INAOE
Instituto Nacional de Astrofísica,
Optica y Electrónica

Ultra Fast Outflows and their connection to accretion and ejection processes in AGN

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Talk Outline

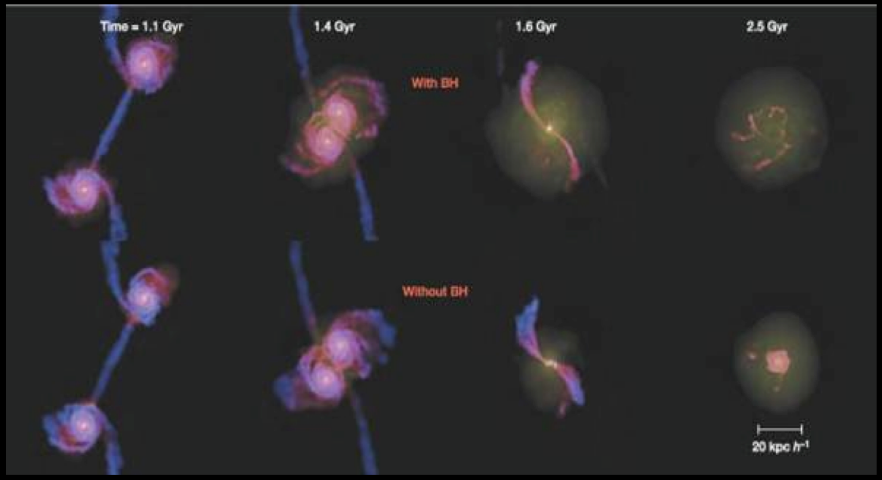
- Brief overview of Ultra Fast Outflows and X-ray spectra
- Connection of UFO with winds in other bands
- Multi-components UFO and shocked outflows signatures
- The latest GTM result on an AGN Energy Driven Wind
- Conclusions and future perspectives

AGN winds: why they are relevant? (I)

The observed velocity shift (almost always to the blue) provides evidence that material is traveling outward from the central region of AGN.

If this material eventually leaves the AGN, then outflows might carry significant mass out of the AGN and, as a consequence, give a substantial contribution to the chemical enrichment of the intergalactic medium (IGM)

Credit: ESA/ATG Medialab, The Why Files

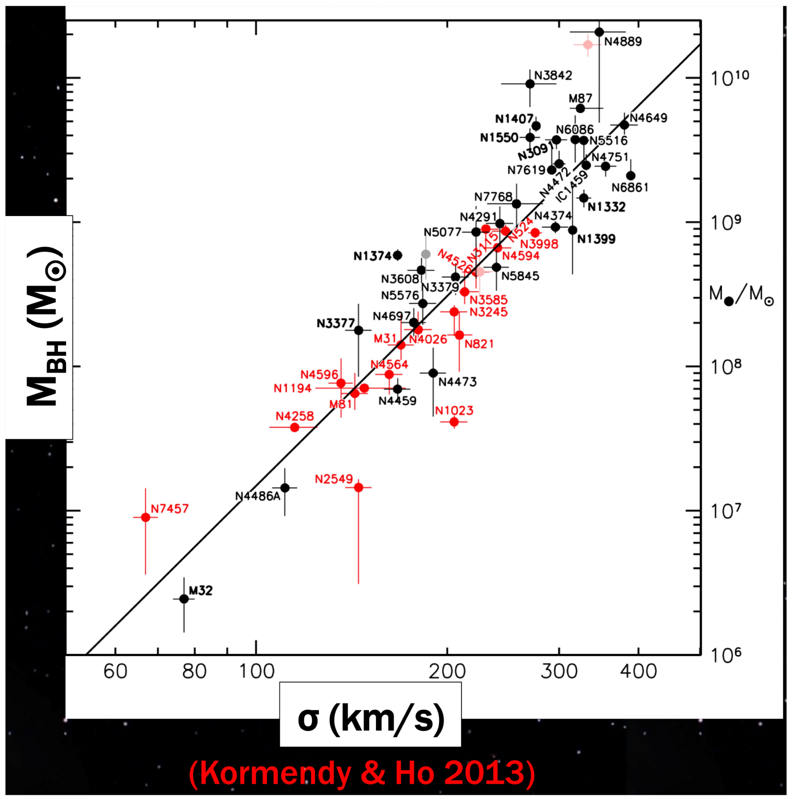


Di Matteo et al. 2005

Outflows may provide the connection between BH and host galaxies

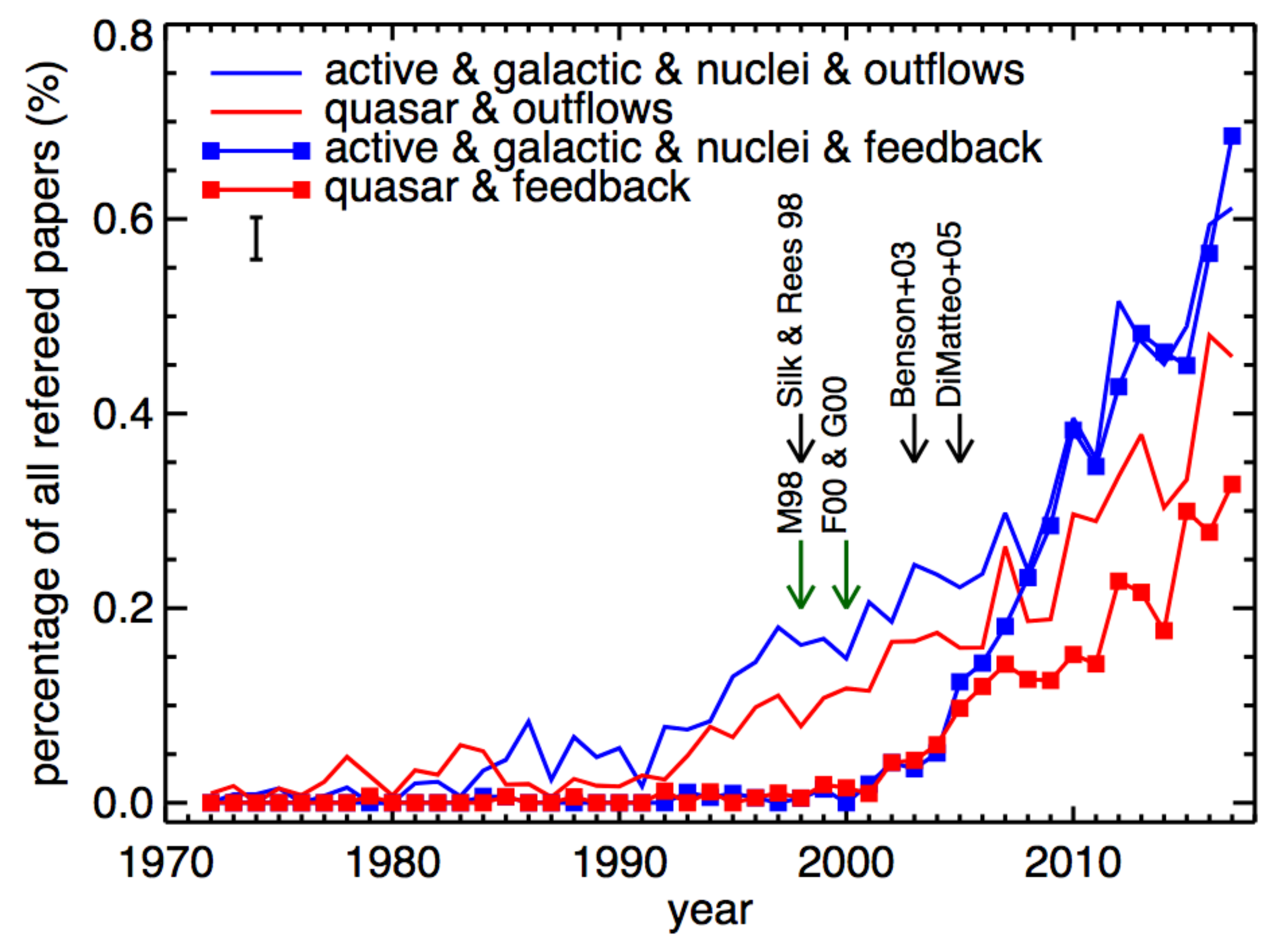
If AGN feedback is 0.5–5% of the AGN luminosity it can regulate the growth of the galaxy and of the central black hole

Hopkins et al. 2010



(Kormendy & Ho 2013)

AGN, Feedback and Outflows in perspective



Harrison et al. 2018 Nat As 2 198H

Abstracts with word combinations of: AGN, quasar, outflows and feedback as a function of time.
The curves show the percentage of all refereed astronomy publications on SAO/NASA ADS with abstracts containing the combination of keywords shown in the legend, each year.

The rapid growth is related to 3 papers that characterise M_{BH}–host galaxy relationships:

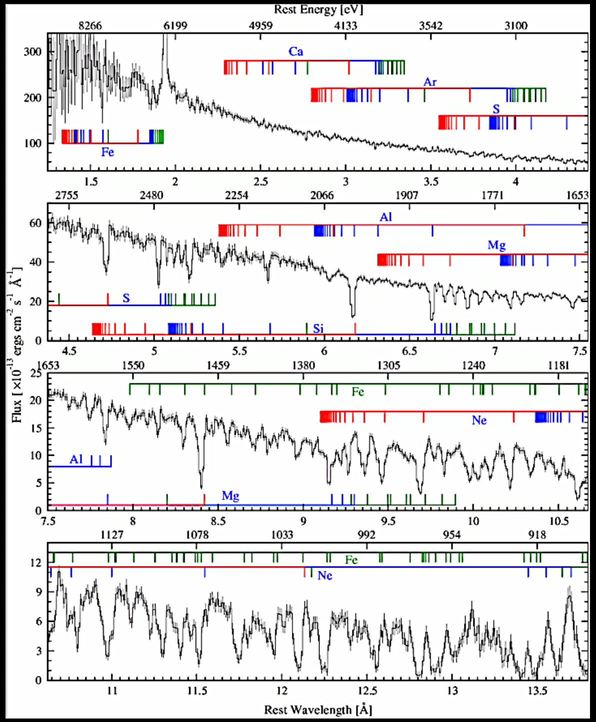
Magorrian et al. 1998
Ferrarese & Merritt 2000
Gebhardt et al. 2000

and a series of papers on galaxy formation analytical and semi-analytical models and hydrodynamical simulations that require AGN-driven outflows to explain the observables properties:

Silk & Rees 1998
Benson et al. 2003
Di Matteo et al. 2005

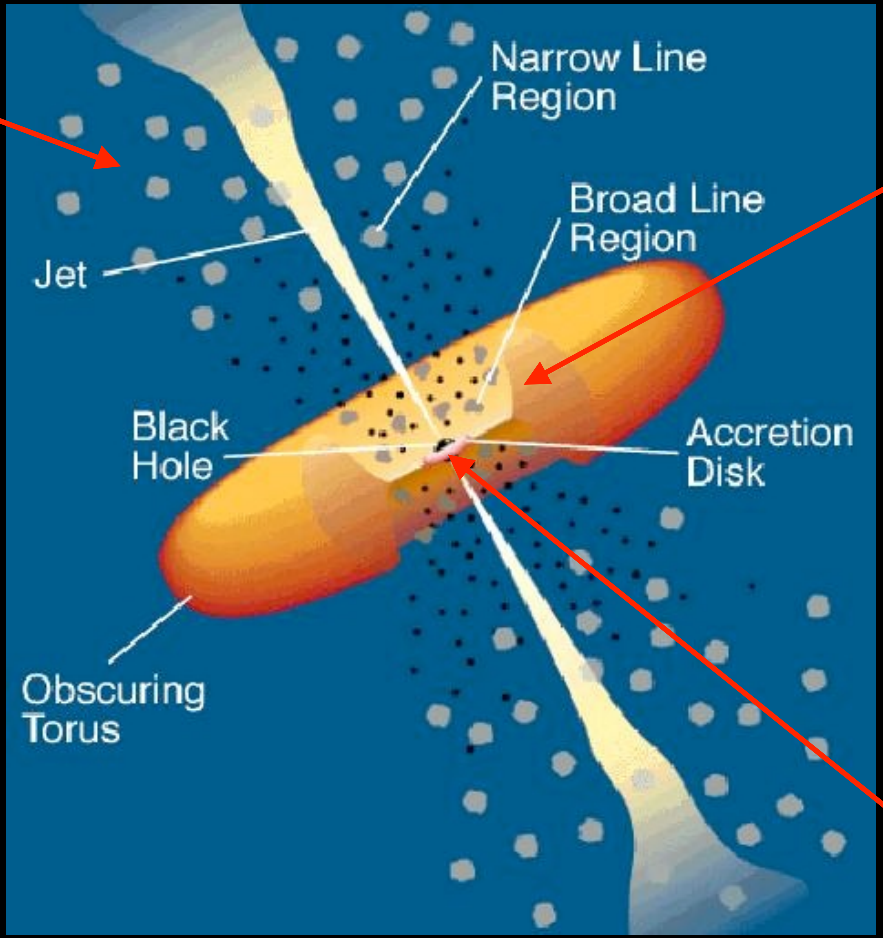
AGN winds: why they are relevant? (II)

The ionized gas revealed in the spectra does not have a definitive collocation in the classical Unification model

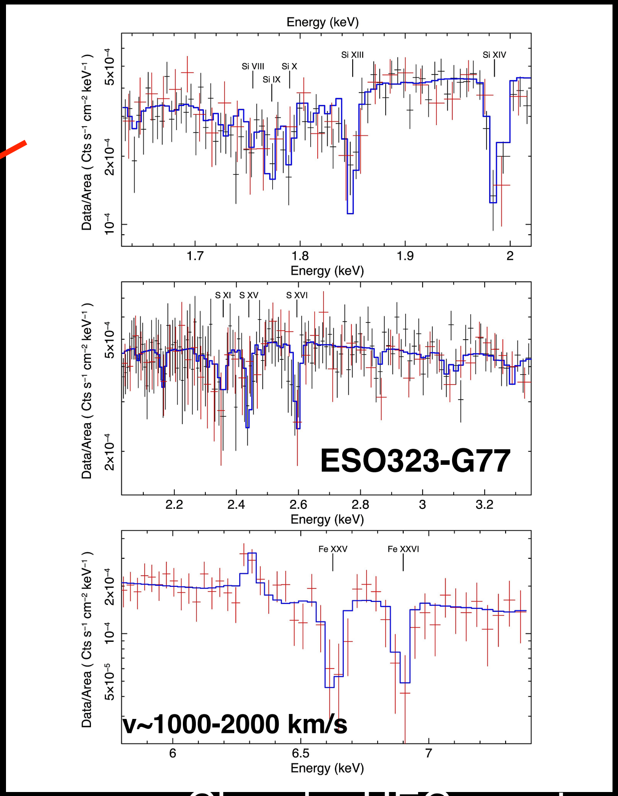


NGC 3783 Chandra HETG 900 ks

Kaspi et al. 2002, Krongold+03

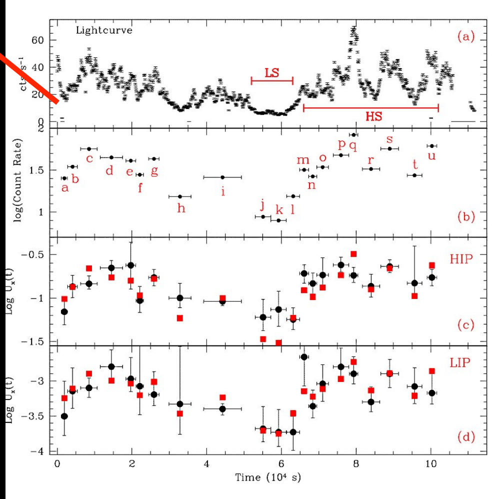


Sanfrutos et al. 2016



Chandra HEG spectrum

NGC4051



Krongold et al. 2007

Wind location (and launching radius) is key to understand how they form

⬇

Theoretical models & Simulations

Properties of AGN Winds in X-rays spectra (in a nutshell)

Gratings spectra (E/ΔE~1000) offer higher detail diagnostics (historically on warm absorbers):

-Outflow velocity (generally 10^{2-3} km/s but see UFO)
-Wide range of Ionization states in the outflowing gas
-Column density 10^{20-22} cm^{-2}
-Associated to UV outflow (kinematics)
-Location mostly probed by variability studies (torus, accretion disk, NLR)
-Covering factors of ionized gas

CCD spectra (E/ΔE~30-40) offer photons and (often) larger samples in the archives:

-50% of Seyfert 1
-Column density 10^{20-23} cm^{-2}
-Ionized gas in high z sources (higher Luminosity range) often not accesible by grating spec
-Path for variability studies (more photons, repeated observations, multiple exposures in archives)

Wind Output Rate: UFO vs Warm Absorbers

Outflow velocity makes the difference (not only in the name!):

$$\dot{M}_{\rm out} \sim \Omega\, N_{\rm H}\, m_{\rm p}\, v_{\rm out}\, R_{\rm in}$$

Mass outflow rate

Solid angle

Column density

Outflow v

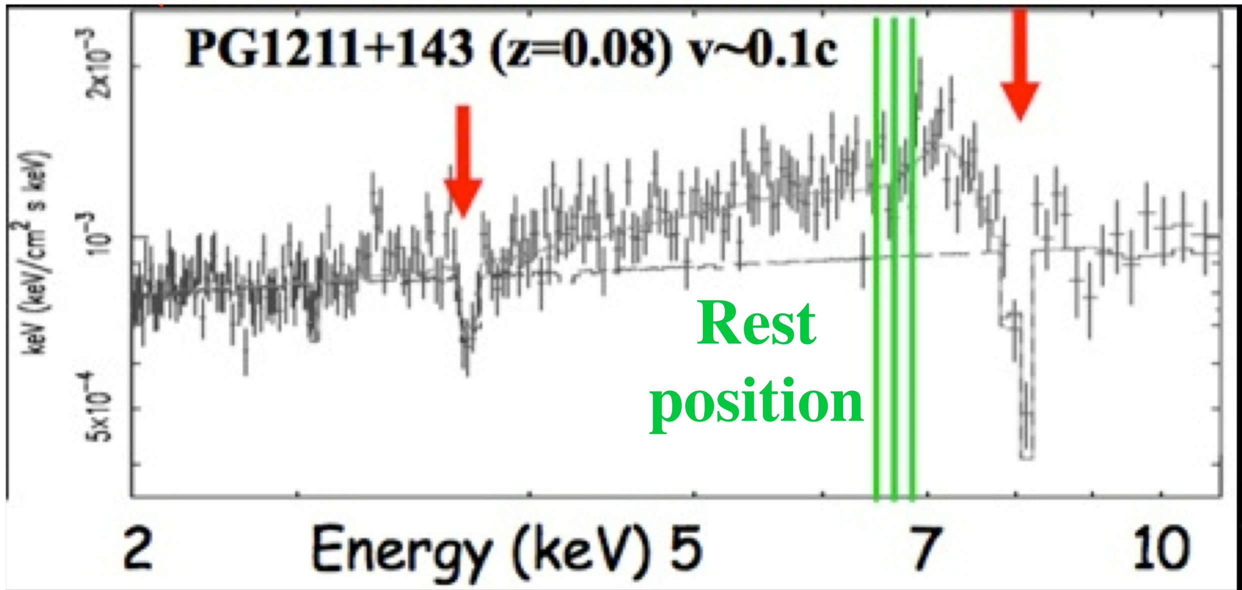
Launching radius

$$\dot{E} = \frac{1}{2}\dot{M}_{out} \mathrm{v}_{out}^{2}$$

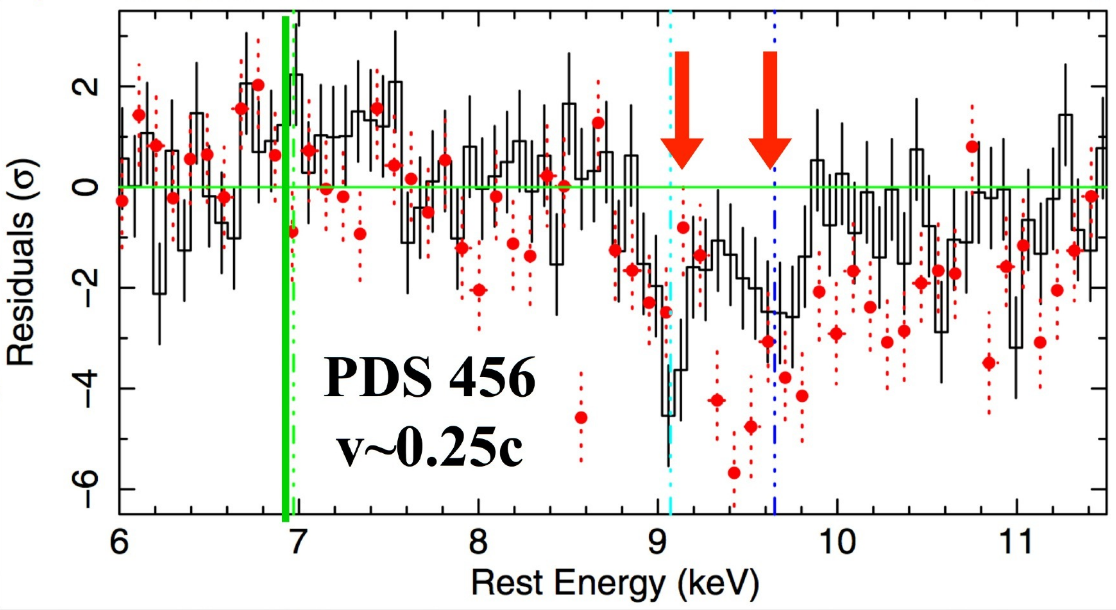
The mechanical power of the wind depends strongly on velocity

Ultra Fast Outflows (UFOs): what are they?

Observed in the Fe K band as blue shifted absorption lines by highly ionized Fe



(Pounds et al. 2003)



(Reeves et al. 2009)

Properties from systematic studies at CCD resolution (XMM-EPIC, Suzaku) (Tombesi et al. 2010, 11,13; Gofford et al. 2013,2015)

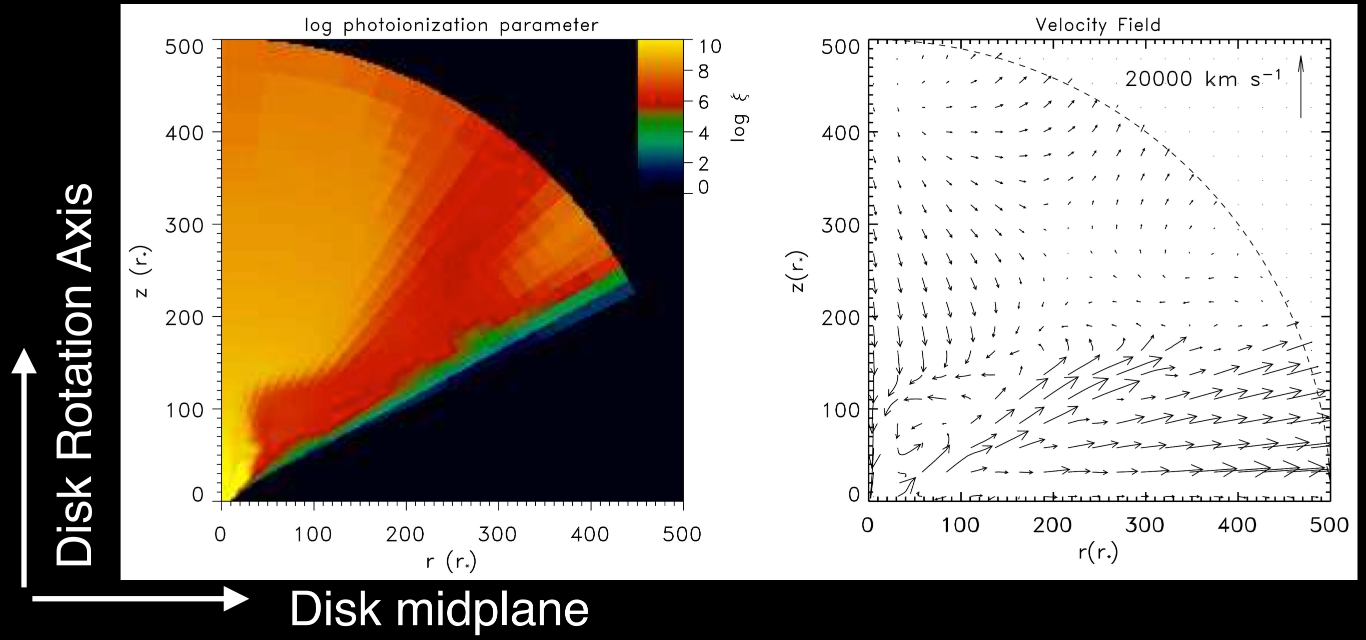
- -Present in 30-40% of X-ray samples
- -Outflow velocity ~ 0.1-0.3c
- -Mass outflow rate ~0.01-1 $M_\odot$ yr^{-1}

~~-Long and animated debate on their reality in the X-ray community~~

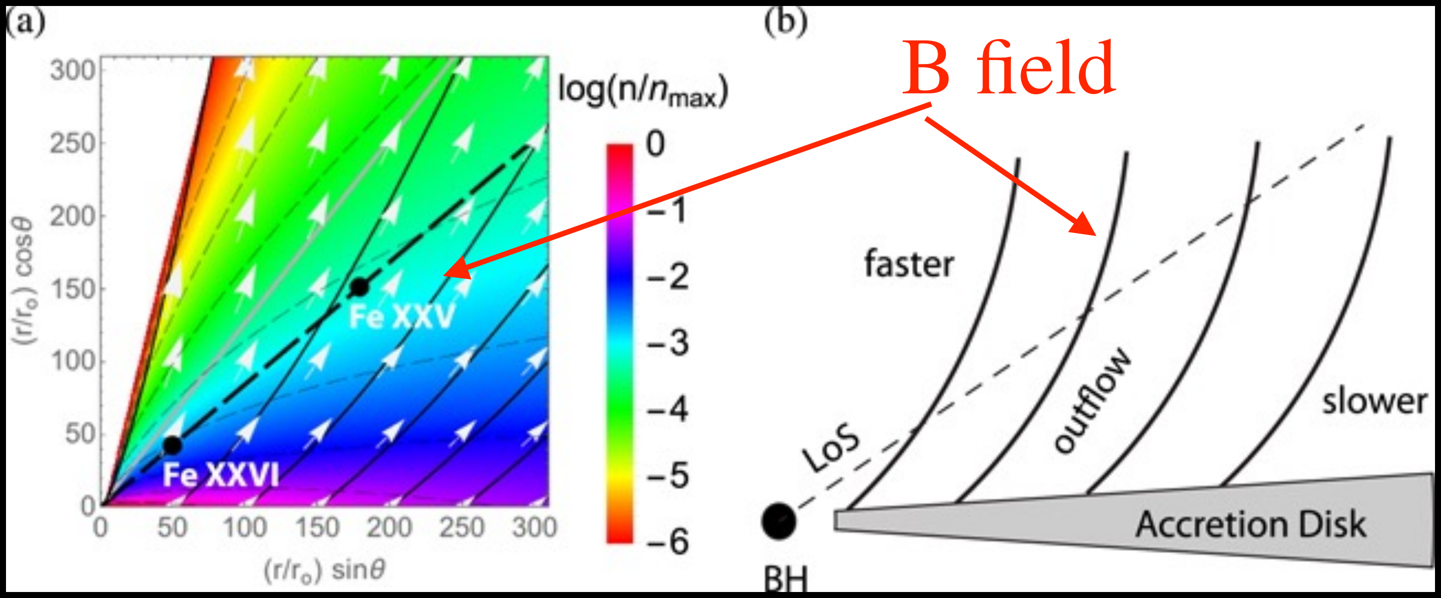
UFO Launching mechanism: disk winds

Color map of ionization parameter

Velocity Field



Simulations of radiatively driven disk winds produce blue-shifted highly ionized Fe absorption
Proga & Kallman 2004
Sim et al. 2008, 2010

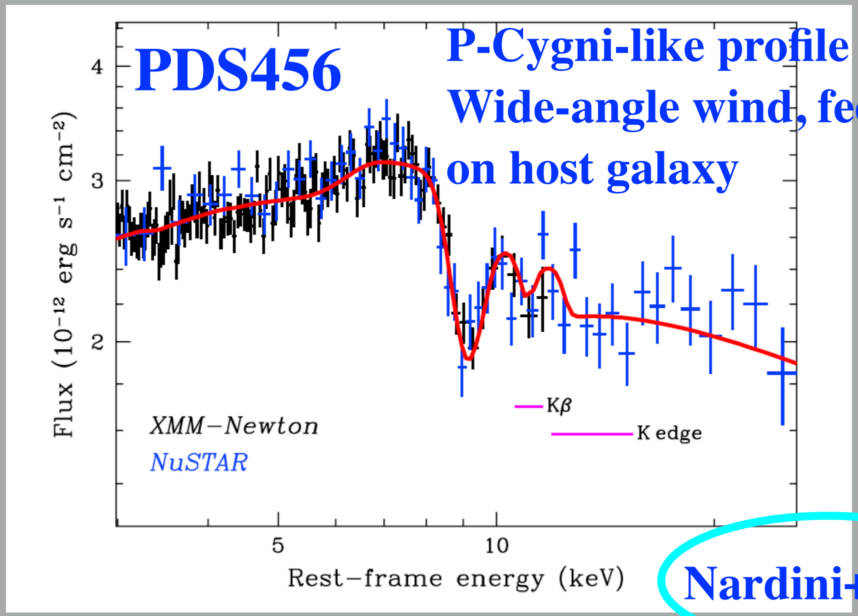


Magnetically driven outflows reproduce observed properties of highly ionized ultra fast outflows
Fukumura et al. 2015

UFO observed in RL sources
Tombesi et al. 2013

2015: Golden year for AGN fast winds

Several new discoveries, most of all supported by evidence for multi-phase AGN outflows



PDS456

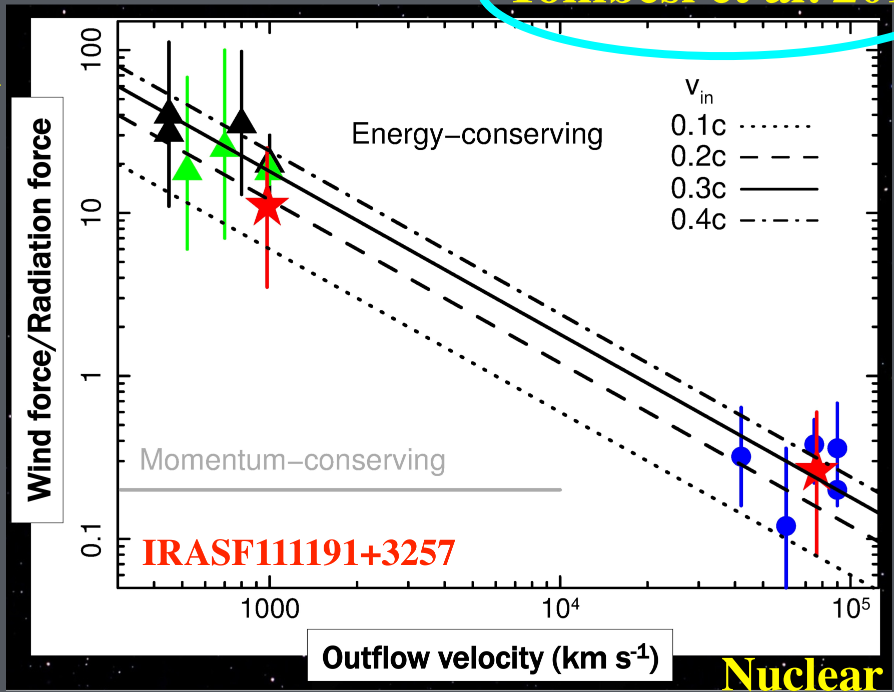
P-Cygni-like profile
Wide-angle wind, feedback on host galaxy

Nardini+2015

Molecular winds at Kpc-scale

Tombesi et al. 2015

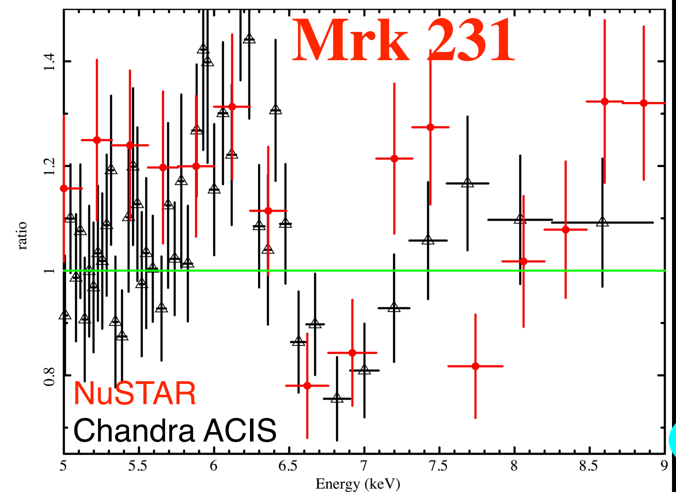
Connection of X-ray fast wind and massive molecular outflows follows the prescription of an energy driven outflows (momentum not constant)

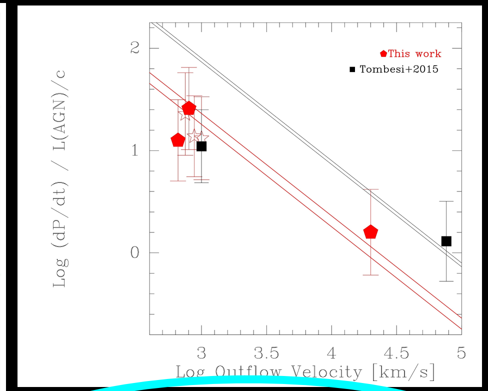


Nuclear Disk Winds

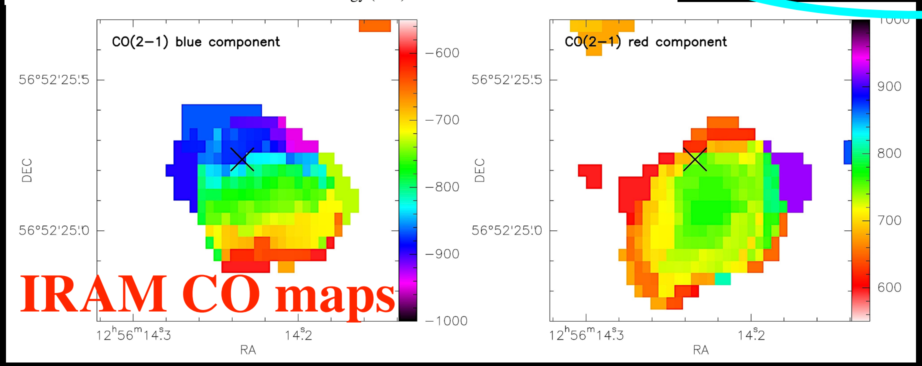
see also Cicone et al. 2014

Mrk 231





Feruglio et al. 2015

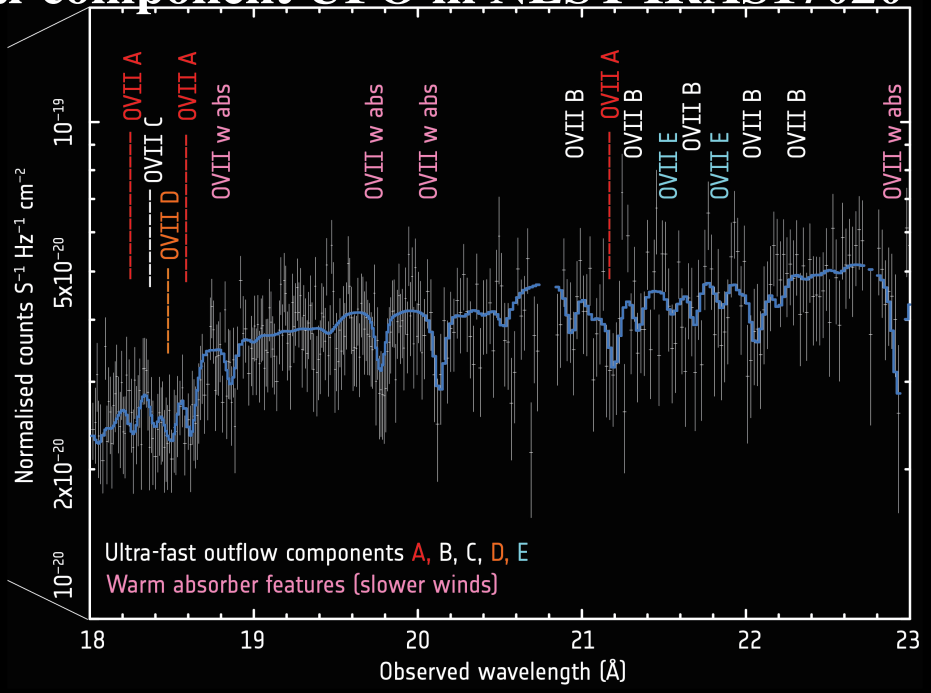


IRAM CO maps

The relation of the momentum flux for the two wind phases suggests that the nuclear wind is driving the giant molecular outflow

Multi-component UFO in NLSY IRAS17020

Longinotti+2015



Recent chronology of multiple components of soft X-ray UFO in grating spectra

- **Tentative evidence for soft X-ray fast winds at V≤0.1c reported in Chandra gratings of NLSy1 Akn 564 and Mrk 590** *Gupta et al. 2013, 2015 ApJ*

- **XMM gratings revealed outflowing highly ionized Ne and L-shell Fe in PDS456 at 0.1-0.2c probably associated to the massive FeK wind** *Reeves et al. 2016 ApJ*

- **Outflow at v=0.23c responding to flux variation in NLSy1 IRAS13224-3809, soft and FeK UFO stronger at low flux** *Parker et al. 2017, Nature*

- **Two ionization components (H and He-like N, O, Ne and Fe L) of wind at v ~ 0.06c found in PG1211+143** *Reeves et al. 2018 ApJ*

- **Multi-components fast and slow outflows in NLSy1 IRAS17020+4544** *Longinotti et al. 2015 ApJL, Sanfrutos et al. 2018, Longinotti et al. in prep.*

- **Four wind components outflowing at v=0.08-0.16c in the NLSy1 Mrk 1044** *Krongold et al. in prep.*

Let’s move beyond Fe K

More Ions other than Iron!

Multi-components UFO in Mrk 1044

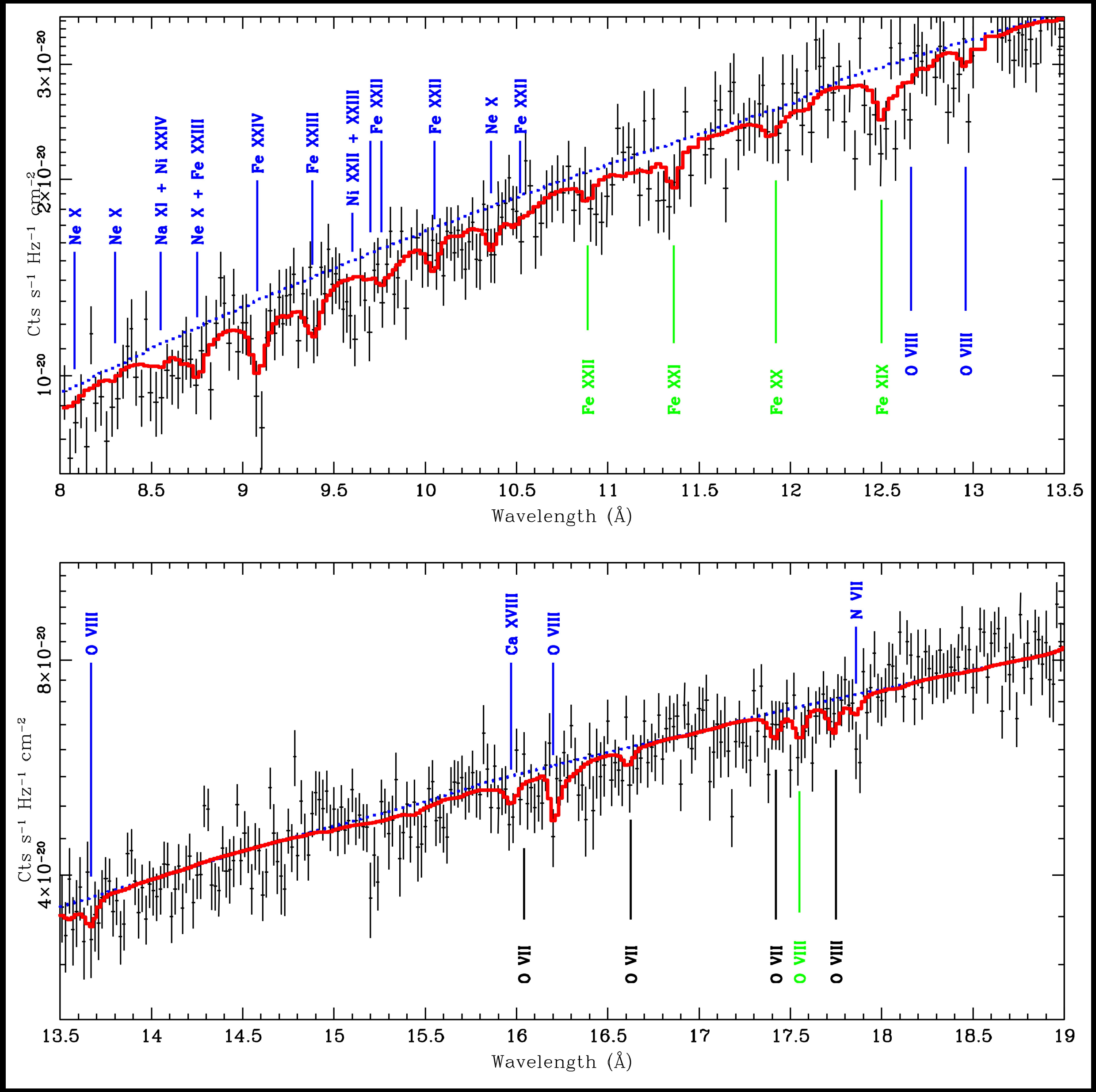
MRK 1044 NLSy1 L_{bol}=5x10^{44}erg/s M_{BH} ~1.4x10^{6} $M_{\odot}$

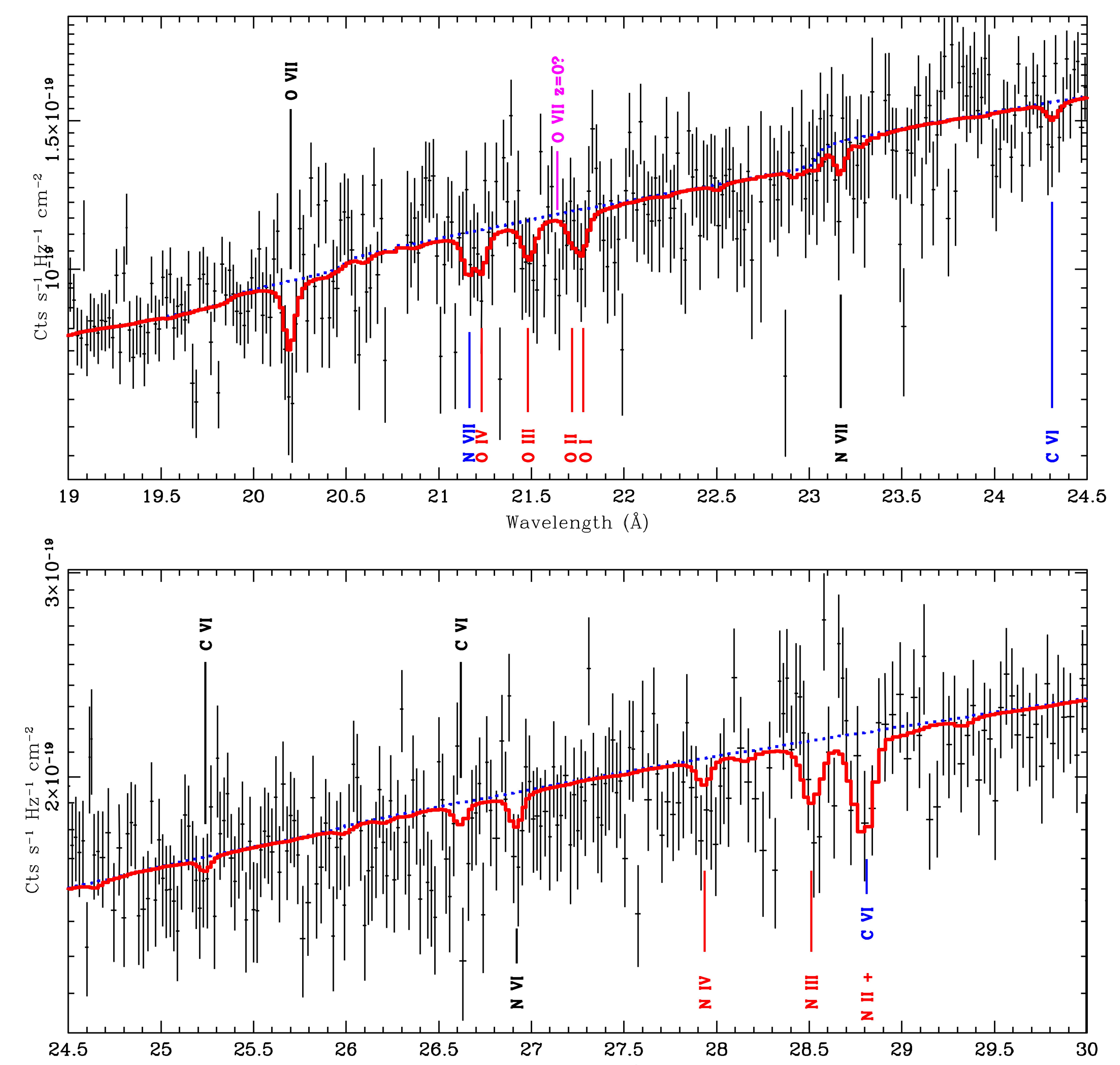
4 components of fast wind in RGS spectra, the strongest detected at 9σ

LogU = 2.12 LogNH= 23.32 v_outflow~ 48000 km/s

Other three outflowing at ~ 25000 km/s

Krongold et al. in prep.





Multi-component ultra fast outflow in IRAS17020+4544

Longinotti et al. 2015 ApJ Letters

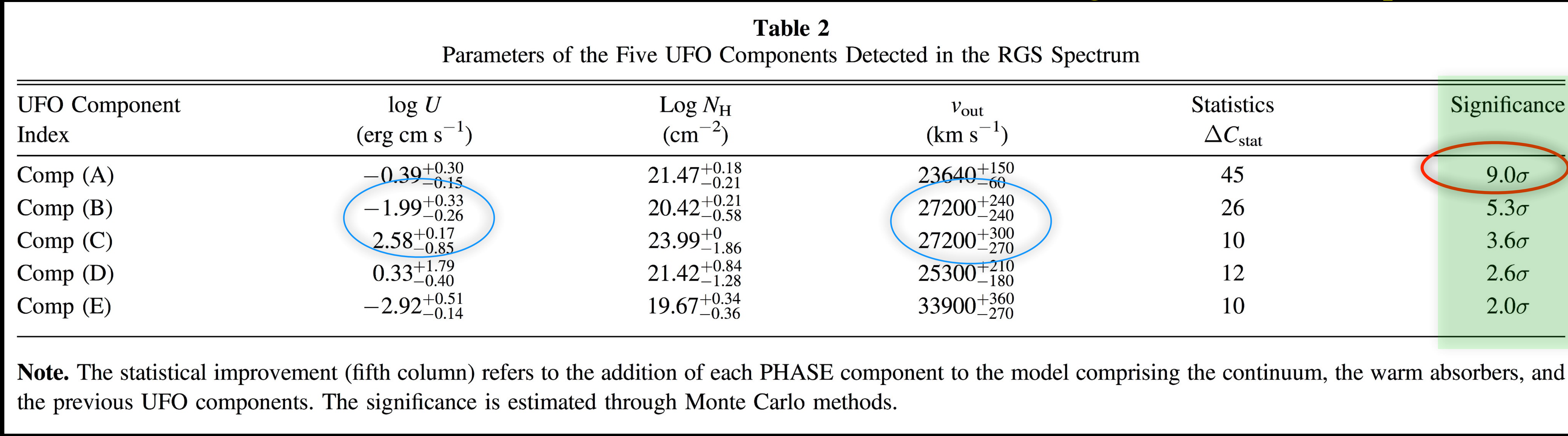


Table 2

Parameters of the Five UFO Components Detected in the RGS Spectrum

UFO Component Index	log U (erg cm s^{-1})	Log N_H (cm^{-2})	v_{out} (km s^{-1})	Statistics ΔC_{stat}	Significance
Comp (A)	$-0.39^{+0.30}_{-0.15}$	$21.47^{+0.18}_{-0.21}$	23640^{+150}_{-60}	45	9.0σ
Comp (B)	$-1.99^{+0.33}_{-0.26}$	$20.42^{+0.21}_{-0.58}$	27200^{+240}_{-240}	26	5.3σ
Comp (C)	$2.58^{+0.17}_{-0.85}$	$23.99^{+0}_{-1.86}$	27200^{+300}_{-270}	10	3.6σ
Comp (D)	$0.33^{+1.79}_{-0.40}$	$21.42^{+0.84}_{-1.28}$	25300^{+210}_{-180}	12	2.6σ
Comp (E)	$-2.92^{+0.51}_{-0.14}$	$19.67^{+0.34}_{-0.36}$	33900^{+360}_{-270}	10	2.0σ

Note. The statistical improvement (fifth column) refers to the addition of each PHASE component to the model comprising the continuum, the warm absorbers, and the previous UFO components. The significance is estimated through Monte Carlo methods.

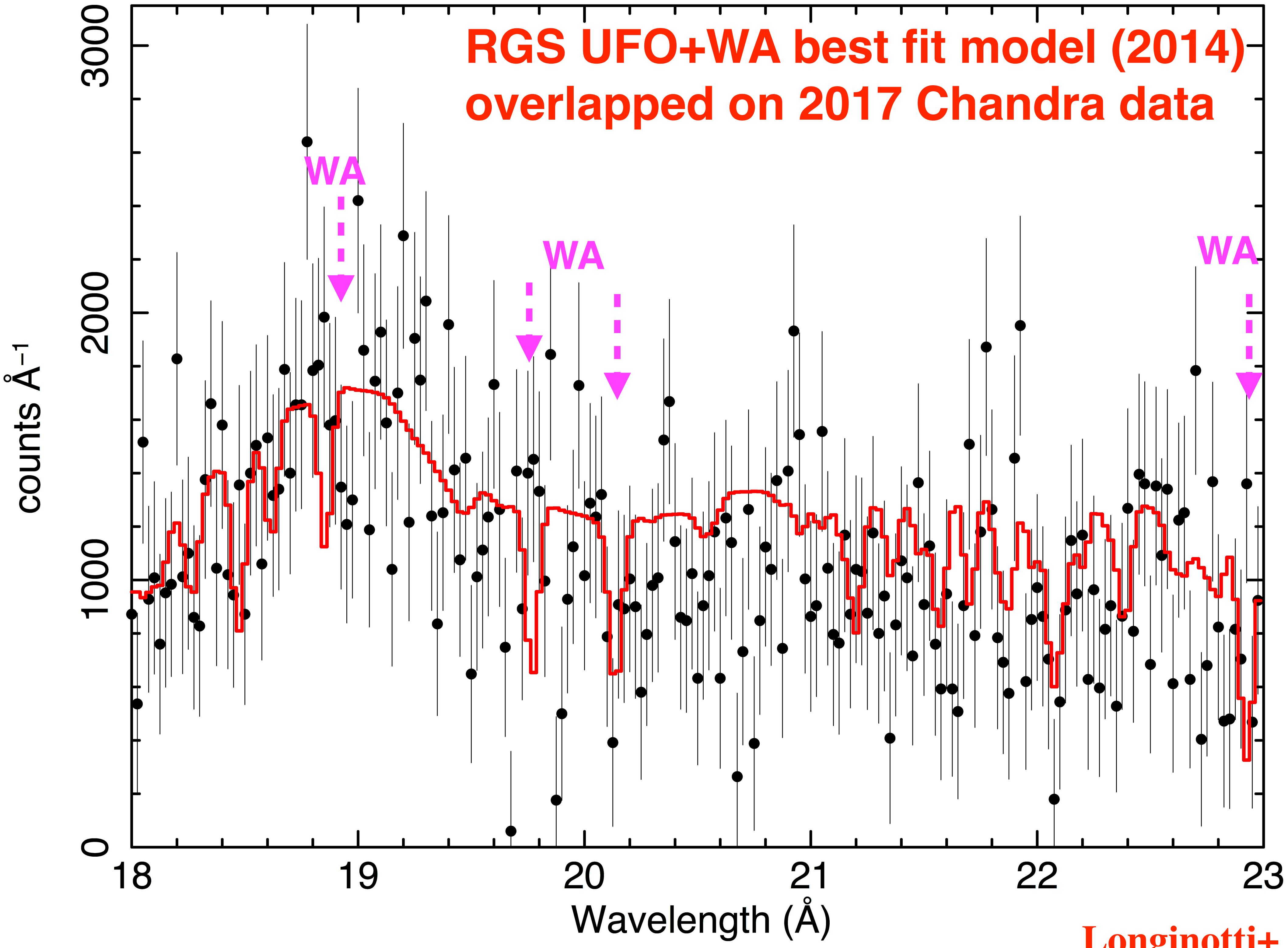
Detailed UFO properties seen for the first time in an X-ray spectrum

Five distinct components with wide range of ionization and N_H outflowing at same velocity

Lack of variation in RGS spec of 2004 implies outflow is stable on ~10 yr time scale

Disk ultra fast wind does not have to produce only Fe K absorption

Chandra LETG look at IRAS17020+4544 (250 ks)



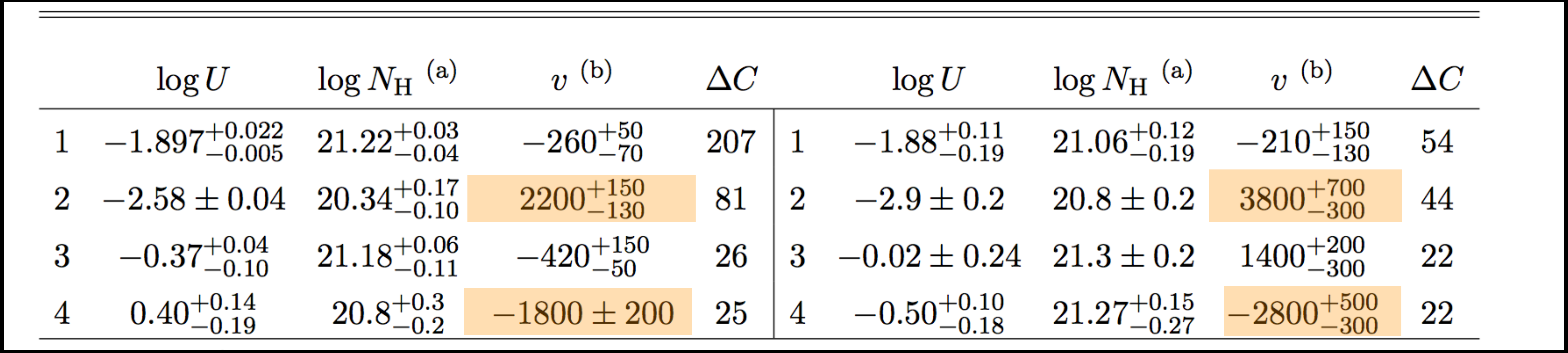
Longinotti+ in prep.

M. Sanfrutos et al. ApJ Accepted SEE TALK on Thursday

Slow wind in IRAS17020+4544

Both XMM-grating data of 2014 and 2004 show warm absorber in outflow and inflow

Wa in 2014 **Wa in 2004**



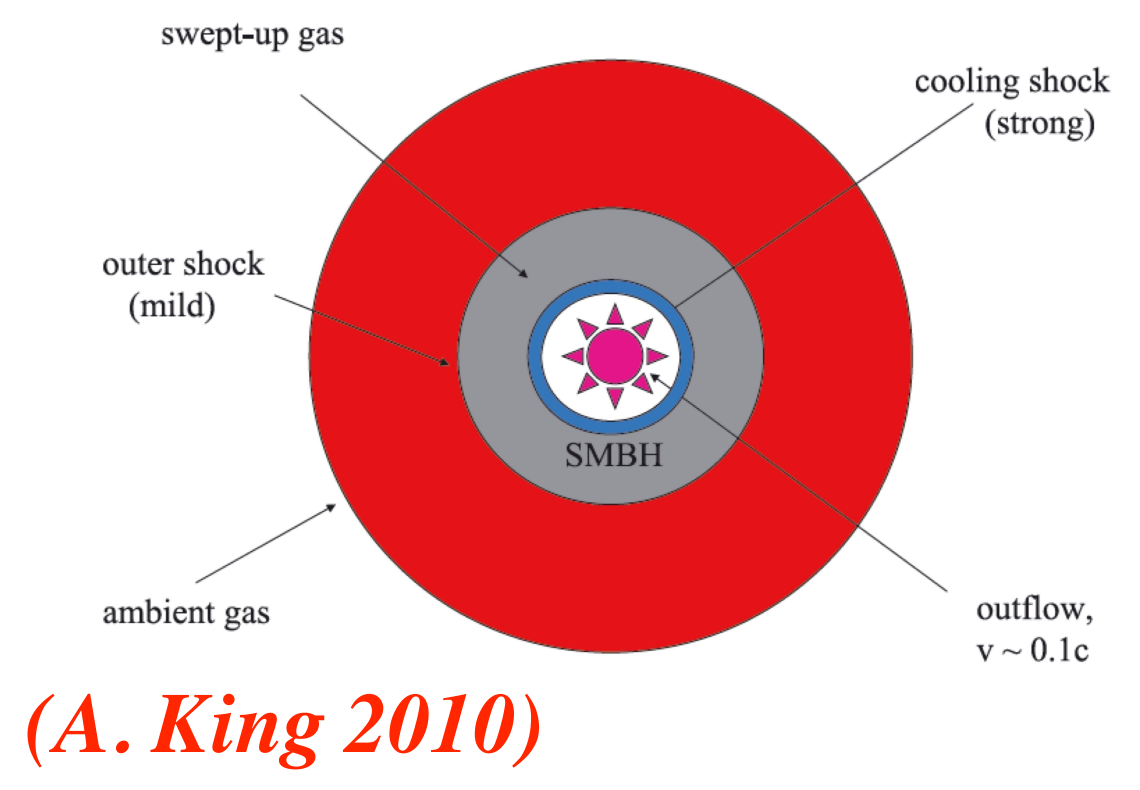
	$\log U$	$\log N_{\rm H}$ (a)	v (b)	ΔC		$\log U$	$\log N_{\rm H}$ (a)	v (b)	ΔC
1	$-1.897^{+0.022}_{-0.005}$	$21.22^{+0.03}_{-0.04}$	-260^{+50}_{-70}	207	1	$-1.88^{+0.11}_{-0.19}$	$21.06^{+0.12}_{-0.19}$	-210^{+150}_{-130}	54
2	-2.58 ± 0.04	$20.34^{+0.17}_{-0.10}$	2200^{+150}_{-130}	81	2	-2.9 ± 0.2	20.8 ± 0.2	3800^{+700}_{-300}	44
3	$-0.37^{+0.04}_{-0.10}$	$21.18^{+0.06}_{-0.11}$	-420^{+150}_{-50}	26	3	-0.02 ± 0.24	21.3 ± 0.2	1400^{+200}_{-300}	22
4	$0.40^{+0.14}_{-0.19}$	$20.8^{+0.3}_{-0.2}$	-1800 ± 200	25	4	$-0.50^{+0.10}_{-0.18}$	$21.27^{+0.15}_{-0.27}$	-2800^{+500}_{-300}	22

Slow Wind components 2 and 4 are faster than 10 years later
Fast wind seems persistent (confirmed by Chandra’s look in 2017)
Source luminosity stays constant

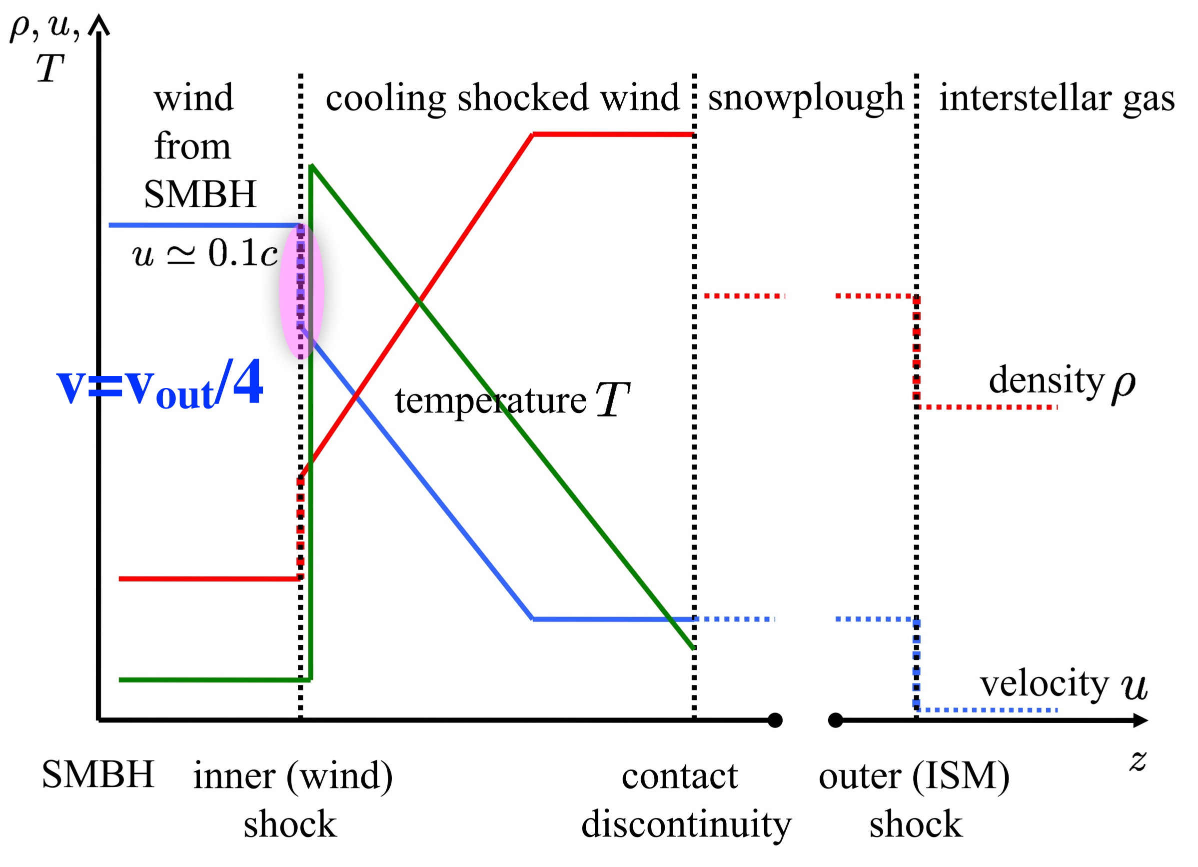
How can we explain co-existence of a stable UFO with a variable warm absorber without continuum flux variations?

Shocked outflow model and IRAS17

In this model the accretion disc wind launched with velocity v_out suffers an isothermal shock with the circumnuclear gas that produces the effect of slowing the wind to a velocity v ~v_out/4.

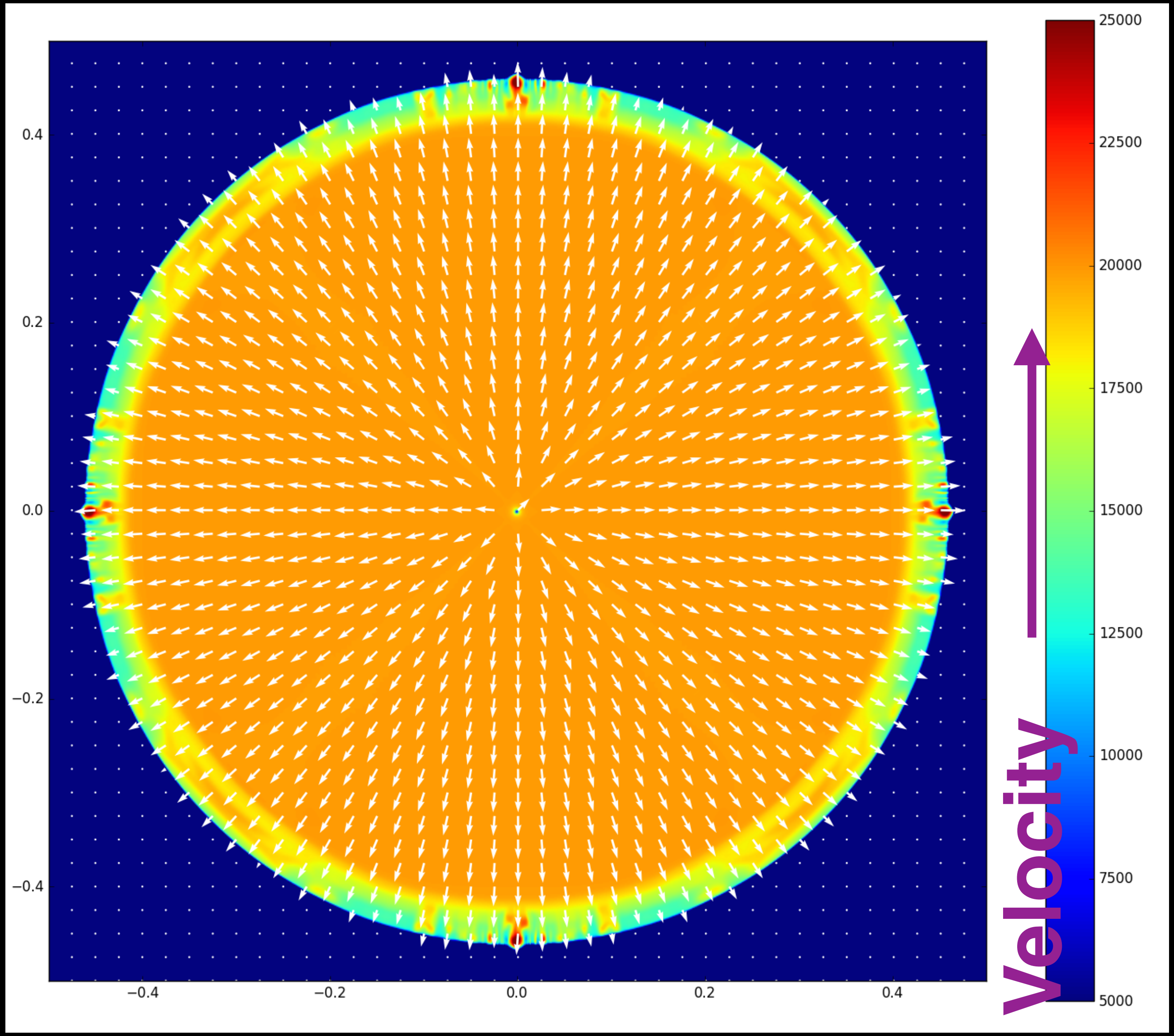


(A. King 2010)



In the impact of the wind with the gas at a radius where $V_{escape} < V_{outflow}$, a reverse shock is produced. The wind keeps sweeping up the surrounding material and develops a second forward shock. The two shock fronts are separated by a contact discontinuity. The density of the impacting wind and of the impacted medium are different.

Simulated shocked outflow



3-D numerical hydrodynamical simulation

Mean density of outer medium: 1/cm^3

BH mass: $10^6 M_\odot$ (IRAS17 M_{BH})

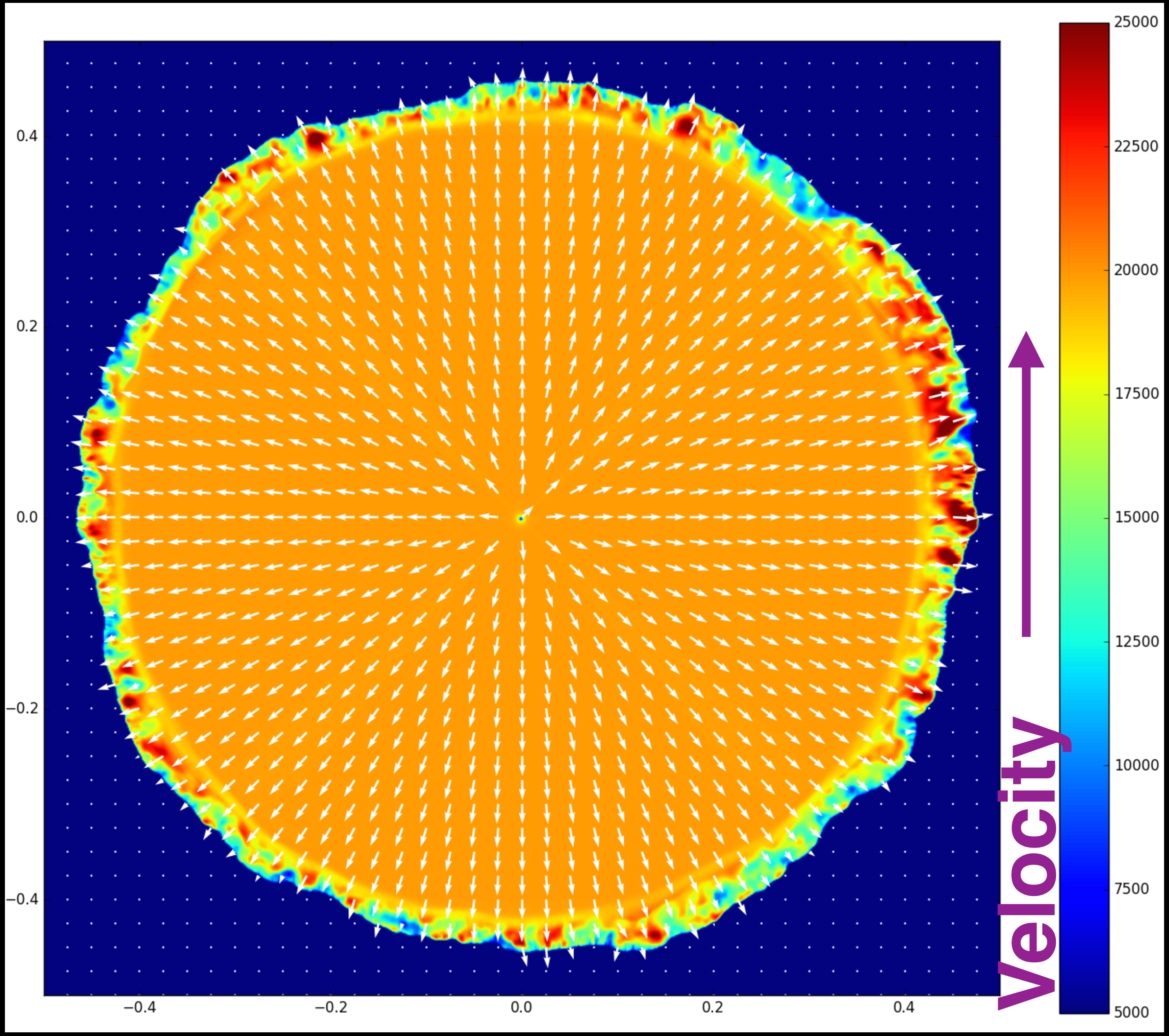
Density gradient (in and out of the shock) induce Rayleigh-Taylor instability that keeps slowing down shocked gas (similar to SN remnants)

Expanding shock pushed within a turbulent medium by an inner wind with V_{out}=20,000 km/s

Expansion time: 20 yr

Sim by P. Velazquez, based on GUACHO code
Esquivel & Raga 2013 ApJ
(Instituto de Ciencias Nucleares, UNAM)

Simulated shocked outflow with instabilities



3-D numerical hydrodynamical simulation

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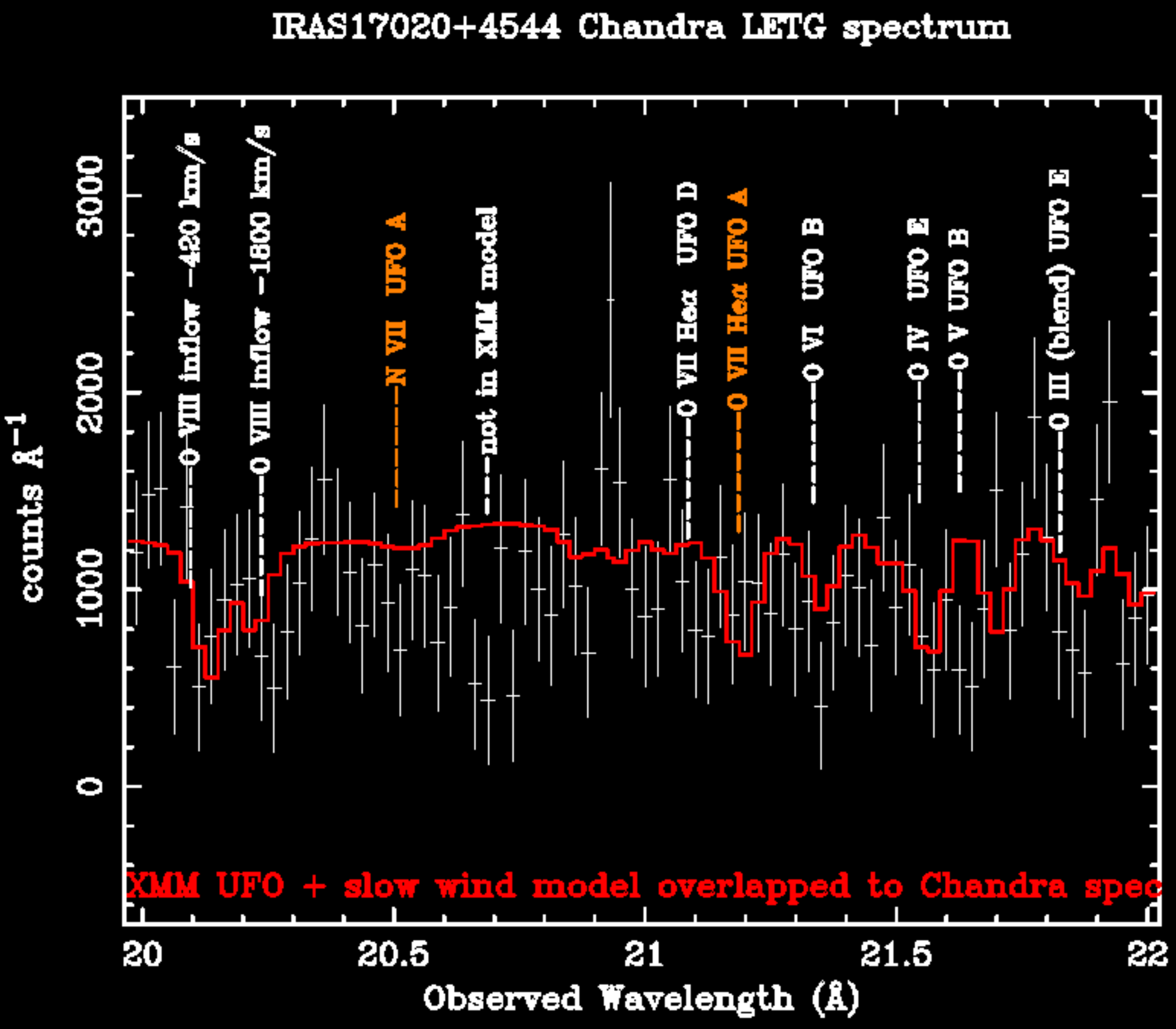
Esquivel & Raga 2013 ApJ

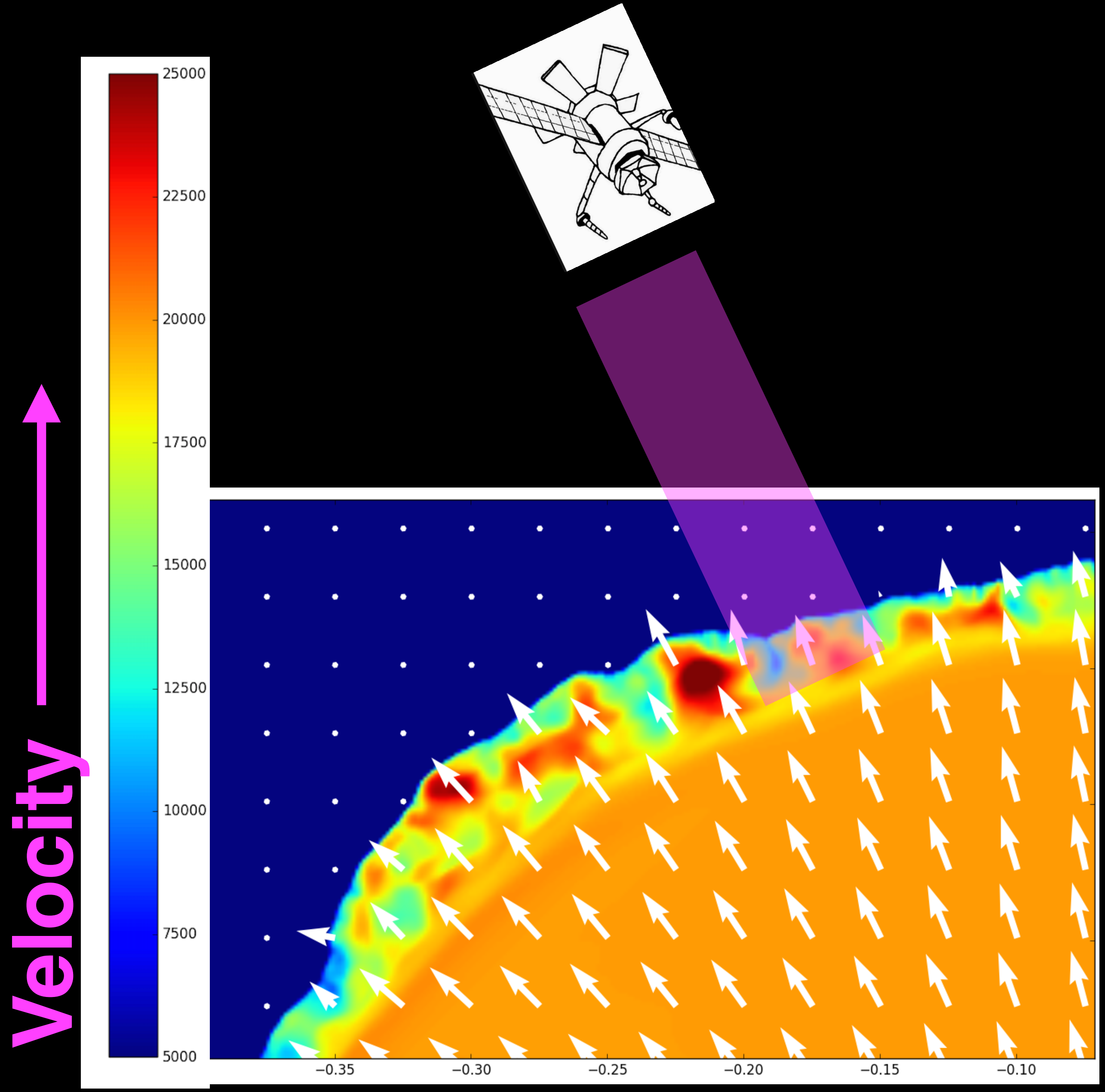
(Instituto de Ciencias Nucleares, UNAM)

Shocked outflow with instabilities may explain multi-velocity wind components

Our line-of sight crosses several “fingers” of gas with different V_{out}

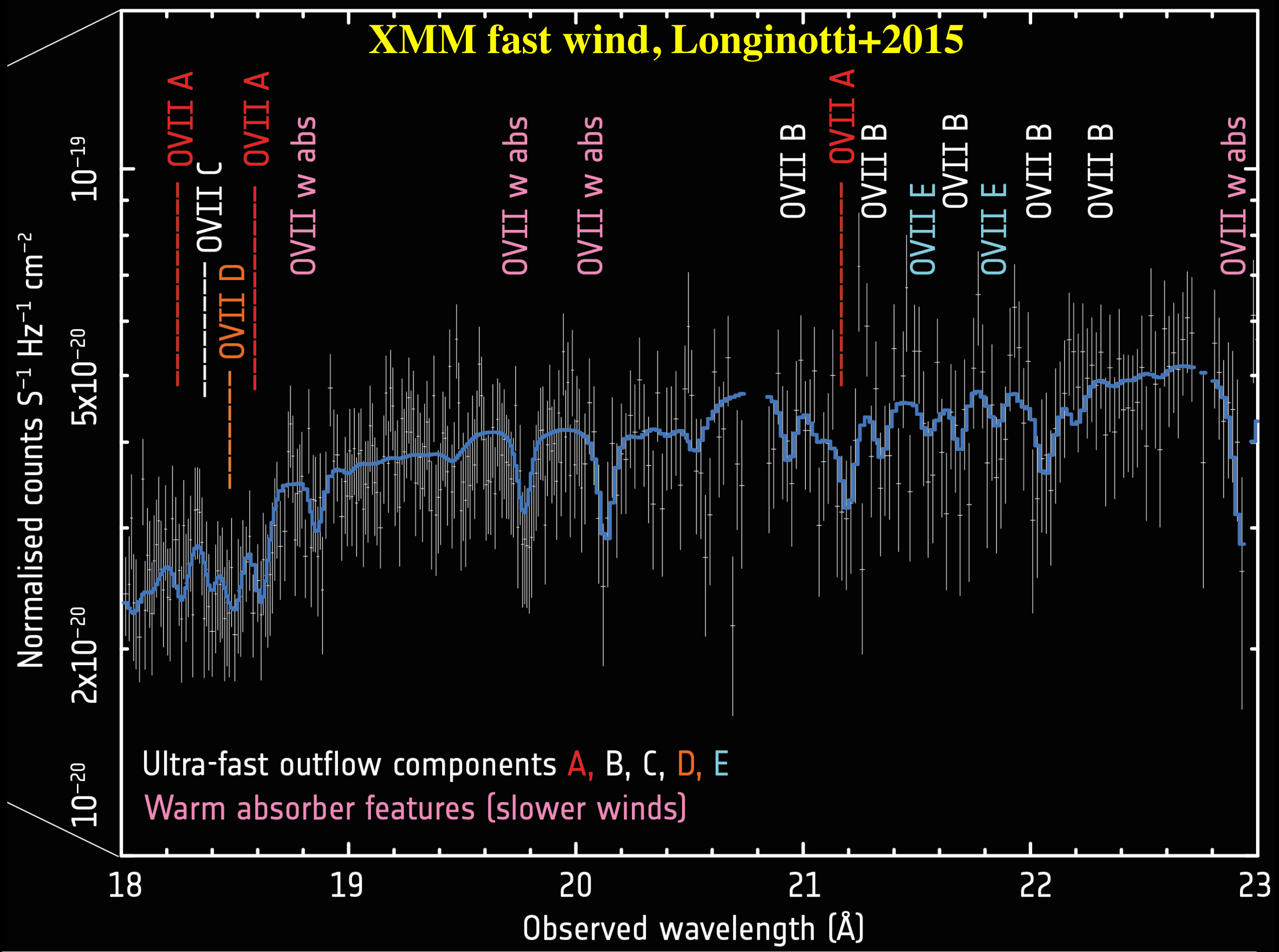
Work in progress on column density and temperature (ionization) distribution





Other hints of a shocked outflow in IRAS17020+4544 beside X-rays:

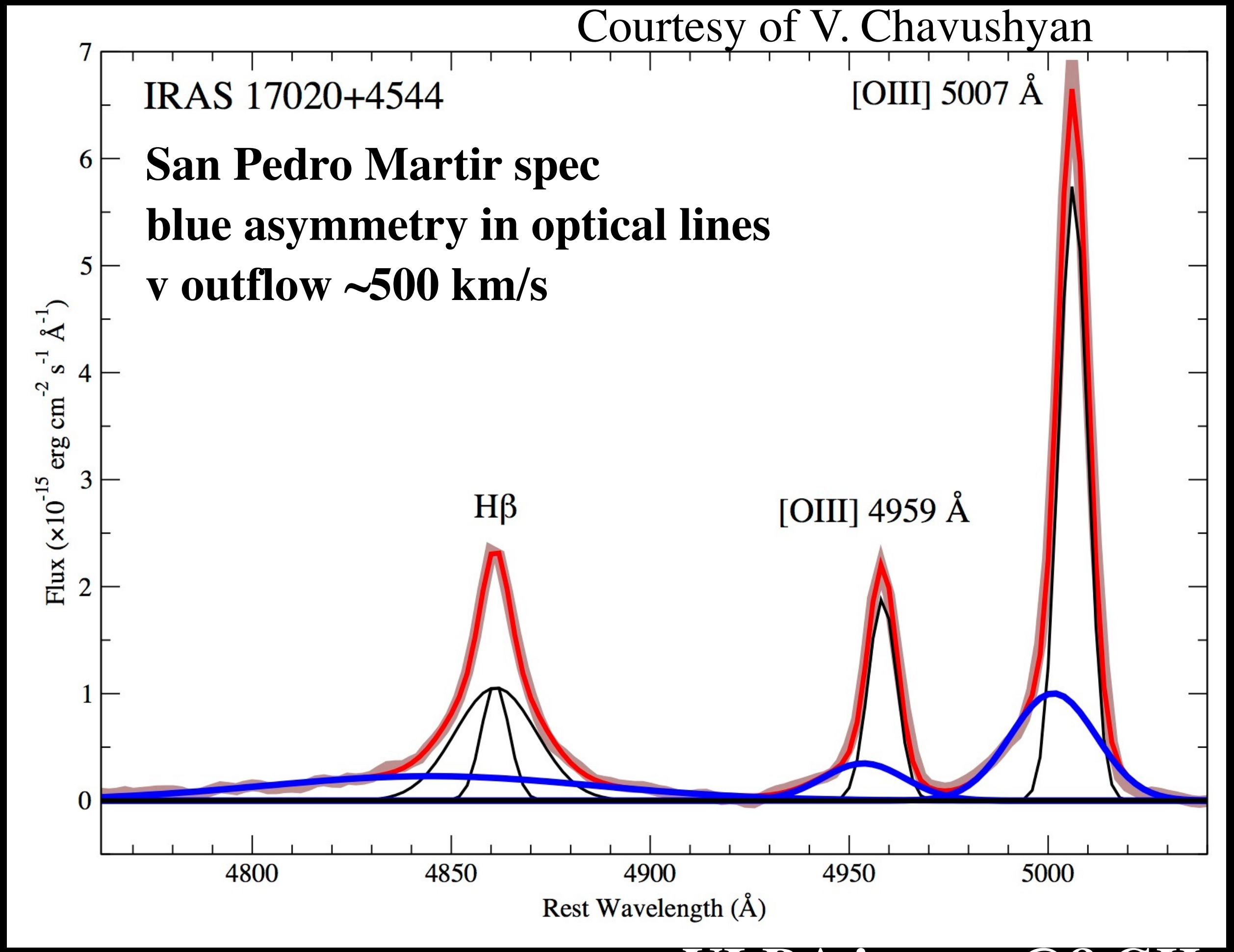
we have evidence for multi-phase winds suggesting that an AGN-driven wind may be affecting the galaxy at large scales



XMM fast wind, Longinotti+2015

Ultra-fast outflow components A, B, C, D, E

Warm absorber features (slower winds)



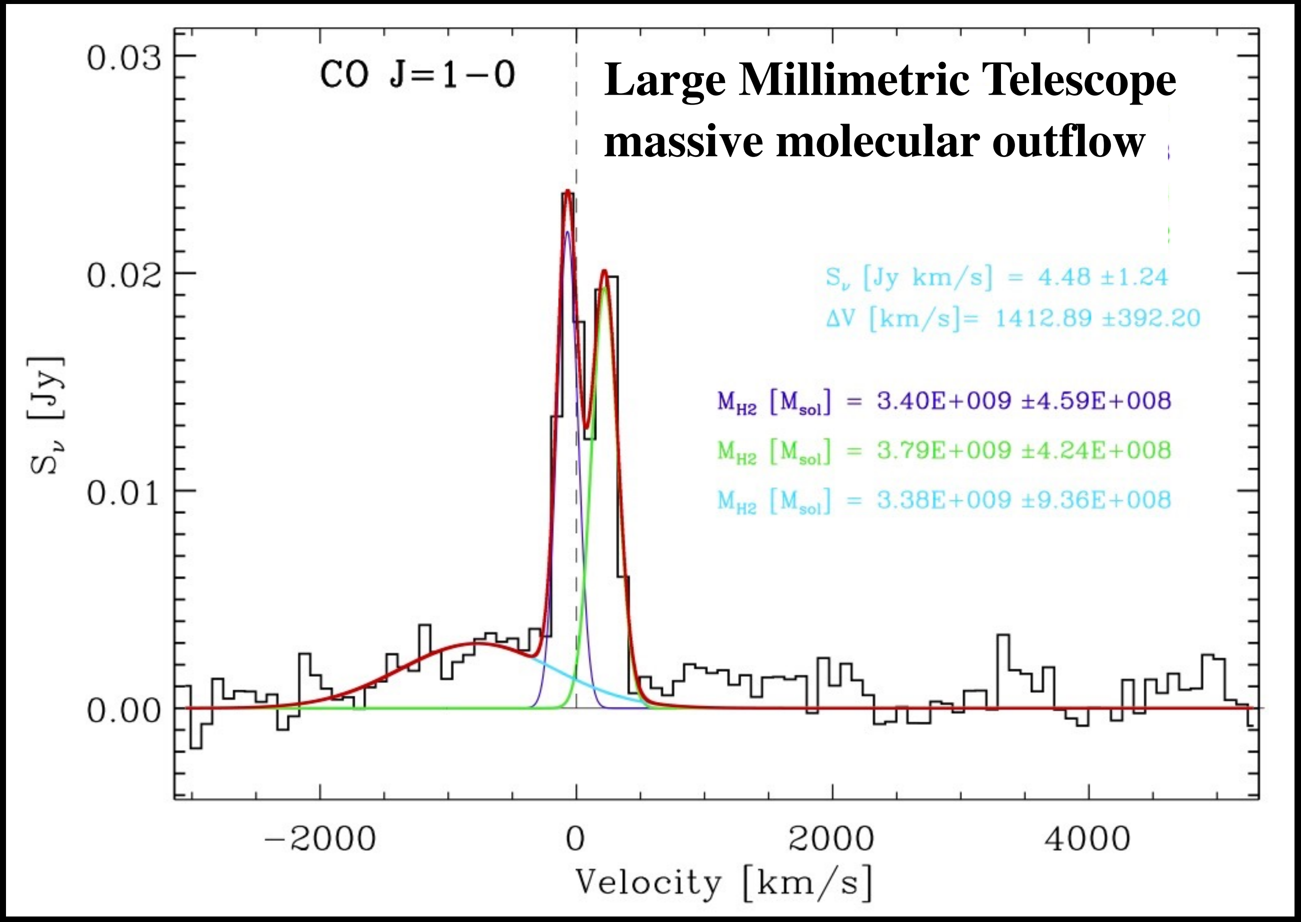
Courtesy of V. Chavushyan

IRAS 17020+4544

San Pedro Martir spec

blue asymmetry in optical lines

v outflow ~500 km/s

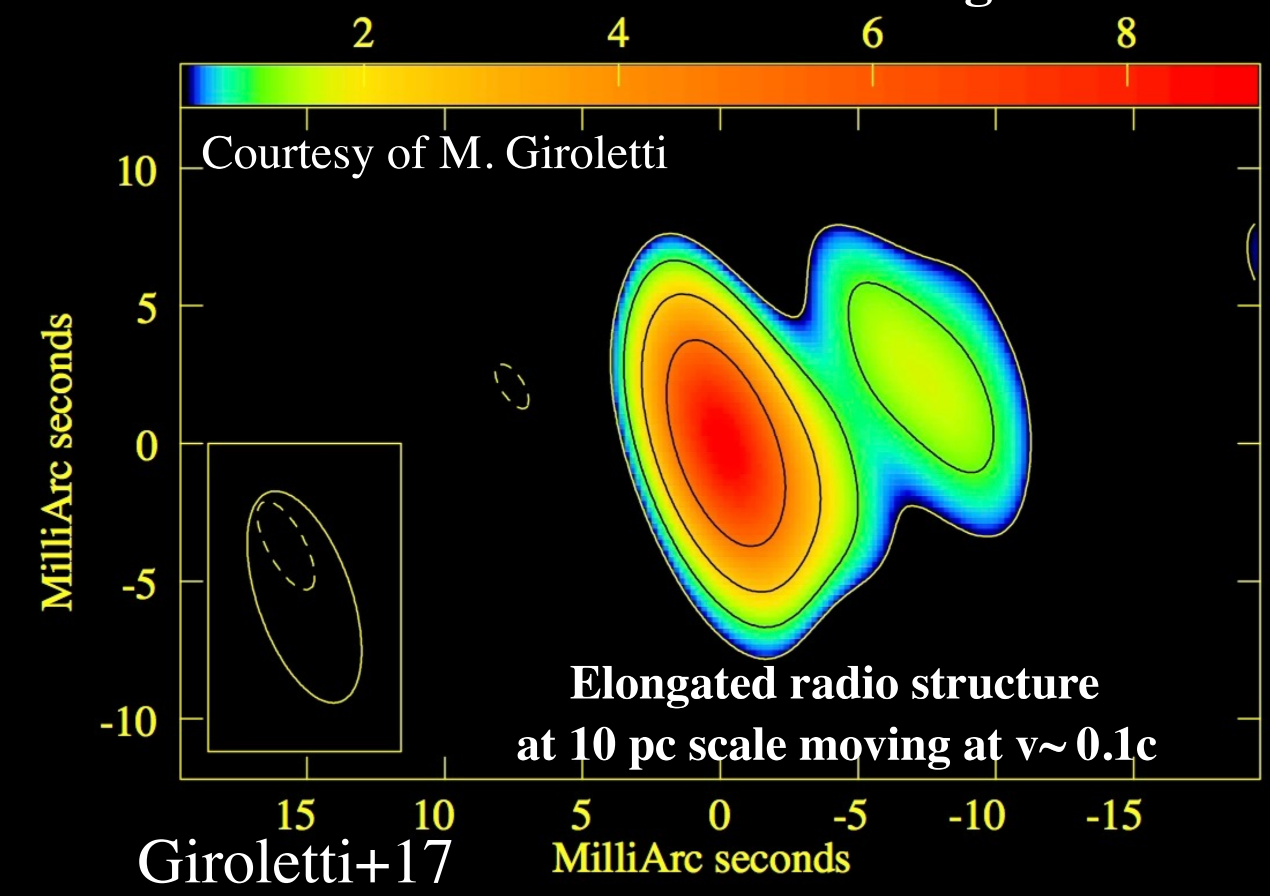


Large Millimetric Telescope

massive molecular outflow

Courtesy of O. Vega Casanova

VLBA image @8 GHz

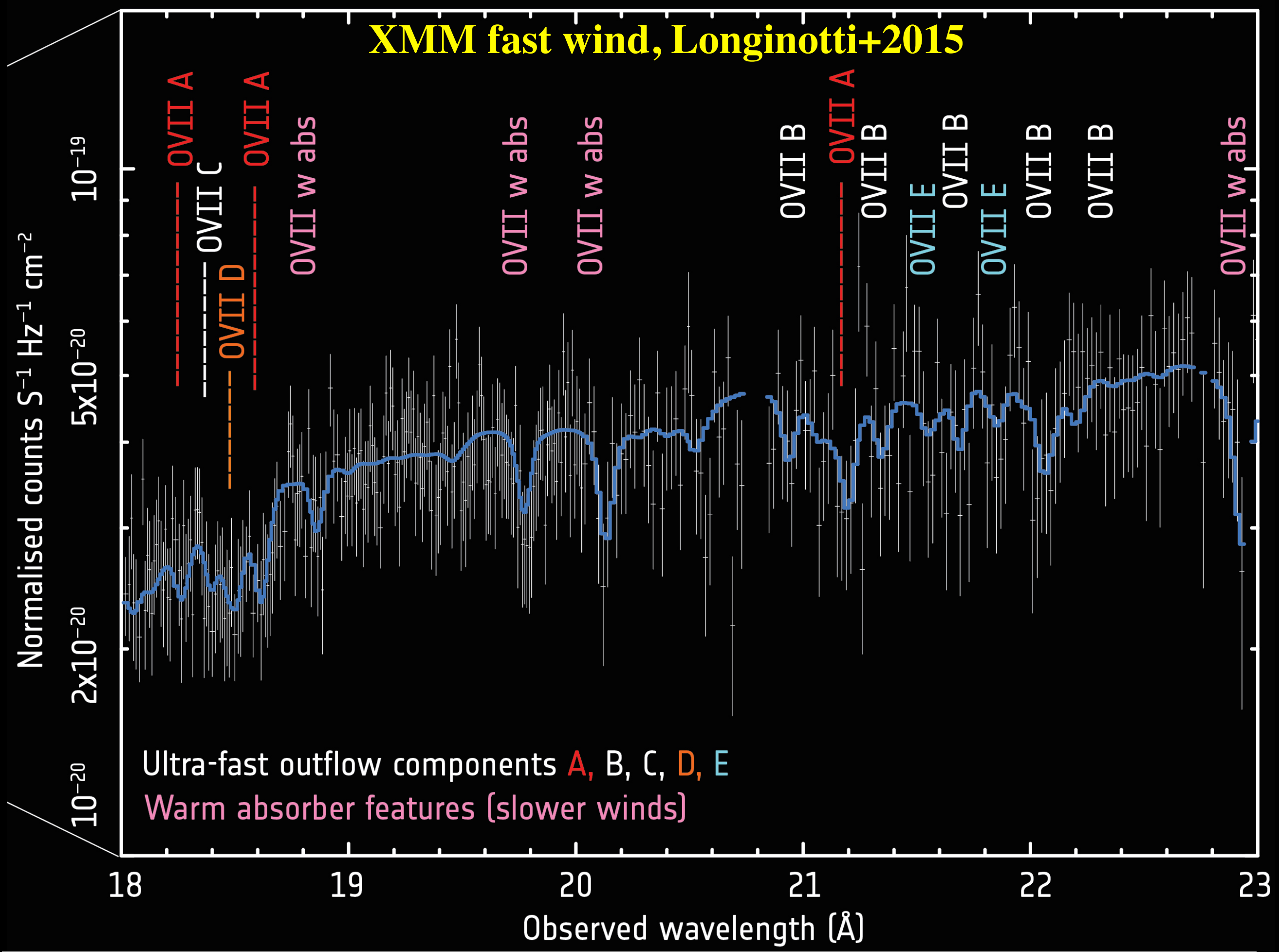


Courtesy of M. Giroletti

Elongated radio structure

at 10 pc scale moving at v~ 0.1c

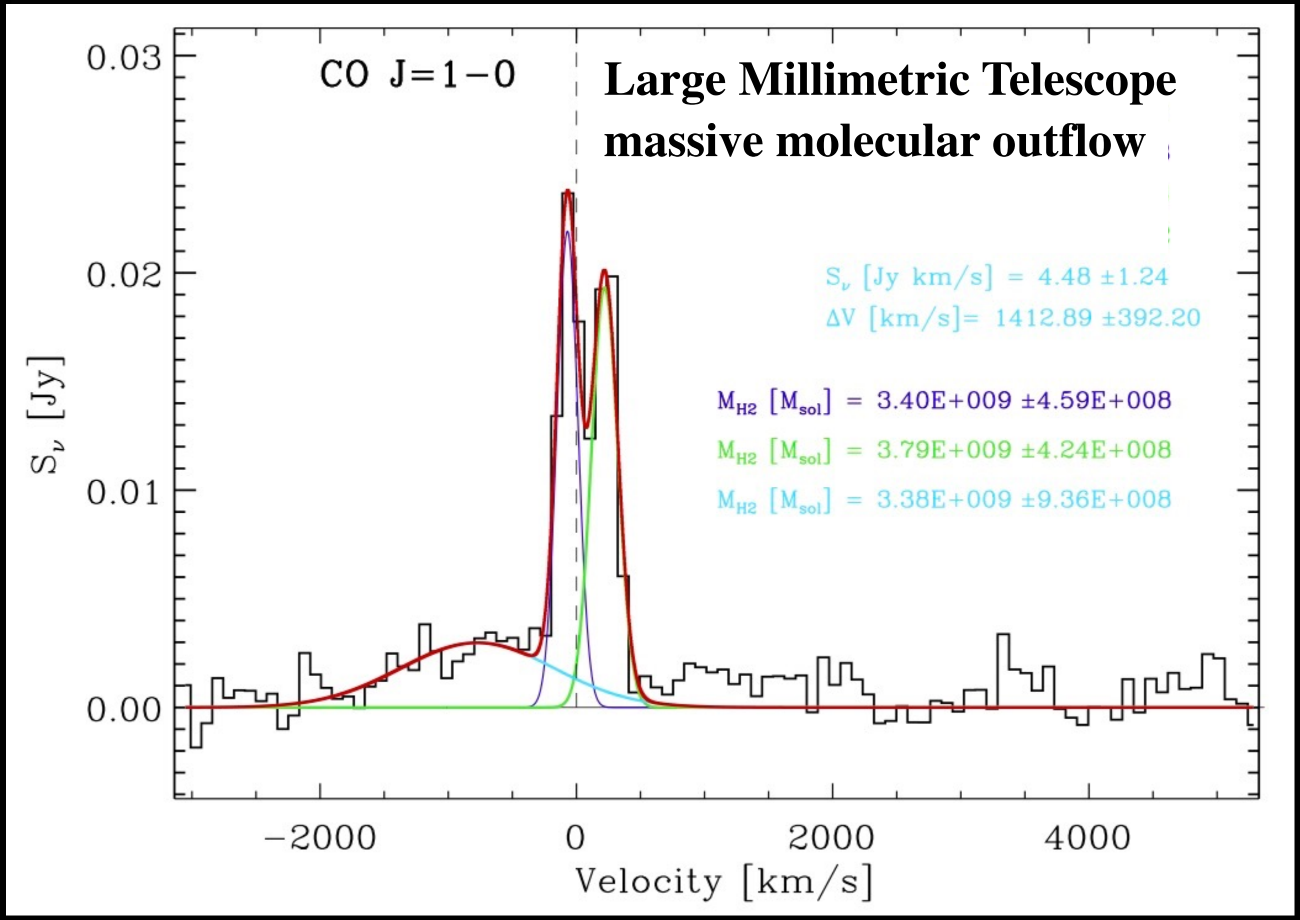
Giroletti+17


XMM fast wind, Longinotti+2015

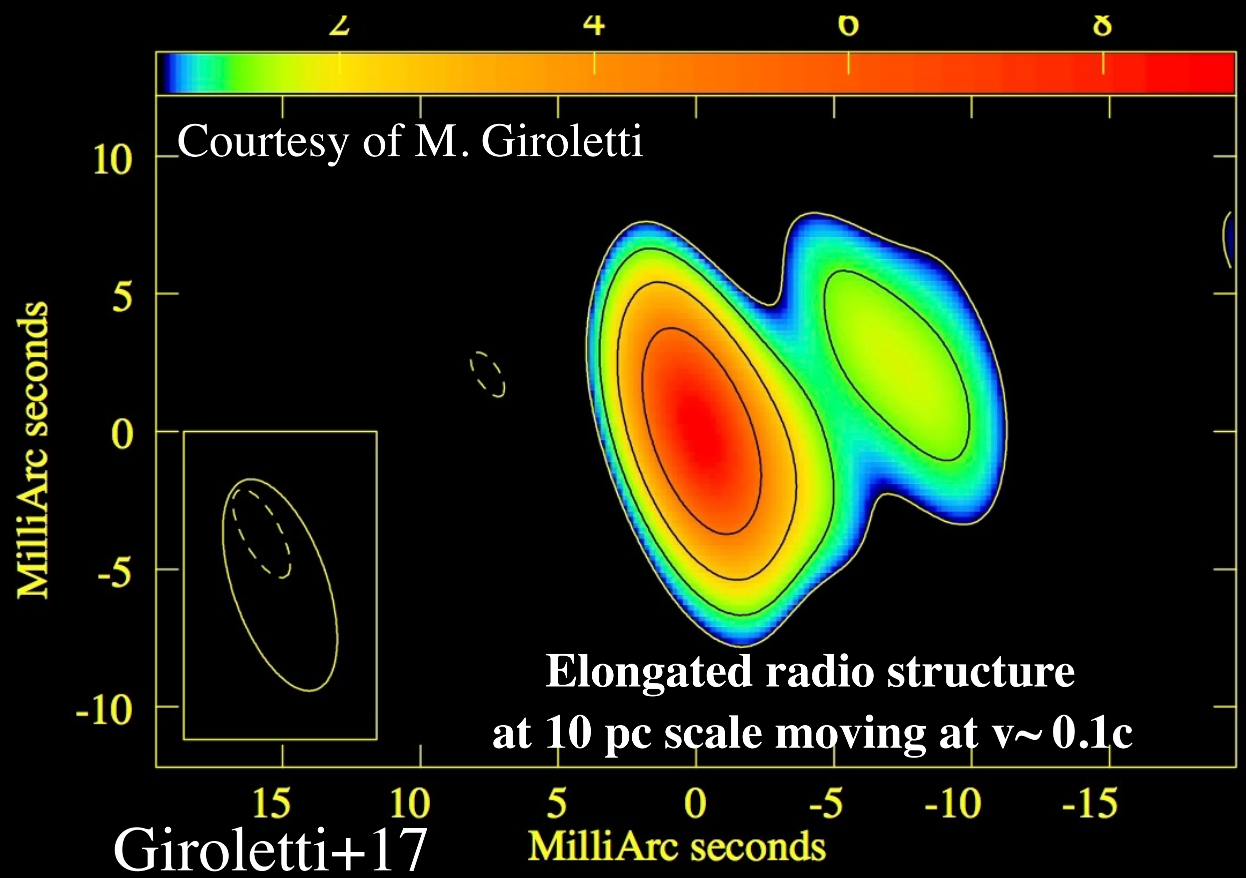
AWAITING NEW DATA:

NOEMA-IRAM
(map molecular gas,
obtained in May 2018)

HST COS
(UV counterpart of fast wind
planned for Nov 2018)


Large Millimetric Telescope massive molecular outflow

Courtesy of O. Vega Casanova

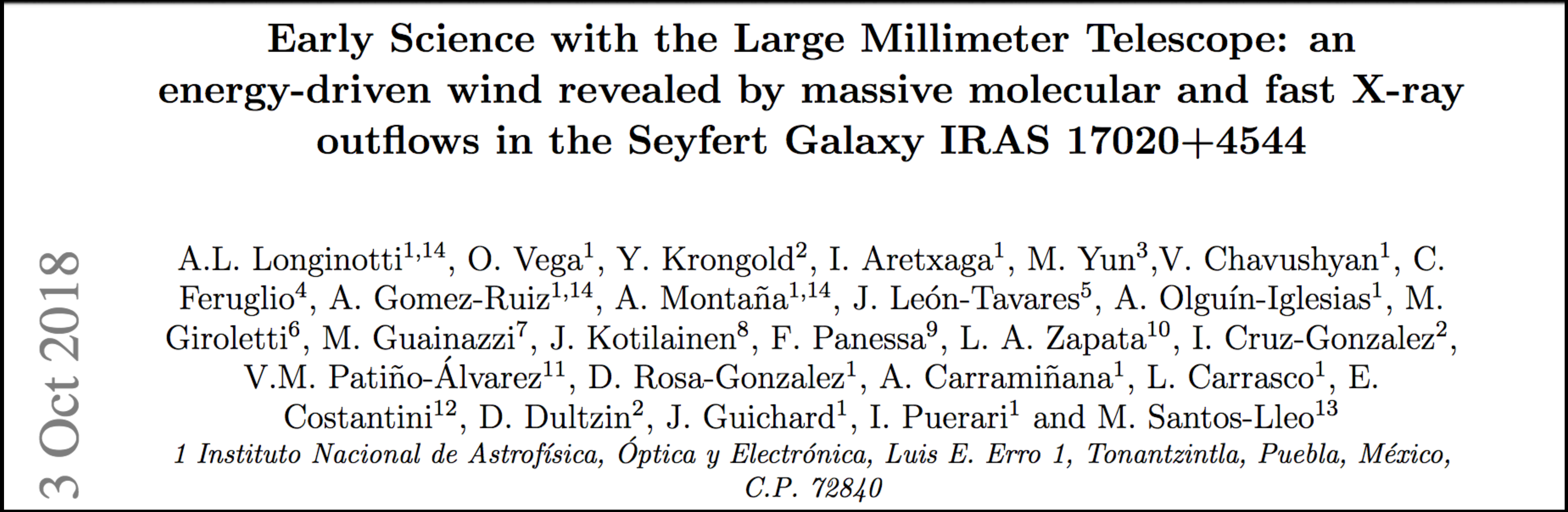

Courtesy of M. Giroletti

Elongated radio structure at 10 pc scale moving at v~ 0.1c

Giroletti+17

Connection X-ray-Molecular Outflows in IRAS17

to appear on ApJ Letters arXiv:1810.01941



3 Oct 2018

Early Science with the Large Millimeter Telescope: an energy-driven wind revealed by massive molecular and fast X-ray outflows in the Seyfert Galaxy IRAS 17020+4544

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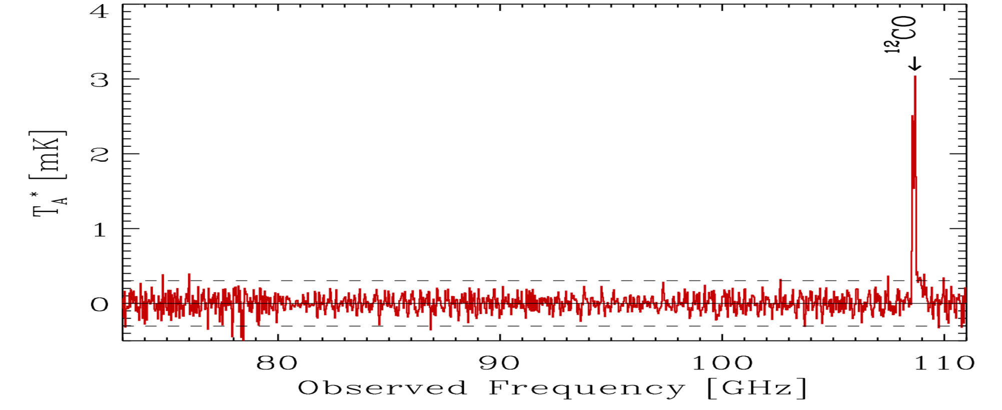
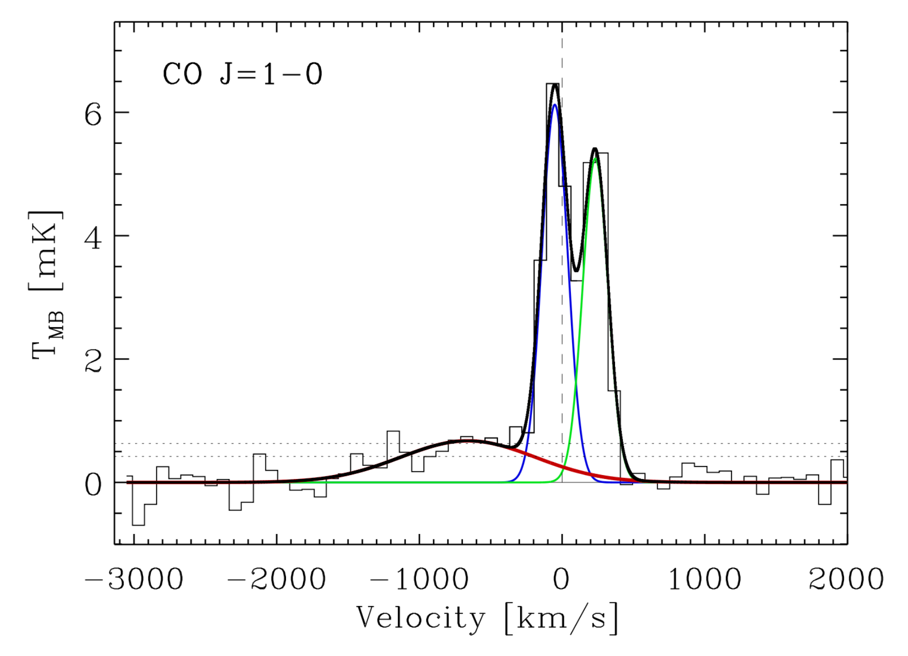
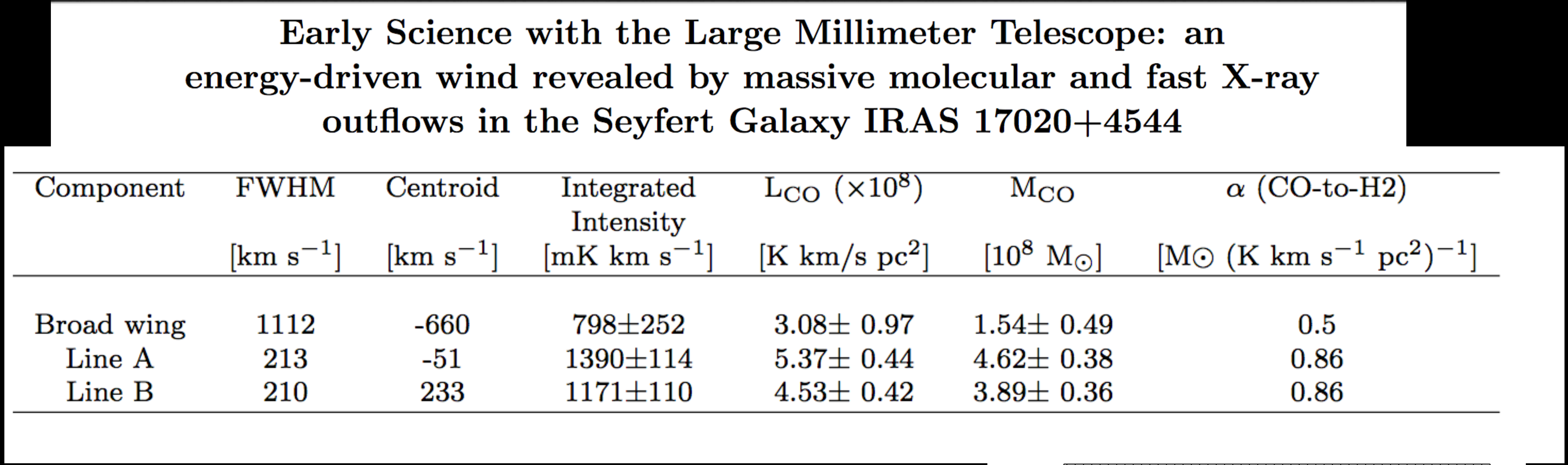


GTM -RSR Spectrum



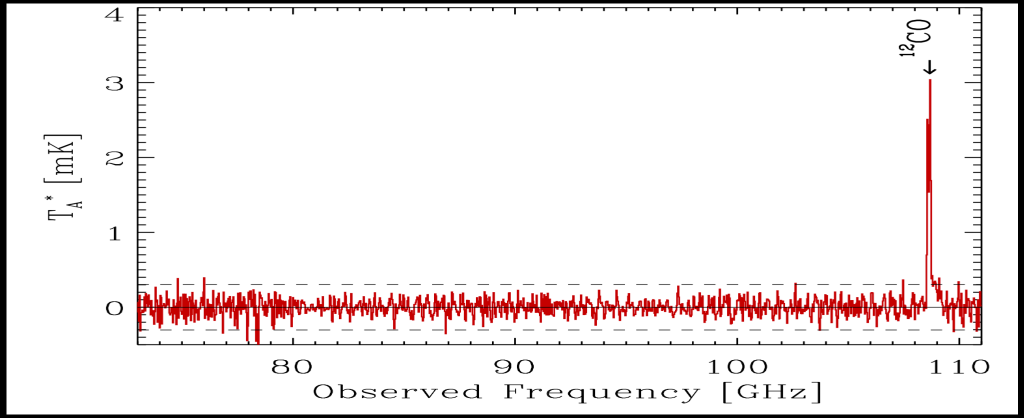
Connection X-ray-Molecular Outflows in IRAS17

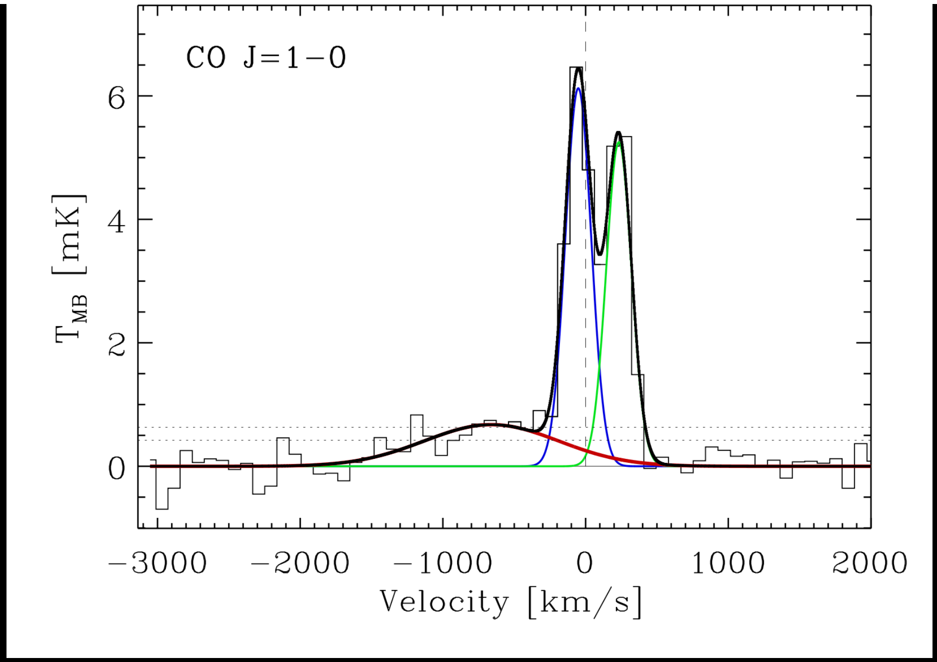
to appear on ApJ Letters arXiv:1810.01941



Early Science with the Large Millimeter Telescope: an energy-driven wind revealed by massive molecular and fast X-ray outflows in the Seyfert Galaxy IRAS 17020+4544

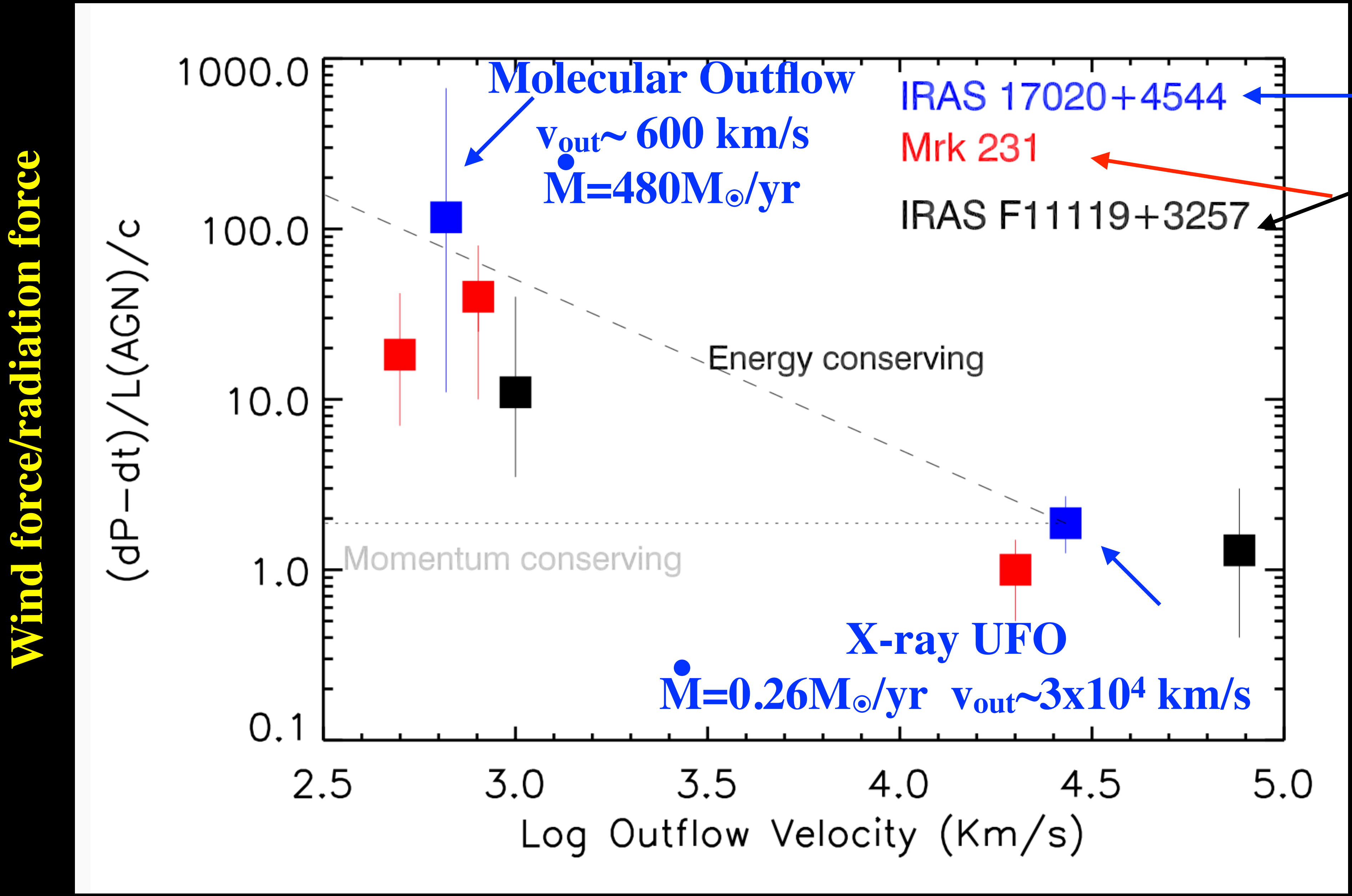
Component	FWHM [km s^{-1}]	Centroid [km s^{-1}]	Integrated Intensity [mK km s^{-1}]	L_{CO} ($\times 10^8$) [K km/s pc^2]	M_{CO} [10^8 $M_\odot$]	α (CO-to-H2) [M⊙ (K km s^{-1} $pc^2)^{-1}$]
Broad wing	1112	-660	798±252	3.08± 0.97	1.54± 0.49	0.5
Line A	213	-51	1390±114	5.37± 0.44	4.62± 0.38	0.86
Line B	210	233	1171±110	4.53± 0.42	3.89± 0.36	0.86





GTM -RSR Spectrum

Connection X-ray-Molecular Outflows in IRAS17



NL Seyfert Galaxy

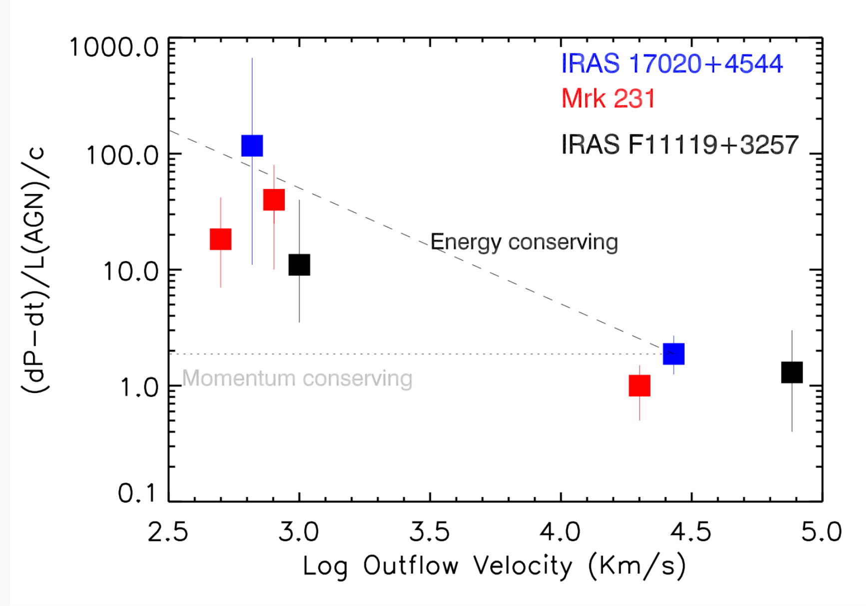
QSO-ULIRG

$$\dot{P}_{out} = \dot{M}_{out} \times \mathrm{v}_{out}$$

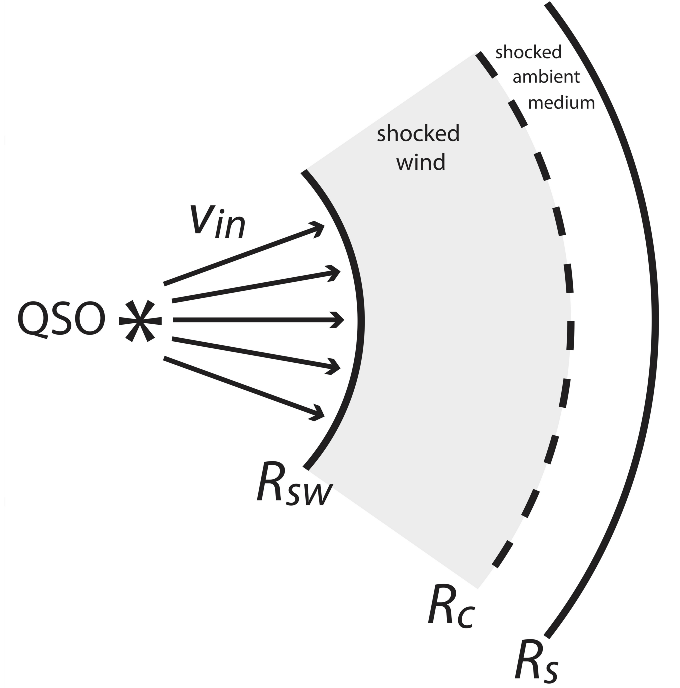
The momentum flux of the wind is related to the velocity with which the gas is pushed outward.

The relative proportion of the wind momentum and of the radiation force determines if the wind is momentum-conserving or energy-conserving

Connection X-ray-Molecular Outflows in IRAS17



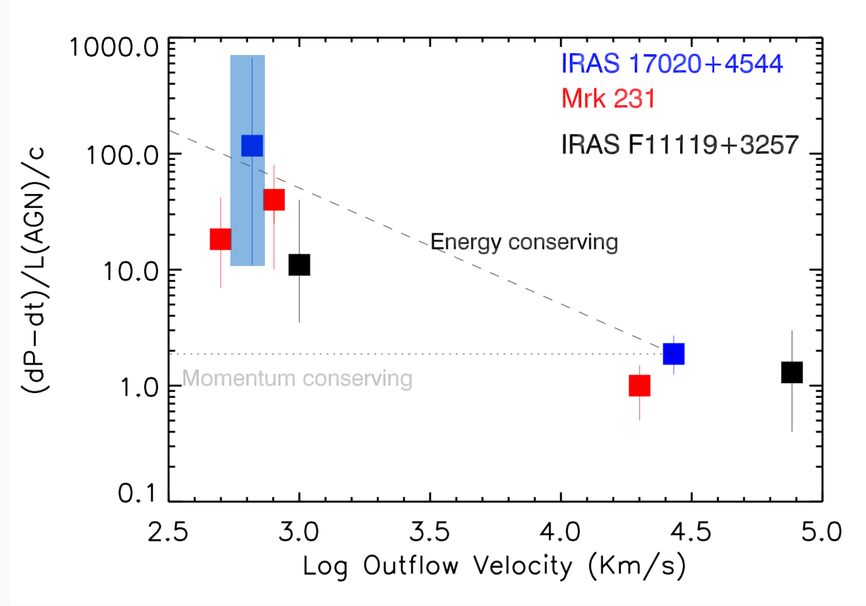
Longinotti+ 2018
ApJ Letters



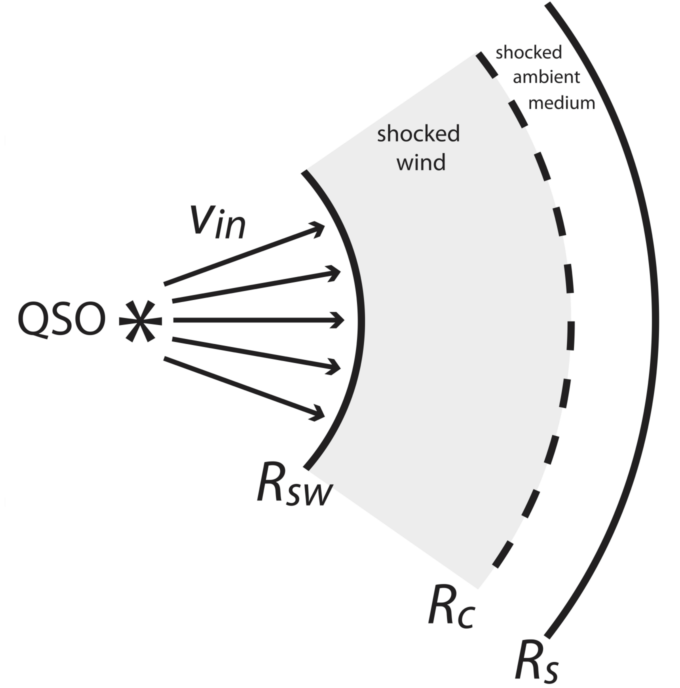
Faucher-Giguere & Quataert
MNRAS 2012

This plot compares the prediction for the behaviour of an energy-conserving wind where the outer molecular outflow is driven by a sub-relativistic wind arising at a much inner scale, as postulated by several authors (e.g. Faucher-Giguere & Quataert 2012, Zubovas & King 2012)

Connection X-ray-Molecular Outflows in IRAS17



Longinotti+ 2018
ApJ Letters



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How many source of uncertainties ? **Many!**

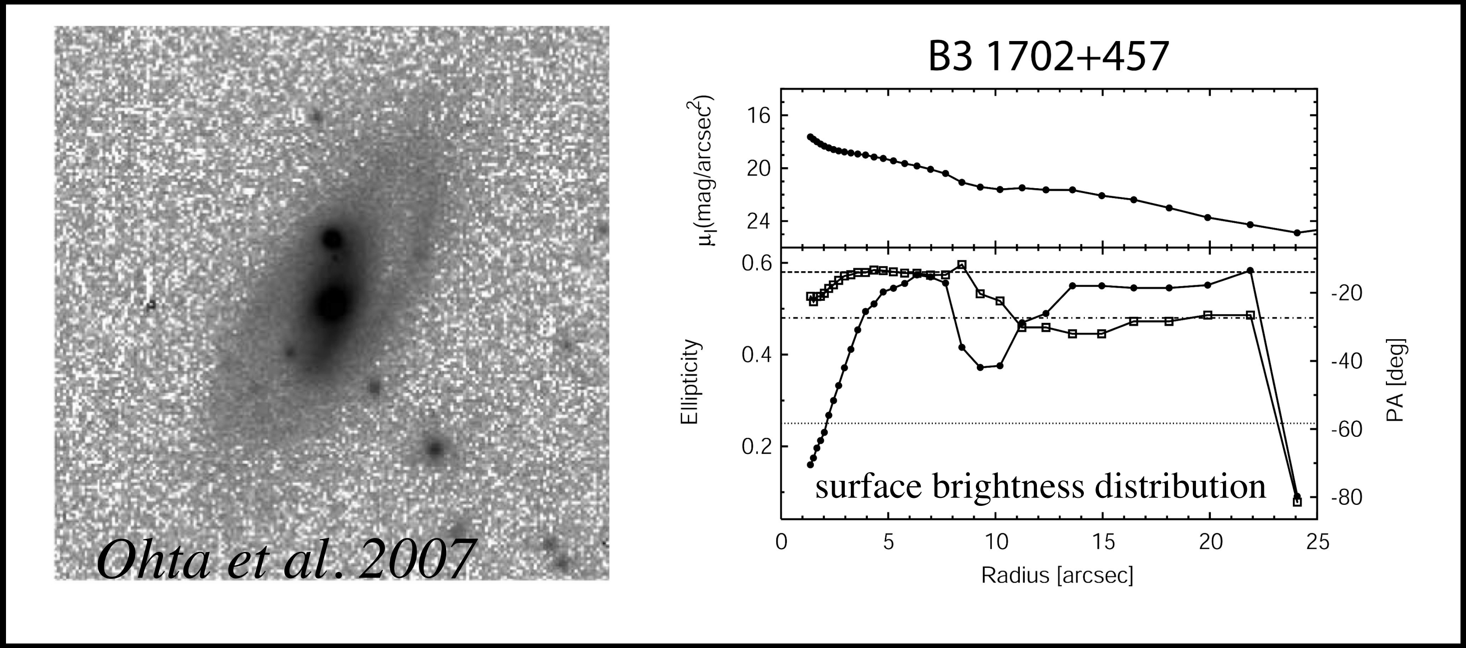
- mass outflow rates (outflow velocity)
- wind spatial extent and geometry
- bolometric luminosity

NOEMA PdB Interferometer

(hopefully) mitigated in our interferometry data (ongoing analysis)…stay tuned!

Feedback in IRAS17

Assuming the outflow velocity of the wind equal to the escape velocity, the energy output rate is sufficient to power feedback to the host galaxy (Hopkins & Elvis 2010)



Ohta et al. 2007

UFO component C
$N_H \sim 10^{24}$ cm^{-2}
$v_{out} \sim 27{,}000$ km s^{-1}

$\dot{M}_{out}(C) \sim 0.26\ Cf\ M_\odot\ yr^{-1}$
$\dot{E}(C) \sim 6 \times 10^{43}\ Cf\ erg\ s^{-1}$

$$\frac{\dot{E}(C)}{L_{bol}} = 11\%\ Cf$$

- **IRAS17020+4544 host galaxy is a barred Spiral**
- **$L_{bol} \sim 5\times10^{44}$ erg s^{-1} much lower than other cases of feedback from X-ray winds (QSO, ULIRG)**
- **No evidence of merger/disturbed morphology/dust obscuration**
- **Small black hole $\sim 6 \times 10^6\ M_\odot$**
- **High Accretion Rate**

To Feed or not to Feed?

Large injection of energy into the ISM of the AGN host galaxy requires high outflow velocity and column density.
Sources that feedback above the “magical” threshold of 0.5–5% of the AGN luminosity

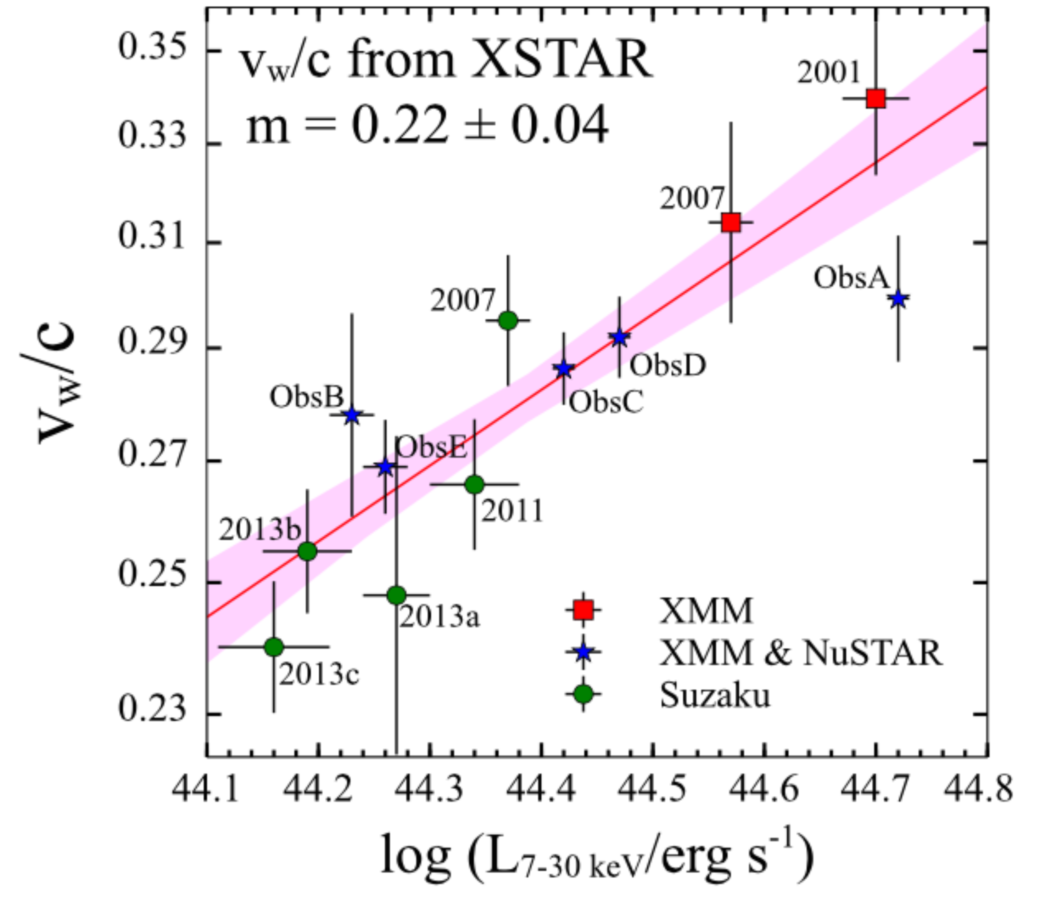
QSO/ULIRGS	**PDS456**	$L_{bol} \sim 10^{47}$ erg/s	$M_{BH} = 10^{9}\ M_{\odot}$
	Mrk 231	$L_{bol} \sim 5 \times 10^{45}$ erg/s	$M_{BH} = 8.7 \times 10^{7}\ M_{\odot}$
	IRASF111191+3257	$L_{bol} \sim 10^{46}$ erg/s	$M_{BH} = 1.6 \times 10^{7}\ M_{\odot}$
NLSy1	**IRAS 17020+4544**	$L_{bol} \sim 5 \times 10^{44}$ erg s^{-1}	$M_{BH} = 6 \times 10^{6}\ M_{\odot}$
	Mrk 1044	$L_{bol} \sim 5 \times 10^{44}$ erg s^{-1}	$M_{BH} = 1.4 \times 10^{6}\ M_{\odot}$
	IRAS13224-3809	$\langle L_{bol} \rangle \sim 5 \times 10^{44}$ erg s^{-1}	$M_{BH} = 6 \times 10^{6}\ M_{\odot}$

PG1211+143 (Chandra/HST UFO 2018): 0.02%

Luminosity dependence of UFO

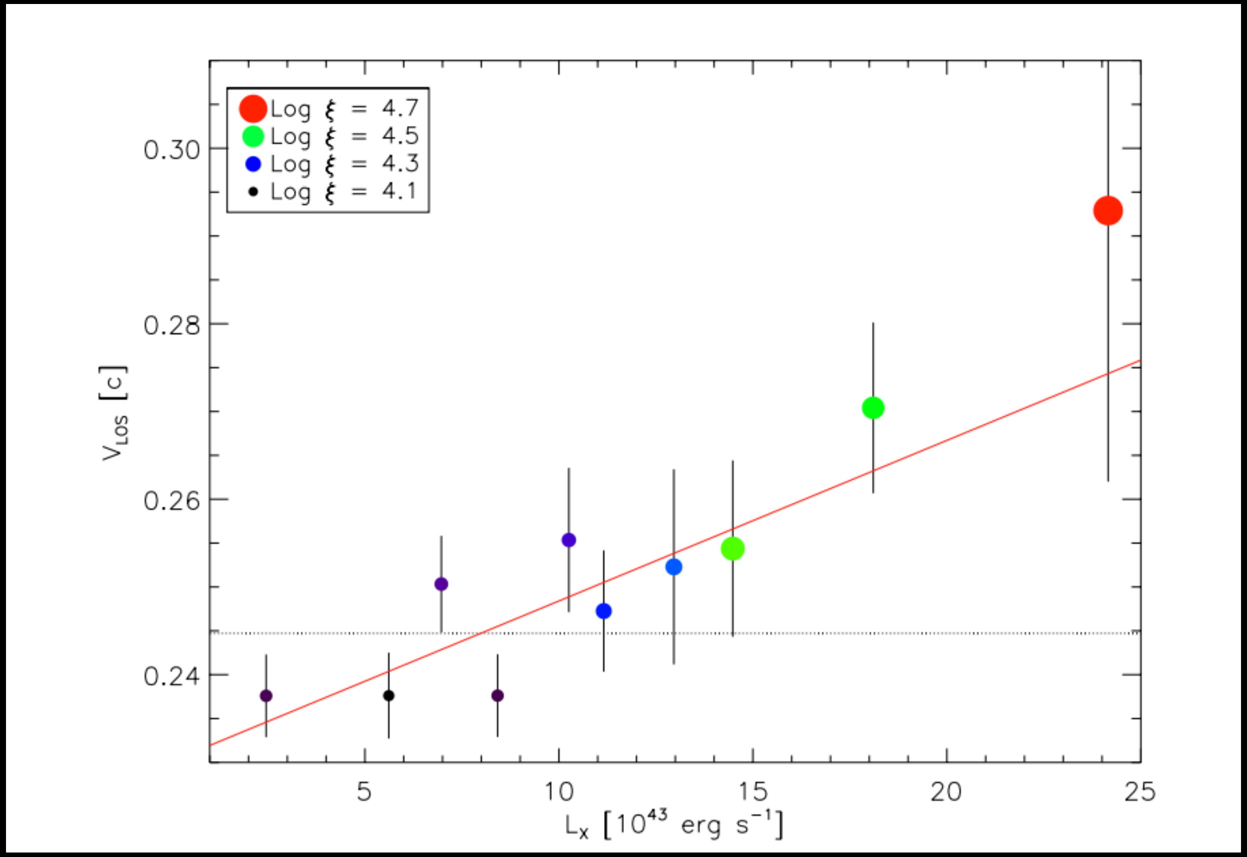
QSO PDS 456

Matzeu et al. 2017



NLSy1 IRAS13224-3809

Pinto et al. 2018

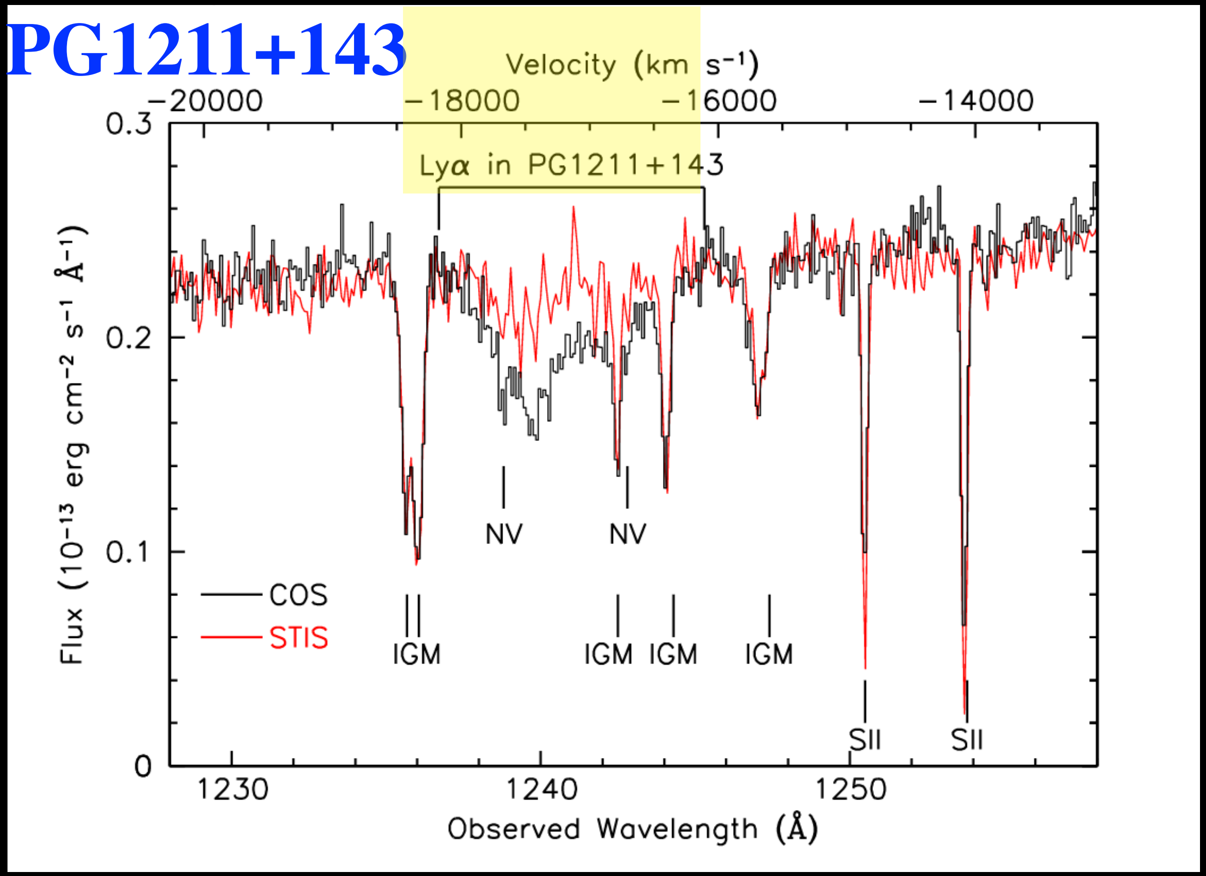


Correlations between the outflow velocity and the X-ray continuum luminosity seem to imply that

the disk wind is faster at higher luminosity

UFO in HST/COS spectra: clumpy winds

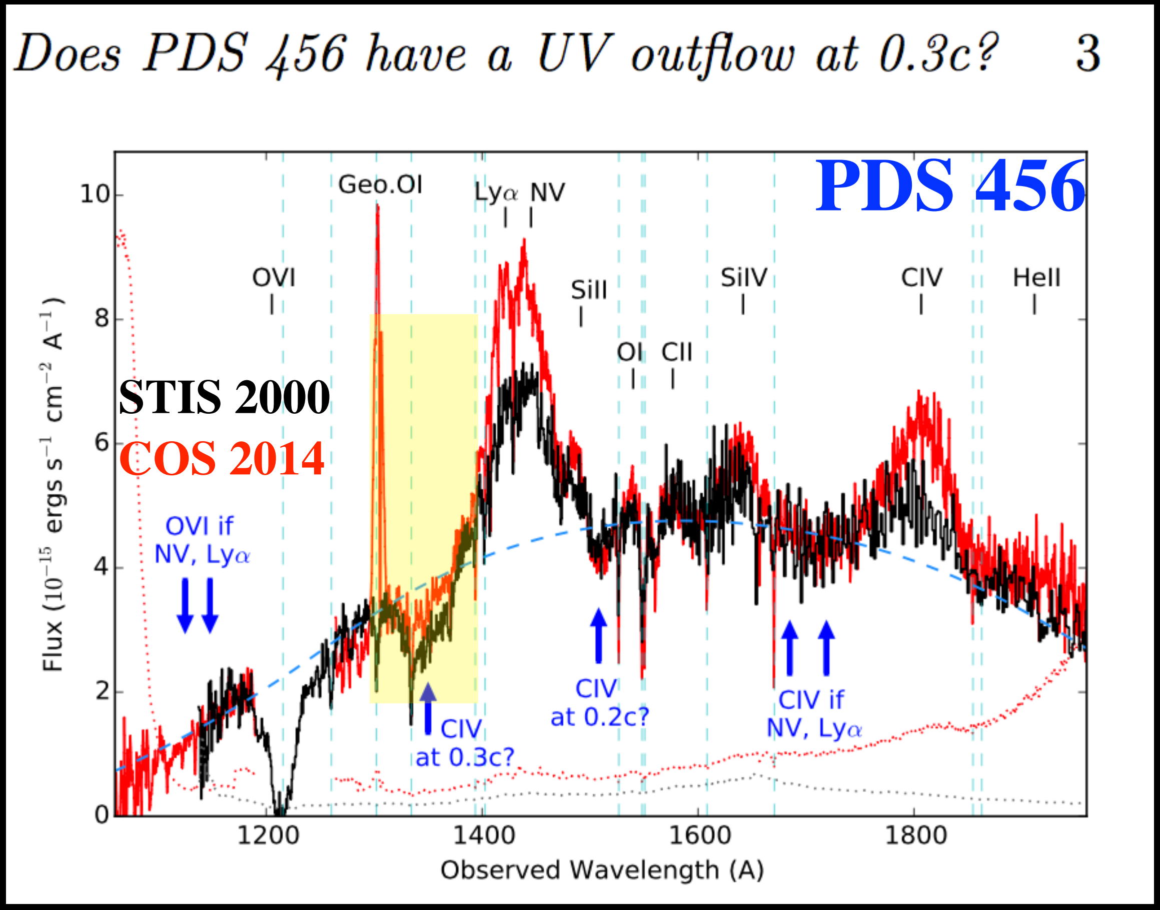
UFO QSO PG1211 ***Kriss et al. 2018***



Broad HI Lyα outflowing at -17,000 km/s

Simultaneous detection of X-ray UFO (H-He-like Ne, Mg, Si) outflowing at -17,300km/s in Chandra HETG (*Danehkar+ 2018*)

UFO QSO ***Hamann et al. 2018***



CIV BAL outflowing at ~0.3c would be the fastest UV wind ever detected

Velocity matches well the X-ray UFO, although data are not simultaneous…

Systematic search in UV spectra of X-ray UFO sources: negative result ***Kriss+2018***

Postdoc position available to work on AGN outflows: talk to me!

Conclusions and outlook

- **NLSy1 sources seem preferred to host multi-components UFO (but mind the "archival bias"). Analogy with high L QSO and role of high accretion rate to be investigated**

- **Connect X-ray winds with outflows in other bands to effectively test energy-driven outflows: mapping/observing radio and molecular outflow in sources with X-ray UFO is fundamental:**
  KEY ROLE OF GTM-50m

- **Feedback in "normal" Seyfert Galaxies (smaller BH) to be considered**

- **Even if no feedback, understanding accretion disc winds in local sources, how they are produced and how they interact with the host galaxy material is very important for gaining insights on high-Z sources where X-ray winds are difficult to observe by current facilities!**

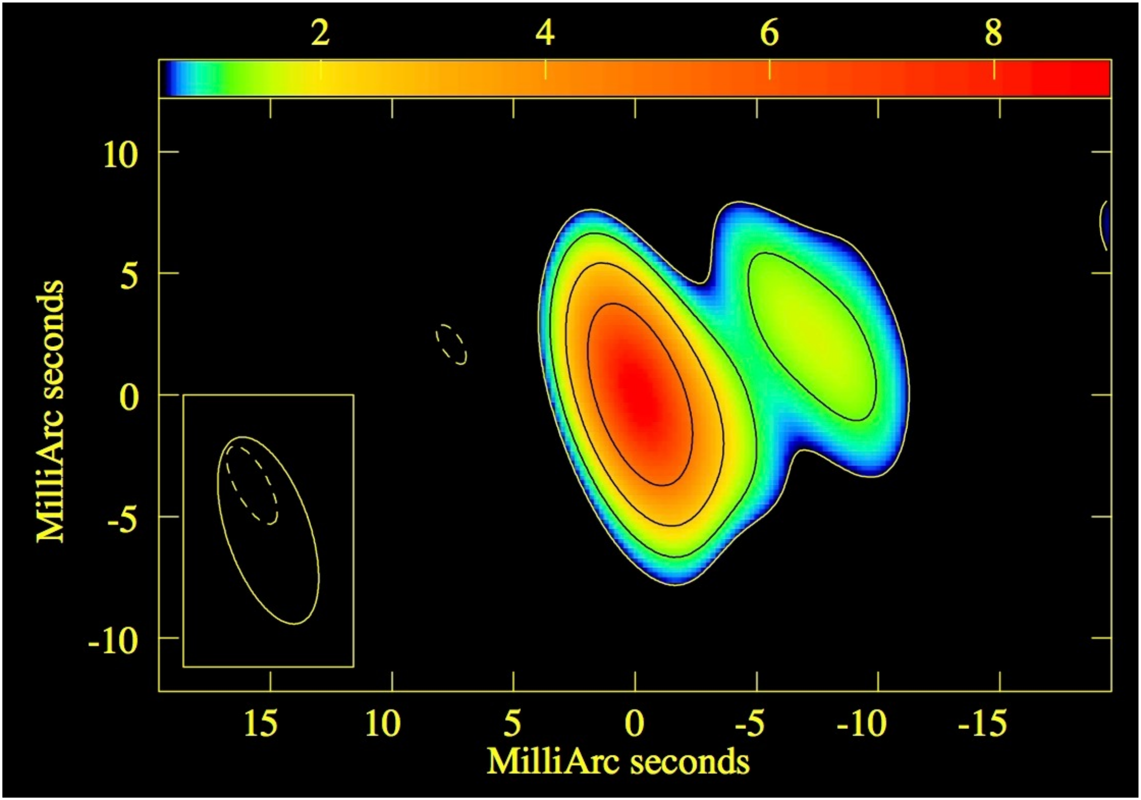
Thanks for your attention!

Additional material

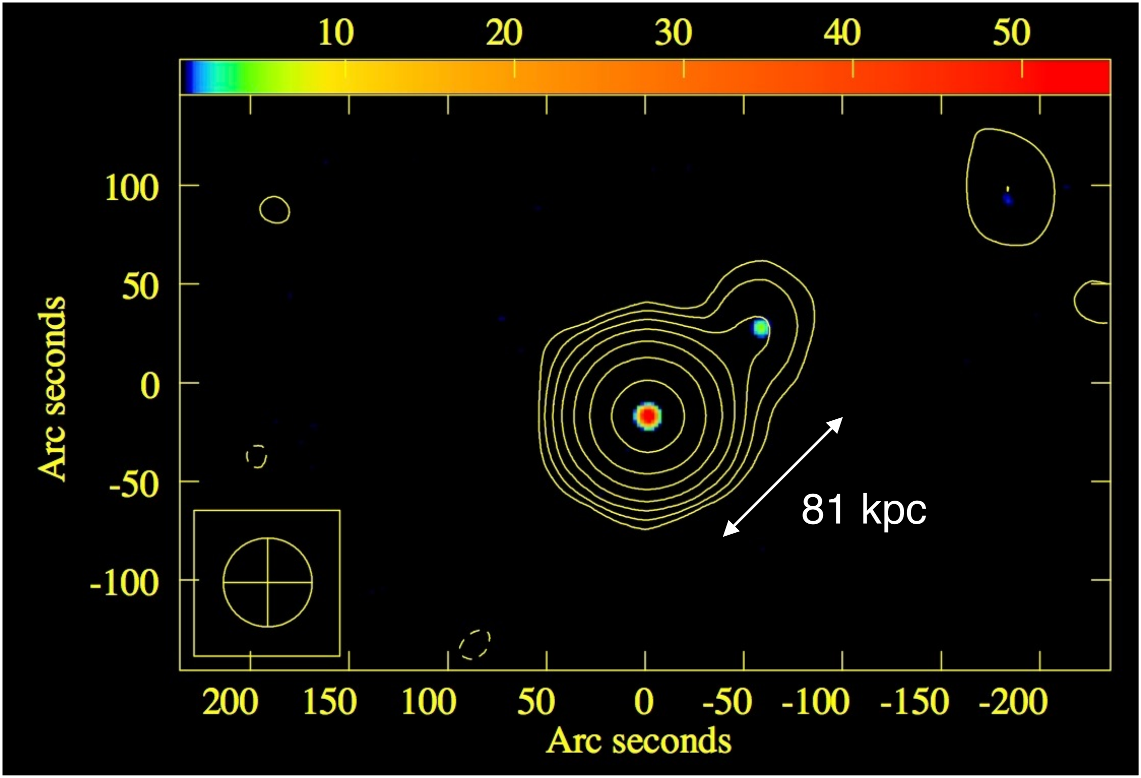
Radio Properties of IRAS17020+4544

Giroletti et. al 2017 A&A

VLBA image @8 GHz



Large scale image @1.4 GHz:
FIRST (colours) and NVSS (contours)



$P_{1.4\ GHz}=10^{24}$ W Hz^{-1} $T_b=10^8$ K

VLBA Observations in 2000 and 2014

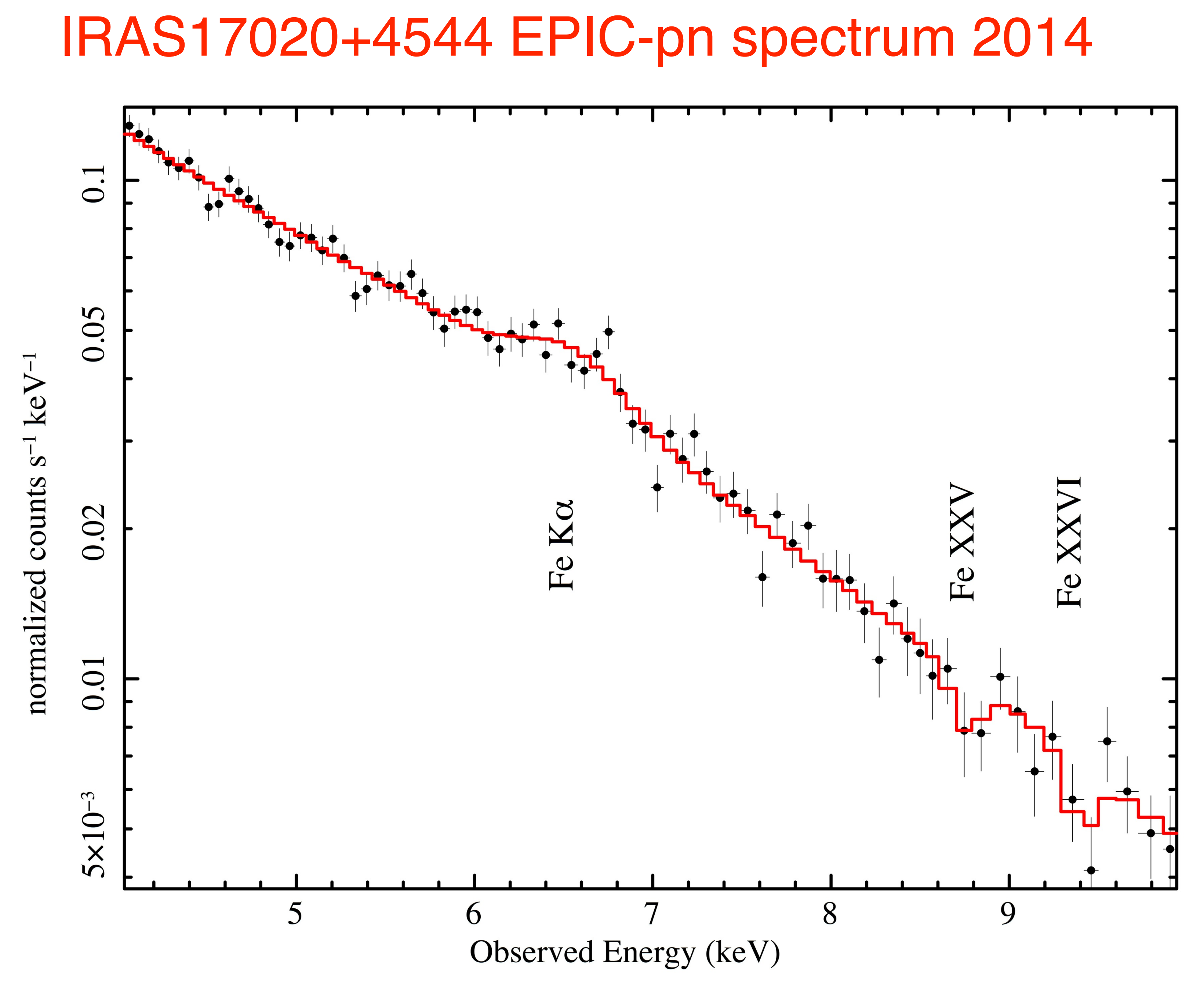
Compact bright core plus a secondary fainter component at 1.2'

Steep spectral index indicates synchrotron spectrum (magnetic fields)

Elongated jetted structure /outflow at ~10 pc scale moving at v~ 0.1*c*

Possible connection with X-ray outflow?

A fast outflow in the Fe K band too?



Highly ionized absorption very marginally observed

Fe XXV
E=8.75± 0.13 keV
EW=49±43 eV

Fe XXVI
E=9.39± 0.10 keV
EW= 64±50 eV

v_{out}~ 0.34c

X-ray AGN winds: where we stand now ?

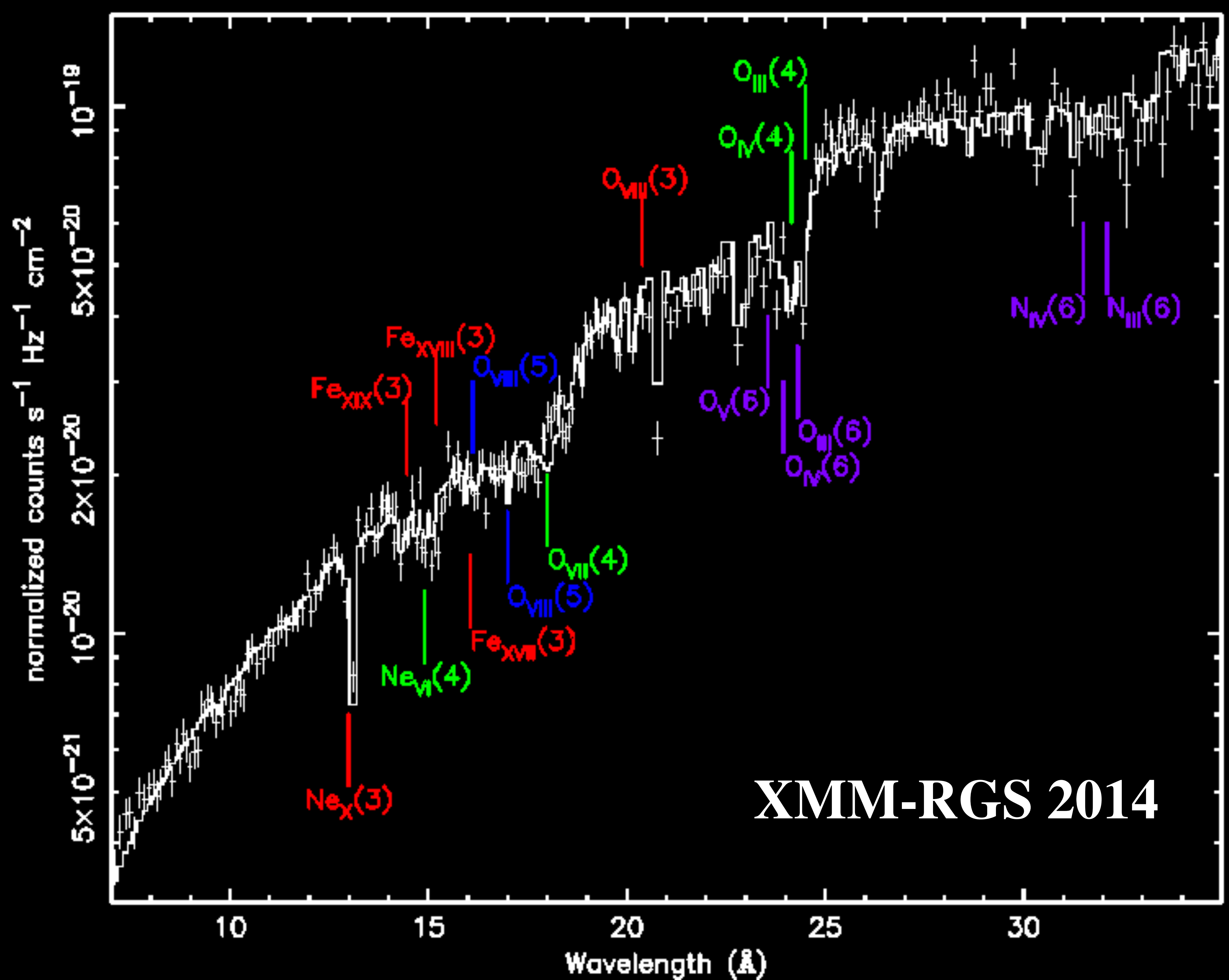
Courtesy of M. Guainazzi

Paper	Instrument	N	Mimimum incidence
McKernan+07	HETG	15 Type I AGN	WA: ~67%
Tombesi+10	EPIC-pn	42 RQ-AGN	WA: ~60% UFOs: ~34%
Gofford+13	XIS	51 Type 1-1.9 AGN	UFO: ~40%
Laha+14 (WAX)	EPIC-pn+RGS	26 Seyferts 1-1.5 + 1 LINER	WA: $77\pm9^{+3}_{-14}$%
Tombesi+14	EPIC-pn/XIS	26 RL-AGN	UFO: 50±20%

"RQ"=Radio-Quiet; "RL"=Radio-Loud

The slow wind in IRAS17020+4544

M. Sanfrutos et al. submitted


4 WAs + 5 UFOs

XMM-RGS 2014