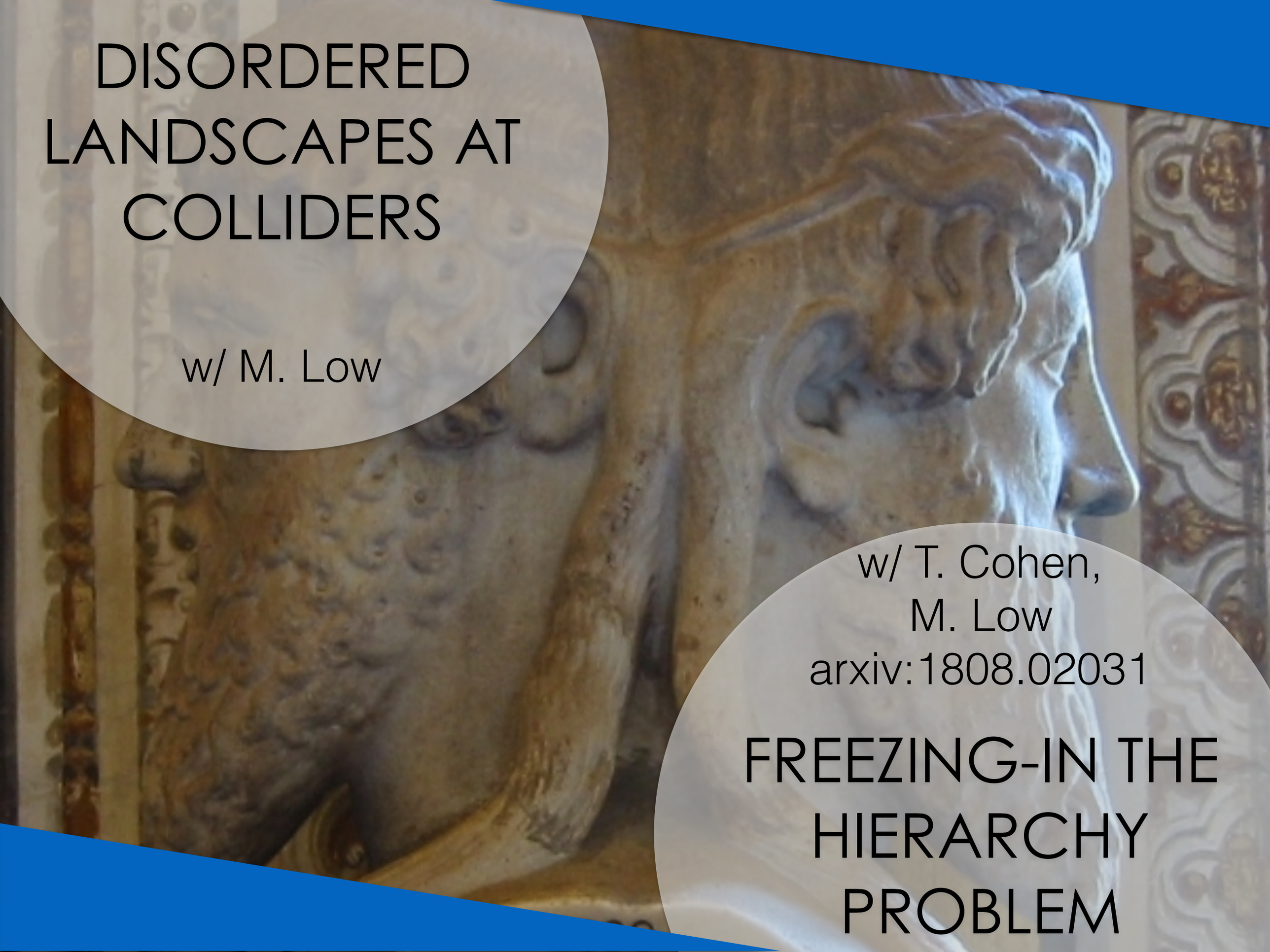
DISORDER IN MODEL BUILDING: FROM THE HIERARCHY PROBLEM TO COLLIDERS

Raffaele Tito D’Agnolo (SLAC)

KEK - December 2018

DISORDERED LANDSCAPES AT COLLIDERS

w/ M. Low

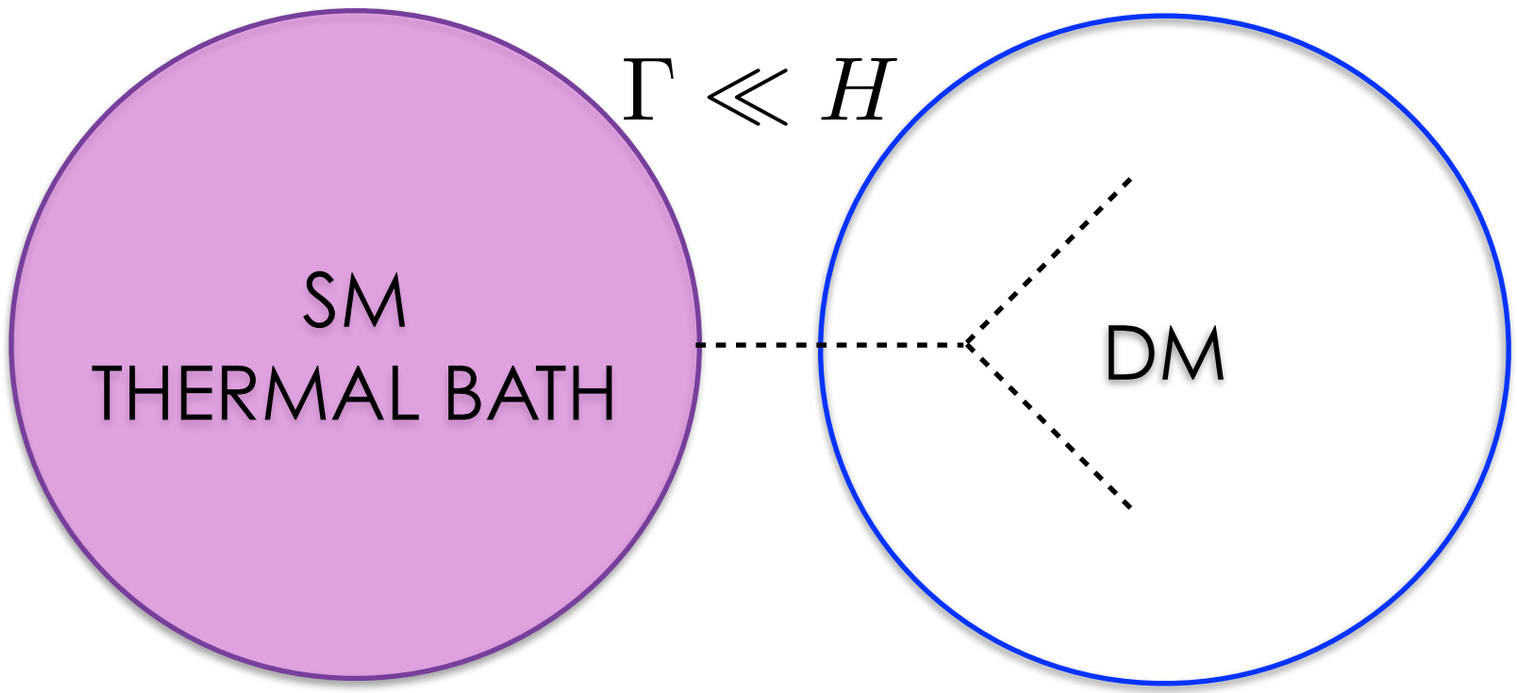


w/ T. Cohen,
M. Low
arxiv:1808.02031

FREEZING-IN THE HIERARCHY PROBLEM

FREEZE-IN DARK MATTER

INITIAL CONDITIONS: $Y_{DM} \equiv \frac{n_{DM}}{s} = 0$



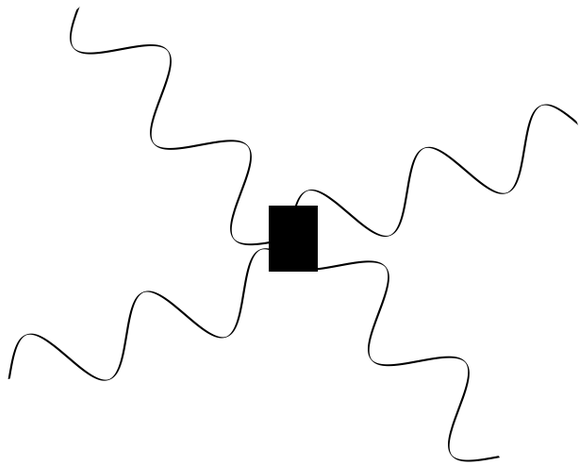
OBSERVATION

$m_{\rm SM} \gtrsim m_{\rm DM} \approx v$

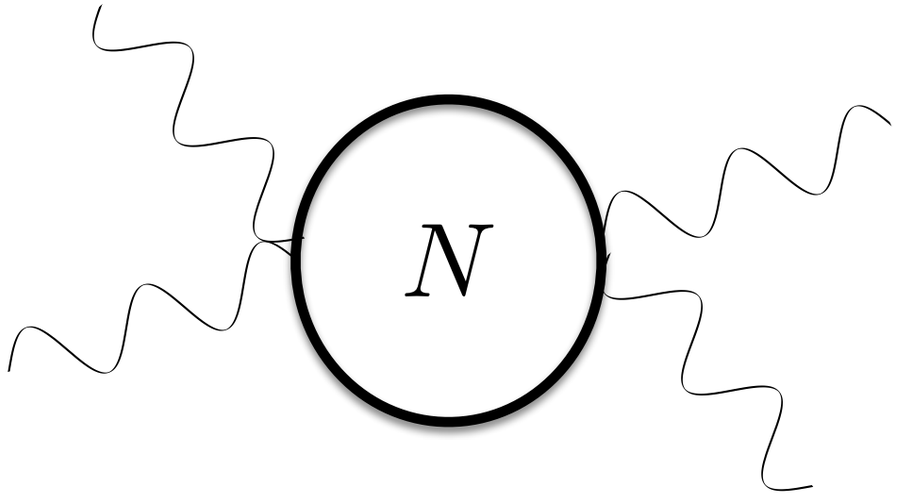
$$\lambda \sim \frac{v}{M_{\rm Pl}} \sim \frac{1}{\sqrt{N}}$$

TEMPTING SPECULATION

GRAVITY



$$\sim \frac{E^2}{M_{\rm Pl}^2}$$



$$\sim \frac{N E^4}{(4\pi)^2 M_{\rm Pl}^4}$$

$$\Lambda_{\rm UV} \sim 4\pi \frac{M_{\rm Pl}}{\sqrt{N}} \sim {\rm TeV}$$

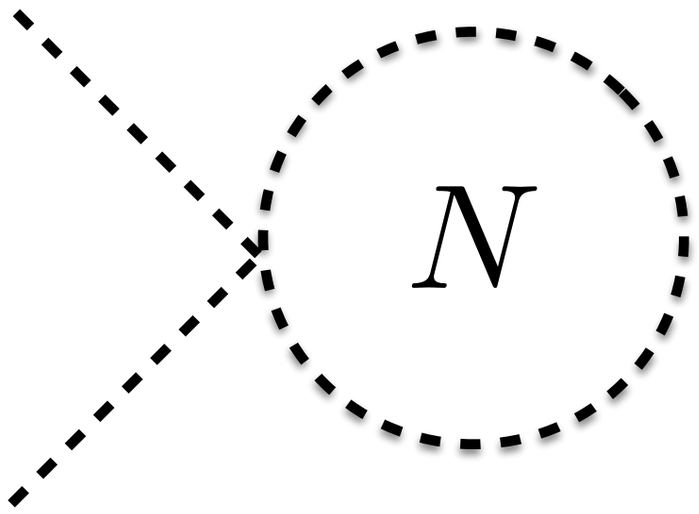
SOLUTION TO THE HP

arXiv:0706.2050

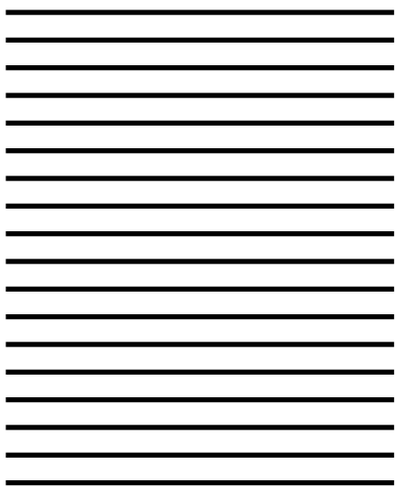
arXiv:0710.4344

LARGE N BASICS

$$\lambda |H|^2 \sum_{i=1}^{N} \phi_i^2$$



$$\lambda \sim \frac{1}{N}$$

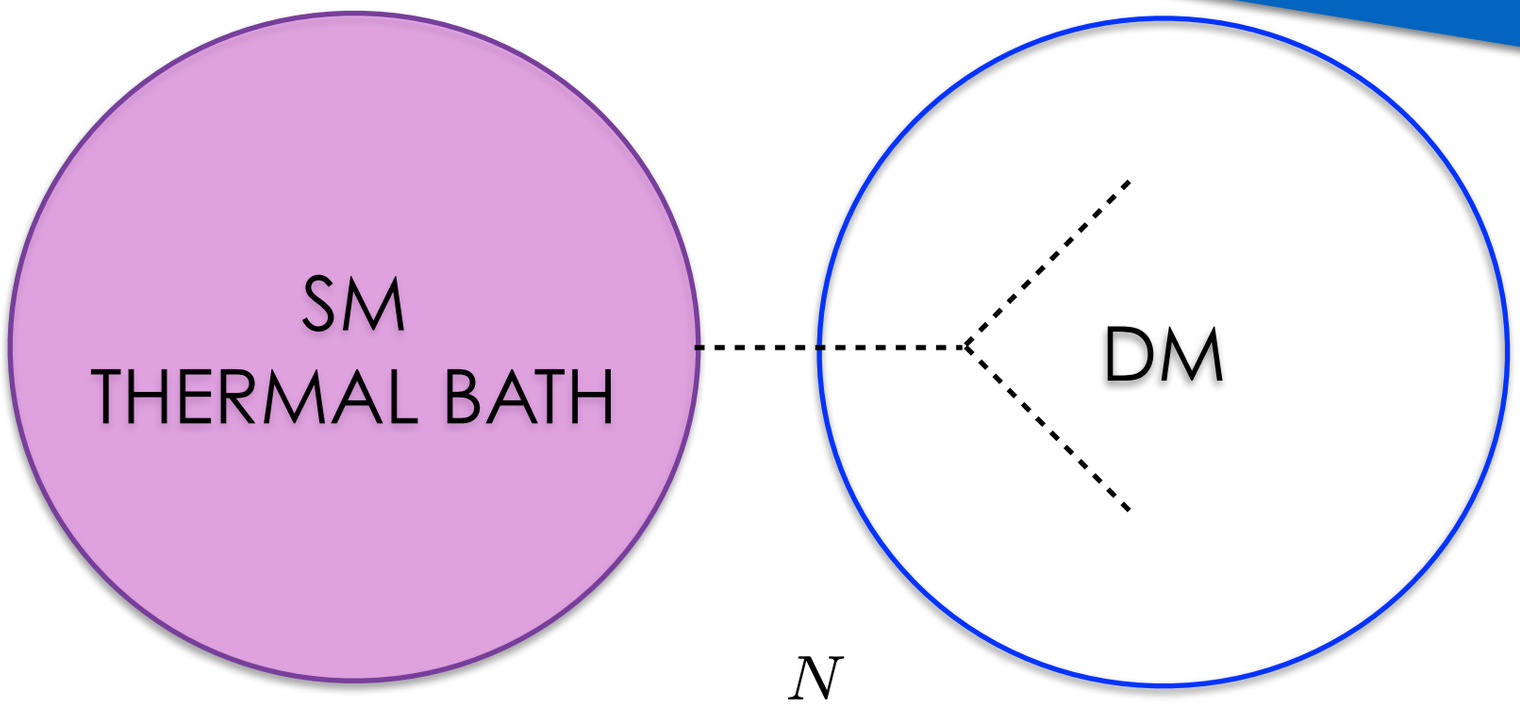


ϕ_i

$$r \sim \lambda^V N^{L_\phi} = (\lambda N)^V N^{-P+n}$$

$$P \geq n$$

N DARK MATTER SPECIES



$$\lambda |H|^2 \sum_{i=1}^{N} \phi_i^2$$

$$Y_{DM} = \sum_{i=1}^{N} Y_i \approx N \lambda^2 \frac{M_{\rm Pl}}{m_{\rm SM}}$$

$$\lambda \sim \frac{1}{N}$$

$$N \sim \frac{M_{\rm Pl}^2}{v^2}$$

NO HIERARCHY PROBLEM

(BUT MANY OTHER ISSUES)

PARAMETRICS OF FREEZE-IN

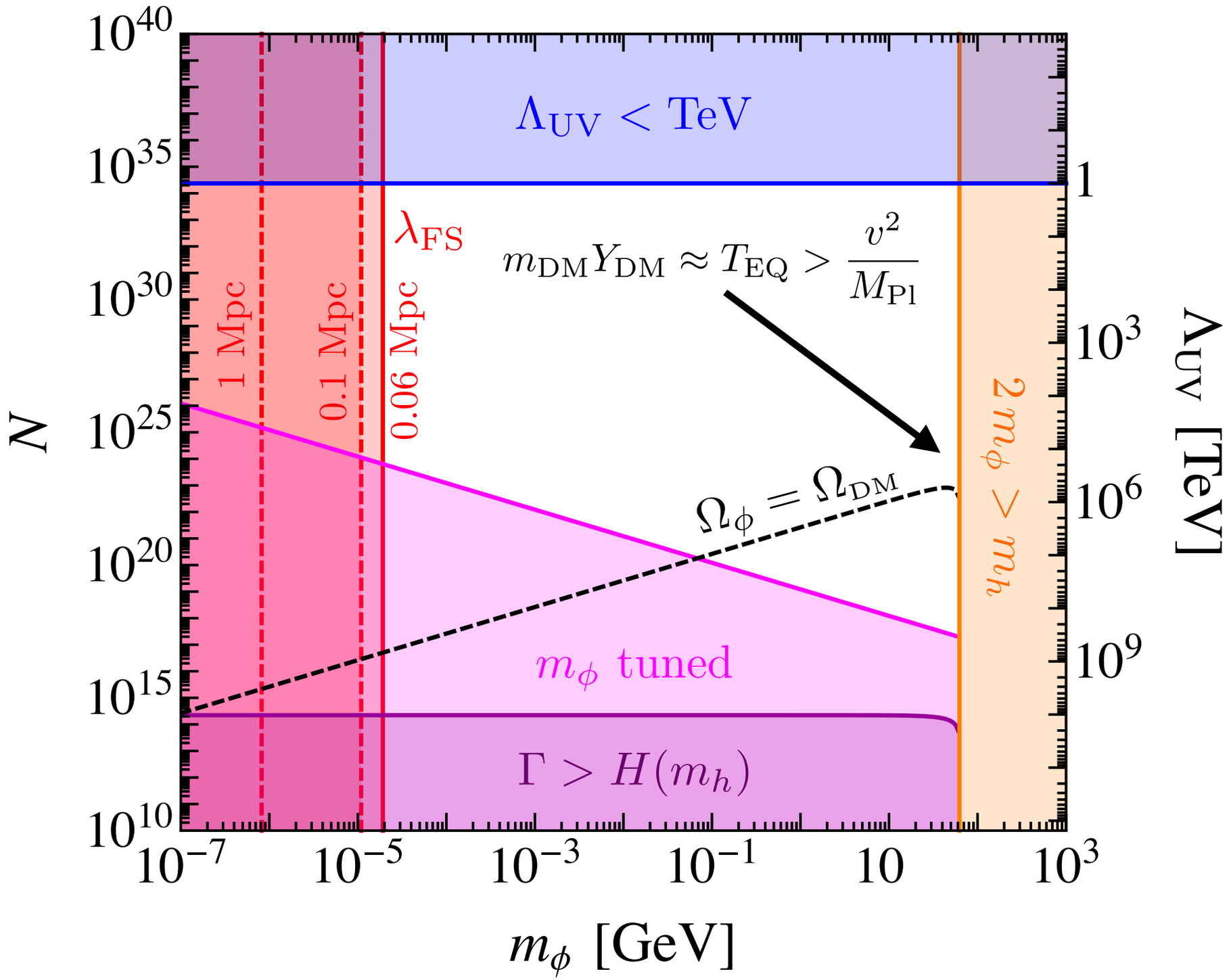
$$\Gamma \equiv \Gamma(\mathrm{SM} \to \mathrm{DM}\ \mathrm{DM})$$

$$\frac{dY_{\mathrm{DM}}}{dt} \approx \Gamma Y_{\mathrm{SM}} \quad \Rightarrow \quad Y_{\mathrm{DM}} \approx \frac{\Gamma Y_{\mathrm{SM}}}{H(m_{\mathrm{SM}})} \approx \lambda^2 \frac{M_{\mathrm{Pl}}}{m_{\mathrm{SM}}}$$

$$m_{\mathrm{DM}} Y_{\mathrm{DM}} = \frac{\rho_{\mathrm{DM}}}{s_0} \approx T_{\mathrm{EQ}} \sim \frac{v^2}{M_{\mathrm{Pl}}} \quad \Rightarrow \quad \lambda \sim \frac{v}{M_{\mathrm{Pl}}} \sqrt{\frac{m_{\mathrm{SM}}}{m_{\mathrm{DM}}}}$$

$$m_{\mathrm{DM}} \leftrightarrow \Lambda_{\mathrm{UV}}$$

SCALAR PHENOMENOLOGY



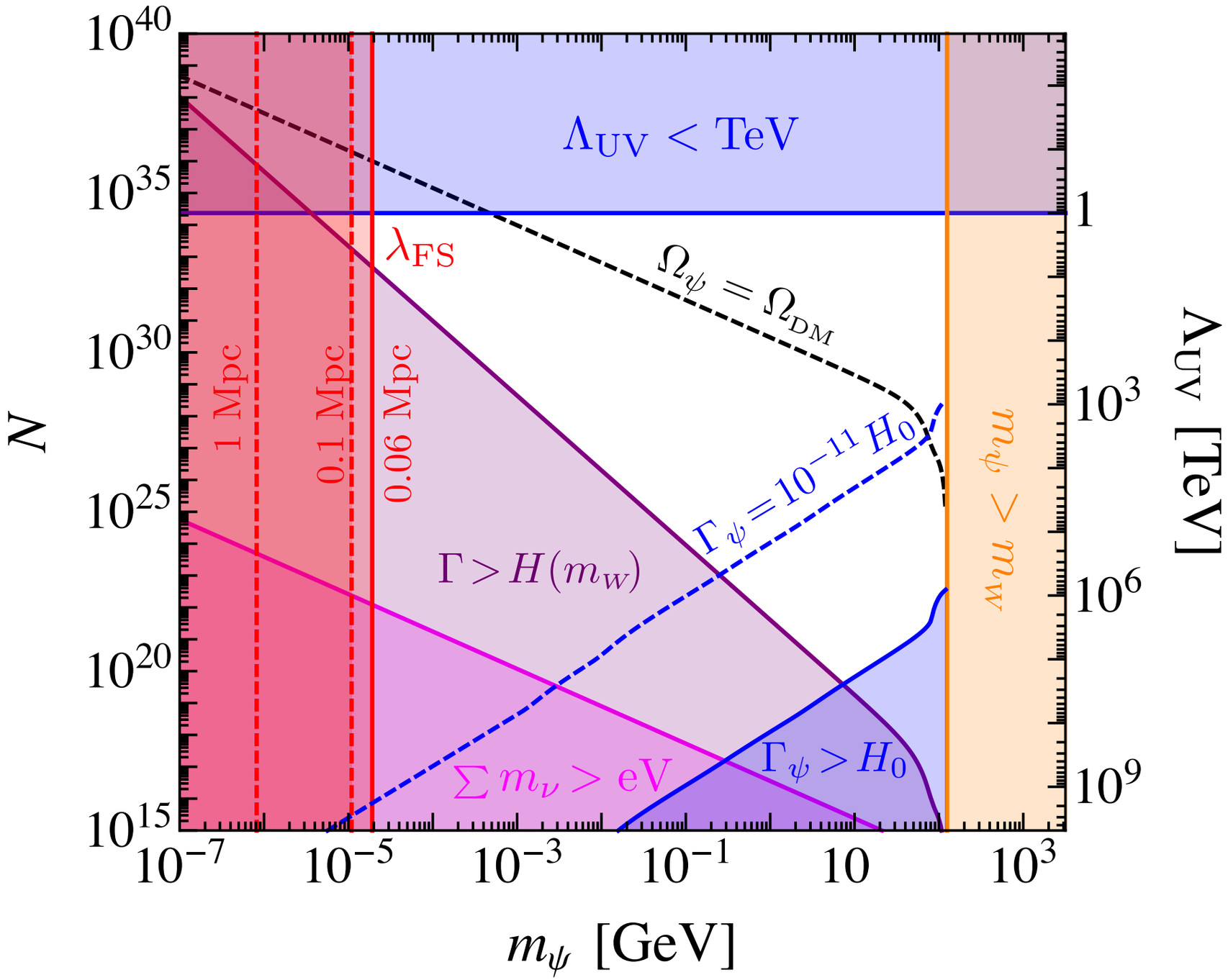
TEV CUTOFFS

$$y_\psi L_e H \sum_{i=1}^{N} \psi_i$$

1. $r \sim y_\psi^V N^{I_\psi} = (y_\psi^2 N)^V N^{-E_\psi} \longrightarrow y_\psi \lesssim \frac{1}{\sqrt{N}}$

2. $\Gamma(W \to e\psi) \sim \frac{y_\psi^2 v^3}{m_\psi^2} \longrightarrow m_{\rm DM} Y_{\rm DM} \sim \frac{1}{m_{\rm DM}}$

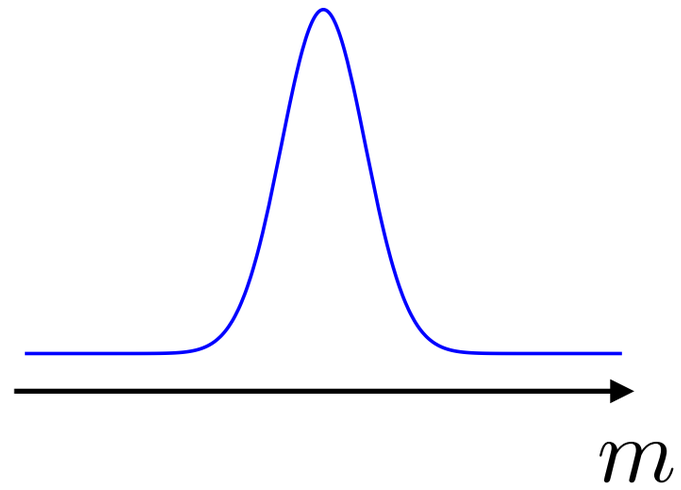
FERMION PHENOMENOLOGY

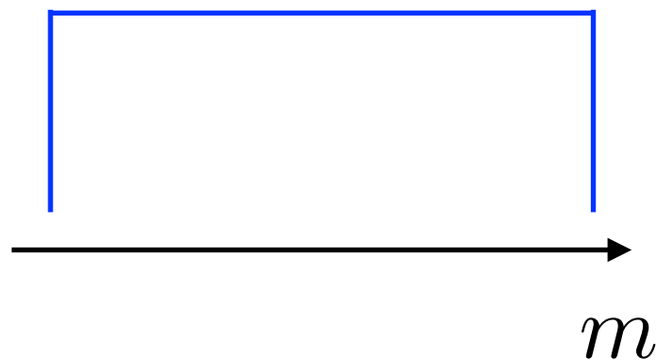


A DISTRIBUTION OF MASSES

FOR ILLUSTRATIVE PURPOSES I HAVE TAKEN ALL N MASSES TO BE EQUAL

$$\frac{d\rho_{\rm DM}}{dm} \sim$$





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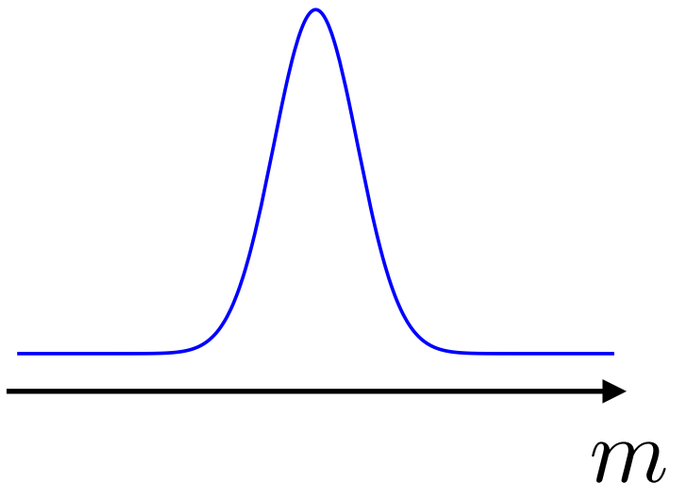
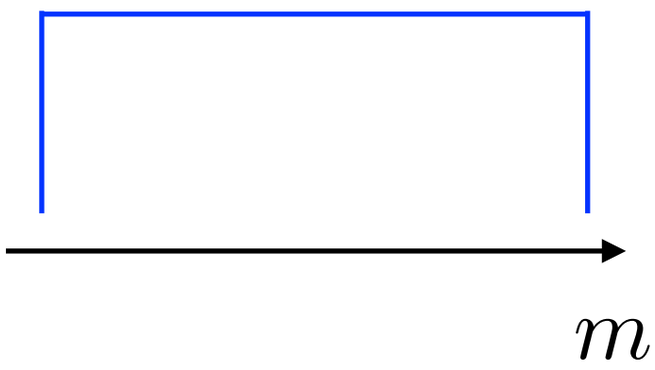
A DISTRIBUTION OF MASSES

CONTINUOUS ENERGY INJECTION THROUGHOUT THE HISTORY OF THE UNIVERSE



$$\frac{d\rho_{\rm DM}}{d\tau} = \frac{d\rho_{\rm DM}}{dm}\left|\frac{d\tau}{dm}\right|$$



PHENOMENOLOGY SIMILAR TO DYNAMICAL DARK MATTER

arXiv:1106.4546

arXiv:1107.0721

SUMMARY & SMOKING GUNS

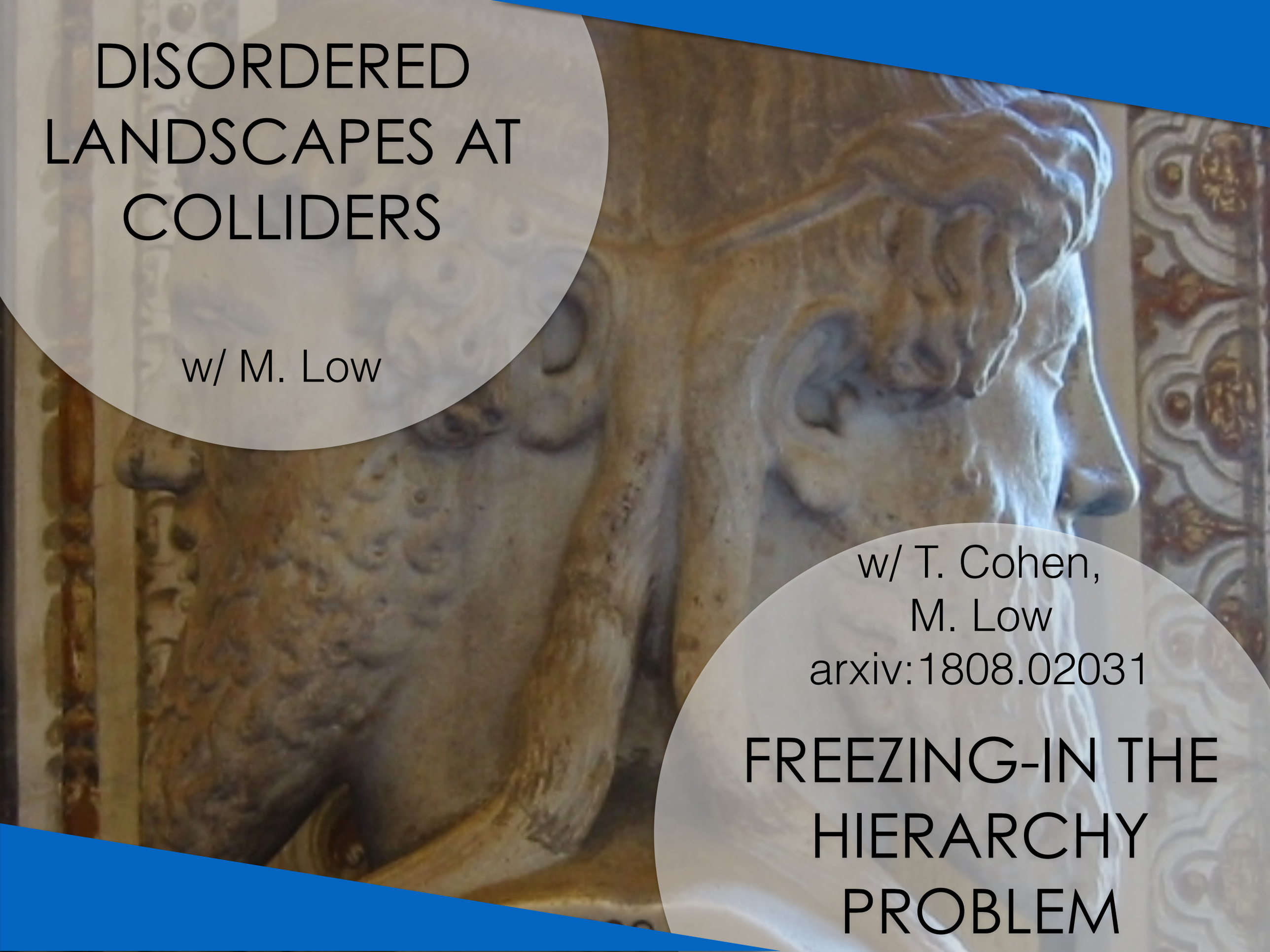
- NEW CONNECTION BETWEEN DARK MATTER AND THE HIERARCHY PROBLEM (ANOTHER FACE OF THE "WIMP MIRACLE"). FOR OTHER "FLAVORS" OF LARGE-N DM SEE: 0903.0660 AND 1607.06821

- RATHER UNIQUE SIGNATURES: DARK MATTER IS VERY WEAKLY COUPLED TO US, BUT IT CAN BE PRODUCED AT COLLIDERS THROUGH ITS GRAVITATIONAL INTERACTIONS. ITS FREEZE-IN COUPLING MIGHT BE PROBED IN INDIRECT DETECTION

- IF WE ALLOW FOR A DISTRIBUTION OF MASSES WE GET A NEW CHARACTERISTIC SIGNAL: ENERGY INJECTION THROUGHOUT THE HISTORY OF THE UNIVERSE

DISORDERED LANDSCAPES AT COLLIDERS

w/ M. Low



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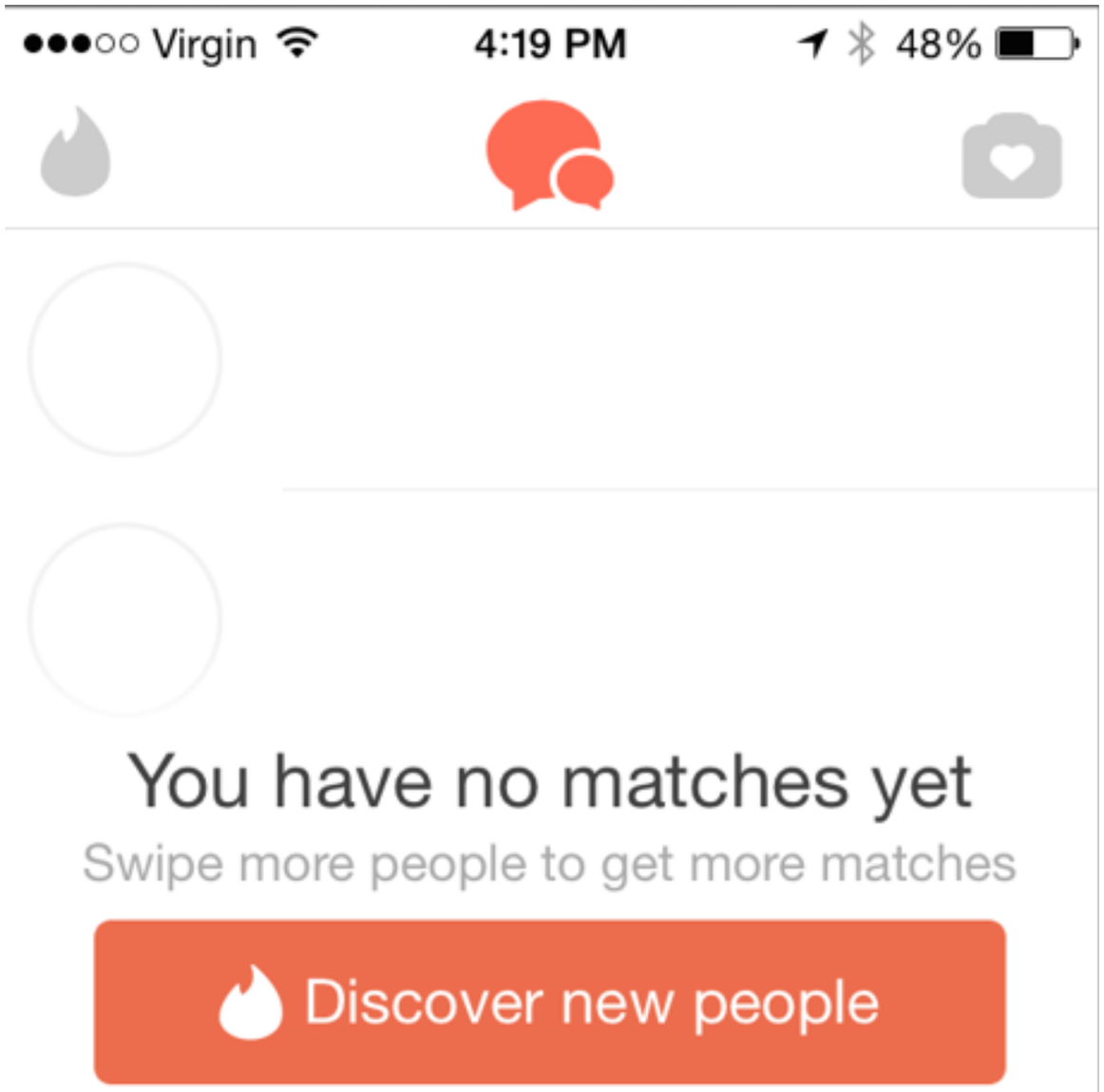
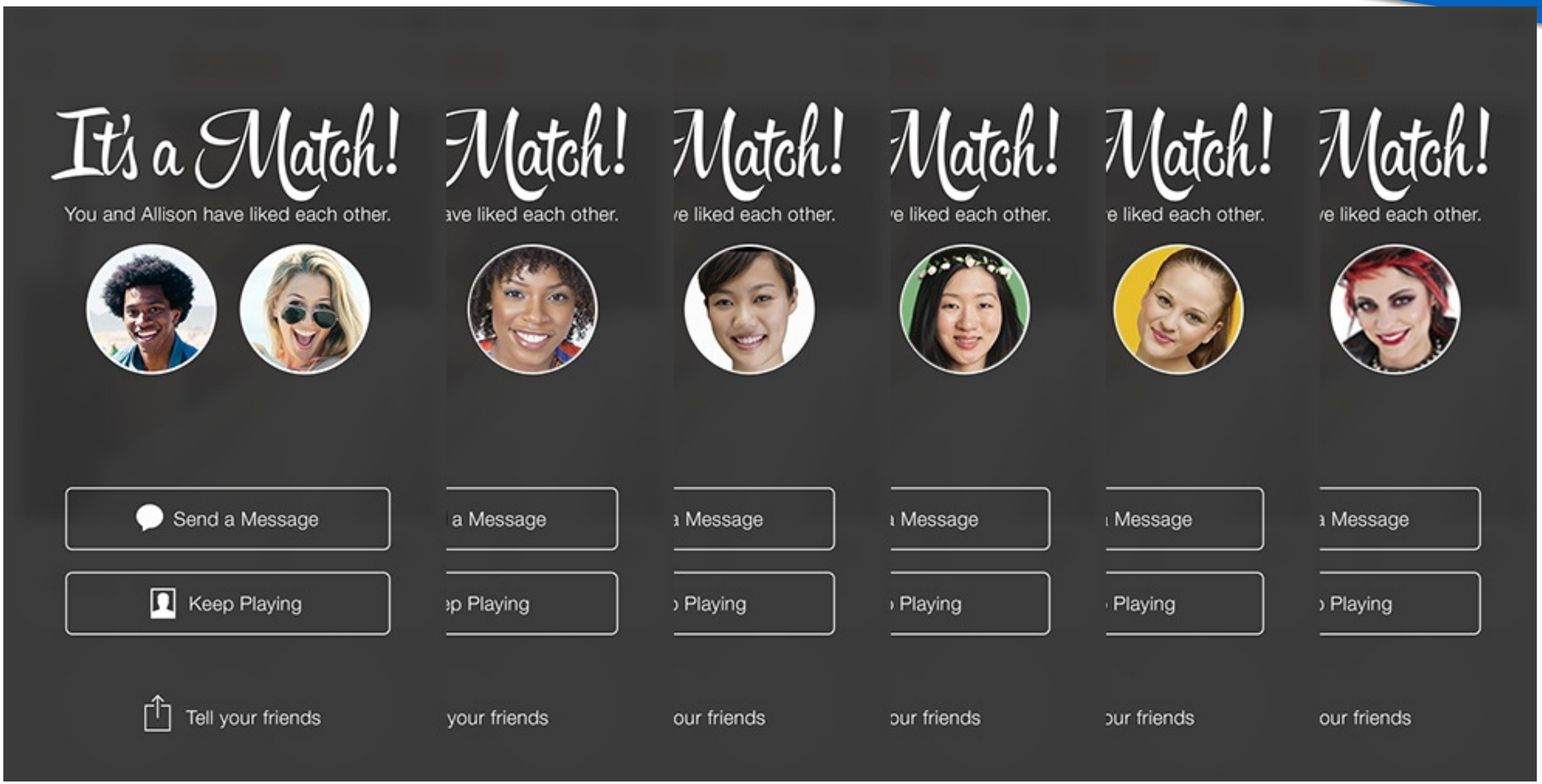
FREEZING-IN THE HIERARCHY PROBLEM

WHY HAVE WE SEEN NOTHING SO FAR?



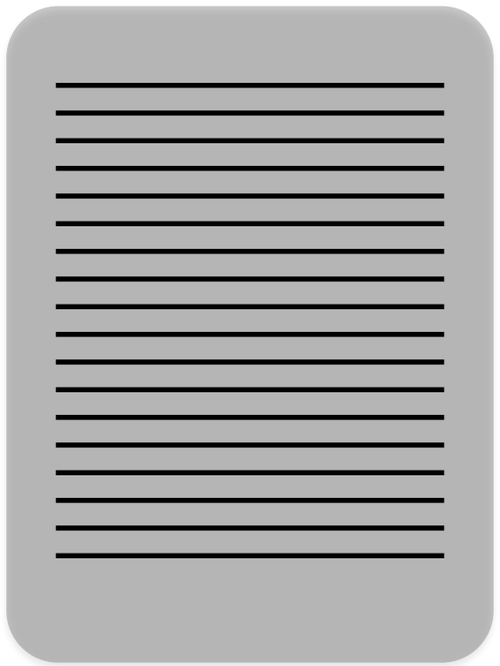
EXPLANATION #1:
THERE IS NOTHING TO SEE



EXPLANATION #2:
THERE ARE TOO MANY NEW PARTICLES

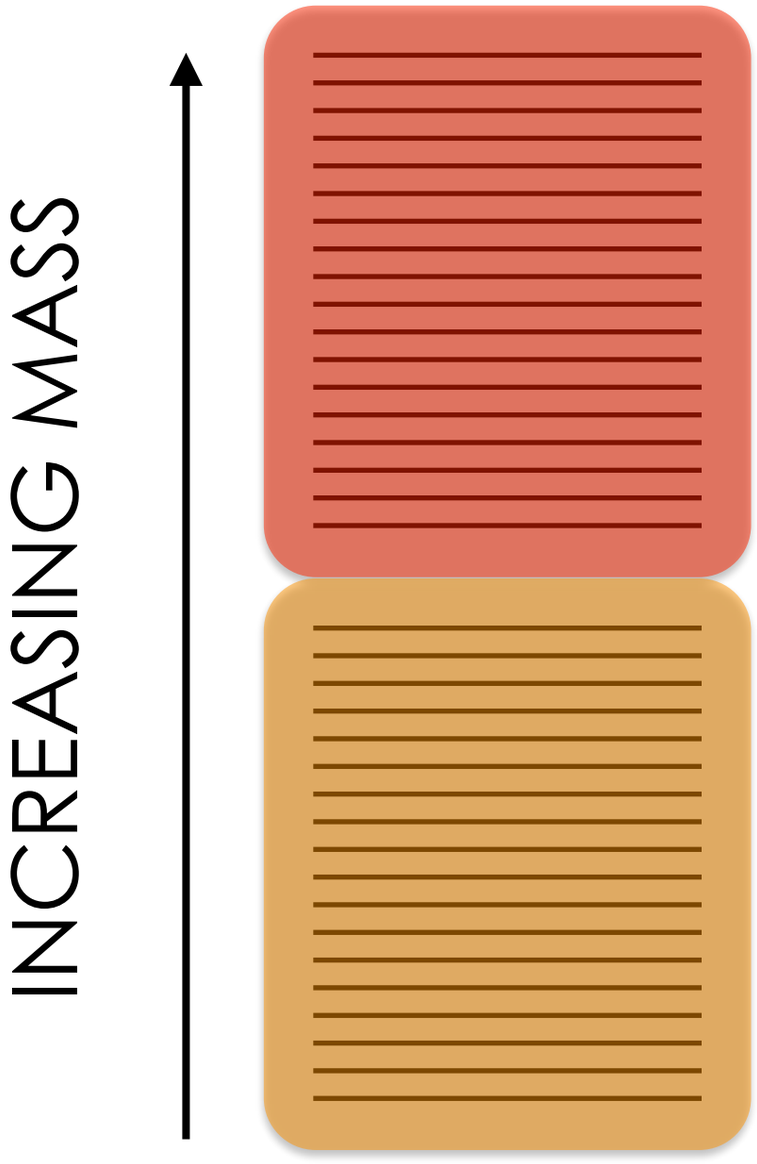
LARGE N CONSEQUENCES

OUT OF REACH



$$\sigma \sim \frac{1}{N}$$

LARGE N CONSEQUENCES



LONG DECAY CHAIN,
LOW PT FINAL OBJECTS,
LOW VISIBLE ENERGY

=

MISSED BY CURRENT TRIGGERS

SHORT DECAY CHAIN,
SMALL MASS

=

TOO MUCH BACKGROUND OR "UNTRIGGERABLE"

TODAY'S MODEL

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi_\alpha)^2 - \frac{m_\alpha^2}{2}\phi_\alpha^2 - a_{\alpha\beta\gamma}\phi_\alpha\phi_\beta\phi_\gamma - \lambda_{\alpha\beta\gamma\delta}\phi_\alpha\phi_\beta\phi_\gamma\phi_\delta$$

SMALL LOW ENERGY SECTOR OF THE LANDSCAPE EXPANDED AROUND A MINIMUM

(TUNED MODULI, GOLDSTONES ASSOCIATED TO THE POSITION OF BRANES, (PSEUDO) SCALARS FROM HIGHER FORMS IN STRING THEORY, …)

$$\mathcal{L}_\psi \supset i\psi_\alpha^\dagger \overline{\sigma}^\mu \partial_\mu \psi_\alpha - m_\alpha \psi_\alpha^\dagger \psi_\alpha - y_{\alpha\beta}\psi_\alpha^\dagger \psi_\beta \phi + \text{h.c.}$$

LOW ENERGY REMNANTS OF COMPACTIFICATIONS

(FROM STRINGS ENDING ON BRANE STACKS FOR EXAMPLE)

CONCRETE MODELS

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \phi_\alpha)^2 - \frac{m_\alpha^2}{2}\phi_\alpha^2 - a_{\alpha\beta\gamma}\phi_\alpha\phi_\beta\phi_\gamma - \lambda_{\alpha\beta\gamma\delta}\phi_\alpha\phi_\beta\phi_\gamma\phi_\delta$$

LOW ENERGY SECTOR OF THE LANDSCAPE EXPANDED AROUND A MINIMUM

$$\mathcal{L}_{\phi H} \supset -a_\alpha^{\mathrm{SM}}\phi_\alpha|H|^2 - \lambda_{\alpha\beta}^{\mathrm{SM}}\phi_\alpha\phi_\beta|H|^2$$

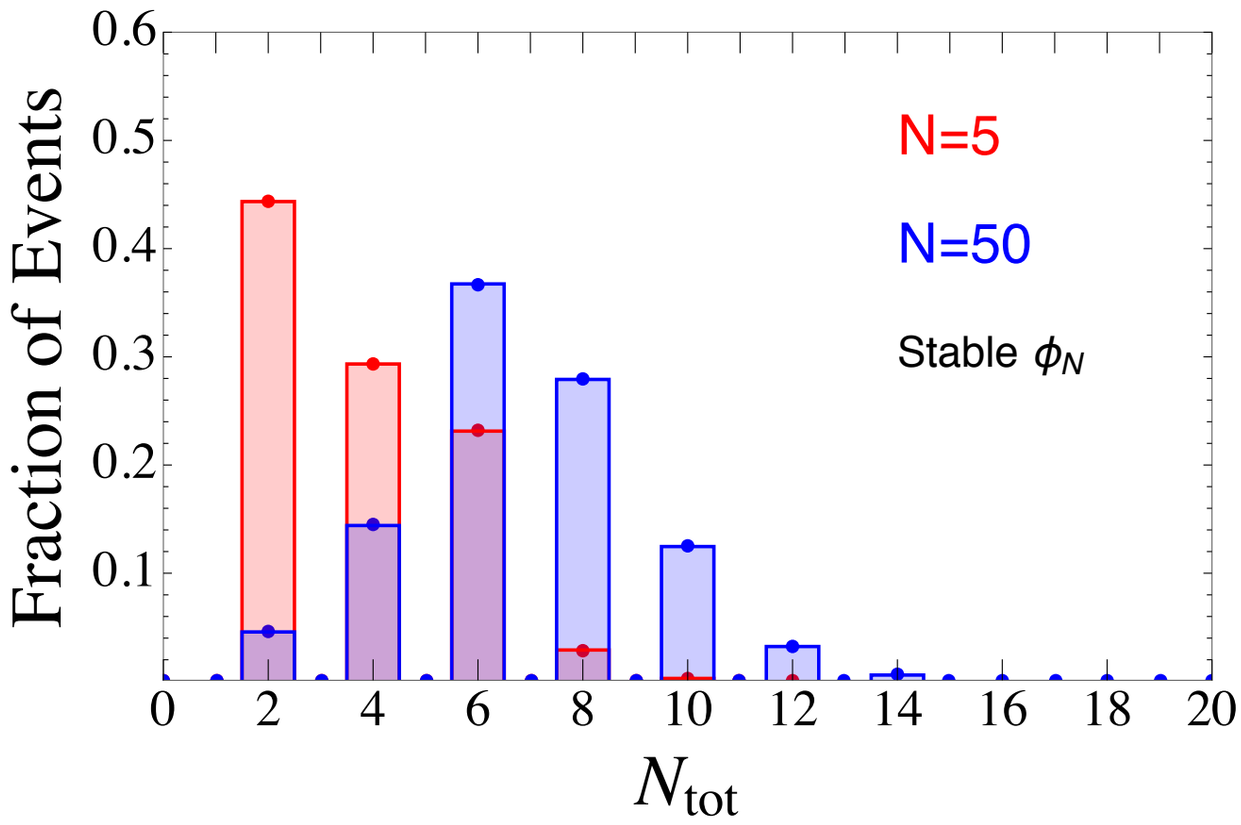
WITH SMALL COUPLINGS TO THE SM

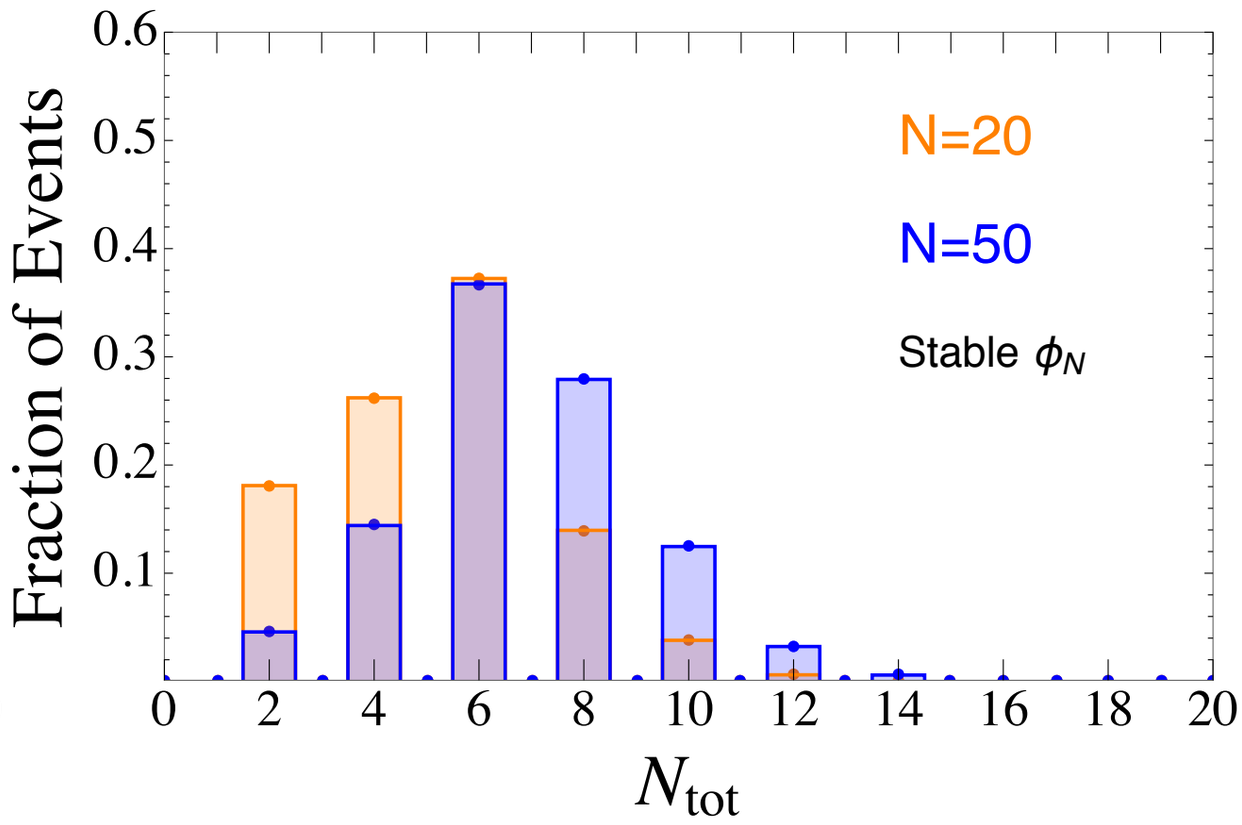
$$a^{SM} \ll a$$

PARTICLE MULTIPLICITIES

$$N_{\rm tot} = b, c, \mu, s, W, Z, g, \gamma, \phi_N$$

$$a_{\alpha\beta\gamma} = a_\alpha^{\rm SM} = 0 \qquad m_\alpha \in [100, 600]$$

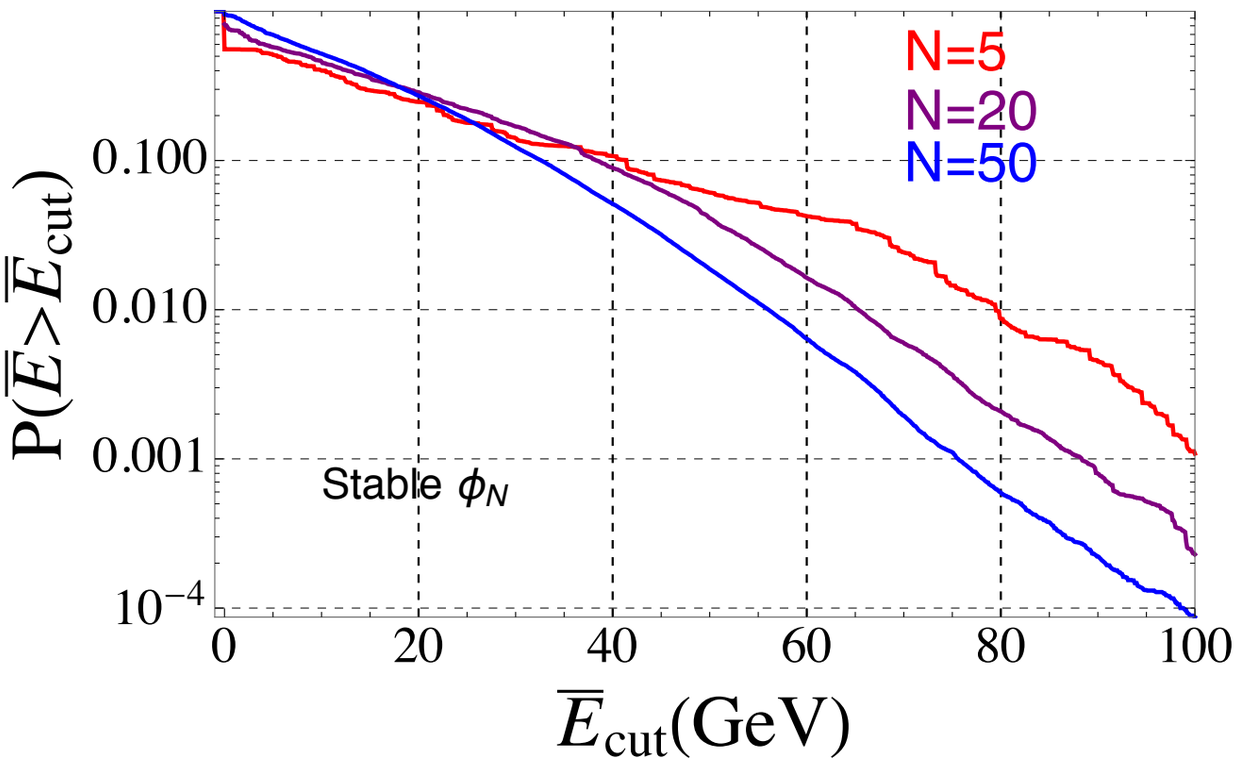




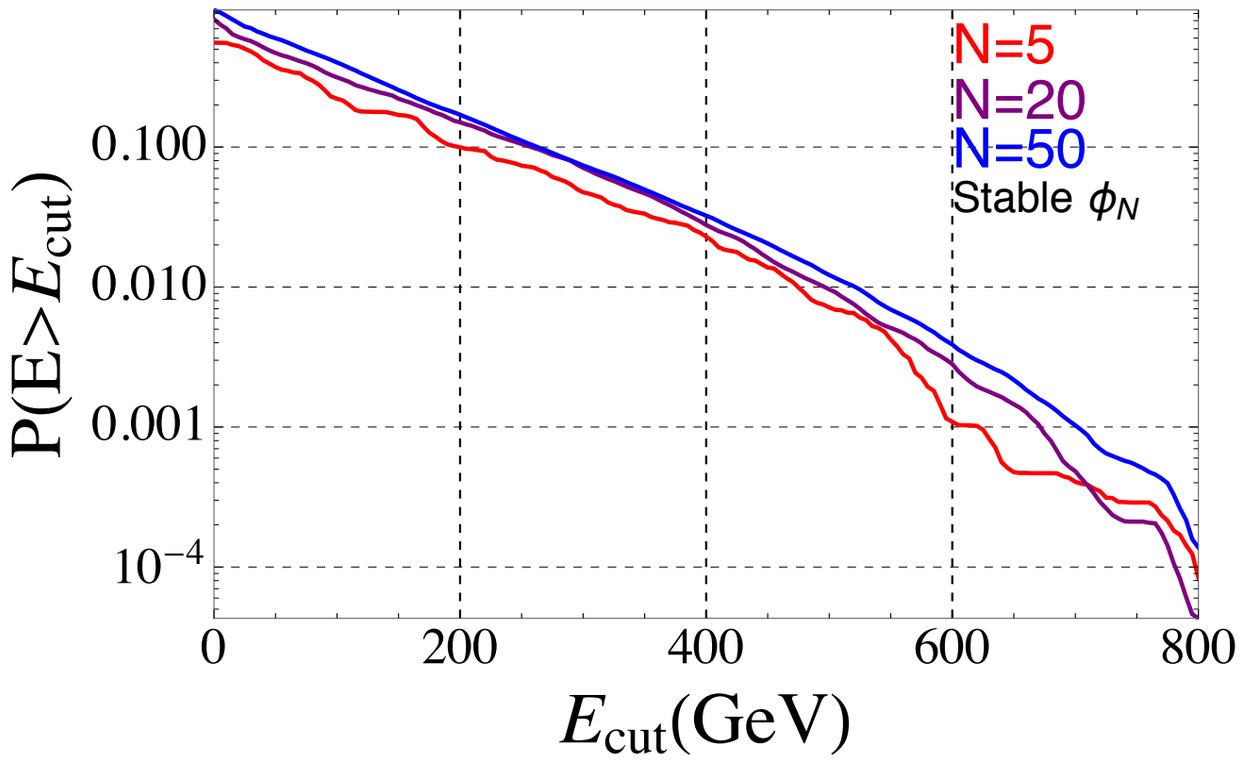
N.B. ALMOST ONLY JETS AND B-JETS
(EVENTS WITH TAU's AND W's <10%)

FINAL STATE ENERGIES

AVERAGE VISIBLE ENERGY PER PARTICLE



TOTAL VISIBLE ENERGY IN THE EVENT

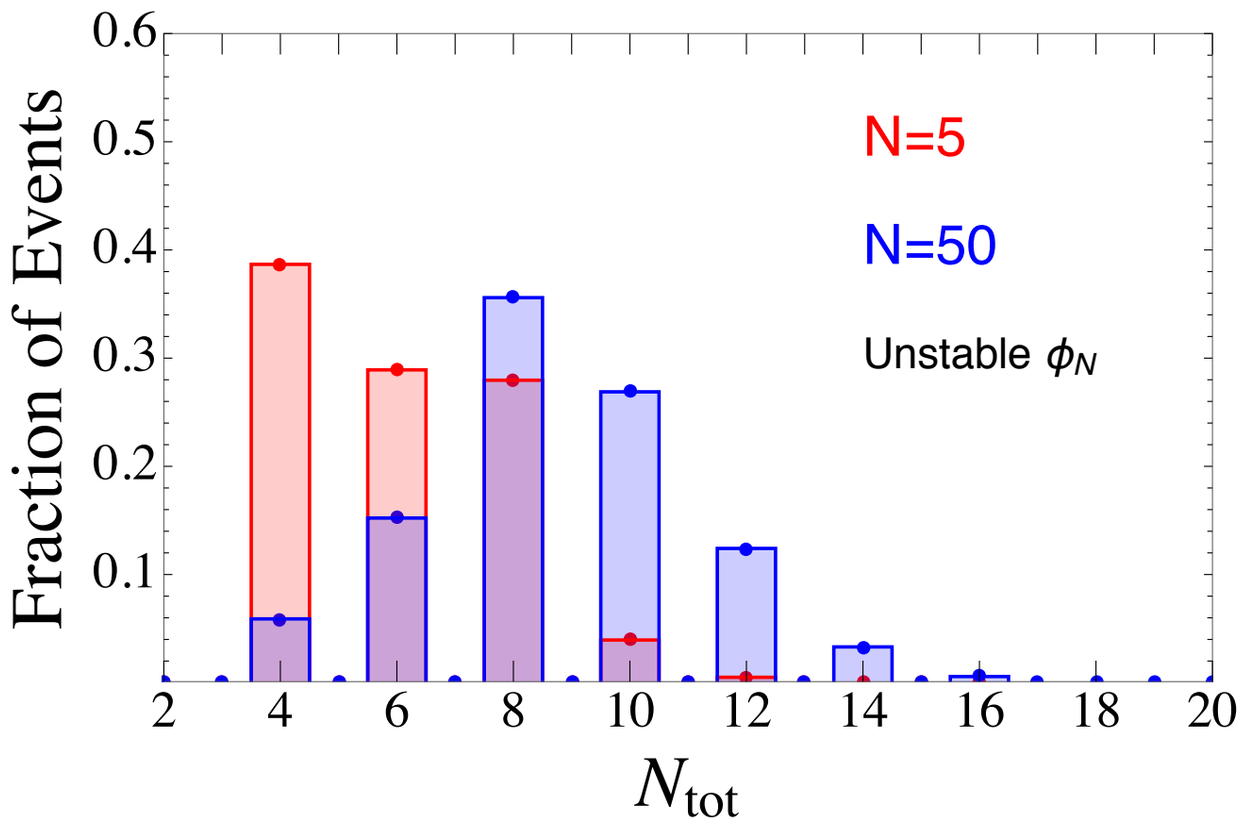


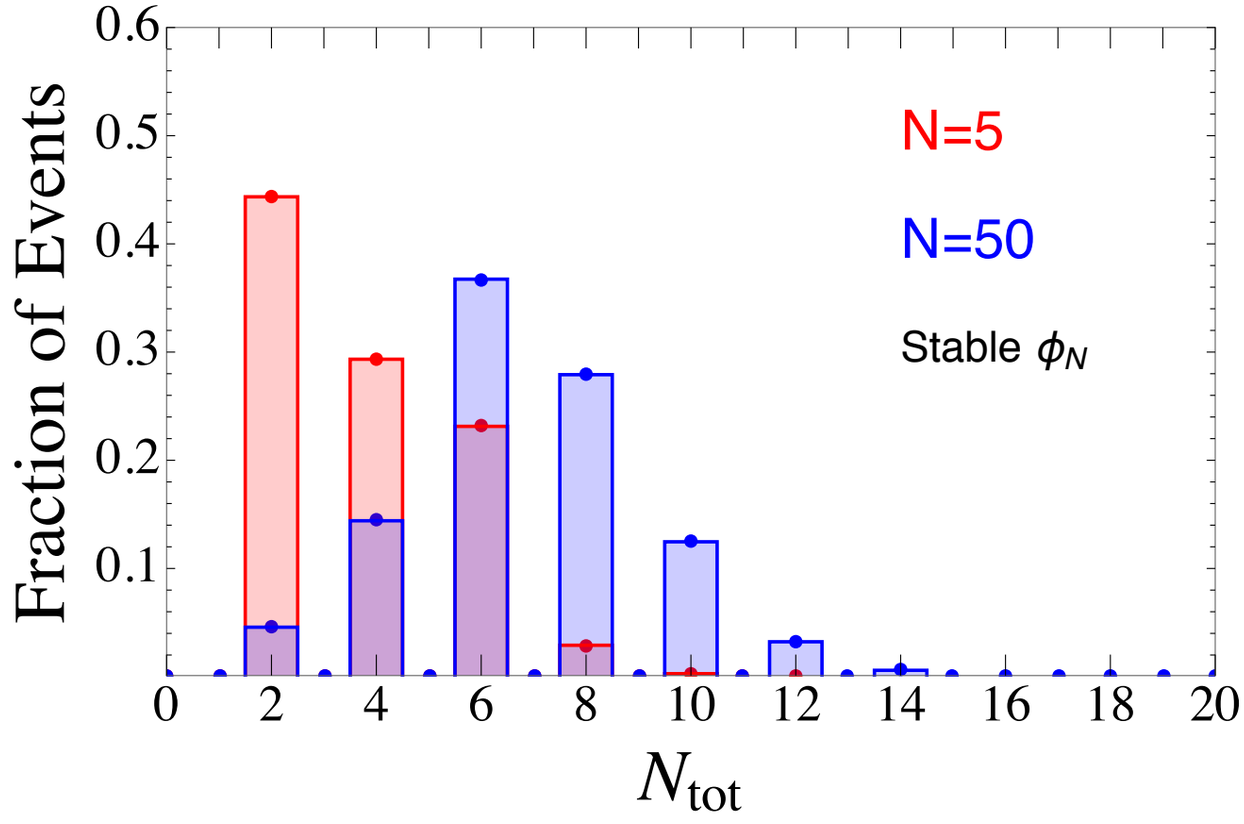
N.B. THERE ARE ALWAYS TWO INVISIBLE PARTICLES

$$a_{\alpha\beta\gamma} = a_{\alpha}^{\mathrm{SM}} = 0$$

PARTICLE MULTIPLICITIES

$$N_{\rm tot} = b, c, \mu, s, W, Z, g, \gamma$$

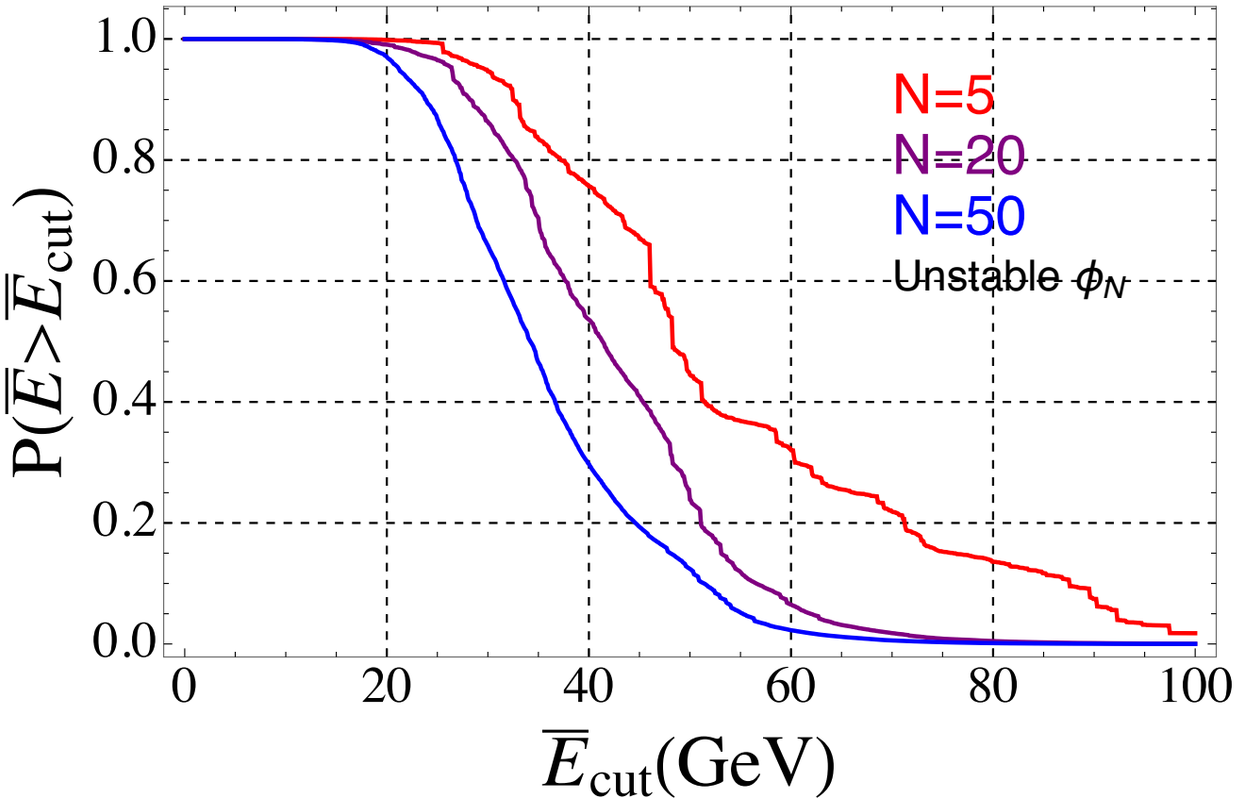




$$a_{\alpha\beta\gamma} = 0 \quad a_\alpha^{\rm SM} \neq 0 \quad a_\alpha^{\rm SM} \ll \lambda_{\alpha\beta}^{\rm SM} v$$

FINAL STATE ENERGIES

AVERAGE VISIBLE ENERGY PER PARTICLE



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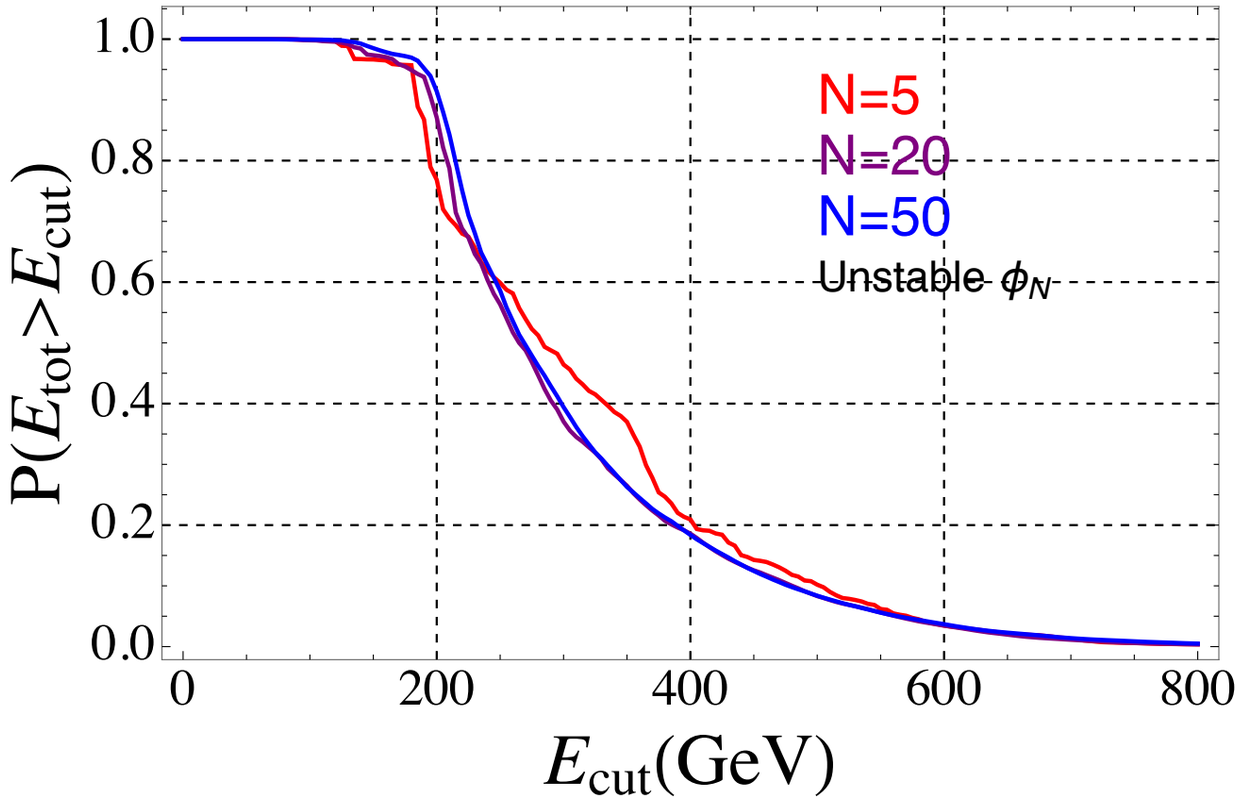
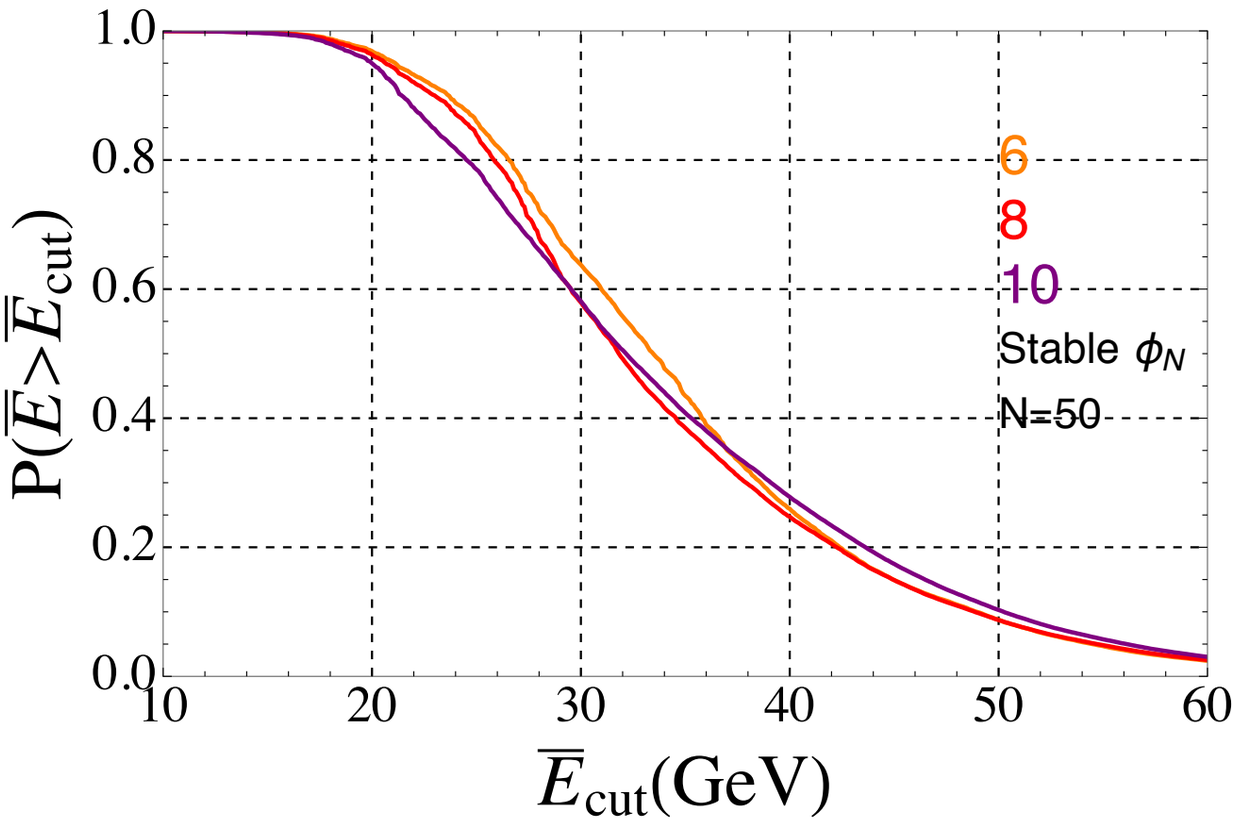
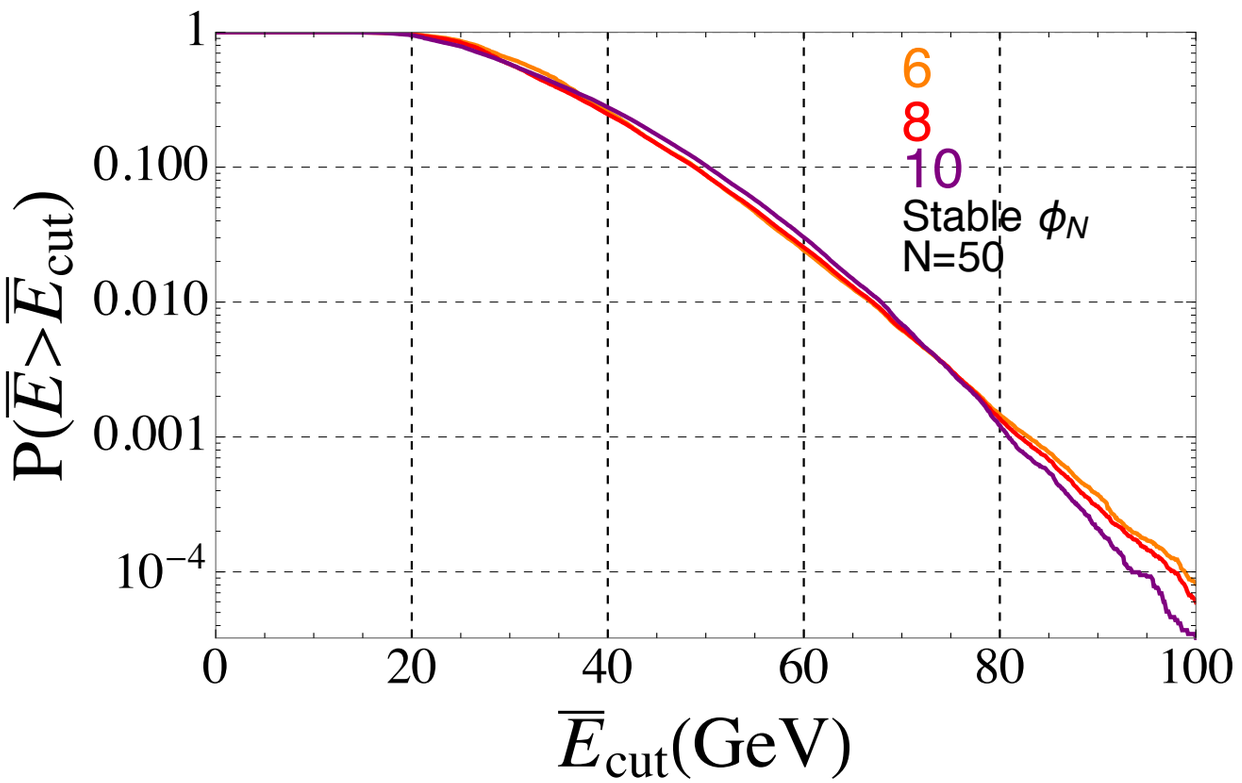


FINAL STATE ENERGIES

AVERAGE VISIBLE ENERGY PER PARTICLE
HIGH MULTIPLICITY EVENTS





ASIDE ON DISORDER

DISORDER IN THE MASS MATRIX

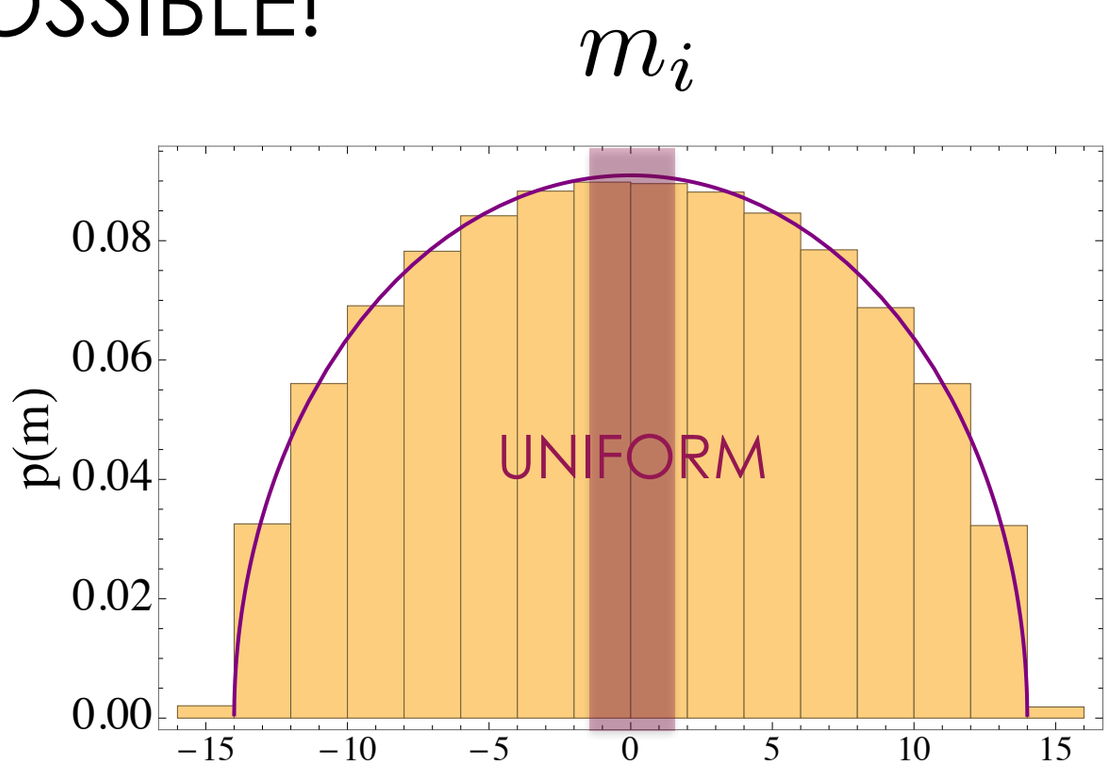
WE FOCUS ON A REASONABLE POSSIBILITY INSPIRED BY THE CENTRAL LIMIT THEOREM. MANY PHENO EXPLORATIONS ARE POSSIBLE!

REAL AND SYMMETRIC $N \times N$

$$\begin{pmatrix} \omega_{11} & \omega_{12} & \dots & \dots \\ \omega_{21} & \omega_{22} & \dots & \dots \\ \dots & \dots & \omega_{33} & \dots \\ & & & \dots \end{pmatrix}$$

$$p(\omega) \propto e^{-(\omega-\mu)^2/2\sigma^2}$$

$$\omega_{ij} = \omega_{ji}$$



$\sim -\sqrt{N}\sigma$ $\sim \sqrt{N}\sigma$

EIGENVALUES

COMBINATORICS AND PLANARITY

AVERAGE OVER DISORDER = PATH INTEGRAL IN A MATRIX MODEL (MANY ANALOGIES WITH SYK)

$$\langle (M^{2n})^i_j \rangle = \frac{1}{Z} \int DM e^{-\frac{N}{2}\mathrm{Tr}[M^2]} (M^{2n})^i_j$$

LARGE-N = PLANAR DIAGRAMS

$$\int_{-2}^{2} dm \frac{1}{2\pi} \sqrt{4-m^2} m^{2n} = C_n = \frac{(2n)!}{(n+1)!n!}$$

CATALAN NUMBERS: REMARKABLE COMBINATORIAL PROPERTIES, THEY ALSO COUNT OUR DECAY CHAINS!

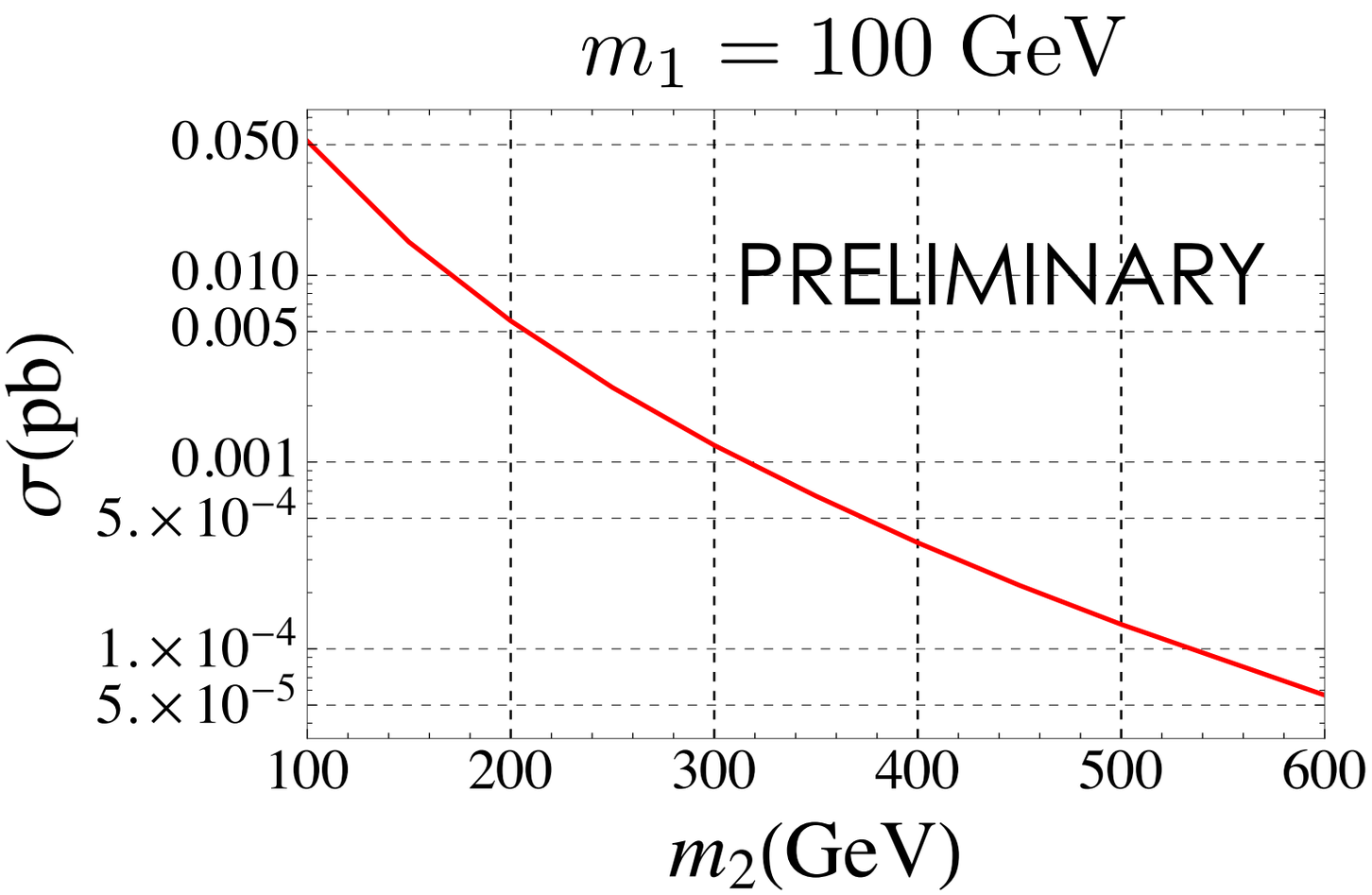
OUTLOOK

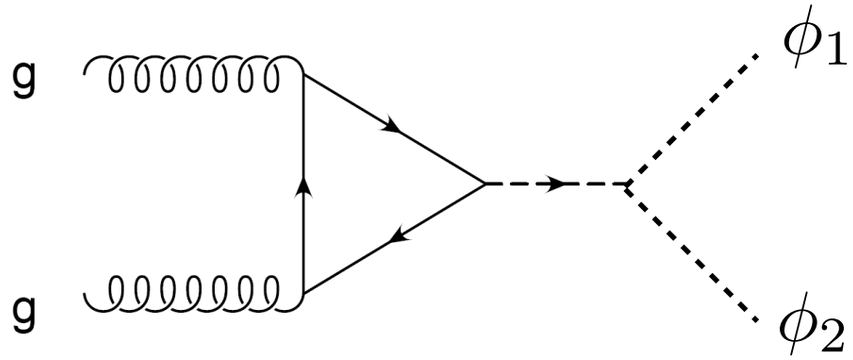
- NEW SECTORS WITH MANY NEW PARTICLES ARE A REALISTIC POSSIBILITY WITH A PLAUSIBLE TOP-DOWN MOTIVATION FROM THEORIES WITH EXTRA DIMENSIONS, INCLUDING STRING THEORY

- A LARGE NUMBER OF NEW PARTICLES DOES NOT NECESSARILY MAKE NEW PHYSICS EASIER TO DETECT, ESPECIALLY GIVEN THE CURRENT BIAS IN THE TRIGGER TABLES TOWARDS HIGH ENERGY EVENTS

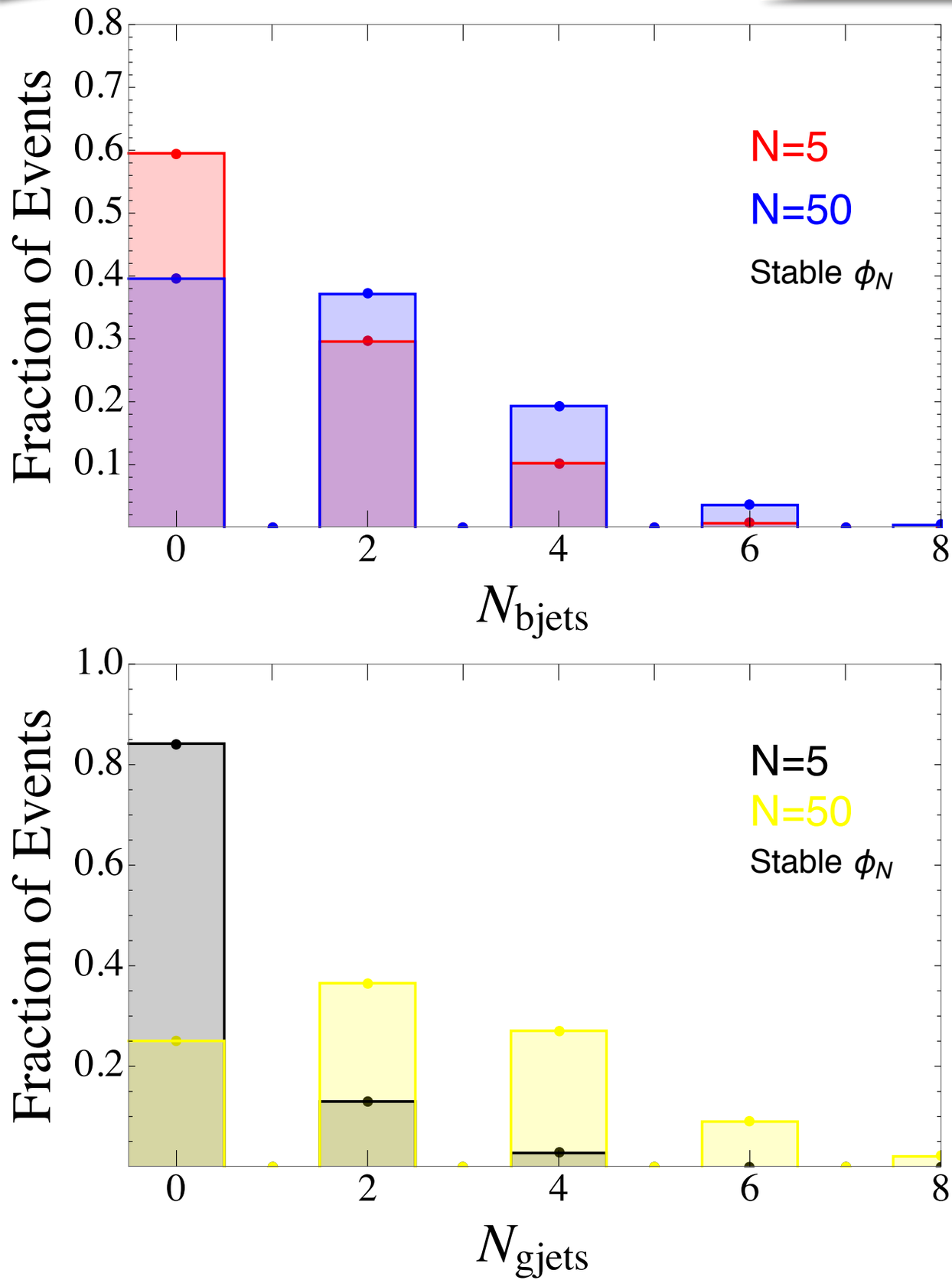
- DISORDER AND HIGH MULTIPLICITIES HAVE NOT BEEN EXPLORED MUCH AT THE WEAK SCALE, BUT THEY CAN GIVE RISE TO INTERESTING NEW PHENOMENA (MAYBE A WAY TOWARDS ANSWERING THE QUESTIONS THAT WE TRULY CARE ABOUT?)

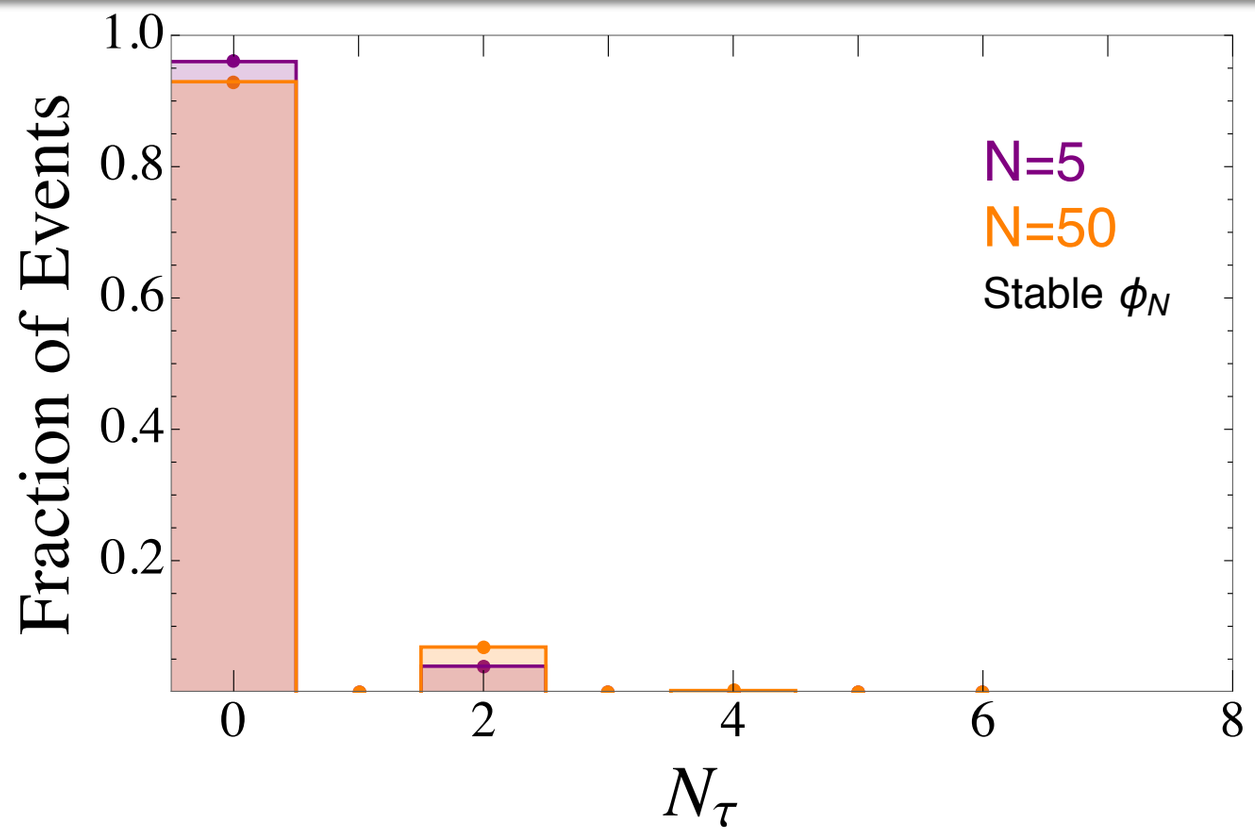
PAIR PRODUCTION CROSS SECTION

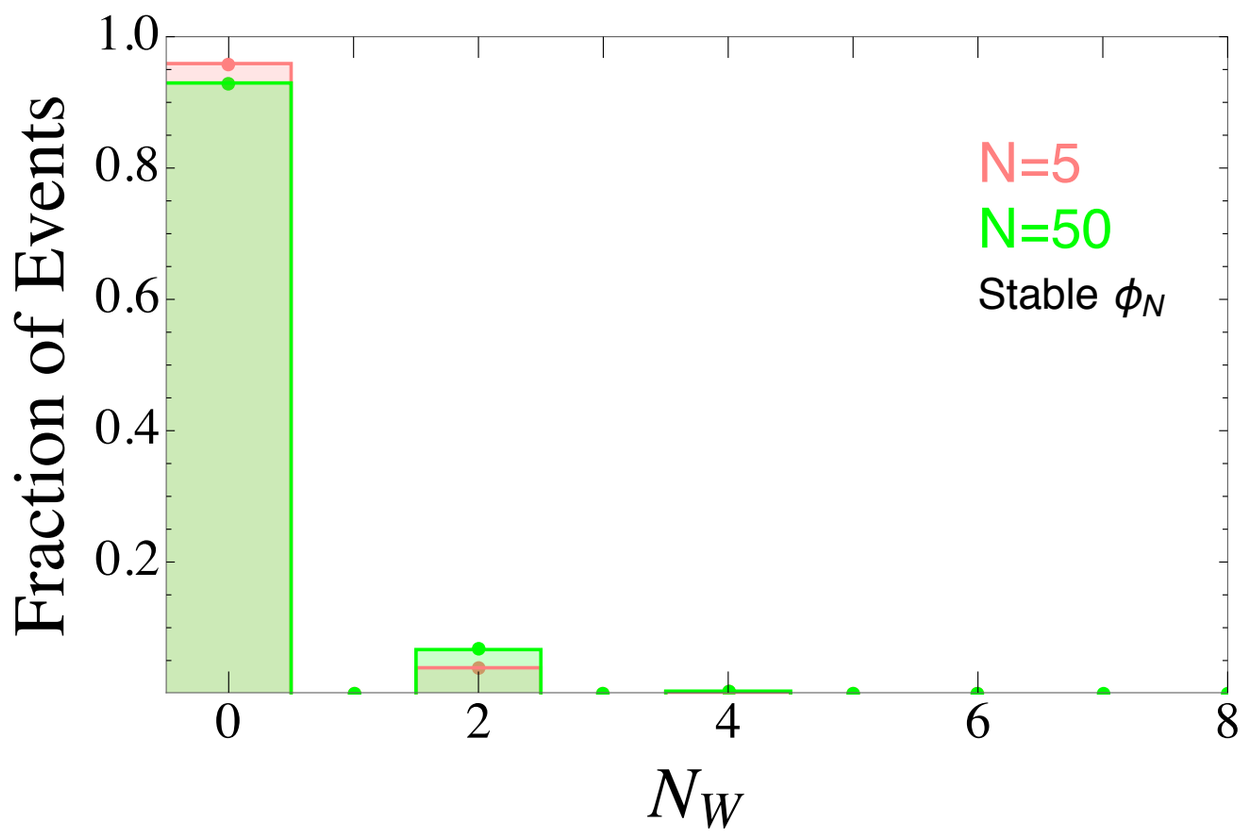




FINAL STATE PARTICLES







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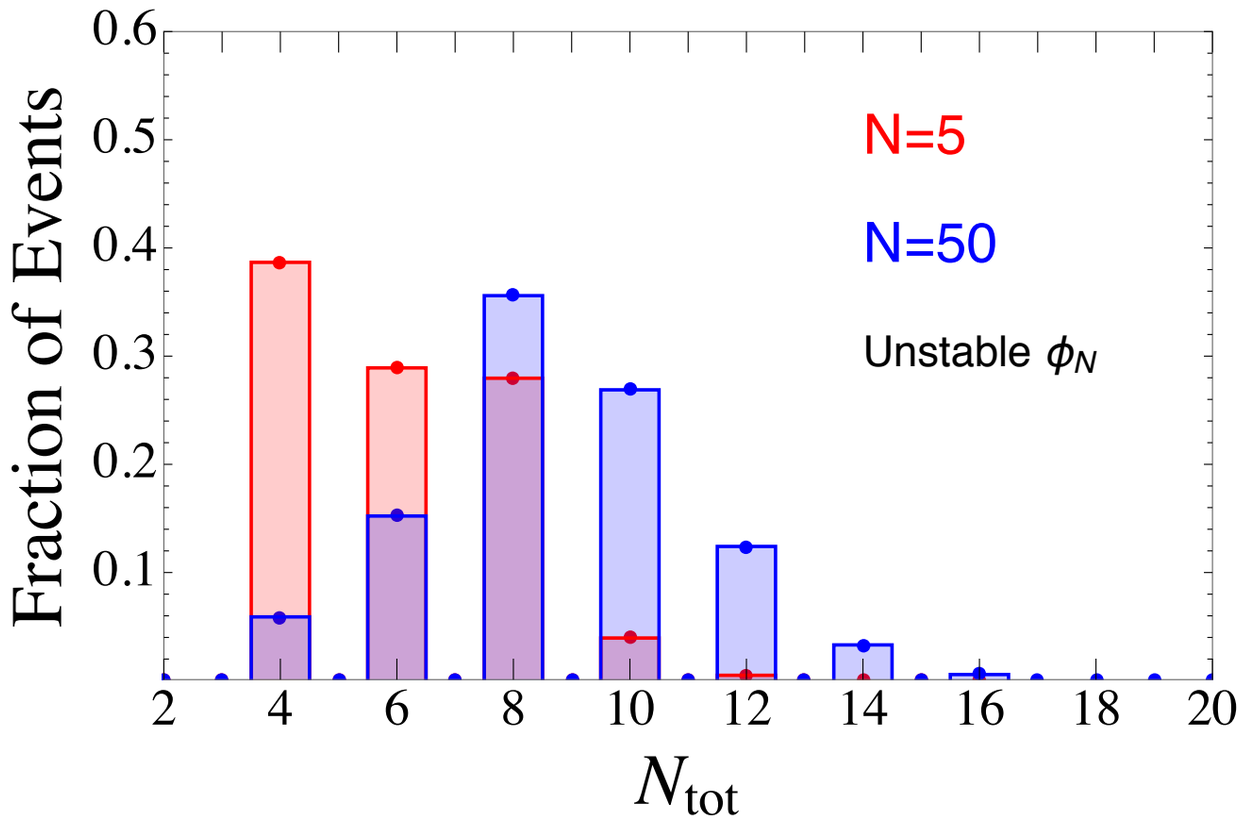

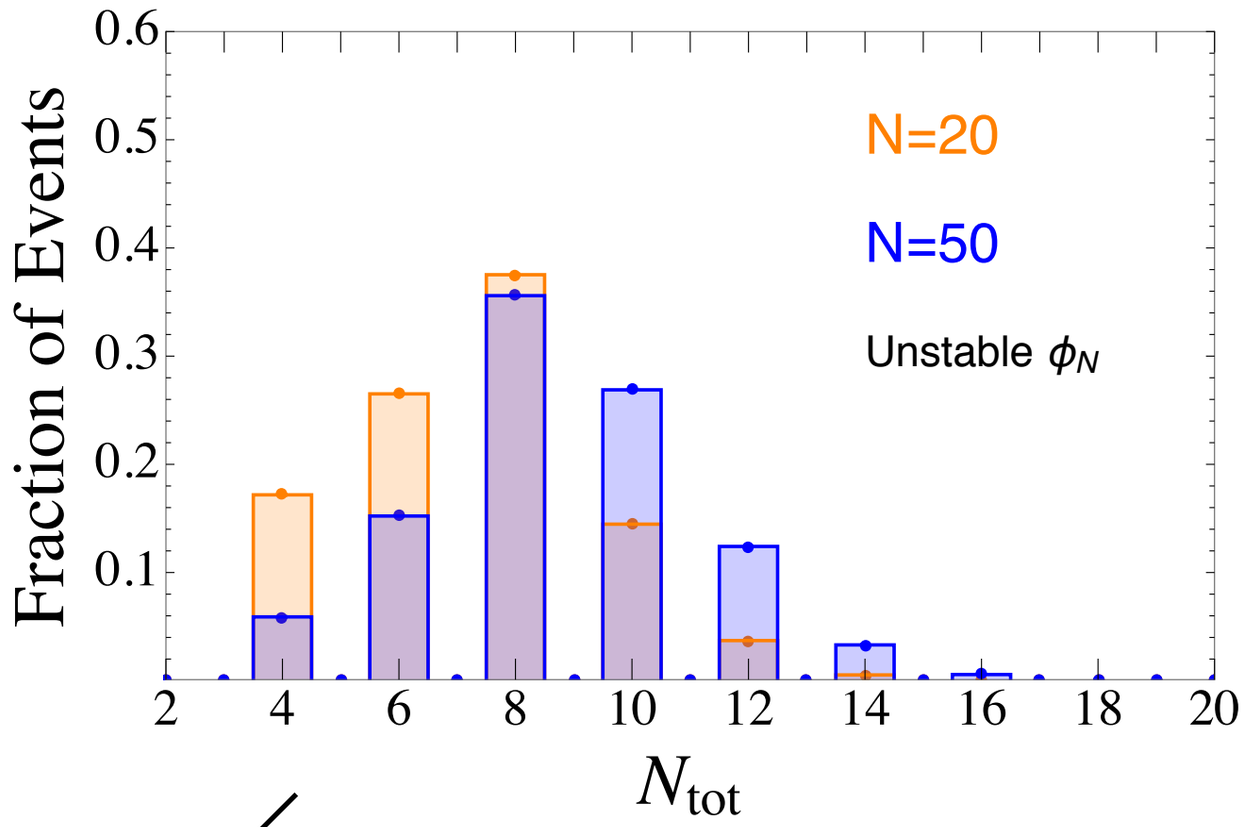

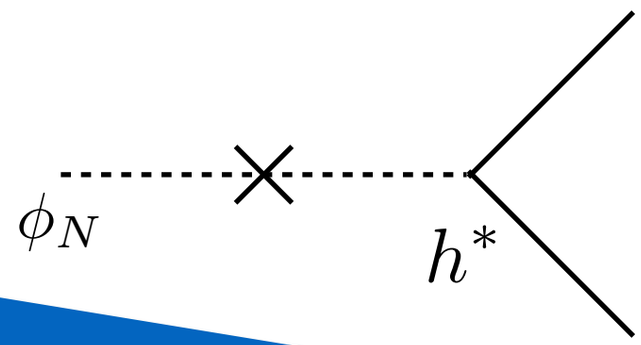
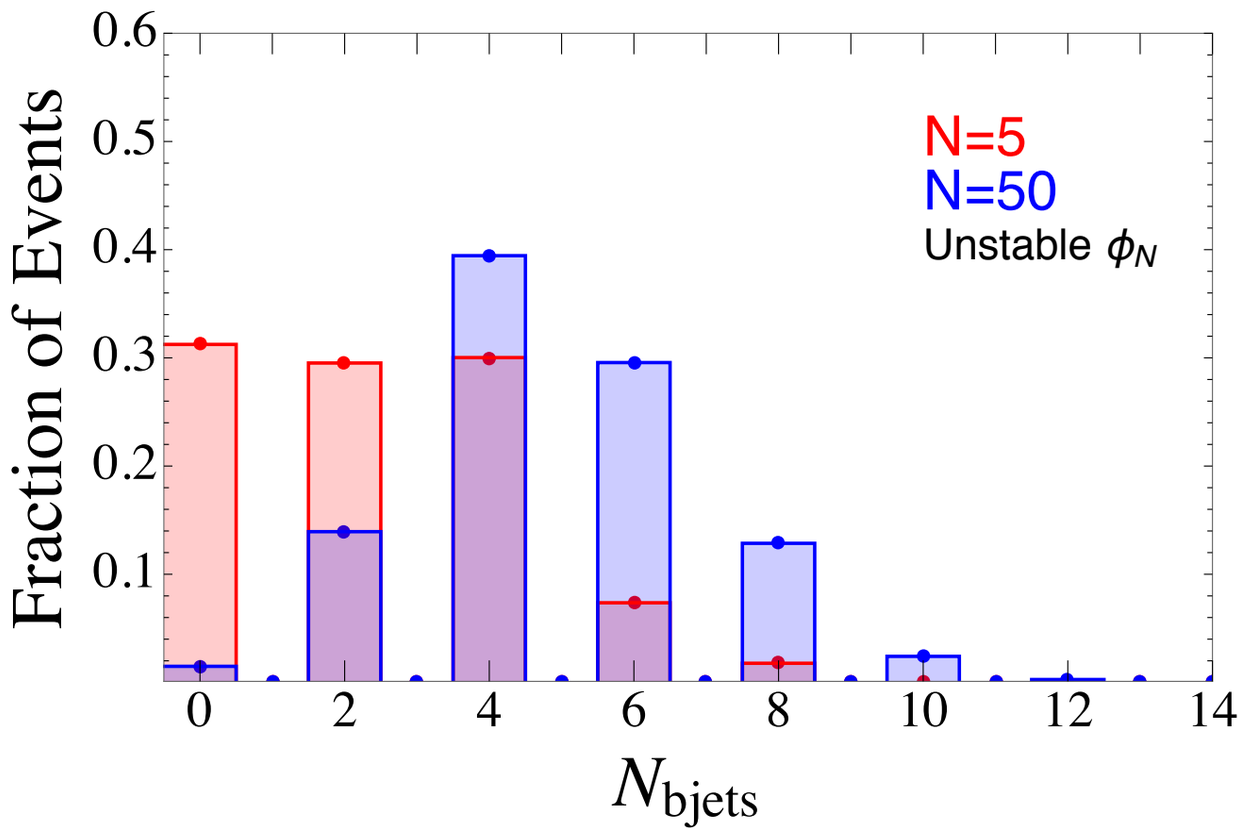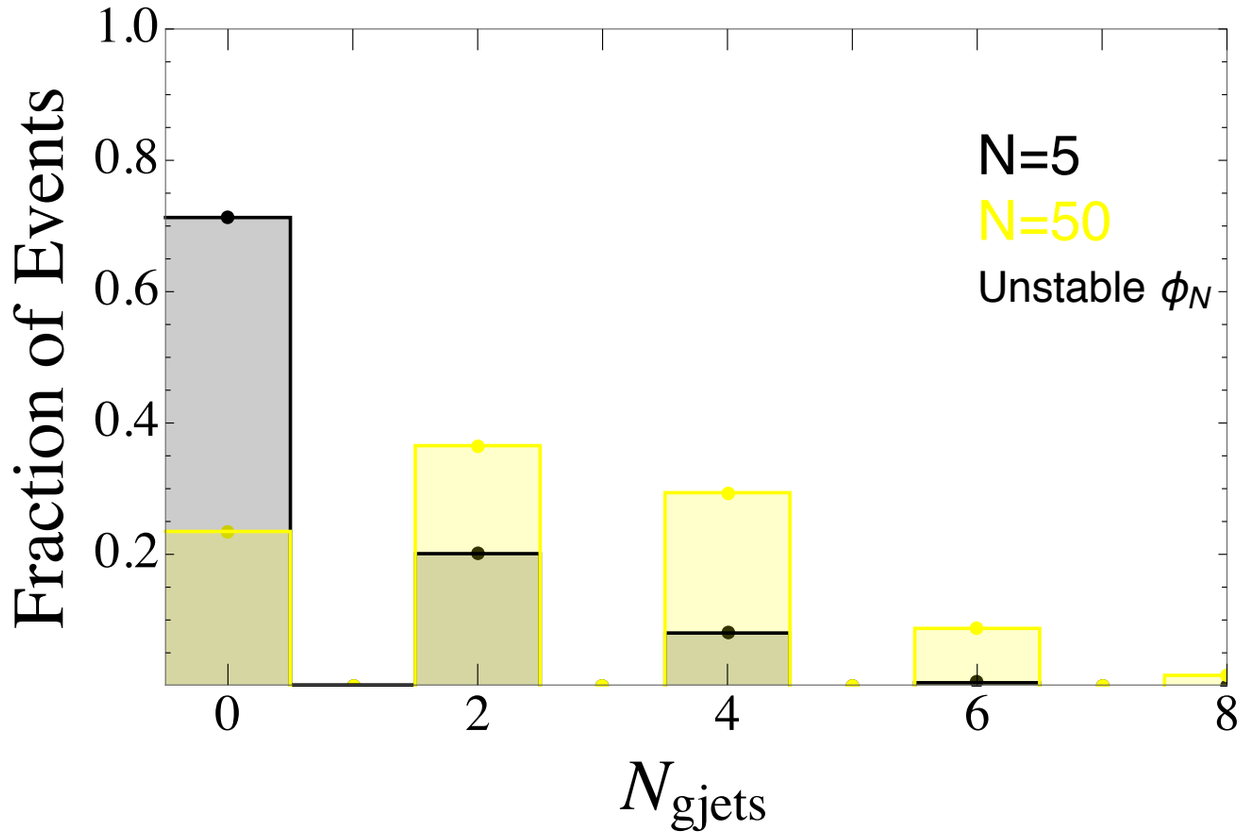
FINAL STATE PARTICLES