FEEDBACK ON SUB-GALACTIC SCALES: INSIGHTS FROM STARBURST REGIONS

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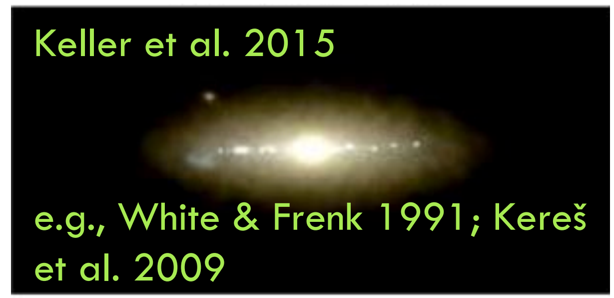
How Galaxies Form Stars
Aug. 24, 2016

Why We Need Feedback

- SF is inefficient

e.g., Zuckerman & Evans 1974; Krumholz & Tan 2007; Evans et al. 2009

- Simulated galaxies need feedback

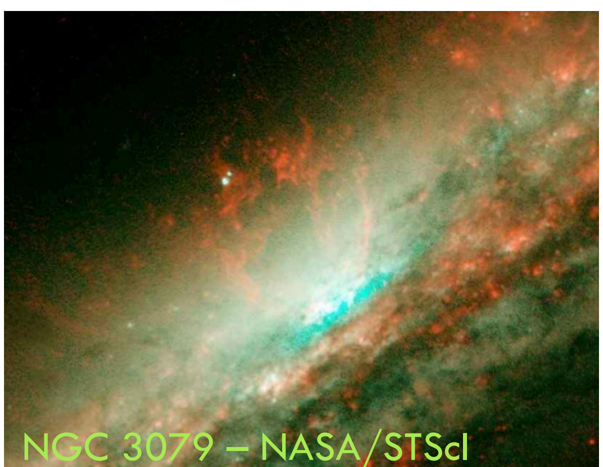


Keller et al. 2015

e.g., White & Frenk 1991; Kereš et al. 2009

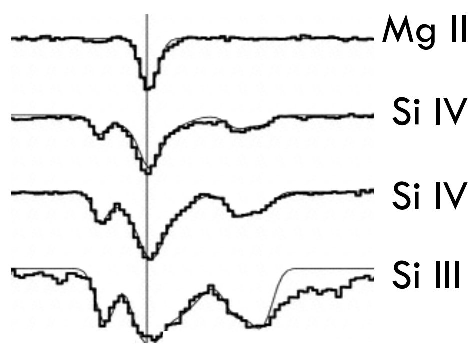
See talk by O. Agertz

- We observe it



NGC 3079 – NASA/STScI

- CGM metals



e.g., Simcoe et al. 2006; Steidel et al. 2010; Tumlinson et al. 2011

- Reionization

e.g., Robertson et al. 2015

Credit: lunar.colorado.edu, Caltech

Outline

- Types of feedback
  - Which mechanisms dominate?
- Sources of feedback
  - Which massive stars matter?
- When and how do galaxies clear out neutral gas?
  - LyC-leaking H II regions, starbursts, and extreme emission line galaxies

Types of feedback

- Warm ionized gas pressure
  - H II region heated by photoionization
    - $P_{HII}=n_{HII}kT_{HII}$
- Radiation pressure
  - Direct radiation
    - $P_{dir}=3L/(4\pi R^2c)$
  - Dust-processed radiation
    - $P_{IR}=(1/3)u_{\nu}$
- Stellar winds and SNe
  - Shock-heating
    - $P_X=n_XkT_X$

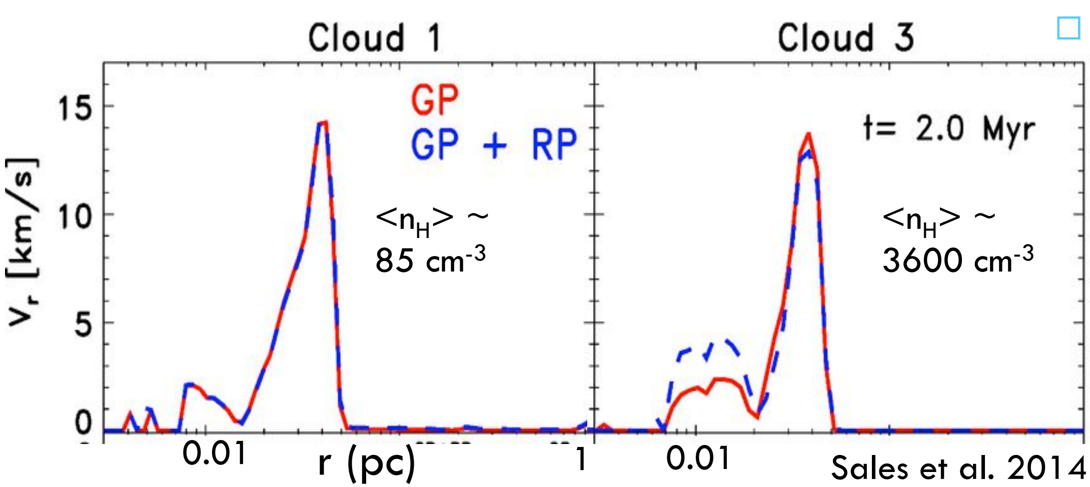
Early Stage Feedback

Radiation Pressure

- Dominates at young ages
- Effective in high mass, gas-rich systems
- e.g., *Krumholz & Matzner 09, Murray +10, Hopkins+12, Gupta+16*

Photoionization

- Important in less massive, less dense clusters
- Acts more rapidly
- Evacuates bubbles within first 3 Myr
- e.g., *Dale+12, 13, Sales+14*



Sales et al. 2014

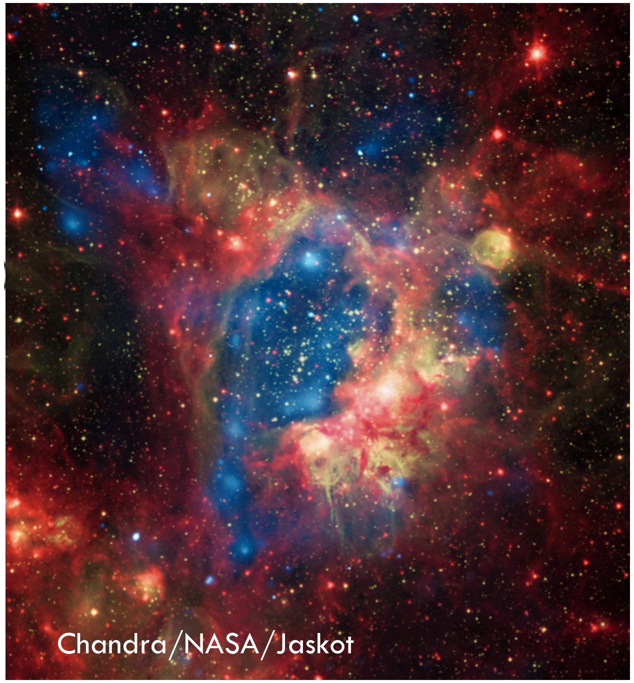
Winds?

Energy may be easily lost through holes

e.g., Harper-Clark & Murray 09; Yeh & Matzner 12; Rosen+14

By 1 Myr 50-60% of hot gas can leak *(Dale+14)*

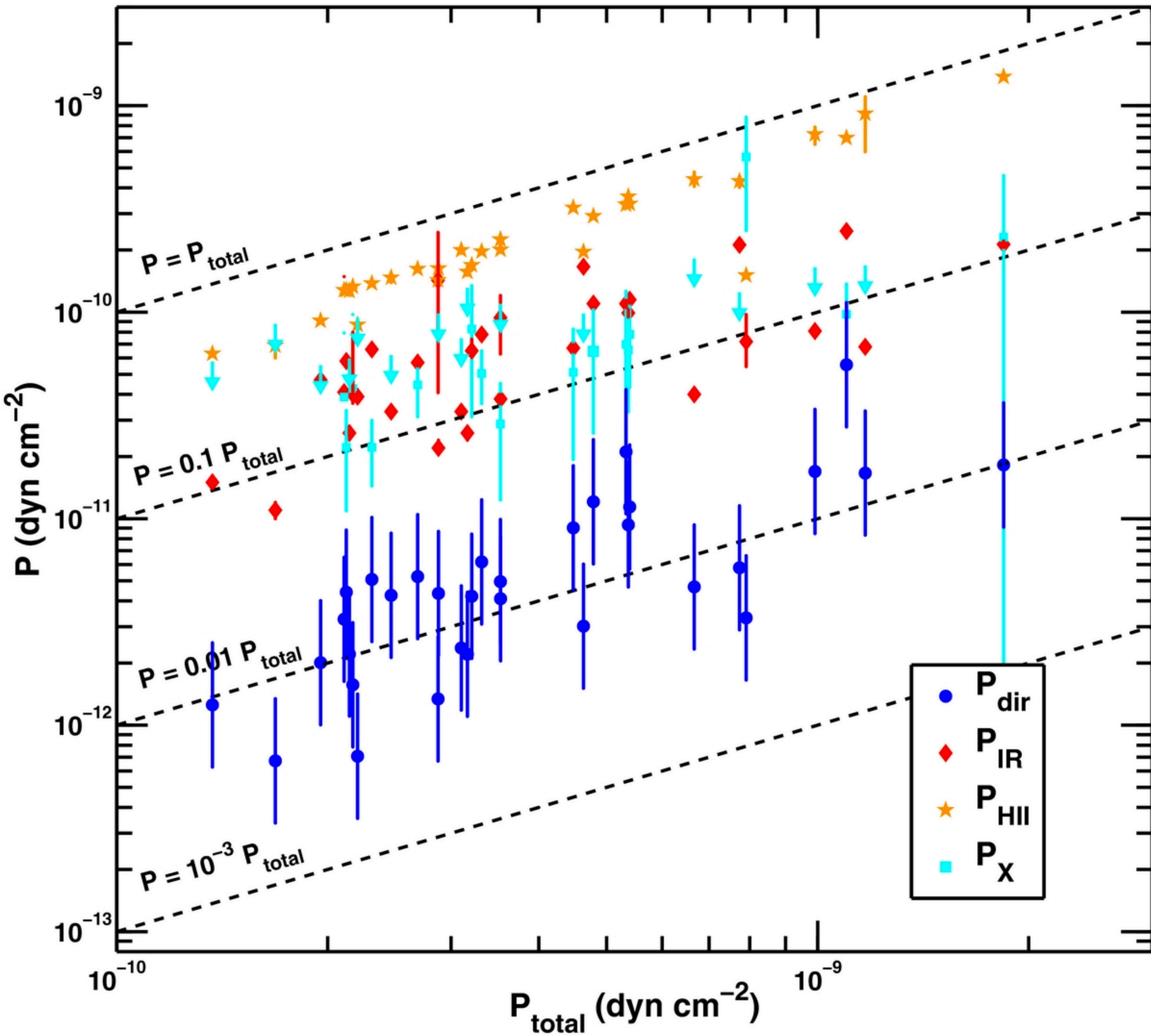
Harper-Clark & Murray 2009



Observations

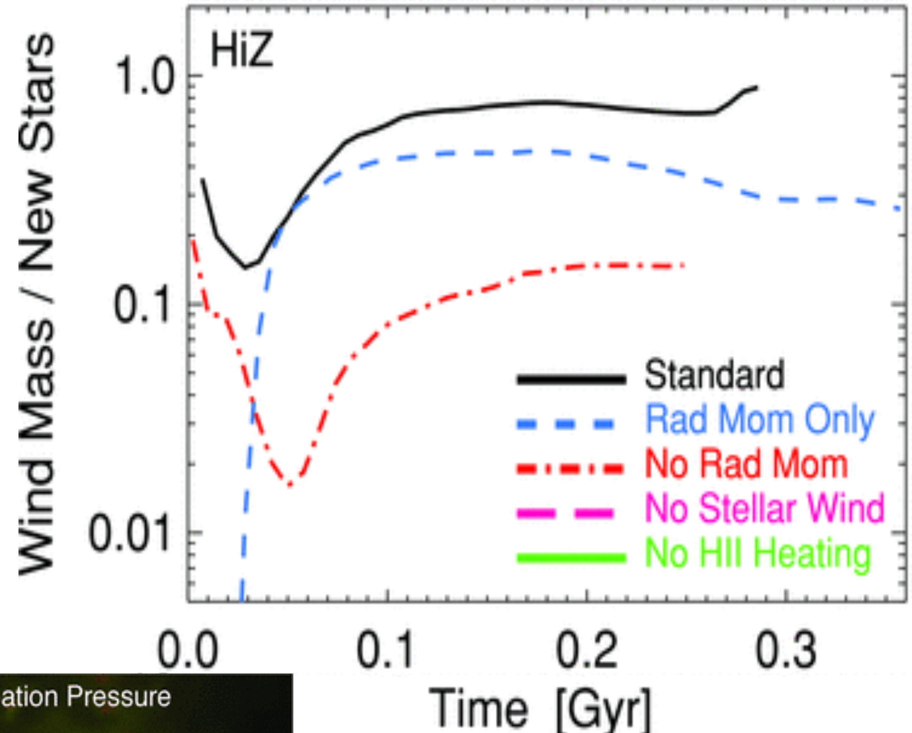
- Lopez+14
- 32 H II regions aged 3-10 Myr
- Gas pressure dominant

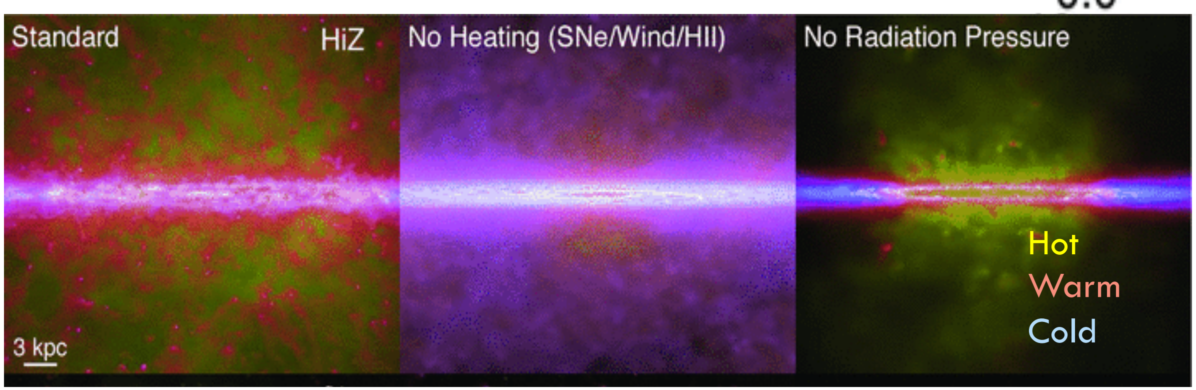
See talk by S. Longmore



Feedback Mechanisms Interact

- Early photoionization increases porosity –*Dale+12*
- Early winds help clear gas near central source – *Dale+14*
- Early radiative feedback - SNe can heat larger, lower density volumes – e.*g., Agertz+13, Hopkins+12, 14*





Hopkins+12

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  Mostly H II gas pressure early on, but all are needed
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Sources of Feedback: The Usual and Unusual Suspects

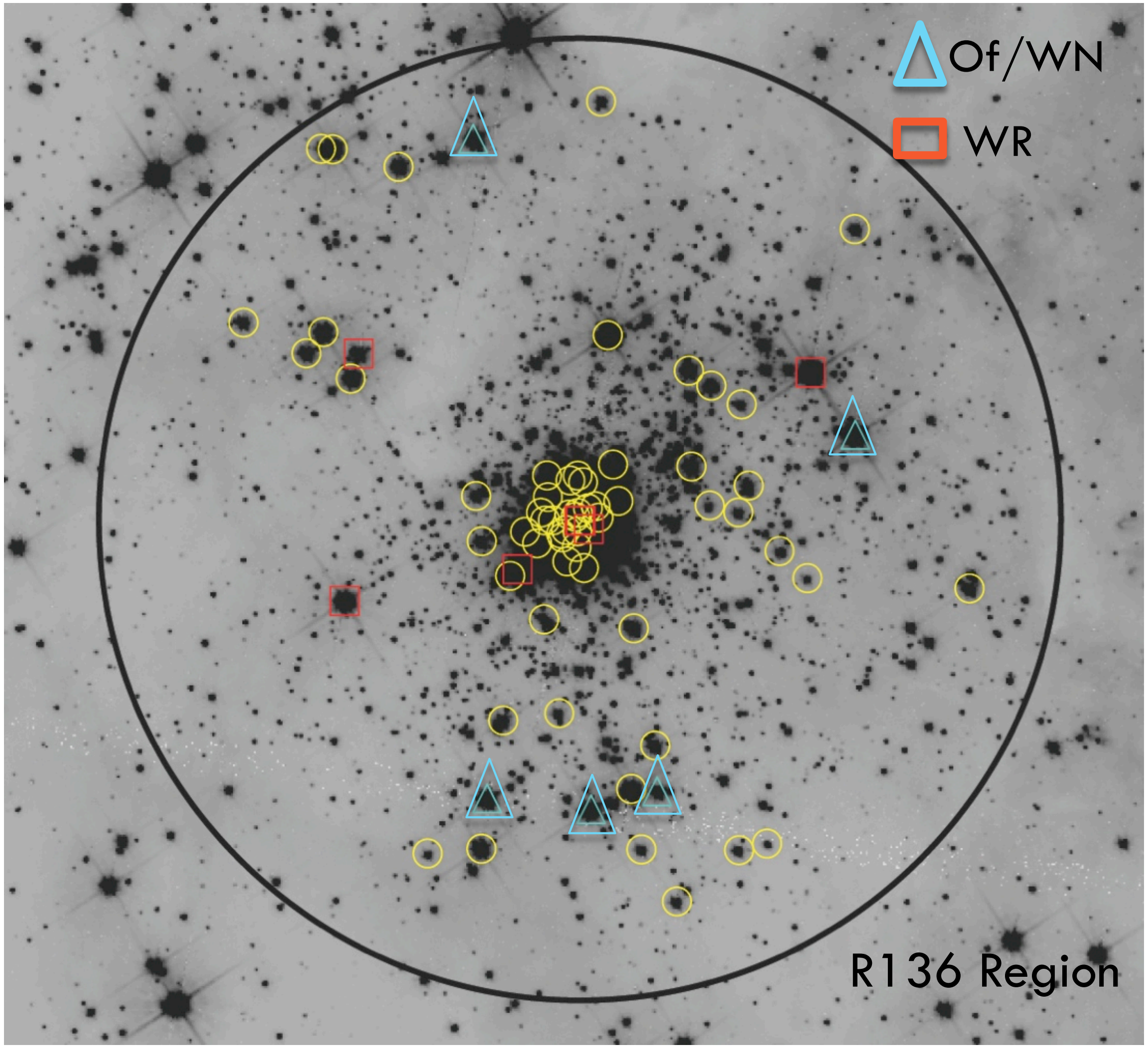
- Main Sequence OB Stars: 8-100 $M_\odot$
- Very Massive Stars (VMS): >100 $M_\odot$
  - *< 3 Myr*
- Wolf-Rayet (WR) Stars: M_i > 40 $M_\odot$?
  - *~3-5 Myr*

(Broad He II and N emission — VMS and WR stars)

- Binary massive stars
  - High mass X-ray binaries (HMXBs)
    - *> 4 Myr*
- Supernovae
  - *> 3.5 Myr*

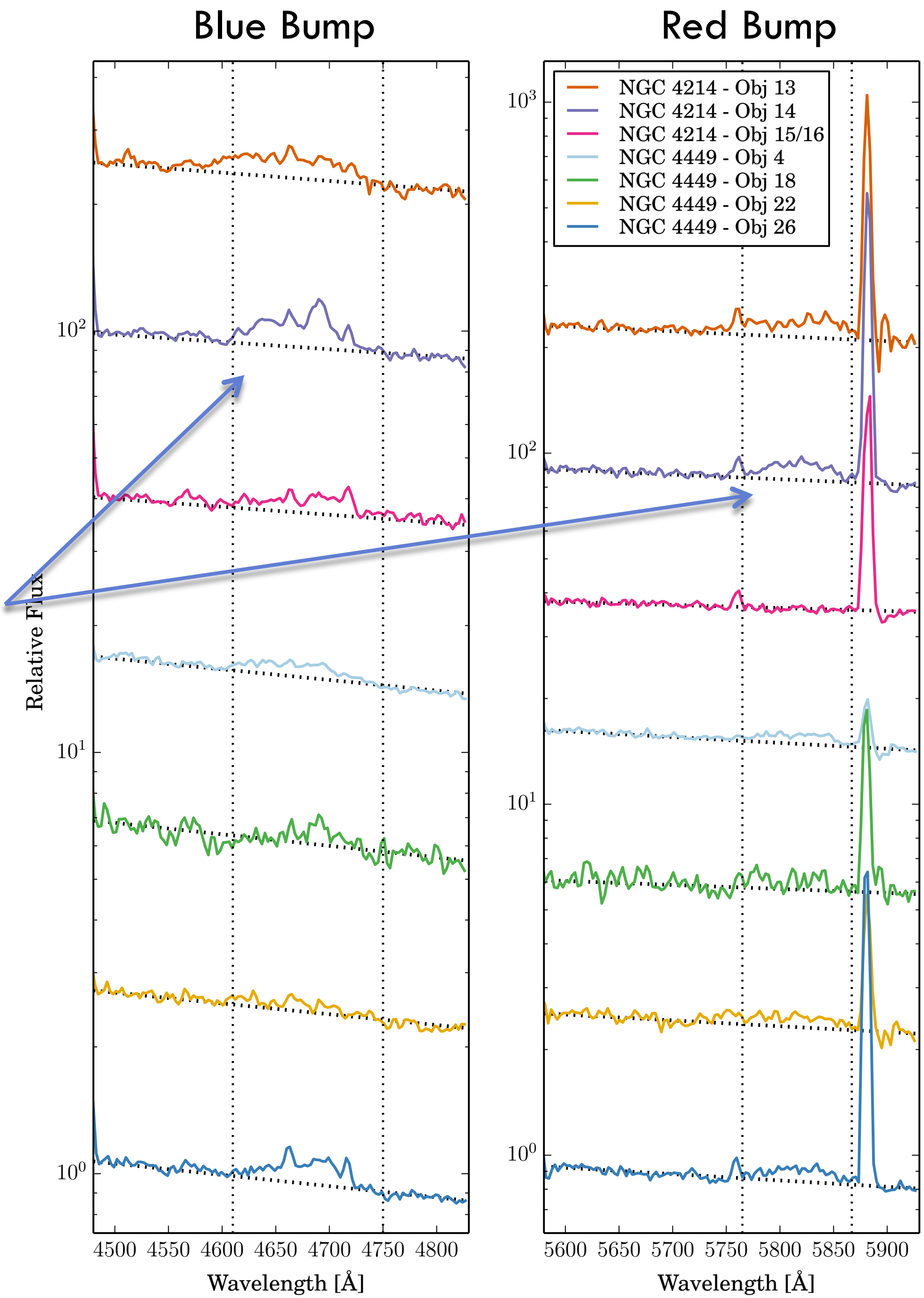
Very Massive Stars

- *Doran+13*
- 10 stars, $M_i > 100\ M_\odot$
  - 2% of massive stars
  - 28% of ionizing photons
  - 25% of wind luminosity

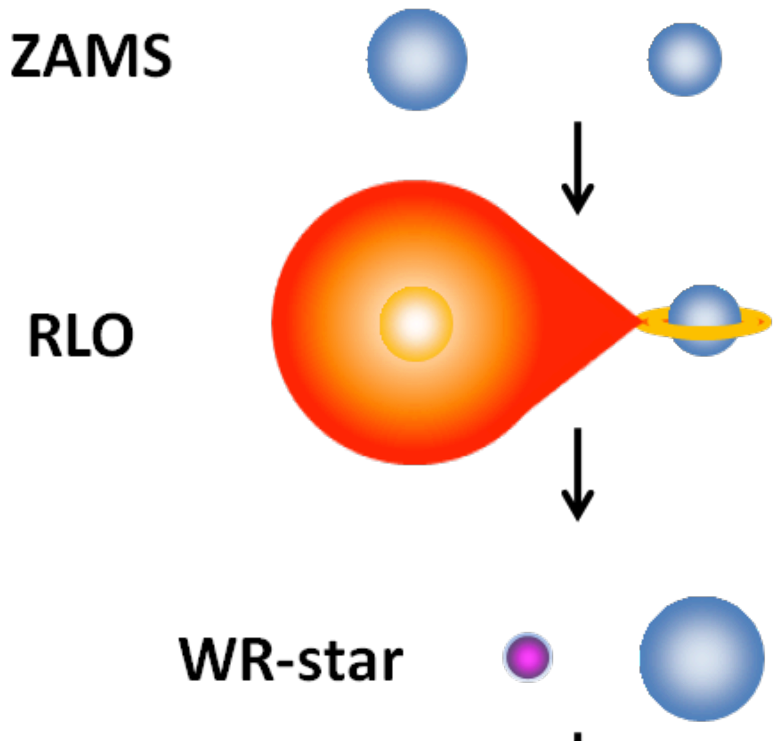


WR Stars

- *Sokal+16*
- 42 emerging massive star clusters
  - 50% show WR spectral features
- < 3 Myr emergence *(Bastian+14)*
- Some embedded for 5 Myr *(Reines+08)*



Massive Binaries – What They Do



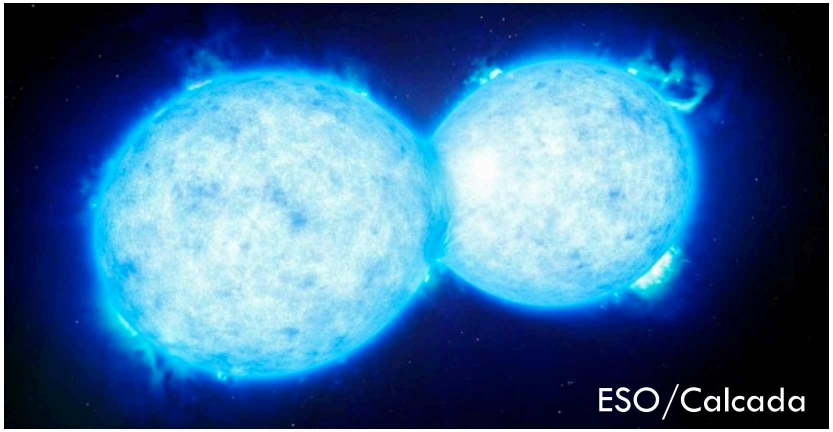
Marchant et al. 2016

More/harder ionizing photons later

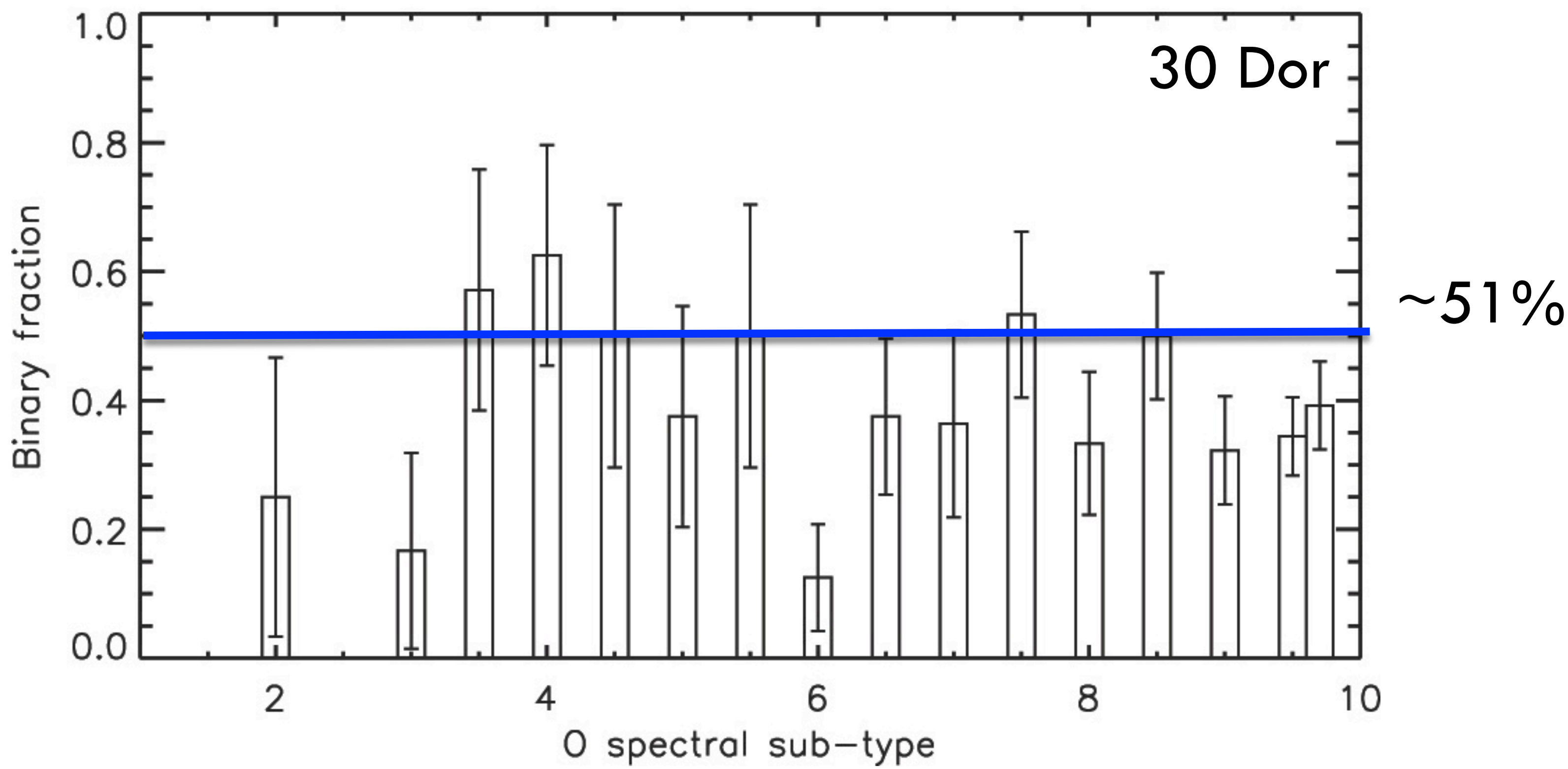
- *e.g., Eldridge+08, Stanway+16*

- HMXBs
  - esp. important at low Z

(e.g., , *Brorby+16, Basu-Zych+16, Douna+15, Linden+10, Mapelli+10*)



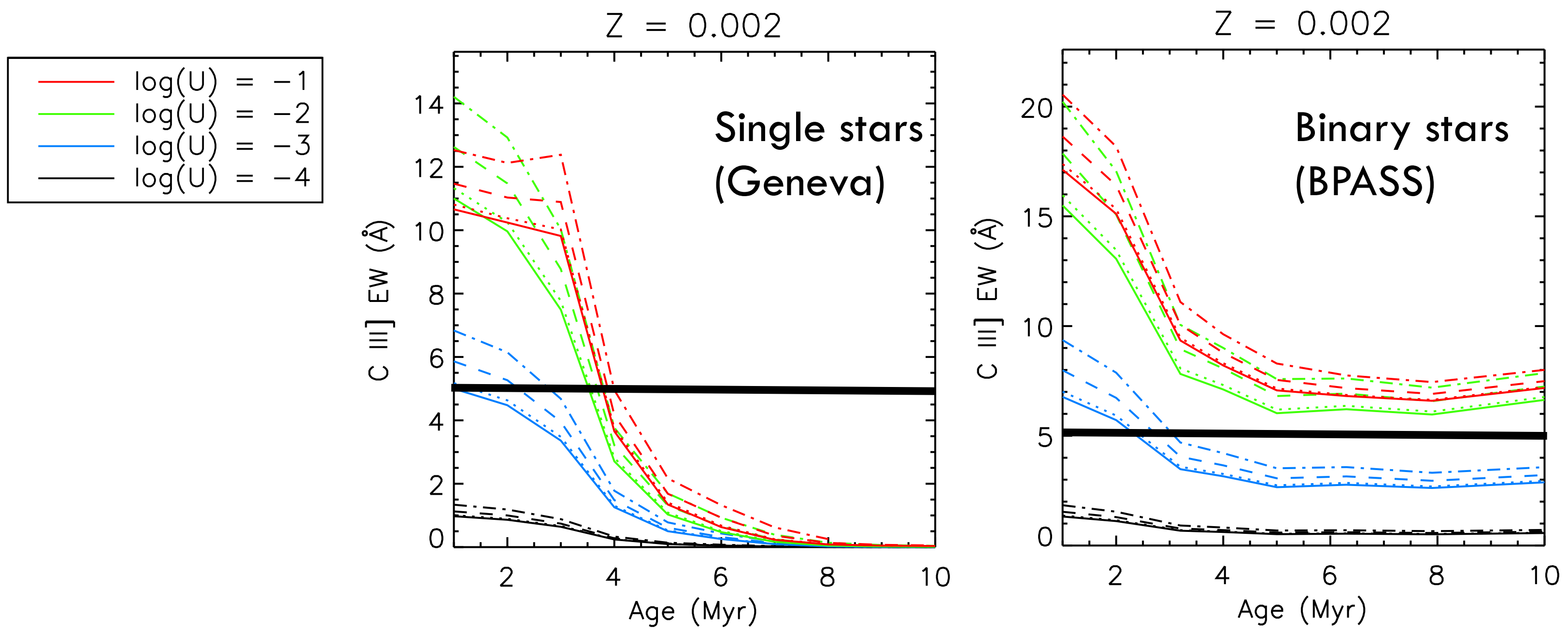
Binaries Matter



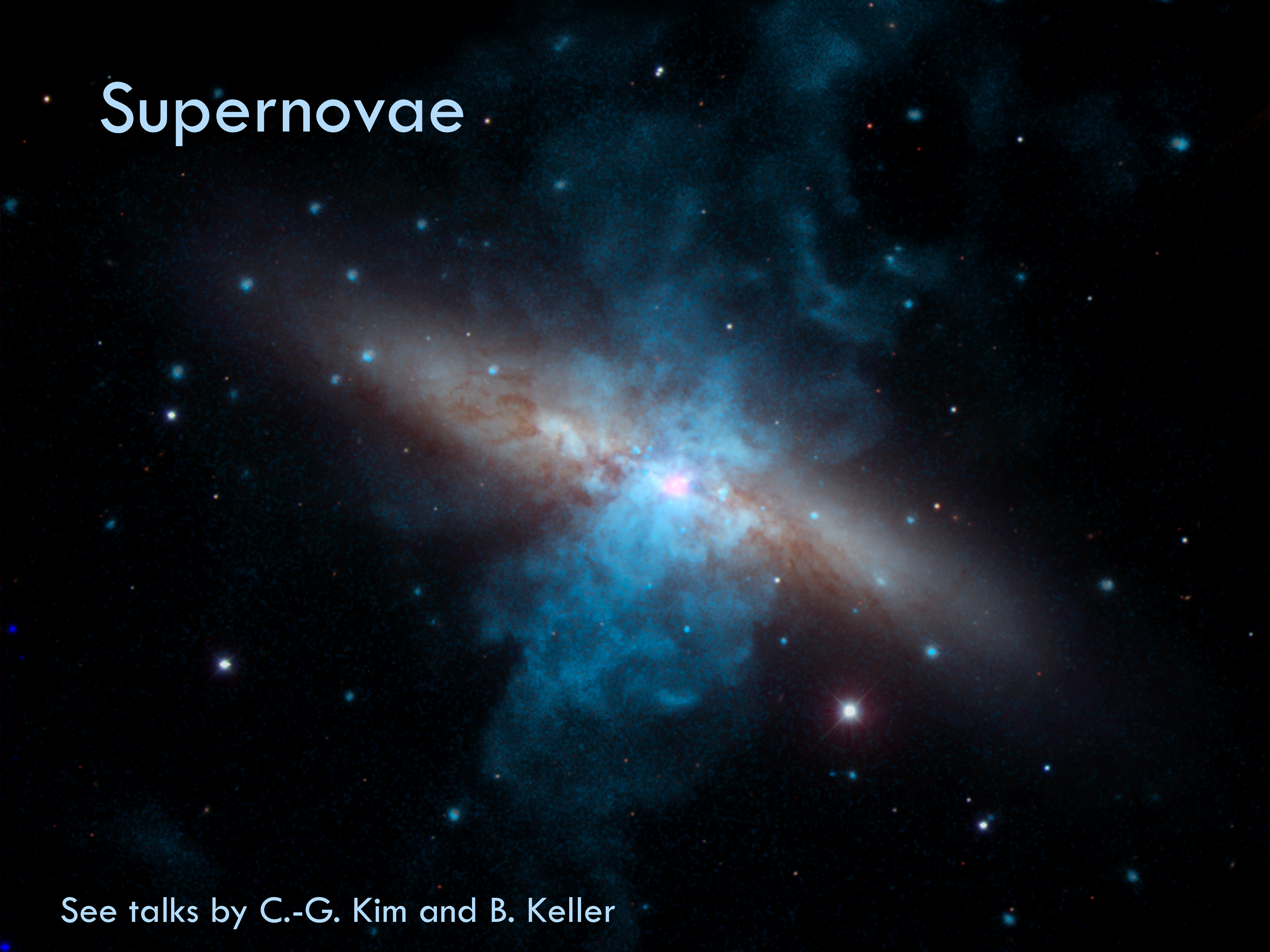
- > 50% of O stars will exchange mass
  - *Sana+13*

Binaries Matter

- Binary stellar population models (e.g., BPASS – *Eldridge+ in prep*)
  - Stellar cluster SEDs (*Wofford+16*)
  - Line ratios at z=2-3 (*Strom+16*)
  - C III] 1909 EWs in low Z galaxies (*Jaskot & Ravindranath in prep*)



Supernovae



See talks by C.-G. Kim and B. Keller

Outline

- Types of feedback
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  Mostly H II gas pressure early on, but all are needed
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  We need to include VMS, WR stars, and binaries
- When and how do galaxies clear out neutral gas?
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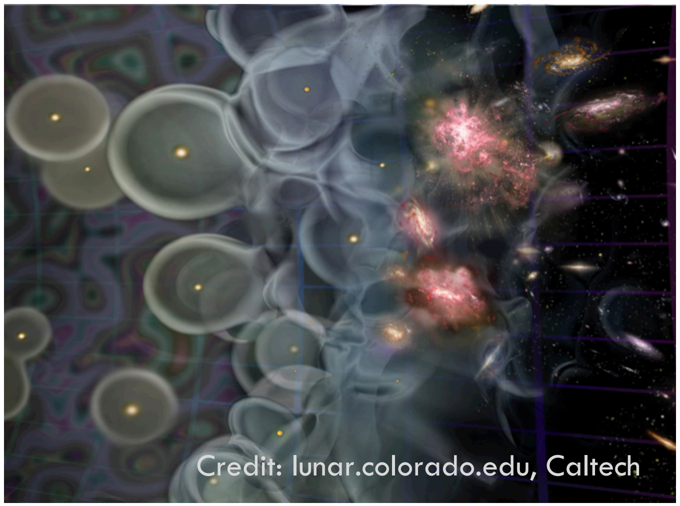
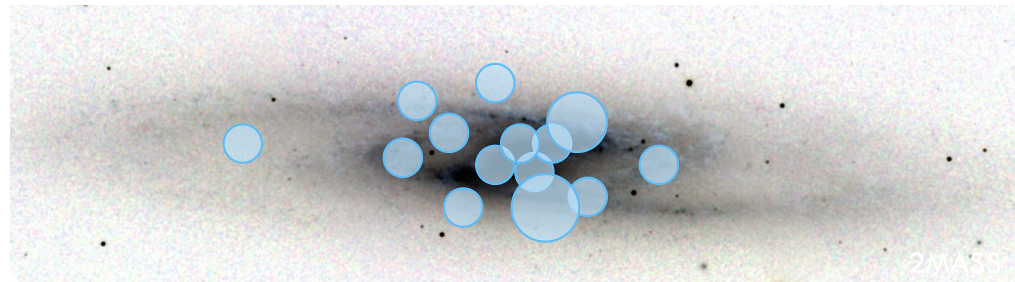
How to Get Rid of Ionizing Photons

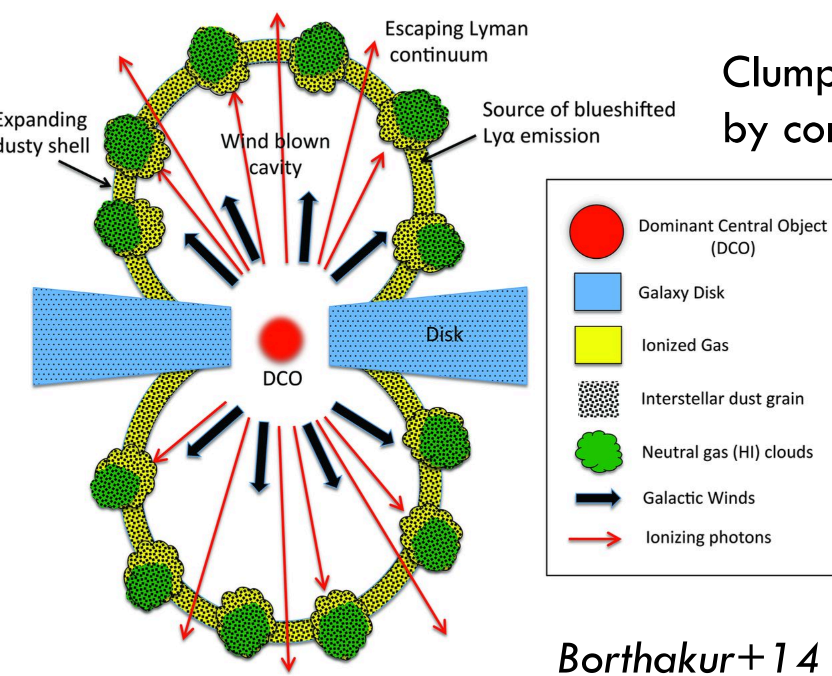




Superbubble porosity threshold *(Clarke & Oey 02)*

The Problem:
At $z > 6$, galaxies need to leak ~5-20% of ionizing photons

(e.g., Robertson+15, Stanway+16)

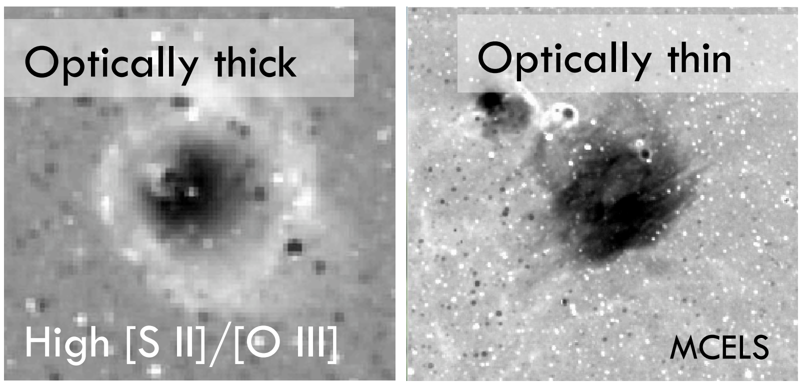


Clumpy wind driven by compact source

Borthakur+14

The LyC Leakers

Leaky H II regions



LMC+SMC

H II region f_{esc} ~ 40%

Pellegrini+12

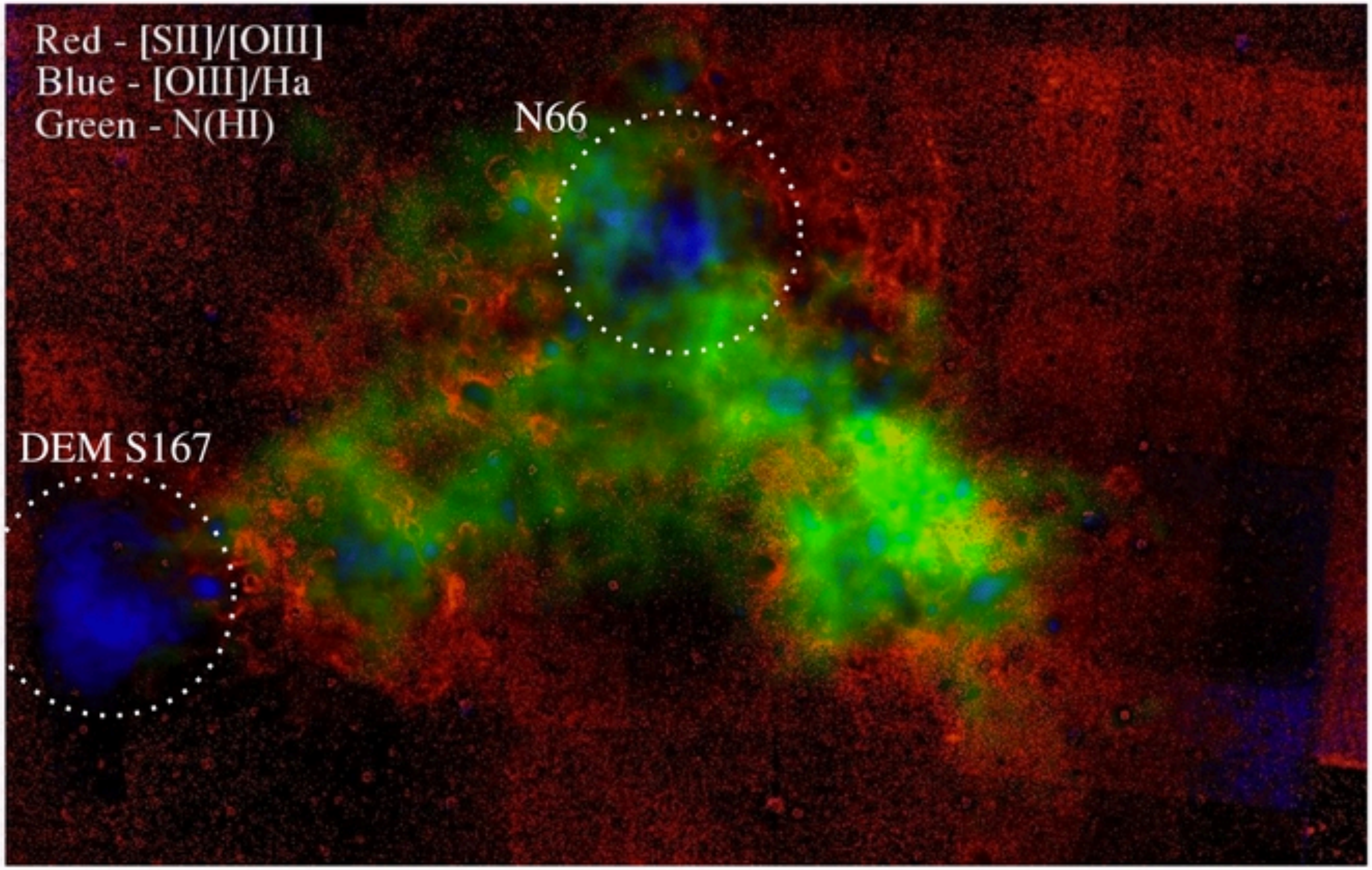
The LyC Leakers

Strong Leakers – The Green Peas

- High [O III]/[O II]
  (Jaskot & Oey 13; Nakajima & Ouchi 14)
- Compact sizes, high sSFRs, $0.2Z_\odot$
  (Cardamone+09; Izotov+11; Amorín+12a)
- 5 GPs at z~0.3: f_{esc}=6-13%
  (Izotov+16a,b)
- 1 GP at z~3: $f_{esc} > 50\%$
  (Vanzella+16)

The Role of Geometry

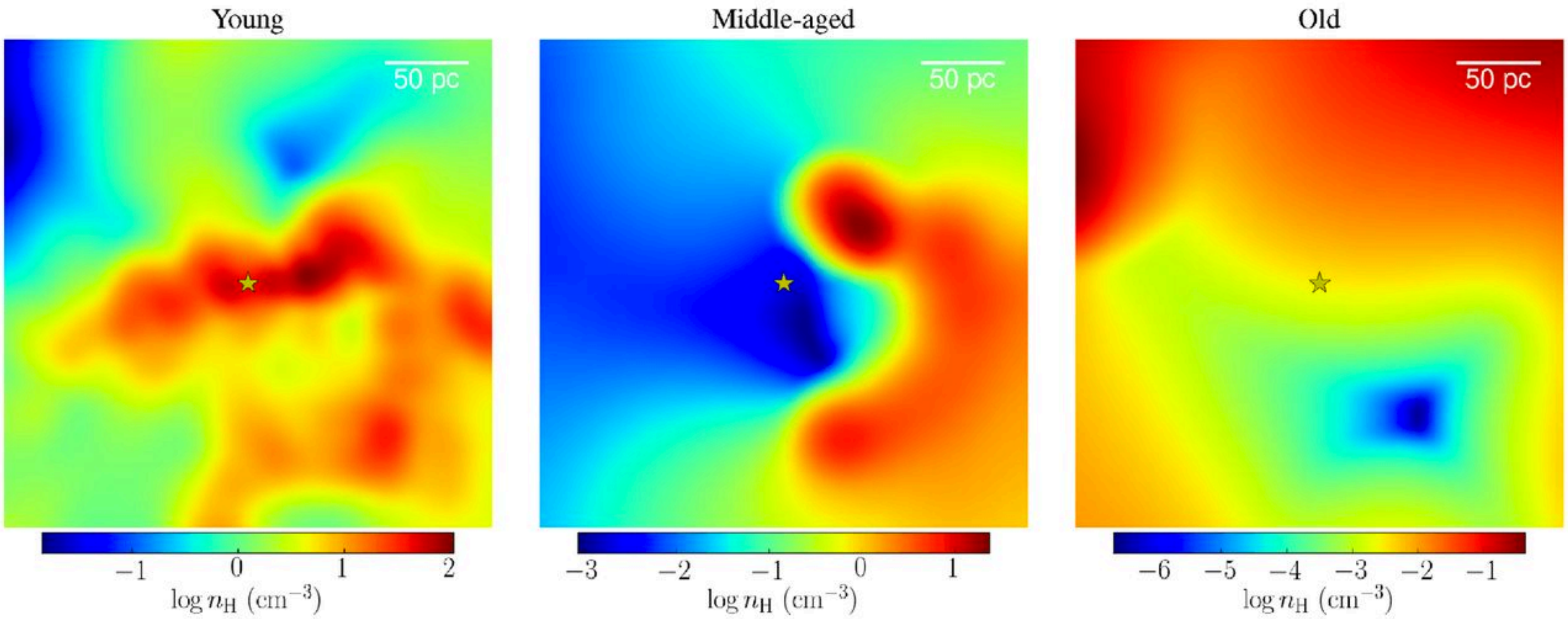
- Location
  - *Gnedin 08, Pellegrini+12*
- Low N_{HI}
  - *Pellegrini+12*



(b) SMC

The Role of Age

Too young? | Just right! | Too old?

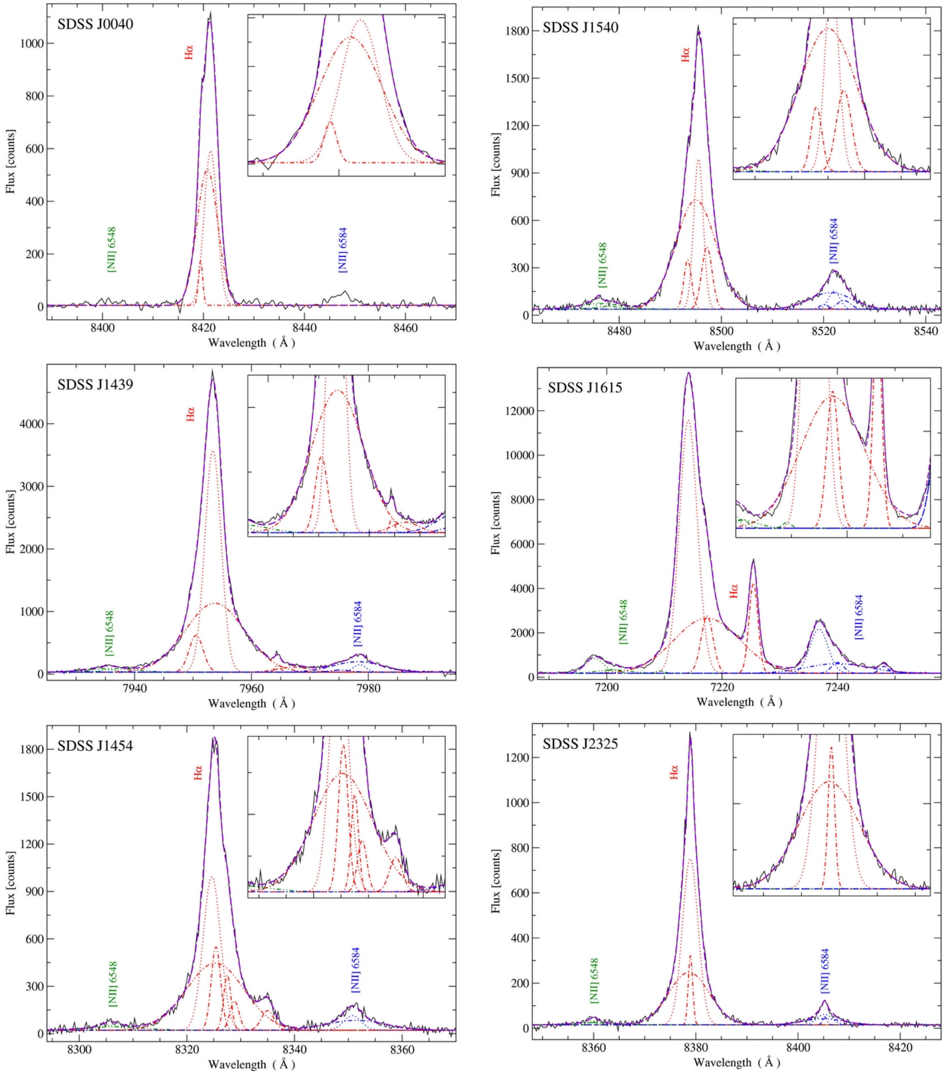


But binaries help! *(Stanway+16, Ma+16)*

Ma+15

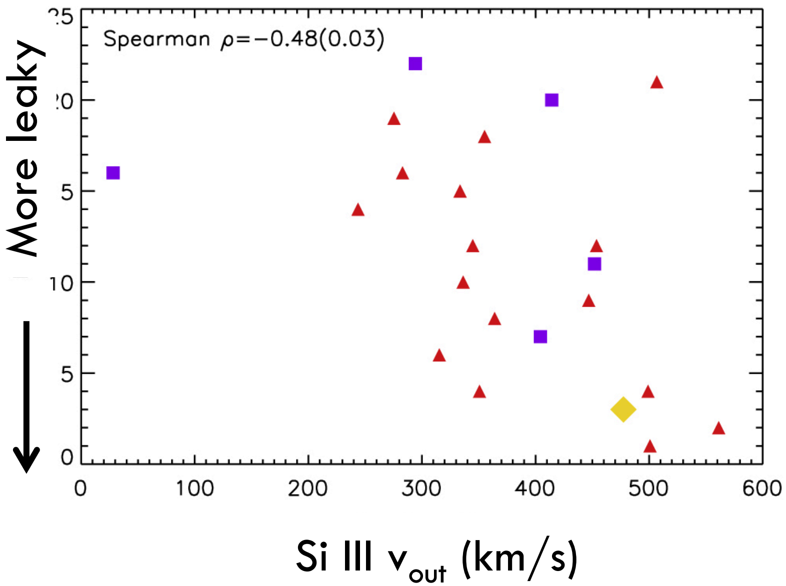
The Role of Outflows

- Green Pea kinematics
  - Up to 1000 km/s outflows from SNRs and WR stars
  - *Amorín+12b*

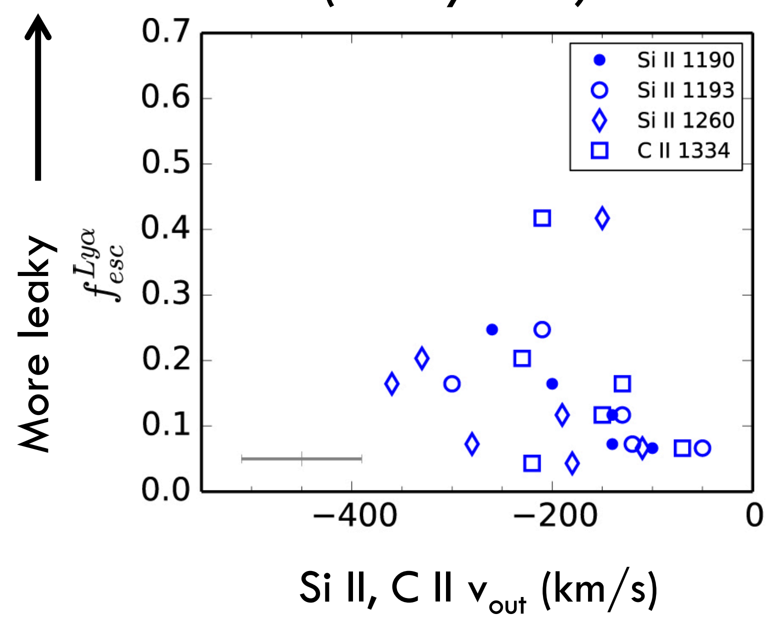


The Role of Outflows

LBAs *(Alexandroff+15)*



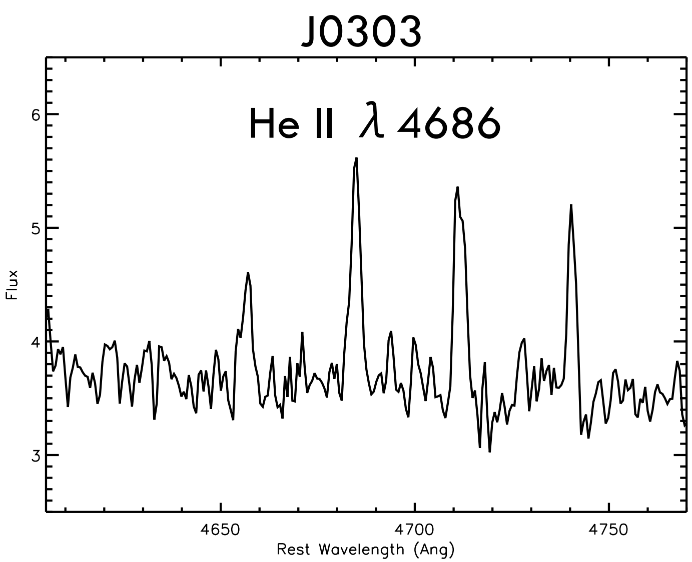
GPs *(Henry+15)*



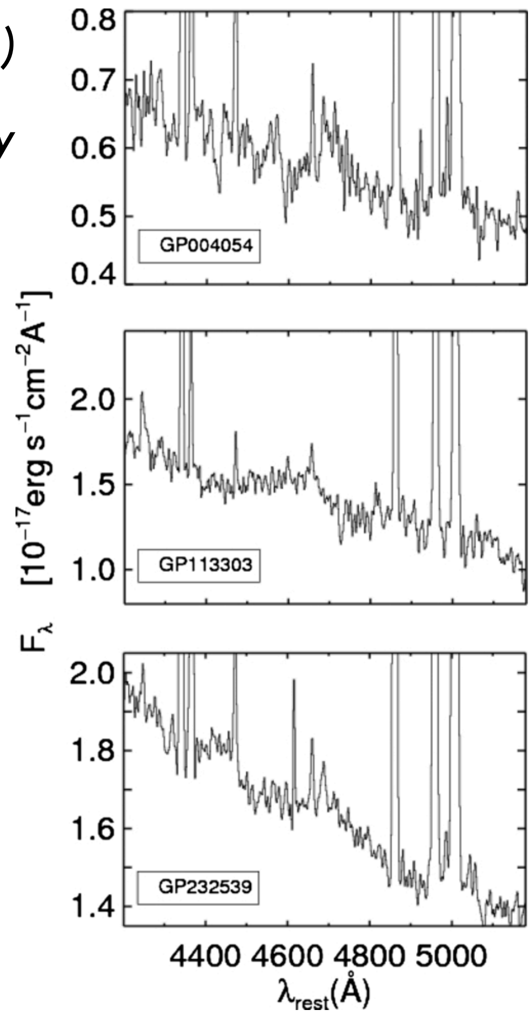
- Outflow velocity and SFR/Area = best correlation with "leakiness"
- High-ionization gas velocities = marginal correlation
- Low-ionization gas velocities = no correlation

The Role of WR Stars

- WR "blue bump" *(Amorín+12a)*
- Nebular He II emission *(Hawley +12; Jaskot & Oey 13)*
  - WR stars?
  - Fast, radiative shocks?



Jaskot+, in prep.

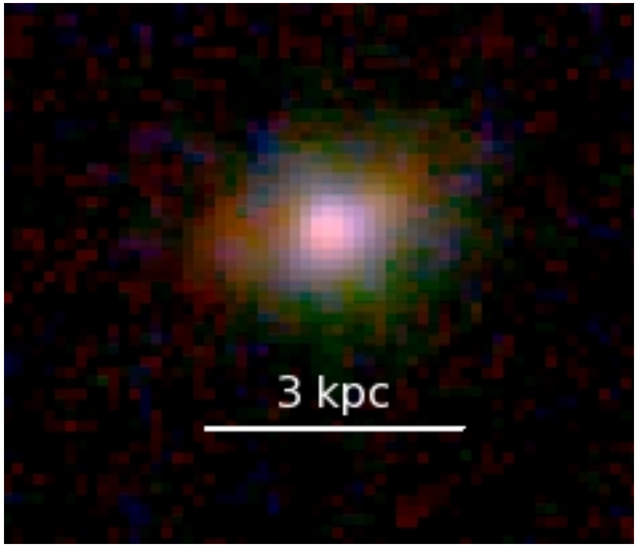


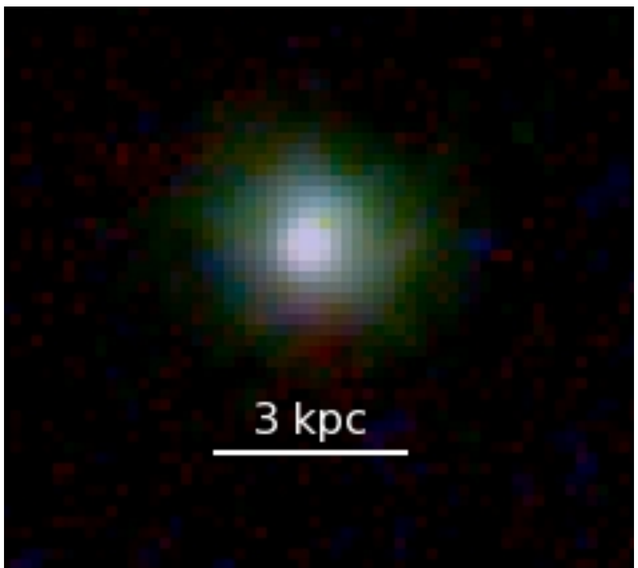
Amorín+12a

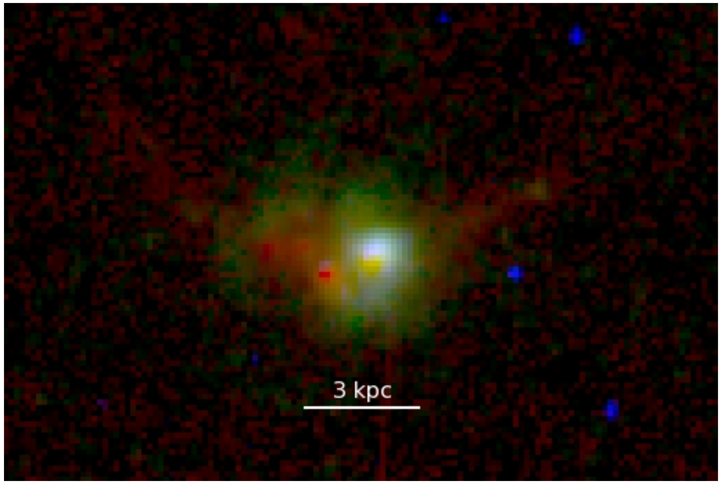
Just the right age?

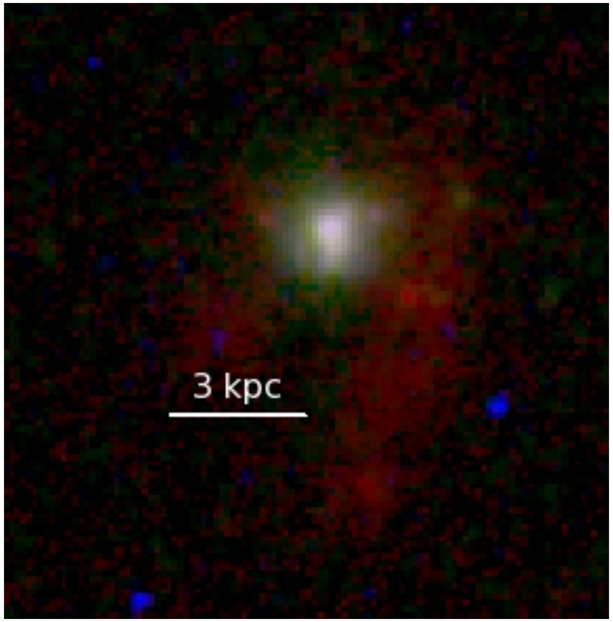
High [O III]/[O II] Case Study

Jaskot & Oey 14
Jaskot+, in prep.







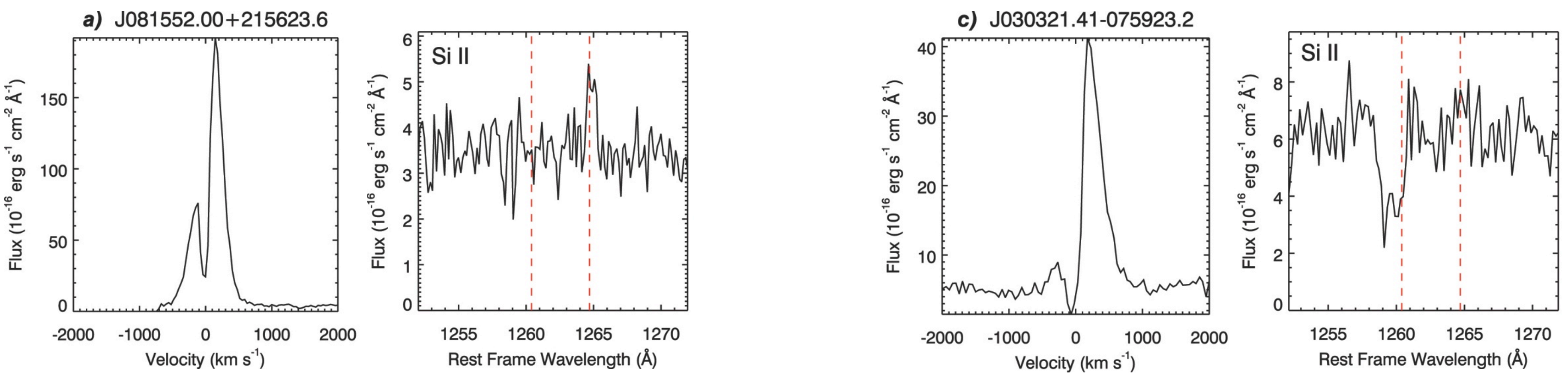


5100 Å Continuum
[O III]
[O II]

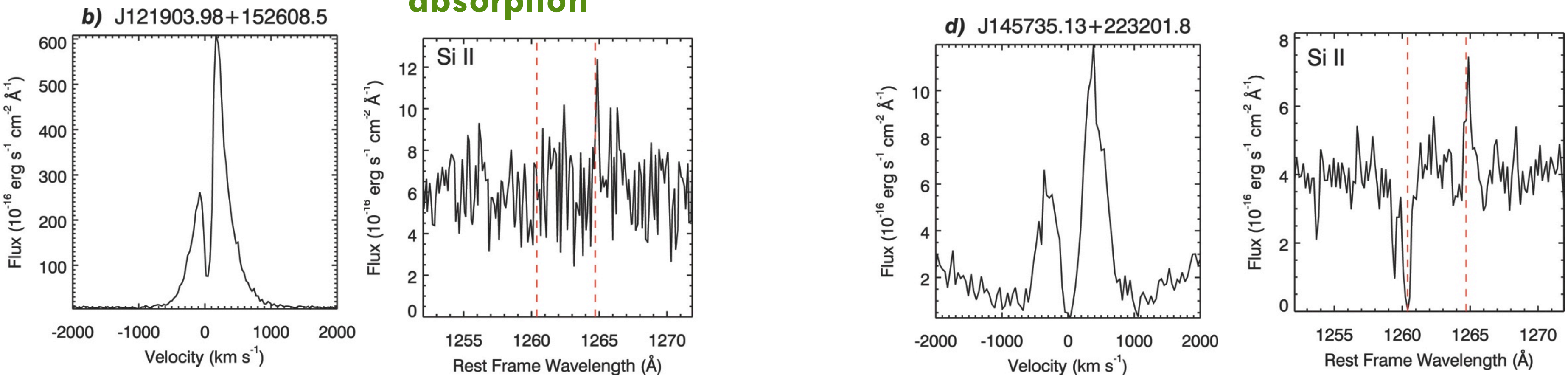
HST GO-13293

Jaskot & Oey 14
Jaskot+, in prep.

High [O III]/[O II] Case Study



Strong, narrow Ly α — **No low-ionization absorption** — **Weak, broad Ly α** — **Strong absorption**



HST GO-13293

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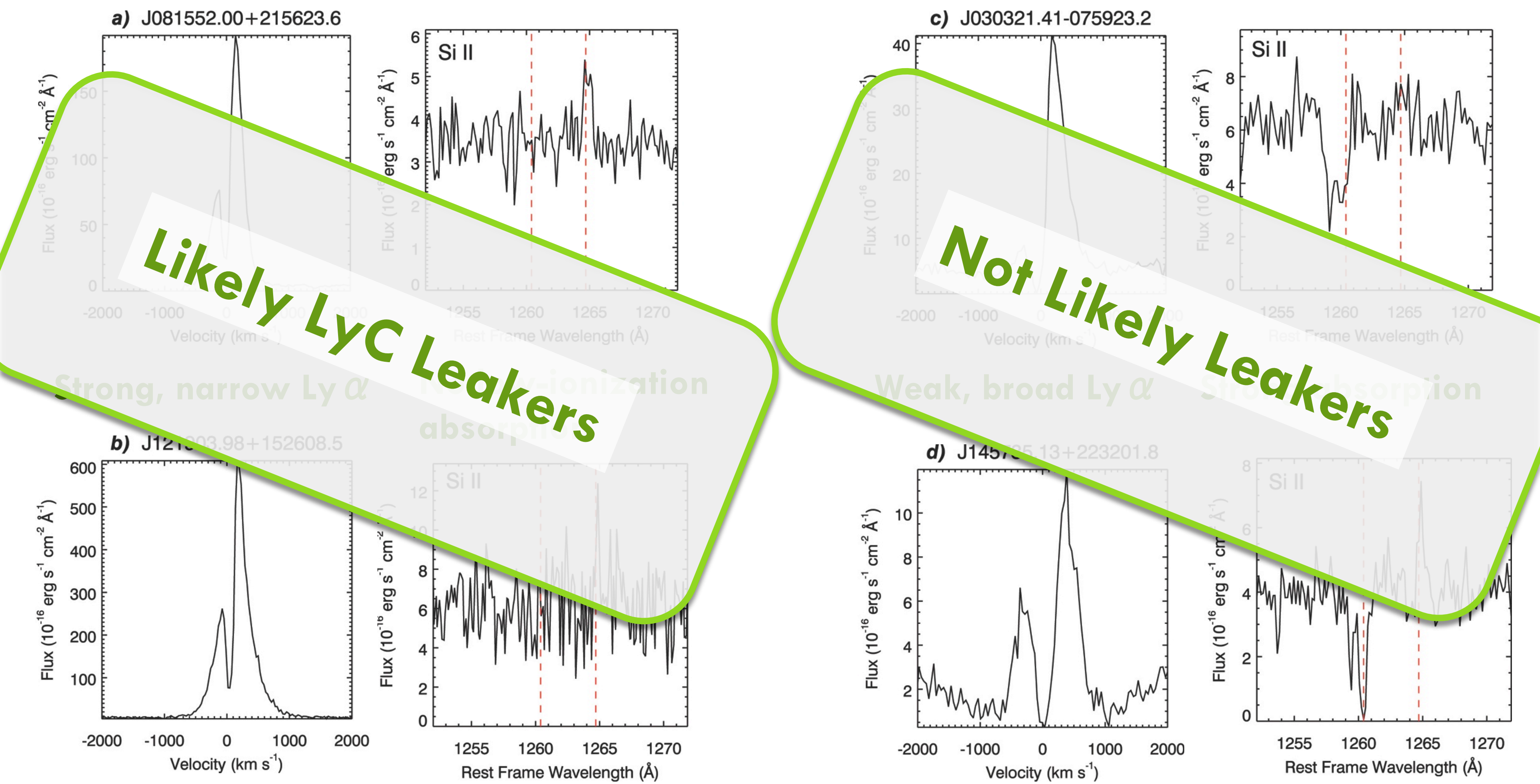
High [O III]/[O II] Case Study

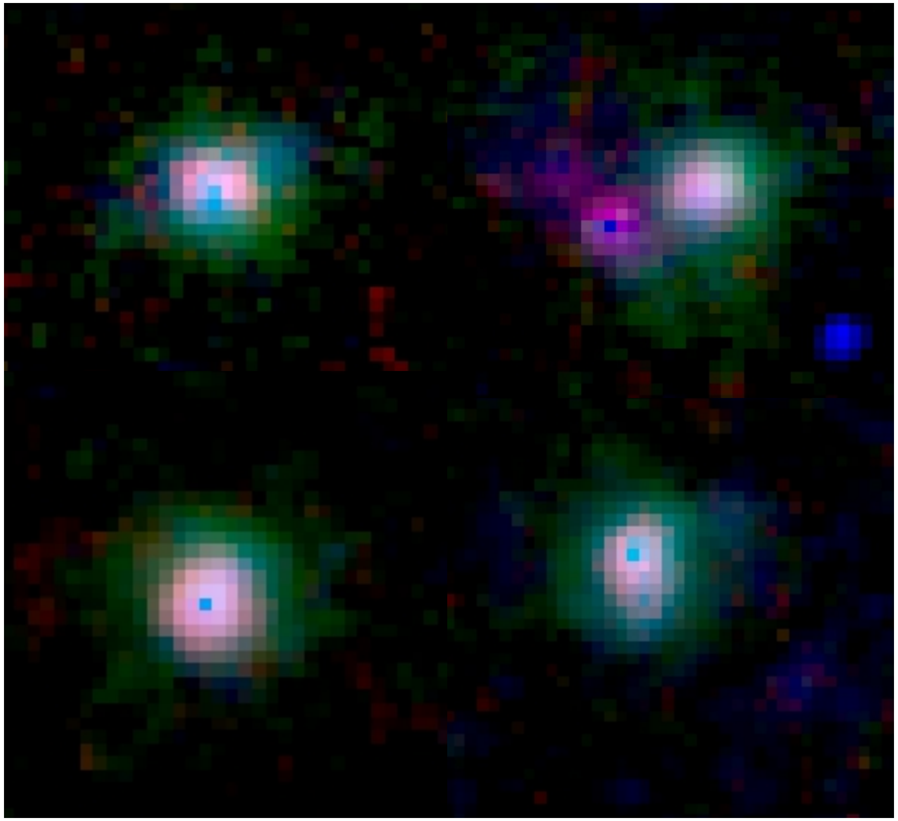


HST GO-13293

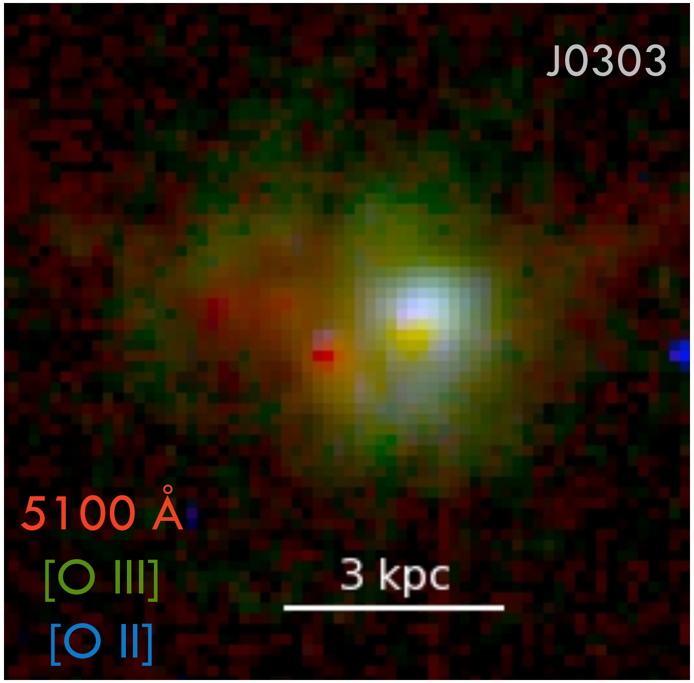
Jaskot+, in prep.

Supernovae?

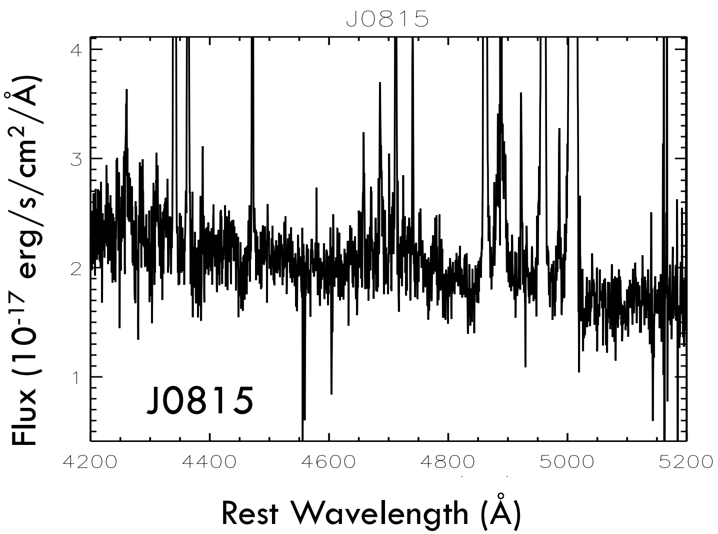
- High ionization shock lines? (e.g., Thuan & Izotov 05)
  - No [Ne V] in MagE spectra of 5 GPs
- He II co-spatial with young clusters
- Extended [O III]



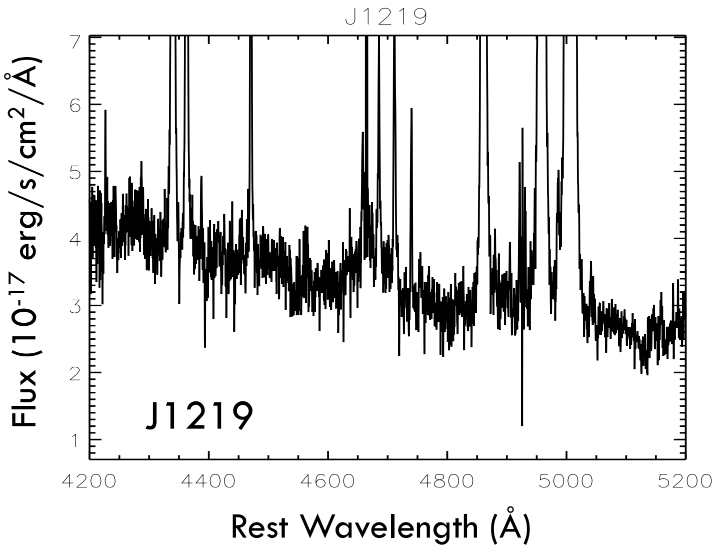
He II   Hβ 4000 Å Continuum

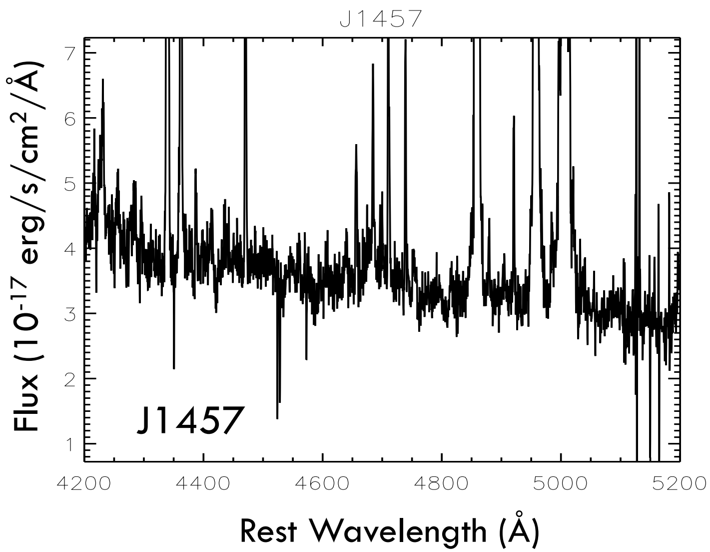


WR Stars?

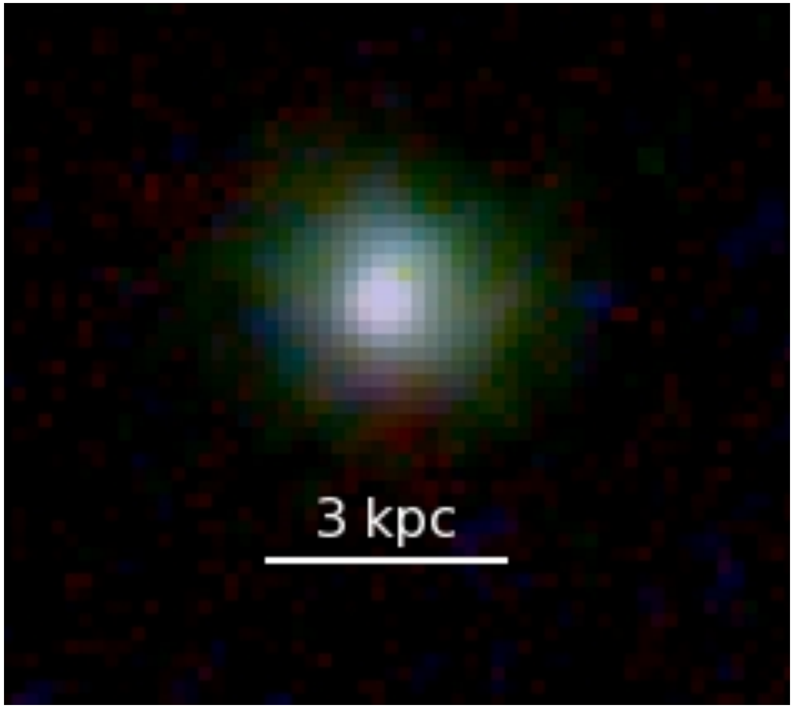


- Broad He II "blue bump" detected in 3 high [O III]/[O II] GPs





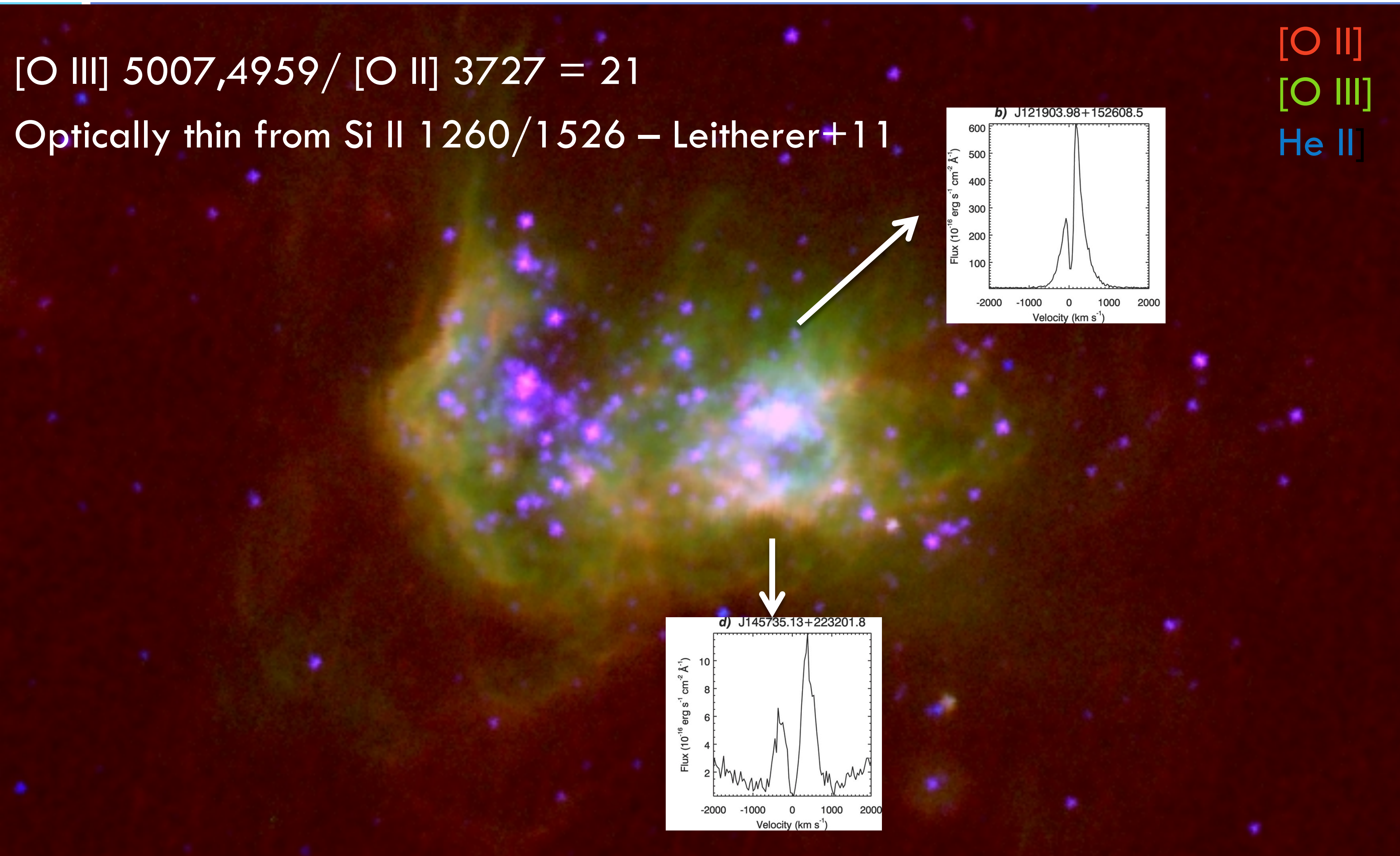
Not much sub-galactic scale info



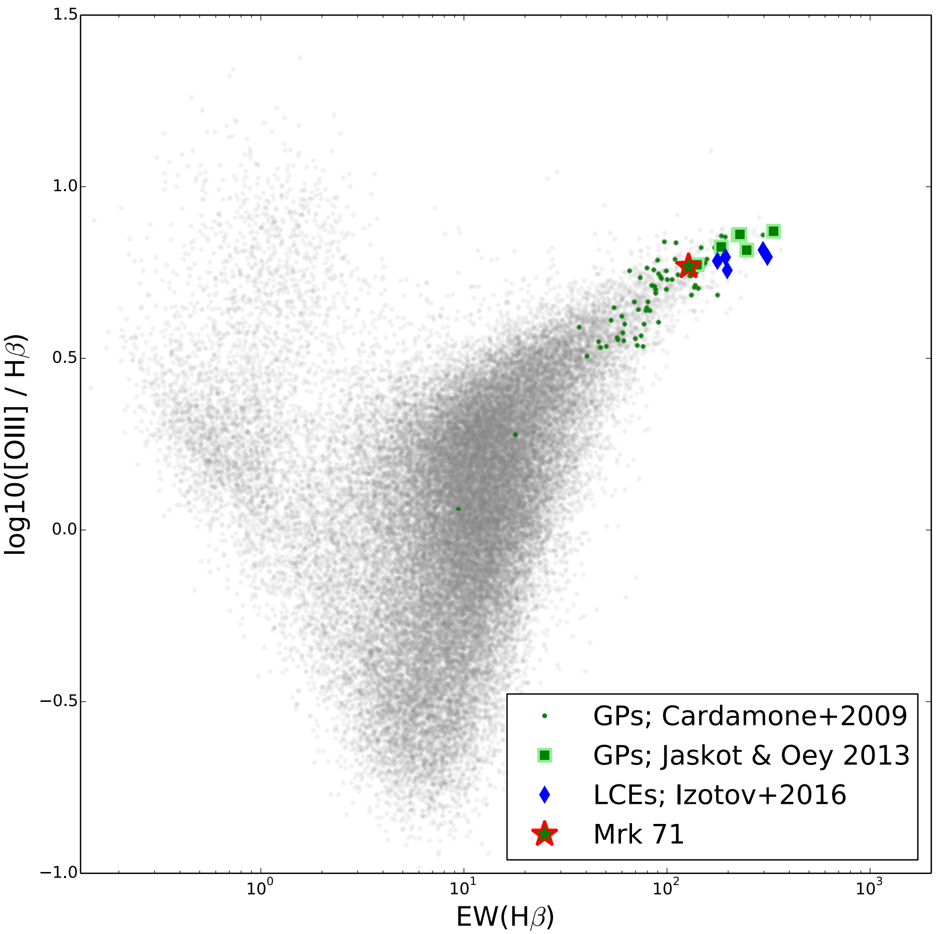
Mrk 71

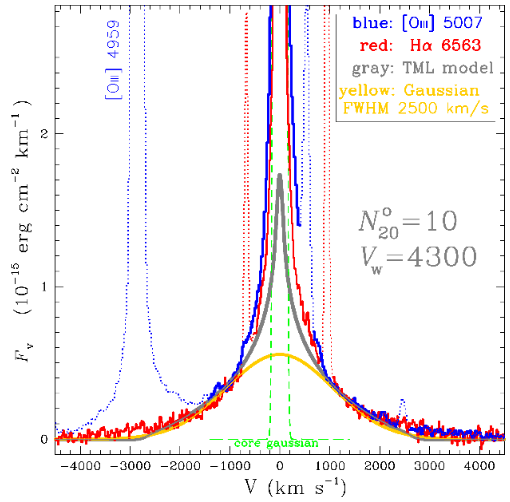
Micheva+, in prep.

Mrk 71



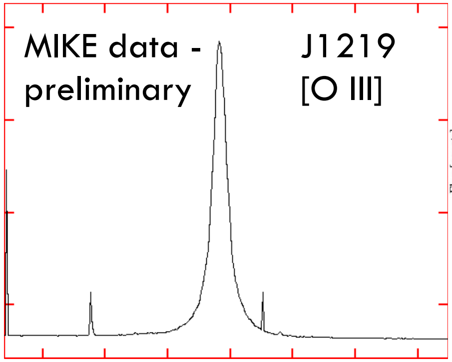
Mrk 71

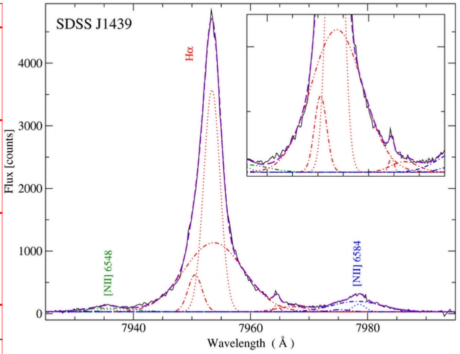




Binette+09

Green Peas

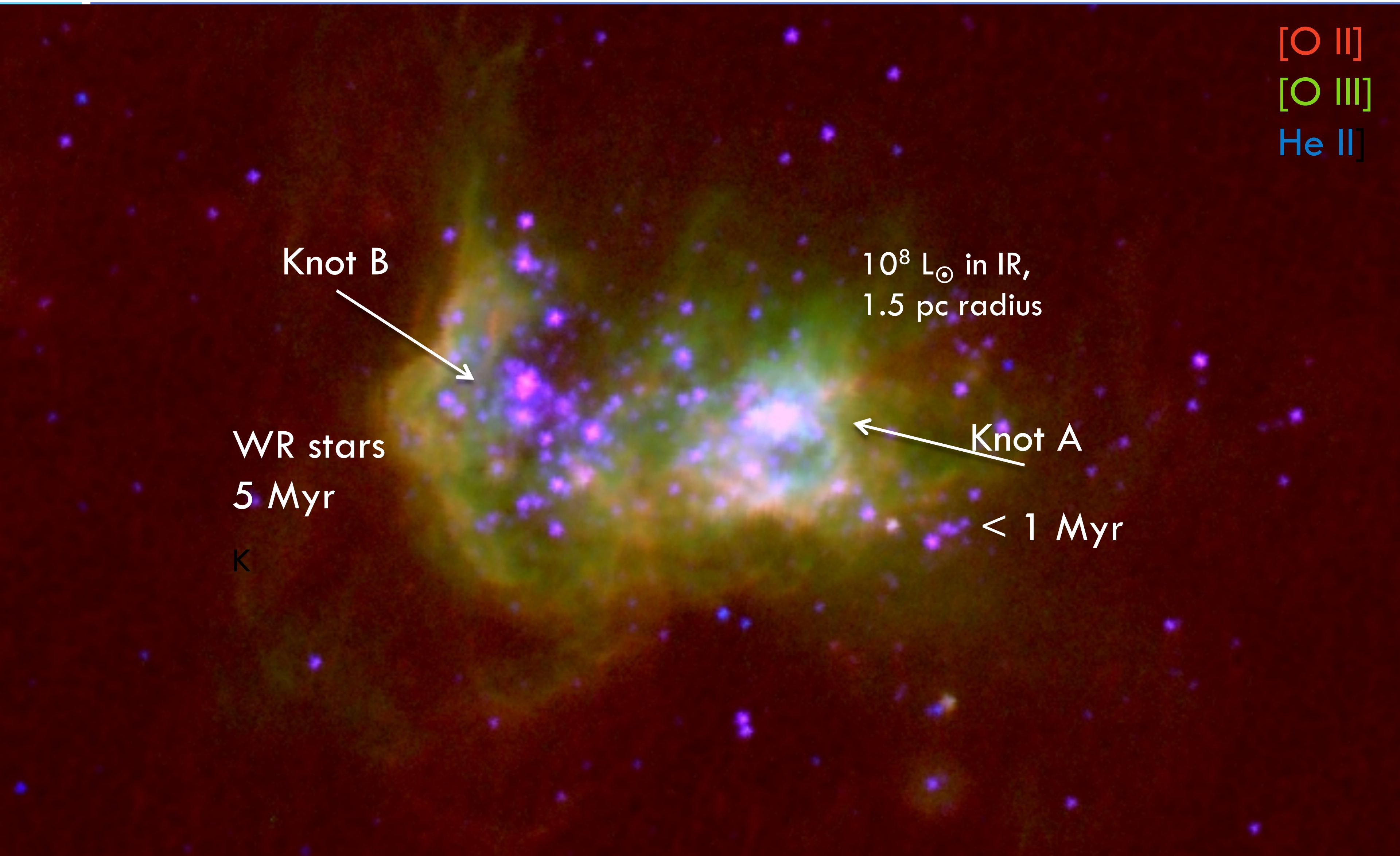




Amorín+12a

Micheva+, in prep.

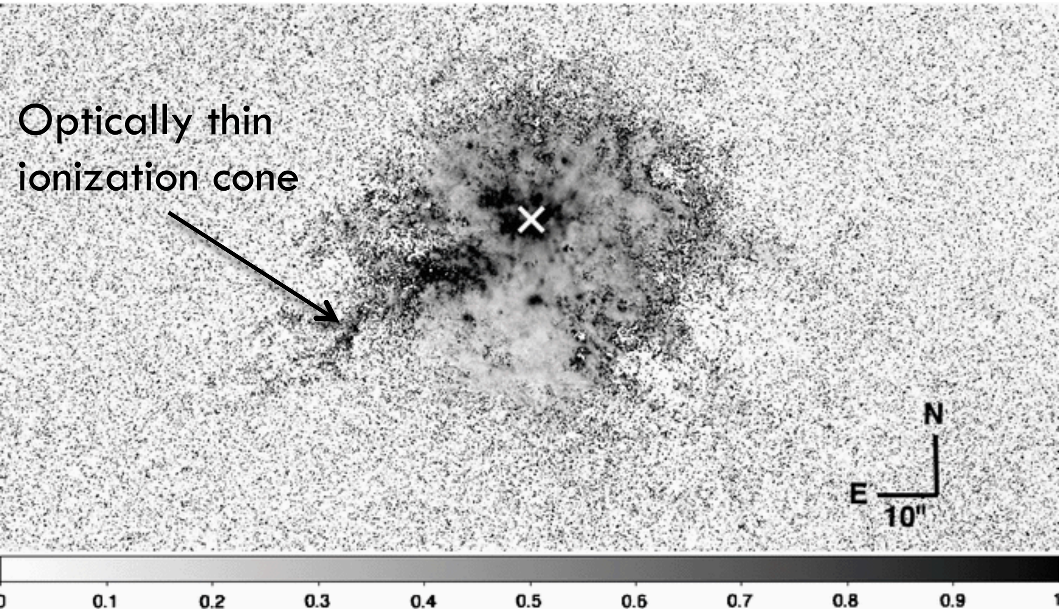
Mrk 71



See talk by A. Bik

Similarly…

Zastrow+11,13



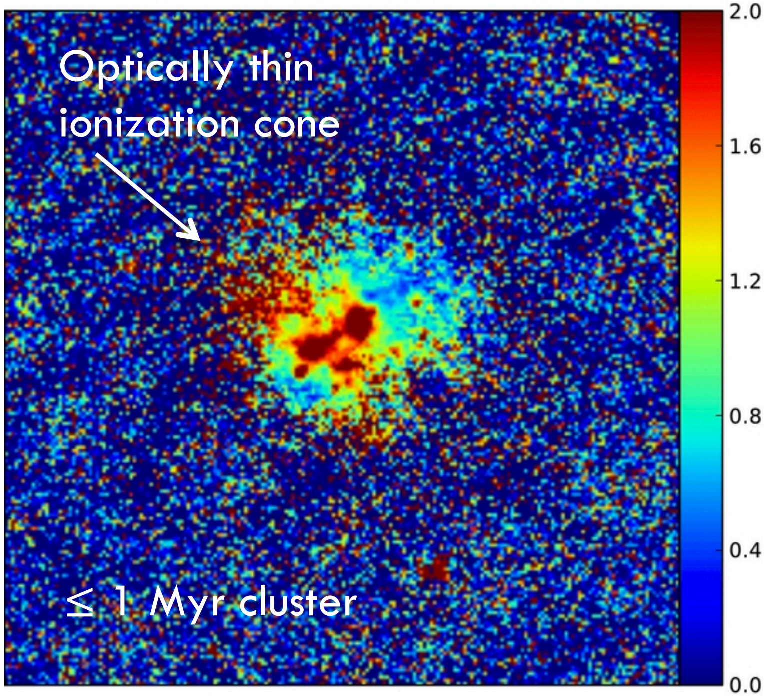
NGC 5253 – [S III]/[S II]

< 3 Myr cluster

VMS stars!

Wofford+14, Calzetti+15, Smith+16

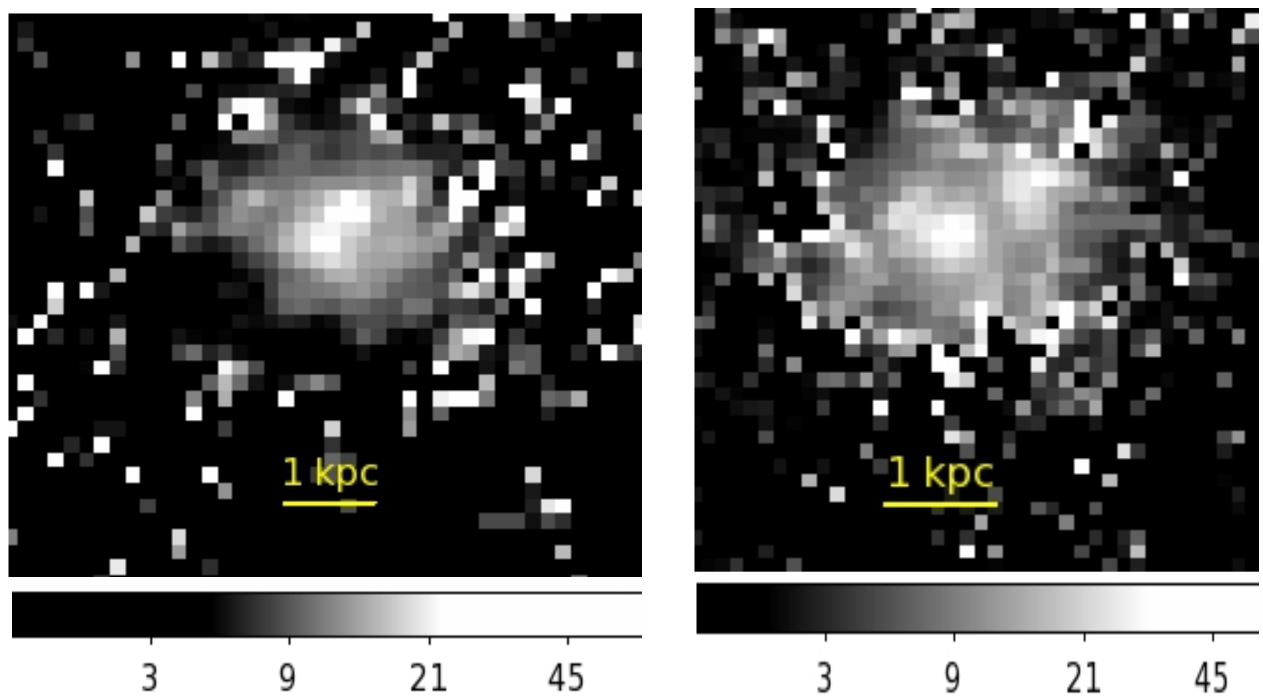
NGC 3125 – [S III]/[S II]



(a) [SIII]/[SII]

Are the GPs young?

[O III] 4959,5007 /[O II] 3727

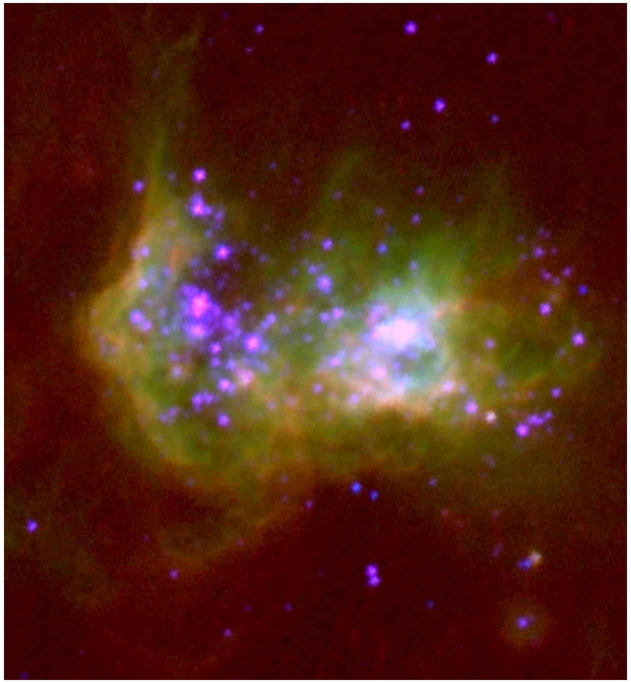


- High H α , H β , C III] EWs
  - *Jaskot & Oey 13, Ravindranath+ in prep.*
- He I 3819, full Balmer series
  - *González Delgado+99*
- Blue Bump – VMS stars?

What if LyC Leakers are Young?

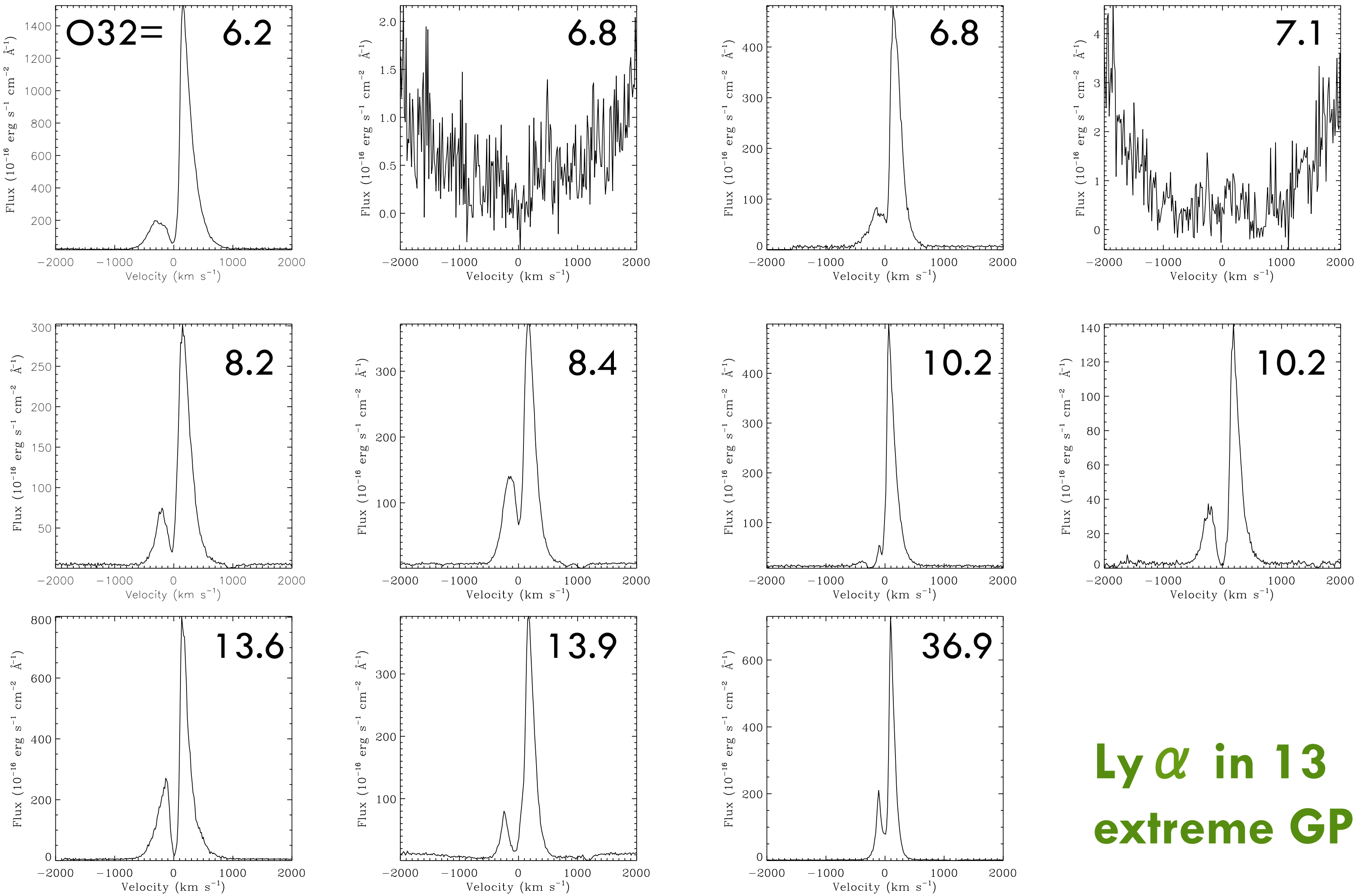
- Plenty of LyC
- Feedback source?
  - VMS stars?
  - Radiation?
- Neutral gas surroundings
  - Shaped by previous generations
  - Highly efficient star formation
    - e.g., Dale+14, Turner+15 (NGC 5253)

See talk by D. Kruijssen



Preview

HST GO-14080
PI Jaskot



Lyα in 13 extreme GPs

Summary

- Early stage feedback, esp. radiative is critical
- Need to consider binaries, VMS, WR stars, and multiple feedback mechanisms
- LyC leakers may be extremely young objects
- Open questions
  - Are all LyC leakers young?
  - Which feedback mechanism dominates in LyC leakers?
  - Do very massive stars play a role?
  - Is sequential SF important?