Green Peas

– the X-ray brightest star forming galaxies?

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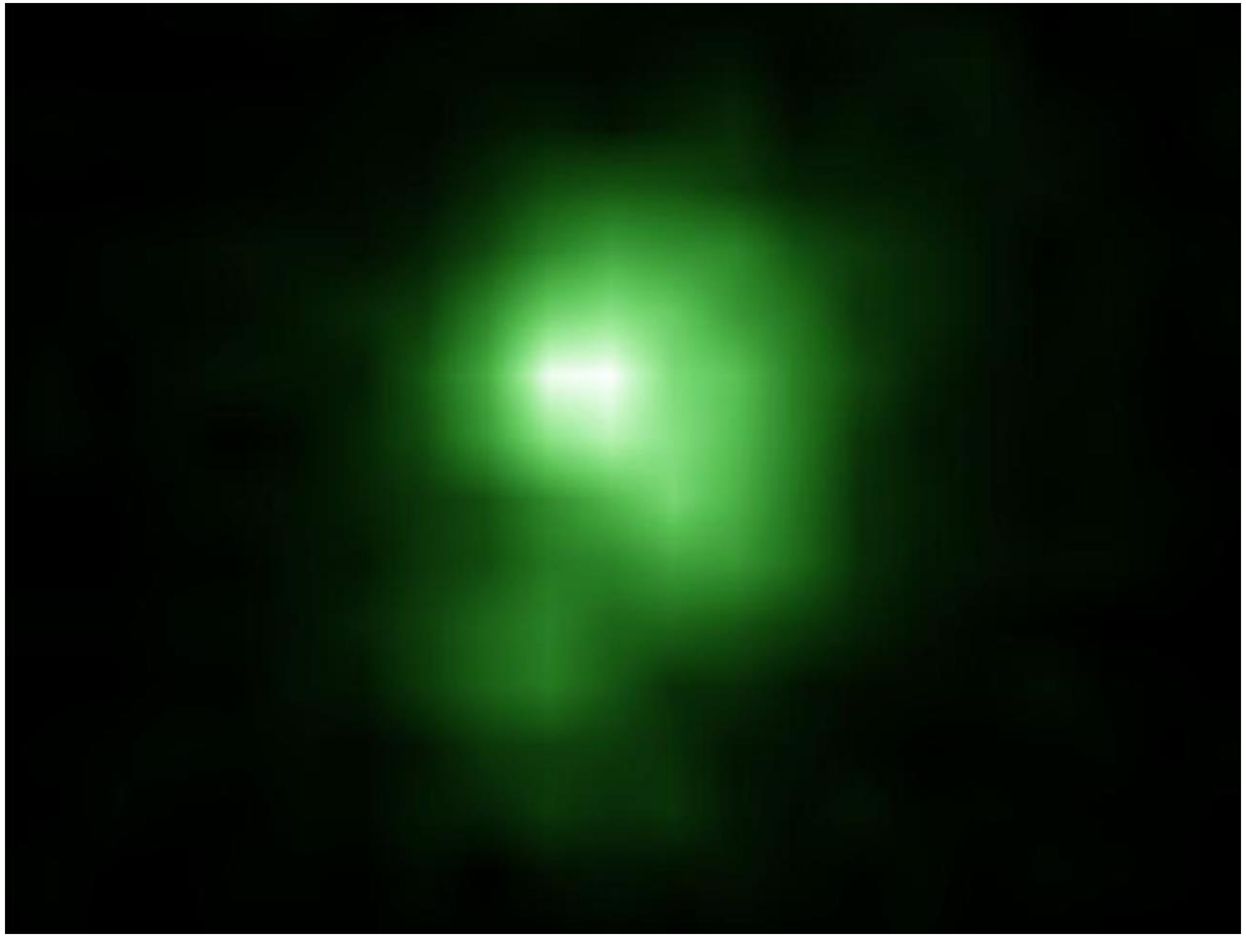
X-ray Astronomy 2019, Bologna, 10th Sep 2019

Green Peas (GPs)

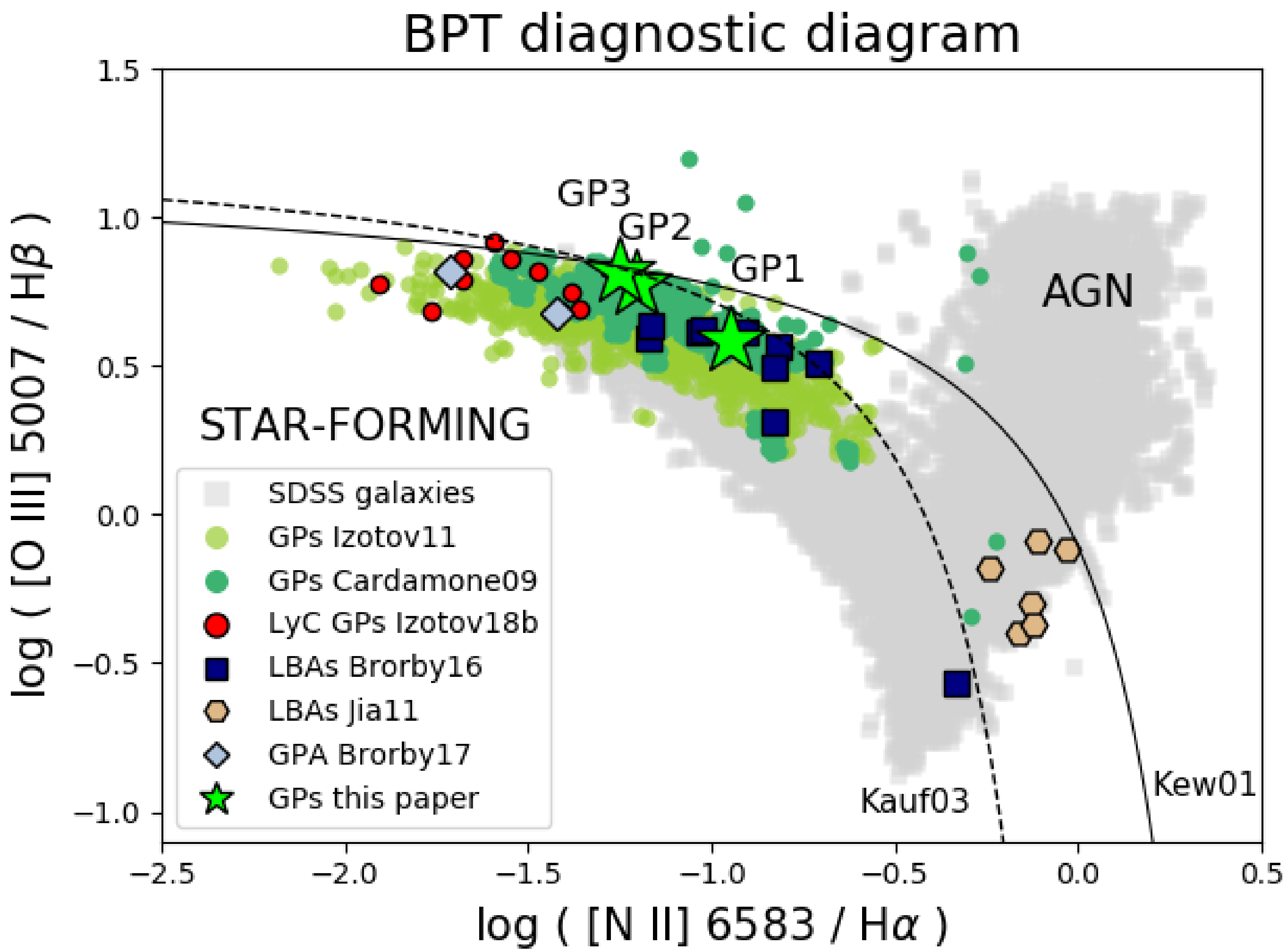


- compact, low-mass ($\approx 10^9$ $M_\odot$), highly star-forming ($\approx$ 10 $M_\odot$/yr) galaxies at redshift z $\approx$ 0.2-0.3 (Cardamone et al., 2009)
- strong UV Lyα lines, comparable to high-z starburst galaxies known as Lyman-Alpha Emitters (Henry et al. 2015, Verhamme et al. 2017, Orlitová et al. 2018)
- some were found to be leaking Lyman continuum (Verhamme et al. 2017, Izotov et al. 2018)

Lyman Continuum (LyC) escape

- LyC efficiently ionizes hydrogen atoms
- LyC leakage from star-forming galaxies could play an important role in Re-ionisation of the Universe
    - quasars represent a competitive scenario
- LyC escape reported in several GPs
    - the fraction of LyC escape varies from 5 to 70% (Izotov+18)
    - star forming galaxies numerous in early Universe, 20% of leakage shoud be sufficient (Yajima+09, Paardekooper+15)
    - GPs share the same properties with high-z star-forming galaxies and thus can be considered as their low-redshift analogs

Optical characteristics of Green Peas



- optical sky survey with SDSS
  - GPs discovered by citizen project on galaxy classification
- most GPs are purely star-forming galaxies according to the optical lines
- what are their X-ray properties?

Our project with XMM-Newton

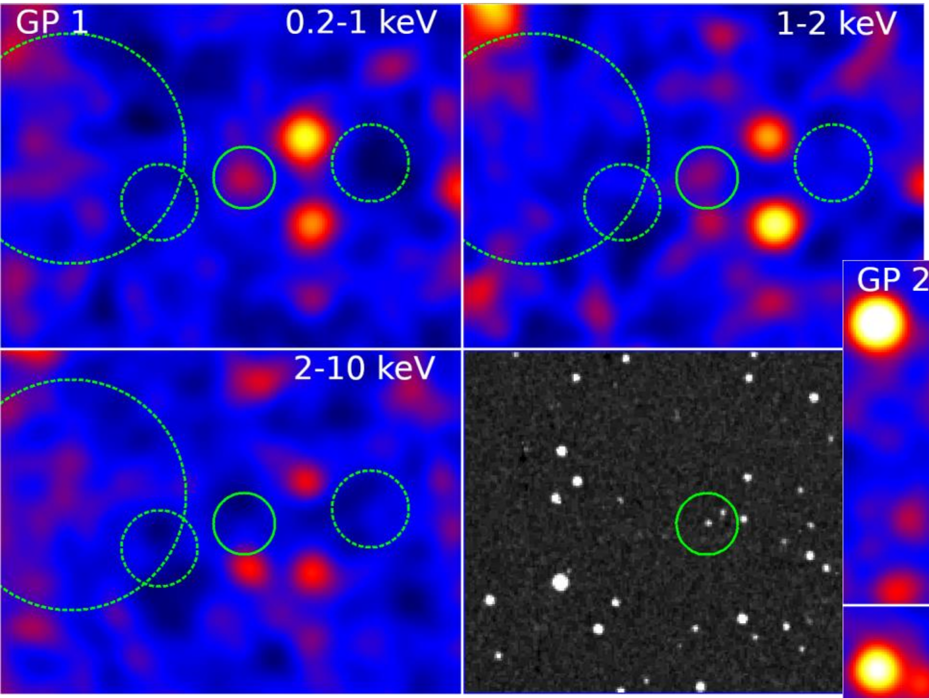
- XMM-Newton observed three GPs (PI M. Ehle)
  - sources selected as purely star-forming according to the BPT classification
  - highest SFR (**SFR ≈ 20-60 $M_\odot$/yr**) – to maximize chance of X-ray detection

source	redshift	SFR[a] [$M_\odot$/yr]	Metallicity[b] Log[O/H] + 12	Net count rate [10^{-3} cts/s]	L_X (0.5-8 keV, rest frame) [10^{42} erg s^{-1}]
SDSSJ074936.7+333716 **(GP 1)**	0.2733	58.8	8.3	3.1 ± 0.7	1.2 ± 0.4
SDSSJ082247.6+224144 **(GP 2)**	0.2162	37.4	8.1	6.4 ± 0.7	1.2 ± 0.3
SDSSJ133928.3+151642 **(GP 3)**	0.1920	18.8	8.1	-	< 0.13

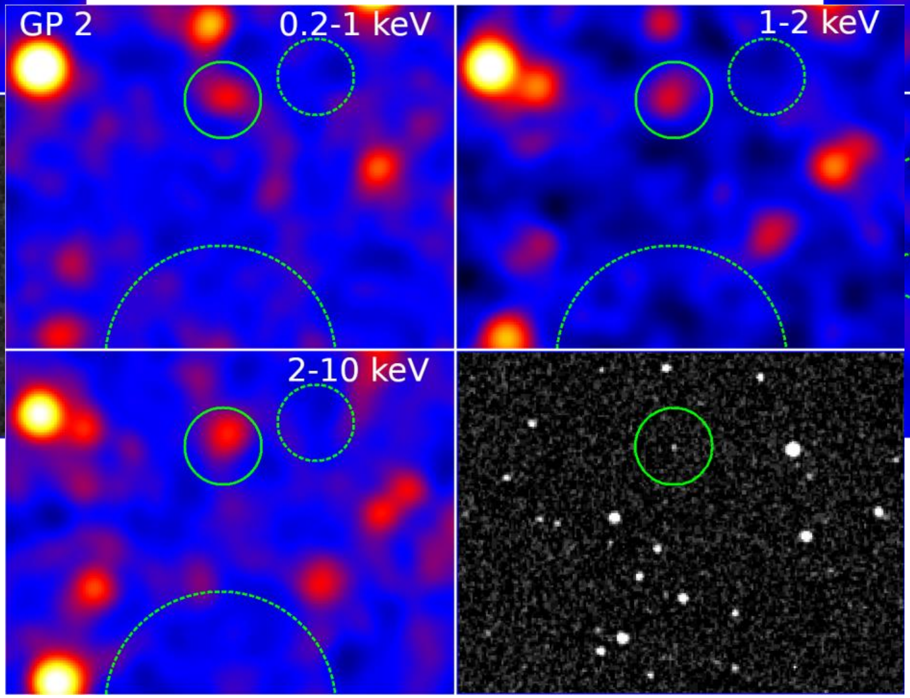
[a] SFR determined from Hα (Cardamone+09)

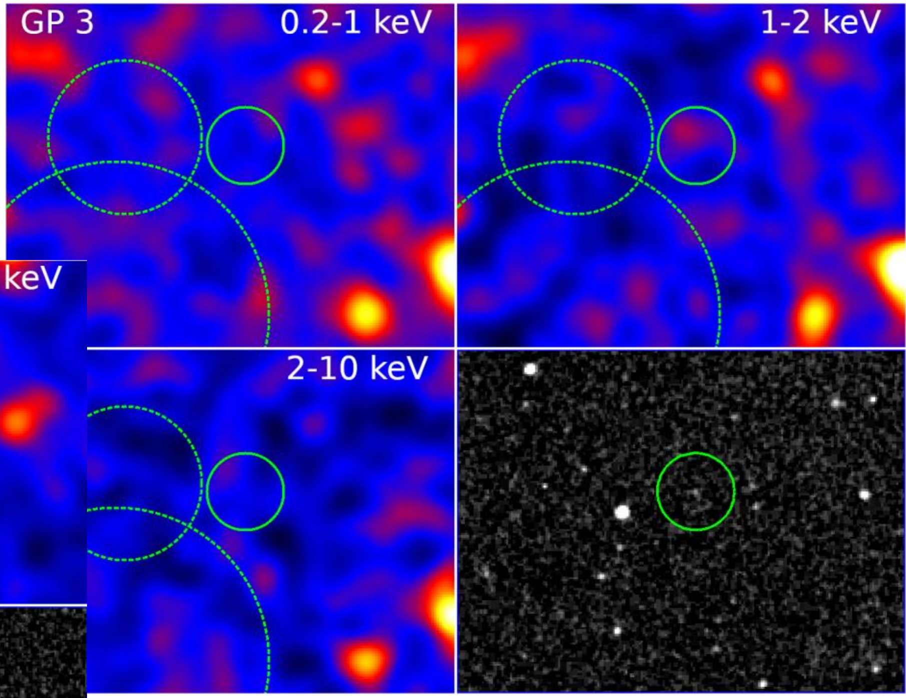
[b] we measured metallicity based on O3N2 method (Pettini&Pagel, 04)
03N2 method employs [O III]λ5007/Hβ and [N II]λ6583/Hα emission line ratios

X-ray images



GP 2:
detection in full X-ray band (0.5-10 keV)

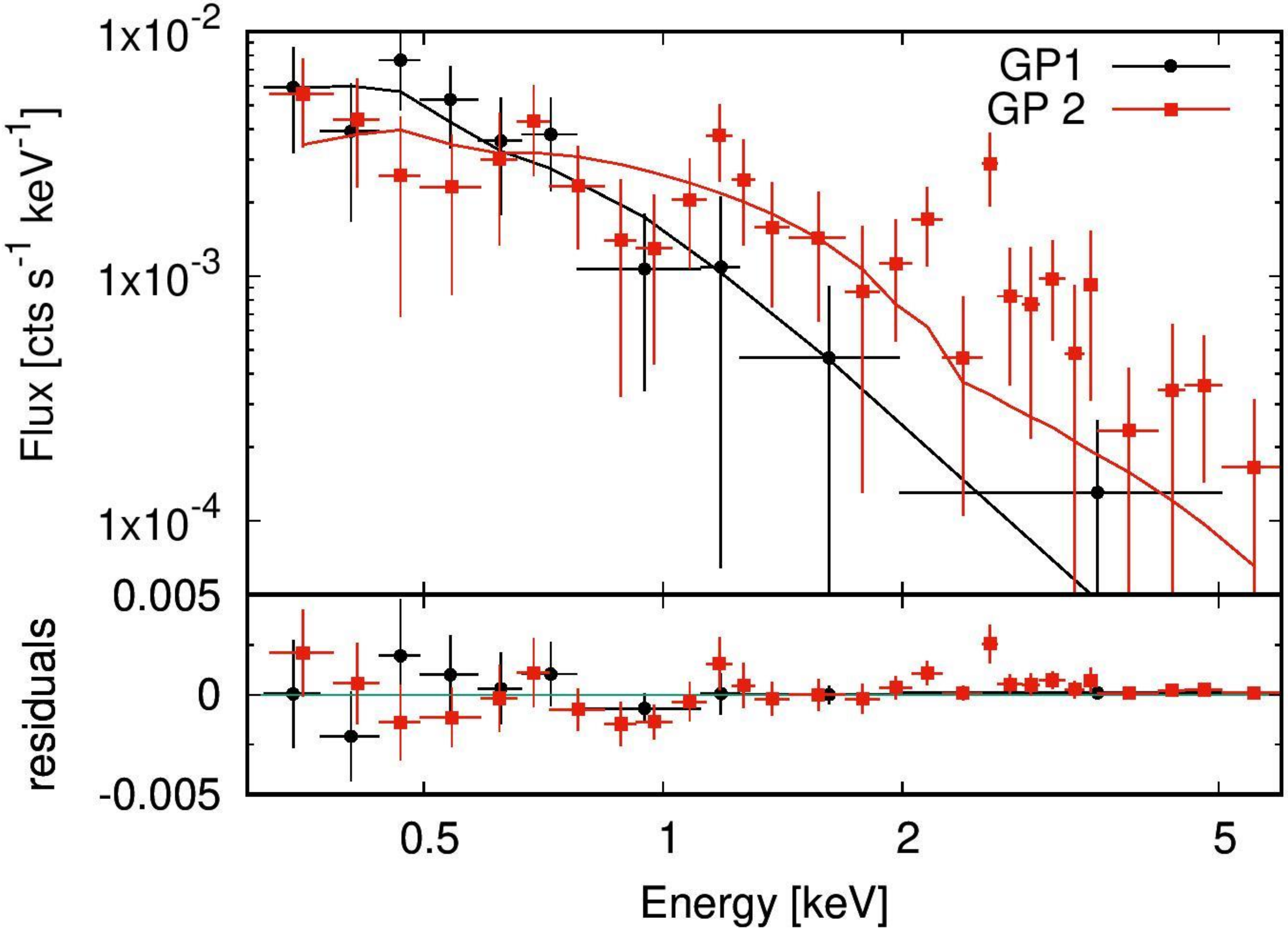




GP 1:
clear detection in soft X-rays (<2 keV)

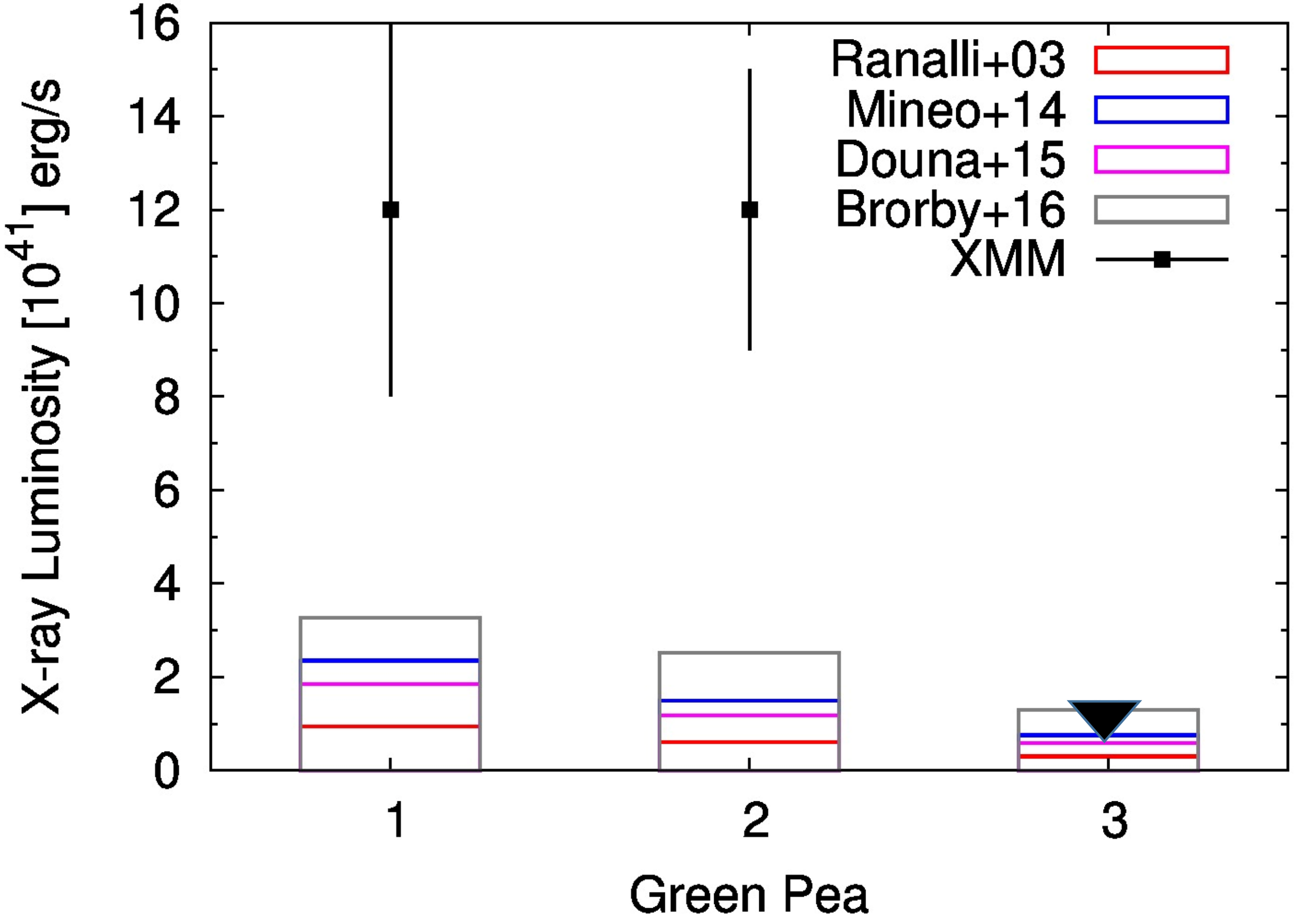
GP 3:
no clear detection

X-ray spectra



- different spectral slope:
  - Γ ≈ 3 for GP1
  - Γ ≈ 2 for GP 2

Measured X-ray luminosity



- **GP 1** and **GP 2** are largely above different L_X-SFR- (metallicity) empirical relations
- their X-ray excess is of order of **10^{42} erg/s**
- GP 3 only upper limit consistent with predictions

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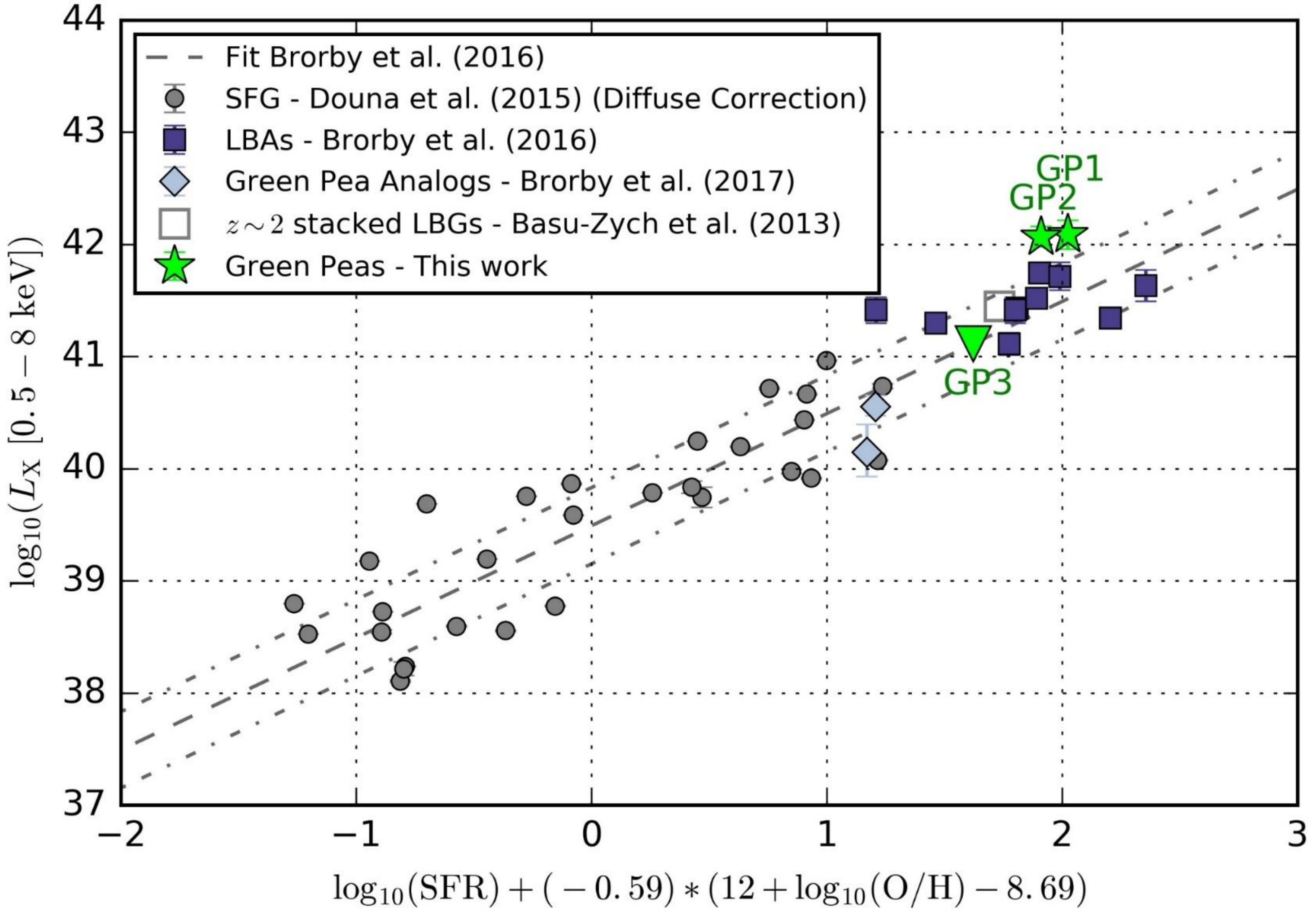
Comparison with other star-forming galaxies



- **L_X-SFR-metallicity** relation based on ***Brorby et al. 2016***
- GP 1 and GP 2 are significantly above the correlation
- are X-ray brighter than Lyman-Break Analogs, Lyman-Break Galaxies, Green Pea Analogs, or other nearby star forming galaxies

Explanation of the X-ray excess

- stochasticity?
  - cannot explain dispersion at high SFR
  - Gilfanov+04 showed that the probability of detecting $L_X = 2\langle L_X \rangle$ is $p < 0.001$ for SFR ≈ 40 $M_{\odot}$/yr (see also, Justham & Schawinski 12), our GPs have SFR ≈ 20-60 $M_{\odot}$/yr

Explanation of the X-ray excess

- stochasticity? X
- larger number of HMXBs? (due to different IMF?)
  - number of HMXBs: N ≈ 13 SFR (Gilfanov & Merloni, 2014)
  - measured L_x is at least 4-6x larger than predicted

    → SFR from L_x excess is SFR ≈ 300 $M_{\odot}$/yr

	SFR (from Hα)	N (HMXB) expected	N (HMXB) from L_x excess
GP 1	58.8	764	3000
GP 2	37.4	486	3400

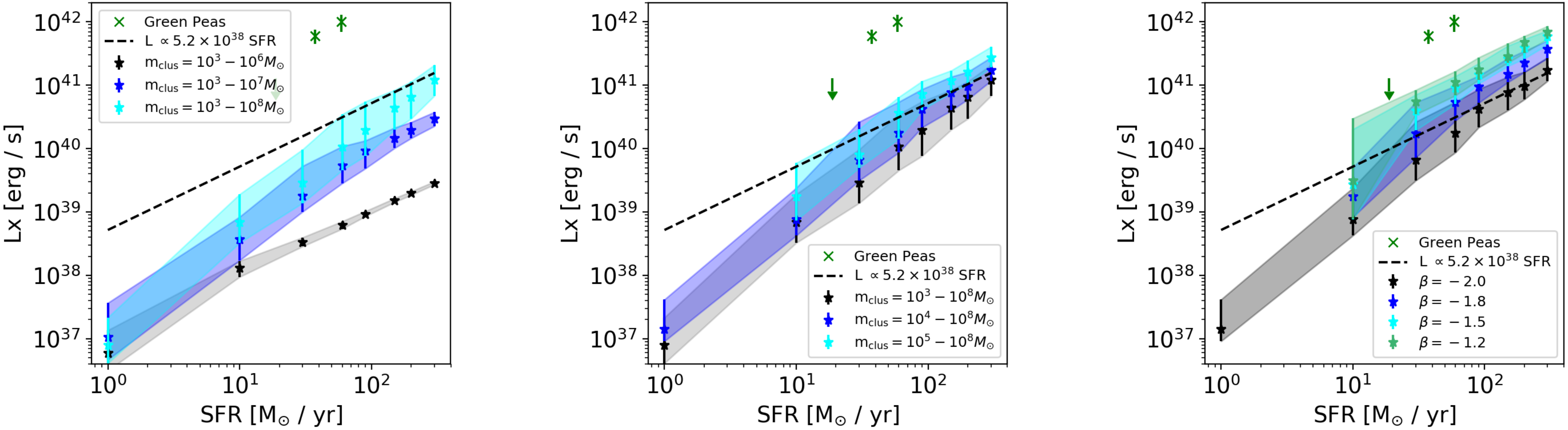
Explanation of the X-ray excess

- stochasticity? X
- larger number of HMXBs? ?
- ULXs? SNe?
  - observed in star forming galaxies (Basu-Zych+13, Kaaret+17)
  - X-ray luminosity of ULXs is 10^{39}-10^{41} erg/s, at least **10-1000 ULXs** needed to explain the observed X-ray excess
  - luminous SNe? *(see talk by Dwarkadas)*
    - for SFR ≈ 50 $M_{\odot}$/yr star with M > 8$M_{\odot}$ every 2-3 years

Explanation of the X-ray excess

- stochasticity? X
- larger number of HMXBs? ?
- ULXs? SNe? ?
- hot gas?

Explanation of the X-ray excess – hot gas?



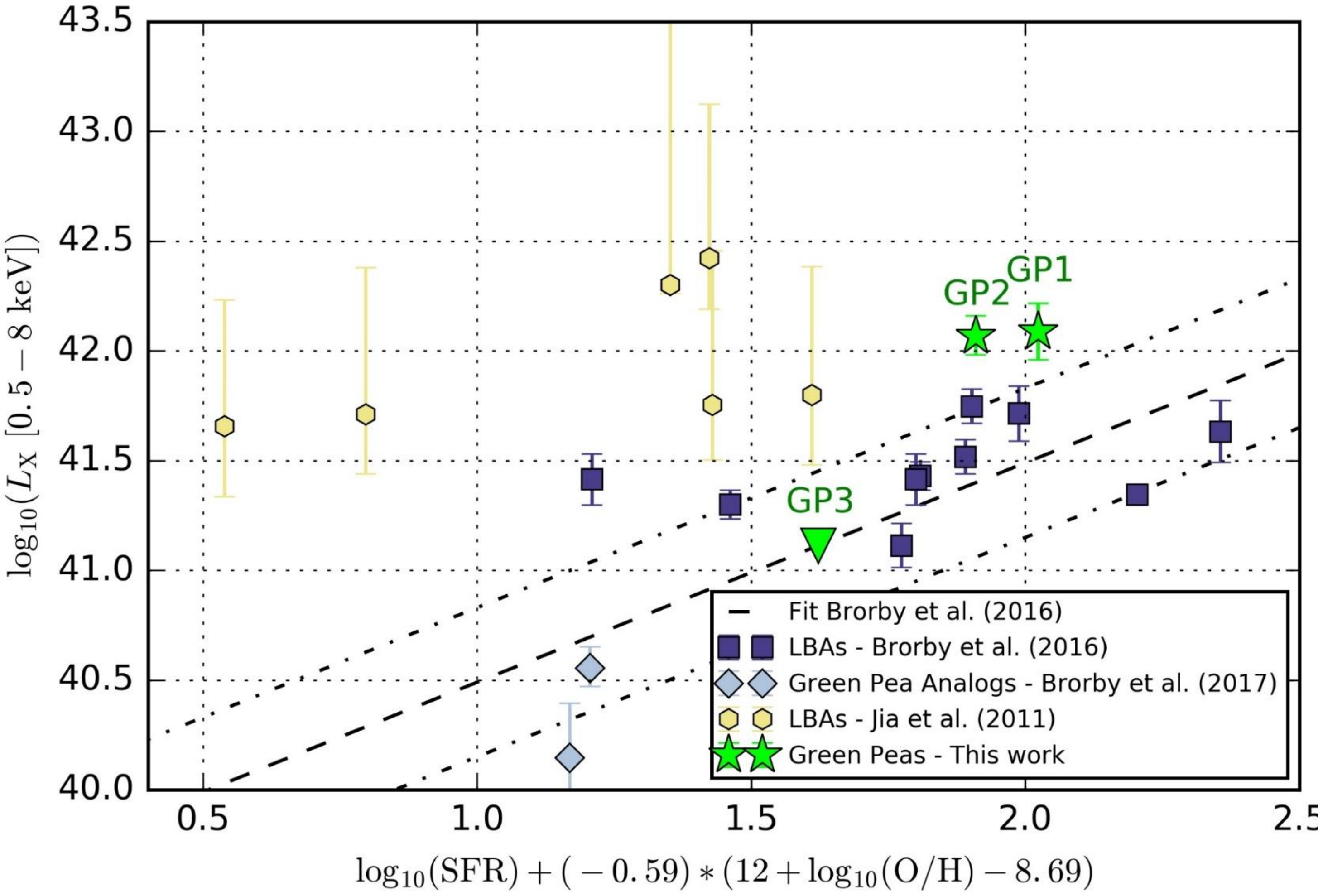
- simulations of hot gas X-ray luminosity from star clusters do not reach the observed luminosity of GPs

Franeck et al., in prep.

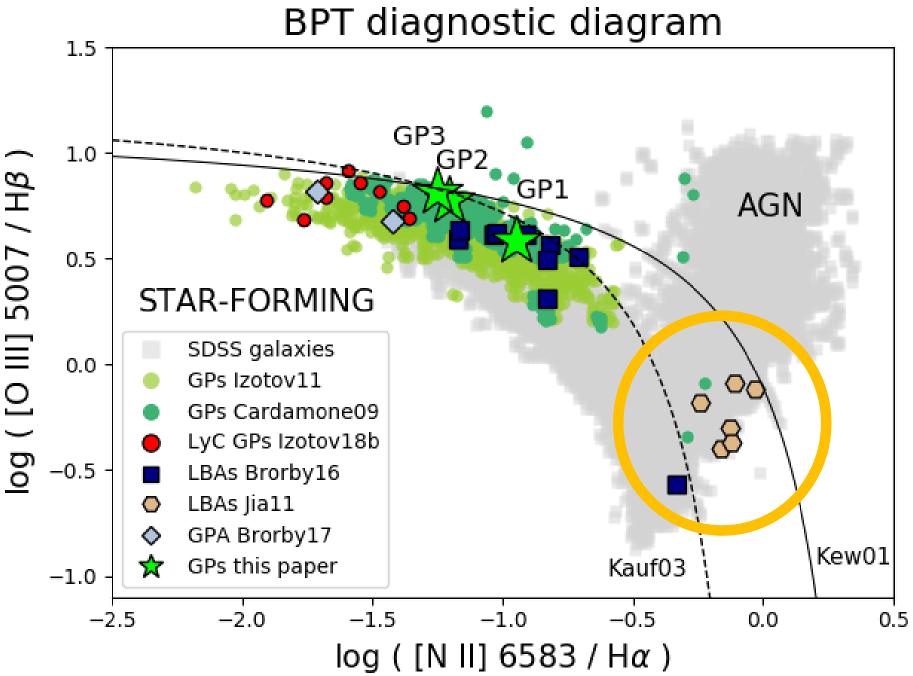
Explanation of the X-ray excess

- stochasticity? X
- larger number of HMXBs? ?
- ULXs? Sne? ?
- hot gas? X
- AGN?

Explanation of the X-ray excess – AGN?

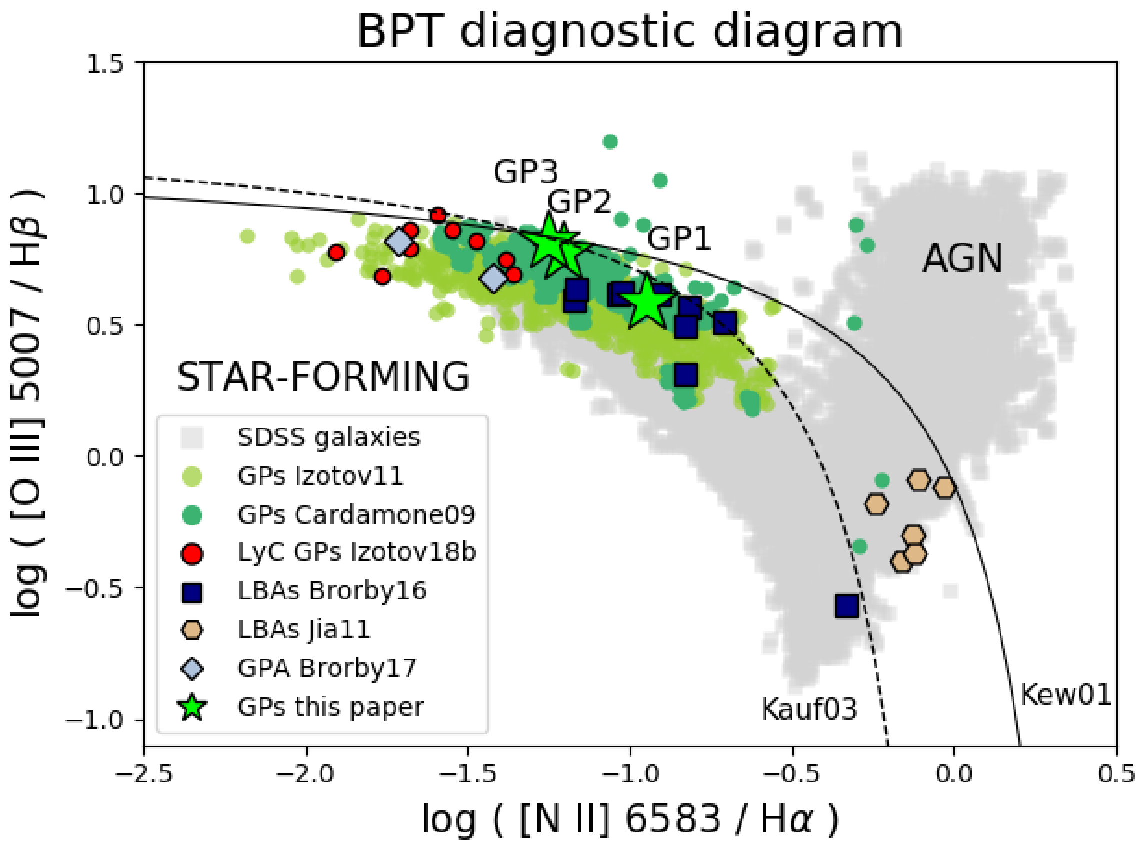


- comparison of GPs with LBAs with the composite spectrum (Jia+11)



Explanation of the X-ray excess

- stochasticity? X
- larger number of HMXBs? ?
- ULXs? SNe? ?
- hot gas? X
- AGN? ?



- the excess is present in two out of three GPs
  - GP2 and GP3 very similar in optical light, but largely different in X-rays
  - easiest to be explained by an AGN (on/off), probably with $M_{BH}<10^5 M_{\odot}$

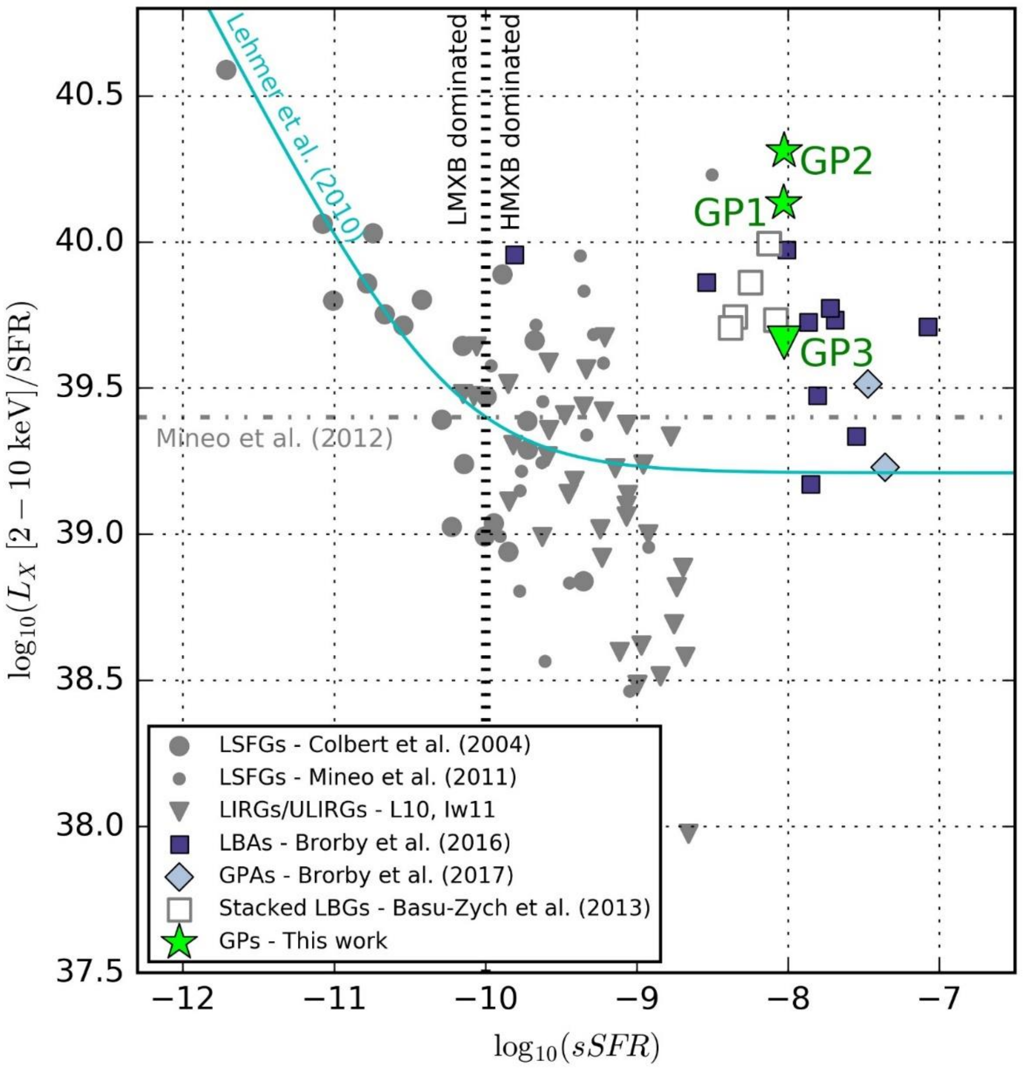
Conclusions

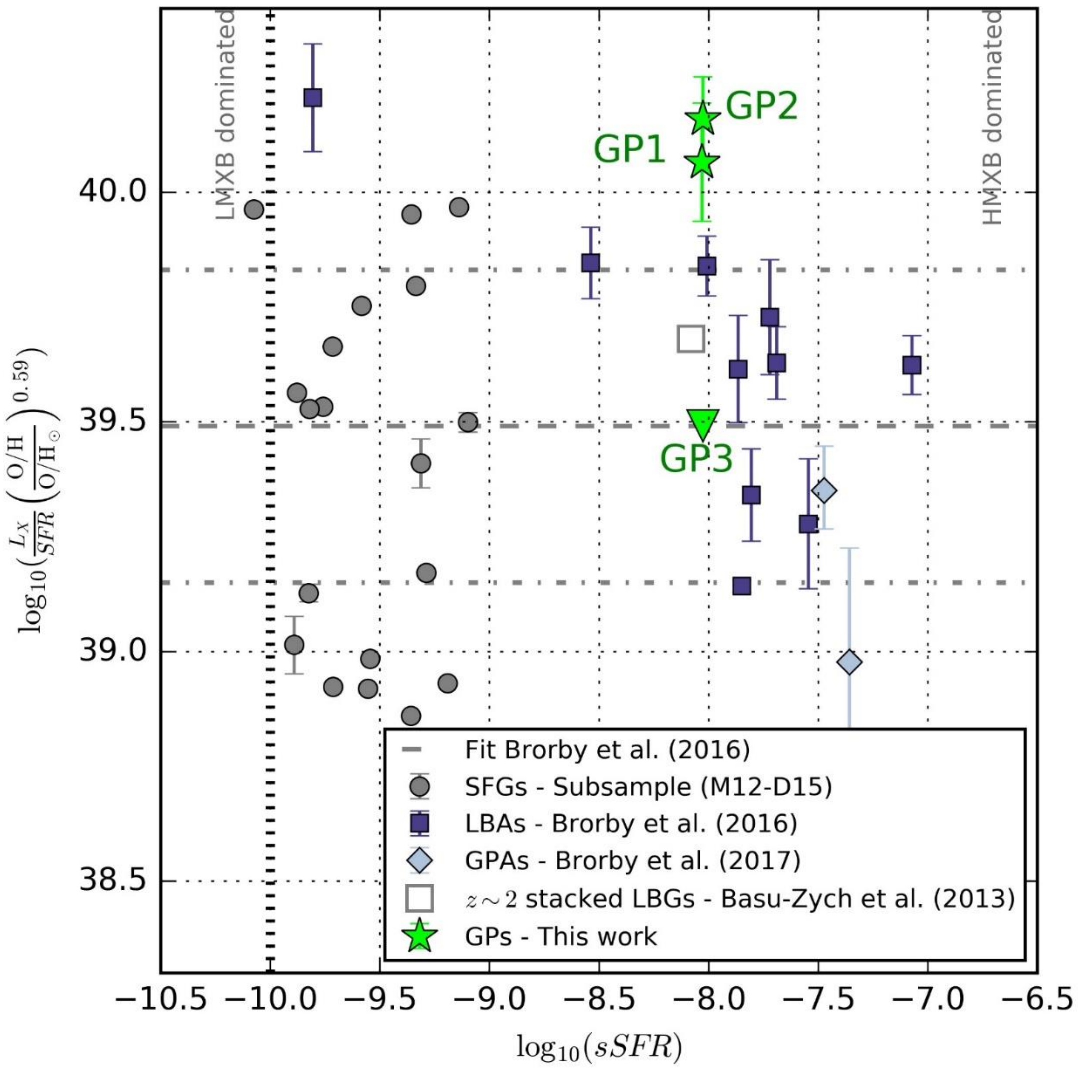
- XMM-Newton observations of three Green Pea galaxies showed a significant **X-ray excess of $L_x \approx 10^{42}$ erg/s in GP 1 and GP 2**
- the X-ray excess needs to be of the physical origin
  - possible explanations include AGN (IMBH), ULXs, IMF?
  - is not present in all GPs, not simply related to SFR or metallicity
- more deep X-ray observations of similar sources desired
- more details in our recent paper:

Svoboda J., Douna V., Orlitová I. & Ehle M., 2019, ApJ, 880, 144S

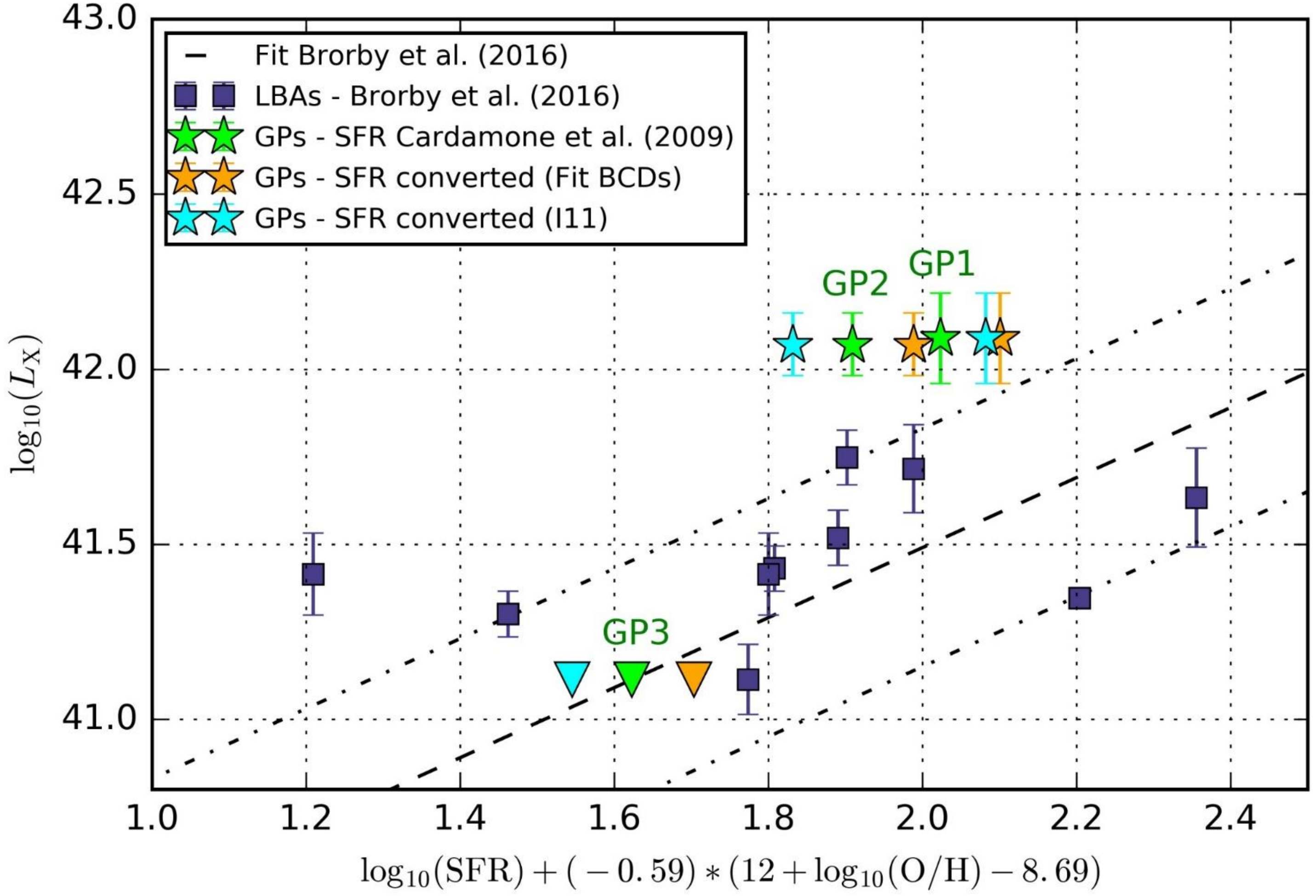
Thank you very much for your attention!!!

Measured X-ray luminosity





Comparison of different SFR methods



XMM-Newton look at Green Peas

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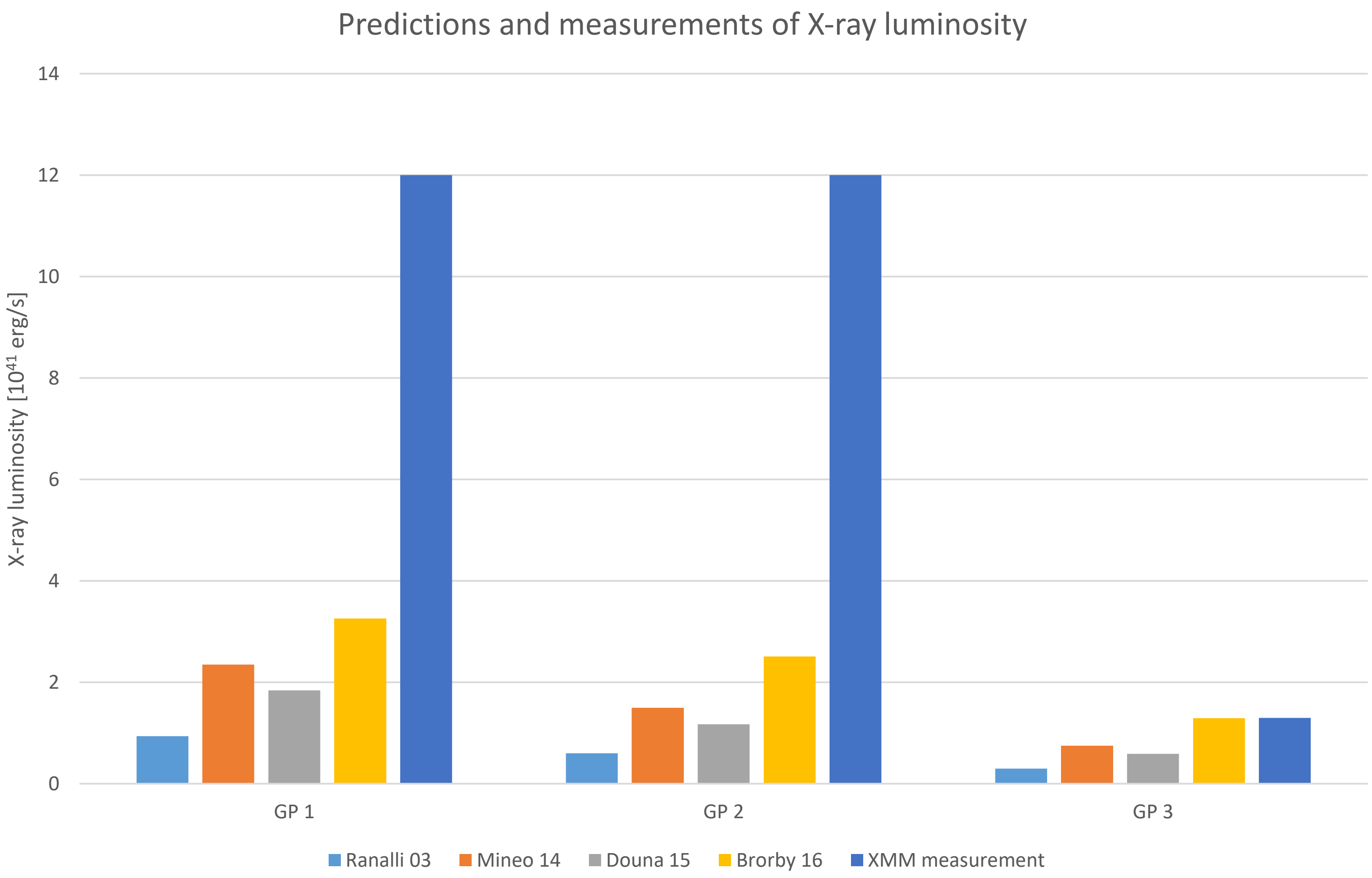

- GP 1 and GP 2 are above the L_X-SFR-metallicity correlation based on *Brorby et al. 2016*
- their X-ray excess is of order of **10^{42} erg/s**