Future Directions in Theoretical High Energy Physics: Bias, Babble, Brouhaha

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It is said from time to time:
'Particle physics has gone through a stagnant spell ever since the mid-1960's —- a spell not exactly broken even by the Higgs discovery event'

Q: Is that indeed the situation?

Look at some developments since 1967.....

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- *1980's: W,Z discovered*
  Charmless B-decay: $V_{ub} \neq 0$

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- *2012: A 125-GeV scalar identified (as 'the Higgs' or 'a Higgs')*

In the meantime...

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- *Theoretical principles of QCD leading to sophisticated calculational tools, semi-empirical procedures devised to make realistic calculations despite the roadblocks caused by the confinement issue.....*
- *A huge mass of astrophysical data, the development of precision cosmology, formulation of inflation, the dark matter issue on firm grounds, quantification of dark energy, relations established between particle physics, light element abundance, structure formation etc.....*

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- *Are we complaining of stagnancy because we are spoilt by the 'thirty years that shook physics'?*
- *The reason for frustration: we are learning many things, but they all reinforce the same structure—* **the Standard Model**— *rather than yielding hints for new ones....*

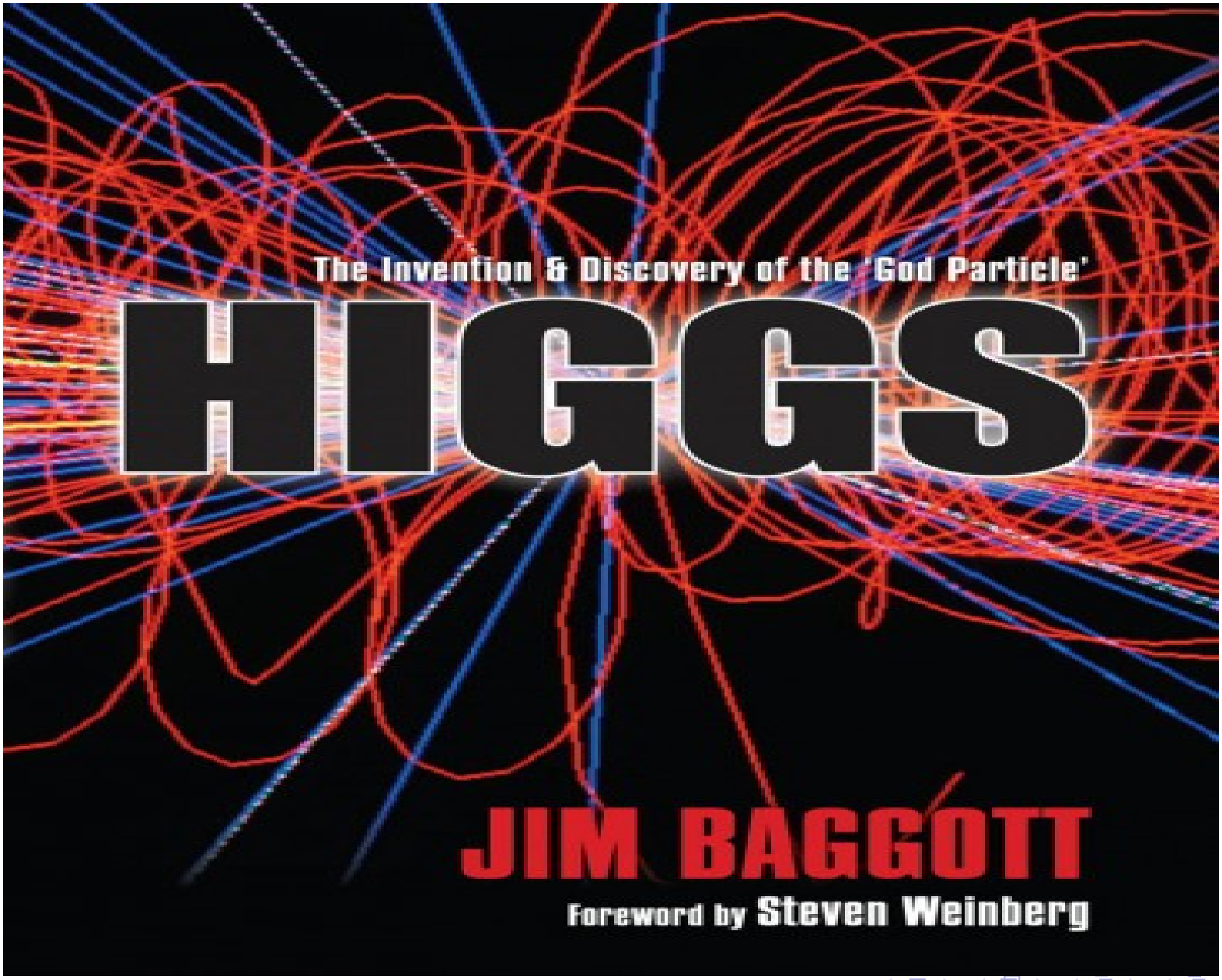
The bias of the present discussion: mostly 'bottom-up'
(piecemeal approach to start with)

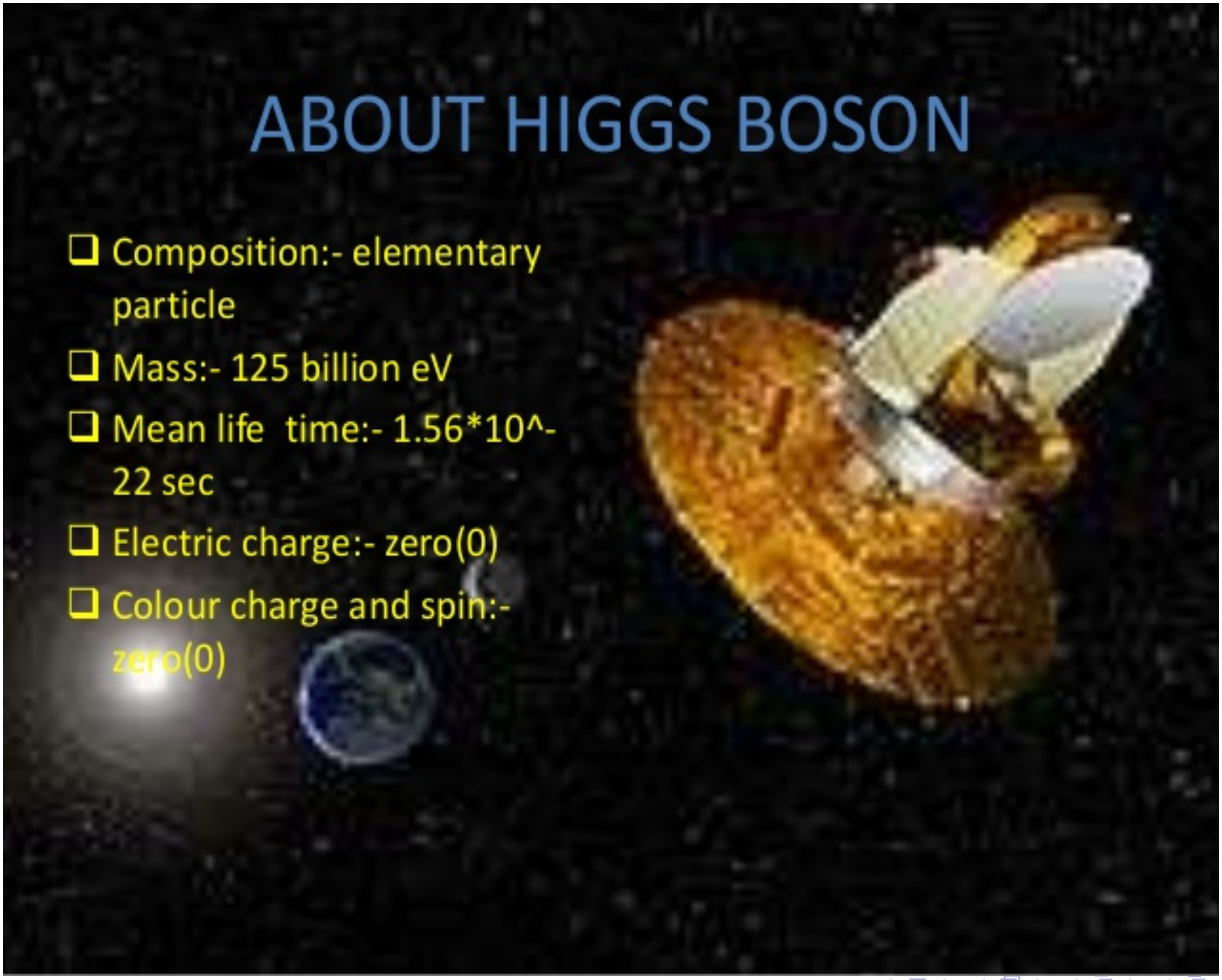
The observations that persistently imply going beyond the SM are

- Dark matter
- Neutrino masses and mixing
- Baryon asymmetry
- Dark energy (perhaps)

We mostly discuss directions of thinking related to the first two
But start with the Higgs, the most recent toy gifted by Nature.....

Invented in the 1960's, discovered in 2012.....




ABOUT HIGGS BOSON
Composition:- elementary particle
Mass:- 125 billion eV
Mean life time:- 1.56*10^-22 sec
Electric charge:- zero(0)
Colour charge and spin:- zero(0)

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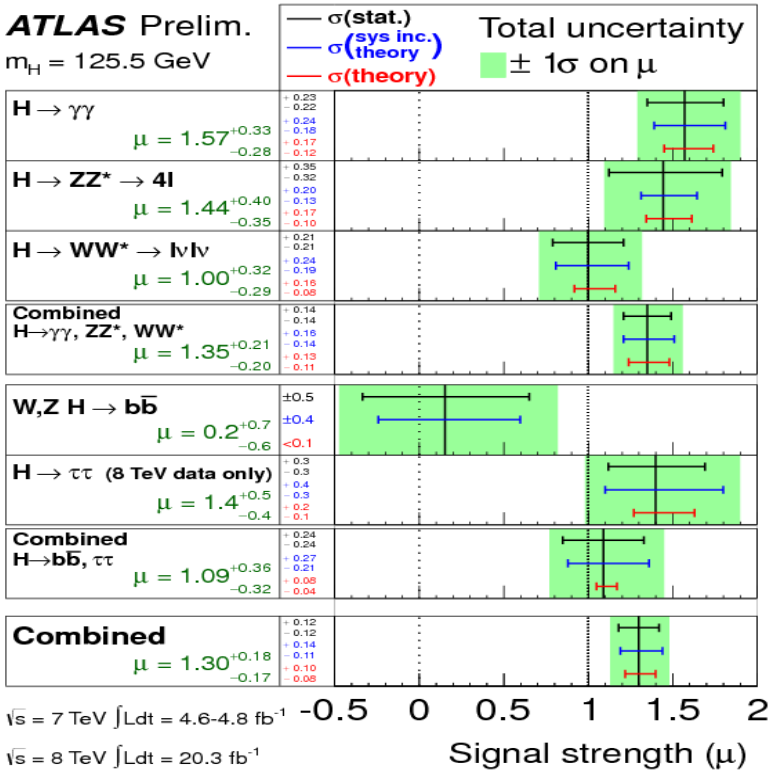
- *But there is still scope for departure from SM interactions!*



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- *Departure from SM coupling can be of two kinds:*
  - *Coupling strengths scaled w.r.t. SM coupling*
  - *Different Lorentz structure, mostly driven by higher-dimensional operators*

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  - $\Rightarrow$ *Either h or the particles to which it couples are mixed with something unknown*
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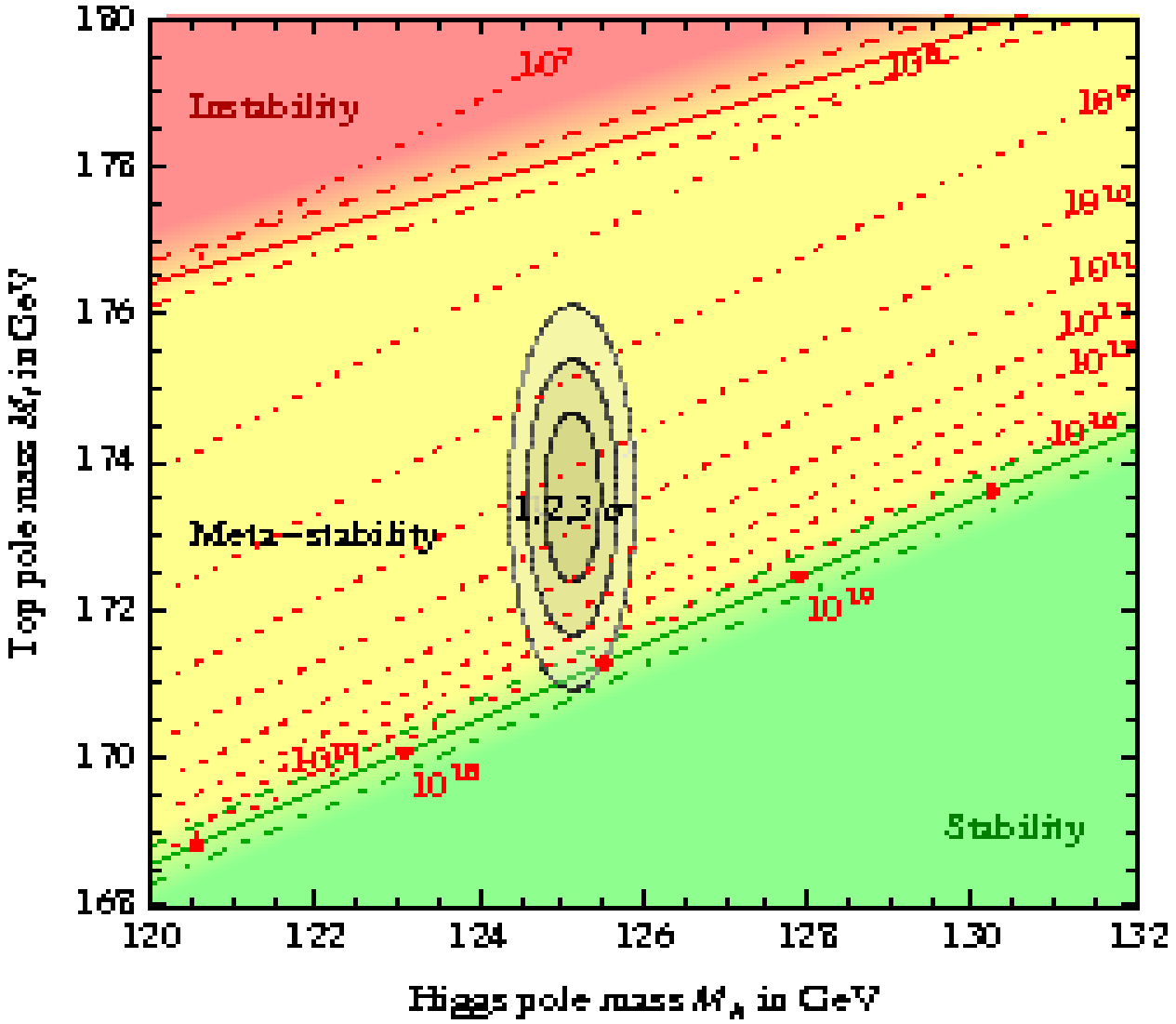
A wealth of information can come from the measurement of the Higgs self-coupling λ

The LHC has rather poor sensitivity to λ— di-Higgs limits can be effectively put for rather large values only
An e^+e^- machine too may find it difficult to achieve more than $\approx$15% precision
Does this mean a no-go?
Can combined data on di-Higgs or $t\bar{t}h$ help?
A great achievement: to formulate some novel effects/observable(s) that yields precision information on λ

The Higgs and vacuum stability....



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- *Example: With two Higgs doublets,* **stable** *vacuum + unitarity assured upto M_P*
  Q: (i) Can we develop guidelines on high-scale physics from vacuum stability and related issues??
  (ii) Is a stable vacuum preferable to a metastable one?

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- *Various mass generation mechanisms may address some of the other issues, too*

  The goal: integrate mass models with new physics issues in other sectors

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- *Type-I seesaw:*
  GUT-inspired scenario $\Rightarrow$ *one* ν *− mass eigenvalue* $\approx m_t^2/m_N$

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- *CP-violating phase, octant information, mass hierarchy measurement,....*
  $\longrightarrow$ Connection between ν's and the overall canvas of new physics?

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- *Neutrino factories:*
  - *High-energy muon beam*
    (capable of tau-production)
    can reveal useful facts
  - *Near detector data is quite important*
    in exploring new non-oscillation physics

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- *The mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ are in fact* **mixing angles of the lepton sector** *Important conclusions are expected via the demonstration of deeper connections between PMNS elements and lepton flavour violation*

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- *However, all these constraints can be bypassed/modified: food for considerable thought in the near future*

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- *Some points that deserve serious thought in the near future:*
  - *Multi-component DM*
  - *Asymmetric DM*
  - *Thermal and Non-thermal DM candidates coexisting*
  - *How much importance to accord to the 'WIMP miracle'?*
  - *All implications of composites, solitons BE condensates... as DM candidates*

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- *R-parity violating SUSY: leads to neutrino mass generation and is consistent with long-lived axino/gravitino DM*
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- *A 'Dark Sector' (χ) with $n_\chi \approx n_B$ to start with*

  $\chi - \overline{\chi}$ *asymmetry generated*

  Dilution via expansion as well as annihilation

  $\chi\overline{\chi} \longrightarrow f\overline{f}$ *(say)*

  $\Rightarrow$ *One bewteen* χ *and* $\overline{\chi}$ *left*

  Finally, $\Omega_B/\Omega_\chi \approx m_B/m_\chi$

  $\Rightarrow$ *Relatively light DM implied*

Asymmetry between χ and $\overline{\chi}$ may arise via

- *Out-of-equilibrium decays of heavy particles*
- *Affleck-Dine mechanism*
- *First order phase transition as in electroweak baryogenesis*
- *Asymmetric freeze-out or freeze-in*
- *Violation of Sakharov conditions through CPT-violation*

Curiosity: some possible link between the dynamics underlying baryon asymmetry and residual dark matter density

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- *A 'Grander Design' ?*
  We ought to know sooner or later...

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- *But maybe one can worry why gymnastics is required in MSSM to reproduce* m_h*...*

General remarks: SUSY

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  - *DM candidate(s): not-so-artificially*
  - *Quadratic divergence cancellation to all orders*
  - *A better achievement of Grand Unification*
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- *High-scale scenarios with Grand Deserts may not be viable.....richer, step-by-step UV completion may be envisioned*

GUT and left-right symmetry.....

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  - *Does the imperfect convergence of coupling constant trajectories indicate something other than SUSY?*
- *L-R symmetry*
  - *Aesthetic appeal*
  - *A bottom-up approach to GUT?*
  - *The neutrino sector: the possibility of relating Dirac and Majorana mass matrices*
  - *Q: Why should the scale (of W_R) be within our experimental reach?*
  - *If it is not, can an effective field approach uncover signatures?*

TeV-scale signature of extra dimensions...

- *Scenarios with flat extra dimensions: it may be difficult to sustain motivation*
- *Warped geometry: still promising, if resonances are hinted at least at high-luminosity LHC*
- *Some germane issues: explanation of flavour—effect of back reaction—multiple warping*
- *Extra warped dimension with graviton as well torsion in the bulk: an explanation of why the 4d universe is controlled by curvature rather than torsion*
- *.....*

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- *the strong interaction sector: how can one remain undisturbed about confinement, and continue with semi-empirical approaches?*
- **A billion-dollar question: Are we thinking of new physics all in the wrong direction?**

Extremely risky to guess, so....

'Build today, then, strong and sure,

With a firm and ample base

And ascending and secure

Shall tomorrow find its place'

— H. W. Longfellow