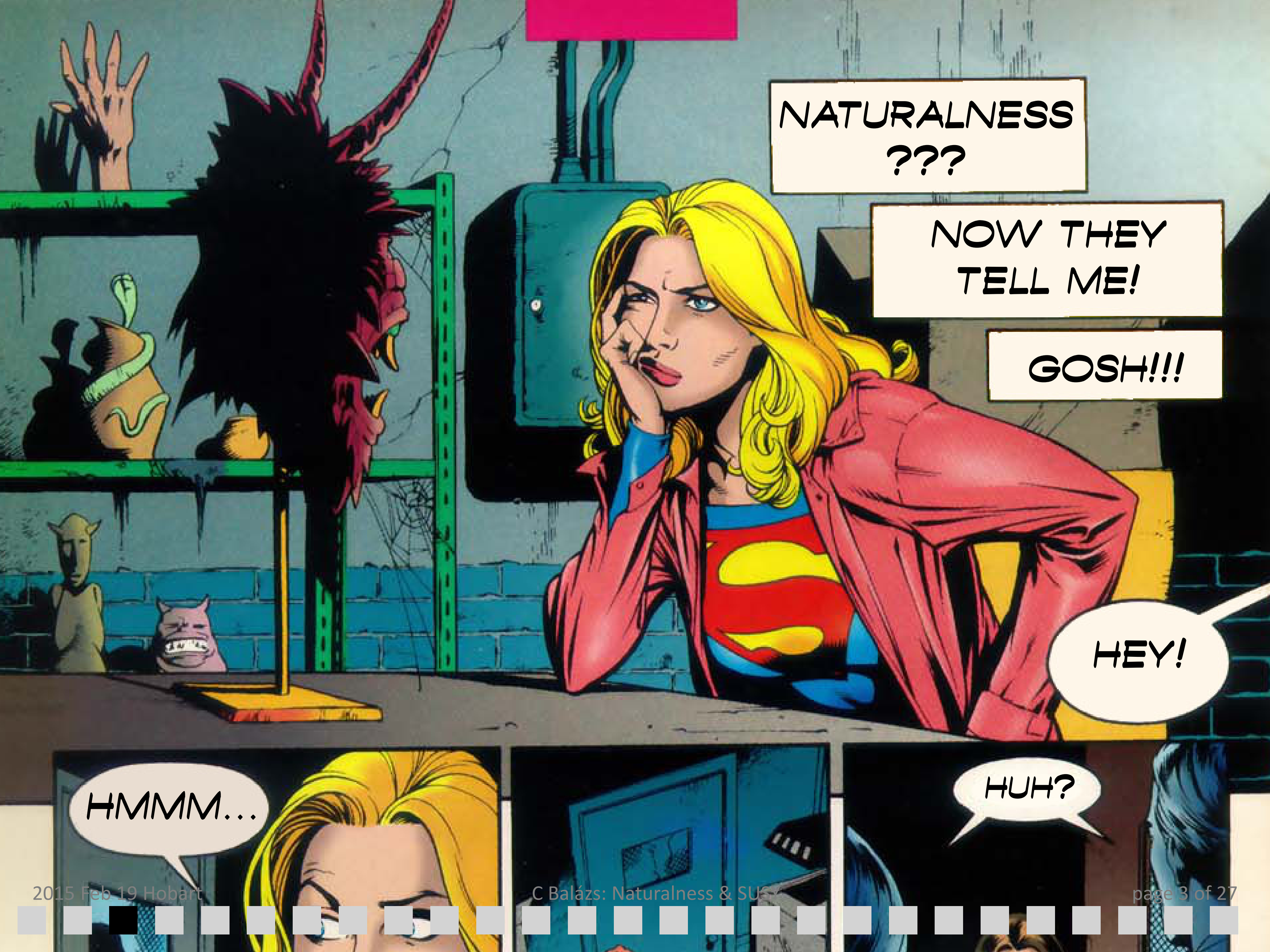
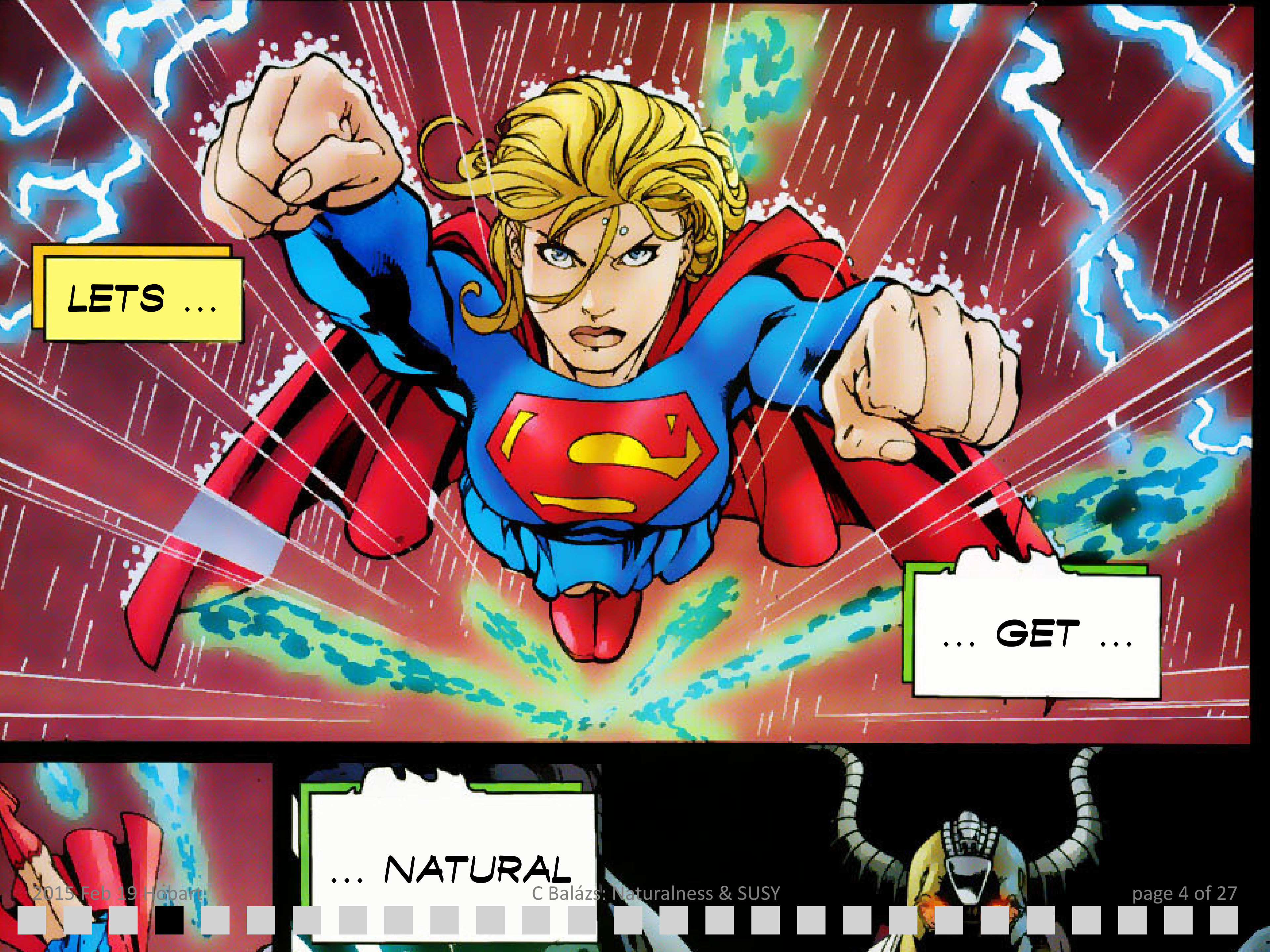
Naturalness & Supersymmetry

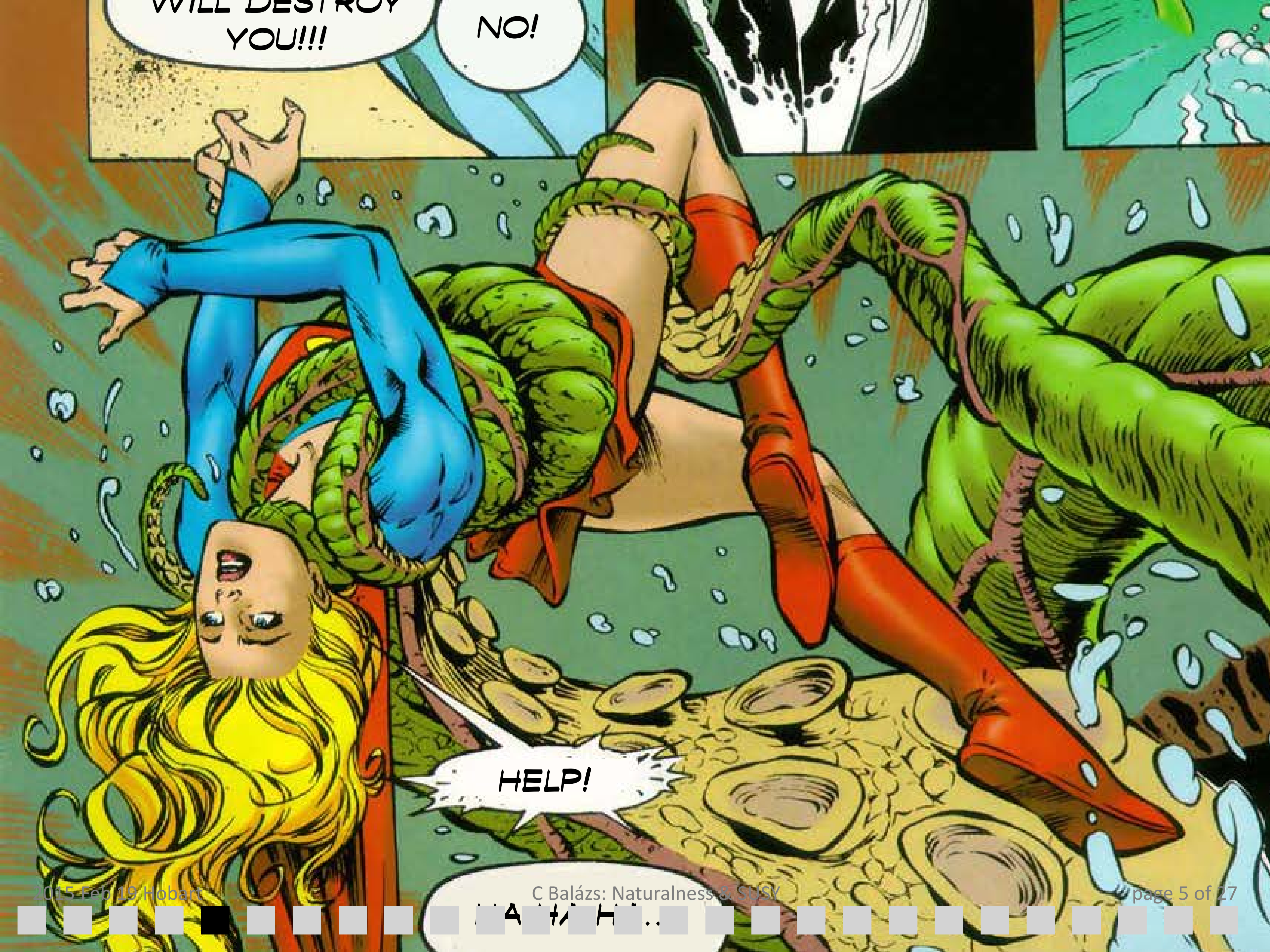
Peter Athron, Csaba Balázs, Ben Farmer, Doyoun Kim

PRD90 5 055008 (2014)

outline


NATURALNESS ???
NOW THEY TELL ME!
GOSH!!!
HEY!
HMMM...
HUH?


LETS ...
... GET ...
... NATURAL


WILL DESTROY YOU!!!
NO!
HELP!


PREPARE …
… TO …
… DIE !!!

a brief experimental history of SUSY

…

ca. 1990 LEP

ca. 2000 Tevatron

ca. 2010 LHC

ca. 2020 HL-LHC ?

…

Why do we expect SUSY to be found?

we expect to find a natural extension of the SM…

… and SUSY became synonym with that

What is naturalness?

physical phenomena characterized by disparate (energy or length) scales are separated

their governing laws can be understood largely independently from each other

when viewed as an effective theory

the Standard Model Higgs mass receives corrections from the Planck scale

$$m_H = 125\ \mathrm{GeV}$$

implies that the Standard Model is unnatural

What is natural?

naturalness is quantified by a fine-tuning measure

Barbieri-Ellis-Giudice EW FT measure:

$$\frac{\partial(electroweak\ observable)}{\partial(theory\ parameters)}$$

- Why does $\frac{\partial m_Z}{\partial \mu}$ measure EW fine-tuning?
- What is the normalization for $\frac{\partial m_Z}{\partial \mu}$?
- Observables: why m_Z and not m_H or v or …?
- Parameters: why μ and not $tan\beta$ or B or …?
- Form: $\frac{\partial m_Z}{\partial \mu}$ or $\frac{\partial ln m_Z}{\partial ln \mu}$ or $\frac{\partial ln m_Z^2}{\partial ln \mu^2}$ or …?
- Expression: $\sum_i \frac{\partial m_Z}{\partial p_i}$ or $\max_i \left(\frac{\partial m_Z}{\partial p_i}\right)$ or …?
- What does $\frac{\partial m_Z}{\partial \mu}$ have to do with Δm_H, μ, $m_{\tilde{t}}$, $m_{\tilde{g}}$, …?
- Beyond MSSM, NMSSM, SUSY, …?

too many hard questions …

tempted to give up and do something else

Bayesian evidence

$$\mathcal{E} = \int \mathcal{L}(\mu)\, \pi(\mu)\, d\mu$$

for a theory with a single parameter μ

$\mathcal{E}$ quantifies the plausibility of the theory the theory predicts $m_Z(\mu)$

so $m_Z(\mu)$ is invertible

$$m_Z(\mu) \ \Rightarrow \ \mu(m_Z)$$

write $\mathcal{E}$ as an integral over m_Z

$$\mathcal{E} = \int \mathcal{L}(m_Z)\, \pi(m_Z) \frac{d\mu}{dm_Z} dm_Z$$

Allanach, Hooper JHEP 0810:071 (2008)

if m_Z is very well measured…

$$\mathcal{L} \sim \delta\left(m_Z - m_Z^{exp}\right)$$

… we can evaluate the integral

$$\mathcal{E} \approx \int \delta(m_Z - m_Z^{exp})\, \pi(m_Z) \frac{d\mu}{dm_Z} dm_Z$$

$$\mathcal{E} \approx \pi(m_Z^{exp}) \left.\frac{d\mu}{dm_Z}\right|_{m_Z^{exp}}$$

Bayesian evidence = inverse of fine-tuning measure!

$$\mathcal{E} \approx const * \left(\left. \frac{dm_Z}{d\mu} \right|_{m_Z^{exp}} \right)^{-1}$$

plausibility that the theory correctly predicts m_Z

fixing μ using m_Z automatically induces $\frac{dm_Z}{d\mu}$ in $\mathcal{E}$!

this is Occam's razor at work!

MSSM

$$\text{trade } \{m_Z, m_t, tan\beta\}$$
$$\text{for } \{\mu,\ y_t,\ B_0\}$$

$$naturalness\ prior = \begin{vmatrix} \frac{\partial m_Z}{\partial \mu} & \frac{\partial m_t}{\partial \mu} & \frac{\partial tan\beta}{\partial \mu} \\ \frac{\partial m_Z}{\partial y_t} & \frac{\partial m_t}{\partial y_t} & \frac{\partial tan\beta}{\partial y_t} \\ \frac{\partial m_Z}{\partial B_0} & \frac{\partial m_t}{\partial B_0} & \frac{\partial tan\beta}{\partial B_0} \end{vmatrix}$$

Cabrera, Casas, deAustri JHEP 0903:075,2009 single parameter & observable:

fine tuning measure = inverse of evidence

more parameters & observables:

fine tuning measure = inverse of prior

Barbieri-Ellis-Giudice EW FT measure:

$$\frac{\partial(electroweak\ observable)}{\partial(theory\ parameters)}$$

- evidence = integral over parameters
  observables can be used to eliminate parameters
- evidence ratios have clear normalization scale
- Observables: subjective choice!
- Parameters: subjective choice!
- Form: depends on prior!
- Expression: determinant!
- What does $\frac{\partial m_Z}{\partial \mu}$ have to do with $\Delta m_H, \mu, m_{\tilde{t}}, m_{\tilde{g}}, \ldots$?
- Beyond MSSM, NMSSM, SUSY: evidence can be defined!

NMSSM

$$\text{trade}\ \{\ln m_Z^2,\ \ln\lambda, \ln tan\beta\}$$
$$\text{for}\ \{\ln m_S^2, \ln\lambda_0,\quad \ln\kappa_0\}$$

$$naturalness\ prior = \begin{vmatrix} \frac{\partial \ln m_Z^2}{\partial \ln m_S^2} & \frac{\partial \ln\lambda}{\partial \ln m_S^2} & \frac{\partial \ln tan\beta}{\partial \ln m_S^2} \\ \frac{\partial \ln m_Z^2}{\partial \ln\lambda_0} & \frac{\partial \ln\lambda}{\partial \ln\lambda_0} & \frac{\partial \ln tan\beta}{\partial \ln\lambda_0} \\ \frac{\partial \ln m_Z^2}{\partial \ln\kappa_0} & \frac{\partial \ln\lambda}{\partial \ln\kappa_0} & \frac{\partial \ln tan\beta}{\partial \ln\kappa_0} \end{vmatrix}$$

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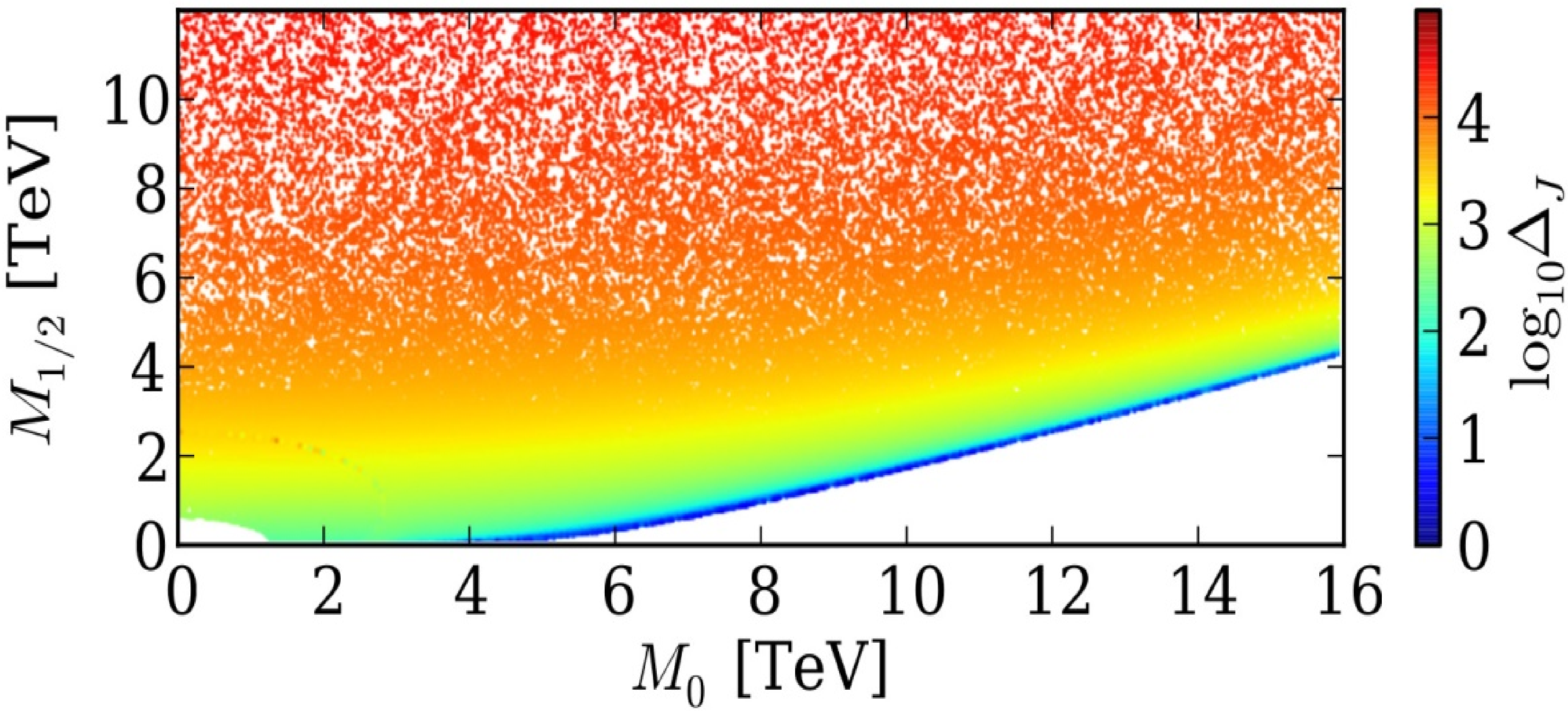
Naturalness prior map in the CMSSM

$$A_0 = -2.5\ \mathrm{TeV}, tan\beta = 10$$



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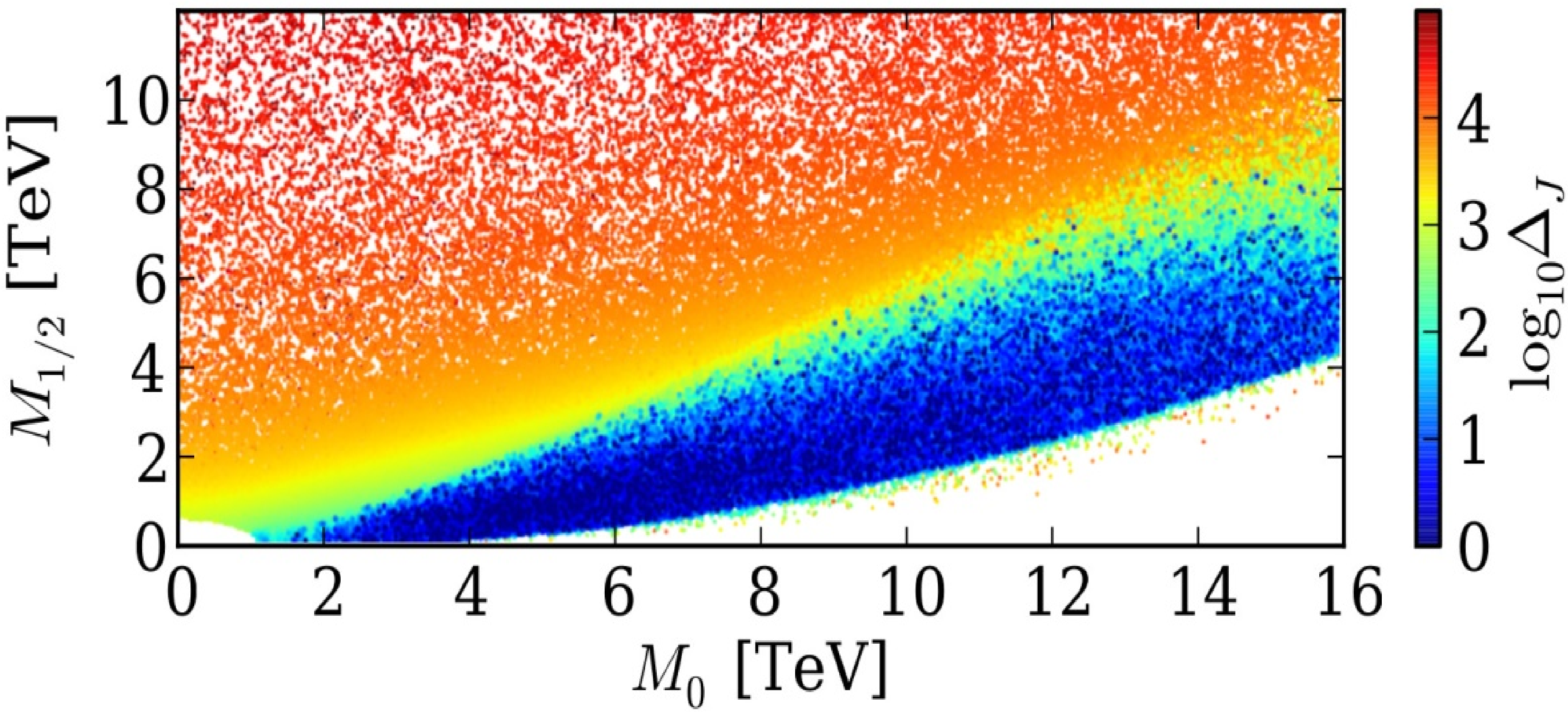
Naturalness prior map in the CNMSSM

$$A_0 = -2.5\ \mathrm{TeV}, tan\beta = 10$$



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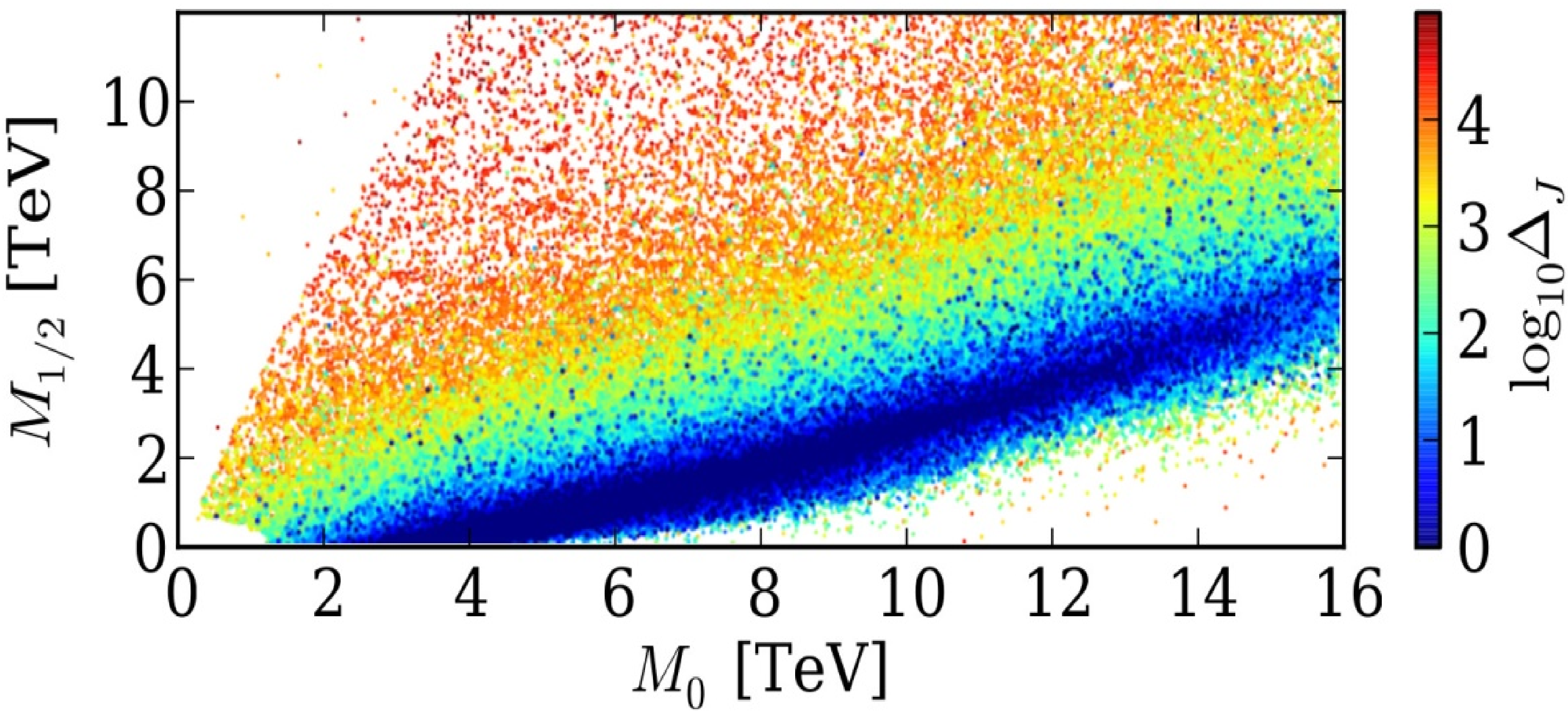
Naturalness prior map in NMSSM-11

$$A_0 = -2.5\ \mathrm{TeV}, tan\beta = 10$$



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conclusions

naturalness is a robust fundamental principle

it can be quantified within the Bayesian framework

Fine tuning is measured by the naturalness prior

according to Bayesian naturalness SUSY is not dead (yet)