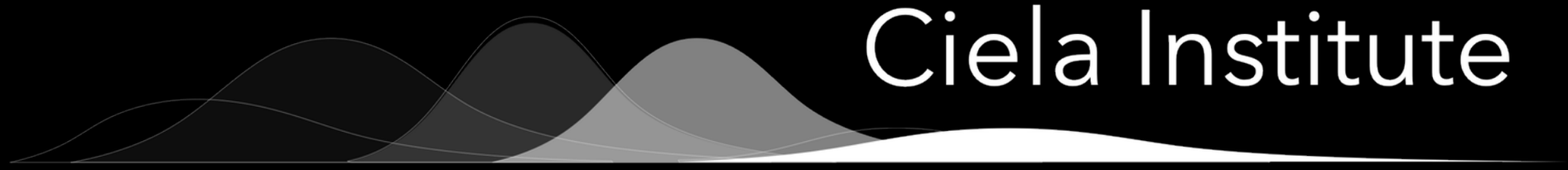
Windy Quasars: Investigating the Physical Properties of Broad Absorption Line Outflows with *SimBAL*

Joseph Choi
X-TRA (Prof. Julie Hlavacek-Larrondo; CIELA)

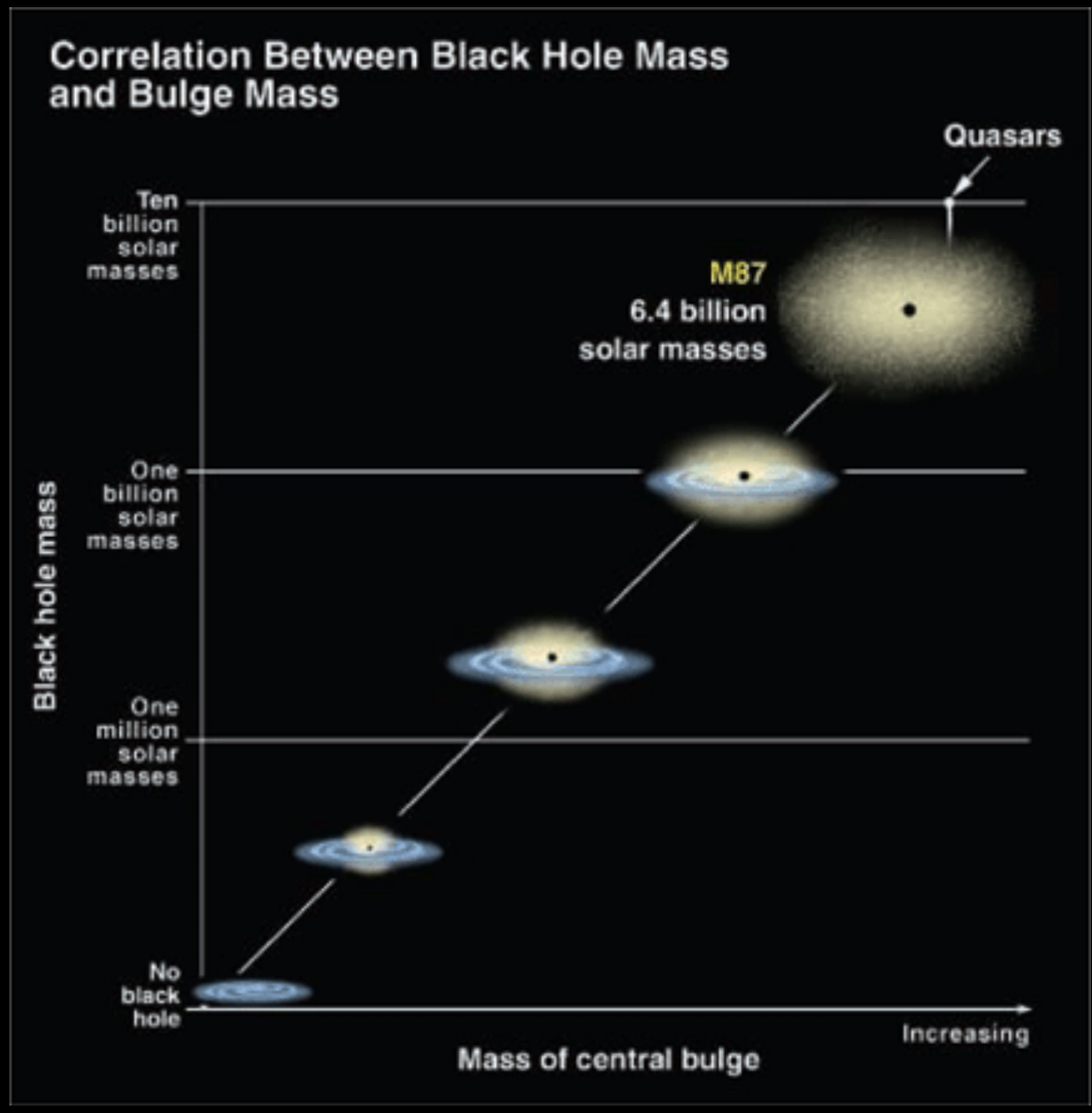


SimBAL Collaboration: Dr. Karen Leighly (P.I., OU), Dr. Sarah Gallagher (UWO), Dr. Donald Terndrup (OSU), Dr. Gordon Richards (Drexel)
CRAQ Rencontre Annuelle 2023

Central Black Holes and Their Host Galaxies

Co-Evolution and Feedback from Supermassive Black Holes (SMBHs)

- A strong correlation between the properties of the SMBHs and their host galaxies.
  - The SMBHs and their hosts seem to evolve together.



Credit: Tim Jones/University of Texas, Austin,
after K. Cordes & S. Brown/STScI

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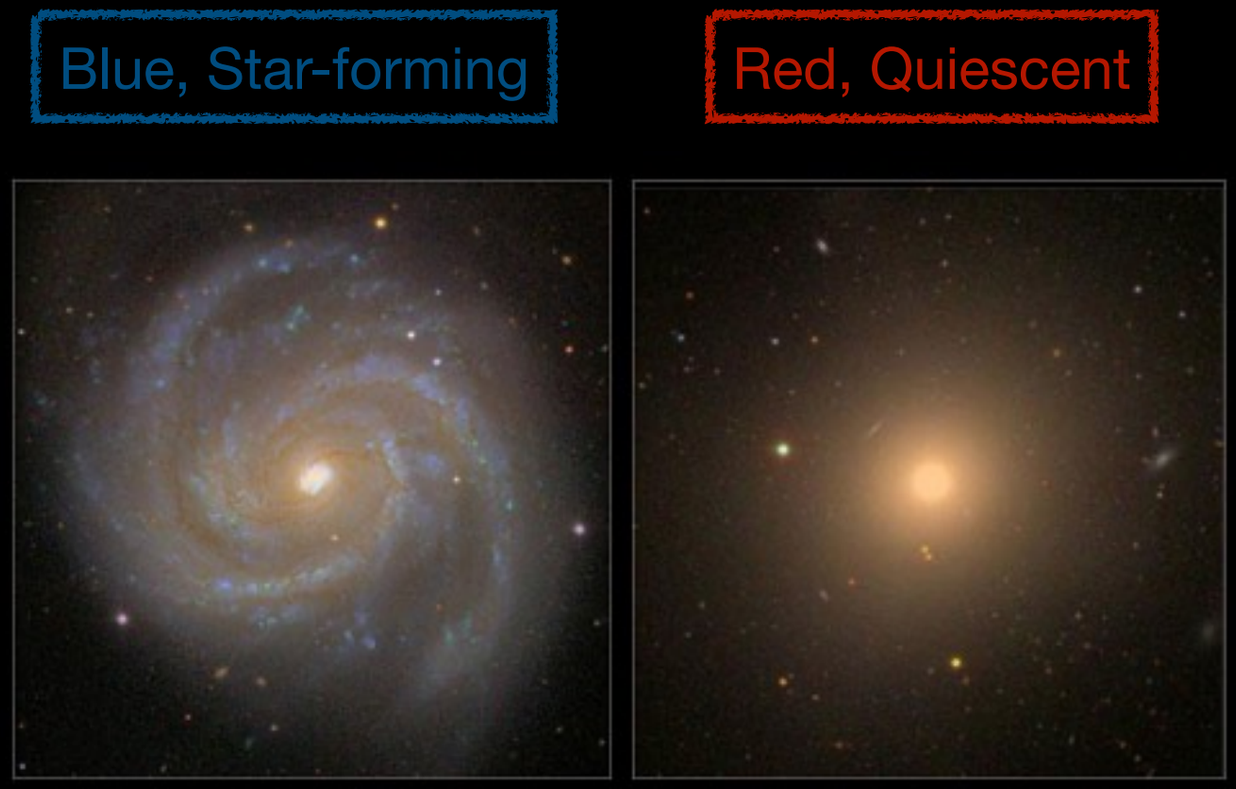
  - Central SMBHs impart energy, mass, and radiation to the host galaxies



Credit: SDSS

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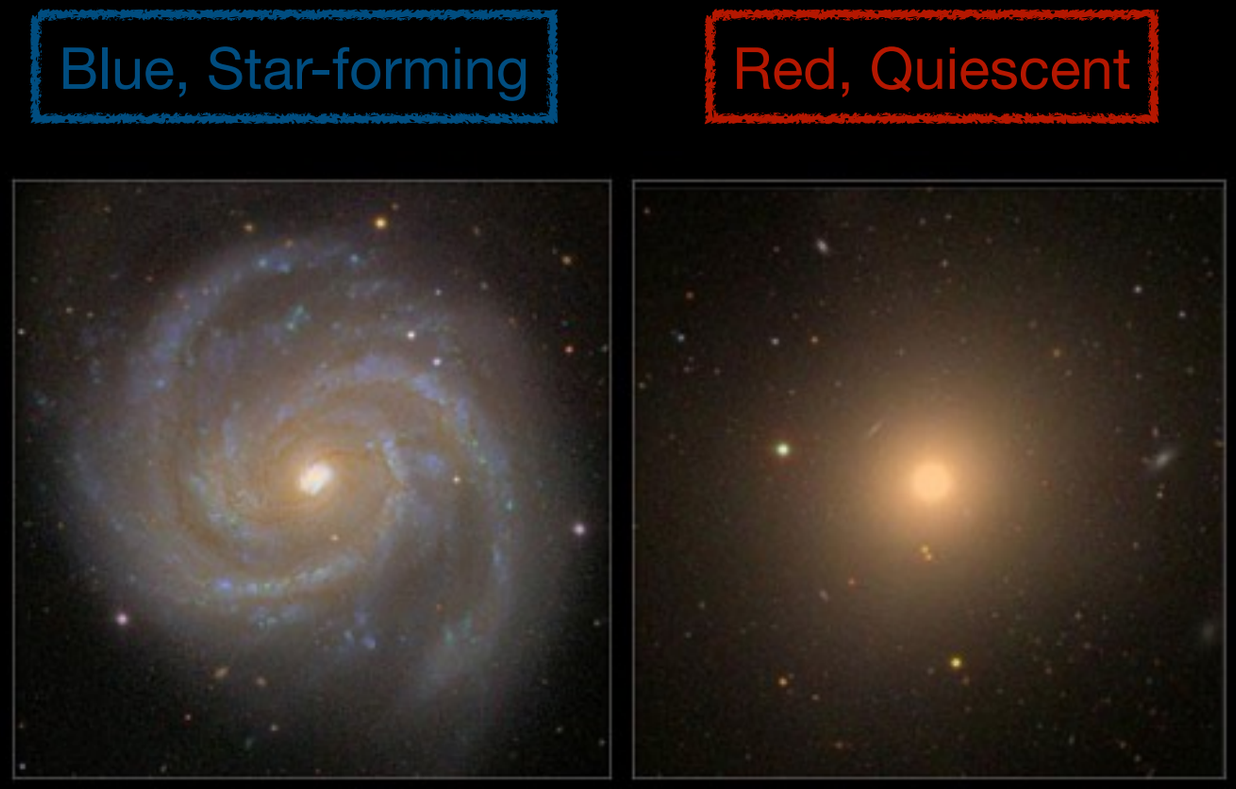
- **How do the central SMBHs communicate with the host galaxies?**

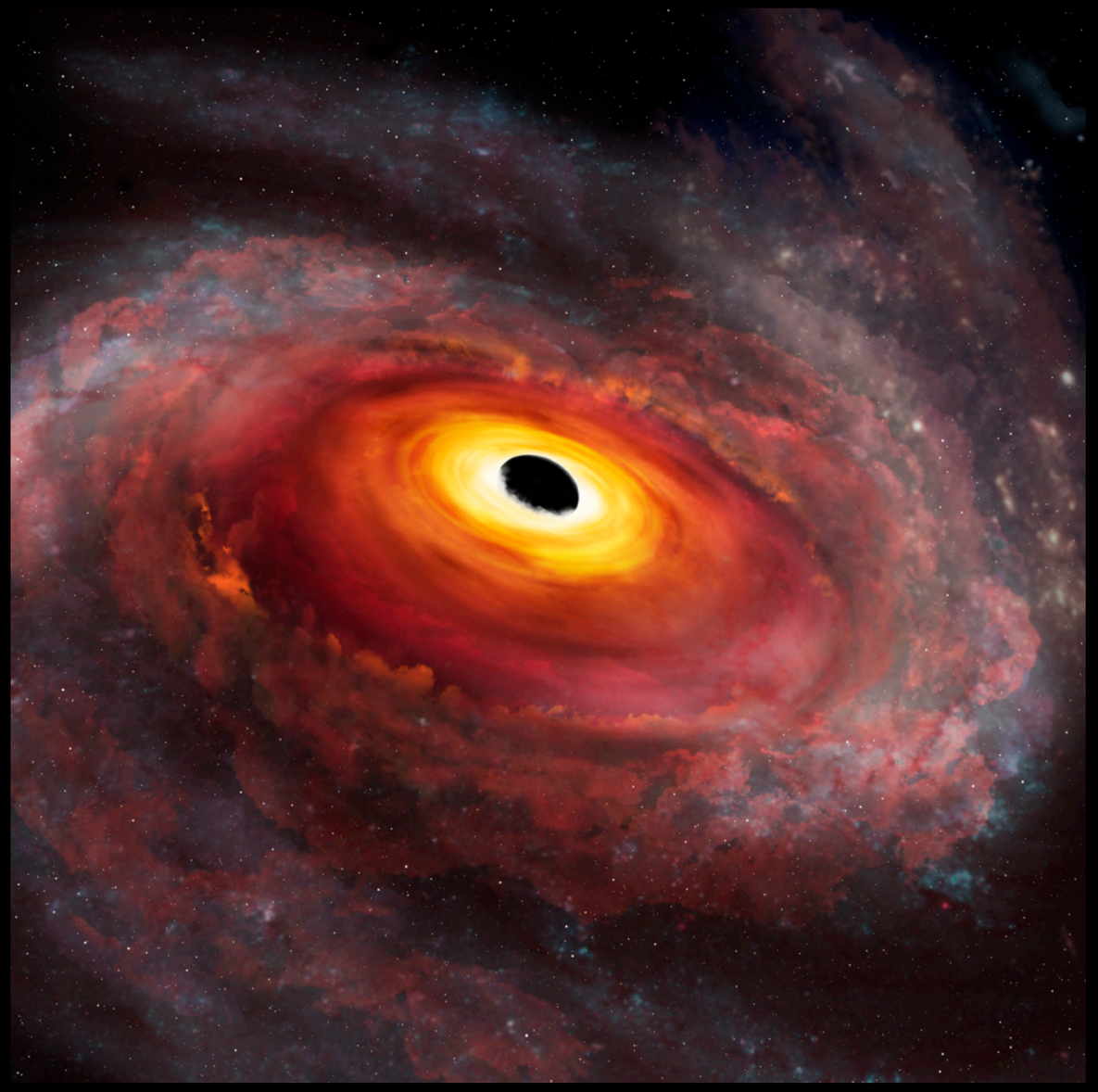


Credit: SDSS

Quasars

and supermassive black holes

- Most (all) massive galaxies have supermassive black holes (SMBHs) in their centers.
- SMBH in Milky Way: ~ 4 million $M_\odot$
  ➜ quasars: M_{BH} ~ 10-1,000 million $M_\odot$
- Accreting SMBH forms an active galactic nucleus (AGN)
  ➜ accretion disk, torus, broad/narrow line clouds
- One of the brightest extragalactic objects
  ➜ emits in radio ~ x-ray



Credit: International Gemini Observatory/
NOIRLab/NSF/AURA/P. Marenfeld

Broad Absorption-Line Quasars

Powerful outflows that drive feedback from the central supermassive black holes

- Quasar outflows
  ➜ AGNs feeding energy and gas to their host galaxies.
- ***Broad absorption-lines (BAL) features show clear evidence for energetic winds***
- Found in ~ 15—40 % of the rest-ultraviolet (UV) quasar spectra
- *Feedback and Galaxy Evolution*
  ➜ BAL quasars are prime targets for investigating the potential mechanism of feedback on galaxies

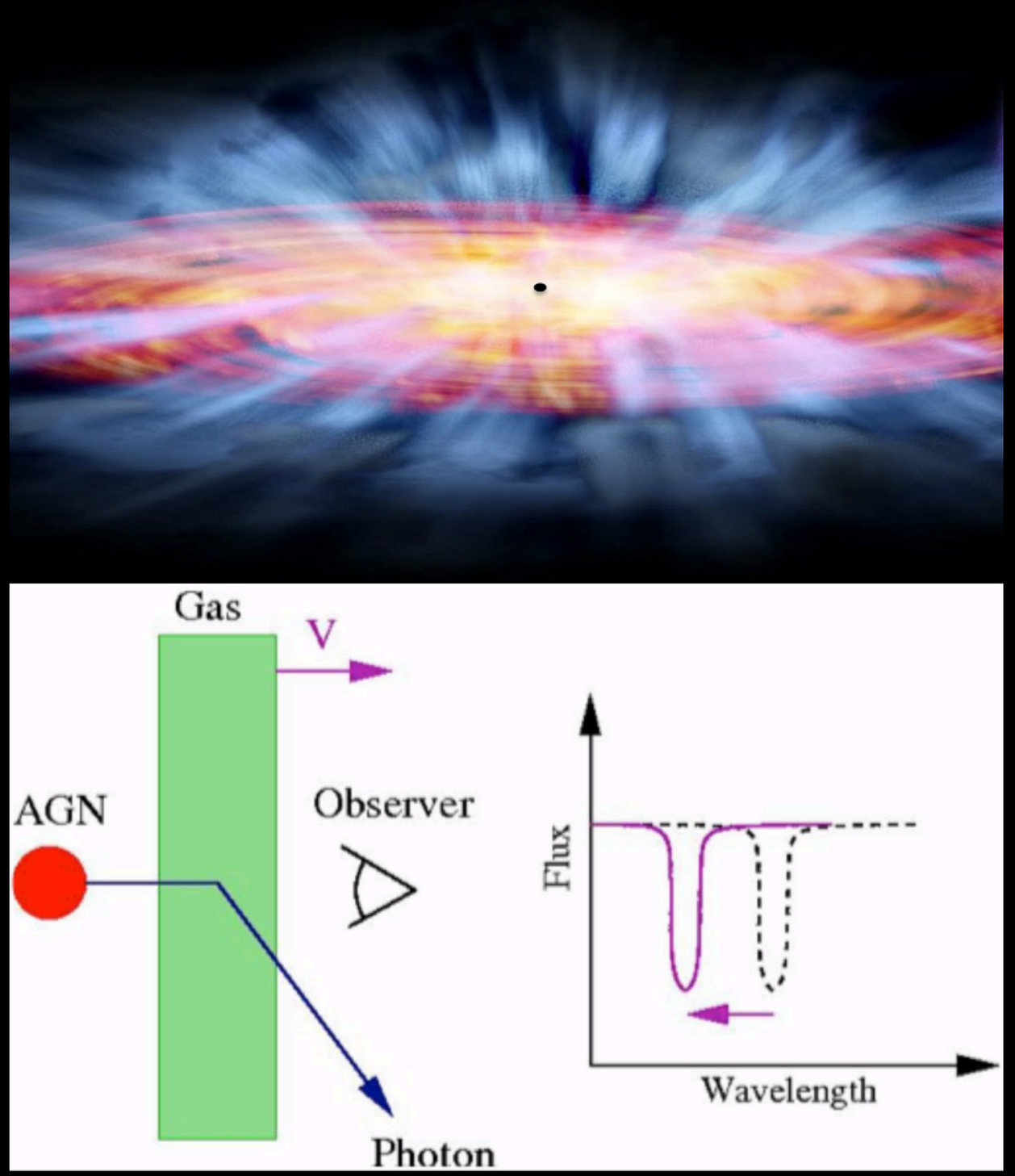
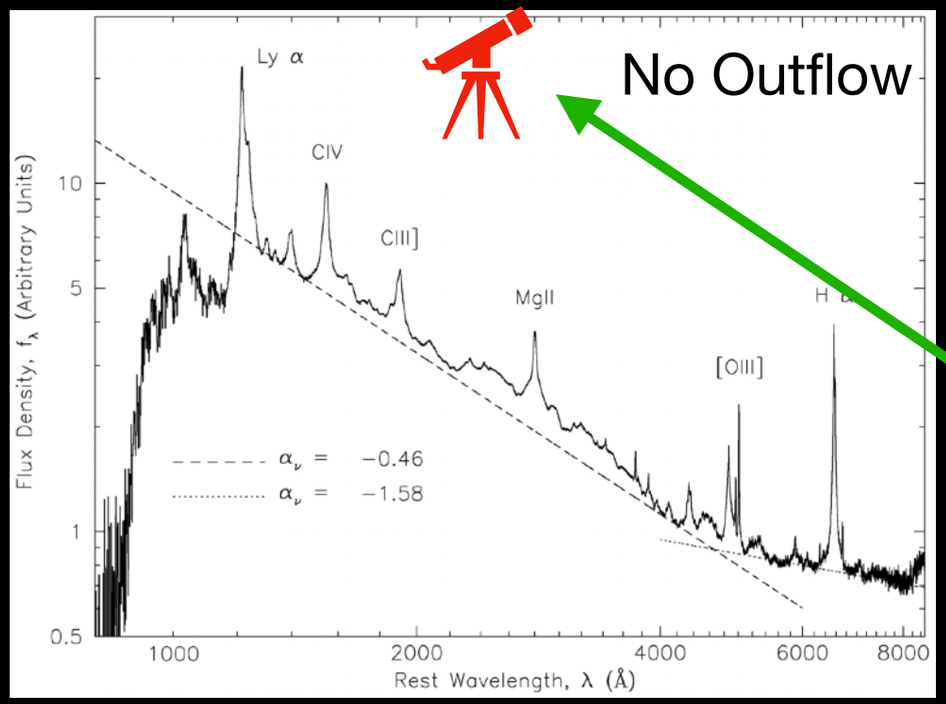
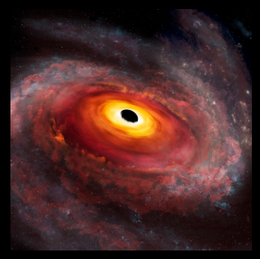


Image Credits: NASA/CXC{top); A. Lucy (bottom)

Iron Low-Ionization BAL Quasars

BAL quasars with the most energetic outflows





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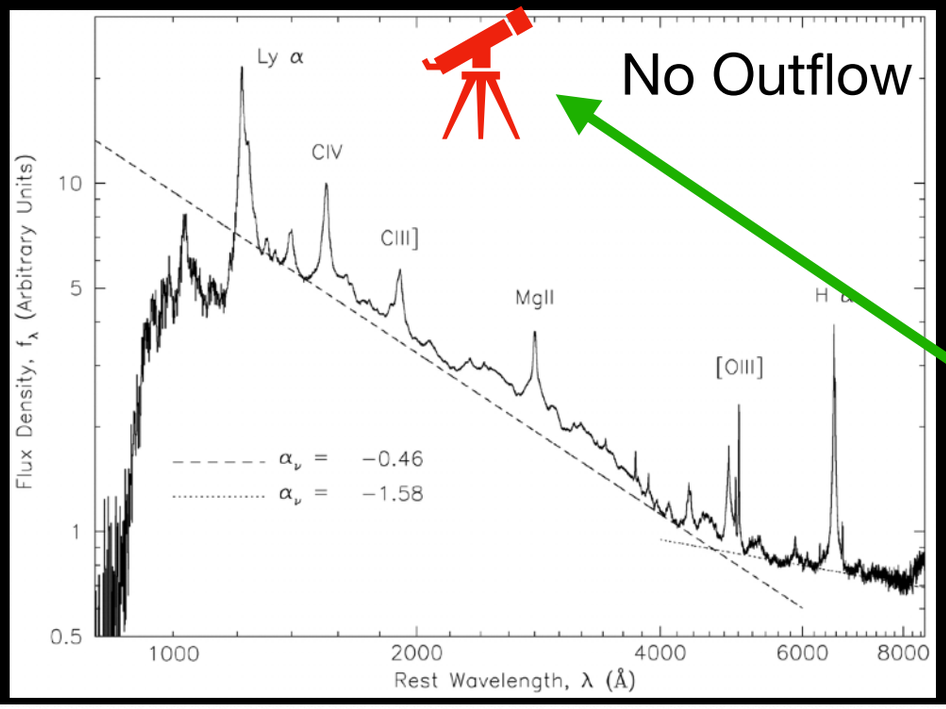

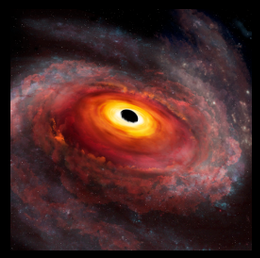

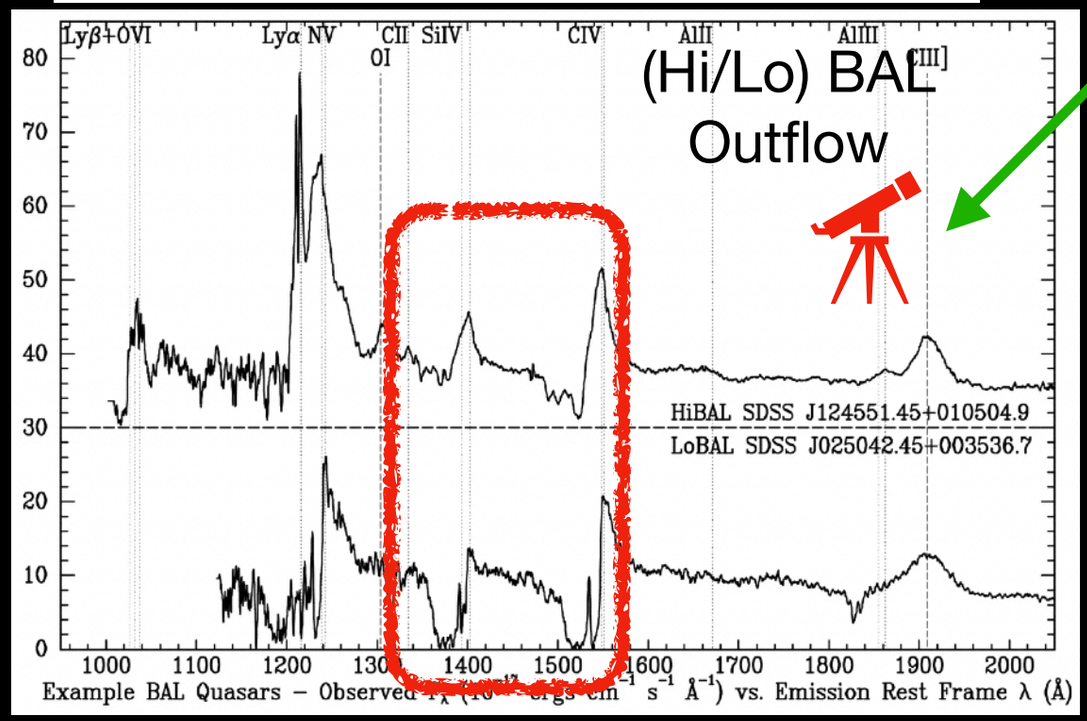

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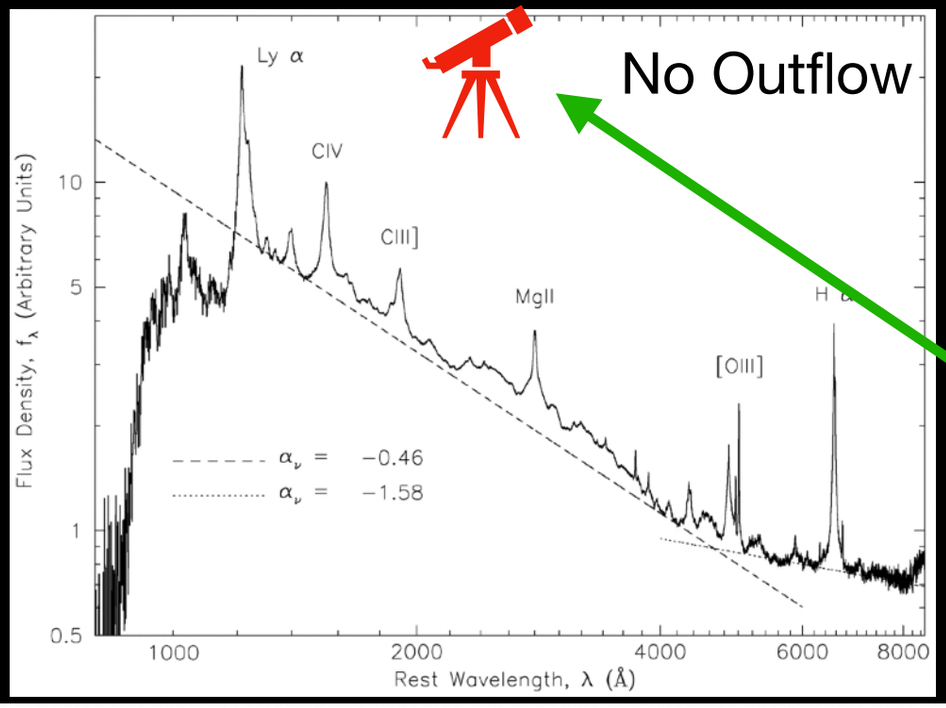

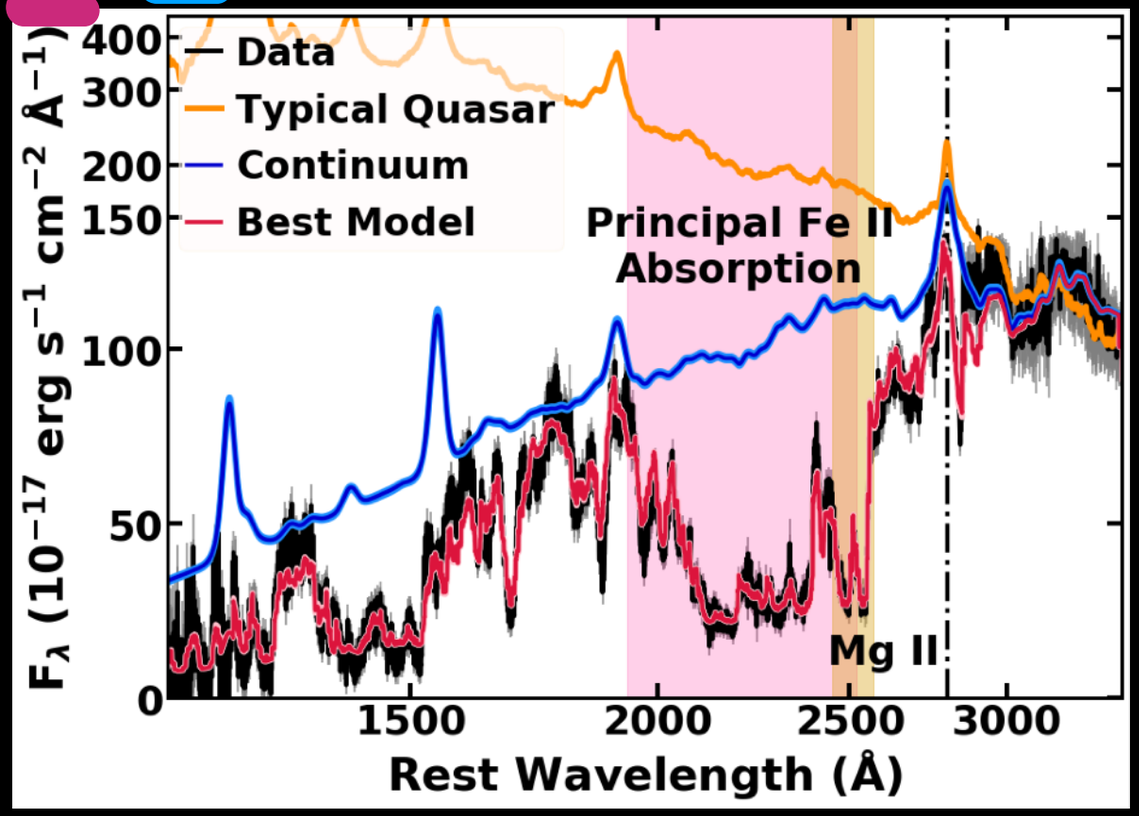

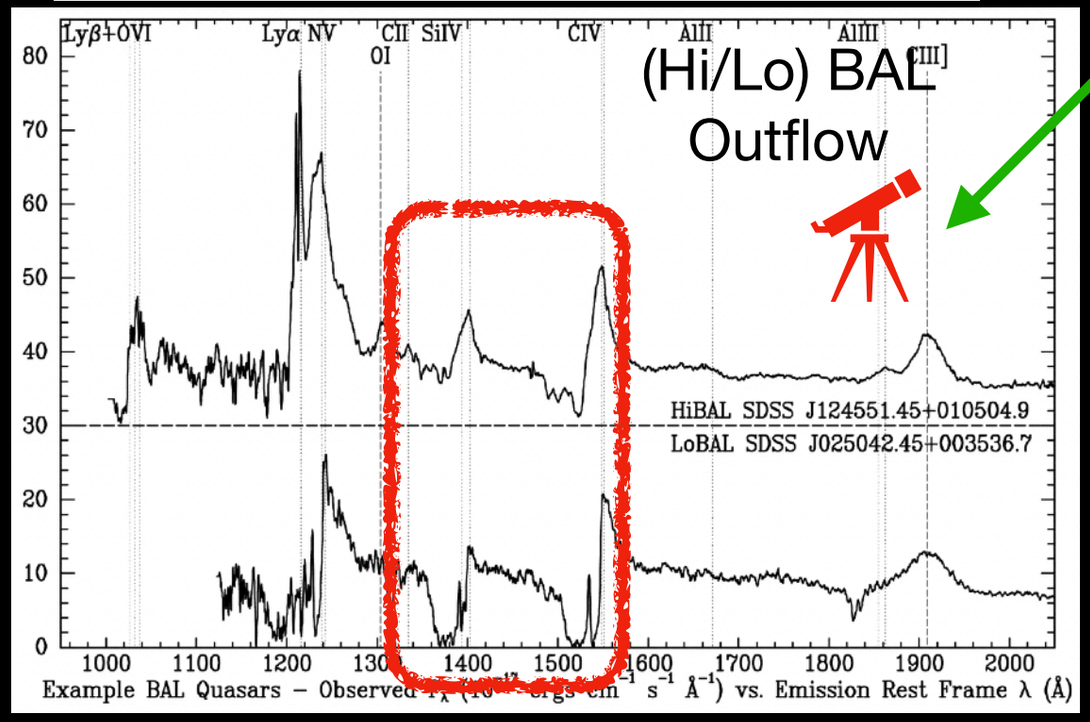

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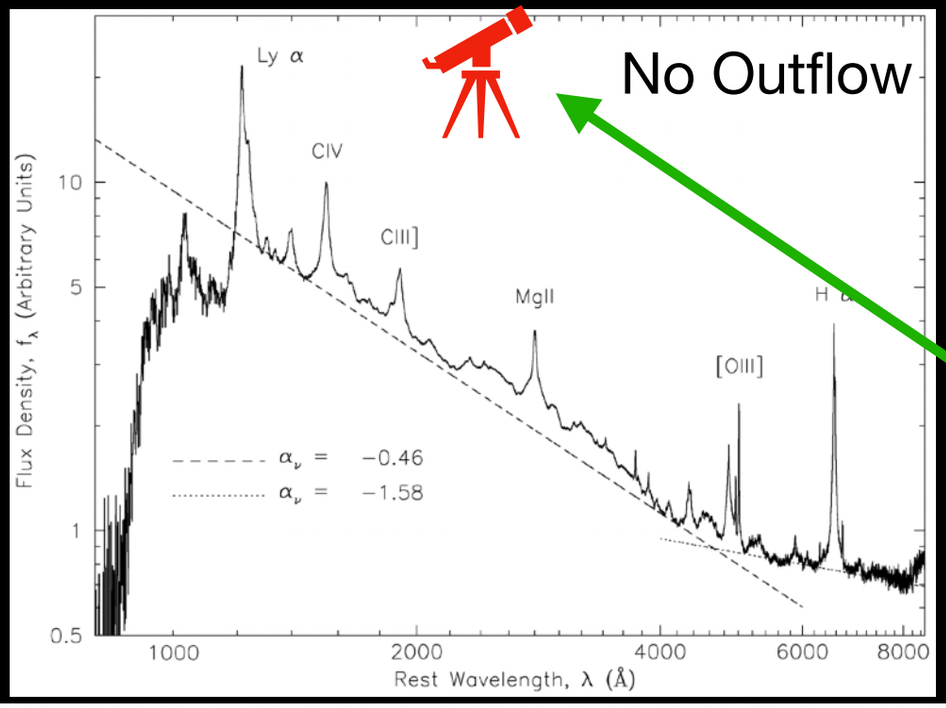

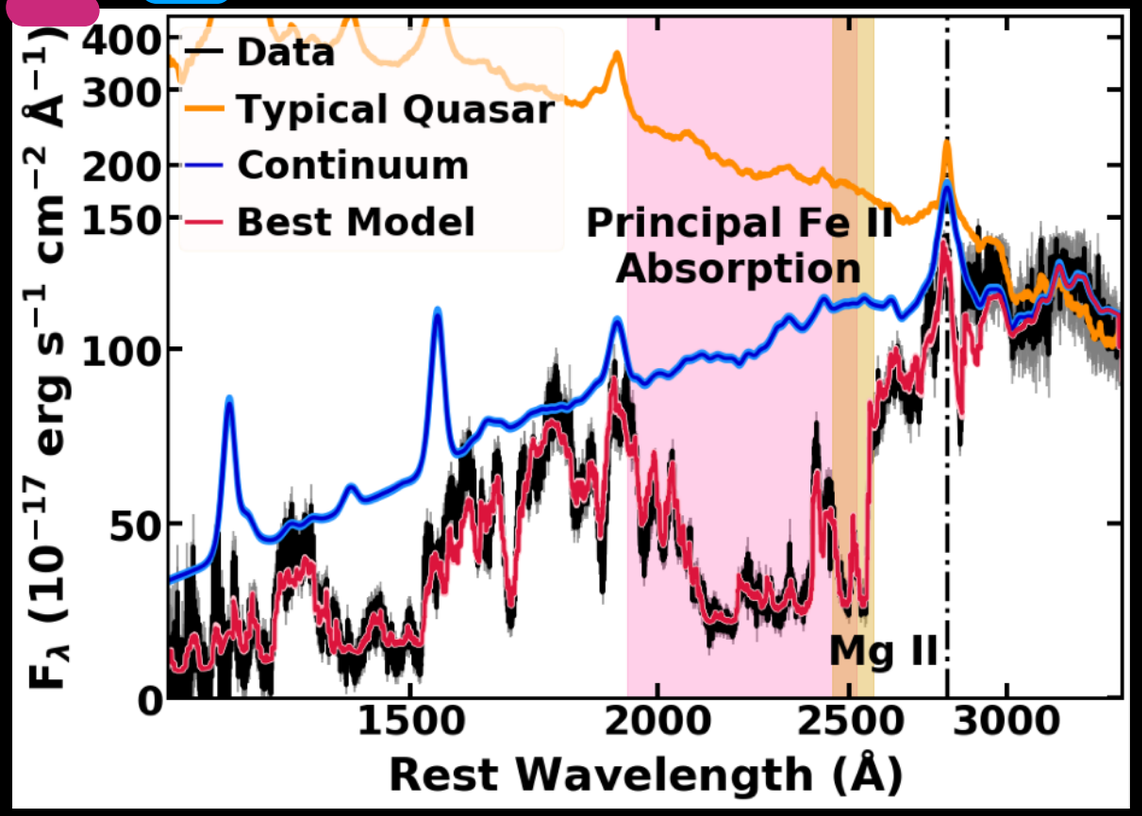

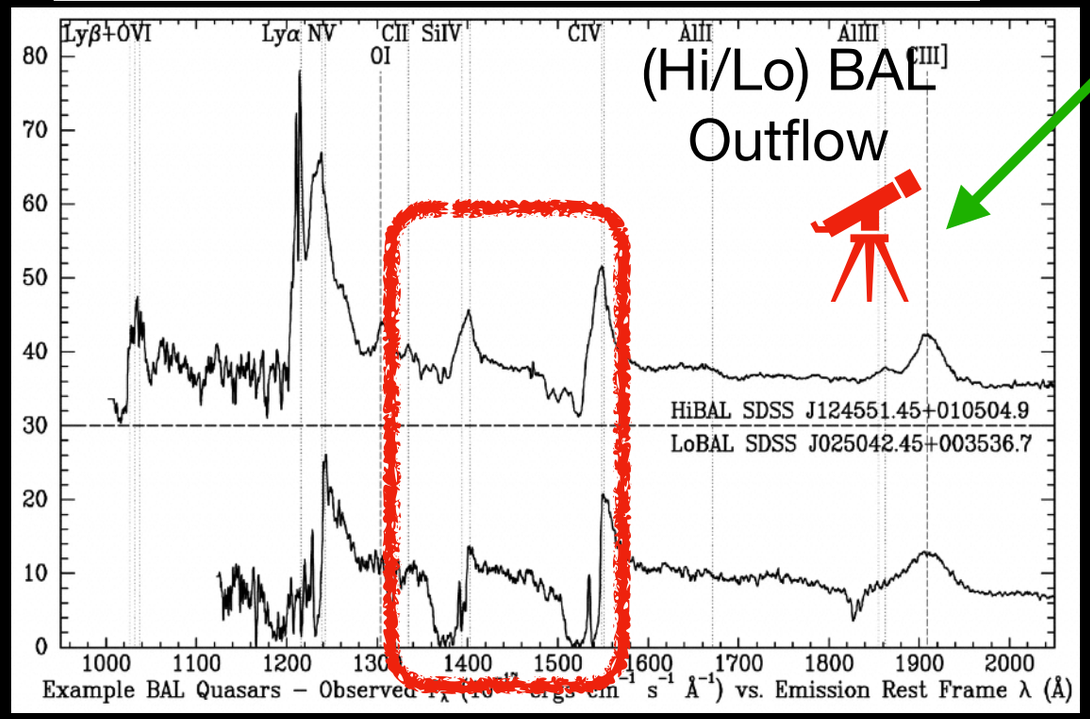

- High column density outflowing gas

➜ ***massive and energetic winds***

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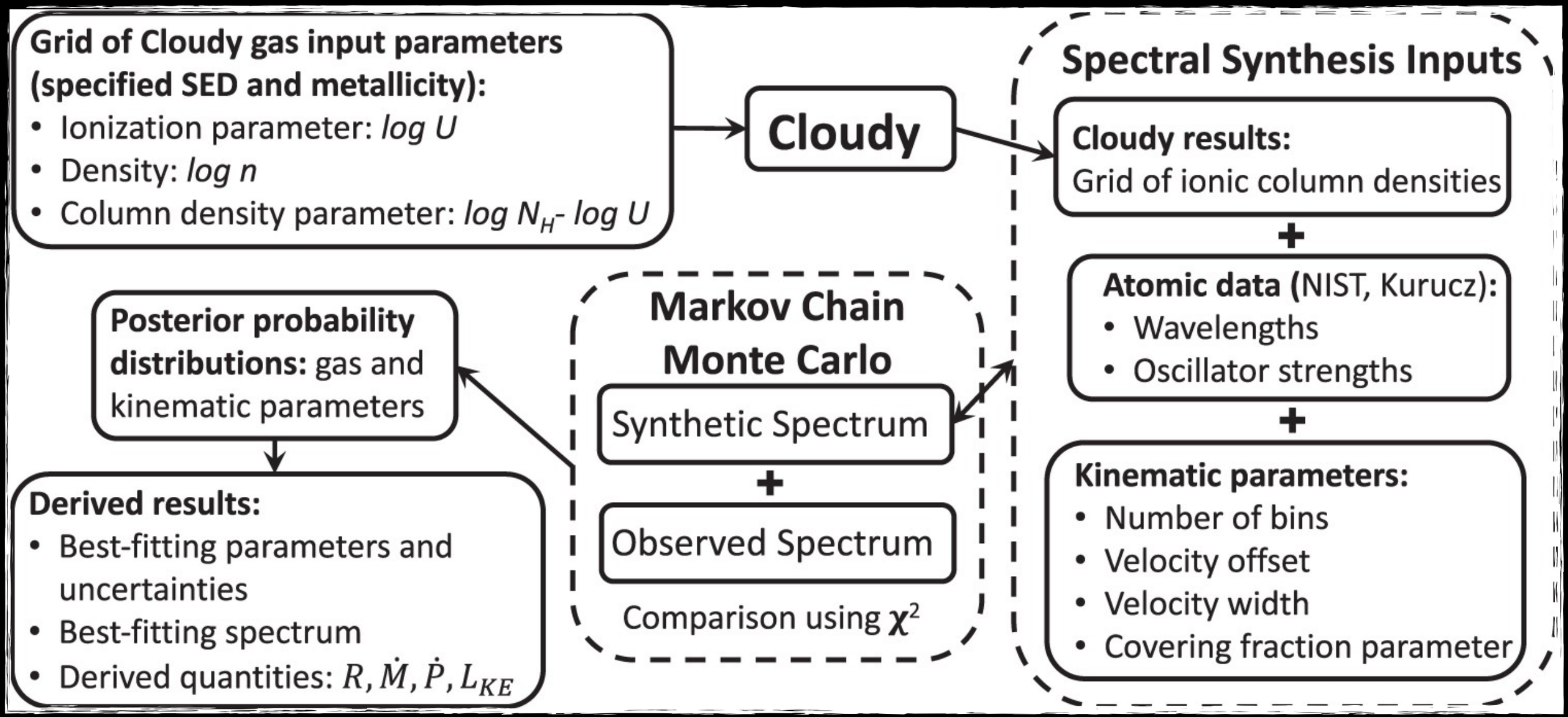
SimBAL

A spectral-synthesis forward-modeling method for analyzing BAL quasar spectra



Leighly et al. 2018

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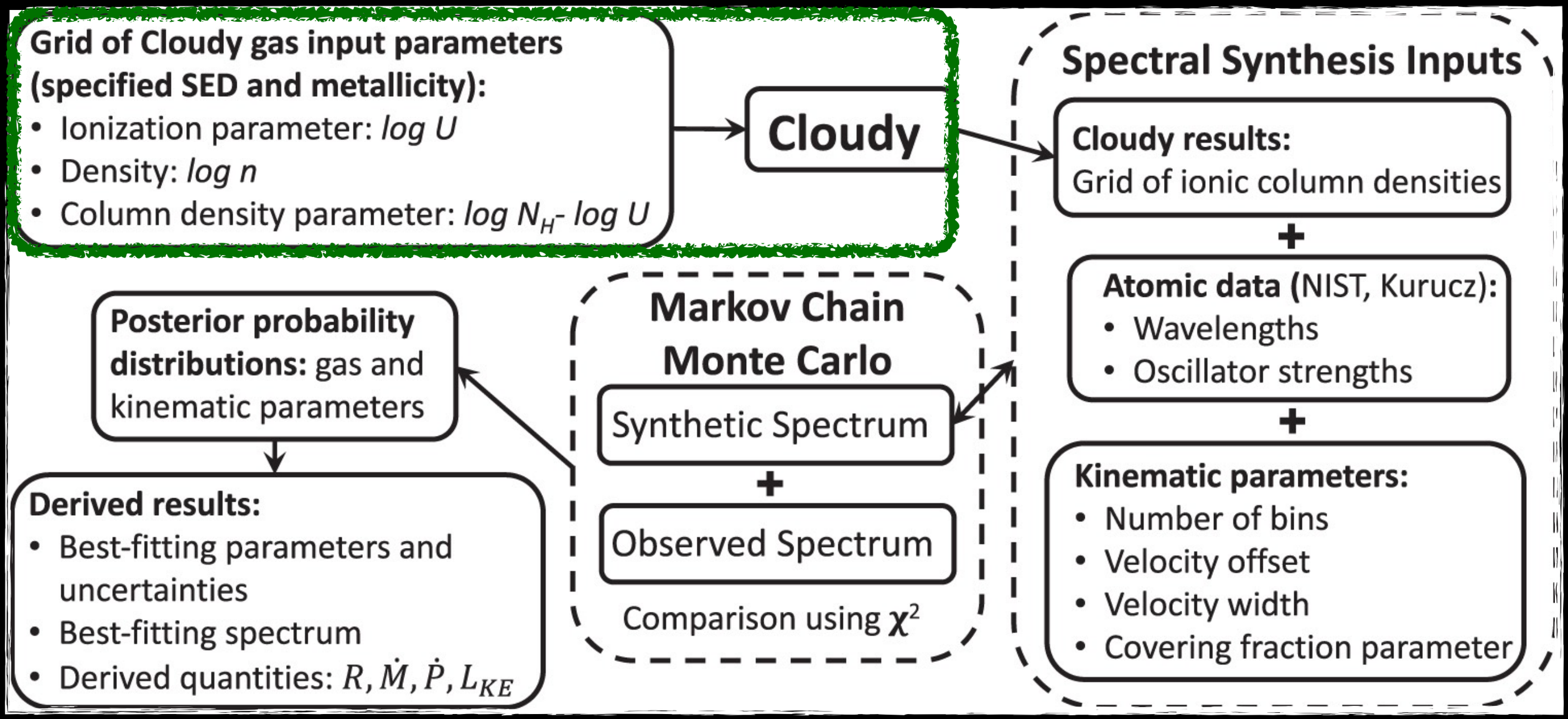

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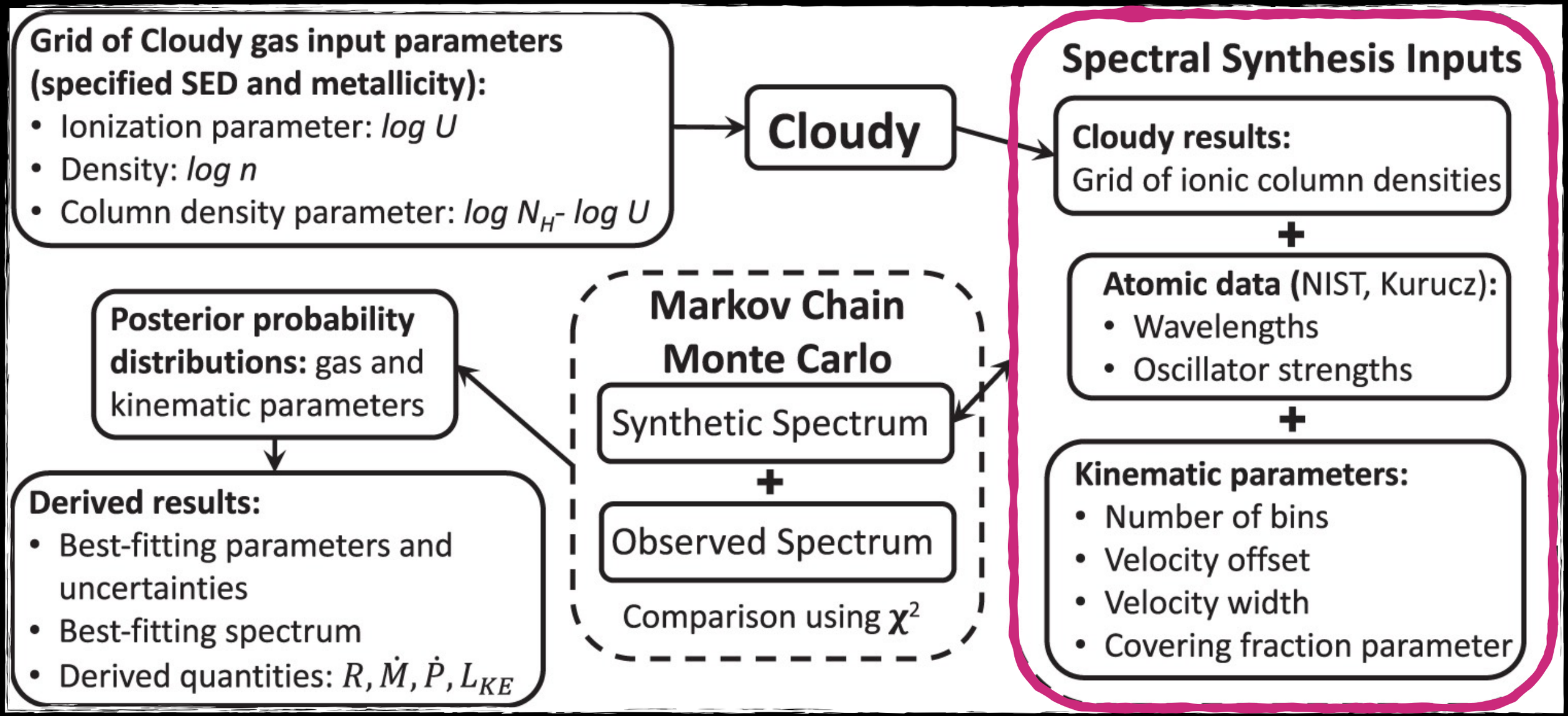

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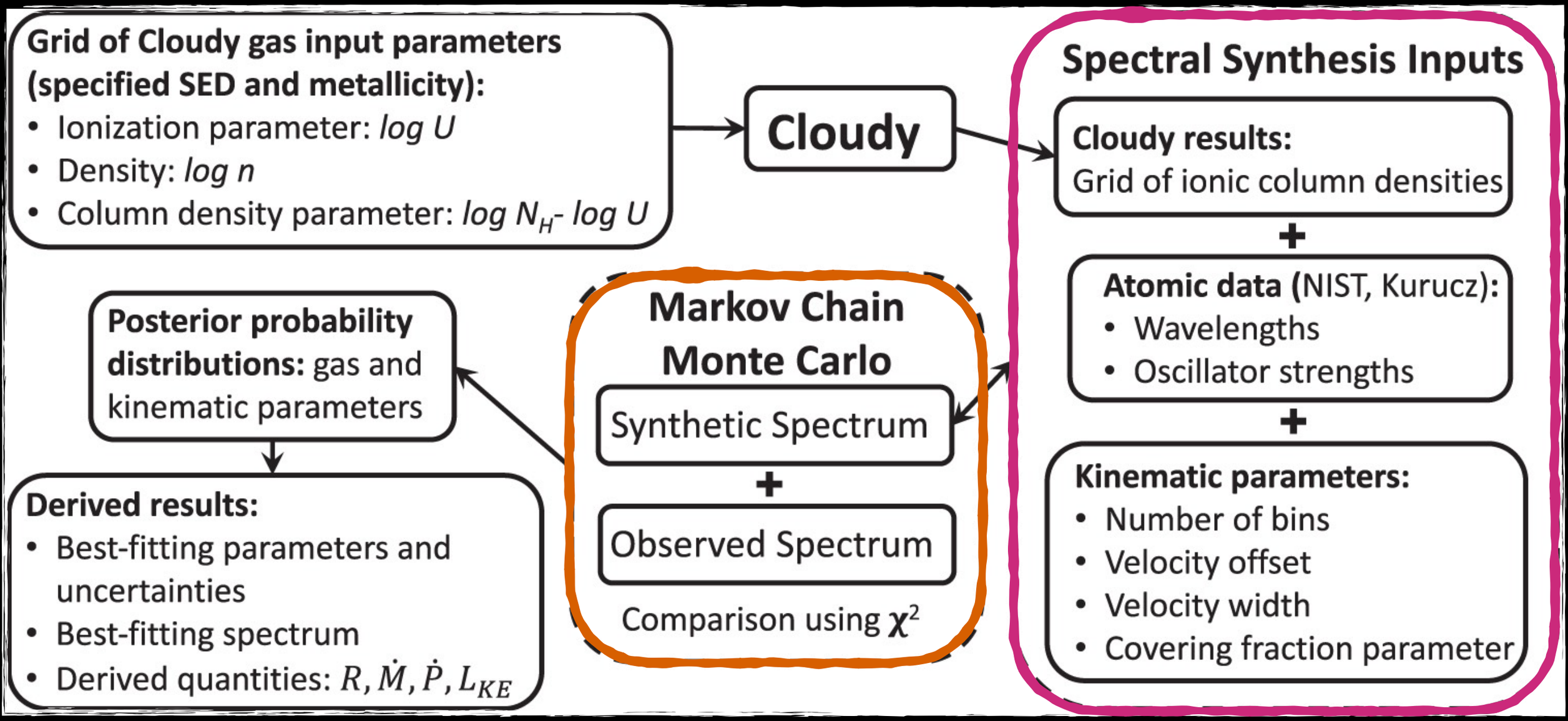

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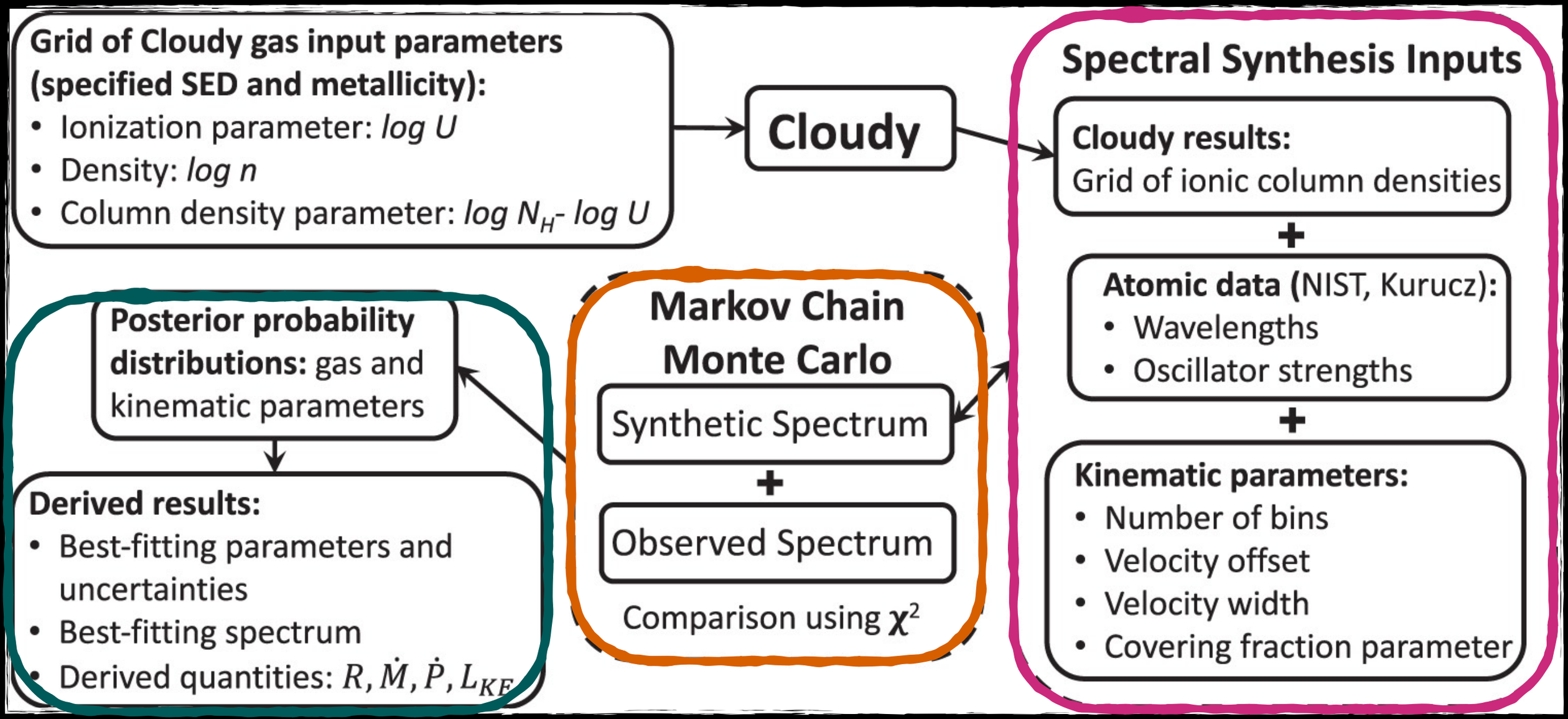


Leighly et al. 2018

The Physical Properties of Low-redshift FeLoBAL Quasars

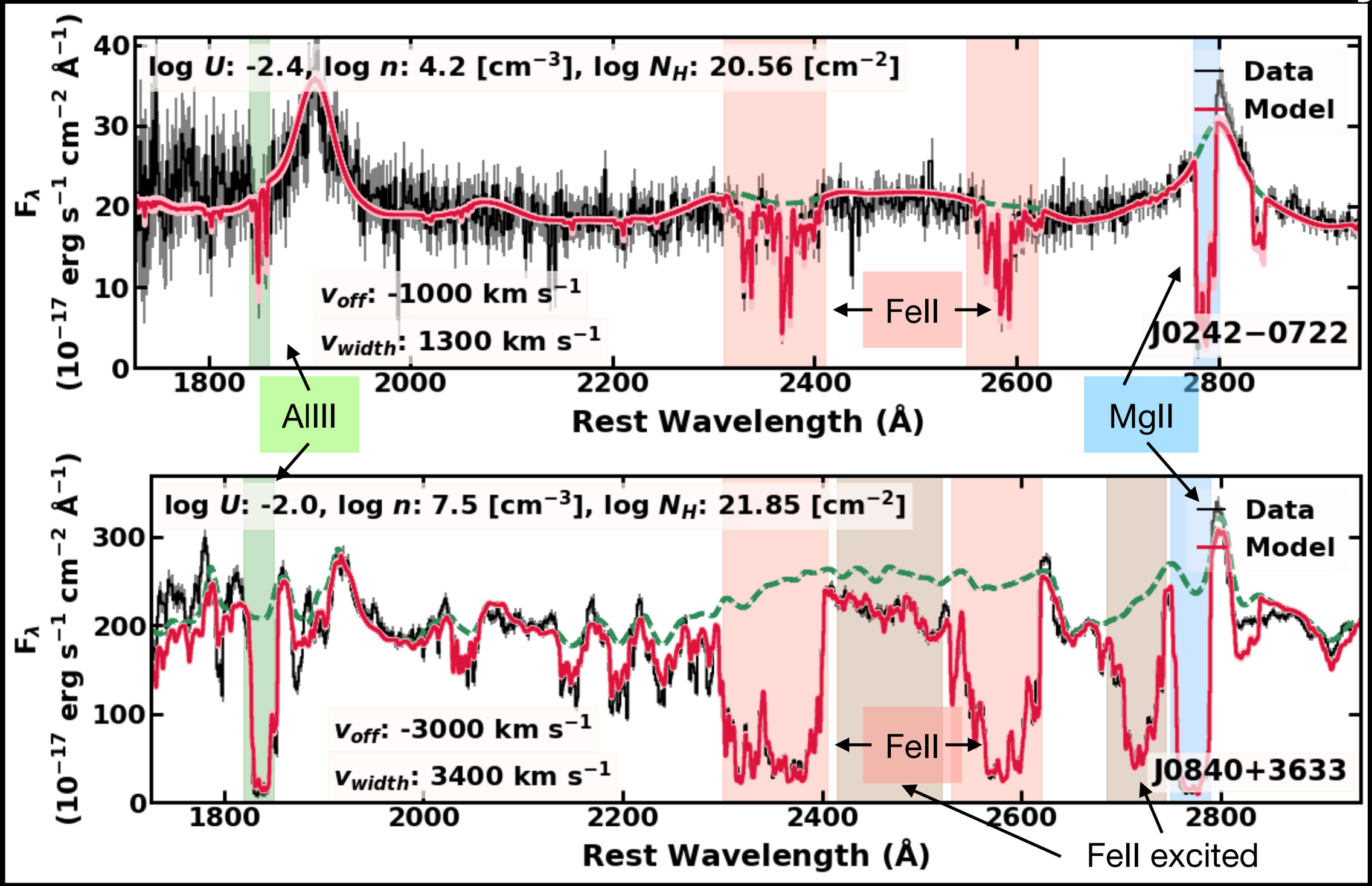
Detailed spectral analysis of 50 FeLoBAL quasars at 0.66 < z < 1.63

- **First systematic study of a large sample of FeLoBALQs (50; more than fivefold increase)**
  ➜ identified ~ 60 BAL systems using *SimBAL* from the Sloan Digital Sky Survey spectra
- Analyze the distributions, trends, and correlations among the outflow properties
  ➜ what are their *physical properties*?
  ➜ where are the FeLoBAL outflow gas clouds *located*?
  ➜ how *massive/energetic* are the FeLoBAL outflows?

Choi et al. 2022, ApJ, 937, 74

FeLoBAL gas at 10s ~ 1000s pc from the central SMBH

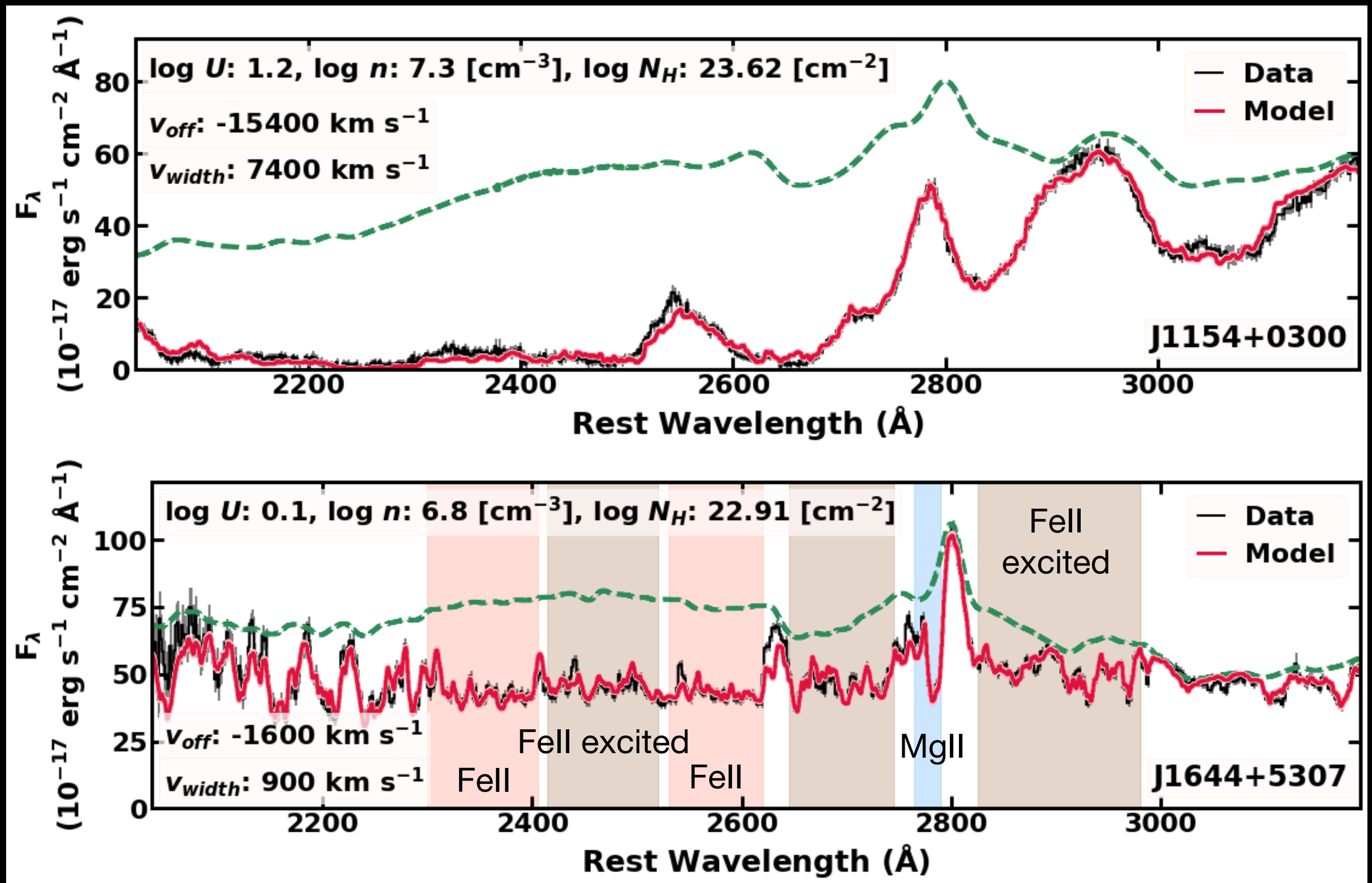
Gas clouds with lower ionization and column density



Please see **Choi et al. 2022, ApJ, 937, 74** to view *SimBAL* model fits of 50 objects

FeLoBAL gas at 1s ~ 10s pc from the central SMBH

FeII and iron-peak elements (e.g., Ni, Cr) create wide blended troughs



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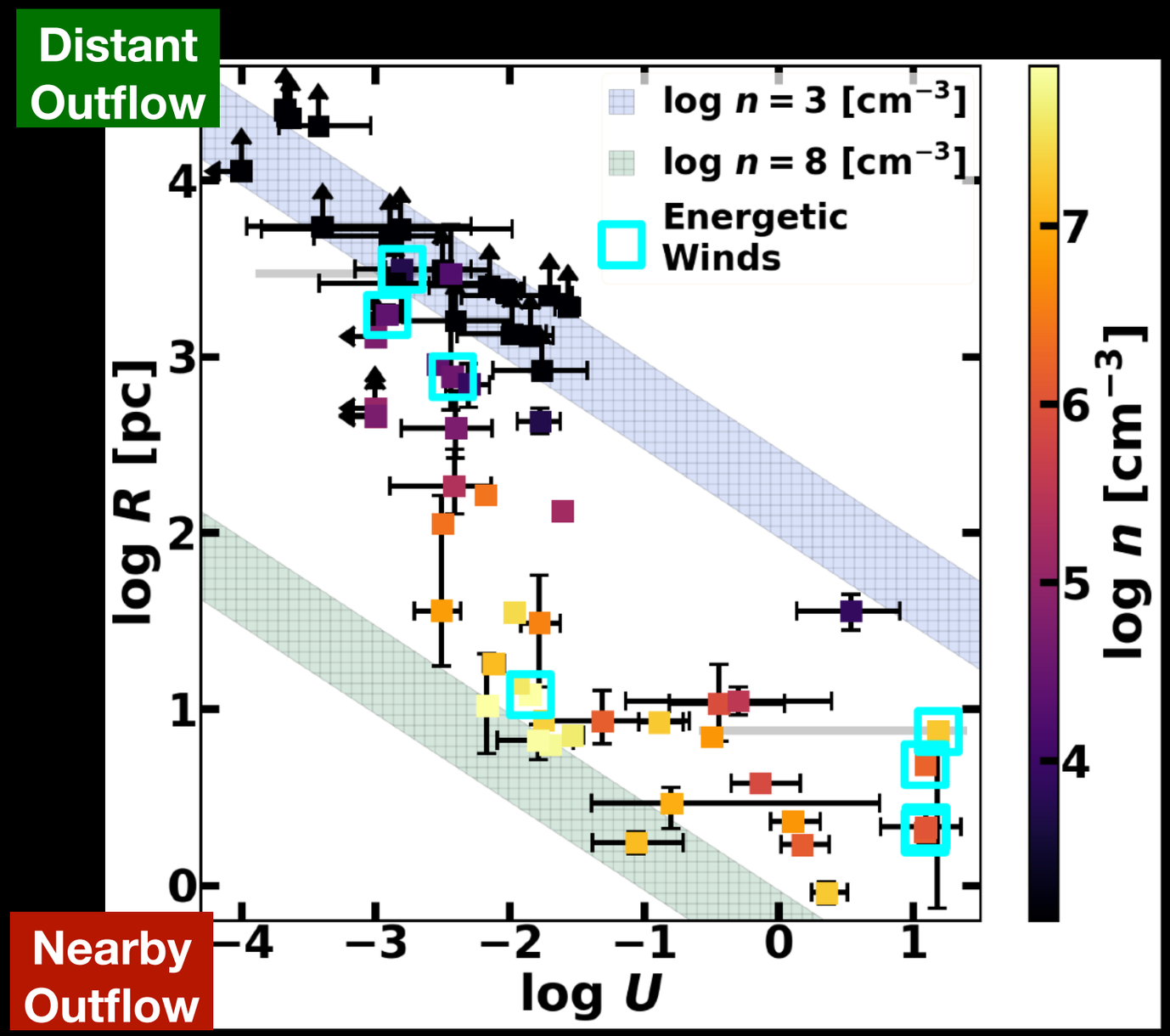
Physical Properties of FeLoBAL Winds

The location of absorbing clouds and their potential origins



Ionization Parameter
(~ionizing photon flux/gas density)

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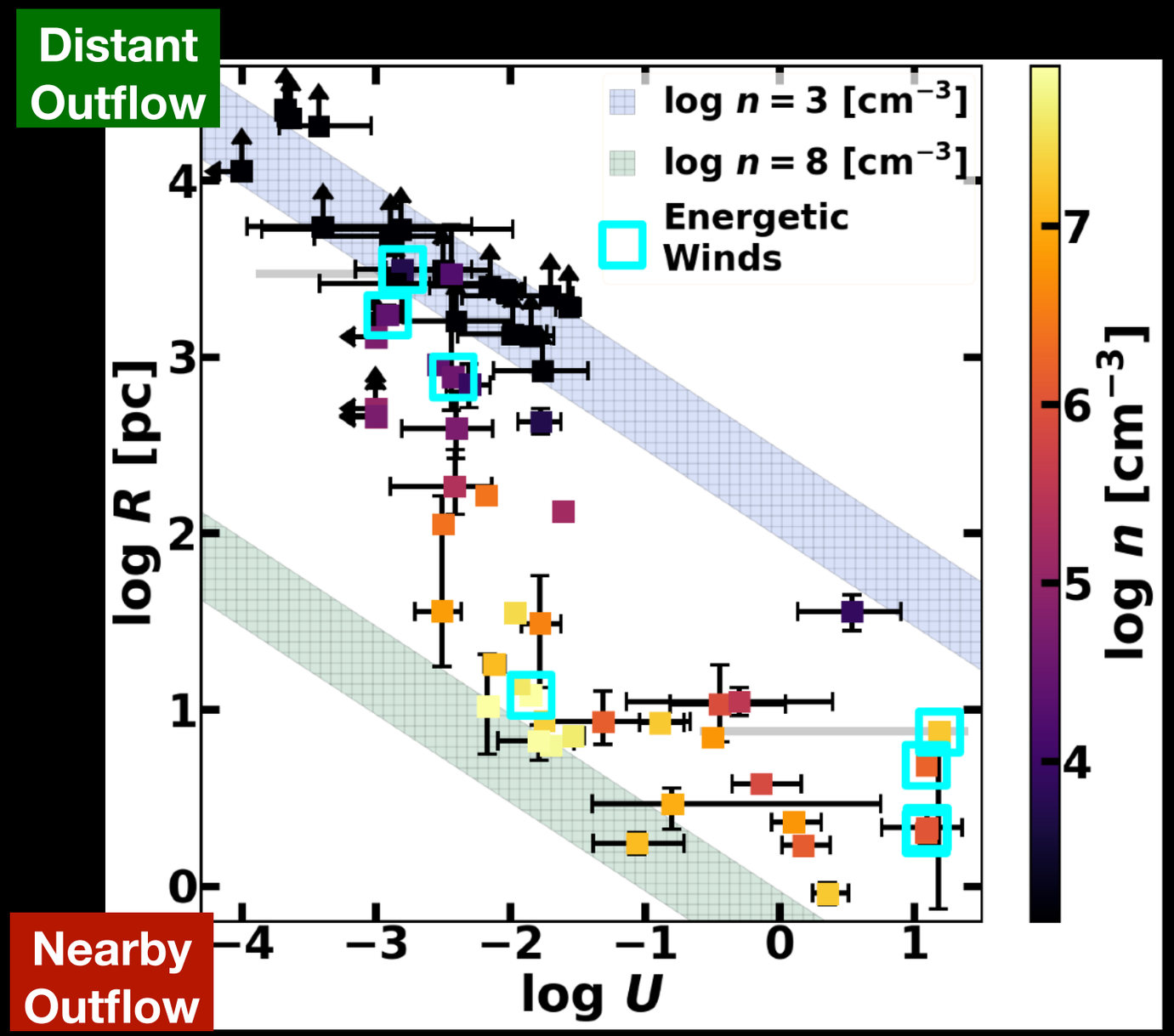
- <u>FeLoBAL winds at a wide range of scales</u>
  ➜ nuclear/torus-scales (~ pc) to galactic-scale (~ kpc)



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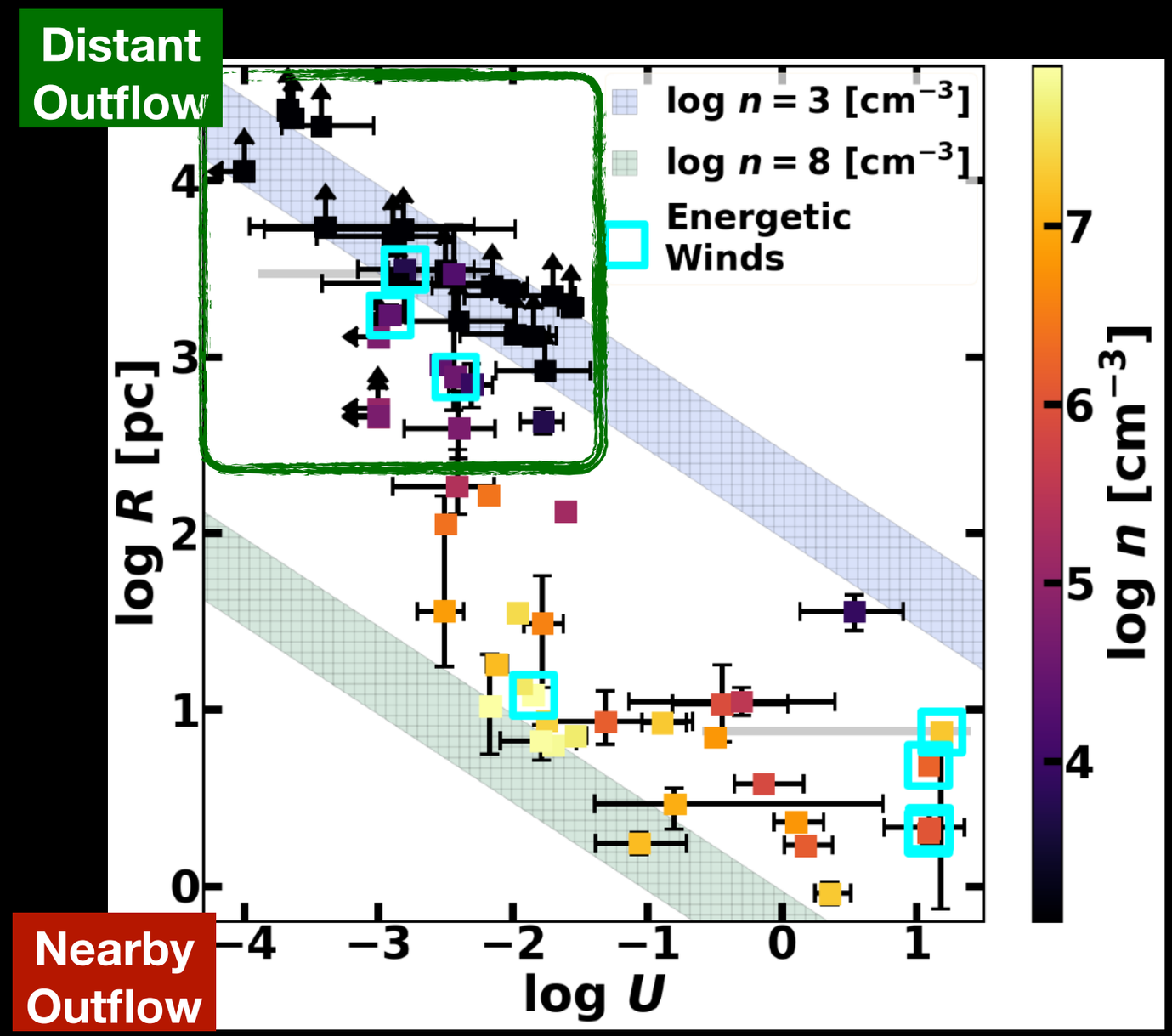
- R > 500 pc: host galaxy ISM
  ➜ "cloud-crushing" (Faucher-Giguière et al. 2012); in-situ formation in radiative shocks



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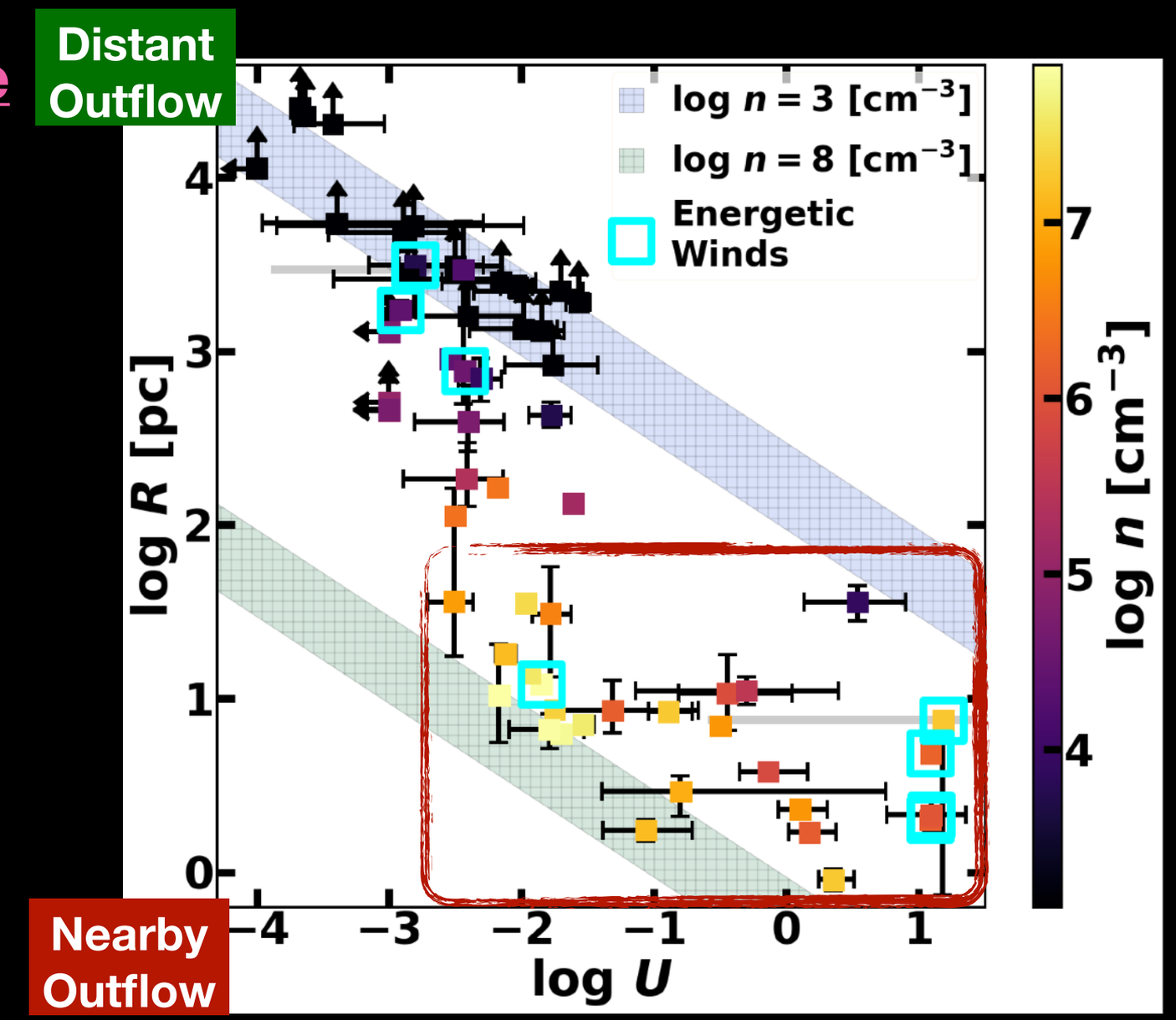
- 10 < R < 500 pc: Torus, Polar Dust, Narrow Line Region (e.g., [OIII])

- 1 < R < 10 pc: Torus
  ➜ radiative line driving, dust acceleration

- *No disk winds (R~0.01 pc)*



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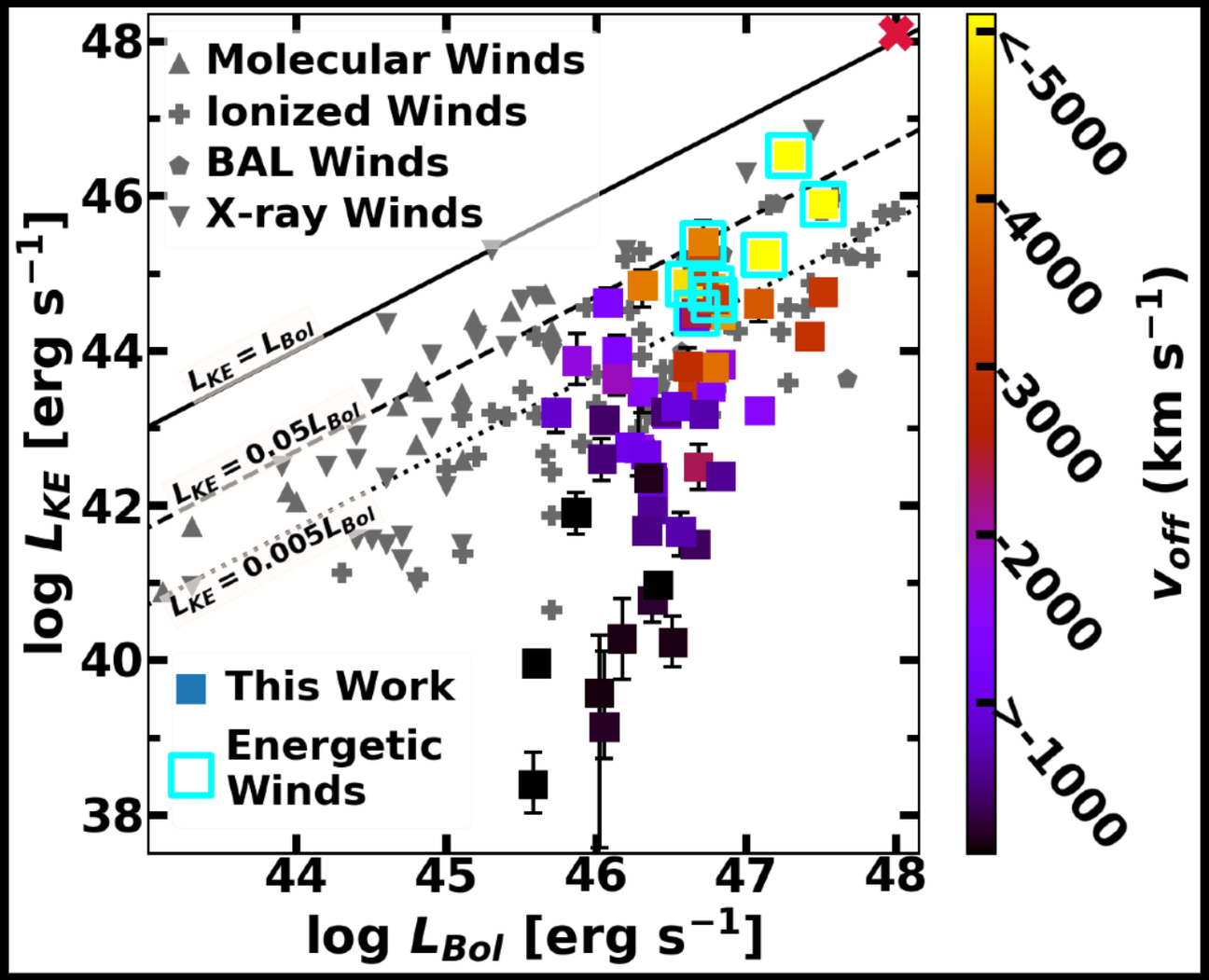
Energetic FeLoBAL Outflows in Luminous Quasars

Faster FeLoBAL winds are found in more luminous quasars

- **Higher luminosity quasars have faster FeLoBAL outflows**
  ➜ more energetic winds that are capable of feedback
  ➜ expected for radiatively driven winds $(L_{KE} \propto v^3)$
- *Luminous BAL quasars are excellent targets for studying the outflow's role in feedback on galaxies*



Outflow compilation by Fiore et al. 2017 + this Work

Summary and Future

A new chapter in the study of BAL quasar outflows

- *First systematic study of a large sample of low-redshift FeLoBAL quasars*
  ➜ wide range of physical properties, large range of distances from the central SMBHs (4 orders of magnitude)
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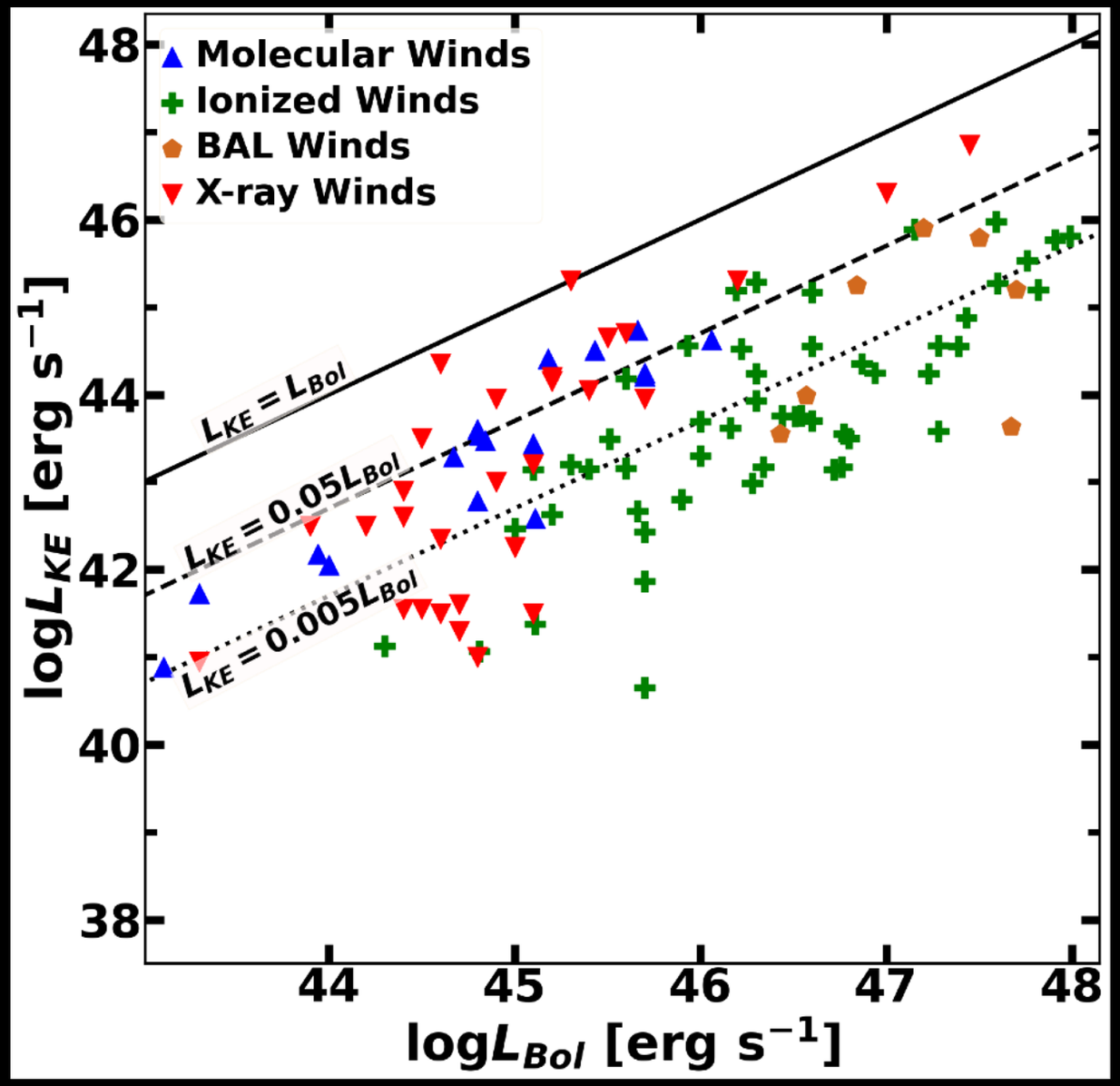

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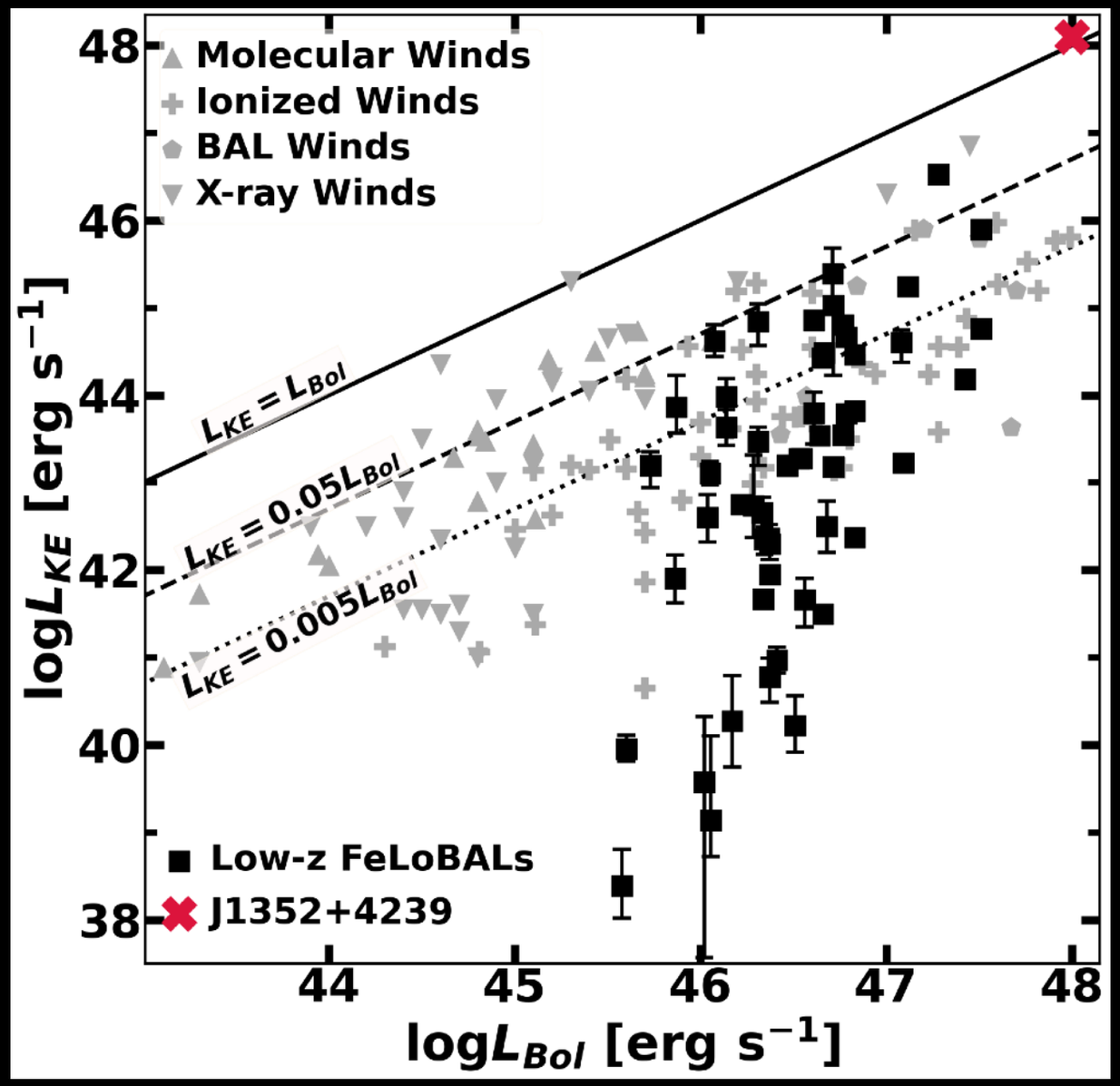

+ Choi et al. 2020, 2022a

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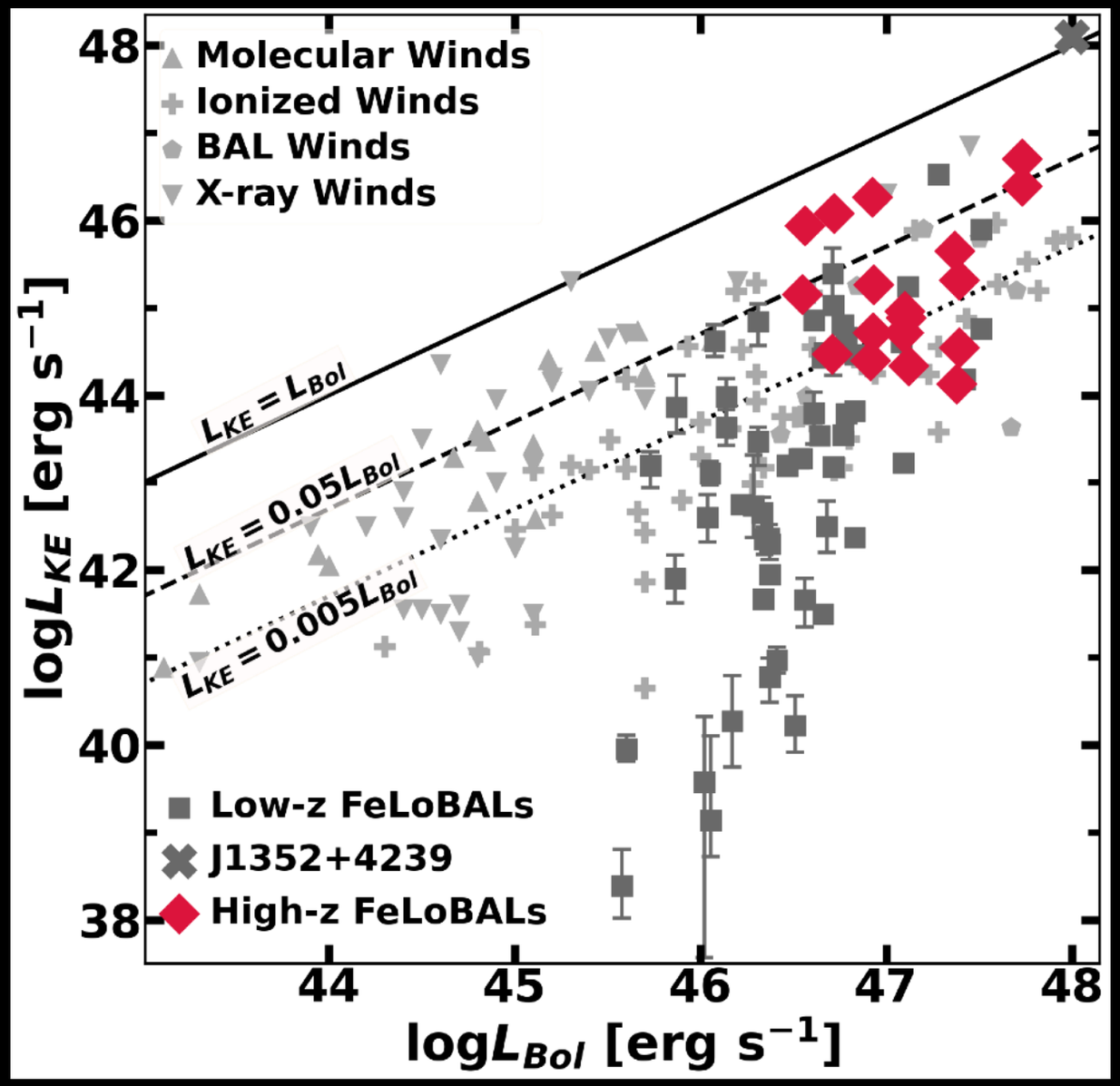


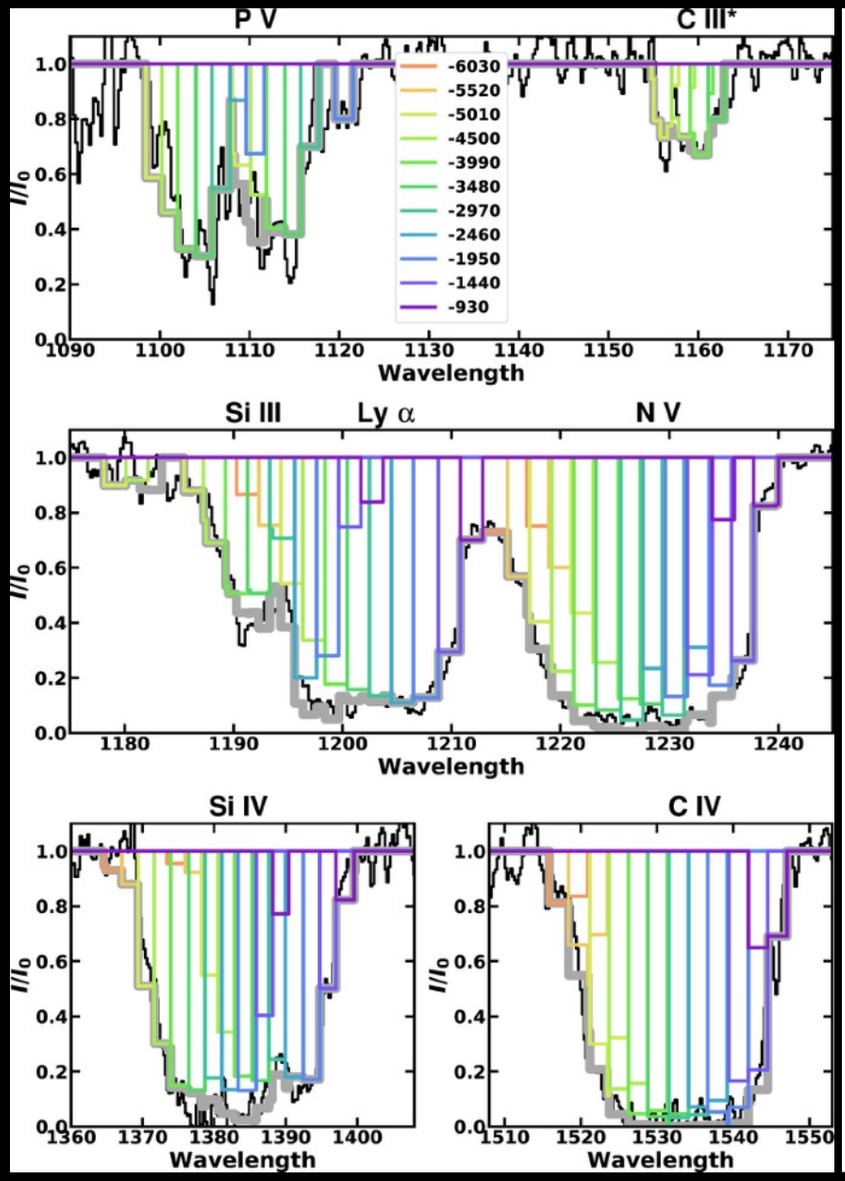
+ Choi et al. 2020, 2022a
+ Choi et al. in prep.

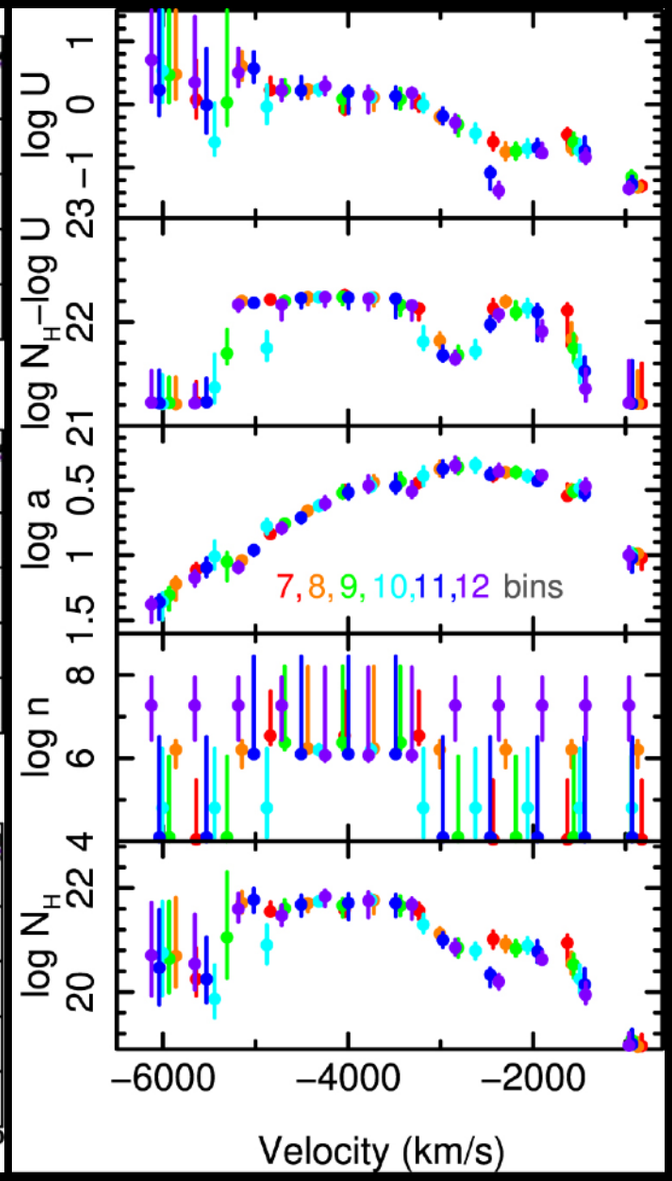
Extra

What else can SimBAL do?

Detailed physical properties of outflowing gas

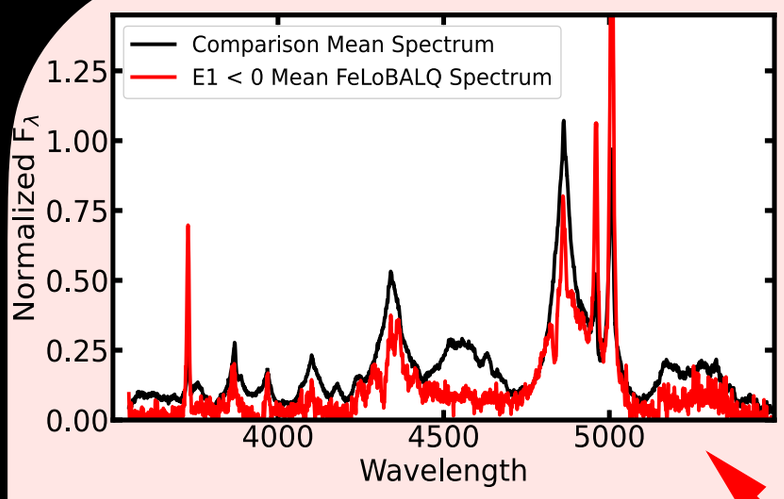
- Use “tophat accordion model” to analyze complex opacity profiles
- Extract physical properties of the gas as a function of velocity
- Useful technique for studying BAL variability (Green et al. under review)

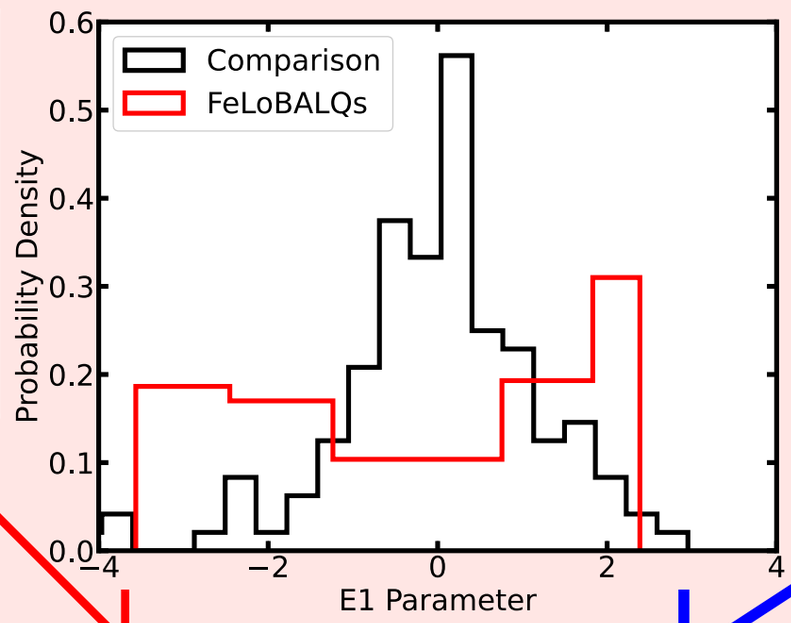


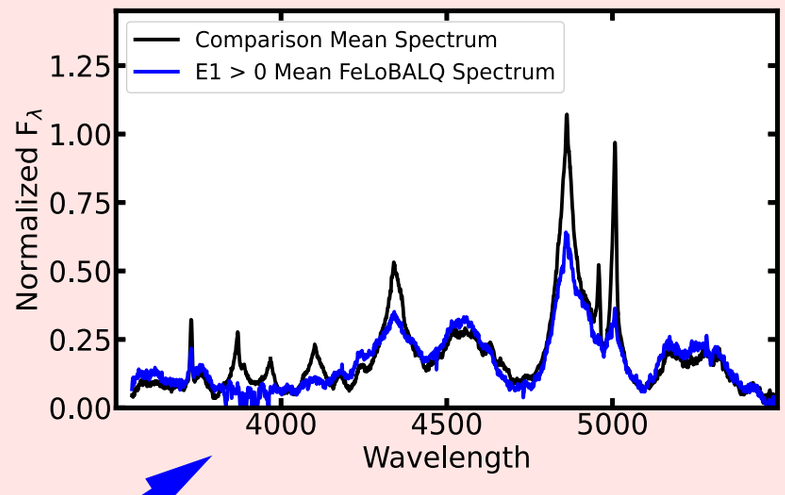


Leighly et al. 2018, ApJ, 866, 7

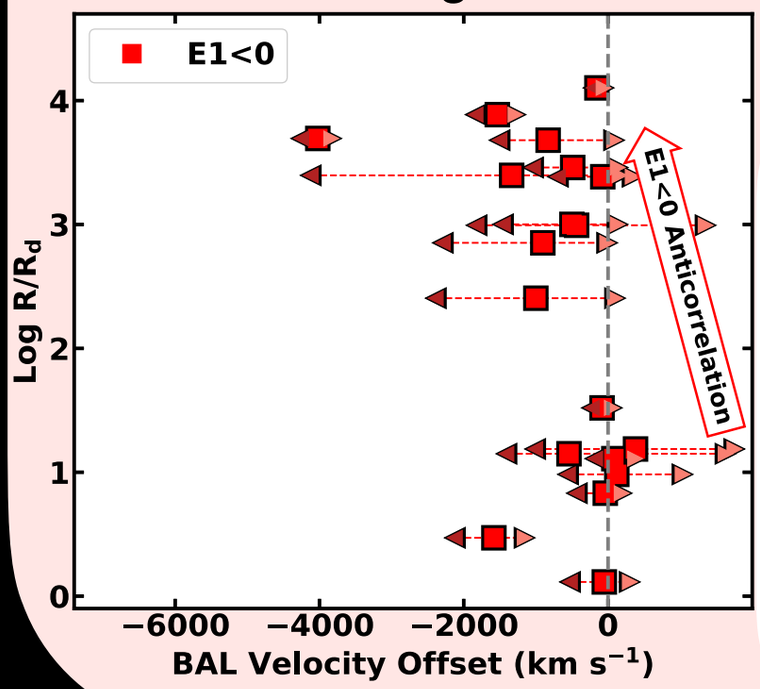
Outflow Properties and Quasar Accretion Properties: Two Populations Different Eddington Ratios and outflow properties







Low Eddington Ratio

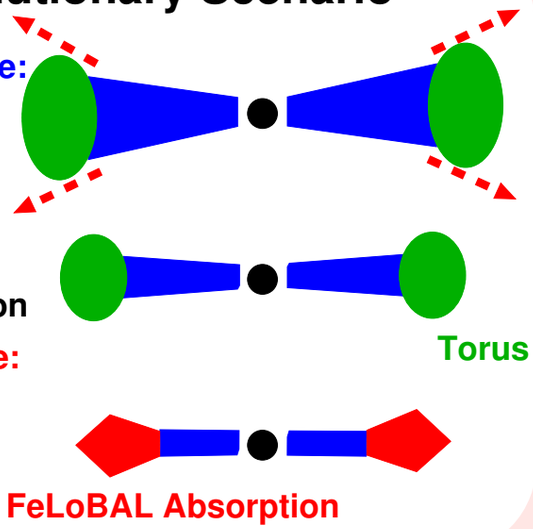


An Evolutionary Scenario

High Accretion Rate:
- Powerful Wind
- Fell Absorption

Intermediate Accretion Rate:
- Thin wind
- No Fell absorption

Low Accretion Rate:
- Failing Torus
- Low Velocities
- Fell Absorption



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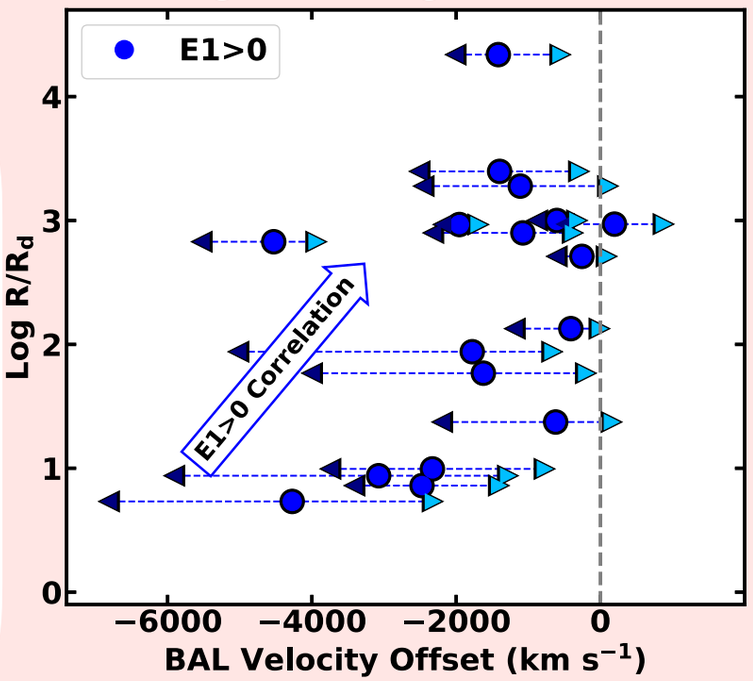

Leighly et al. 2022, ApJ, 935, 92; Choi et al. 2022, ApJ, 936, 110; Leighly et al in preparation