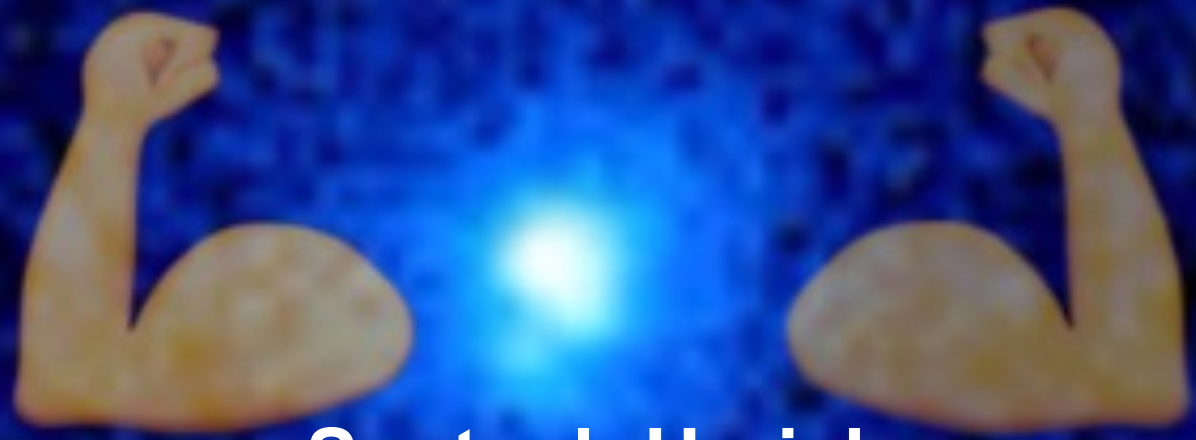
Evidence for black holes in Green Peas based on variability and colors



tiny mighty galaxies

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ASU School of Earth and Space Exploration
Arizona State University

OAC, Crete
Escape of Lyman radiation from galactic labyrinths
2023

RIT Rochester Institute of Technology

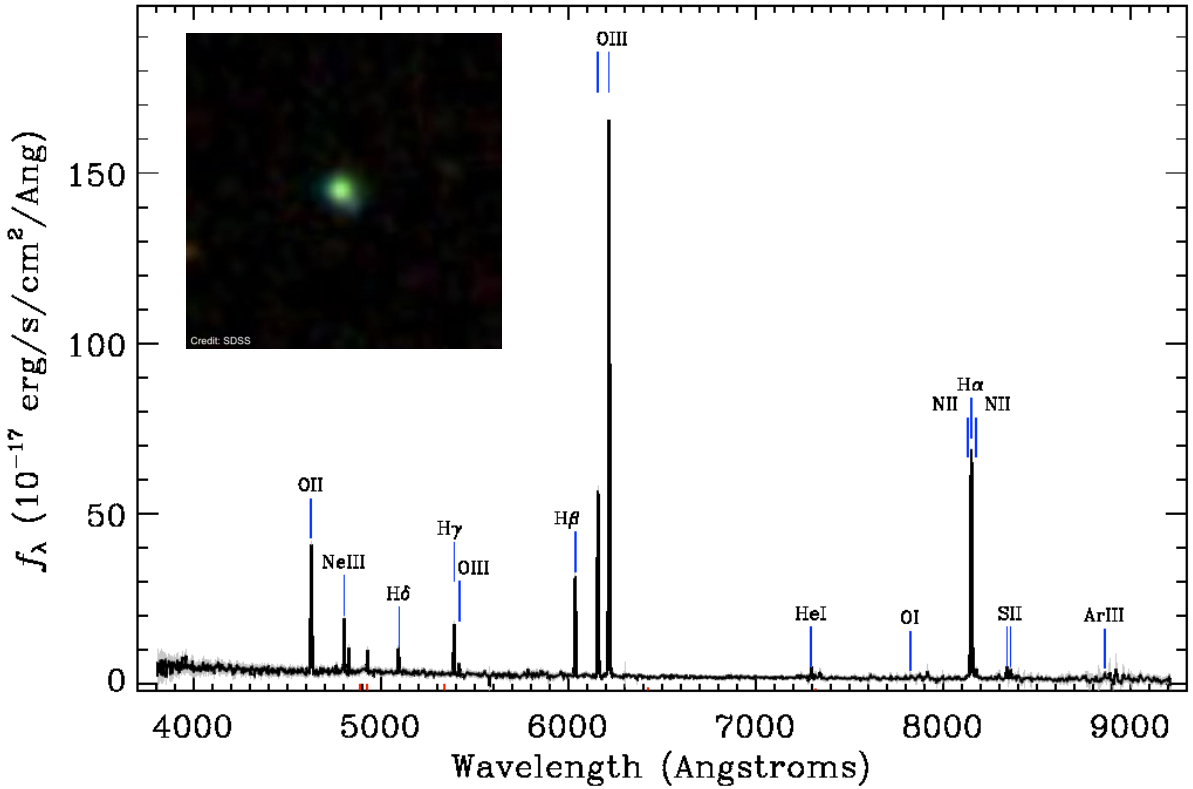
Local Analogs of High-redshift Galaxies

- Unlike galaxies in the present-day universe, it is challenging to obtain good signal-to-noise or spatially resolved data for high redshift Lyα emitters (LAE), because of their small angular sizes (e.g., Malhotra+12) and low fluxes

- Alternative way → study analogs in the local universe where detailed, multi-wavelength studies can be performed.

- **Green Peas** (GP) are a class of compact, low-mass, highly star-forming, low-metallicity, low-redshift galaxies ($z < 0.3$) with extreme [OIII] and/or Hβ emission lines

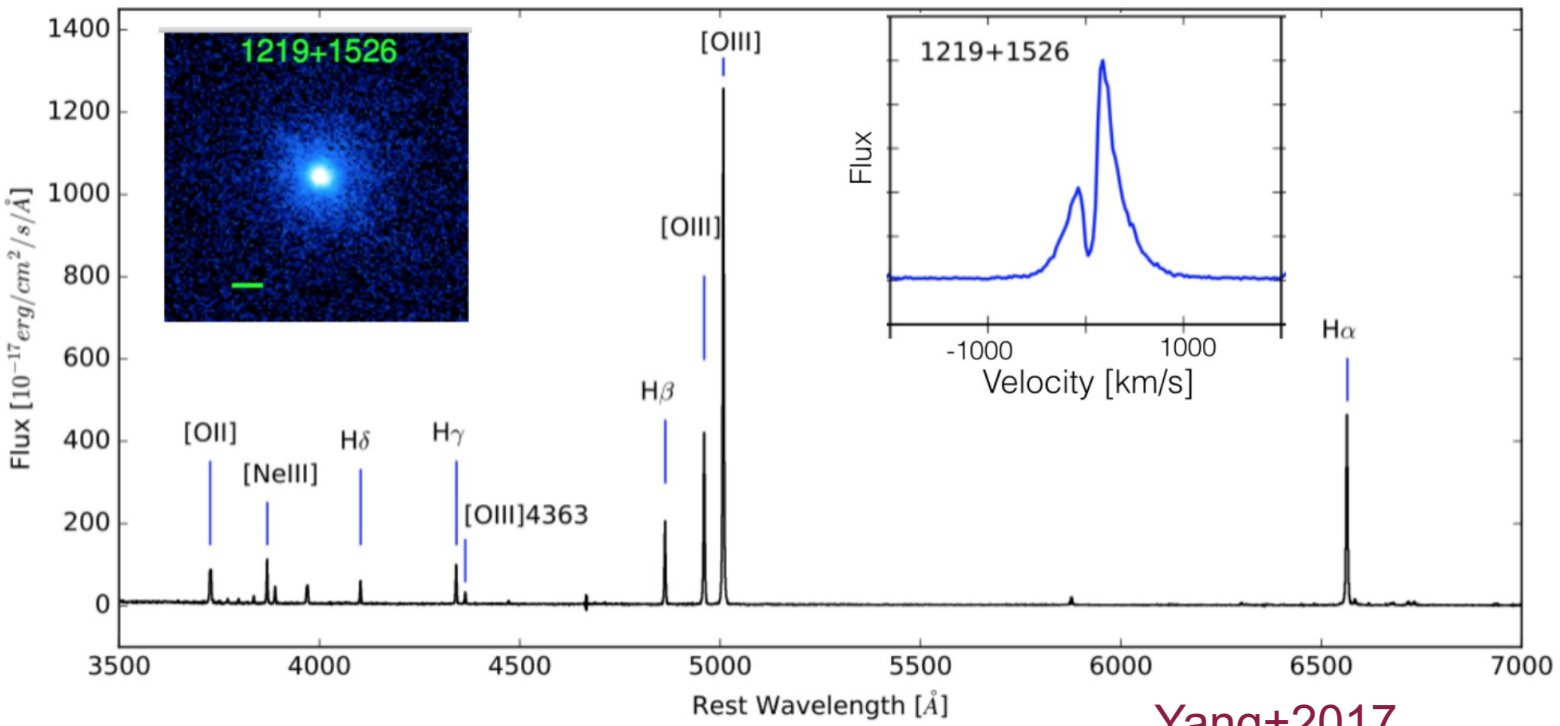
  (e.g., Izotov+2011; Jaskot & Oey, 2013; Yang+2016, 2017a; Jiang+2019; Kim et al. 2020)



- They are the best analogs of high-redshift Lyα as well as strongest known Lyman continuum leakers

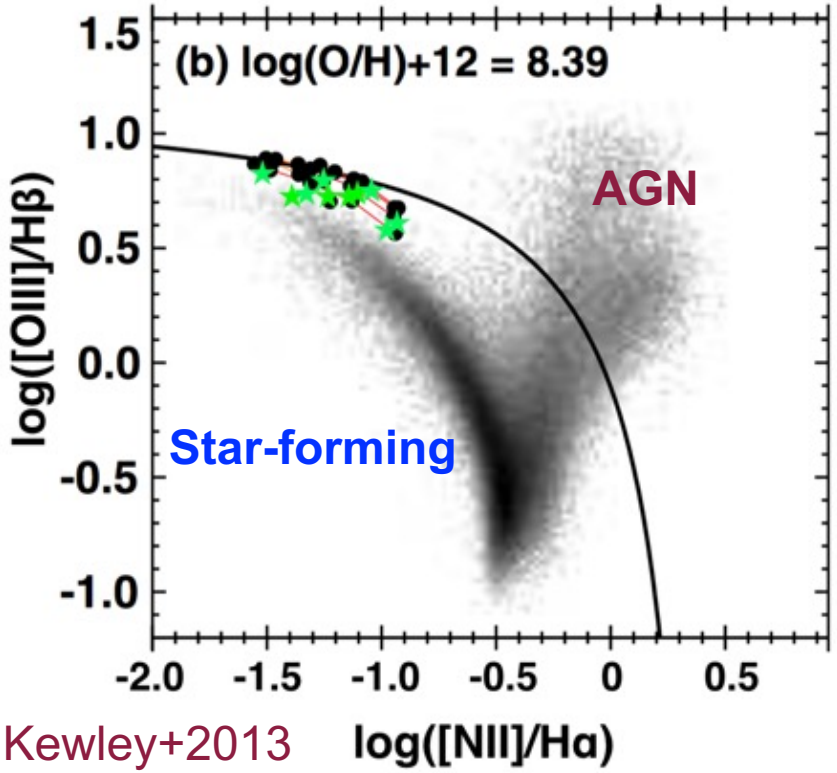
  (e.g., Henry+2015, Yang+2016; Izotov+2017, 2018; Yang+2017b)

One of the many reasons why Green Peas are interesting…



Yang+2017

- Optical spectra of GP contain other high ionization emission lines such as HeII and [NeIII], that indicate the presence of a hard-ionizing source.



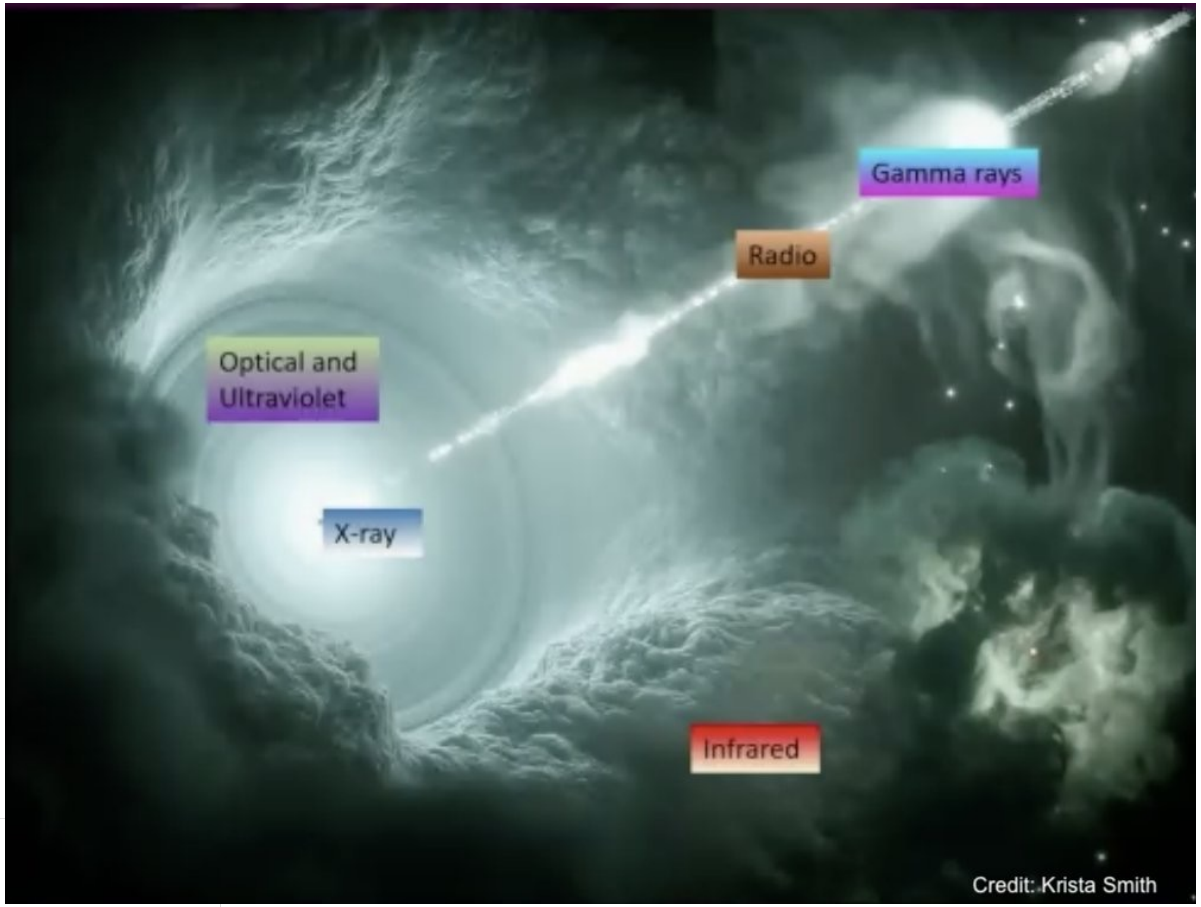
Kewley+2013

- On the standard BPT diagram, GP are indistinguishable from low-metallicity AGN

What is the extent to which these emission lines are purely due to star-formation?

Could this emission also arise due to accretion in an active galactic nuclei (AGN)?

Mid-infrared (MIR) view of Green Peas

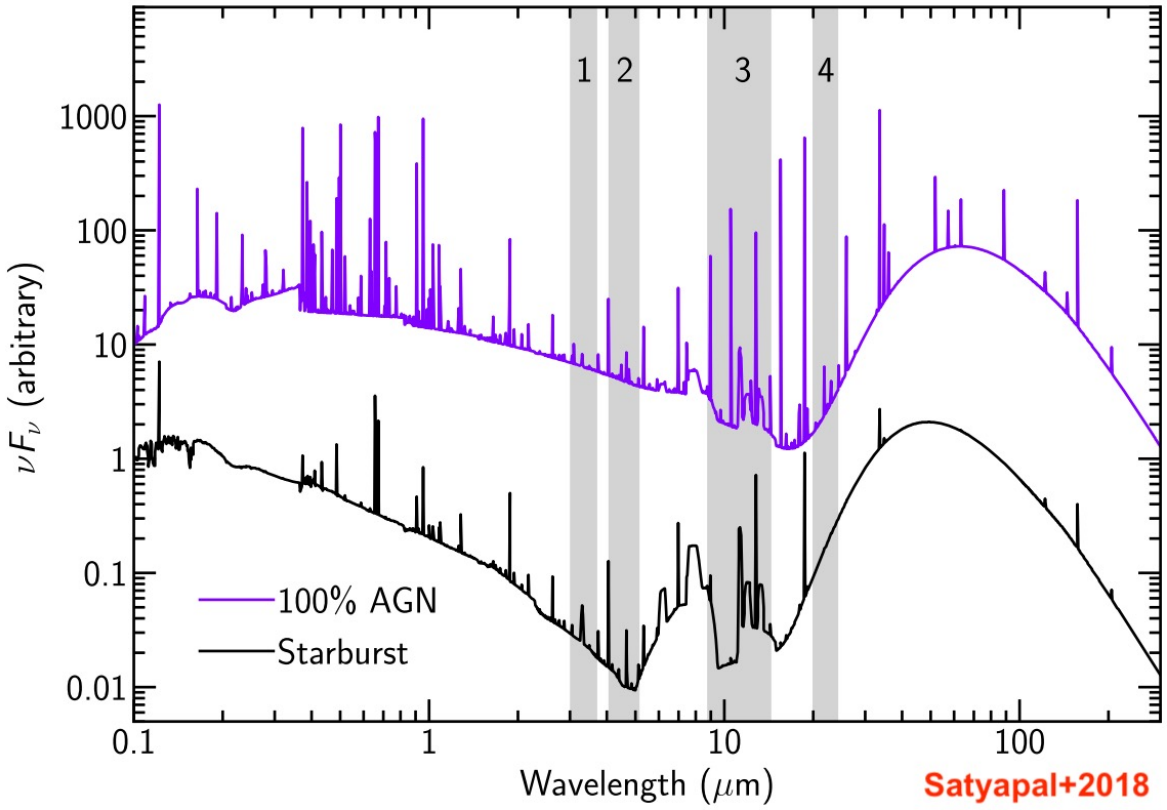


- Thermal emission in the mid-infrared is expected from reprocessed radiation of gas and dust heated by the central black hole.
- MIR diagnostics can select obscured, low-mass AGN that are missed by typical selection methods in the optical and X-ray wavelength range.
- The Wide Infrared Space Explorer (WISE) / Near-Earth Objects WISE (NEOWISE) mission is a mid-infrared space telescope imaging the entire sky using four different broadbands centered at 3.6 (W1), 4.6 (W2), 12 (W3) and 22 (W4) um.

Mid-infrared (MIR) view of Green Peas

Color-color AGN selection

- MIR color-based selection relies on the fact that hard radiation from an AGN heats the surrounding dusty torus which produces a power-law continuum in the mid-IR, distinguishable from stars and star-forming galaxies.



Mid-infrared (MIR) view of Green Peas

Color-color AGN selection

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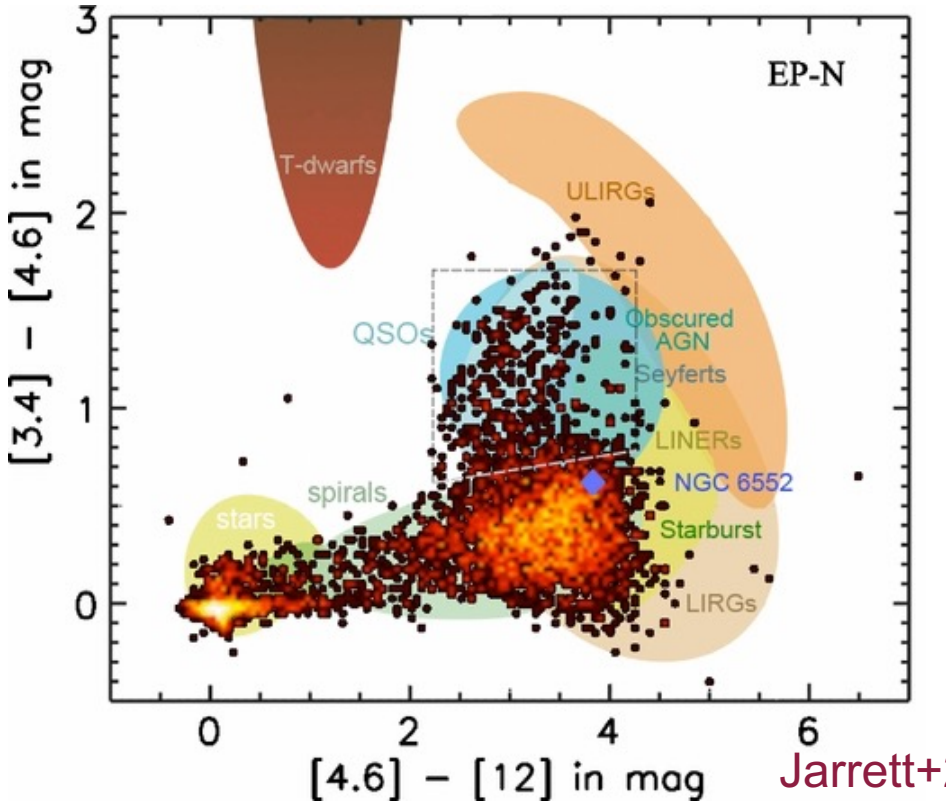
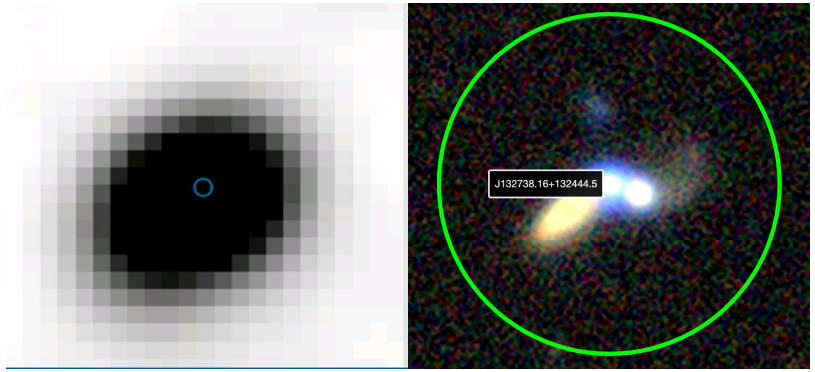
- Using photometry from the AllWISE Source Catalog, we select AGN candidates from our GP sample using the **3-band mid-IR color selection** criteria proposed by Jarrett+2011.
- Given the large PSF of WISE, the photometry of several GP sources is contaminated by close neighbors, so we exclude those sources from our selection.



Jarrett+2011



WISE W1 Optical

Mid-infrared (MIR) view of Green Peas

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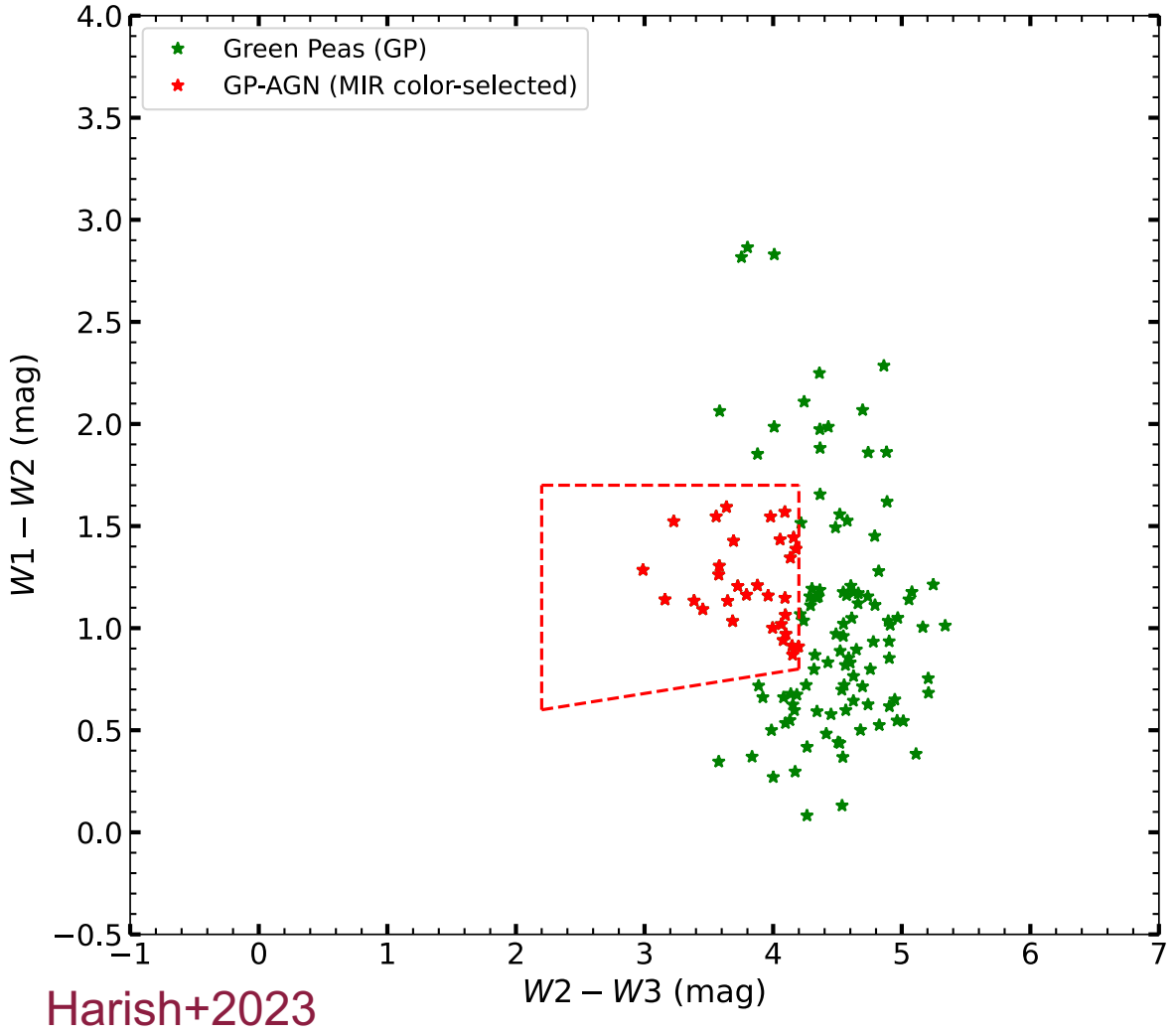


Harish+2023

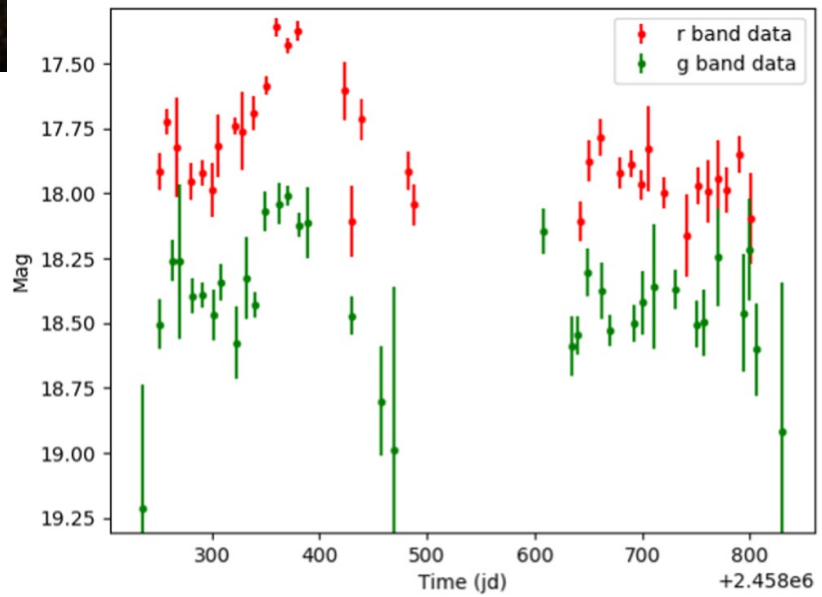
31 AGN candidates out of 134 GP

Mid-infrared (MIR) view of Green Peas

(Photo credit: NASA GSFC)

Variability selection

- Flux variability is thought to be related to instabilities in the accretion disk of an AGN.
- Several recent studies are finding AGN candidates using optical variability in low-mass/dwarf galaxies (e.g., Baldassare+2018, 2020, Ward+2022)



Ward+2022

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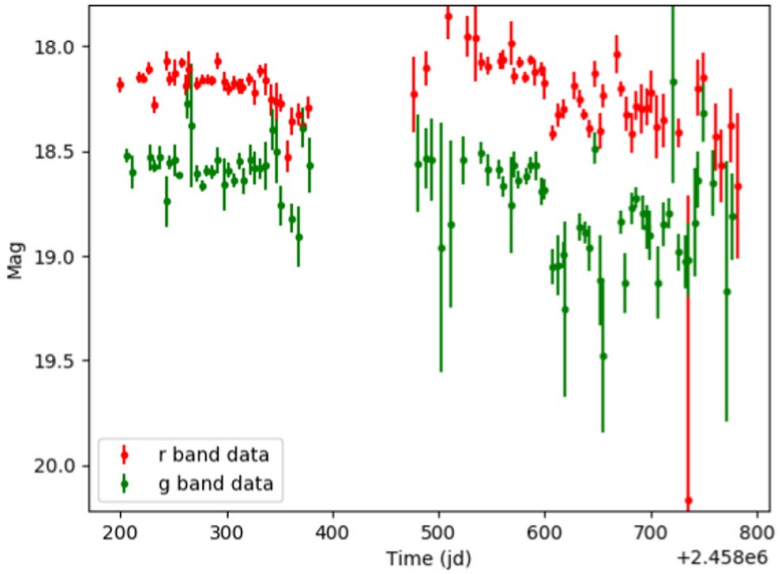


NSA212423

Mid-infrared (MIR) view of Green Peas

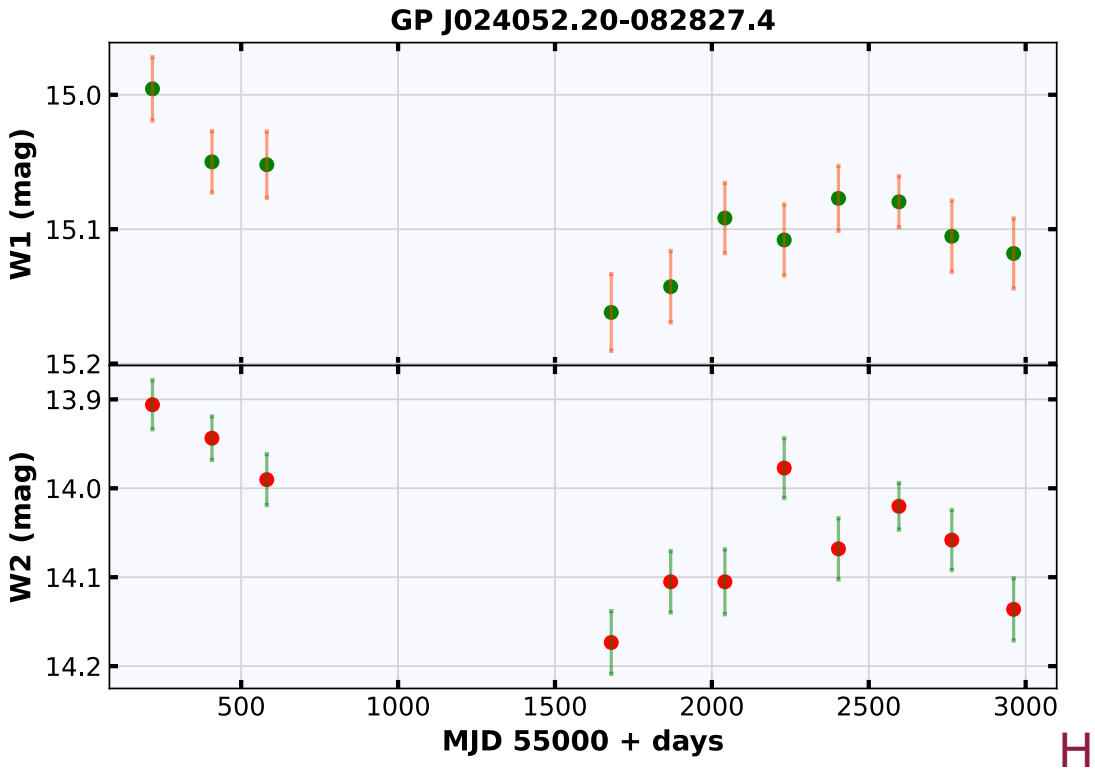
(Photo credit: NASA GSFC)

Variability selection

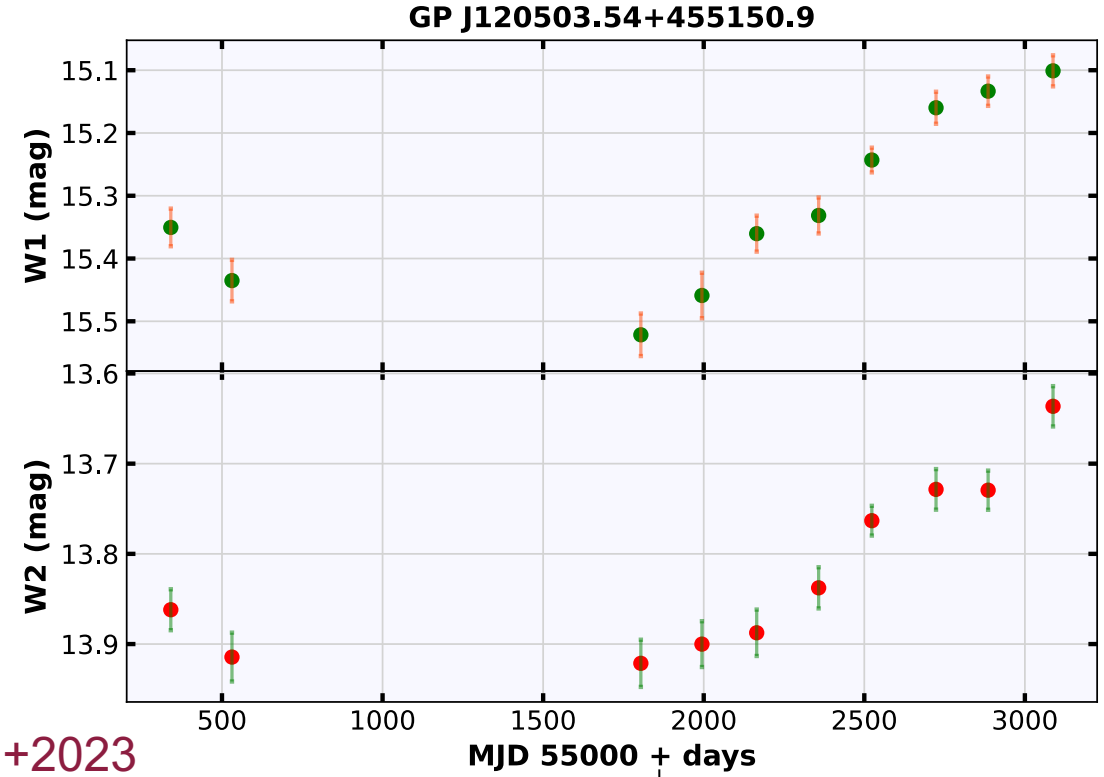
- A typical sky location is imaged every six months by WISE with ≳12 exposures per visit. These individual exposures are stacked to produce one coadd per visit per band by the unWISE project.
- Using time-domain photometry in W1 and W2 bands based on unWISE coadd images, we construct light-curves for all GP with multi-epoch measurements.
- Considering the completeness and reliability estimates of the unWISE catalog, we restrict our analysis to a subset of GP sources with W1 ≤ 16 mag and W2 ≤ 15.7 mag. Our final sample consists of 112 GP objects.

Mid-infrared (MIR) view of Green Peas

$\sigma_{W1} = 0.03$ mag; $\sigma_{W1} = 0.07$ mag; $r_{12} = 0.85$



$\sigma_{W1} = 0.09$ mag; $\sigma_{W1} = 0.14$ mag; $r_{12} = 0.96$



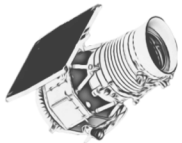
Harish+2023

Two variable AGN candidates were selected based on amplitude of variability (σ_m) and Pearson correlation coefficient (r_{12}) metrics.

$$\sigma_m = \begin{cases} \sqrt{\Sigma^2 - \epsilon^2}, & \text{if } \Sigma > \epsilon \\ 0, & \text{otherwise} \end{cases} \qquad \epsilon^2 = \frac{1}{N}\sum_i^N \epsilon_i^2 + \epsilon_s^2$$

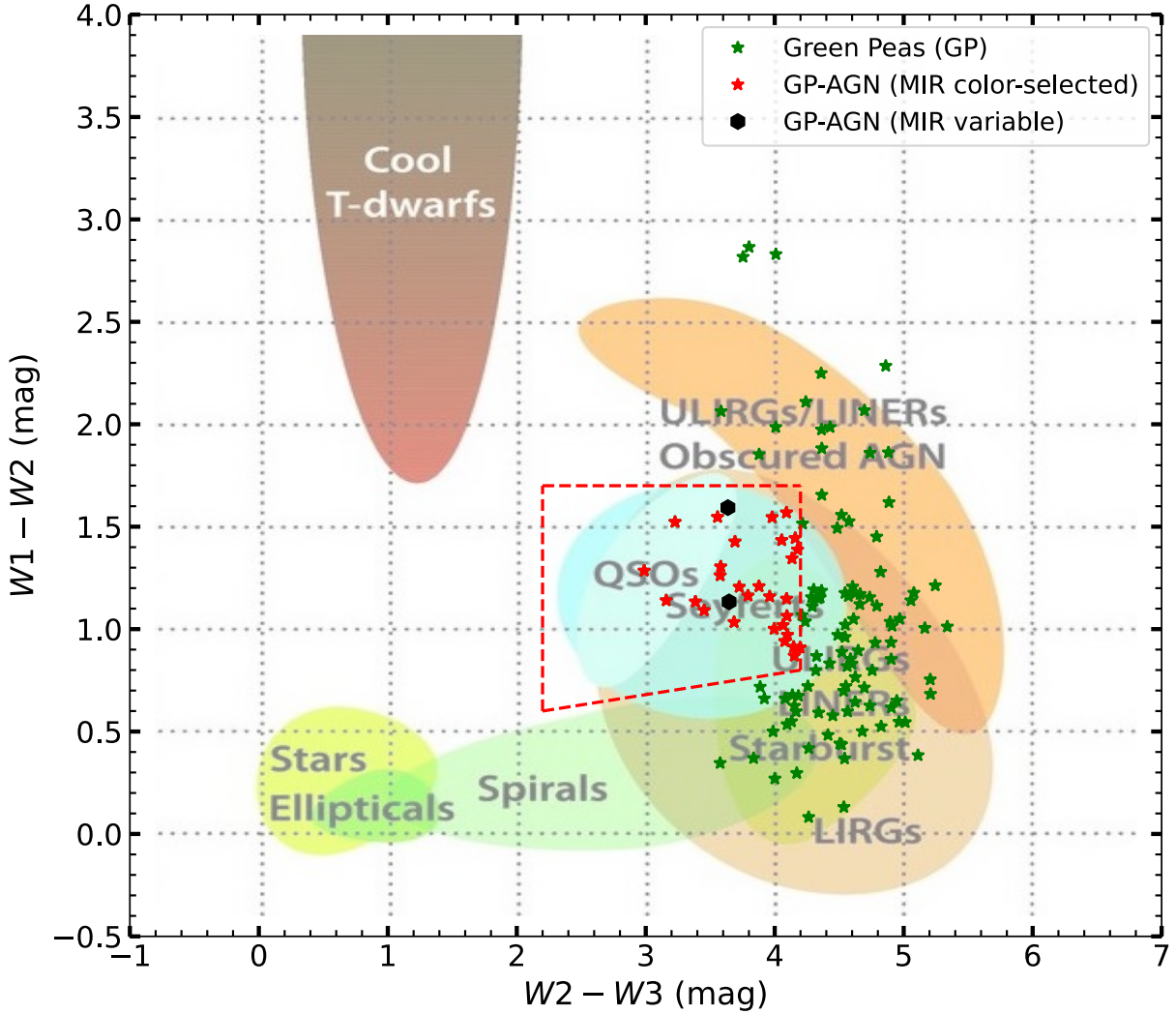
$$r_{12} = \frac{C_{12}}{\Sigma_{W1}\Sigma_{W2}}$$

C_{12} is the covariance between W1 and W2
Σ_{W1} and Σ_{W2} are std. deviations in W1 and W2



Mid-infrared (MIR) view of Green Peas

- Variable GP candidates are also selected as AGN by the MIR color-color criterion.
- Based on our study, we expect the AGN fraction among GP to be between ~2 – 23%

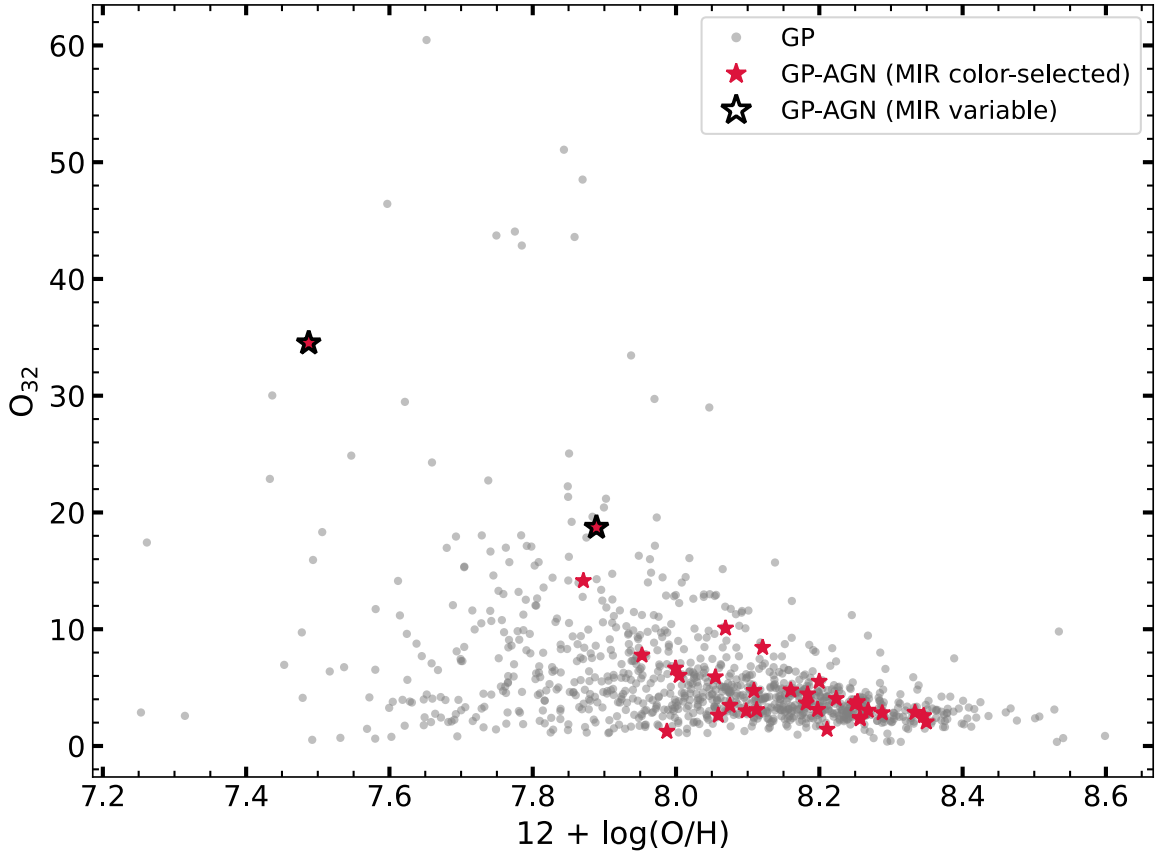


Harish+2023

Mid-infrared (MIR) view of Green Peas

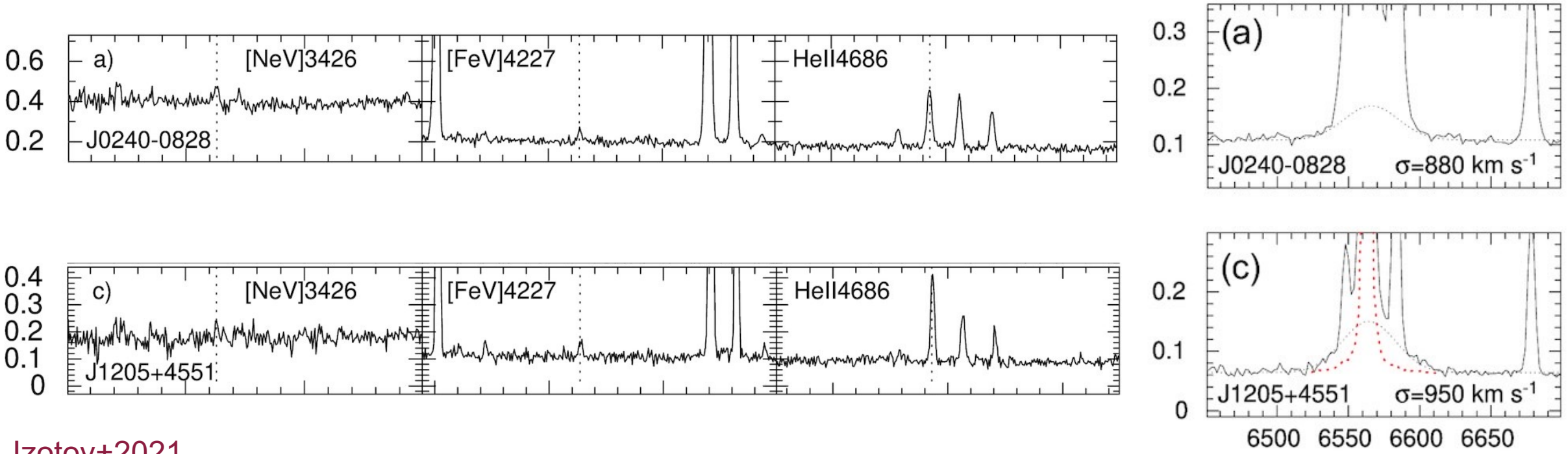
- Variable GP candidates are also selected as AGN by the MIR color-color criterion.
- Based on our study, we expect the AGN fraction among GPs to be between ~2 – 23%
- Variable GP candidates have the
  - highest [OIII]/[OII] or O32 ratio (>18)
  - the lowest gas-phase metallicities (12+log O/H < 7.9)

  among all AGN-selected GP candidates. Sources with high values of O32 are typically found to be strong Lyman continuum leakers.



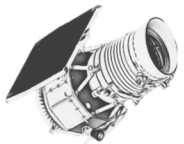
Harish+2023

More evidence of hard ionizing radiation

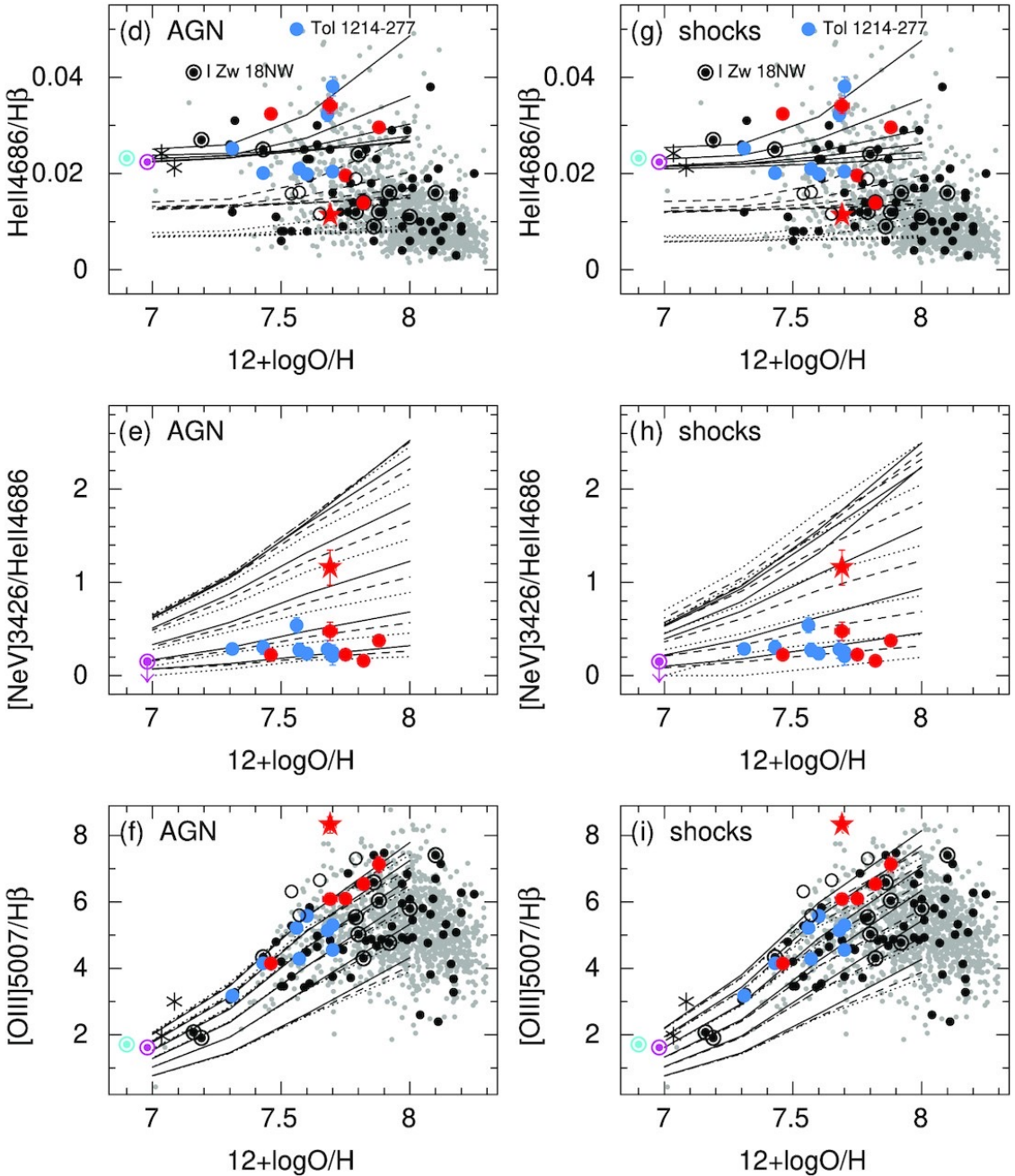


Izotov+2021

- A recent study showed that the optical spectra of these variable GP contain high-ionization emission lines such as [NeV] (97 eV) and [FeV] (54 eV)
- Broad Hα line due to transient stellar process such as supernovae is unlikely since the broad emission line has persisted over a period of ~12 years



Possible mechanisms for hard ionizing radiation



Comparison of observations with models of photoionized HII regions using CLOUDY, in combination with ionizing radiation derived from

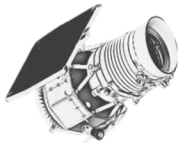
- BPASS stellar population models (Eldridge+2017)
- Combination of stellar radiation from STARBURST99 models (Leitherer+1999) with ionizing radiation produced by
  - Fast radiative shocks
  - Non-thermal radiation from an AGN

Izotov+2021

The best known AGN candidates among GP

	J1205+4551	J0240-0828
EW (Hβ)	~520 Å	~345 Å
12 + log O/H	7.46	7.88
Log M_*	8.36	8.49
E (B-V)	0.016	0.042
O_{32}	23	11
f_esc (LyA)	~16.2 %	-
f_esc (LyC)	~19.5 %	-

Based on values from Izotov+2017, 2020, 2021; Jiang+2019

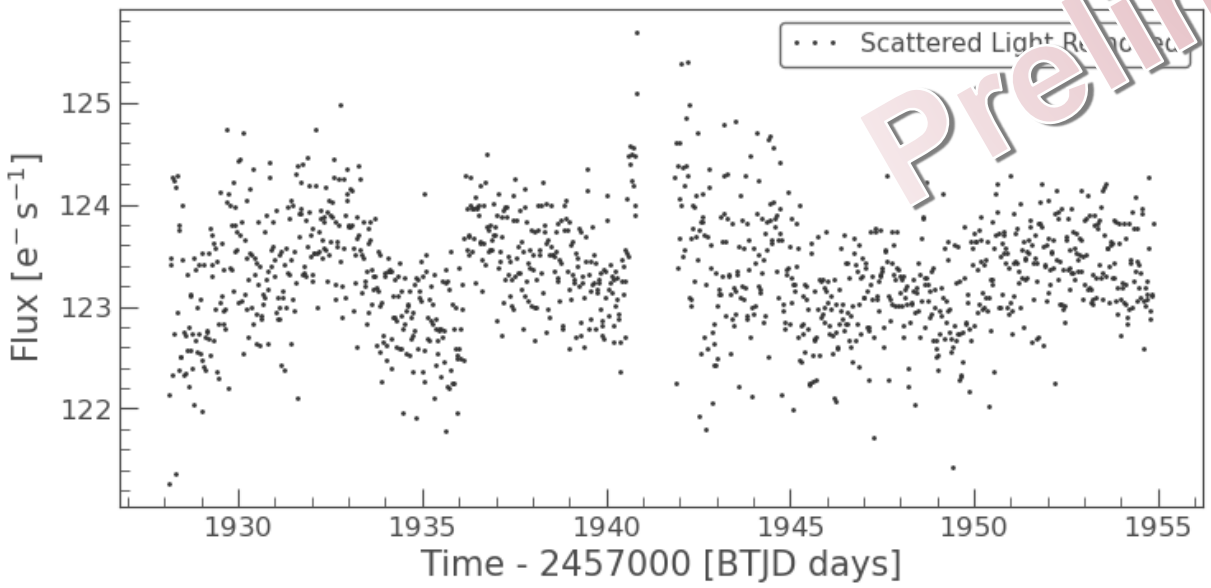


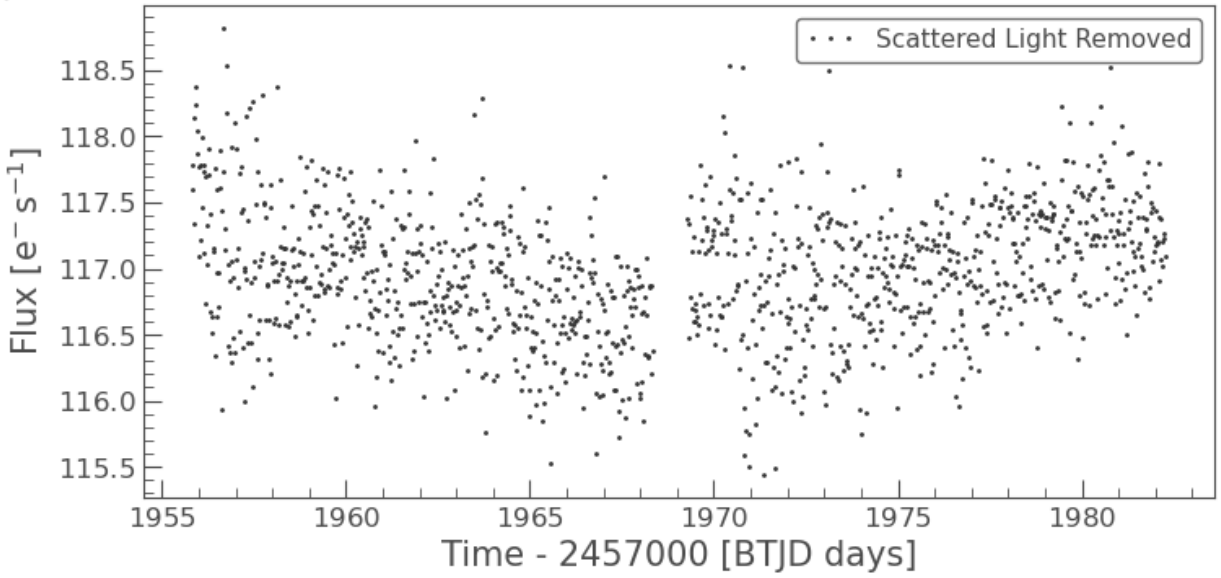
Search for variable AGN in GP using TESS

J. Sarmiento

- Analyzing optical light curves of >200 GP using TESS
- Using von Neumann statistic, >10 GP with high η

Preliminary !





Summary

- Green Peas are best analogs of high-redshift LAEs. Using *WISE* mid-infrared photometry, several sources with BH/AGN signatures are found based on **redder colors** and **variability**
- Multi-wavelength follow-up observations of these sources will be crucial in validating the AGN presence and constraining their properties, including **BH masses** and **accretion rates**.
- Even if it might not contribute to LyC emission in these sources, it might facilitate the escape of LyC from these sources.

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Evidence for Black Holes in Green Peas from WISE Colors and Variability

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Thank you!