Modelling the Stellar Soft-photon Energy Density of Globular Clusters

presented by

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Level: BSc Honours

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Presentation Outline

1. Globular Clusters (GCs):
    - Millisecond pulsar (MSP) hosts
    - Recent gamma-ray observations
2. Inverse Compton (IC) scattering
3. Energy density profiles
    - Application to Terzan 5
4. Resulting IC-spectra
5. Model accuracy and improvements

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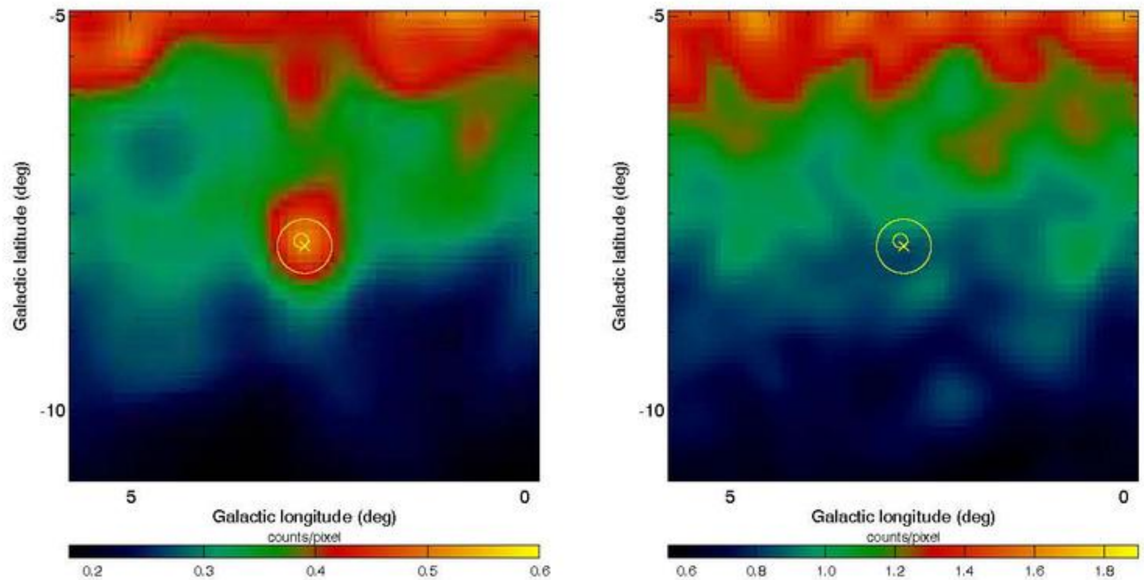
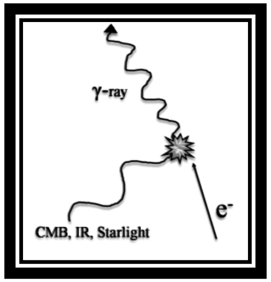
❖ *Fermi* LAT and H.E.S.S. revealed GCs as sources of HE (>100 MeV) and VHE (>100 GeV) gamma-radiation
→ for example, Terzan 5 (Ter5)
→ 34 MSPs

Globular clusters (GCs)



(Freirre et al. 2011: *Fermi*-LAT gamma-ray (>100MeV) count map of NGC6642)

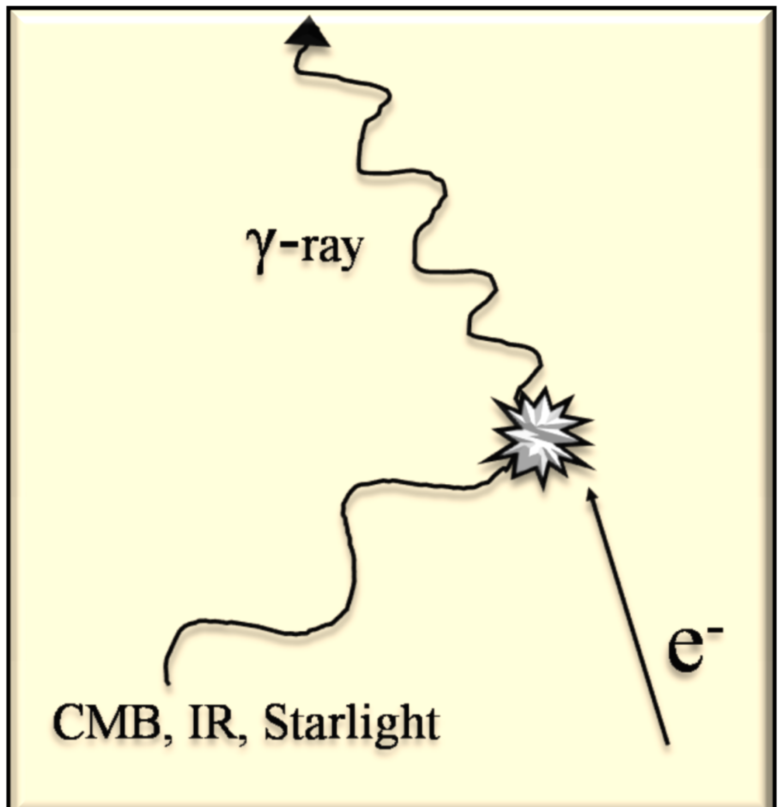


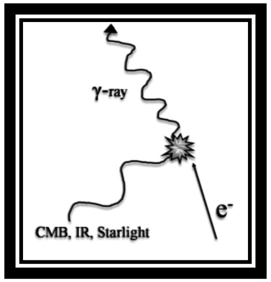
Inverse Compton (IC) scattering

❖ Particles ejected by the MSP are accelerated to relativistic speeds (either in magnetosphere of MSP or due to relativistic shocks where pulsar winds collide).

❖ Particles diffuse out of the globular cluster and interact with soft photons (CMB, IR, starlight).

❖ The soft-photons are up-scattered as γ-rays in the TeV-band.





Inverse Compton (IC) scattering

❖ To calculate the IC-spectrum, consider the emissivity, given by Zhang *et al.* (2008):

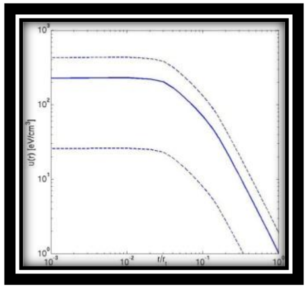
$$Q_{Comp,j}(E_\gamma, t) = 4\pi \int_0^\infty n_j(\epsilon, r) d\epsilon \int_{E_{e,thresh}}^{E_{e,max}} J_e(E_e, t) F(\epsilon, E_\gamma, E_e)\, dE_e$$

❖ The component of interest for our purposes is

$$n_j(\epsilon) = \frac{15U_j}{(\pi k T_j)^4} \frac{\epsilon^2}{\left[e^{(\epsilon/kT_j)} - 1\right]}$$

❖ Energy density U_j

- Prominent stellar component in GCs
- Must decrease with increasing distance from cluster centre
- Our objective is to derive an energy density profile for the stellar/starlight component, and solve it for the case of Ter5.



Derivation of the energy density profile

❖First, we consider the contribution of a single star:

- Assume all stars in GCs radiate like blackbodies.

- Write down the result for the energy density contribution of a single star.

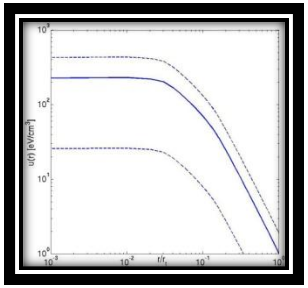
- Scale this result
    - down to compensate for the distance ‘d’ from the observer to the star,

    - and up to account for the total radiating surface.

$$I_\nu = \frac{2h}{c^2}\frac{\nu^3}{e^{\frac{h\nu}{kT}}-1}$$

$$u = \frac{4\pi}{c} I$$

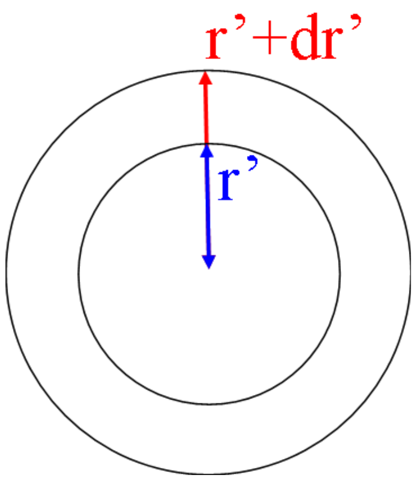
$$u_s = \left(\frac{4\pi}{c}\right)\left(\frac{4\pi R^2}{4\pi d^2}\right) I$$
$$= \left(\frac{4\pi}{c}\right)\left(\frac{R^2}{d^2}\right) I$$



Derivation of the energy density profile

❖ We expand our result to include the contributions of all the stars:

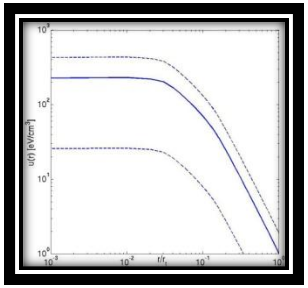
- We approximate all the stars to have solar properties, and assume spherical symmetry.



$$u_s = \left(\frac{4\pi}{c}\right)\left(\frac{R^2}{d^2}\right) I$$

$$u(r) = \int u_s N(r')dr' = \int u_s\, n(r')dV = \int u_s \frac{\rho(r')}{\bar{m}} dV$$

$$u(r) = \frac{4\pi R^2}{c}\frac{I}{\bar{m}}\int \frac{\rho(r')}{d^2} dV$$



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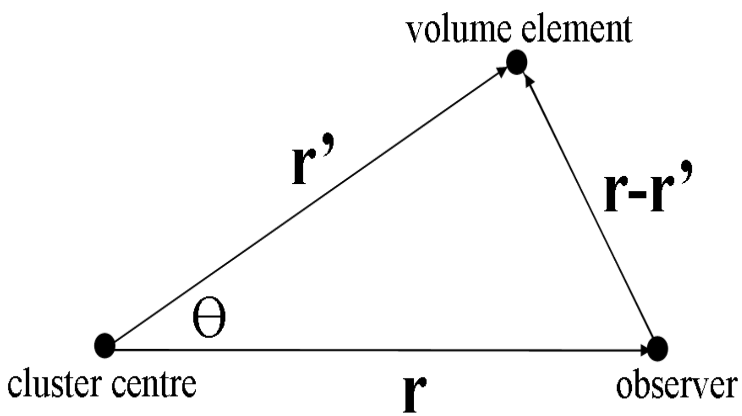
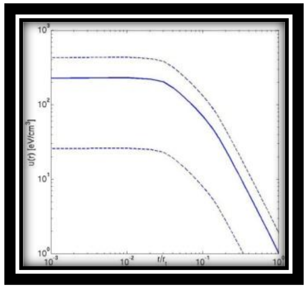


$$u(r) = \frac{4\pi R^2}{c} \frac{I}{\overline{m}} \int \frac{\rho(r')}{d^2} dV$$

$$d^2 = |\boldsymbol{r} - \boldsymbol{r}'|^2$$
$$= (r')^2 + r^2 - 2r'r\cos\theta$$

$$dV = (r')^2 \sin\theta \, dr' d\theta d\phi$$

$$u(r) = \frac{8\pi^2 R^2}{c} \frac{I}{\overline{m}} \frac{1}{r} \int_0^{r_t} \rho(r') r' \ln \frac{|r' + r|}{|r' - r|} dr'$$

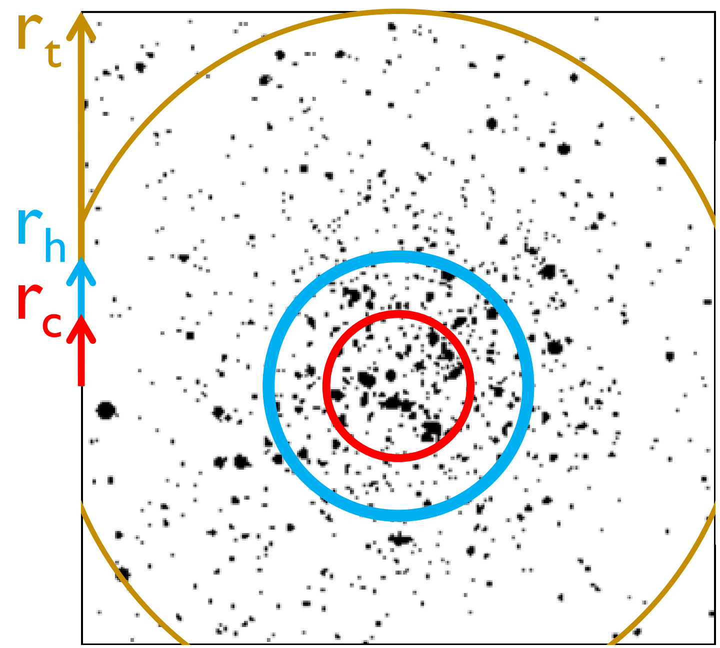


Derivation of the energy density profile

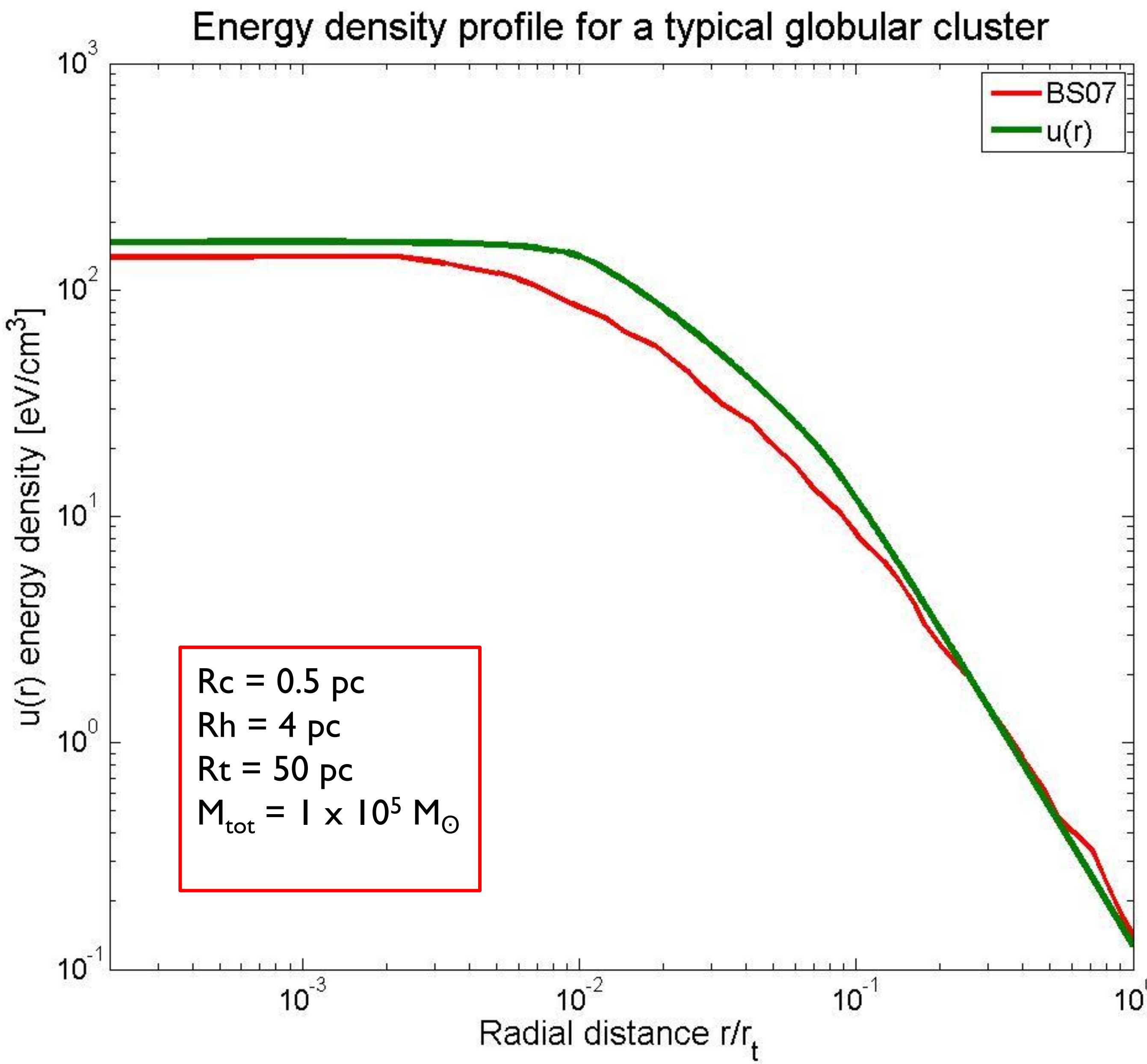
❖ We consequently normalise the mass-density profile:

(Kuranov & Postnov 2006):

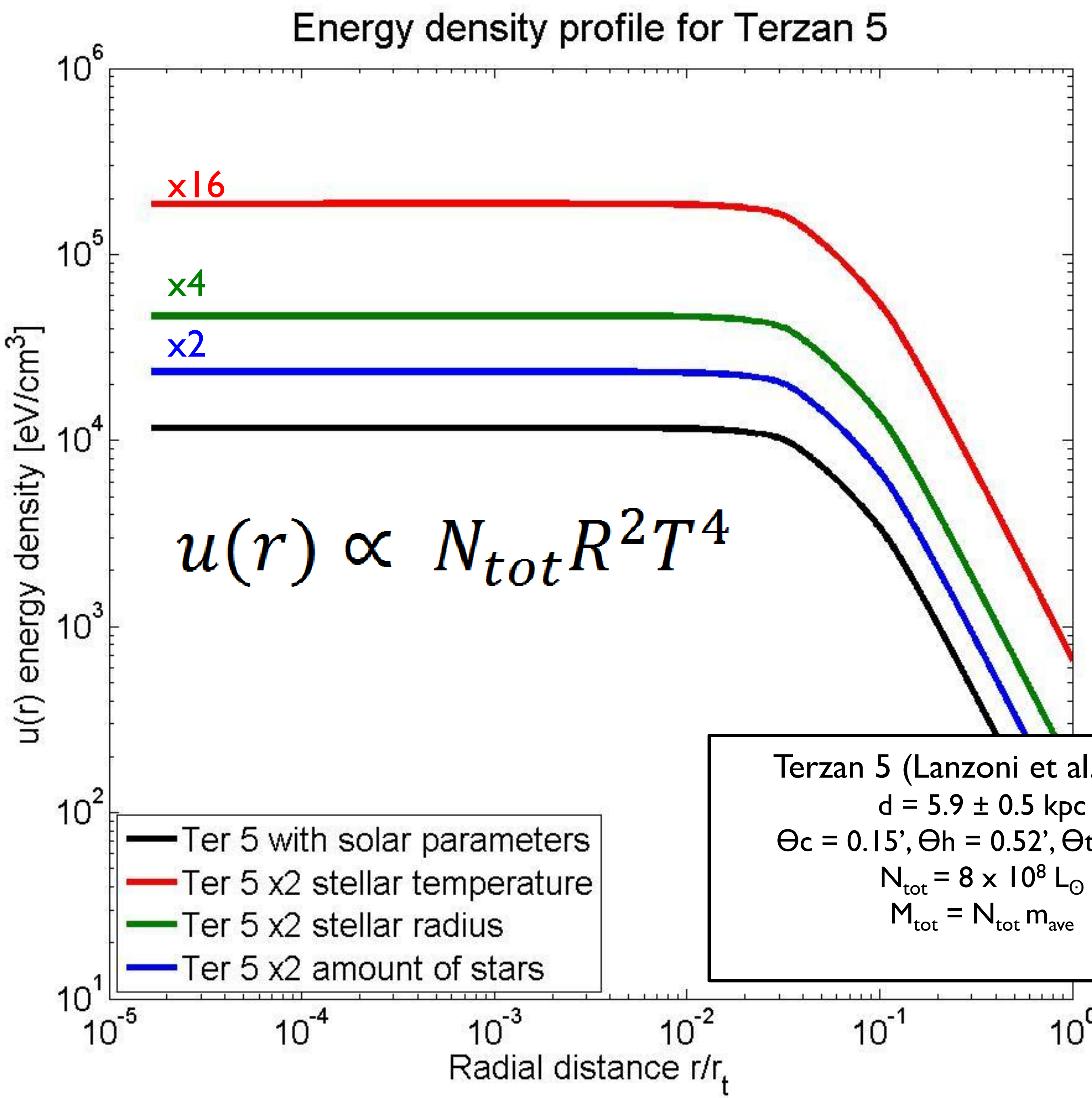
$$\rho(r) = \rho_0 \begin{cases} 1 & 0 < r < r_c \\ \left(\frac{r_c}{r}\right)^2 & r_c < r < r_h \\ \frac{(r_c r_h)^2}{r^4} & r_h < r < r_t \end{cases}$$



$$M_{total} = N_{tot}\overline{m}$$
$$= \int \rho(r) dV = 4\pi \int \rho(r) r^2 dr$$



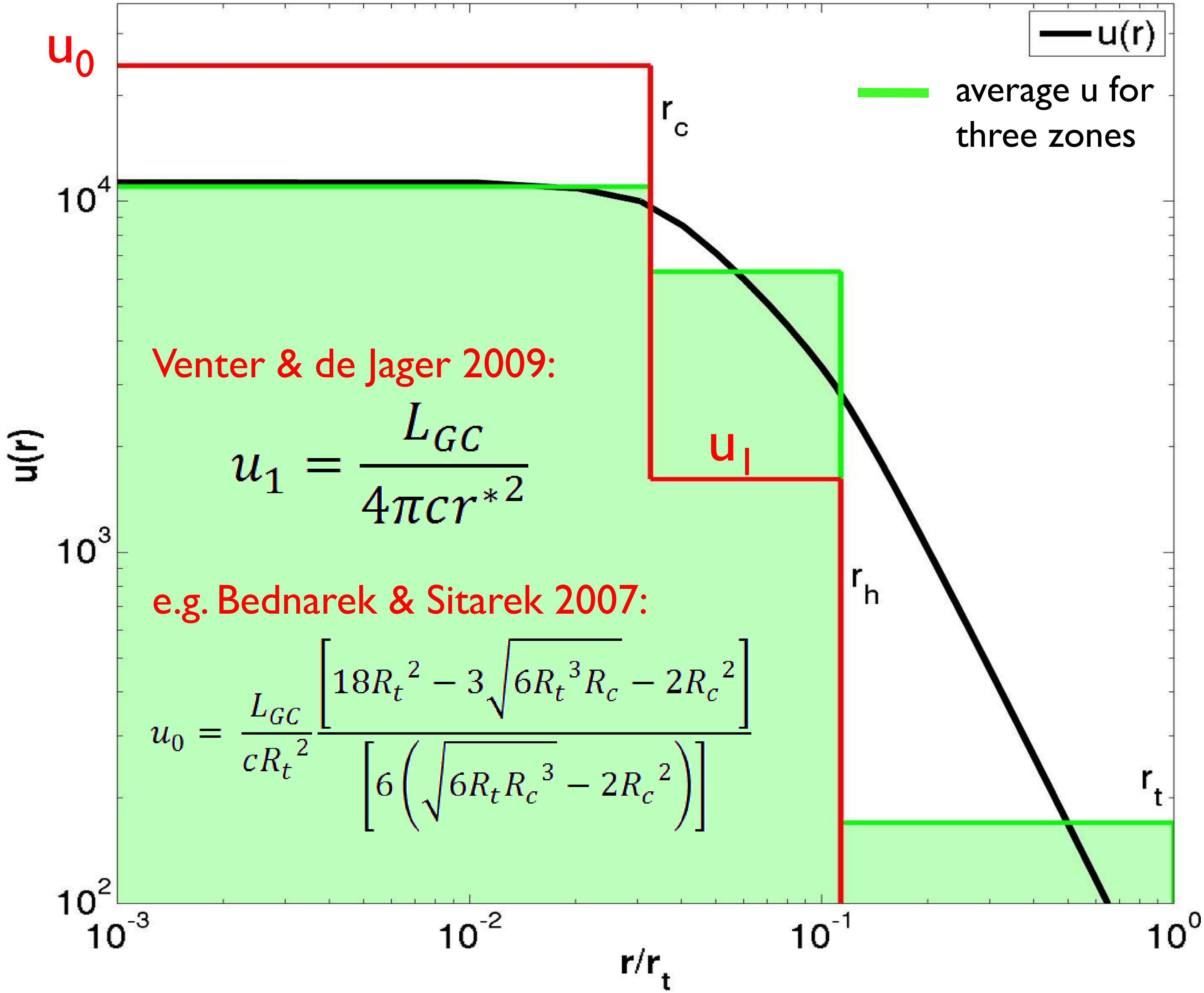
Energy density profile for a typical globular cluster
BS07
u(r)
u(r) energy density [eV/cm³]
Radial distance r/r_t
10^3
10^2
10^1
10^0
10^-1
10^-3
10^-2
10^-1
10^0
Rc = 0.5 pc
Rh = 4 pc
Rt = 50 pc
M_tot = 1 x 10^5 M_⊙



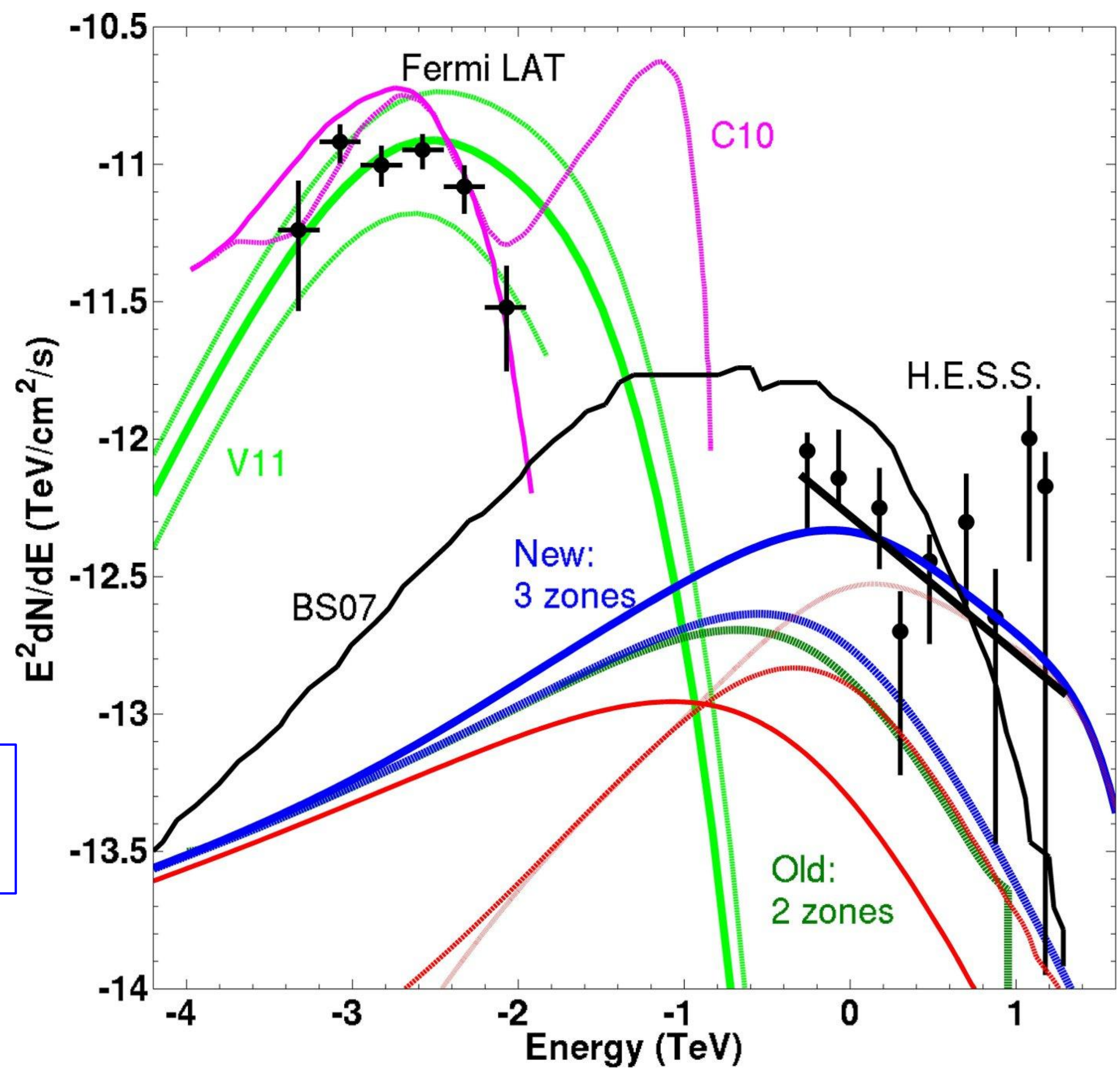
$$u(r) \propto N_{tot} R^2 T^4$$

Terzan 5 (Lanzoni et al. 2010):
$d = 5.9 \pm 0.5$ kpc
$\Theta c = 0.15'$, $\Theta h = 0.52'$, $\Theta t = 4.62'$
$N_{tot} = 8 \times 10^8 L_{\odot}$
$M_{tot} = N_{tot} m_{ave}$

Comparison of energy densities for Ter5

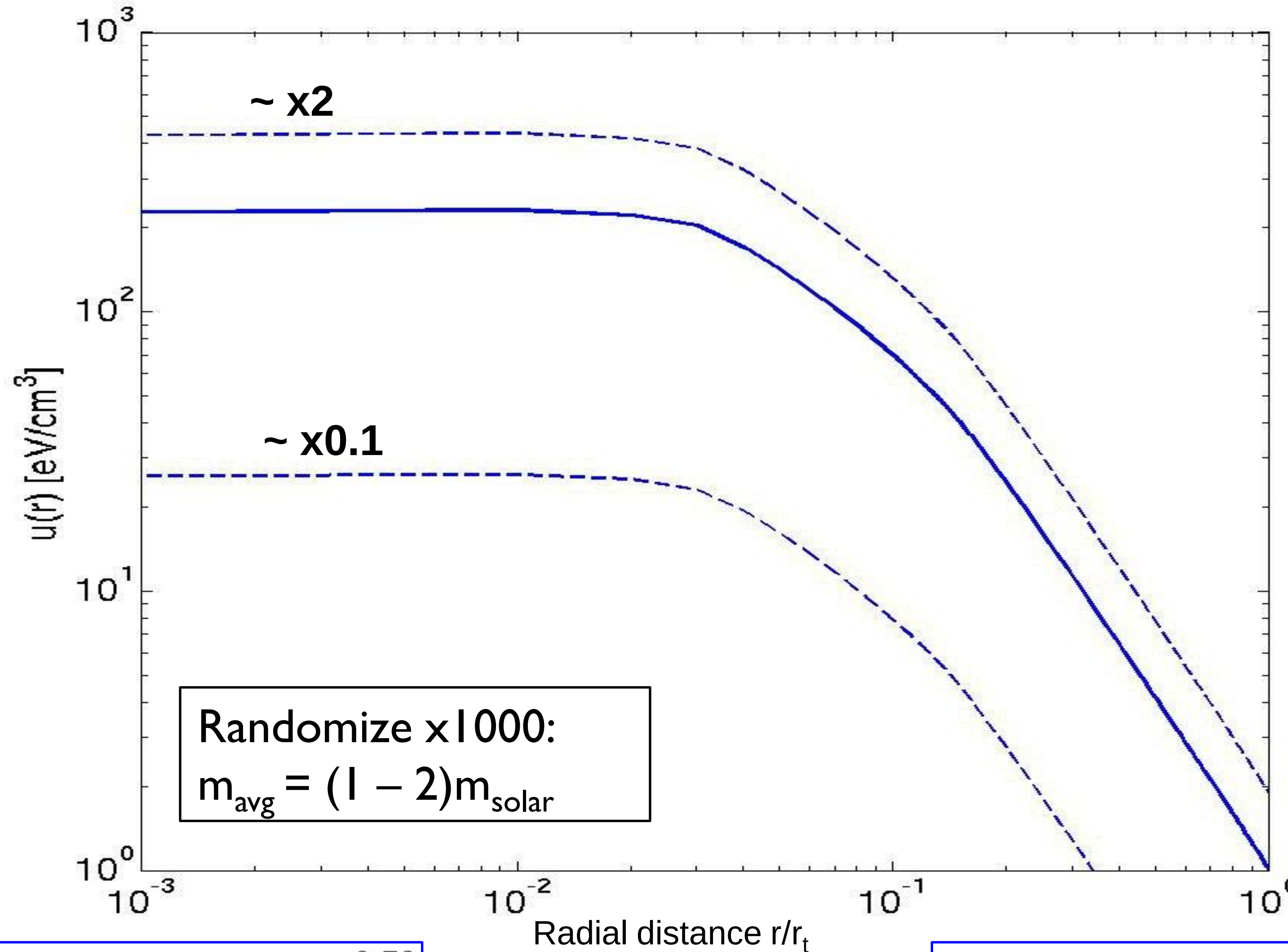


Curvature and IC-spectra for Ter5



Scaled up with ~x3

Estimating the systematic error on the energy-density profile

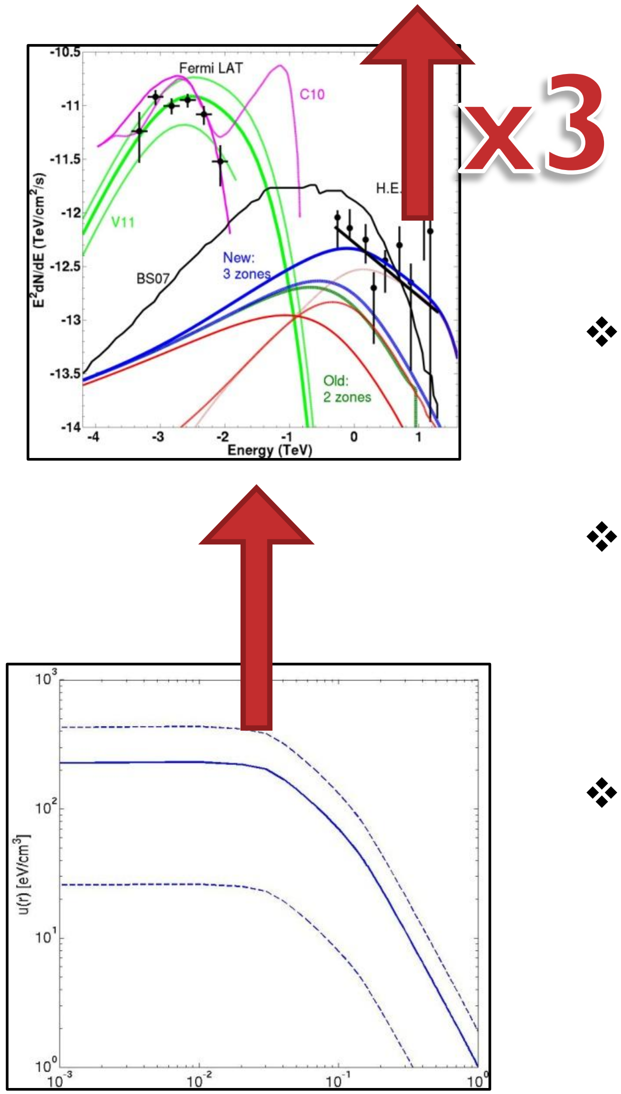


Randomize x1000:
$m_{avg} = (1 - 2) m_{solar}$

$$\frac{R}{R_{\mathrm{Sun}}} = \left(\frac{M}{M_{\mathrm{Sun}}}\right)^{0.78}$$

$$\frac{T}{T_{\mathrm{Sun}}} = \left(\frac{M}{M_{\mathrm{Sun}}}\right)^{0.22}$$

Concluding remarks



❖Predicted IC-spectrum:

- Provides a good fit to the H.E.S.S. data if scaled up by a factor 3
- N_star, N_MSP, eta and <E_dot> scaled up by ~1.3
- shows improvement

❖The error margins on u(r):

- Propagated to the IC-spectrum in a linear fashion
- H.E.S.S. data included within these error margins.

❖Improvements on the energy density profile:

- HR diagrams of GCs: Upper-limit masses, correct stellar relations.
- Surface brightness profiles

❖ Improvements on the IC-calculation:

- Construct a cluster magnetic field profile
- Use refined transport equations:
  - Greater number of zones in radiation code without loss of stability

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