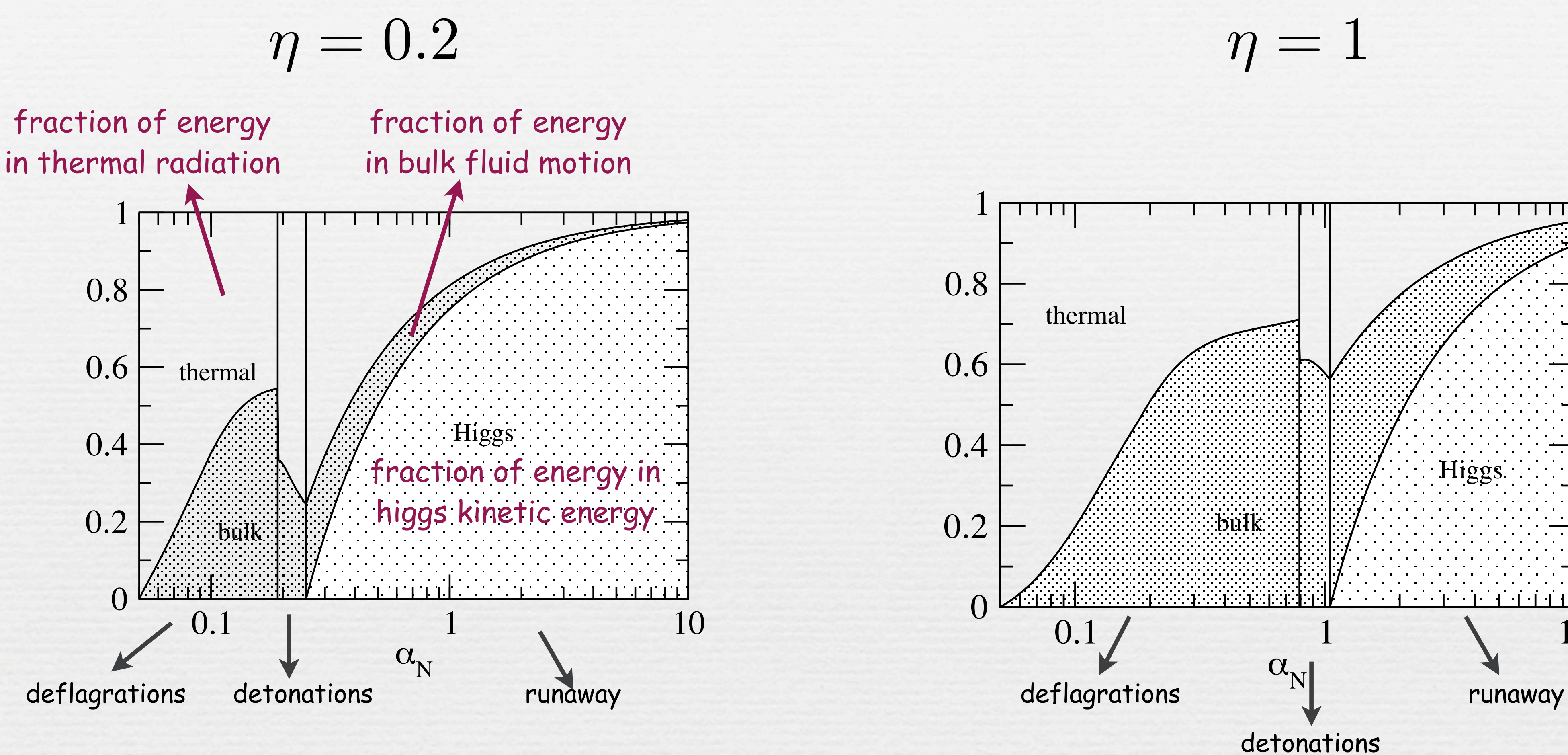


$$\eta_{\rm SM} \sim 10^{-3}$$

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

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

Baryogenesis at the weak scale: off the beaten tracks

Baryogenesis without $\not{B}$ nor $\not{L}$ nor $CP\not{T}$

Possible if dark matter carries baryon number

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

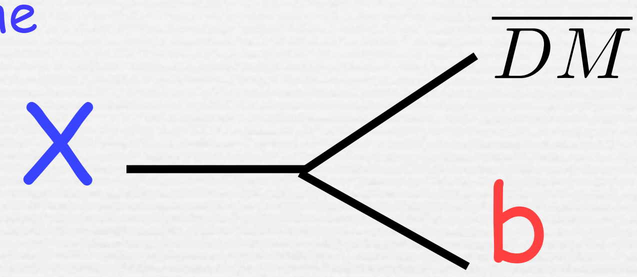
In a universe where baryon number is a good symmetry, Dark matter would store the overall negative baryonic charge which is missing in the visible quark sector

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

$Q_{universe}$ = 0 = Q + (-Q)

Q: carried by baryons; (-Q): 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

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

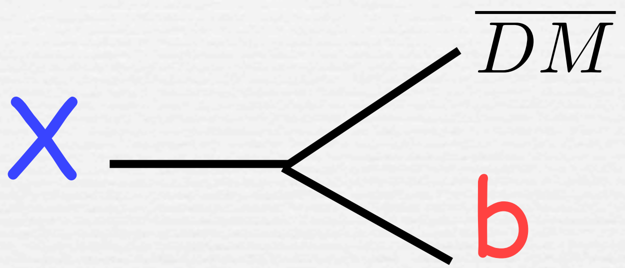
If efficient annihilation between DM and $\overline{DM}$, and b and $\bar{b}$:

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

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

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

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



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

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

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

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

A unified explanation for DM and baryogenesis $\qquad \Omega_b \approx \frac{1}{6}\Omega_m$

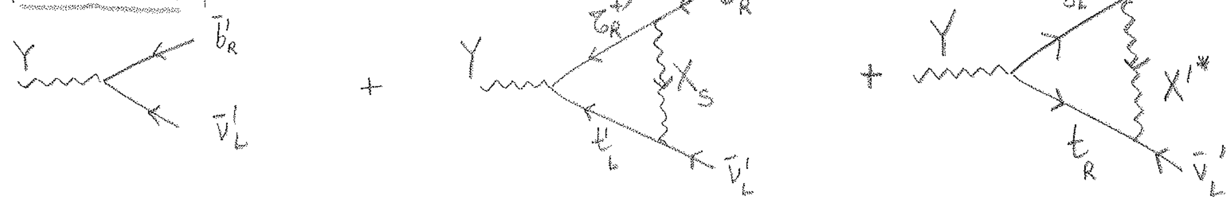
turns out to be quite natural in warped GUT models...

GUT baryogenesis at the TeV scale !

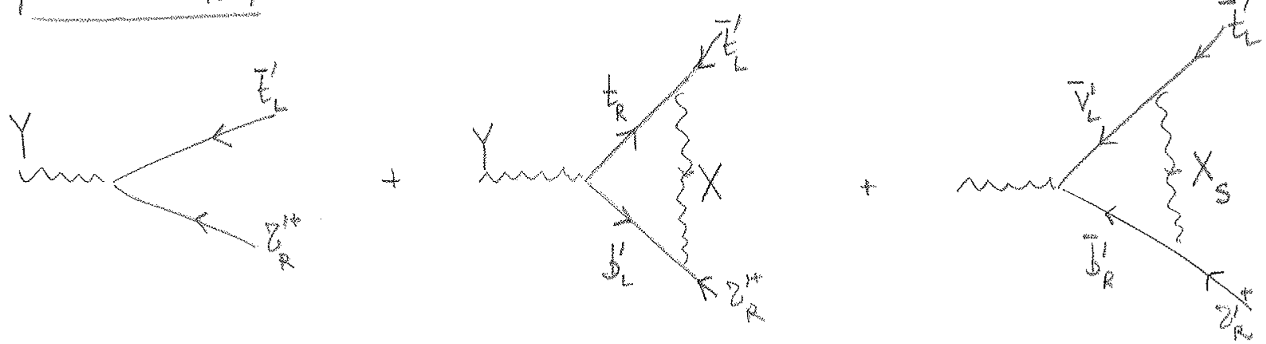
Agashe-Servant-Tulin in progress

Y DECAYS

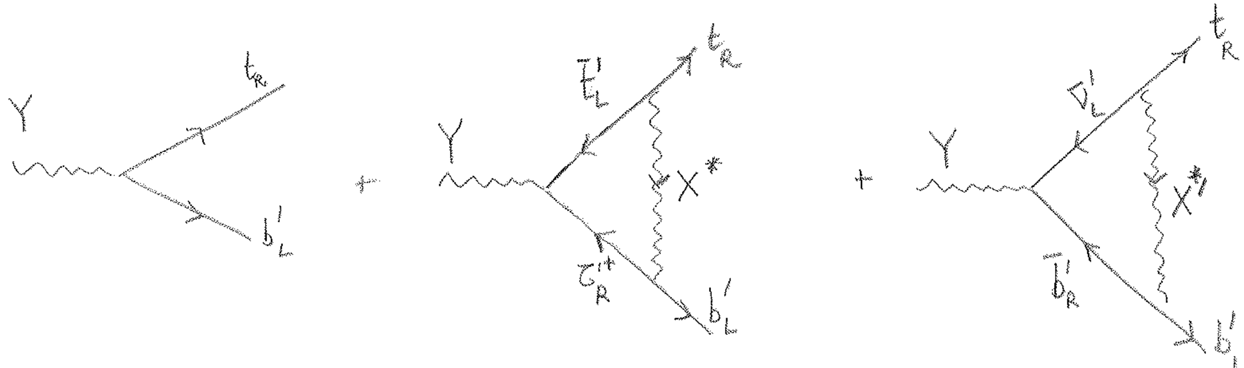
$Y \to \bar{b}'_R \, \bar{\nu}'_L$



$Y \to \bar{t}'_L \, \tau^{+\prime}_R$



$Y \to t_R \, b'_L$



Z_3 symmetry in the SM:

Agashe-Servant'04

number of color indices

$$\Phi \longrightarrow \Phi \; e^{2\pi i \left[B - \frac{(\alpha - \bar{\alpha})}{3} \right]}$$

conserved in any theory where baryon number is a good symmetry

any non-colored particle that carries baryon number will be charged under Z_3

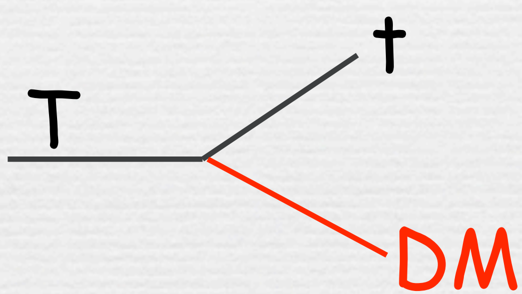
e.g warped GUTs

Z_2 versus Z_3 Dark Matter

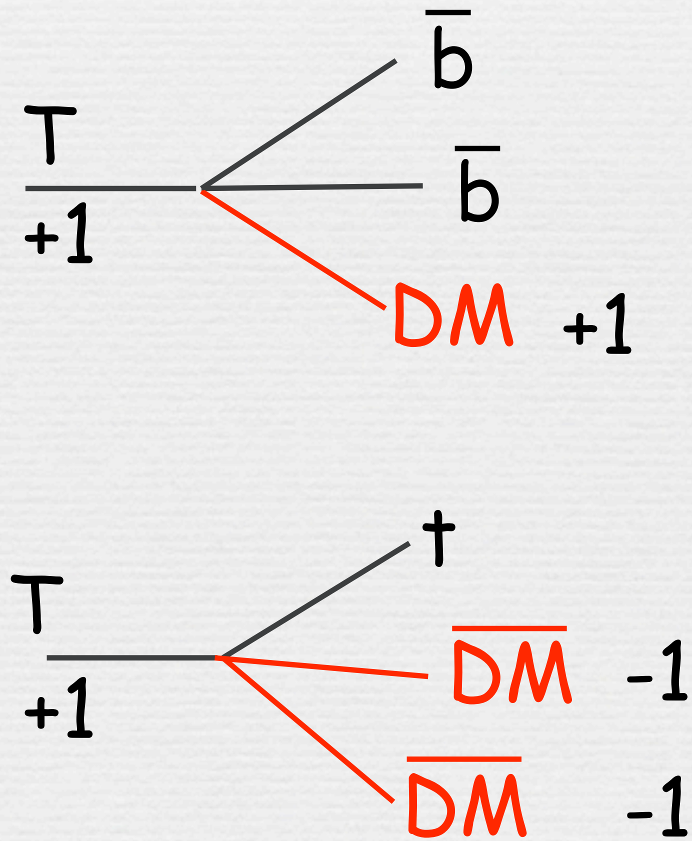
Agashe et al, 1003.0899
Mahbubani-Servant, in progress.

Most Dark Matter models rely on a Z_2 symmetry. However, other symmetries can stabilize dark matter. Can the nature of the underlying symmetry be tested?

Z_2

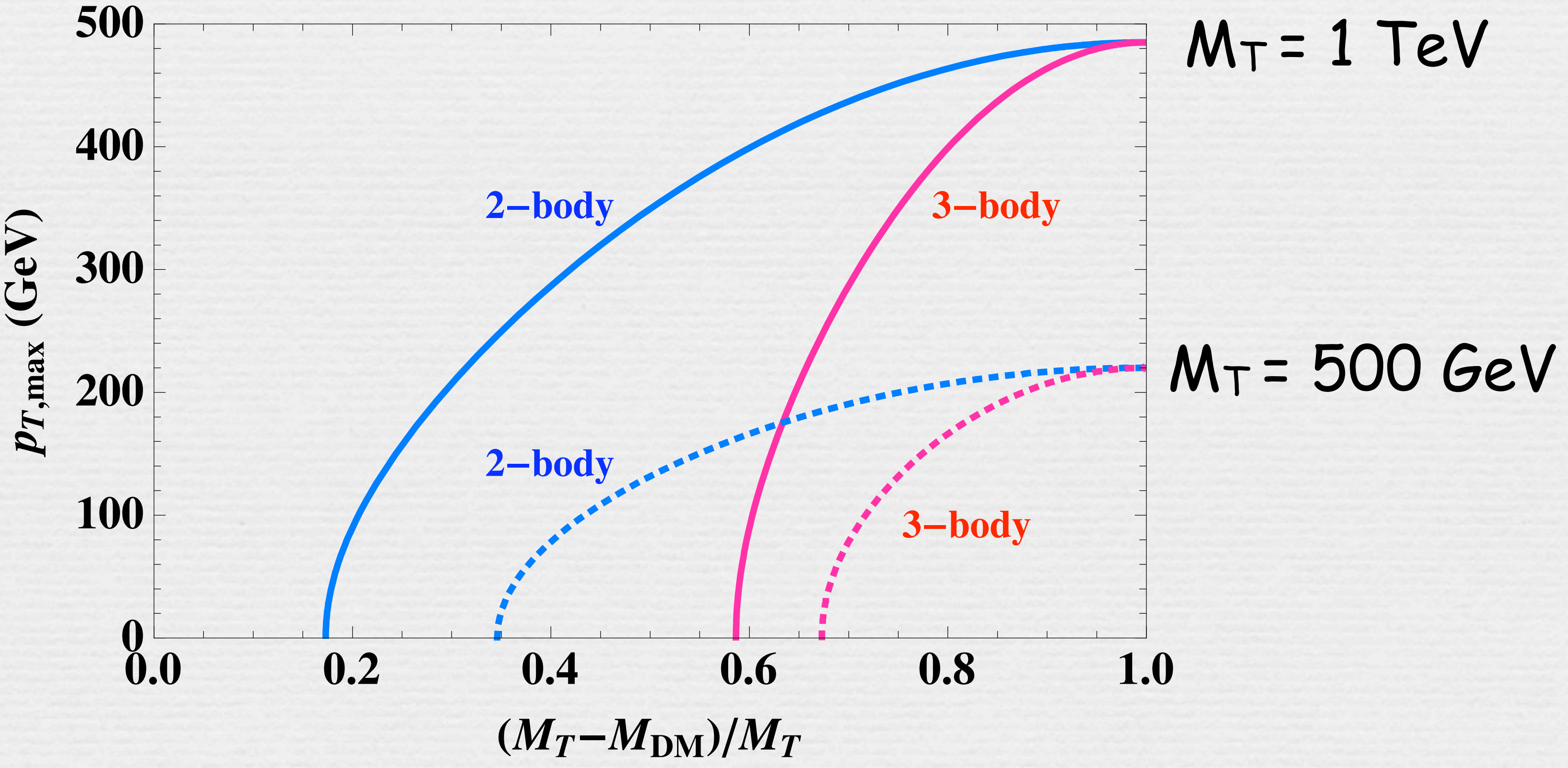


Z_3 (+1=-2)



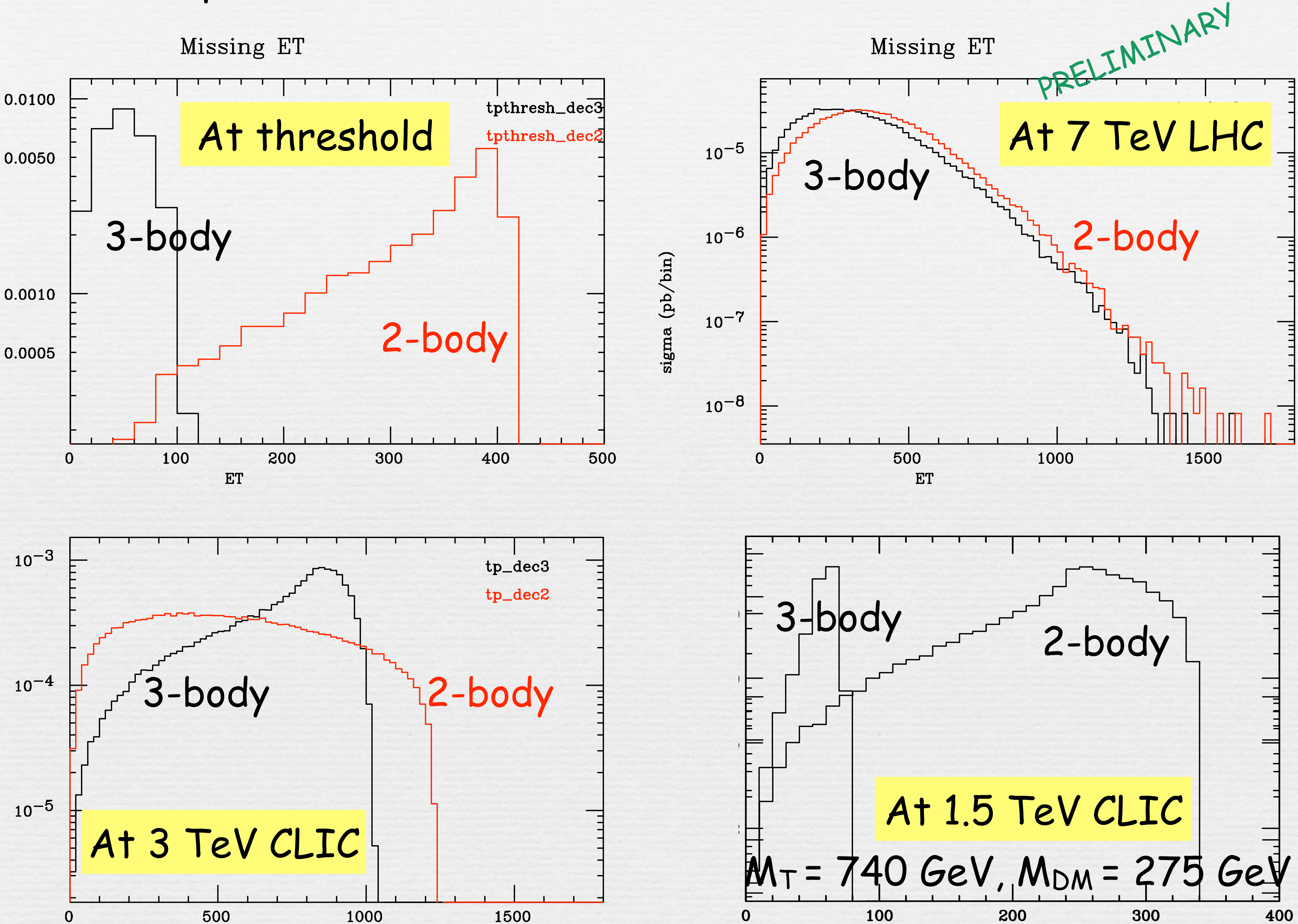
Z_2 versus Z_3 Dark Matter

In rest frame of the mother particle, the maximum of the p_T distributions is different in these 2 cases:

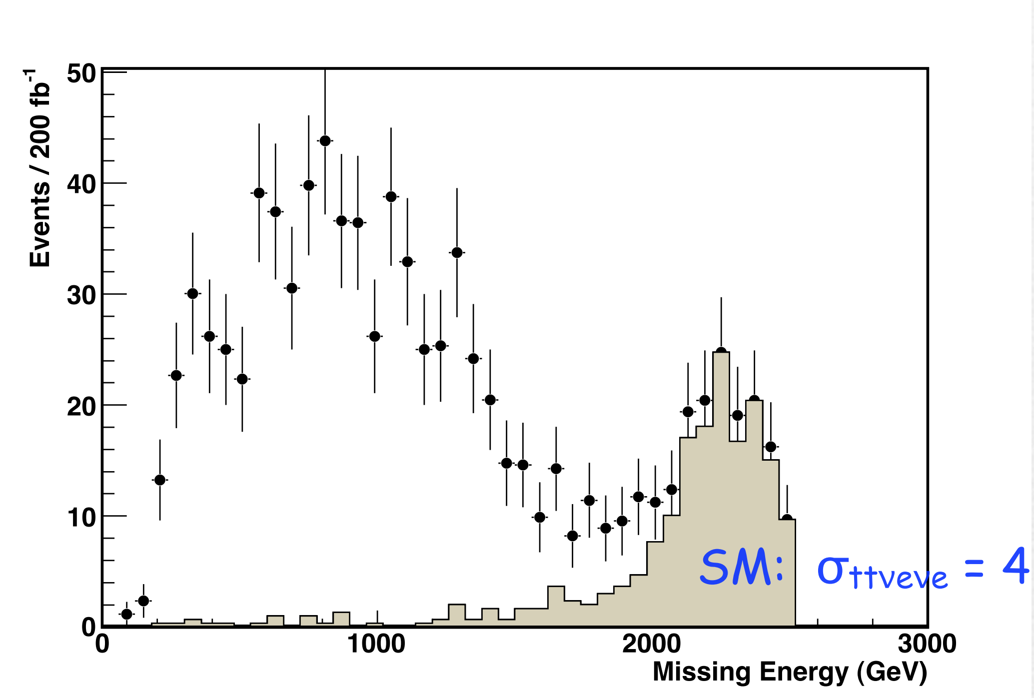


Example: $M_T = 1$ TeV, $M_{DM} = 400$ GeV

Mahbubani-Servant



$e^+ e^- \to t\bar{t} + \not{E}_T$ @ 3 TeV CLIC



$M_{Z'}$ =200 GeV

$(g^{Z'}_{t_R} = g^{Z'}_{DM} = 3)$

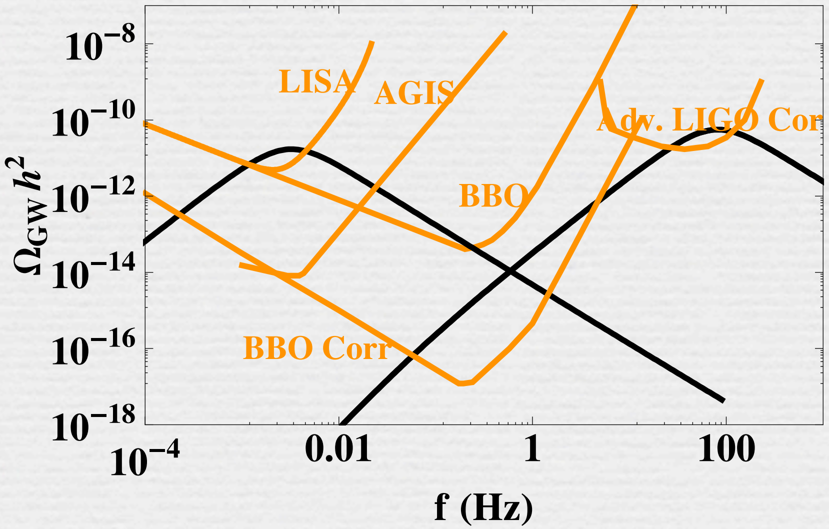
Battaglia-Servant 1005.4632

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)



Conclusion

There are interesting cosmological implications of EW symmetry breaking