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Fragmentation of SQM in astrophysical events

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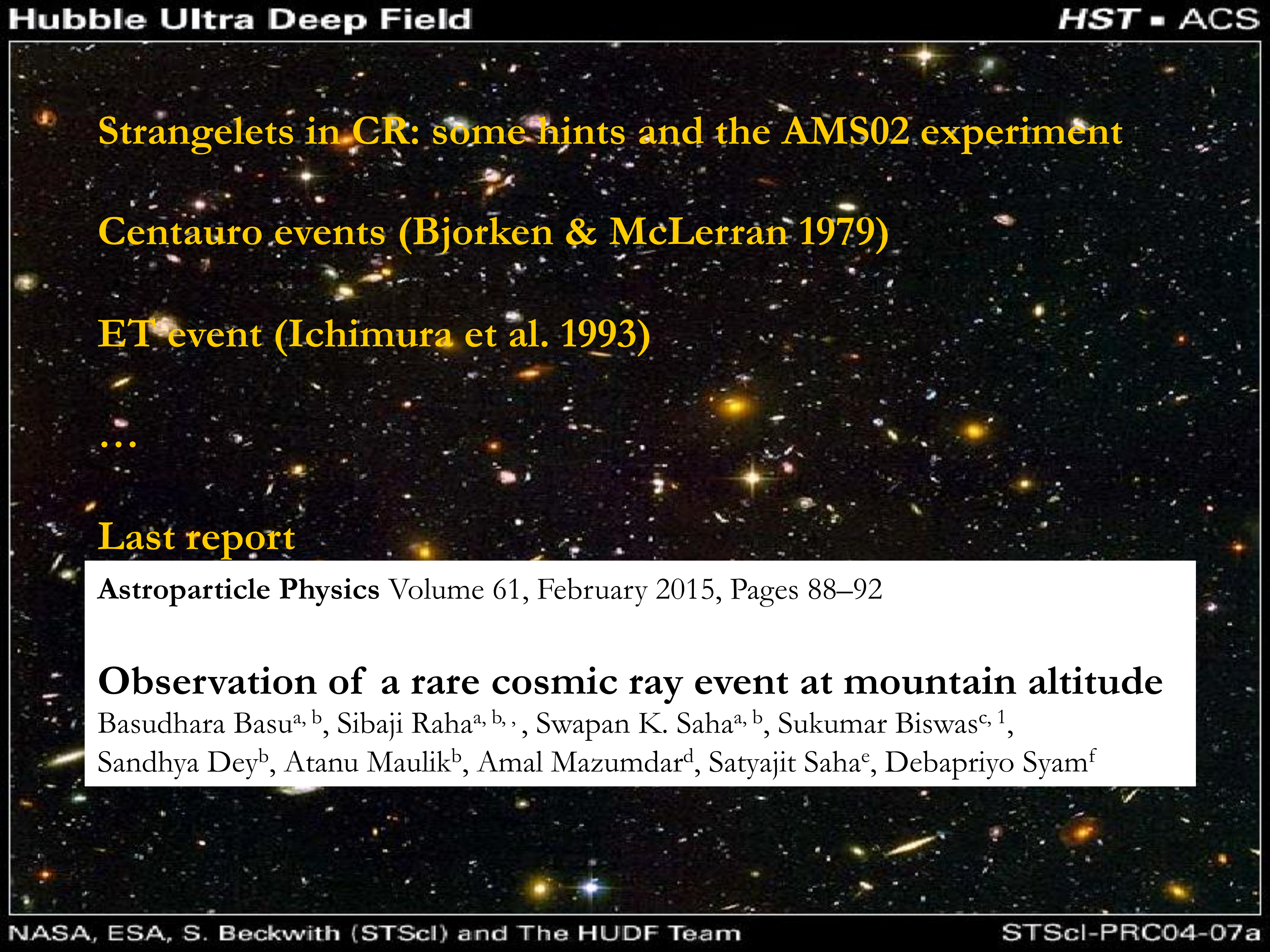

Strangelets in CR: some hints and the AMS02 experiment

Centauro events (Bjorken & McLerran 1979)

ET event (Ichimura et al. 1993)

…

Last report

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Observation of a rare cosmic ray event at mountain altitude

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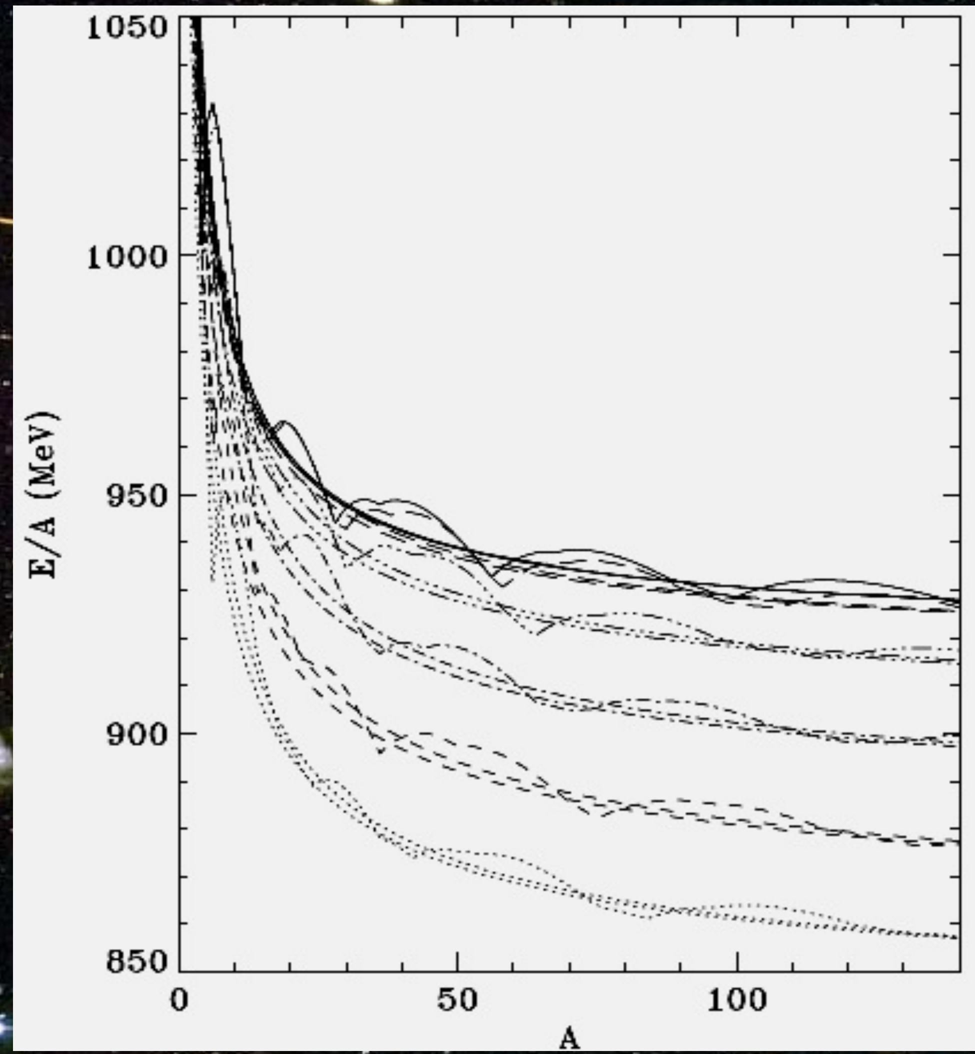
The problem: what happens when SQM is ejected?

- SS mergers
- Type II supernovae

Tentative answer:

(almost) nothing



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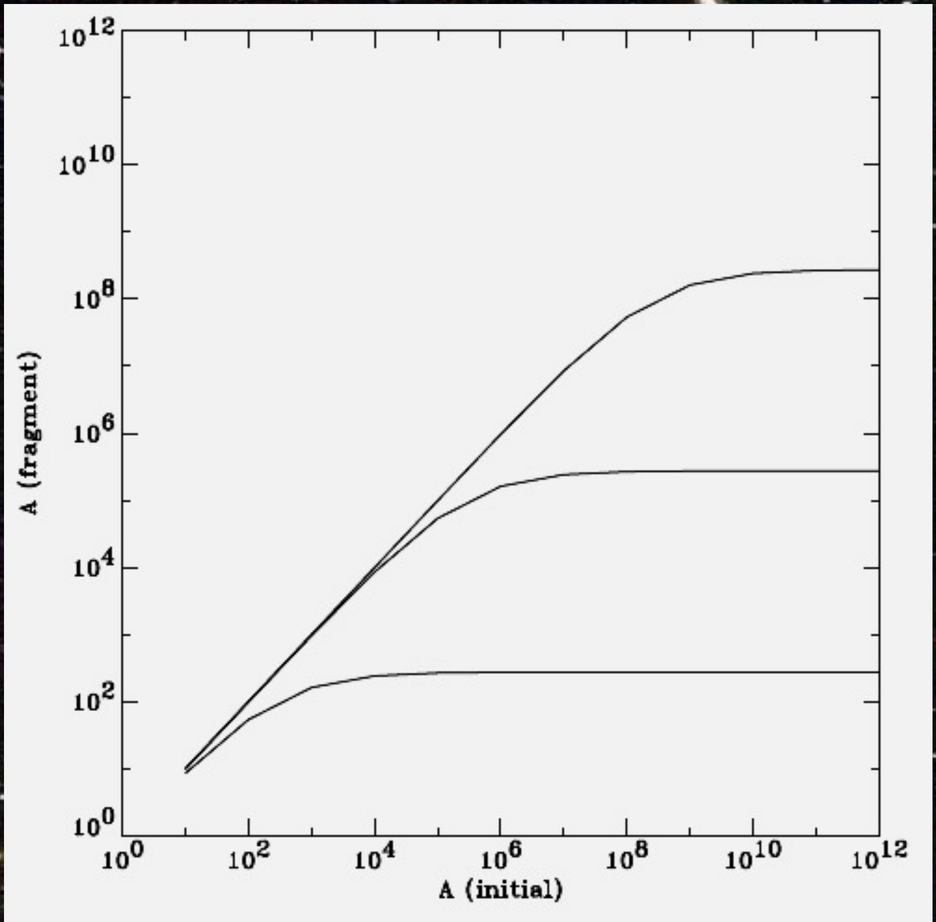
Madsen (2002):

A number for which gravity equals surface energy ~ 10^{38}

Further collisions between chunks in orbit fragment into strangelets down to ~ 10^3



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Horvath & Vucetich (1998): fragmentation of strangelets on their way out a massive (SNII) oxygen envelope

Spallation cross-section of a fragment Δ with oxygen (Boyd & Saito 1993)

$$\sigma(\Delta) = \sigma_0 \left(\frac{m}{m_0}\right)^{2/3} \exp(-\Delta/\Delta_0)$$

Heavy strangelets colliding with oxygen will loss mass ad baryon number

$$A + {}^{16}O \rightarrow A' + {}^{16}O' + \Delta + energy$$

$$\frac{dm}{dt} = -\int d\Delta\, n(t)\, \sigma(\Delta)\, v$$

$$m\frac{dv}{dt} = -C\frac{\pi}{2} m_{ox}\, n(t)\, v^2 R_0^2 \left(\frac{m}{m_0}\right)^{2/3} + \dot{m}\, \xi\, v$$

$$n(t) = n_0 \exp(-t/\tau_{exp})$$

Fowler & Hoyle (1964)

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Whenever $D = (\pi C\, m_{ox}\, R_0^2)/(2\Delta_0\, \sigma_0) + \xi > 1$, strangelets loose mass and kinetic energy, freezing out at

$$E_{i,ox} \left(\frac{m}{m_i}\right)^{2(D-1)} = \frac{\Delta_0}{m_p} E_b \, .$$

$$\frac{m_F}{m_i} = \left(\frac{\Delta_0}{m_p} \frac{E_b}{E_{i,ox}}\right)^{1/2(D-1)}$$

Scaling law for the escaping strangelet mass m_F

Strangelet total mass must be small, since SNII are frequent. Herzog & Ropke (2011) showed that instabilities leading to turbulent fast deflagrations (Horvath & Benvenuto (1988); Horvath (2010)) do their job, but it is unclear whether any SQM is ejected at all…

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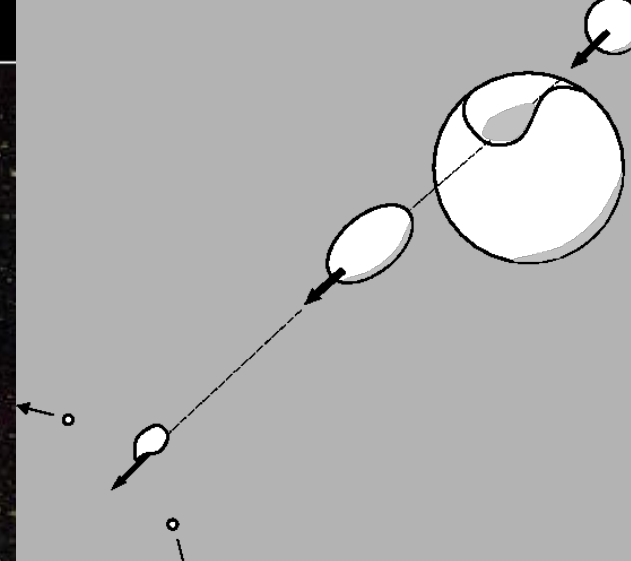
Abrasion-ablation model of spallation (GEANT4 and others)

$$\Delta_{abr} = F\, A_p[1 - \exp(-C_T/\lambda)]$$

Fraction of projectile in interaction

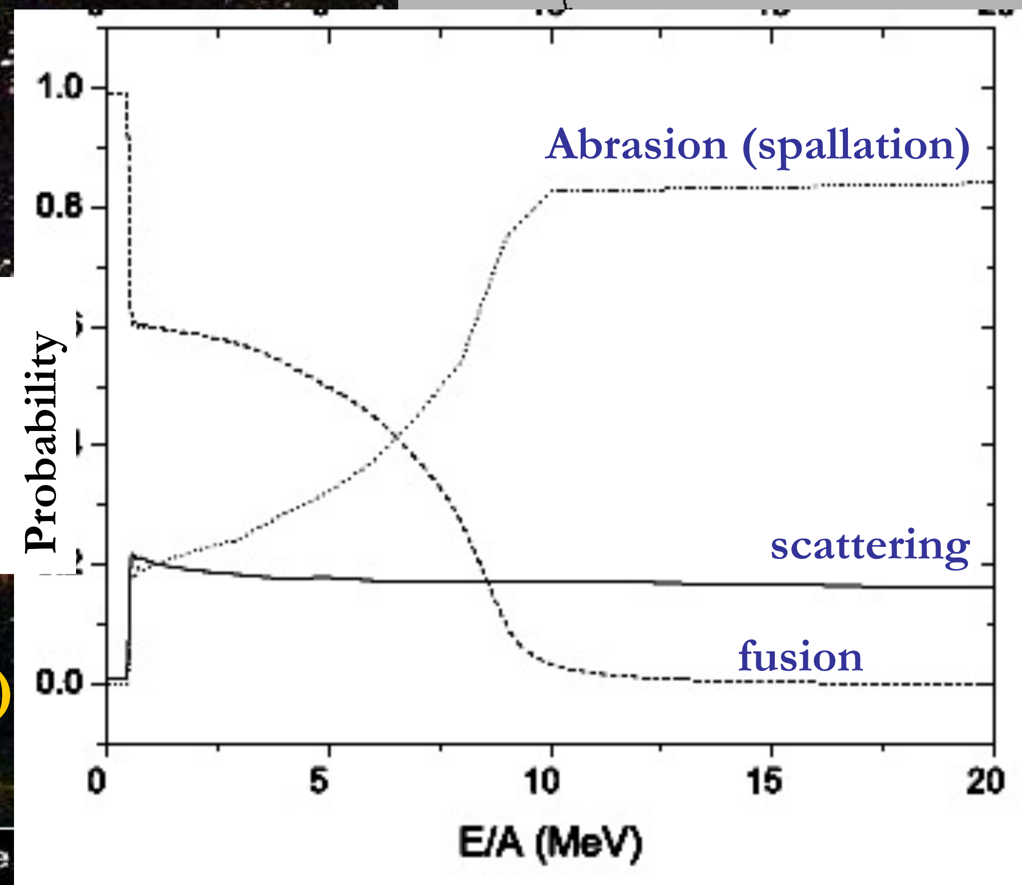
Baryon number of projectile

Mean free path of N-N interaction



Strangelet + nitrogen w/GEANT4: few tens of A stripped

(Paulucci & Horvath JPG 2011)



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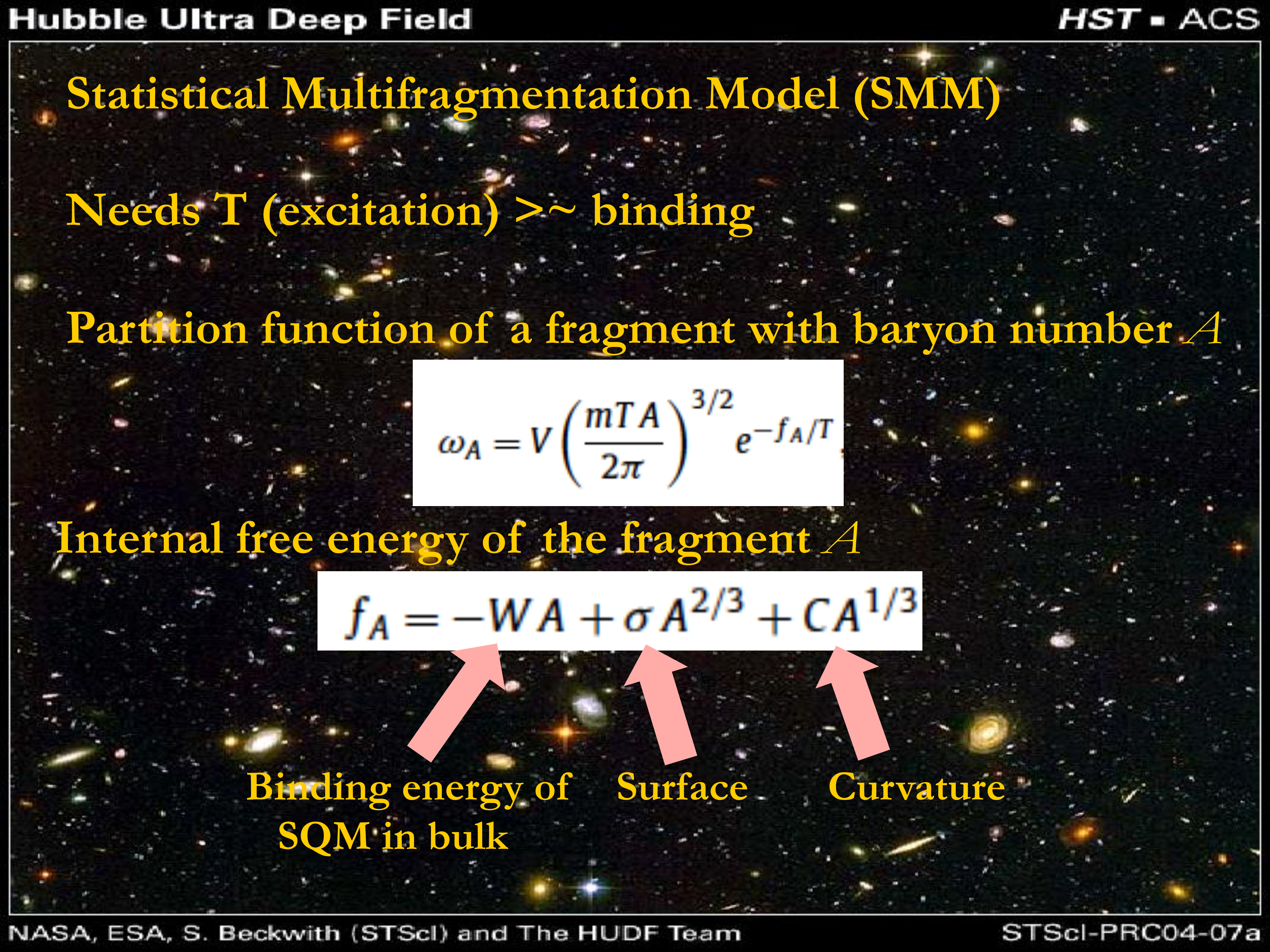
On the other hand, in mergers free expansion + cooling of ejected matter should be relevant to fragmentation, independently of collisions



Statistical Multifragmentation Model (SMM)

Needs T (excitation) >~ binding

Partition function of a fragment with baryon number A

$$\omega_A = V\left(\frac{mTA}{2\pi}\right)^{3/2} e^{-f_A/T}$$

Internal free energy of the fragment A

$$f_A = -WA + \sigma A^{2/3} + CA^{1/3}$$

Binding energy of SQM in bulk

Surface

Curvature

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In the grand canonical ensamble the pressure is

Fourier transform of the partition function

$$p(T,\mu) = T \lim_{V\to\infty} \frac{\ln \mathcal{Z}(V,T,\mu)}{V}$$

The pressures of each phase are obtained from the singularires of the isobaric partition function

$$p_g(T,\mu) = T\left(\frac{mT}{2\pi}\right)^{3/2}\left\{ z_1 e^{\frac{\mu - bp_g}{T}} + \sum_{A=2}^{\infty} A^{3/2} e^{[(\nu - bp_g)A - \sigma A^{2/3} - CA^{1/3}]/T} \right\}$$

$$p_l(T,\mu) = \frac{\nu}{b}$$ with $$\nu = \mu + W$$

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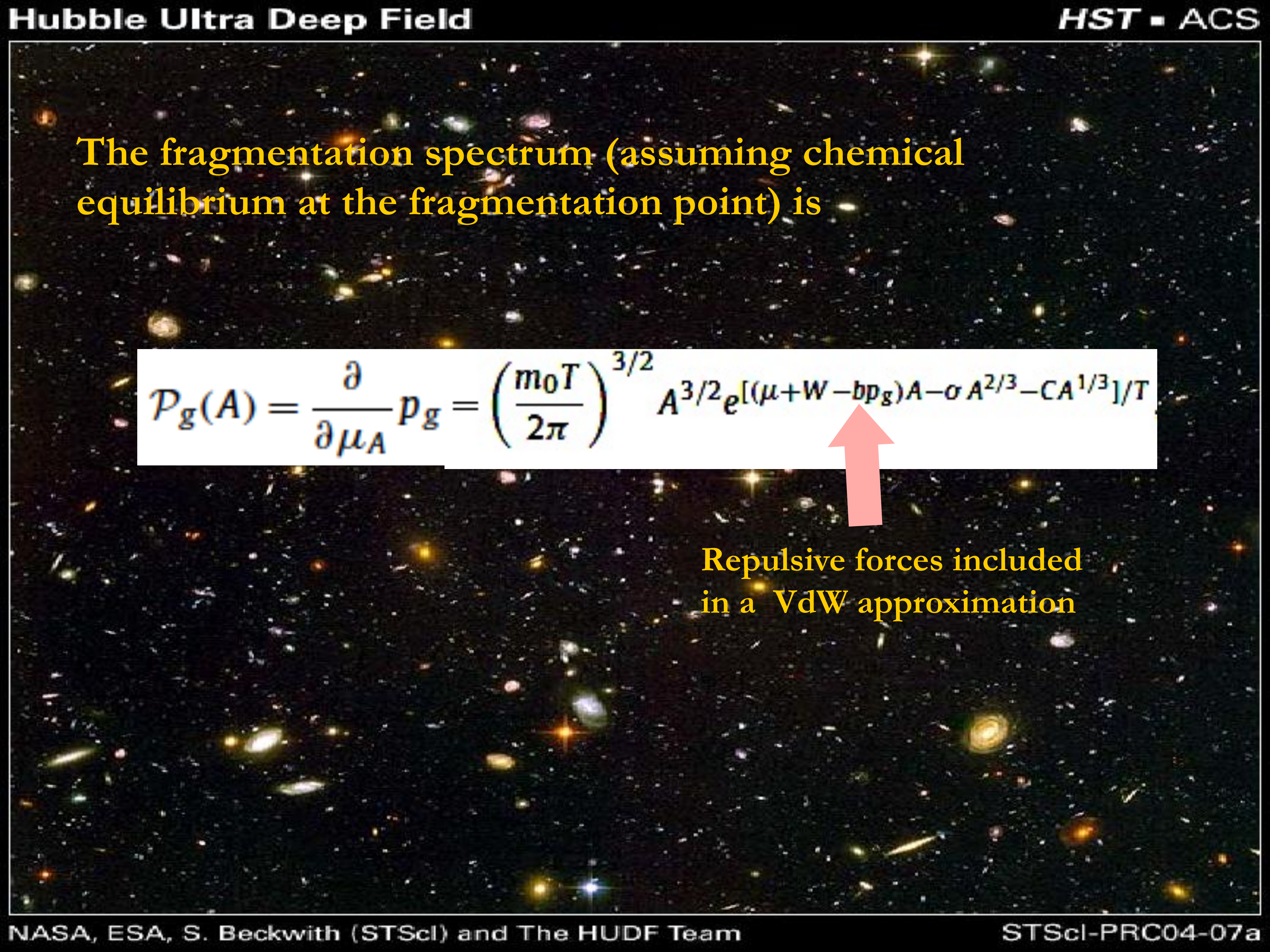

The fragmentation spectrum (assuming chemical equilibrium at the fragmentation point) is

$$\mathcal{P}_g(A) = \frac{\partial}{\partial \mu_A} p_g = \left(\frac{m_0 T}{2\pi}\right)^{3/2} A^{3/2} e^{[(\mu + W - b p_g)A - \sigma A^{2/3} - C A^{1/3}]/T}$$

Repulsive forces included in a VdW approximation

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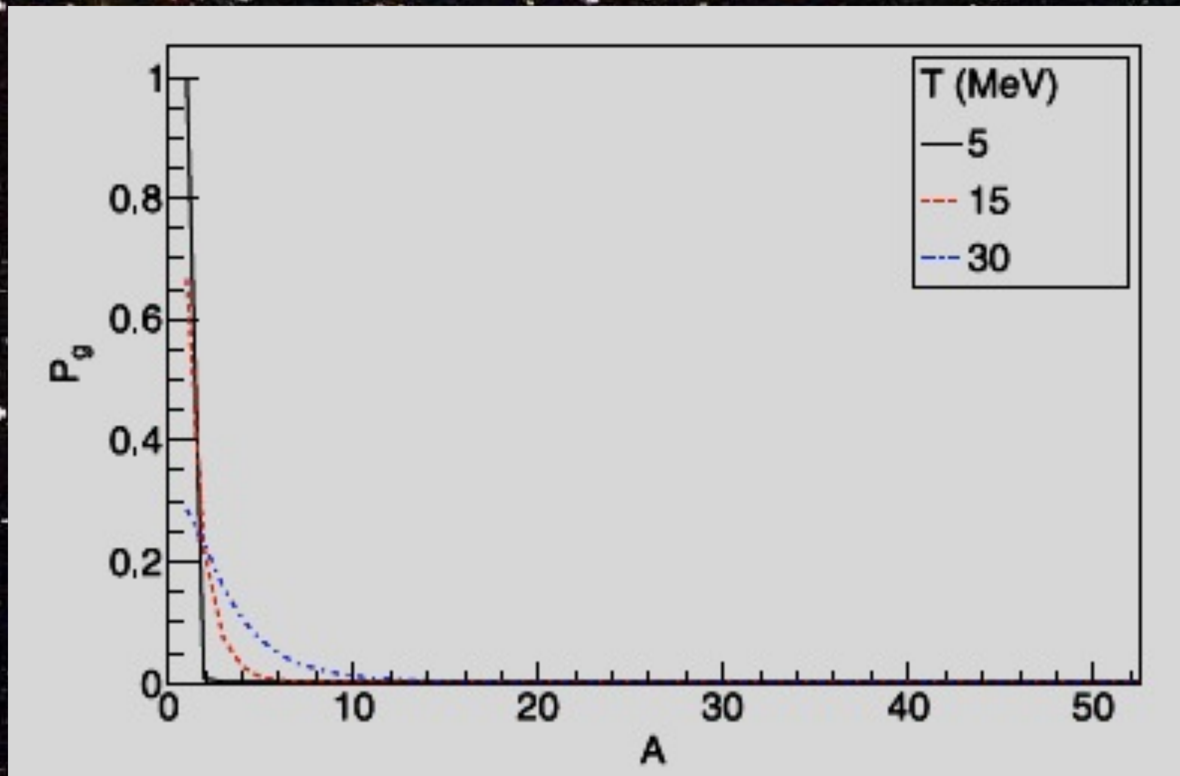
The crisis: $A_{peak} << 1$



$B^{1/4} = 145$ MeV, $m_s = 100$ MeV, and $\Delta = 50$ MeV

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The role of the bag: melting the vacuum

A fraction of the vacuum energy is being used to create the surfaces, hence there is an energy density difference between both phases

$$W_l = W_0 + Bv_{liq},$$
$$W_g = W_0 + Bv_{gas}.$$

In the coexistence phase

$$[\nu - bp_g^*]A = [\nu_g - \nu_l^*]A = [\mu_g + W_g - \mu_l - W_l]A = \left[B(v_{gas} - v_{liq})\right]A$$

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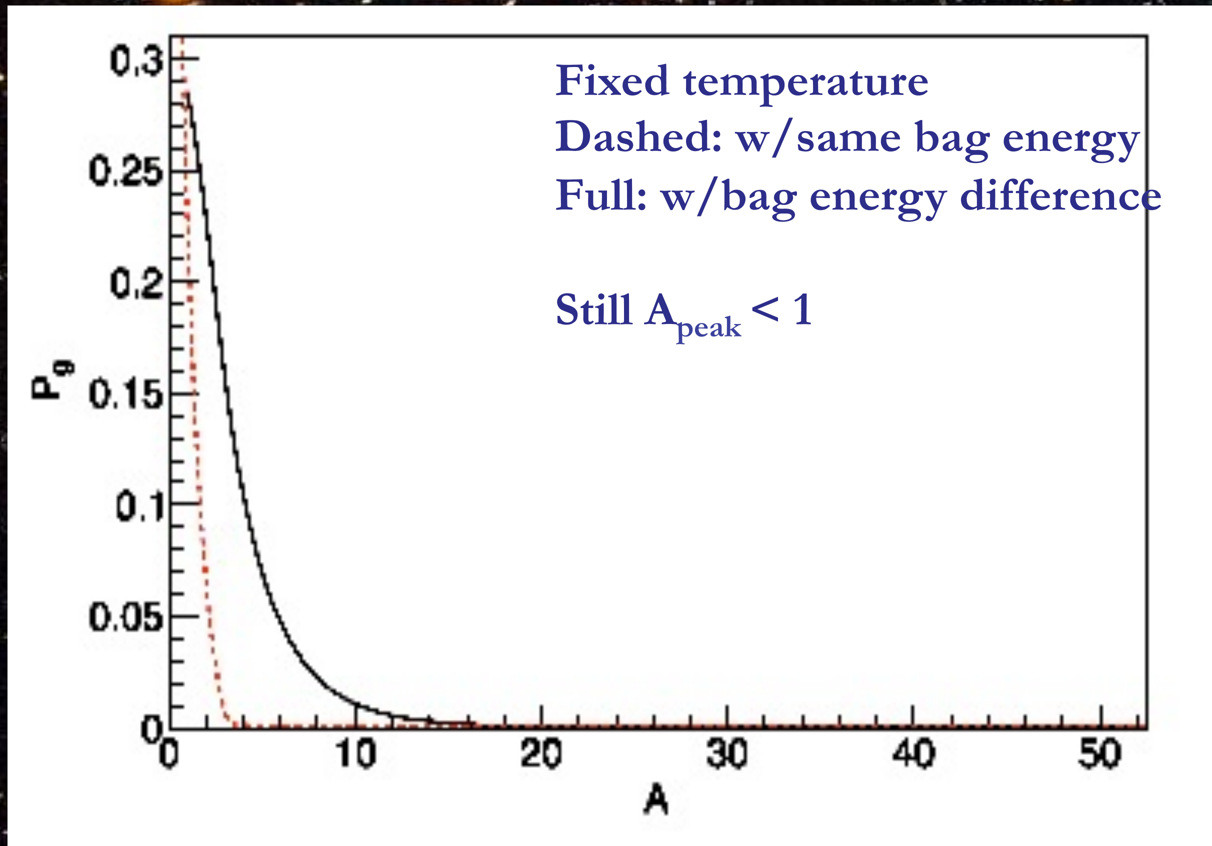
The crisis does not go away:



$B^{1/4} = 145$ MeV, $m_s = 100$ MeV, and $\Delta = 50$ MeV

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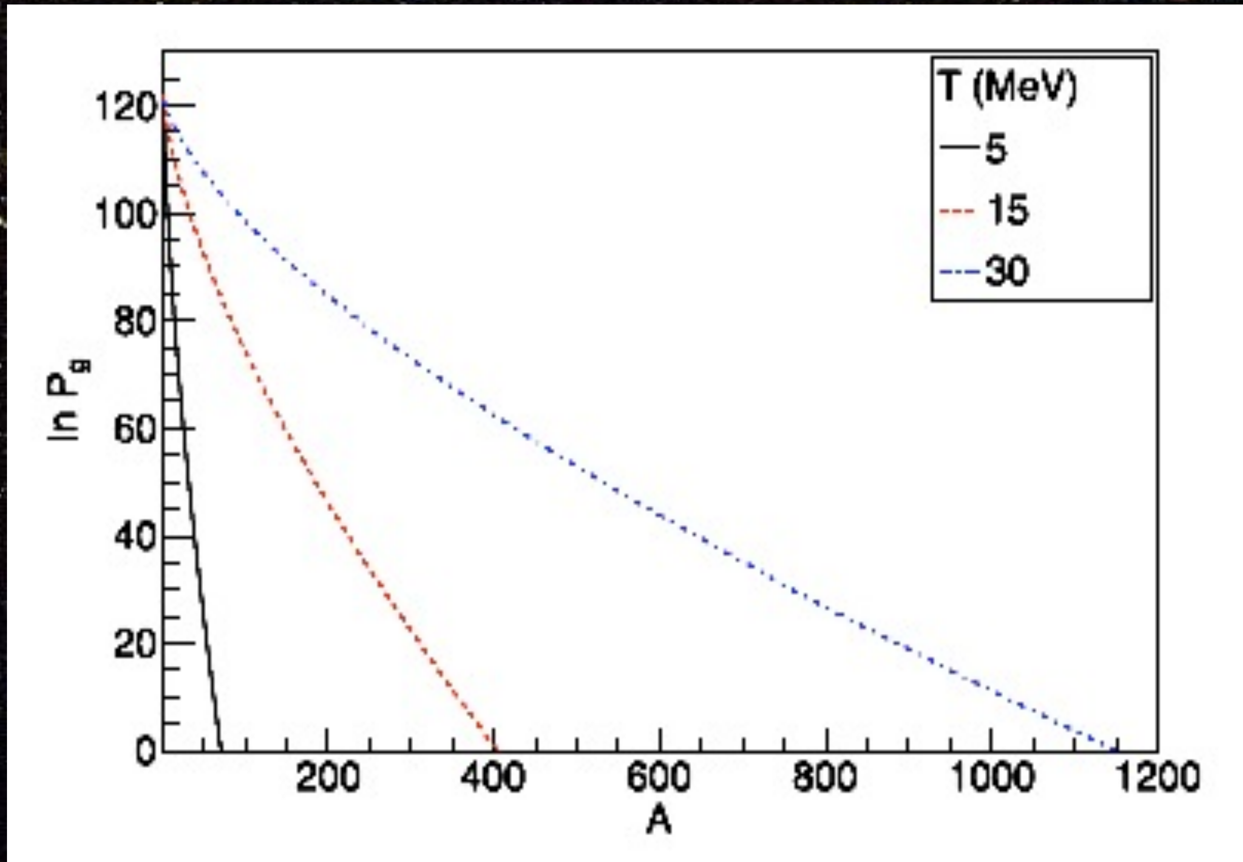

$B^{1/4} = 145$ MeV, $m_s = 100$ MeV, and $\Delta = 50$ MeV.

Probability distribution for a fixed $10^{-4}M_{\odot}$ ejected mass of SQM

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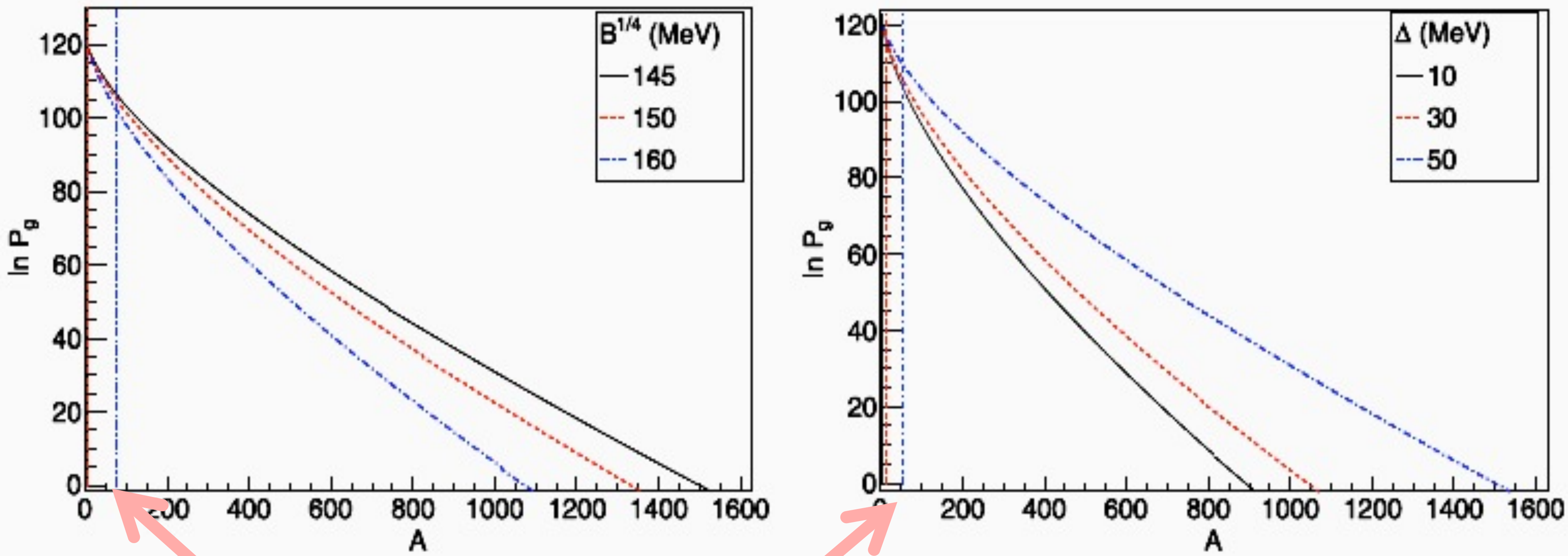
Effects of B and pairing Δ



Note the self-consistent determination of A_{min}

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Conclusions

*

- SQM does not like to fragment, since most of the fragmentation spectrum peaks at $A_{peak} << 1$

*

(Biswas *et al.* (PLB 2012) just present the normalized probabilities but do not mention this problem, in their work $m_s = 0$)

*

- Strangelets with $A > 1$ in the exponential part of the distribution subject to decay into ordinary hadrons because they are smaller than A_{min}

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- A very small fraction of the total ejected SQM would produce strangelets ➡ the flux should be minuscule in anomalous CR detection experiments

$$F \approx 5 \times 10^5 (\mathrm{m}^2\ \mathrm{y}\ \mathrm{sterad})^{-1} \times R_{-4} \times M_{-2} \times V_{100}^{-1} \times t_7,$$

Rate of mergers

There is an very small "efficiency" factor ~ 10 $^{-5}$ to be inserted here

➡ Bauswein et al. (2010) : the ejection may even be zero (independently of efficiency)

- It is possible that fragmentation happens out of (chemical and mechanical?) equilibrium

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Danken !
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