Extreme Outflows in an AKARI-selected ULIRG at z=0.5

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Ultra-Luminous InfraRed Galaxies

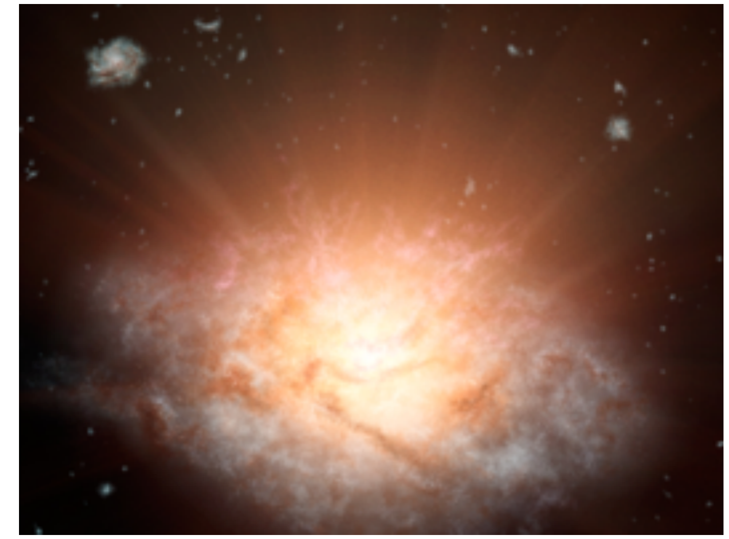
Def:

LIRG : $L_{8\text{-}1000\mu m} > 10E+11\ L_{\odot}$

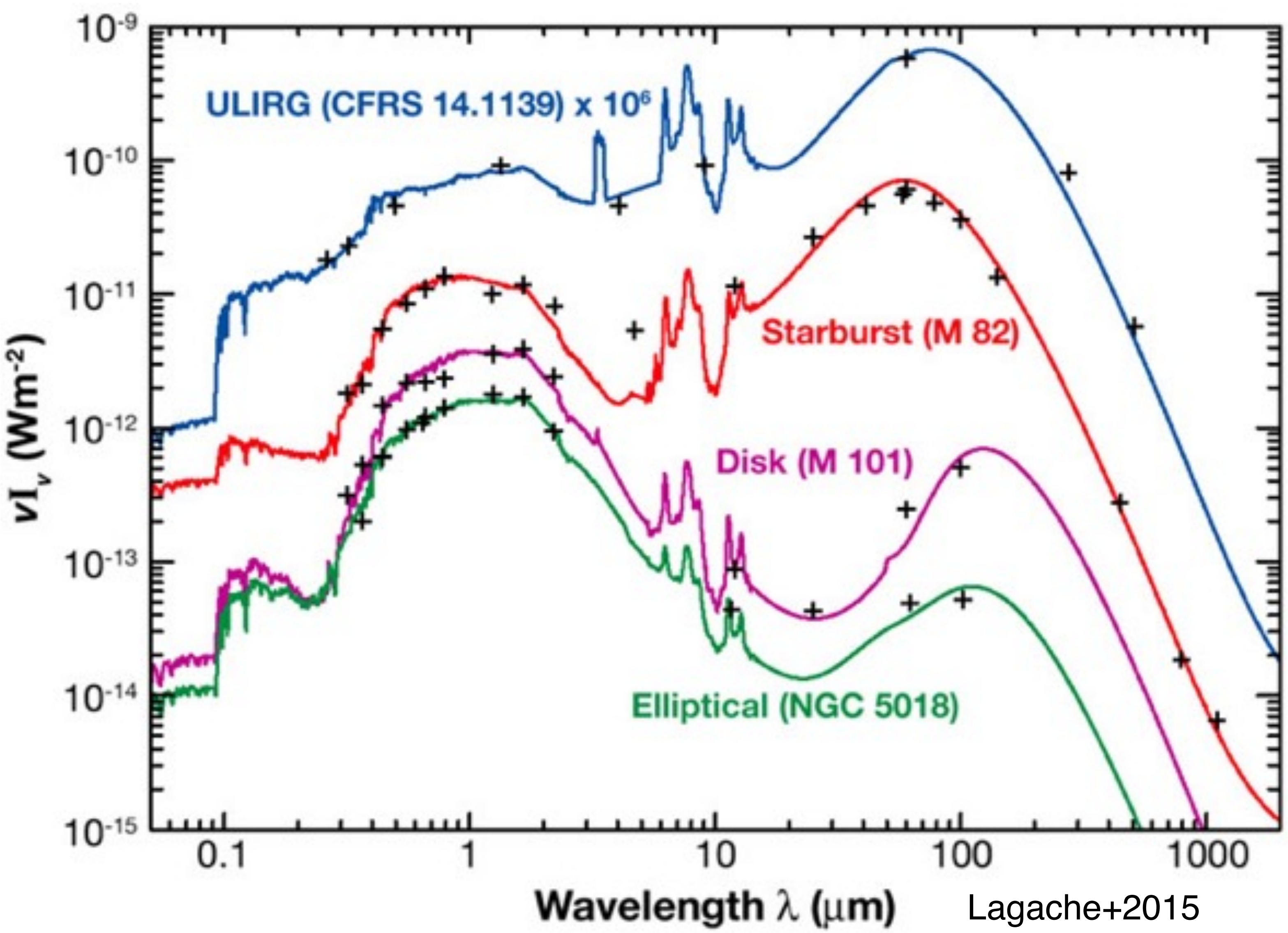
Ultra-LIRG : $L_{8\text{-}1000\mu m} > 10E+12\ L_{\odot}$

Hyper-LIRG : $L_{8\text{-}1000\mu m} > 10E+13\ L_{\odot}$

Extremely-LIRG : $L_{8\text{-}1000\mu m} > 10E+14\ L_{\odot}$



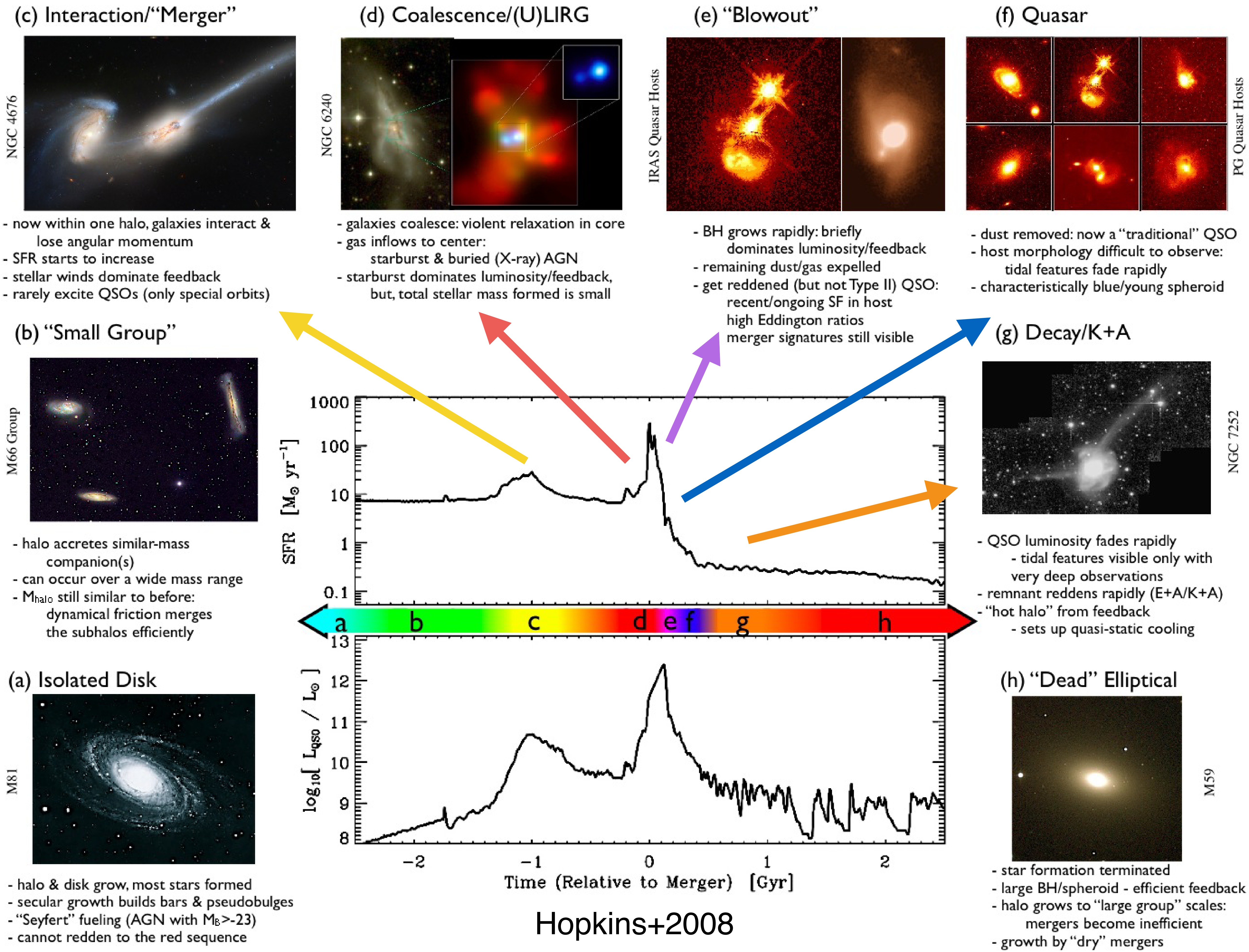
ELIRG : WISE J224607.57-052635.0 (NASA/ART)



Lagache+2015

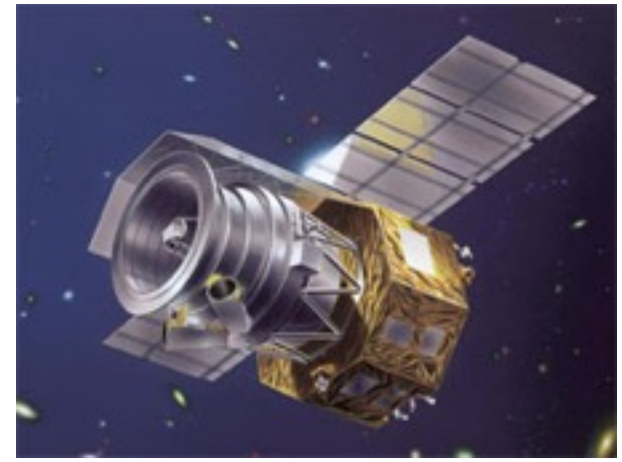
~90% radiation emitted in infrared band by dust heated by starburst (O/B stars) and/or AGN.

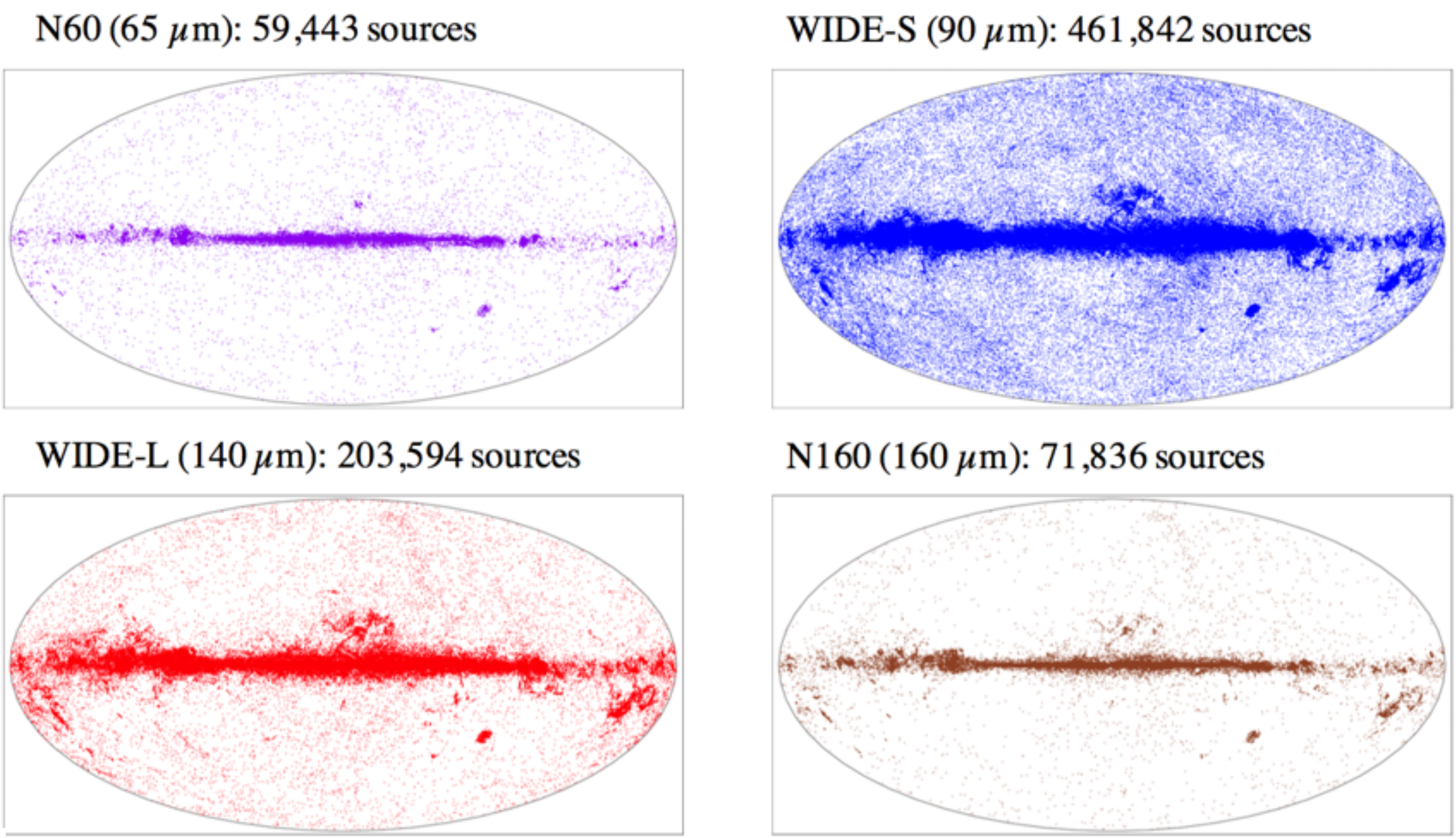
Important stage in the evolution of galaxies.



Hopkins+2008

- Searching ULIRG in the **AKARI FIS Bright Source Catalogue (Ver.2)**.
- Covering **10 times wider** survey area compared to the **Herschel-ATLAS** survey at the similar depth.





Yamamura et al.

AKARI-FIS Bright Source Catalogue Ver.2 Release Note (preliminary version 1.1; 2016/04/26)

- **WISE pinpointing** to narrow down the positional uncertainty of the AKARI FIR sources
- An optical follow-up program for optically-faint AKARI FIS Bright sources to construct a unique sample of ULIRGs at z ~ 0.5-1.0.
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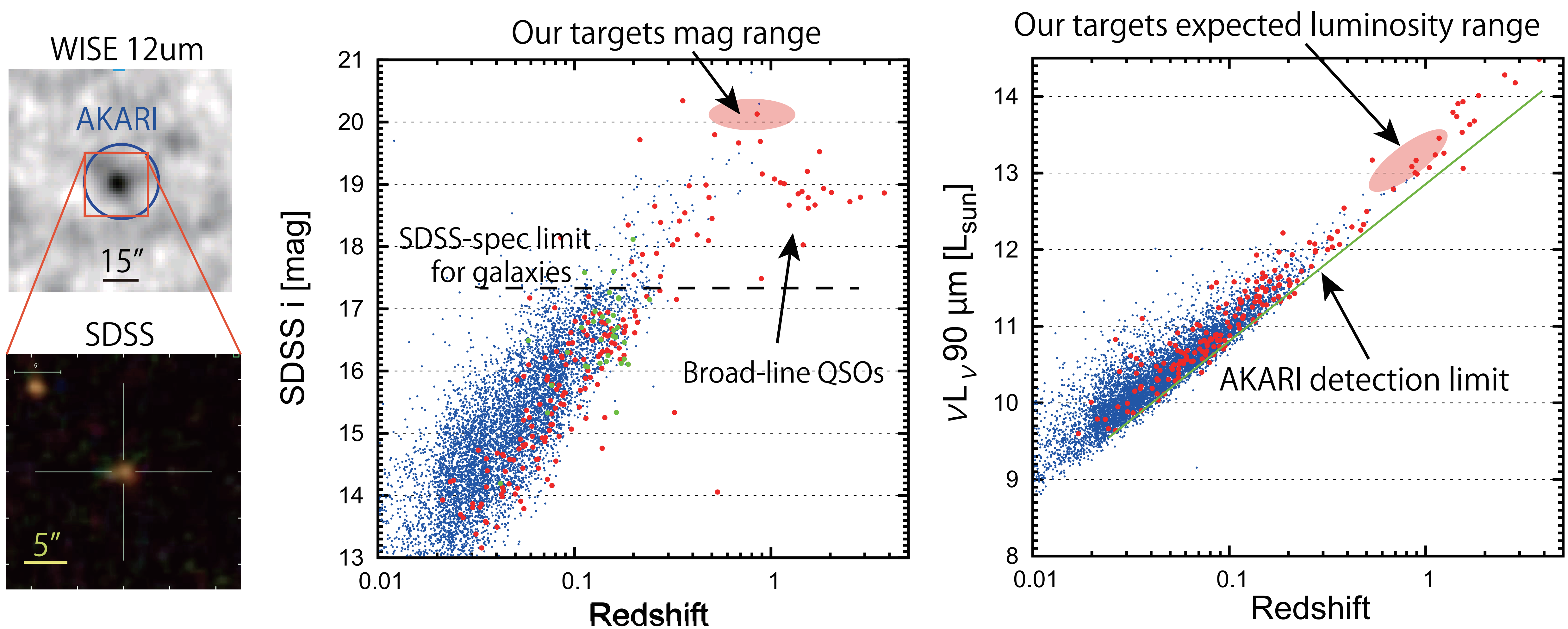

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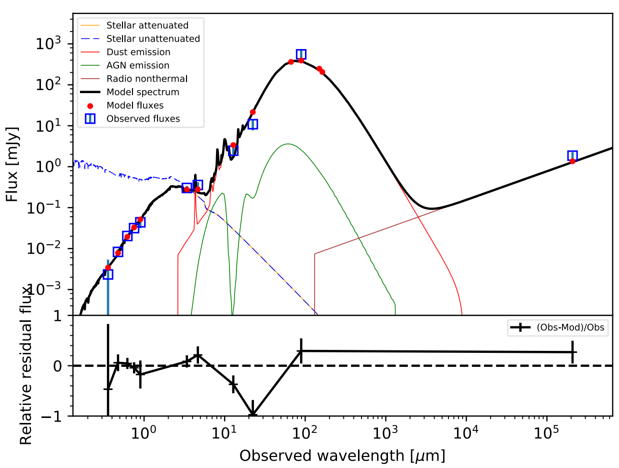
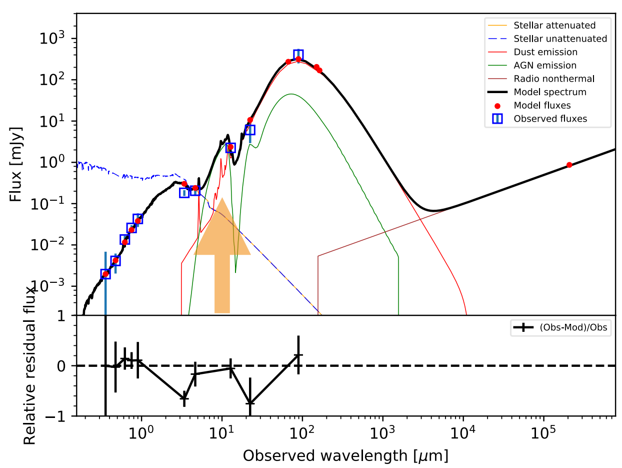
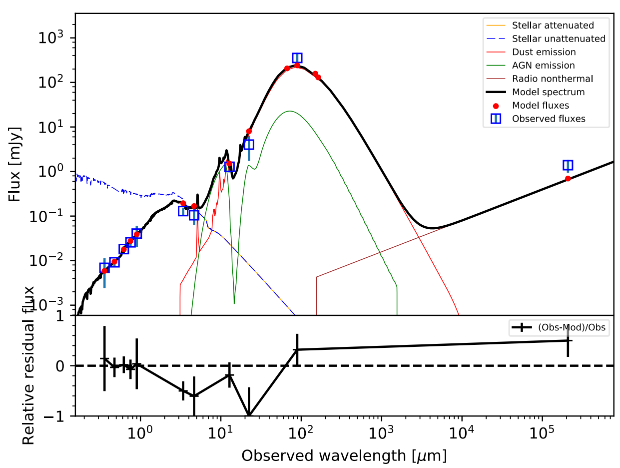
SDSS J0818



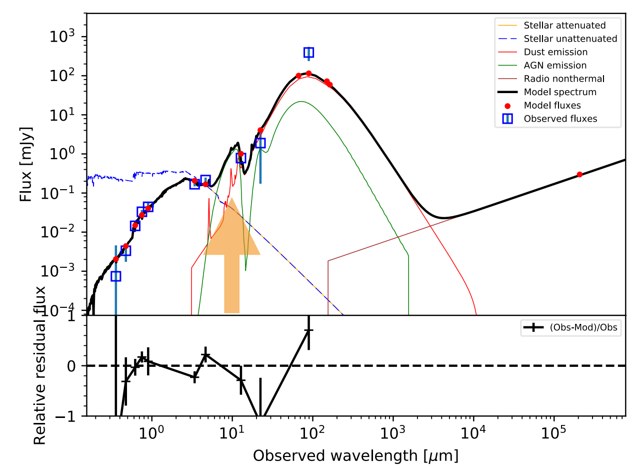
SDSS J1010



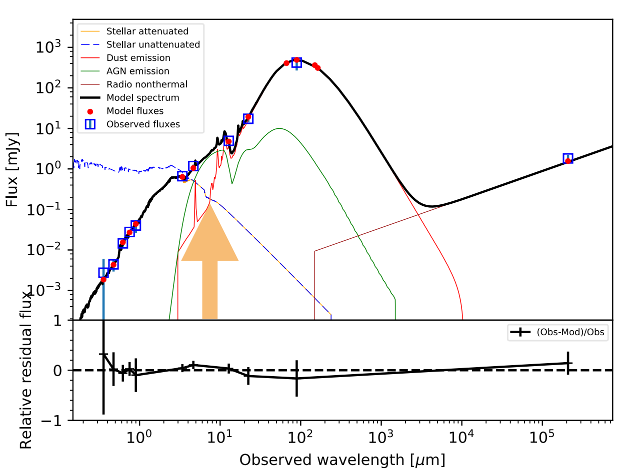
SDSS J1219



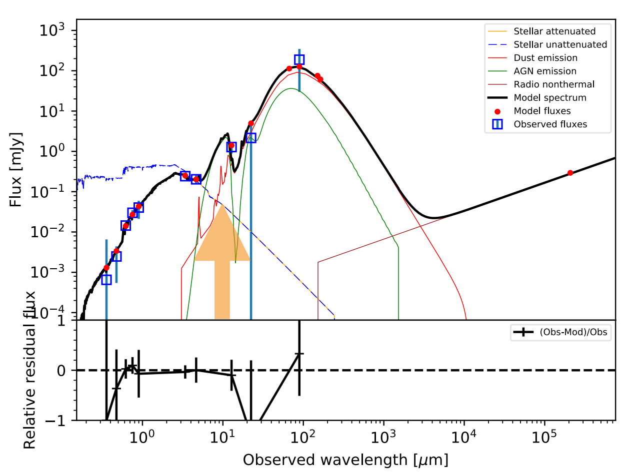
SDSS J1348



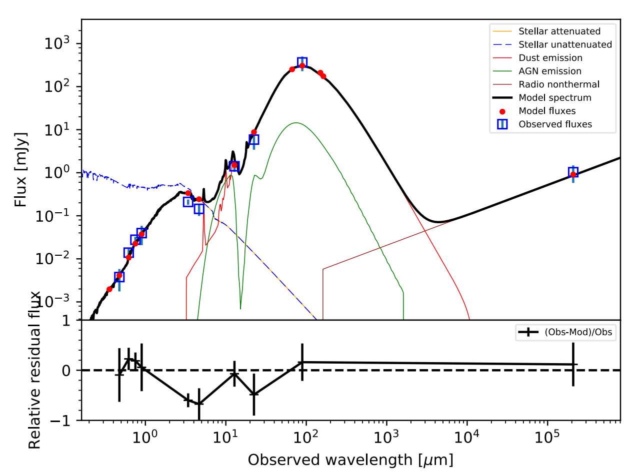
SDSS J0916



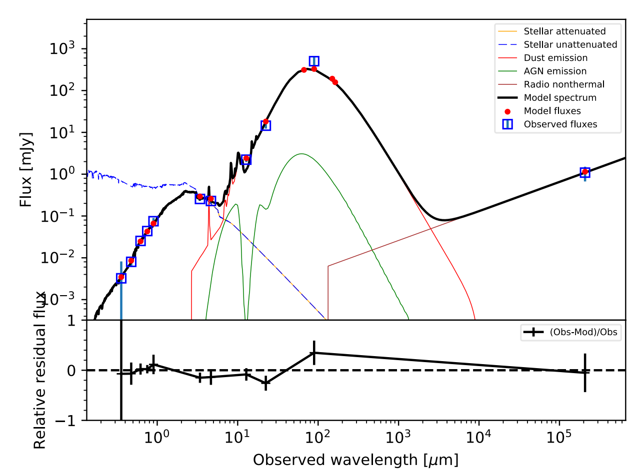
SDSS J1034



SDSS J1227



SDSS J1402



MIR excess Blue: Stellar Green: AGN Red: Dust

identified by Subaru/FOCAS

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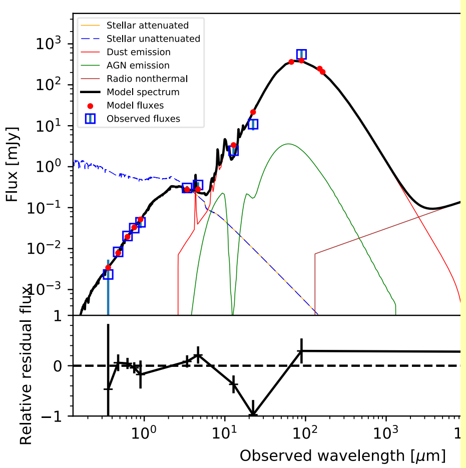
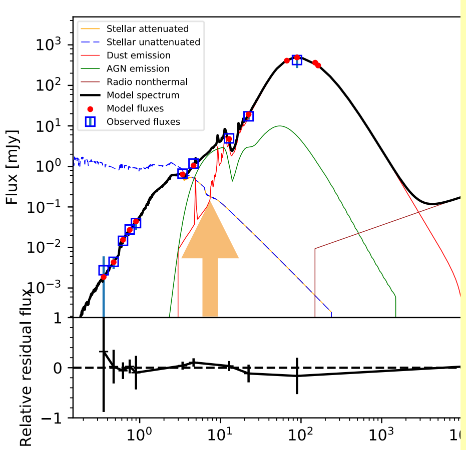
SDSS J081



SDSS J091



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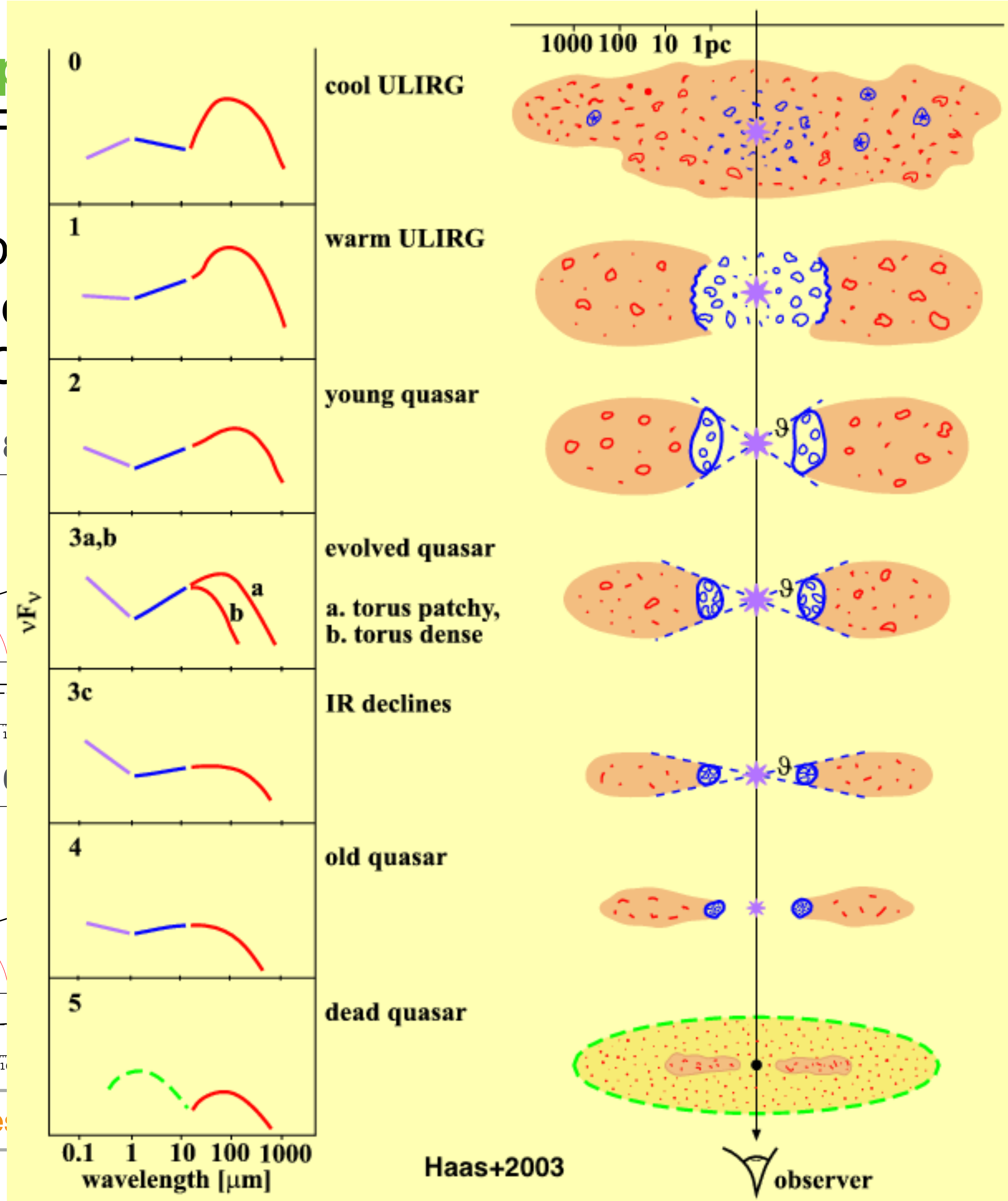
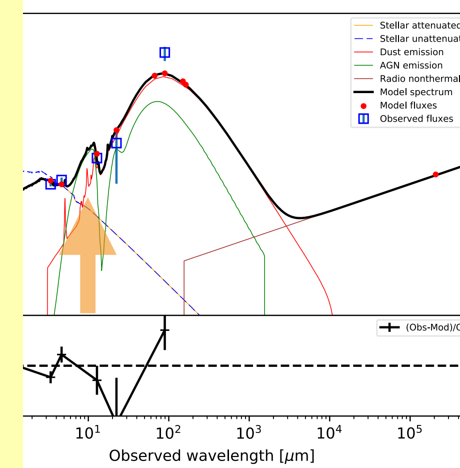


SDSS J1348



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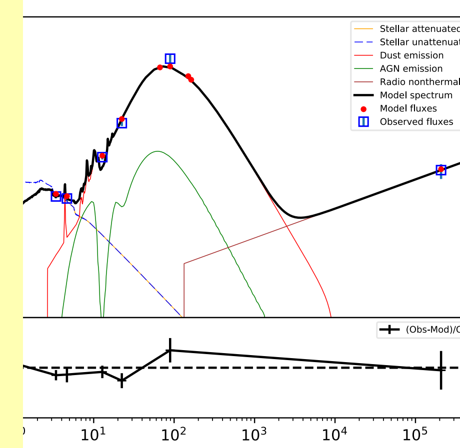

Subaru/FOCAS

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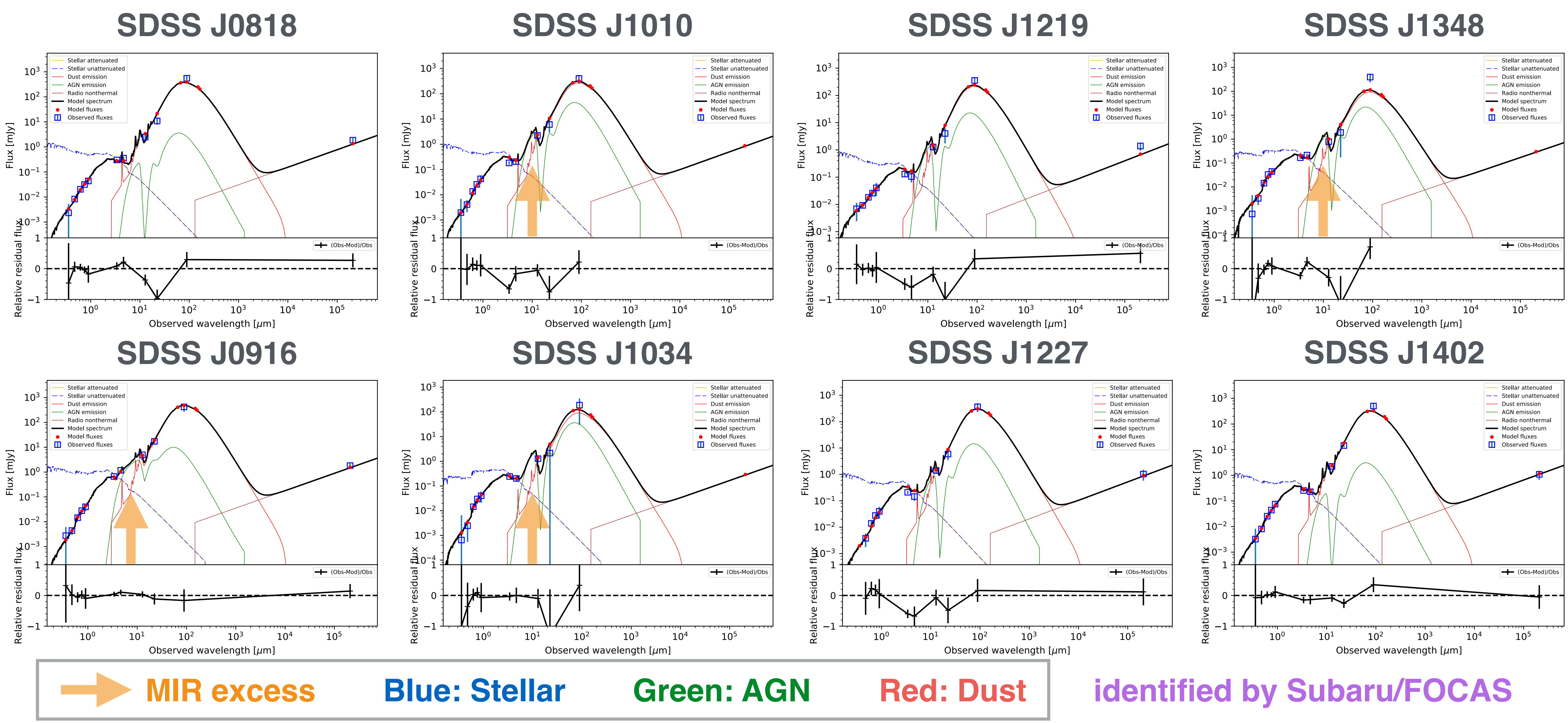

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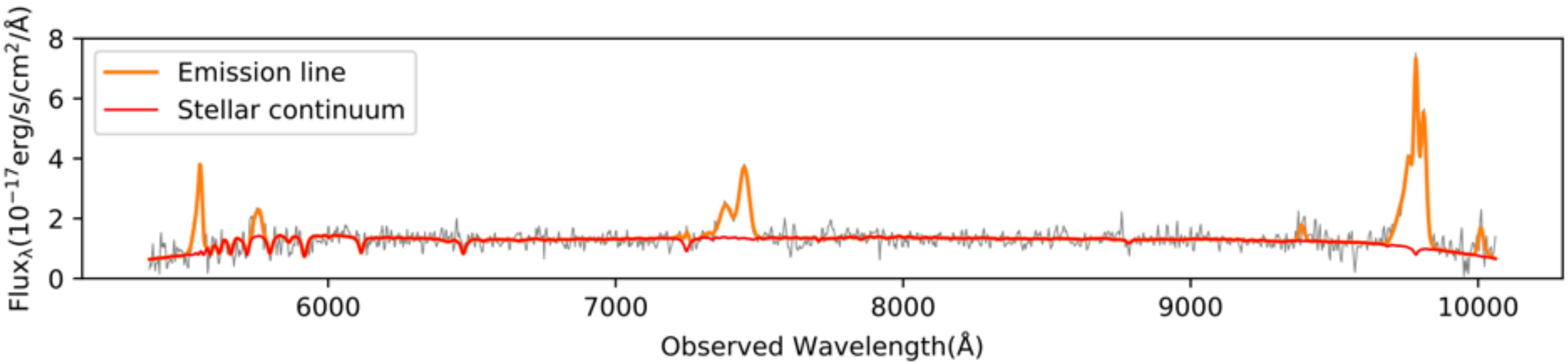

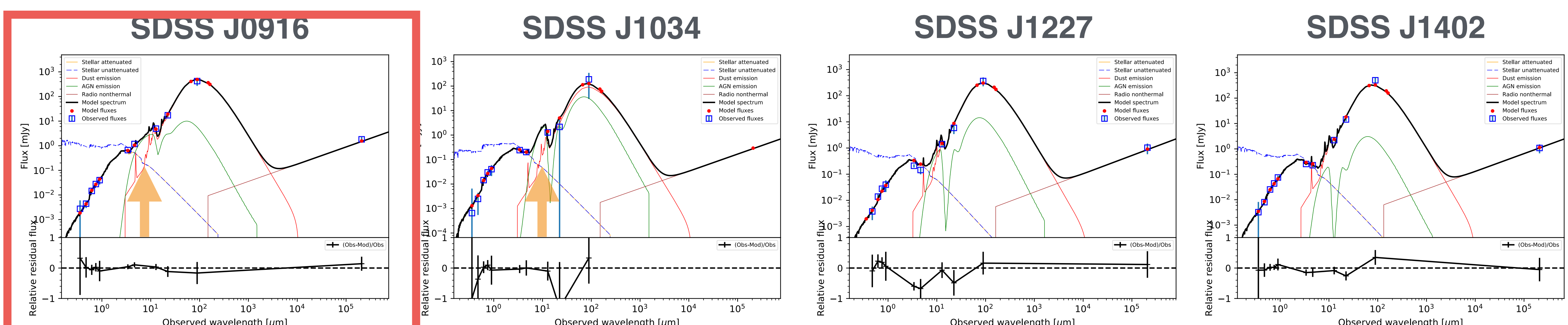

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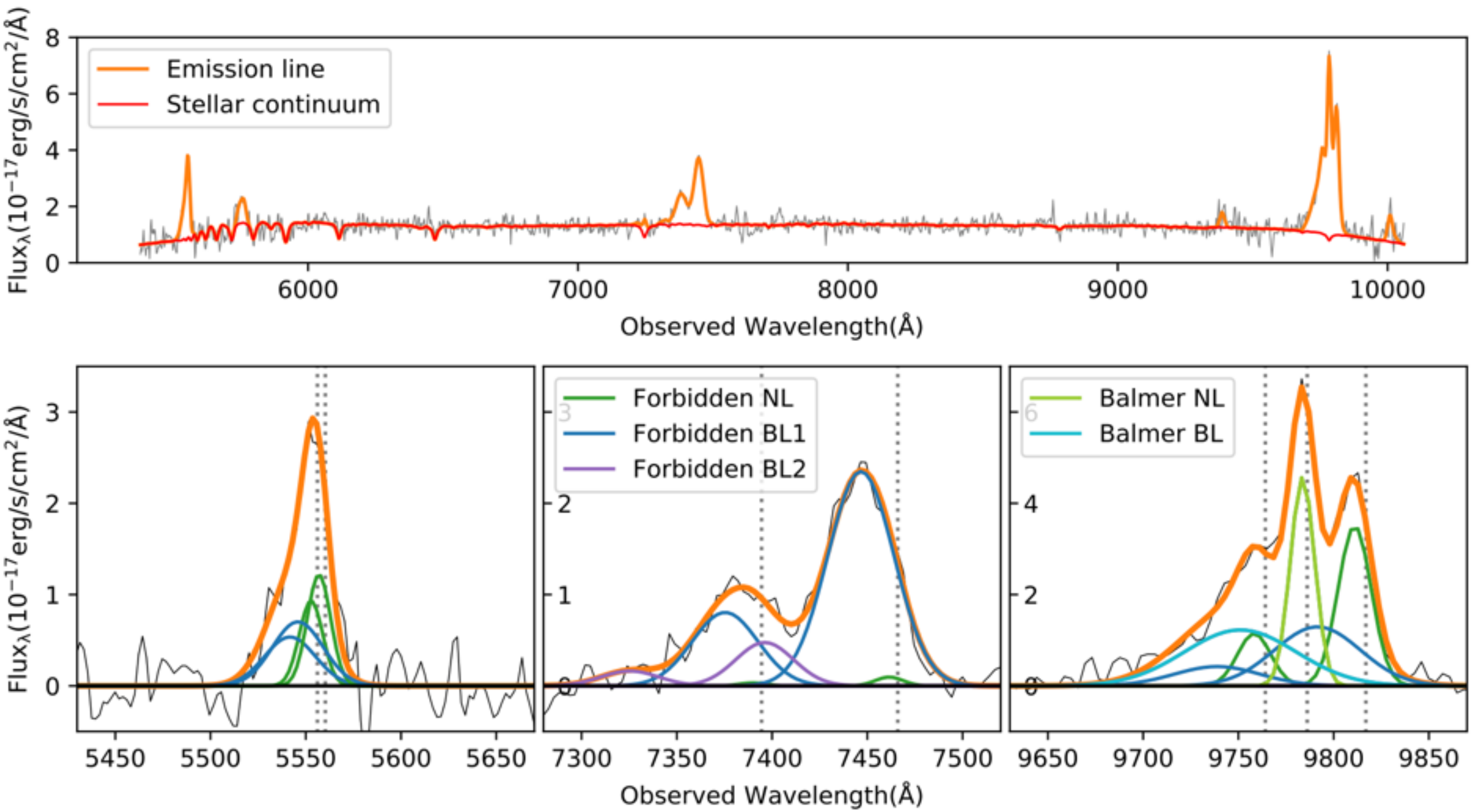
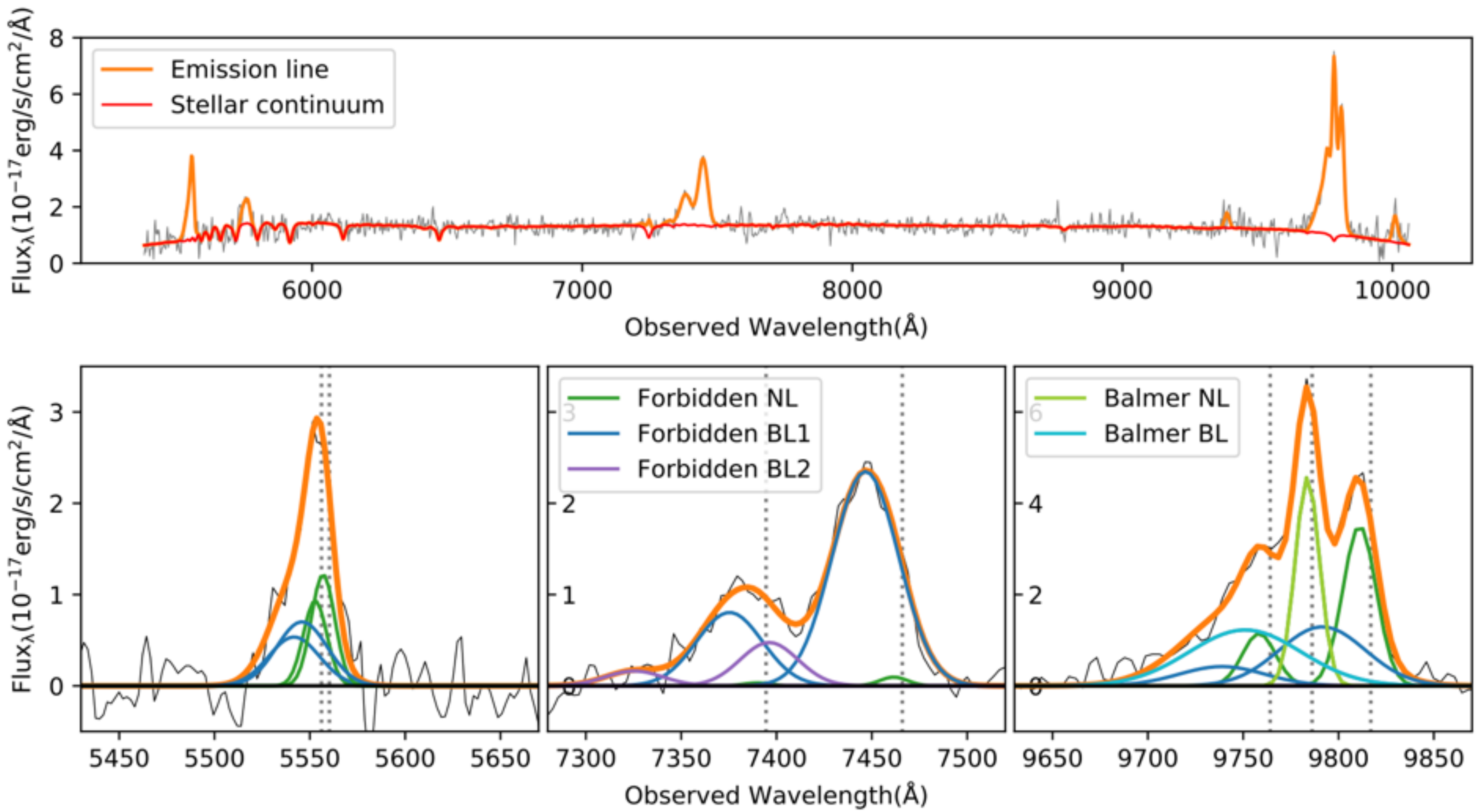
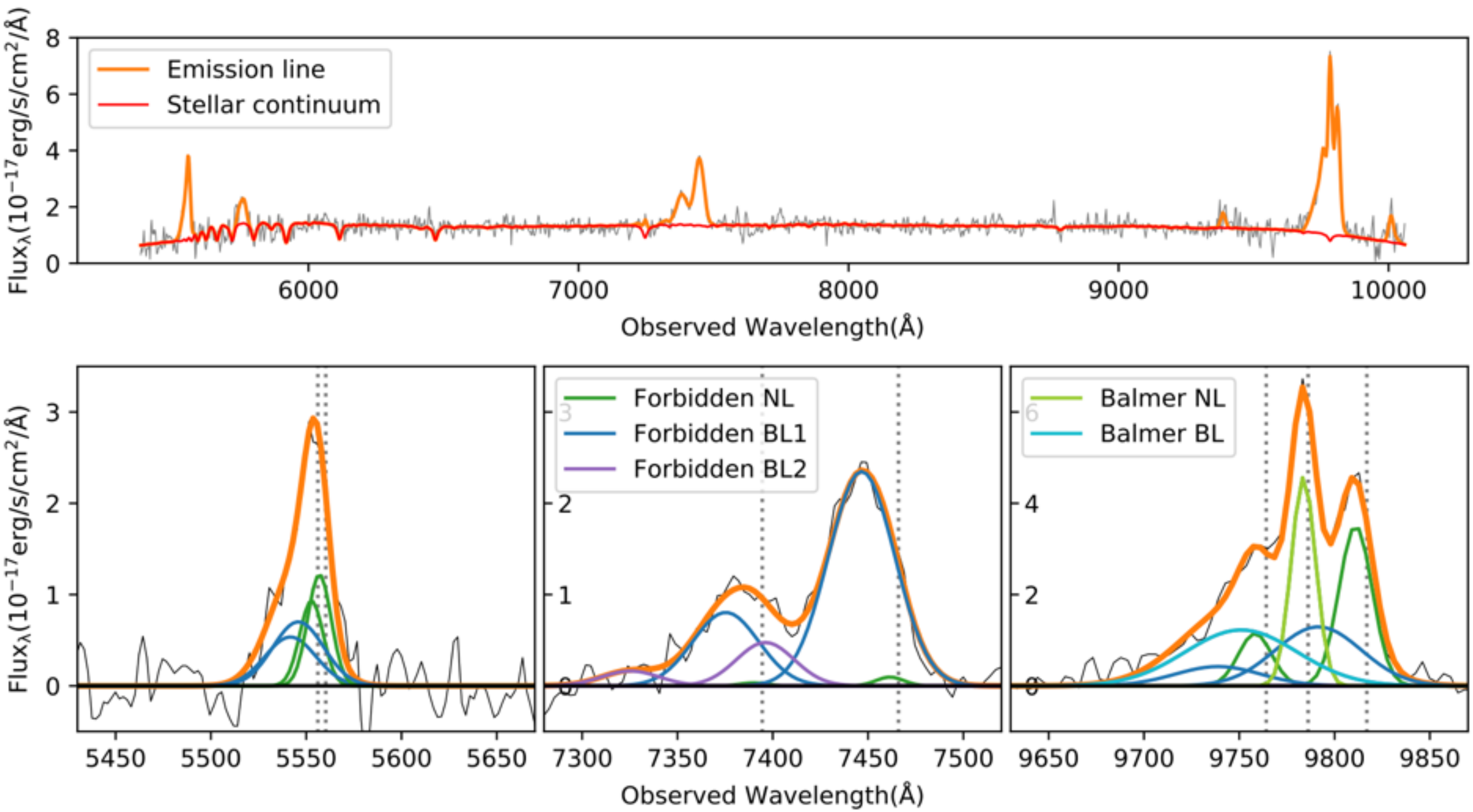


- Using ***pPXF*** to subtract stellar continuum and Balmer absorptions from the galaxy spectrum.
- Using ***PySpecKit*** to fit the emission line features of gases.
  - tie the kinetics (position and dispersion)
  - only set amplitude as free parameter



	shift to Balmer Abs	FWHM	w80 (= v90 - v10)
[OIII] 5007	- 917 km/s	1658 km/s	2607 km/s
[OII] 3726,3729	- 406 km/s	997 km/s	1555 km/s



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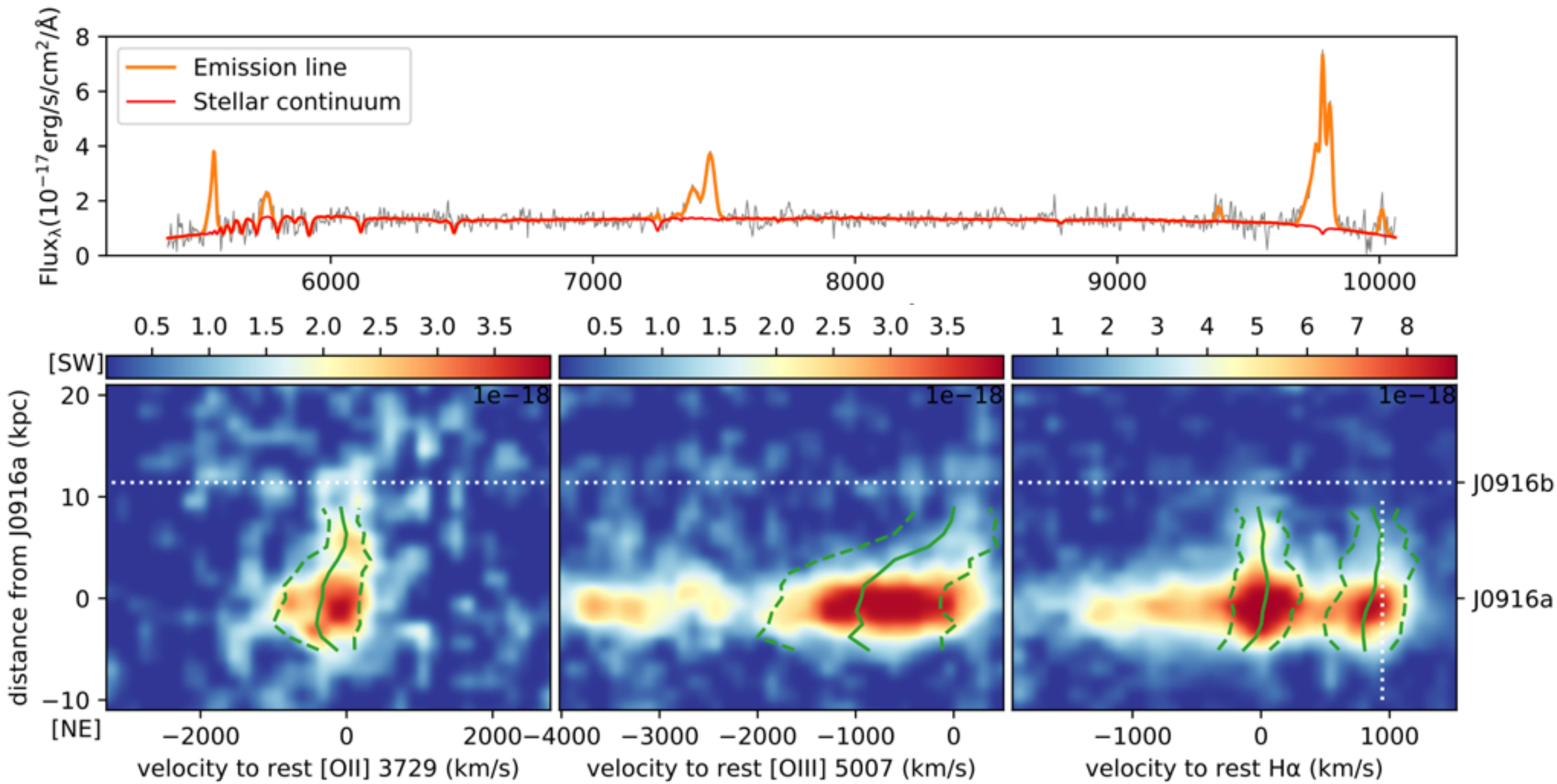

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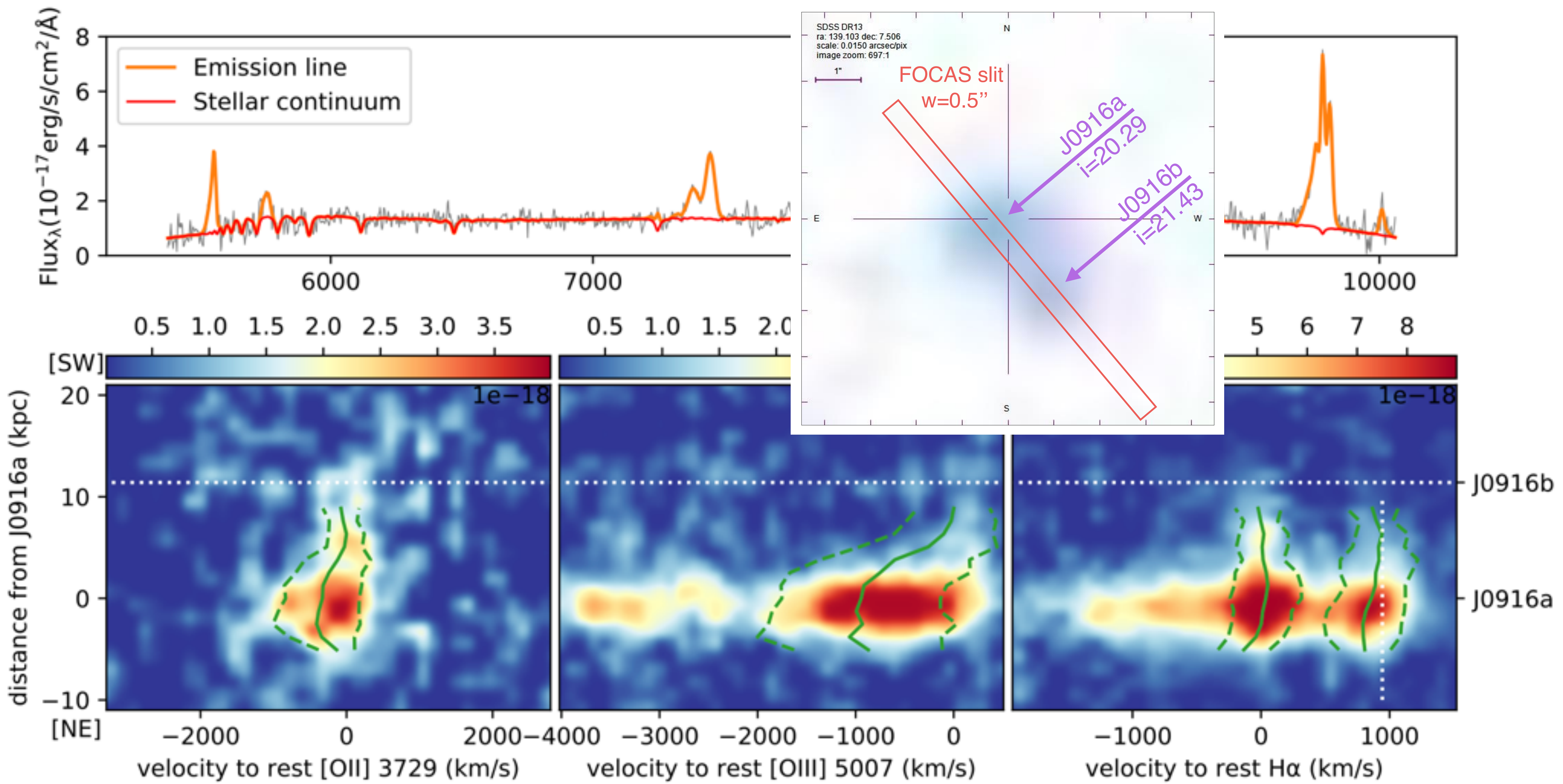

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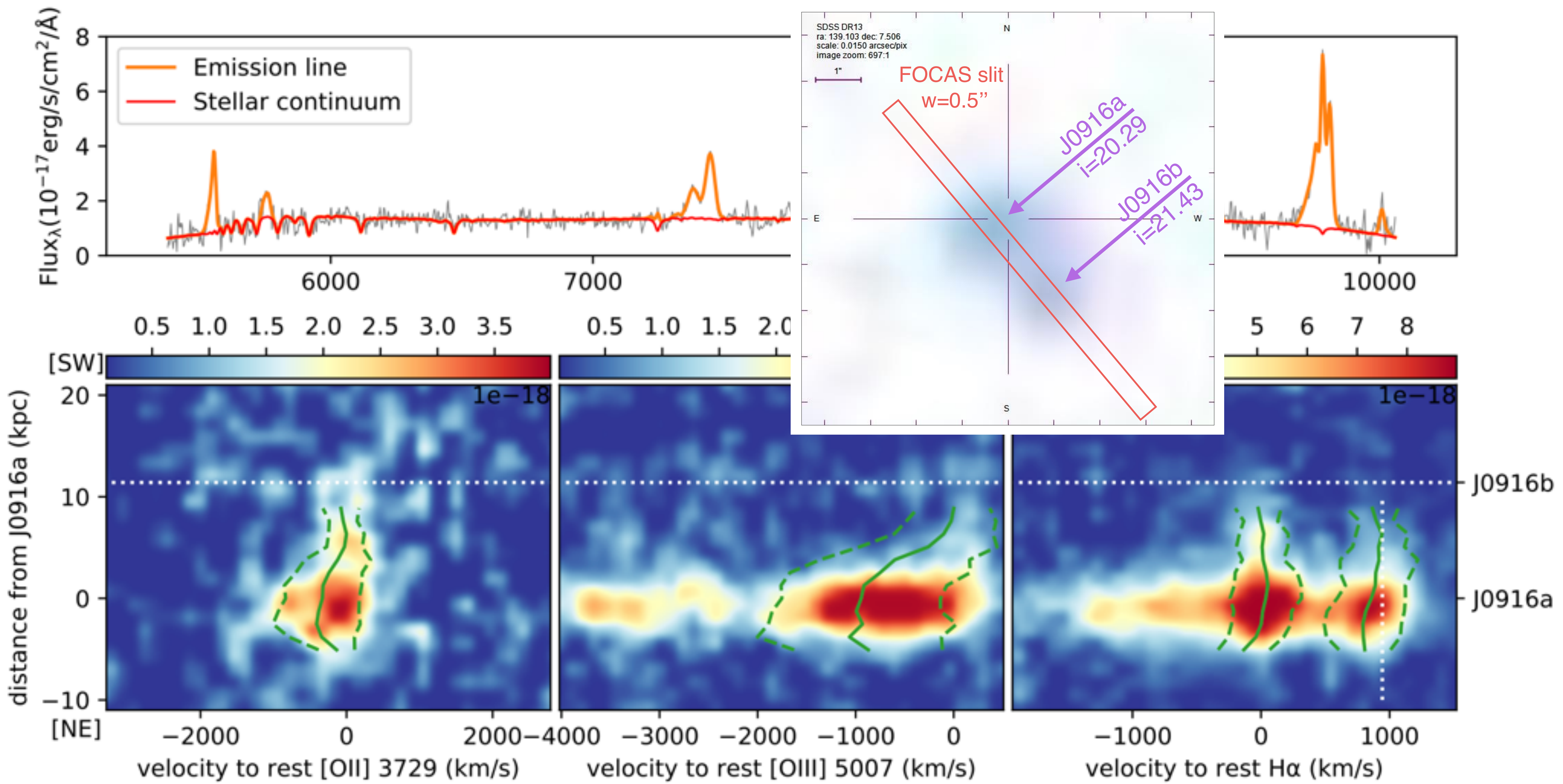

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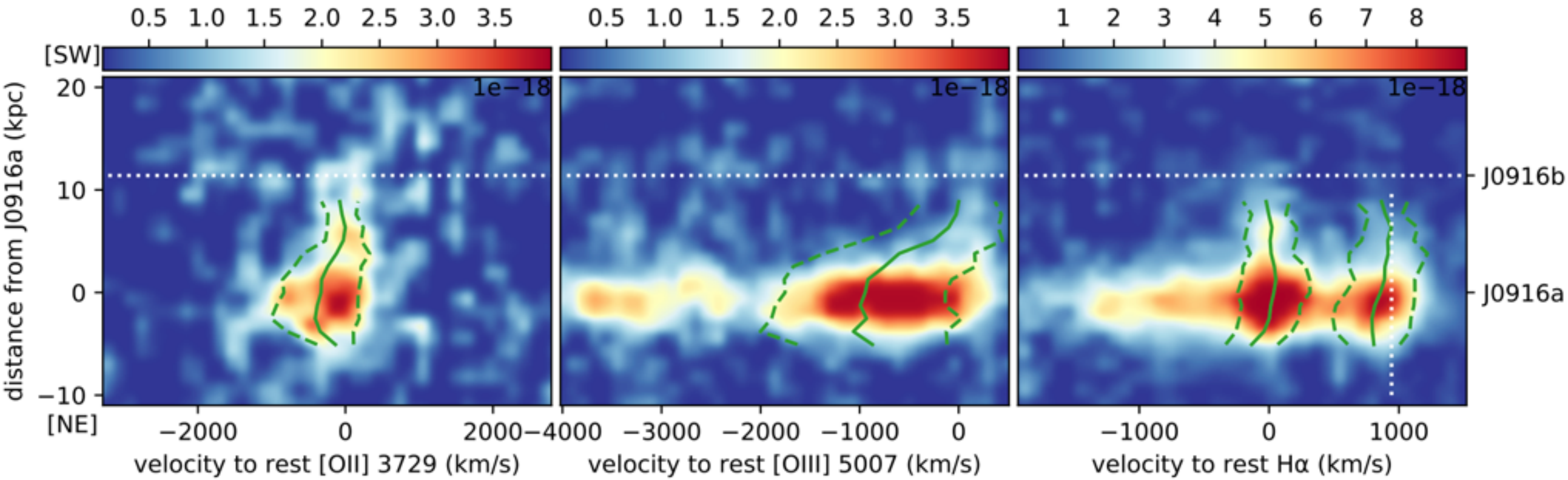
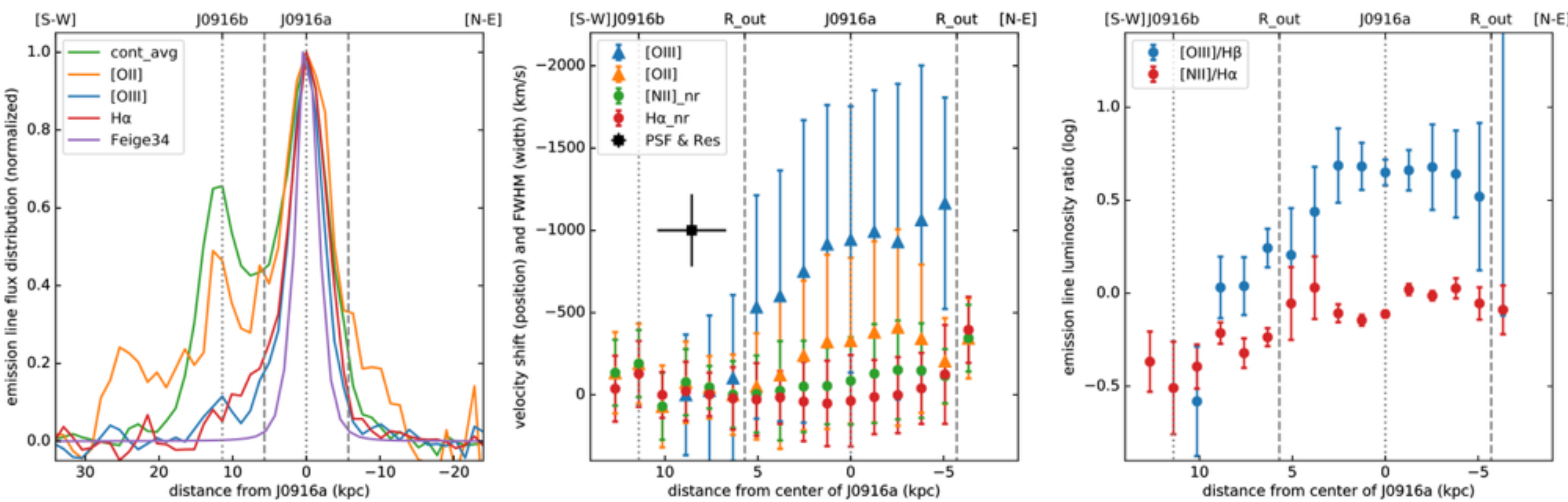
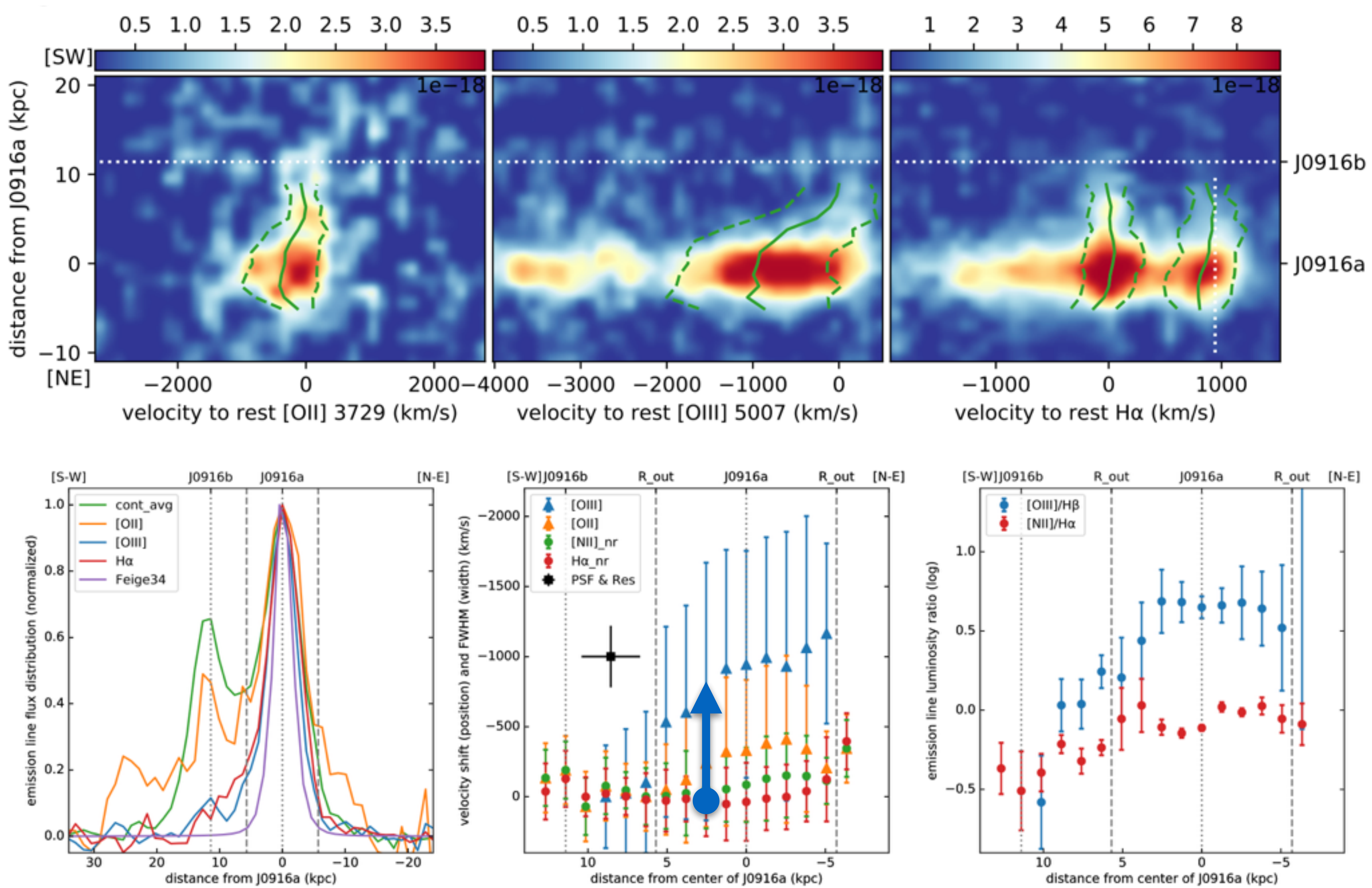




Flux distribution

Velocity shift & FWHM

[OIII]/Hβ & [NII]/Hα



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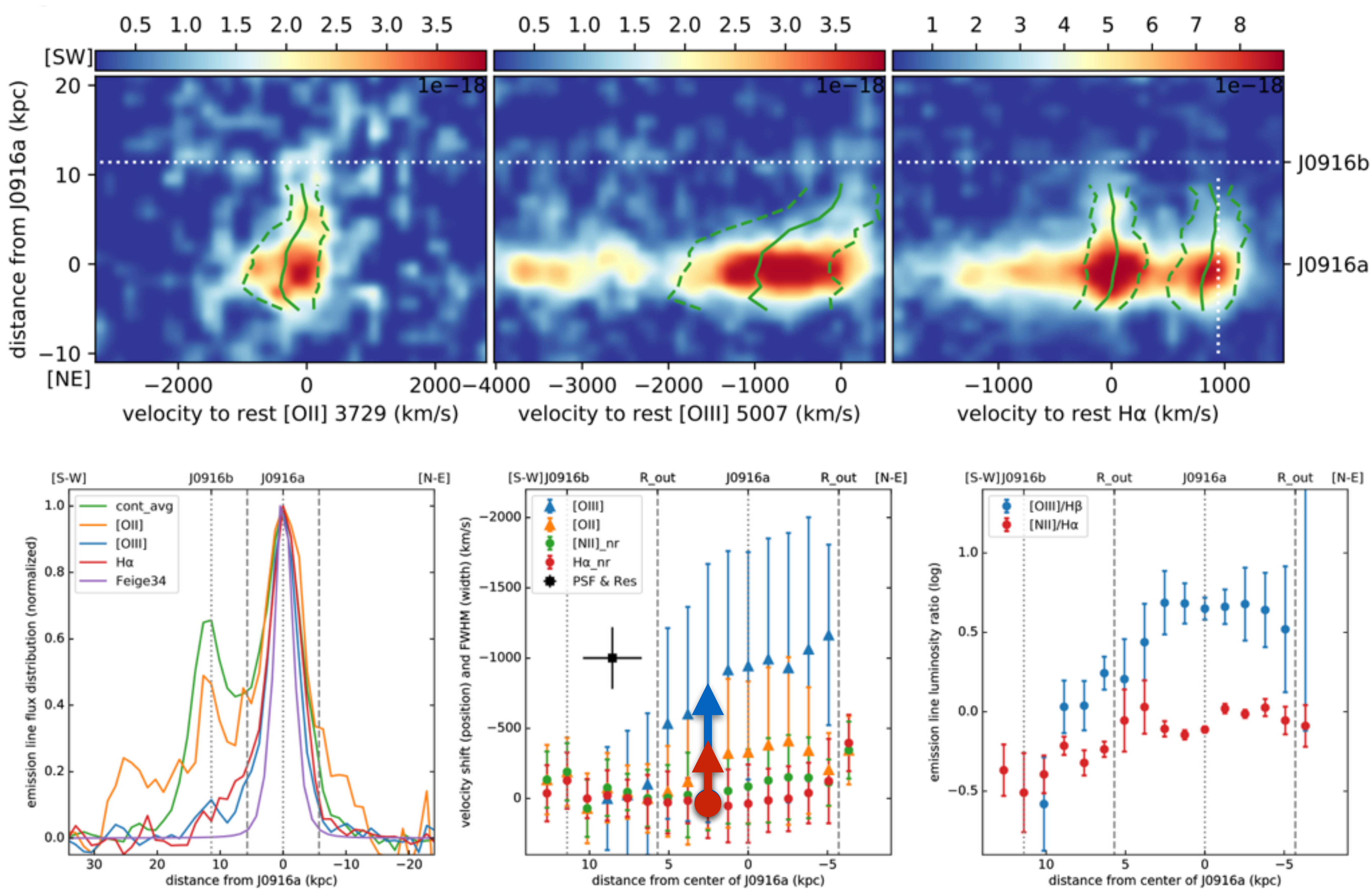
$V_{[OIII]}$ - $V_{H\alpha\_nr}$



Flux distribution

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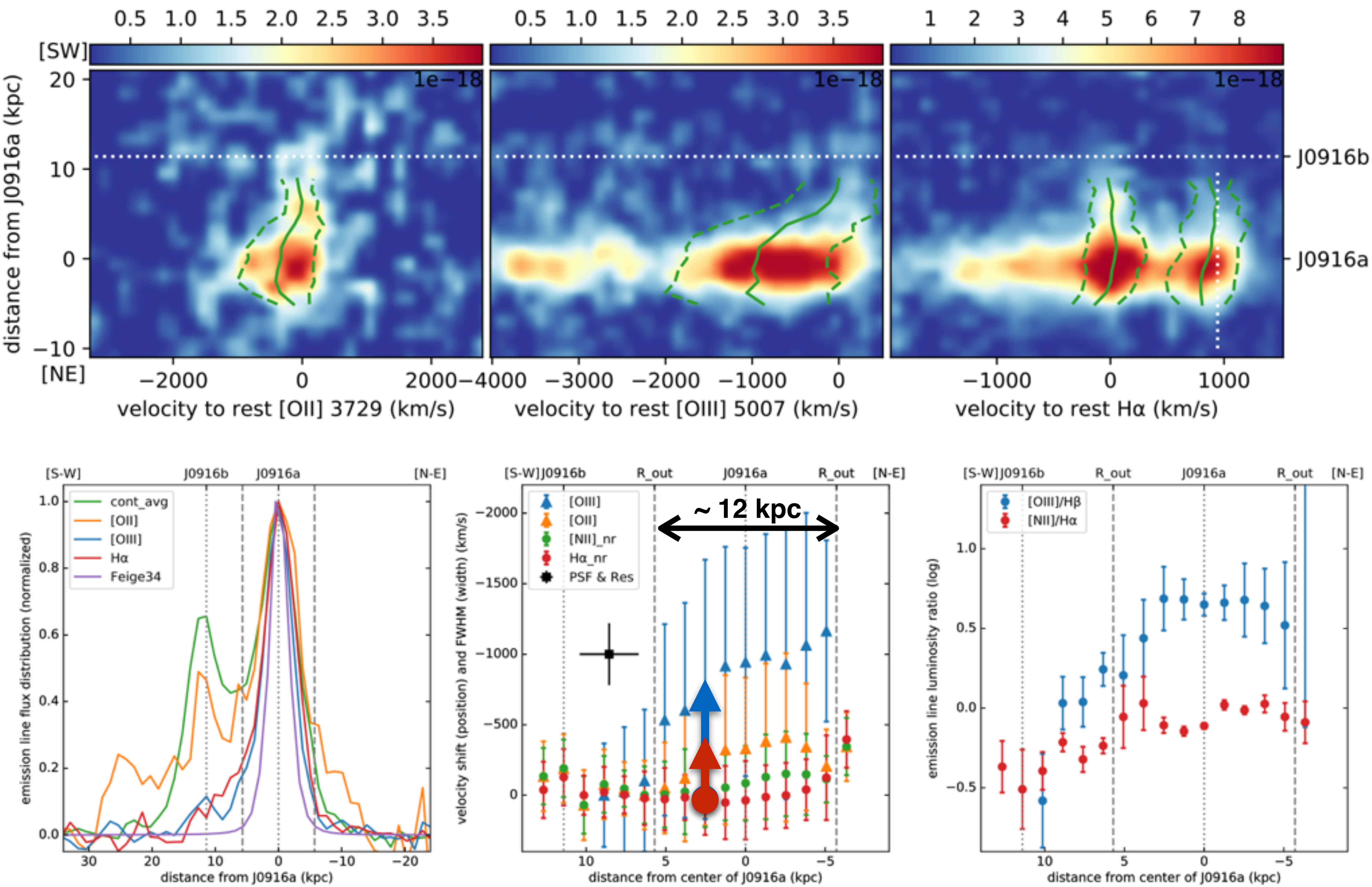

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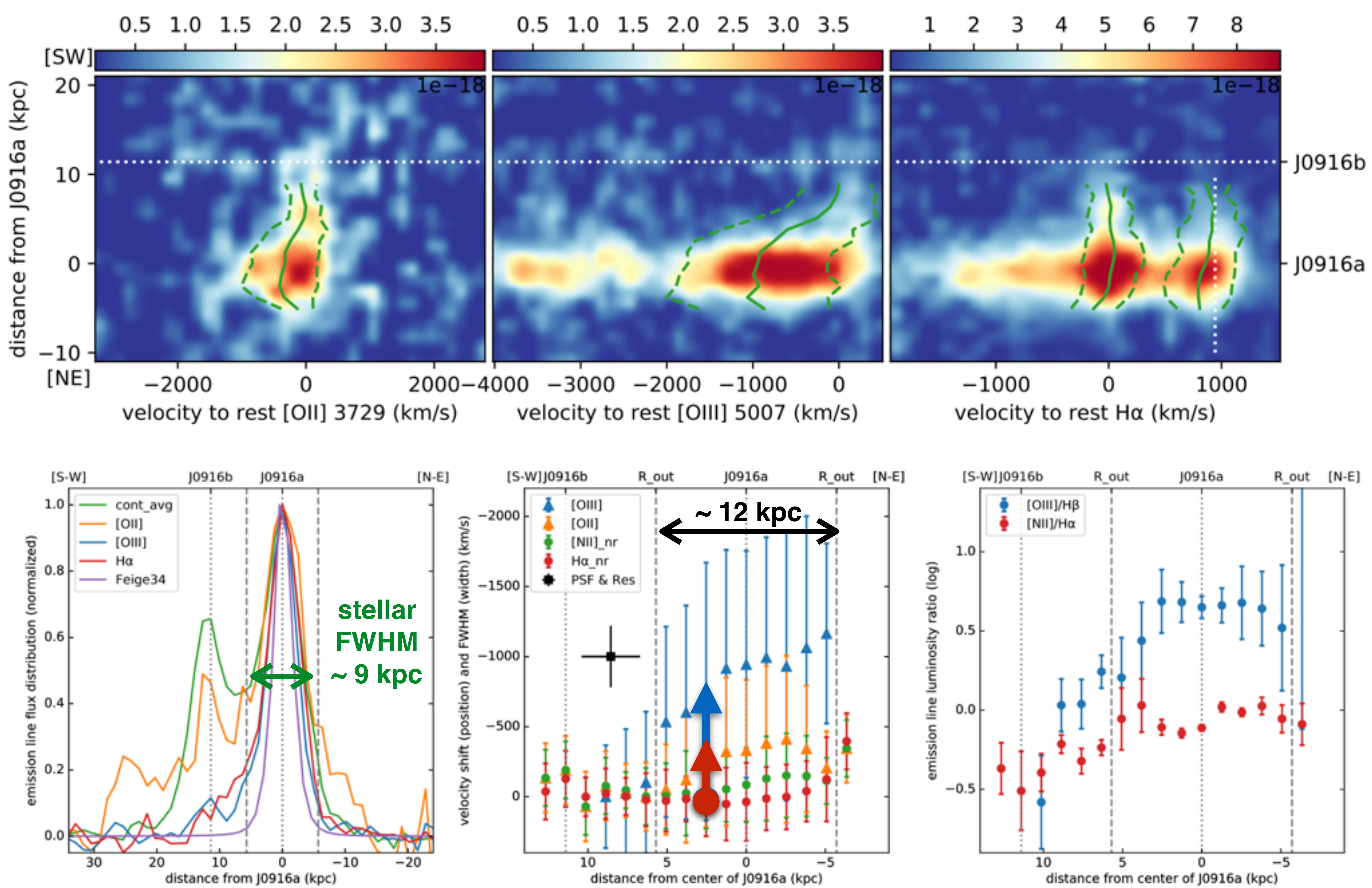

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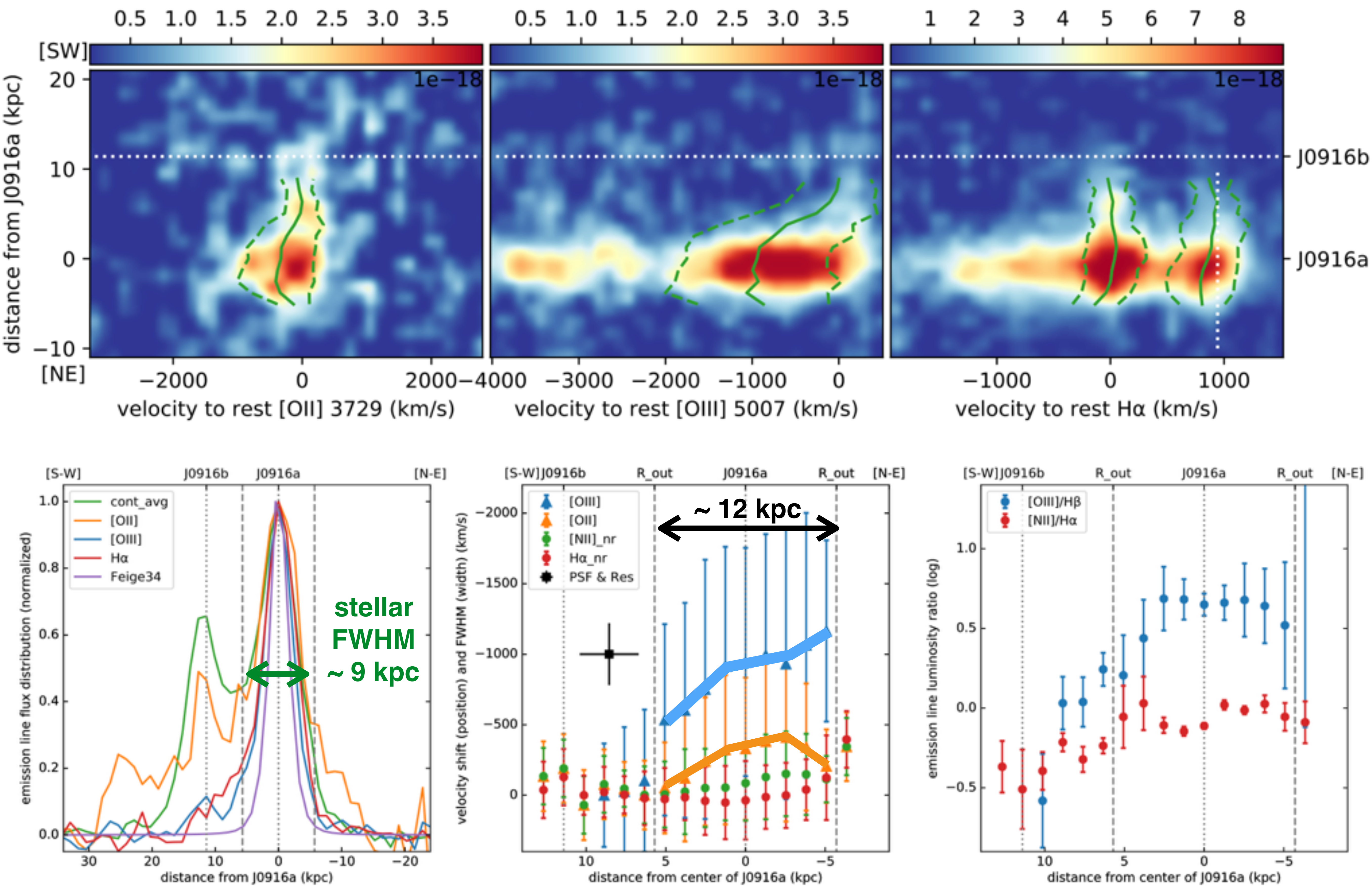

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Ionization potential (IP)

- High-IP emission line: [OIII] 5007 (35.12 eV), [NeIII] 3869 (40.96 eV), usually is ionized by AGN, although O/B stars and shock driven stellar wind can also contribute in some intense starburst case.
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> Can the fast outflow shown by [OII] come from star-forming regions?

Power source of fast outflow: 1) in BPT-diagram view

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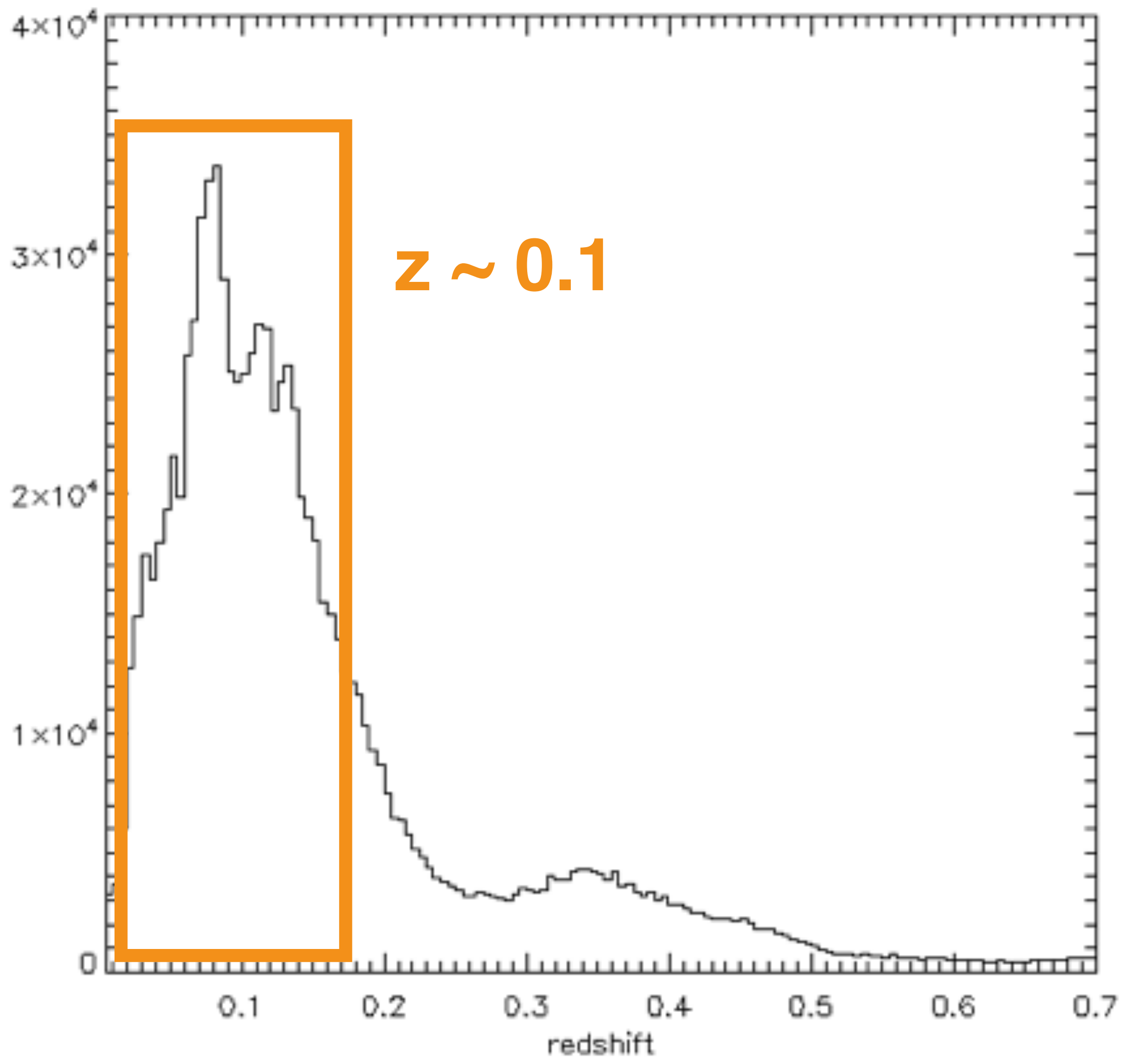

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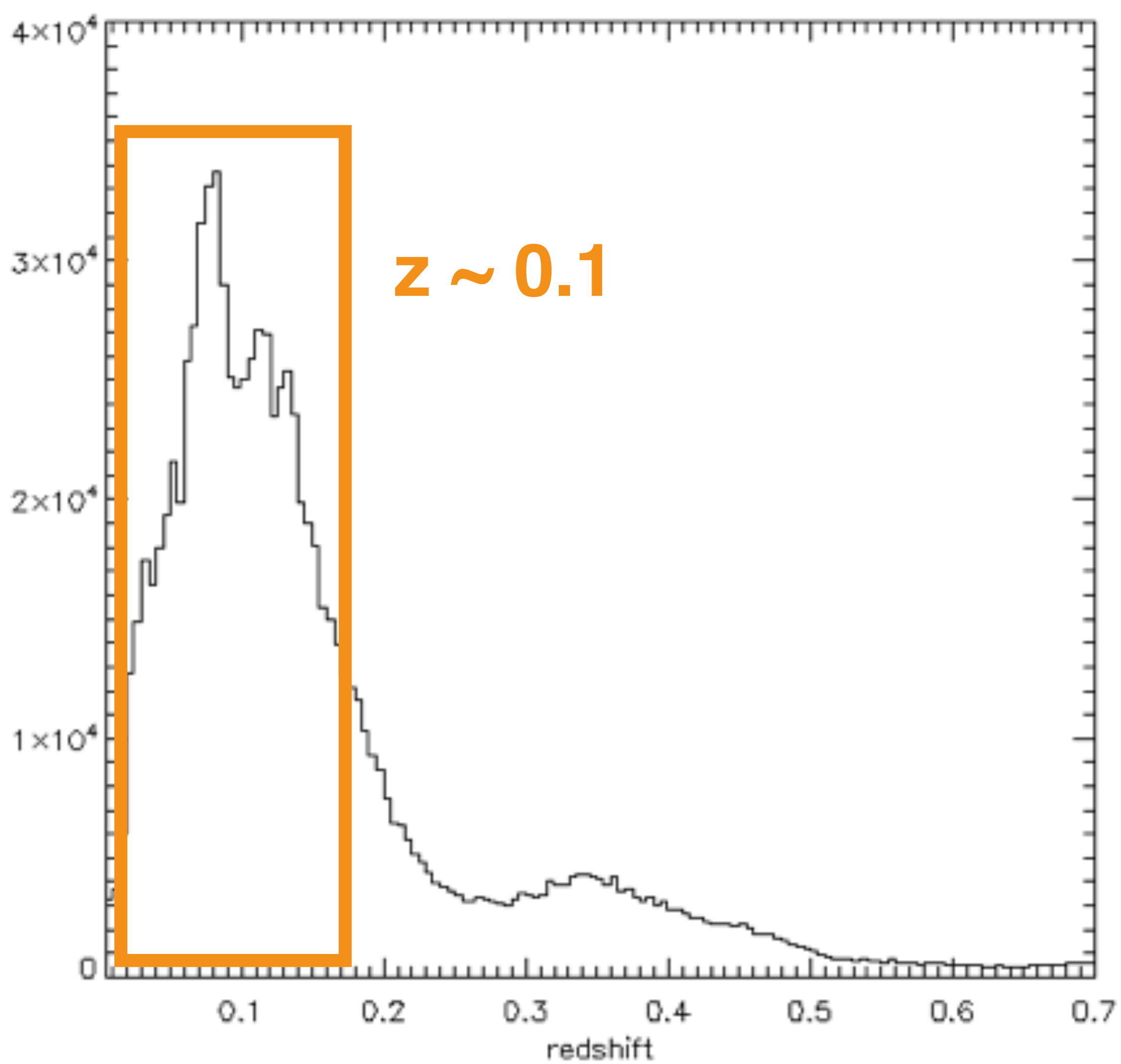

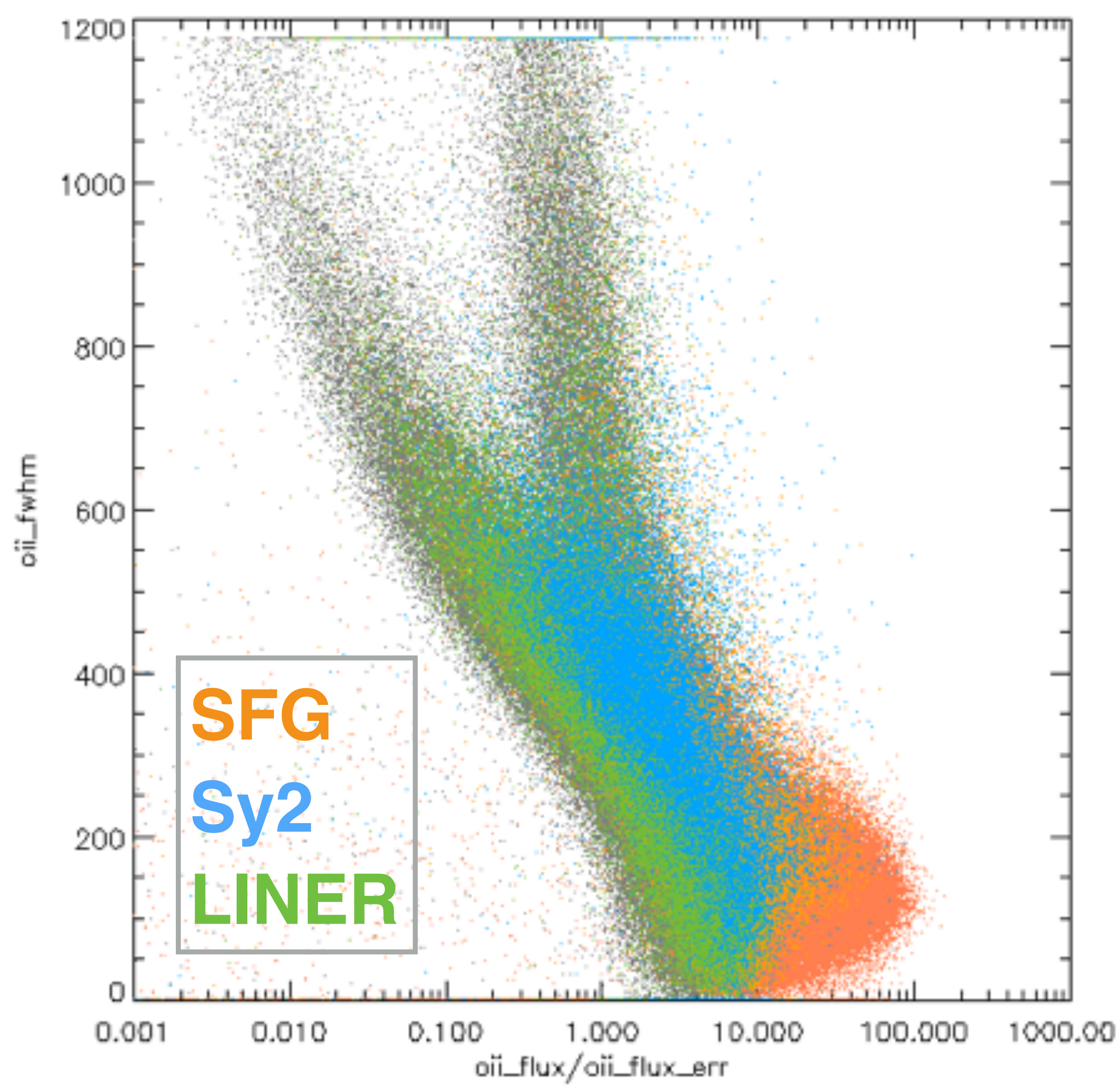

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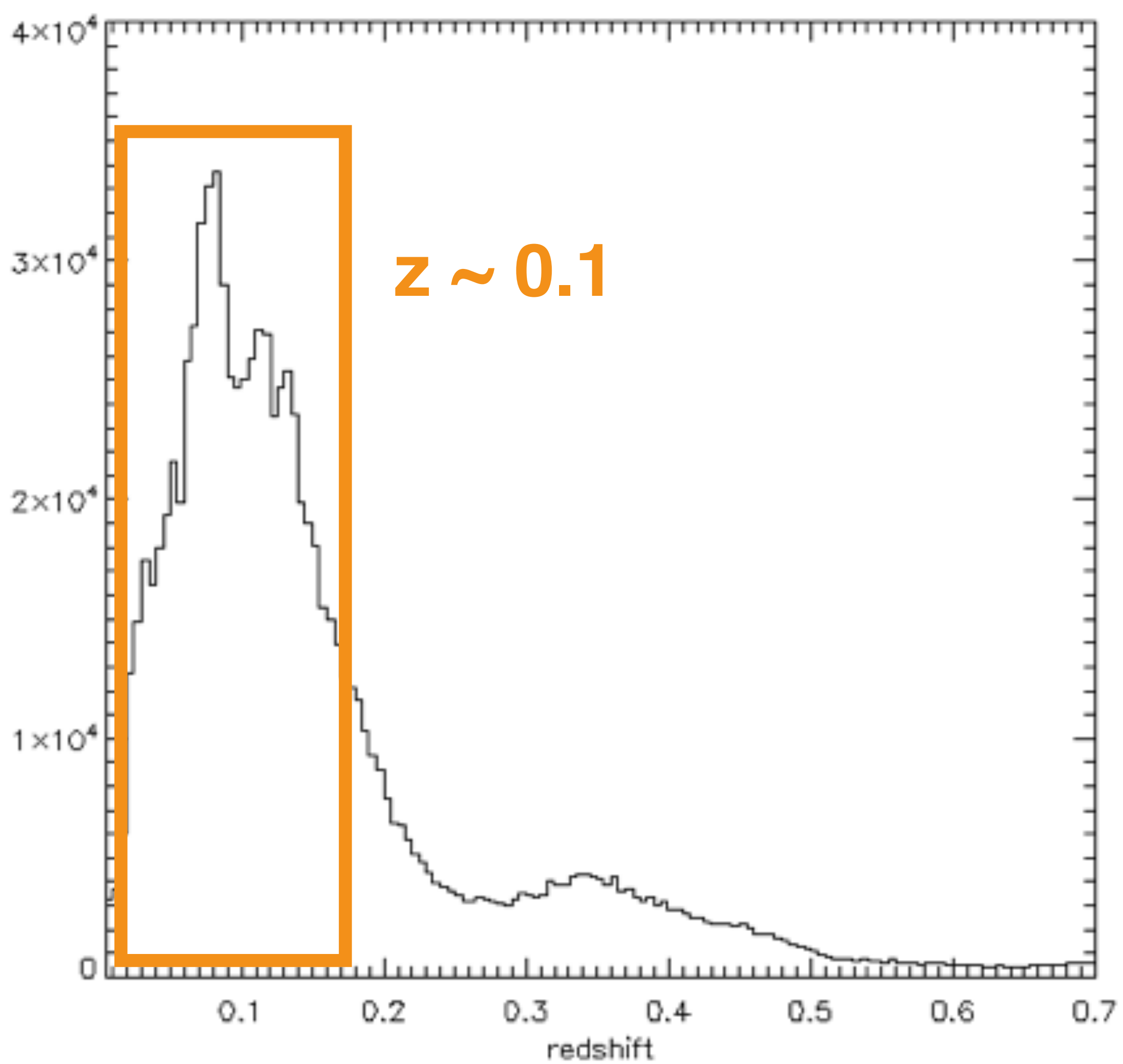

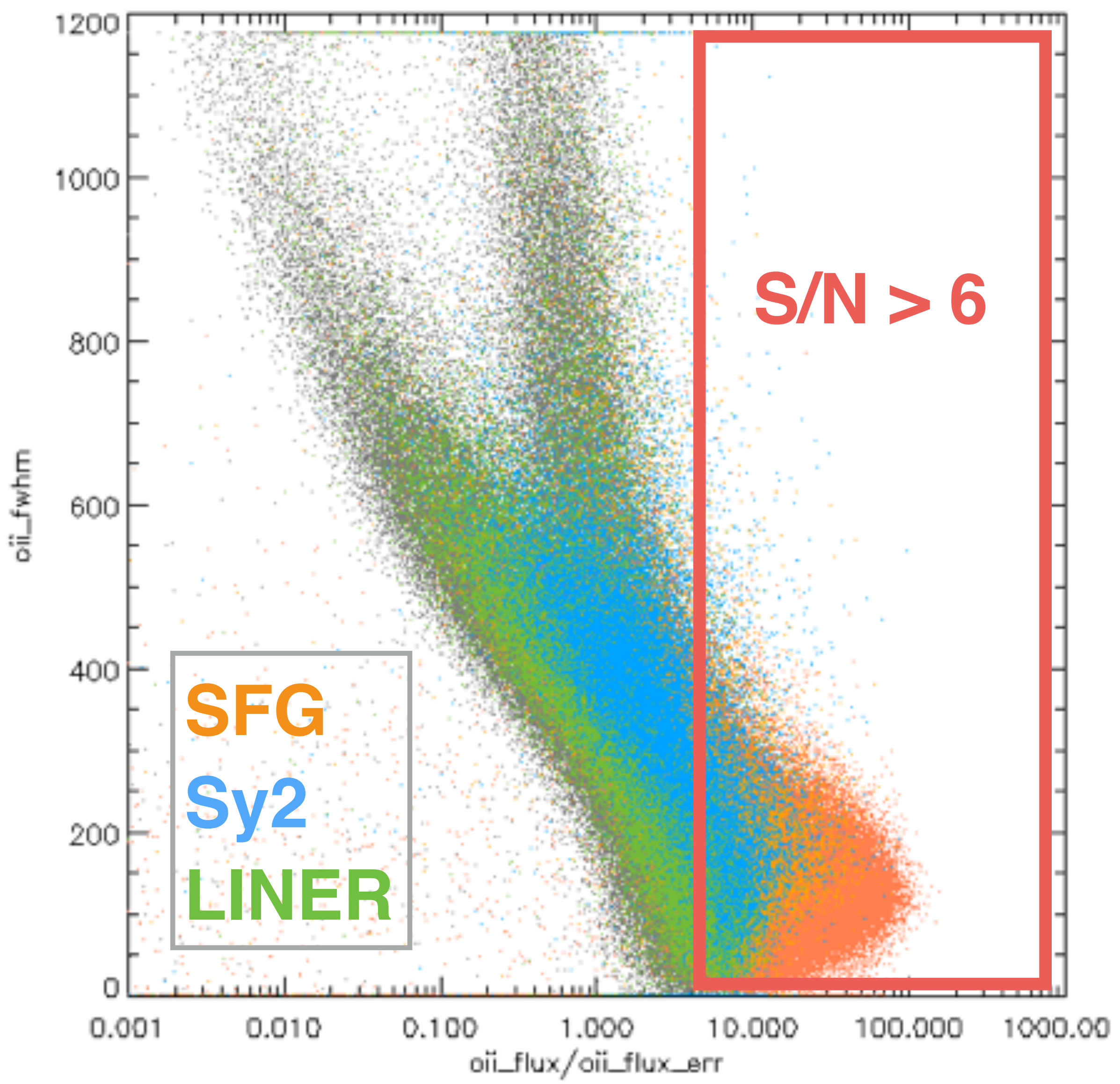

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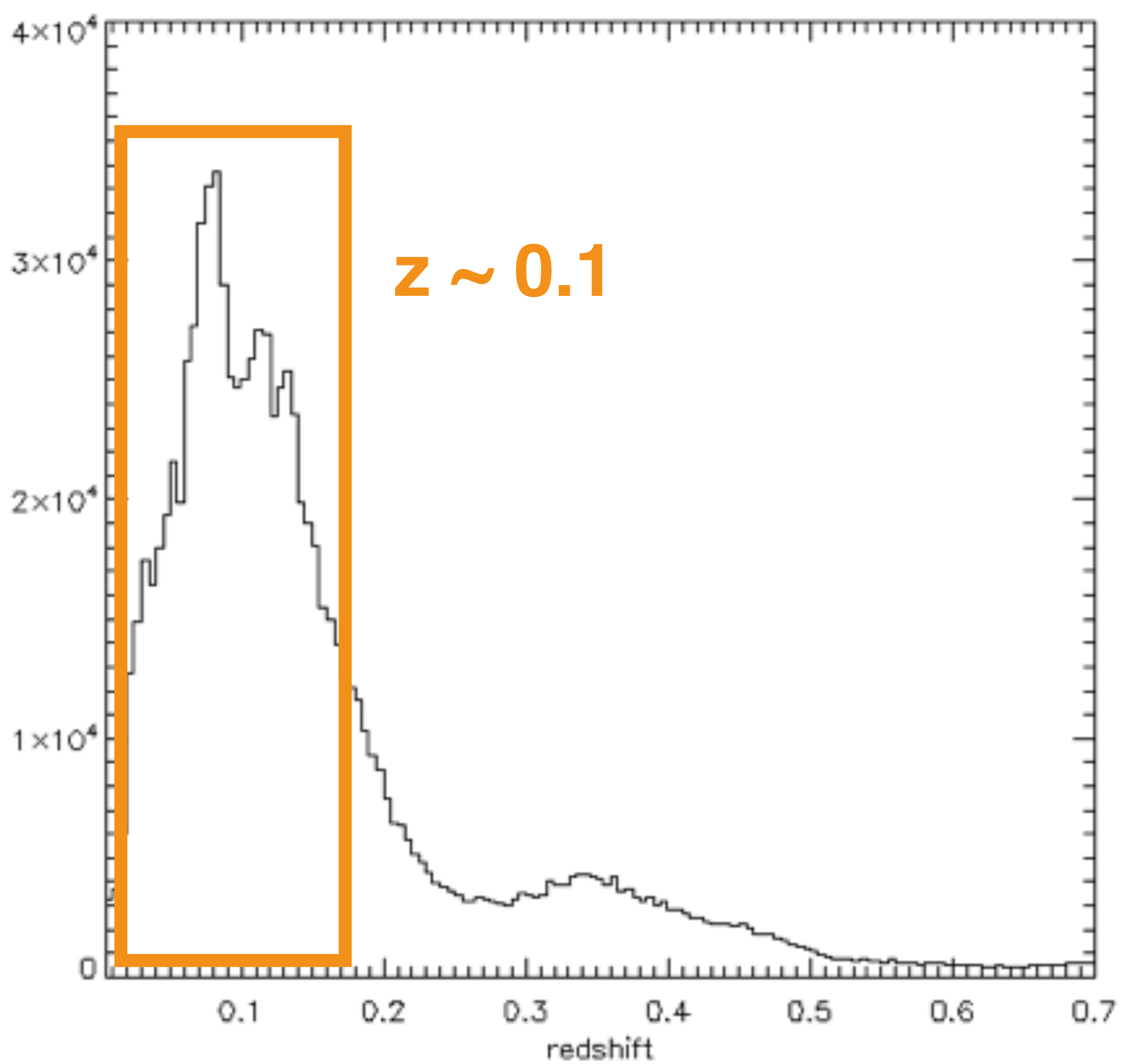

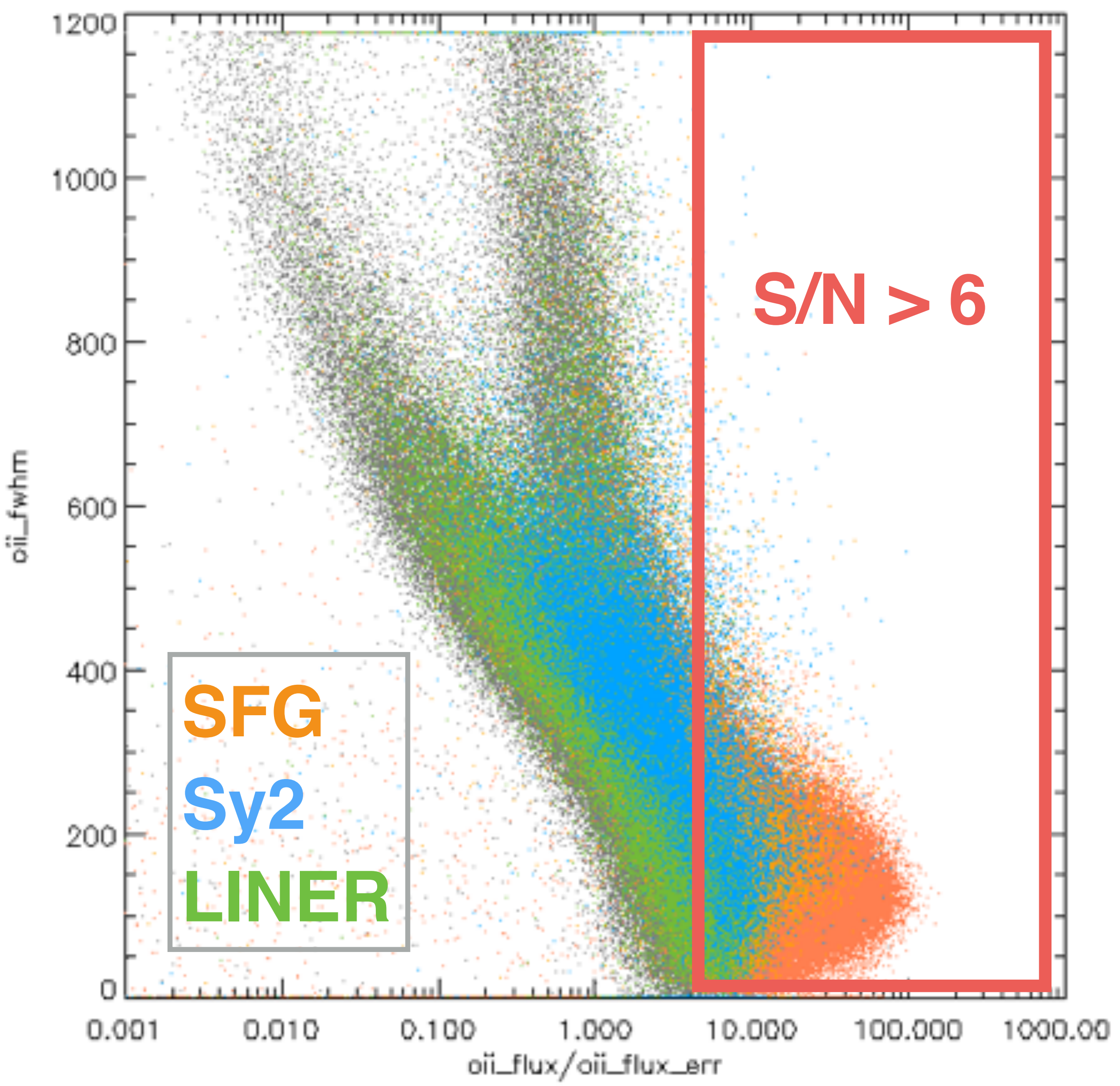

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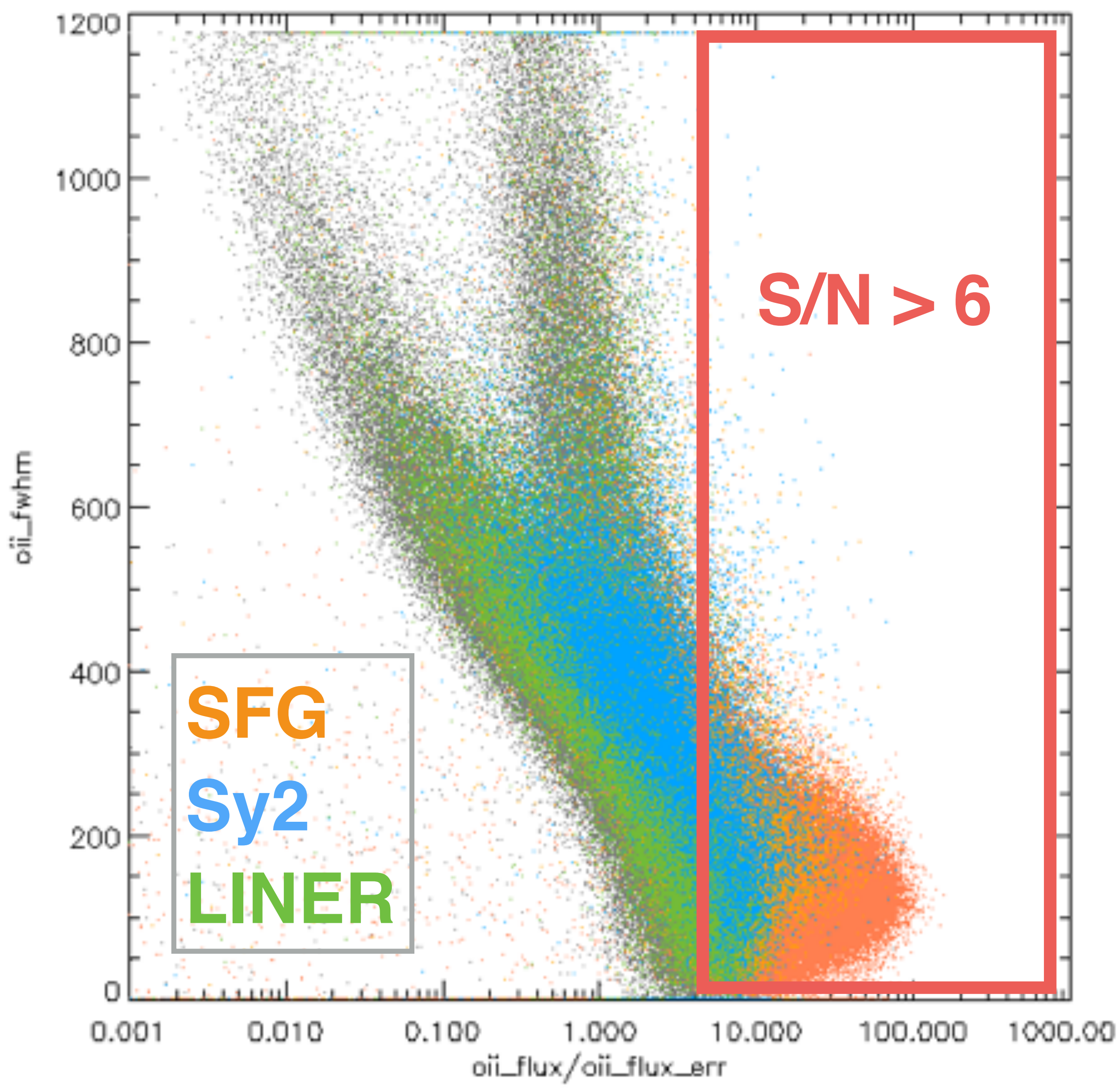

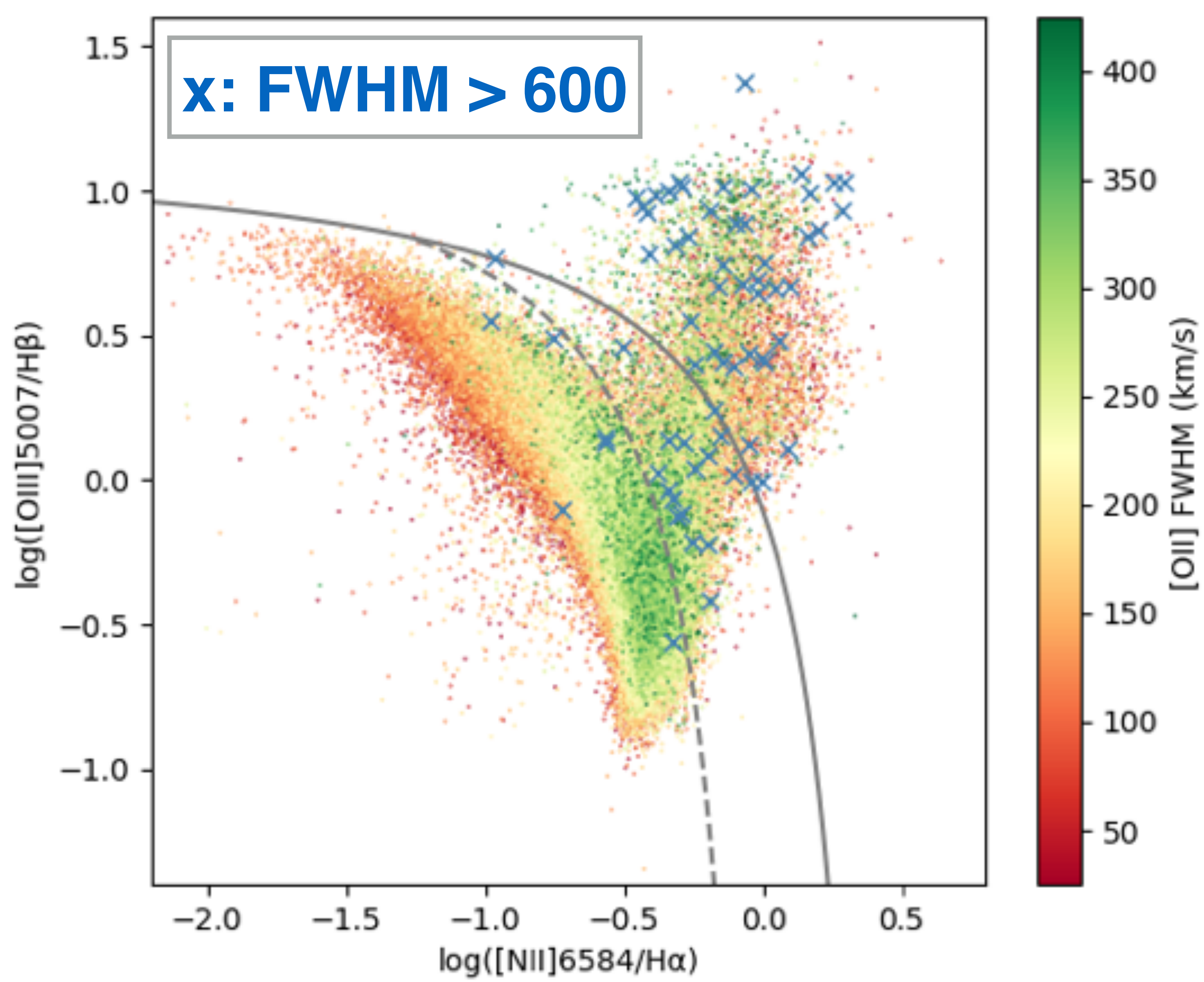

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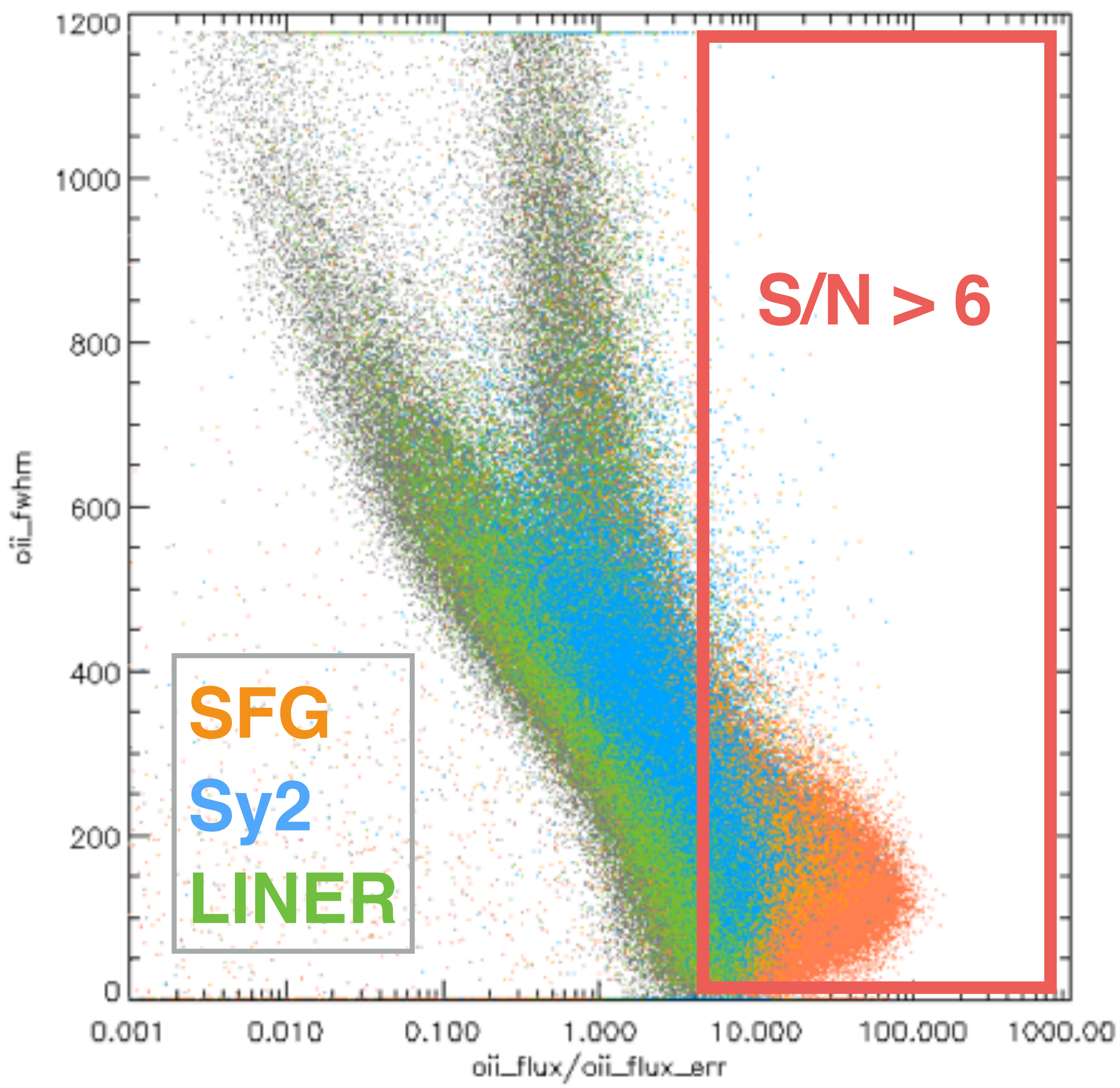

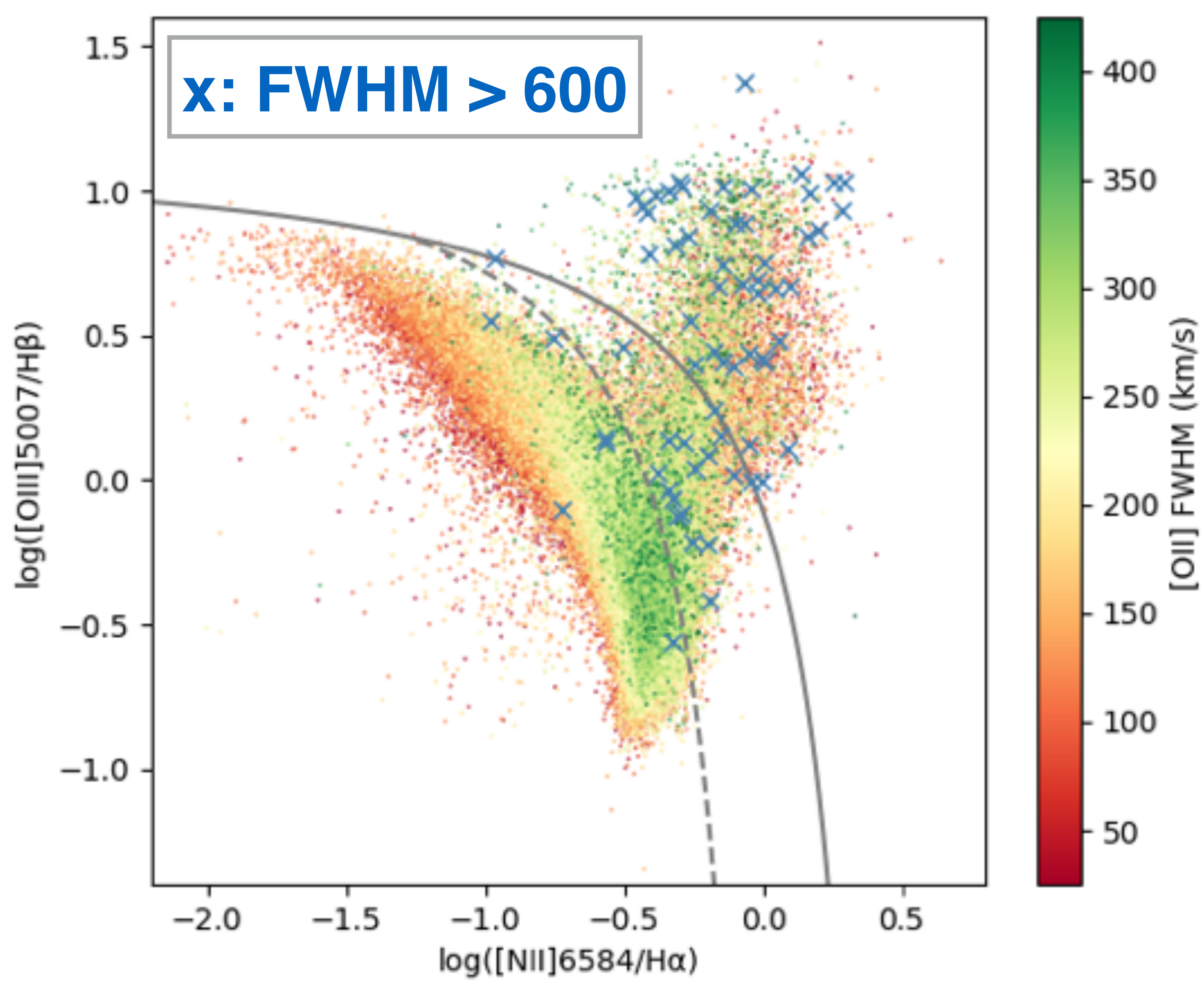

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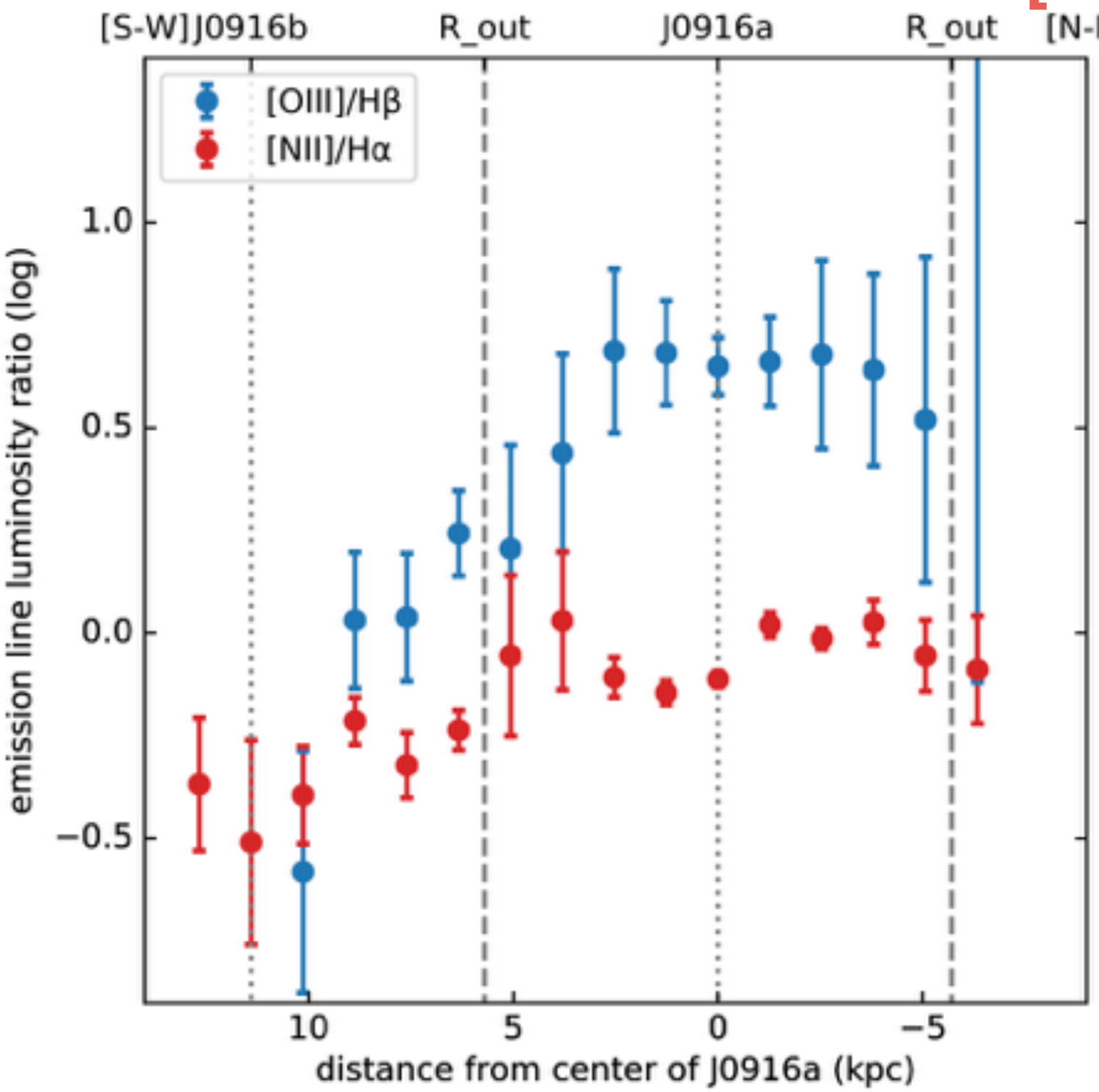

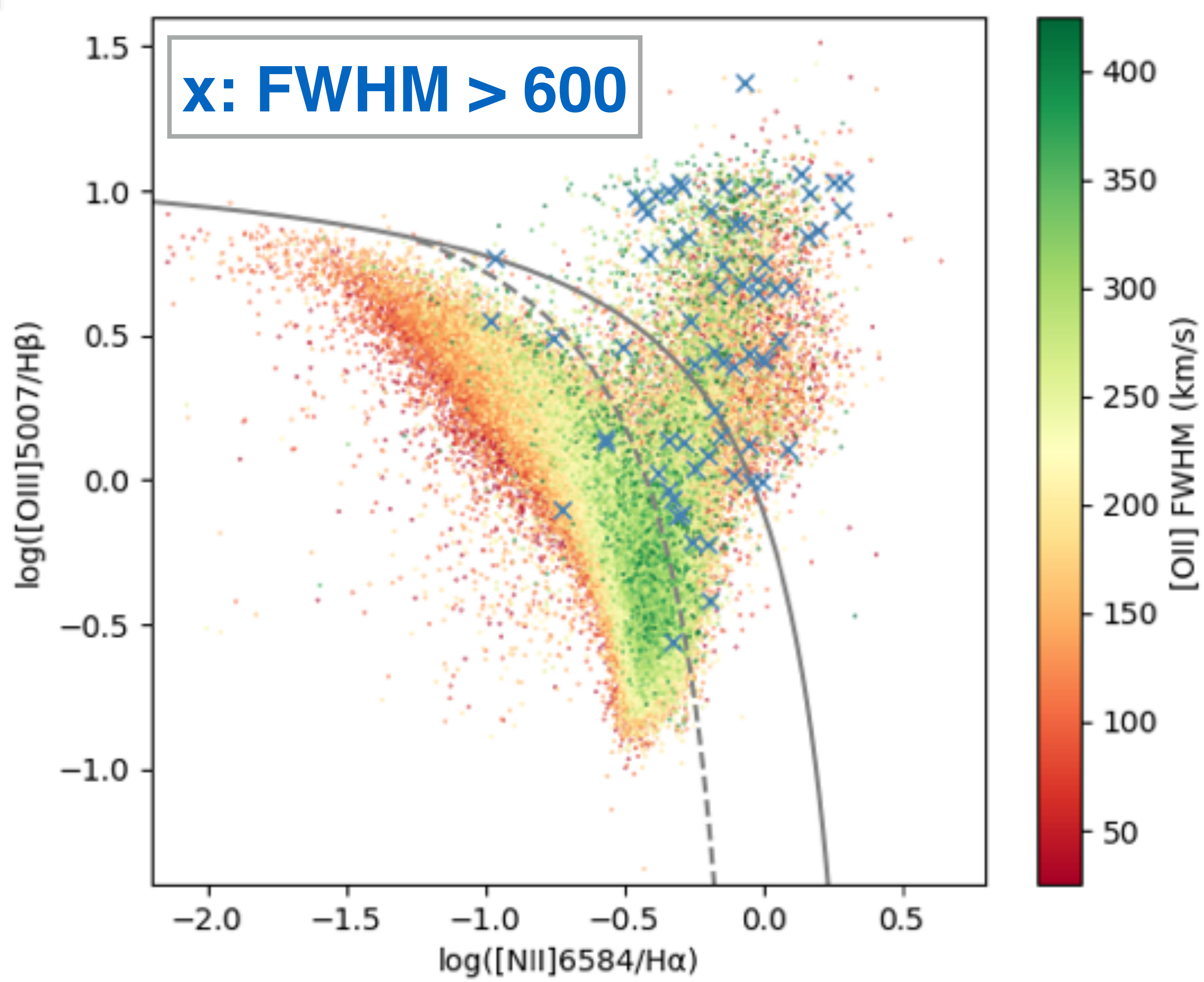

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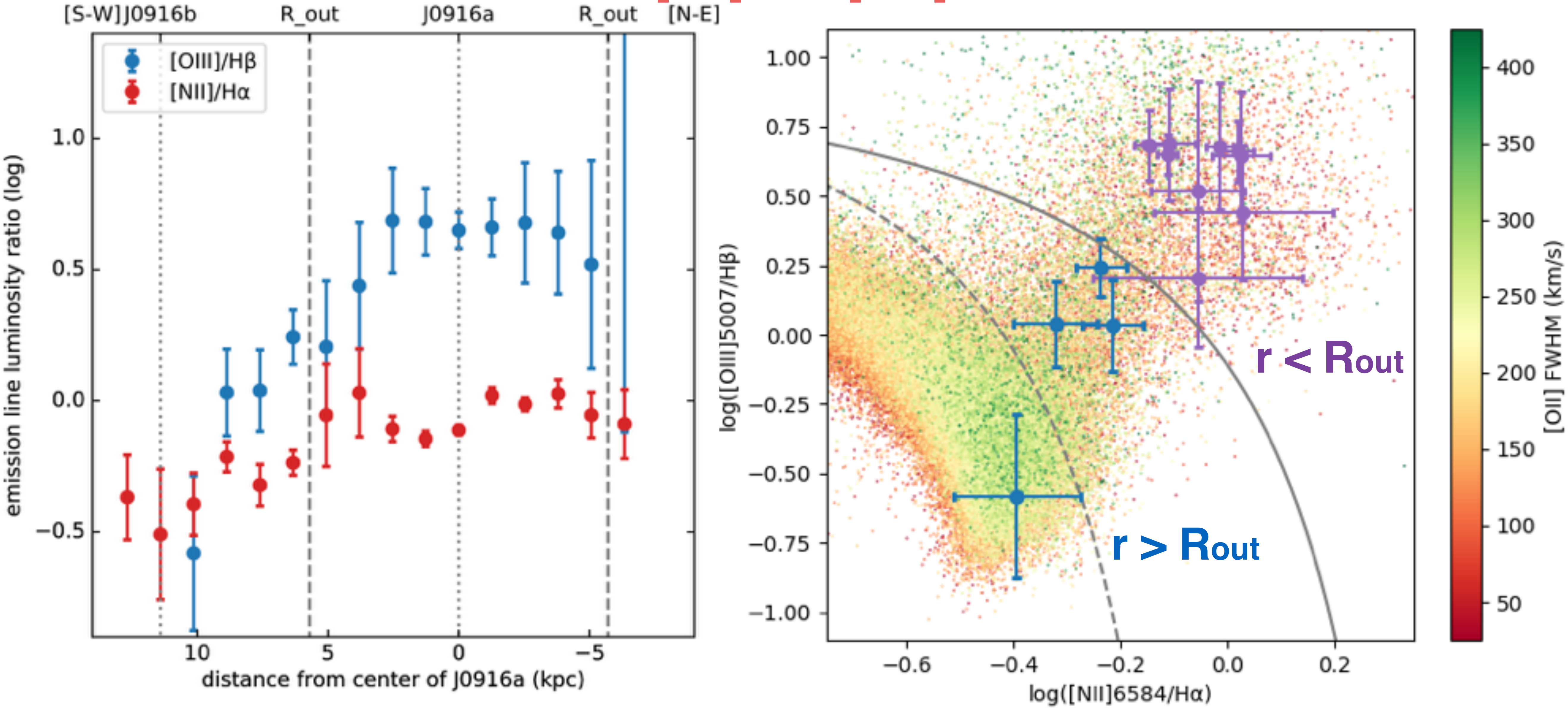

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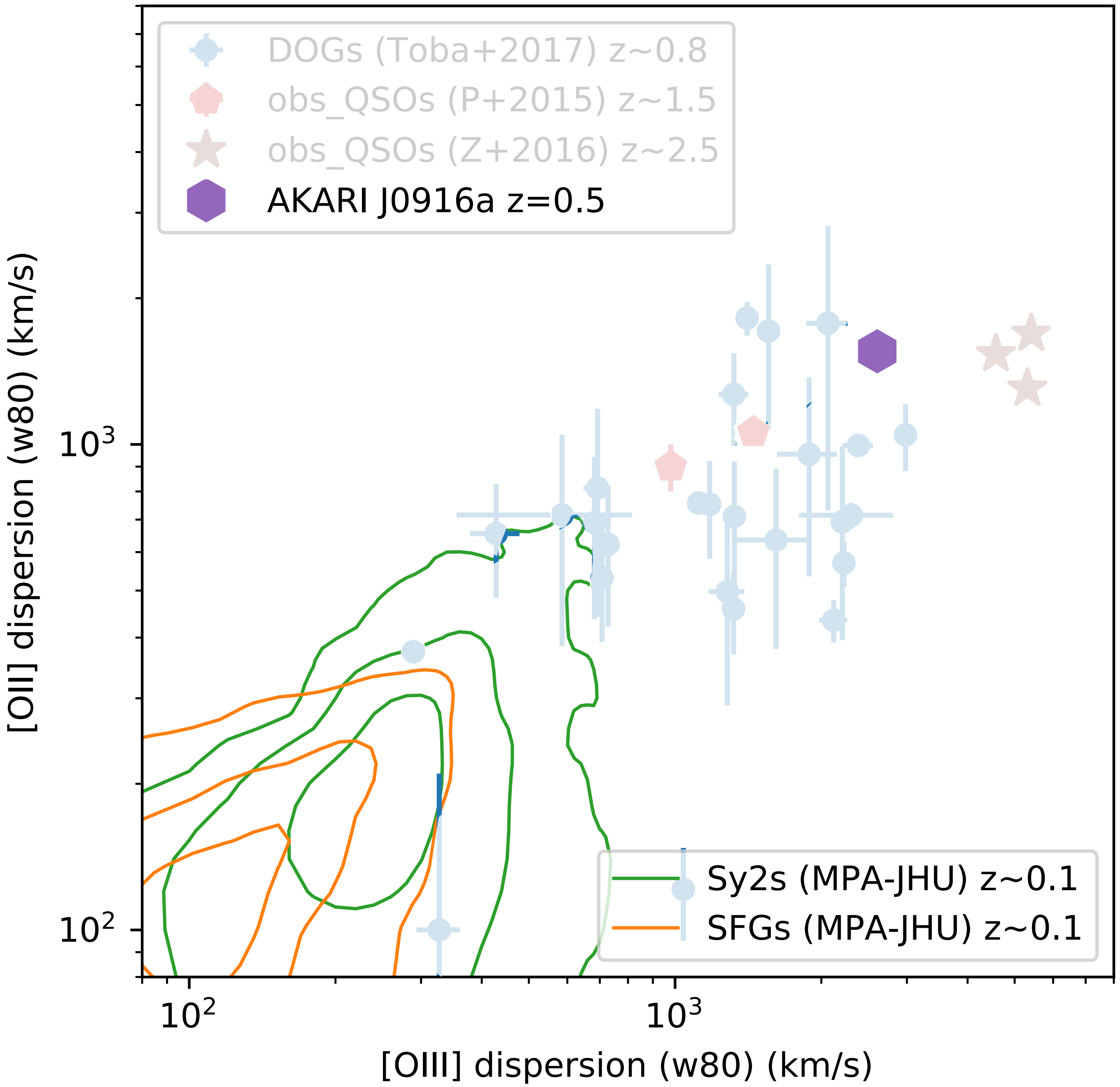

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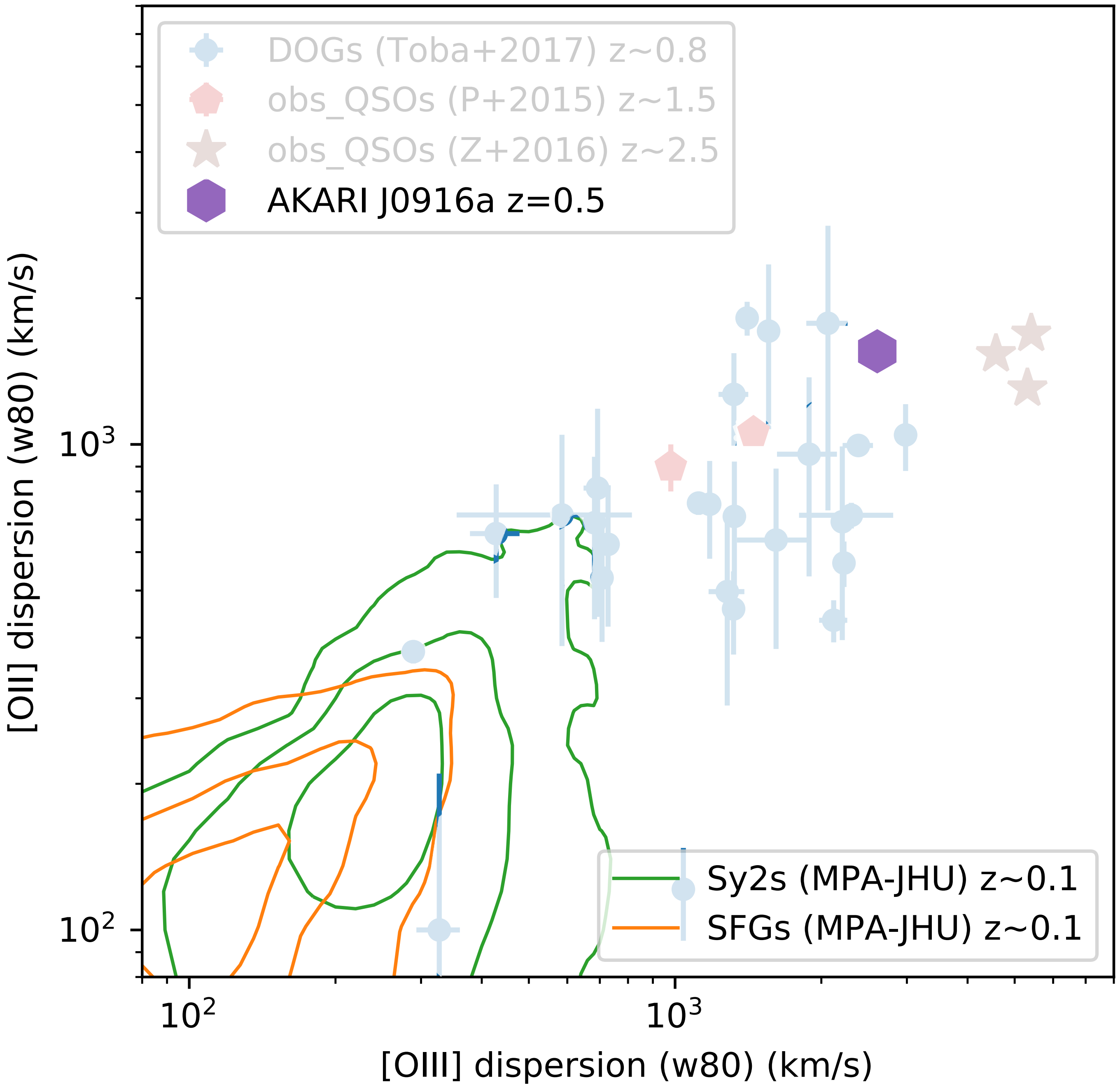

- [OII] width: Sy2s > SFGs

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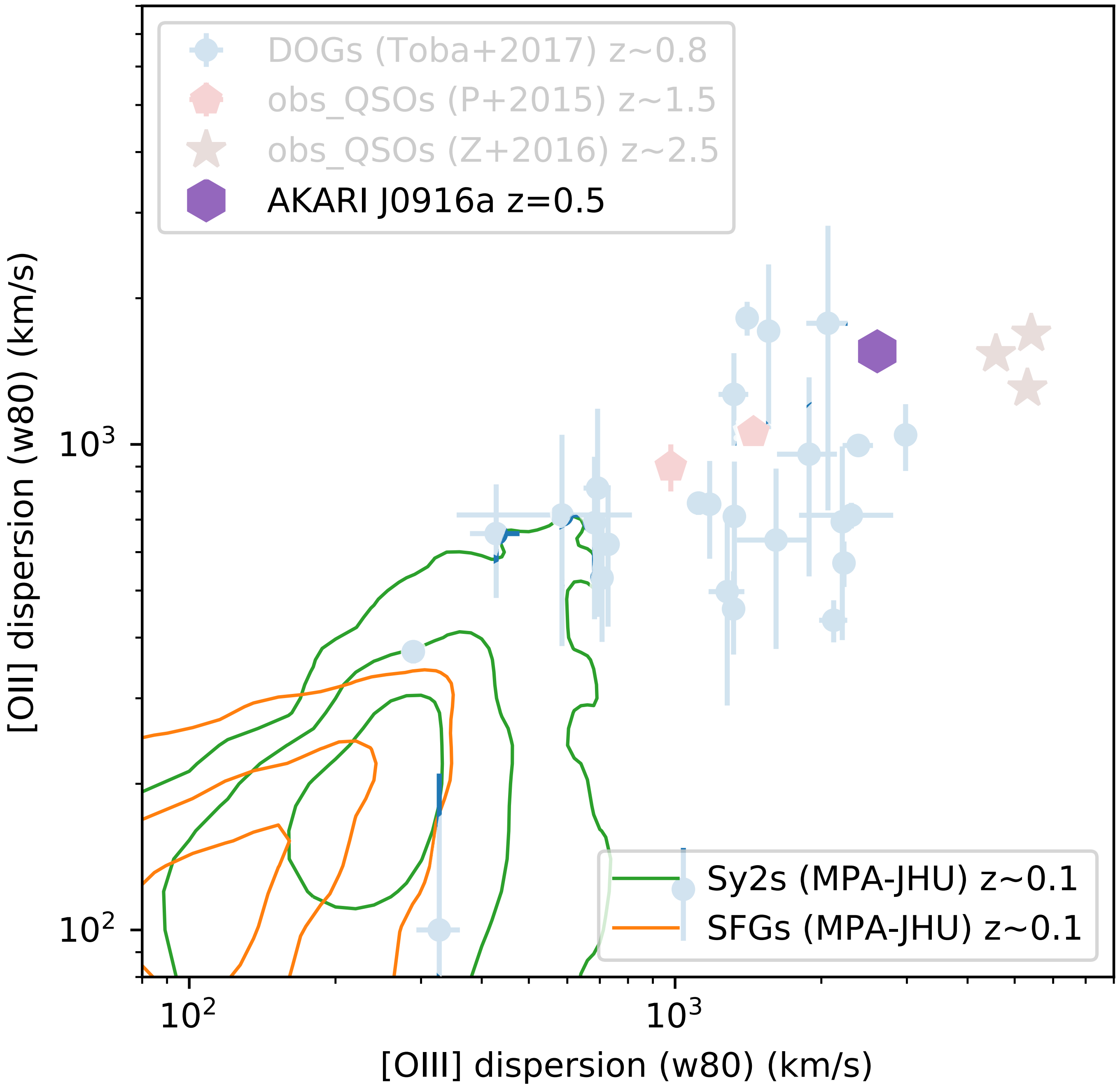

- [OII] width: Sy2s > SFGs
- J0916a >> local SFGs and Sy2s

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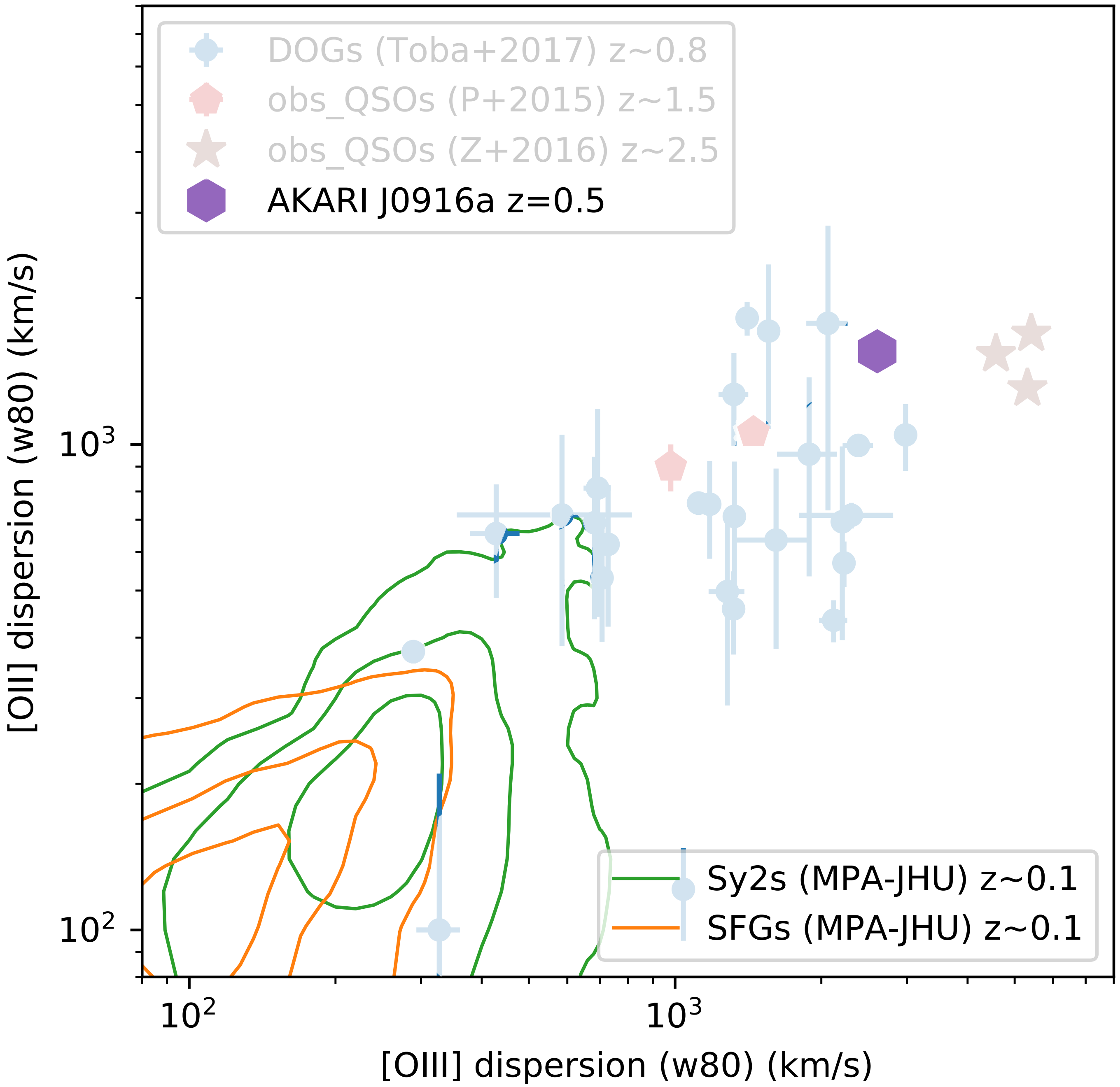

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- Compared with higher-z samples observed with fast outflow and [OII] detection:

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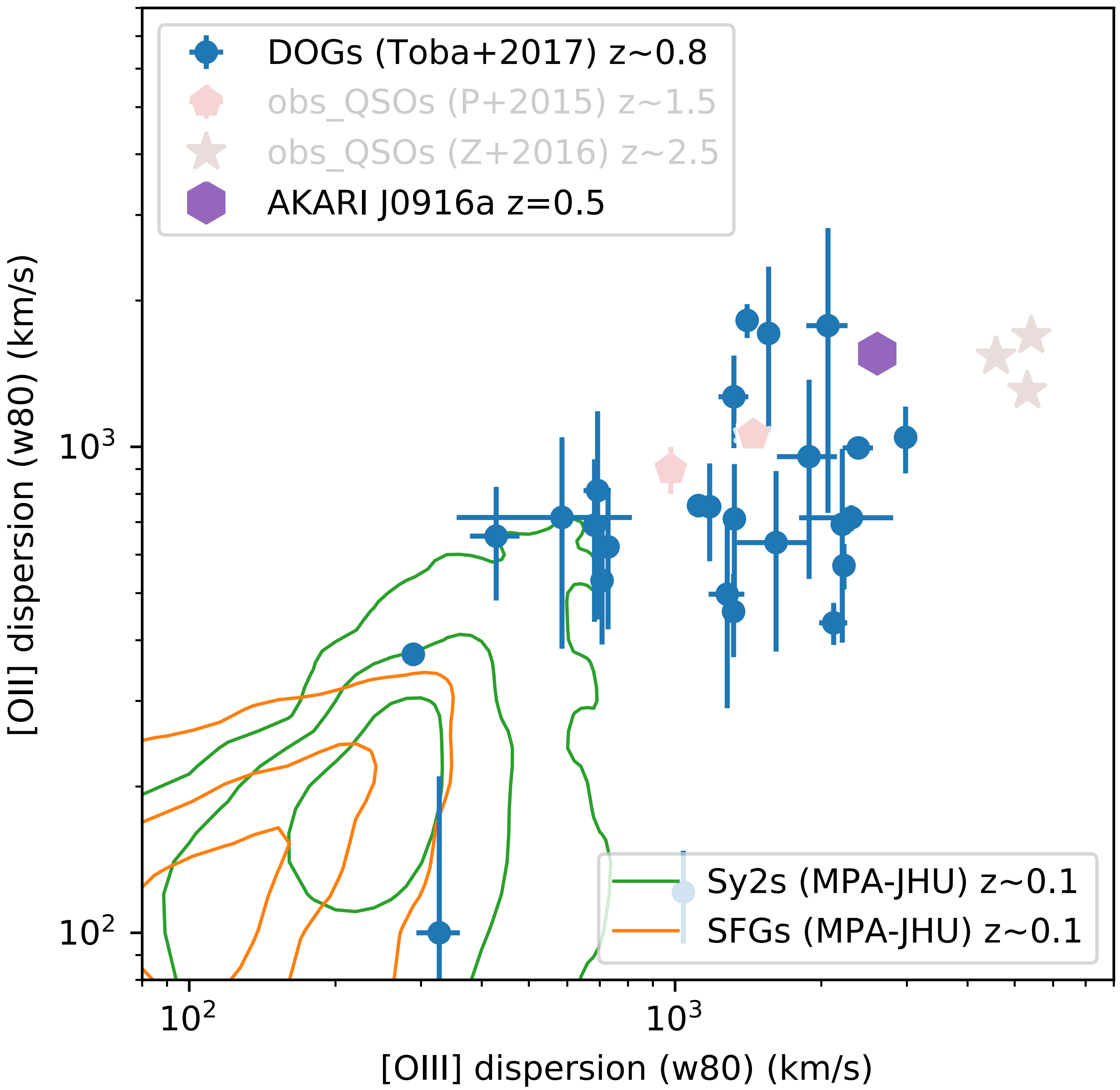

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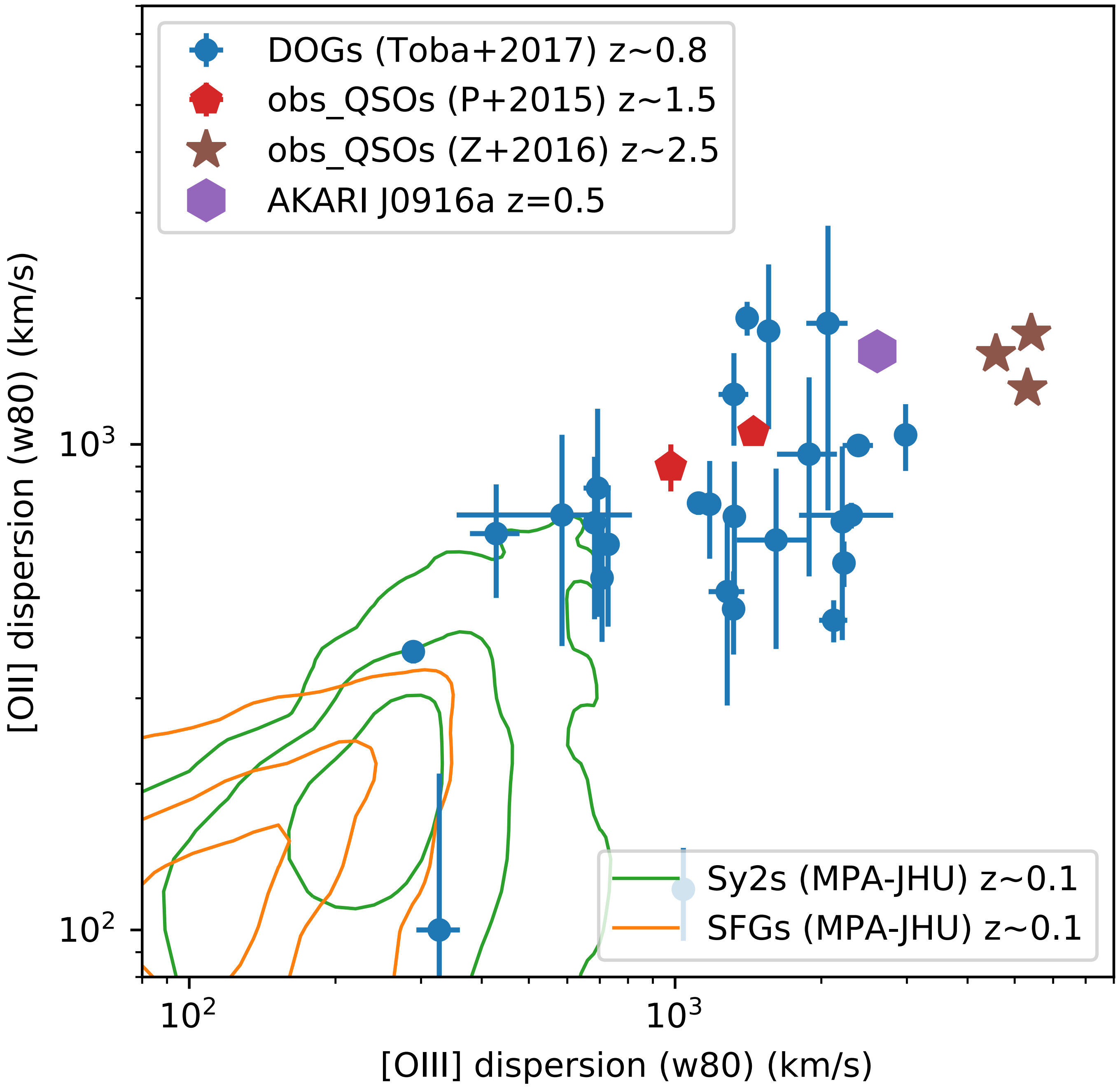

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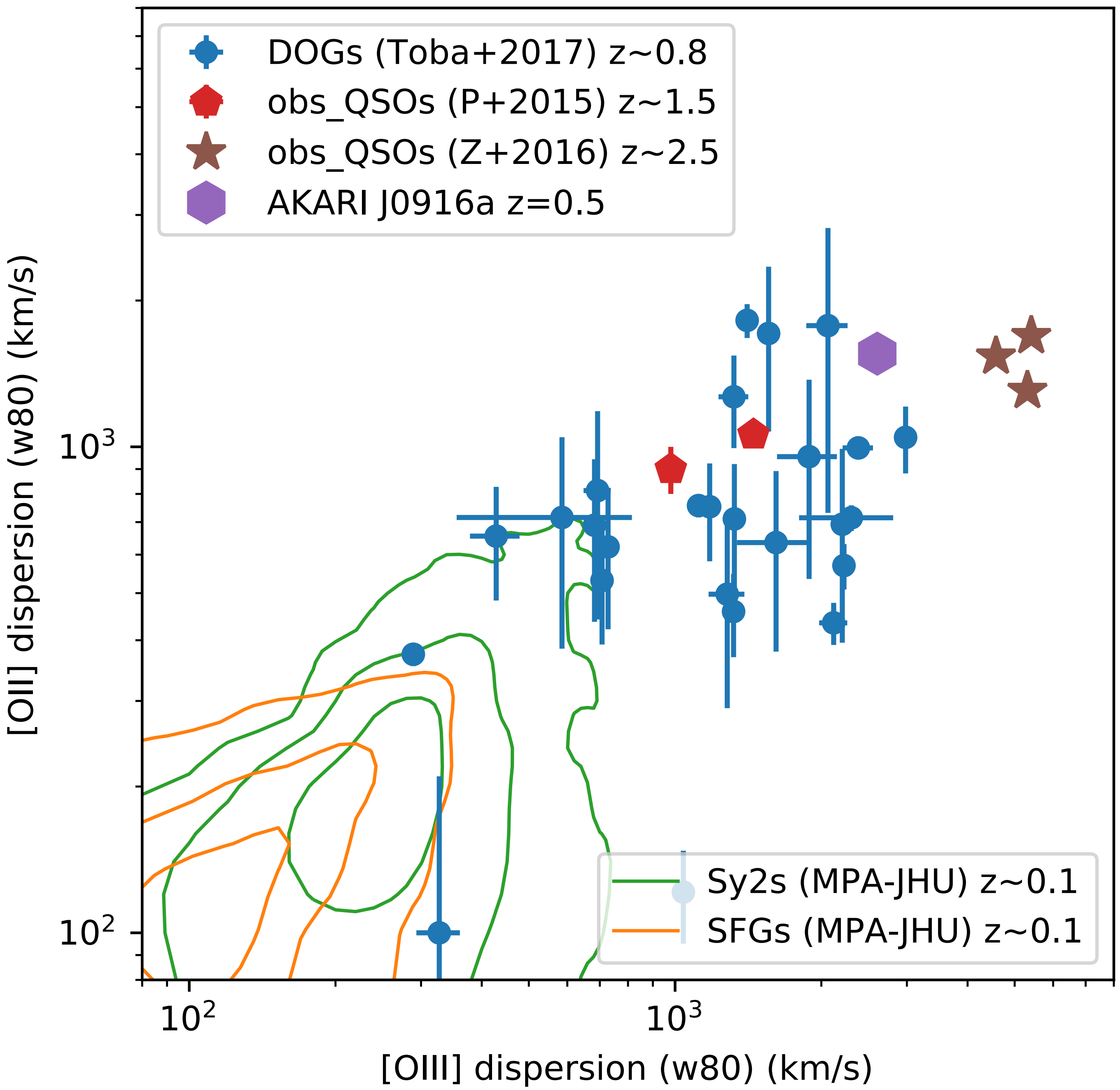

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  J0916a:
- one of the fastest at inter-z;
- even comparable with samples at peak-epoch of AGN activity

Power source of fast outflow: 2) in Energetics view

- Method: calculate the energy ejection rate **dE_{out}/dt**, then derive the cupping efficiencies of **dE_{out}/dt** with the AGN bolometric luminosity **L_{AGN}** and star-formation power **P_{SF}**.

- 1) estimate L_{AGN} and P_{SF}

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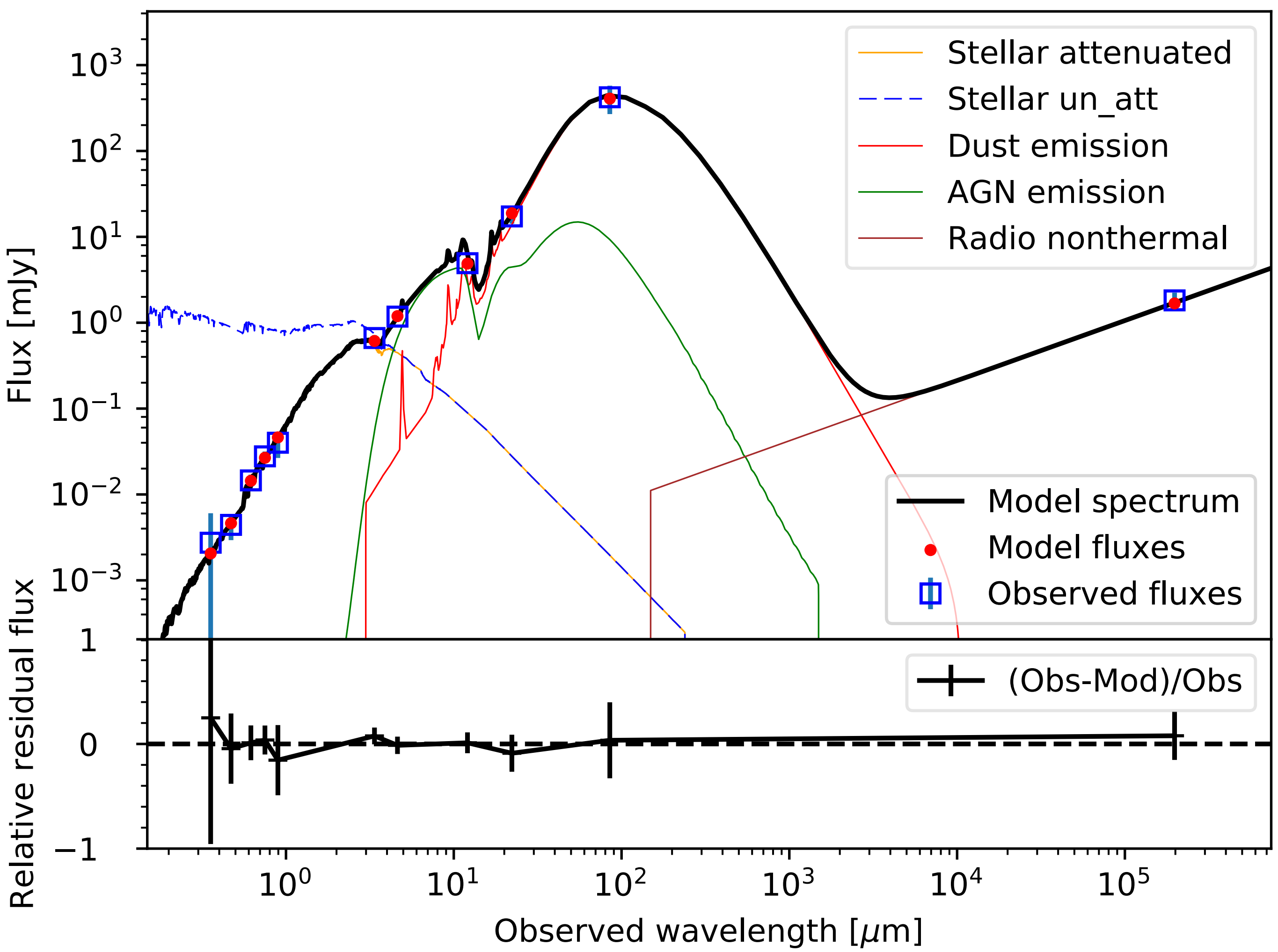

- SED fitting via ***CIGALE***

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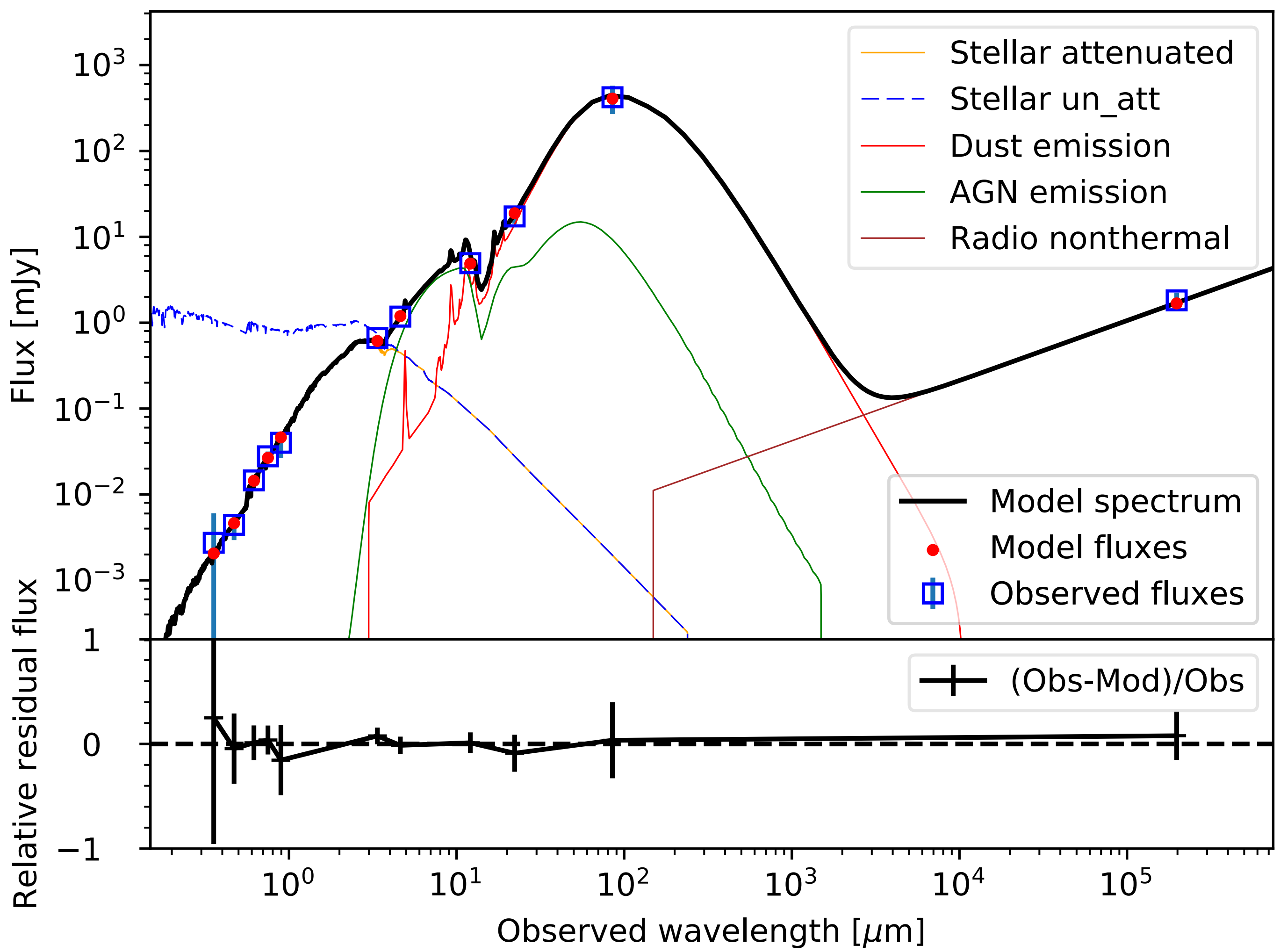

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  Stars+AGN+Dust+Radio

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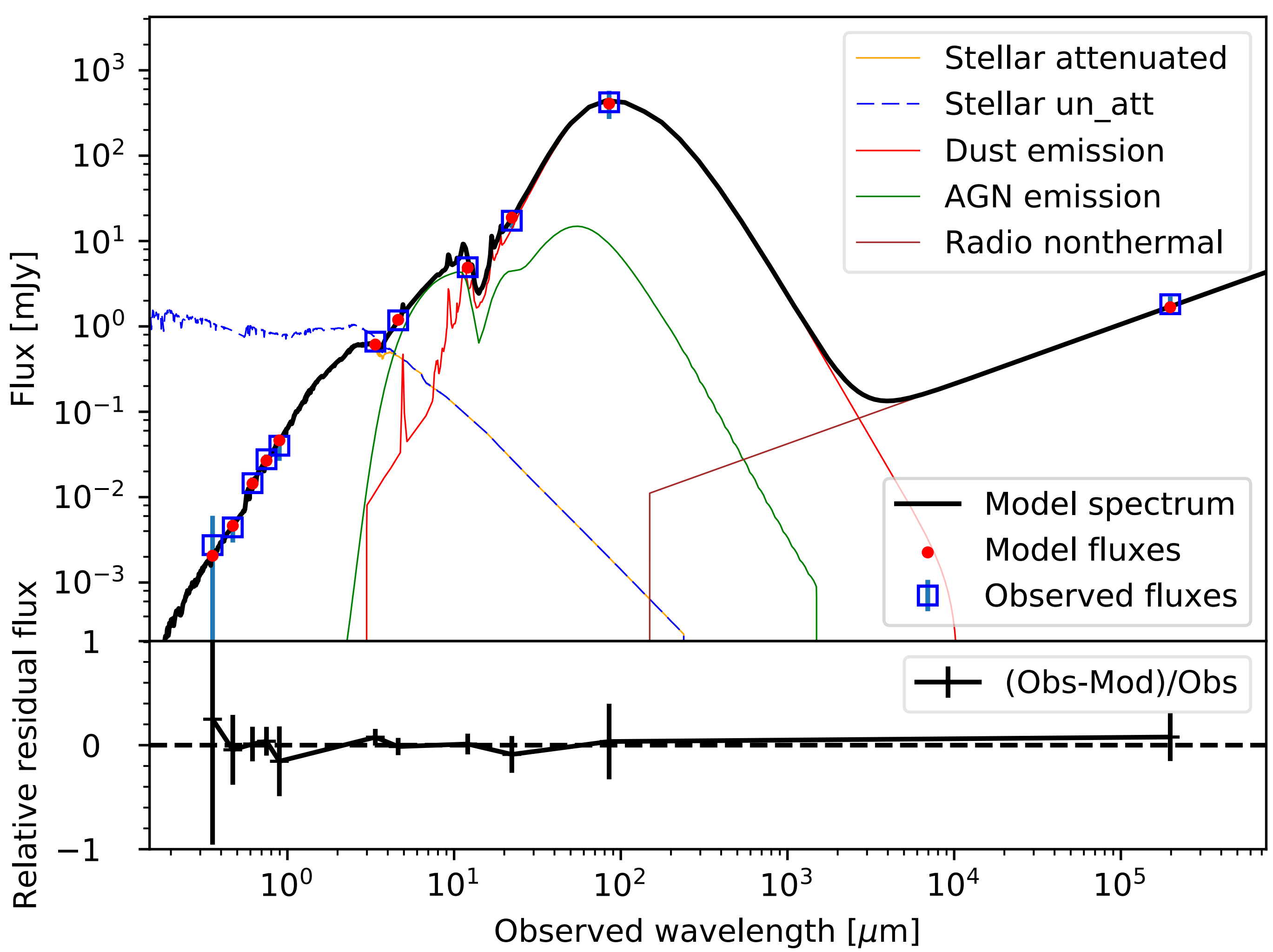

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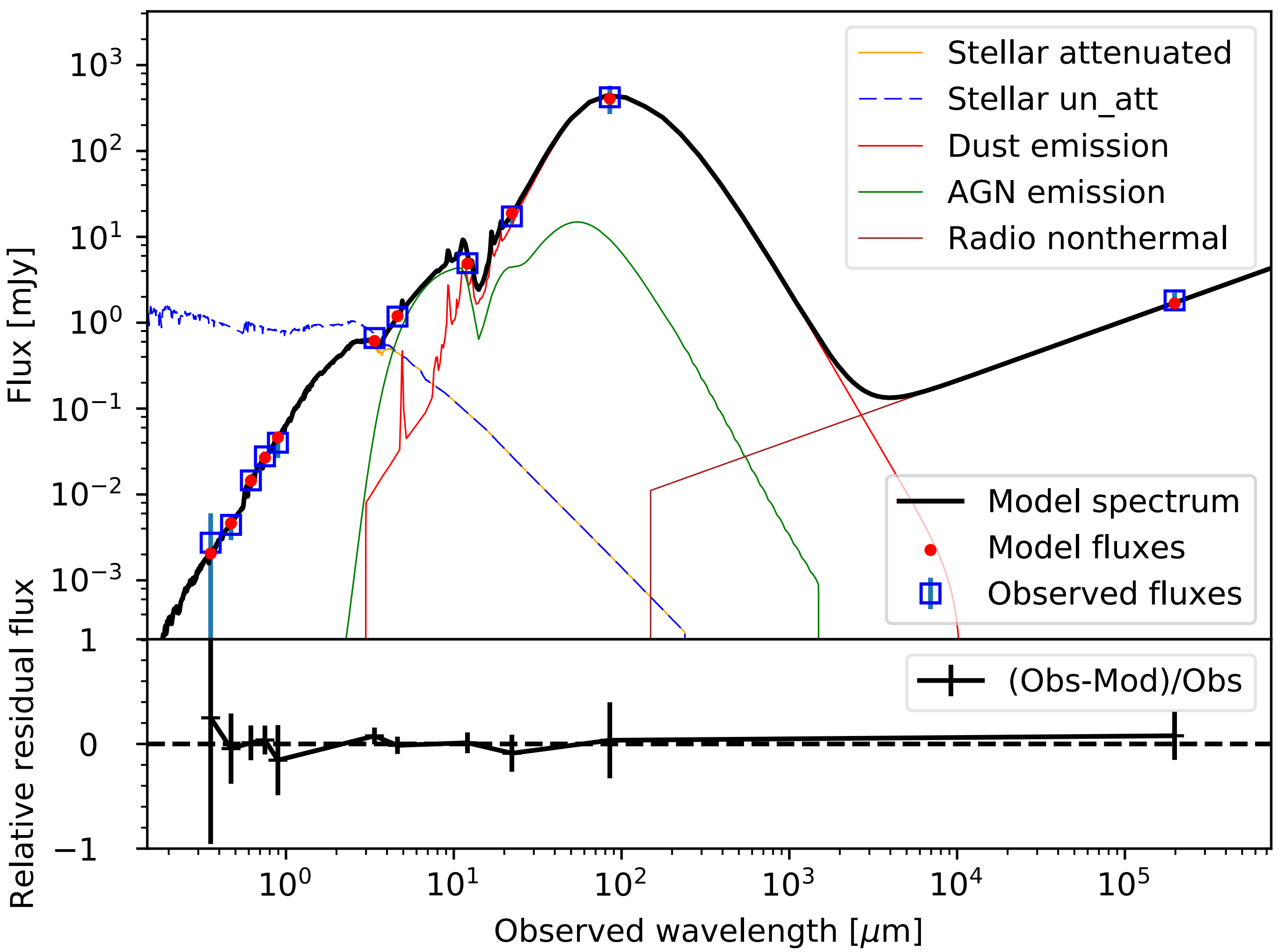

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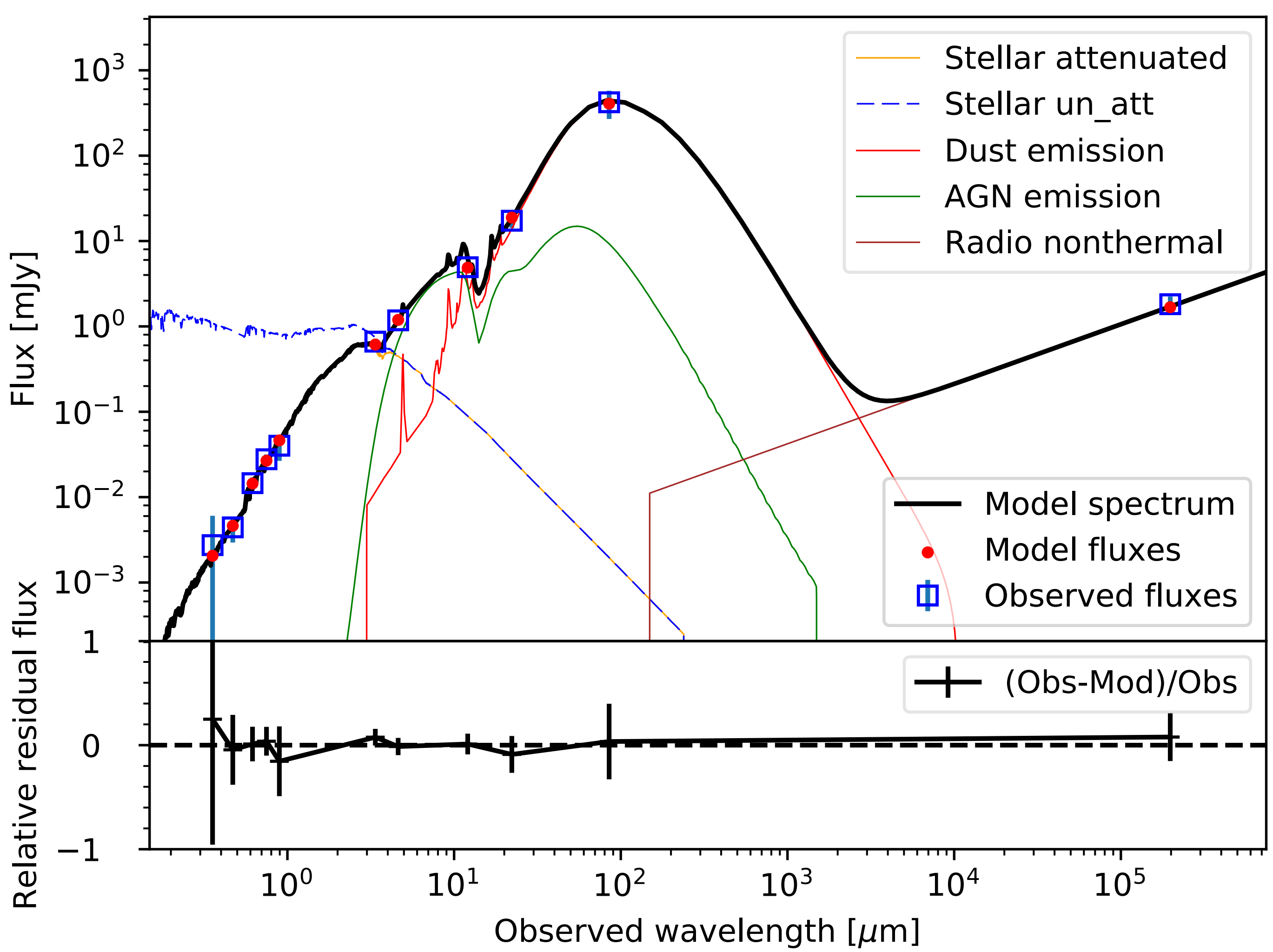

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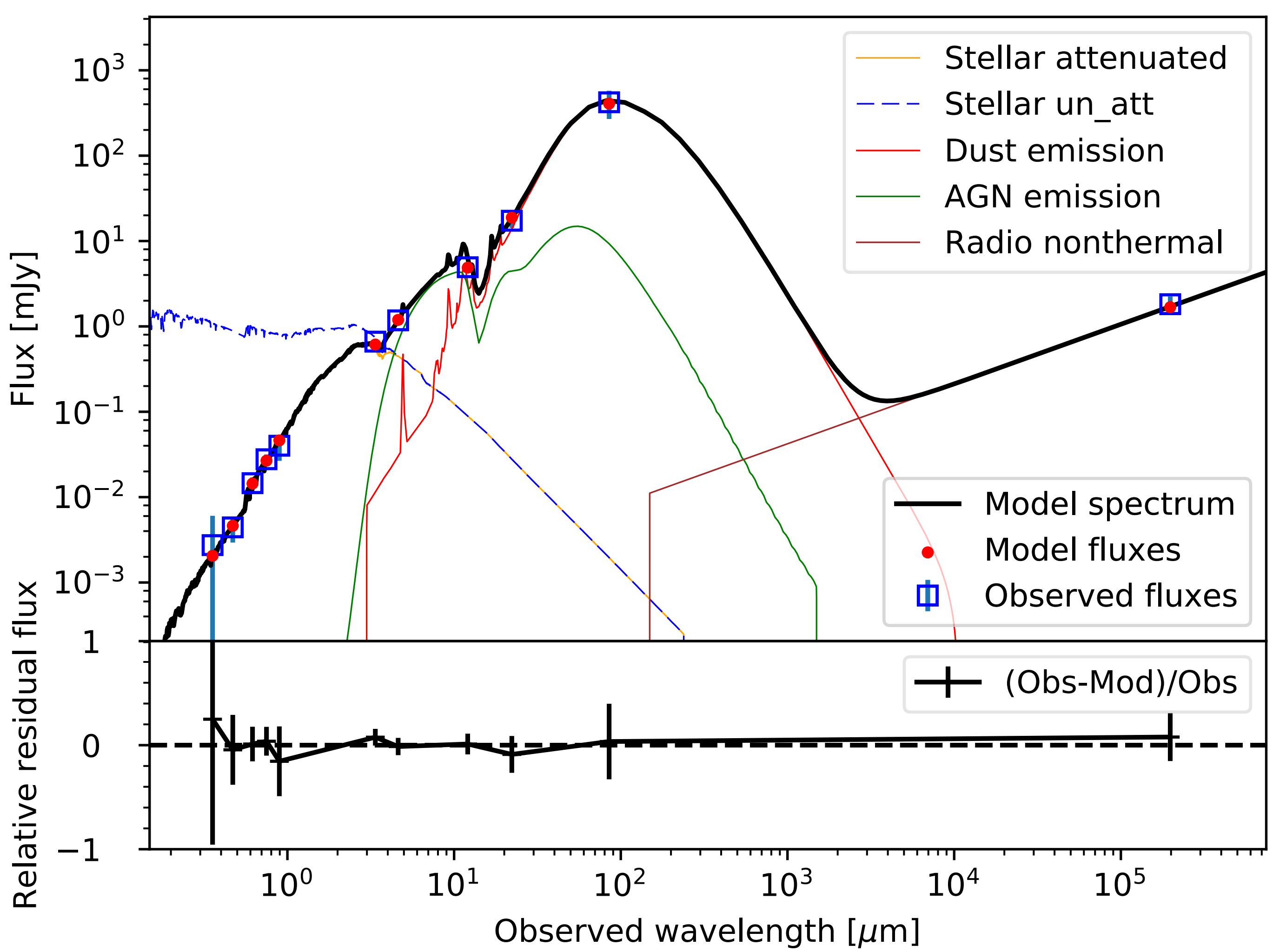

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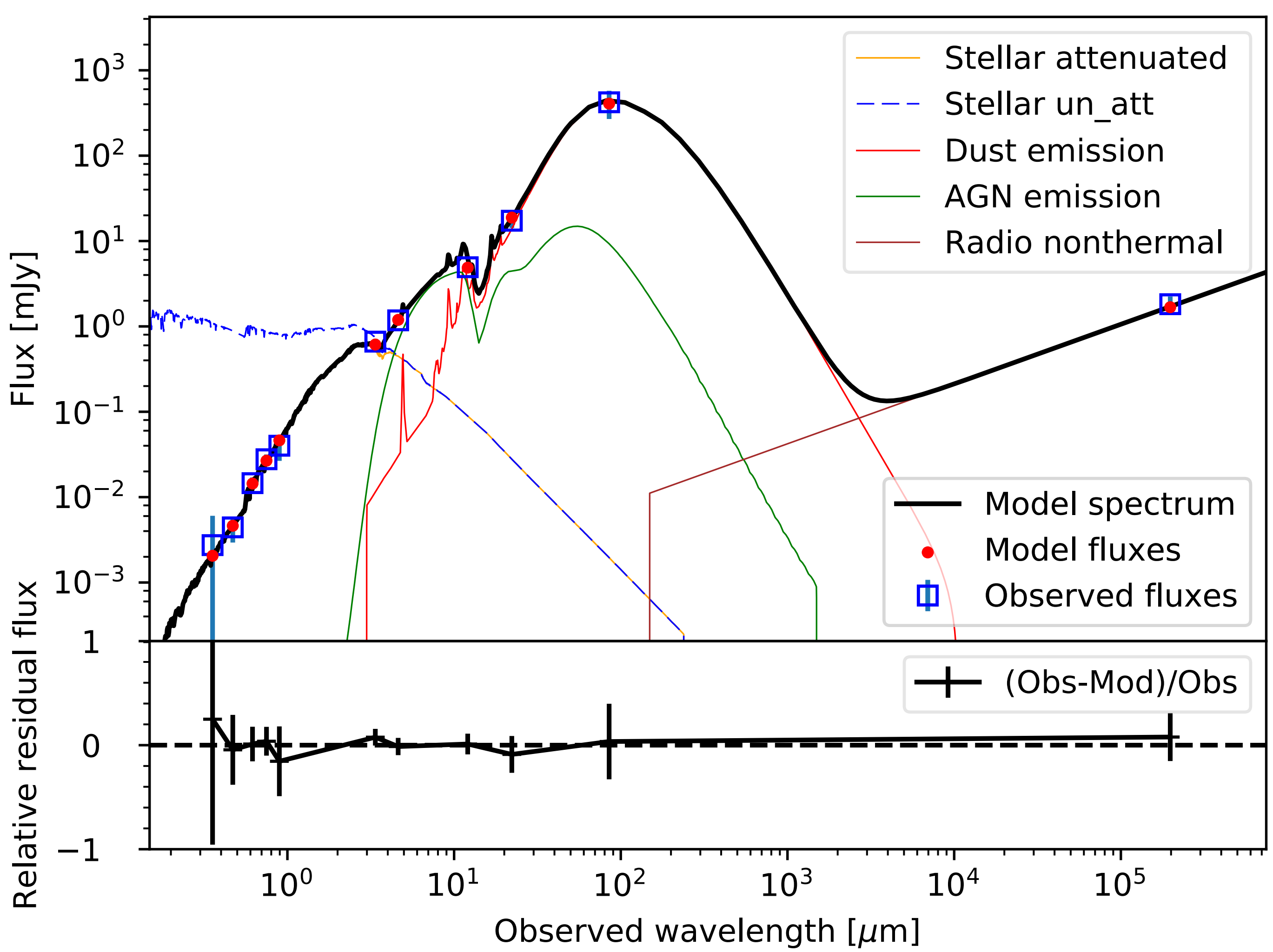

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  P$_{SF}$ = 7E+41 * SFR
  6.41E+44 erg/s

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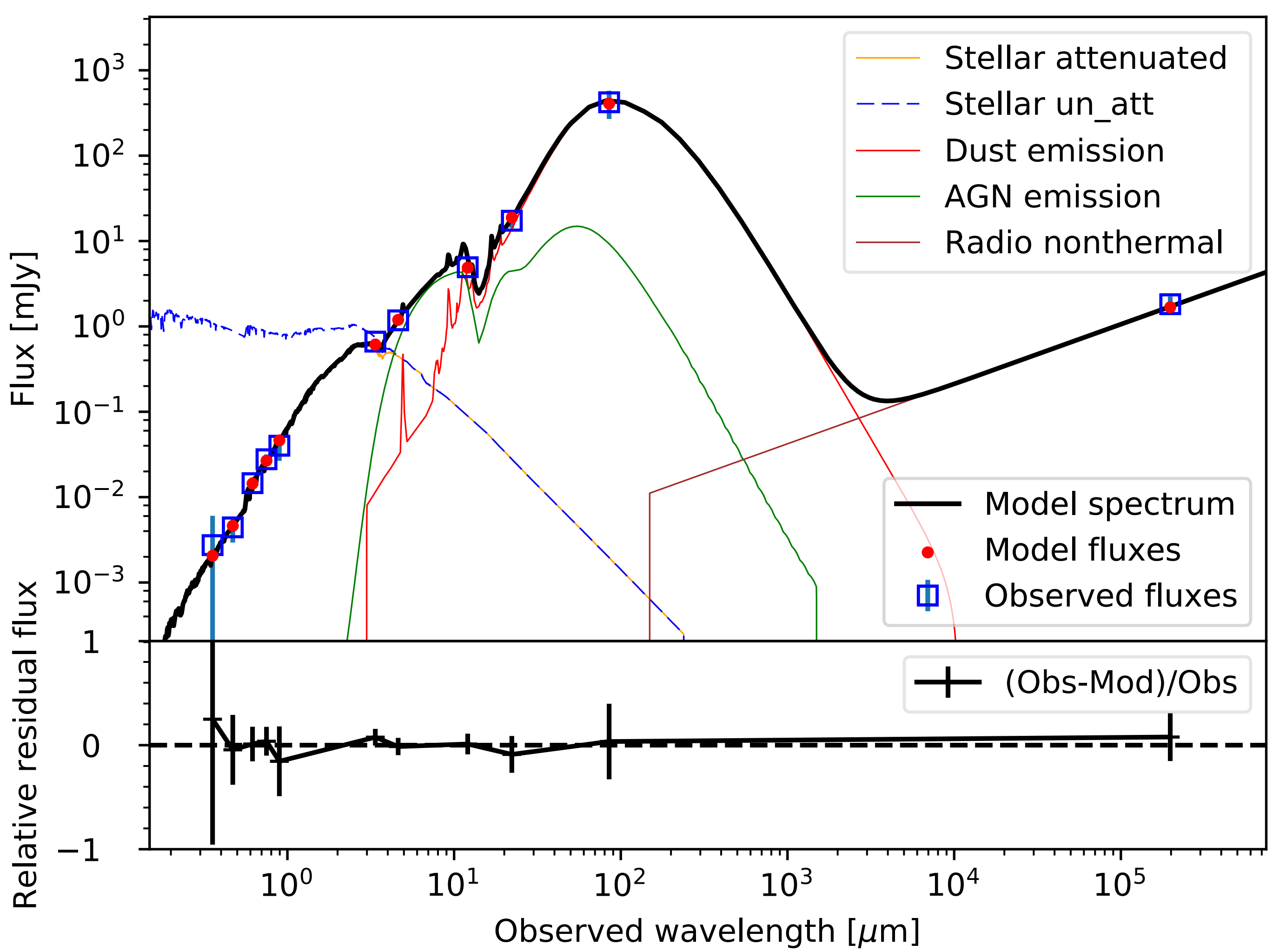

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- FracAGN = 0.09±0.01
  the maximum mechanical energy injection from supernovae and stellar winds (Veilleux+2005)
  P_{SF} = 7E+41 * SFR
  6.41E+44 erg/s

Power source of fast outflow: 2) in Energetics view

- 1) estimate L_{AGN} and P_{SF}
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- Assuming a spherical volume of outflowing ionized gas (Harrison +2014), dM_{out}/dt and dE_{out}/dt can be derived via:

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where the mass of outflowing gas can be obtained from [OIII] or Hα (broad component):

$$M_{\rm out}([{\rm OIII}]) = 5.33 \times 10^8 (\frac{L_{\rm cor}([{\rm OIII}])}{10^{44}\ {\rm erg\ s^{-1}}})(\frac{n_e}{100\ {\rm cm^{-3}}})^{-1} {\rm M_\odot}$$

$$M_{\rm out}({\rm H}\alpha) = 2.33 \times 10^8 (\frac{L_{\rm cor}({\rm H}\alpha)}{10^{43}\ {\rm erg\ s^{-1}}})(\frac{n_e}{100\ {\rm cm^{-3}}})^{-1} {\rm M_\odot}.$$

Power source of fast outflow: 2) in Energetics view

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	dMout/dt	dEout/dt	dEout/dt / L_{AGN}	dEout/dt / P_{SF}
[OIII] 5007	588 $M_\odot$/yr	6.89E+44 erg/s	29.70%	107.49%
Hα (broad)	467 $M_\odot$/yr	3.52E+44 erg/s	15.17%	54.91%

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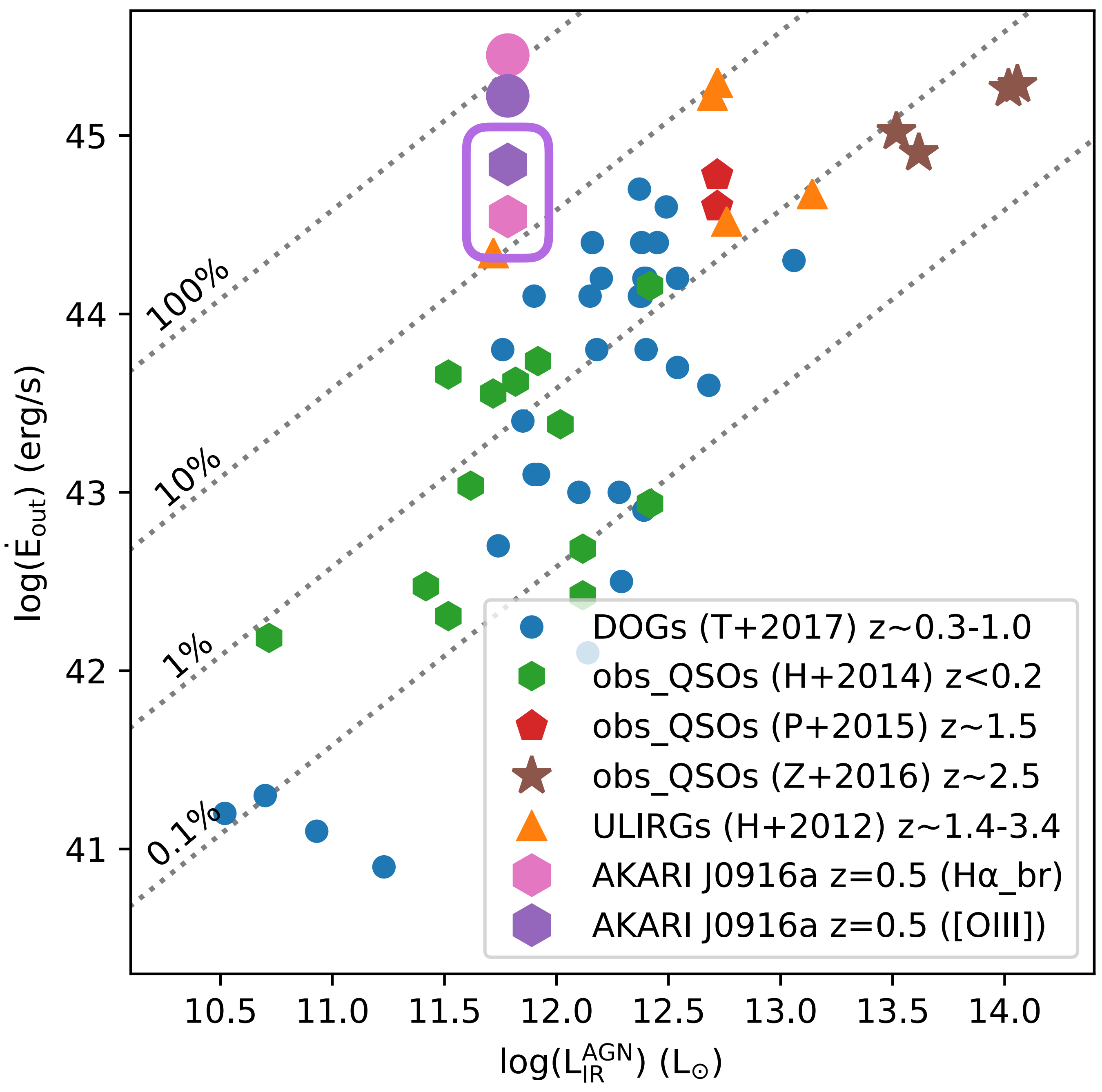
- Based on the BPT-diagram and energetics analyses, we suggest that **AGN may play a dominant role in powering the outflow.**

Power source of fast outflow: 2) in Energetics view



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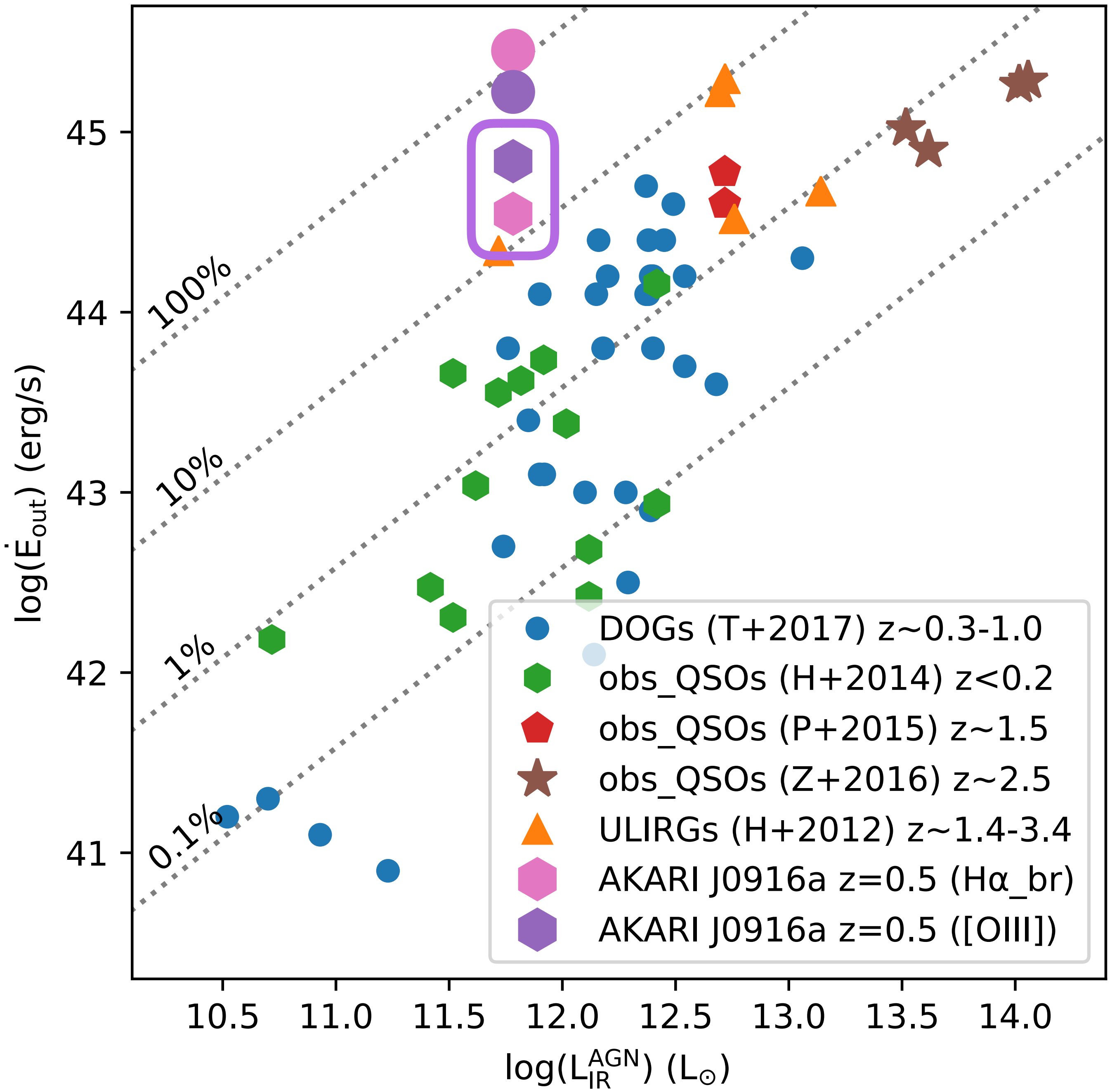

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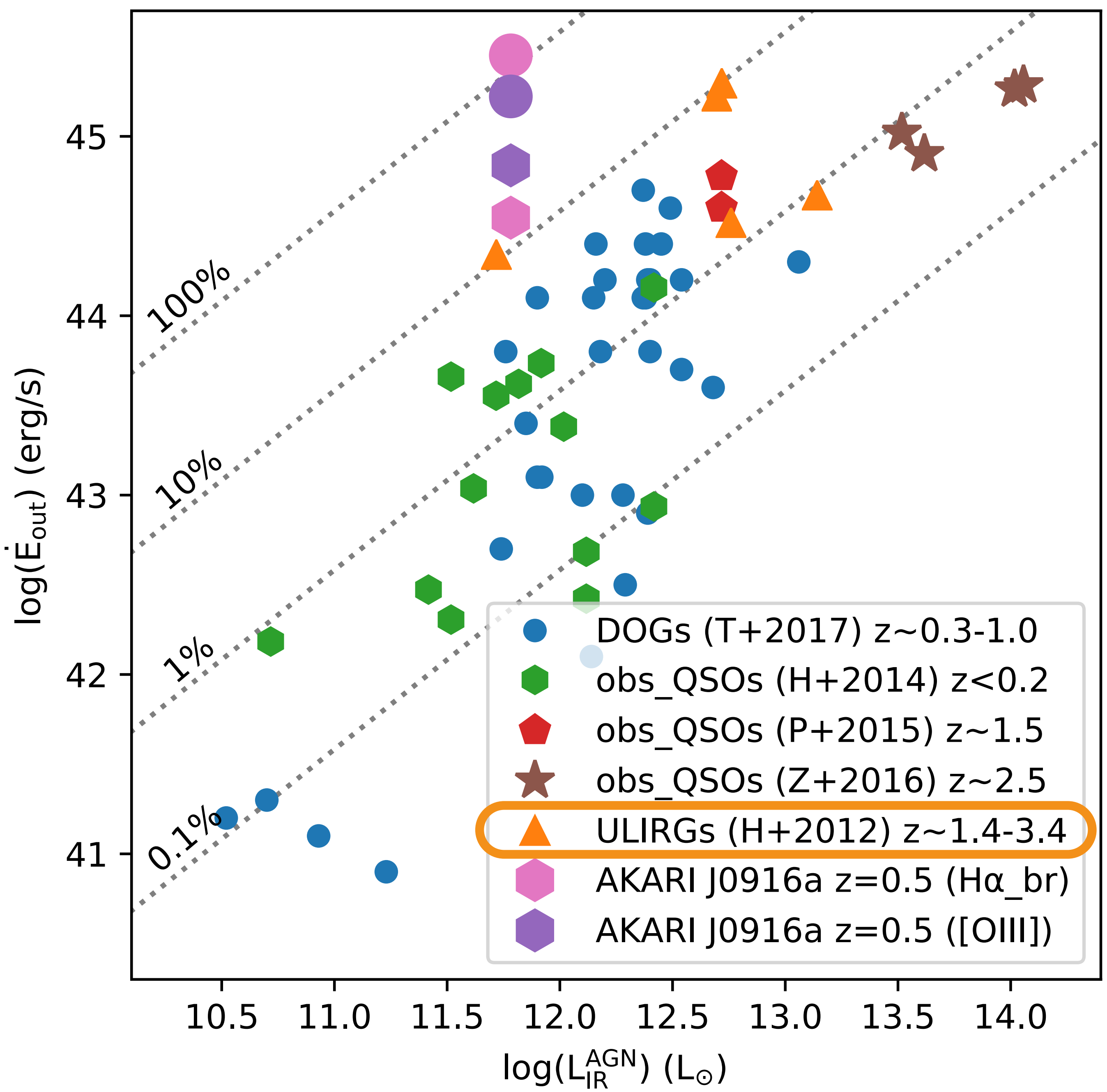

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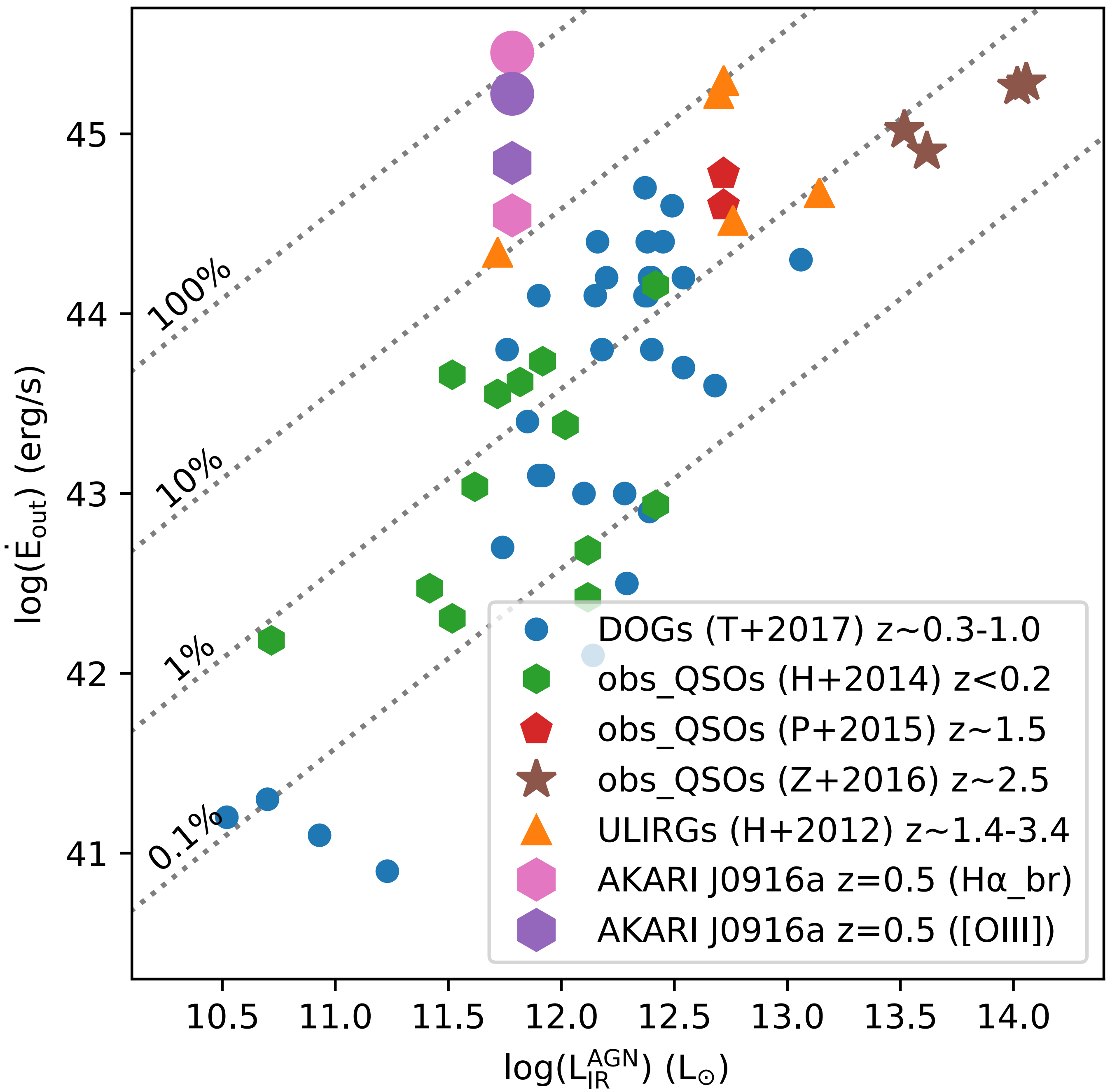

- The estimation of dE_{out}/dt depends on the assumption of outflow velocity.

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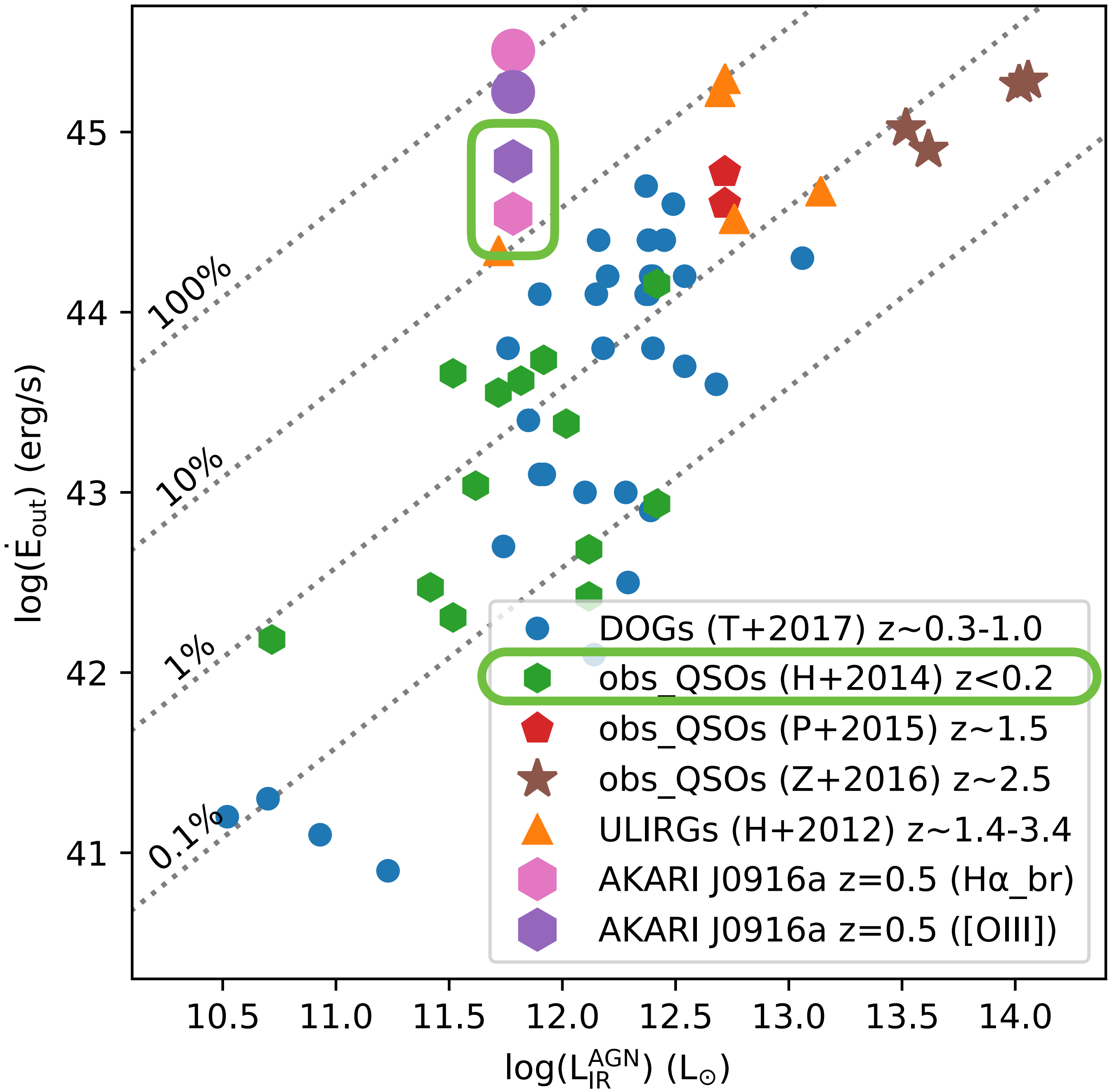

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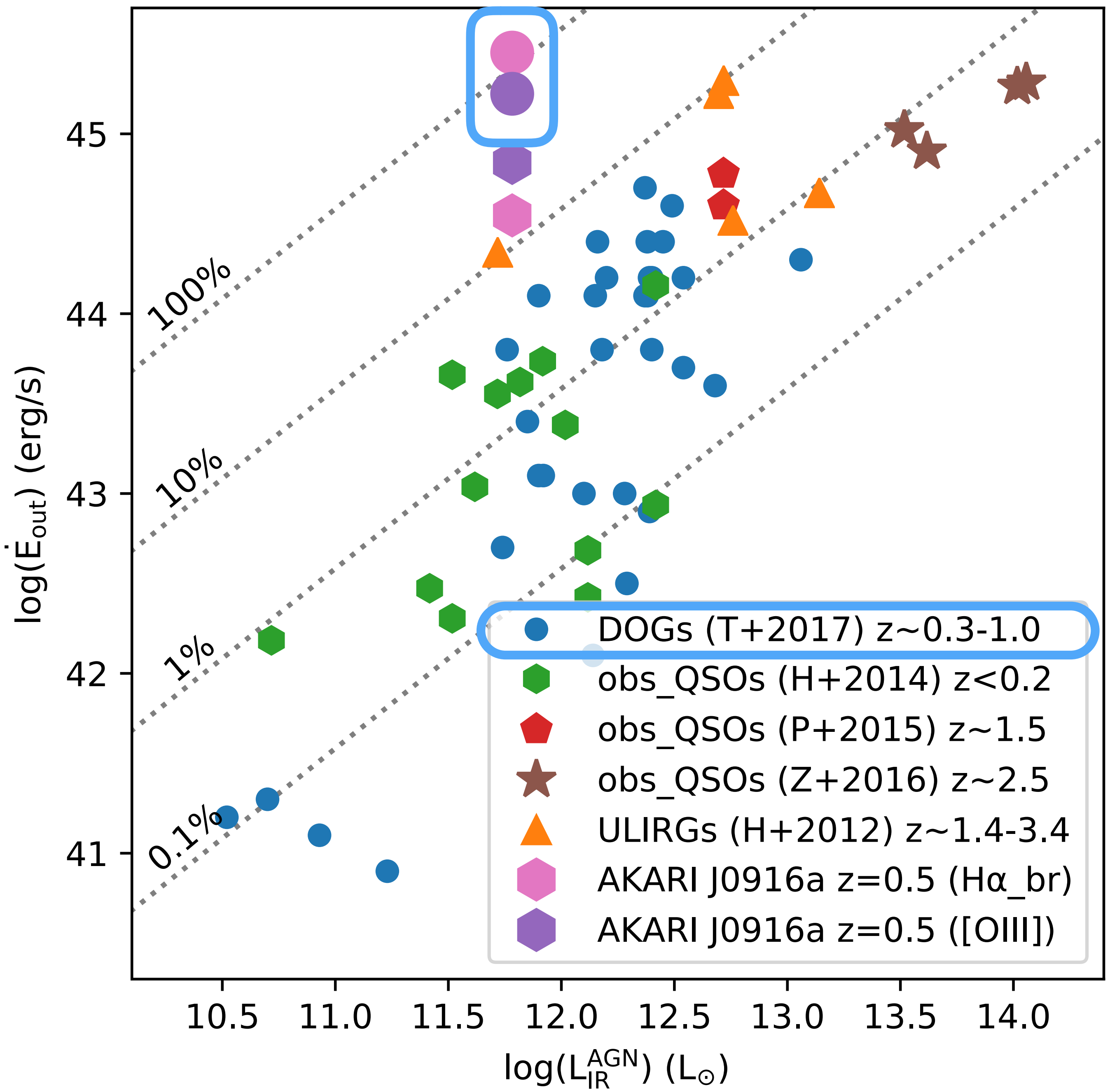

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$$\dot{M}_{\rm out} = \frac{3M_{\rm out}2\sqrt{v^2+\sigma^2}}{R_{\rm out}},$$

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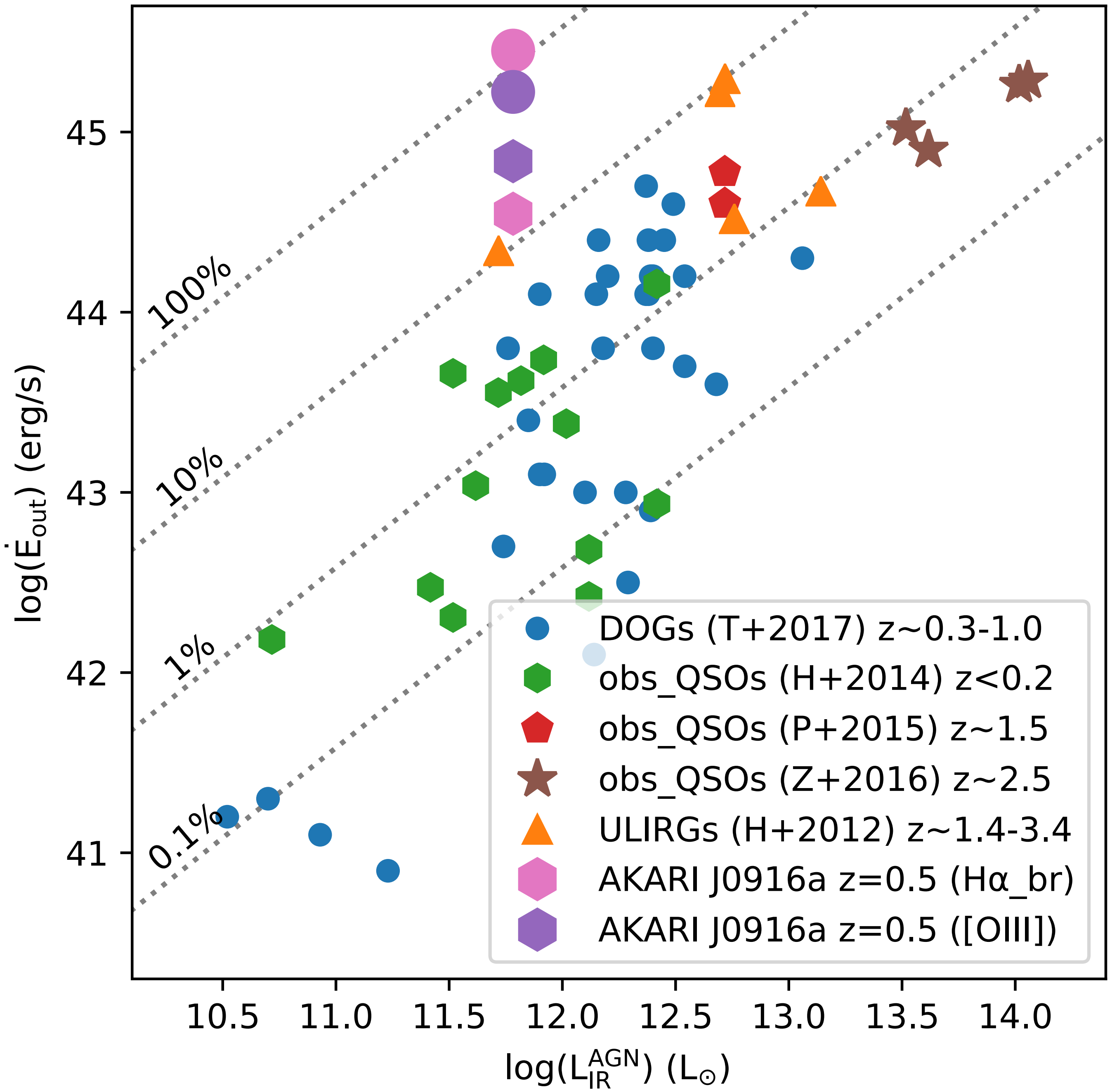

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- electron density -> 100 cm^-3

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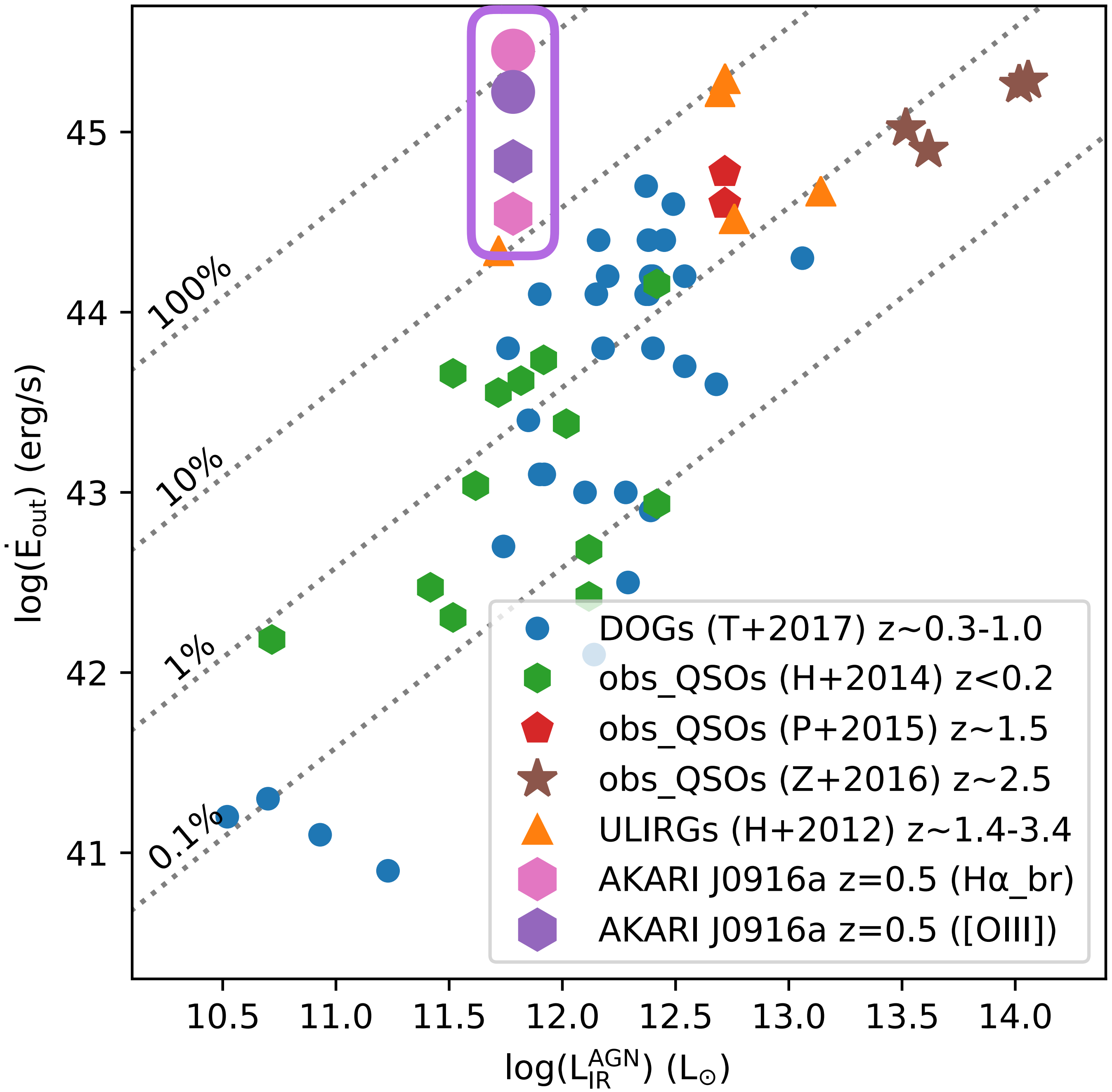

- Intense outflow in J0916a

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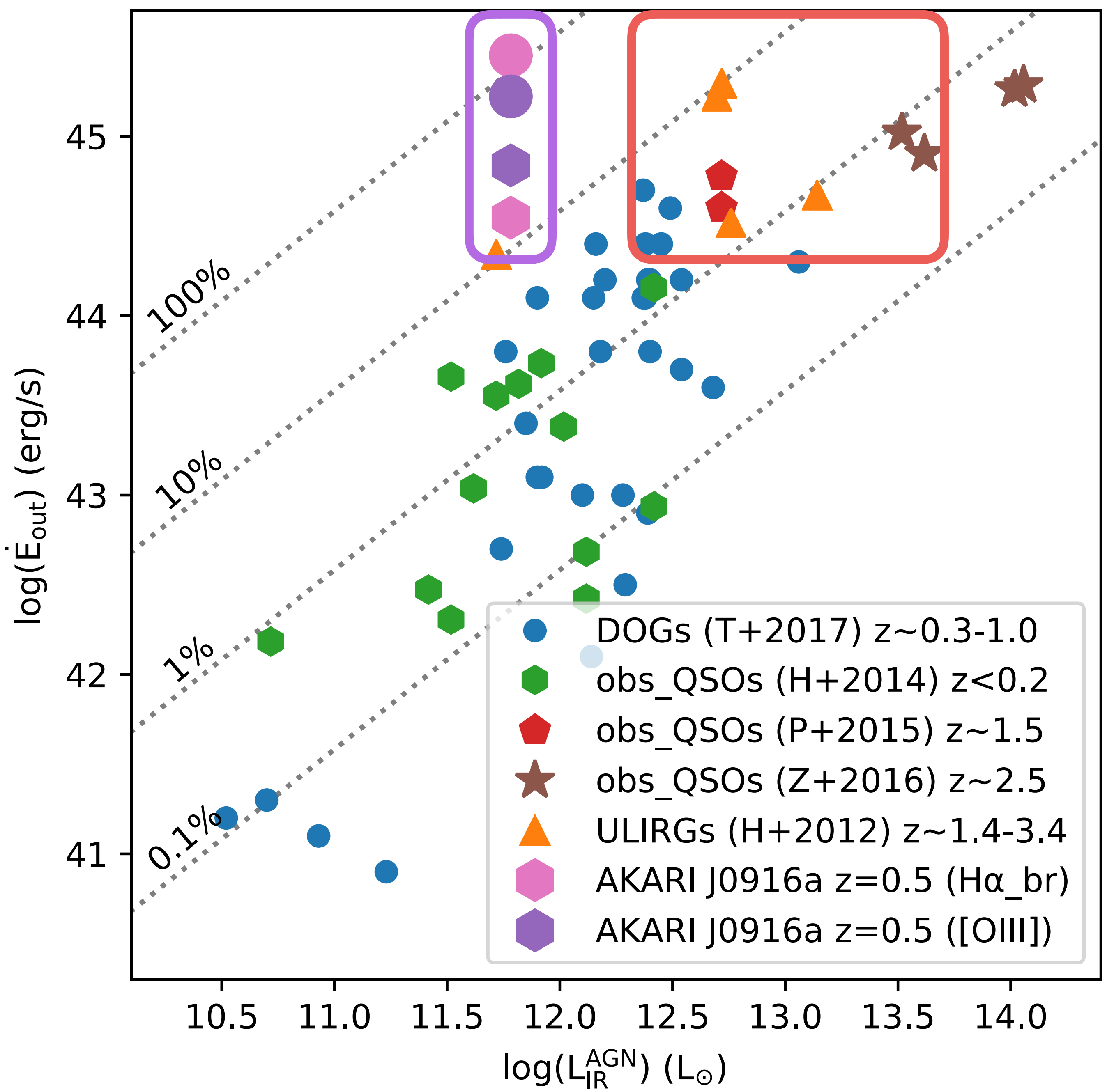

- Intense outflow in J0916a ~ objects with 10-30 times brighter luminosity.

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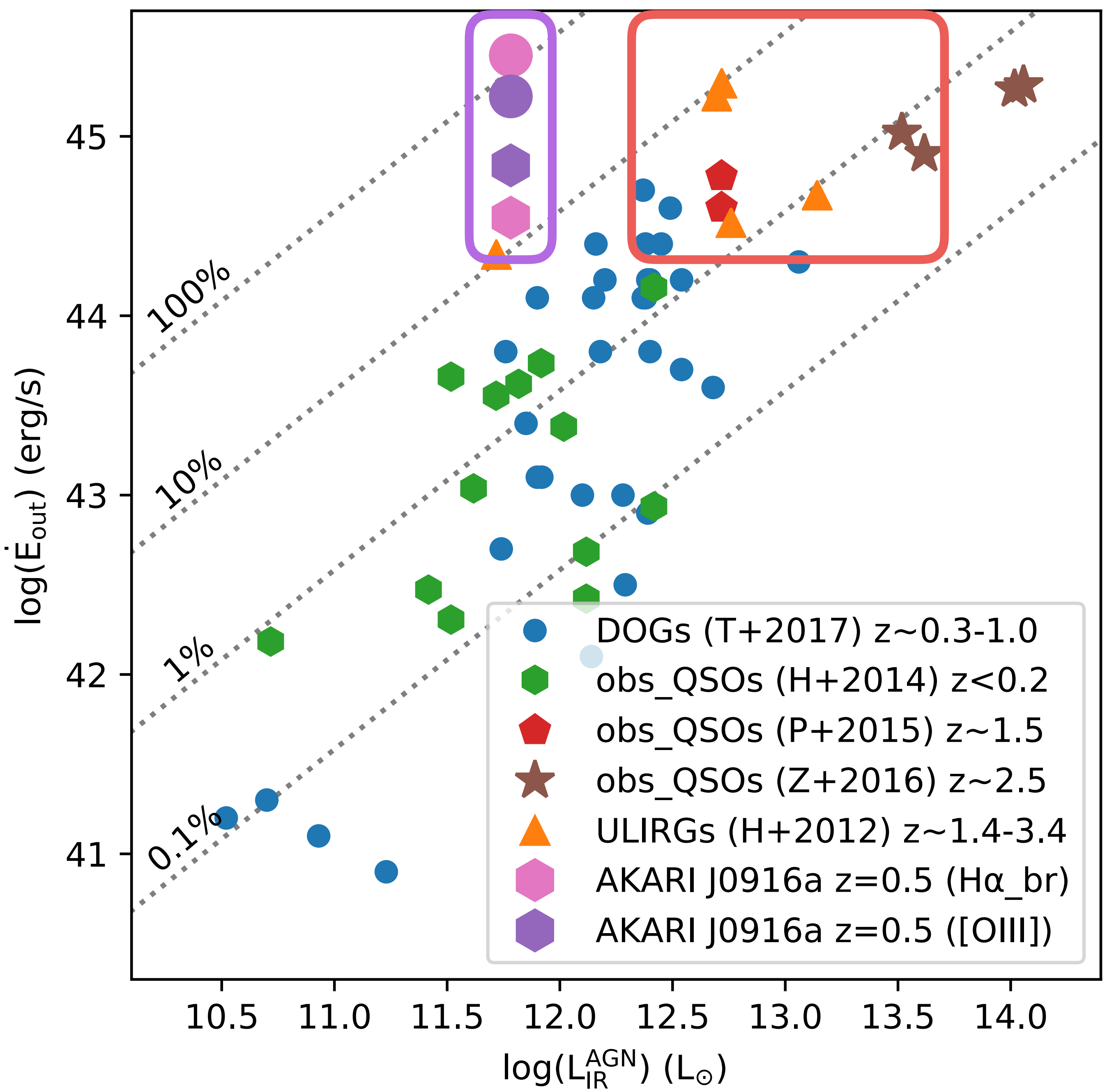

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- Why is the AGN relatively faint?

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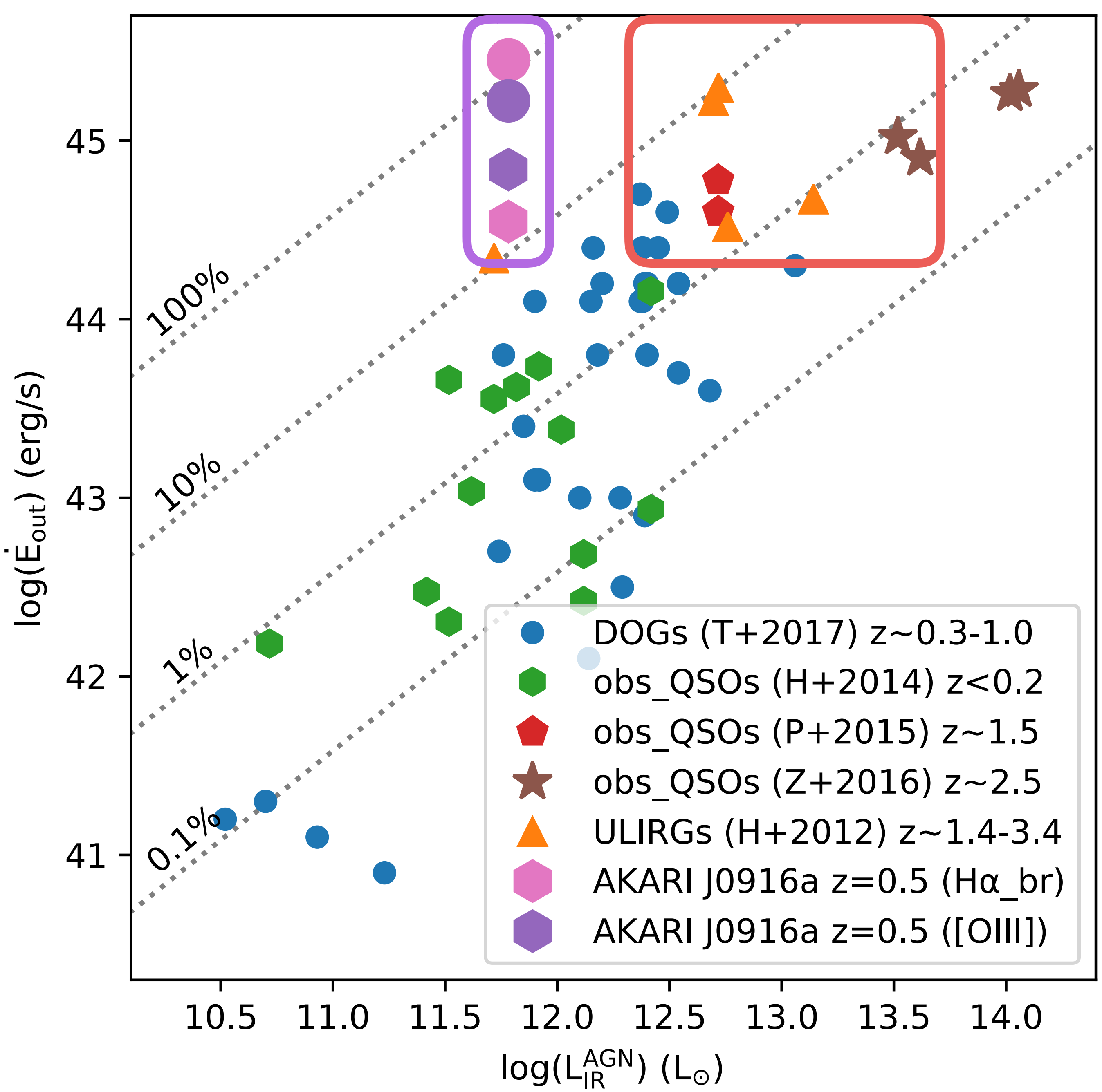

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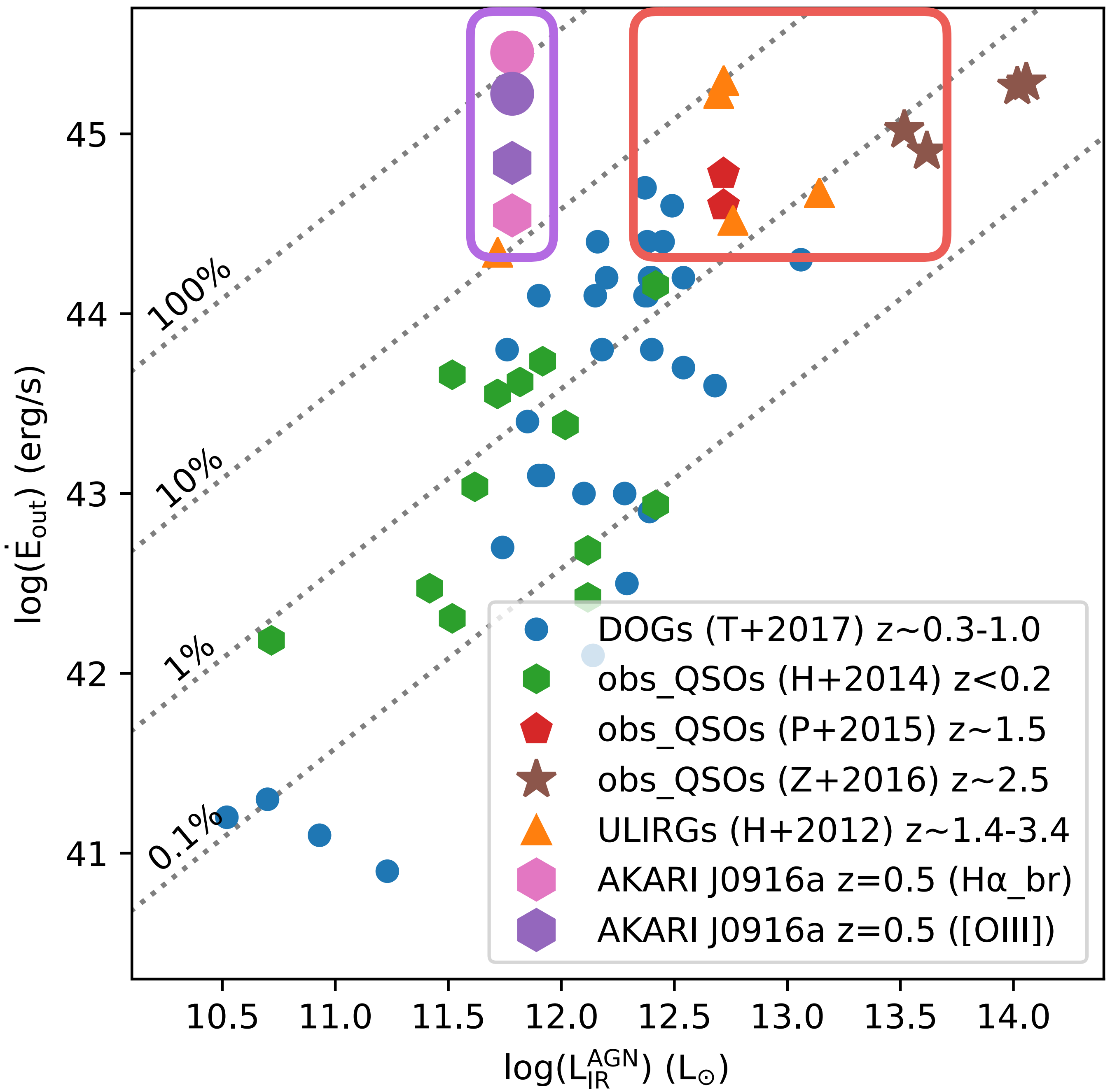

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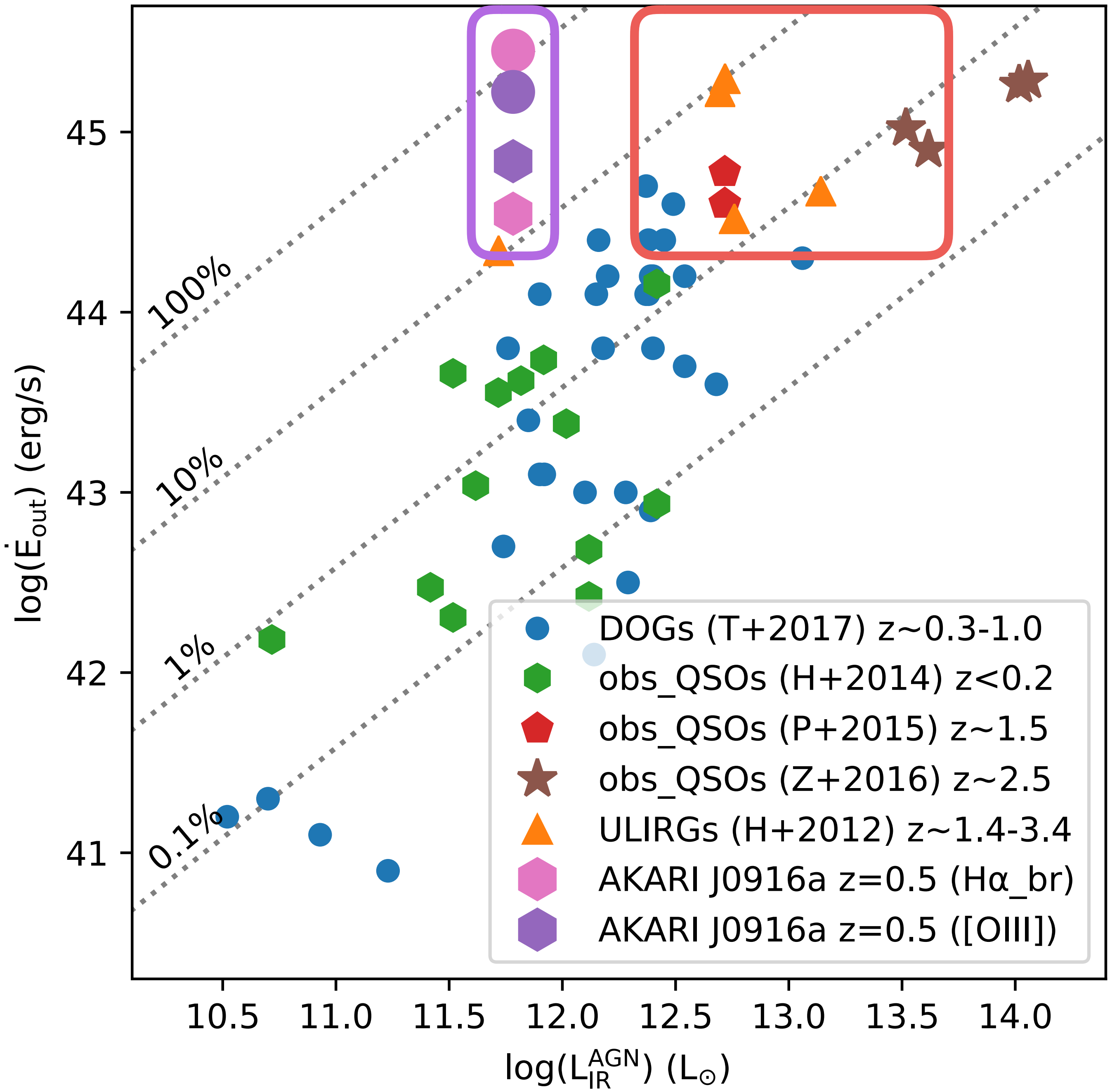

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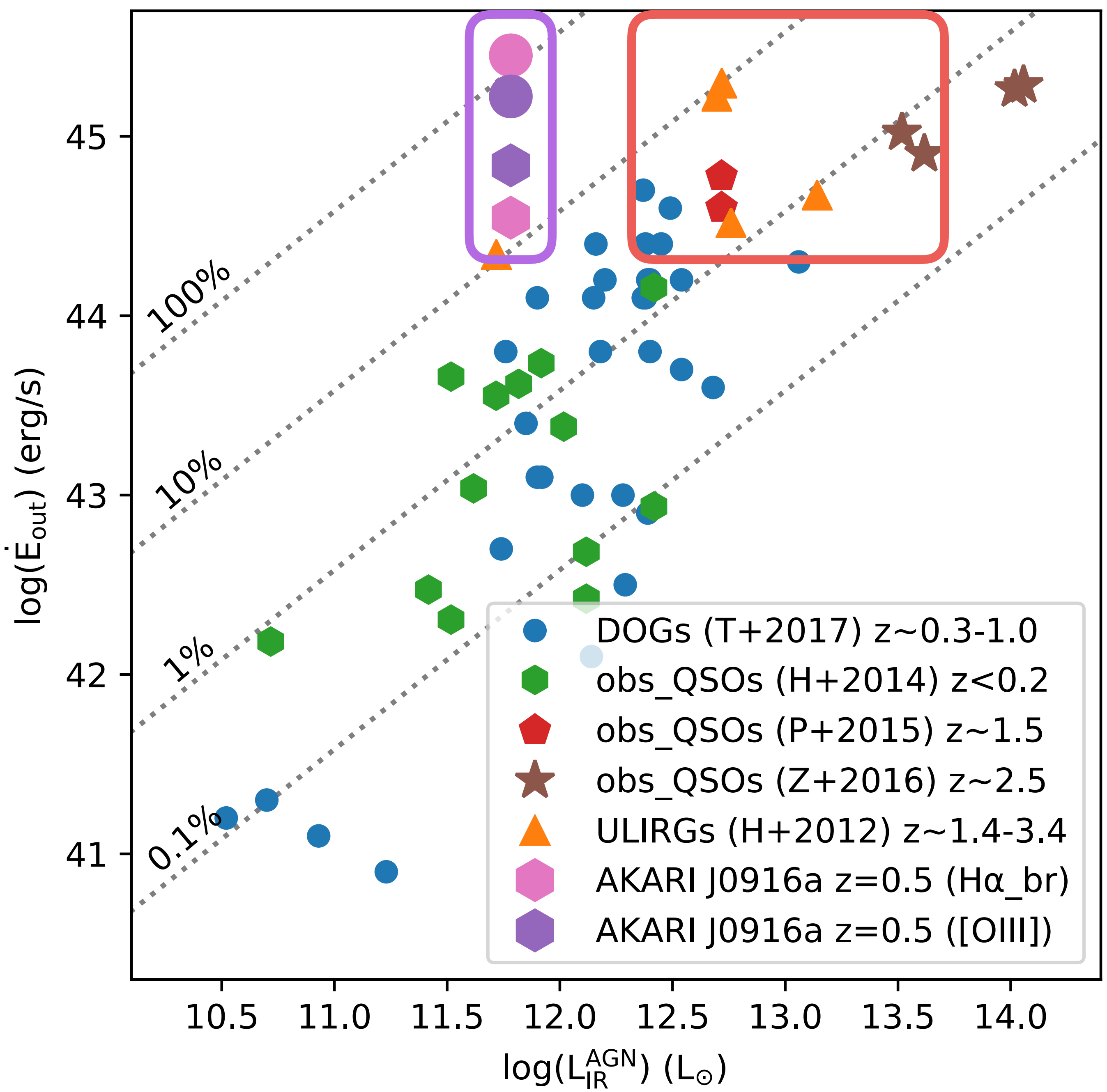

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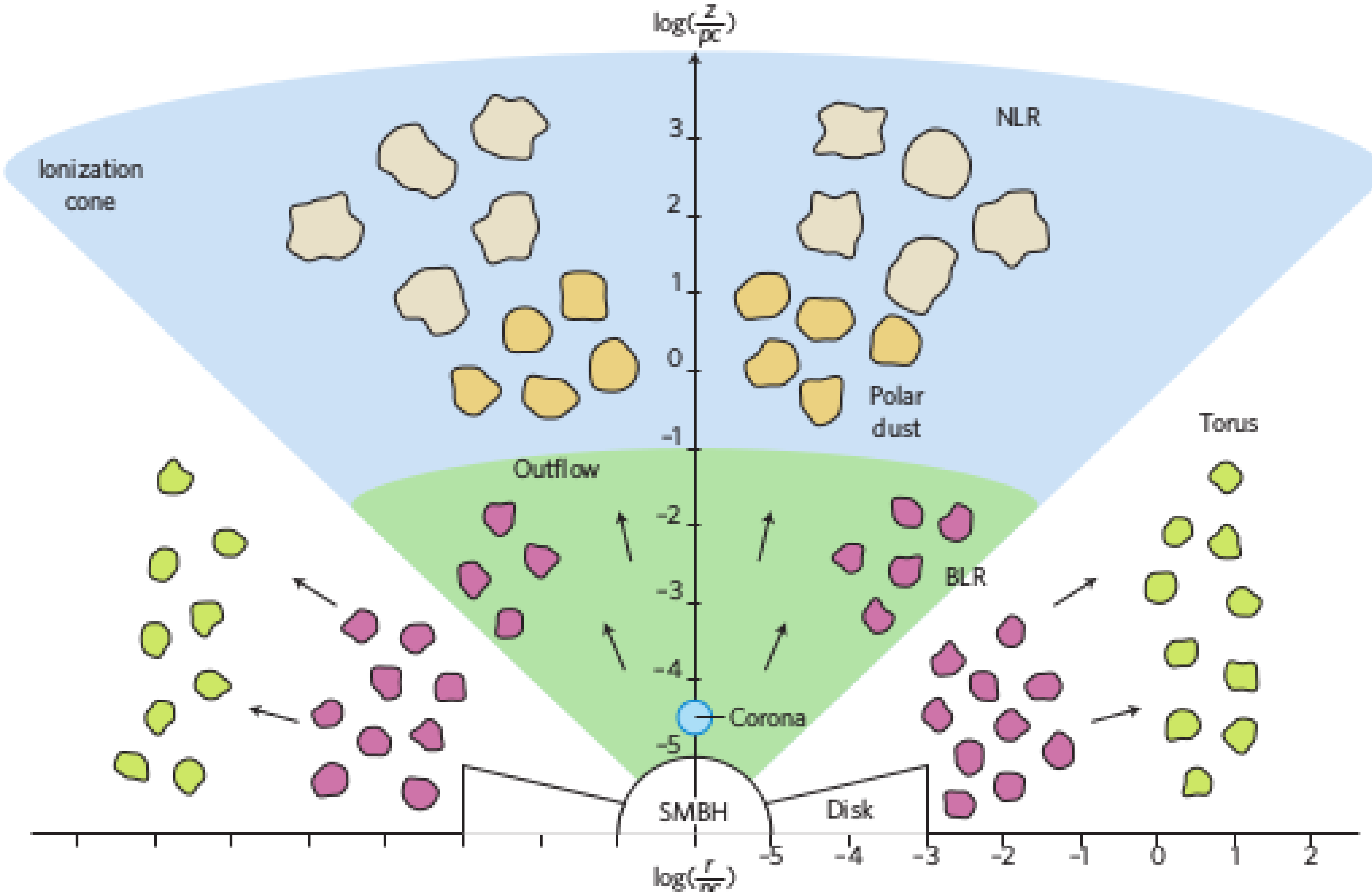
Extreme outflow with fading AGN



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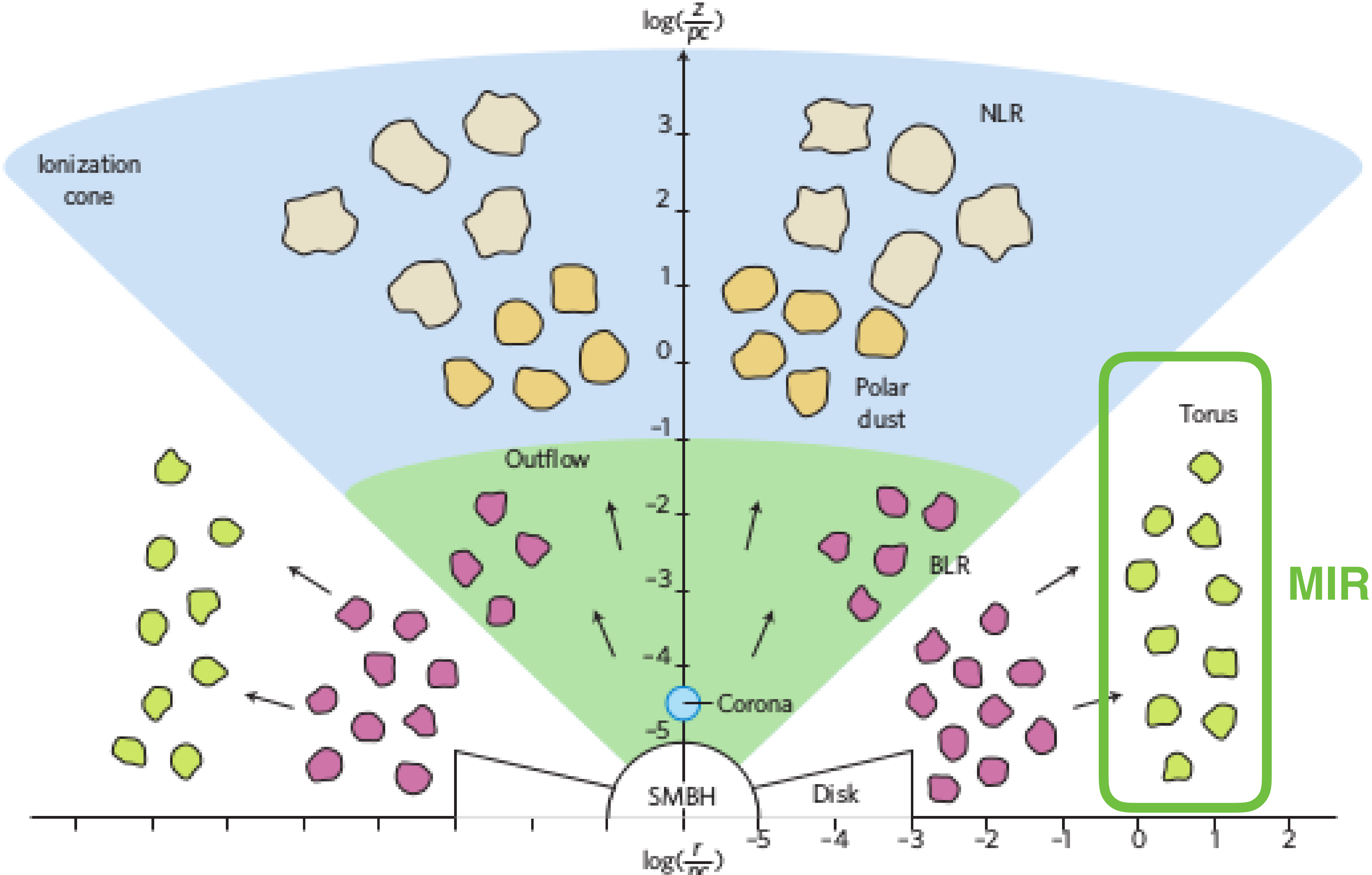

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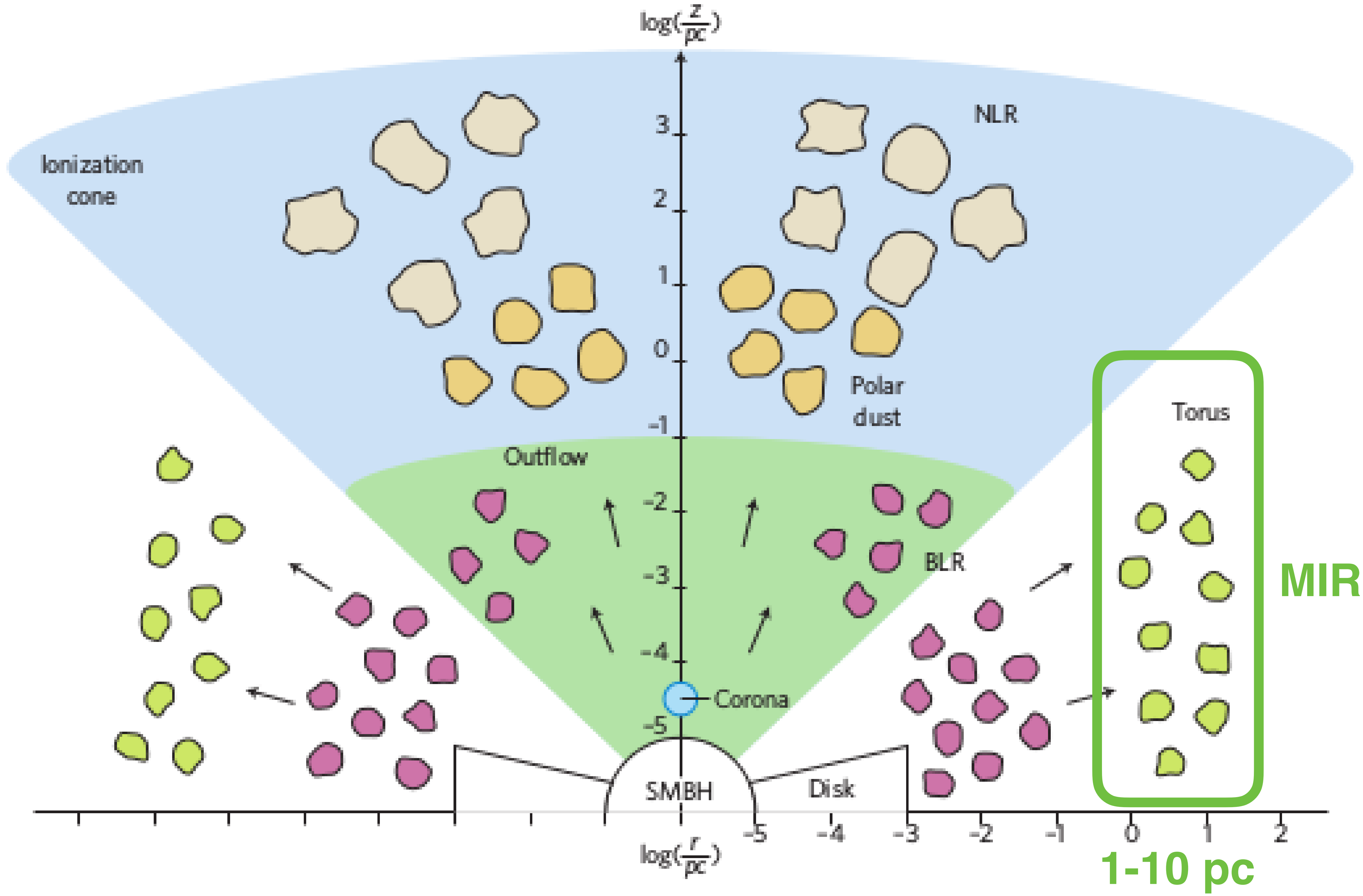

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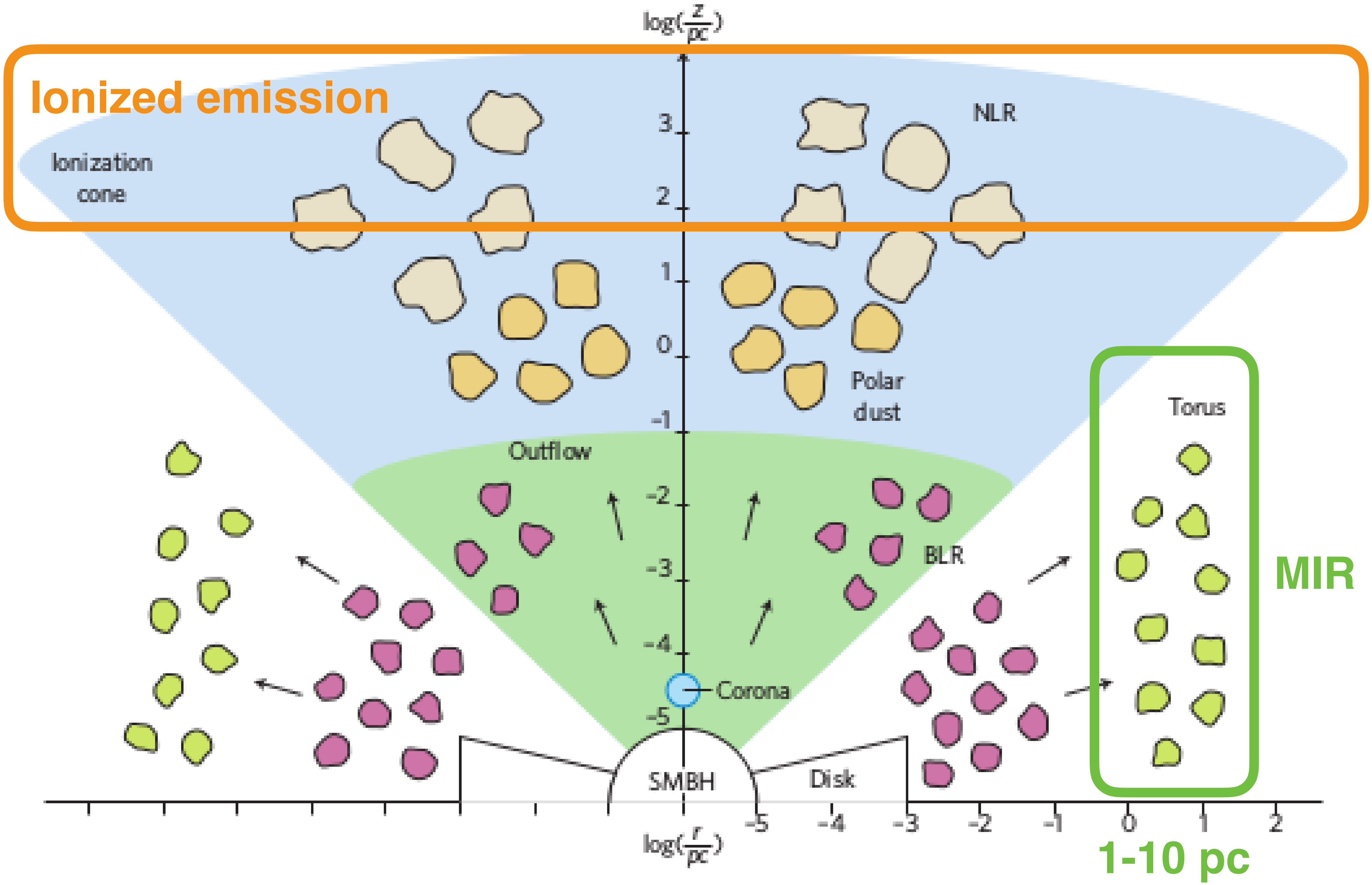

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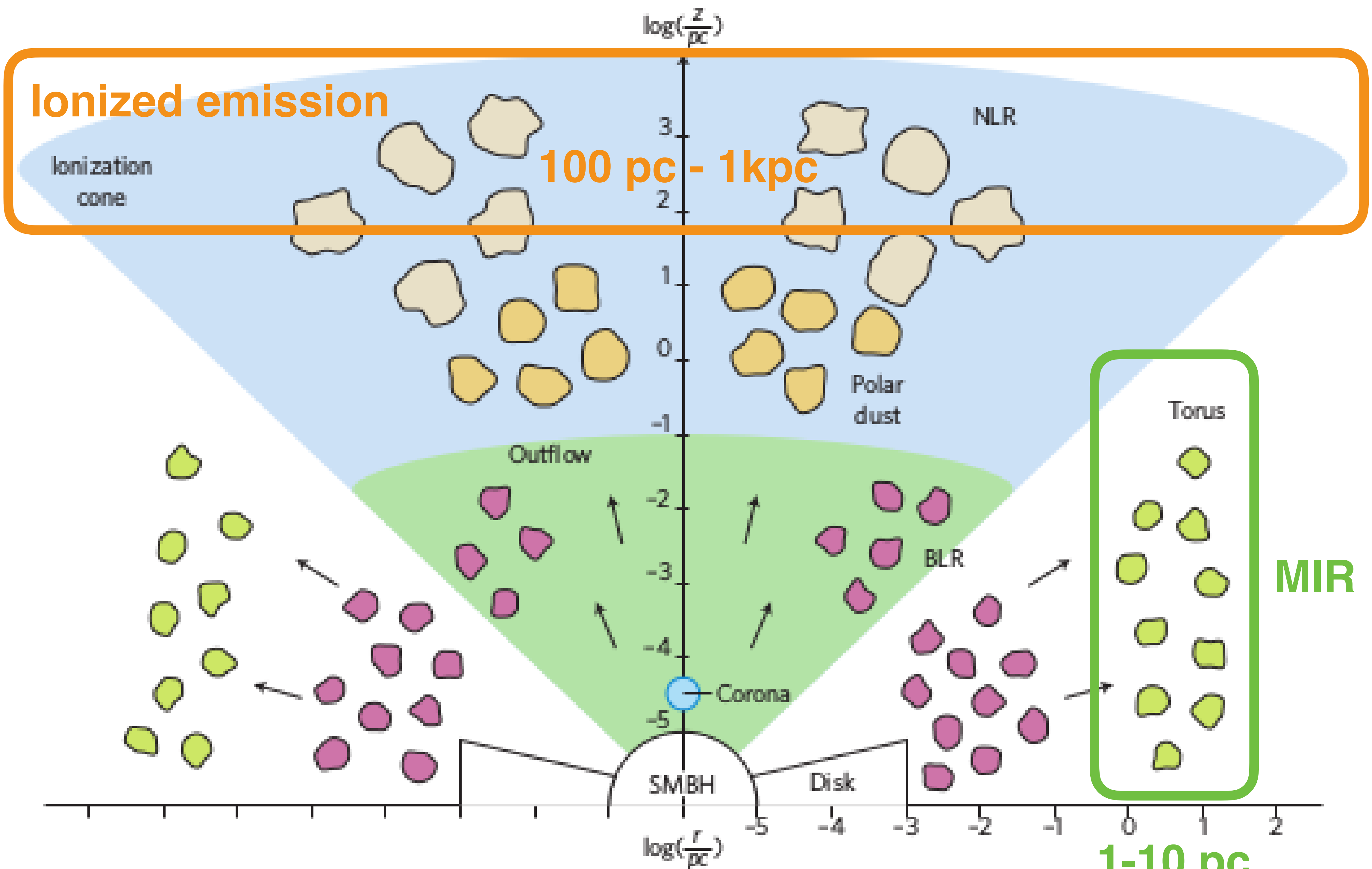

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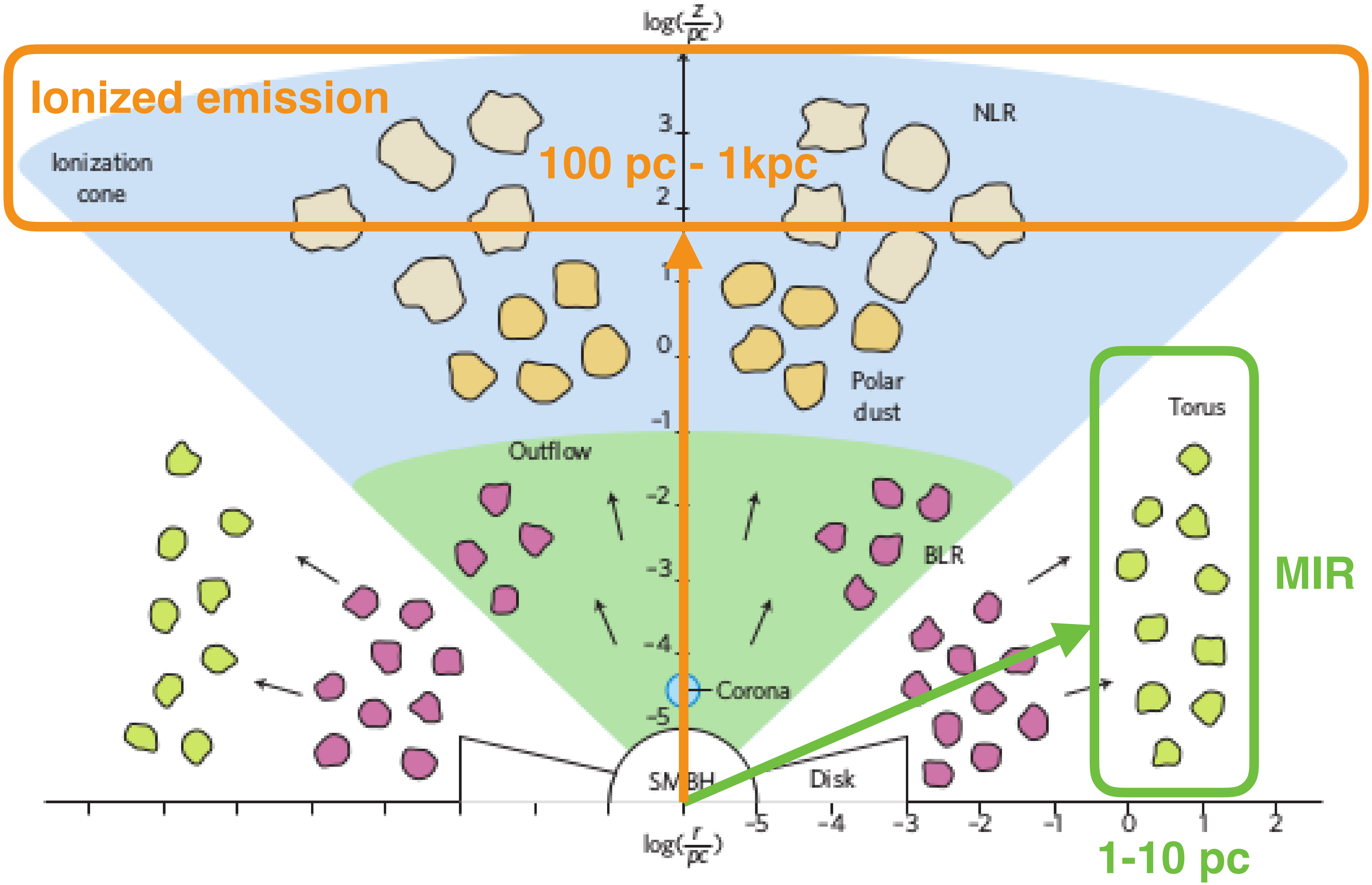
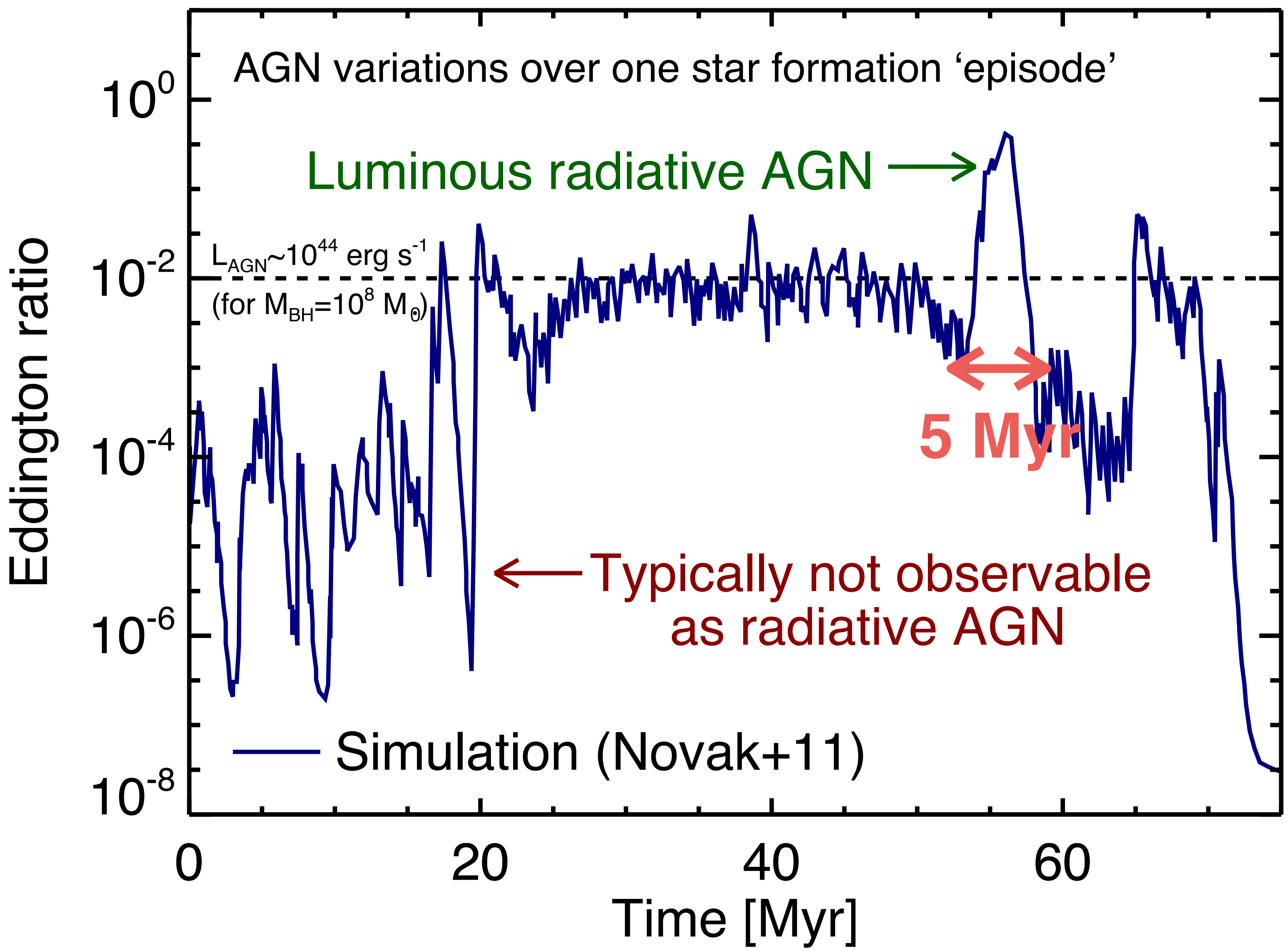


Possible explanation: the outflow traced by ionized emission reflects the **historical effect** of AGN when it was brighter.

Extreme outflow with fading AGN

- Outflow reflects historical effect of AGN
  —> Currently AGN is in a fading process.

- 1) Due to the variability of AGN
  Transmission timescale: R_{out} / v_{out} ~ 6 kpc / 1000 km/s ~ 6 Myr



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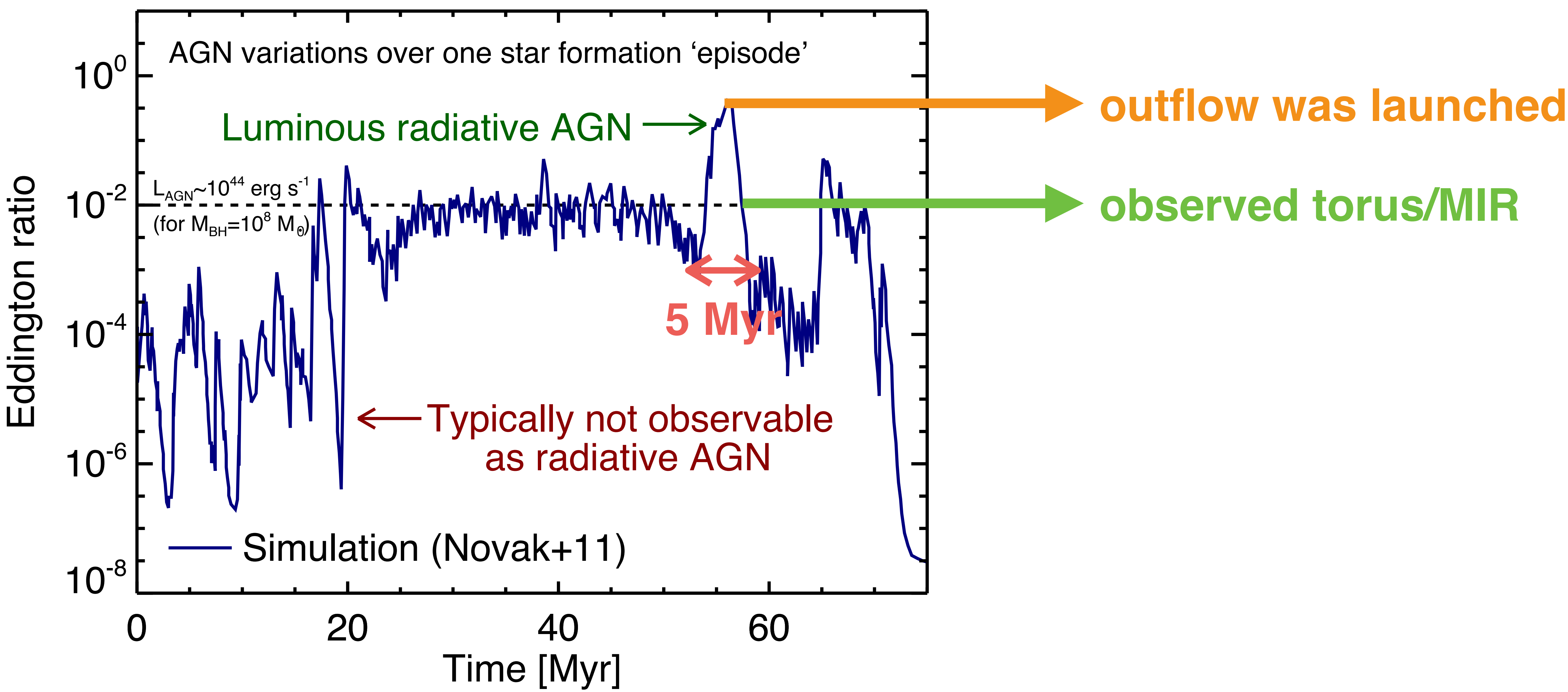

Extreme outflow with fading AGN

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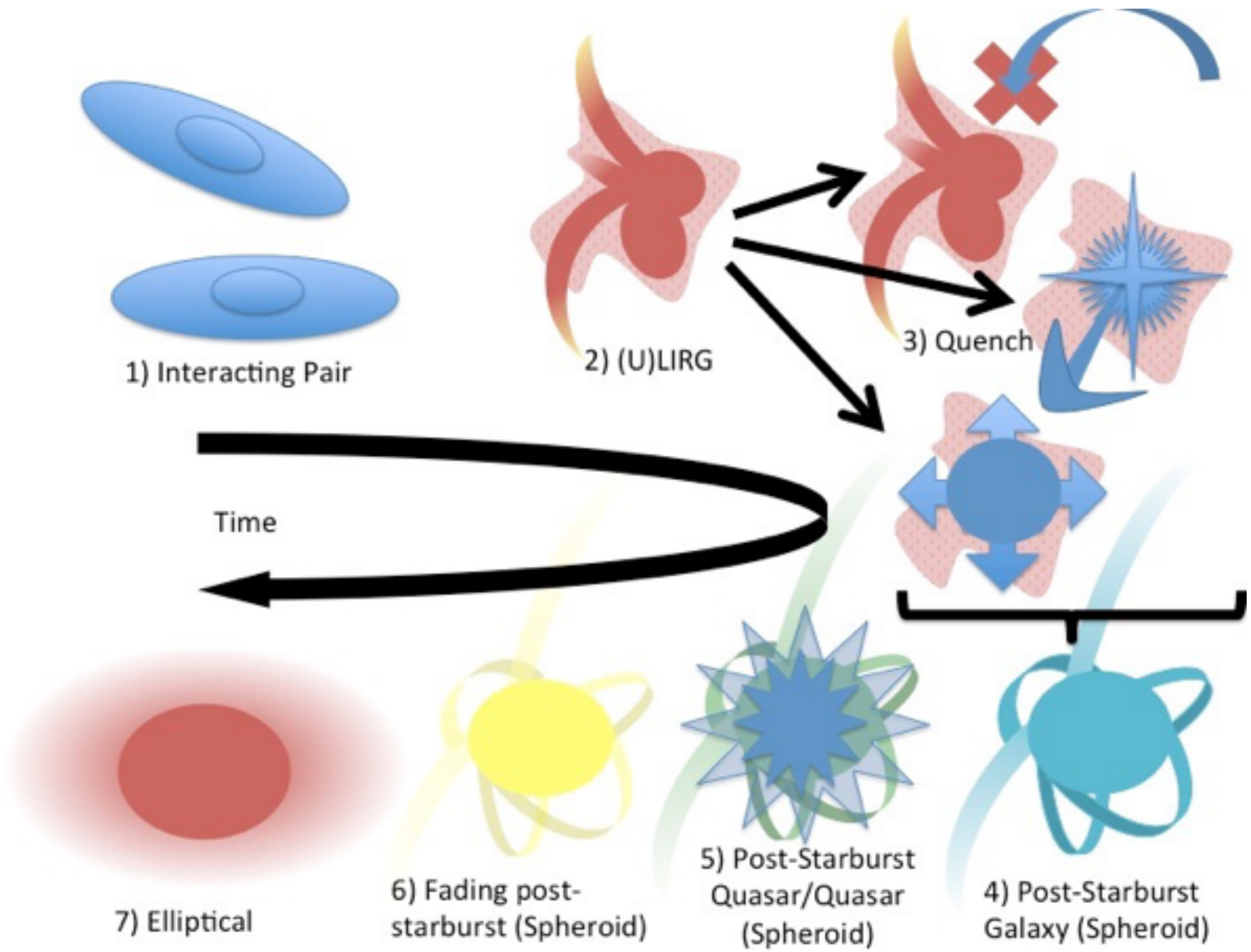

Extreme outflow with fading AGN

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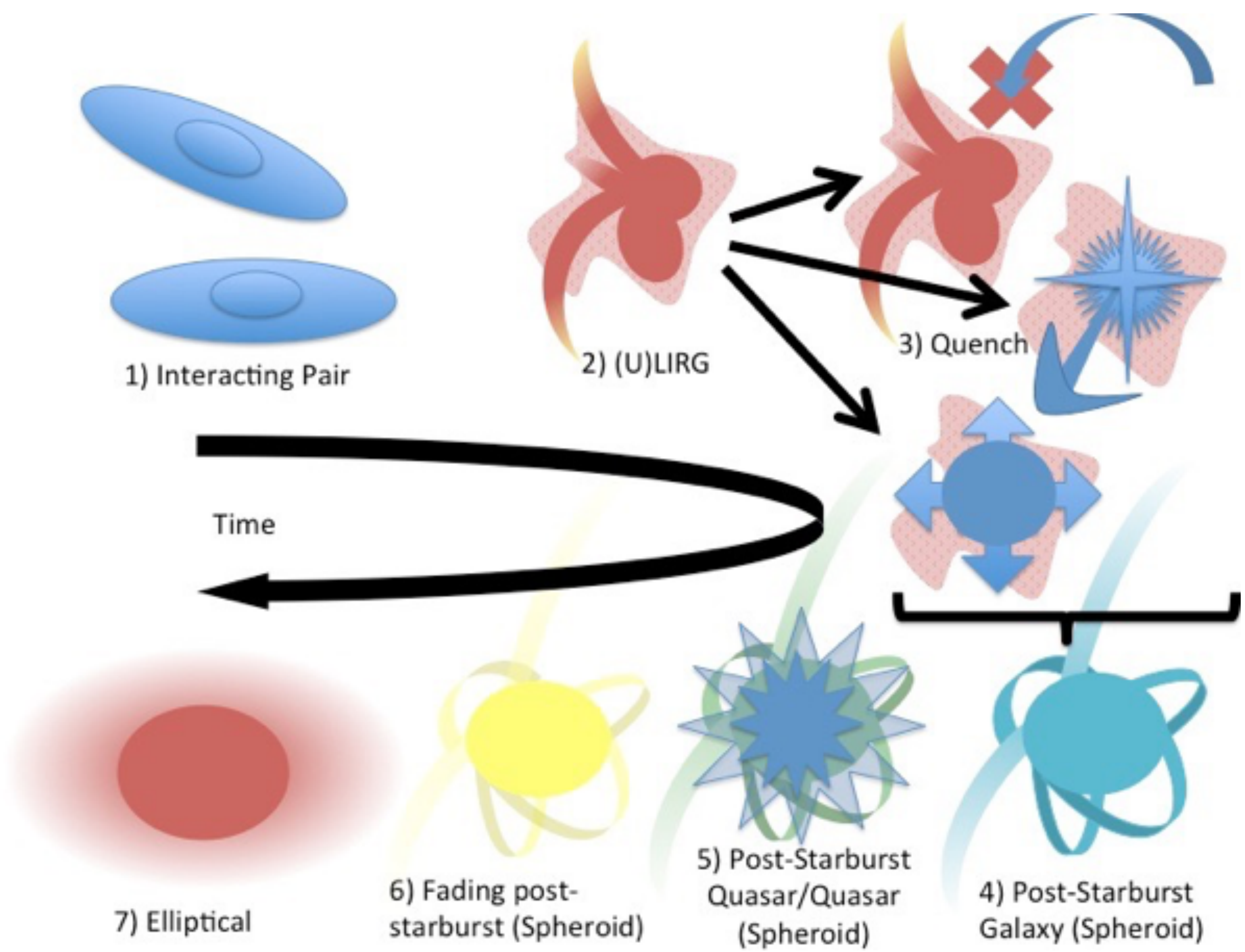

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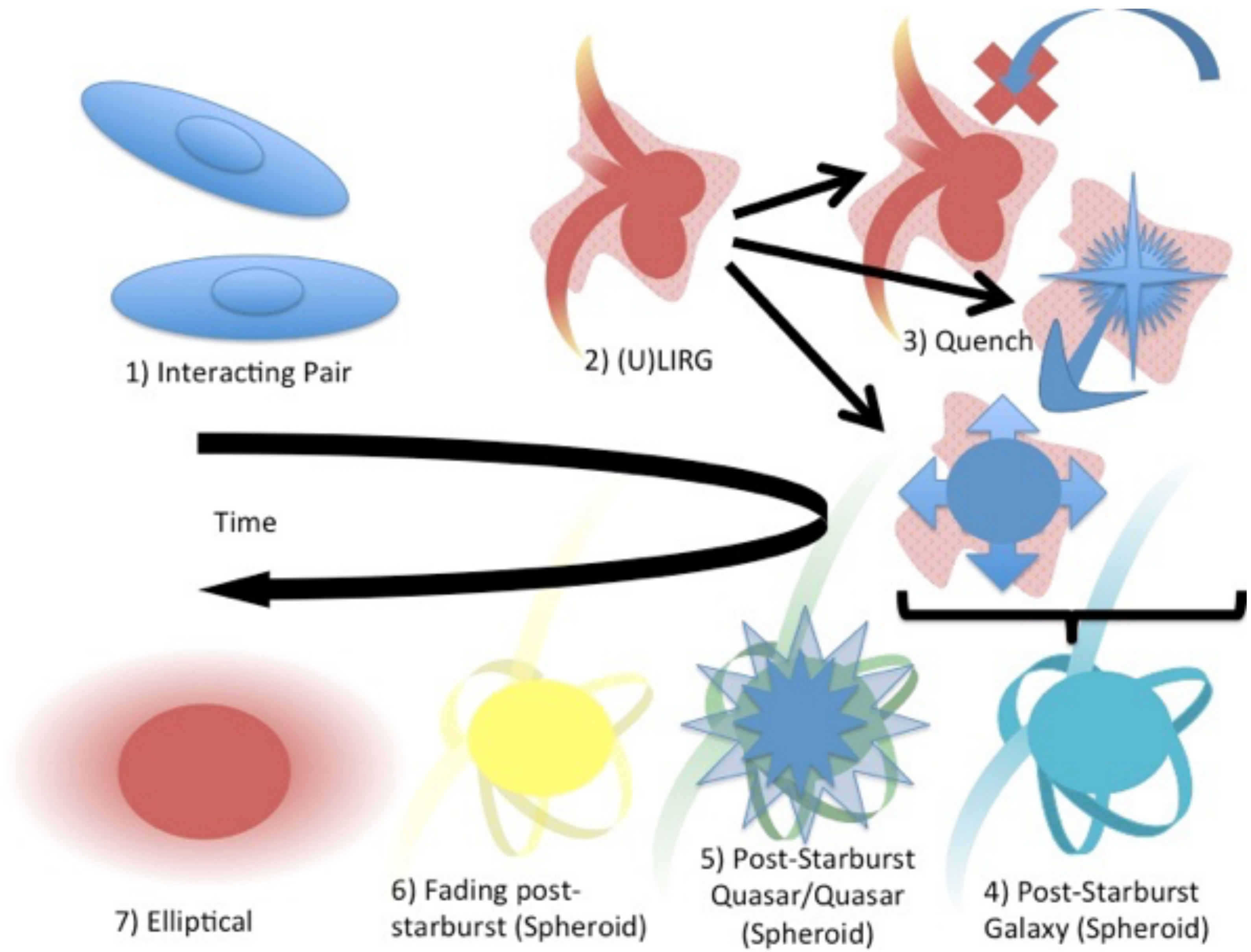

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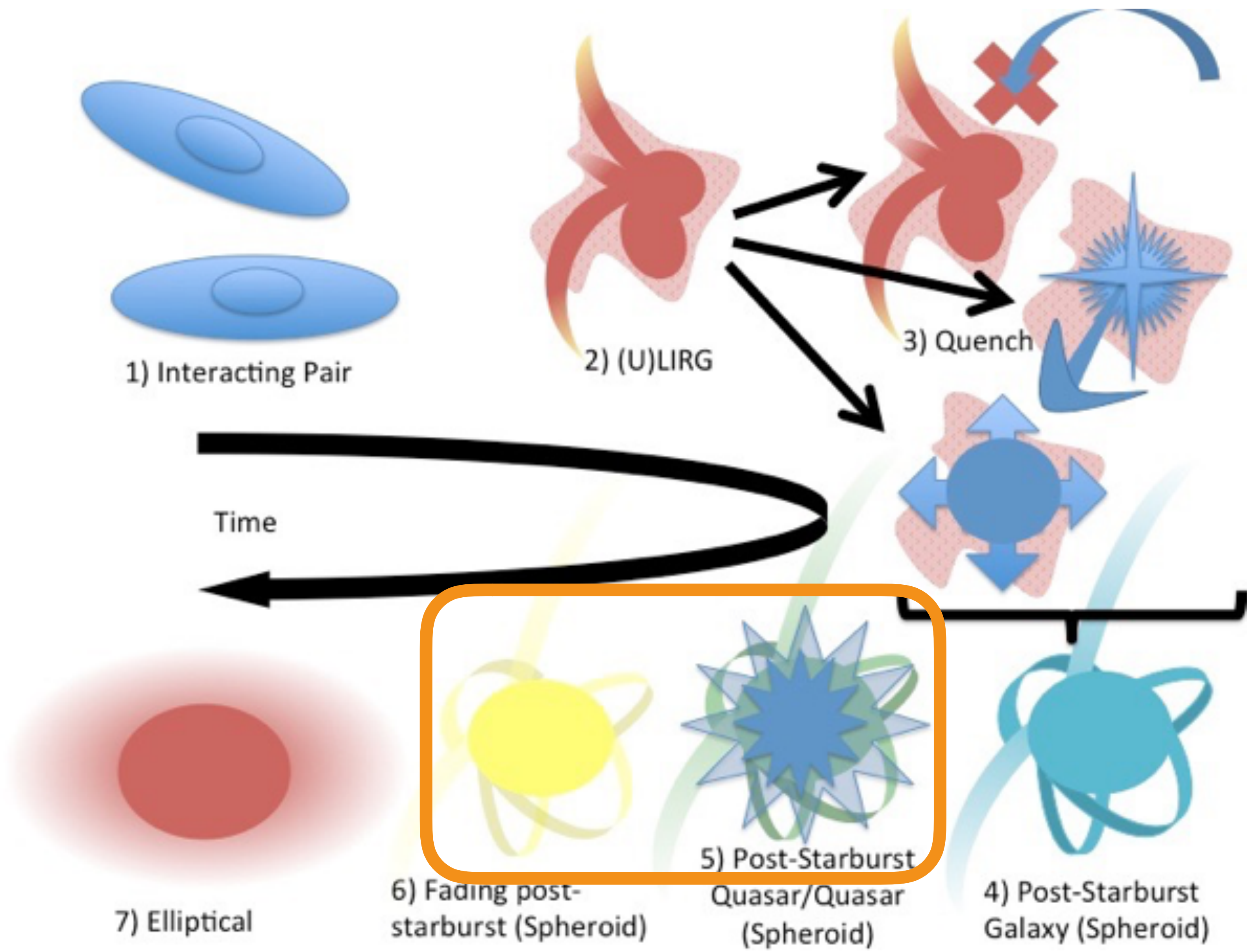

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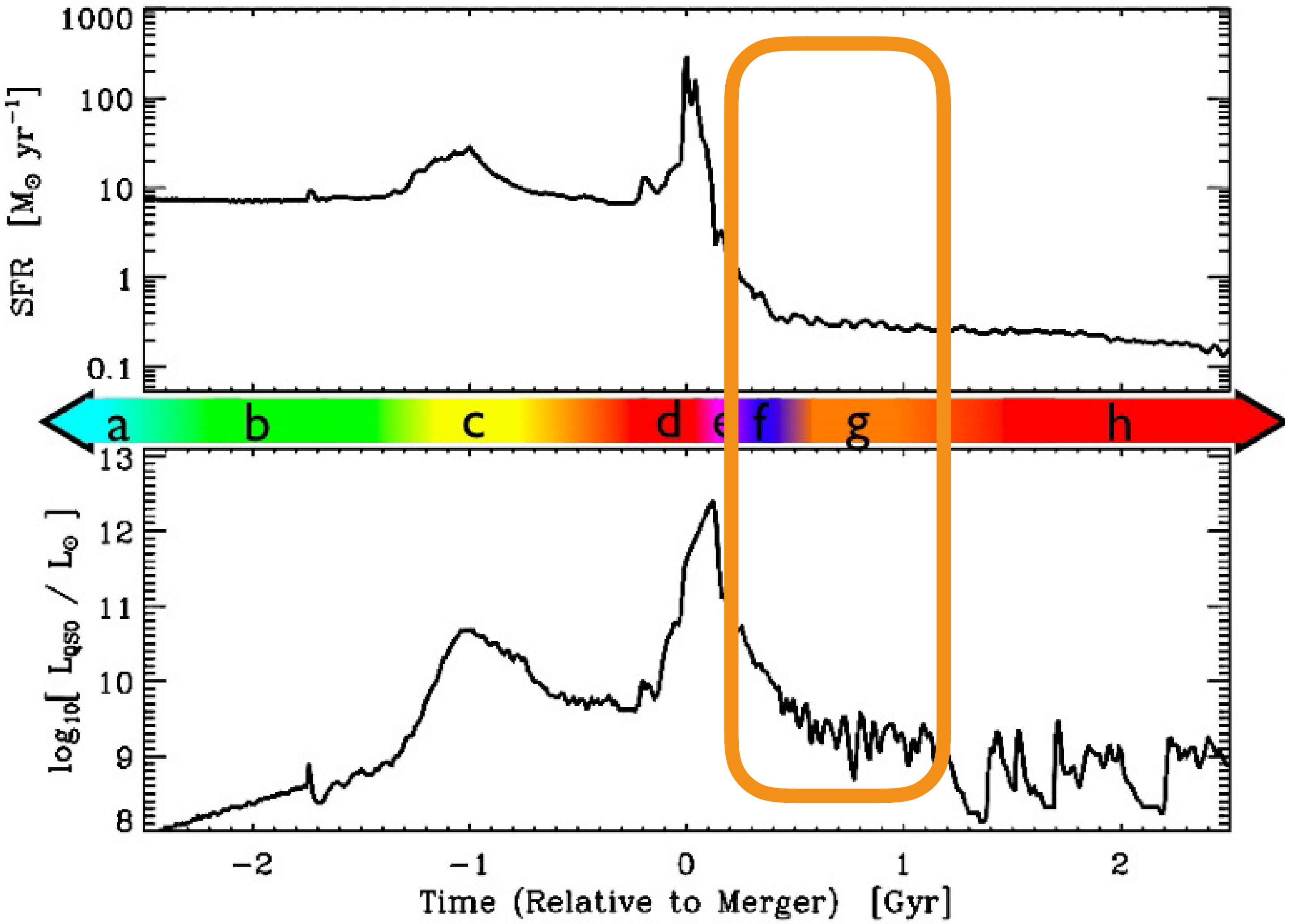

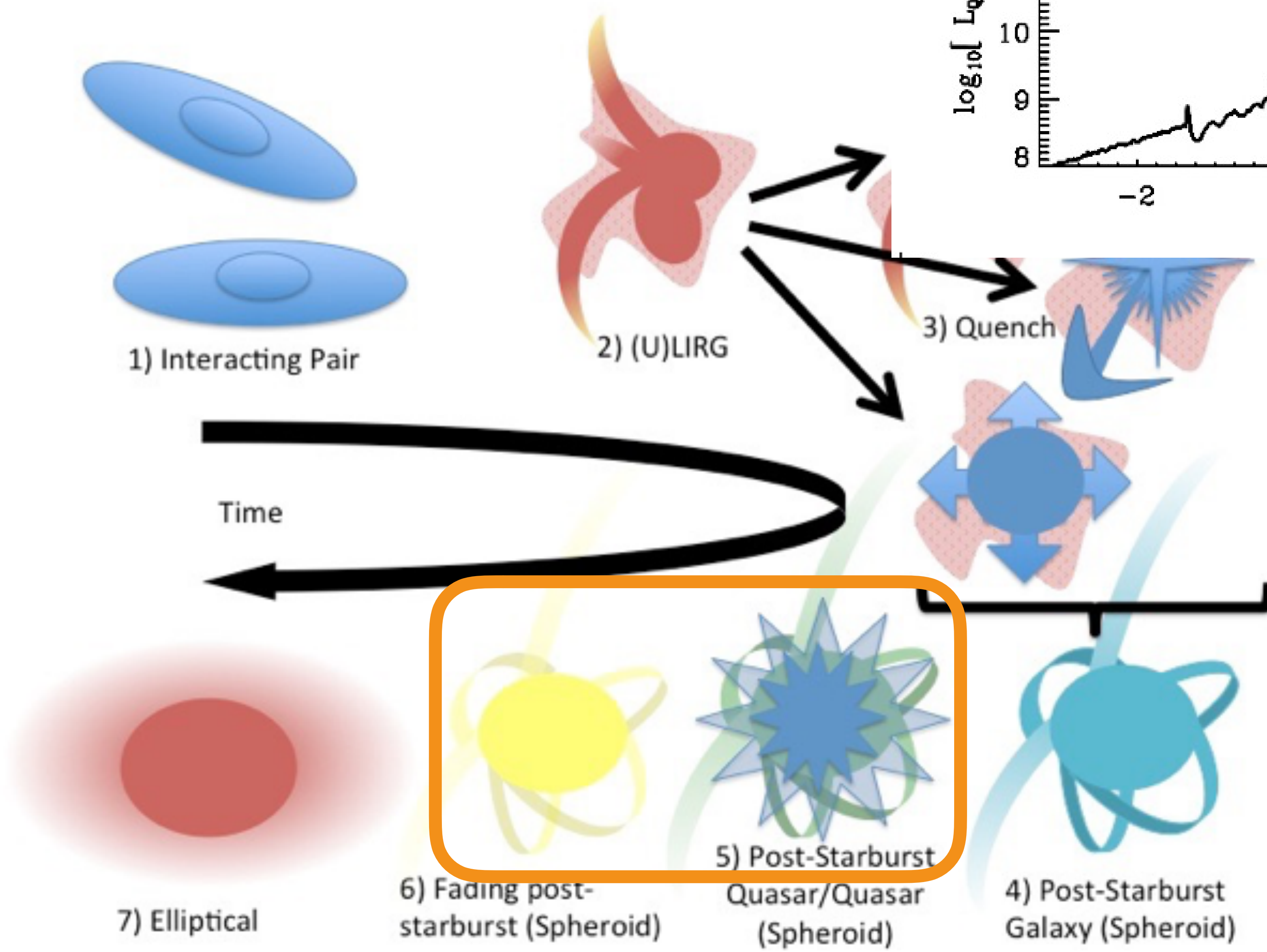

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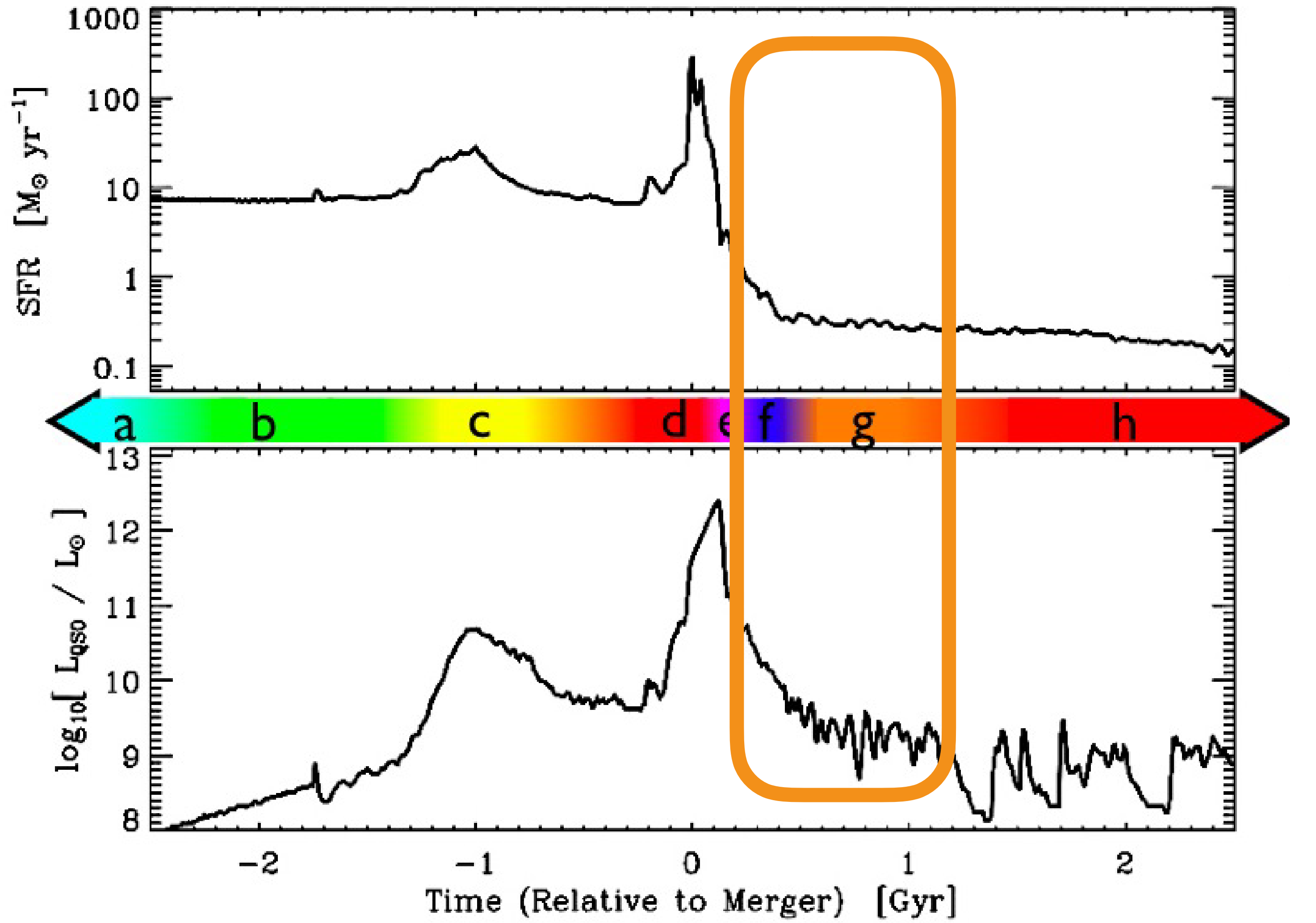

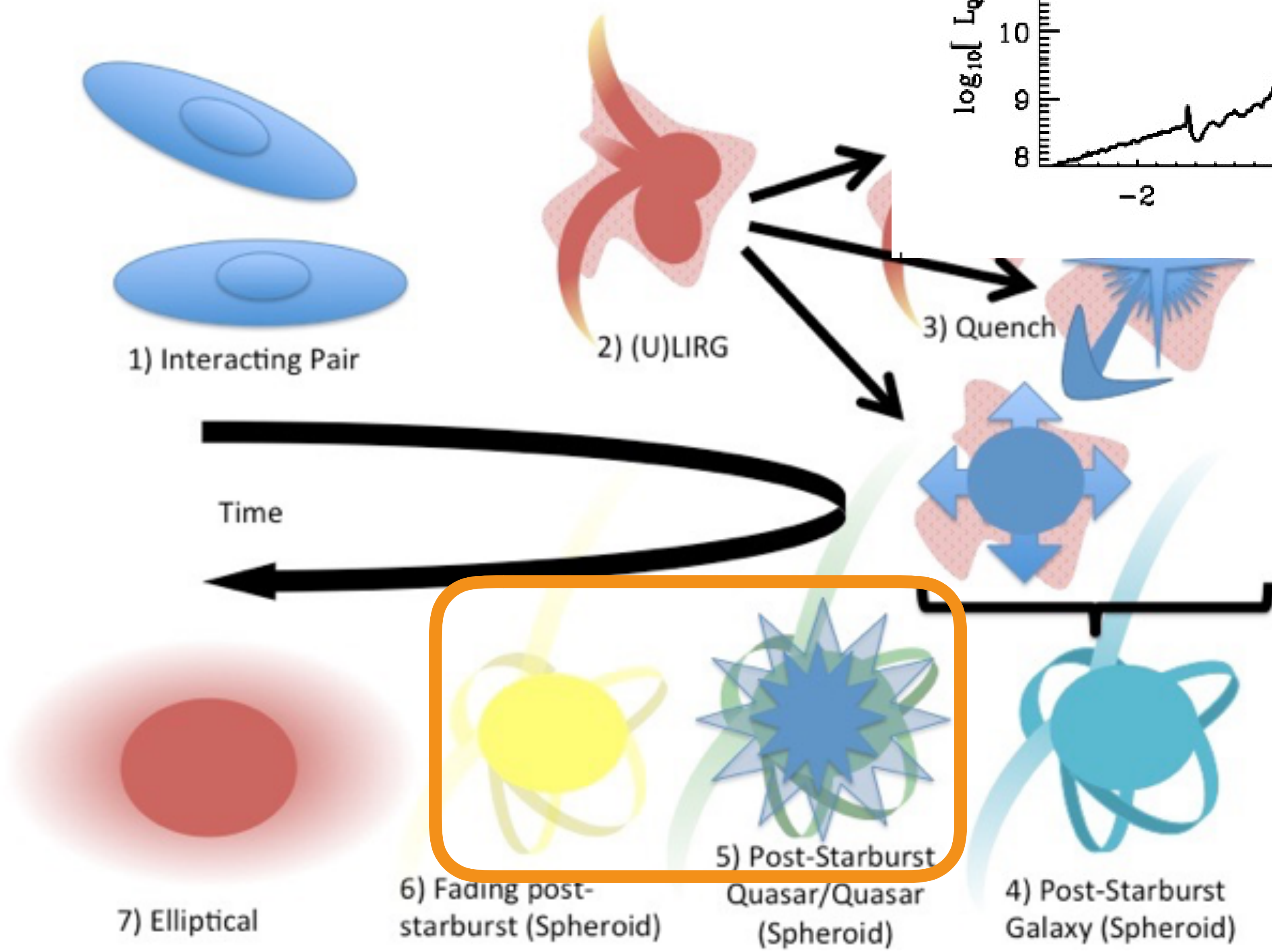

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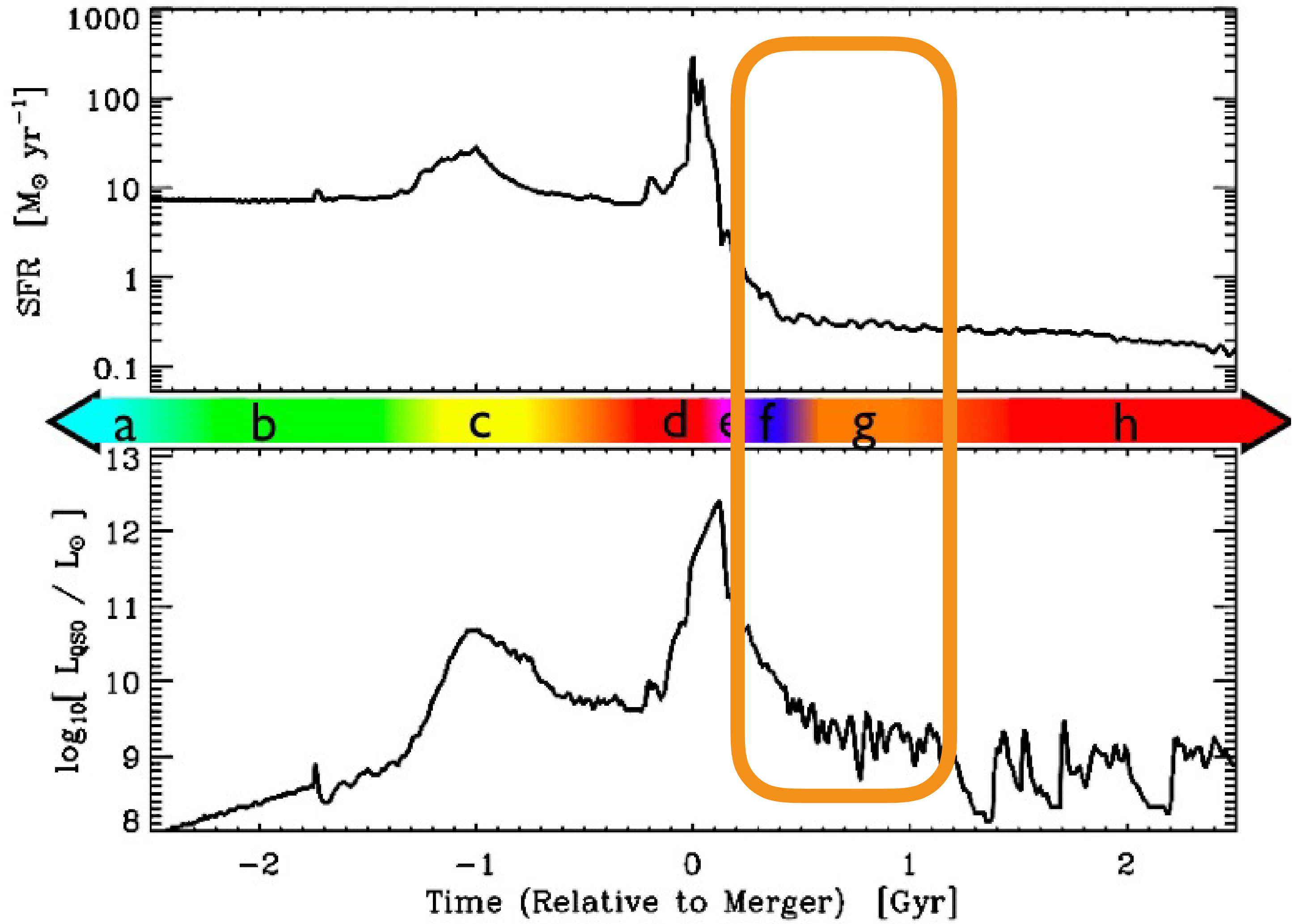

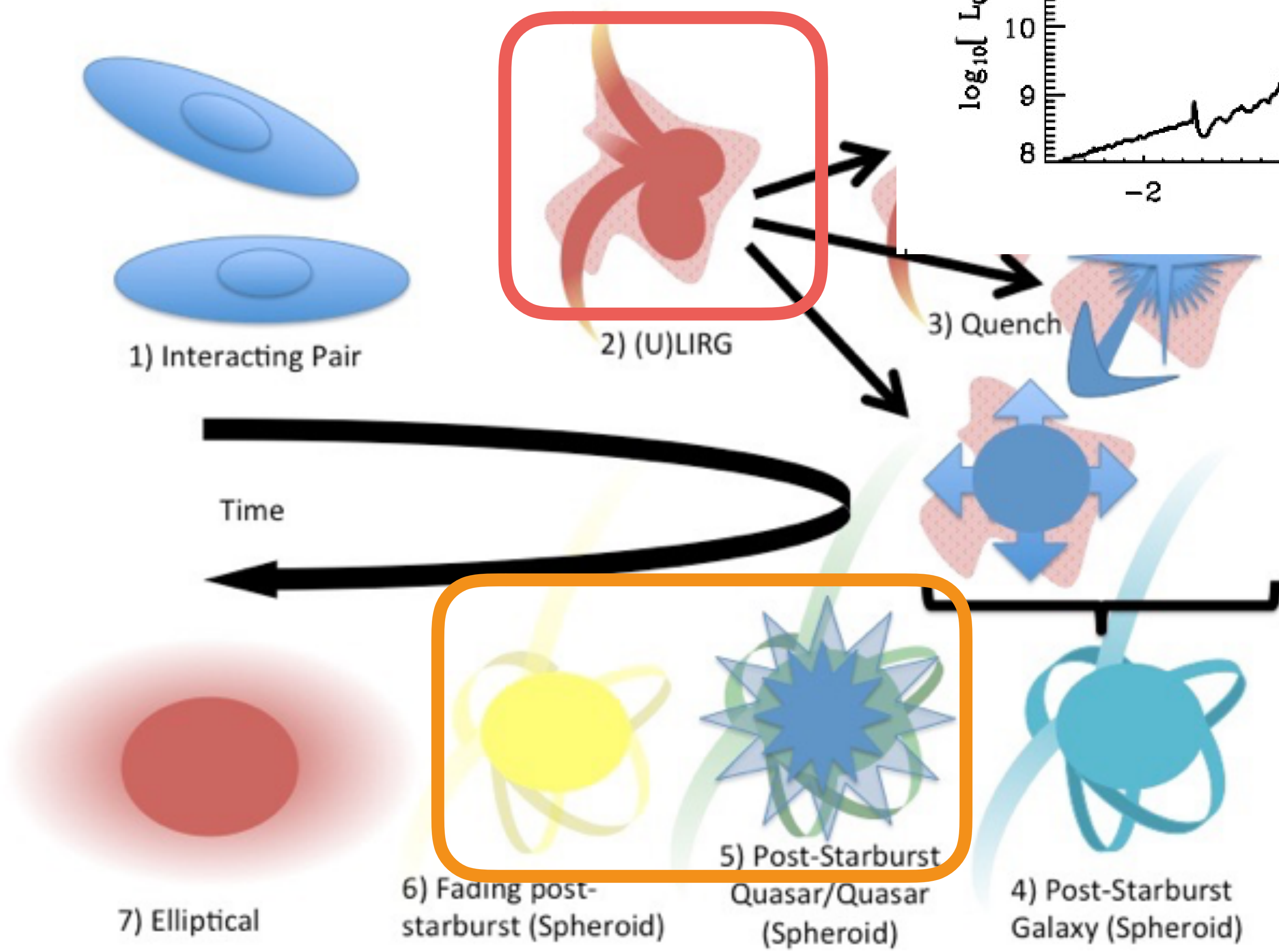

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- The co-existence of the **high SFR (~ 900 $M_\odot$/yr)** with the **strong outflow** can indicate that the galaxy is possibly in the intermediate stage of evolutionary that the **feedback just become effective and begin to sweep out the gas reservoirs.**

Summary and Future Work

- Further observations are required to reveal the characteristics of the galaxy, e.g.,
  - **IFU** observation to find more details of the **outflow structure**,
  - **Hard X-ray** observation to penetrate the dust and **directly detect the AGN radiation**,
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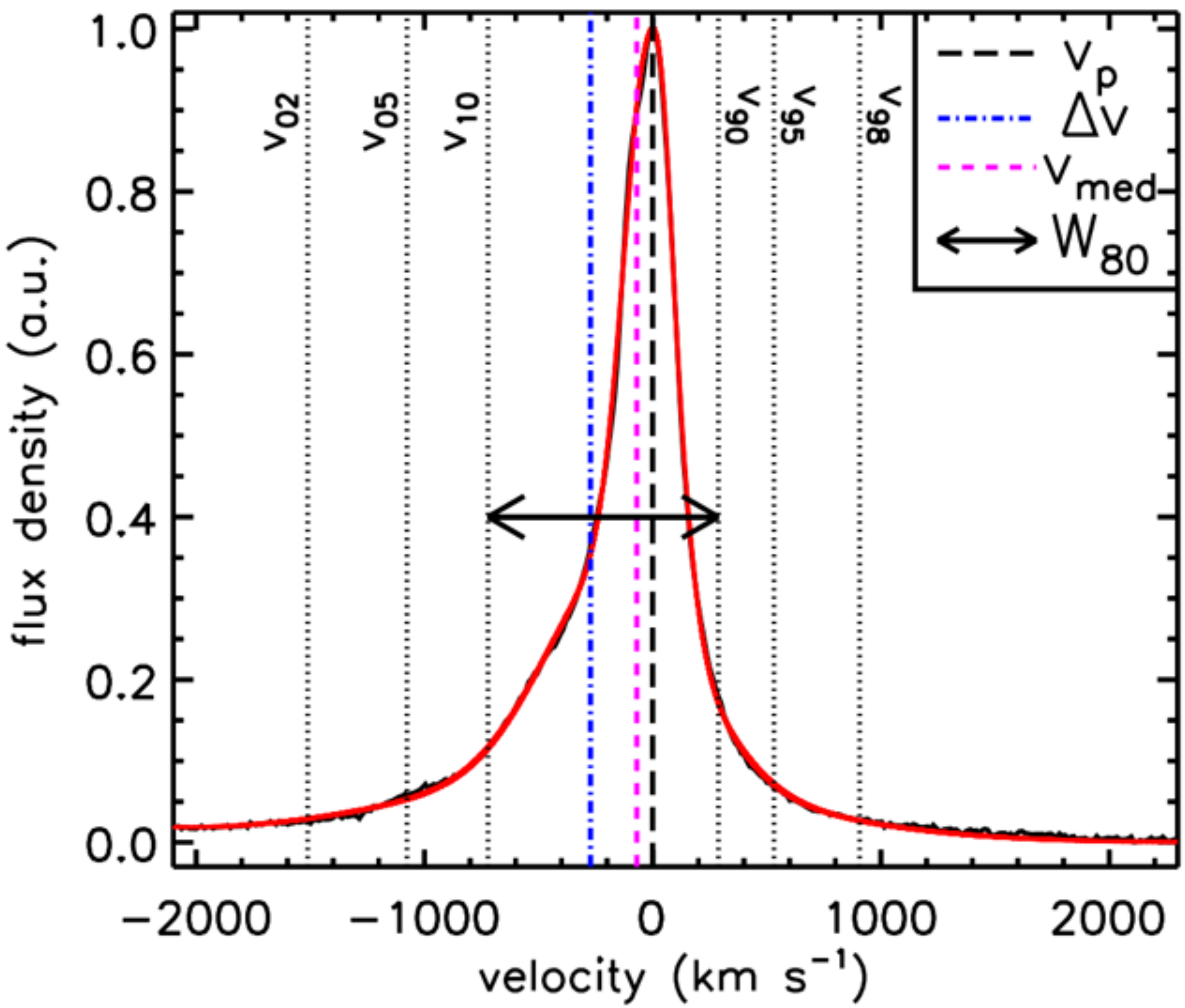
Thanks for your attention!

Appendix.

No parameter velocity

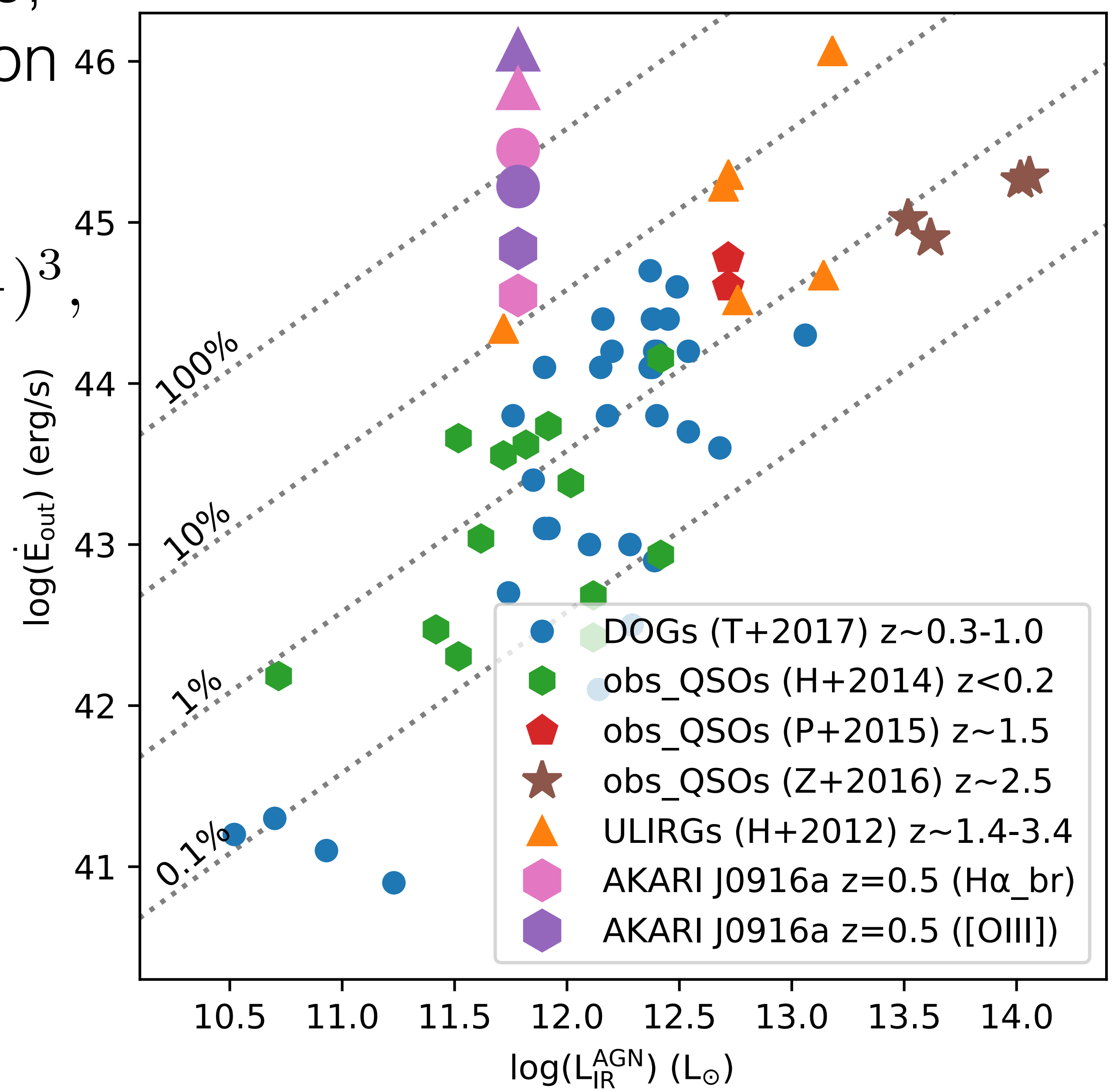


Energy conserving bubble

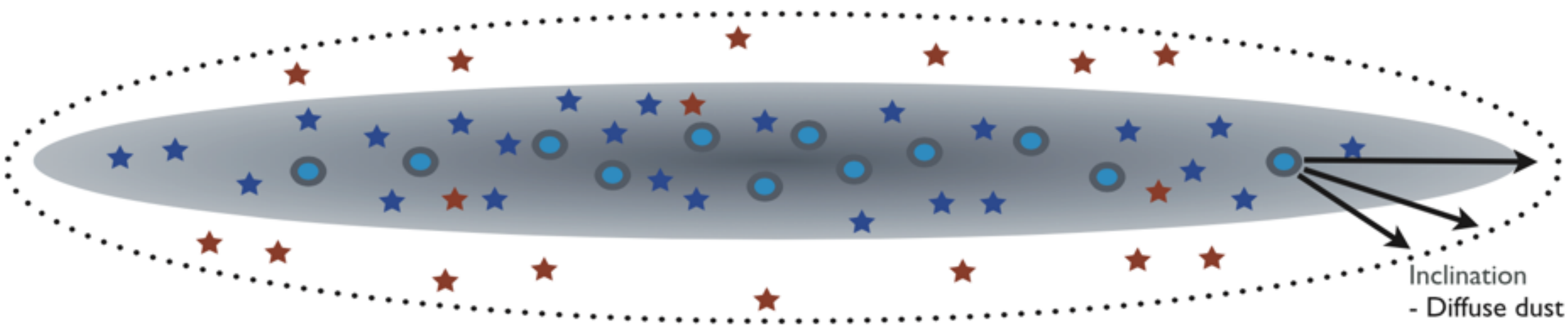
The method assuming an energy conserving bubble in a uniform medium is also widely used to estimate the upper limit of energy ejection rates (Heckman+1990, Nesvadba+2006, Harrison+2012, Harrison +2014), which results in the formula:

$$\dot{E}_{\rm out} = 3.0 \times 10^{46} n_0 (\frac{R_{\rm out}}{10\ {\rm kpc}})^2 (\frac{v_{\rm out}}{1000\ {\rm kms}^{-1}})^3,$$

where n_0=0.5 is the ambient density.



Dust Extinction, Hβ

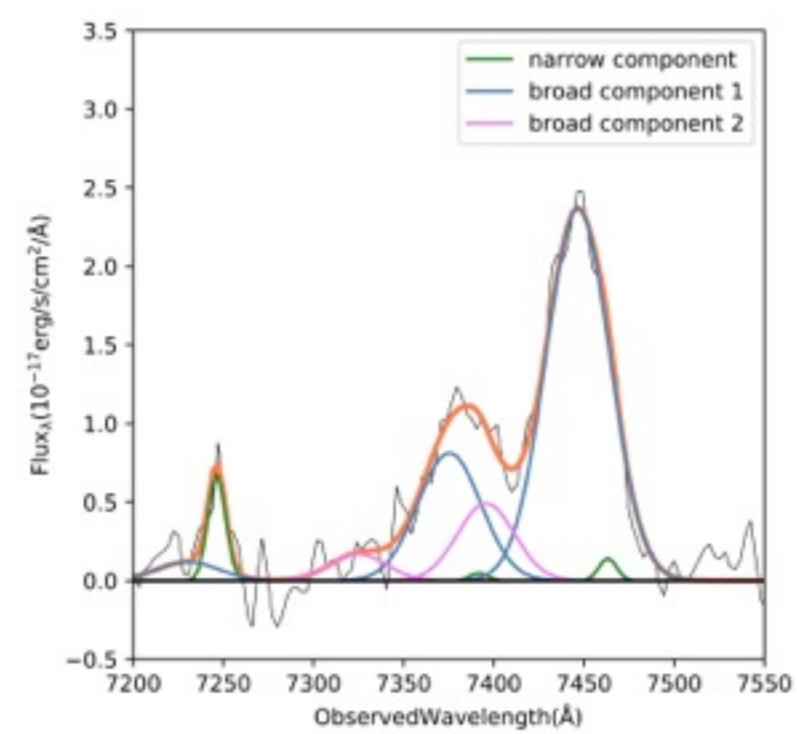


Star-forming regions + Birth clouds
- OB stars produce nebular emission lines
- dust opacity dominated by birth clouds
- predominantly (spherical) screen-like extinction
- $\tau \sim \tau_{\text{Birth Cloud}}$

Intermediate-age stars
- mixed star-dust geometry
- attenuation primarily from diffuse ISM dust
- $\tau \sim \tau_{\text{ISM}}$

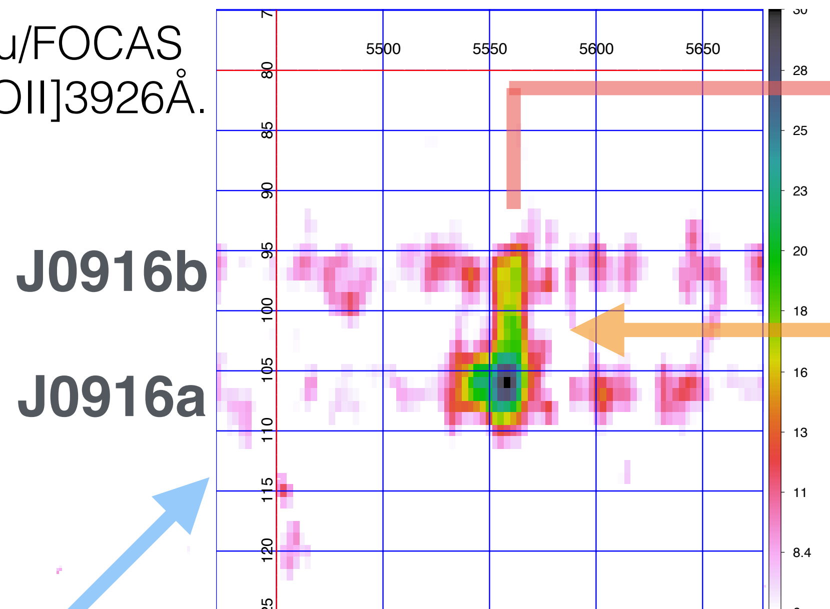
Old stars (also in bulge, not pictured)
- predominantly responsible for NIR light
- higher fraction in bulge and/or thick disk
- screen-like extinction (far-side)
- no attenuation (near-side)
- observe extinction law in NIR ($\tau \sim \tau_{\text{ext}}$)

Diffuse ISM dust (with radial gradient)



- Interacting components around broad [OII]3926Å region.

Fig.1 Subaru/FOCAS spectral on [OII]3926Å.



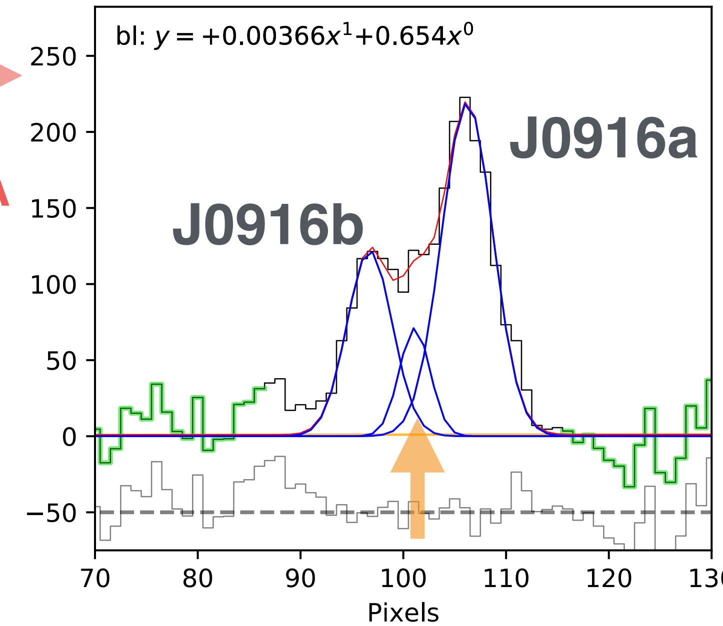
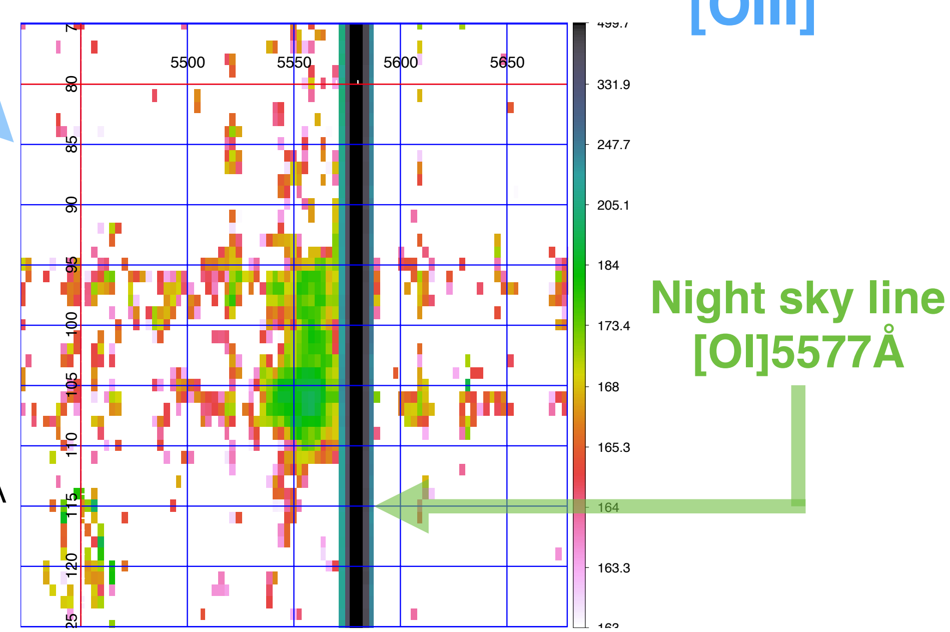


Fig.3 Flux distribution along slit direction on [OII]3926Å. An inter-component is required when fitting the outline (orange arrow). The ratio of integrated flux is 2.5:1.0:5.1 (J0916b:inter:J0916a).

Fig.2 Subaru/FOCAS spectral on [OII]3926Å without subtracting night sky background.



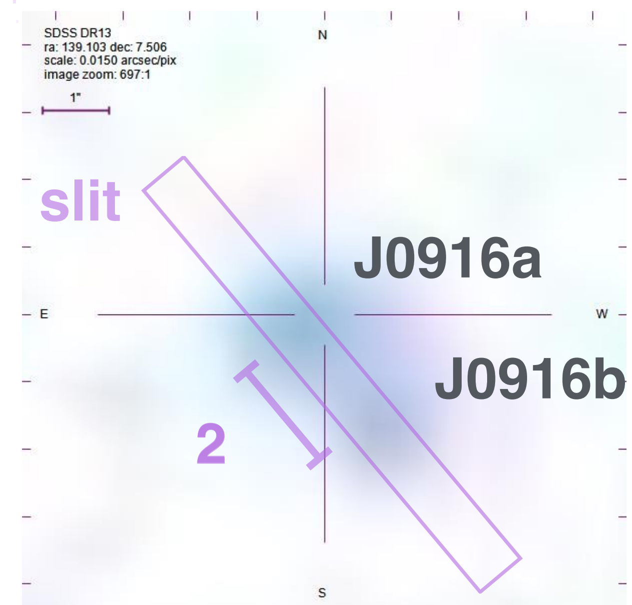


Fig.4 SDSS image (inverted). The distance between the cores of two galaxies is 2″ (~ 12 kpc).

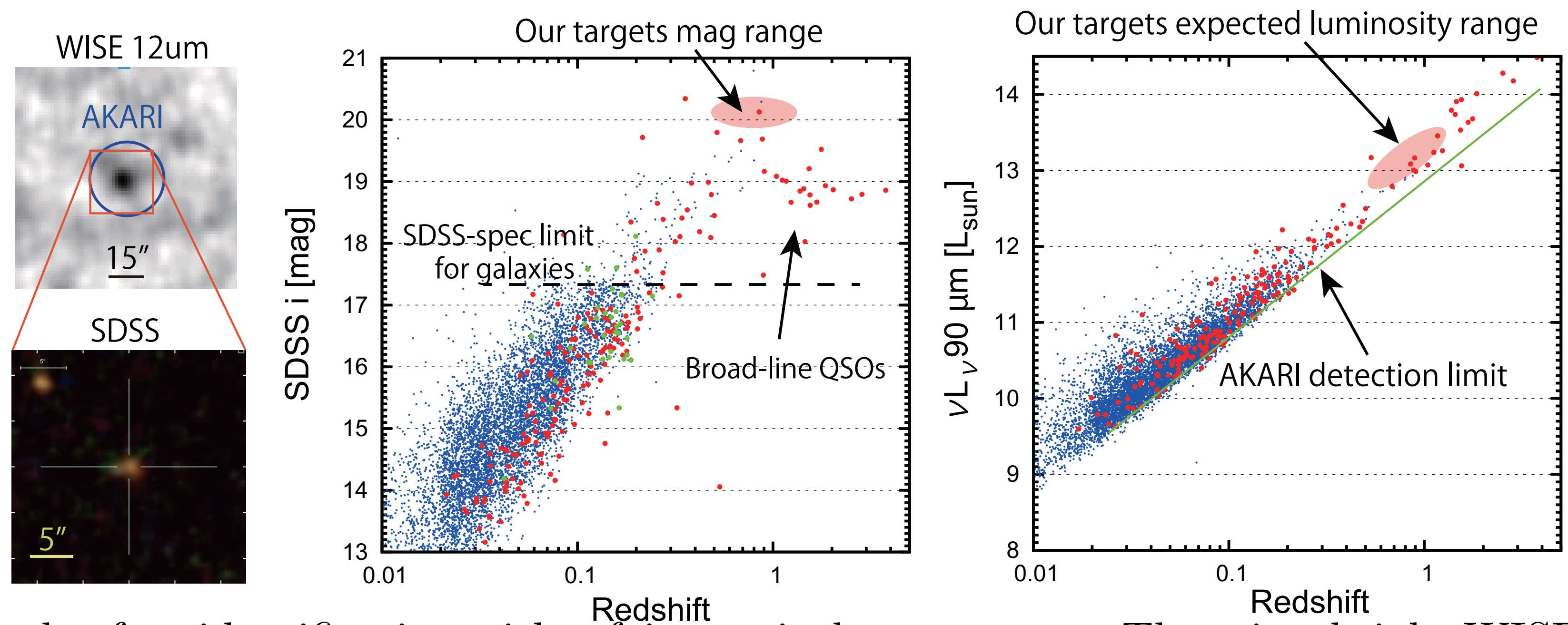


Figure 1: Left) Example of an identification with a faint optical counterpart. There is a bright WISE 12μm source within the AKARI error circle (blue). A galaxy with $i = 20.3$ mag is associated with the WISE position. Left) Redshift vs. i-band magnitude of the AKARI FIR sources spectroscopically-identified in the SDSS survey (blue and red). Red dots indicate broad-line QSOs. Green dots represents LIRGs/ULIRGs in the IRAS 1Jy sample (Kim et al. 1998). Systematic follow-ups of IRAS sources only roughly go down to SDSS spectroscopy limit. Right) Redshift vs. FIR luminosity. Same symbols as in the left panel.