Cosmology through very high energy gamma ray observations

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Teaser: recent Fermi-LAT results

Sciencexpress Reports

The Imprint of the Extragalactic Background Light in the Gamma-Ray Spectra of Blazars

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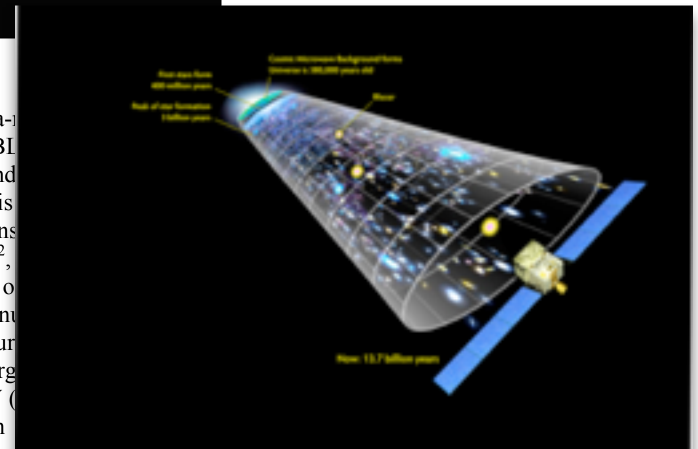
The light emitted by stars and accreting compact objects through the history of the universe is encoded in the intensity of the extragalactic background light (EBL). Knowledge of the EBL is important to understand the nature of star formation and

process, a gamma-r… gy E_γ and an EBL… E_{EBL} annihilate and… positron pair. This… head-on collisions… $\times E_{EBL} \geq 2(m_e c^2)^2$, … rest mass energy o… introduces an attenu… of gamma-ray sour… gamma-ray energ… $170(1+z)^{-2.38}$ GeV (…

The detection … horizon (i.e., the point beyond which the emission of gamma-ray sources is strongly attenuated) is one of the primary scientific drivers of the Fermi

… with redshift. We searched for an attenuation of the spectra of blazars in the 1-500 GeV band using the first 46 months of observations of the Large Area Telescope (LAT) on board the Fermi satellite. At these energies gamma rays are absorbed by EBL photons in the optical to UV range. Thanks to the large energy and redshift coverage, Fermi-LAT measures the intrinsic (i.e., unabsorbed) spectrum up to ~100 GeV for any blazar at $z < 0.2$



The light emitted by stars and accreting compact objects through the history of the universe is encoded in the intensity of the extragalactic background light (EBL). Knowledge of the EBL is important to understand the nature of star formation and galaxy evolution, but direct measurements of the EBL are limited by galactic and other foreground emissions. Here, we report an absorption feature seen in the combined spectra of a sample of gamma-ray blazars out to a redshift of $z \sim 1.6$. This feature is caused by attenuation of gamma rays by the EBL at optical to ultraviolet frequencies and allowed us to measure the EBL flux density in this frequency band.

The Fermi-LAT collaboration, Science Express, 1 November 2012

Executive summary

Gamma-rays are an excellent probe for cosmology

- Star formation rate density (SFRD)
- Intergalactic magnetic fields (IGMs)
- Quantum gravity (QG)
- Axion like particles (ALPs)

Current observations deliver relevant constraints

- Strong limits on the extragalactic background light
  - Constraints on the SFRD and IGMF
- Interesting constraints on QG and ALPs

The future holds exciting possibilities

- CTA
  - 10x improved sensitivity over current installations
  - Extended energy range (20 GeV - 100 TeV)
- VHE gamma-ray observations will address some of the key questions of current cosmology

Overview

Introduction

- Very high energy gamma ray astronomy
- Ground based detection and experiments

Cherenkov Telescope Array (CTA)

- Basic idea
- Expected performance

Cosmology through VHE gamma-ray observations

- Cosmology science cases
- Case study: constraining the cosmic star formation history

Summary / Conclusions

Introduction

At a party ...

"So, what do you do?"

"I work in astroparticle physics on very high energy gamma-rays."

"Very high energy ....

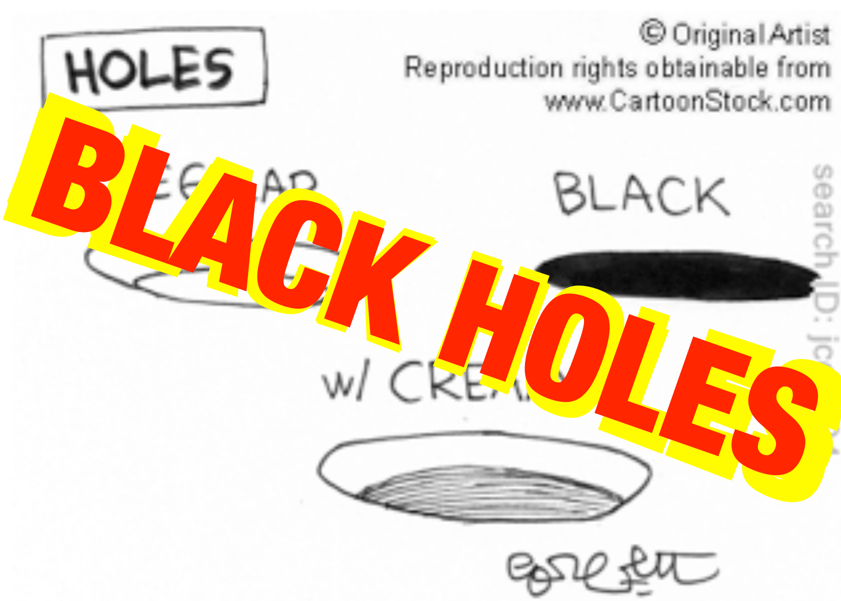
WHAT???

Very high energy gamma-rays!

EXPLOSIONS

DARK MATTER

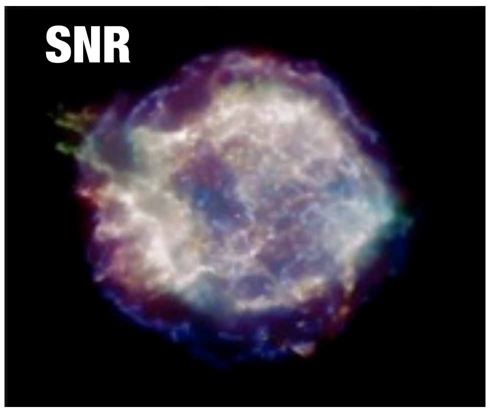
RELATIVISTIC JETS

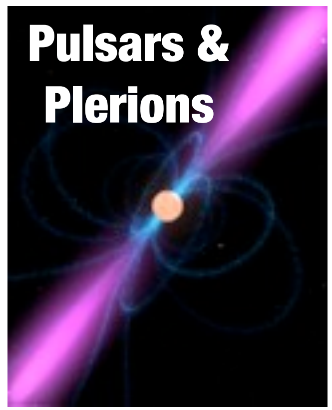


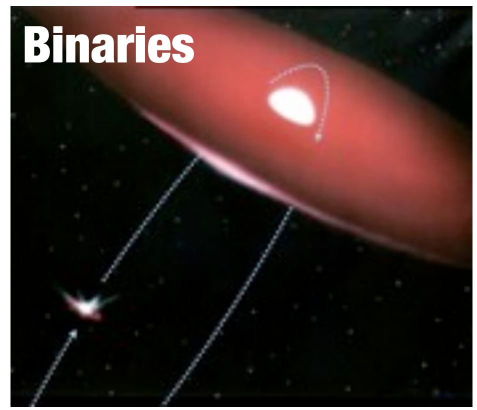
BLACK HOLES

VHE gamma-rays: sources

“Probing the non-thermal universe”







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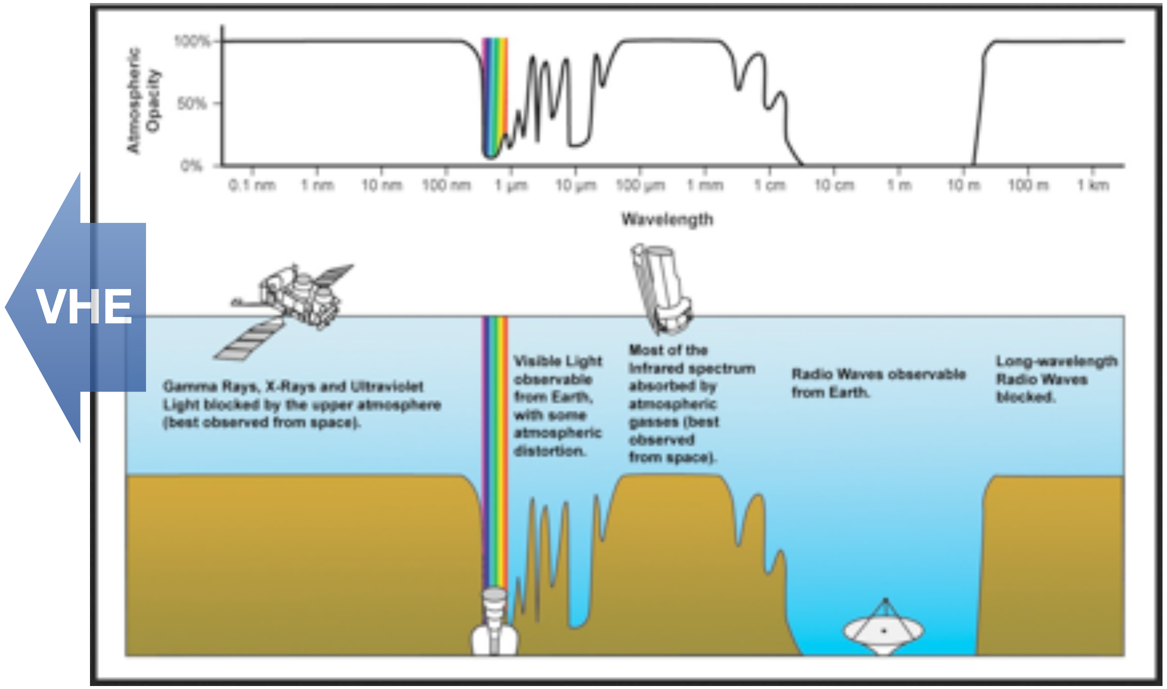
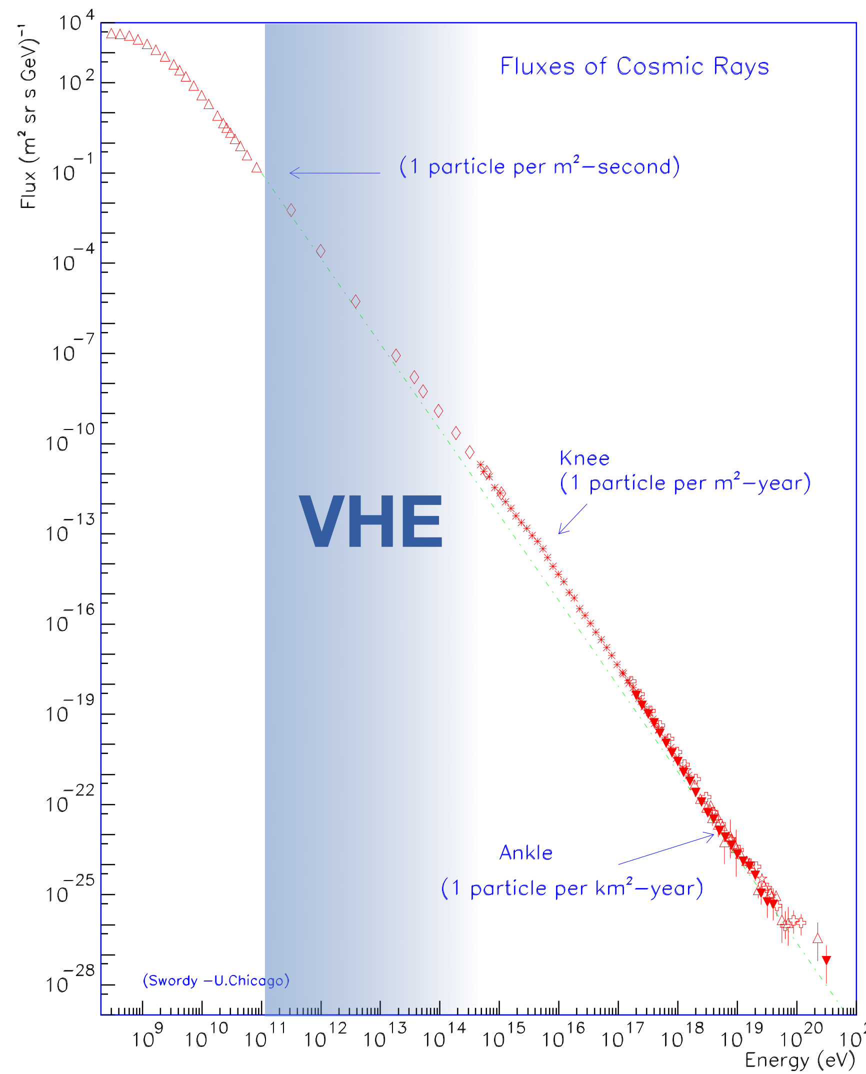
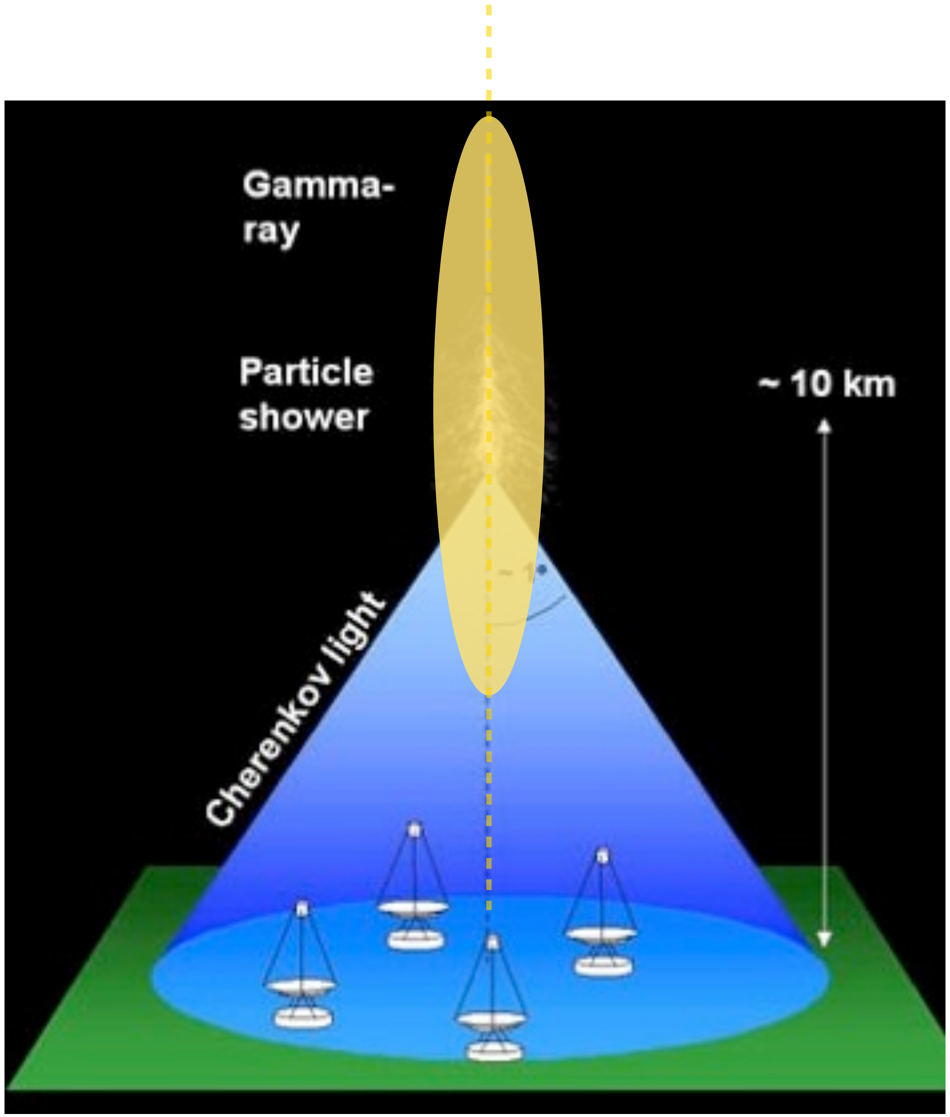
How to detect VHE gamma-rays?



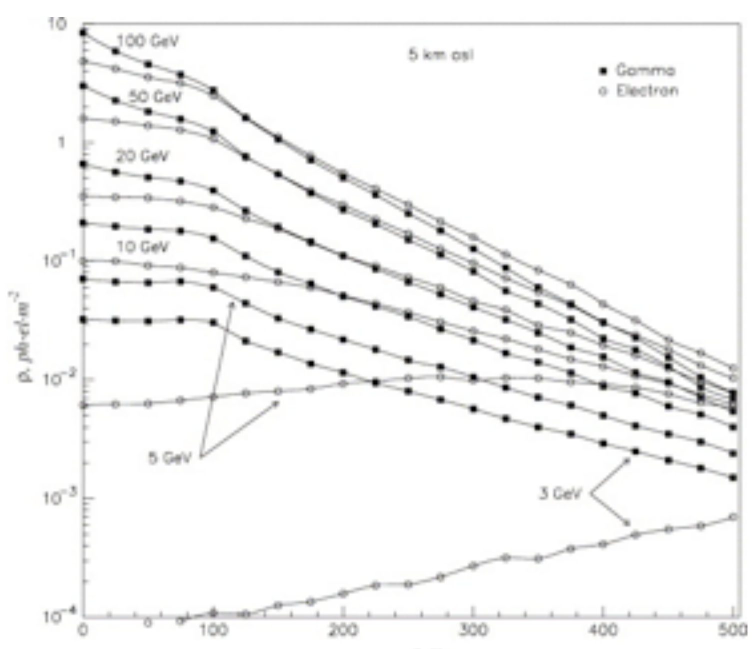


- VHE = very high energy
  E > 100 GeV / 10^{11} eV
- Earth's atmosphere: opaque
  Satellites, e.g., Fermi-LAT for HE
- Expected flux is low ...
  Typically $10^{-(11..12)}$ photons cm^{-2} s^{-1}

Ground based VHE gamma-ray detection

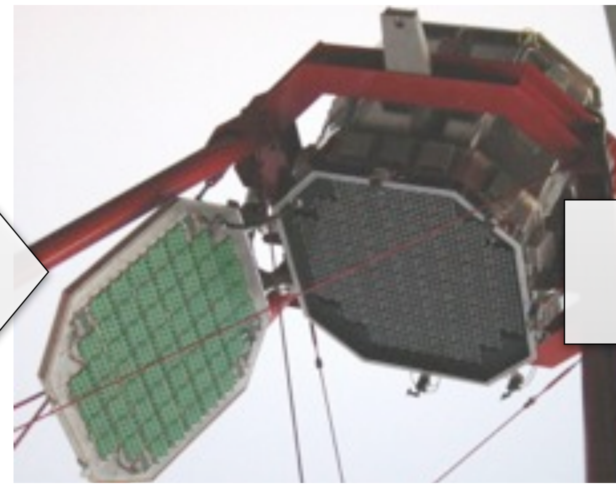


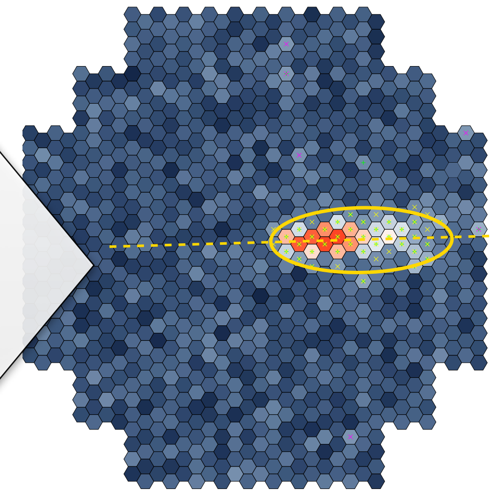
- Detection of Cherenkov light flashes from extended air-showers
- Atmosphere as part of the detector (calorimeter)
- Large collection areas ~10^{5-6} m



V. Sahakian, ,A. Akhperjanian, 2006

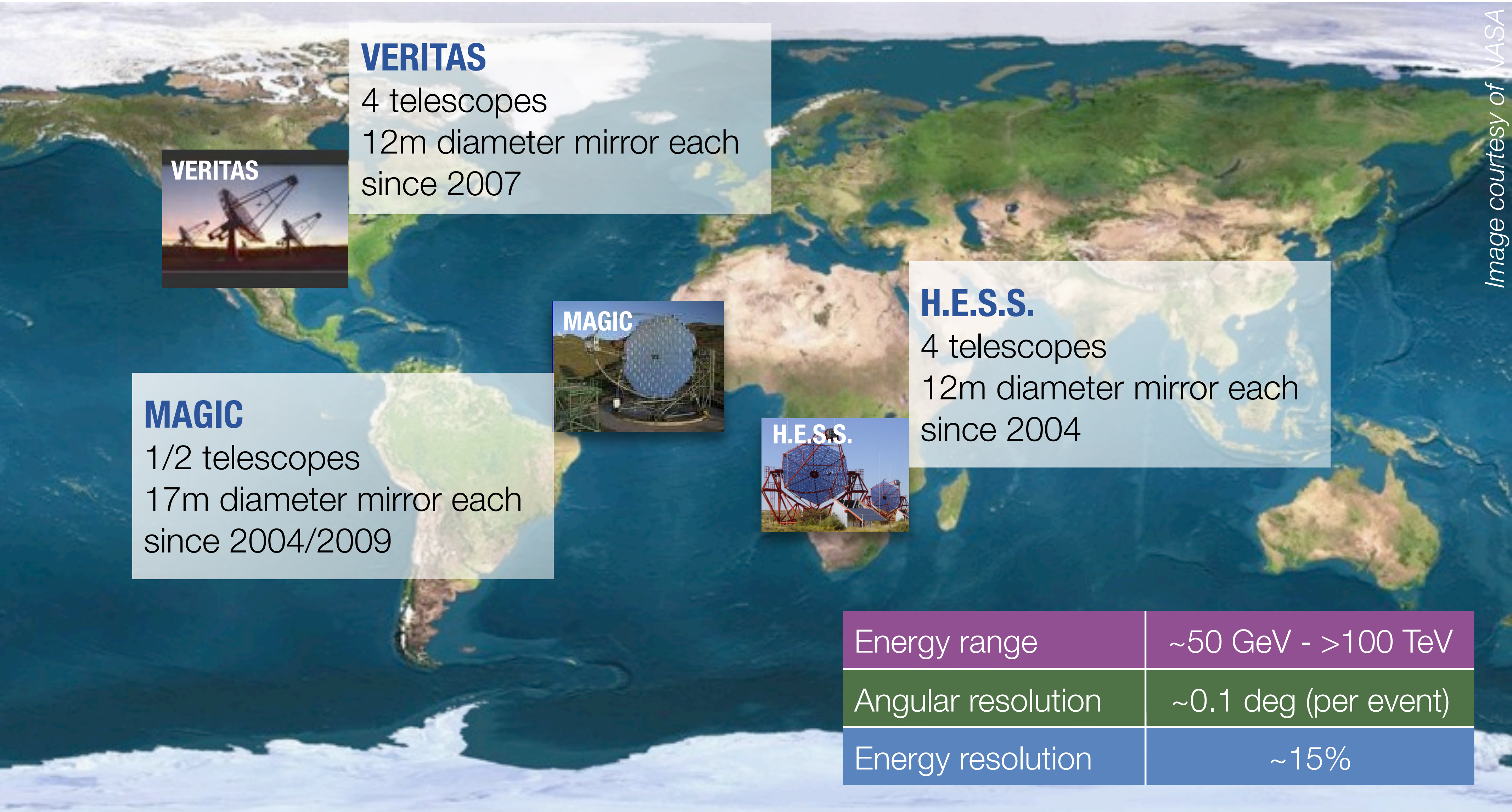
Imaging atmospheric Cherenkov telescopes (IACT)





- Shower "image" recorded with matrix of fast photon detectors (PMTs)
- Image analysis
  - Shower parameters
  - Primary particle parameters (direction, energy, particle type, ..)
- Background dominated
  - Charged cosmic rays: p, e+/-, nuclei, ...

Current major IACT installations



VERITAS
4 telescopes
12m diameter mirror each
since 2007

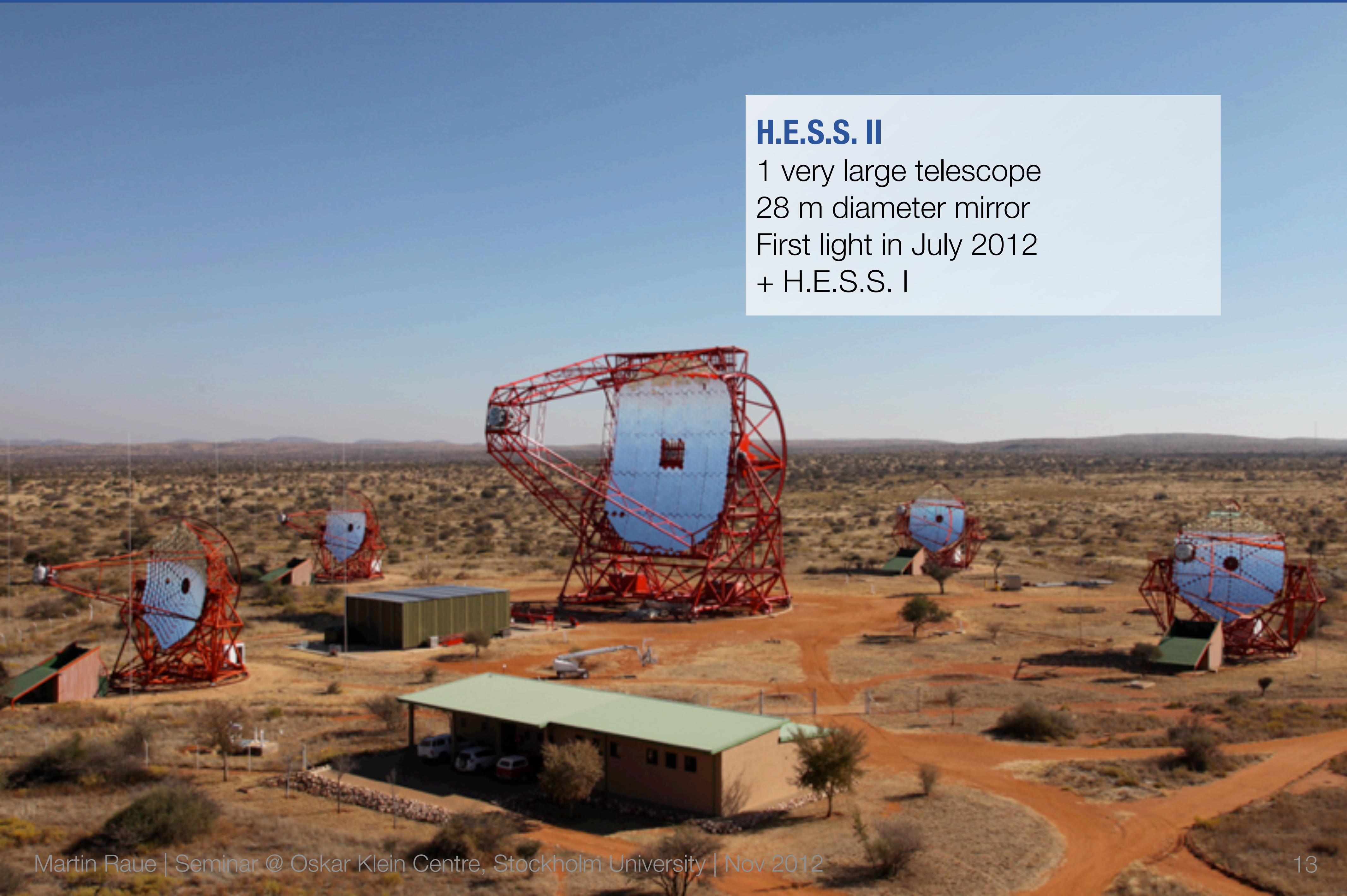
MAGIC
1/2 telescopes
17m diameter mirror each
since 2004/2009

H.E.S.S.
4 telescopes
12m diameter mirror each
since 2004

Energy range	~50 GeV - >100 TeV
Angular resolution	~0.1 deg (per event)
Energy resolution	~15%

Image courtesy of NASA

H.E.S.S. II



H.E.S.S. II

1 very large telescope

28 m diameter mirror

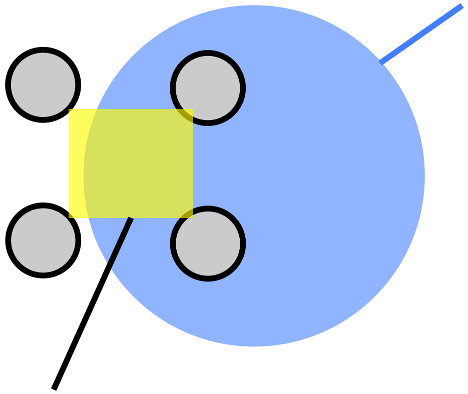
First light in July 2012

+ H.E.S.S. I

The future: CTA

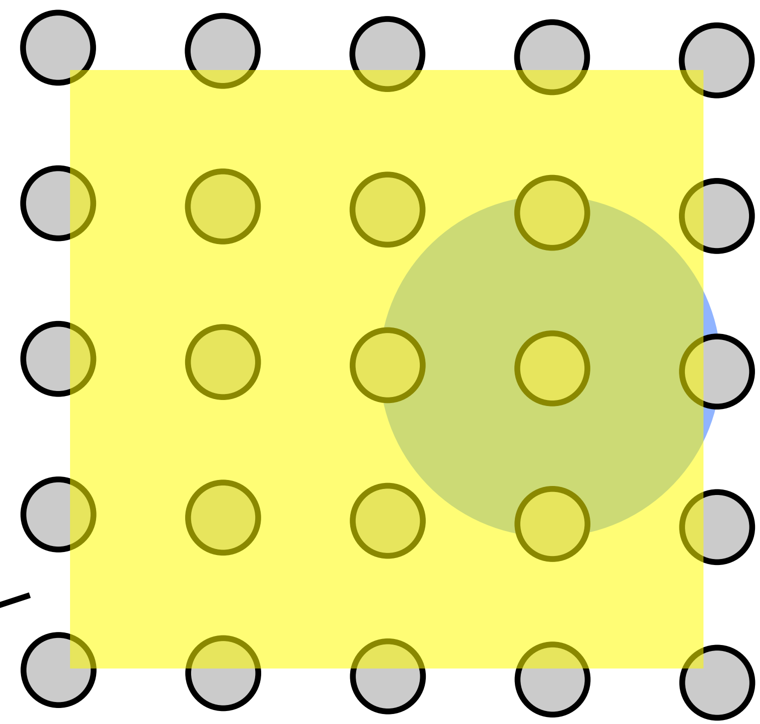
Performance limitations for IACTs

following W. Hofmann @ Gamma 2012



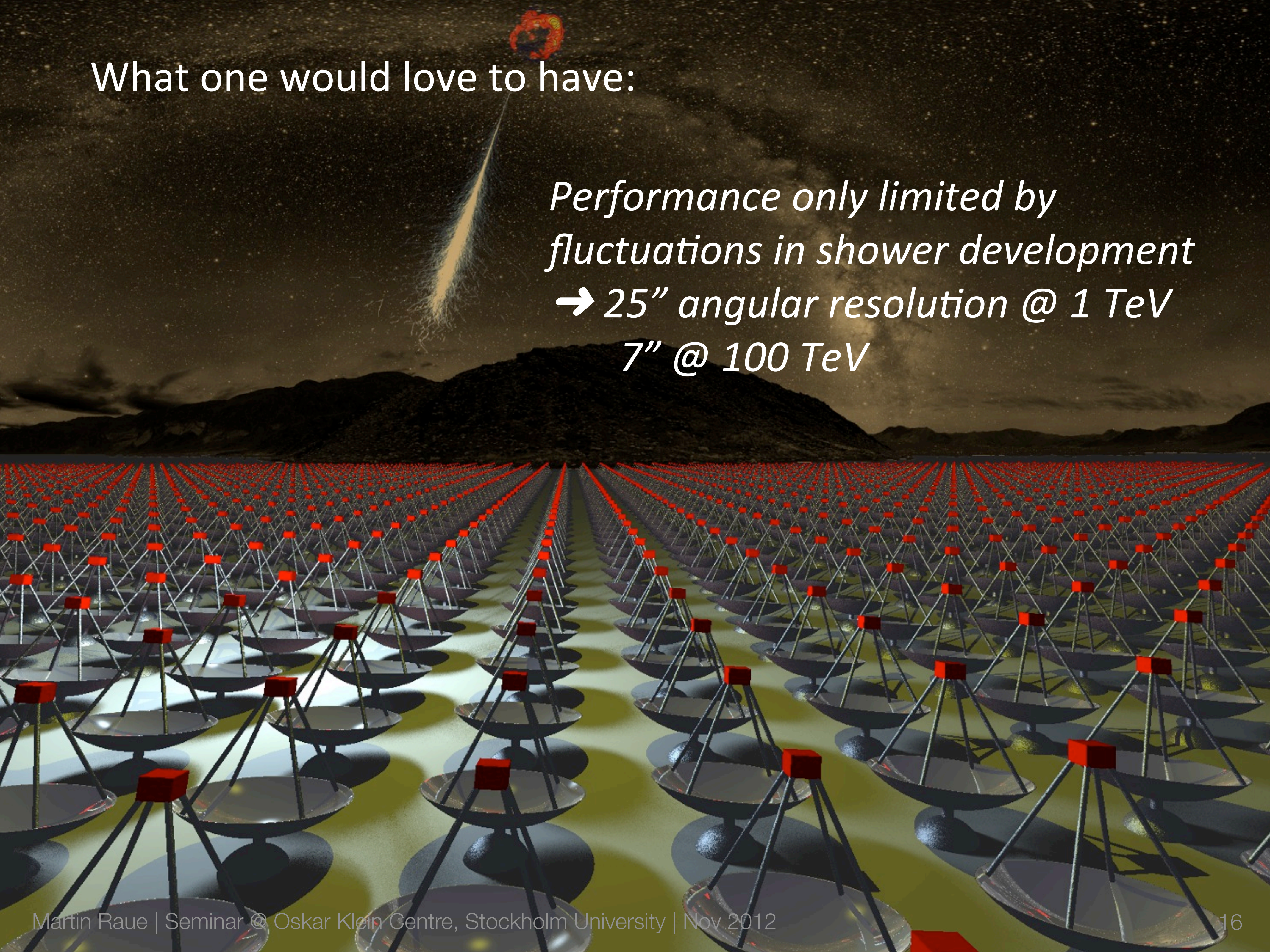
light pool radius
R ≈100-150 m
≈ typical telescope spacing

Sweet spot for
best triggering
and reconstruction:
most showers miss it!



large detection area
more images per shower
lower trigger threshold

What one would love to have:



Performance only limited by fluctuations in shower development
➜ 25” angular resolution @ 1 TeV
7” @ 100 TeV

What one can (hopefully) afford:

(one) possible configuration

Southern 100 M€ Array (2006 costs)

Low-energy section:
4 x 23 m tel. (LST)
- Parabolic reflector
- FOV: 4-5 degrees

energy threshold of some 10 GeV

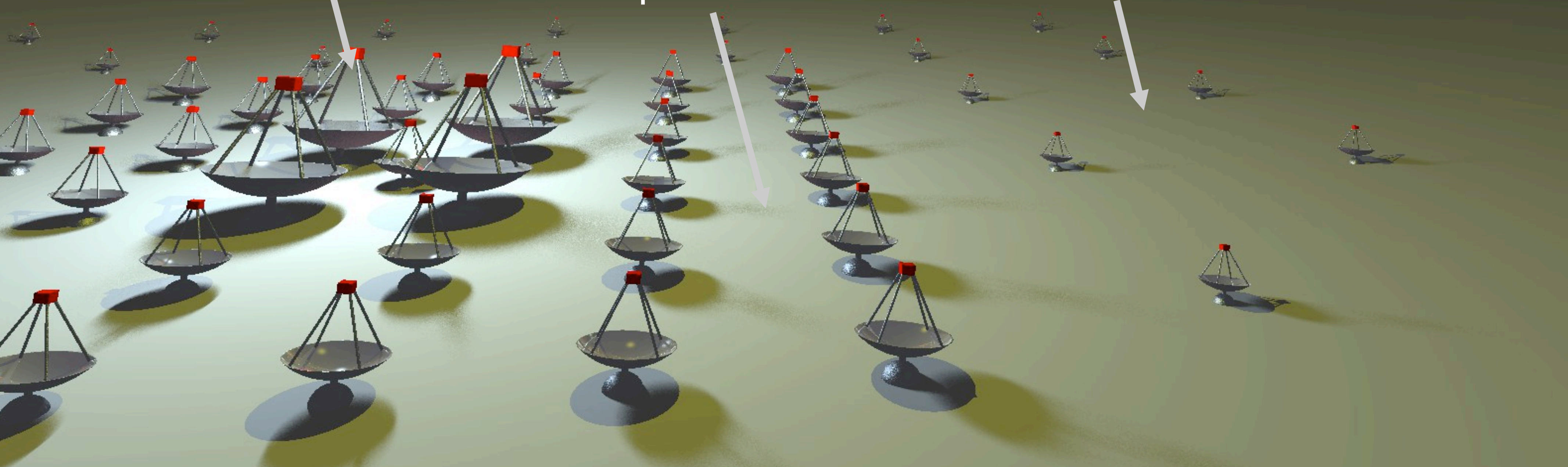
Core-energy array:
23 x 12 m tel. (MST)
Davies-Cotton reflector
- FOV: 7-8 degrees

mCrab sensitivity in the 100 GeV–10 TeV domain

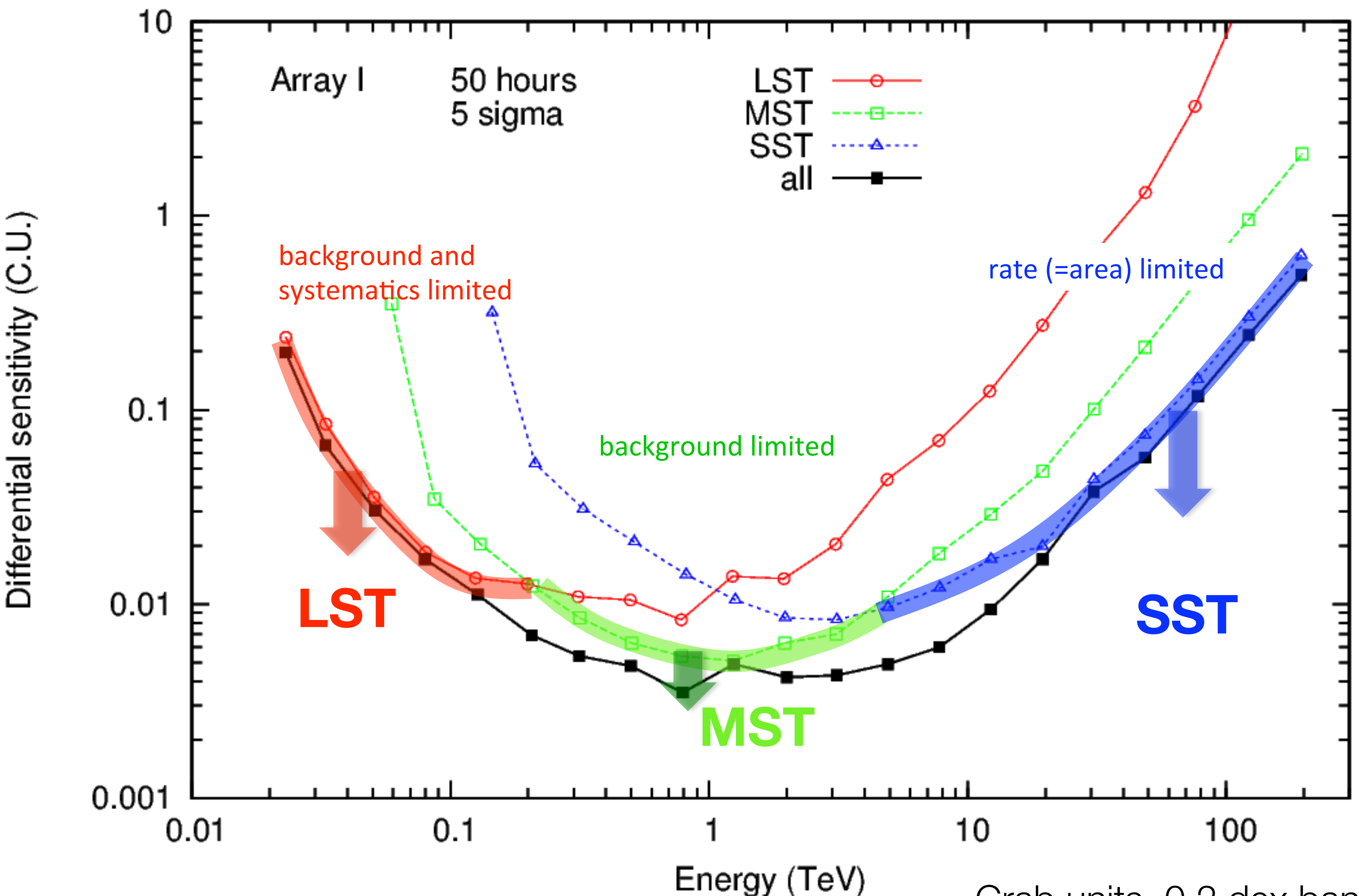
Core array expansion
with dual-mirror telescopes

High-energy section:
30-70 x 4-6 m tel. (SST)
Davies-Cotton reflector
(or Schwarzschild-Couder)
- FOV: ~10 degrees

10 km^2 area at multi-TeV energies

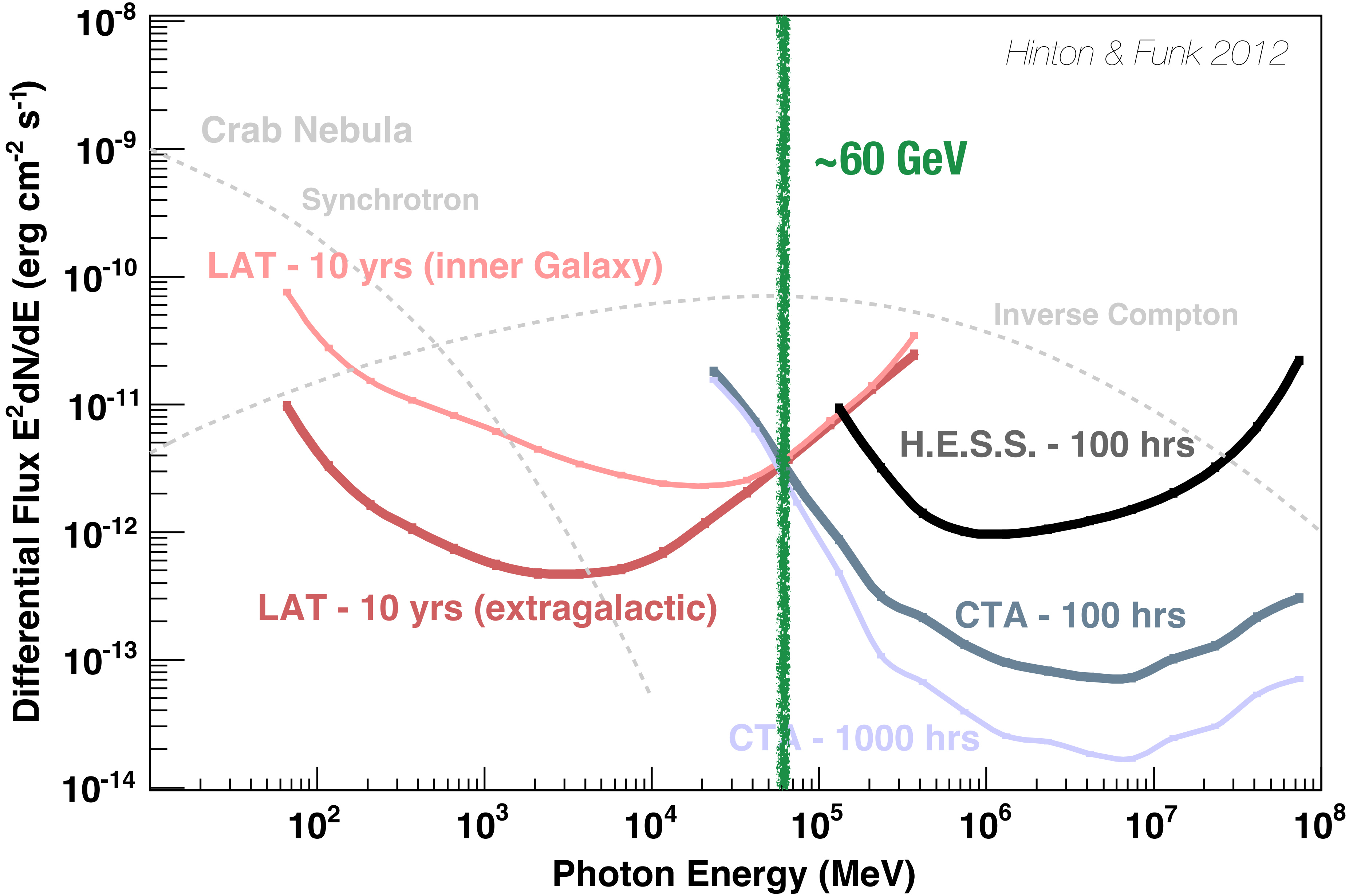


CTA differential sensitivity

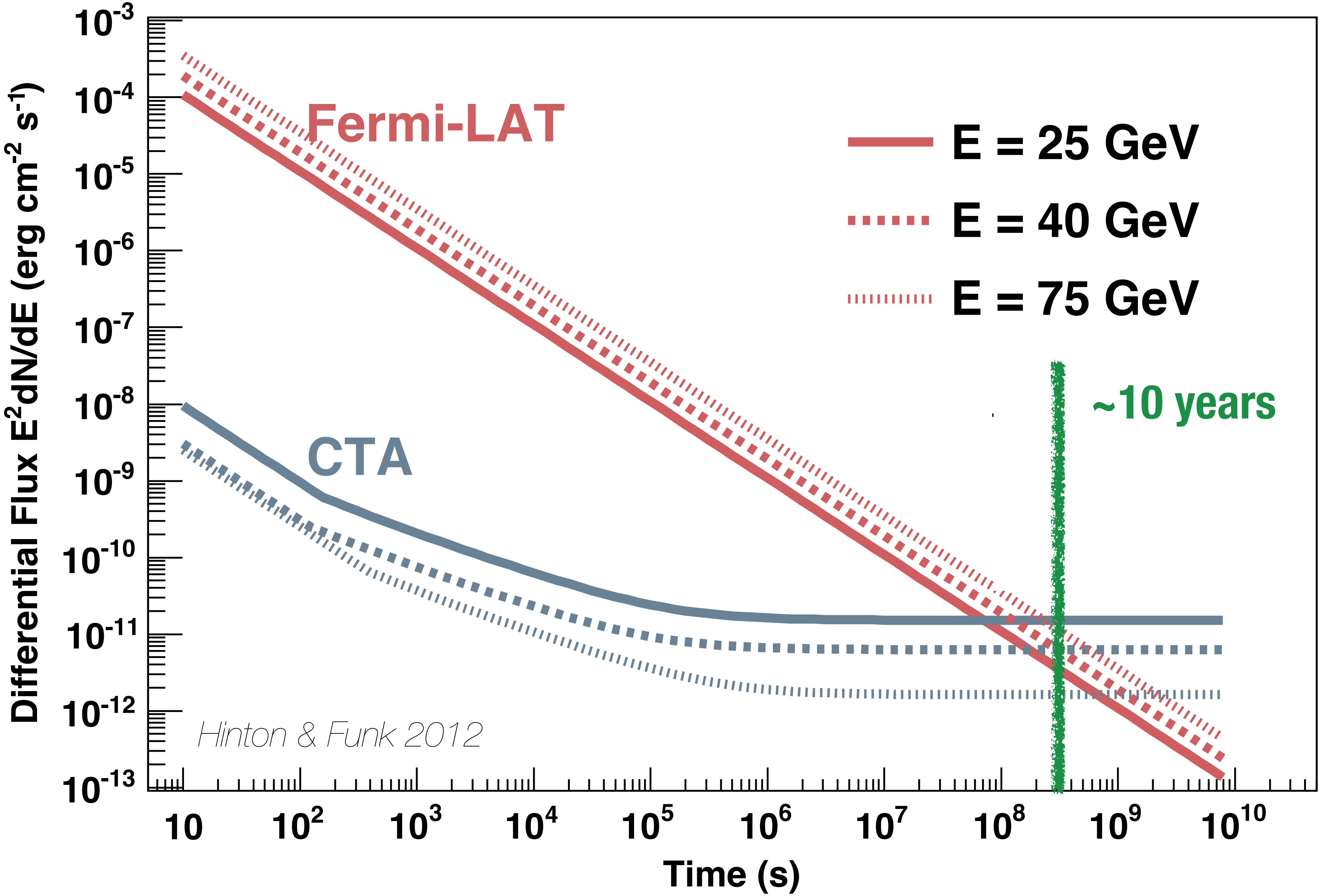


- Crab units, 0.2 dex bands

CTA sensitivity: steady sources



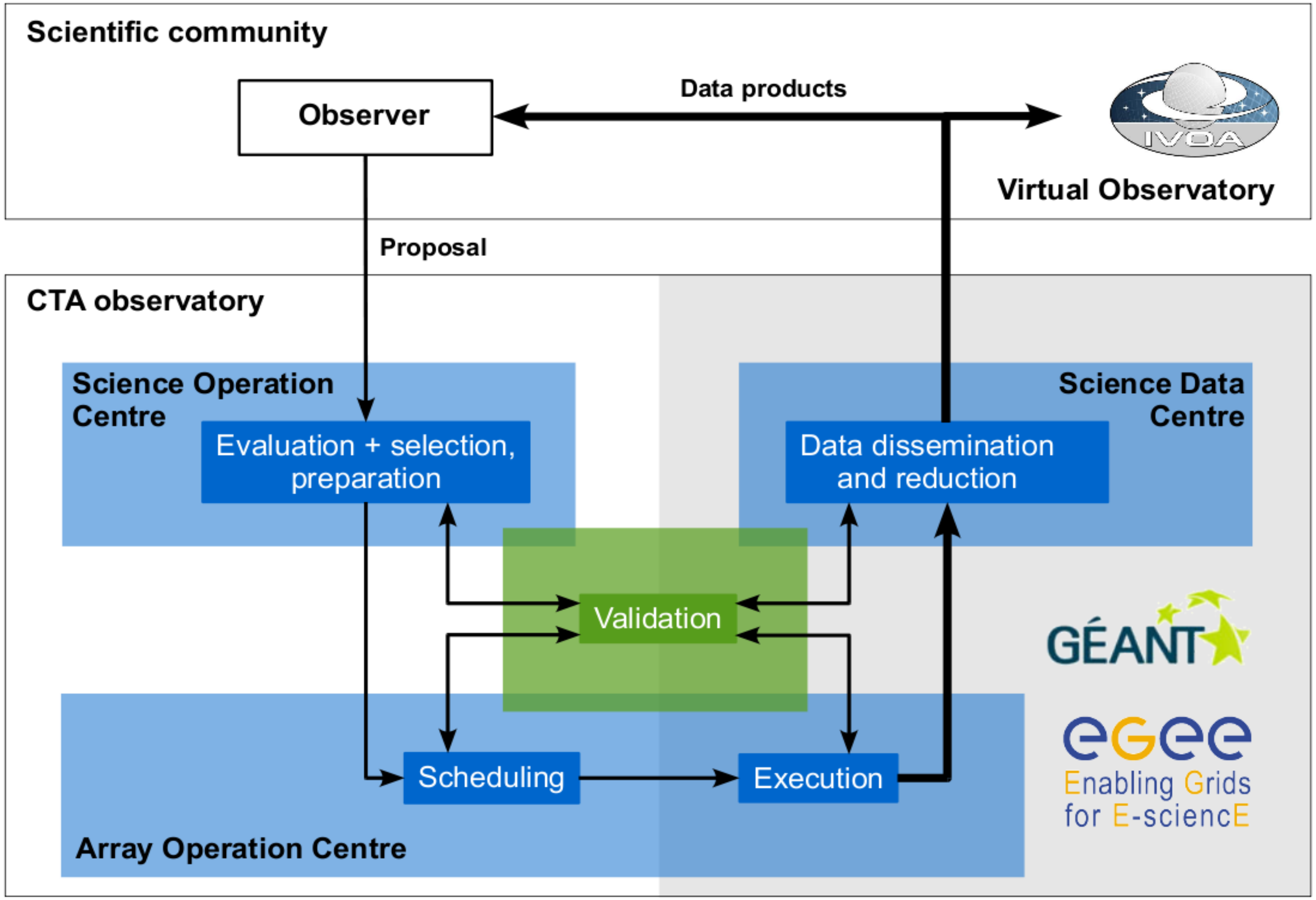
CTA sensitivity: variable sources



CTA: open observatory

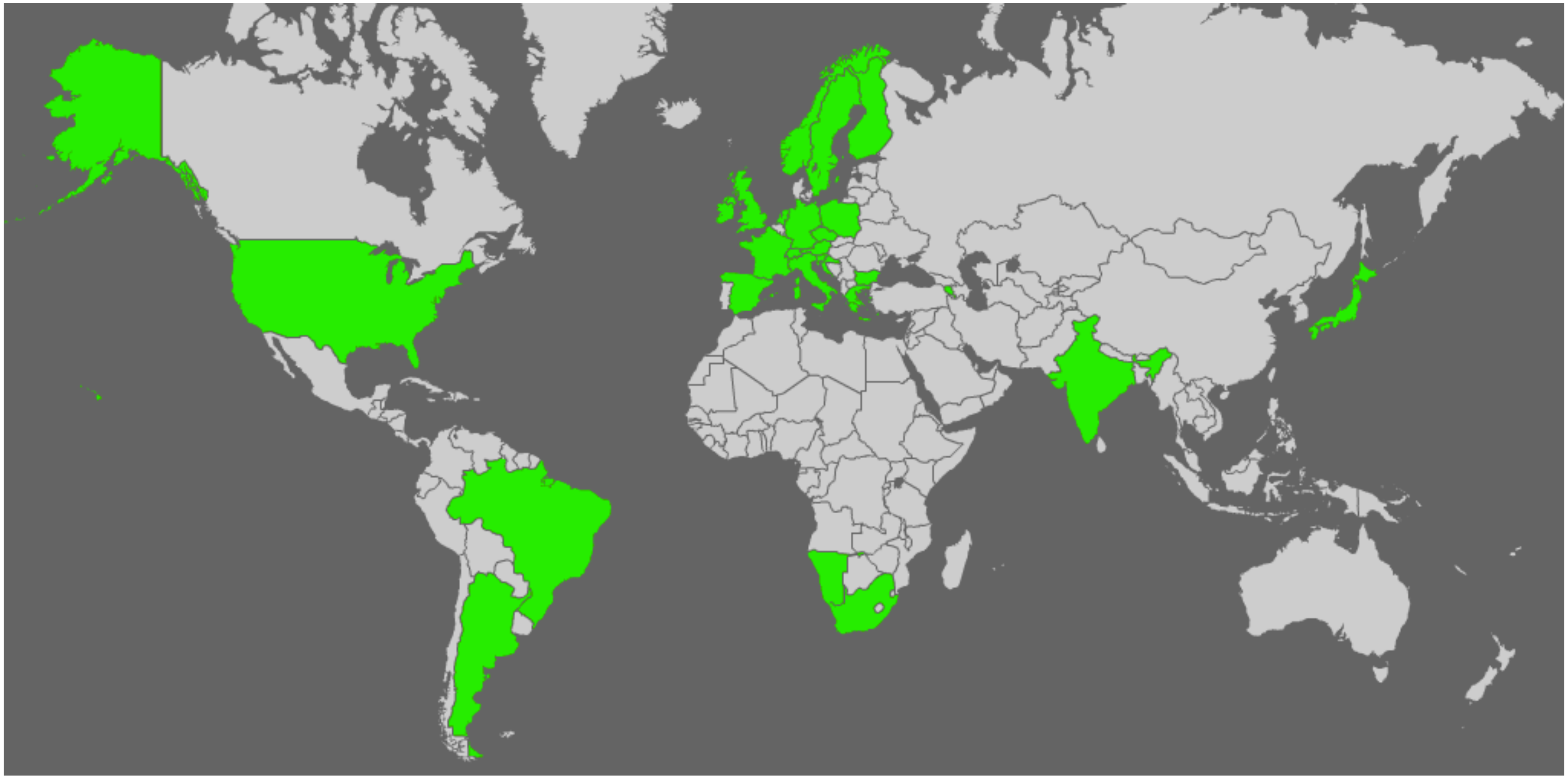
CTA

- First open observatory in the VHE domain
- Large number of users from different fields of science



CTA collaboration

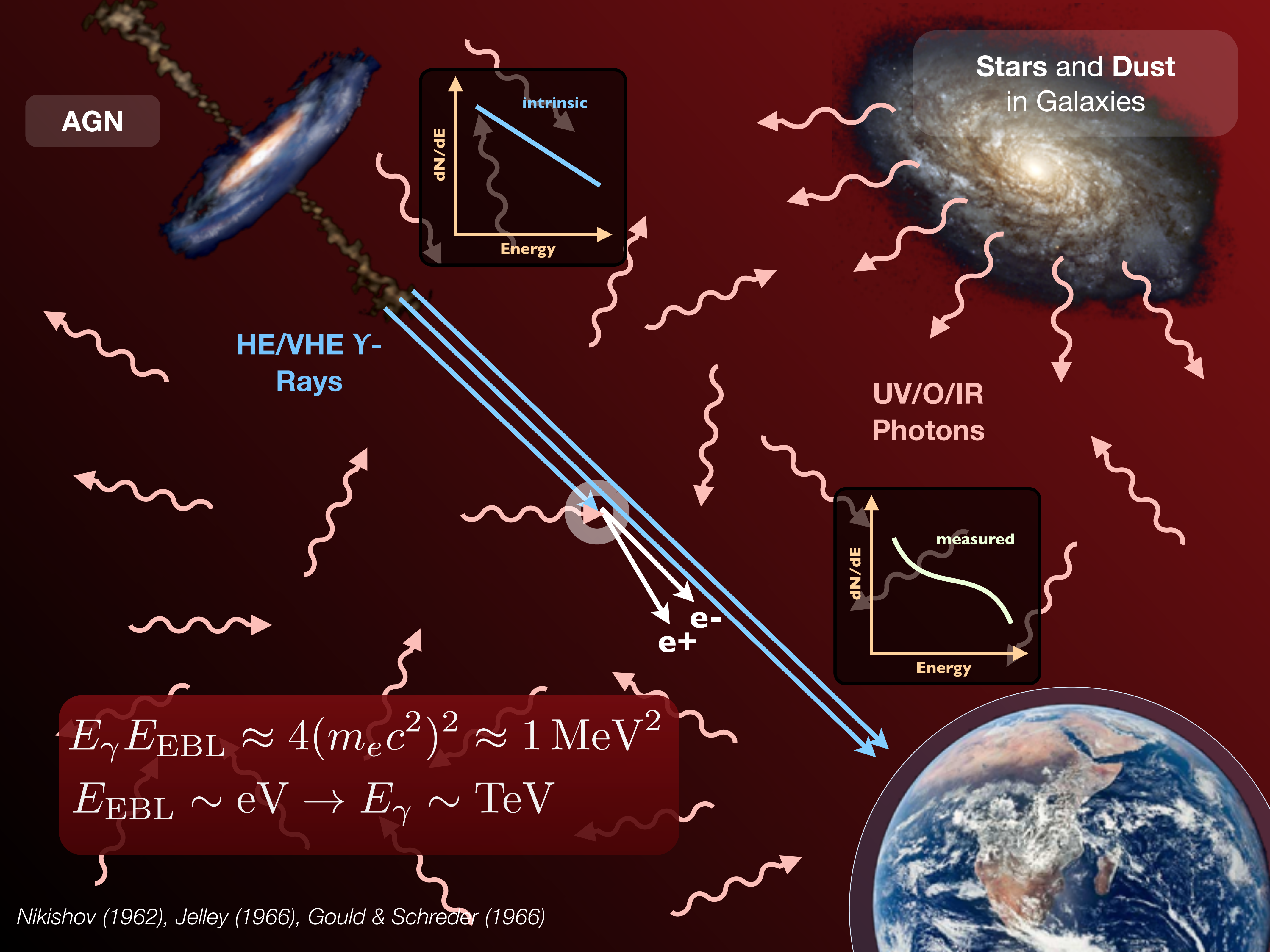
Over 1000 members from 163 institutions in 26 countries.



Argentina, Armenia, Austria, Brazil, Bulgaria, Czech Republic, Croatia, Finland, France, Germany, Greece, India, Italy, Ireland, Japan, Namibia, Netherlands, Norway, Poland, Slovenia, Spain, South Africa, Sweden, Switzerland, UK, USA

CTA: recommended by relevant roadmaps

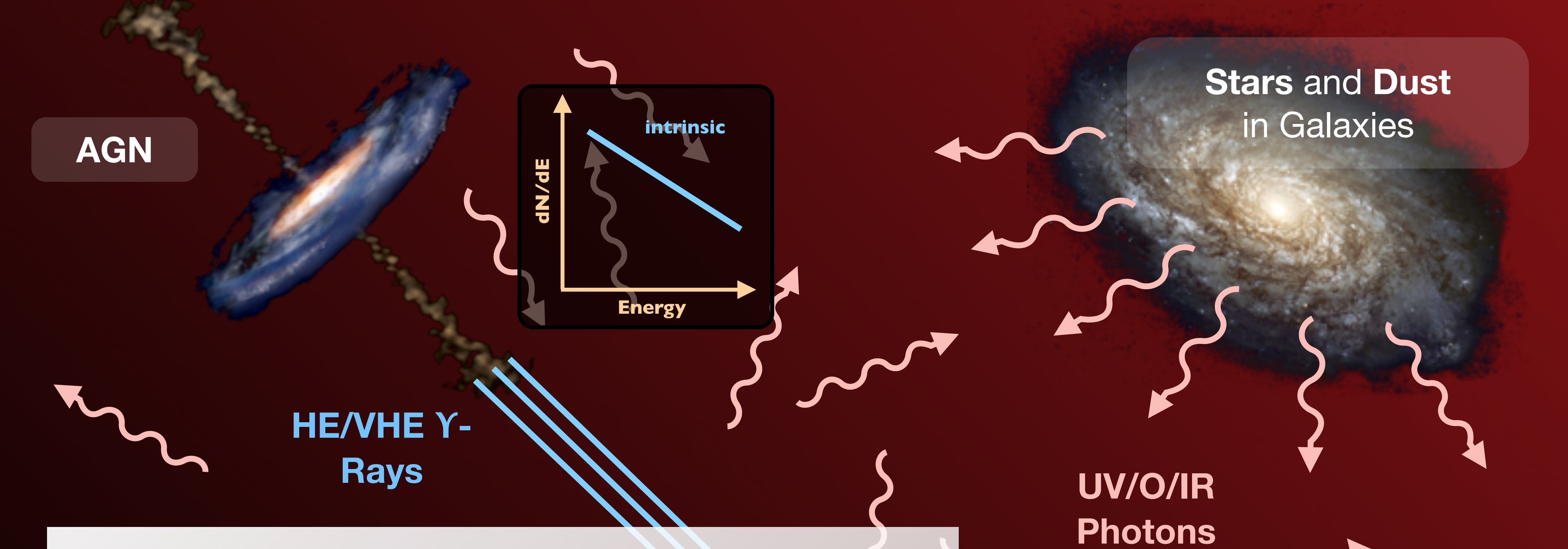
Cosmology through VHE gamma-ray observations



$$E_\gamma E_{\rm EBL} \approx 4(m_e c^2)^2 \approx 1\,{\rm MeV}^2$$

$$E_{\rm EBL} \sim {\rm eV} \rightarrow E_\gamma \sim {\rm TeV}$$

Nikishov (1962), Jelley (1966), Gould & Schreder (1966)

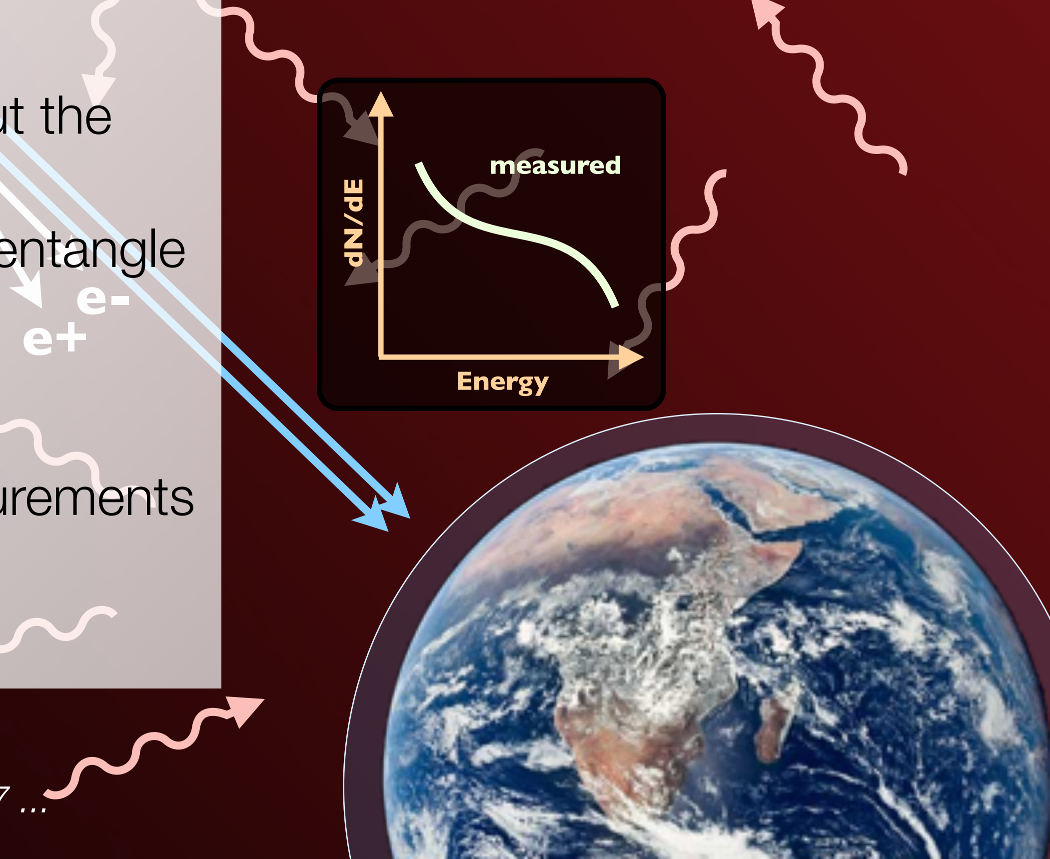


Constrain the EBL density

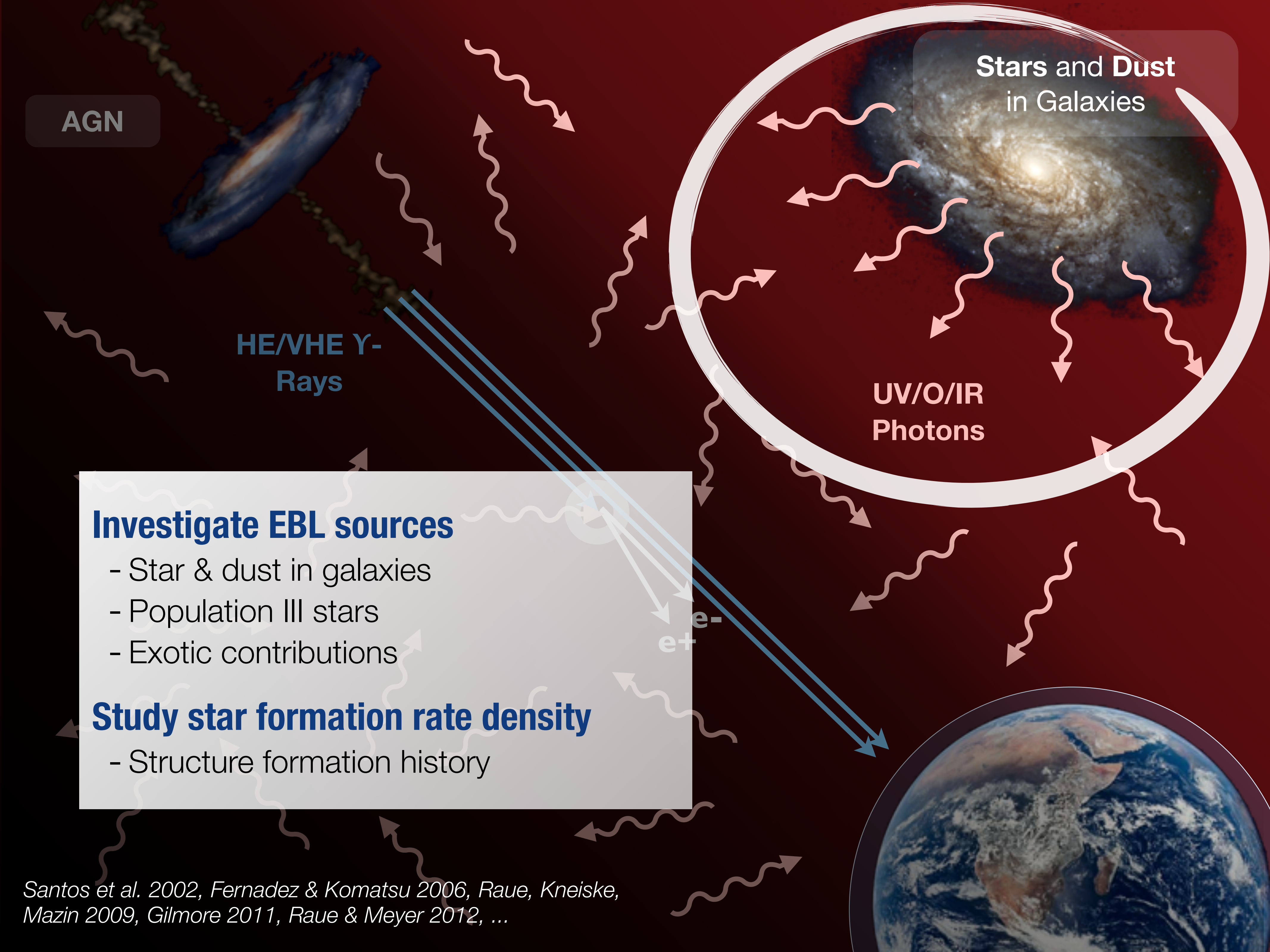
- Measured spectrum + assumptions about the intrinsic spectrum
- Many sources at different redshifts to disentangle EBL and intr. spectrum

Unique information

- Strong foregrounds hamper direct measurements
- Redshift resolved
- True integrated measurement



Stecker, de Jager 1992, Aharonian et al 2006, Mazin & Raue 2007 ...



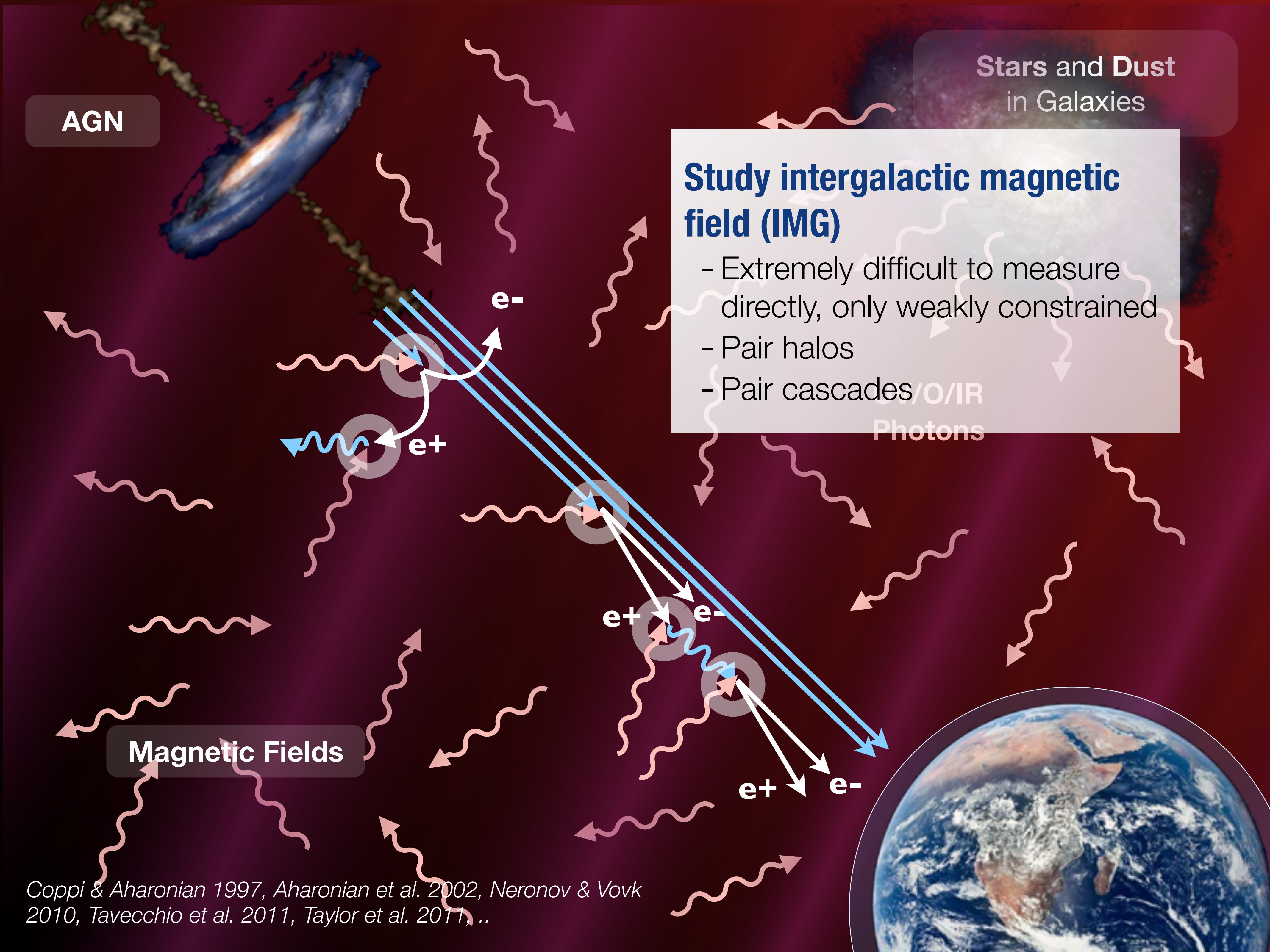
Investigate EBL sources

- Star & dust in galaxies
- Population III stars
- Exotic contributions

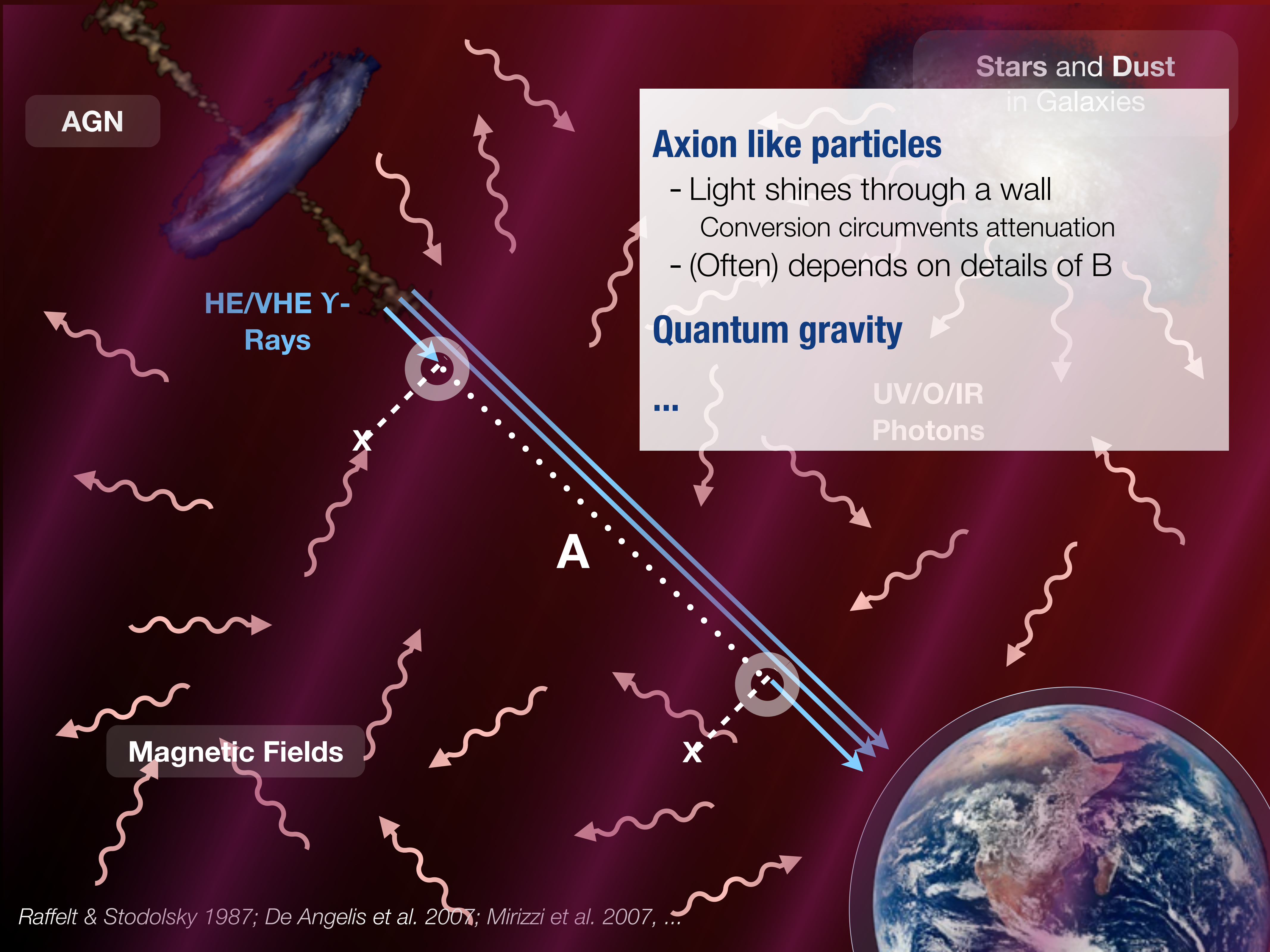
Study star formation rate density

- Structure formation history

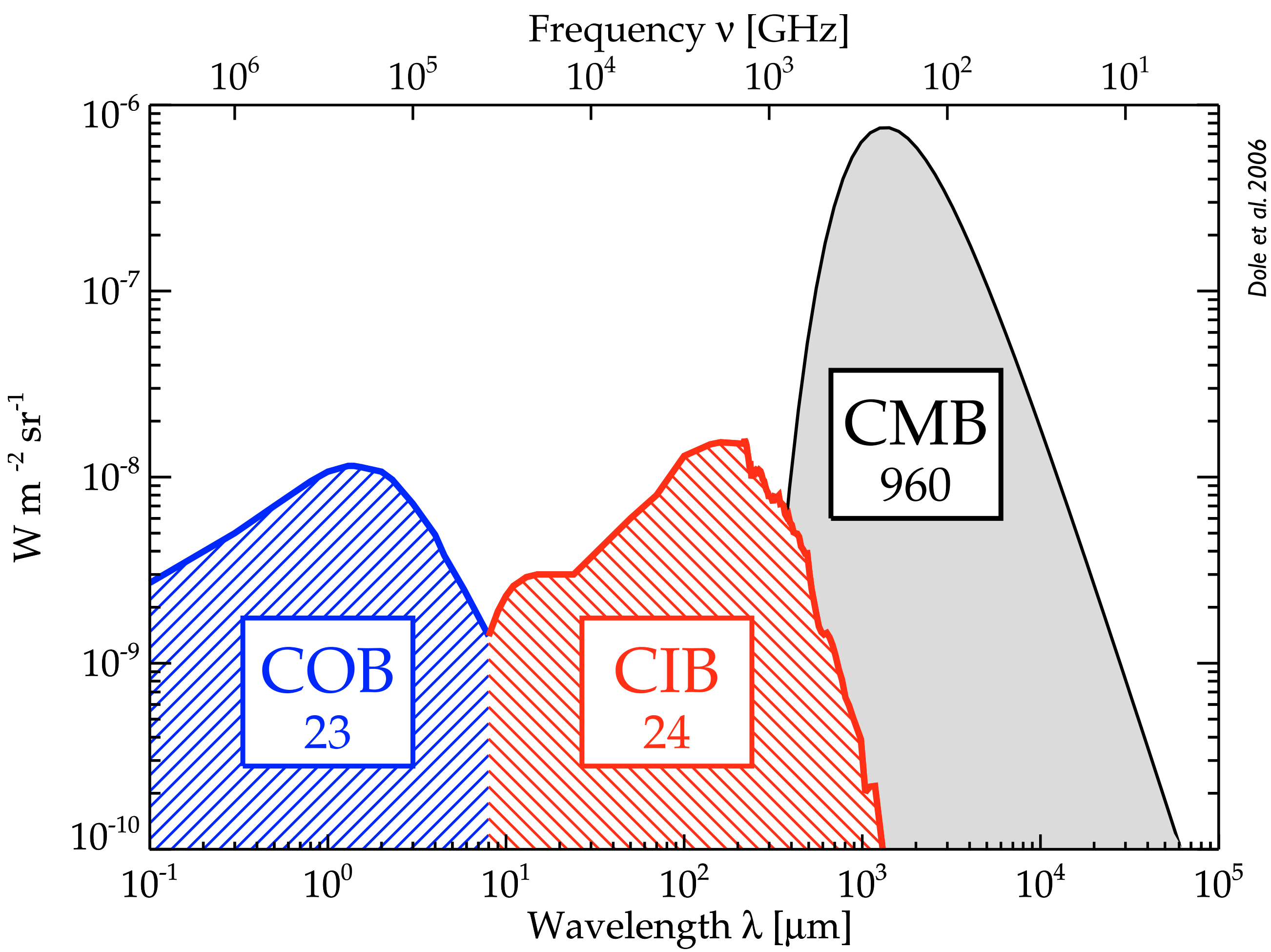
Santos et al. 2002, Fernadez & Komatsu 2006, Raue, Kneiske, Mazin 2009, Gilmore 2011, Raue & Meyer 2012, ...



AGN
Stars and Dust
in Galaxies
Study intergalactic magnetic field (IMG)
- Extremely difficult to measure directly, only weakly constrained
- Pair halos
- Pair cascades
/O/IR
Photons
e-
e+
e+
e-
e+
e-
Magnetic Fields
Coppi & Aharonian 1997, Aharonian et al. 2002, Neronov & Vovk 2010, Tavecchio et al. 2011, Taylor et al. 2011, ..


AGN
Stars and Dust
in Galaxies
Axion like particles
- Light shines through a wall
Conversion circumvents attenuation
- (Often) depends on details of B
Quantum gravity
...
UV/O/IR
Photons
HE/VHE γ-
Rays
x
A
x
Magnetic Fields
Raffelt & Stodolsky 1987; De Angelis et al. 2007; Mirizzi et al. 2007, ...

Extragalactic Background Light (EBL)



"Redshifted integrated thermal emission history of the universe."

UV, O, NIR

- Stellar emission

MIR, FIR

- Stellar light re-emitted by dust
- Starburst
- AGN

Case study: SFRD vs EBL

How to connect stellar formation with the EBL?

$$P_\nu(z) = \nu I_\nu(z) = \nu \frac{c}{4\pi} \int_z^{z_m} \mathcal{E}_{\nu'}(z') \left| \frac{dt'}{dz'} \right| dz'$$

EBL

$$\mathcal{E}_\nu(z) = \int_z^{z_m} L_\nu(t(z) - t(z'))\dot{\rho}_*(z') \left| \frac{dt'}{dz'} \right| dz'$$

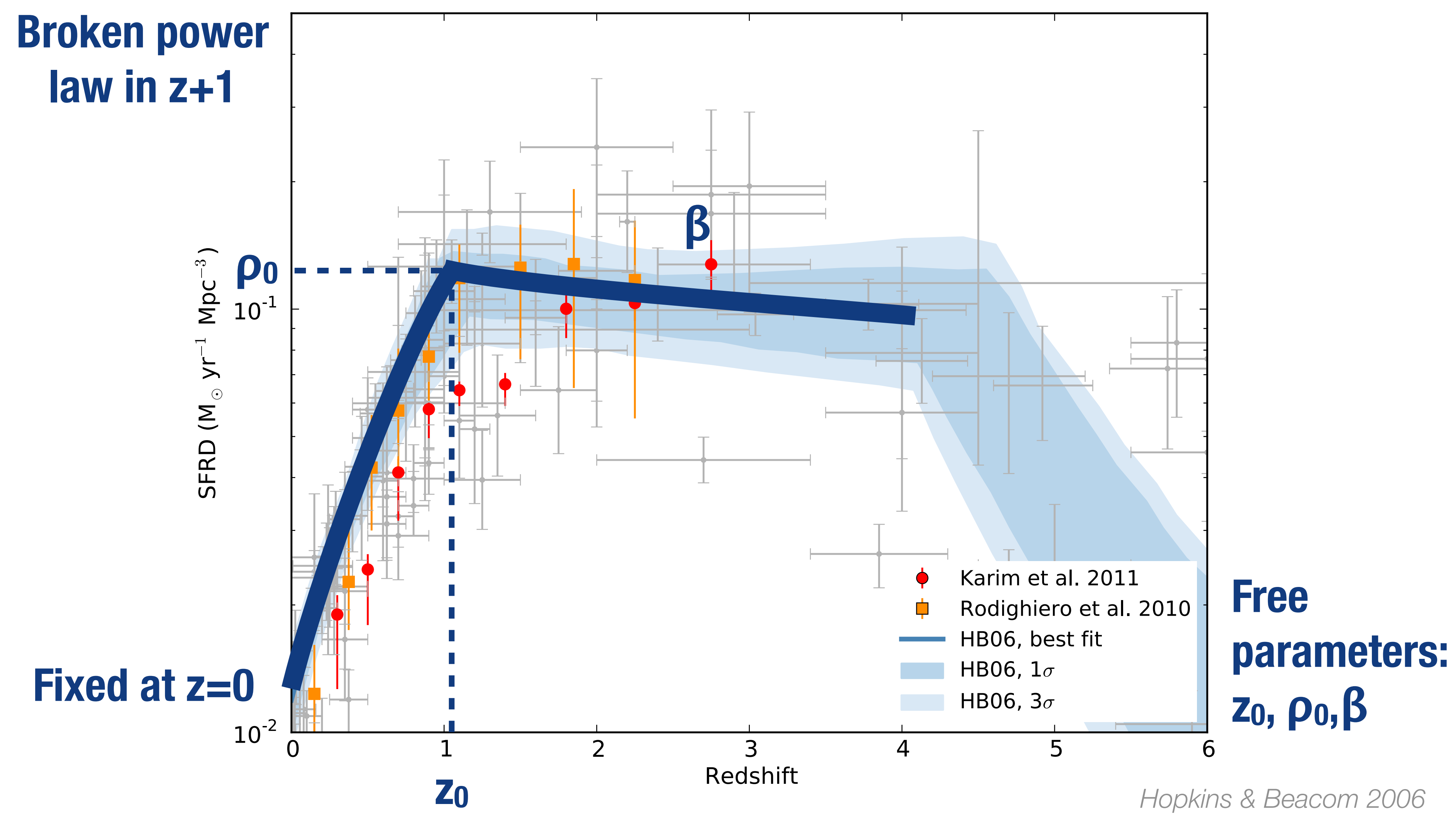
Emissivity

Stellar population spectra (SPS)

Star formation rate density (SFRD)

e.g. Dwek et al. 1998, Kneiske, Mannheim, Hartmann 2002

Star formation rate density (SFRD)



Hopkins & Beacom 2006

Stellar population emission models

Emission from an evolving stellar population

Parameters

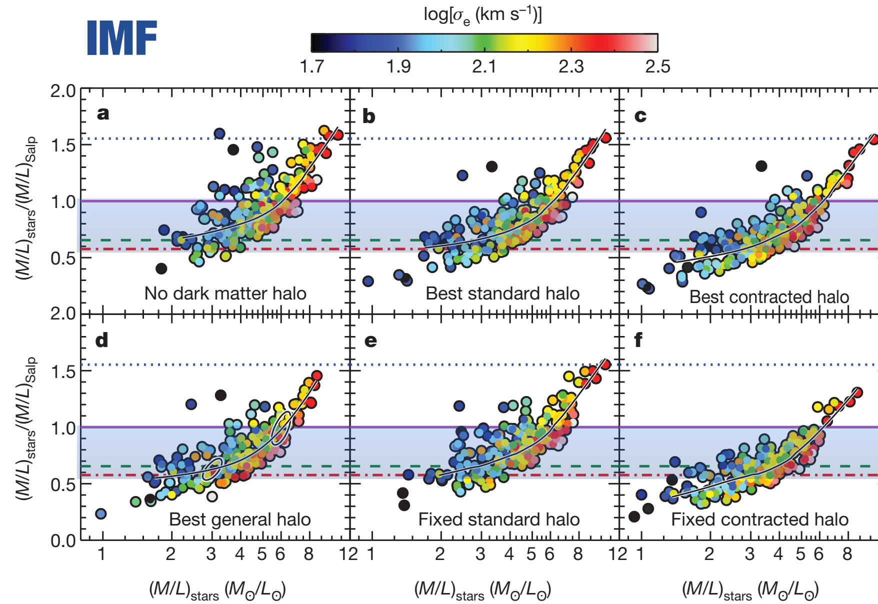
- Initial mass function (IMF)
  Chabrier, Salpeter
- Metallicity (Z)
  $2 \times Z_\odot$ - $5 \times 10^{-3} \times Z_\odot$
- Dust absorption & reemission
  Using IR SED from Chary & Elbaz 2001

Fiducial model

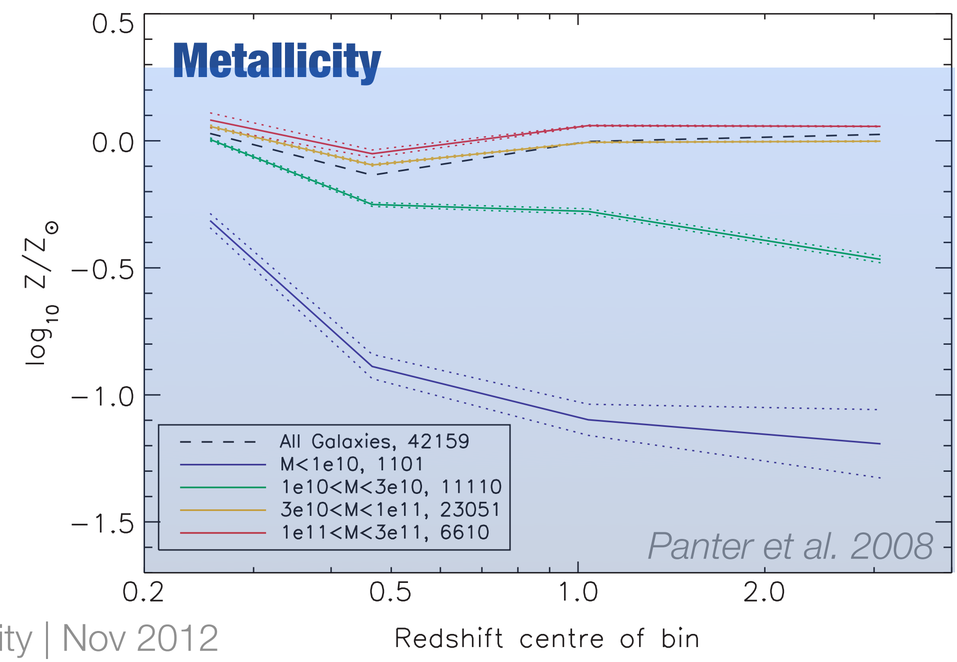
- Chabrier IMF
- $Z_\odot$
- Minimal dust abs./em. model matched to EBL UL limit
- SFRD: β=0.3

} conservative

IMF

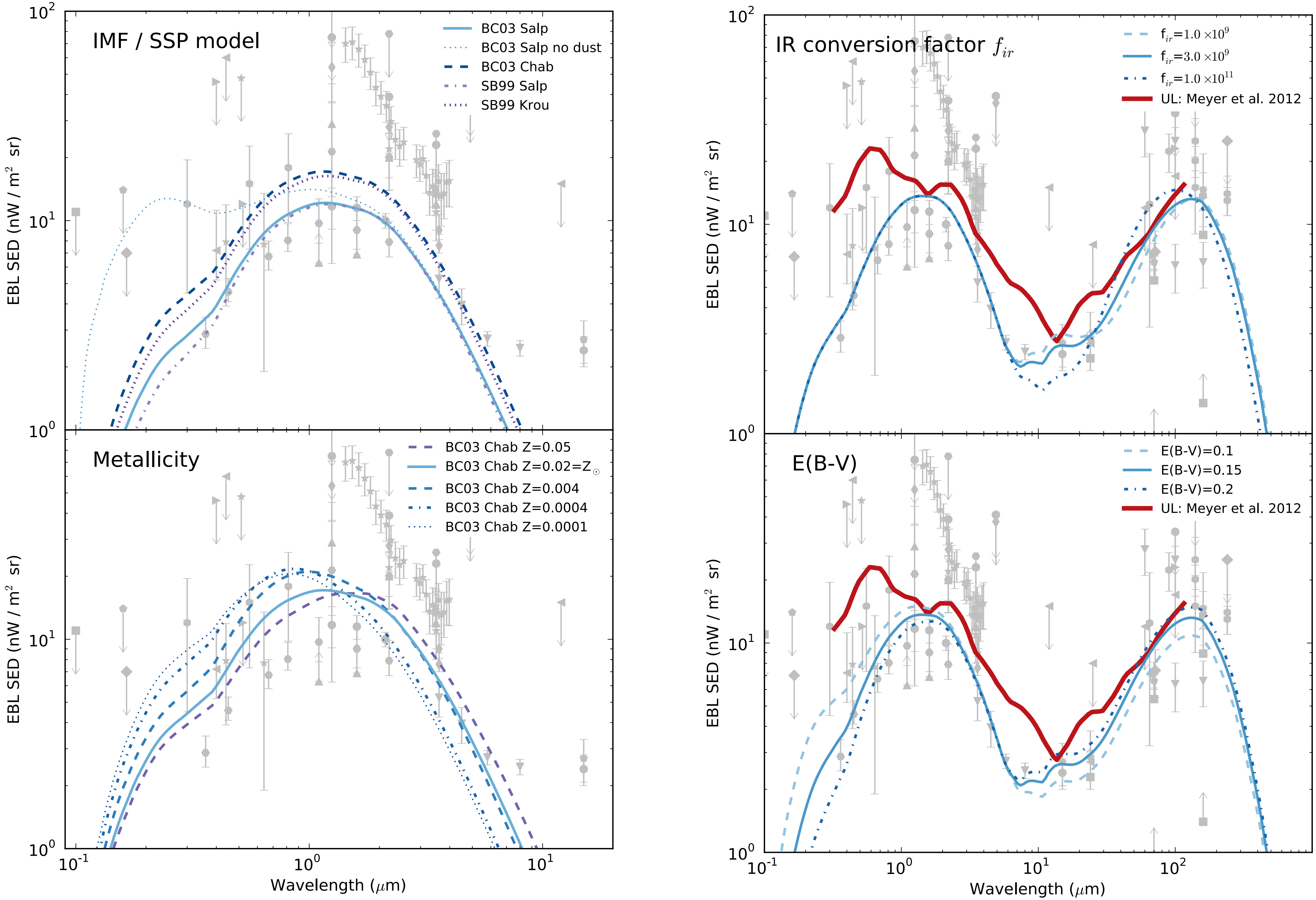


Cappellari et al. 2012

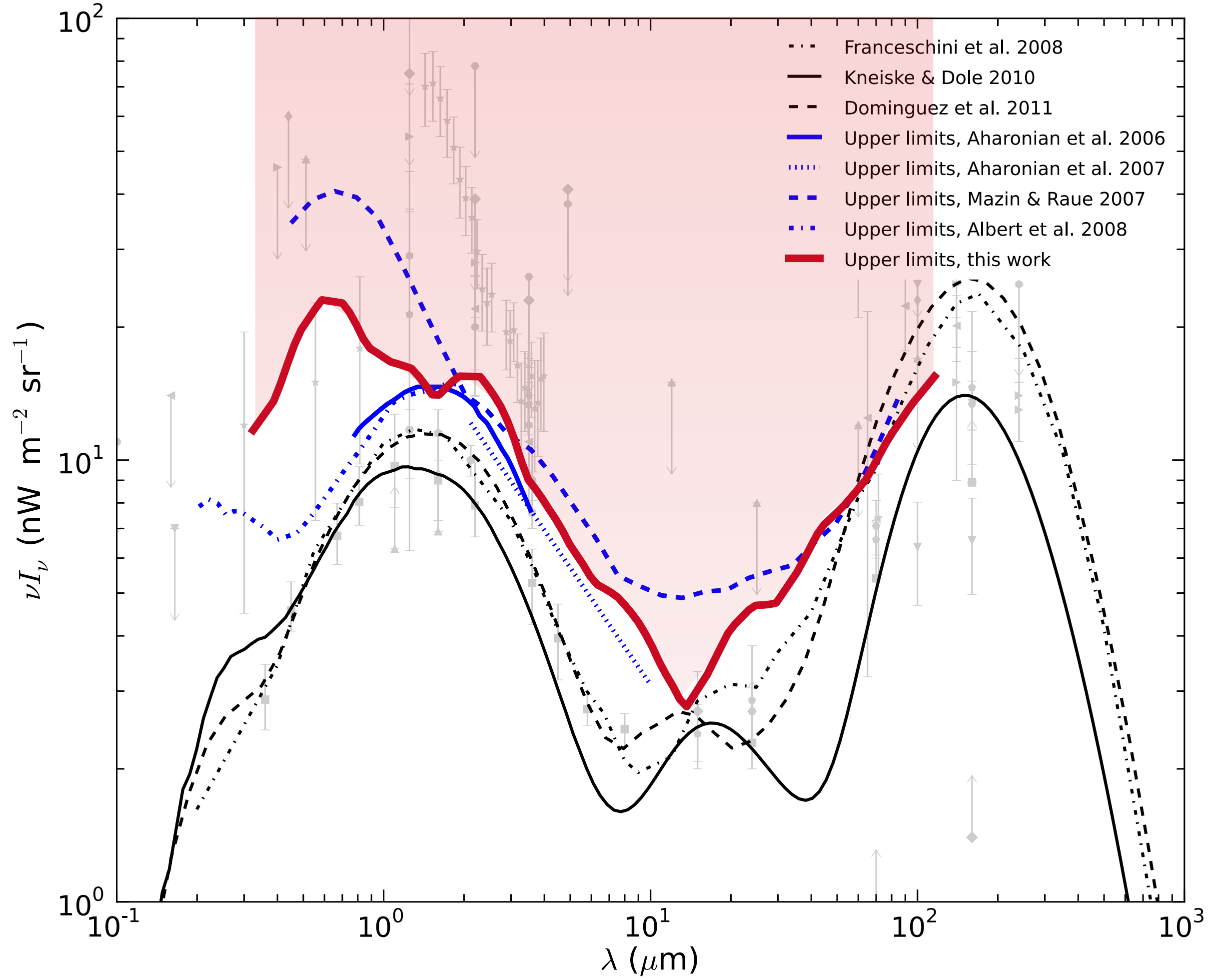


Panter et al. 2008

Resulting EBL: examples



Compare to EBL limits at z=0

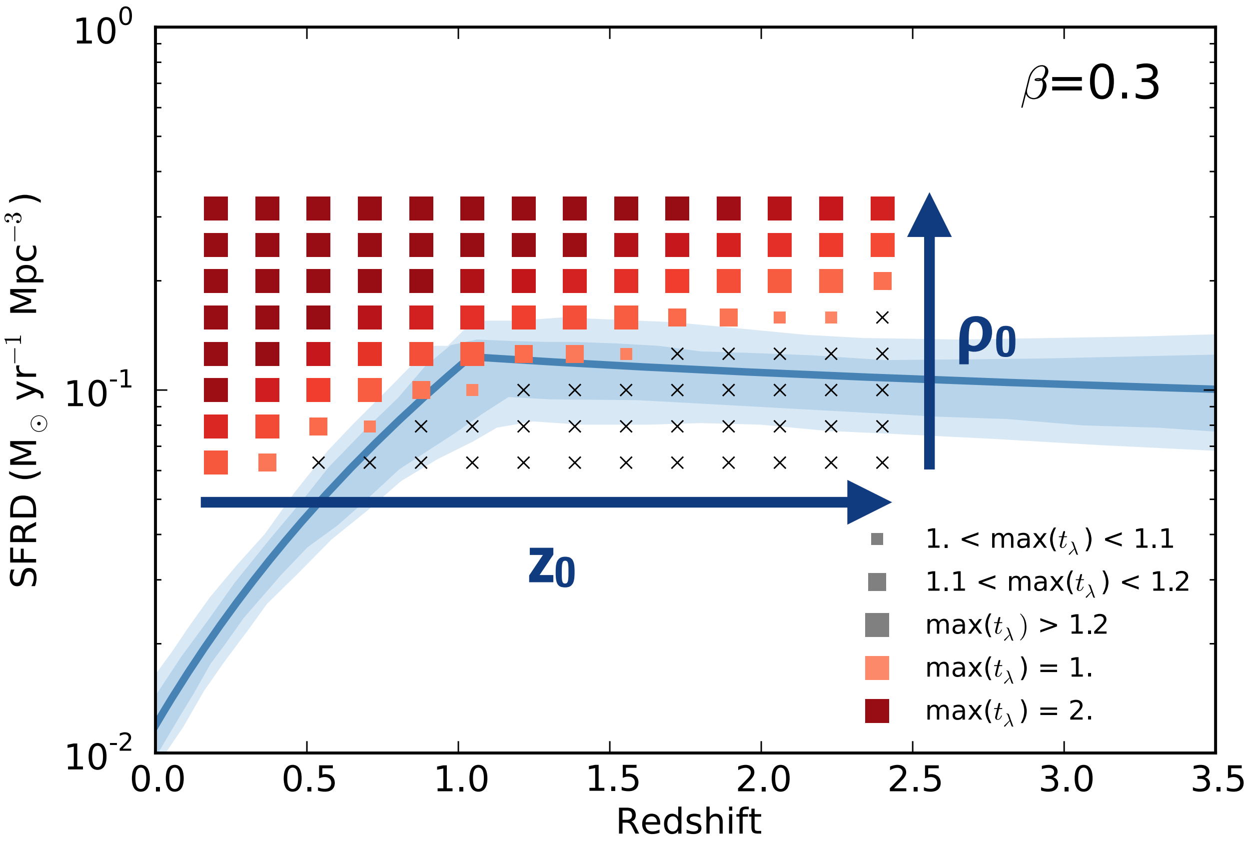


EBL limits

- Meyer, Raue, Mazin, Horns 2012, A&A 542
- Fermi-LAT + VHE
- Wide wavelength range
  - UV to FIR
- Close to lower limits from integrated galaxy counts

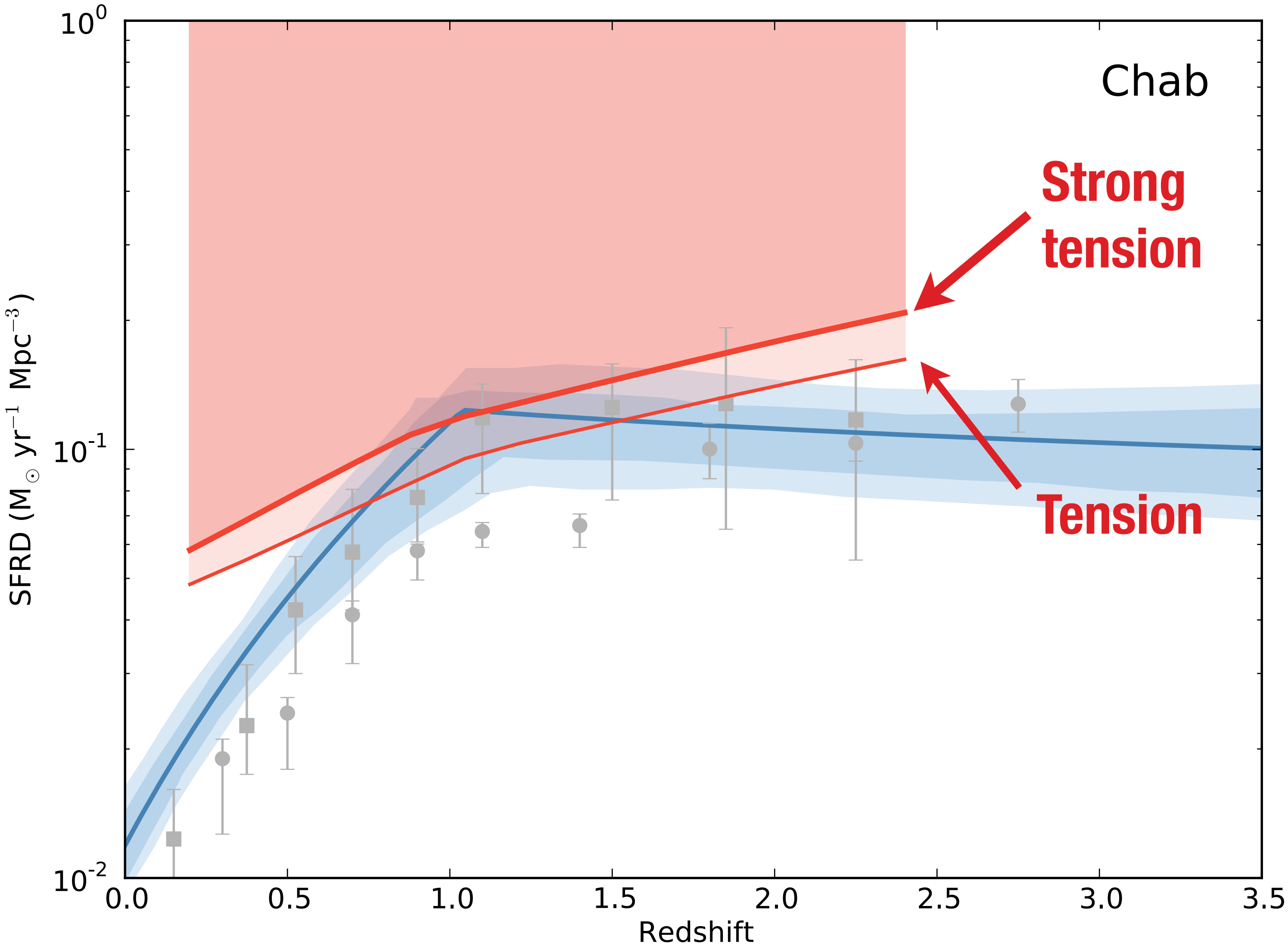
Raue & Meyer 2012

Method

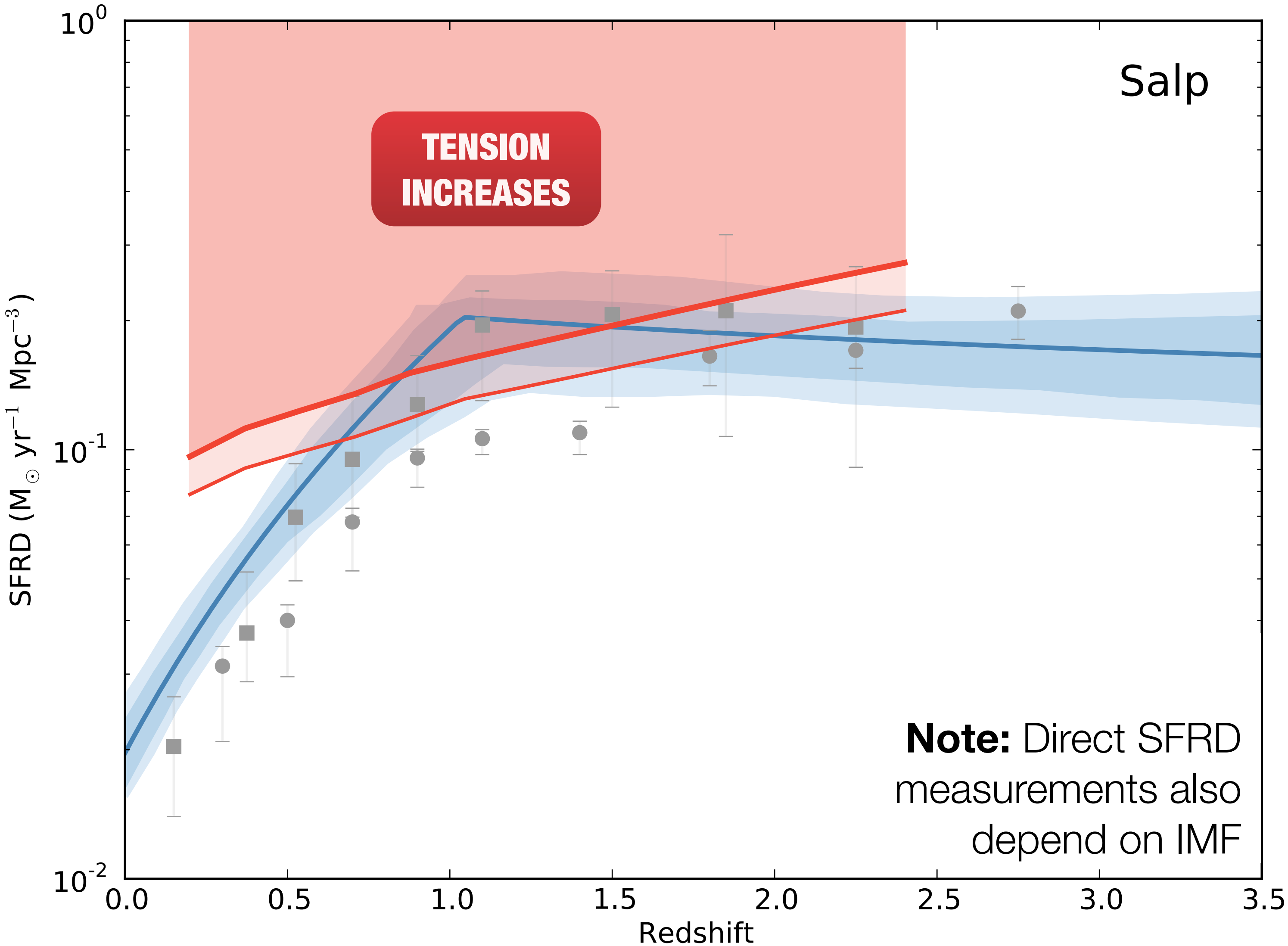


- Fix β + SFRD(0)
- Calculate EBL SED for grid in **ρ_0** and **z_0**
- Divide each EBL SED by the EBL UL:
  - t = SED / UL
  - t > 1: tension
  - t > 1.2: strong tension
- Calculate SFRD limit from t=1 (1.2) SFRDs

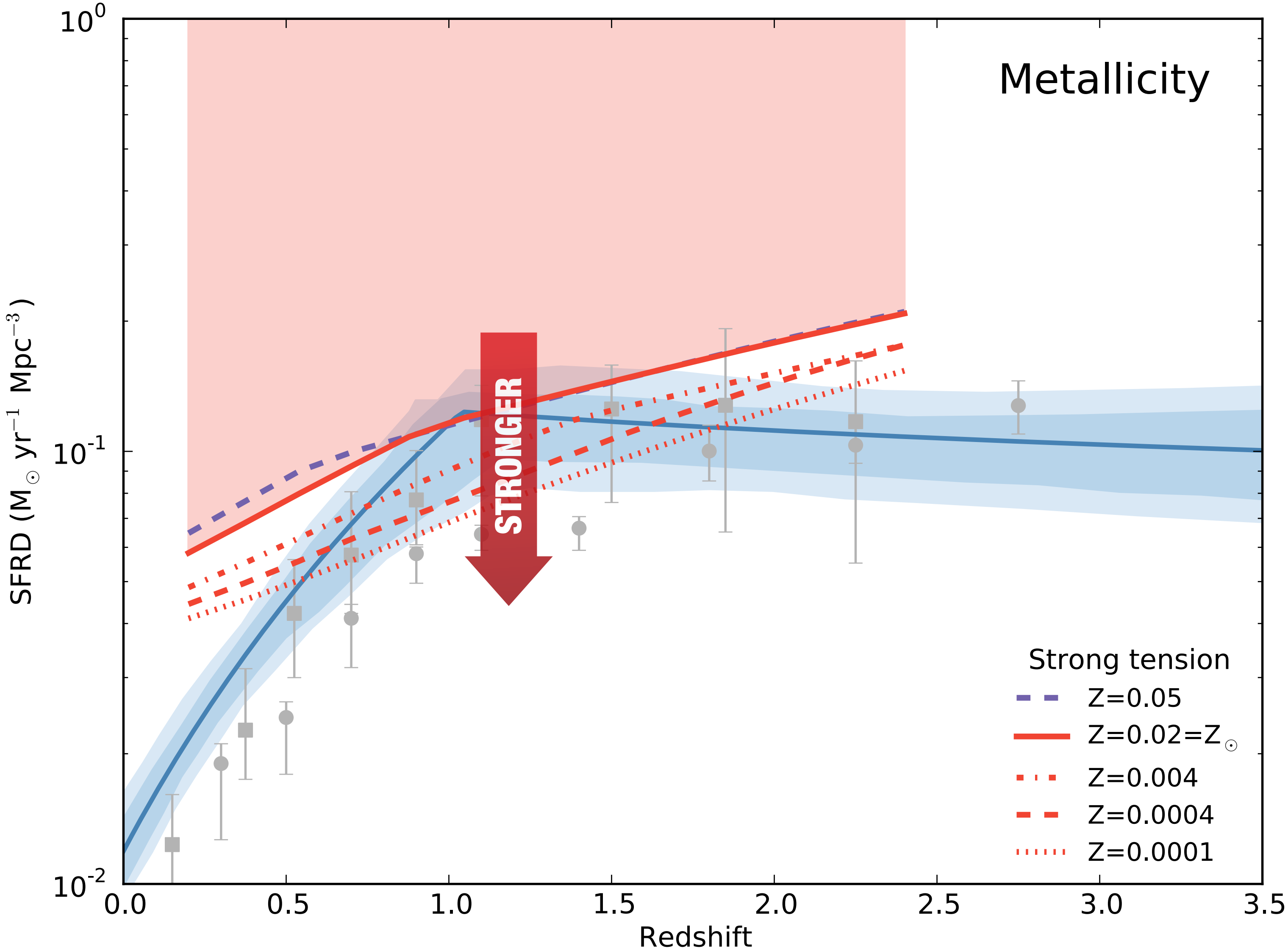
Results: fiducial model (Chabrier IMF, $Z_\odot$, β=.3)



Results: Salpeter IMF

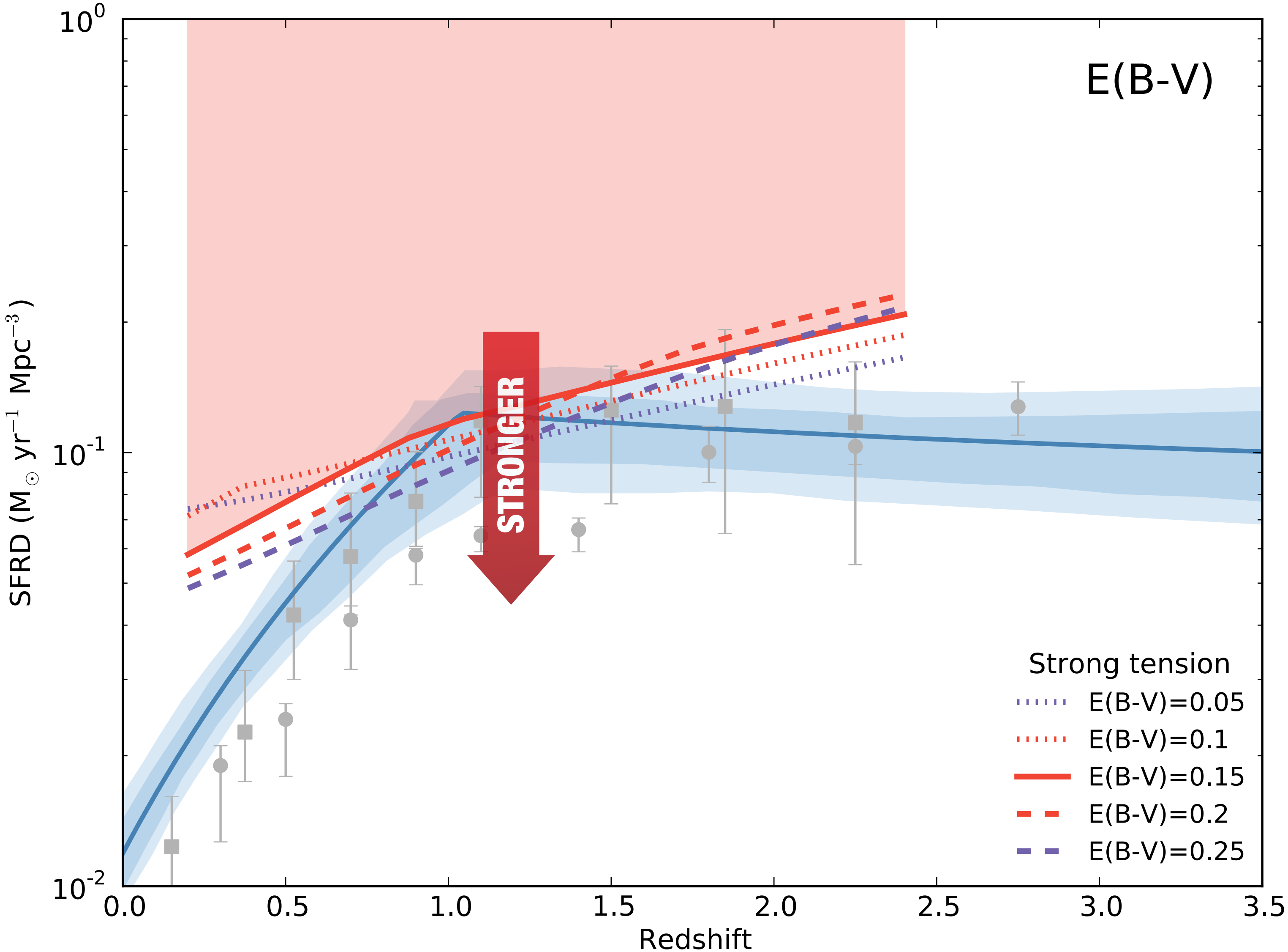


Results: metallicity

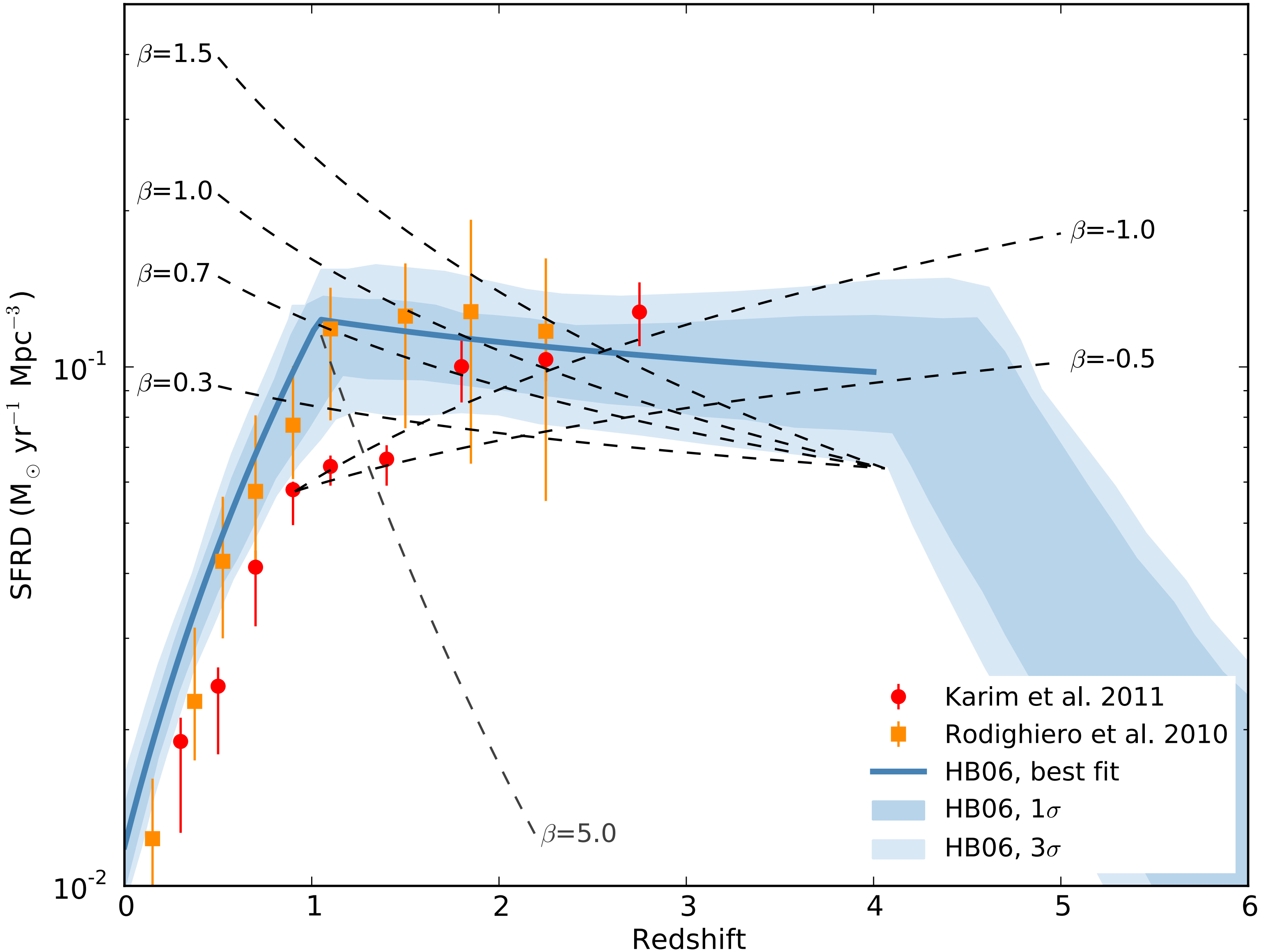


Raue & Meyer 2012

Results: IR attenuation - E(B-V)

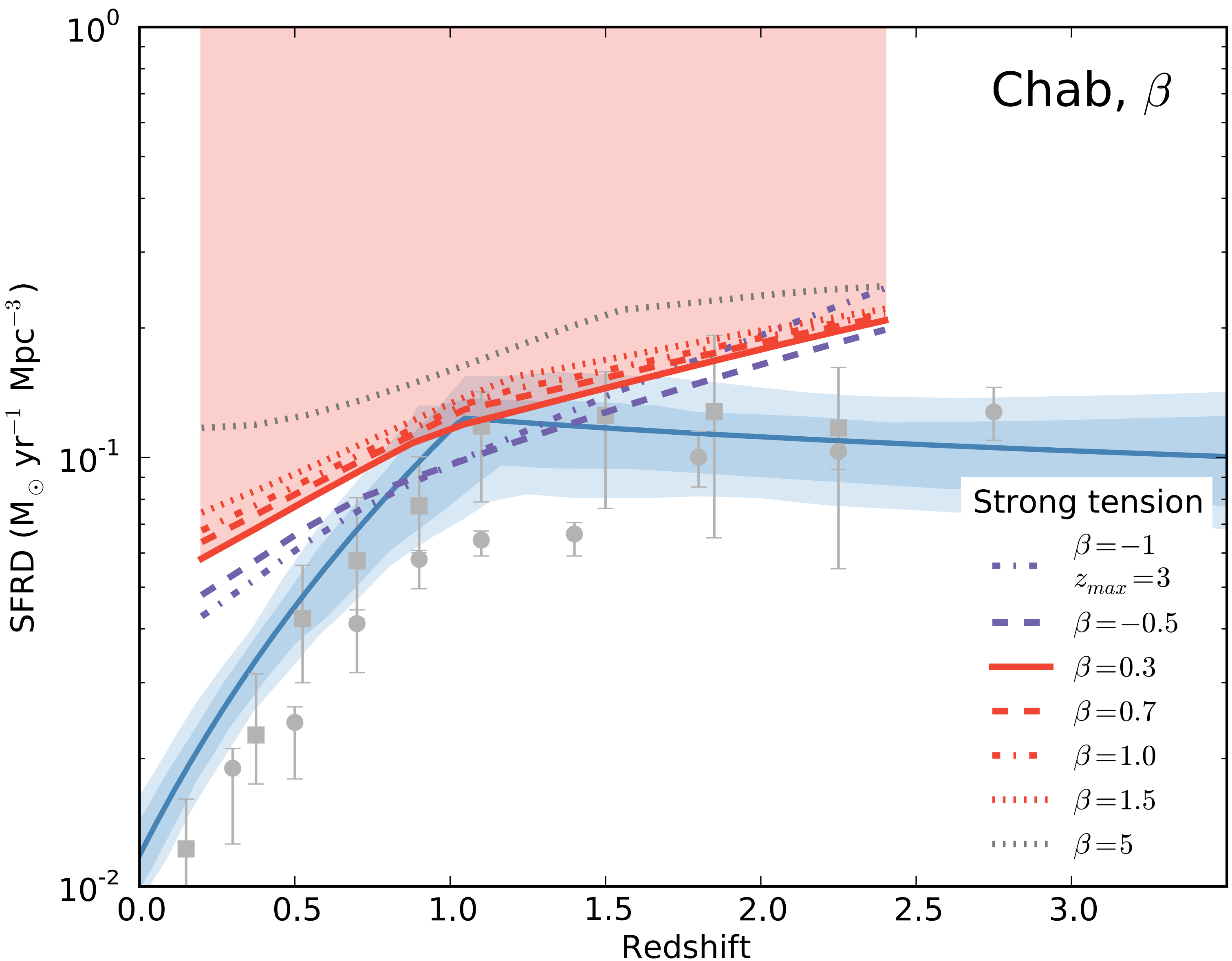


SFRD: β



Raue & Meyer 2012

Results: β



Raue & Meyer 2012

First stars and the EBL

Population III stars

- Formation starts at z ≫ 5
- Primordial metallicity ➠ H2/H cooling
- Massive stars >100 M⊙ (?)
- UV photons ➠ start reionization
- Fast transition to 2nd generation through feedback?

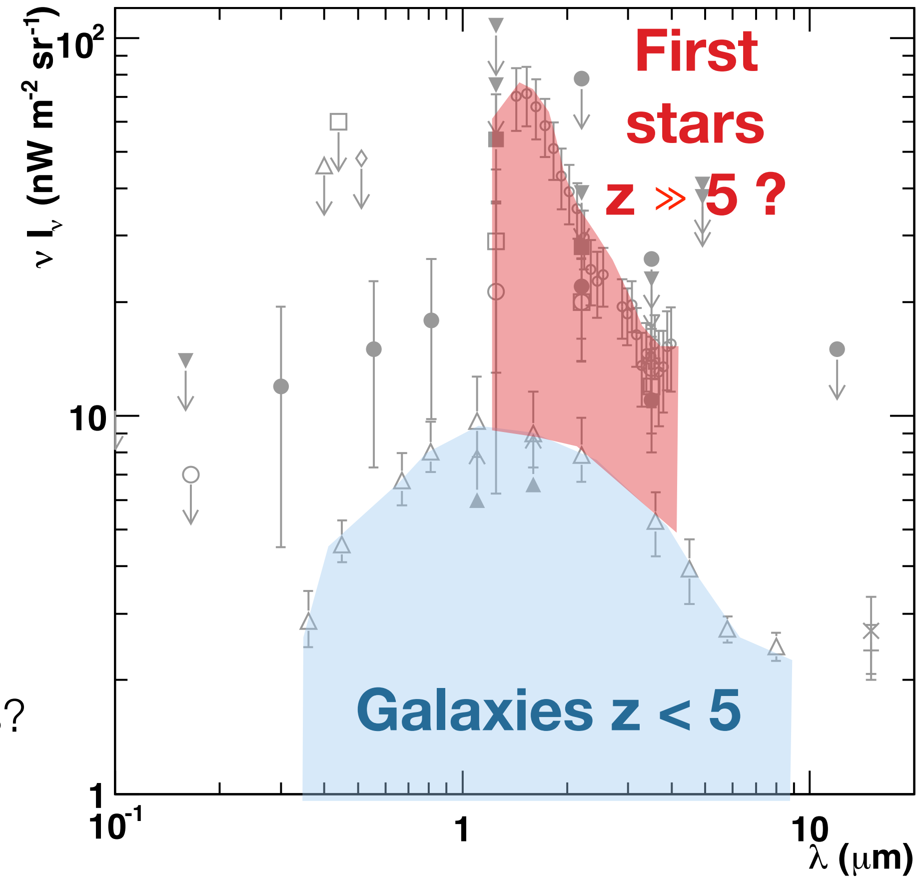
Not direct observable

- GRBs?
- Studied via simulations

  Fragmentation? Smaller masses? Magnetic fields?

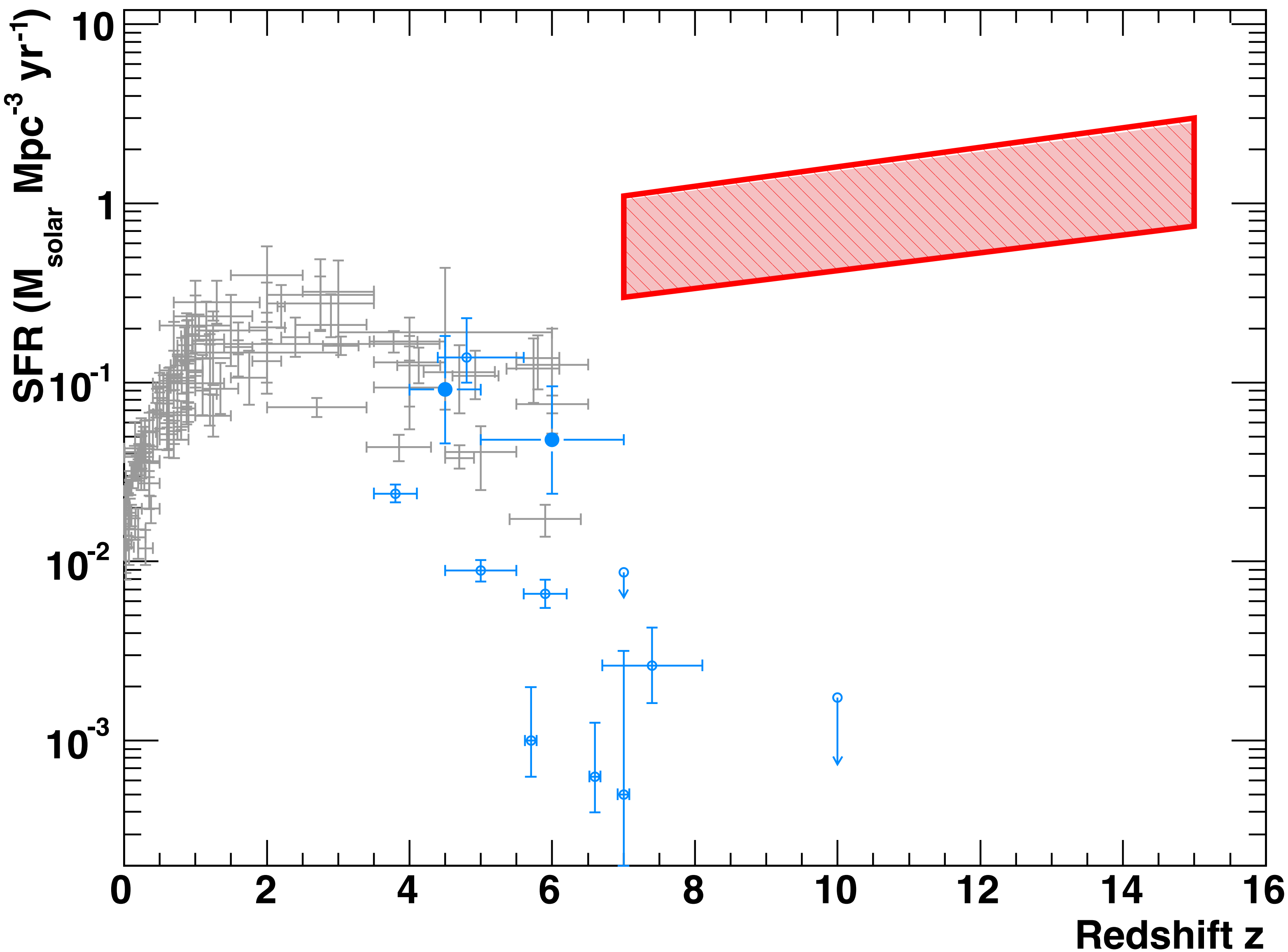
Imprint on the EBL?

Santos et al. 2004, Dwek et al. 2005, Salvaterra & Ferrara 2003, Fernandez & Komatsu 2006, Raue et al. 2009, Gilmore 2011



reviews e.g. Bromm & Larson 2004, Ferrara 2005

EBL constraints on stars in the early universe



Raue, Kneiske, Mazin 2009

Miscellaneous remarks

Early universe

- GRBs detect up to high redshifts
- VHE gamma-rays can probe the UV EBL => reionization

Hubble constant

- Attenuation depends on H_0
- If EBL and intrinsic spectrum well understood, use distant VHE sources as beacons (similar to 1aSN)

Quantum gravity

- Lorentz invariance violation
  c depends on energy
- Time of flight experiment

Distant, variable gamma-ray sources (GRB/AGN)

Broad energy coverage (lever arm)

Summary and outlook

Gamma-rays are an excellent probe for cosmology

- Star formation rate density (SFRD)
- Intergalactic magnetic fields (IGMs)
- Axion like particles (ALPs)
- Quantum gravity (QG)

Current observations deliver relevant constraints

- Strong limits on the extragalactic background light
  - Constraints on the SFRD and IGMF
- Interesting constraints on QG and ALPs

The future holds exciting possibilities

- CTA
  - 10x improved sensitivity over current installations
  - Extended energy range (20 GeV - 100 TeV)
- VHE gamma-ray observations will address some of the key questions of current cosmology

The CTA EBL and cosmology physics case

Workshop

MPI for Physics, Munich, Germany

November 28-30, 2012

Thank you!

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

LEXI
LANDESEXZELLENZINITIATIVE
HAMBURG

cta
cherenkov telescope array

BACKUP SLIDES

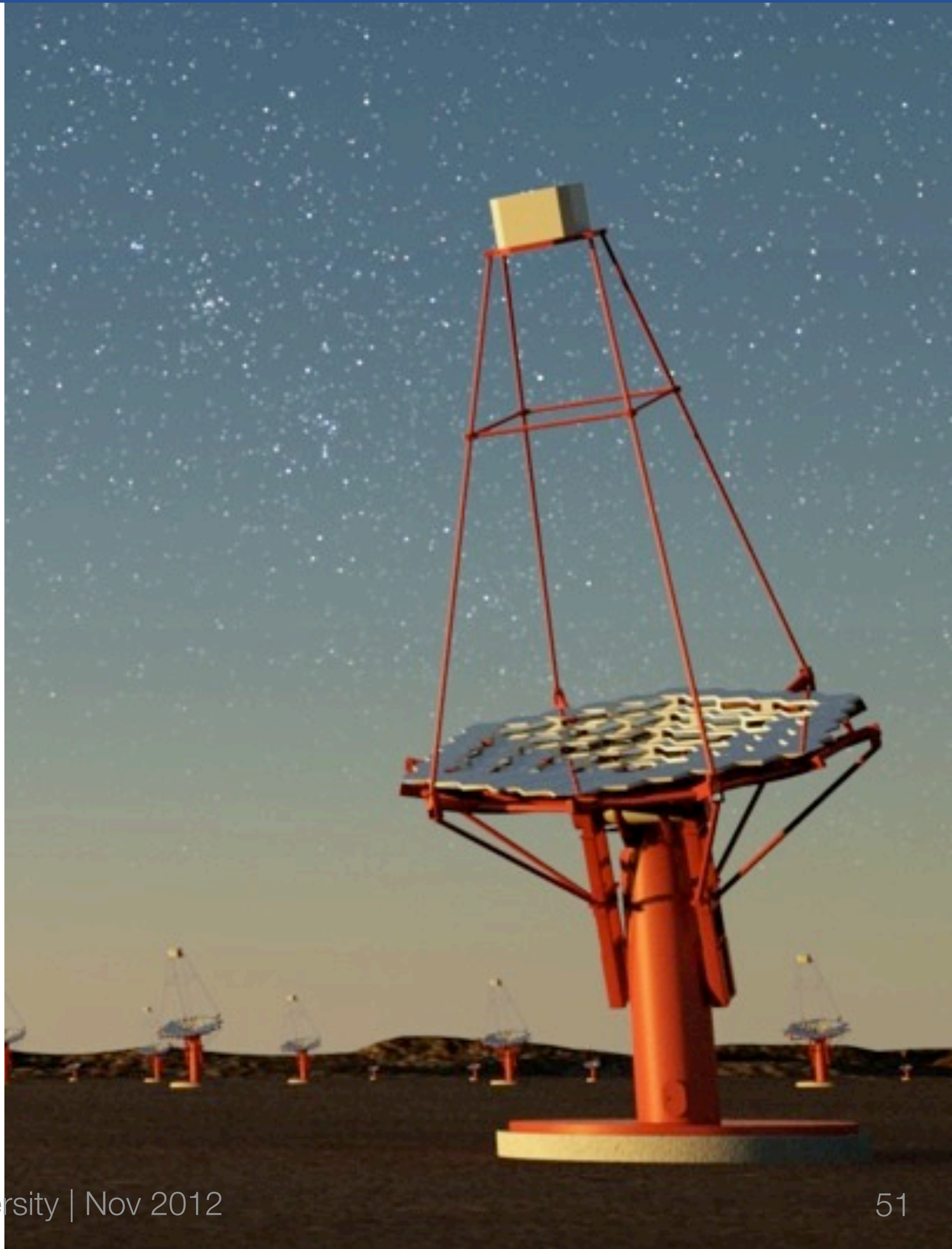
CTA Design

Proven technology as baseline

- Long experience with IACT technology
  - Whipple, HEGRA, CANGAROO, HESS, MAGIC, VERITAS, ...
- Operation as observatory & large number of telescopes requires improved reliability and ease of maintenance
- Many detail improvements

Advanced options developed in parallel

- Dual mirror
- Advanced photo detectors
- ...



MEDIUM-SIZED 12 M TELESCOPE

P

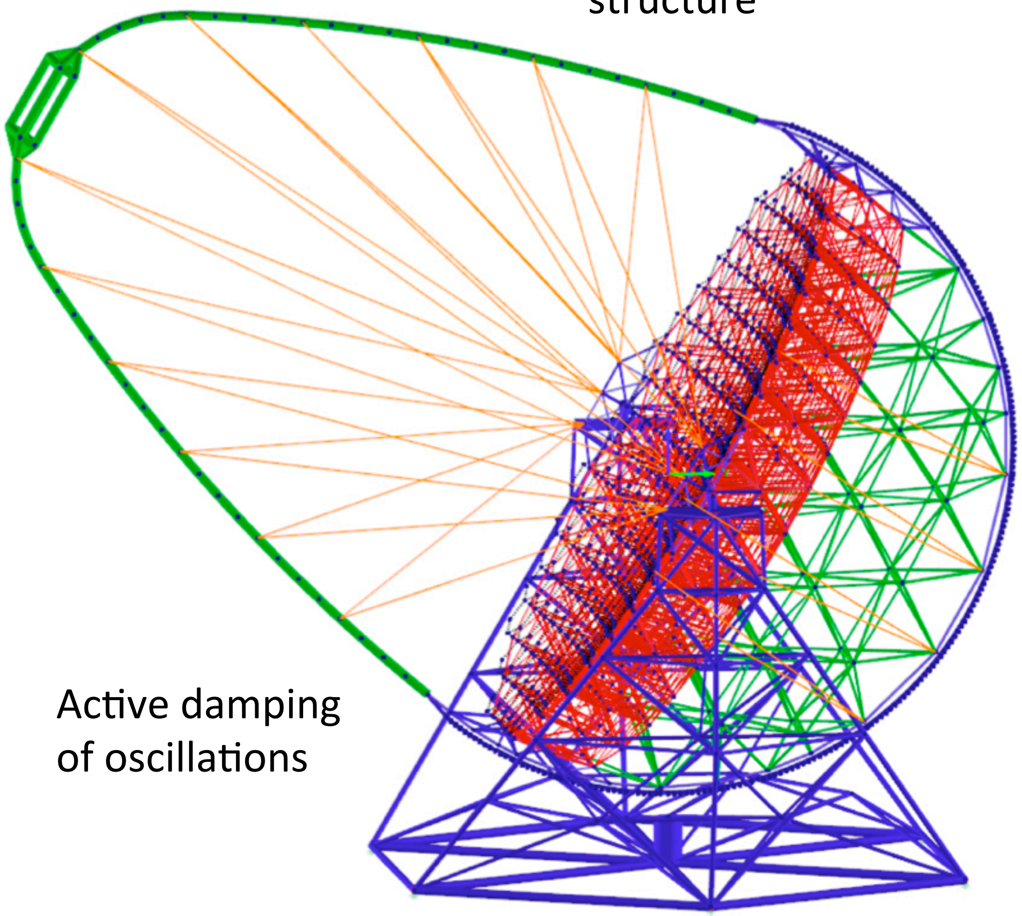
ngth
iew

DESIGN: 23 M LARGE TELESCOPES

OPTIMIZED FOR THE RANGE BELOW 200 GEV

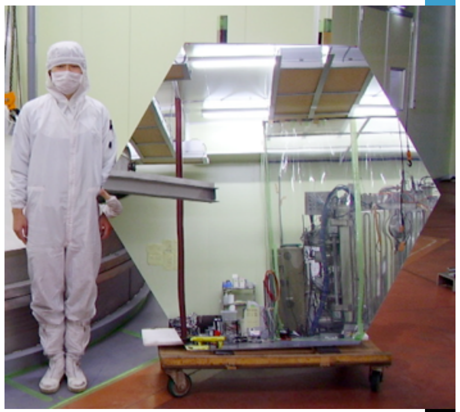
27.8 m focal length
4.5° field of view
0.1° pixels

Carbon-fibre structure

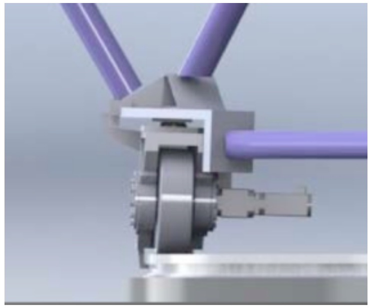


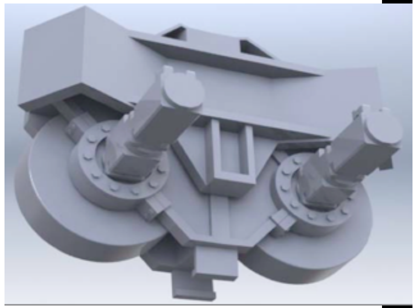
Active damping of oscillations

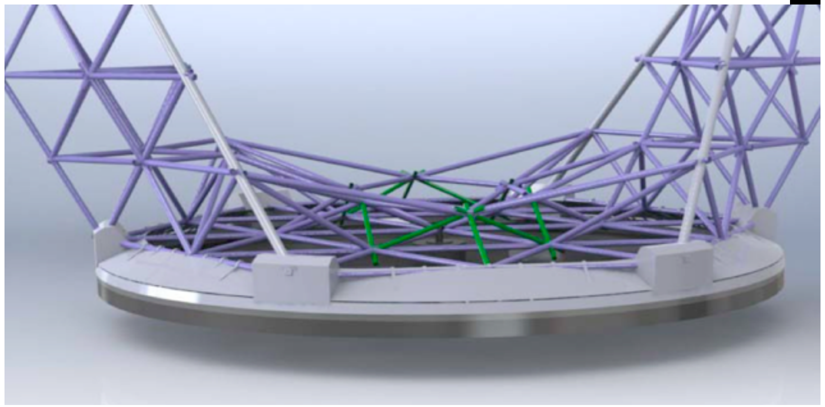
400 m² dish area
1.5 m sandwich mirror facets



On (GRB) target in < 20 sec.







DUAL MIRROR OPTION

FOR MEDIUM-SIZED TELESCOPE

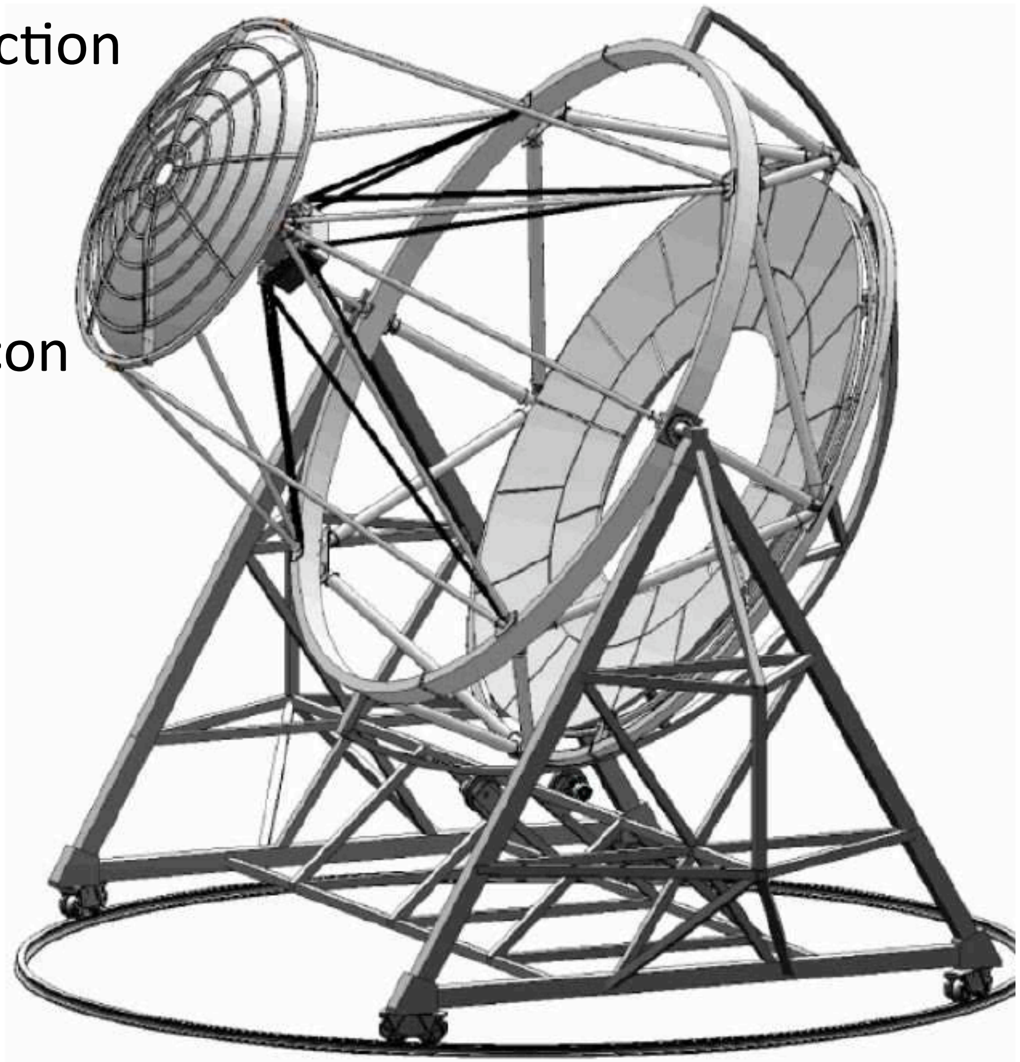
V. V. Vassiliev, S. J. Fegan,
P. F. Brousseau
Astropart.Phys.28:10-27,2007

- Improved point spread function and improved angular resolution
- Small plate scale
- Suitable for MAMPT or silicon sensors

  but also

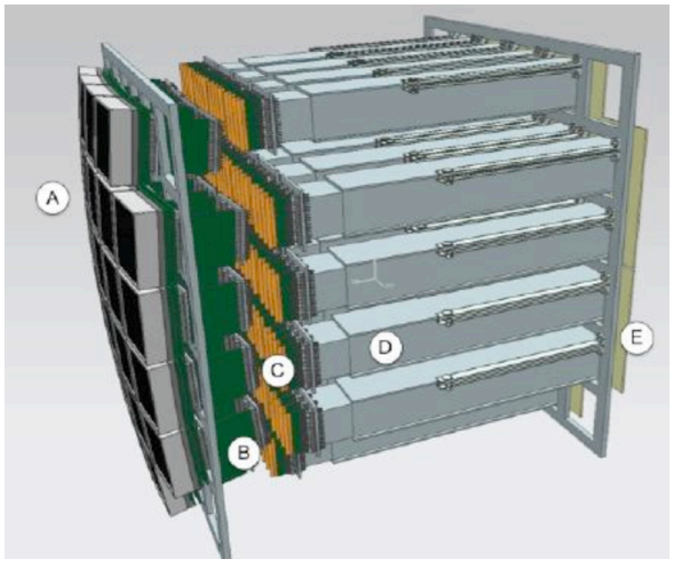
- Non-spherical mirrors
- Challenging alignment
- Not prototyped yet

Aim at expanding MST array with dual-mirror telescopes

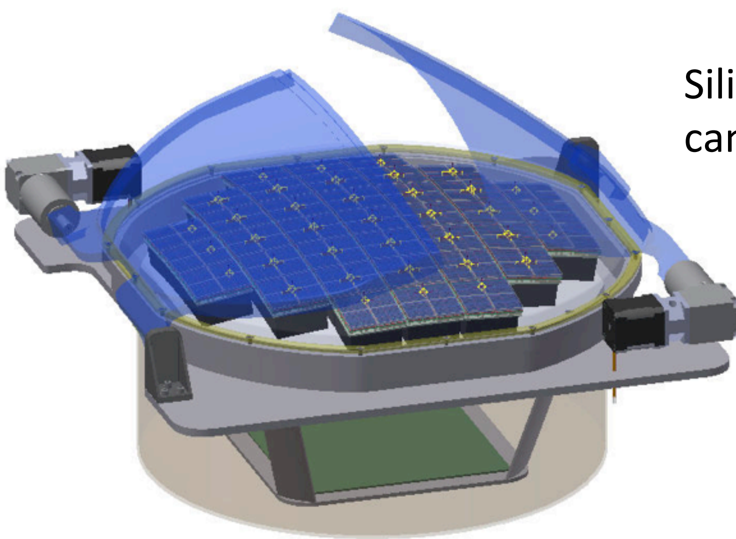


DUAL-MIRROR SMALL TELESCOPES

ALLOW USING LOWER-COST SENSORS

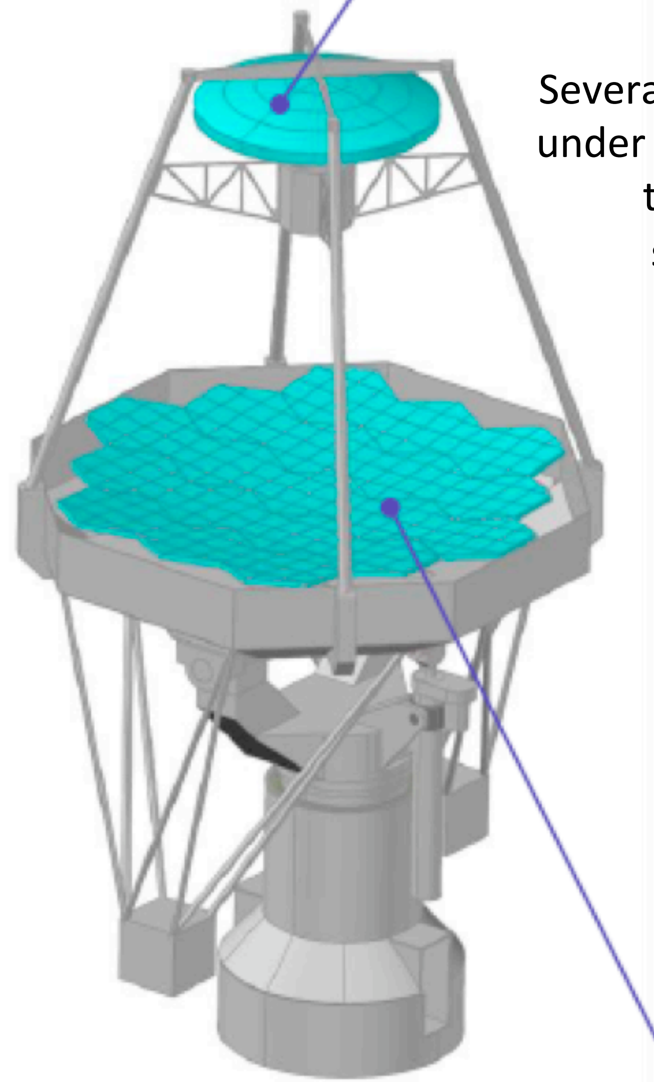


Multi-Anode PMT camera option



Silicon sensor camera option

Monolithic secondary mirror



Several options under study for telescope structure

Primary mirror with hexagonal panels

CTA: standard data formats & public analysis tools

CTA data formats

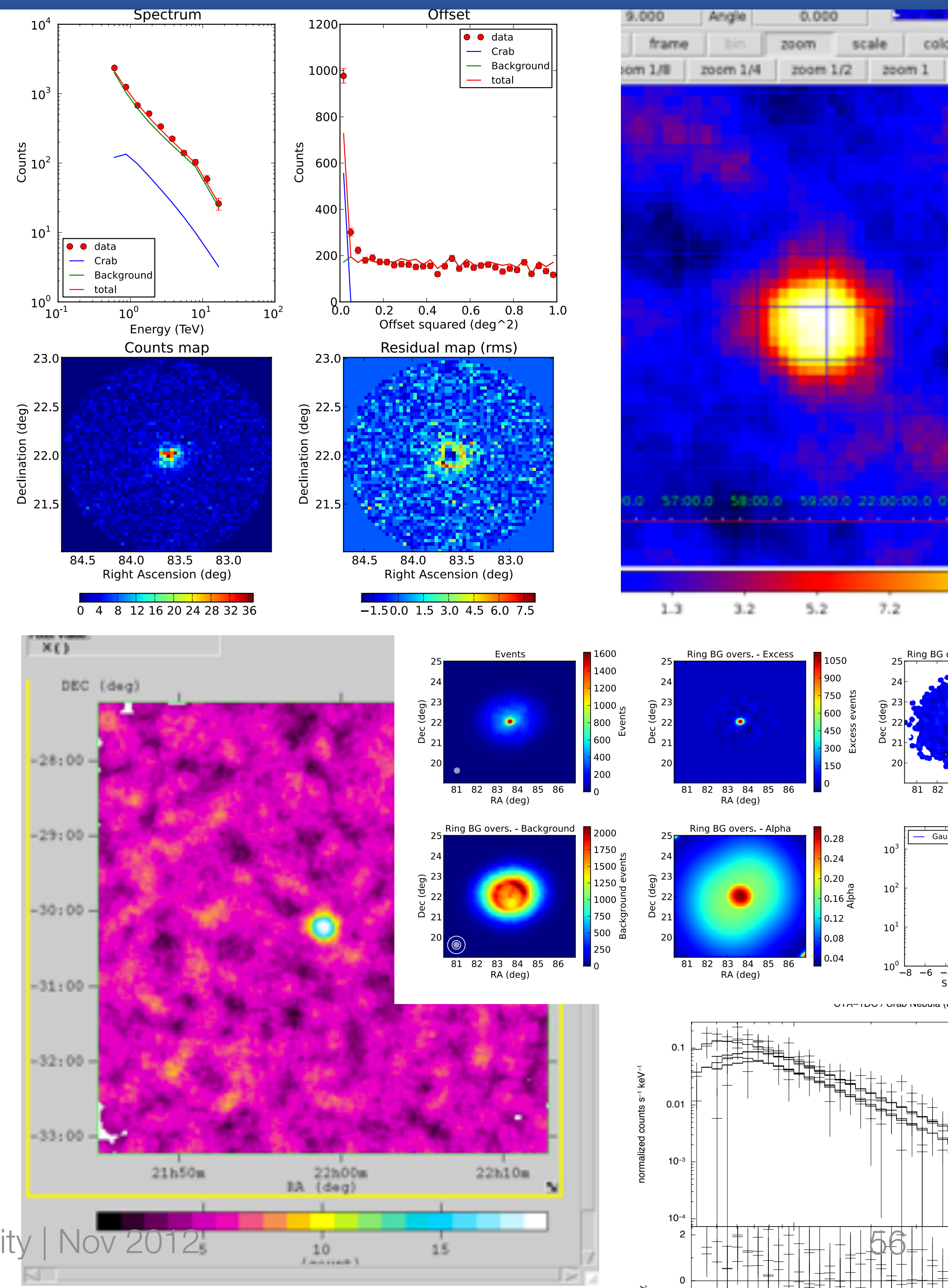
- Astronomy standards (FITS)

CTA analysis software

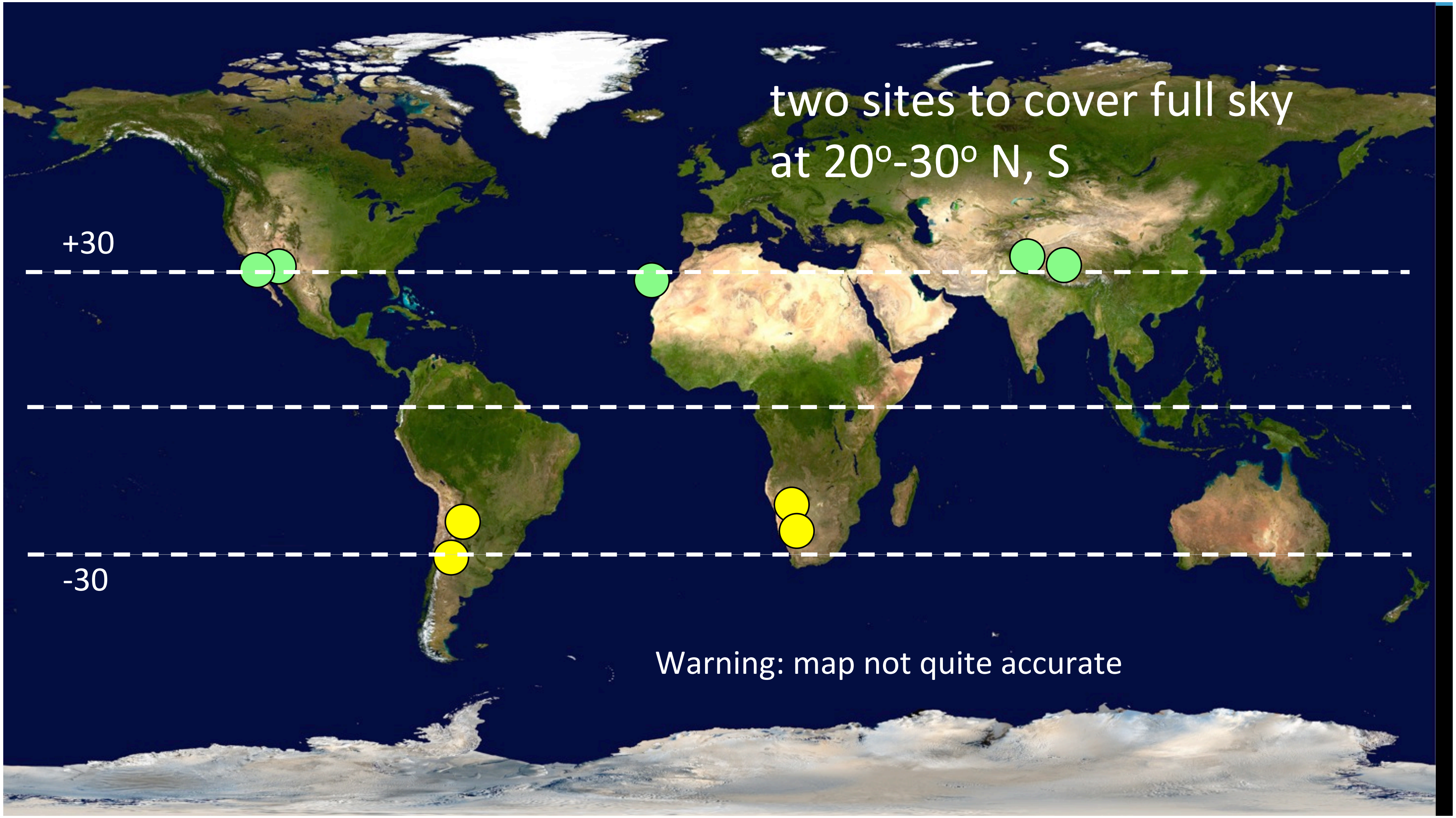
- Public
- Connect with existing tools & platforms in astronomy
- MWL integration

CTA 1st data challenge

- 1st steps have been taken
- High level DF defined, first tools available



Site candidates



- Working towards quantifying site-dependent differences in performance and cost

DARK STARS

WIMP: self-annihilate /decay

- ➠ Energy injection

Impact of DM annihilation in stars

- PopII/I: No (cooling, DM dens.)
- PopIII: yes! maybe! ...

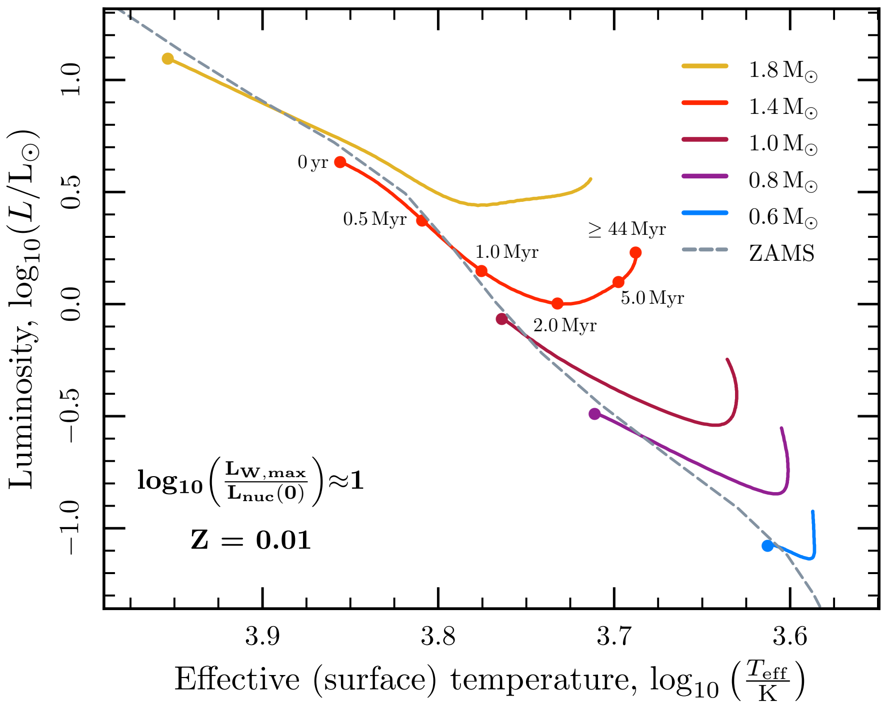
Pop III vs DM

- Less efficient cooling (H, H_2)
- Collapse inside DM halo
- DM density enhanced by adiabatic contraction & scattering ?

➠ **DM powered star / Dark Star**

Spolyar et al. 2008, Iocco 2008

Dark Star properties



Scott et al. 2009

Large model uncertainties!!!

- DM (mass, σ)
- Halo (DM density)

Cool but bright (and long lived)

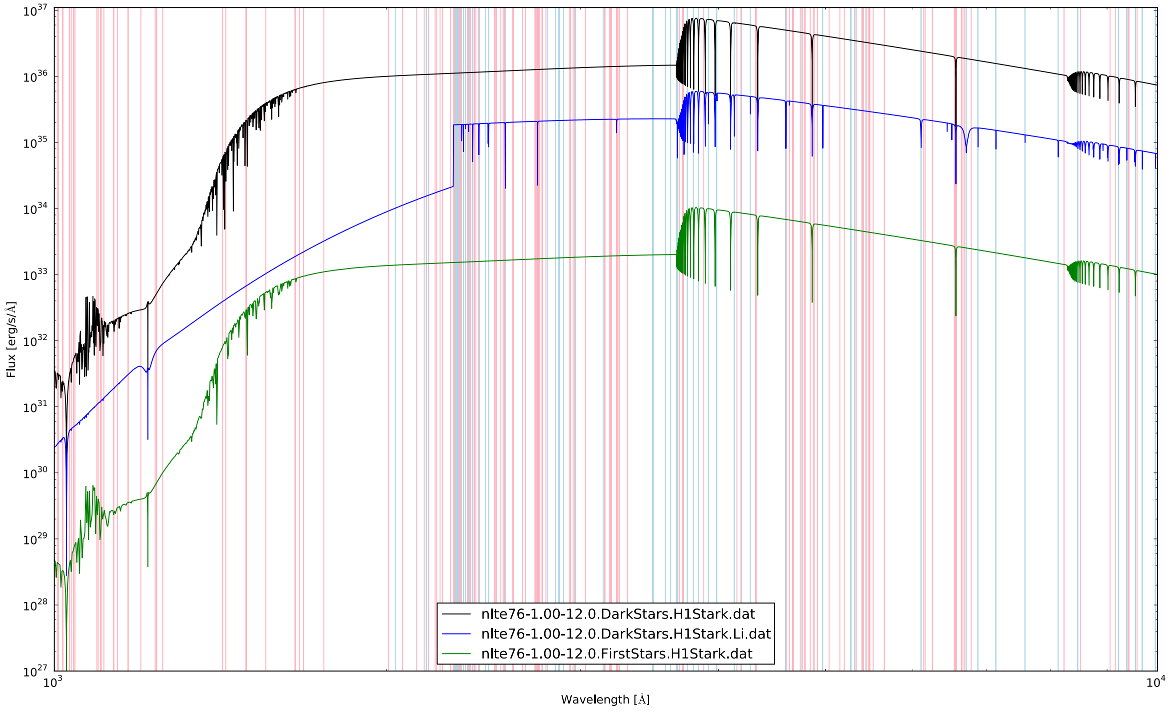
Direct detection unlikely

JWST? No ... (Zackrisson et al. 2010)

	Temperature	L☉/M☉	Lifetime
PopIII	~10^5K	10^{3-4}	10^6 years
Dark Star	~5000-10000K	10^{2-5}	10^{5-9} years

Spolyar et al. 2009, Iocco et al.2008, Scott et al. 2009 Freese et al. 2010

Dark Star spectra with Phoenix



Phoenix

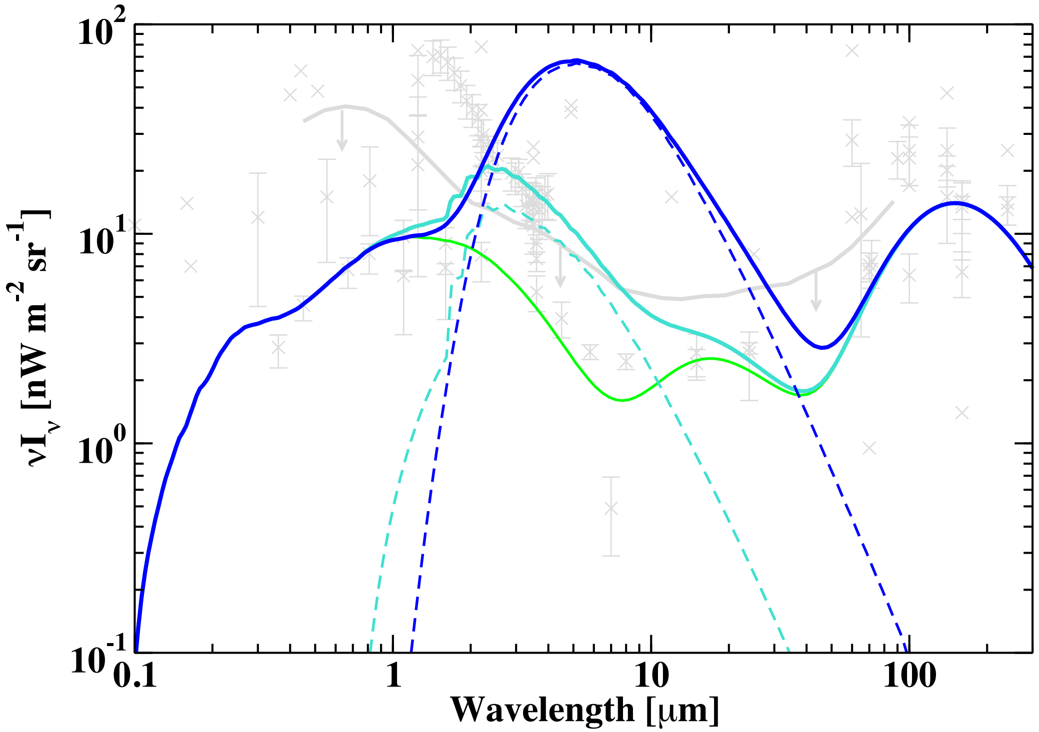
- State of the art NLTE atmosphere model code

DS with Phoenix

- Spectral signature of DS?
- Explore region 5000-30000K
- NLTE / molecules / VdW, Stark
- Li lines?

Hauschildt & Baron (1999), Hauschildt & Baron (2010), Maurer, Raue et al. (2010/2011), F. Laatz

EBL contribution from DS?



DS contributes NIR/MIR EBL

- New window for DM search?

Calculate DS EBL contribution for large model parameter space

Extreme scenarios excluded

EBL limits ➠ limit DS properties

- Lifetime, SFR, z, ..

$$(\nu I_\nu)_{\max} = 2 \times 10^{-5}\ \mathrm{nW\ m^{-2}\ sr^{-1}} \times \left(\frac{\Delta t_{\mathrm{DS}}}{10^7\ \mathrm{years}}\right) \times \left(\frac{\mathrm{SFR_{Norm}}}{10^{-5}}\right) \times \left(\frac{\mathrm{LMR}}{10^3\ \mathrm{L_\odot / M_\odot}}\right) \times \left(\frac{z_{\min}}{10}\right)^{-2.5}$$

Maurer, Raue, Kneiske, Horns, Elsässer, Hauschildt (2010/2011)