Astrophysics and Cosmology of LARGE Volume String Compactifications

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Strings and Cosmology, Trieste, June 2007

arXiv:0705.3460 [hep-ph] (JC, F. Quevedo)

Talk Structure

- LARGE Volume Models
- Review of Moduli Cosmology
- LARGE Volume Moduli Spectrum
- LARGE Volume Moduli in the Early Universe
- LARGE Volume Moduli in the Late Universe
- Conclusions

LARGE Volume Models

IIB flux compactifications are described by

$$
\begin{aligned}
K &= -2\ln\left(\mathcal{V}+\frac{\xi}{g_s^{3/2}}\right) - \ln\left(i\int\Omega\wedge\bar{\Omega}\right) - \ln\left(S+\bar{S}\right), \\
W &= \int G_3\wedge\Omega + \sum_i A_i e^{-a_i T_i}.
\end{aligned}
$$

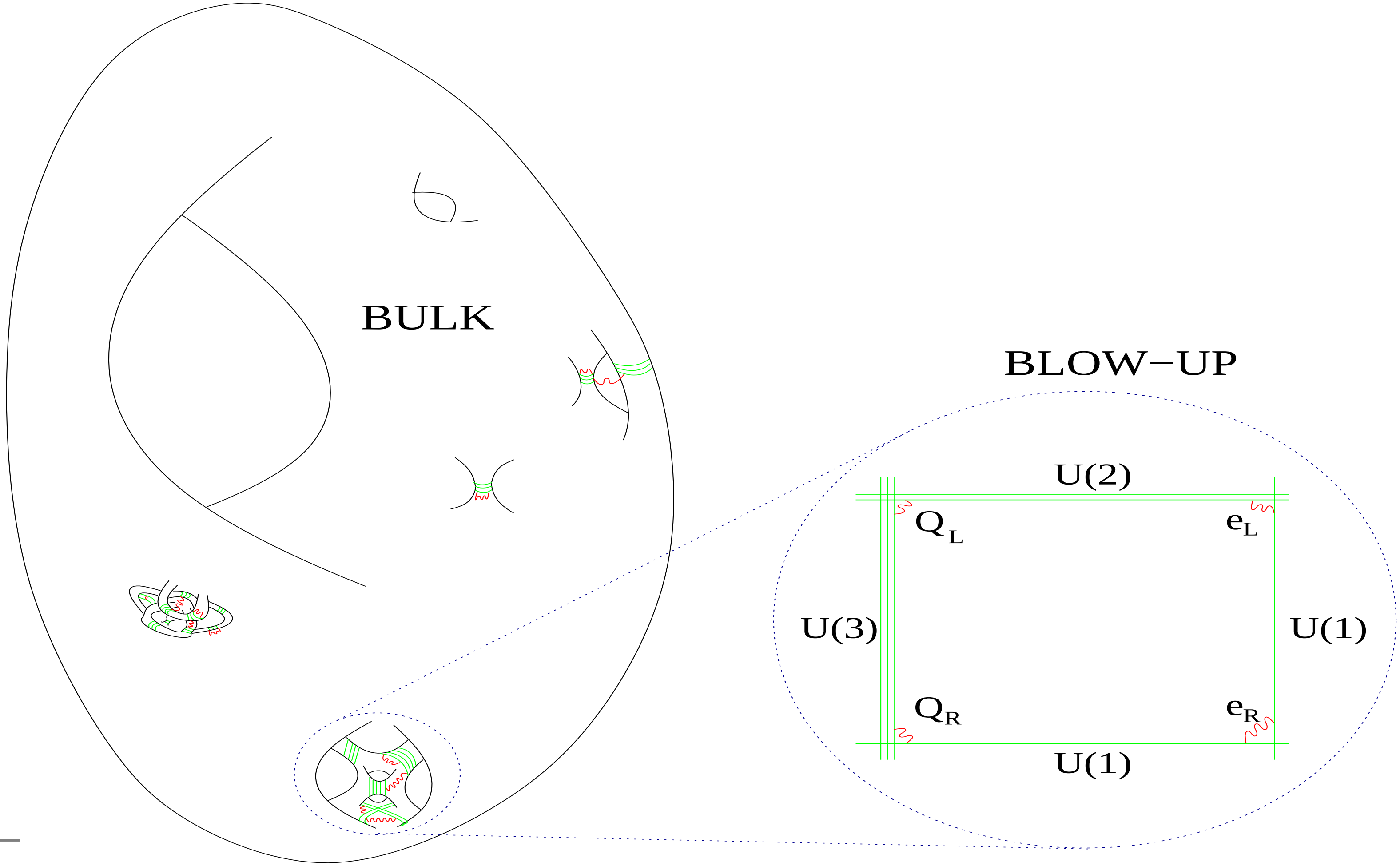
α' corrections in the Kähler potential dramatically change the structure of the potential.

$\Longrightarrow$ a new minimum appears at exponentially large volume $\mathcal{V} \gg 1$ (BBCQ, 2005)

LARGE Volume Models: Geometry

The simplest example has two moduli, τ_b and τ_s.

$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2}$ (a Swiss cheese form).



Moduli Stabilisation: LARGE Volume

The supergravity theory is

$$\begin{aligned} K &= -2\ln\left((T_b+\bar{T}_b)^{3/2}-(T_s+\bar{T}_s)^{3/2}+\frac{\xi}{g_s^{3/2}}\right) \\ W &= W_0+\sum_i A_i e^{-a_i T_i} \\ f &= T_s. \end{aligned}$$

with scalar potential

$$V = e^K\left(K^{i\bar{j}}D_iWD_{\bar{j}}\bar{W}-3|W|^2\right).$$

Moduli Stabilisation: LARGE Volume

The supergravity potential is:

$$V = \underbrace{\frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W_0| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2}} + \frac{\xi |W_0|^2}{g_s^{3/2} \mathcal{V}^3}.$$

$$V = - \frac{|W_0|^2 (\ln \mathcal{V})^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2} \mathcal{V}^3}.$$

A minimum exists at

$$\mathcal{V} \sim |W_0| e^{c/g_s}, \qquad \tau_s \sim \ln \mathcal{V}.$$

This minimum is non-supersymmetric AdS and at exponentially large volume.

LARGE Volume Models

- The stabilised volume is naturally exponentially large.
- Large volume lowers string scale and gravitino mass

$$m_s = \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad m_{3/2} = \frac{M_P}{\mathcal{V}}.$$

- Get TeV supersymmetry by

$$\mathcal{V} = 10^{14} l_s^6, \qquad m_s = 10^{11}\text{GeV}.$$

- This also gives

$$\text{axion decay constant } f_a \sim 10^{11}\text{GeV},$$

$$\text{neutrino suppression scale } \Lambda \sim 10^{14}\text{GeV}.$$

LARGE Volume Models

We take the overall volume to be $\mathcal{V} = 10^{14} l_s^6$.

The mass scales present are:

- Planck scale: $M_P = 2.4 \times 10^{18}$GeV.
- Neutrino/dim-5 suppression scale: $\Lambda = \frac{M_P}{\mathcal{V}^{1/3}} \sim 10^{14}$GeV.
- String scale: $M_S = \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{11}$GeV.
- Axion decay constant $f_a \sim M_S \sim 10^{11}$GeV.
- KK scale $M_{KK} = \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^9$GeV.
- Gravitino mass $m_{3/2} = \frac{M_P}{\mathcal{V}} \sim 30$TeV.
- Soft terms $m_{susy} \sim \frac{m_{3/2}}{\ln(M_P/m_{3/2})} \sim 1$TeV.

LARGE Volume Models

- stabilises all moduli
- eliminates fine-tuning problems of KKLT
- generates the hierarchy $m_{3/2} \sim \frac{M_P}{\mathcal{V}} \sim 10^4\text{GeV}$
- dynamic susy breaking $m_{soft} \sim \frac{M_P}{\mathcal{V}\ln(\mathcal{V})} \sim 10^3\text{GeV}$
- gives correct axion scale $f_a \sim \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{11}\text{GeV}$
- gives correct neutrino mass scale $\Lambda \sim \frac{M_P}{\mathcal{V}^{1/3}} \sim 10^{14}\text{GeV}$

  $$m_\nu \sim \frac{v^2}{\Lambda} \sim 0.1\text{eV}$$
- cosmology?

Moduli Cosmology

- Moduli are good candidates for inflatons.
- There exist many inflationary models using open/closed string moduli as inflatons.

  (brane inflation, tachyon inflation, racetrack inflation, Kähler moduli inflation, Nflation...)
- Tension between inflationary scales ($m_{3/2} \gg 1$TeV) and particle physics scales ($m_{3/2} \sim 1$TeV) (Kallosh's talk)
- Different scales may apply at different epochs

  ($m_{3/2} \sim 10^{13}$GeV during inflation does not imply $m_{3/2} \sim 10^{13}$GeV now)
- I focus on post-inflationary cosmology.

Moduli Cosmology

- Focus on late-time moduli cosmology.

  (‘Late-time’ $\equiv$ between end of inflation and now)

- Use particle physics scales for moduli stabilisation.
- Moduli are scalar fields and are displaced from their minimum in the early universe.
- They subsequently oscillate about the minimum, redshift as matter and come to dominate the energy density of the universe.

Moduli Cosmology: Lifetimes

- Moduli are gravitationally coupled scalars.
- Generic moduli interact very weakly and decay through gravitational interactions with

$$\Gamma \sim \frac{1}{4\pi}\frac{m_\Phi^3}{M_P^2}.$$

- The moduli lifetime is

$$\tau \sim 5 \times 10^4 \mathrm{s} \times \left(\frac{1\text{TeV}}{\mathrm{m}_\phi}\right)^3$$

- This causes a conflict with TeV-scale supersymmetry.

Moduli Cosmology: Problems

Moduli get masses through supersymmetry breaking.

- Gravity-mediation:

  typical moduli masses are $m \sim m_{3/2} \sim 1$TeV.

- Gauge-mediation:

  typical moduli masses are $m \sim m_{3/2} \ll 1$TeV.

Moduli decay late with a low reheating temperature

$$T_{rh} \sim 0.02\text{MeV} \left(\frac{m_\phi}{1\text{TeV}}\right)^{3/2}$$

Generic scenarios of TeV susy breaking spoil nucleosynthesis - the cosmological moduli problem.

Moduli Cosmology: More Problems

1. If $m_\phi \gg m_{3/2} \sim 1$TeV, moduli decay into gravitini with an $\mathcal{O}(1)$ branching ratio.

   Gravitini are overproduced and again spoil nucleosynthesis.

2. Susy relic abundance computations assume a thermal cosmology up to $T \sim 10$GeV.

   Late-decaying moduli with $T_{rh} \sim \mathcal{O}(1)$MeV overproduce susy dark matter

3. Large entropy production at $T_{rh} \sim \mathcal{O}(1)$MeV dilutes any primoridal baryon asymmetry.

Moduli Cosmology: Dark Matter

- If moduli are light and their abundance diluted, they can be (part of) dark matter.
- We can write the moduli lifetime as

$$\tau \sim H_0^{-1} \left(\frac{100\text{MeV}}{m_\phi} \right)^3$$

- Moduli lighter than 100MeV could survive today as part of the dark matter.

LARGE Volume Moduli

- For LARGE-volume models, we can compute the moduli spectrum, couplings and branching ratios.
- We assume TeV-scale supersymmetry.
- The canonically normalised moduli divide into
  1. ‘Heavy’ moduli Φ associated with small cycles.
  2. ‘Light’ modulus χ associated with overall volume.
- Detailed computations are in the paper...

LARGE Volume Moduli: Couplings

example: coupling of small modulus to radiation

Lagrangian couplings are

$$\mathcal{L} \sim \frac{3}{4\tau_b^2}\partial_\mu \tau_b \partial^\mu \tau_b + \frac{3}{8\tau_s^{\frac{1}{2}}\mathcal{V}}\partial_\mu \tau_s \partial^\mu \tau_s + \frac{\tau_s}{M_P} F_{\mu\nu}F^{\mu\nu} + \dots$$

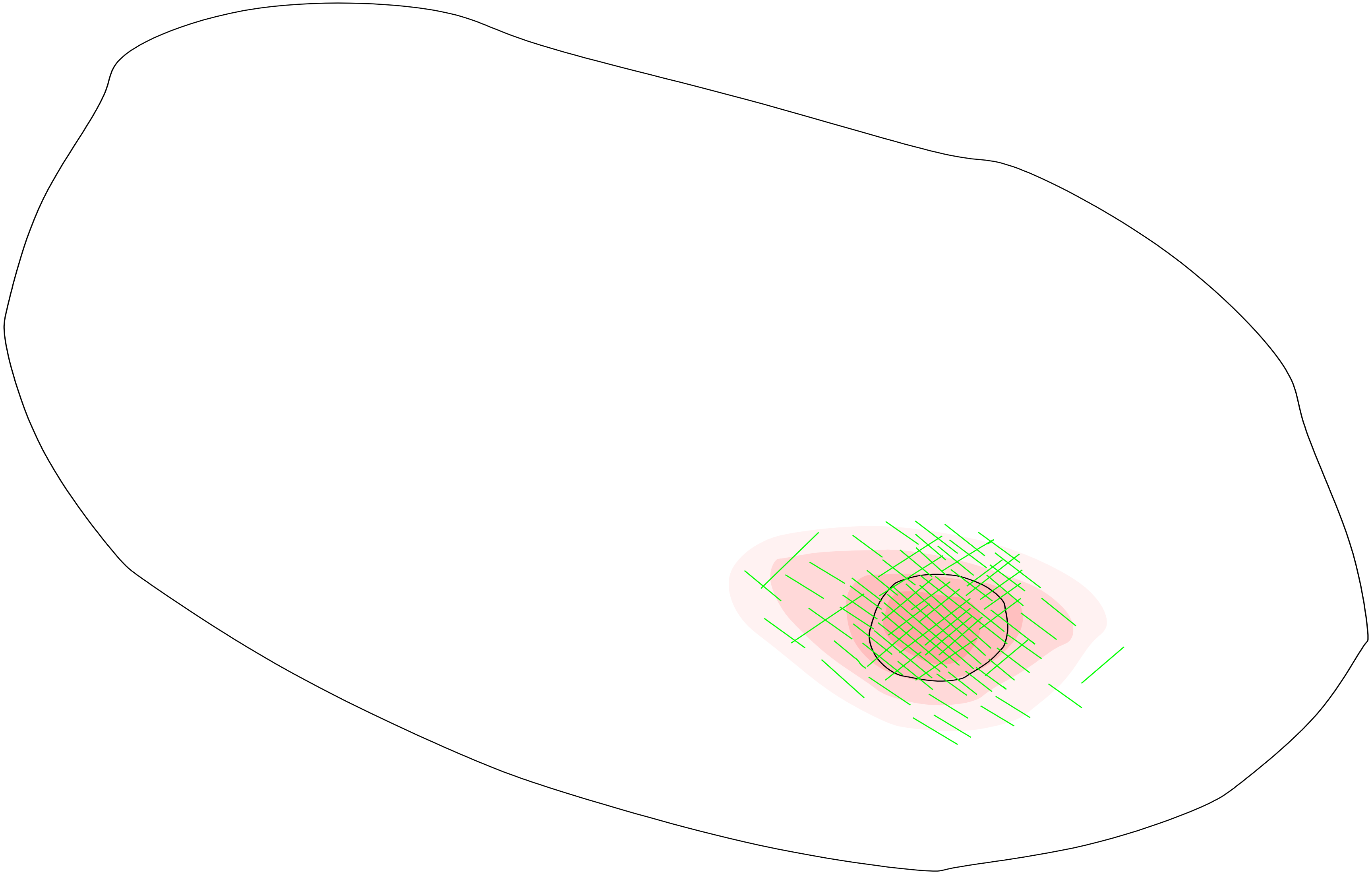
Canonically normalised moduli:

$$\delta\tau_b \sim \mathcal{V}^{1/6}\Phi + \mathcal{V}^{2/3}\chi, \qquad \delta\tau_s \sim \mathcal{V}^{1/2}\Phi + \mathcal{O}(1)\chi$$

gives $\mathcal{L} \sim \frac{1}{2}\partial_\mu \Phi \partial^\mu \Phi + \frac{1}{2}\partial_\mu \chi \partial_\mu \chi + \frac{\mathcal{V}^{\frac{1}{2}}\Phi}{M_P} F_{\mu\nu}F^{\mu\nu} + \dots$

- Canonical coupling of Φ to radiation is suppressed by M_S^{-1} (not M_P^{-1})

LARGE Volume Moduli: Couplings



LARGE Volume Moduli Spectrum

Full computations give

	Light modulus χ	Heavy Moduli Φ
Mass	$\sim m_{3/2}\left(\frac{m_{3/2}}{M_P}\right)^{\frac{1}{2}} \sim$ 2MeV	$2m_{3/2}\ln\left(\frac{M_p}{M_{3/2}}\right) \sim$ 1200TeV
Matter Couplings	M_P^{-1} (electrons) $\left(M_P \ln\left(\frac{M_P}{m_{3/2}}\right)\right)^{-1}$ (photons)	$m_s^{-1} = (10^{11}\text{GeV})^{-1}$
Decay Modes		
$\gamma\gamma$	$\text{Br} \sim 0.025, \quad \tau \sim 6.5 \times 10^{25}\text{s}$	$\text{Br} \sim \mathcal{O}(1), \quad \tau \sim 10^{-17}\text{s}$
e^+e^-	$\text{Br} \sim 0.975, \quad \tau \sim 1.7 \times 10^{24}\text{s}$	$\text{Br} \sim \mathcal{O}(1), \quad \tau \sim 10^{-17}\text{s}$
$q\bar{q}$	inaccessible	$\text{Br} \sim \mathcal{O}(1), \quad \tau \sim 10^{-17}\text{s}$
$\psi_{3/2}\psi_{3/2}$	inaccessible	$\text{Br} \sim 10^{-30}, \quad \tau \sim 10^{13}\text{s}$

How does this affect moduli cosmology?

The Early Universe

- The heavy modulus Φ is an excellent candidate for reheating, with $m_\Phi \sim 1000$TeV $\sim (\ln(M_P/m_{3/2}))^2 m_{susy}$.
- Φ couples to matter at the string scale (10^{11}GeV) rather than the Planck scale and has a decay rate

$$\Gamma \sim \frac{1}{4\pi}\frac{m_\Phi^3}{m_s^2} \sim (10^{-17}\mathrm{s})^{-1}$$

$$T_{rh} \sim \sqrt{M_P \Gamma} \sim 10^7 \mathrm{GeV}$$

- Φ couples to gravitini at the Planck scale and does not overproduce gravitinos

$$\mathrm{BR}(\Phi \to 2\psi_{3/2}) \sim 10^{-30}$$

The Early Universe

- The decays of the heavy modulus Φ can generate a Hot Big Bang at $T \sim 10^7 \mathrm{GeV}$.
- However -

The Early Universe

- The decays of the heavy modulus Φ can generate a Hot Big Bang at $T \sim 10^7 \mathrm{GeV}$.
- However - the light modulus χ will still come to overclose the universe and must be diluted.

- To avoid this, we require a late period of e.g. thermal inflation, driven by the high temperatures attained from the decays of the heavy modulus.
- We assume this can be achieved.

The Late Universe

- The light modulus χ has mass and lifetime

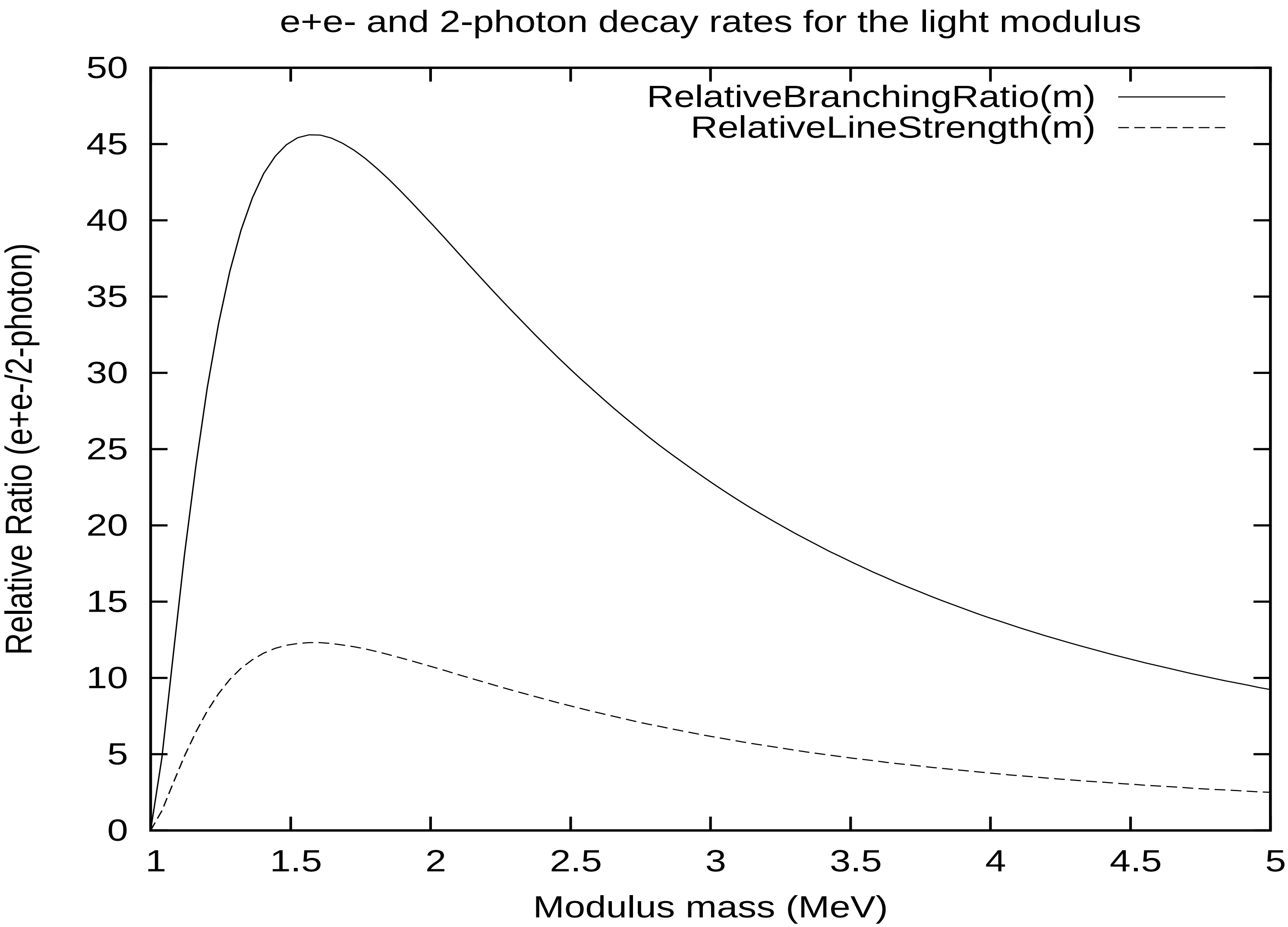
$$m_\chi \sim m_{3/2}\left(\frac{m_{3/2}}{M_P}\right)^{\frac{1}{2}} \sim 2\text{MeV}, \qquad \tau_\chi \sim \frac{M_P^2}{m_\chi^3} \sim 10^{24}\text{s}.$$

- It is stable and can form part of the dark matter.
- χ couples to

$$\begin{array}{rll} e^+e^- & \text{with strength} & M_P^{-1} \\ \gamma\gamma & \text{with strength} & (M_P \ln(M_P/m_{3/2}))^{-1} \end{array}$$

- The dominant decay mode is $\chi \to e^+e^-$.
- The decay modes of χ can be used to constrain Ω_χ.

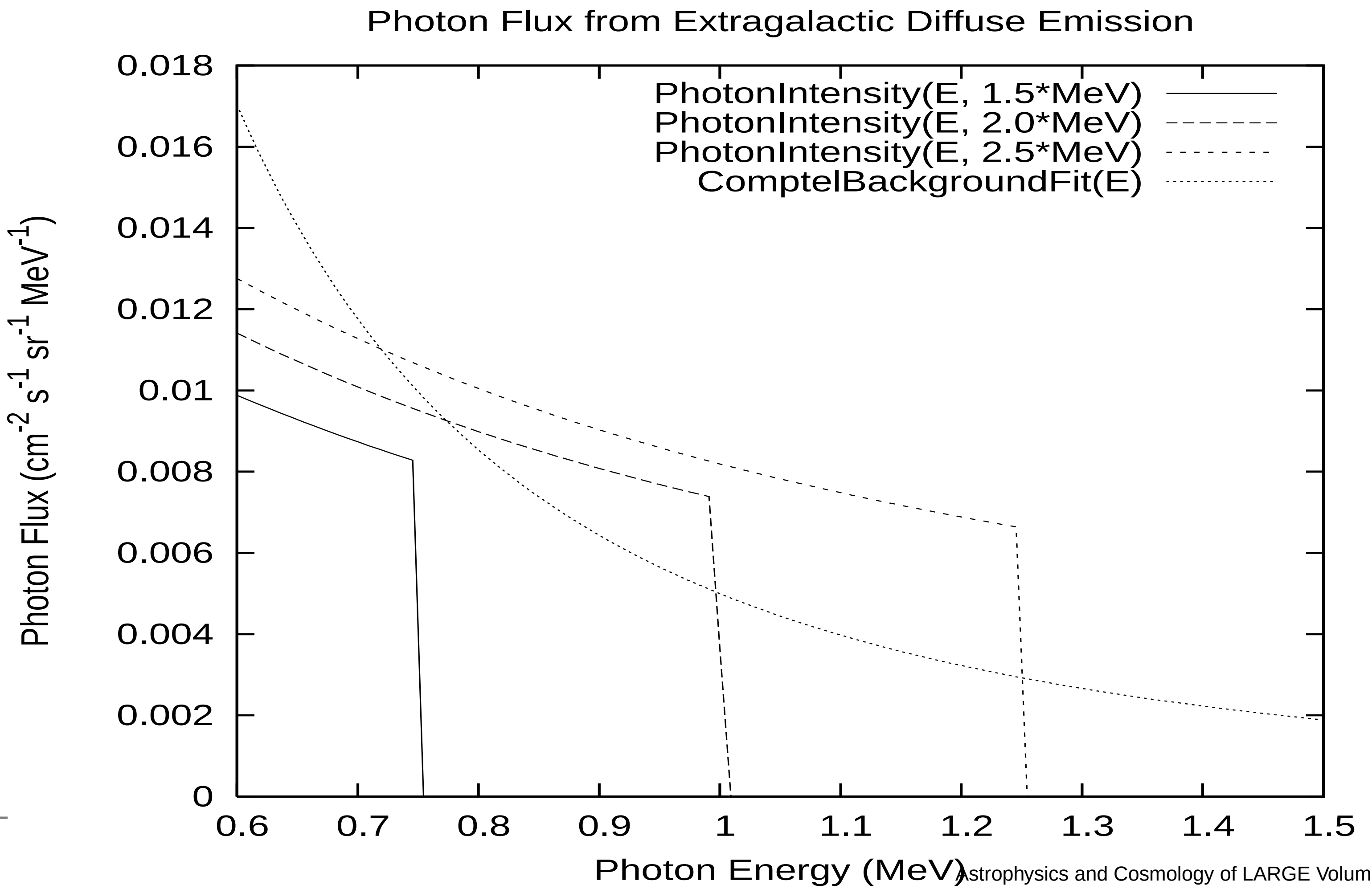
The Late Universe



Diffuse Gamma-Ray Background

Using the diffuse γ-ray background, the $\chi \to 2\gamma$ decay mode constrains

$$\frac{\Omega_\chi}{\Omega_{dm}} \lesssim \left(\frac{1\mathrm{MeV}}{m_\chi} \right)^{-3.5}$$



Galactic Halo

- Stronger constraints arise from the galactic halo.
- Dark matter clumps at the galactic center
- $\chi \to \gamma\gamma$ decays would give a monochromatic photon line.
- Signal depends on halo profile - use NFW to get constraint

$$\Omega_\chi \lesssim 2 \times 10^{-4} \left(\frac{2\text{MeV}}{m_\chi} \right)^2$$

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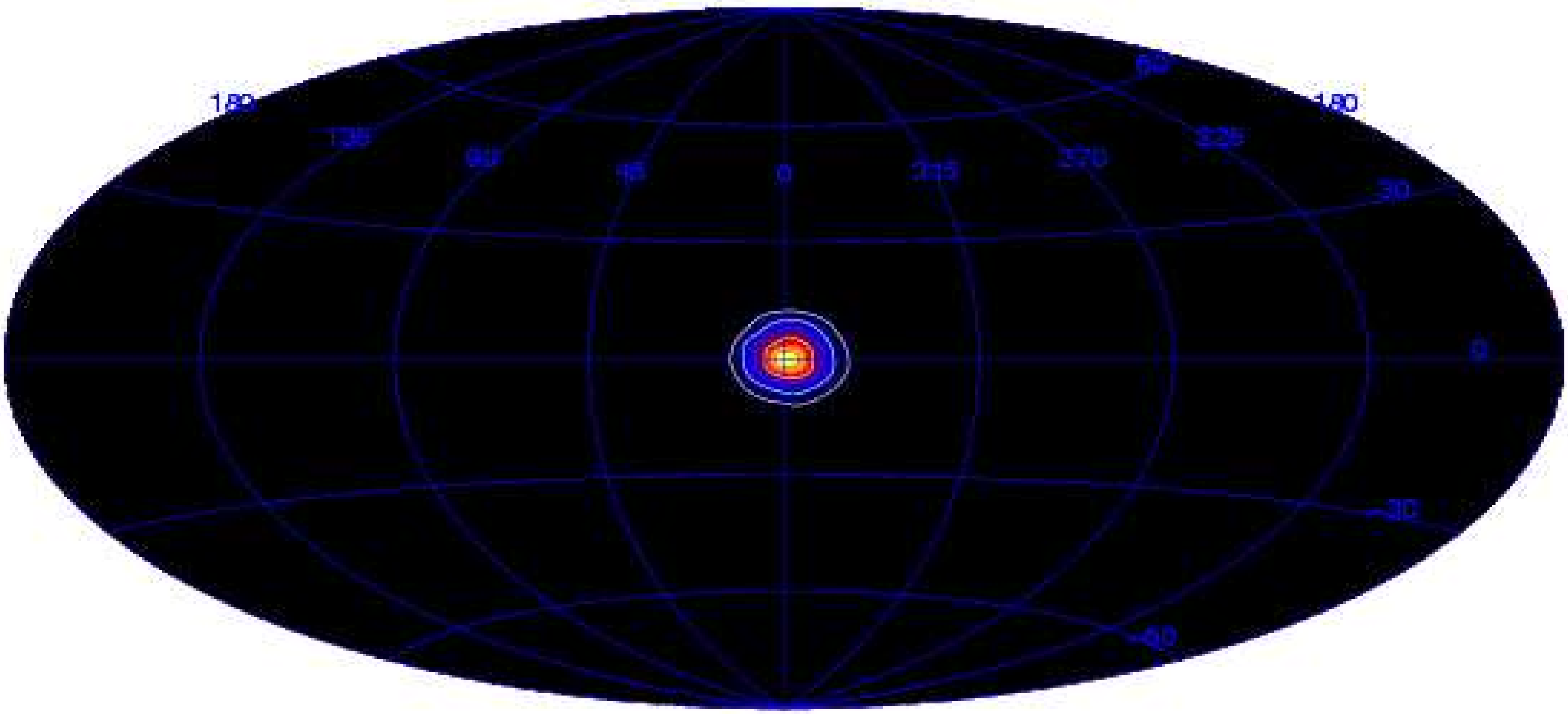
- What about $\chi \to e^+e^-$ decays?

The sky at 511keV



(INTEGRAL/SPI, ESA)

The sky at 511keV

- There is a 511keV line from the galactic center of strength

$$\mathcal{N}_\gamma \sim 1.0 \times 10^{-3} \mathrm{photons\,cm}^{-2}\,\mathrm{s}^{-1}.$$

- Line comes from positronium annihilation.
- Positron origin is unknown.
- Source must be diffuse and localised at the galactic center.
- No conventional astrophysical explanation.
- The line may arise from annihilating or decaying dark matter.

The sky at 511keV

- Positron source must
  1. Inject at low energies

     $$E_{e^+} \lesssim 3\text{MeV}$$

     (to avoid large contributions to the diffuse γ-ray background from inflight annihilation $e^+e^- \to \gamma\gamma$).
  2. Not overproduce photons, as no comparable γ-ray line is seen.
- For decaying dark matter, the light modulus χ is attractive as
  1. It has the right mass $m_\chi \sim m_{3/2}\left(\frac{m_{3/2}}{M_P}\right)^{\frac{1}{2}} \sim 2$MeV.
  2. Its decays to $\gamma\gamma$ are suppressed.

Light Modulus and 511keV line

- For the decays of χ to generate the 511keV line, we need

$$\Omega_\chi \sim (\text{a few}) \times 10^{-4}$$

- Normalising to 511 line, the tree-level $\chi \rightarrow 2\gamma$ branching ratio gives

$$I_\gamma \sim 8 \times 10^{-5} \text{photons}\, \text{cm}^{-2} \text{s}^{-1}$$

- INTEGRAL constrains gamma-ray lines from the galactic center to have strength

$$I_\gamma \lesssim 5 \times 10^{-5} \text{photons}\, \text{cm}^{-2} \text{s}^{-1}$$

- A 2γ line should be close to observational limits.

Conclusion

- LARGE volume models have two classes of moduli:
  1. Heavy moduli Φ,
  $$m_\Phi \sim 1000\text{TeV}, \qquad \tau_\Phi \sim 10^{-17}\mathrm{s}, \qquad \mathrm{T}_{\mathrm{rh}} \sim 10^7\text{GeV}.$$
  2. A light modulus χ,
  $$m_\chi \sim 2\text{MeV}, \qquad \tau_\chi \sim 10^{24}\mathrm{s}.$$
- Φ gives a high reheat temperature without gravitinos.
- χ must be diluted to $\Omega_\chi \lesssim 10^{-4}$ but may give rise to 511 keV line.
- Spectrum is not problem-free, but differs from ‘generic’ models and has exciting observational possibilities.