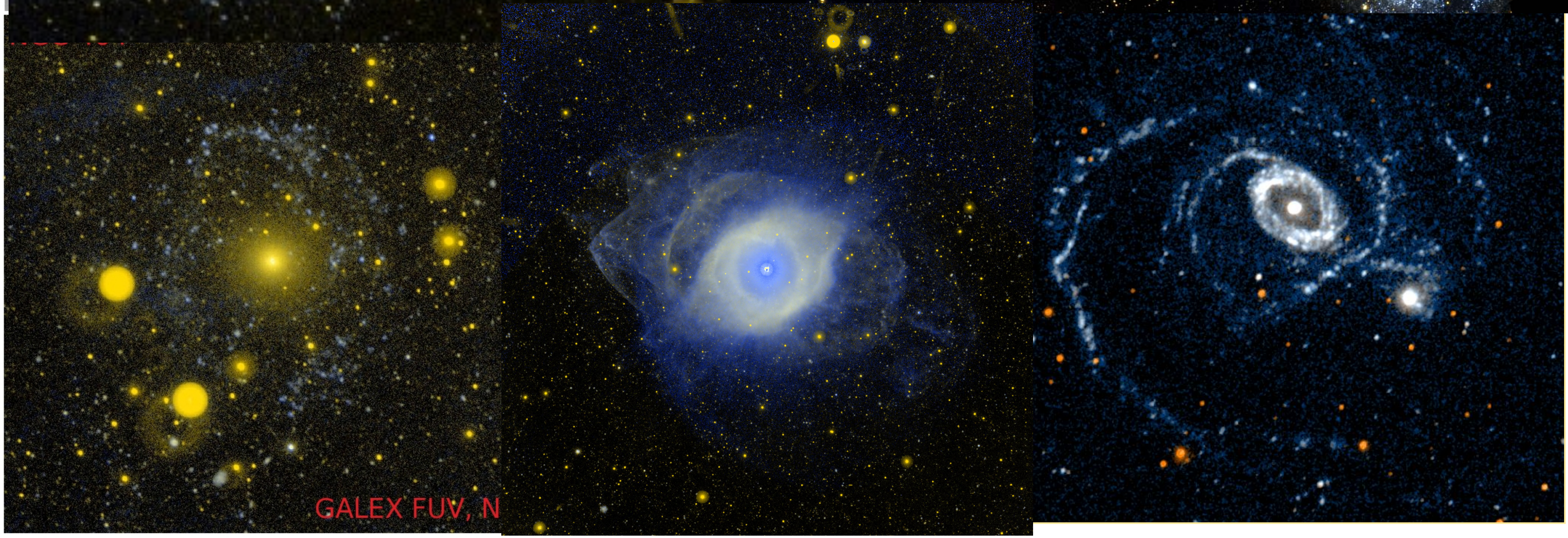
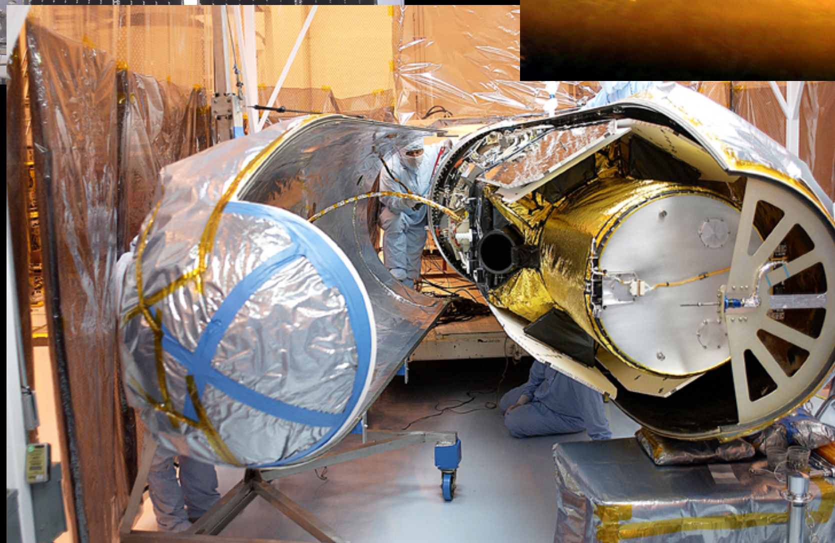
GALEX : review of results

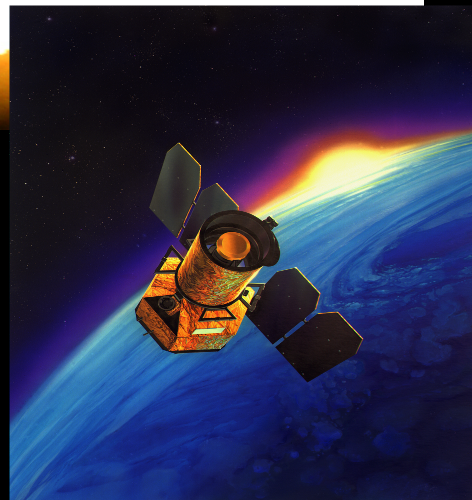
Luciana Bianchi
(JHU)

NUVA/ESO conference
October 2013 ESO,Garching

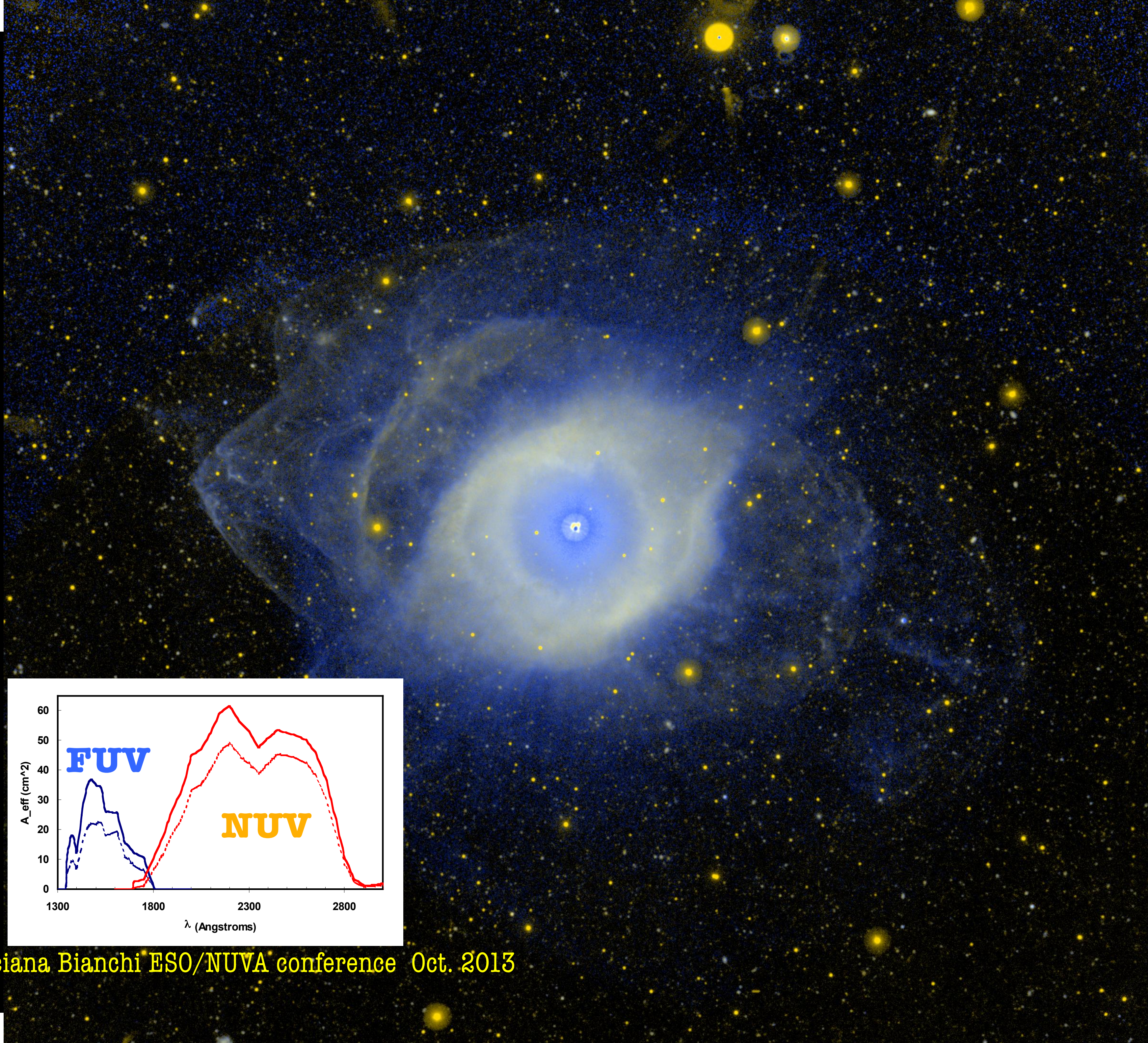


GALEX: launched April 28, 2003
NASA ops funding ended Dec.2011
(MOU May 2012) decommissioned May 2013





ADS: 2167 papers (with GALEX in abstract) 480 in title

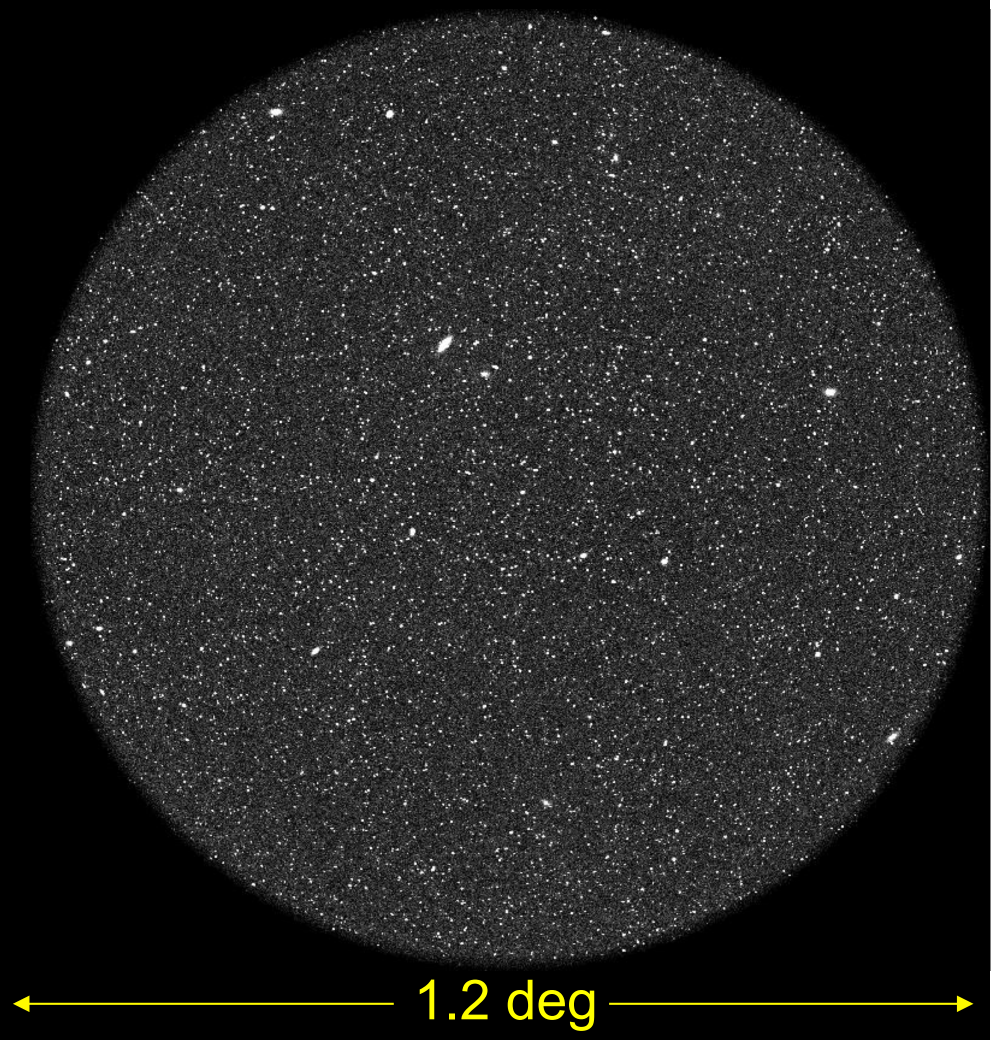

FUV
NUV
A_eff (cm^2)
60
50
40
30
20
10
0
1300
1800
2300
2800
λ (Angstroms)

wide-field of view: 452x HST; 45x lower resolution

large-format photon-counting detector with low background

* Field of view
  → 1.2 degree diameter

Moon shown for size comparison



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Objectives of the UV sky survey:

1) understand star formation:
   - local calibration
   - history of SF redshift 0...2
   - coevolution of dust and SF
2) explore the UV sky:
   - find elusive stellar populations
   - to clarify stellar evol. & galaxy enrichment

Objective 2: the UV sky

214,499,551

210,691,504

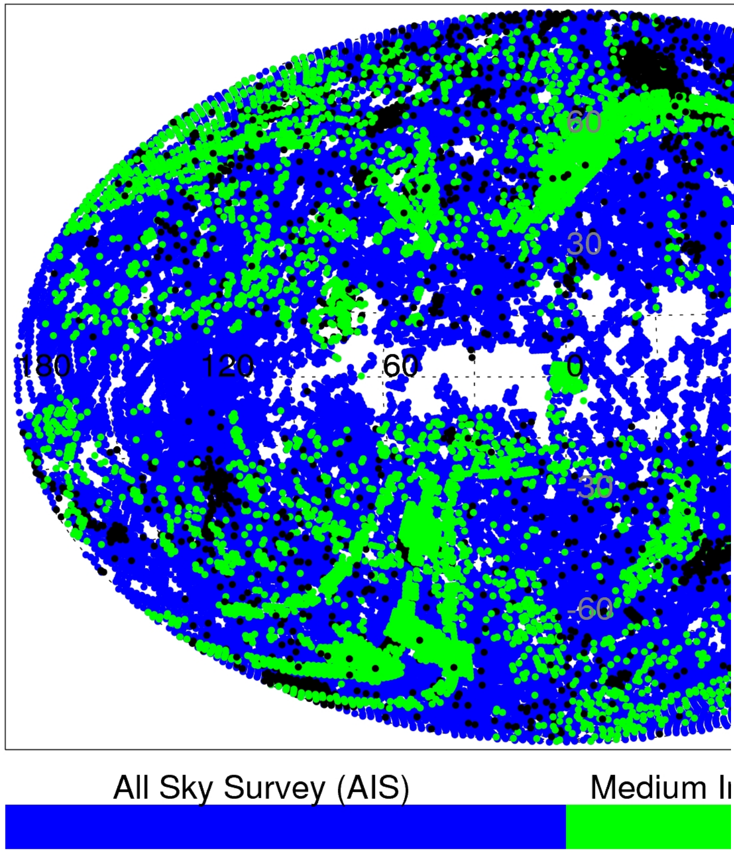
FUV & NUV

200+ million UV sources:

Where are they ?
What [classes of objects] are they ?
What are their mags / luminosities?
What do we learn?

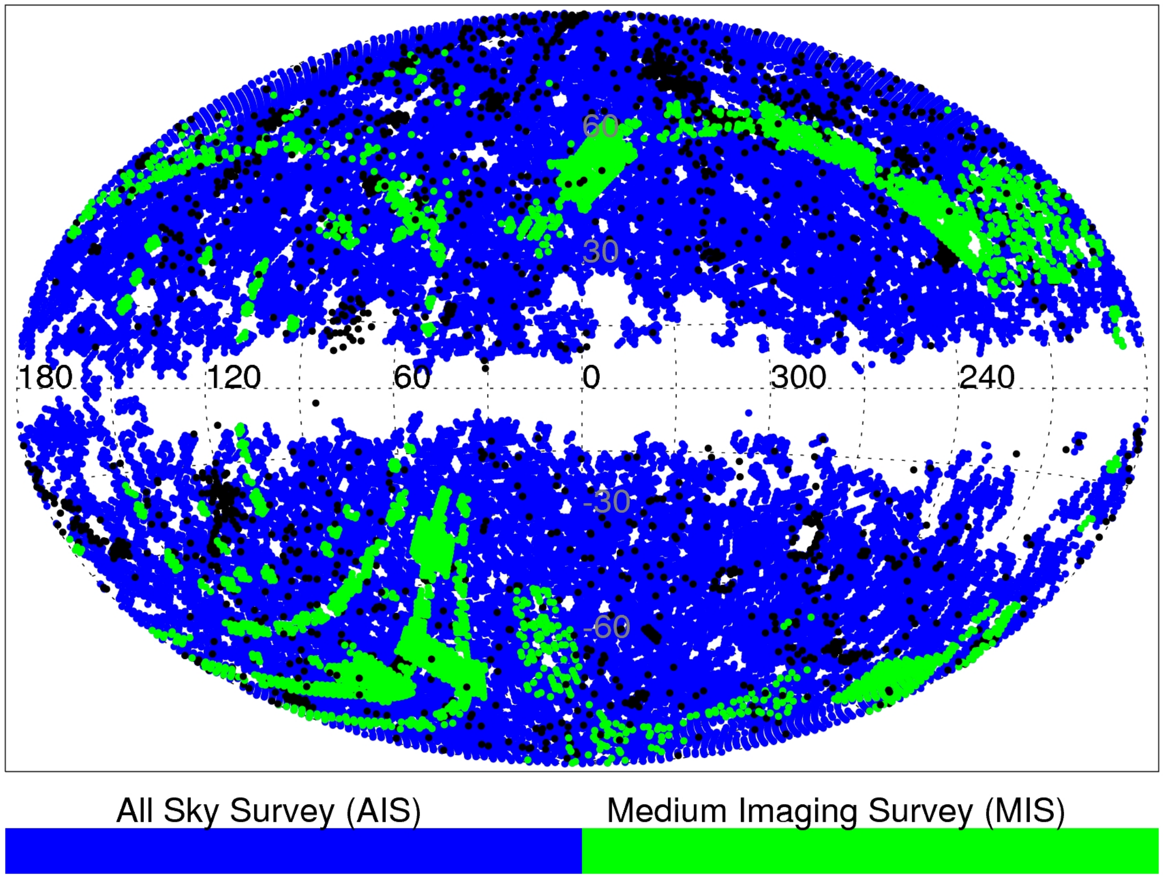
GALEX : the UV sky

GALEX GR6/7 NUV



Figures from Bianchi et al 2013,
J.ASR DOI: 10.1016/j.asr.2013.07.045

GALEX GR6/7 FUV and NUV



ABmag 19.9/ 20.8 (FUV/NUV) 22.6/ 22.7 (FUV/NUV)

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Catalogs of unique UV sources

TOTAL 43717 fields

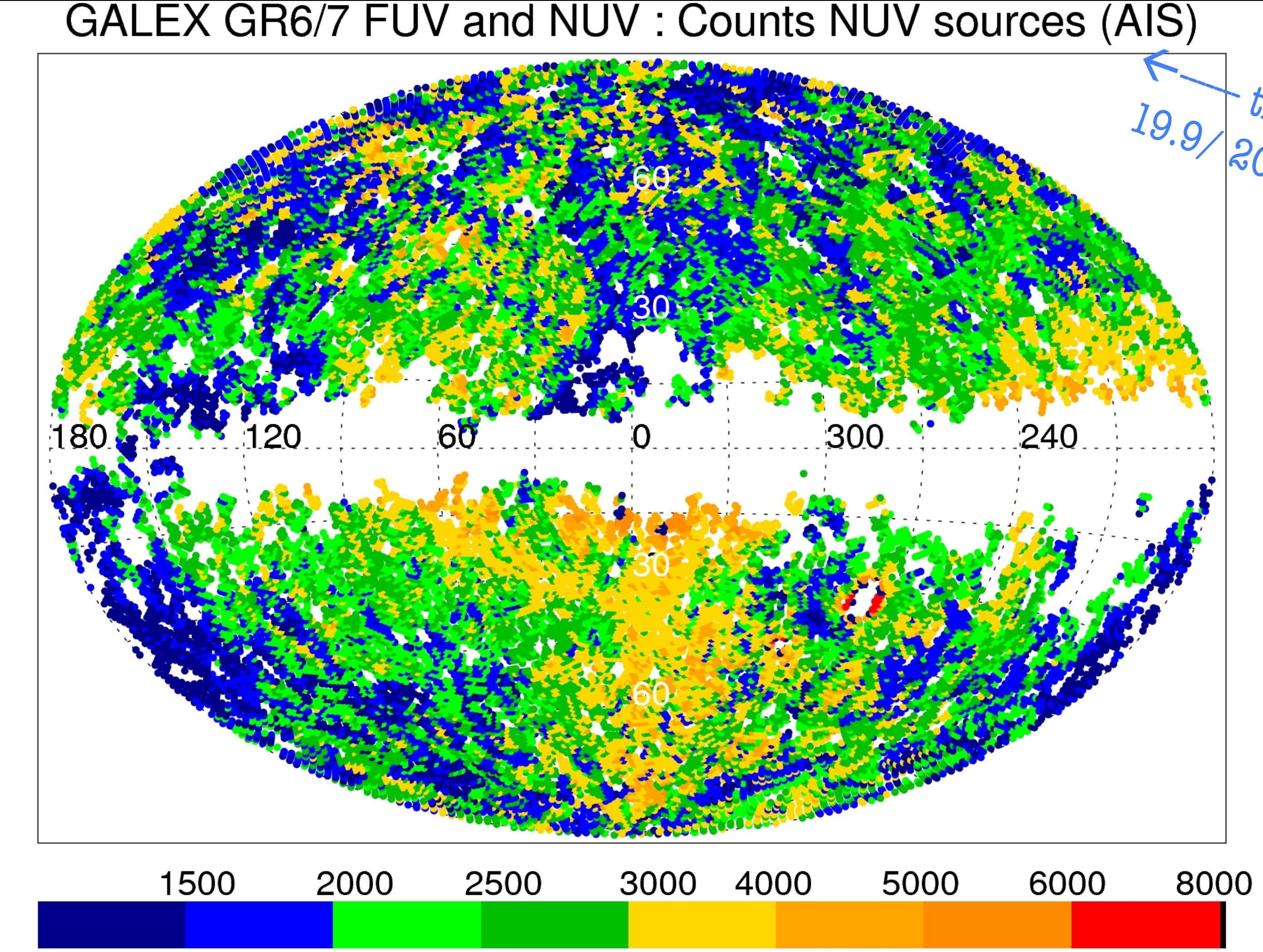
Surv	# flds	#sources / sq. deg	Depth ABmag FUV	NUV
AIS	34207	~5000	19.9	20.8
MIS	6489	13000	22.6	22.7
DIS	>350	30000	24.8	24.4
NGS	480		27.5m/sq”	
GI	1380			
Spectra	271	127,414		

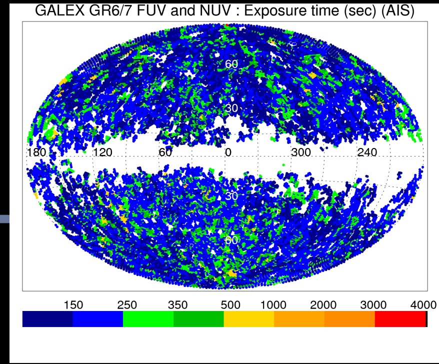
remove duplicates, edge artifacts, ..

71 million AIS
17 million MIS

(last version: Bianchi et al 2013, J.ASR, DOI:10.1016/j.asr/2013.07.045
1st version: Bianchi et al. 2011, MNRAS [catalogs in MAST, Vizier])

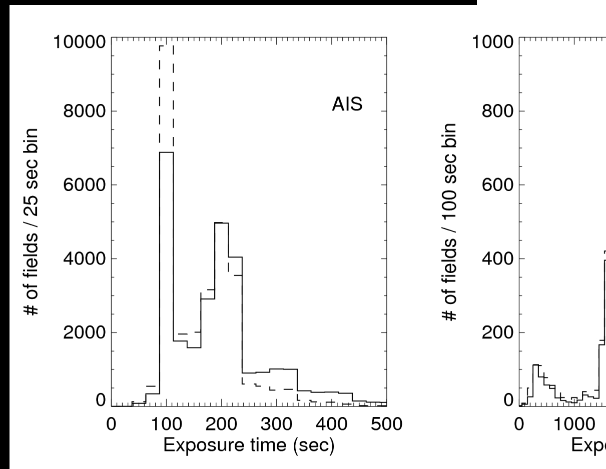
GALEX : the UV sky





the shallowest survey

19.9/ 20.8 (FUV/NUV) AB mag



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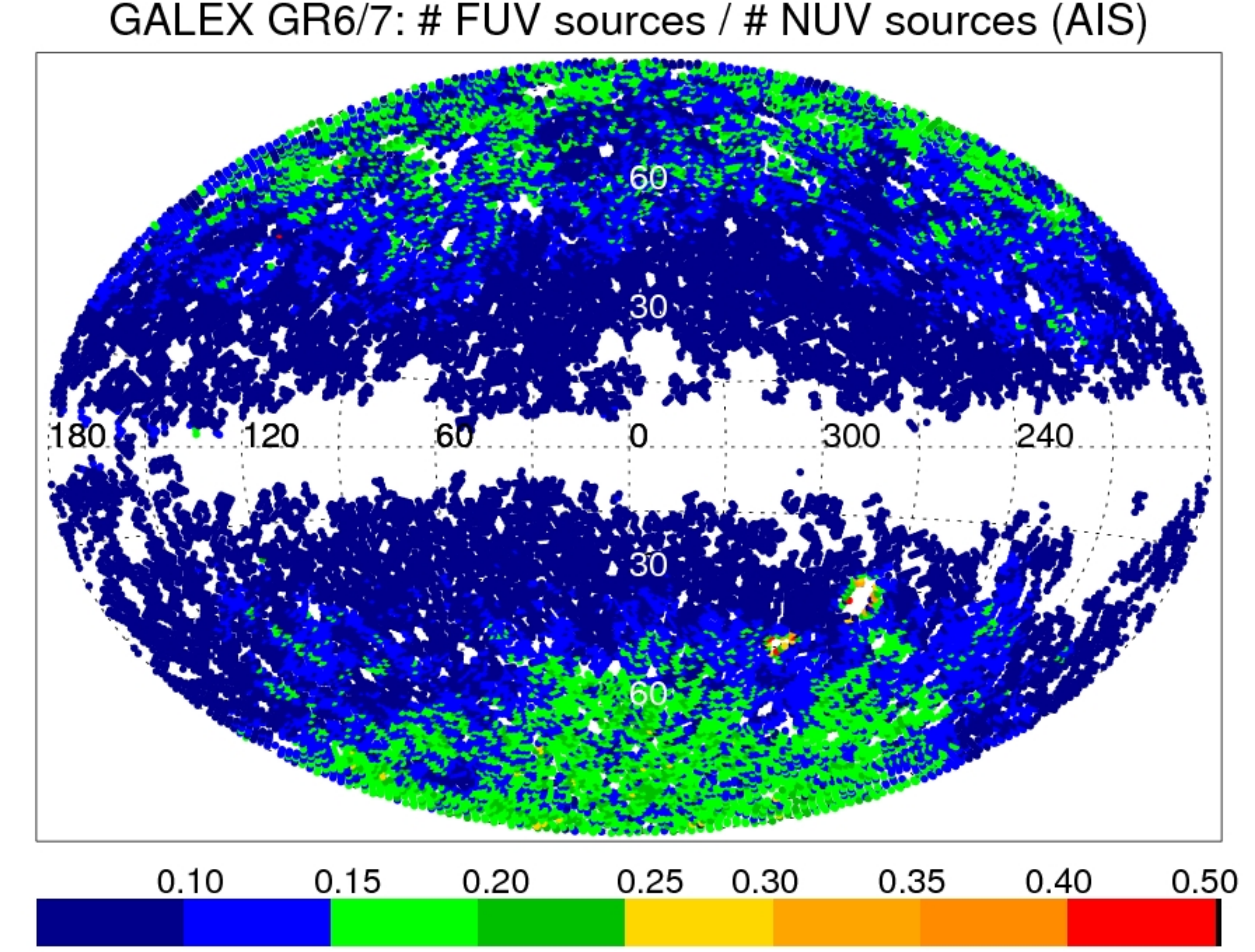
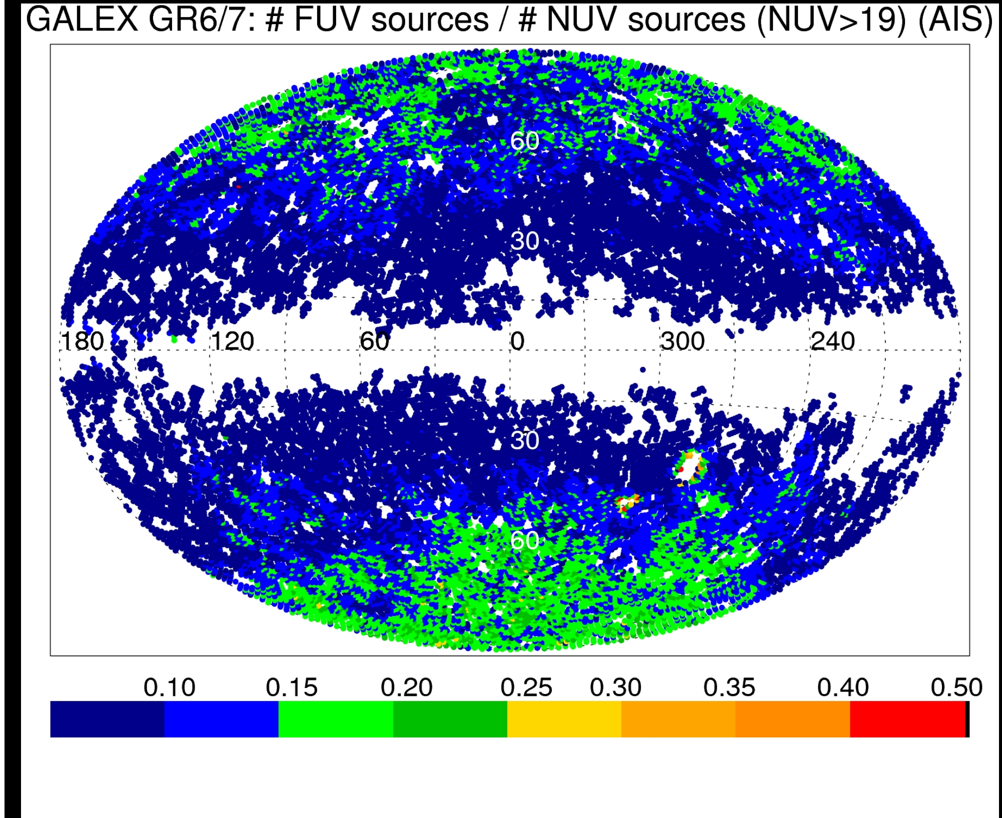
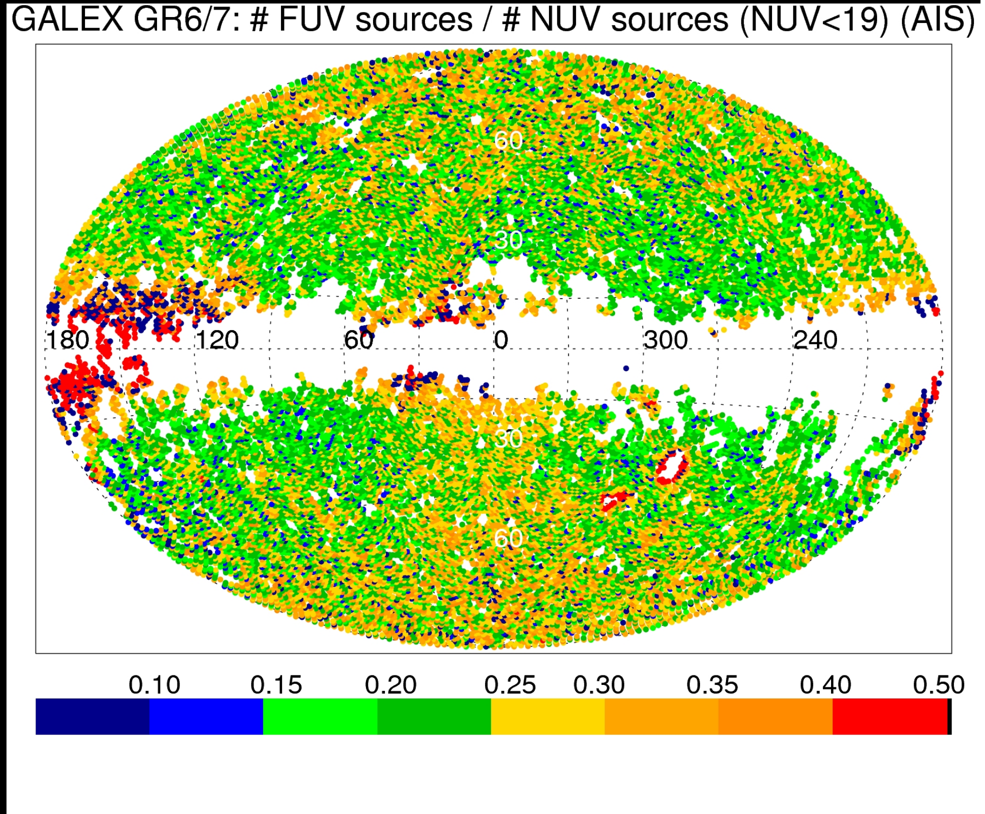
GALEX : the UV sky

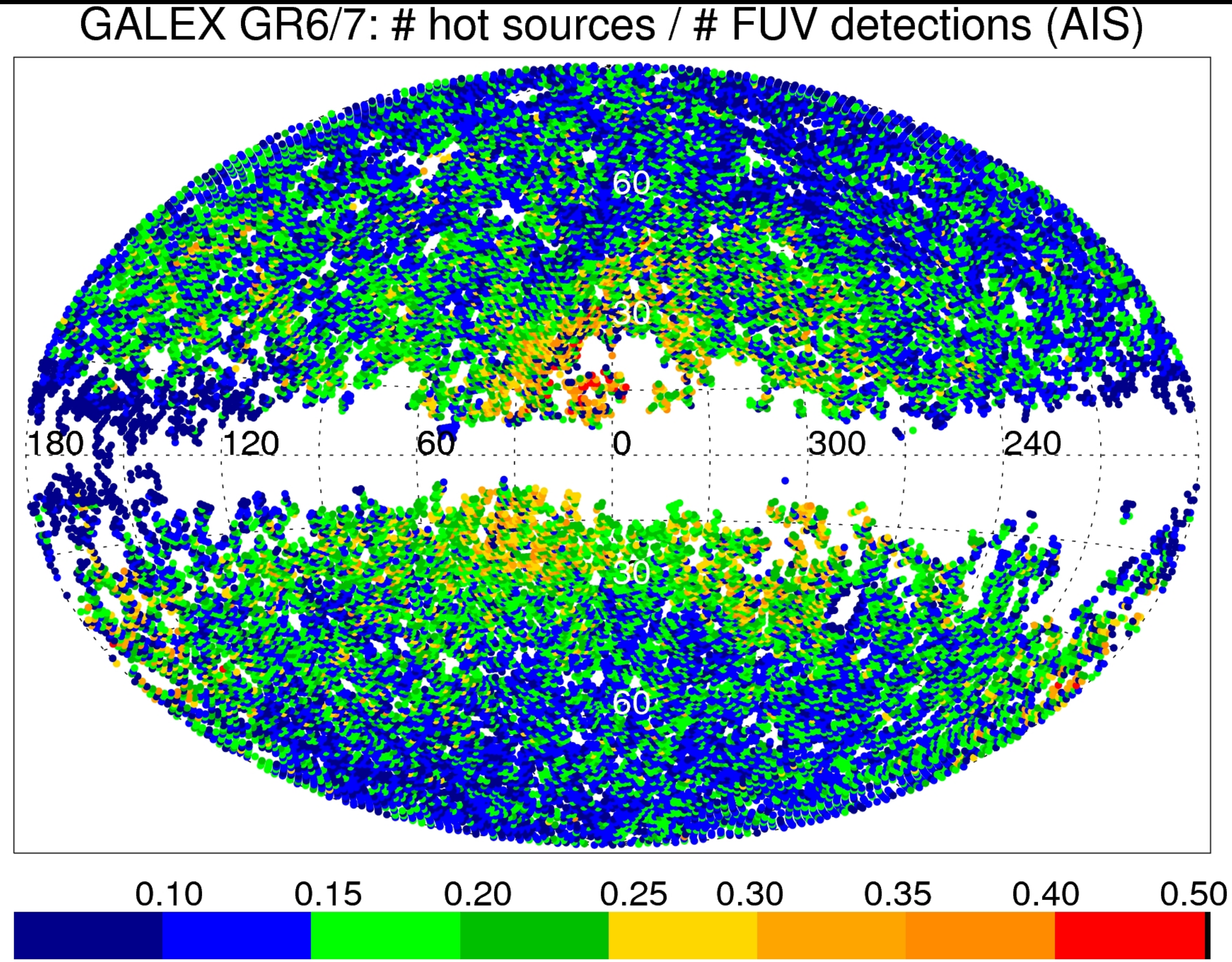


GALEX : the UV sky





GALEX : the UV sky



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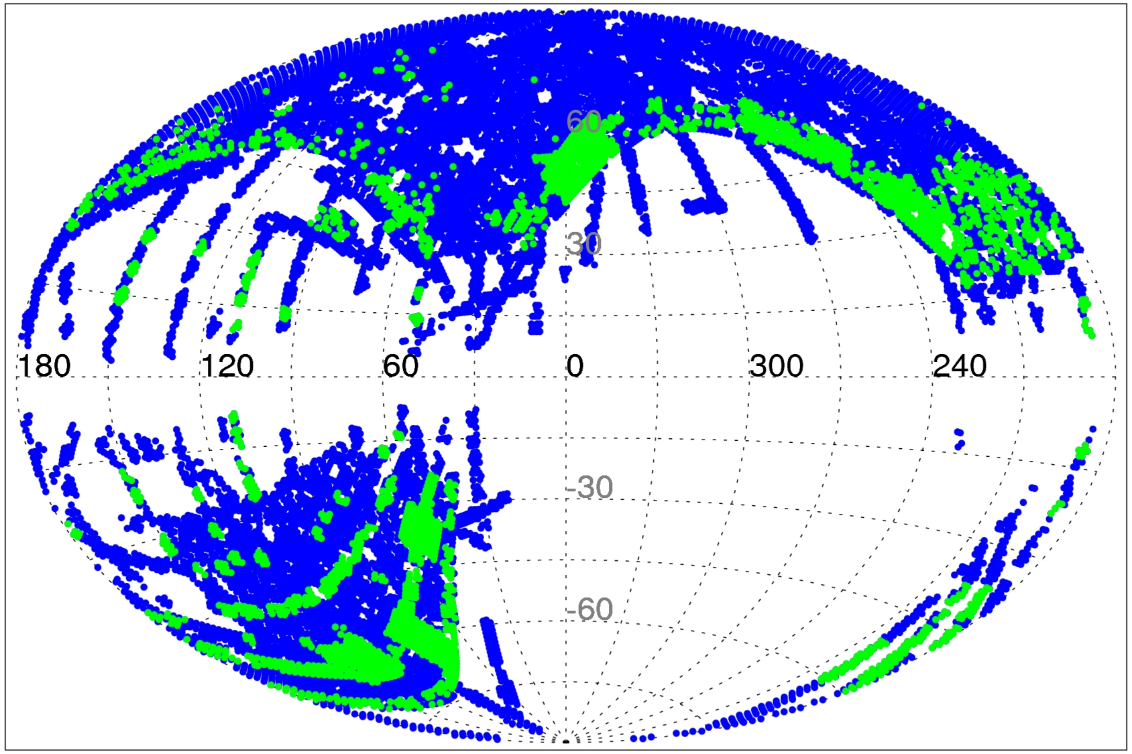
Sky coverage – GALEX GR7 ax SDSS DR9

TOTAL 43717 fields

Surv	# flds	#sources / sq. deg	Depth ABmag FUV	NUV
AIS	34207	~5000	19.9	20.8
MIS	6489	13000	22.6	22.7
DIS	>350	30000	24.8	24.4
NGS	480		27.5m/sq”	
GI	1380			
Spectra	271	127,414		

GALEX GR6/7 FUV and NUV with SDSS DR9



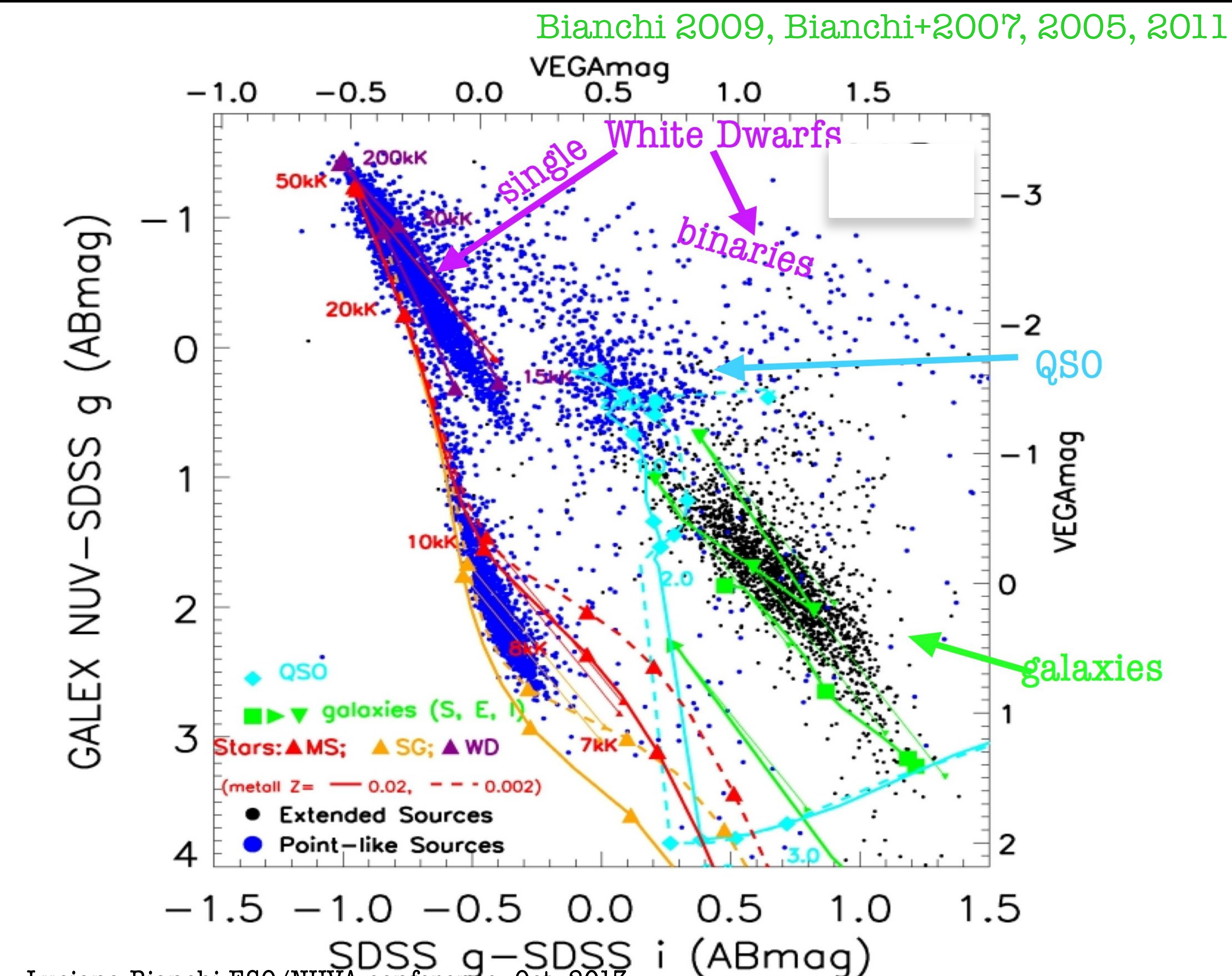
All Sky Survey (AIS) 19.9/ 20.8 (FUV/NUV) AB mag Medium Imaging Survey (MIS) 22.6/ 22.7 (FUV/NUV)

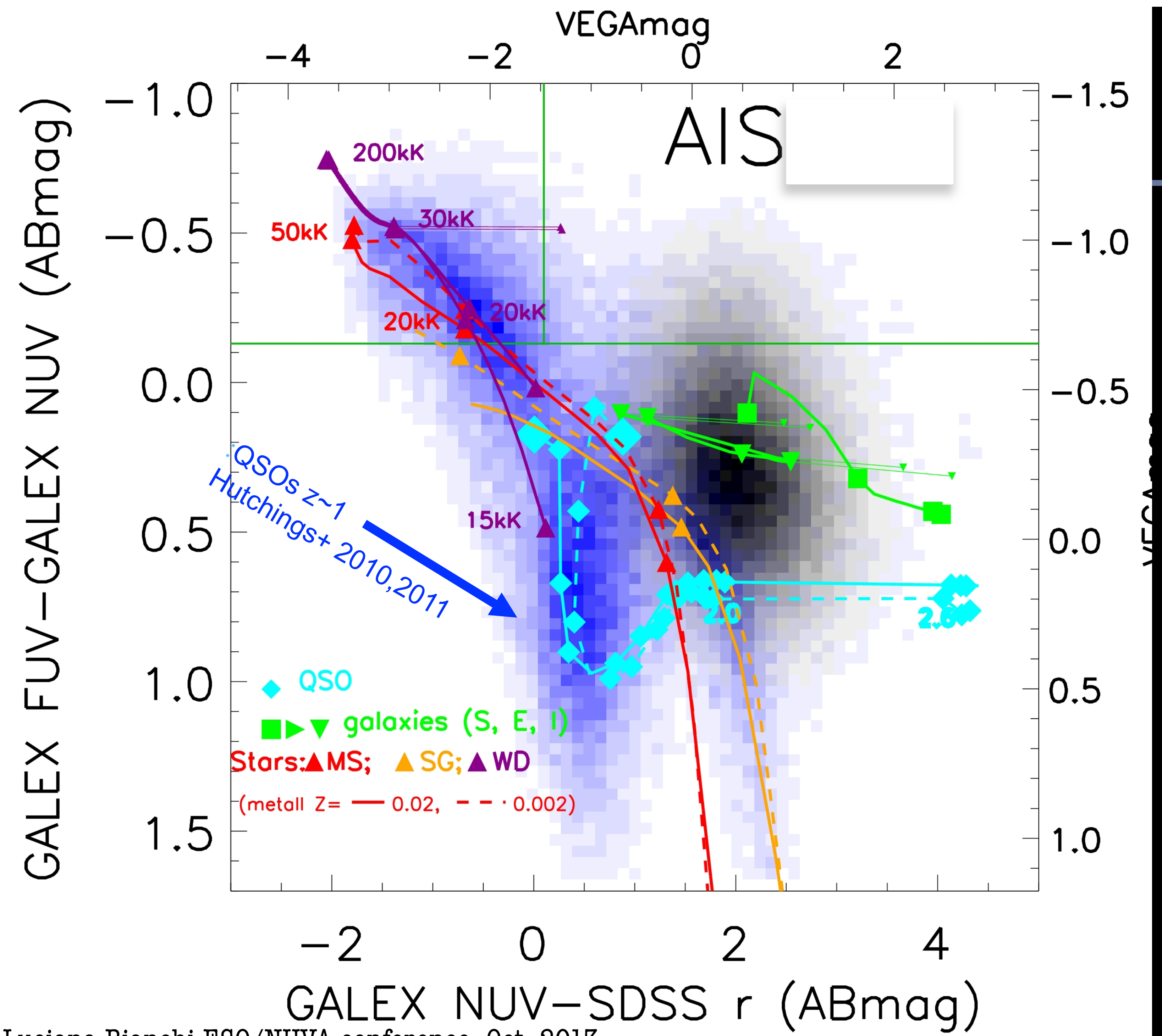
A

GALEX x SDSS → FUV, NUV, u g r i z

 # unique sources: 70.9 million AIS/ 16.6m MIS

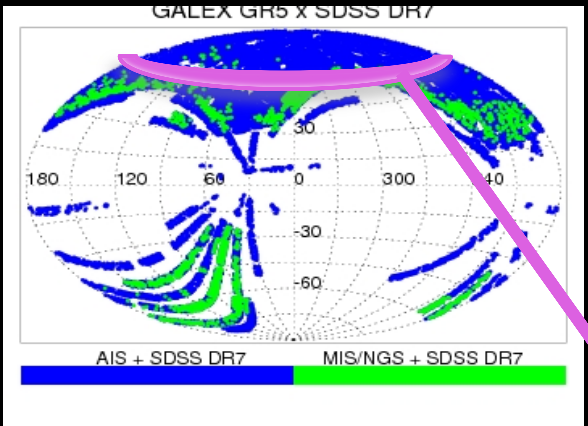
reducing field radius to 0.5deg, err <0.5mag (Bianchi et al. 2013, JASR)


Bianchi 2009, Bianchi+2007, 2005, 2011
VEGAmag
SDSS g−SDSS i (ABmag)
GALEX NUV−SDSS g (ABmag)
White Dwarfs
single
binaries
QSO
galaxies
200kK
50kK
30kK
20kK
15kK
10kK
8kK
7kK
2.0
3.0
QSO
galaxies (S, E, I)
Stars: MS; SG; WD
(metall Z= 0.02, 0.002)
Extended Sources
Point−like Sources



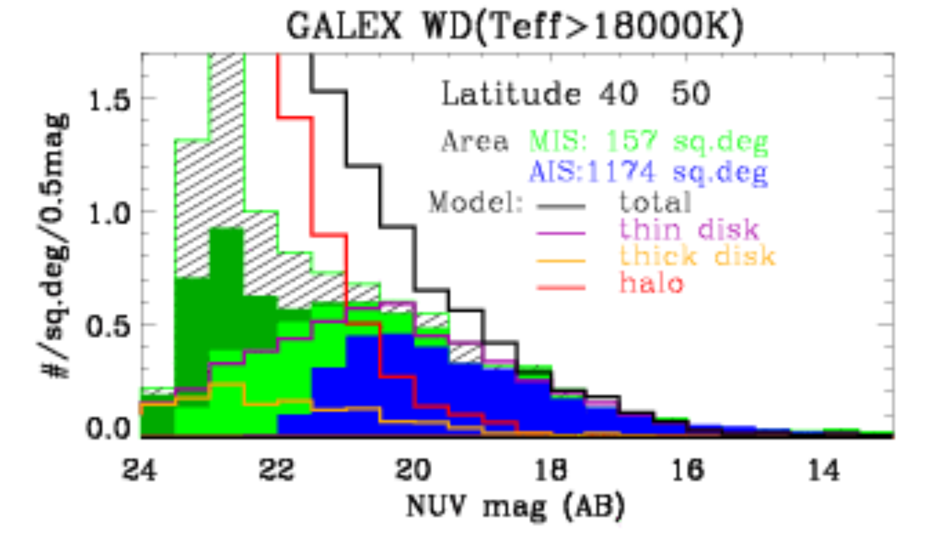
VEGAmag
AIS
200kK
30kK
50kK
20kK
20kK
15kK
QSOs z~1
Hutchings+ 2010,2011
2.0
QSO
galaxies (S, E, I)
Stars: MS; SG; WD
(metall Z= 0.02, 0.002)
GALEX FUV−GALEX NUV (ABmag)
GALEX NUV−SDSS r (ABmag)

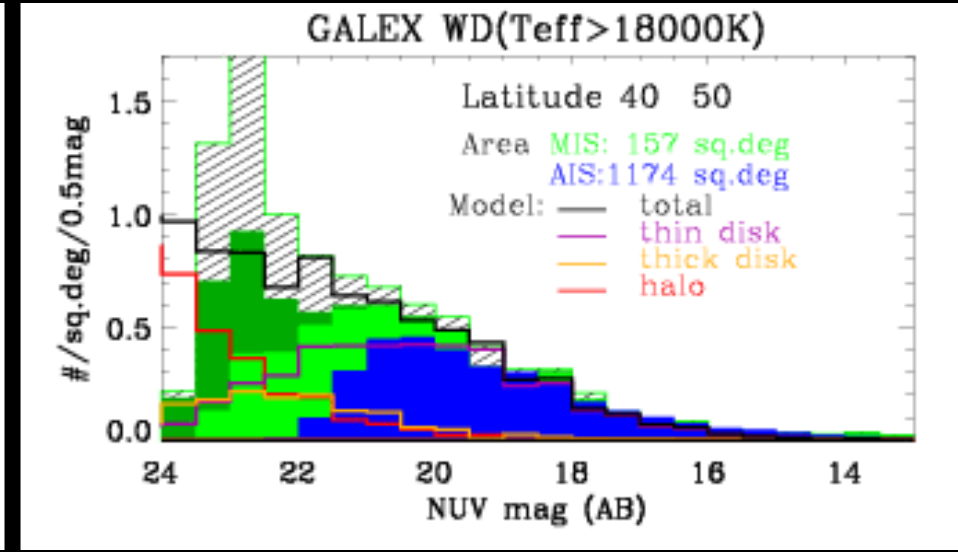
Hot WD in the Milky Way: 2dex larger sample: IFMR



We modeled WD counts with TRILEGAL (Girardi + 2005, and updates :

thin +thick disk, halo, [bulge]
Dust disk





Dashed histogram = UV-blue QSOs (see Bianchi et al 2009)

Bianchi et al. 2011, MNRAS
Bianchi et al. 2011, ApSS

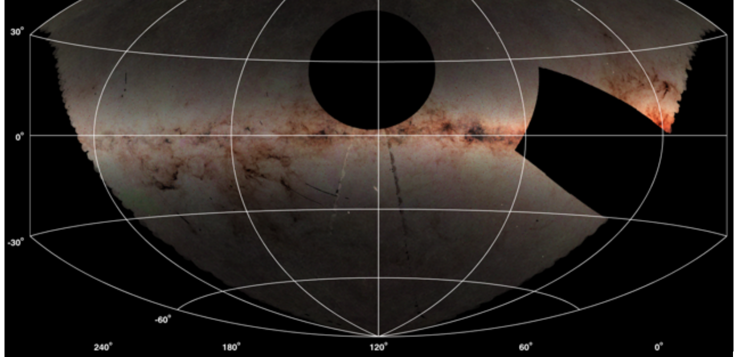
GALEX PanSTARRS PS1 3π: both FUV NUV

Pan-Starrs PS1 **3π** survey

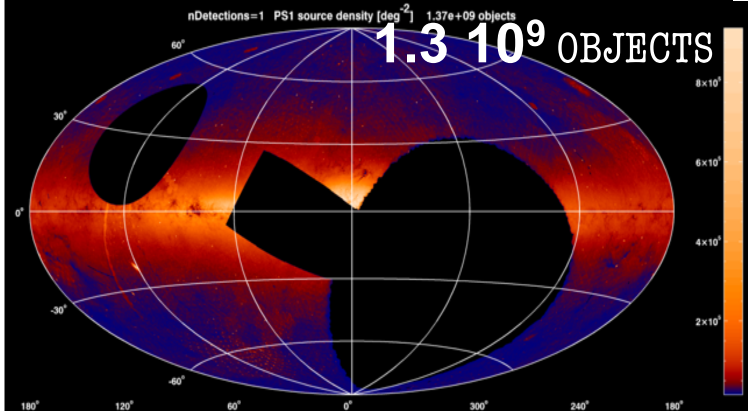
g r i z y

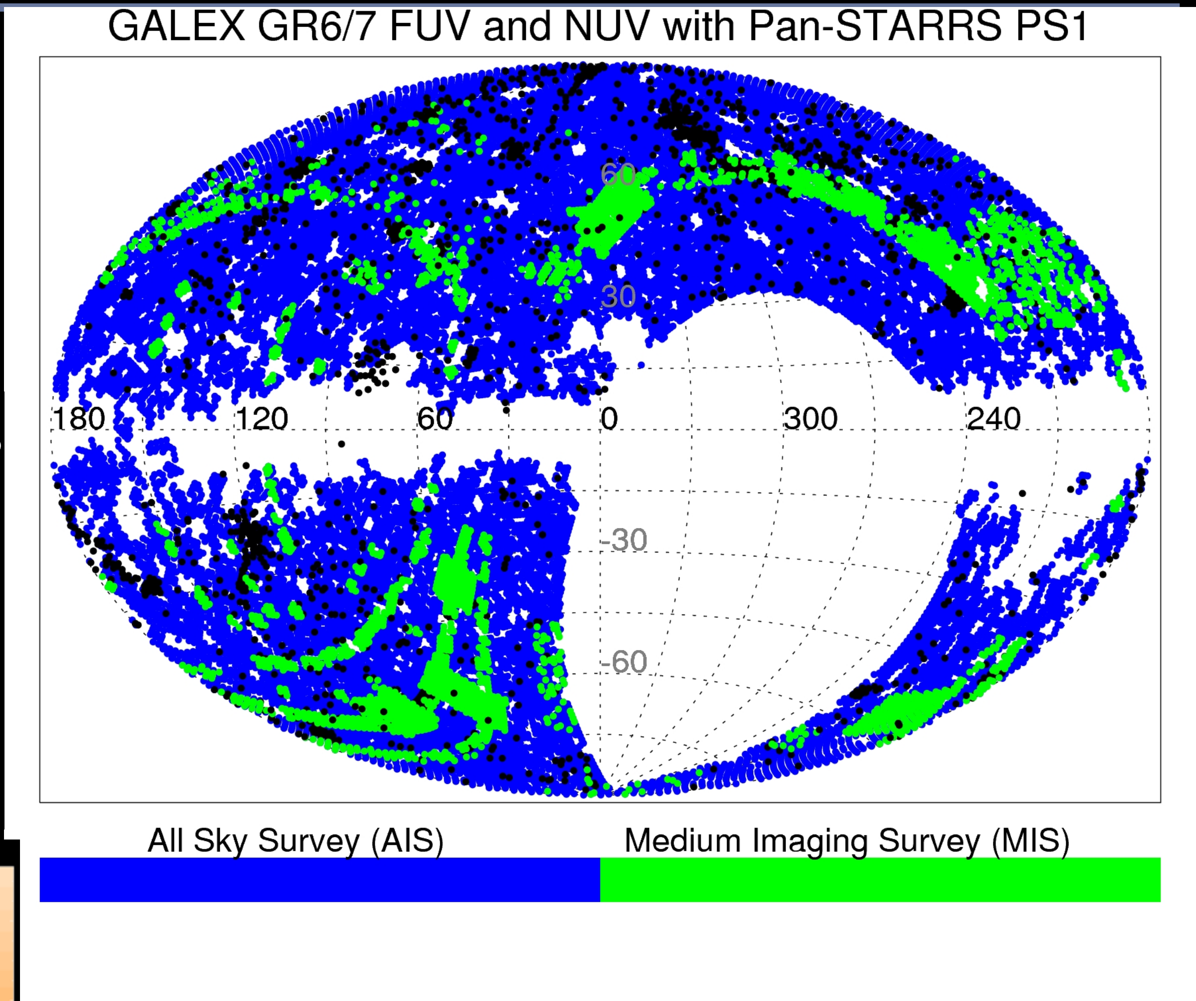
half mag deeper than SDSS,
3.6x the area coverage

mean gry color 10^8 obj w 5colors

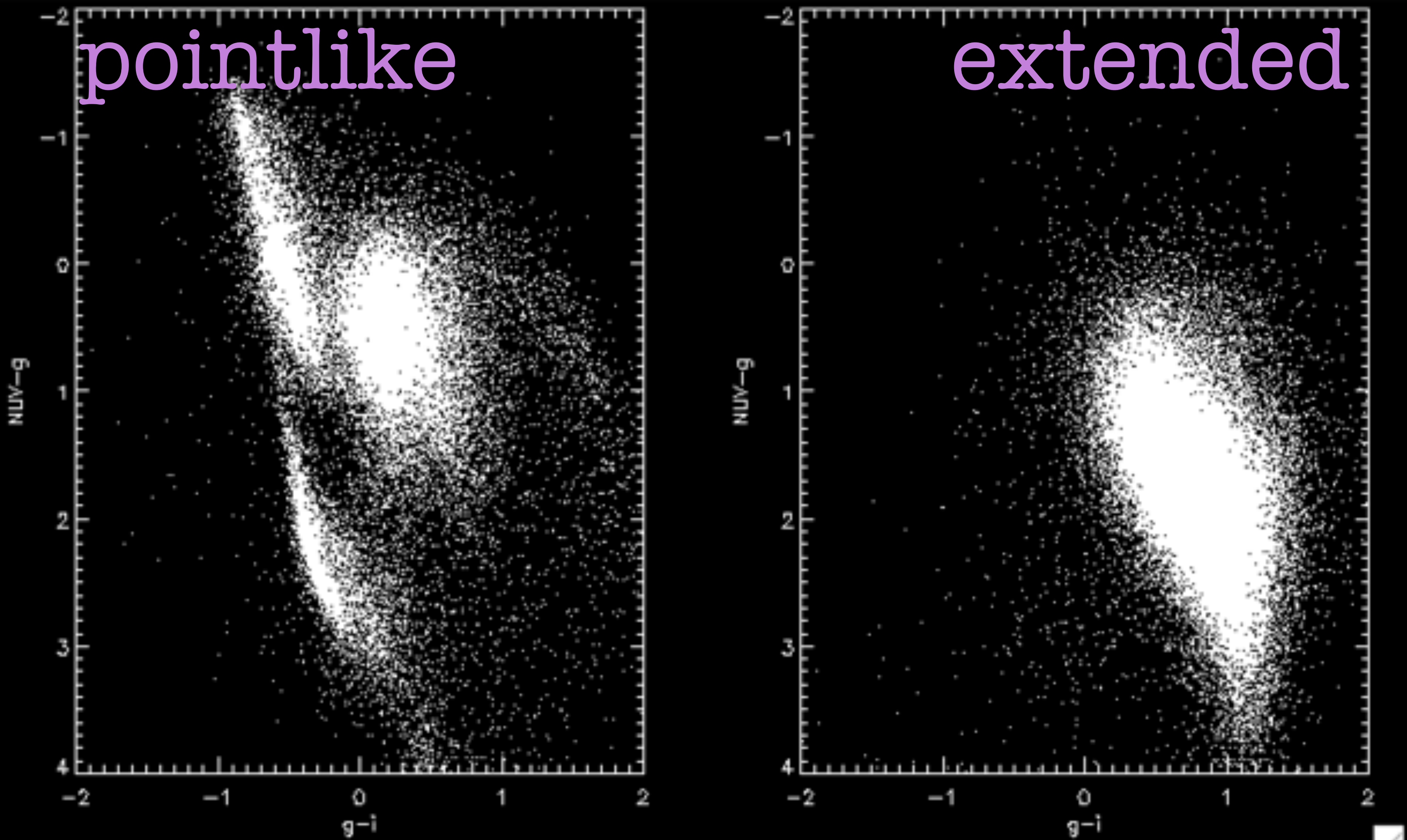


1.3 10^9 OBJECTS





GALEX x PanSTARRS PS1



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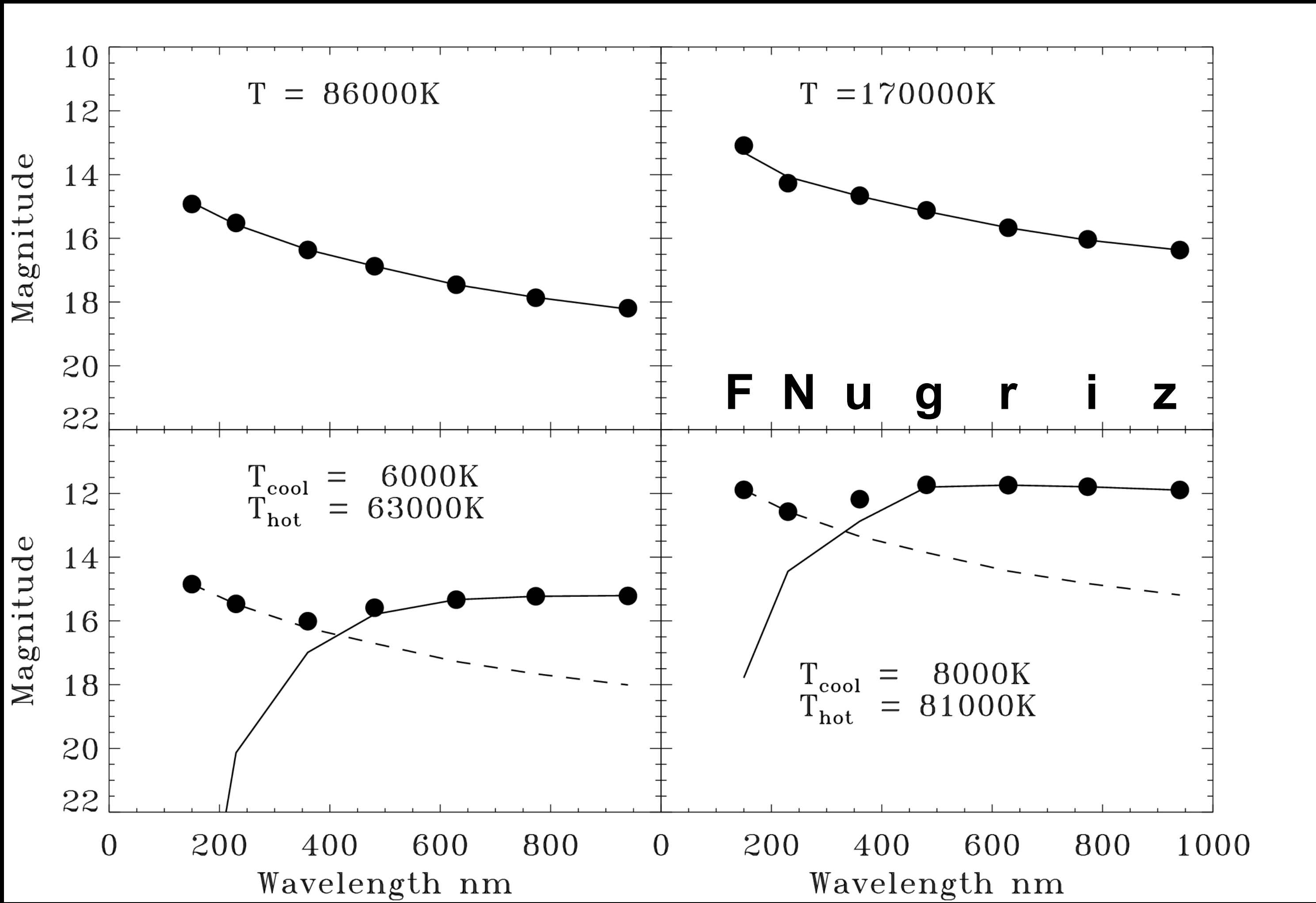
Hot WD: physical parameters



waiting for Gaia!

hot WDs , single and binaries:

elusive at all wavelengths except the UV

2dex larger sample, unbiased:

populate high-mass, hot post-AGB tracks,

important for chemical yield

(Karakas+ 2010, 2002, Marigo 2001, 2012, Bianchi+2011)

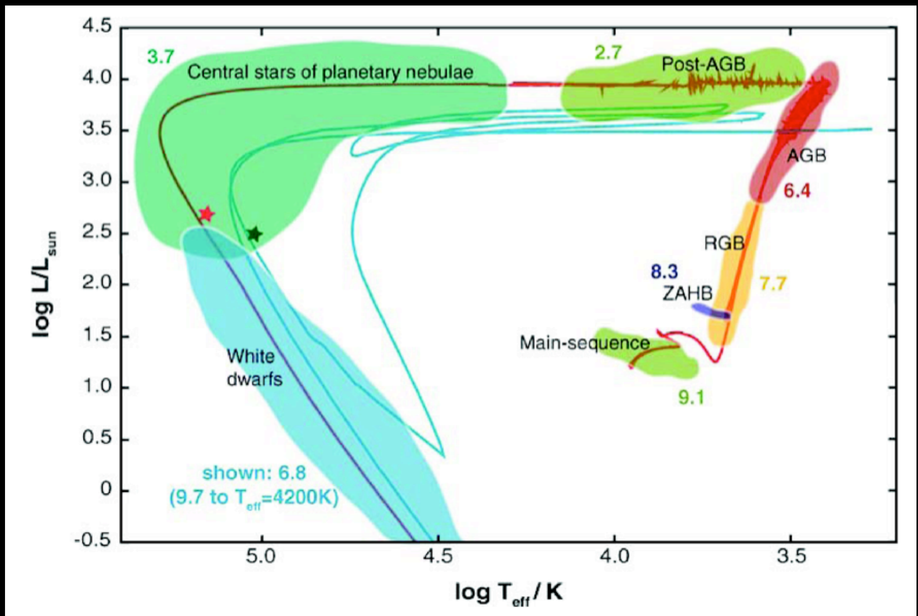


fig. from Herwig 2005

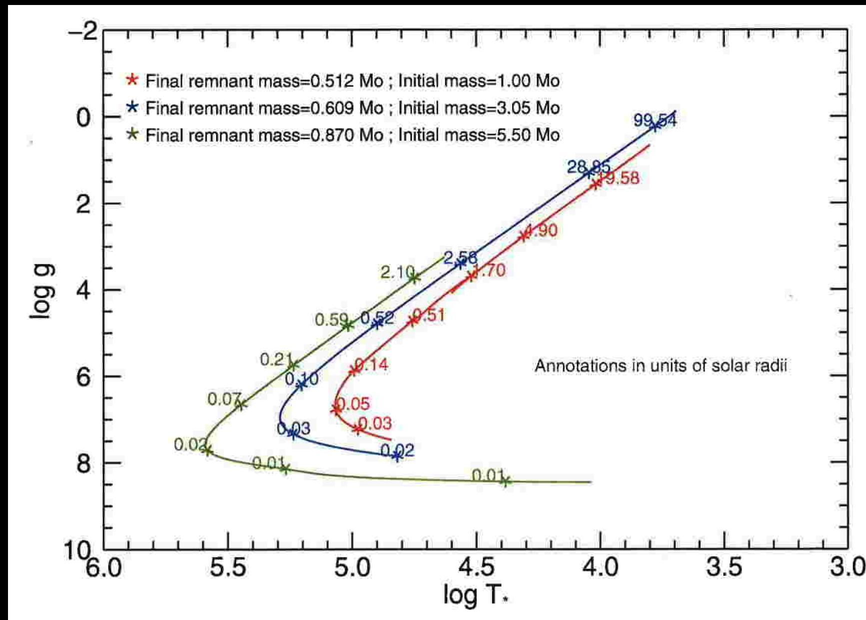


fig. credit: G.Keller

hot WDs , single and binaries:

Where are the Sirius-B systems? (WD+ m.s. K or earlier: 98 known, Holberg+ 2013, 2012, Barstow+ 2003, 2001; 8% <20pc, 1-2% <500pc -) WD harder to identify if companion earlier than M-type GALEX candidates: >>100x sample increase

Mass transfer, IFMR, SNIa progenitors?, upper mass for WD-progenitor? (pr. mass from age of the system, = of the m.s.), mass and mass-ratio of m.s. in binaries, do all barium stars need WD companion?, WD mass-radius relation

other works: Gomez de Castro+ 2011, Rodriguez+2013AAS (nearby cool young stars), Lepine+2013AAS Mdwarfs, Nemeth Kawka Vennes 2012 181 hot SD, ...

GALEX variability catalogs

Welsh et al. 2005, 2006, 2007, 2011, Wheatley et al. 2005, 2008, 2012 ;
Browne et al. 2005; Gezari et al. 2013 (~1000 w/ PanSTARRS), Cao+2012 (M31novae)

Conti et al 2013, J.ASR.2013.07.022: → 410,418 unique sources
⇒7264 at least 30 meas
w/ serend. time coverage
⇒ RR Lyrae, eclipsing binaries, flare stars, transients, QSOs

Criteria from Wheatley+2008, larger dataset

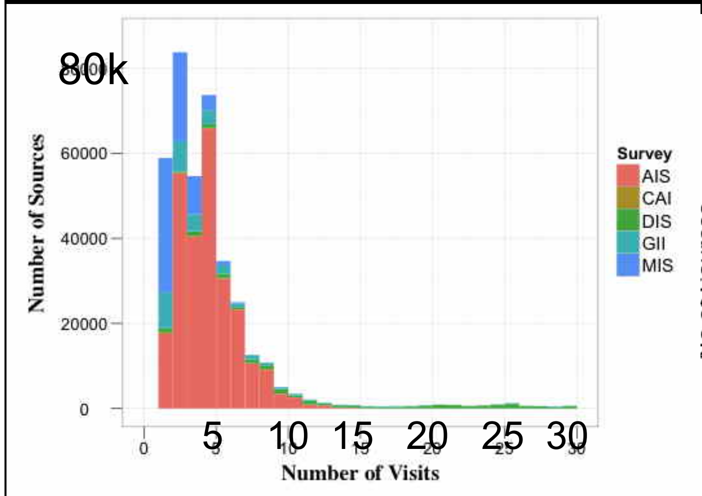
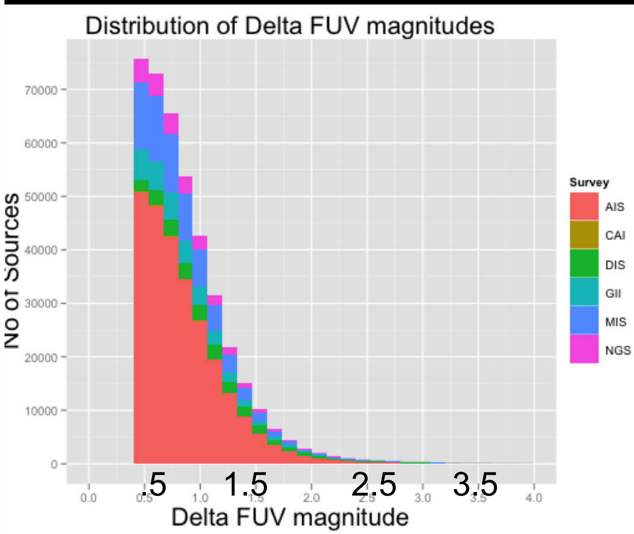
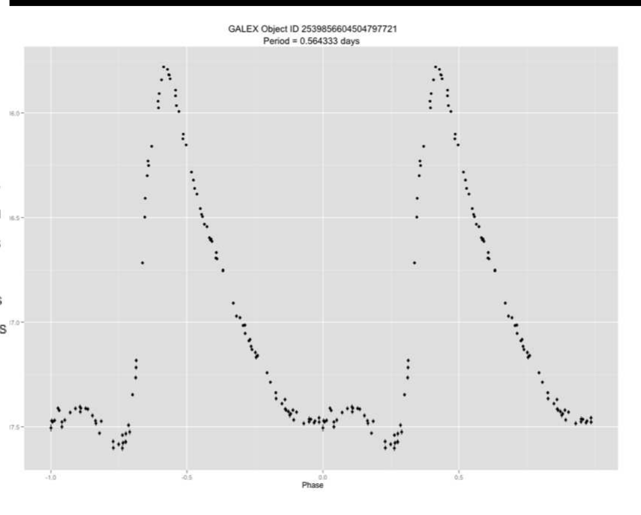


Fig. 3. GALEX Measurements per source. All sources that were observed in AIS and MIS have less than 20 and 30 visits respectively.





New GALEX Data Products arriving at MAST: http://galex.stsci.edu

Source Catalogs With Duplicates Removed

(available in CasJobs before Jan.2014)

-GCAT (Seibert et al.) AIS and MIS through GR6

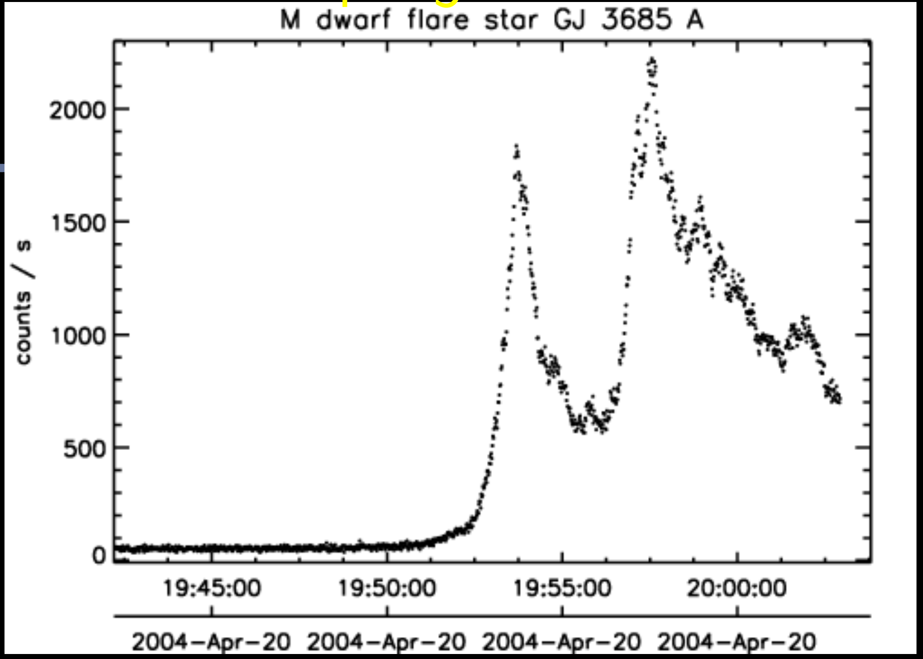
-Kepler-field-only version including GR7

-Bianchi et al. 2013 catalogs of unique sources:

- Includes all AIS and MIS tiles through GR7
- Sources cross-matched with SDSS DR9, GSC-II, PanSTARRS, 2MASS

(also at http://dolomiti.pha.jhu.edu/uvsky)

MC source photometry (Thilker, Bianchi et al)



gPhoton

- Time-tagged database of every photon observed with GALEX (~1.5 trillion photons).
- Python-based package + web interface.
- Users can create light-curves, movies, stacked intensity maps, using any set of photons.
- User-defined coordinates, apertures, time resolution.
- Beta testing is available now! Contact Chase Million at chase.million@gmail.com

main MAST portal: http://mast.stsci.edu/explore

credit: Scott Fleming

Objective 1: star formation:

follow the hot stars (+ dust)

Hot massive stars are fundamental players in galaxy evolution:

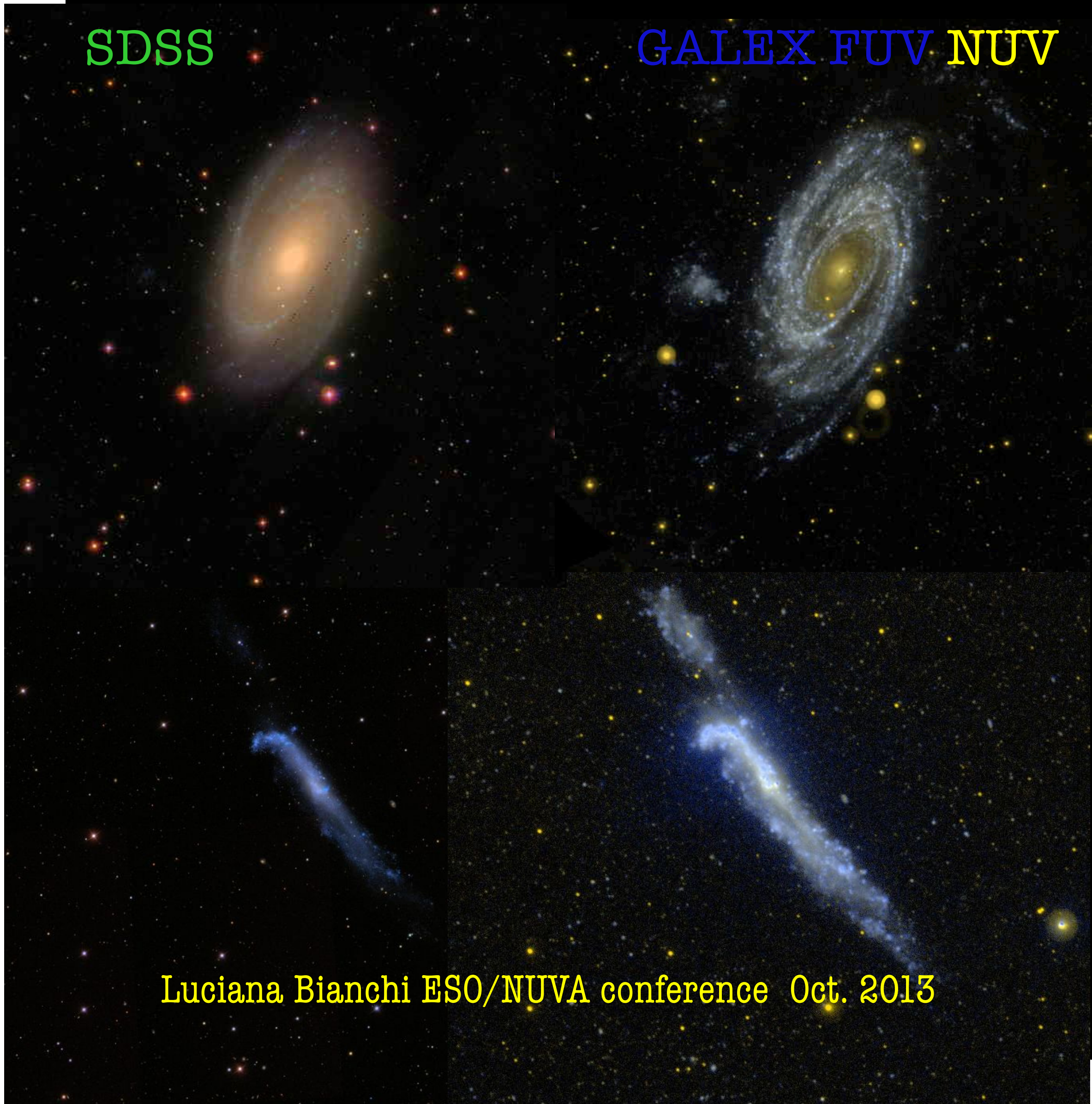
- they trace star formation: age-date, *intensity, spatial structure,*
- drive chemical and dynamical evolution of galaxies
- produce/modify dust,
- luminous: dominate light of starburst galaxies
- critical to interpret integrated light from distant galaxies

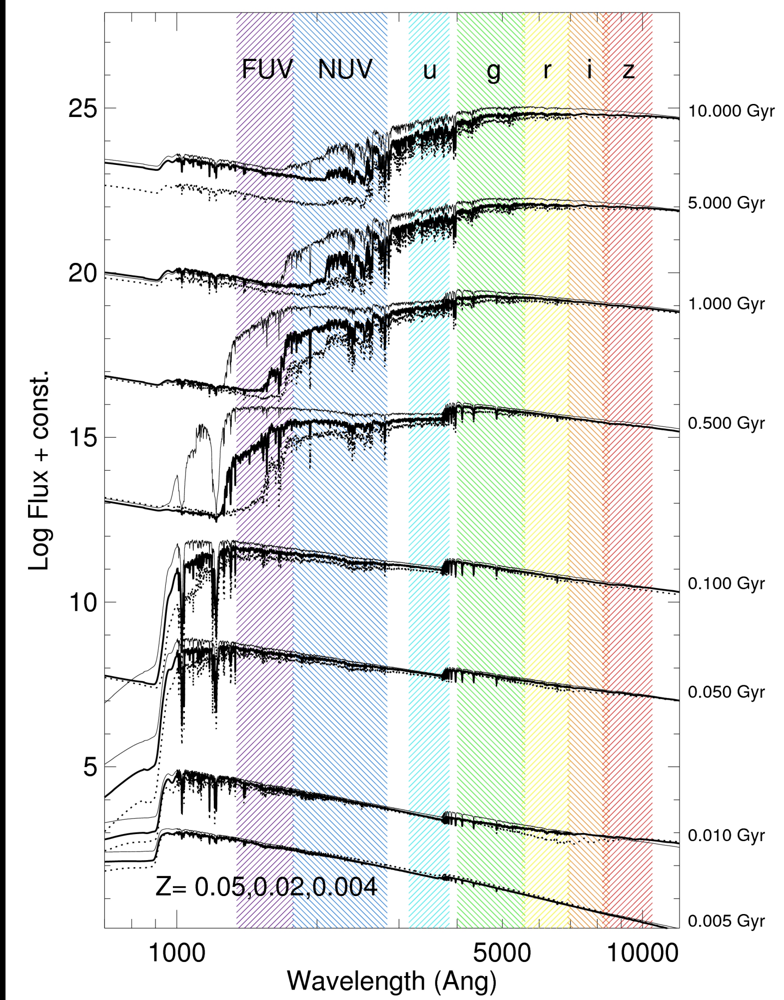
UV is needed:

UV to *identify* hot massive stars and *measure* their properties

to *identify* and characterize young stellar populations and IS dust (UV: precise age-dating, sensitive to dust properties)

UV sensitivity to SF: age, metallicity, IMF, extinction





see Bianchi 2011

M31 UV vs. Optical: Extent, structure

Limits:
FUV NUV
27.6 27.9
8e-19 4e-19

UV out to 27kpc
Ha HII reg. 20kpc

Scale ~20pc

Andromeda Galaxy
GALEX

Andromeda Galaxy
Visible light image (John Gleason)

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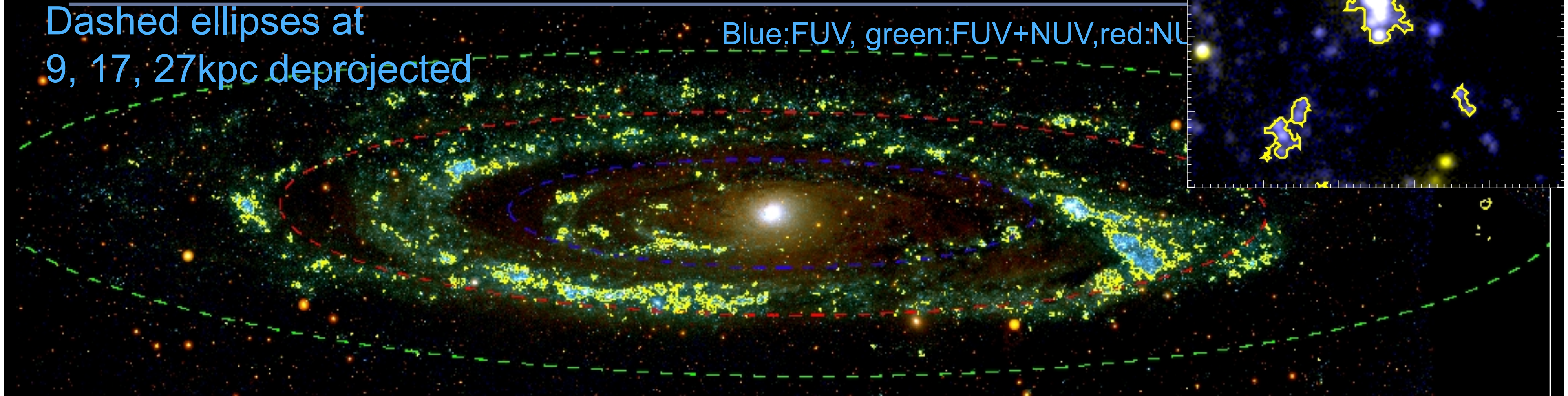
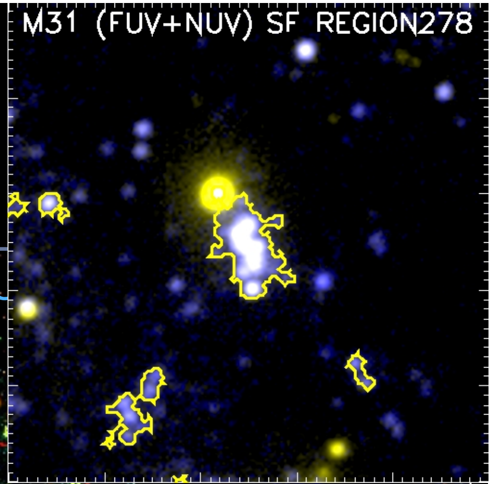
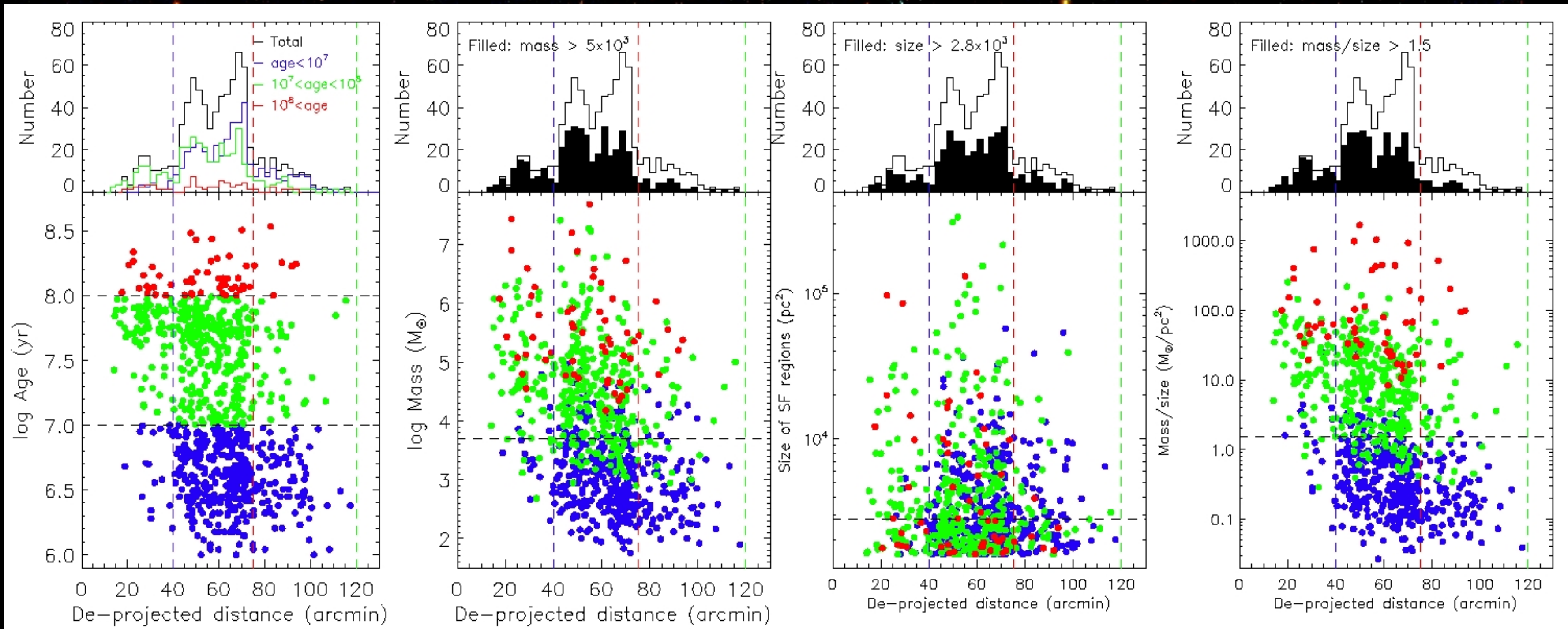
M31: SFr (Kang+2009,2013)







The result depends on the assumed type of dust, metallicity

L. Bianchi et al. / Advances in Space Research xxx (2013) xxx–xxx 9

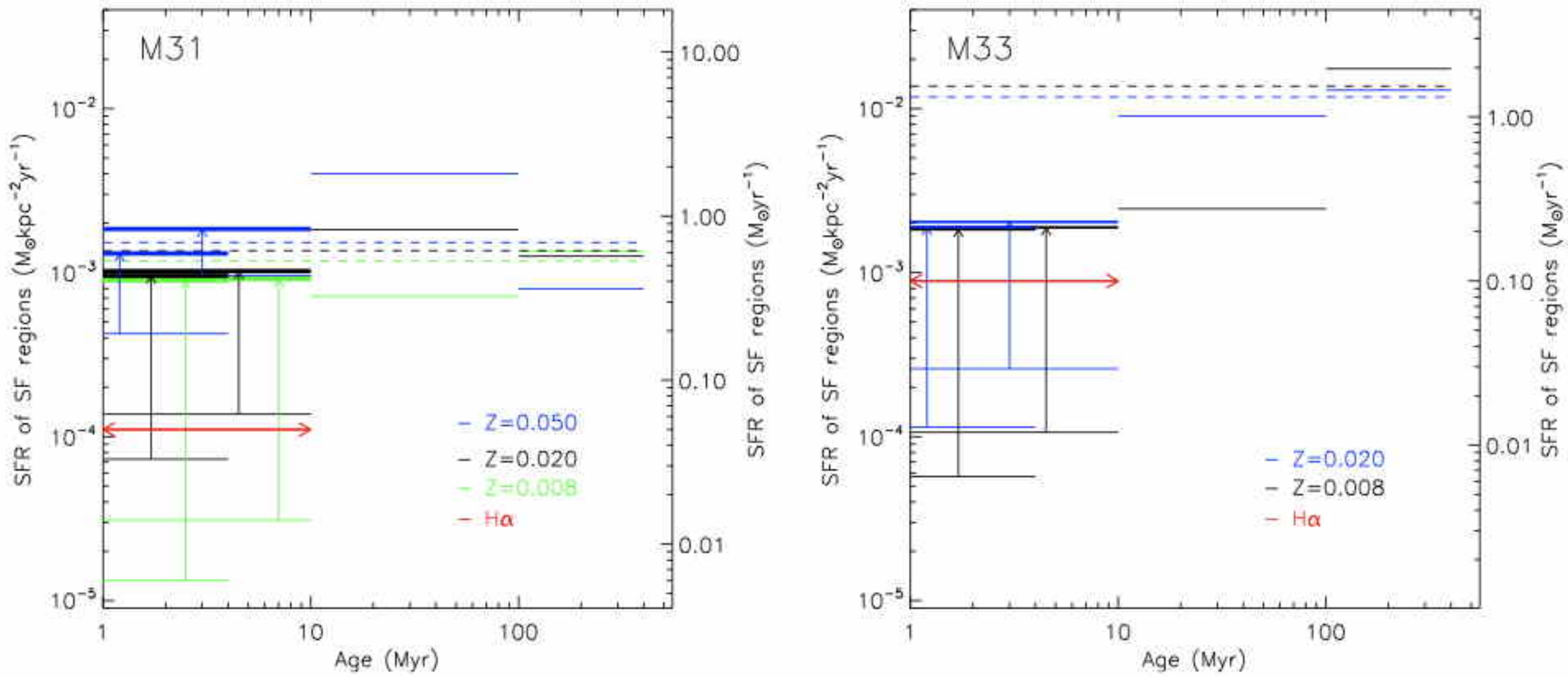


Fig. 9. The SFR estimated in recent age intervals from the FUV and NUV integrated fluxes of star-forming regions, for M31 and M33 (figures adapted from the results of Kang et al. (2009, 2013) respectively). The scale on the left Y-axis show SFR per unit area and the right side the SFR. Different colors plot results obtained assuming different metallicity values. Thick lines indicate the SFR estimated from UV and IR data combined (emerged and embedded respectively, see Kang et al. (2009, 2013) for details). Red lines are estimates from H_α.

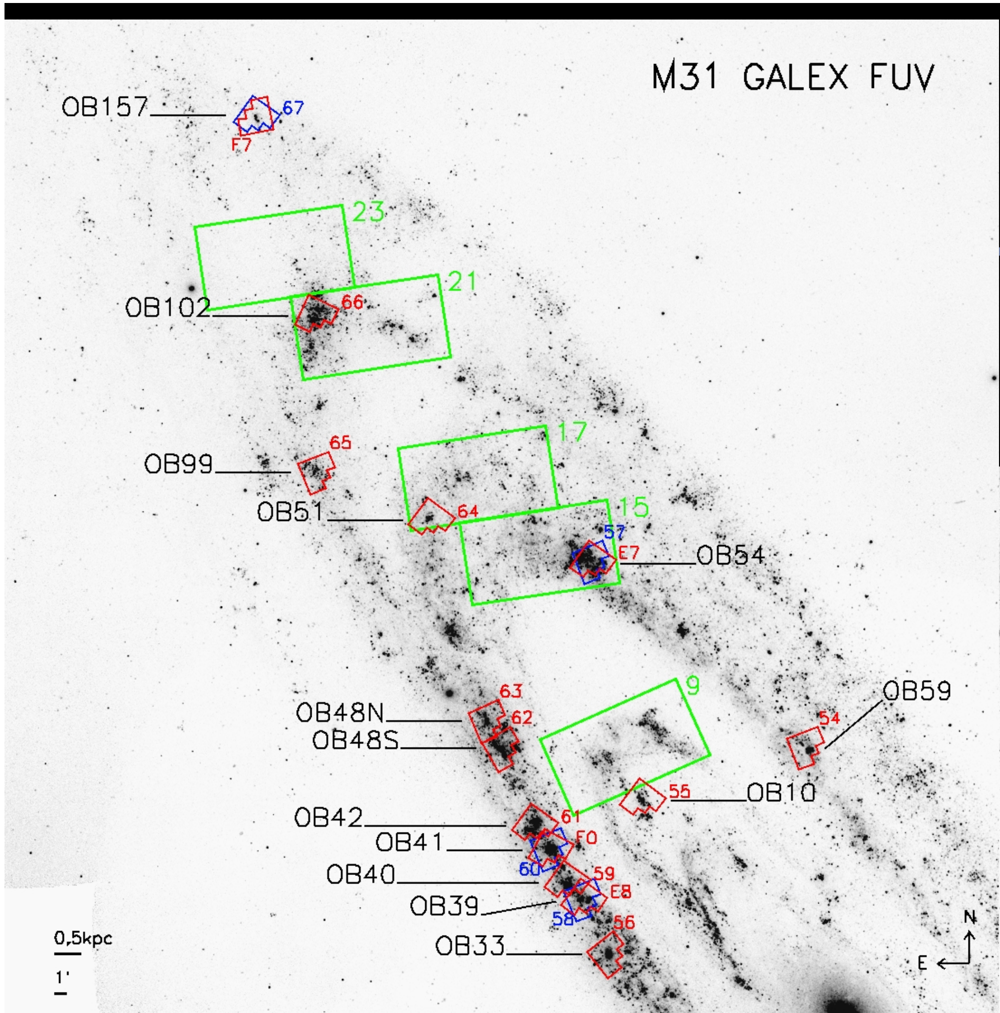
see also Simones, J, 2013,

TrimS:

Bianchi HST treasury:

FUV, NUV, U B V I

8 galaxies, 882 HST images



PHAT M31 brick(6x3)

NUV , U G 2IR

465 sq.arcmin 24.2kpc²

114kpc² 828orbits

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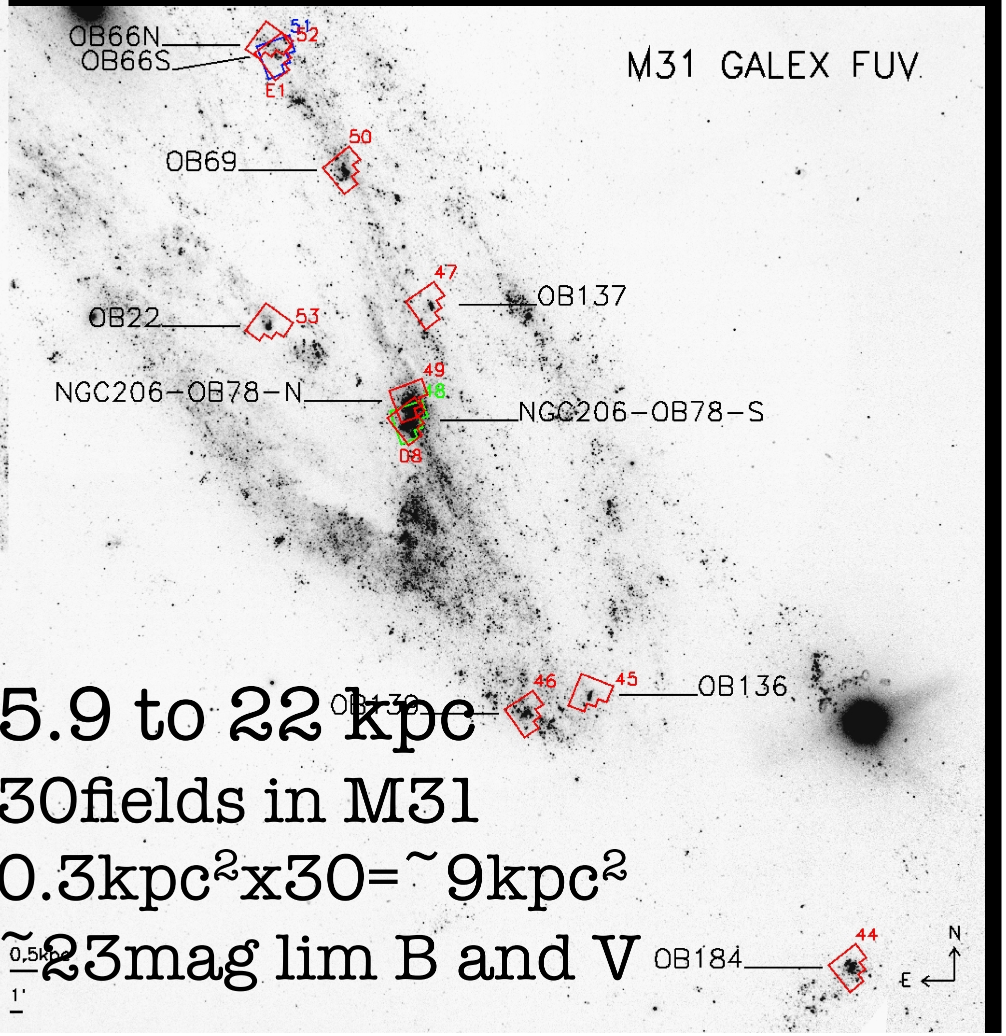
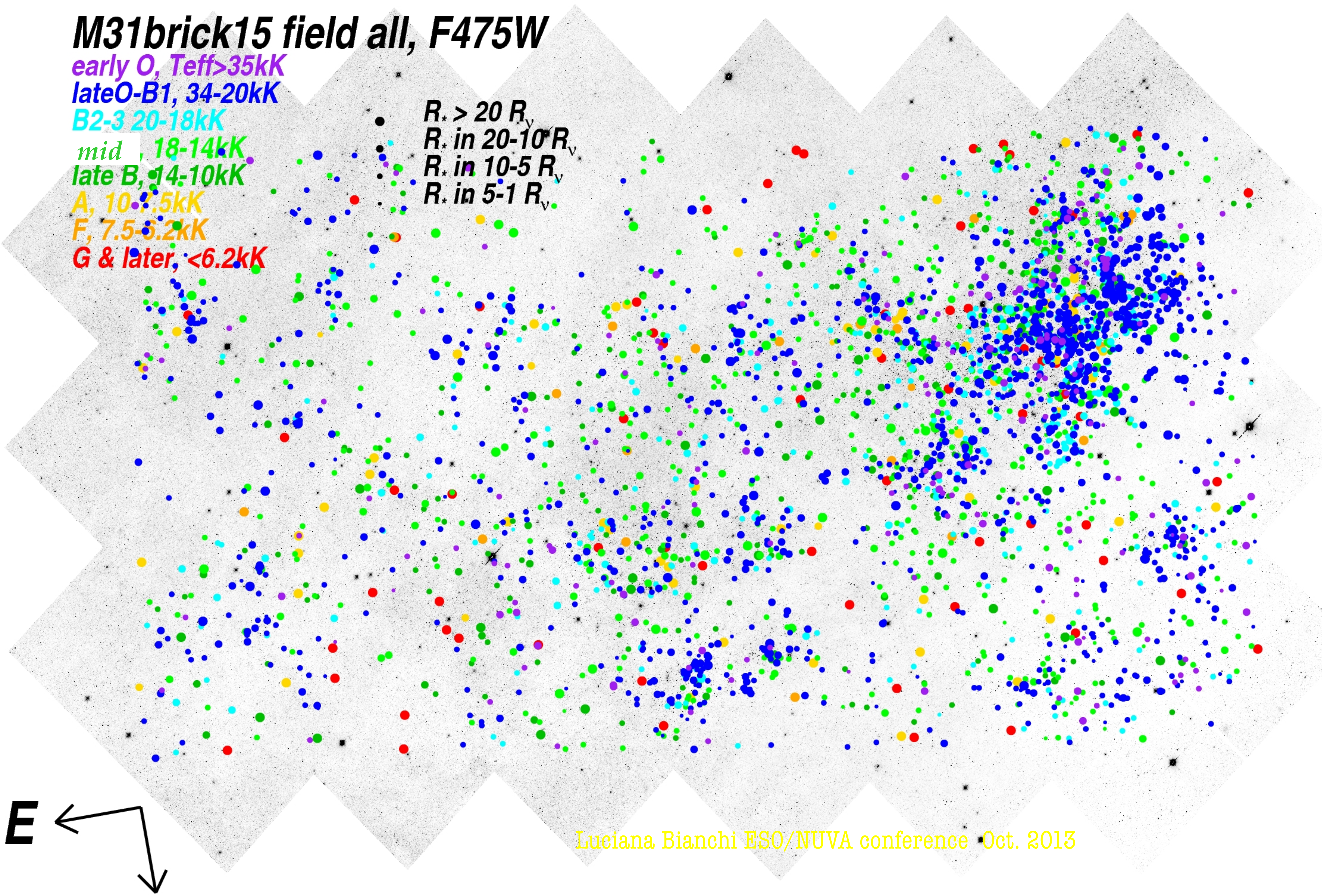


5.9 to 22 kpc

30fields in M31

0.3kpc²x30=~9kpc²

~23mag lim B and V



M31brick15 field all, F475W
early O, Teff>35kK
lateO-B1, 34-20kK
B2-3 20-18kK
mid , 18-14kK
late B, 14-10kK
A, 10-7.5kK
F, 7.5-6.2kK
G & later, <6.2kK
R* > 20 Rν
R* in 20-10 Rν
R* in 10-5 Rν
R* in 5-1 Rν
E
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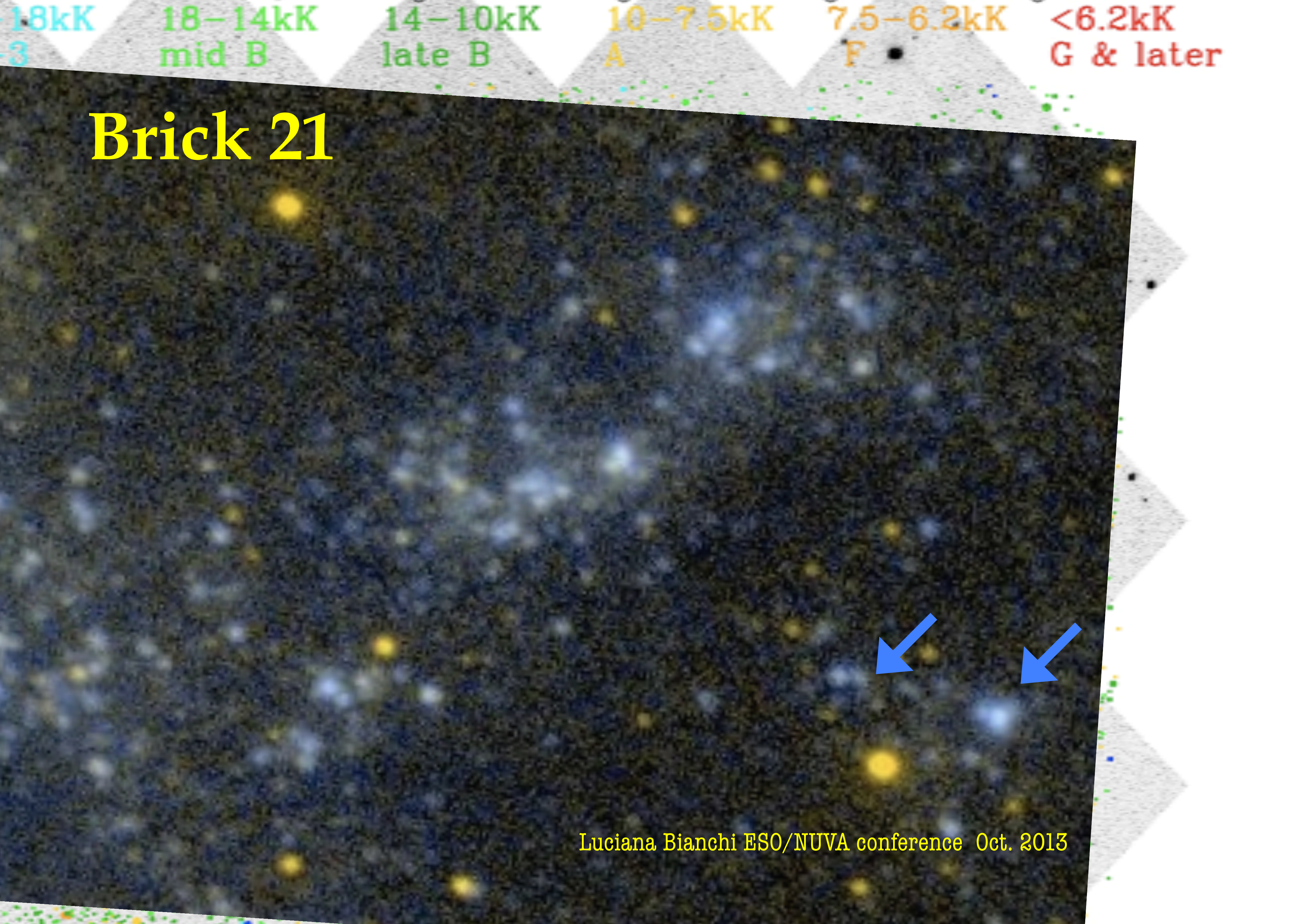
Brick 15 GALEX SF regions from FUV (Kang+ 2009)


18kK
-3
18–14kK
mid B
14–10kK
late B
10–7.5kK
A
7.5–6.2kK
F
<6.2kK
G & later
Brick 21
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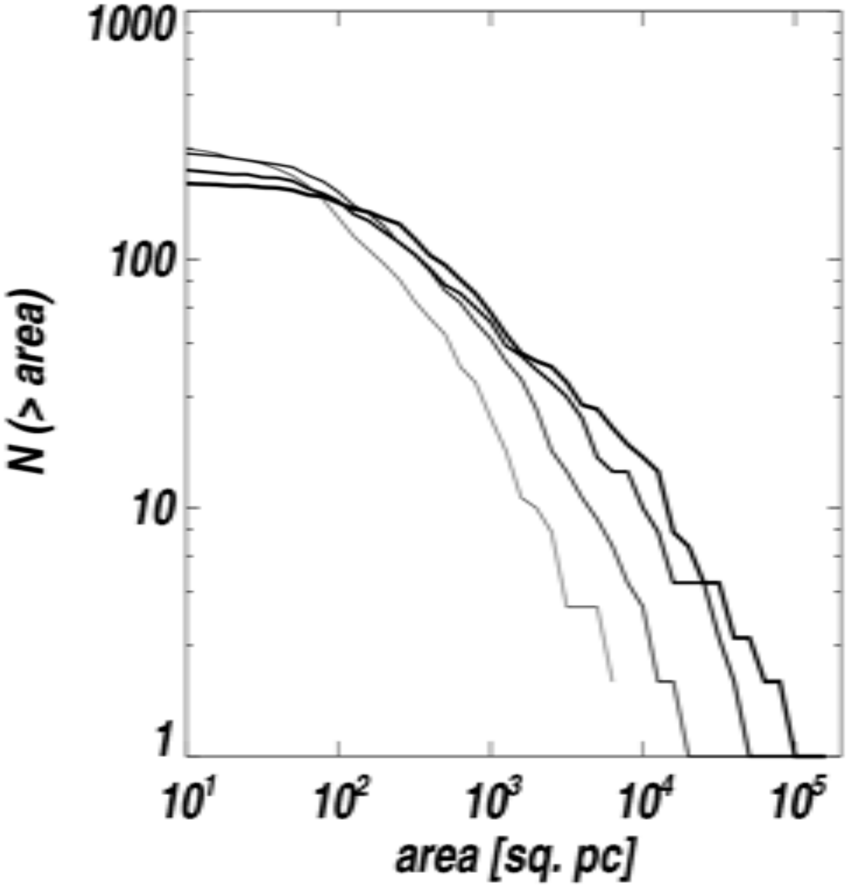
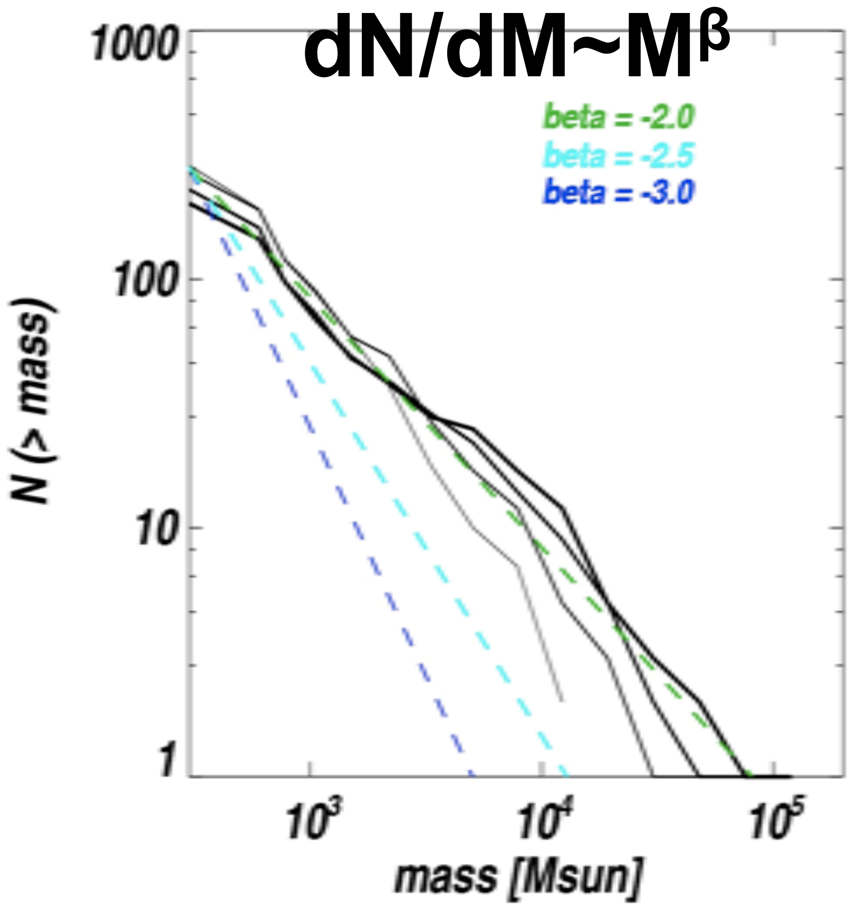
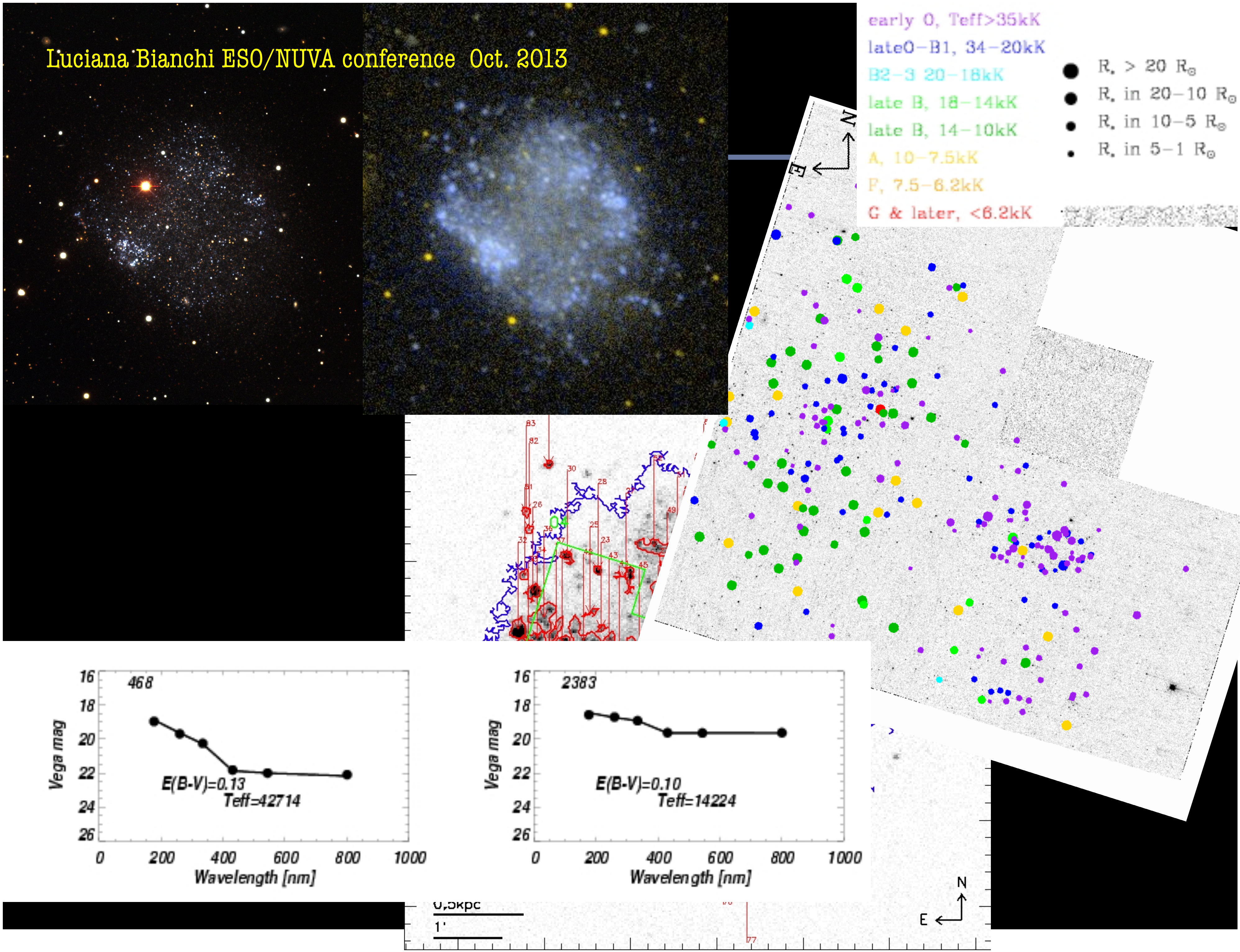
What is the mass function of OB associations?





For star clusters β~-2 . Fig.s from Bianchi et al. 2012 AJ, 2013 J.ASR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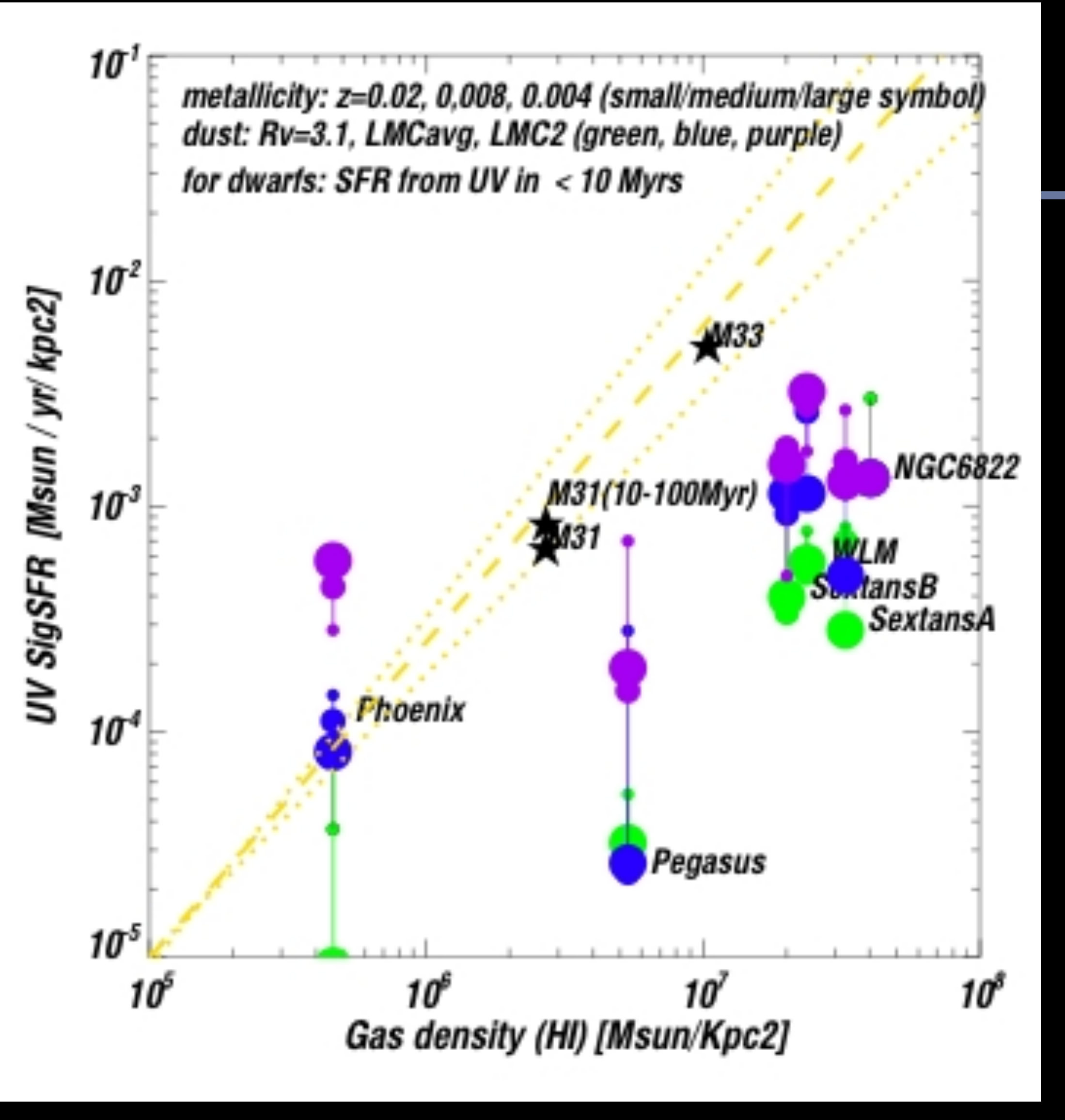
early O, Teff>35kK
lateO-B1, 34-20kK
B2-3 20-18kK
late B, 18-14kK
late B, 14-10kK
A, 10-7.5kK
F, 7.5-6.2kK
G & later, <6.2kK
R* > 20 R⊙
R* in 20-10 R⊙
R* in 10-5 R⊙
R* in 5-1 R⊙
N
E
SEXTANSA field 05, F555W
468
E(B-V)=0.13
Teff=42714
Vega mag
Wavelength [nm]
2383
E(B-V)=0.10
Teff=14224
Vega mag
Wavelength [nm]
0,5kpc
1'
N
E



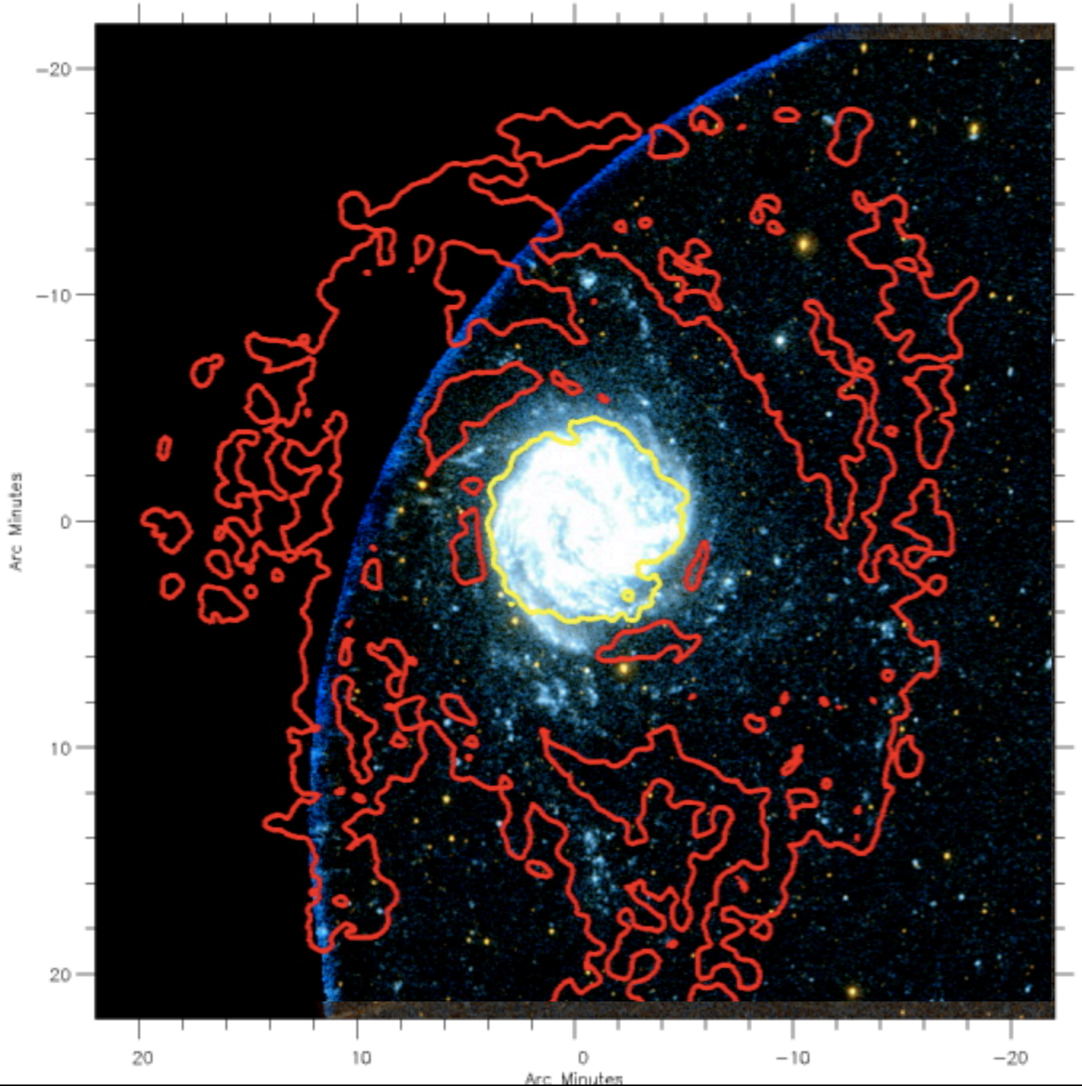
Sensitivity of the results to reddening (dust type) and metallicity. Additional uncertainty comes from the area adopted: it may vary largely between UV, optical, and HI, especially for the dwarfs (Bianchi et al. 2011b, 2012).
The Kennicutt law (yellow) was defined for disk galaxies.

Bianchi et al.2011

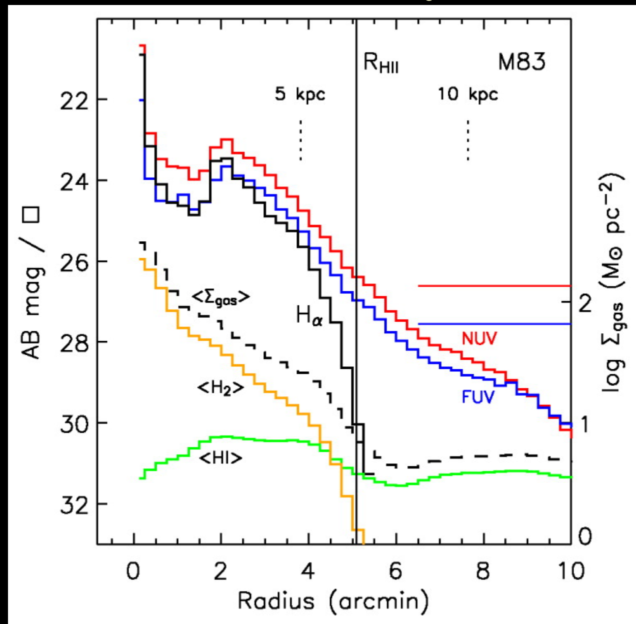
Rest UV Traces Star Formation

in disks with Extended Star Formation

M83 : Extended UV disk – discovery



Outer disk UV-clumps follow HI distribution
Red contour: N_{HI} ~ 2×10^{20} cm^{-2} S_{gas} = 0.4 M_o pc^{-2}
Toomre limit ~ yellow contour: S_{gas} = 10 M_o pc^{-2}

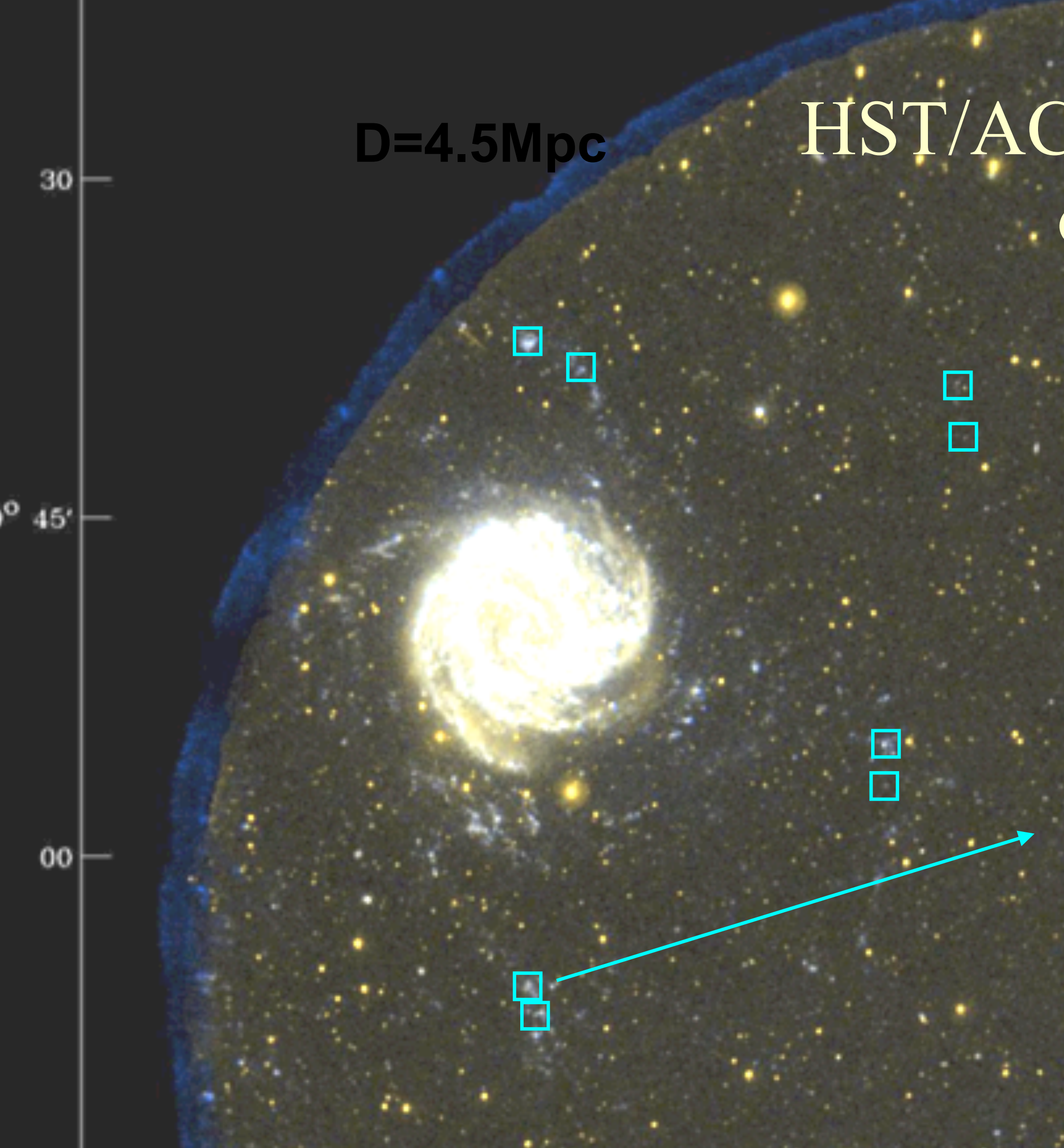


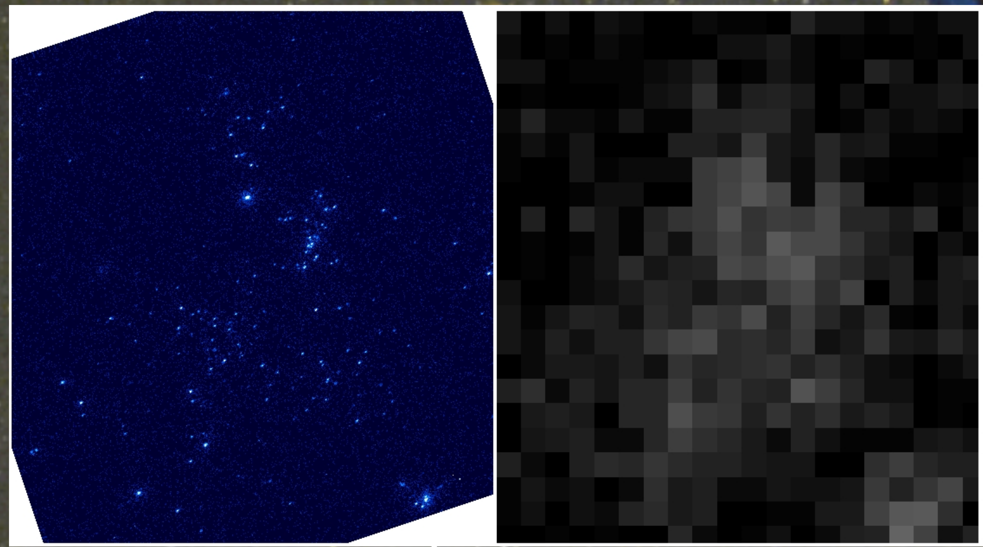
FUV, NUV, Hα median profiles
Hα-> edge , UV -> no edge
Gas profile shows extended "subcritical" disk
Few XUV disk sources have Hα (10-20%)

Thilker et al. 2005, Gil de Paz et al 2005

HST/ACS FUV-optical (B,V,I) imaging of M83's XUV-disk stellar pop.

Thilker et al. .





HST/ACS 1610Å
31x25", 700pc size,
resol 2pc

GALEX NUV
resol. ~ 100pc

– SBC+WFC observations of 8 diverse fields

Avg SFR surface density: $\Sigma \sim 2\ 10^{-5}\ M_{\odot}\ yr^{-1}\ kpc^{-2}$

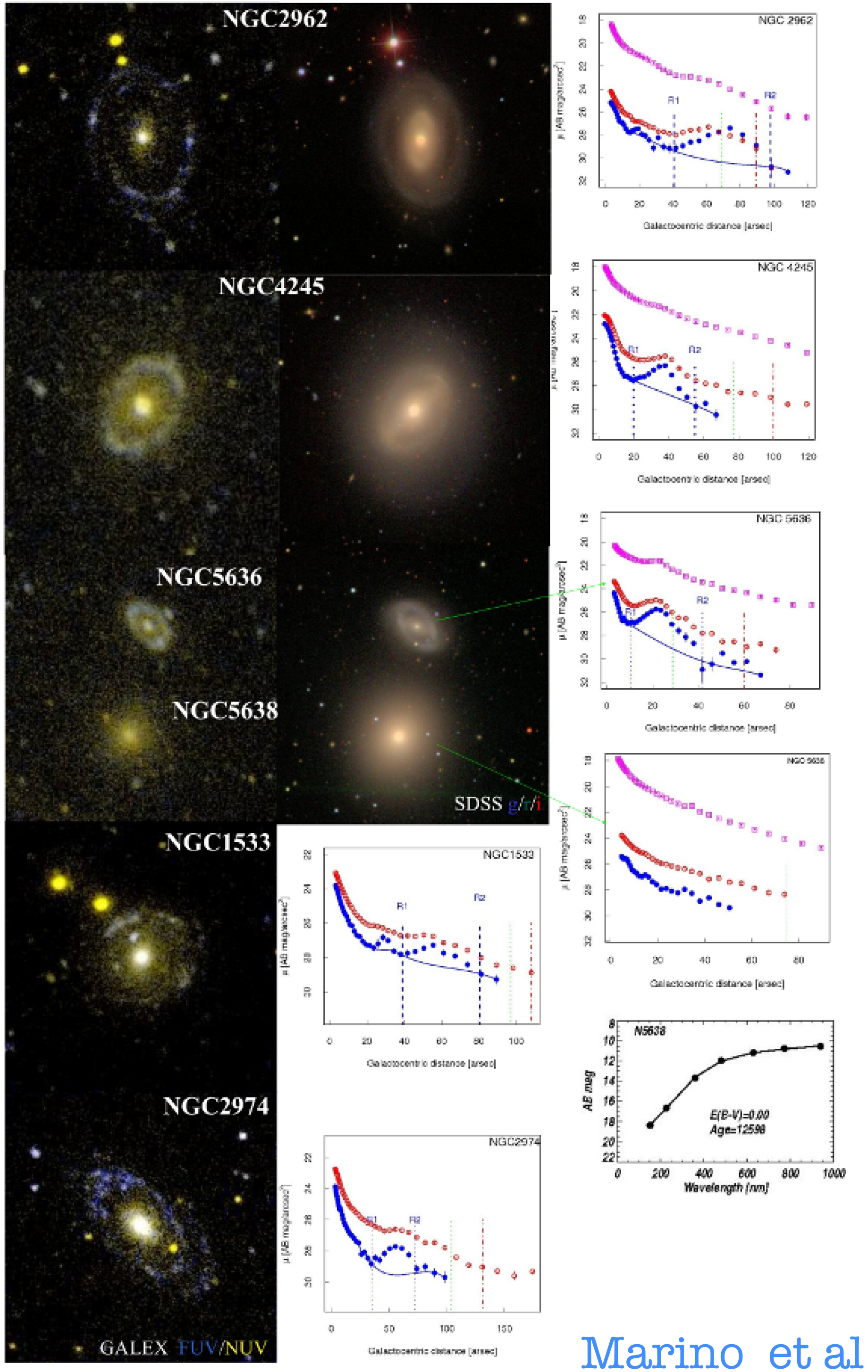
gas comsumption timescale = several times age of the universe

Dong et al., Alberts et al., Spitzer - Age ~ 100Myrs

UV detects SF rings around S0

UV is an excellent tracer of SF, therefore in UV-optical CMD the BC and RS are well separated (Martin et al. 2007, Salim et al. 2007, 2012, Wyder et al. 2007, Schawinski et al. 2007)

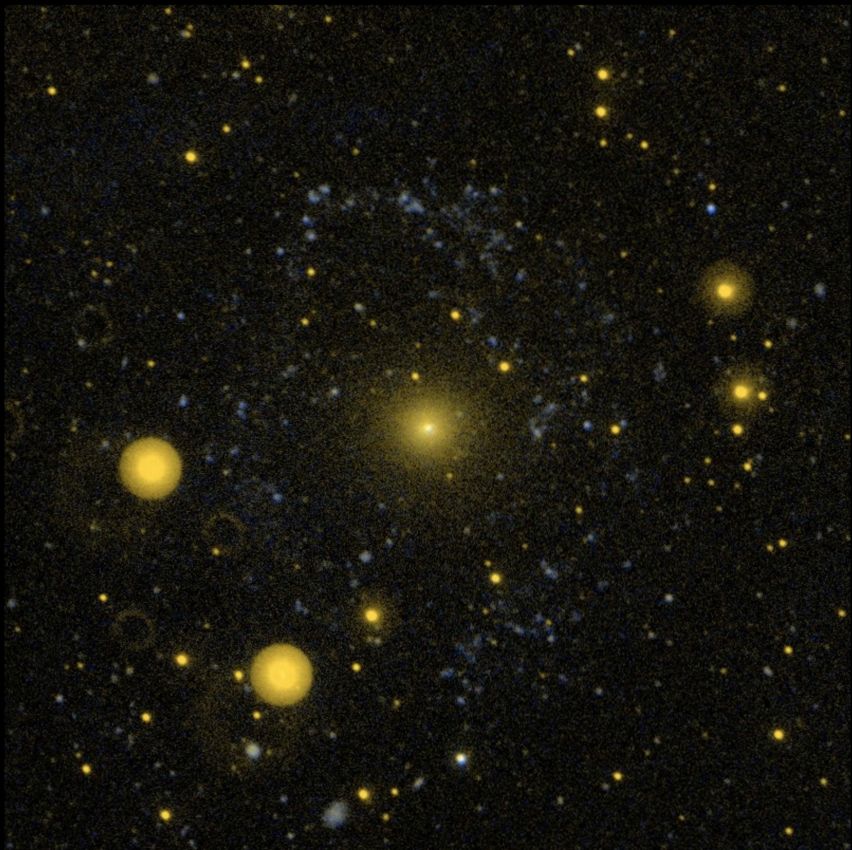
ETGs reveal outer ring-like structures in UV (e.g. Marino+ 2011, Salim et al. 2012) and in nuclear regions (e.g. Rampazzo et al. 2013)
Werk+ 2008, Donovan+2009, Mofflett +2010
chemo-photom. SPH models (Mazzei+2013)

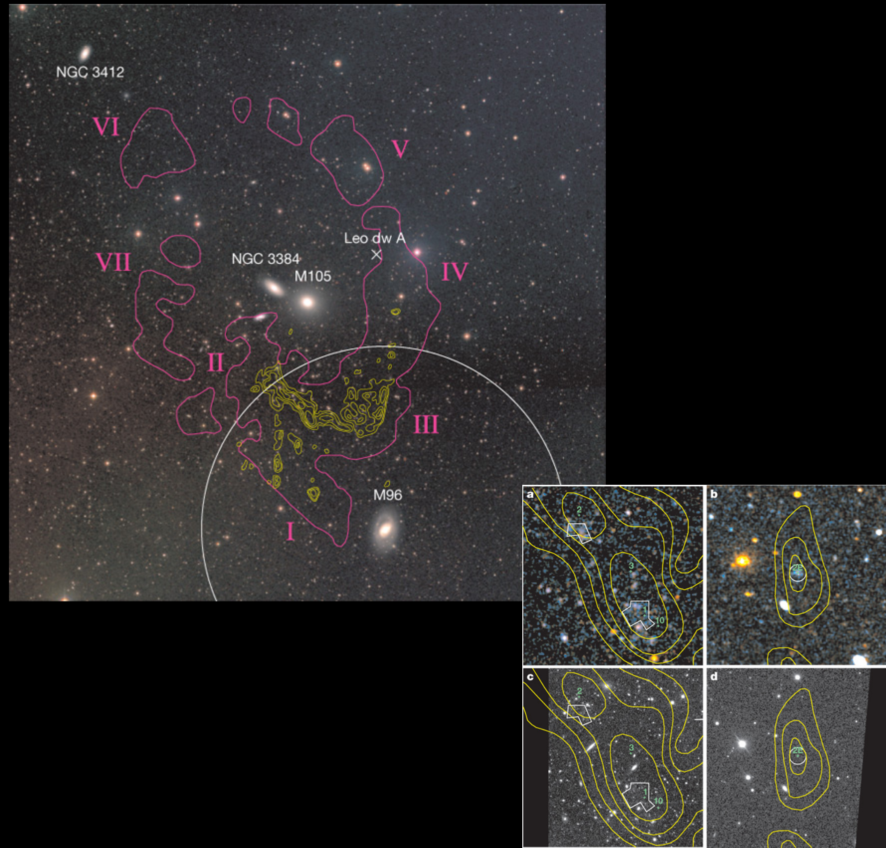


Marino et al

Luciana Bianchi ESO/NUVA conference Oct. 2013

Very low density environments



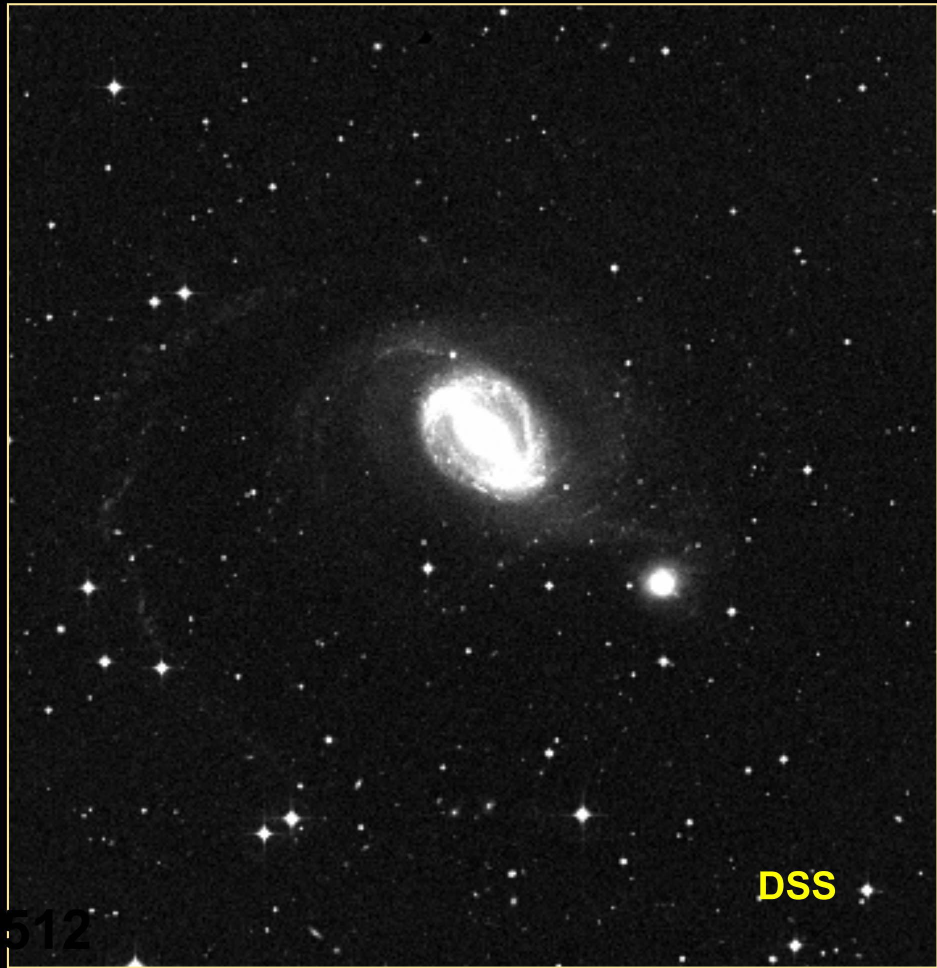


Leo Ring :
2-4 10^{-4} $M_\odot$/yr/Kpc^2
Thilker + 2009 Nature 457,990

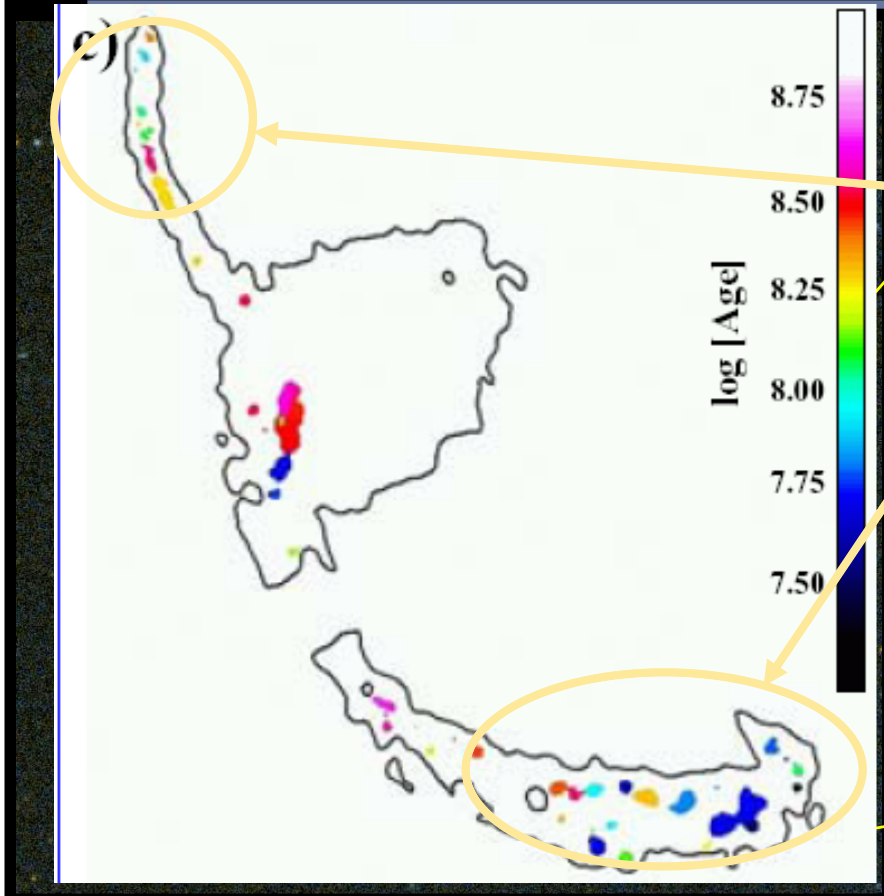
NGC404 (SO) 2 10^{-5} $M_\odot$/yr/Kpc^2
1-4 X D_{25} radius
Thilker, et al. 2009

Rest UV Traces Star Formation

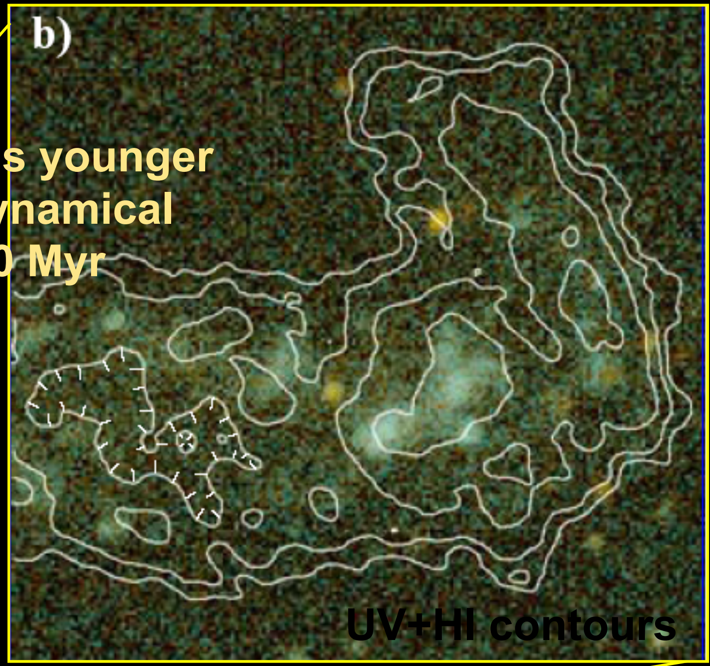
In Disks w/ Strong Driving Dynamics



Rest UV Traces Star Formation
In Merging Galaxies [Tidal Debris]



Regions younger than dynamical age 300 Myr



Hibbard et al.

GALEX (FUV) is a search light for SF:

unique sensitivity

UV colors are sensitive to age-dating, metallicity, and dust

WISH LIST:

filter complement to resolve dust-age dust-Teff degeneracy (UVIT?)

lots of spectra! [hi res. gas,dust maps]

Summary

* UV survey of the sky (FUV, NUV)
  identification and characterization of classes of objects elusive at all other wavelengths (e.g. hot WD, QSOs z~1, UVpeculiar QSOs...)

* Star formation: some of the GALEX signature results:

  calibration of SRF indicators in local Universe, deep UV maps of thousands of galaxies

  detection of SF where it had not been seen before: low SFR, low gas: IMF? disk growth?....

GALEX view of the MC

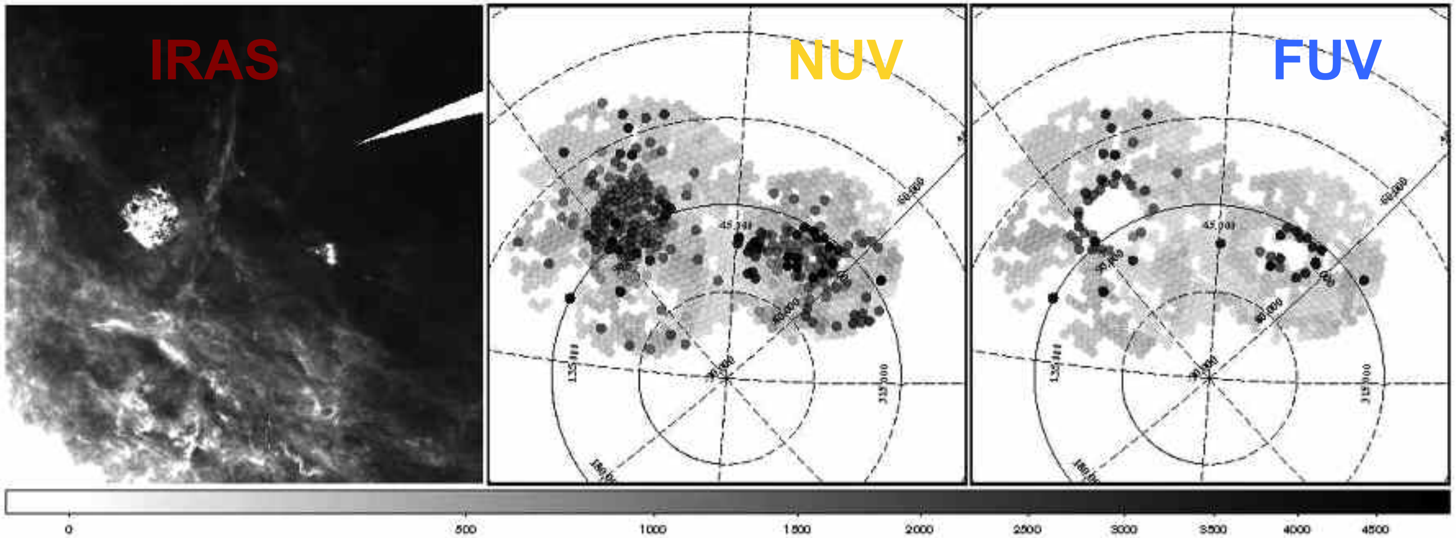


Fig. 2. Distribution of GALEX exposure times in the NUV-band for non-AIS (solid line) and AIS (dashed line) visits falling within 15° of the LMC (top left) or within 10° of the SMC (top right). In the image panel, we display the total accumulated exposure time as a function of position for the NUV (bottom center) and FUV (bottom right), in comparison to the IRAS 100 μm survey data (bottom left) over a 55°-wide field.

fields within 15deg around LMC center, 10deg around SMC:
865 visits (AIS, ~150s)+ 384 (LMC, ~730s)+ 394 (SMC)
=1643 total

NUV 5σ depth 20.8…22.7 ABmag , 6 million unique sources

Simons et al. 2013, Thilker et al. 2014 Luciana Bianchi ESO/NUVA conference Oct. 2013

GALEX view of the MC

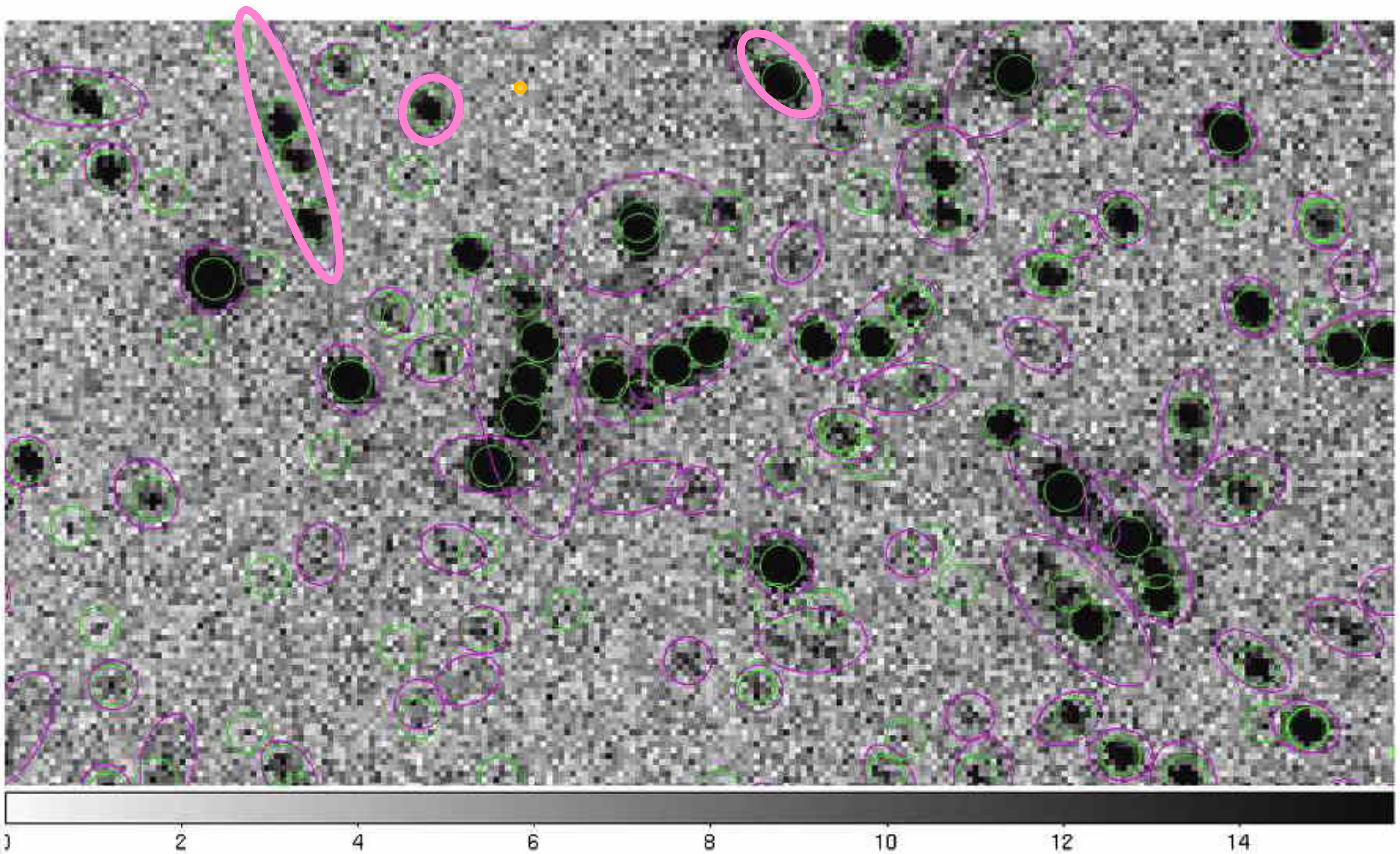


Fig. 3. Example NUV count rate image with a comparison between GALEX-pipeline (purple) and our DAOfind (green) source detections for a tile in the LMC (visit exp. 1017 s). In crowded fields, the GALEX pipeline fails to separate close and overlapping sources. Crowded regions of multiple sources are misidentified as elongated single detections by the pipeline. The DAOfind detections have not yet been pruned by significance, sharpness, or roundness at this pre-merge (see Section 4) stage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

GALEX view of the MC

Within 15deg around LMC center, 10deg around SMC:
1643 visits total , NUV 5σ depth 20.8…22.7ABmag

analyzed 384 (LMC, ~730s):
6 million unique sources (from >11million vetted measurements)

- trace to the lowest hot star density: 430 */kpc^{-2} [NUV<19]

- >2 x10^{5} */kpc^{-2} [19mag]= ~50 */arcmin^{-2} (all mag: 10x)

- trace LMC SF out to 10deg.

presence of dust: bright regions with scattered light

and dark absorptions

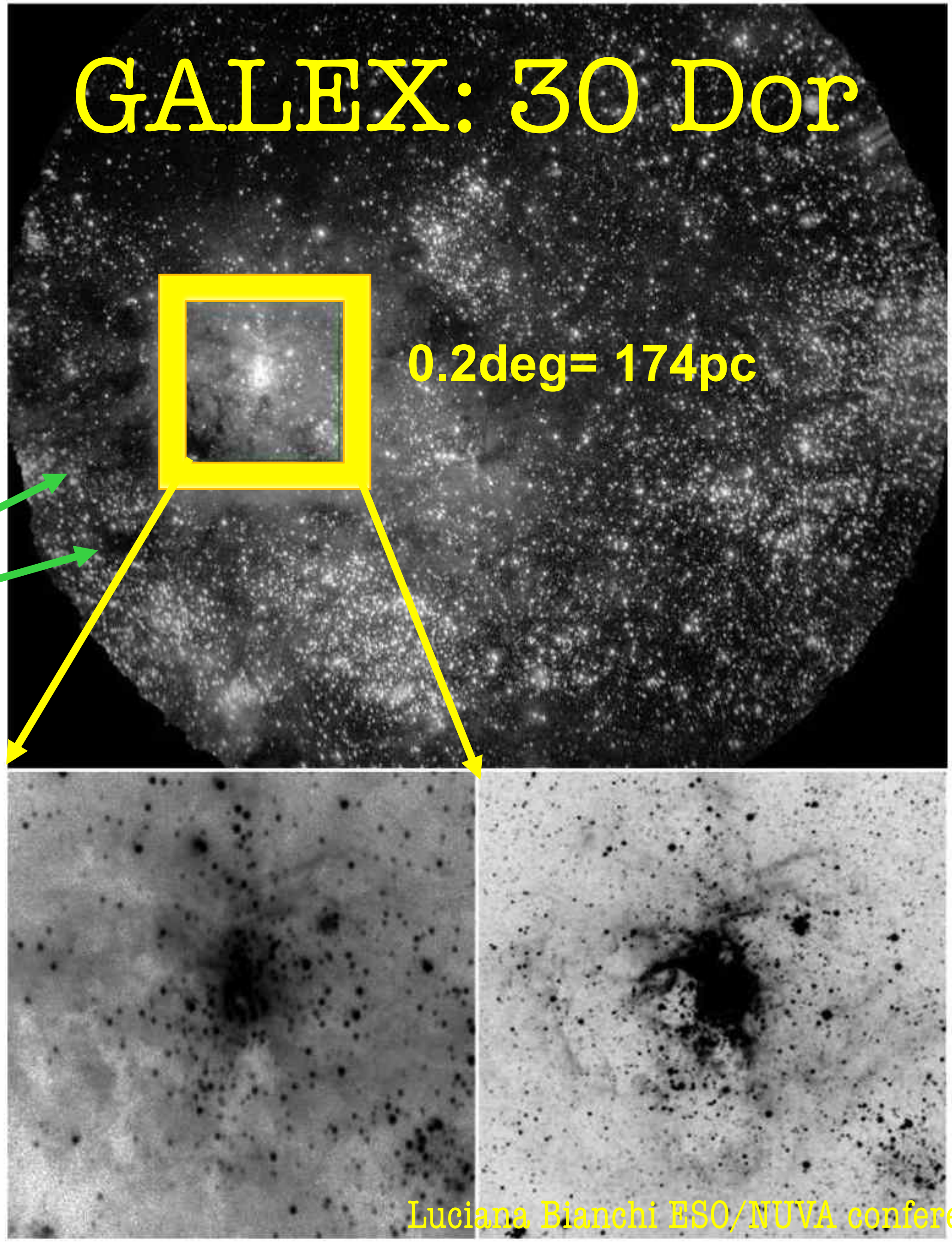
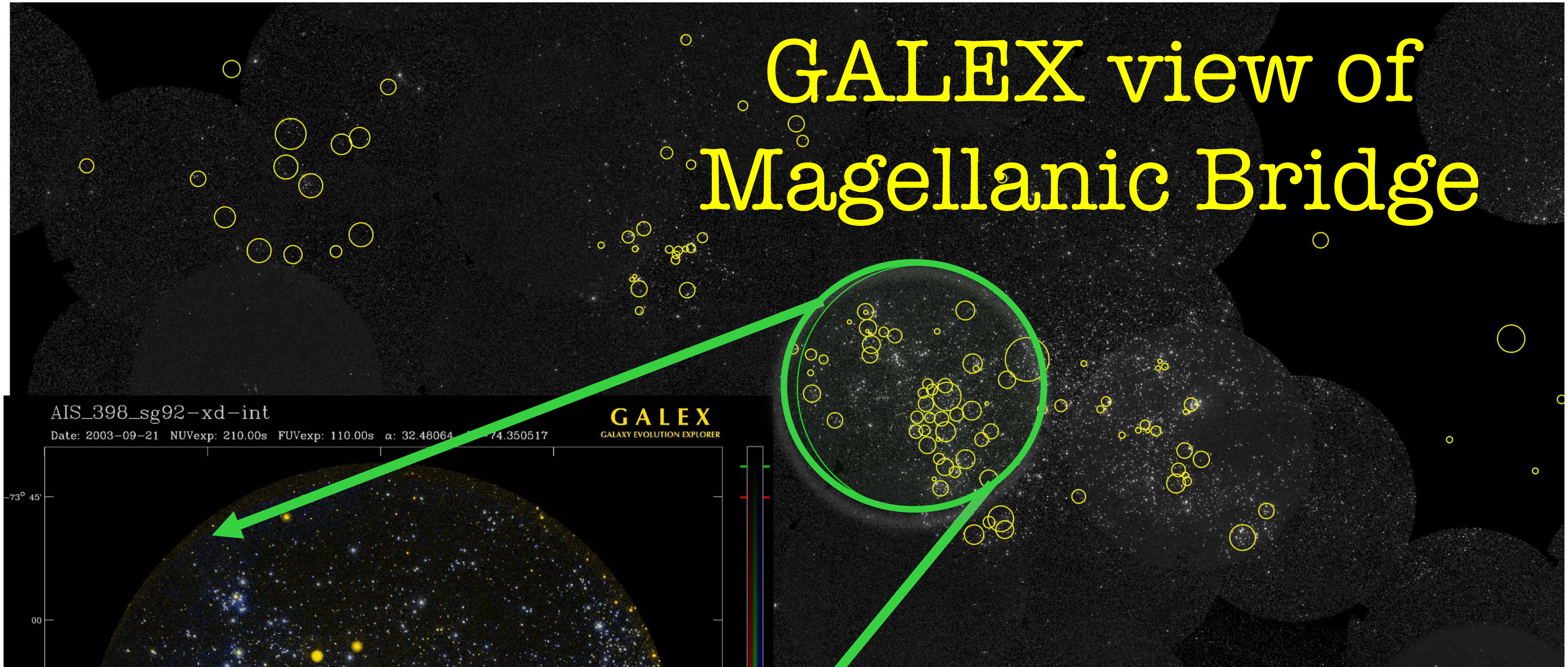
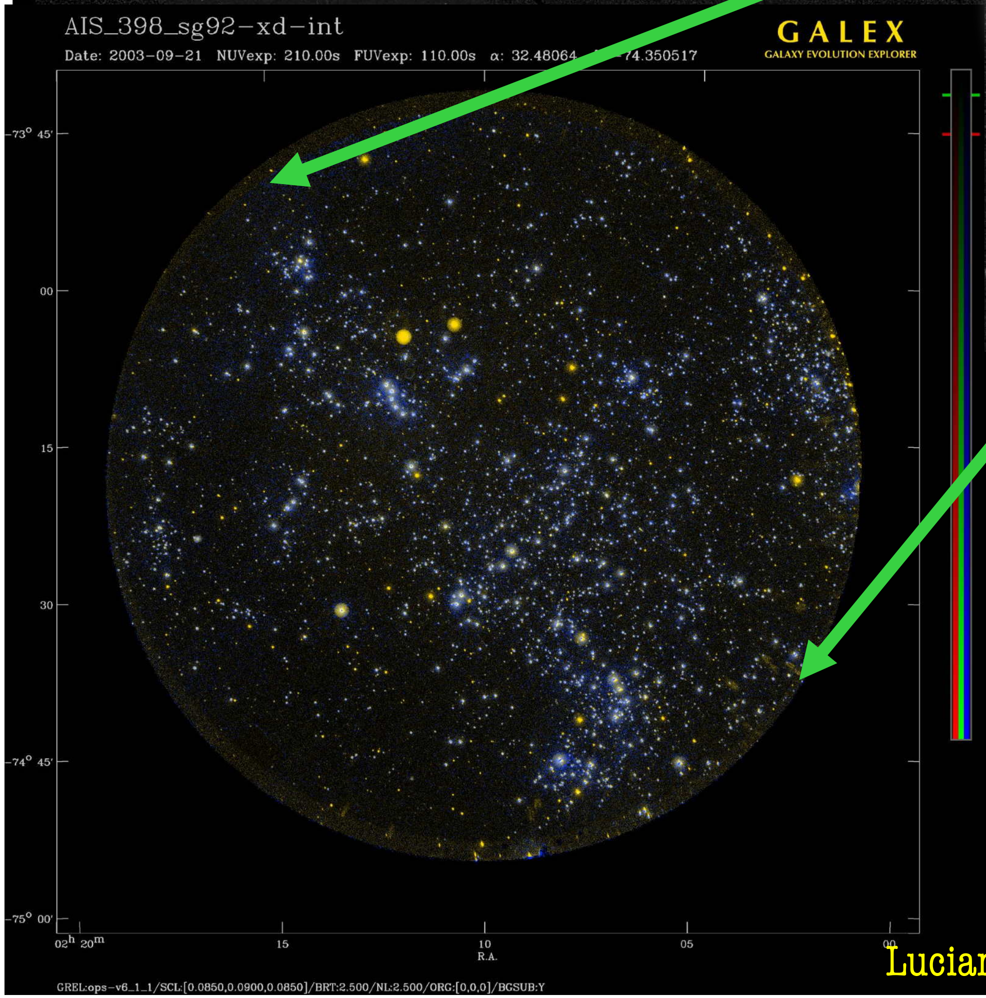


Fig. 5. One GALEX tile containing 30 Doradus and its environment. A close up view in the UV (left) and optical (right) is provided in the inset, and the location of this 0.2° (174 pc) box is marked in the wide-field image. The NUV image prominently displays the presence of dust, via bright regions of scattered light and also in absorption features (especially seen southeast of 30 Dor).

GALEX view of Magellanic Bridge





FUV mosaic of western MB,

OB associations: Bica& Schmidt 1995

<----- field ~ 1.1kpc

UV detects SF down to N(HI) 10^{19} cm^{-2}

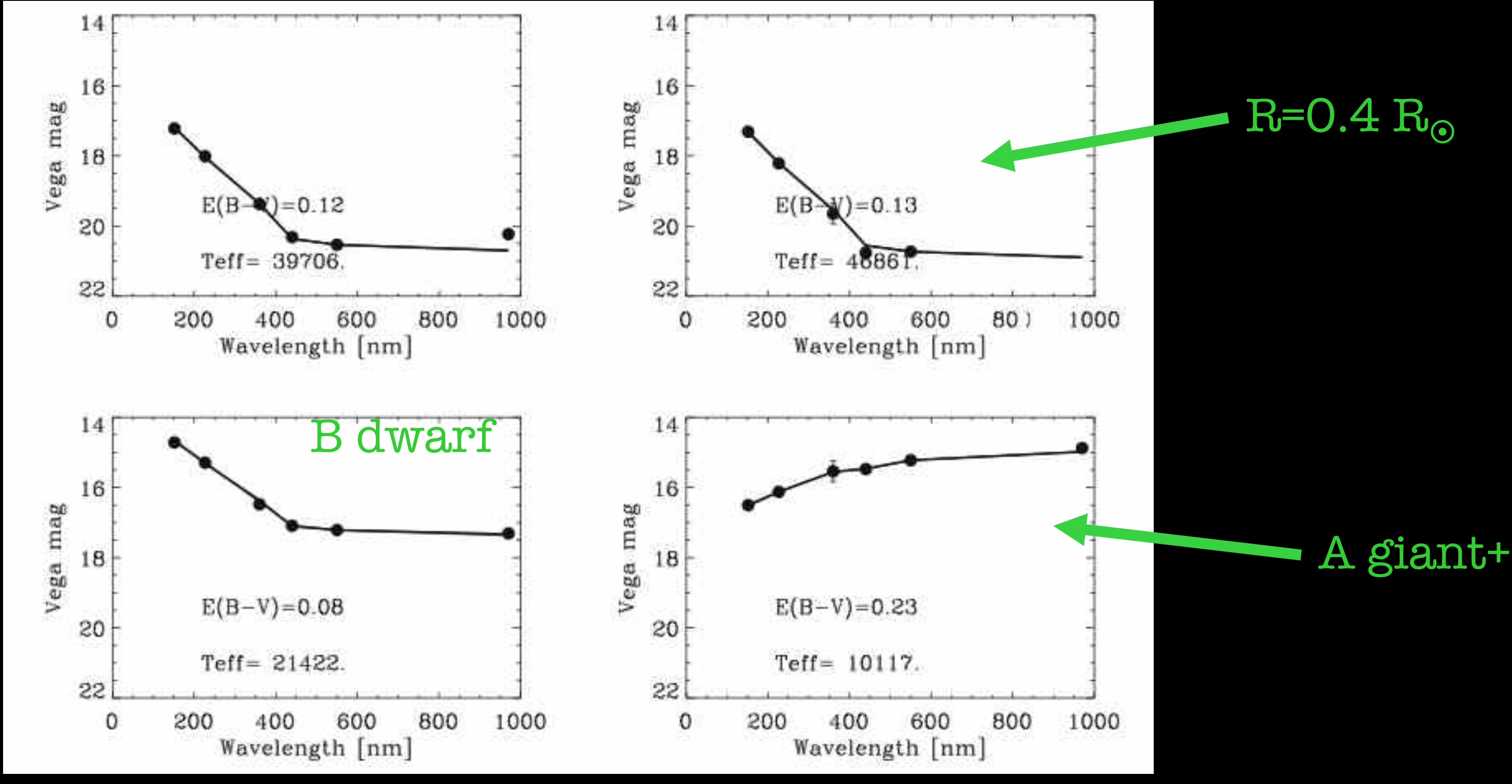
in LMC (peaks of 10^{20} in the MB)

Simons et al. 2013 J.ASR;

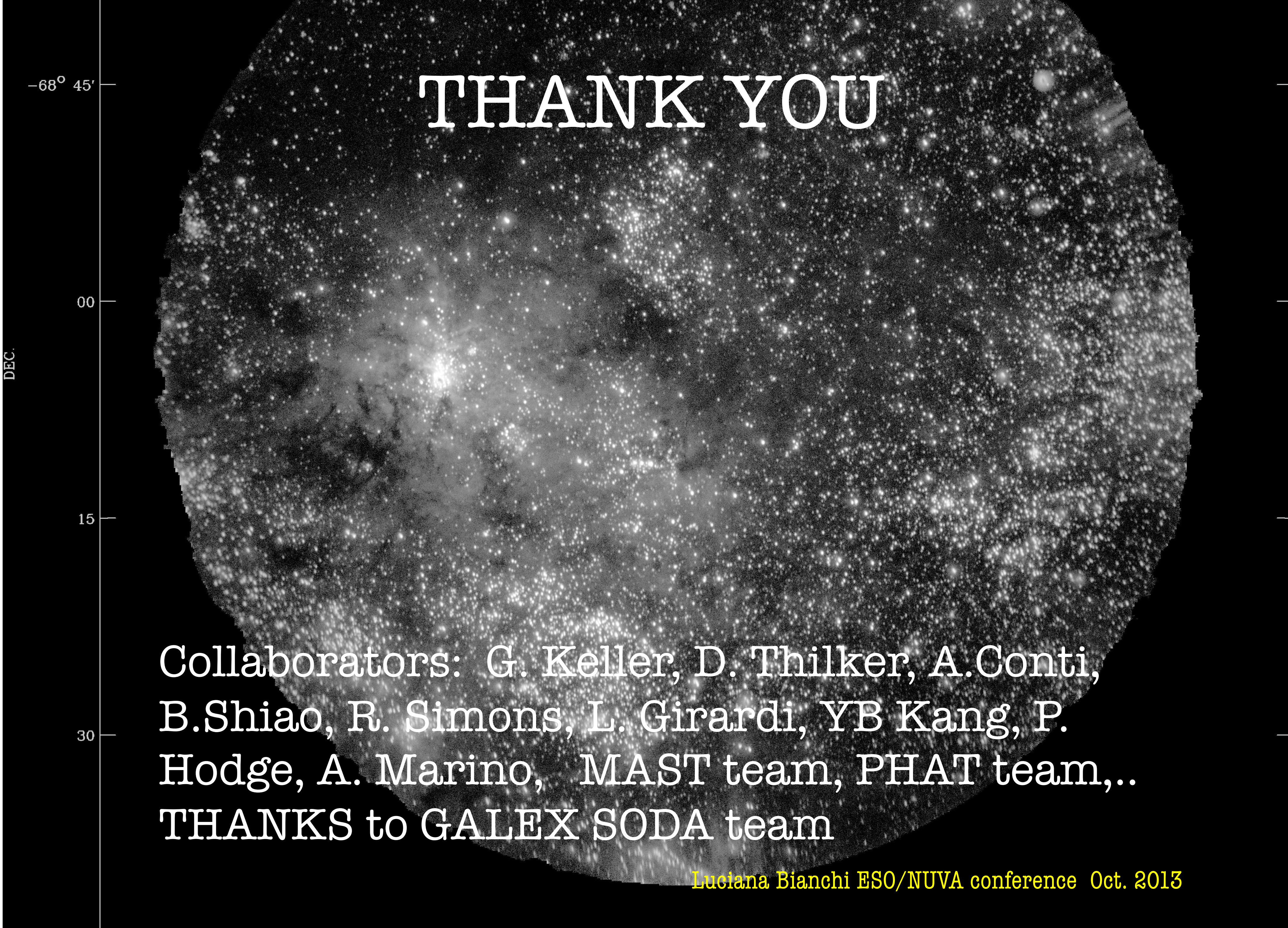
Thilker et al. 2013 in prep.

GALEX view of the MC

We matched LMC UV sources with MCPS (Zaritsky+2004) 8.5x7.5° UBVI for V<20 Vegamag, we derived Teff , E(B-V), $R/R_{\odot}$, L_{bol}
(about 60% with FUV,NUVerr<0.25 and NUV<22 have a MCPS match)



THANK YOU



Collaborators: G. Keller, D. Thilker, A.Conti, B.Shiao, R. Simons, L. Girardi, YB Kang, P. Hodge, A. Marino, MAST team, PHAT team,..

THANKS to GALEX SODA team