Messages from the sky
:Matter, Dark matter and others:
Lecture #1

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The 9th Asian Winter School
on strings, Particles and Cosmology
Busan, Jan 18-27, 2015

my mission (I think)

- KM didnt give me an explicit mission here ...so I would choose topics based on my own taste
- I think it is an exciting time for particle physicists and cosmologists because new experimental missions get funded and some of them produce lots of interesting DATA from Nature
- Some results appear as expected (Higgs) with some un-expected details (mass, etc) but some others are totally unexpected (accelerating universe, cosmic ray, super high energy neutrinos) and have big implications (inflation, CC problem, DM..)
- , which I think is quite relevant for my stringy friends (will give you more evidences later)

my mission (continued)

- Let me try to update "current status" of particle physics & cosmology to you
- Focuses will be on new Dark matter models (WIMP, WIMPless, WIMPZilla, excited DM ...) and their possible detections (direct, indirect, collider...) indeed, some group claimed that they found DM. (Lec #2)
- and also on cosmic inflation with some potential detection of signatures of primordial gravitational waves from inflationary era. I will discuss the possibility of 'Higgs inflation' because I think it interesting. (Lec #3)

Lecture 1

- 5 reasons for BSM

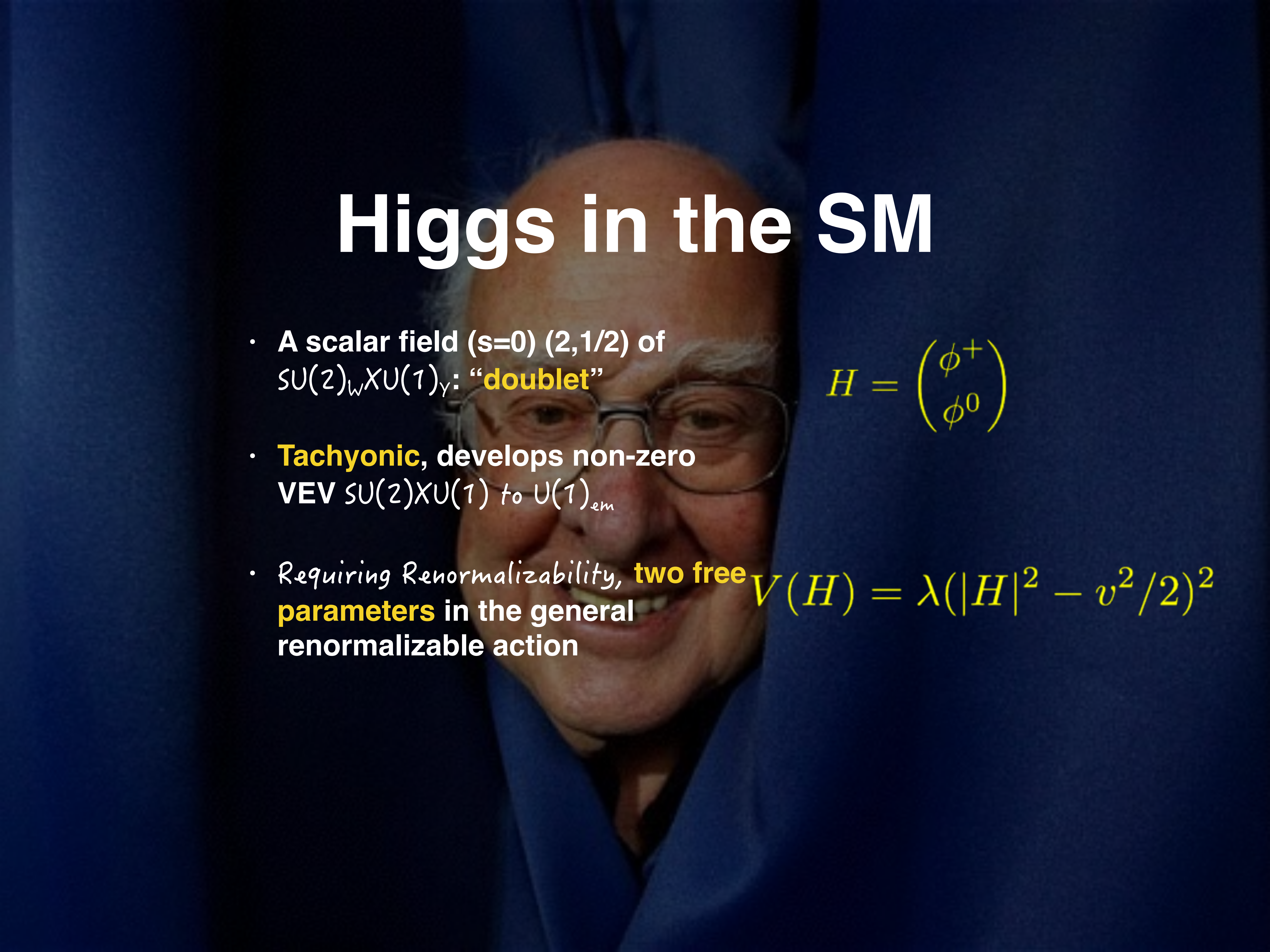
The year of elementary scalars

- March 2013, the CERN officially announced "a Higgs boson" is discovered.
- Planck 2013 data suggests "a single scalar field inflaton"

A Higgs boson

- 1933, Fermi introduced a parameter
  G~ 10^{-5}/ (proton mass)^2 ~(300 GeV)^{-2}
- L = G* qqlv , 4 Fermion operator for beta-decay (non-renormalizable)
- It took a whopping 80 years to come to the place where we now have a UV-complete theory of strong, weak and electromagnetic interactions.

Higgs in the SM



- A scalar field (s=0) (2,1/2) of $SU(2)_W X U(1)_Y$: "**doublet**"
- **Tachyonic**, develops non-zero VEV $SU(2)XU(1)$ *to* $U(1)_{em}$
- *Requiring Renormalizability*, **two free parameters** in the general renormalizable action

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$V(H) = \lambda(|H|^2 - v^2/2)^2$$

Higgs in the SM

- W-mass and gauge coupling measurement or equivalently G_F : vev = 246 GeV

- Mass=125.9 GeV from the LHC!

$$v = \frac{2m_W}{g}$$

$$\lambda = \frac{m_H^2}{2v^2} \approx 1/8$$

Now, *all* the parameters in the Higgs sector are experimentally measured!

Current status of Higgs mass measurement

$$m_H = 125.03^{+0.26}_{-0.27}(\text{stat})^{+0.13}_{-0.15}(\text{syst})$$

CMS PAS HIG-14-009

$$m_H = 125.36 \pm 0.37(\text{stat.}) \pm 0.18(\text{syst.})\text{GeV}$$

ATLAS arXiv:1406.3827

$$m_H = 125.9 \pm 0.4\text{GeV}$$

PDG new

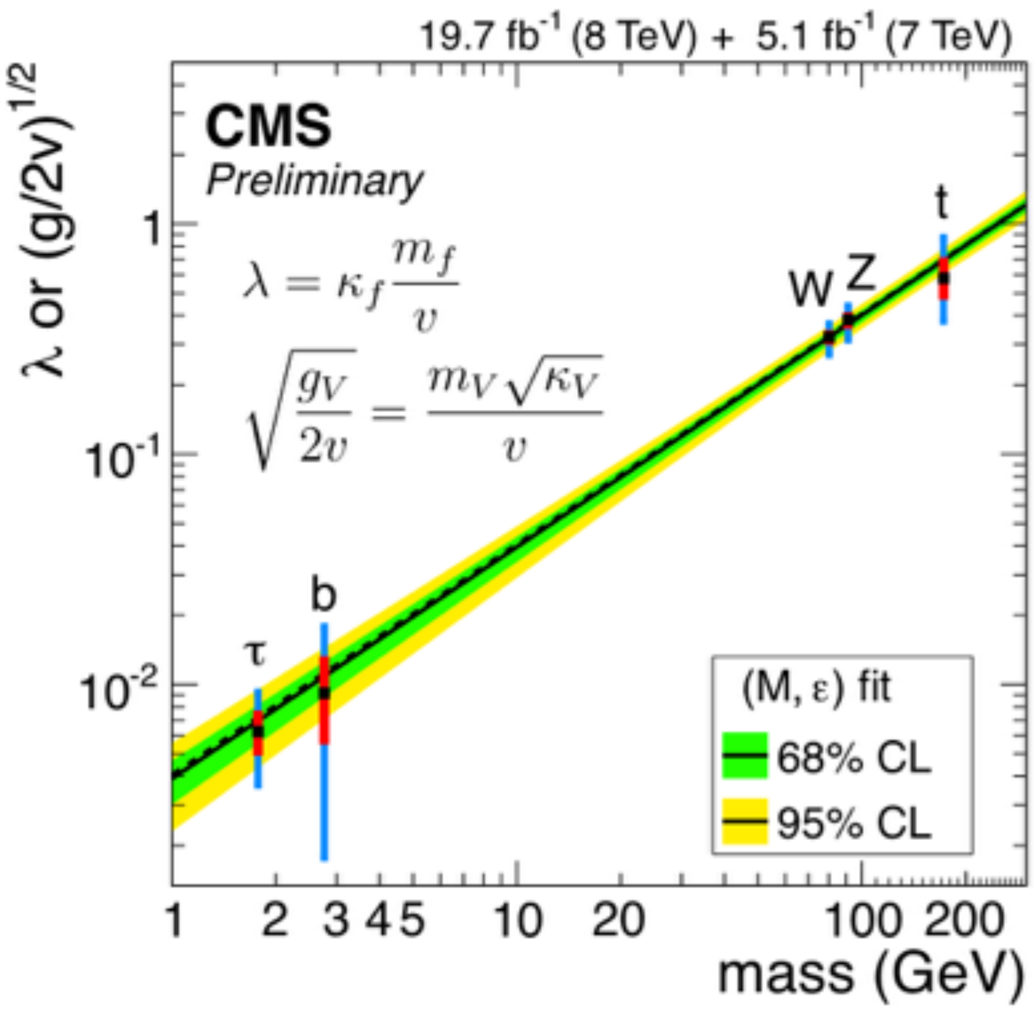
Decay pattern is consistent with the SM!

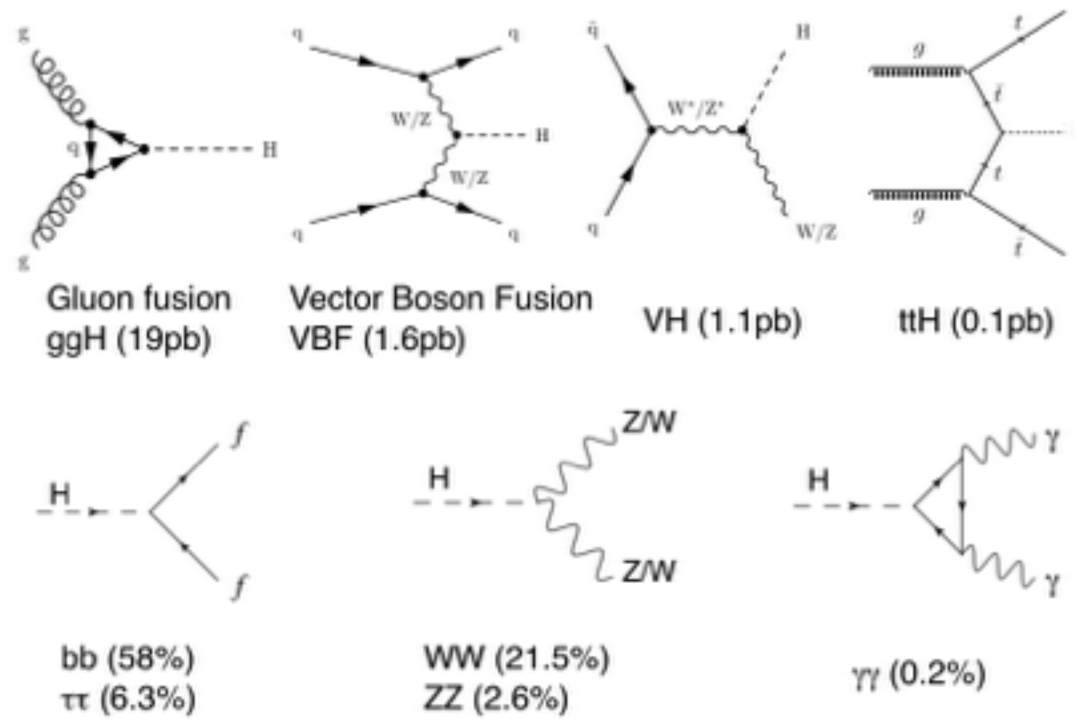
$$\mu = \frac{N_{exp}}{N_{theory}}$$

CMS PAS HIG-14-009

$$\mu = 1.00 \pm 0.09(\mathrm{stat.})^{+0.08}_{-0.07}(\mathrm{theo}) \pm 0.07(\mathrm{syst.})$$

- The Higgs in the SM plays **two main roles:** **EWSB** (or gauge boson masses) and **fermion masses. Both have been** … **ecked!**





Yuta Takahashi's talk

The SM is confirmed!

- all constituents of matter (6 flavors of quarks, 6 flavors of leptons) are all discovered and their properties have been measured
- all gauge interactions are observed and measured with a great precision
- all parameters including 2 parameters in the Higgs sector (mass and self-coupling) are now measured (in total 18 free parameters in the SM)

The SM validity range?

- Having discovered "Higgs boson" (a or the Higgs?) at the LHC, we are now confident that the SM works.
- ...its validity is checked up to electroweak scale (LEP, Tevatron, LHC...)
- ...may be valid all the way up to the Planck scale with renormalizability (though unlikely)

LHC run-1 failed to catch a BSM signal

- e.g. gluinos, squarks are ruled out up to ~O(1.3) TeV in a simple MSSM

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

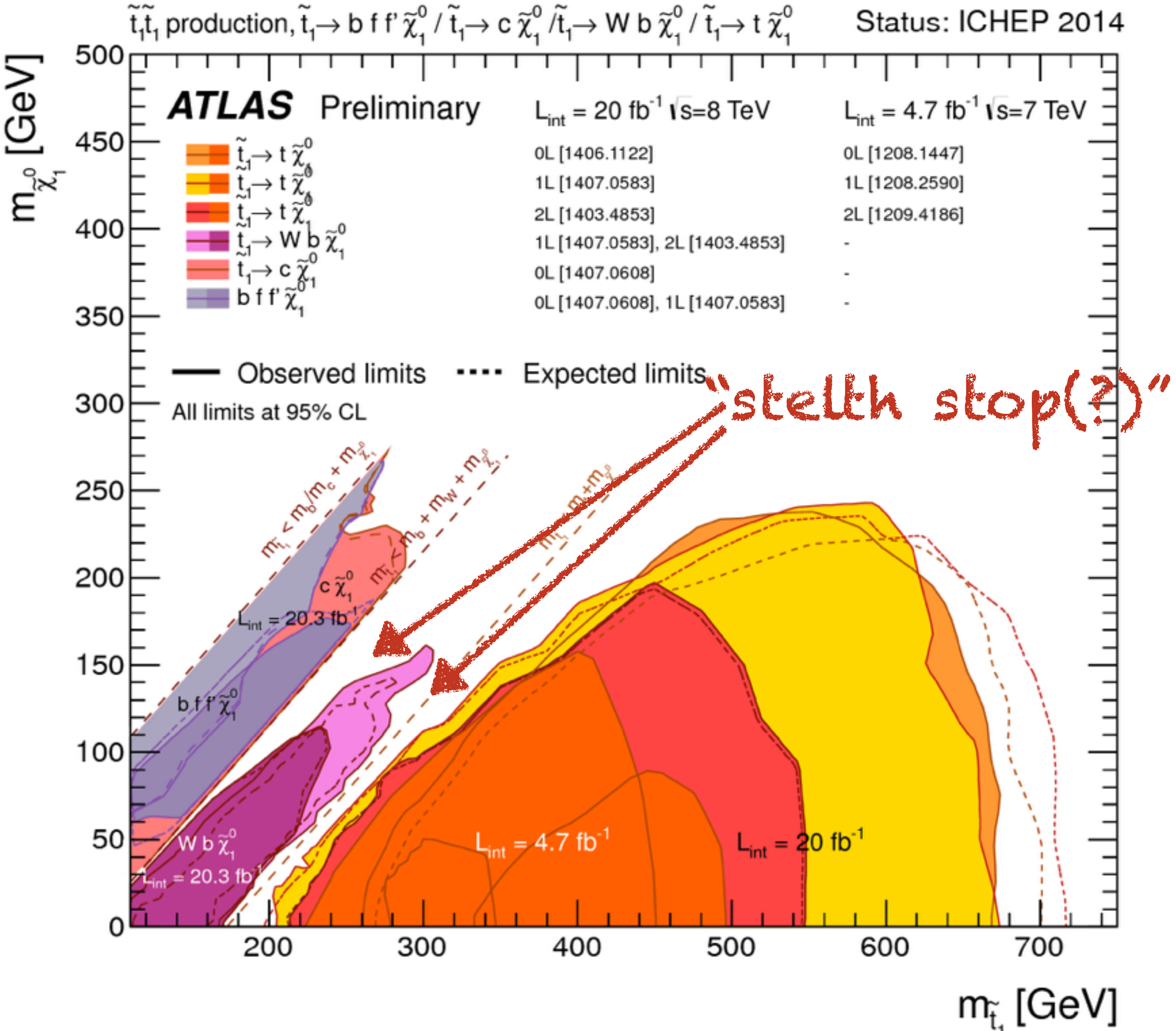
	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[fb^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.7 TeV	$m(\tilde{q})=m(\tilde{g})$	1405.7875
	MSUGRA/CMSSM	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.2 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 850 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.33 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e,μ	3-6 jets	Yes	20.3	$\tilde{g}$ 1.18 TeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}^{\pm})=0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20.3	$\tilde{g}$ 1.12 TeV	$m(\tilde{\chi}_1^0)$=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e,μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta$<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$ 1.6 TeV	$\tan\beta$ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$ 1.28 TeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e,\mu+\gamma$	-	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0)$>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0)$>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e,μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G})>10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$ 1.25 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0)$ <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.34 TeV	$m(\tilde{\chi}_1^0)$<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)$<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-620 GeV	$m(\tilde{\chi}_1^0)$<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$ 275-440 GeV	$m(\tilde{\chi}_1^{\pm})=2\, m(\tilde{\chi}_1^0)$	1404.2500
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 110-167 GeV	$m(\tilde{\chi}_1^0)$=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e,μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 130-210 GeV	$m(\tilde{\chi}_1^0)=m(\tilde{t}_1)-m(W)$-50 GeV, $m(\tilde{t}_1)<<m(\tilde{\chi}_1^{\pm})$	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e,μ	2 jets	Yes	20.3	$\tilde{t}_1$ 215-530 GeV	$m(\tilde{\chi}_1^0)$=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$<200 GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e,μ	1 b	Yes	20	$\tilde{t}_1$ 210-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$ 260-640 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$ 90-240 GeV	$m(\tilde{t}_1)-m(\tilde{\chi}_1^0)$<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0)$>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1+Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$ 290-600 GeV	$m(\tilde{\chi}_1^0)$<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$ 90-325 GeV	$m(\tilde{\chi}_1^0)$=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 140-465 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 100-350 GeV	$m(\tilde{\chi}_1^0)$=0 GeV, $m(\tilde{\tau},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 700 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_1^{\pm})+m(\tilde{\chi}_1^0))$	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 420 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e,μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$ 285 GeV	$m(\tilde{\chi}_1^{\pm})=m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0)$=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$ 620 GeV	$m(\tilde{\chi}_2^0)=m(\tilde{\chi}_3^0)$, $m(\tilde{\chi}_1^0)$=0, $m(\tilde{\ell},\tilde{\nu})=0.5(m(\tilde{\chi}_2^0)+m(\tilde{\chi}_1^0))$	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 270 GeV	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0)$=160 MeV, $\tau(\tilde{\chi}_1^{\pm})$=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$ 832 GeV	$m(\tilde{\chi}_1^0)$=100 GeV, 10 μs<$\tau(\tilde{g})$<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$ 475 GeV	10<$\tan\beta$<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	0.4<$\tau(\tilde{\chi}_1^0)$<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$ 1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, $m(\tilde{\chi}_1^0)$=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e+\mu$	2 e,μ	-	-	4.6	$\tilde{\nu}_\tau$ 1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau+X, \tilde{\nu}_\tau\to e(\mu)+\tau$	1 $e,\mu+\tau$	-	-	4.6	$\tilde{\nu}_\tau$ 1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.35 TeV	$m(\tilde{q})=m(\tilde{g})$, $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 750 GeV	$m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^{\pm})$, $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 450 GeV	$m(\tilde{\chi}_1^0)>0.2\times m(\tilde{\chi}_1^{\pm})$, $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$ 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$ 850 GeV		1404.250
Other	Scalar gluon pair, sgluon$\to q\bar{q}$	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon$\to t\bar{t}$	2 e,μ (SS)	2 b	Yes	14.3	sgluon 350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi)$<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

$\sqrt{s}$ = 7 TeV full data | $\sqrt{s}$ = 8 TeV partial data | $\sqrt{s}$ = 8 TeV full data

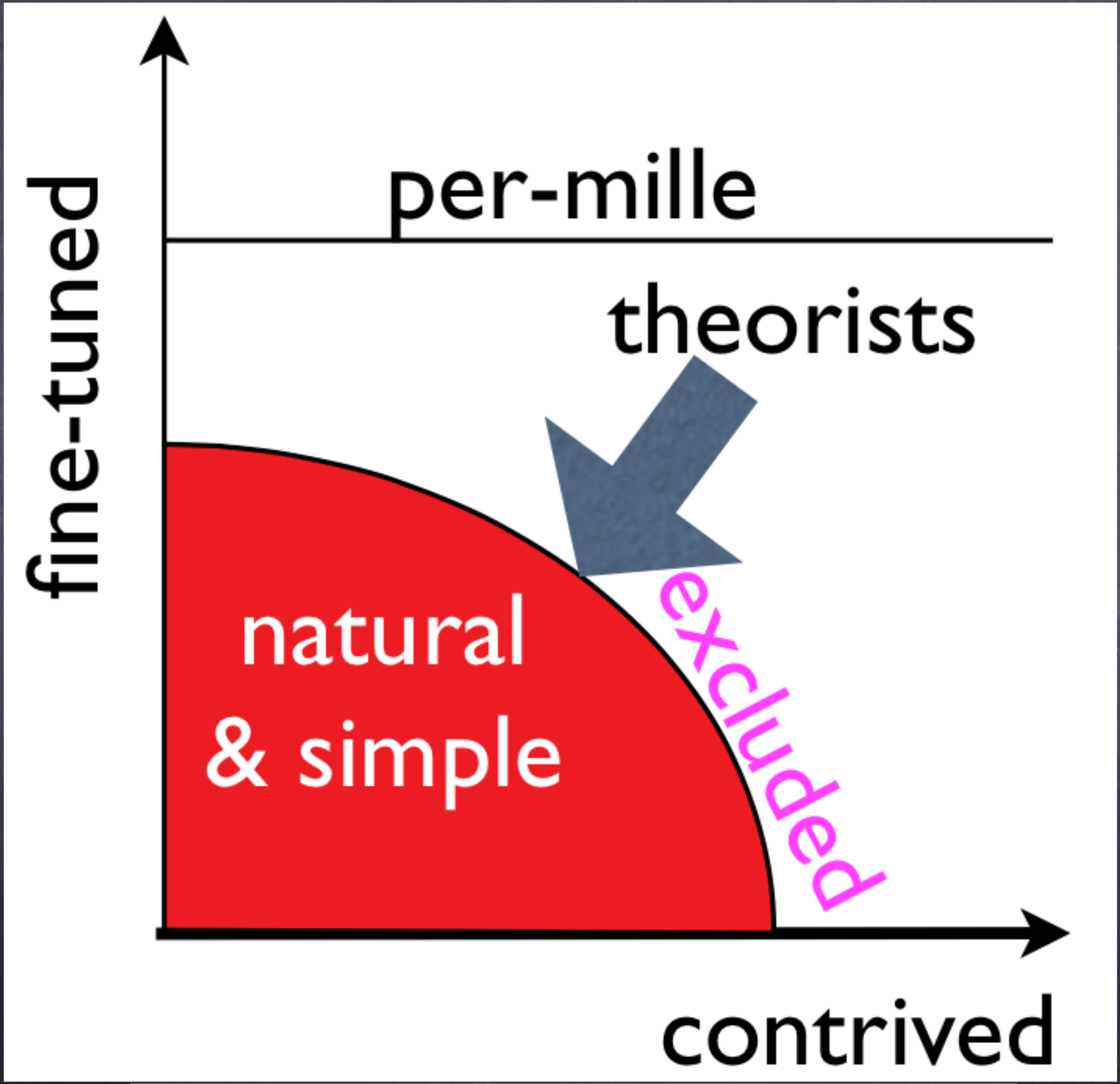
10^{-1} 1 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

- "Naturalness" suggests SUSY particles below 1 TeV to stabilize the Higgs mass 125 GeV
- Physics may be not simple but contrived



$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \to b f f' \tilde{\chi}_1^0$ / $\tilde{t}_1 \to c \tilde{\chi}_1^0$ / $\tilde{t}_1 \to W b \tilde{\chi}_1^0$ / $\tilde{t}_1 \to t \tilde{\chi}_1^0$
Status: ICHEP 2014
ATLAS Preliminary
L_{int} = 20 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
$\tilde{t}_1 \to t \tilde{\chi}_1^0$ 0L [1406.1122] 0L [1208.1447]
$\tilde{t}_1 \to t \tilde{\chi}_1^0$ 1L [1407.0583] 1L [1208.2590]
$\tilde{t}_1 \to t \tilde{\chi}_1^0$ 2L [1403.4853] 2L [1209.4186]
$\tilde{t}_1 \to W b \tilde{\chi}_1^0$ 1L [1407.0583], 2L [1403.4853] -
$\tilde{t}_1 \to c \tilde{\chi}_1^0$ 0L [1407.0608] -
$b f f' \tilde{\chi}_1^0$ 0L [1407.0608], 1L [1407.0583] -
Observed limits
Expected limits
All limits at 95% CL
"stelth stop(?)"
$m_{\tilde{t}_1} < m_b/m_c + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}_1^0}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}_1^0}$
$c \tilde{\chi}_1^0$
L_{int} = 20.3 fb^{-1}
$b f f' \tilde{\chi}_1^0$
$W b \tilde{\chi}_1^0$
L_{int} = 20.3 fb^{-1}
L_{int} = 4.7 fb^{-1}
L_{int} = 20 fb^{-1}
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
50
100
150
200
250
300
350
400
450
500
200
300
400
500
600
700



H. Murayama Phys. Scr. T158 (2013) 014025

Q. Why do we think that BSM really exists?

Beside "naturalness & simplicity"
there are at least 5 reasons for BSM!

[1] DM
:Knowns

- Astronomical search excludes (10^-7, 10) solar mass "dark astronomical objects" [Afonso *et. al.* (EROS Collaboration) 2003 *Astron. Astrophys.* **400** 951]

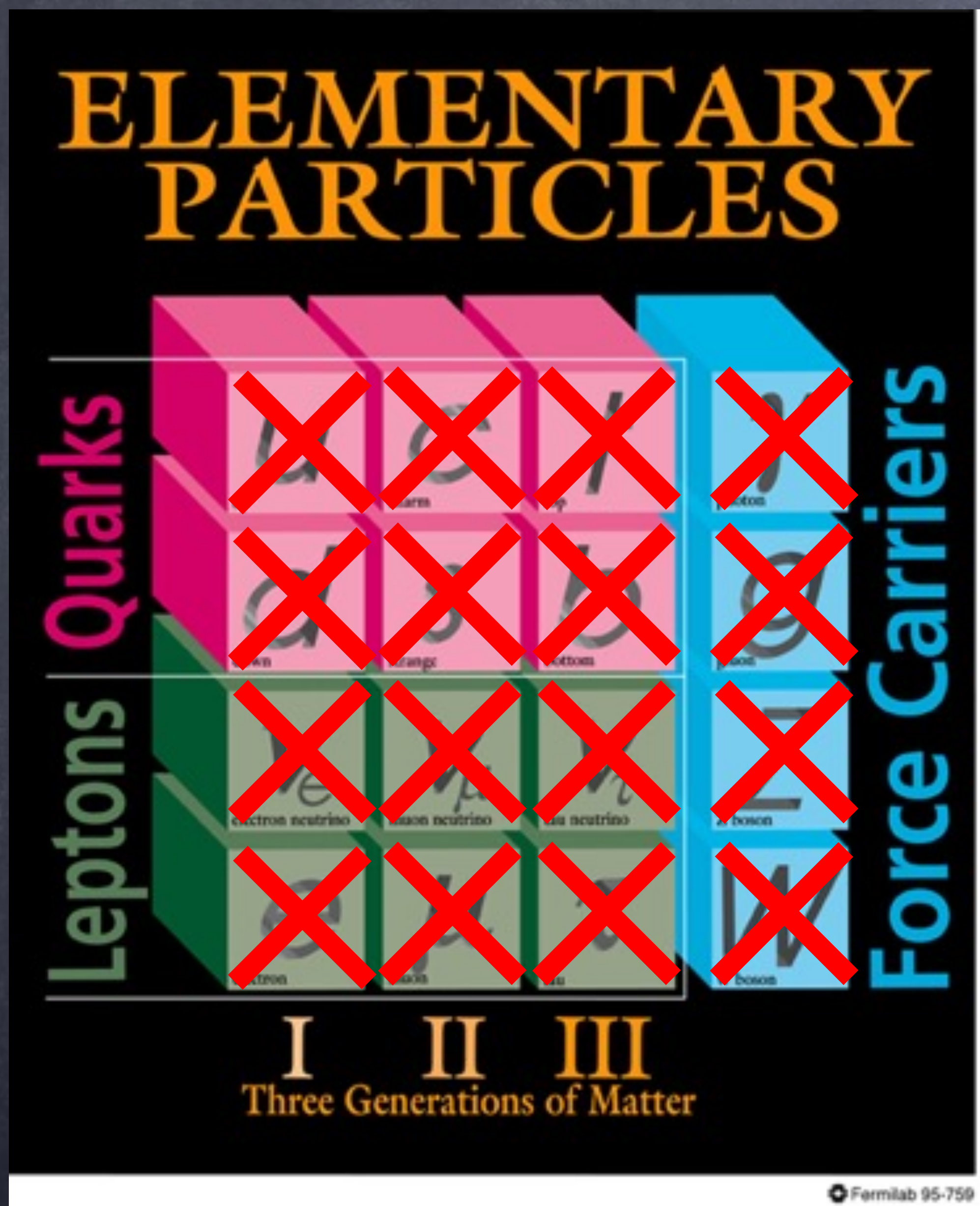
$$\Omega_m h^2 = 0.14 \pm 0.02$$
$$\Omega_b h^2 = 0.024 \pm 0.001$$

- CMB excludes "Baryonic dark matter"
Spergel D N *et al* (WMAP Collaboration) 2003 *Astrophys. J.* Suppl. **148** 175
- gravitational Bohr radius < galaxy scale otherwise a halo wouldnt form.
Hu W, Barkana R and Gruzinov A 2000 *Phys. Rev. Lett.* **85** 1158

Model independent Limit on DM mass

- $M = (10^{-31}, 10^{50})$ GeV (if fermion, bound stronger due to the Pauli pressure)
- not very precise :-(
- ...but certainly improved since the first proposal by Fritz Zwicky in 1930s: $v \sim \langle T \rangle \sim$ Mass (virial motion of astronomical objects)

DM in the SM?



Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

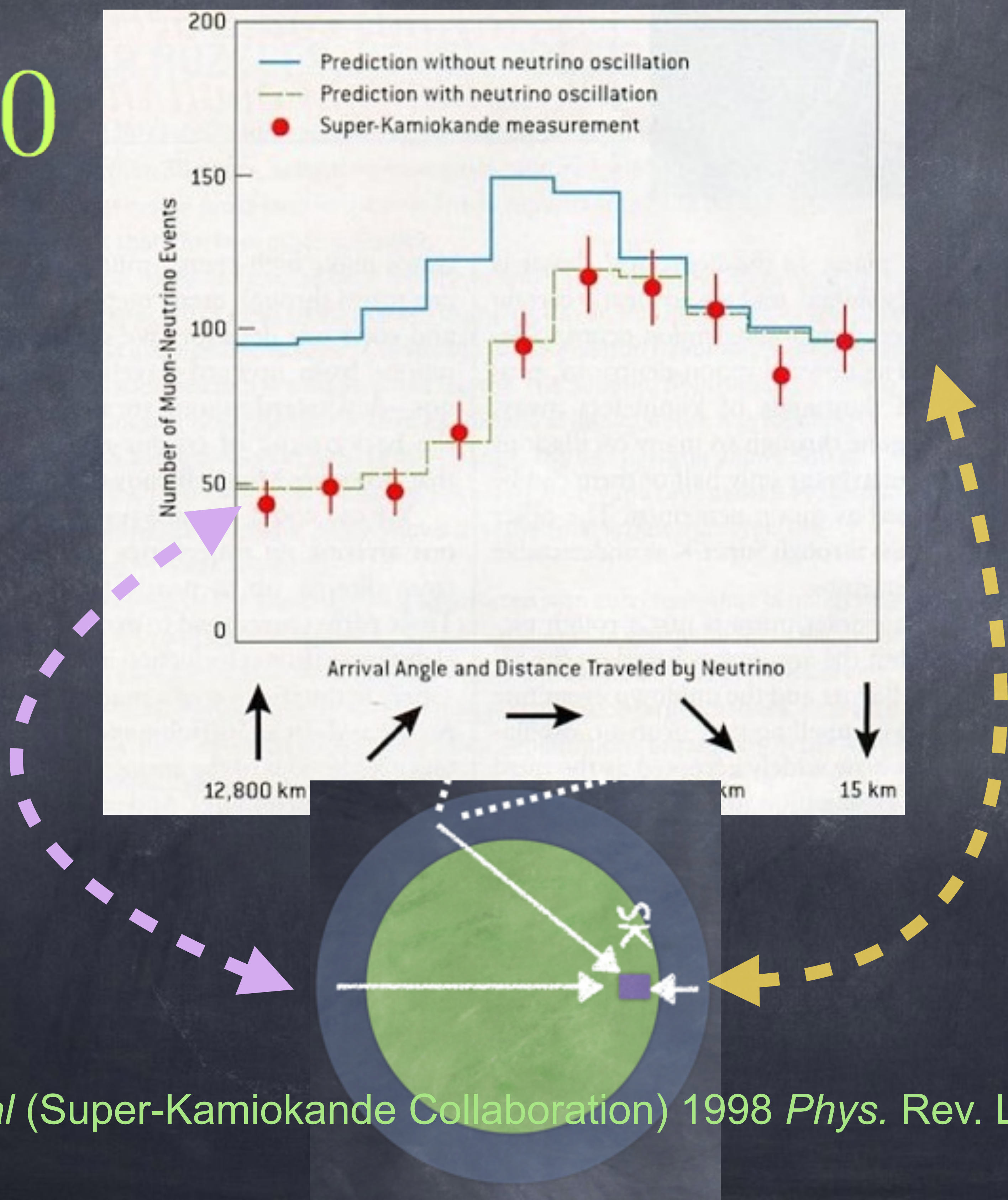
Unambiguous evidence for new particles!

A big irony

- After many years' digging into particle physics, we end up with a conclusion that we only know about 5% of the energy budget of Universe.
- Revealing the nature of DM is one of the most important mission now
- (more in Lec#2)

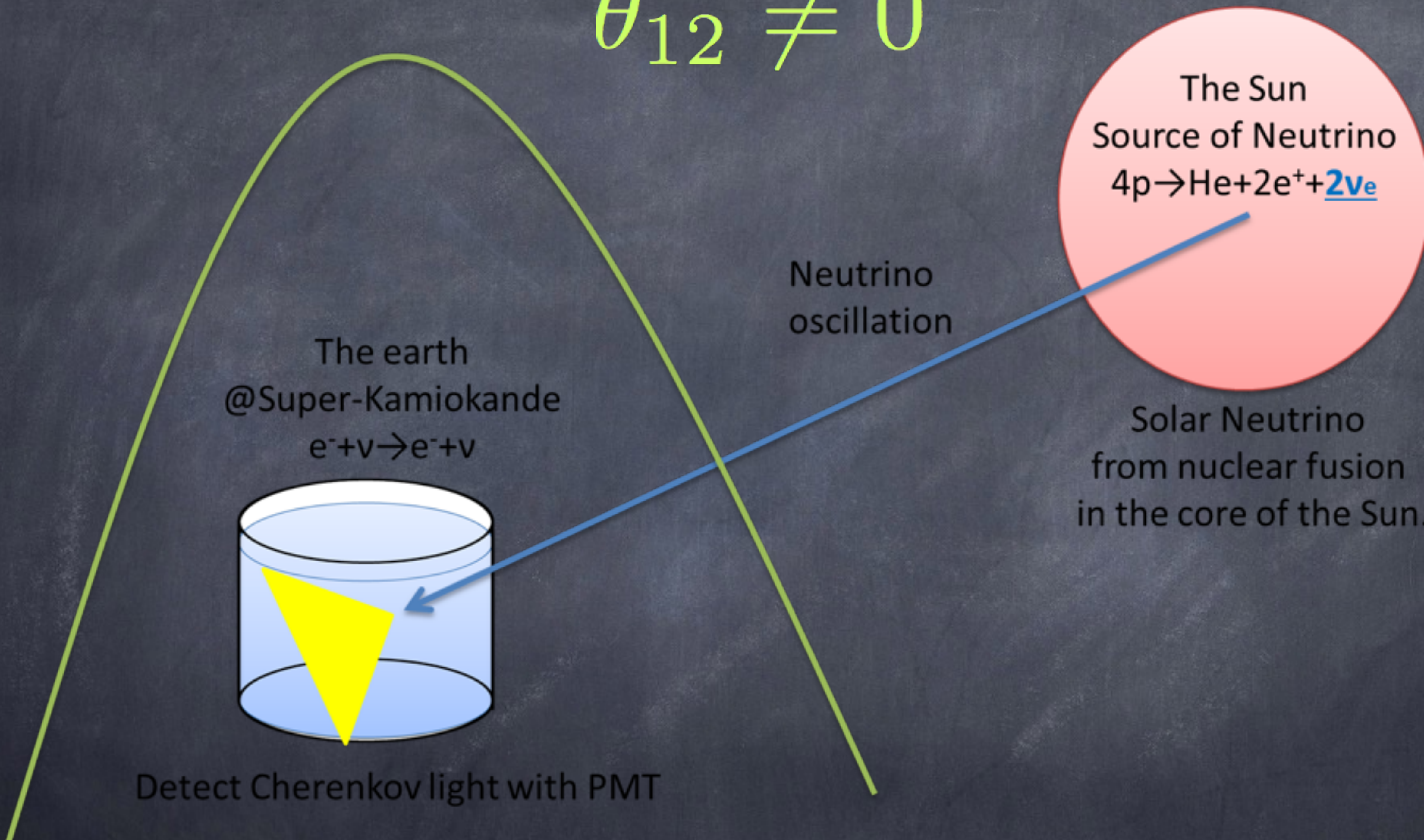
[2] neutrino mass

$\theta_{23} \neq 0$



[Fukuda Y *et al* (Super-Kamiokande Collaboration) 1998 *Phys.* Rev. Lett. **81** 1562]

$$\theta_{12} \neq 0$$

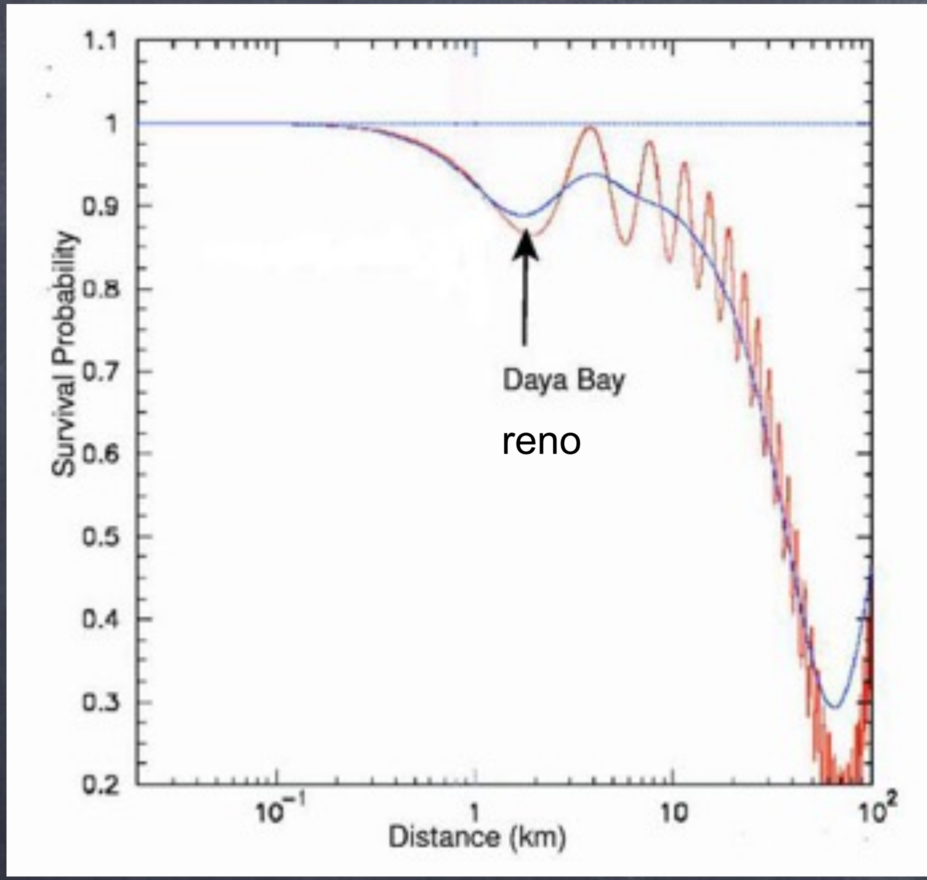


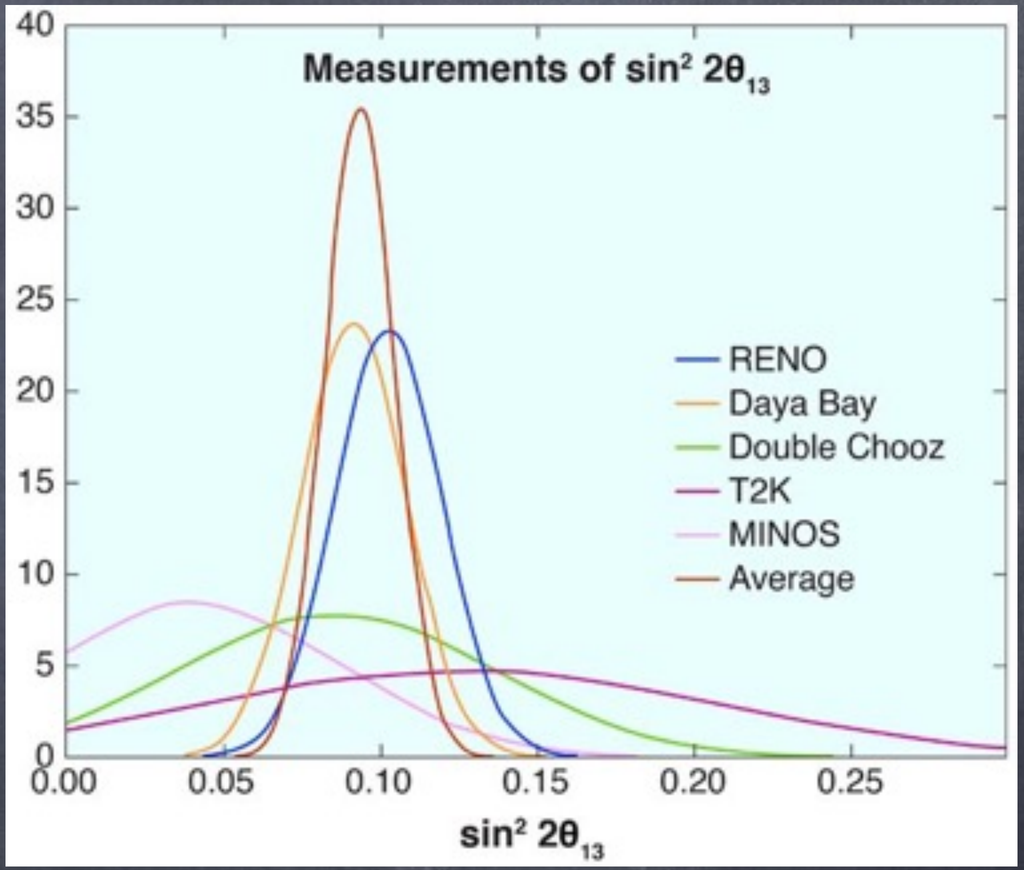
observed =1/3 * expected

Ahmad Q R *et al* (SNO Collaboration) 2002 *Phys. Rev. Lett.* **89** 011301

Eguchi K *et al* (KamLAND Collaboration) 2003 *Phys. Rev. Lett.* **90** 021802

$\theta_{13} \neq 0$





reactor
(nue source)

An F P *et al* (DAYA-BAY Collaboration) 2012 *Phys. Rev. Lett*. **108** 171803

J.K. Any et al (RENO collaboration) Phys.Rev.Lett. 108 (2012) 191802

- In the SM, neutrinos are massless since there's no Yukawa terms

$$\mathcal{L}_{Yuk} = -y^u \bar{Q}_L H u_R - y^d \bar{Q}_L \tilde{H} d_R - y^e \bar{\ell}_L \tilde{H} e_R$$

- A simple extension with singlet scalars (two or more) allows Dirac masses...

$$-y^\nu \bar{\ell}_L H \nu_R$$

- ...even though fairly un-natural (Sum of m_{nu}) < 0.1 eV << m_e << m_{top})
- (more in Lec#3 if I have time)

[3] Accelerated expansion

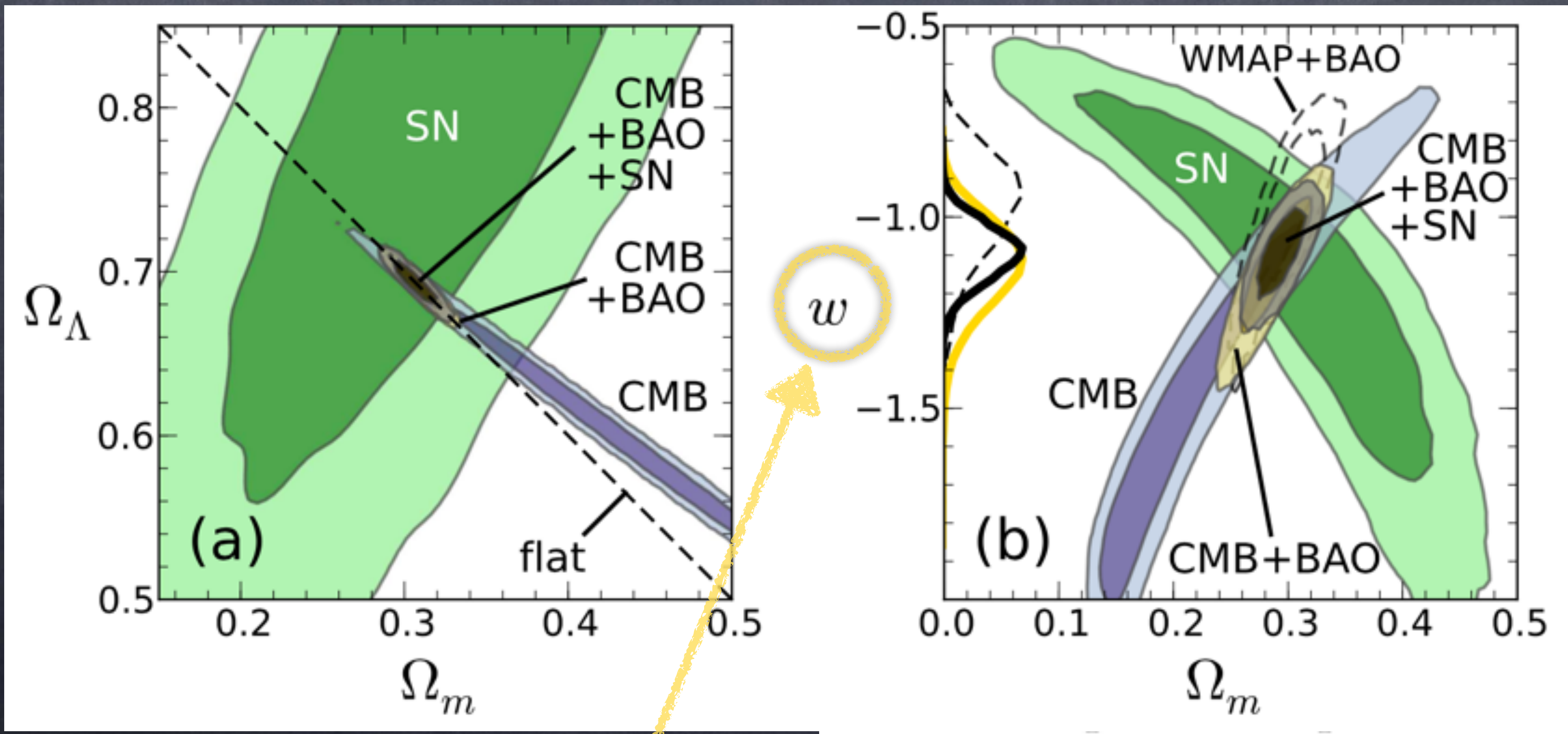
- Accelerated expansion of universe is directly observed with SNs in Type1a, a standard candle due to its absolute luminosity is decided by Chandrasekhar limit

- The expansion rate is consistent with the 'Dark energy' component about 70% of energies.

Perlmutter S *et al* (Supernova Cosmology Project Collaboration) 1999 *Astrophys*. *J*. **517** 565
Riess A G *et al* (Supernova Search Team Collaboration) 1998 Astron. J. **116** 1009

Dark energy

- The data are consistent with cosmological constant, which gives $p_\Lambda = -\rho_\Lambda$



$p = \omega \rho$

$w = -1.10 \pm 0.08$ at 68.3% CL

(PDG 2014)

Naïve estimation of Lambda

$$\mathcal{L}_\Lambda = \sqrt{g}\Lambda$$

SM fields: $\Lambda \sim (300\text{GeV})^4$

GUT: $\Lambda \sim (10^{14}\text{GeV})^4$

Planck scale physics: $\Lambda \sim (10^{19}\text{GeV})^4$

The worst miserable failure in theoretical physics

$$\rho_{measure} = (1.35 \pm 0.15) \times 10^{-123} M_p^4$$

J.D.Barrow, D.J. Show Gen.Rel.Grav. 43 (2011) 2555-2560

nb) Based on WMAP7 but not much change in Planck 2013

[4] Acausality in CMBR

- CMBR is pretty homogeneous and isotropic. Difference is 10^{-5} level. (much smother than billiard ball!)
- cosmological principle: we are not special!
- CMB formed after 380,000 years after "hot big bang" (which is more consistently described by "reheating") but there was no time for different part of CMB communicated before.

They never talked before but share information...acausality happened?

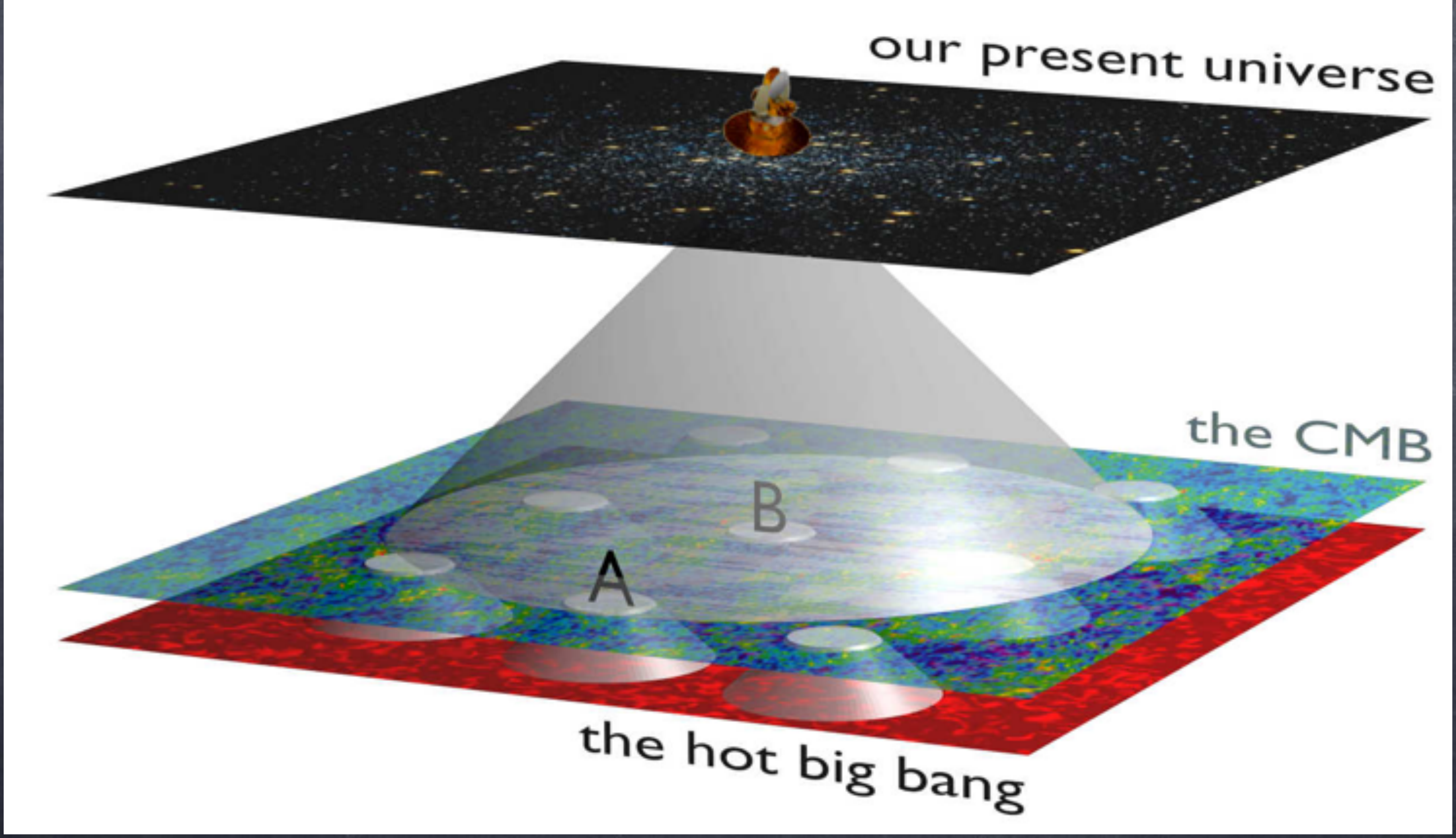
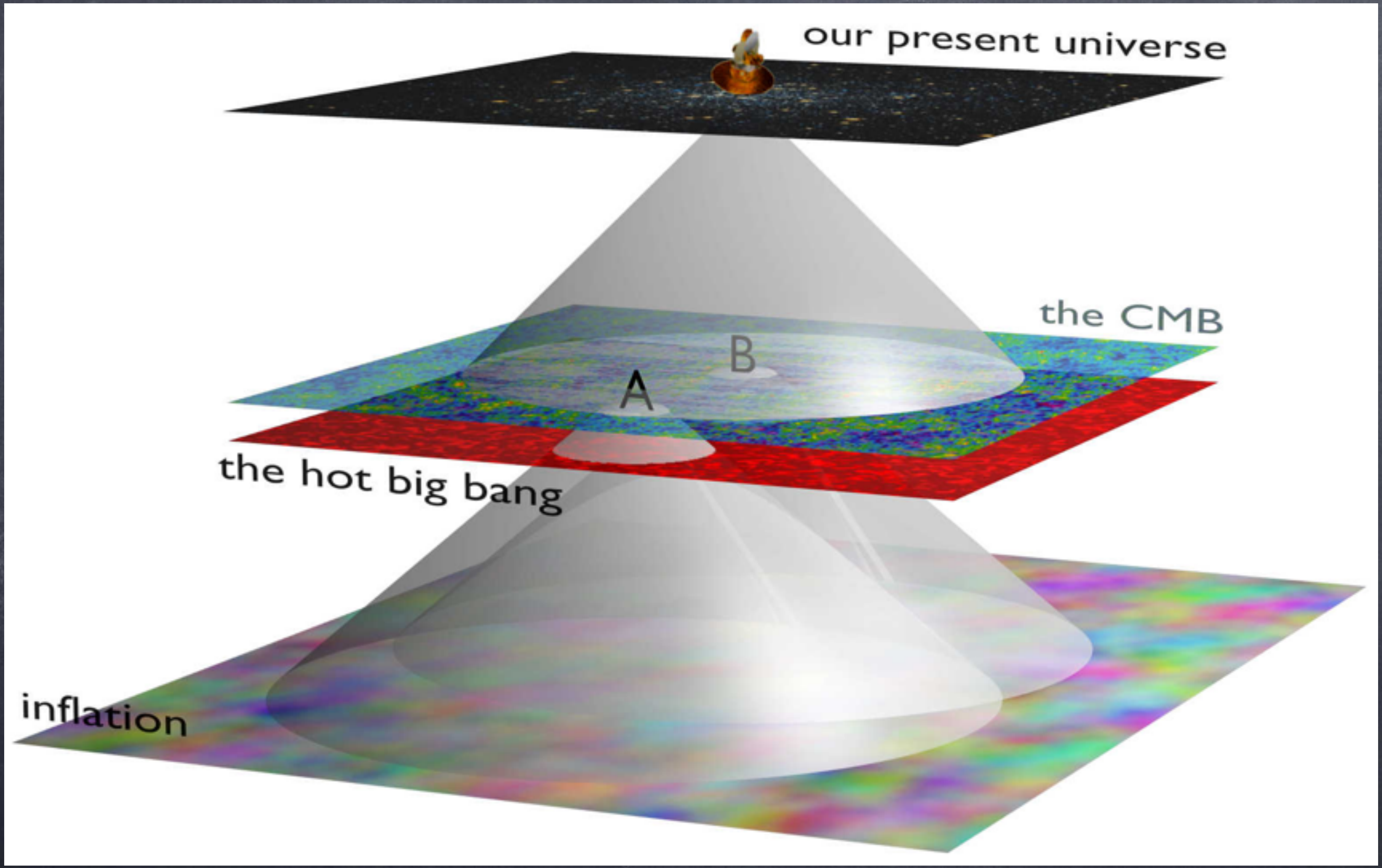


Figure: Wang, Yi [arXiv:1303.1523]

solutions?

- Causality violation in early universe (X)
- different parts of universe were actually in contact before conventional BB expansion
- $r_{univ} < 10^{-15} m \Rightarrow e^{60} r_{univ}$ in a short time explains the phenomena. (Inflation!)



N.B. not realistic

Figure: Wang, Yi [arXiv:1303.1523]

Planck result support inflation

- Omega_k << 1
- Curvature is e^{60} diluted during the inflation so that a small Omega_k is indeed expected by inflation
- but 'direct' confirmation depends on the actual properties of inflationary mechanism
- Is the only scalar in the SM (Higgs) responsible for inflation ??? (more Lec # 3)

[5] Baryon number

- related with [4].
- Inflation erase any sizable amount of primordial baryon density...
- ...so baryons (indeed quarks and leptons) are created after inflation

- The observed amount of baryon density is (n_b/n_photon)~5*10^{-10}
- The SM can create Baryons by (CP-violating phase in KM matrix) + (B-number violating anomalous interactions)+(out of equilibrium) (Sahkarov 3 conditions)
- J ~ 10^{-20} in the SM is not enough :-(

What if no BSM?

- (no DM / large CC) no galaxies thus no stars, no human, no string theorists on earth!
- not enough baryons (thus no atom, no molecules, no string theorists!)
- universe without causality (thus no string theorists!)
- no neutrino masses (Q. is it okay with you?)

“BSM physics is important for lives of string theorists!”

any observation?

Black Holes

and

Superconformal Mechanics

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Abstract

The dynamics of a (super)particle near the horizon of an extreme Reissner-Nordström black hole is shown to be governed by an action that reduces to a (super)conformal mechanics model in the limit of large black hole mass.

Isospin-Violating Dark Matter
Jonathan L. Feng (UC, Irvine), Jason Kumar (Hawaii U.), Danny Marfatia (Kansas U. & Wisconsin U., Madison), David Sanford (UC, Irvine). Feb 2011. 5 pp.
Published in **Phys.Lett. B703 (2011) 124-127**
UCI-TR-2011-03, UH511-1157-2011
DOI: 10.1016/j.physletb.2011.07.083
e-Print: **arXiv:1102.4331 [hep-ph]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service
Detailed record - Cited by 174 records 100+

Explaining the DAMA Signal with WIMPless Dark Matter
Jonathan L. Feng, Jason Kumar, Louis E. Strigari (UC, Irvine). Jun 2008. 8 pp.
Published in **Phys.Lett. B670 (2008) 37-40**
UCI-TR-2008-22
DOI: 10.1016/j.physletb.2008.10.038
e-Print: **arXiv:0806.3746 [hep-ph]** | PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
CERN Document Server ; ADS Abstract Service
Detailed record - Cited by 104 records 100+

You may work together with a particle phono-guy (if he is good :-)

Compact hyperbolic extra dimension: a M–theory solution and its implications for the LHC

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ABSTRACT: We study M–theory solutions involving compact hyperbolic spaces. The combination of a gap *à la* Randall–Sundrum and the topology of an internal Riemann surface allows a geometrical solution to the hierarchy problem that does not require light Kaluza–Klein modes. We comment on the consequences of such a compactification for LHC physics.

So, where's BSM?

- It is not clear whether TeV scale is the right scale of BSM ...
- Don't forget M_{DM} can be anywhere in $(10^{-31}, 10^{50})$ GeV!

Systematic way of thinking BSM

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{UV}}}\mathcal{L}_5 + \frac{1}{\Lambda_{\mathrm{UV}}^2}\mathcal{L}_6 + \cdots .$$

- whatever scale is for BSM, we may systematically analyze low energy phenomena (e.g. 4 jet final states in the LHC run-2) by higher order operators.
- when the available energy approaches to the cut-off scale, higher level physics will be more and more relevant (=> thus experimentally seeable!)

the SM and UV-sensitivity

$$\mathcal{L}_{\rm SM} = -\frac{1}{g^2}F^2_{\mu\nu} + \bar{\psi}\,\mathrm{i}\not{D}\psi + |D_\mu H|^2 - y\bar{\psi}\psi H + \frac{\theta}{64\pi^2}F\tilde{F} - \lambda(H^\dagger H)^2 + \mu^2 H^\dagger H - \Lambda_{\rm CC}.$$

dimensionless parameters
~logarithmic dependence

~ quadratically,
aquatically sensitive

Dim 5 operator (unique!)

$$\mathcal{L}_5 = (LH)(LH)$$

n.b. L and H have exactly same charges!

$$\frac{\mathcal{L}_5}{\Lambda_{UV}} = \frac{v^2 \nu\nu}{\Lambda_{UV}}$$

thus small neutrino mass is realized.

* Find the UV scale for neutrino masses ~0.1 eV

Dim-6 operators : many!

proton decay

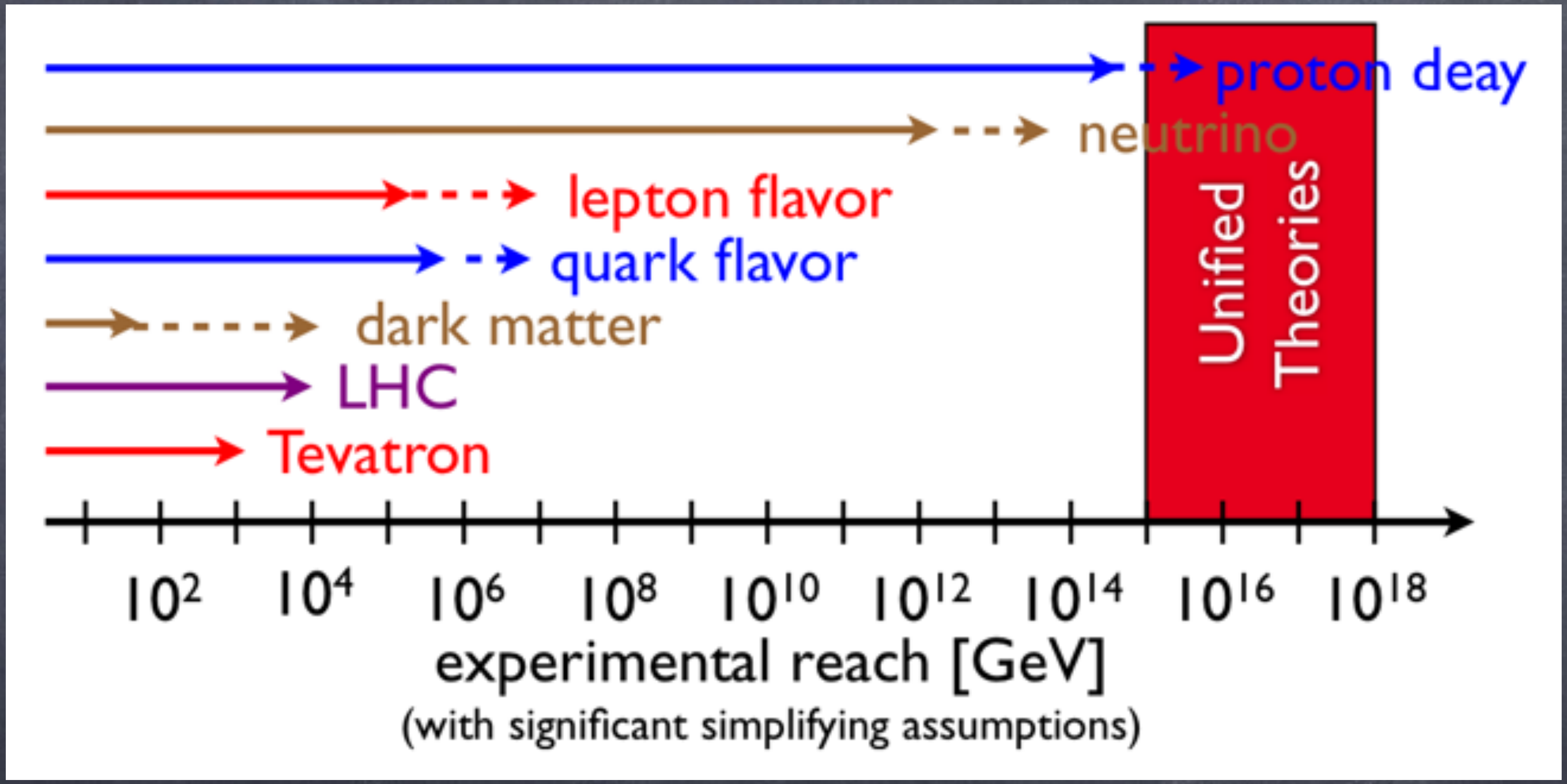
lepton (g-2)

W-triple couplings

$$\mathcal{L}_6 = QQQL,\ \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl,\ \epsilon_{abc}W_{\nu}^{a\mu}W_{\lambda}^{b\nu}W_{\mu}^{c\lambda},\ B_{\mu\nu}H^{\dagger}W^{\mu\nu}H,\ \ldots.$$

S-parameter

experiments for BSM



we need a large range of experimental reach

TeV scale BSM

- ...indeed naturalness argument seems to be the only strong argument for a TeV scale BSM...
- ... which is not in tension with simplicity
- But don't forget sometimes Nature is unkind to us. The LHC run-2 will probe more territories and we will learn more
- Even 100 TeV machines are proposed in Europe and also in China. ILC is proposed in Japan. I don't loose my enthusiasm.

Summary of Lec1

- SM is in good shape but BSM cries out from evidences DM, DE, neutrino, inflation, Baryon asymmetry in nature.
- Different energy scales needed to be checked with various experimental attempts...
- indeed, more evidences will come from new experiments and we will learn more in coming years. (String theorists can contribute to phenomenology!)