# STRINGS 2012

Munich, 23-28 July, 2012

# 40 years since GGRT: some personal considerations


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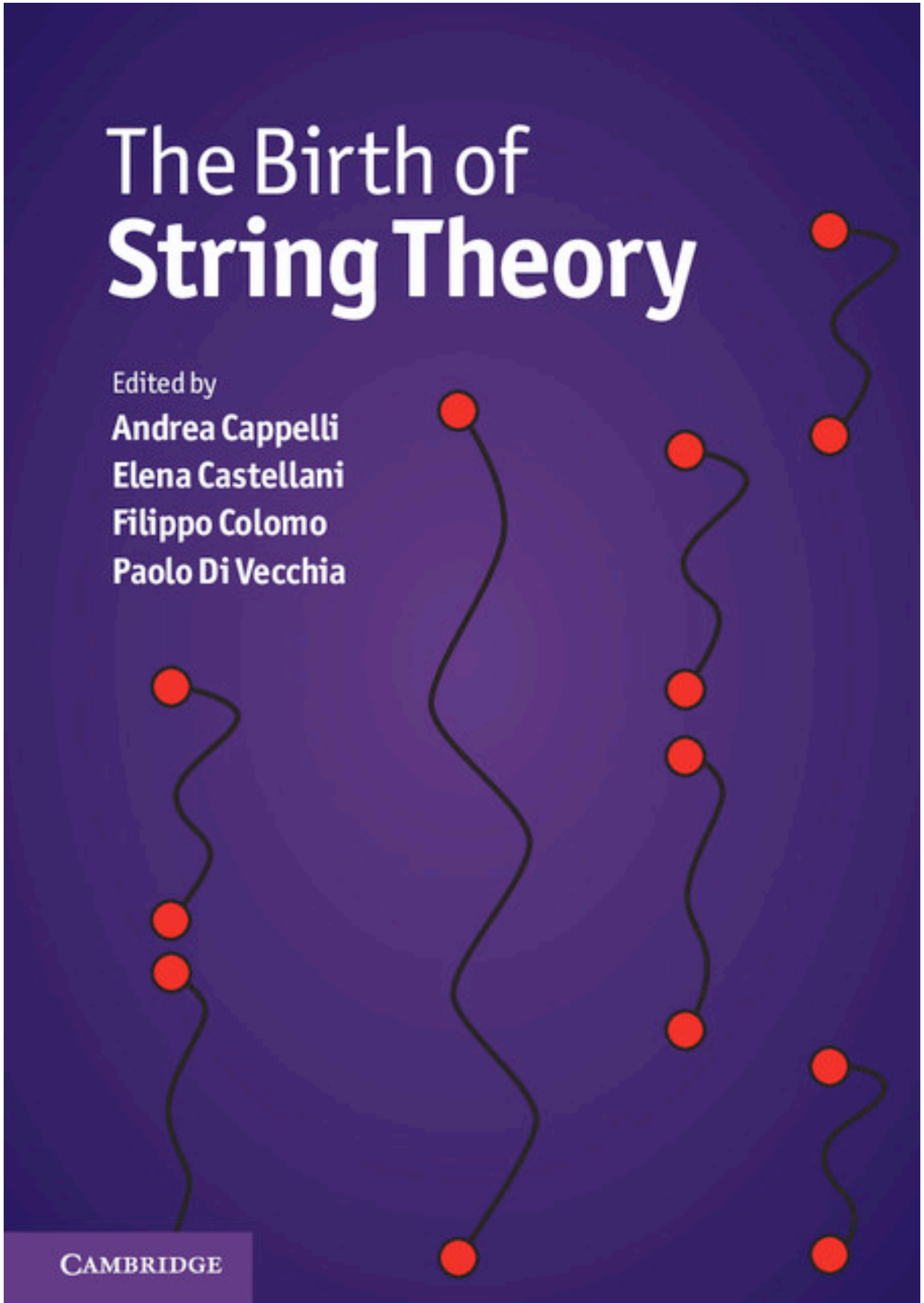
October 1972: GGRT

The Dual Resonance Model

becomes

String Theory!

(and is abandoned soon after...)




# The Birth of String Theory

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# Part I

# Lessons from two success stories

and from their

puzzles/problems

# The Standard Model of Nature (updated July 4th, 2012)

1. A Gauge Theory with a light H for electro-weak and strong interactions.
2. General Relativity with a small $\Lambda$ for gravity.

can be written in one page!

$$\boxed{L_{SMN} = L_{SMG} + L_{SMP}^{(\text{gen. cov.})}}$$

$$\begin{aligned} L_{SMG} &= -\frac{1}{16\pi G_N}\sqrt{-g}\; R(g) \\ &+ \frac{1}{8\pi G_N}\sqrt{-g}\; \Lambda \end{aligned}$$

$$\begin{aligned} L_{SMP} &= -\frac{1}{4}\sum_a F^a_{\mu\nu}F^a_{\mu\nu} + \sum_{i=1}^{3} i\bar{\Psi}_i\gamma^\mu D_\mu\Psi_i + D_\mu\Phi^* D^\mu\Phi \\ &- \sum_{i,j=1}^{3}\lambda^{(Y)}_{ij}\Phi\Psi_{\alpha i}\Psi^c_{\beta j}\epsilon_{\alpha\beta} + c.c. \\ &+ \mu^2\Phi^*\Phi - \lambda(\Phi^*\Phi)^2 \\ &- \frac{1}{2}\sum_{i,j=1}^{3} M_{ij}\;\nu^c_{\alpha i}\nu^c_{\beta j}\epsilon_{\alpha\beta} + c.c. \end{aligned}$$

New!

Confirmed?

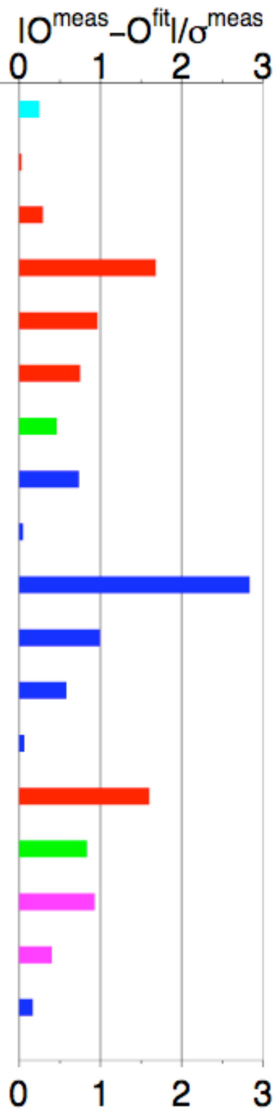
# The SM of Elementary Particles

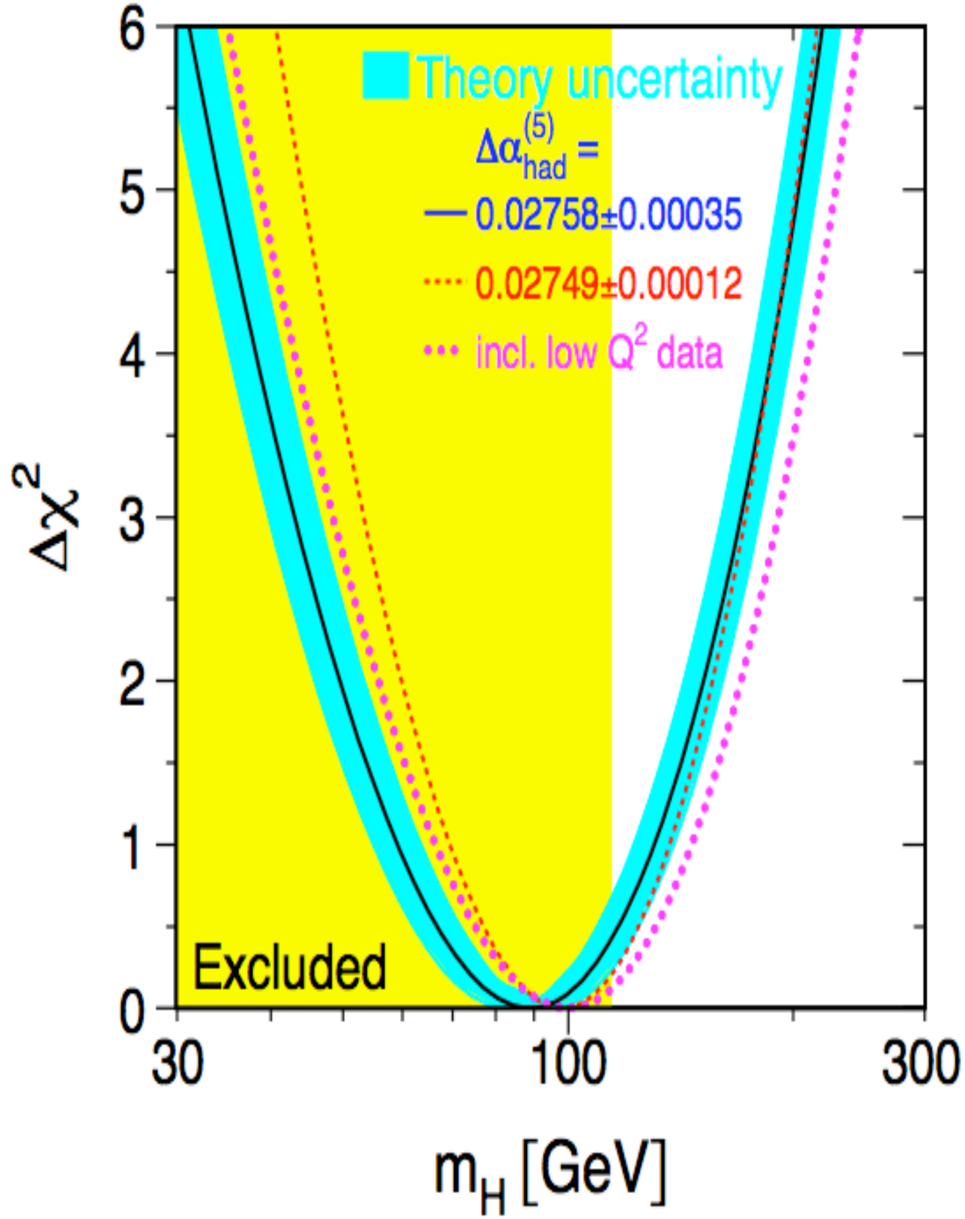
Very widely tested in accelerator experiments
(... LEP, HERA, Tevatron, LHC)

Its quantum-relativistic nature manifests itself
through real and virtual particle production
Taking this into account is essential for agreement
between theory and experiment.
Gave first definite indications in favor of a light H!

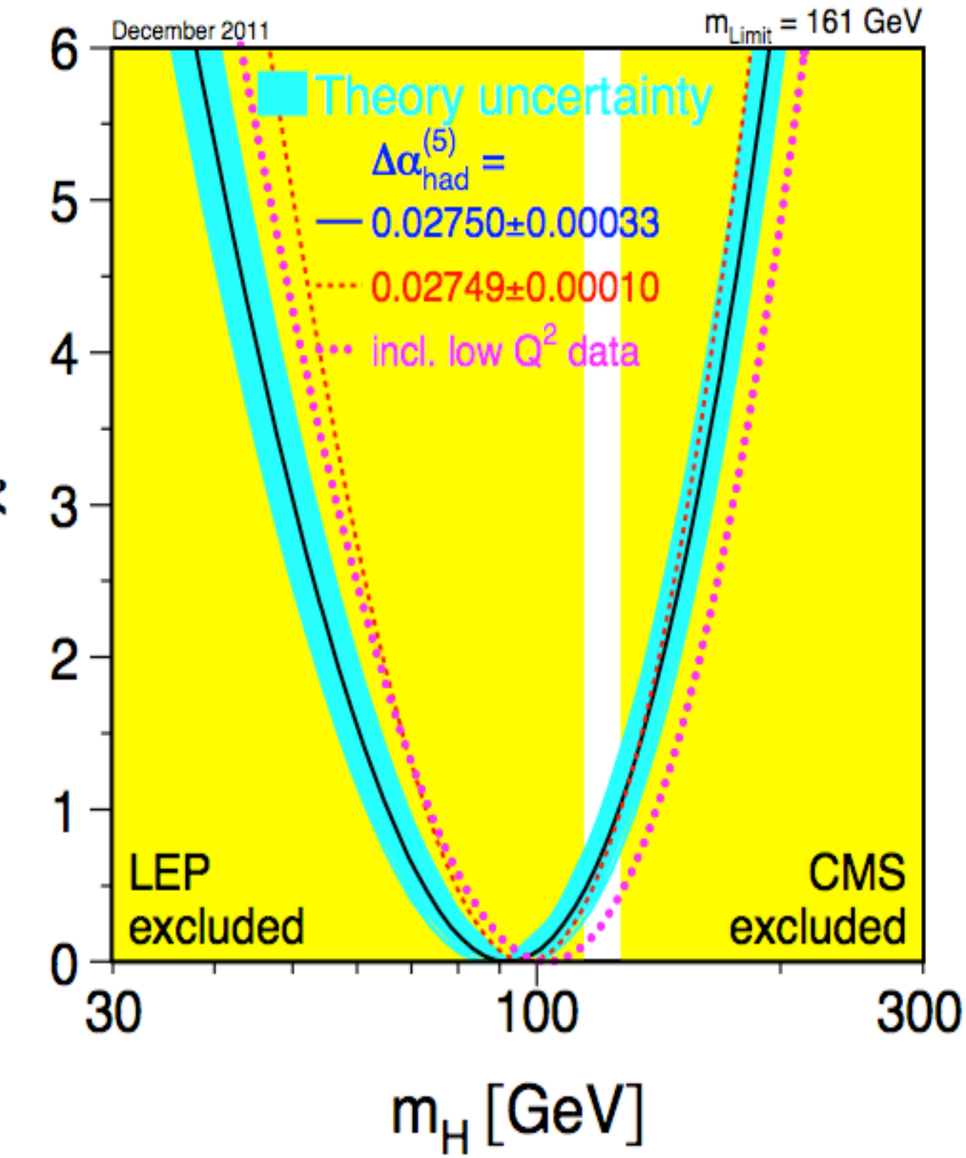
# After LEP

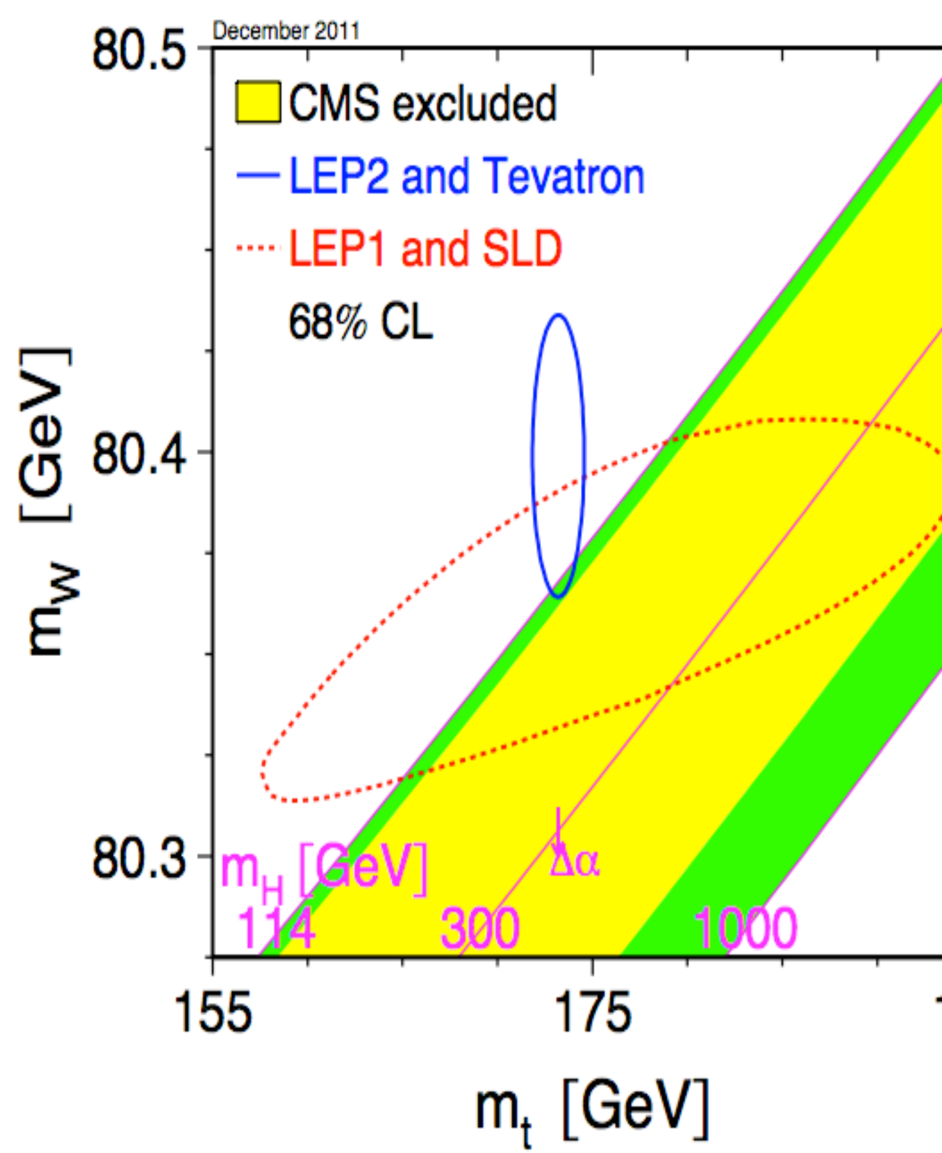
| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02767 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma_{had}^{0}$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.743 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01643 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1480 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21581 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1722 |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1037 |
| $A_{fb}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_b$ | 0.923 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.027 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1480 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.404 ± 0.030 | 80.376 |
| $\Gamma_W$ [GeV] | 2.115 ± 0.058 | 2.092 |
| $m_t$ [GeV] | 172.5 ± 2.3 | 172.9 |



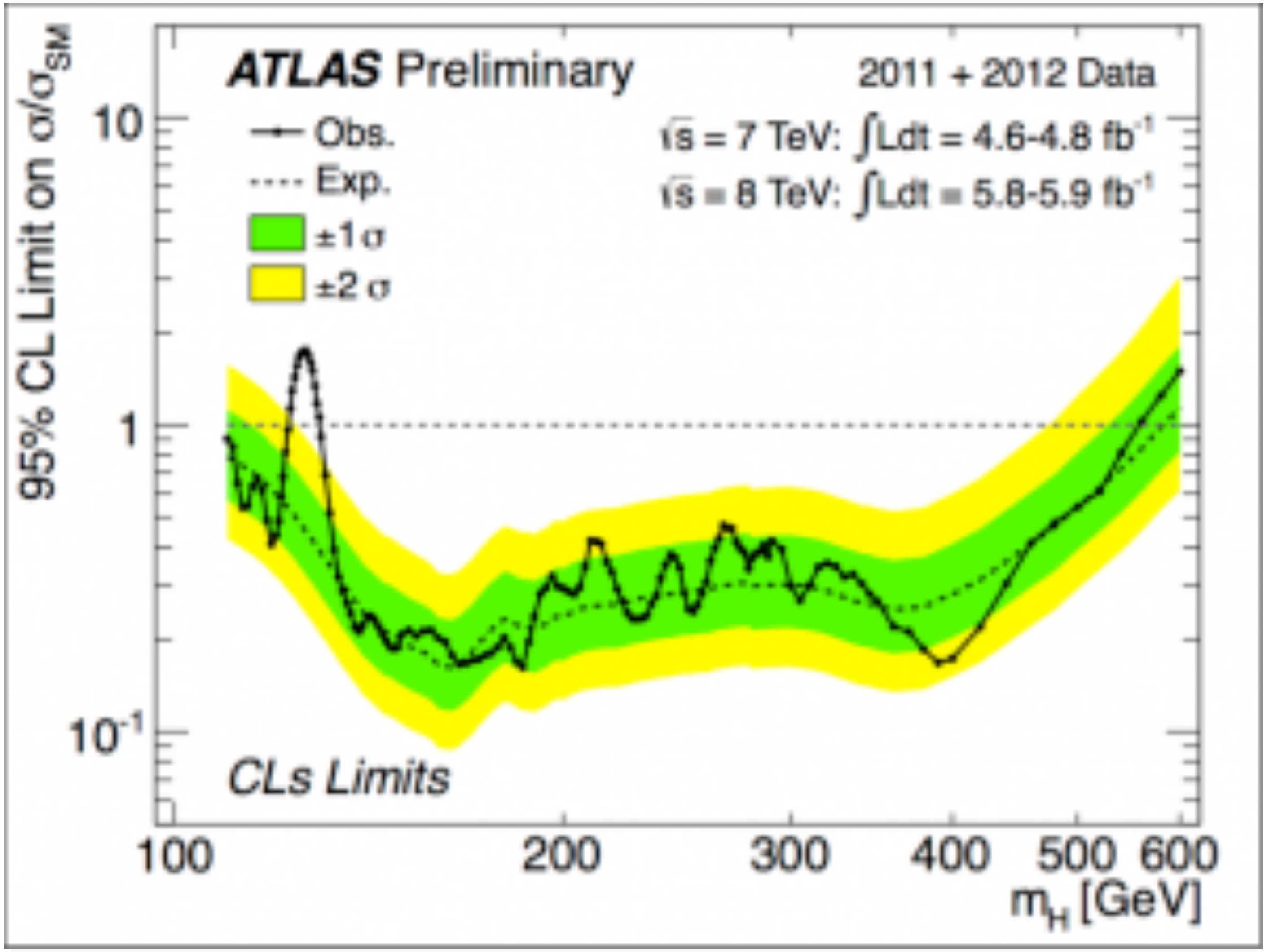



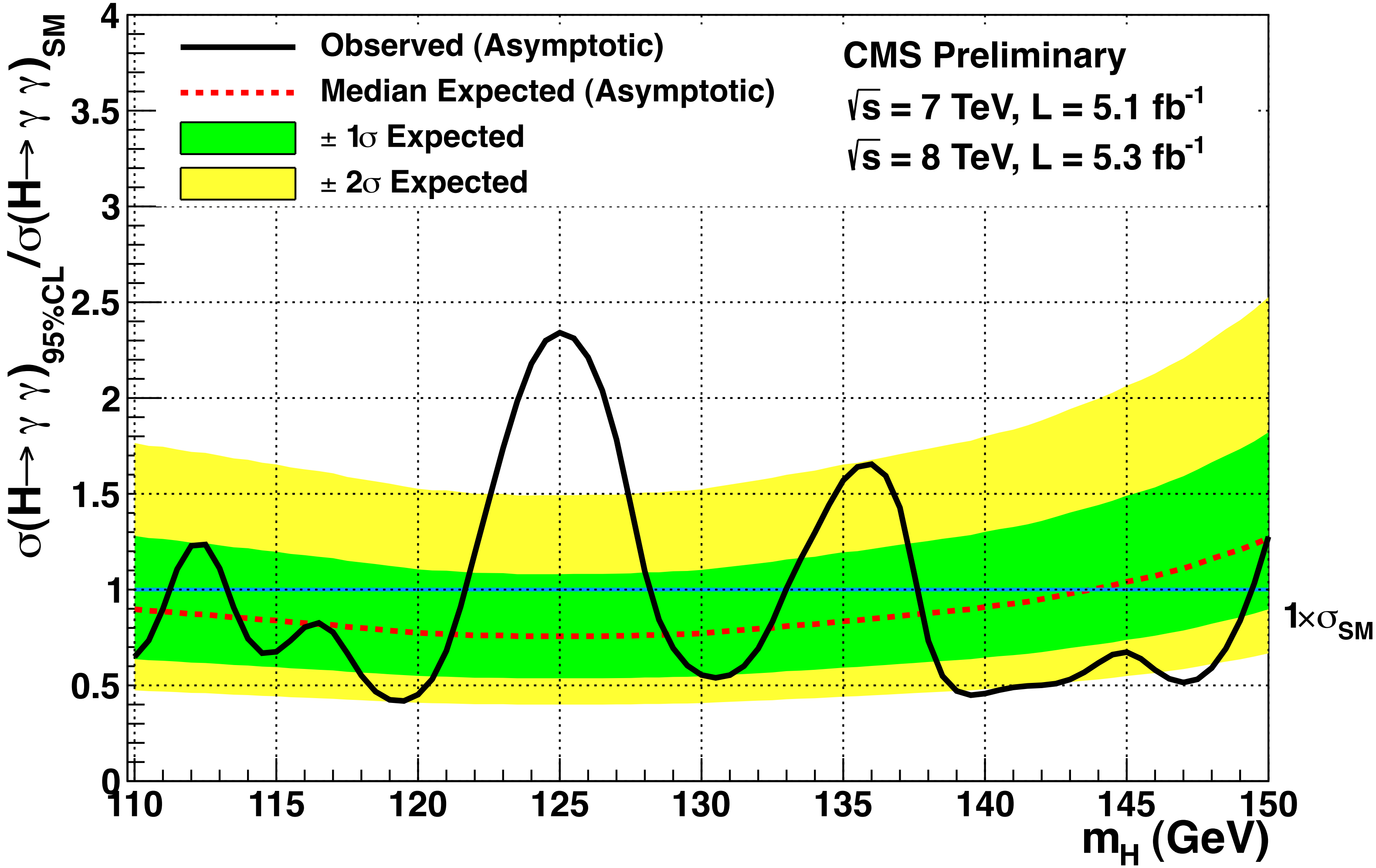
# After 5 $fb^{-1}$ (2011 LHC run @ 7 TeV)



# After ~ 6 $fb^{-1}$ more (2012 run @ 8 TeV)






(a) mass-fit MVA.

# The SM of Gravity

Equivalence pr. tested with incredible precision (universality of free-fall)

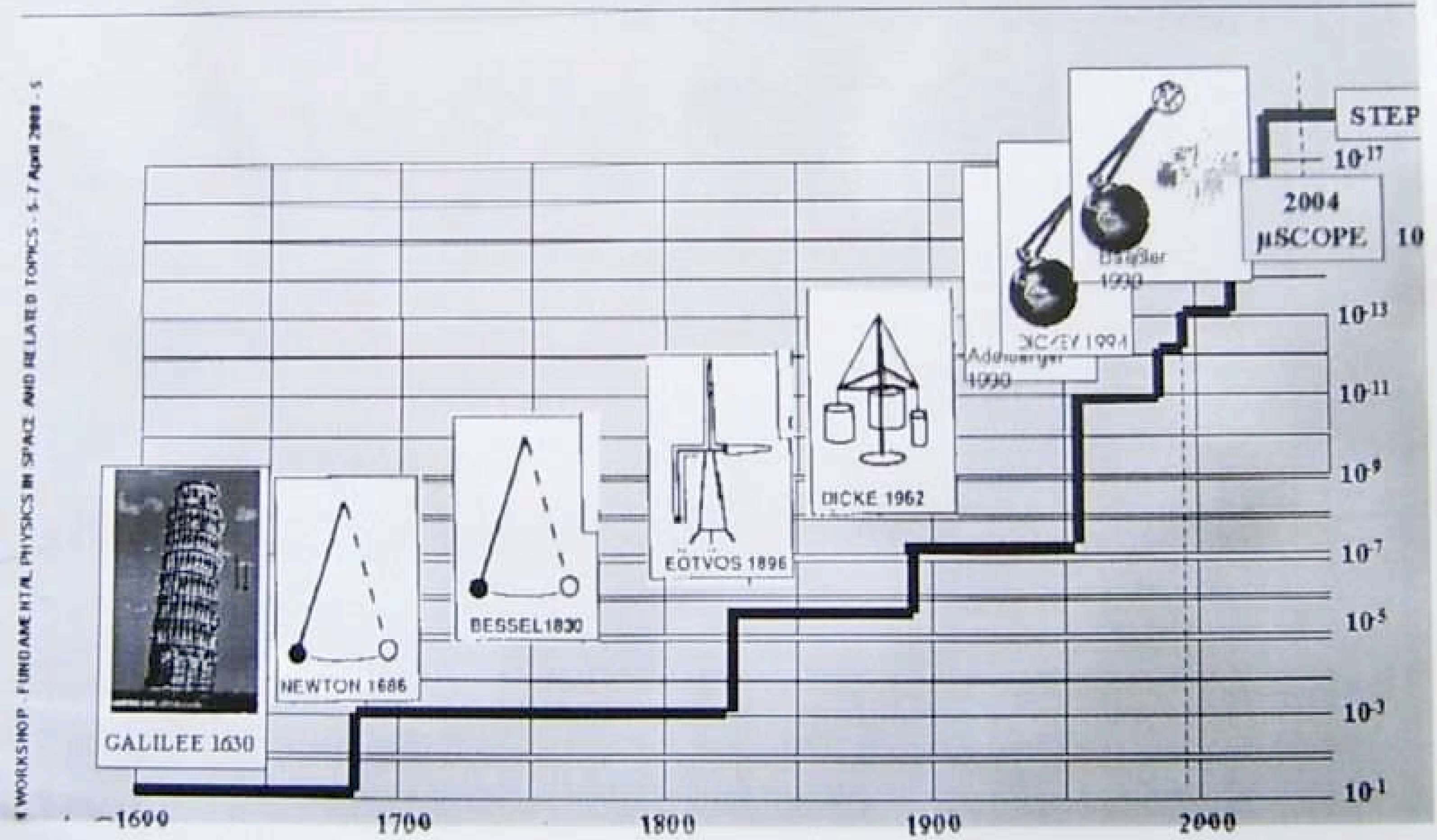
GR corrections better and better tested

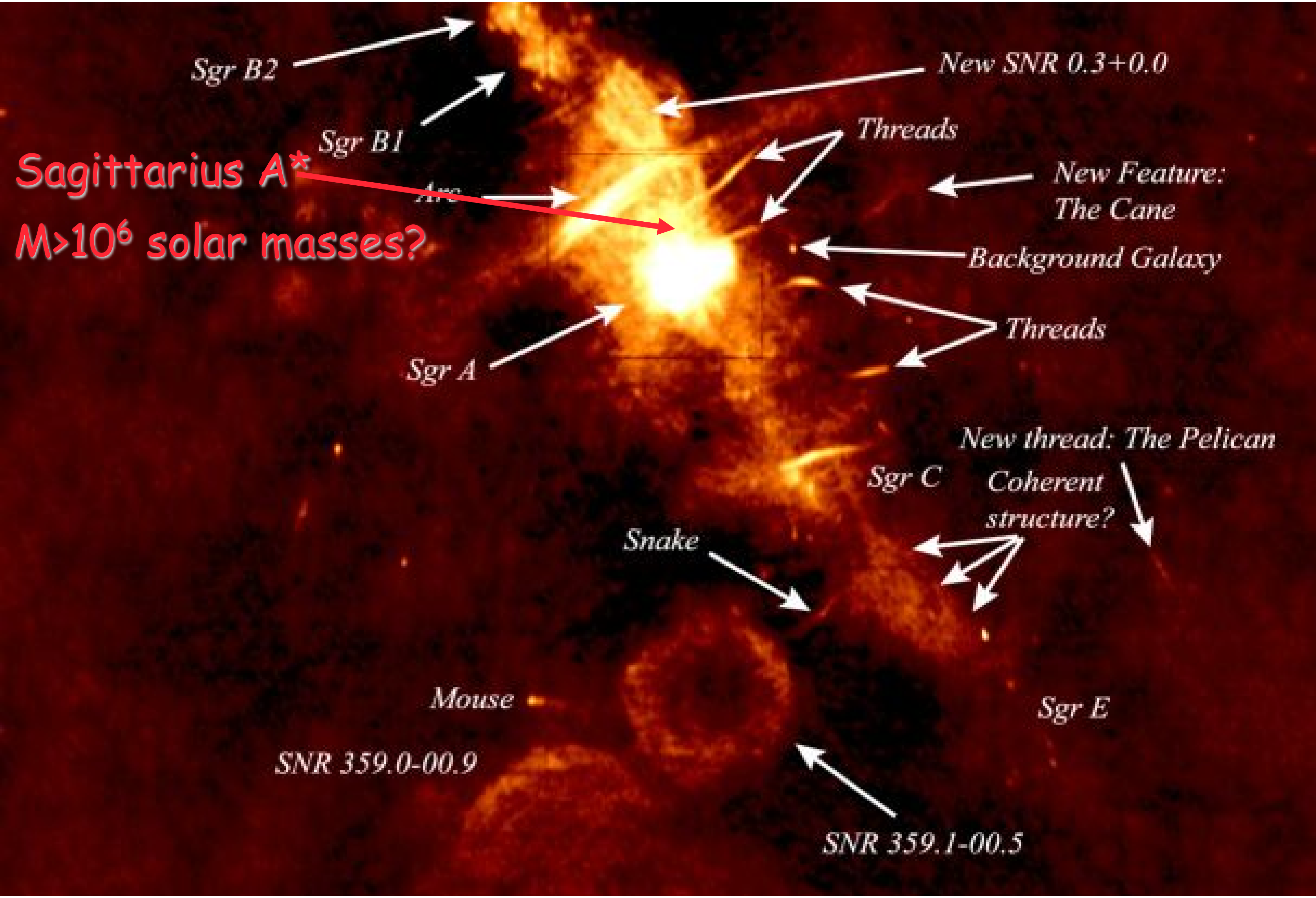
New predictions:

1. Black holes (overwhelming evidence)
2. Gravitational waves (indirect evidence)

NB: All tests of Classical GR!!

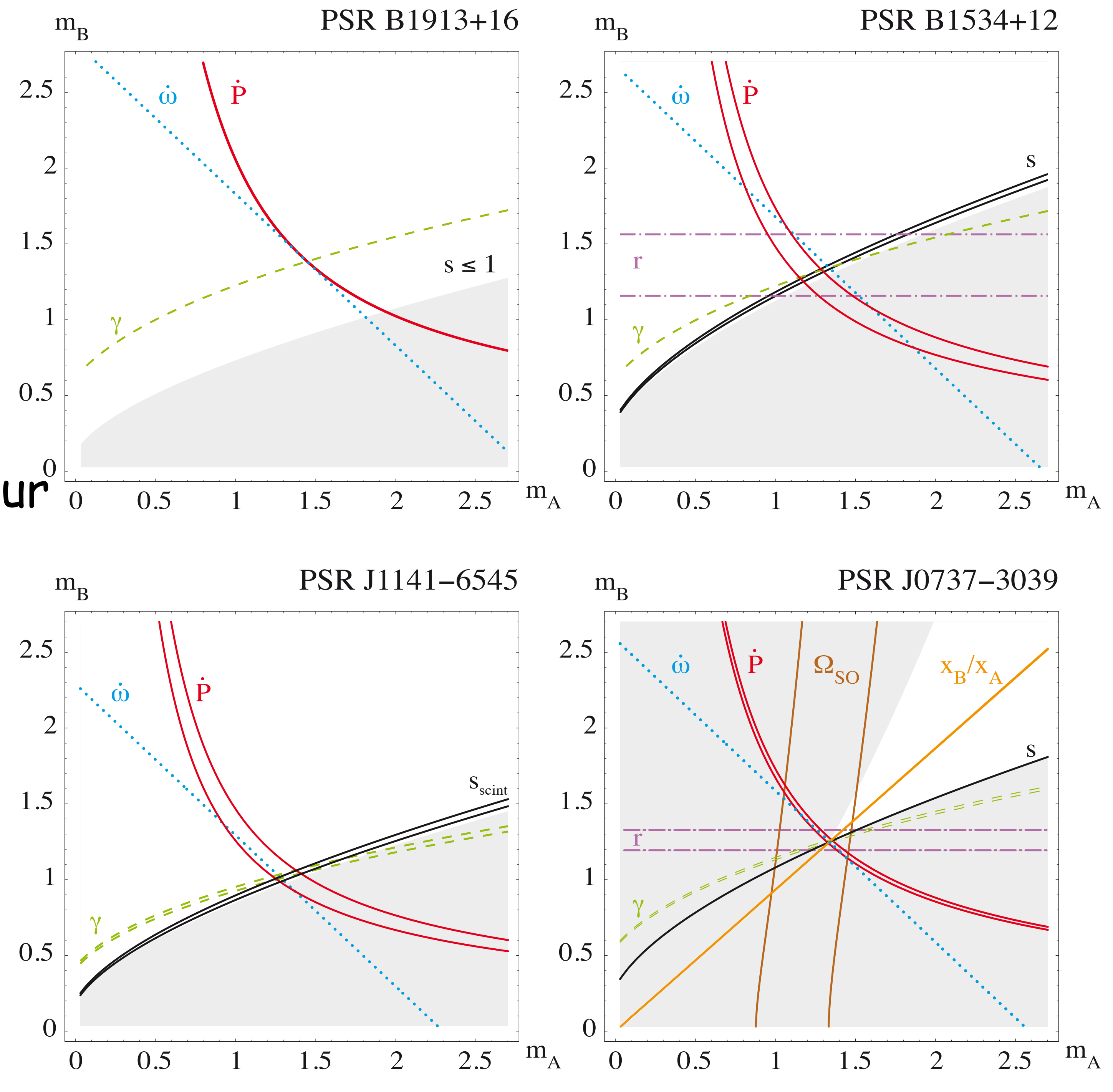
# Increasing precision of UFF tests





Sagittarius A*
M>10^6 solar masses?
Sgr B2
Sgr B1
Arc
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5

Courtesy of Thibault Damour (review for particle data group)

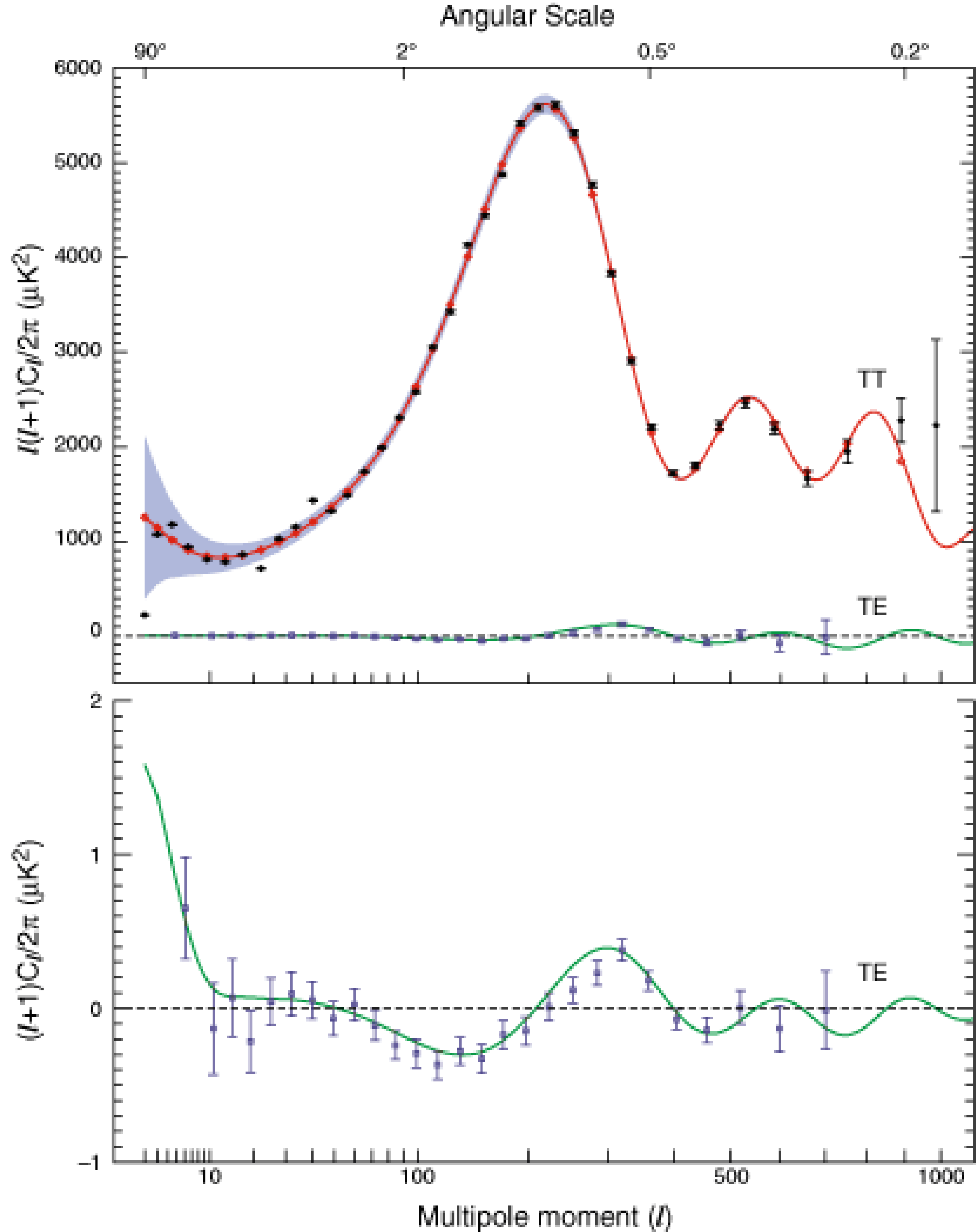


# …and of Cosmology

The "Concordance Model"

# CMB vs. inflation

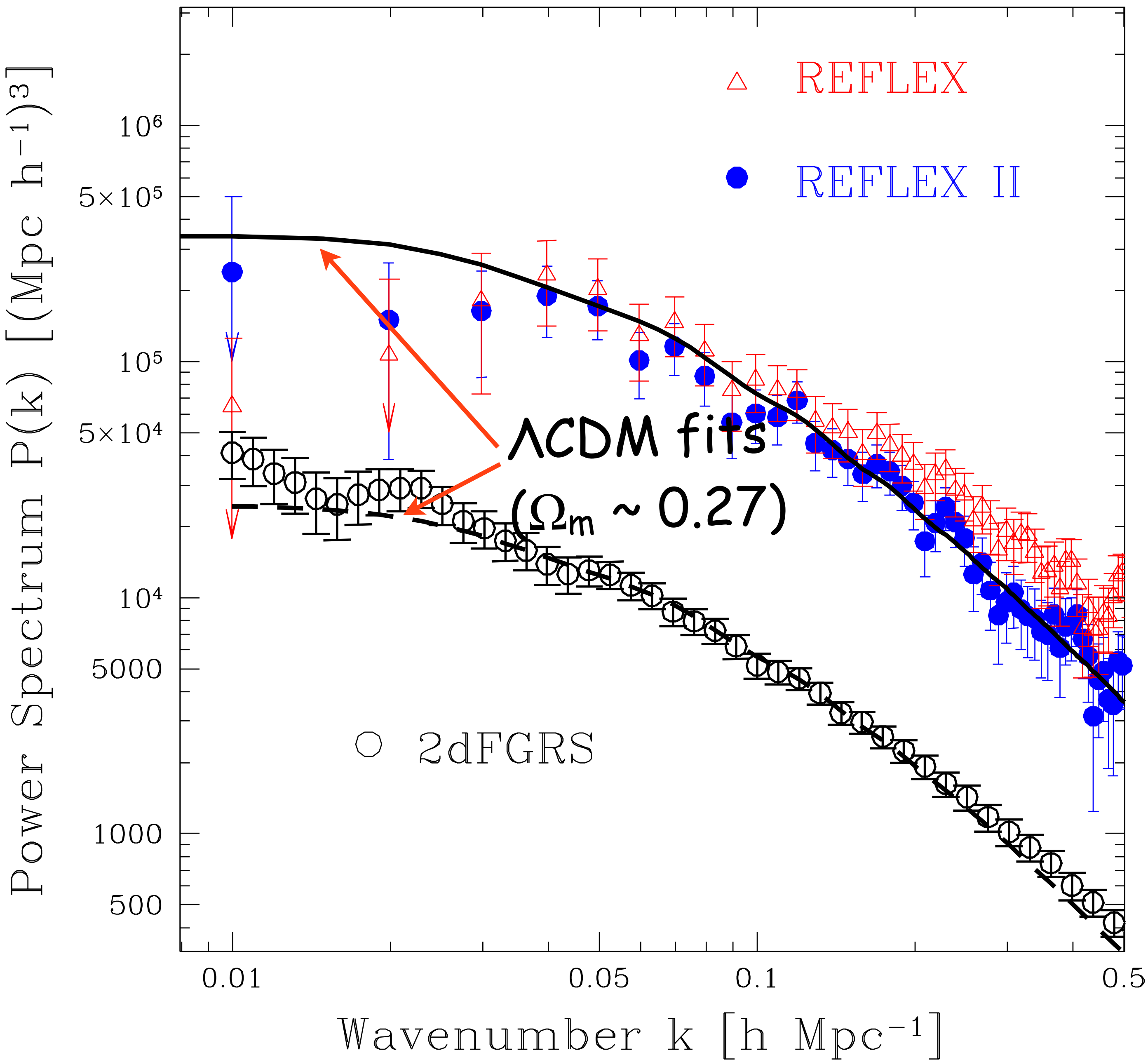
TT and TE correlations from WMAP
(while waiting for PLANCK?)
Peak position favors
spatially flat Universe



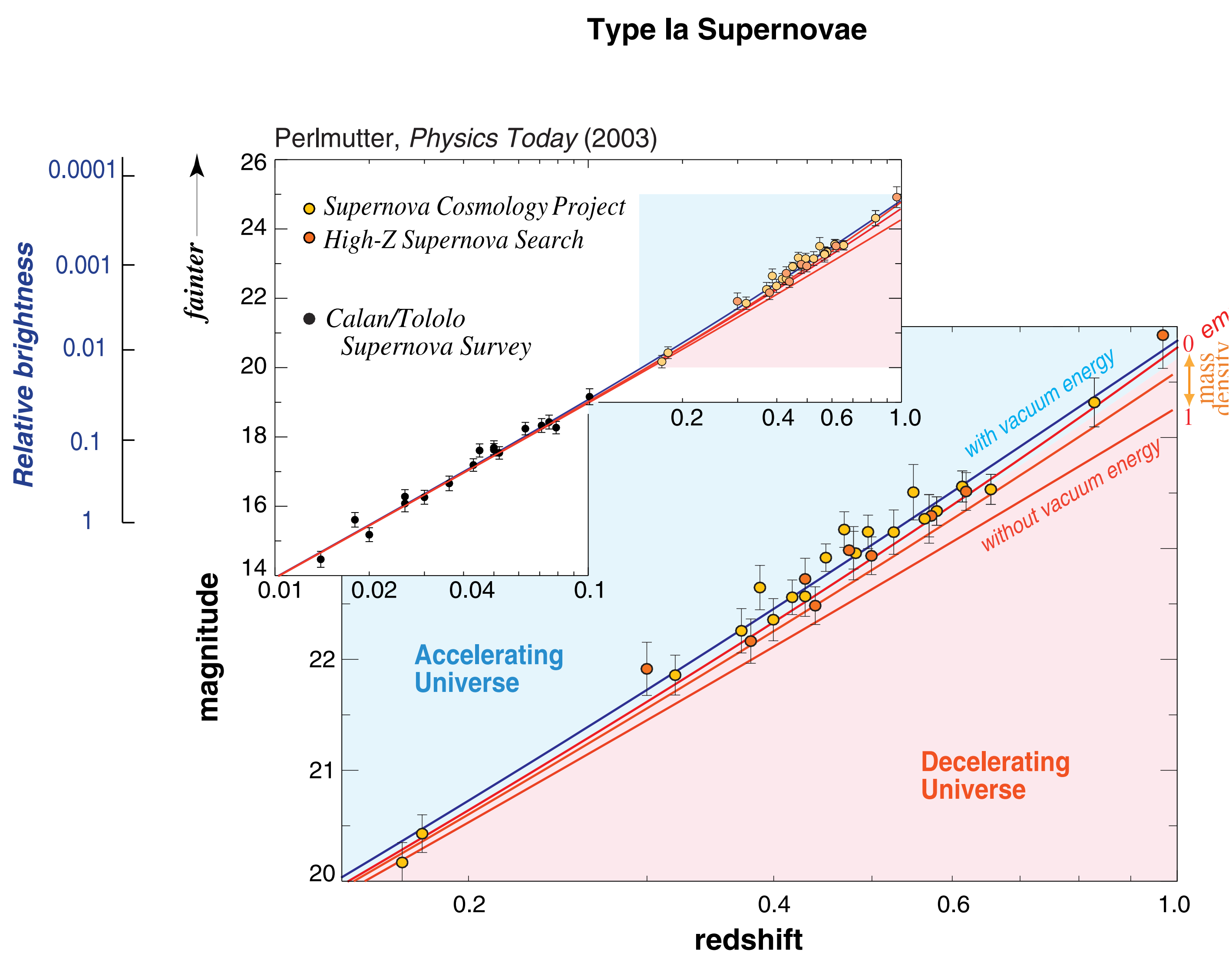
The SMEP and the SMG
nicely combined in inflationary cosmology.
NB: Semiclassical quantization of the geometry is part of the game explaining the large-scale structure of the Universe

# LSS

*Balaguera-Antolínez et al.* Astro-ph.10.12.1322



# Cosmic acceleration



# Is dark energy unavoidable?

- Our Universe is not homogeneous on "small" scales.
- In 1202.1247, 1207.1286 Ben-Dayan, Gasperini, Marozzi, Nugier & GV have re-examined $d_L(z)$ relation using gauge-invariant light-cone averaging in presence of (stochastic) inhomogeneities.
- No IR or UV sensitivity encountered at 2nd order, unlike for other (more formal) averages.
- Effect much larger than naively expected ($10^{-10}$) but still too small to mimic a sizable $\Omega_\Lambda(z)$.
- Could be relevant for its precise determination because of the predicted intrinsic scatter.

# Gauge invariant light-cone averages

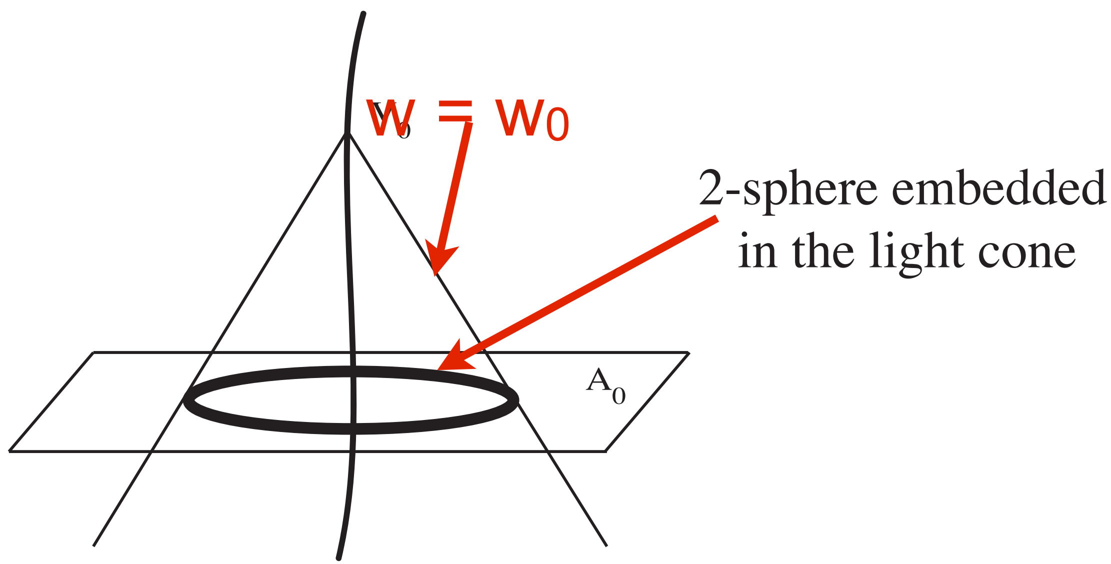
## Adapted coordinates for light-cone averaging

(Gasperini, Marozzi, Nugier & GV, 1104.1167)

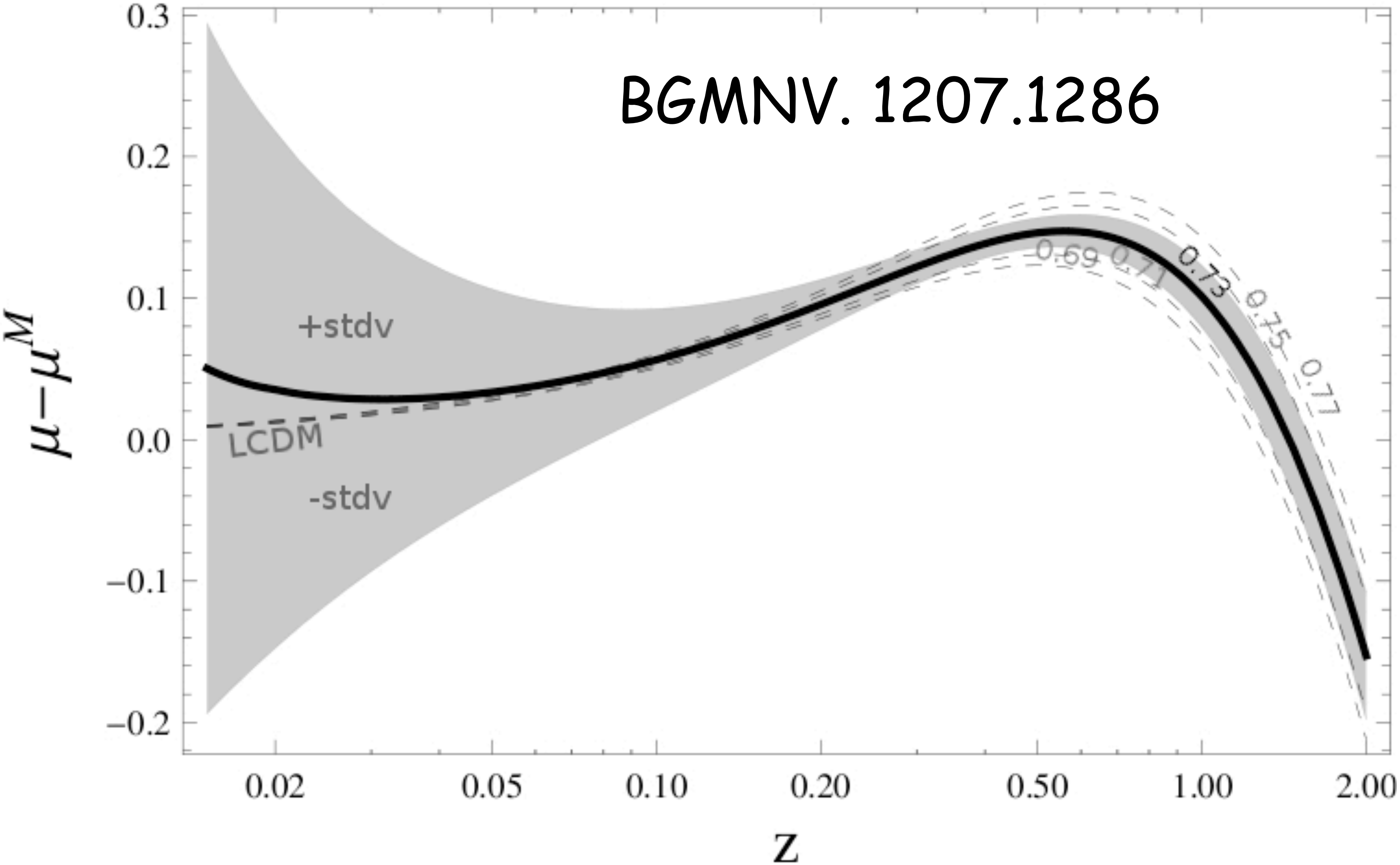
$$ds^2 = \Upsilon^2 dw^2 - 2\Upsilon dw d\tau + \gamma_{ab}(d\theta^a - U^a dw)(d\theta^b - U^b dw)$$

$w = w_0$ defines our past light cone $\qquad (1+z) = \frac{\Upsilon_o}{\Upsilon_s}$

luminosity distance $d_L$ simply related to $\gamma = \det \gamma_{ab}$

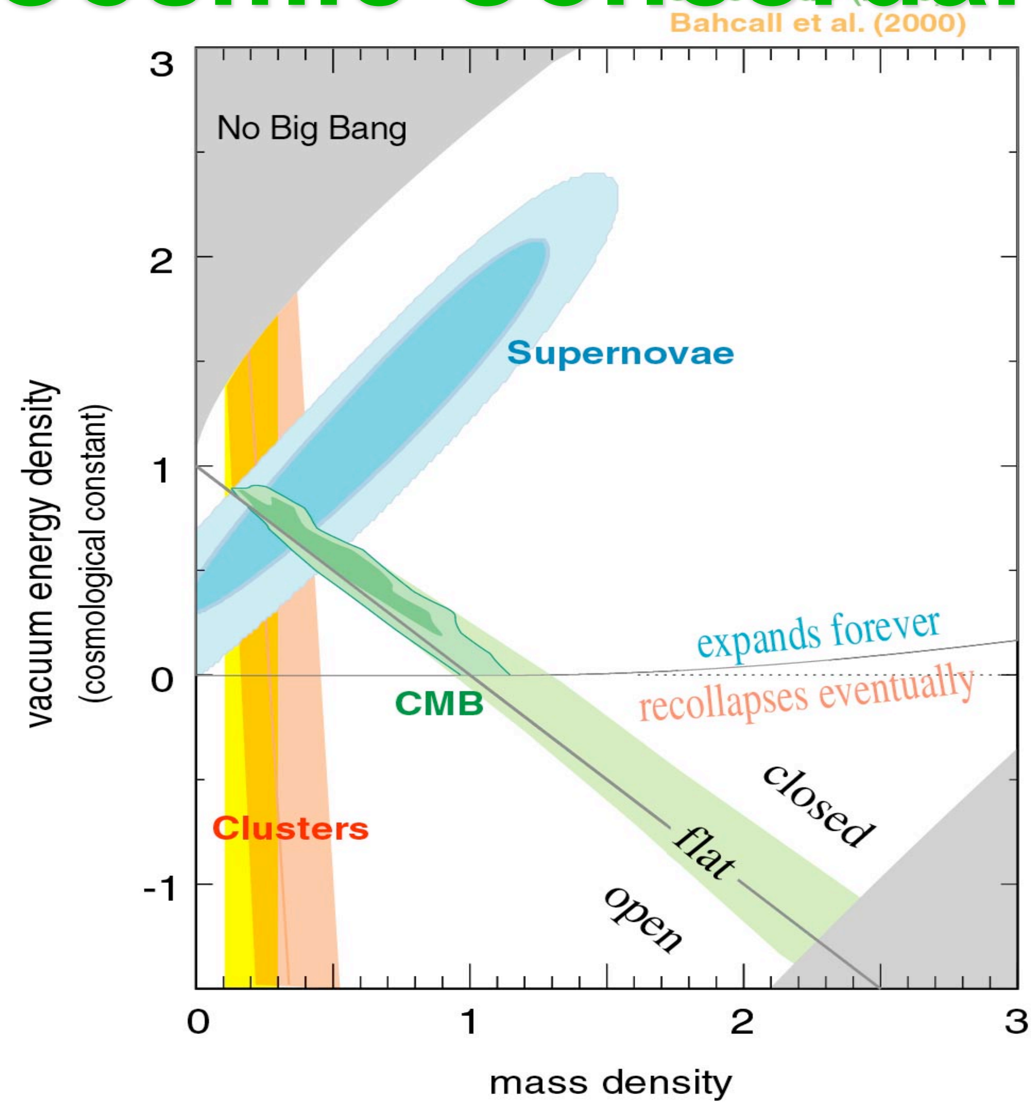


$$\langle d_L^{-2} \rangle(z, w_0) = \frac{4\pi(1+z)^{-4}}{\int d^2\theta \sqrt{\gamma(w_0, \tau(z, \theta^a), \theta^b)}}$$

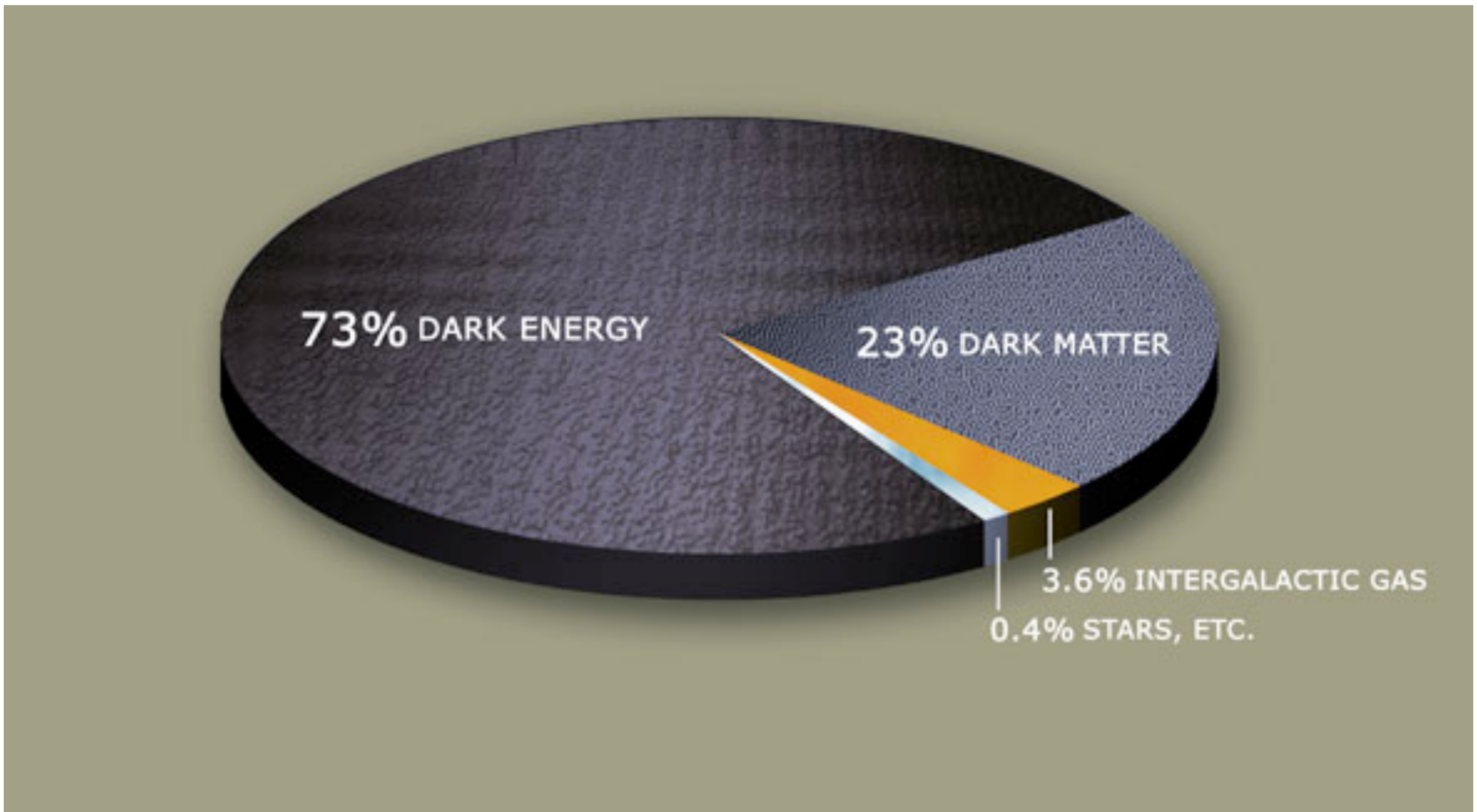


# Putting all together

# Cosmic Concordance



# The cosmic fluid composition pie…



Strong evidence that our SMN cannot be the full story...
but what have we learned?

Nature likes $m=0$, $J=1, 2$ particles...

This is why it is well described by theories with either gauge or diff. invariance

Many phenomenological puzzles for which we find hardly any clues from presently accessible length/energy scales

# Particle physics puzzles

1. Why $G = SU(3) \times SU(2) \times U(1)$?
2. Why do the fermions belong to such a bizarre, highly reducible representation of $G$?
3. Why 3 families? Who ordered them? (Cf. I. Rabi about μ)
4. Why such an enormous hierarchy of fermion masses?
5. Can we understand the mixings in the quark and lepton (neutrino) sectors? Why are they so different?
6. What's the true mechanism for the breaking of $G$?
7. If it's the Higgs mechanism: what keeps the boson "light"?
8. If it is SUSY, why did we see no signs of it yet?
9. Why no strong CP violation? If PQSB where is the axion?
10. ...

# Puzzles in Gravitation & Cosmology

1. Has there been a big bang, a beginning of time?
2. What provided the initial (non vanishing, yet small) entropy?
3. Was the big-bang fine-tuned (homogeneity/flatness problems)?
4. If inflation is the answer: Why was the inflaton initially displaced from its potential's minimum?
5. Why was it already fairly homogeneous ?
6. What's Dark Matter?
7. What's Dark Energy? Why is $\Omega_\Lambda$ O(1) today?
8. What's the origin of matter-antimatter asymmetry?
9. …

# Missing quantum corrections?

- Radiative corrections to marginal and irrelevant operators have been "seen" in precision experiments:
    - running of gauge couplings, anomalous dimensions
    - anomalies in global symmetries (U(1)-problem)
    - effective 4-Fermi interactions (neutral-K system)
- Some to relevant operators have not. Basically:
    - the Higgs mass (hierarchy problem)
    - the cosmological constant (120 orders off?)
- Latter(former) (in)sensitive to short-distance physics.
- Telling us, once more, that SM & GR are not the full story?

# Theoretical/conceptual problems

In spite of the common denominator of gauge and gravity the SMN is "limping".

The two legs it is resting on are uneven.

GR should be elevated to a full quantum theory

Two reasons to be unhappy about leaving gravity classical:

1. Ubiquitous classical singularities;
2. The quantum origin of LSS.

The SMN's puzzles & problems appear to be related to our ignorance about short-distance physics!

Insisting on better UV behavior has paid off

(from Fermi to GWS)

Q: Is it supersymmetry?

Appealing for solving some puzzles (hierarchy, dark matter, grand unification, ...)

It will be explored at LHC up to some energy scale...wait and see...

# Q: Is it Quantum String Theory?

- Provides a UV completion (with a scale!)
- Provides the massless particles the SMN needs... plus more (moduli = Achille's heel?)
- Unifies (or even may reduce) gravity with (to) other forces (AdS/CFT).
- Sheds light on quantum Black-Holes (stat. mech. interpr. of $S_{BH}$, AdS/CFT)

# Part II

## Two gedanken experiments

for exploring

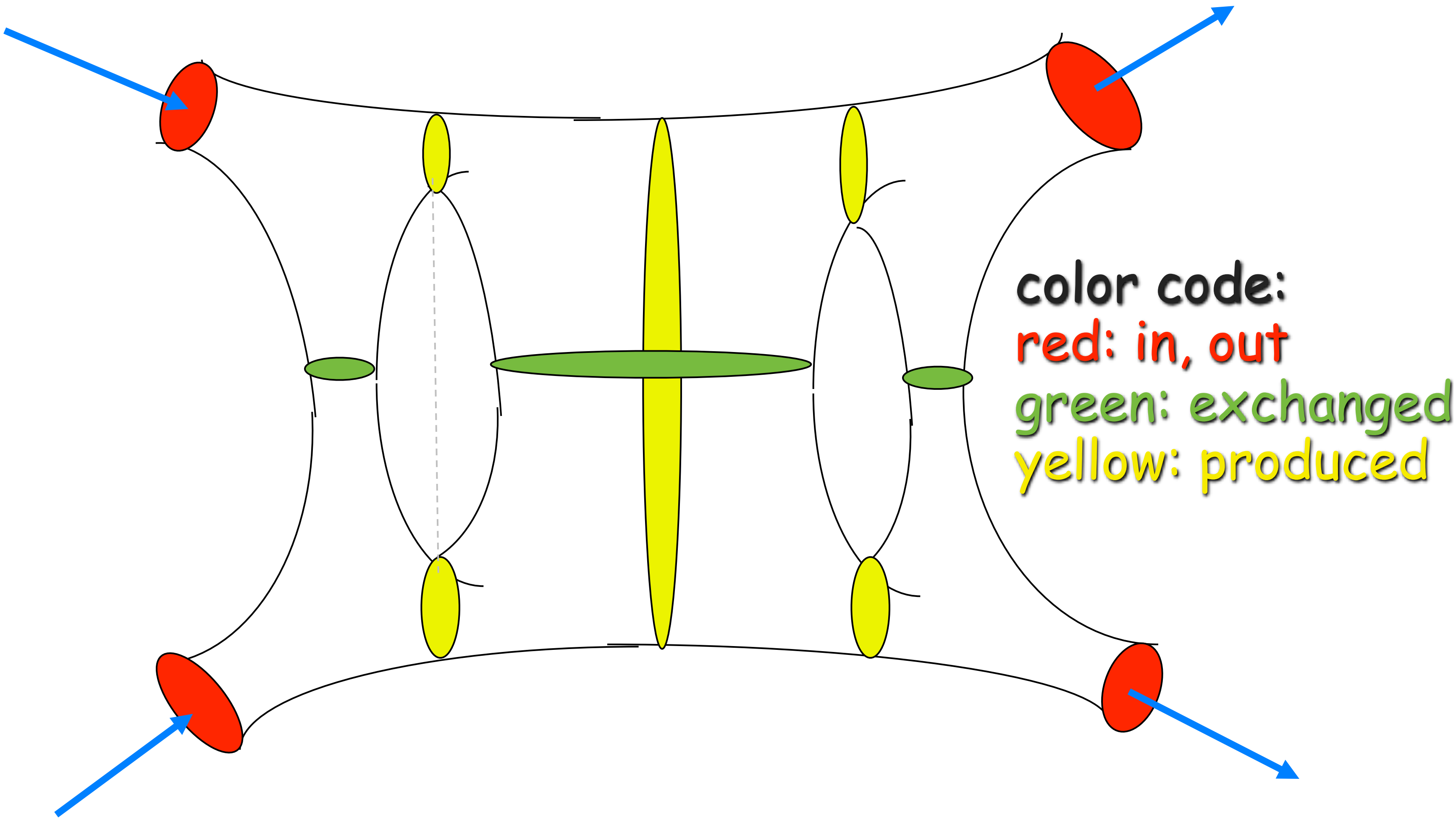
## quantum string gravity

# I. Transplanckian-energy string-string collisions in flat spacetime

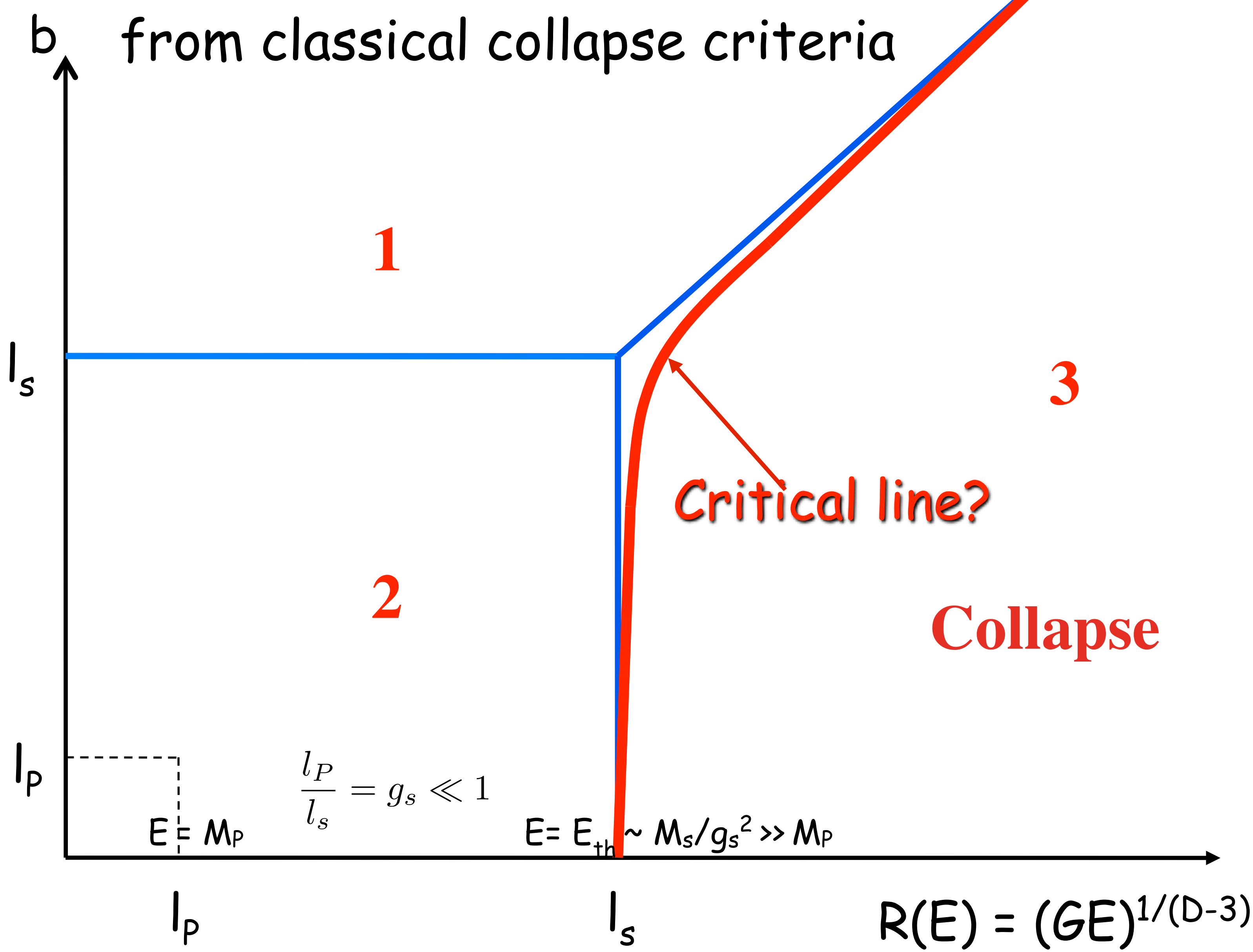
(Amati, Ciafaloni, GV + ...: 1987-2010)

## An executive summary

# Example: a two-loop contribution



expected "phase diagram" from classical collapse criteria



- An ideal theory lab. for studying several conceptual issues arising from interplay of QM and gravity within a fully consistent framework.

- In the weak-gravity regime ($b \gg R, l_s$) we reproduce classical expectations (grav. deflection, tidal effects from emerging geometry) within a unitarity-preserving semiclassical description.

- When string-size effects dominate ($l_s \gg R$) we found no evidence for BH formation (even for $b < R$) but rather a fast growth of multiplicity and softening of the final state resembling Hawking radiation.

- As one moves to $R > l_s$ this should smoothly evolve into a BH-evaporation-like regime (not easy to study!).

- In the strong gravity regime ($R \gg b, l_s$) successes are still limited. Amusingly, a drastic approximation of the dynamics (ACV 2007) appears to reproduce at the semiquantitative level expectations based on classical collapse criteria.

- A general pattern seems to emerge where, at the quantum level, the sharp classical transition between the dispersive and collapse phases is smoothed out by QM.

- Many issues remain unsettled (in particular the saturation of unitarity) possibly due to our drastic approximations and/or to our lack of understanding of the BH singularity.

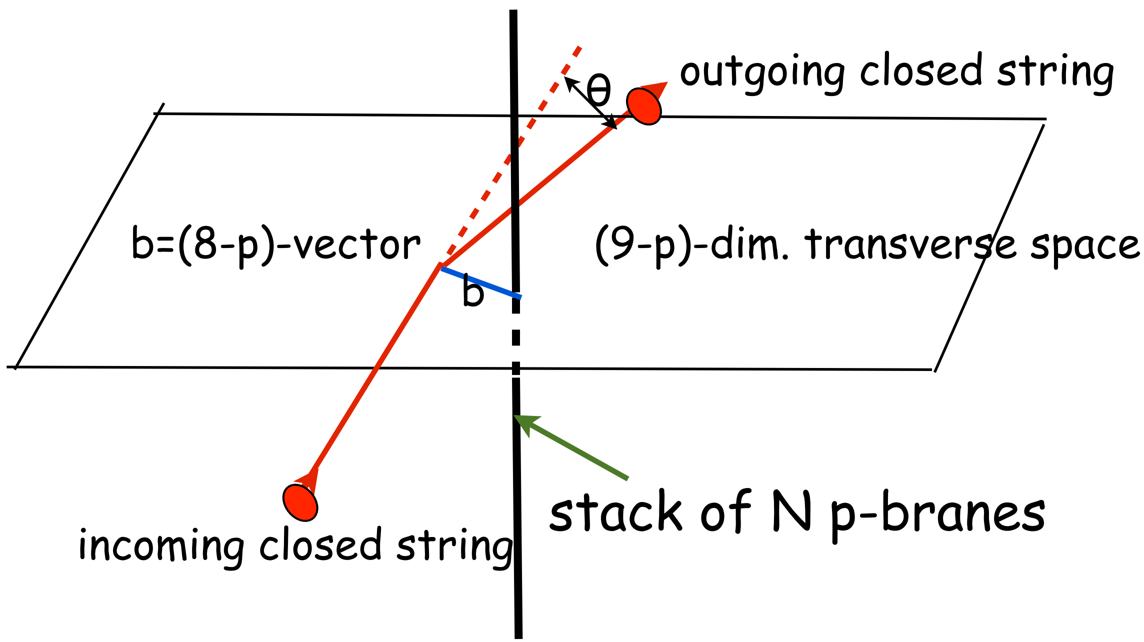
An easier problem?

High-energy string-brane collisions

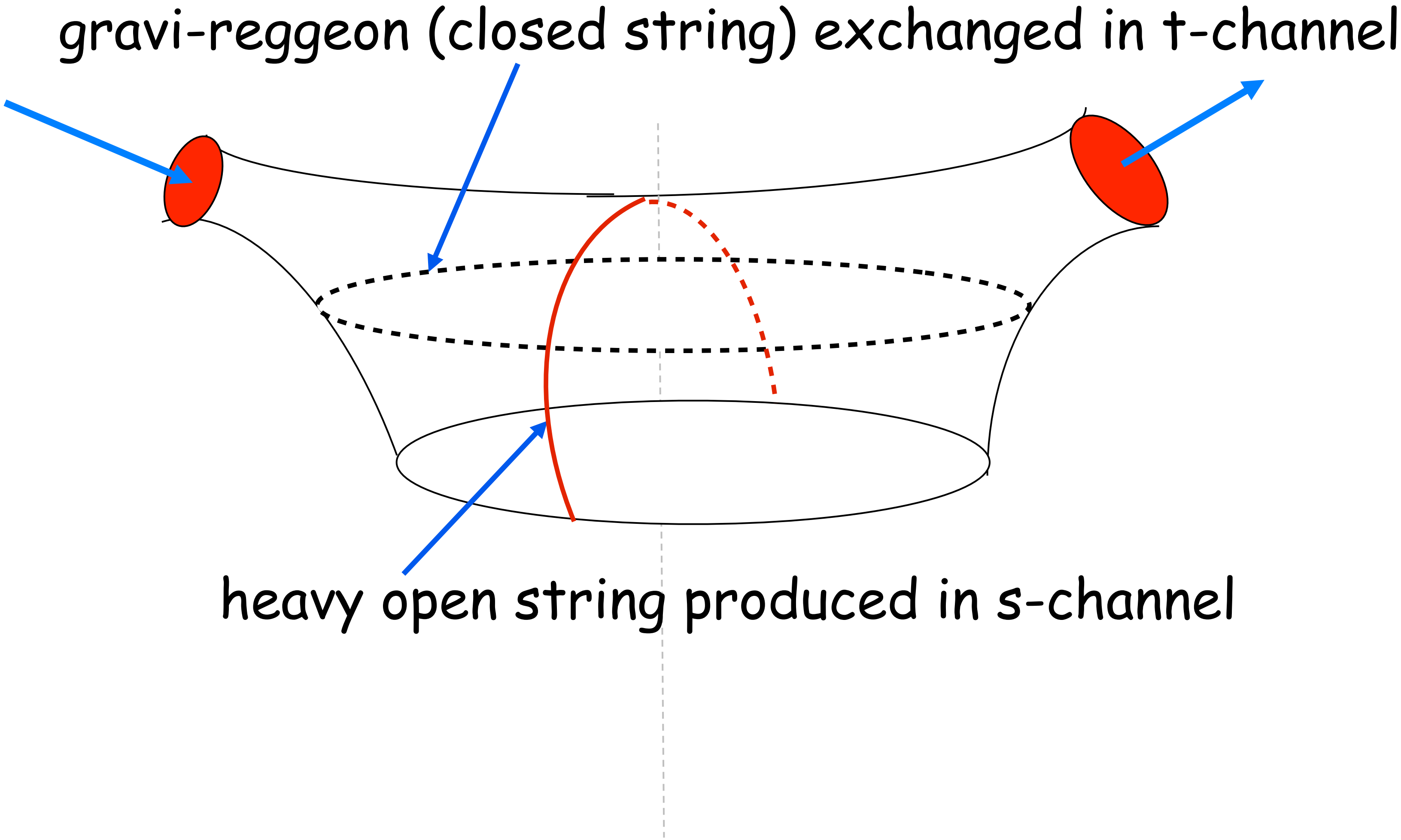
(in flat spacetime)

# High energy string-brane collisions

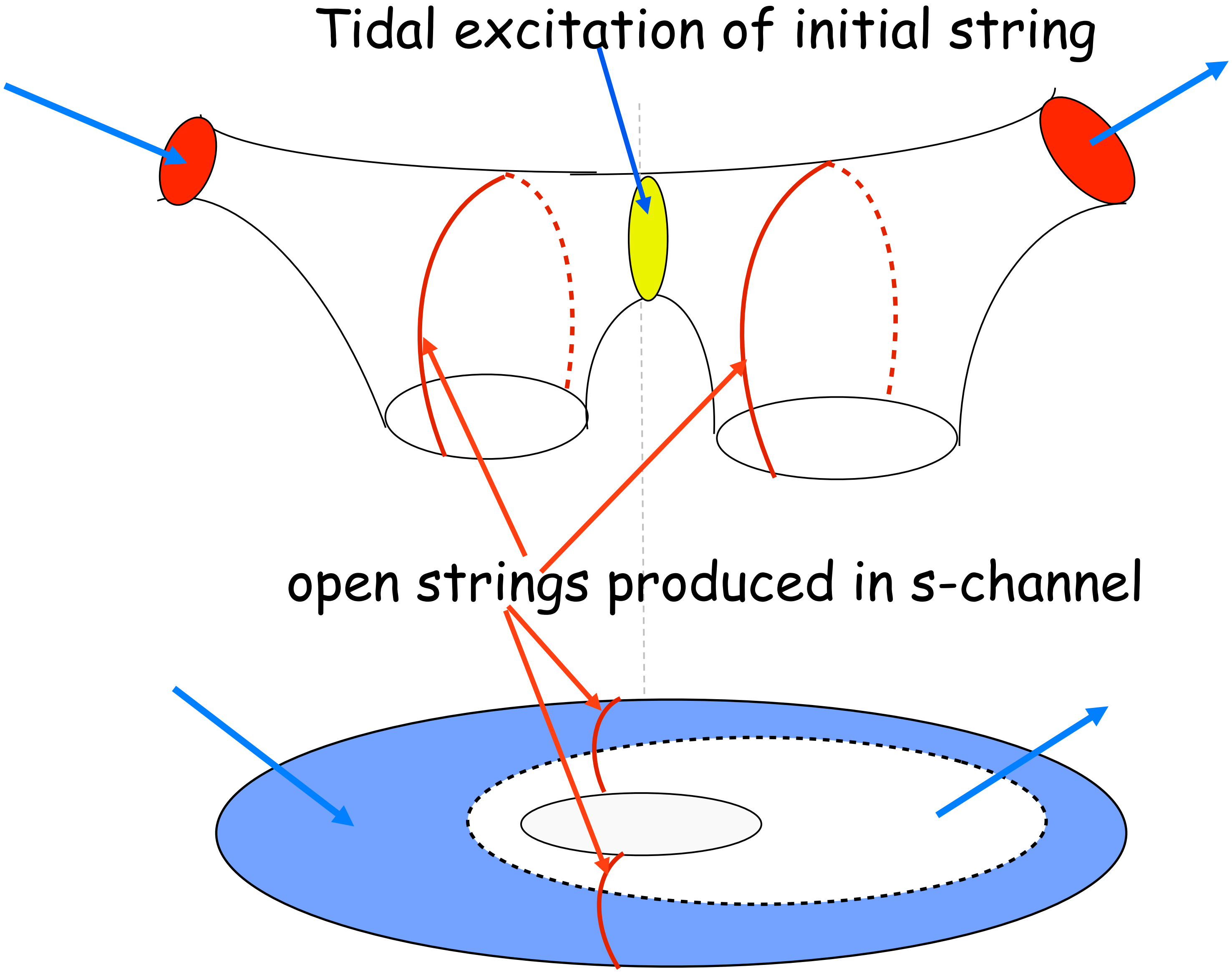
G. D'Apollonio, P. Di Vecchia, R. Russo & G.V.
(1008.4773 and in progress)
W. Black and C. Monni, 1107.4321
M. Bianchi and P. Teresi, 1108.1071



# Disc(tree)-level scattering

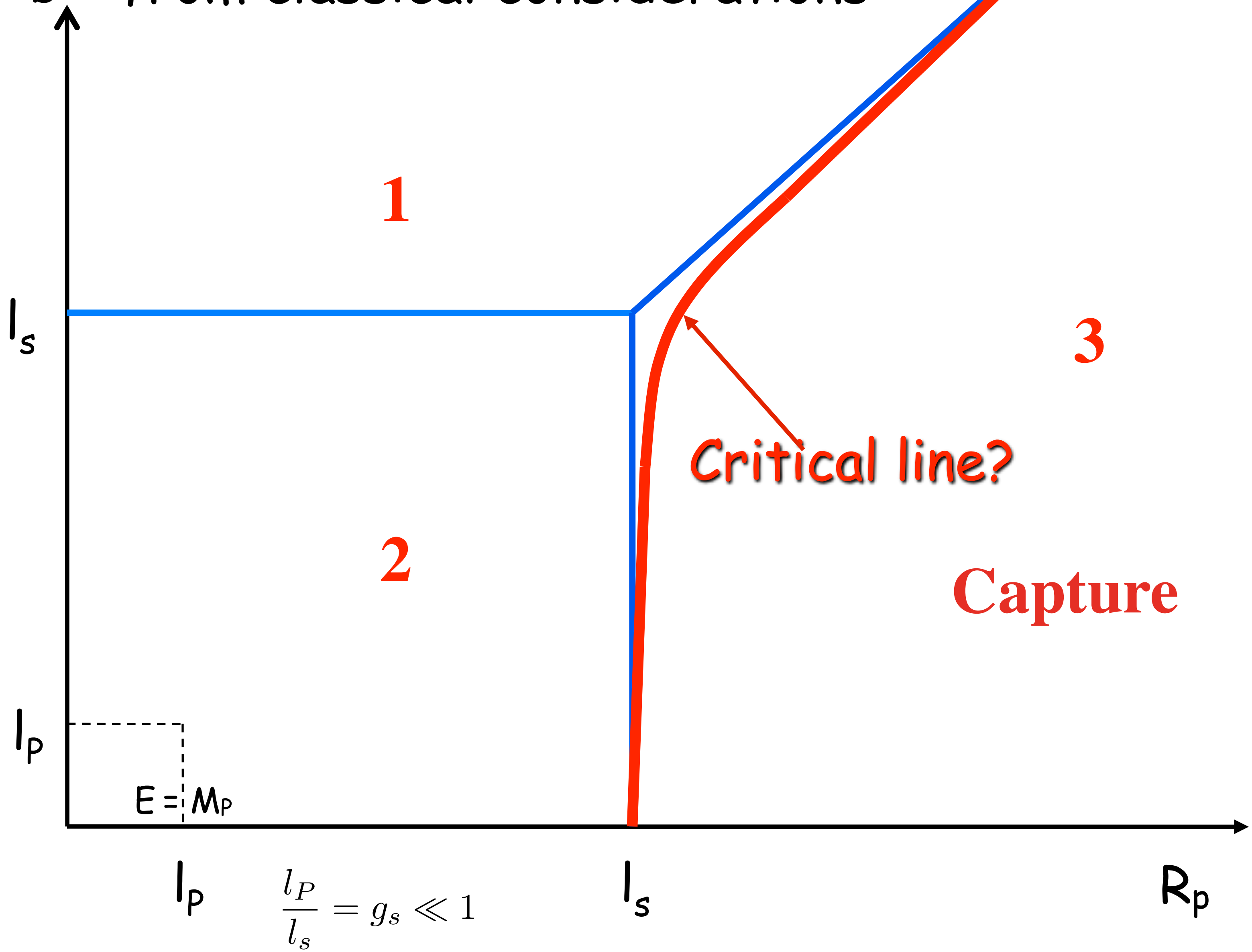


# Annulus (1-loop) level scattering




another representation of the annulus diagram

# expected phase diagram from classical considerations



# The large-b regime

• At the disc and annulus level an effective classical brane geometry emerges through the deflection formulae satisfied at the saddle point of b-integral (after resummation).

• Unlike in ACV this can be done reliably to next-to-leading order in the deflection angle (extension to all orders?).

$$ds^2 = \frac{1}{\sqrt{H(r)}}\left(\eta_{\alpha\beta}dx^\alpha dx^\beta\right) + \sqrt{H(r)}\left(\delta_{ij}dx^i dx^j\right) \ ,$$

$$\mathrm{e}^{\phi(x)} = g\,[H(r)]^{\frac{3-p}{4}} \quad , \qquad \mathcal{C}_{01\ldots p}(x) = \frac{1}{H(r)} - 1 \ ,$$

$$H(r) = 1 + \left(\frac{R_p}{r}\right)^{7-p} \ , \qquad R_p^{7-p} = \frac{gN(2\pi\sqrt{\alpha'})^{7-p}}{(7-p)\Omega_{8-p}} \ , \qquad \Omega_n = \frac{2\pi^{\frac{n+1}{2}}}{\Gamma(\frac{n+1}{2})}$$

• Tidal effects can also be computed. To leading order in $R_p/b$ and $l_s/b$ they come out in complete agreement with what one obtains by quantizing the string in the D-brane metric.

• Tidal excitation spectrum has been double checked even for external massive strings by W. Black & C. Monni. M. Bianchi & P.Teresi have computed some of these processes at the one-loop level.

• We (DDRV) are still finding some discrepancy between the scattering amplitude calculation in flat spacetime and string quantization in the D-brane metric @ subleading order in $R_p/b$

- Extension to classical-capture regime should be possible and would allow to understand how quantum coherence is preserved through the production of a coherent multi-open-string state living on the branes.

- For p = 3 this gedanken experiment should shed new light on the AdS/CFT correspondence within an S-matrix framework (NB: we are in asymptotically-flat spacetime).

# String-string vs string-brane scattering @ b, R < $l_s$ (prelim.)

In string-string scattering:

$$\langle n_{closed} \rangle \sim \frac{E R_S}{\hbar} \left( \frac{R_S}{l_s} \right)^{D-4} \quad \Rightarrow \quad \langle E_{closed} \rangle \sim M_s \left( \frac{l_s}{R_S} \right)^{D-3} \sim \frac{M_s^2}{g_s^2 E}$$

Naively extrapolated to R > $l_s$ gives only massless string modes (Hawking radiation?). Approx. cannot be trusted.

In string-brane scattering (work in progress):

$$\langle n_{open} \rangle \sim \frac{E l_s}{\hbar} \left( \frac{R_p}{l_s} \right)^{7-p} \quad \Rightarrow \quad \langle E_{open} \rangle \sim M_s \left( \frac{l_s}{R_p} \right)^{7-p} \sim M_s (g_s N)^{-1}$$

Calculation should be reliable even for $R_p$ > $l_s$ (large gN).

This is where we hope to make contact with a CFT living on the branes.

# Thank You!