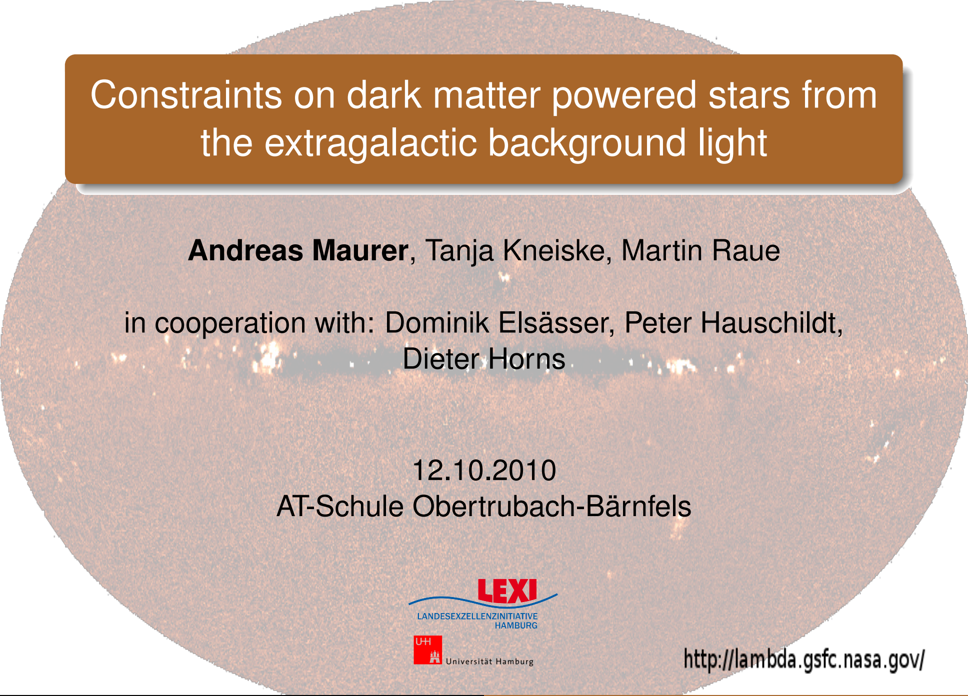
Constraints on dark matter powered stars from the extragalactic background light



http://lambda.gsfc.nasa.gov/

Andreas Maurer, Tanja Kneiske, Martin Raue

in cooperation with: Dominik Elsässer, Peter Hauschildt, Dieter Horns

12.10.2010
AT-Schule Obertrubach-Bärnfels

LEXI
LANDESEXZELLENZINITIATIVE HAMBURG
Universität Hamburg

Astrophysical evidence for dark matter

Properties of (astrophysical) dark matter

- Large scale structure data (e.g. 2dF, SDSS) and N-body simulations (e.g. Millenium Run) ⇒ **COLD**

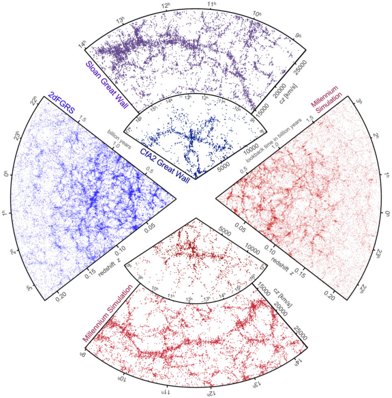


Figure: Measured (blue) and simulated (red) large scale galaxy distribution

Astrophysical evidence for dark matter

Properties of (astrophysical) dark matter

- Large scale structure data (e.g. 2dF, SDSS) and N-body simulations (e.g. Millenium Run) $\Rightarrow$ **COLD**
- Rotational curves of galaxies, gravitational lensing, galaxy clusters $\Rightarrow$ **DARK**

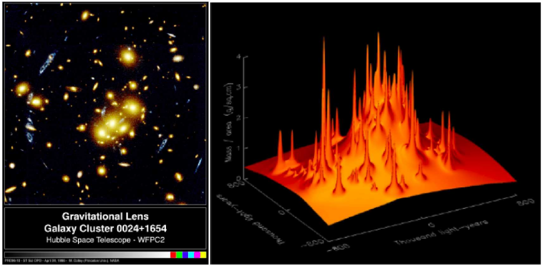


Figure: Gravitational lensing: image from Colley *et al.* (1996), matter distribution reconstruction from Tyson *et al.* (1998)

Astrophysical evidence for dark matter

Properties of (astrophysical) dark matter

- Large scale structure data (e.g. 2dF, SDSS) and N-body simulations (e.g. Millenium Run) ⇒ **COLD**
- Rotational curves of galaxies, gravitational lensing, galaxy clusters ⇒ **DARK**
- Bullet cluster ⇒ **NON-BARYONIC**

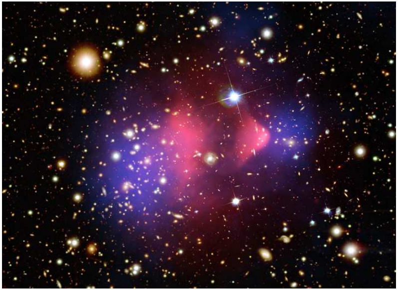


Figure: Bullet cluster, red: baryons, blue: dark matter (Clowe *et al.* 2006)

Dark (matter powered) stars

Influence of DM on first stars

- Self-annihilating dark matter e.g. WIMPs ($m_\chi = 1\,\mathrm{GeV} - 10\,\mathrm{TeV}$, $\langle \sigma v \rangle_{\mathrm{ann}} = 3 \cdot 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$)
- High dark matter density inside a star
- $L_{\mathrm{DM}} \approx \frac{2}{3} \int \rho_\chi^2 \frac{\langle \sigma v \rangle_{\mathrm{ann}}}{m_\chi} \mathrm{d}V > L_{\mathrm{nuclear}}$
- → First stars are good candidates! (Spolyar *et al.* 2008; Iocco *et al.* 2008)

AC vs. DM capture

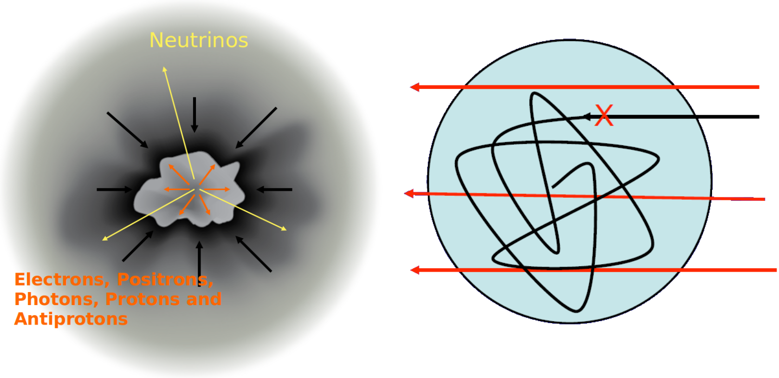


Figure: Left: Adiabatic contracted DM annihilates inside a forming Dark Star (from T. Kneiske, talk @ COSPAR 2010). Right: Scattering processes lead to an high DM density inside the DS (from F. Iocco, talk @ Astroparticle seminar, Hamburg 2010)

Overview Dark Stars

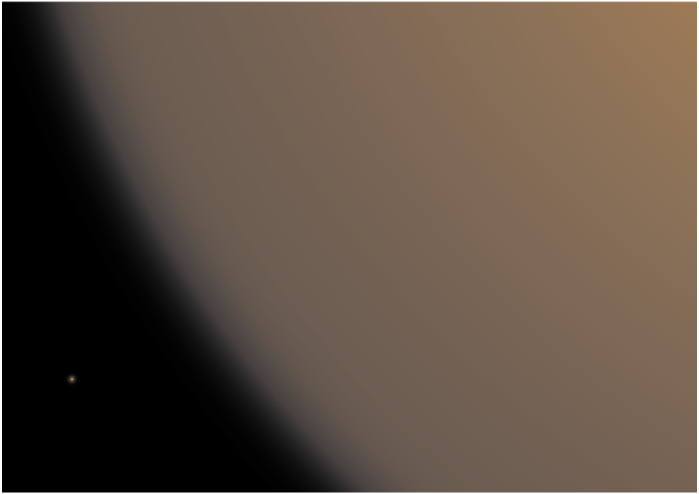


Figure: Sketch of a Dark Star next to a "normal" star (picture by T. Kneiske)

Overview Dark Stars

Properties of DS

	Sun	Dark Stars
T	5778 K	$\sim 5000 - 15000$ K
$L_\odot$ / $M_\odot$	1	$\sim 10^{2-5}$
Δt	$\sim 4.5 \cdot 10^9$ years	$\sim 10^{5-9}$ years
$\log_{10}(g)_{[\log_{10}(\mathrm{cm\,s^{-2}})]}$	4.44	~ -0.7 to 5.5

Dark Stars in the EBL

How to detect them?

- Direct detection can be very difficult (Zackrisson *et al.* 2010a)
- Our approach: extragalatic background light (EBL)
- EBL is isotropic, diffuse radiation field between $\sim 0.1 -$ (a few)100 μm containing informations of star formation history
- Signatures of Dark Stars in the EBL density opens new wavelength range for indirect dark matter search
- Advantage: EBL is sensitive to many **faint** sources
- Disadvantage: EBL is sensitive to **many** faint sources

Multiwavelength data of diffuse background radiation

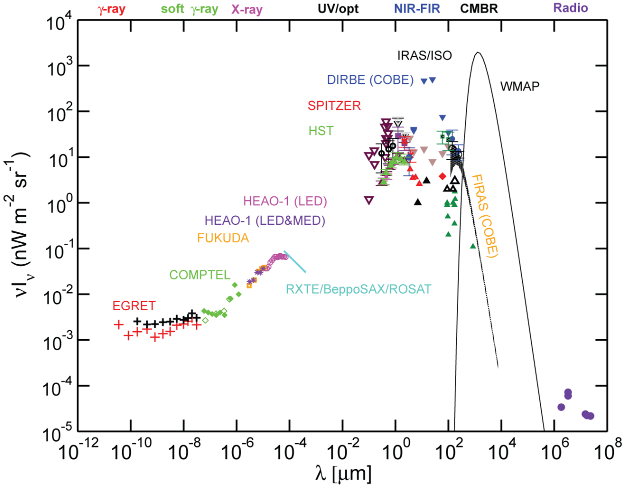


Figure: Spectrum of the cosmic background radiations from T. Kneiske, talk @ COSPAR 2010

Recent data of the EBL and their origin

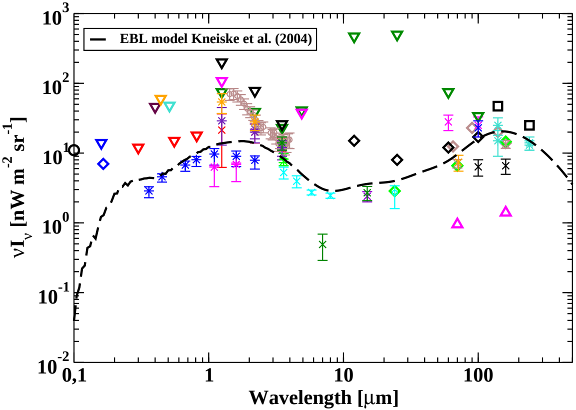


Figure: EBL data based on a collection by Mazin & Raue (2007) updated regularly, EBL model by Kneiske *et al.* (2004)

- Integrated, redshifted em-radiation from all epochs
- Direct measurements, lower limits, upper limits
- Peaks: $\sim 1\ \mu$m (stars) and $\sim 200\ \mu$m (dust)

EBL contribution model: Emissivity

Method

- Calculating the (possible) contribution from Dark Stars to the EBL density
- using a Forward evolution model (see e.g. Hauser & Dwek 2001), assuming minimal radiative transfer (e.g. no reprocessing)
- Concordance ΛCDM cosmological model

Emissivity - comoving luminosity density

$$\begin{aligned}
\varepsilon_\nu(z) &= \int\limits_{z}^{z_{max}} L_\nu(t(z) - t(z'))\dot{\rho}_*(z') \left|\frac{\mathrm{d}t}{\mathrm{d}z'}\right| \mathrm{d}z' \\
L_\nu(t(z) - t(z')) &= L_\nu = \text{constant for } t(z) - t(z') \leq \Delta t_{DS} \\
\dot{\rho}_*(z) &= \mathrm{SFR}_{Norm}[\Theta(z - z_{min}) - \Theta(z - z_{max})]
\end{aligned}$$

Dark Star spectra calculated with the PHOENIX code

(Hauschildt & Baron 2006)

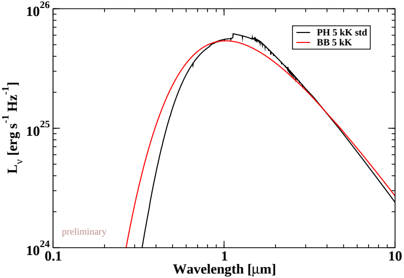


Figure: Dark Star spectrum calculated with PHOENIX vs blackbody with $T_{DS} = 5000\,\mathrm{K}$, $M_{DS} = 106\,\mathrm{M}_\odot$, $R_{DS} = 2.4 \times 10^{12}$ m

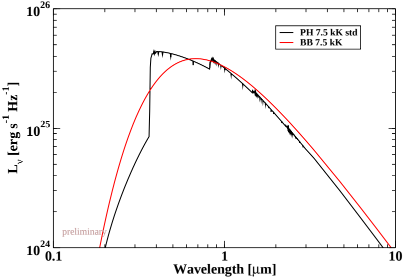


Figure: Dark Star spectrum calculated with PHOENIX vs blackbody with $T_{DS} = 7500\,\mathrm{K}$, $M_{DS} = 690\,\mathrm{M}_\odot$, $R_{DS} = 1.1 \times 10^{12}$ m

DS parameters from Spolyar *et al.* (2009)

Star formation rates: Our model vs. simulations

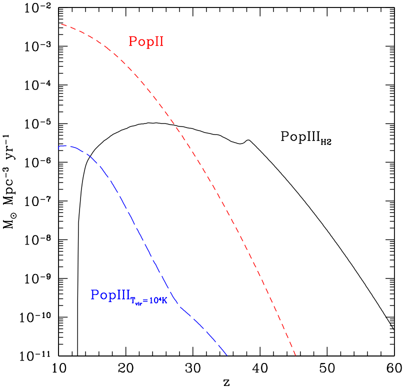


Figure: POPIII SFR from Trenti & Stiavelli (2009)

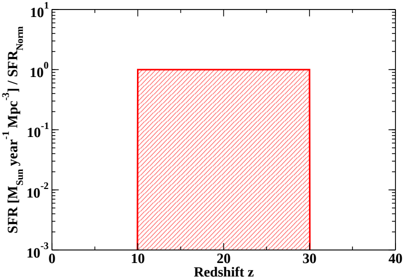


Figure: Model assumption used here

EBL density - redshifted integrated luminosity density

$$\begin{aligned} P_\nu(z) &= \nu I_\nu(z) = \nu \frac{c}{4\pi} \int_z^{z_{max}} \varepsilon_{\nu'}(z') \left|\frac{\mathrm{d}t}{\mathrm{d}z'}\right| \mathrm{d}z' \\ \nu' &= \nu \left(\frac{1+z'}{1+z}\right) \end{aligned}$$

Cosmological parameters

$$\begin{aligned} \left|\frac{dt}{dz}\right| &= \frac{1}{H_0(1+z)E(z)} \\ E(z)^2 &= \Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda \end{aligned}$$

$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	Ω_r	Ω_m	Ω_k	Ω_Λ
70	0	0.3	0	0.7

Calculation of the EBL signatures of Dark Stars

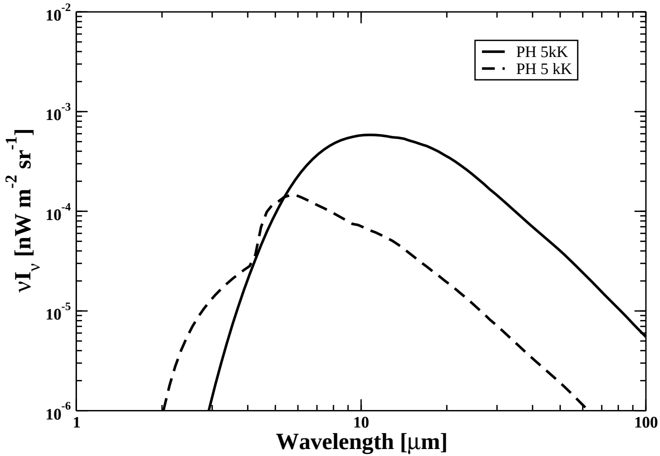


Figure: EBL density: PH 5kK vs. PH7.5 kK

Dark Star parameter space

Parameters

Parameter	minimal	maximal
Δt_{DS}	10^5 years	10^9 years
$z_{\min}$[a]	5	15
(D)SFR$_{Norm}$[b]	10^{-7}	10^{-3}
Luminosity to mass ratio[c]	10^2 $L_\odot/M_\odot$	10^5 $L_\odot/M_\odot$

---

[a] see e.g. Trenti *et al.* (2009); Maio *et al.* (2010)

[b] obtained by using POP III SFR from Trenti & Stiavelli (2009)

[c] calculated from different DS models by Iocco *et al.* (2008); Spolyar *et al.* (2009); Freese *et al.* (2010)

Effect of different DS formation rates

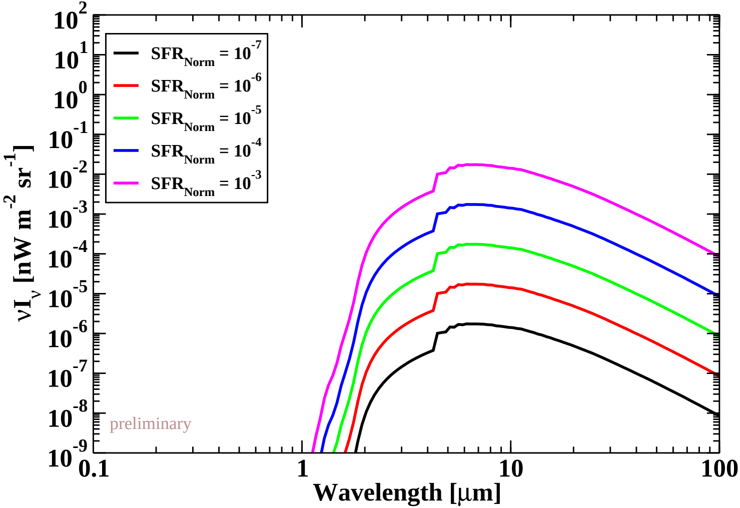


Figure: Dark Star EBL contribution for DS: $T_{DS} = 7500\,\mathrm{K}$, $M_{DS} = 690\,\mathrm{M}_\odot$, $R_{DS} = 1.1 \times 10^{12}\,\mathrm{m}$

Effect of different minimum z formation steps

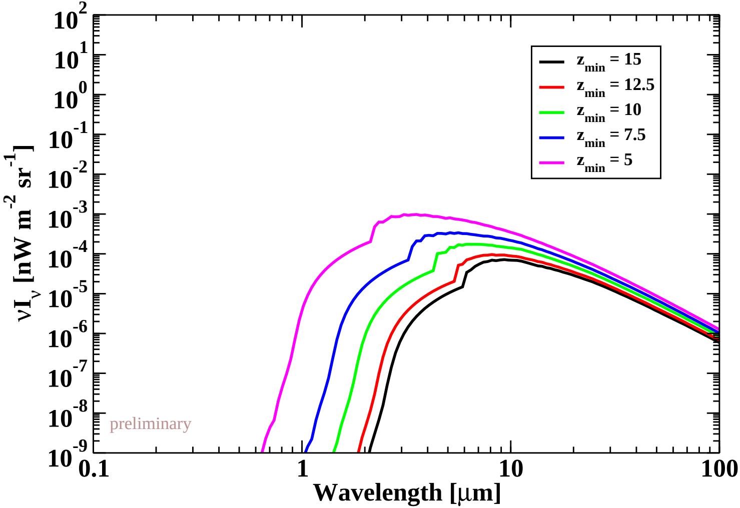


Figure: Dark Star EBL contribution for DS: $T_{DS} = 7500\,\mathrm{K}$, $M_{DS} = 690\,\mathrm{M}_\odot$, $R_{DS} = 1.1 \times 10^{12}\,\mathrm{m}$

Effect of different DS lifetimes

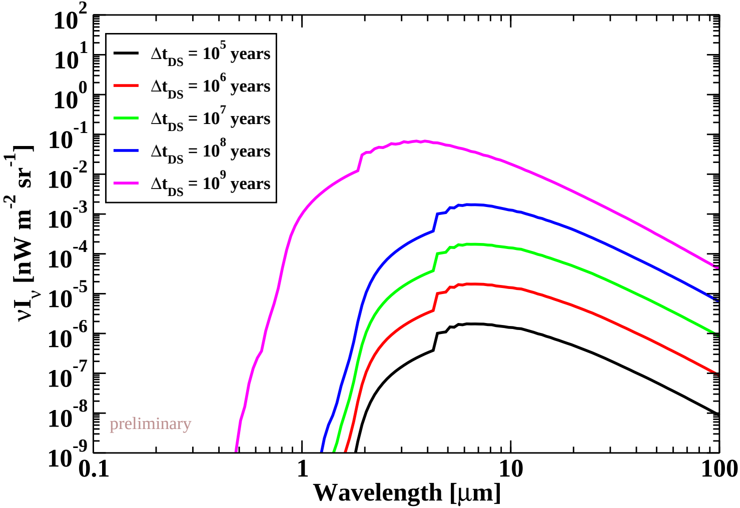


Figure: Dark Star EBL contribution for DS: $T_{DS} = 7500\,\mathrm{K}$, $M_{DS} = 690\,\mathrm{M}_\odot$, $R_{DS} = 1.1 \times 10^{12}\,\mathrm{m}$

Calculated EBL density

Maximum EBL density [nW m^{-2} sr^{-1}]

	5 kK DS	7.5 kK DS
Minimal $z_{min} = 15,\ \mathrm{SFR}_{Norm} = 10^{-7}, \Delta t_{DS} = 10^5 years$	$\sim 3.5 \times 10^{-8}$	$\sim 7.2 \times 10^{-9}$
Medium $z_{min} = 10,\ \mathrm{SFR}_{Norm} = 10^{-5}, \Delta t_{DS} = 10^7 years$	$\sim 8.2 \times 10^{-4}$	$\sim 1.7 \times 10^{-4}$
Maximum $z_{min} = 5,\ \mathrm{SFR}_{Norm} = 10^{-3}, \Delta t_{DS} = 10^9 years$	~ 63	~ 13

Calculated EBL density vs. data

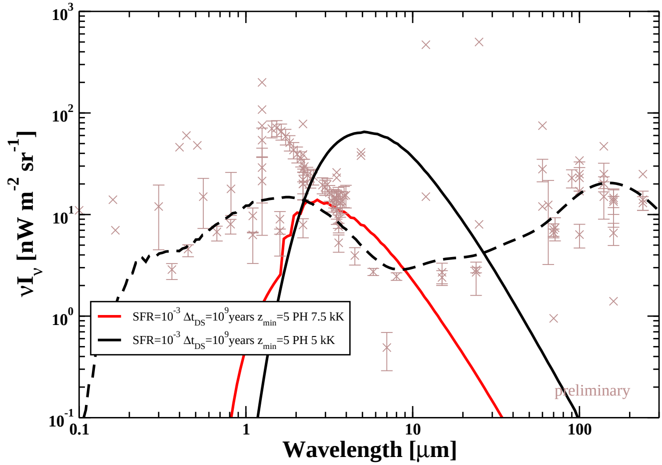


Figure: Maximum EBL contribution scenarios of DS parameters, EBL model by Kneiske *et al.* 2004 (black dashed line)

Results and summary

Summary & Outlook

- EBL offers a new possibility to search for DS / constrain DS parameter space
- Calculated contributions from DS to the EBL density
- EBL density ranges from $\sim 10^{-9}$ to $\sim 60\,\mathrm{nW\,m^{-2}\,sr^{-1}}$
- Some (extreme) parameter sets of DS can be excluded
- New data of the EBL density (e.g. JWST, CIBER) will provide further constraints

Thank you for your attention!

Workshop announcement

CRF2010
HAMBURG

International workshop on
"Cosmic Radiation Fields: Sources in the early Universe"

Date: November 9 - 12, 2010
Location: DESY research center, Hamburg, Germany
Website: http://www.desy.de/crf2010

References I

CLOWE, D., BRADAČ, M., GONZALEZ, A. H., MARKEVITCH, M., RANDALL, S. W., JONES, C., & ZARITSKY, D. 2006. A Direct Empirical Proof of the Existence of Dark Matter. *Astrophys. J., Lett.*, **648**(Sept.), L109–L113.

COLLEY, W. N., TYSON, J. A., & TURNER, E. L. 1996. Unlensing Multiple Arcs in 0024+1654: Reconstruction of the Source Image. *Astrophys. J., Lett.*, **461**(Apr.), L83+.

FREESE, K., ILIE, C., SPOLYAR, D., VALLURI, M., & BODENHEIMER, P. 2010. Supermassive Dark Stars: Detectable in JWST. *Astrophys. J.*, **716**(June), 1397–1407.

HAUSCHILDT, P. H., & BARON, E. 2006. A 3D radiative transfer framework. I. Non-local operator splitting and continuum scattering problems. *Astron. Astrophys.*, **451**(May), 273–284.

HAUSER, M. G., & DWEK, E. 2001. The Cosmic Infrared Backround: Measurements and Implications. *Annual Review of Astronomy and Astrophysics*, **39**, 249.

IOCCO, F., BRESSAN, A., RIPAMONTI, E., SCHNEIDER, R., FERRARA, A., & MARIGO, P. 2008. Dark matter annihilation effects on the first stars. *Mon. Not. R. Astron. Soc.*, **390**(Nov.), 1655–1669.

KNEISKE, T. M., BRETZ, T., MANNHEIM, K., & HARTMANN, D. H. 2004. Implications of cosmological gamma-ray absorption. II. Modification of gamma-ray spectra. *Astron. Astrophys.*, **413**(Jan.), 807–815.

References II

MAIO, U., CIARDI, B., DOLAG, K., TORNATORE, L., & KHOCHFAR, S. 2010. The transition from population III to population II-I star formation. *ArXiv e-prints*, Mar.

MAZIN, D., & RAUE, M. 2007. New limits on the density of the extragalactic background light in the optical to the far infrared from the spectra of all known TeV blazars. *Astron. Astrophys.*, **471**(Aug.), 439–452.

SPOLYAR, D., FREESE, K., & GONDOLO, P. 2008. Dark Matter and the First Stars: A New Phase of Stellar Evolution. *Physical Review Letters*, **100**(5), 051101–+.

SPOLYAR, D., BODENHEIMER, P., FREESE, K., & GONDOLO, P. 2009. Dark Stars: A New Look at the First Stars in the Universe. *Astrophys. J.*, **705**(Nov.), 1031–1042.

TRENTI, M., & STIAVELLI, M. 2009. Formation Rates of Population III Stars and Chemical Enrichment of Halos during the Reionization Era. *Astrophys. J.*, **694**(Apr.), 879–892.

TRENTI, M., STIAVELLI, M., & MICHAEL SHULL, J. 2009. Metal-free Gas Supply at the Edge of Reionization: Late-epoch Population III Star Formation. *Astrophys. J.*, **700**(Aug.), 1672–1679.

TYSON, J. A., KOCHANSKI, G. P., & DELL'ANTONIO, I. P. 1998. Detailed Mass Map of CL 0024+1654 from Strong Lensing. *Astrophys. J., Lett.*, **498**(May), L107+.

ZACKRISSON, E., SCOTT, P., RYDBERG, C.-E., IOCCO, F., EDVARDSSON, B., ÖSTLIN, G., SIVERTSSON, S., ZITRIN, A., BROADHURST, T., & GONDOLO, P. 2010a. Finding High-redshift Dark Stars with the James Webb Space Telescope. *Astrophys. J.*, **717**(July), 257–267.

References III

Zackrisson, E., Scott, P., Rydberg, C.-E., Iocco, F., Sivertsson, S., Östlin, G., Mellema, G., Iliev, I. T., & Shapiro, P. R. 2010b. Observational constraints on supermassive dark stars. *ArXiv e-prints*, June.

Backup slides I

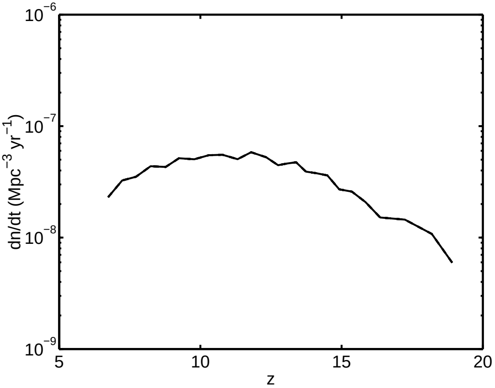


Figure: Comoving halo formation rate for 1-2 $\times 10^8$ DM-halos (Zackrisson *et al.* 2010b)

Backup slides II

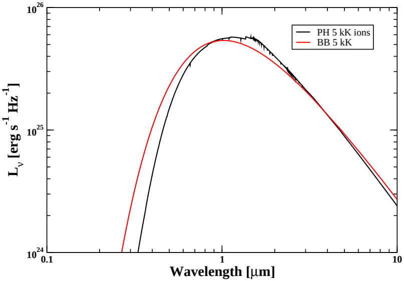


Figure: Dark Star spectrum calculated with PHOENIX vs blackbody with $T_{DS} = 5000\,\mathrm{K}$, $M_{DS} = 106\,\mathrm{M}_\odot$, $R_{DS} = 2.4 \times 10^{12}\,\mathrm{m}$

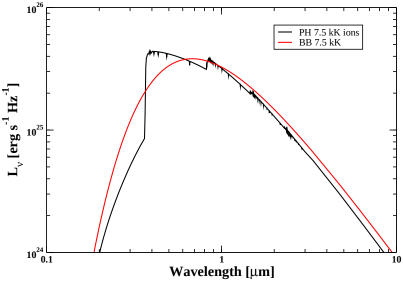


Figure: Dark Star spectrum calculated with PHOENIX vs blackbody with $T_{DS} = 7500\,\mathrm{K}$, $M_{DS} = 690\,\mathrm{M}_\odot$, $R_{DS} = 1.1 \times 10^{12}\,\mathrm{m}$

Backup slides III

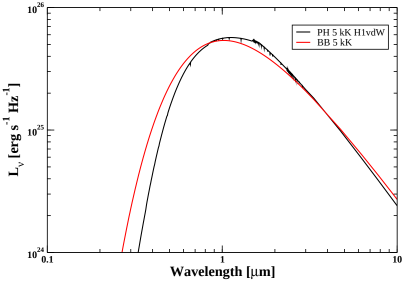


Figure: Dark Star spectrum calculated with PHOENIX vs blackbody with $T_{DS} = 5000\,\mathrm{K}$, $M_{DS} = 106\,\mathrm{M}_\odot$, $R_{DS} = 2.4 \times 10^{12}\,\mathrm{m}$

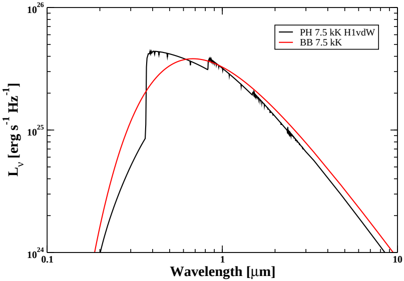


Figure: Dark Star spectrum calculated with PHOENIX vs blackbody with $T_{DS} = 7500\,\mathrm{K}$, $M_{DS} = 690\,\mathrm{M}_\odot$, $R_{DS} = 1.1 \times 10^{12}\,\mathrm{m}$

Backup slides IV

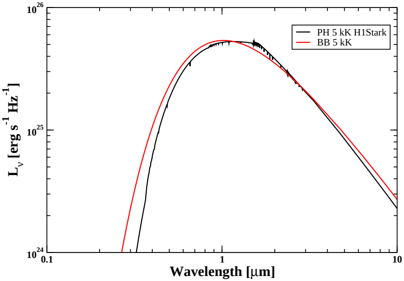


Figure: Dark Star spectrum calculated with PHOENIX vs blackbody with $T_{DS} = 5000\,\mathrm{K}$, $M_{DS} = 106\,\mathrm{M}_\odot$, $R_{DS} = 2.4 \times 10^{12}\,\mathrm{m}$

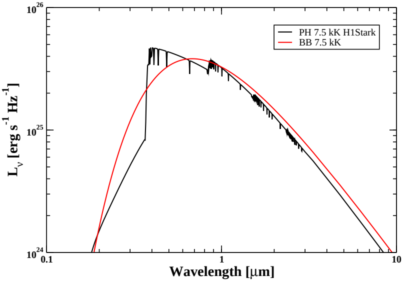


Figure: Dark Star spectrum calculated with PHOENIX vs blackbody with $T_{DS} = 7500\,\mathrm{K}$, $M_{DS} = 690\,\mathrm{M}_\odot$, $R_{DS} = 1.1 \times 10^{12}\,\mathrm{m}$

Backup slides V

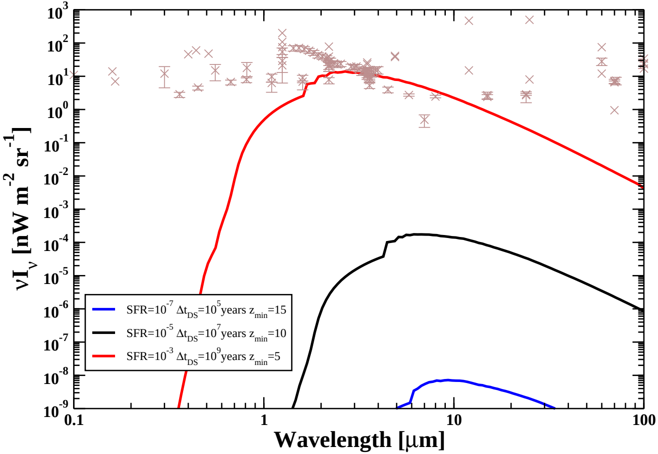


Figure: PH 7.5 kK EBL vs. data

Backup slides VI

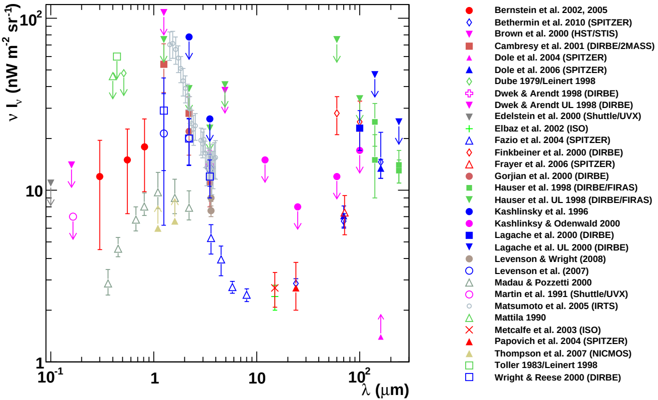


Figure: taken from Mazin & Raue (2007), updated regularly

Backup slides VII

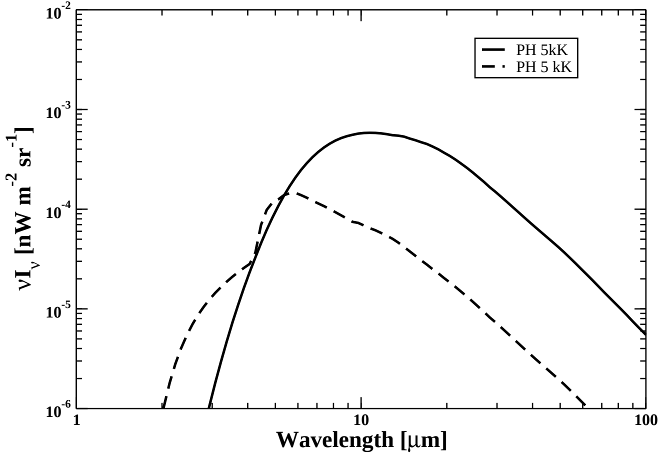


Figure: EBL density: PH 5kK vs. PH7.5 kK