Extragalactic Molecular Outflows and Feedback

Eckhard Sturm (MPE)

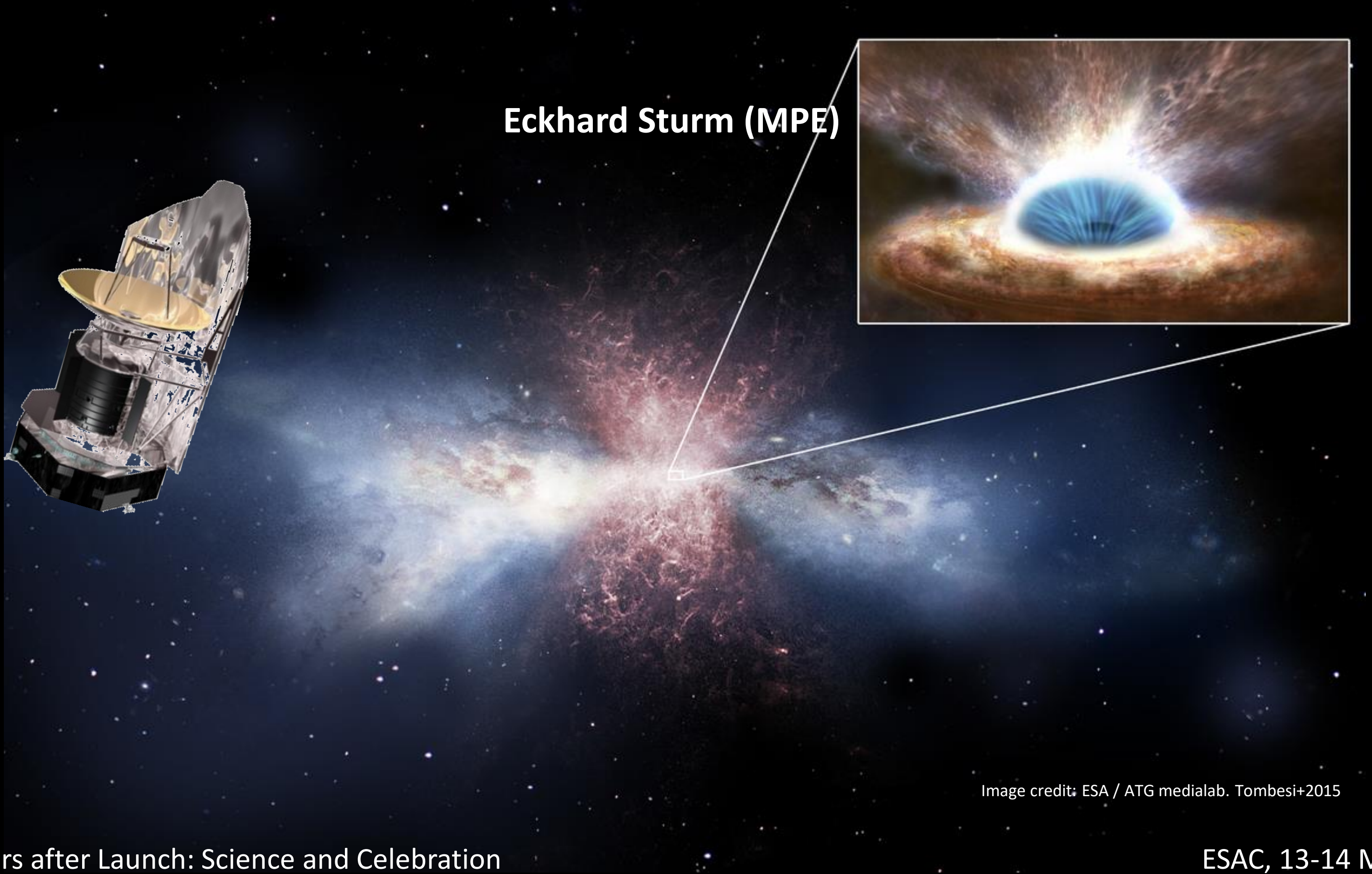
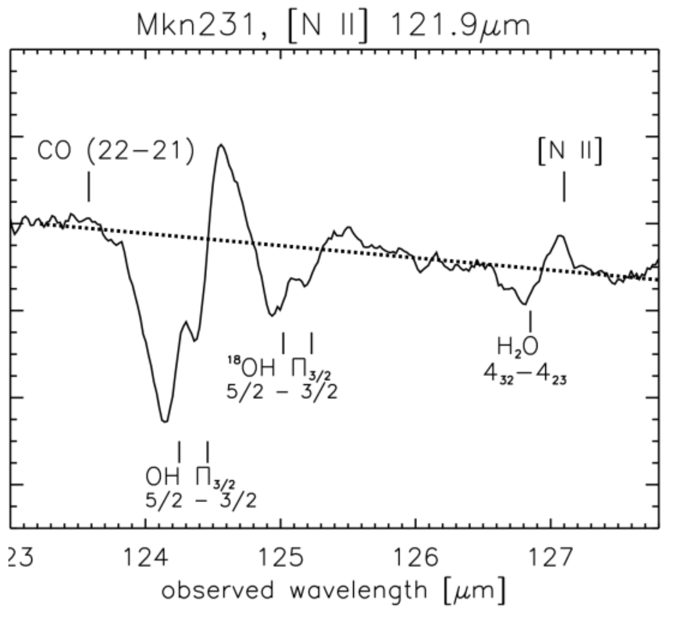
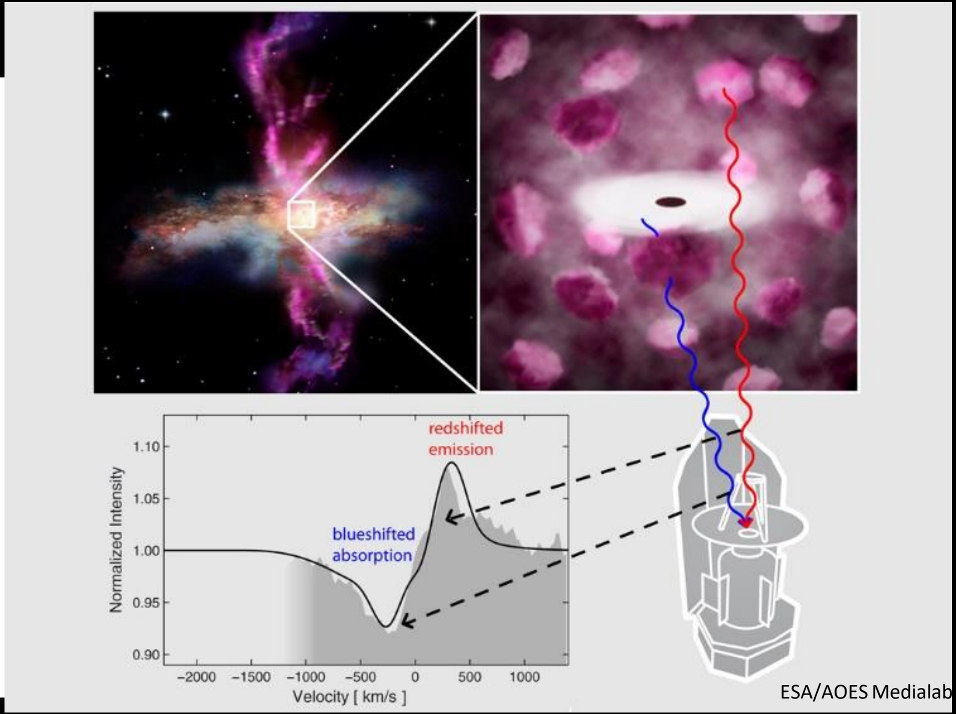


Image credit: ESA / ATG medialab. Tombesi+2015

Some history

Mkn 231: November 9, 2009, OD=179, OBSID=1342186811 (SDP_esturm_3)





1342182011	NGC 5315	13h 53m 57.26s	-66d 30' 53.02"	PACS	PacsLineSpec		91	Calibration_pvpacs_13	Calibration_PVSpecAotVal_1-PVSpecAotVal_521A_StdLineSpec_04A_NGC5315_00
1342186305	he2-10	08h 36m 15.06s	-26d 24' 33.26"	PACS	PacsLineSpec	1	165	SDP_esturm_3	NearGalPACS-lowmet-he2-10-OIIINII-point
1342186306	he2-10	08h 36m 15.12s	-26d 24' 34.14"	PACS	PacsLineSpec	2	165	SDP_esturm_3	NearGalPACS-lowmet-he2-10-4lines-point
1342186307	abell 1068	10h 40m 44.44s	+39d 57' 11.79"	PACS	PacsLineSpec	1	165	SDP_aedge_3	PSpecL-A1068_OI
1342186308	abell 1068	10h 40m 44.46s	+39d 57' 11.71"	PACS	PacsLineSpec	1	165	SDP_aedge_3	PSpecL-A1068_CII
1342186310	HD_169142	18h 24m 29.63s	-29d 46' 48.75"	PACS	PacsLineSpec	6	165	SDP_bdent_3	HD_169142_Ib_dither_OI63
1342186311	HD_181327	19h 22m 59.00s	-54d 32' 16.78"	PACS	PacsLineSpec	5	165	SDP_bdent_3	HD_181327_Ia_dither_OI63
1342186314	J0843.3-7905	08h 43m 18.84s	-79d 05' 17.54"	PACS	PacsLineSpec	5	165	SDP_bdent_3	J0843.3-7905_Ib_dither_OI63
1342186315	HH 46	08h 25m 43.84s	-51d 00' 35.25"	PACS	PacsLineSpec	8	165	SDP_evandish_3	PACS set 1 Class I - HH 46
1342186316	HH 46	08h 25m 43.94s	-51d 00' 35.31"	PACS	PacsLineSpec	7	165	SDP_evandish_3	PACS set 2 - Class I - HH 46
1342186317	HH 46-r	08h 25m 39.75s	-51d 00' 55.74"	PACS	PacsLineSpec	1	165	SDP_evandish_3	PACS HH46 red
1342186318	L 1157	20h 39m 06.24s	+68d 02' 21.88"	PACS	PacsLineSpec	8	165	SDP_evandish_3	PACS - L1157 C
1342186319	L 1157-N	20h 39m 01.05s	+68d 04' 09.54"	PACS	PacsLineSpec	8	165	SDP_evandish_3	PACS - L1157 N
1342186320	L 1157-S	20h 39m 12.05s	+68d 00' 47.02"	PACS	PacsLineSpec	8	165	SDP_evandish_3	PACS - L1157 S
1342186321	NGC 7129 FIRS2	21h 43m 01.69s	+66d 03' 24.47"	PACS	PacsLineSpec	5	165	SDP_evandish_3	PACS setting 1 H2O 212-101 - NGC 7129 FIRS2
1342186322	NGC 7129 FIRS2	21h 43m 01.73s	+66d 03' 24.78"	PACS	PacsLineSpec	4	165	SDP_evandish_3	PACS setting 2 - NGC 7129 FIRS2
1342186571	Neptune	21h 44m 00.64s	-14d 04' 29.96"	PACS	PacsLineSpec	2	170	SDP_pharto01_3	PSpecL-anch42505
1342186650	Neptune	21h 43m 59.74s	-14d 04' 35.79"	PACS	PacsLineSpec		173	Calibration_pvpacs_72	Calibration_PVSpecAotVal_1-PVSpecAotVal_521G_StdLineSpec_B3_Nept_w66_4x
1342186651	Neptune	21h 43m 59.71s	-14d 04' 35.79"	PACS	PacsLineSpec		173	Calibration_pvpacs_72	Calibration_PVSpecAotVal_1-PVSpecAotVal_521G_StdLineSpec_B3_Nept_w66_5x
1342186652	HIP 21479	04h 36m 45.42s	-62d 04' 37.71"	PACS	PacsLineSpec		173	Calibration_pvpacs_72	Calibration_PVSpecFPG_1-PVSpecFPG_411J_stdLineSpec_L7x7_RDor_02
1342186796	Zw3146	10h 23m 39.52s	+04d 11' 10.89"	PACS	PacsLineSpec		178	SDP_aedge_3	PSpecL-Zw3146_OI
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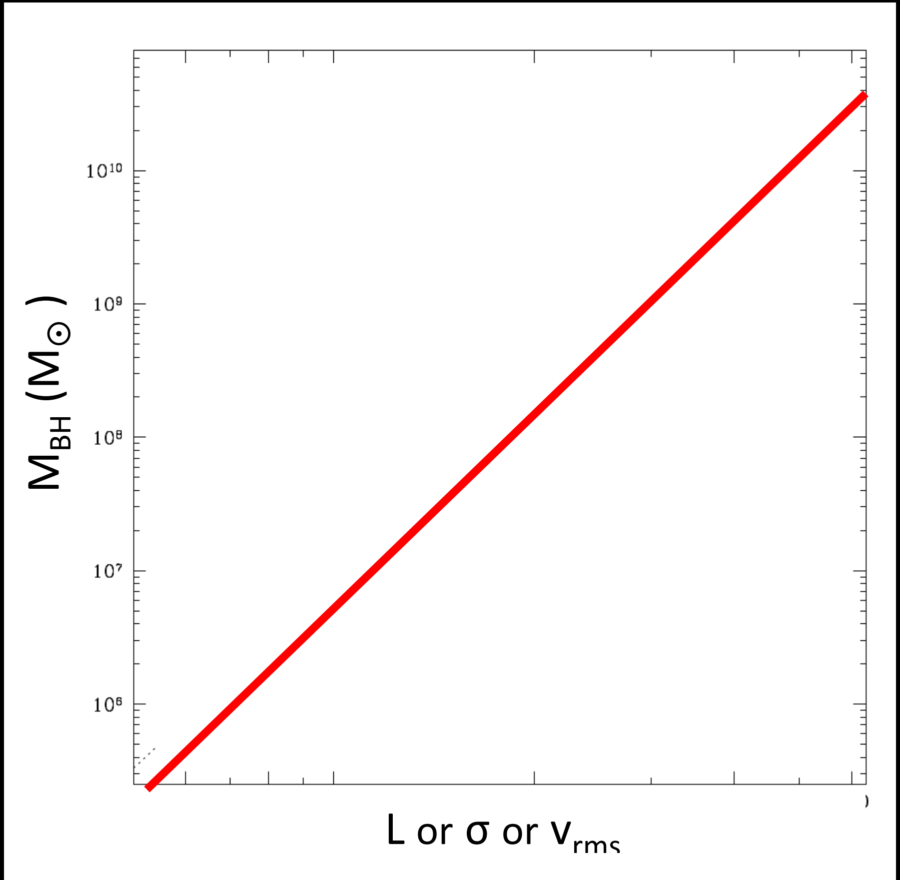
1342186799	M82	09h 55m 51.88s	+69d 40' 47.28"	PACS	PacsLineSpec	2	178	SDP_esturm_3	NearGalPACS-SB-01-blue
1342186802	Christensen (C/2006 W3)	19h 11m 45.00s	-10d 35' 28.63"	PACS	PacsLineSpec	2	178	SDP_pharto01_3	PACS dedicated line spectroscopy - resched
1342186810	HD_181327	19h 22m 58.88s	-54d 32' 18.48"	PACS	PacsRangeSpec	4	179	SDP_bdent_3	HD_181327_Ib_dither_CII_OI145_H2O
1342186811	Mkn 231	12h 56m 14.26s	+56d 52' 24.91"	PACS	PacsRangeSpec	23	179	SDP_esturm_3	Mkn231-RS-long
1342186812	F10214+4724	10h 24m 34.73s	+47d 09' 11.93"	PACS	PacsRangeSpec	4	179	SDP_kmeisenh_3	PacsHigh-0002_OIV_range
1342186970	Neptune	21h 44m 03.66s	-14d 04' 17.56"	PACS	PacsLineSpec		182	Calibration_pvpacs_76	Calibration_PVSpecAotVal_1-PVSpecAotVal_521G_StdLineSpec_R1_Nept_w138_3

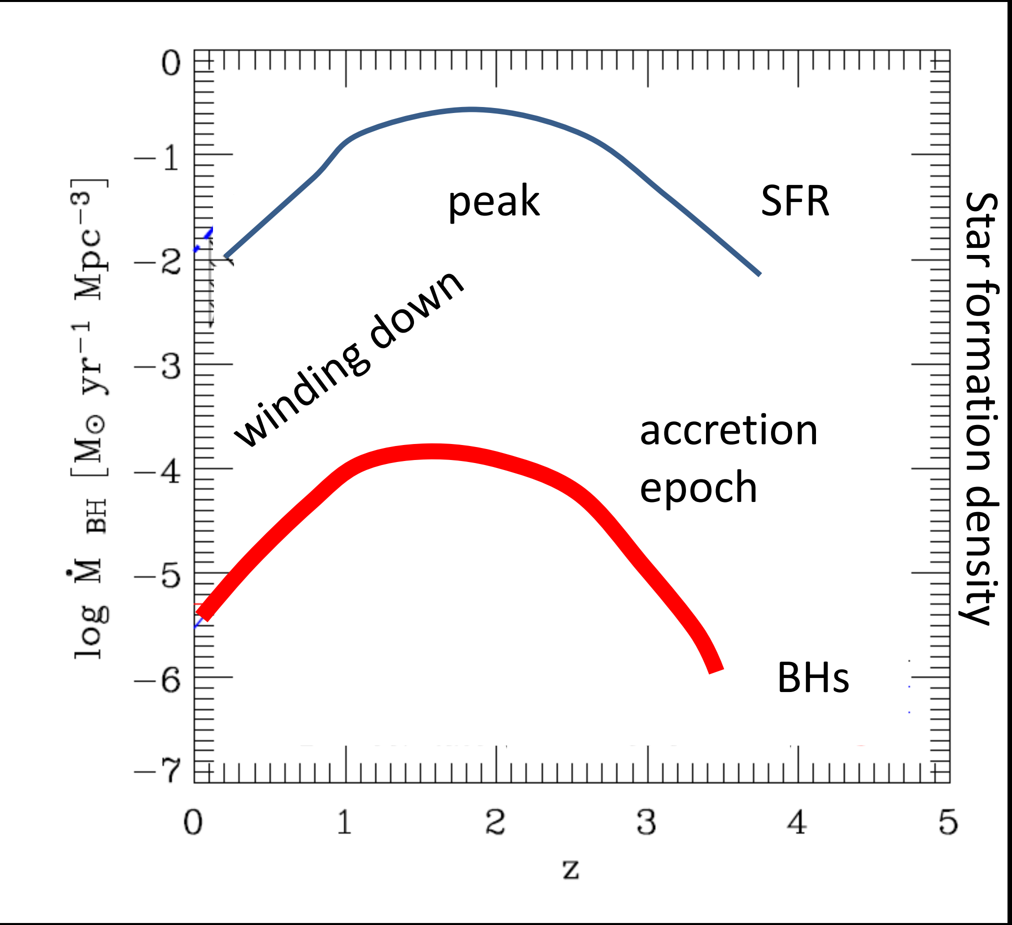
Context: Co-Evolution and Feedback

The masses of supermassive black holes correlate almost perfectly with the luminosities, velocity dispersions and stellar masses of their host bulges (Magorrian+ 1998, Gebhardt+ 2000, Ferrarese & Merritt 2000)

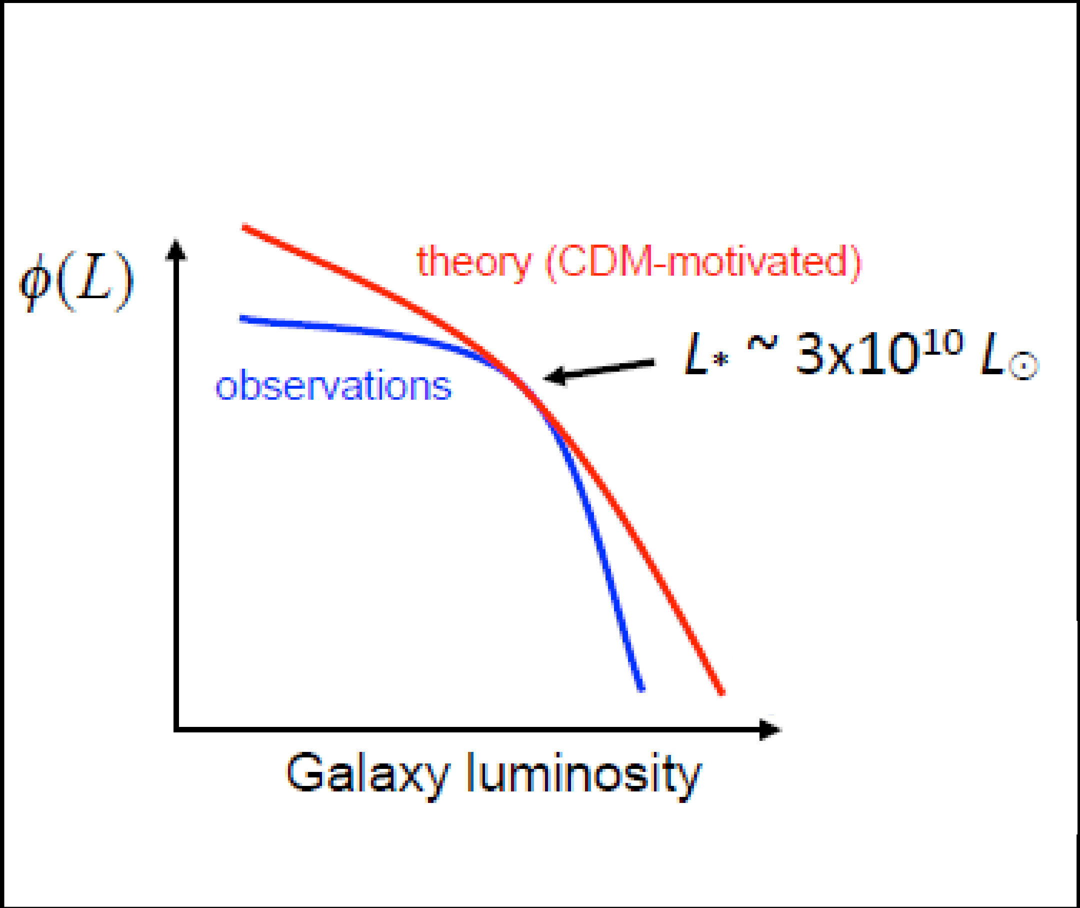


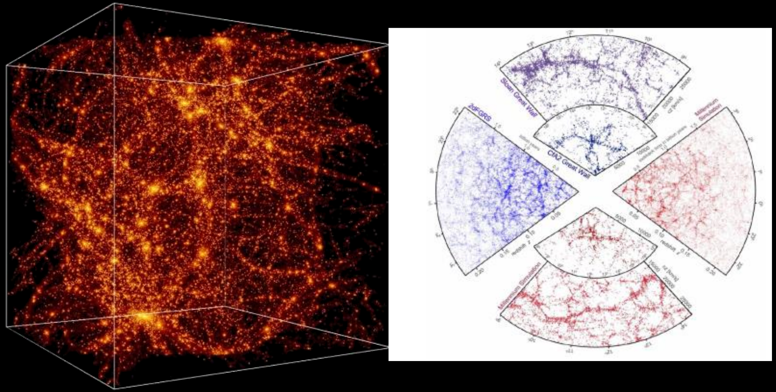
Context: Co-Evolution and Feedback

Both star-formation and AGN activity show peaks at $z > 1$, when the bulk of the activity occurred behind dust.
Is this because there is a physical link between star-formation in galaxies (several kpc scale) and SMBH mass growth (<pc scale, the so-called AGN activity)? Via some feedback mechanism?
Or have galaxies and SMBHs simply co-evolved without directly influencing each other?



Context: Co-Evolution and Feedback





The observed faint-end and bright-end slope of the galaxy mass (or luminosity) function (as described by the Schechter function) is significantly different from the predicted slope of the dark matter halo mass function.

Context: Co-Evolution and Feedback

What are the controlling mechanisms?

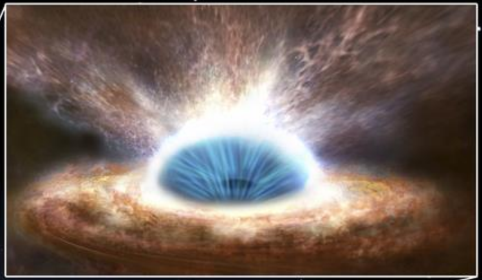
- **Positive feedback**:
  Common feeding, e.g. in Mergers, ‘Secular’ disk instabilities and clumps / bars / nuclear spiral structures/ triggered star formation through winds/shocks from AGN and/or stars
- **Negative feedback**:
  quenching of star formation and starvation of BH, e.g. via tidal stripping, strong winds/outflows from AGN and/or stars

Molecular mass dominates the outflow

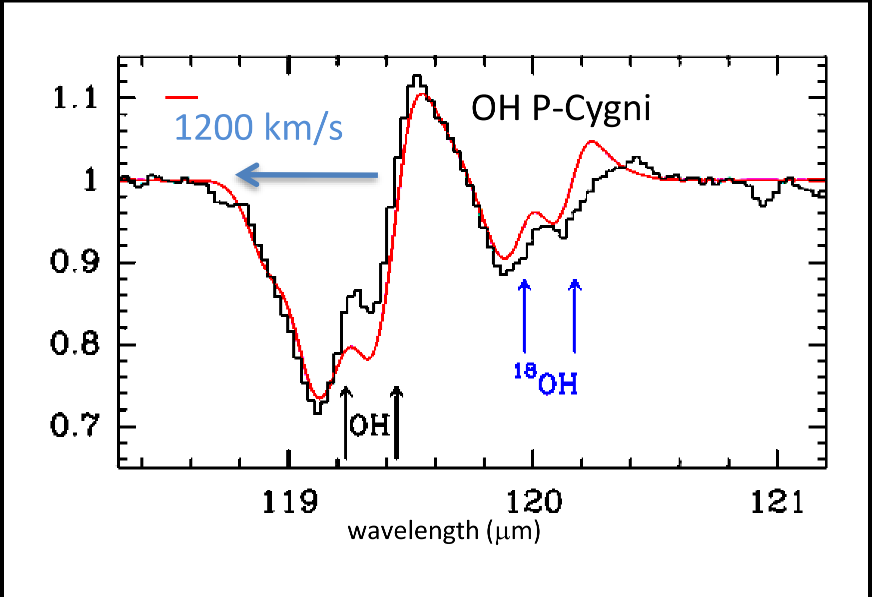
Stars are formed from molecular gas

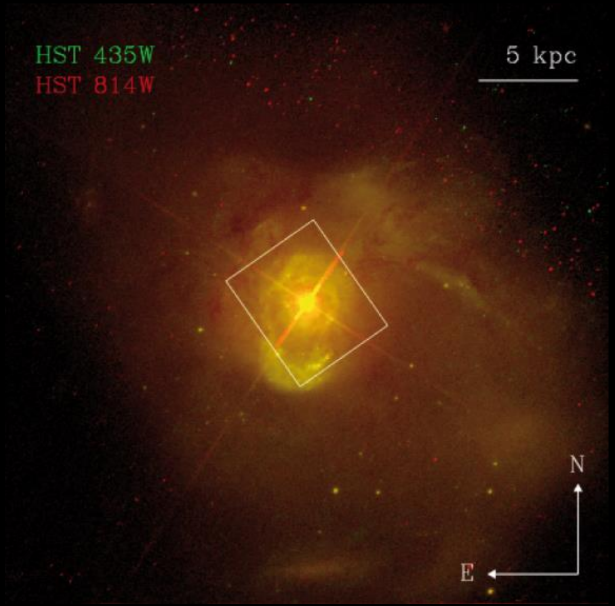
Molecular outflows and feedback

- Tracers (OH, CO, CII)
- Evidence, statistics, simple correlations
- Outflow masses and energetics
  (masses, outflow rates, momentum, luminosities)
- Does it have an effect?
  (mass loading, depletion times)
- Source and mechanism
  (AGN and/or Star formation, momentum and/or energy)

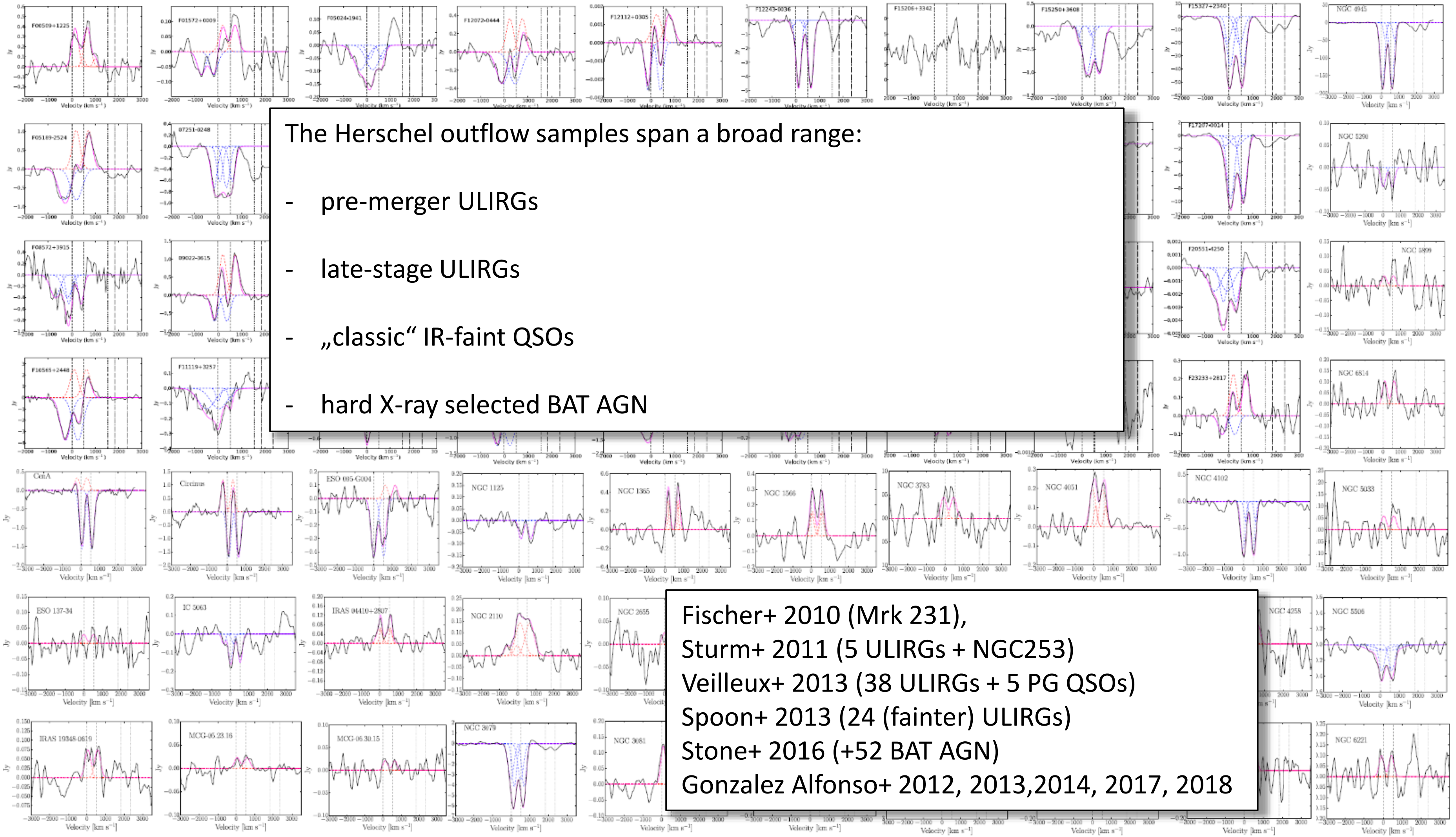


I) OH





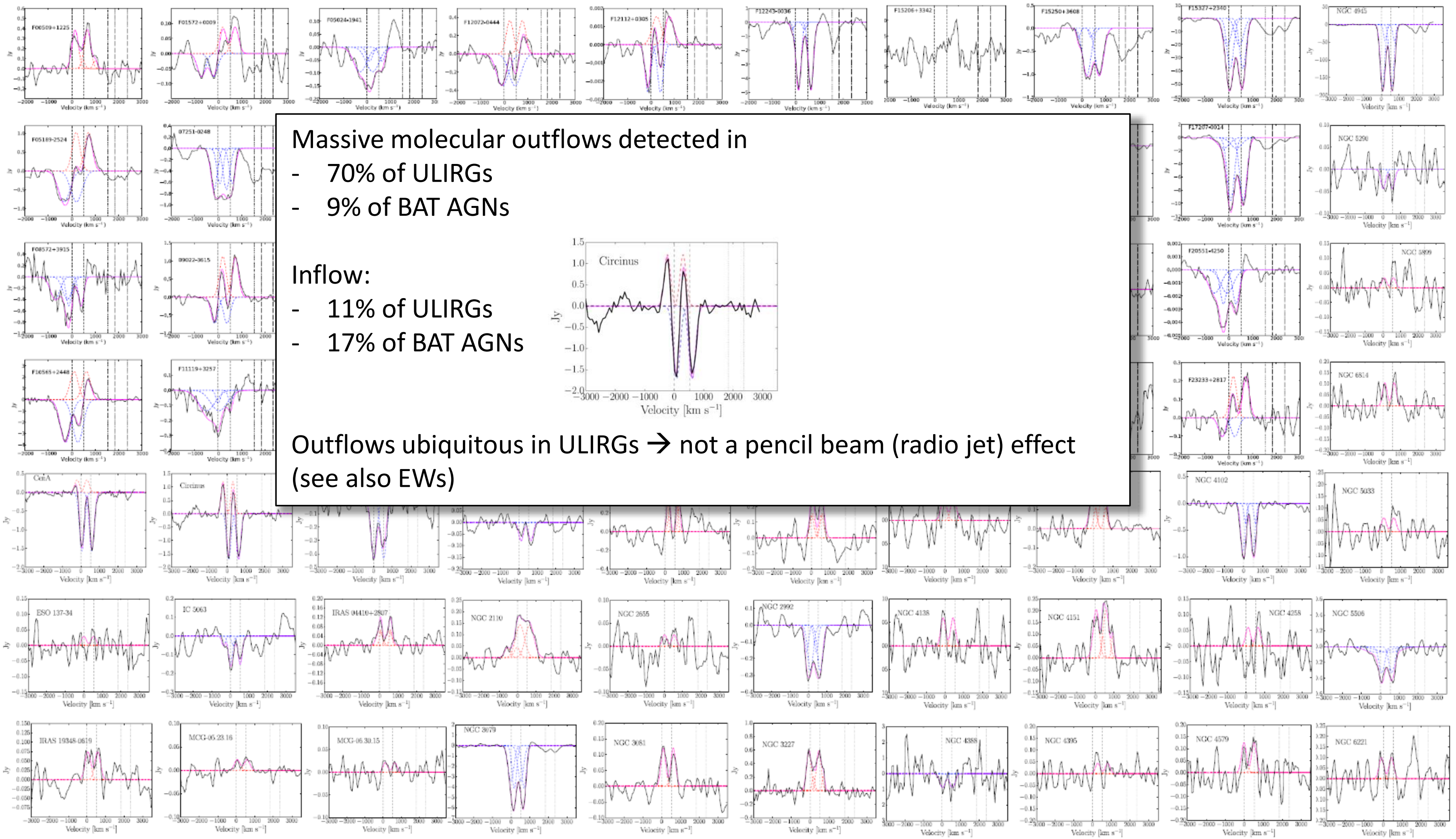
Mrk 231; Fischer+2010, Sturm+2011



The Herschel outflow samples span a broad range:

- pre-merger ULIRGs
- late-stage ULIRGs
- „classic“ IR-faint QSOs
- hard X-ray selected BAT AGN

Fischer+ 2010 (Mrk 231),
Sturm+ 2011 (5 ULIRGs + NGC253)
Veilleux+ 2013 (38 ULIRGs + 5 PG QSOs)
Spoon+ 2013 (24 (fainter) ULIRGs)
Stone+ 2016 (+52 BAT AGN)
Gonzalez Alfonso+ 2012, 2013,2014, 2017, 2018



Massive molecular outflows detected in
- 70% of ULIRGs
- 9% of BAT AGNs

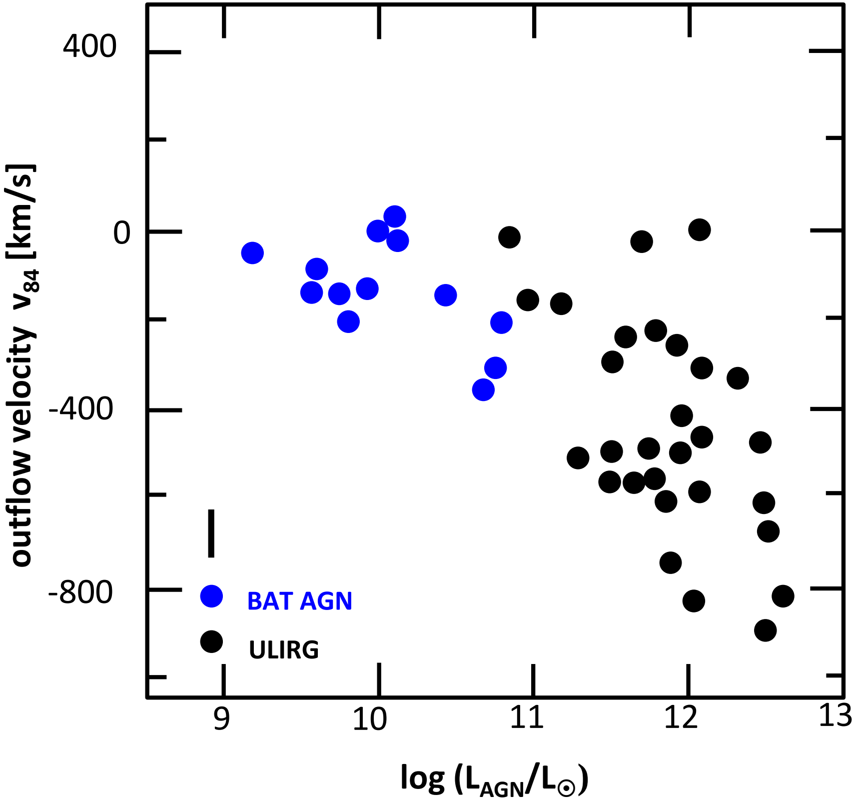
Inflow:
- 11% of ULIRGs
- 17% of BAT AGNs

Outflows ubiquitous in ULIRGs → not a pencil beam (radio jet) effect (see also EWs)

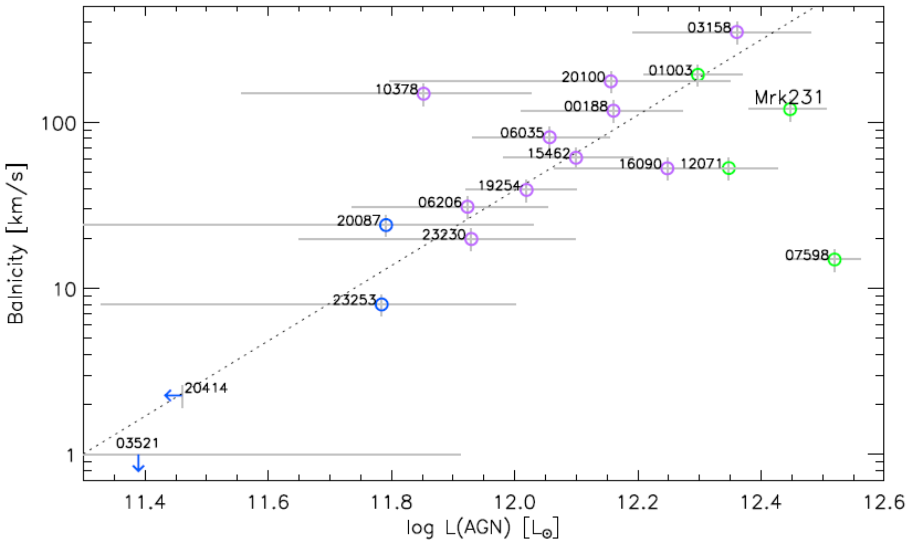
What OH line profiles can tell us (without any modeling):

- P-Cygni → outflow
- Found in ~ALL ULIRGs (→ not a pencil beam effect, but large opening angles)
- Profile sub-structure --> more than one outflowing (+quiescent) component
- Various transitions of different energy levels: hints at geometry
- emission weaker than absorption → spherical symmetry not necessarily the best approximation, and extinction plays some role
- Outflow parameters (e.g. velocity, power) correlated with AGN properties → AGN likely the main driver of powerful molecular outflows in ULIRGs

Outflow velocity ~ L_{AGN}



Sturm+2011, Veilleux+2013, Stone + 2016: 43 ULIRGs and PG QSOs, 52 BAT AGN



Spoon, Farrah, Leboutellier et al. 2013

Info Point – I   statistics and simple correlations

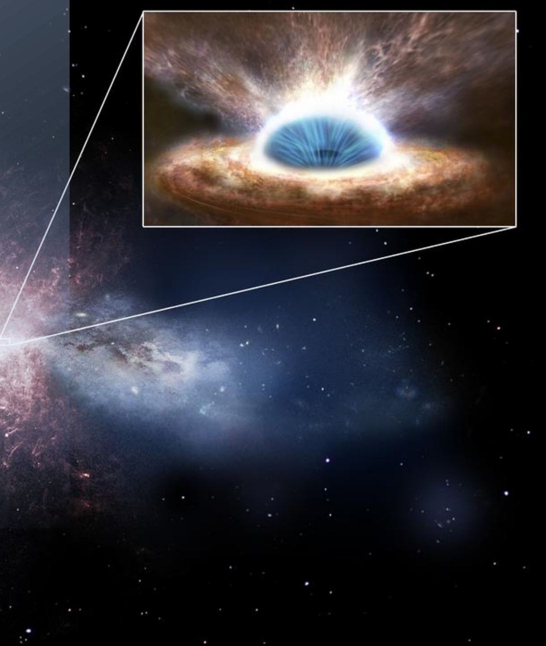
In a Herschel sample of ~50 ULIRGs and ~50 AGN: detections of massive molecular

outflows	in	inflows
70% of ULIRGs		11% of ULIRGs
9% of BAT AGNs		17% of BAT AGNs

- Outflows ubiquitous in ULIRGs → not a pencil beam effect

- Outflow velocity $\sim L_{AGN}$, $v_{max} > 1000$km/s,

- Outflow dominated by AGN, at least for luminous AGN



Fischer+2010, Sturm+2011, Veilleux + 2013, Spoon +2013, Stone+ 2016

Modelling of OH line profiles can

- Further quantify molecular outflows:

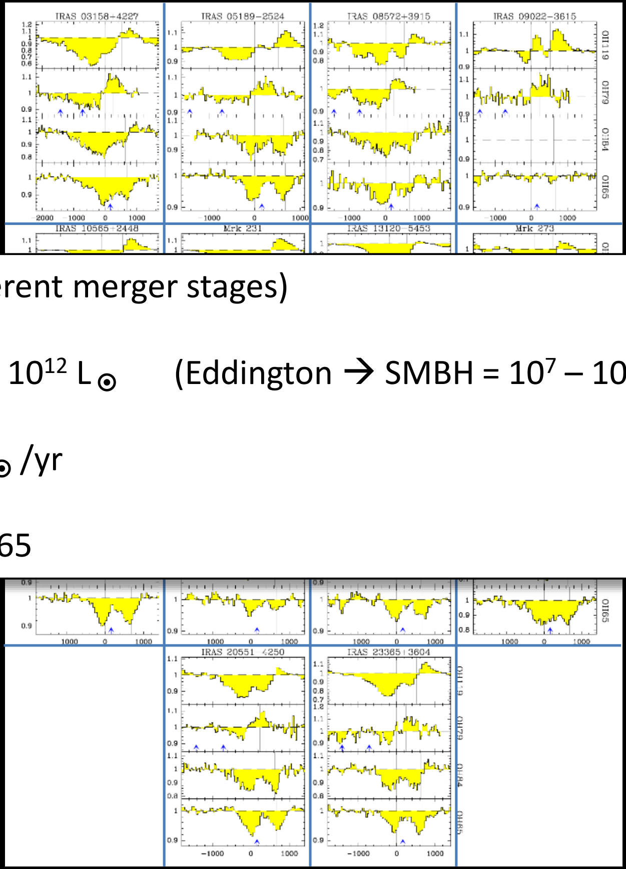
  outflow mass (mass outflow rate), depletion time scale, outflow momentum rate

Comparison to feedback models:

characterise as AGN or star formation driven

characterise if radiatively or momentum driven, coupling efficiencies, …

Modeling and energetics



14 ULIRGs (different merger stages)

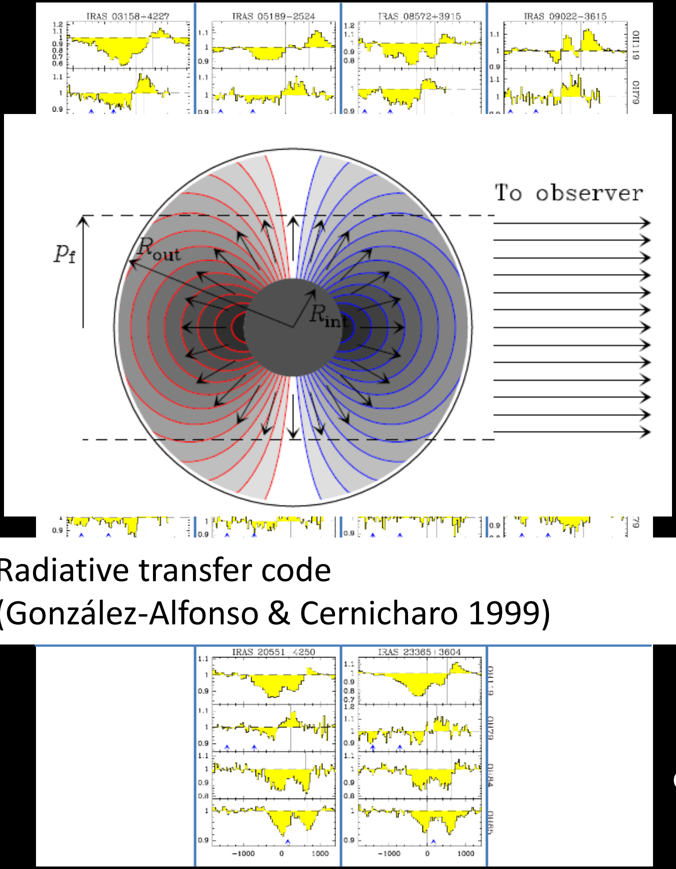
L_{AGN} = (0.3 – 2) x 10^{12} $L_\odot$ (Eddington → SMBH = 10^7 – 10^8 $M_\odot$)

SFR = 50-350 $M_\odot$ /yr

OH 119, 79, 84, 65

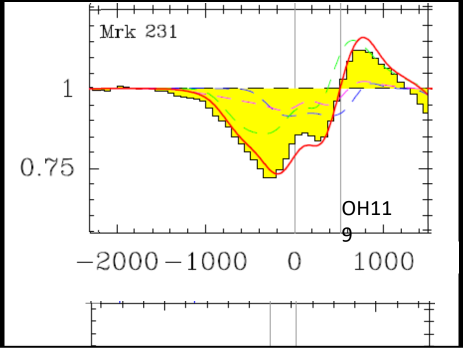
González-Alfonso + 2017

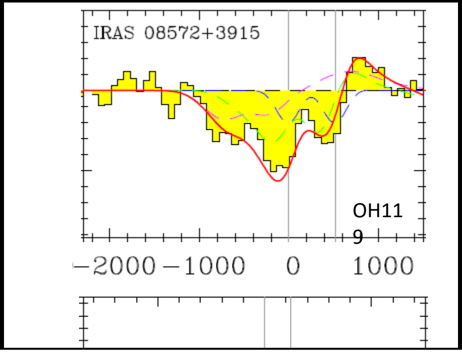
Modeling and energetics



Radiative transfer code
(González-Alfonso & Cernicharo 1999)

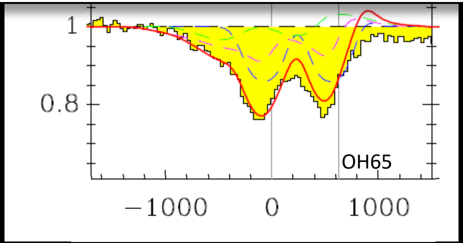
González-Alfonso + 2017

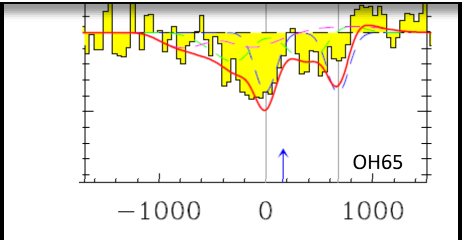




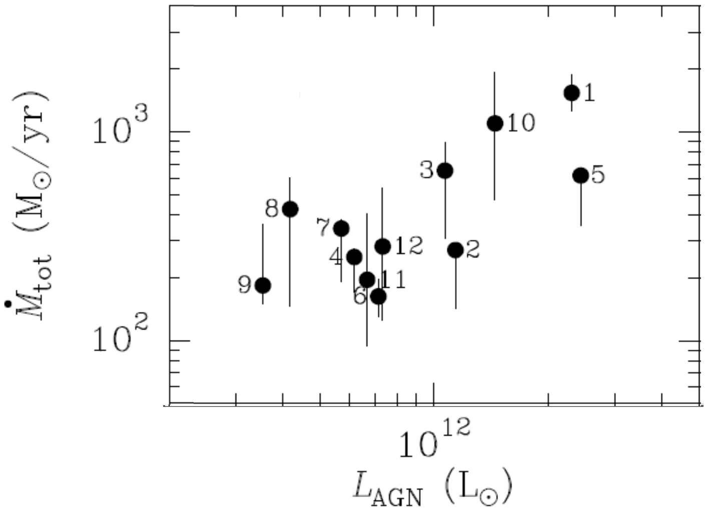
Modelling: →

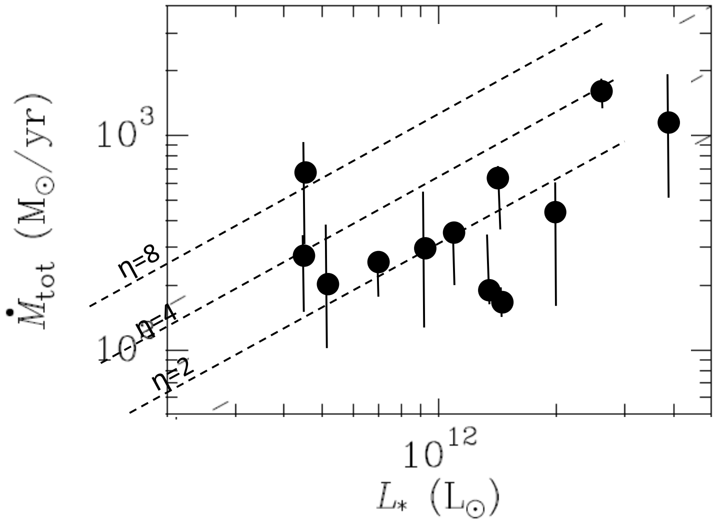
- Radius and covering factor r, f
- outflow mass M_{out}
- outflow rate $\dot{M}_{out} = M_{out}\ v/r$
- Mass loading $\eta = \dot{M}_{out} / SFR$
- Momentum flux: $\dot{P} = \dot{M}v$
- Mechanical luminosity: $\dot{E} = 0.5\ \dot{M}v^2$



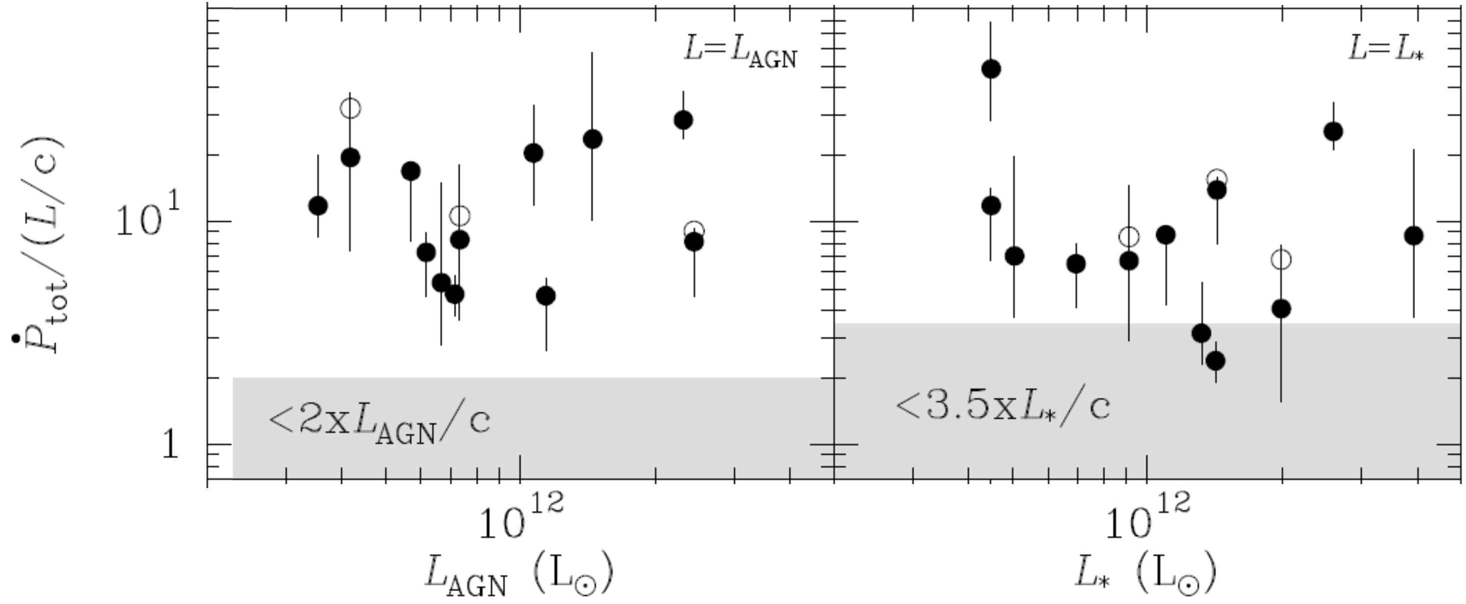


- Outflow masses: M = (100 – 2900) $10^6 M_\odot$
- Mass outflow rate $\dot{M}_{out}$ = 200 – 1500 $M_\odot$ /yr
- Mass loading: $\eta = \dot{M}_{out}$ / SFR = 1 – 10





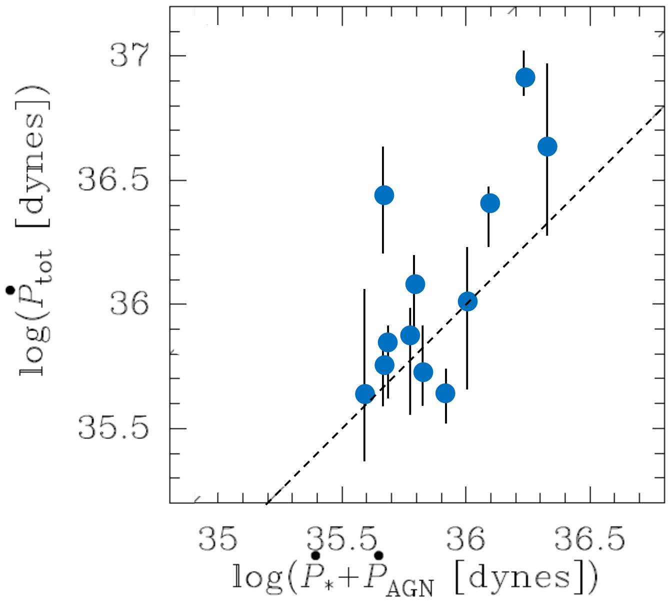
AGN- or Starburst-driven? Momentum-conserving or energy-conserving?



Starburst99 (Leitherer + 1999): starbursts supply a maximum momentum of ~3.5 L_*/c (including ram pressure of winds and radiation pressure on dust grains) (Heckman+2015)

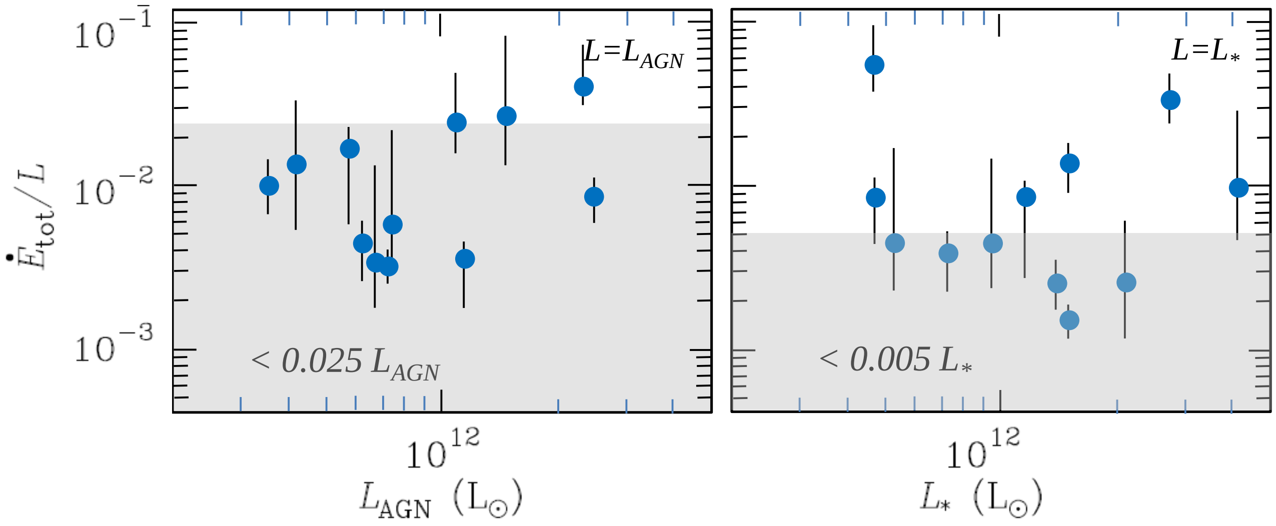
AGN may supply a maximum momentum of ~2 L_{AGN}/c

AGN- or Starburst-driven? Momentum-conserving or energy-conserving?



The **combined** momentum rates from the starburst and the AGN may be able to drive the observed outflows in moderate cases. High momentum boosts (5-20) require energy-driven outflows.

AGN- or Starburst-driven? Momentum-conserving or energy-conserving?

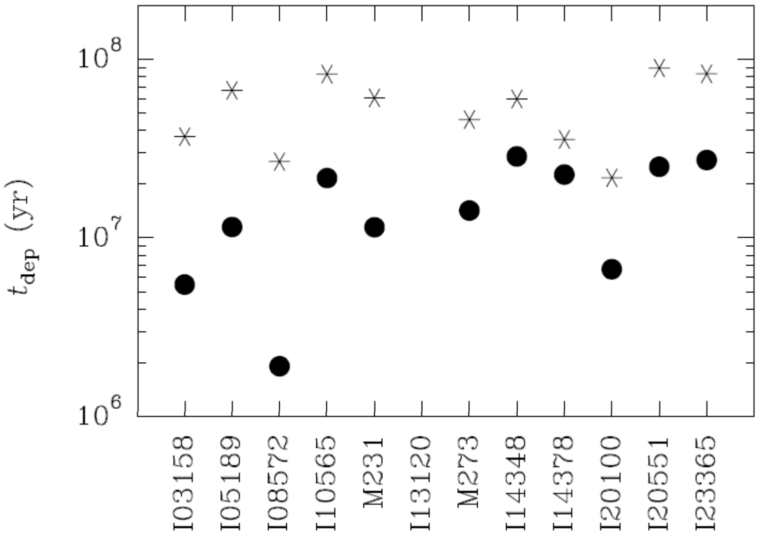


*S*upernovae and stellar winds can provide a mechanical luminosity of up to ~1.8% of L_* (Leitherer + 1999, Veilleux+2005, Harrison+ 2014) of which less than ¼ will go into bulk motion of the ISM → energy-conserving winds from the starburst unable to drive the observed molecular outflows, at least in the strong outflow cases.

Energy-conserving bubbles created by AGN winds supply up to ~5% of L_{AGN} (e.g. King&Pounds 2015) with ½ going into bulk motion of the ISM (Faucher-Giguère & Quataert 2012)

Does it matter? (Aka can we convince Peter B.?)

- ● Gas depletion time $t_{dep} = M(H2) / \dot{M}_{out}$
- ∗ Gas consumption time $t_{con} = M(H2) / SFR$

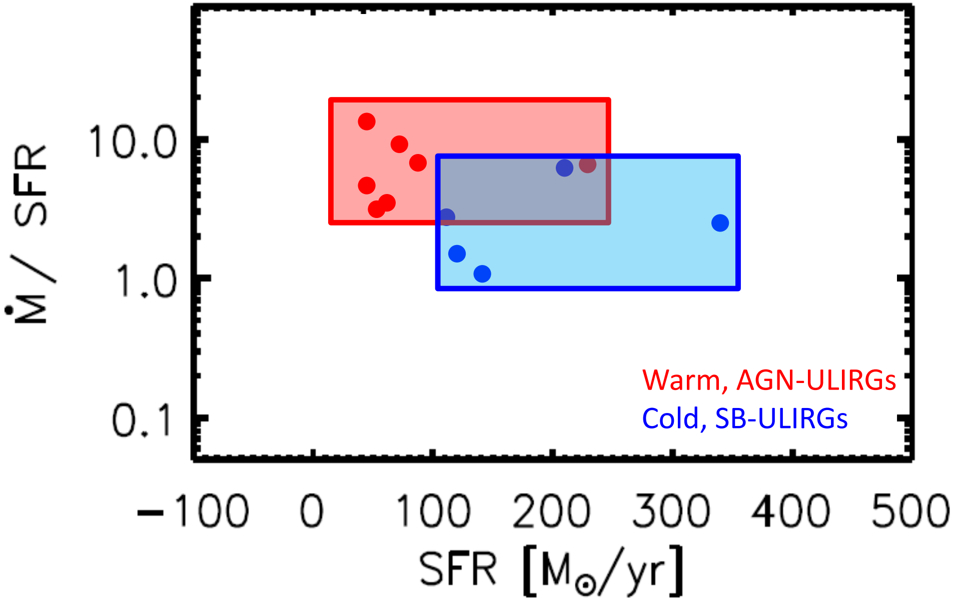


$t_{con} / t_{dep} = 1.5 – 15$ *)

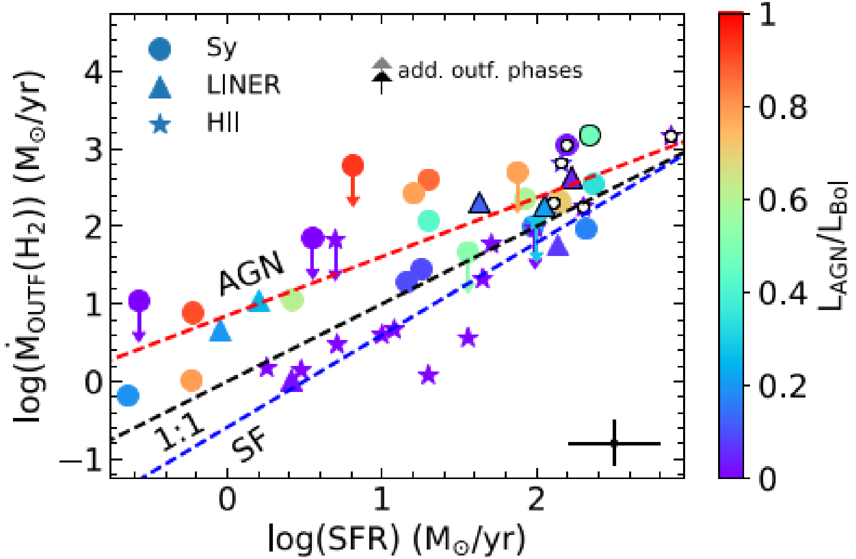
Mass loading $\eta = 1 - 10$

*) assuming continuous flow and no replenishment

Does it matter?



SHINING (OH)



Fluetsch+ 2019 (CO)

Info Point – II Results from OH spectral modeling

- Combined momentum from AGN and starburst can drive the outflows in weak and moderate cases.

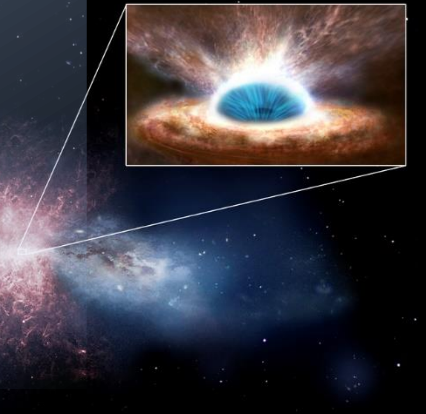
- The strongest outflows require energy-driven AGN mechanism

- t_{con} / t_{dep} = 1.5 – 15, Mass loading η = 1 - 10

- Best fits are found for decelerating or constant velocity fields

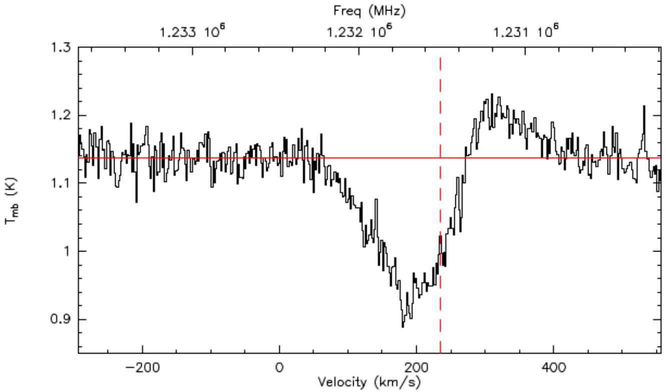
Gonzalez-Alfonso+ 2012, 2013, 2014, 2017

Caveats: OH-based outflow parameters like momentum, energy, mass loss rate require modeling with uncertain assumptions (geometry, OH abundance)
(For and OH abundance study see Stone+ 2018)



Other molecular outflow tracers in the FIR

Monje+ 2014



HF (J = 1–0) in NGC 253 (HIFI)

Outflow mass: $M(H2)_{out} \sim 1 \times 10^7\ M_\odot$
Outflow rate: $\dot{M} \sim 6.4\ M_\odot\ yr^{-1}$
Consistent with OH and CO

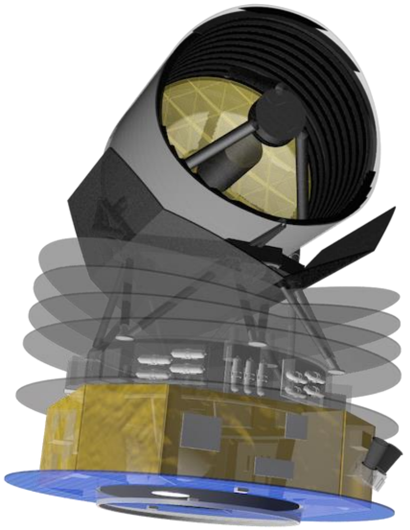
Future of OH

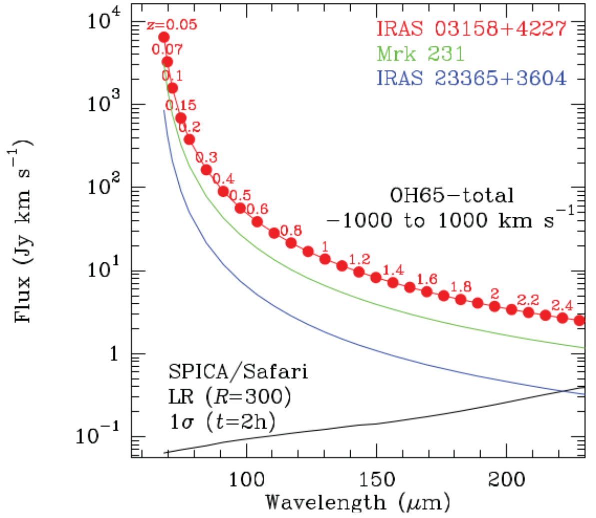
Still some Herschel archival work to be done

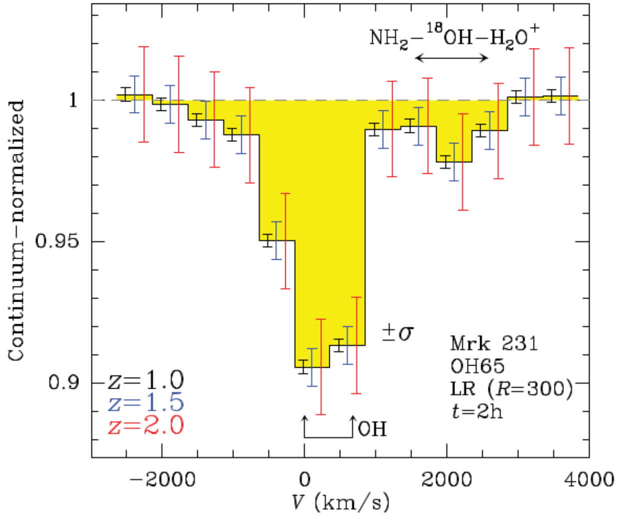
ALMA, NOEMA: extend the Herschel OH studies to the high redshift Universe.
e.g. OH 119 μm doublet is redshifted to the ALMA band 9 for galaxies
in the redshift range $z \sim 2.5 – 3.1$, and to the ALMA band 7 for galaxies at $z \sim 5.8 - 8.0$.

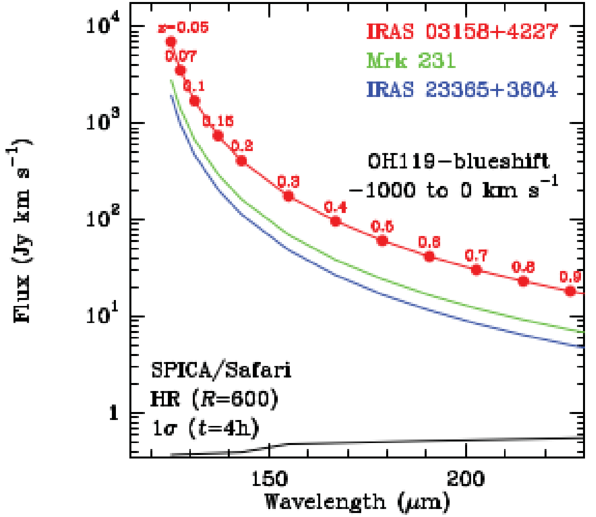
Future of OH

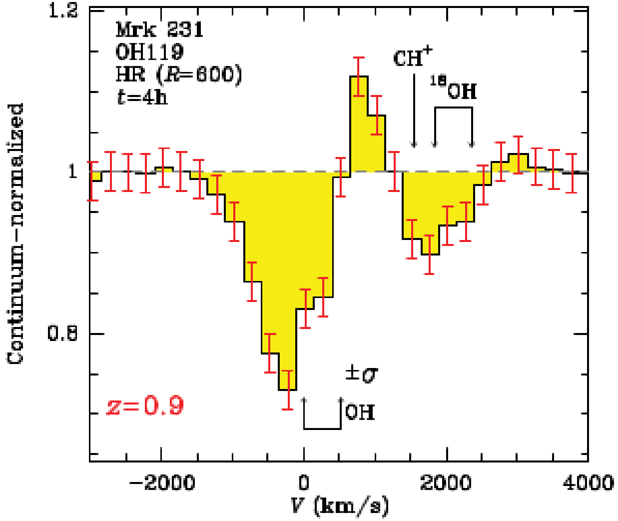
SPICA 0<z<2





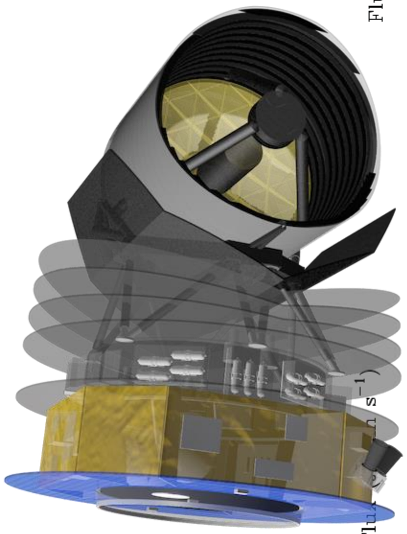


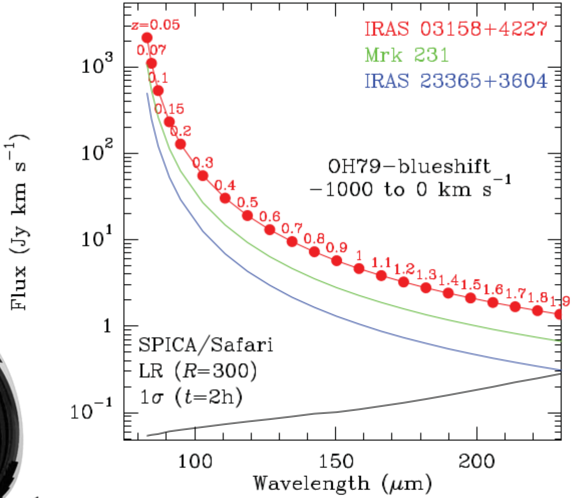


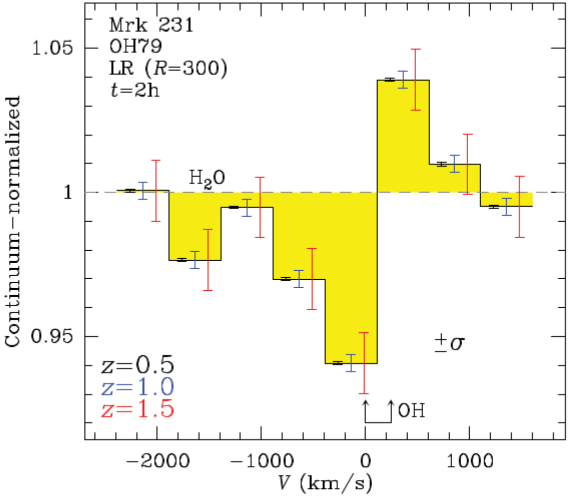


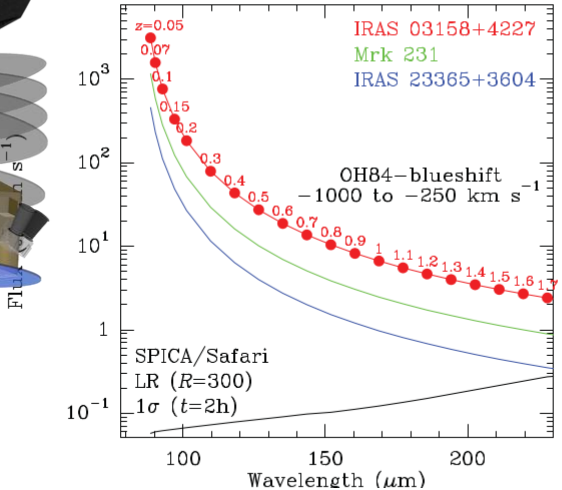
Future of OH

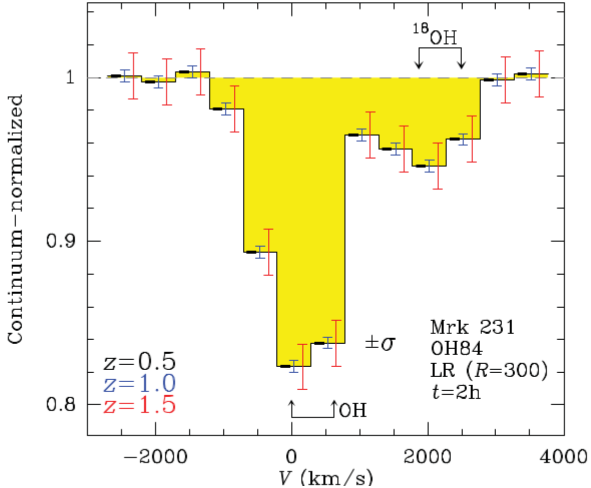
SPICA 0<z<2









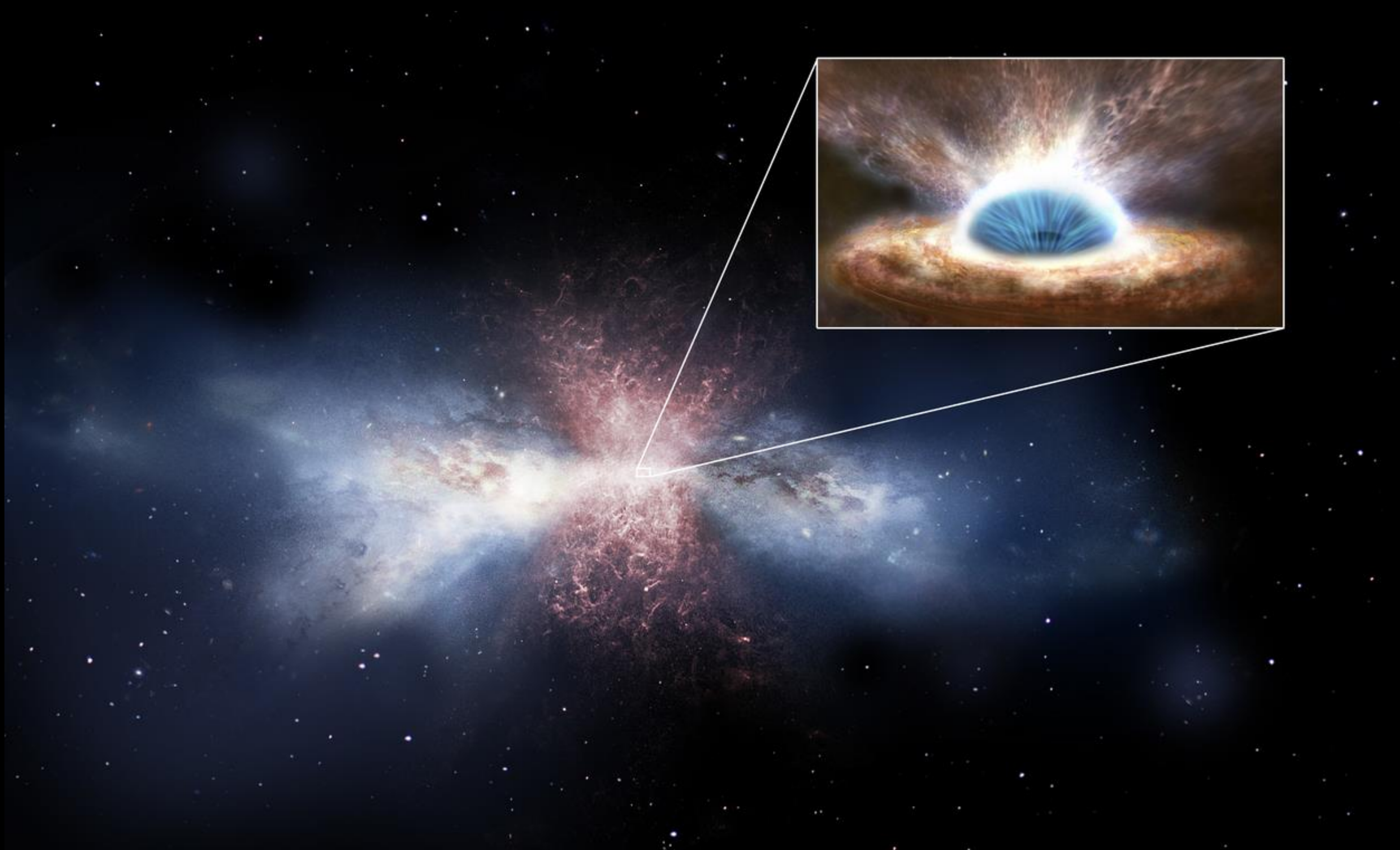


But:

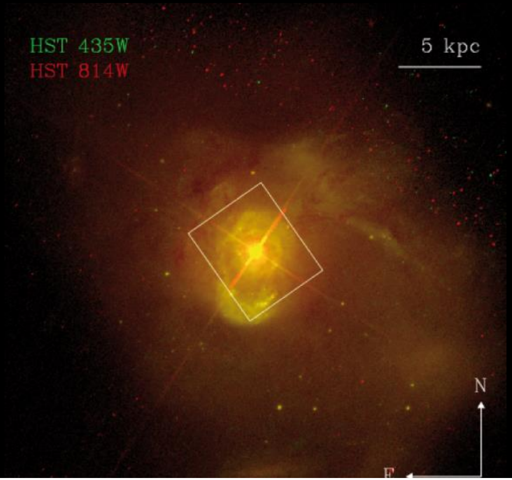
- no new Herschel observations,
- mm-interferometry of OH absorption at high z difficult
- SPICA not (yet) reality
- OH-based outflow parameters like momentum, energy, mass loss rate require modeling with uncertain assumptions (geometry, OH abundance)

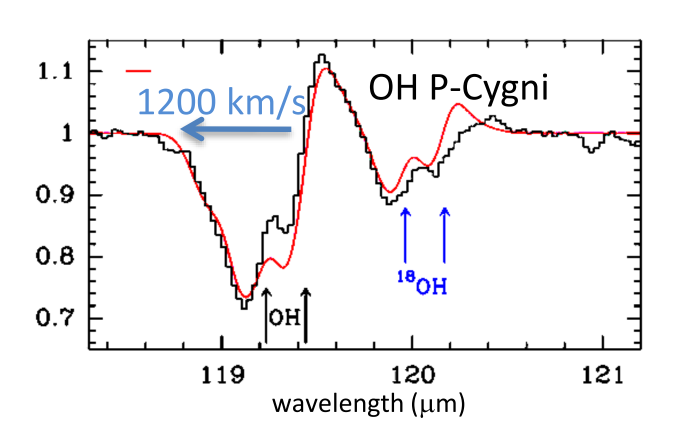
→ **Need complementary/alternative tracers**

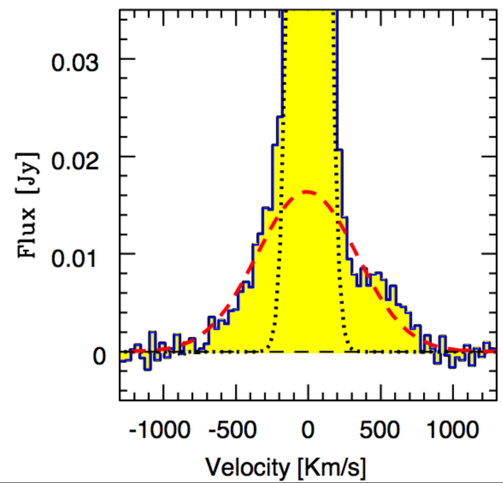
II) CO



Mrk 231

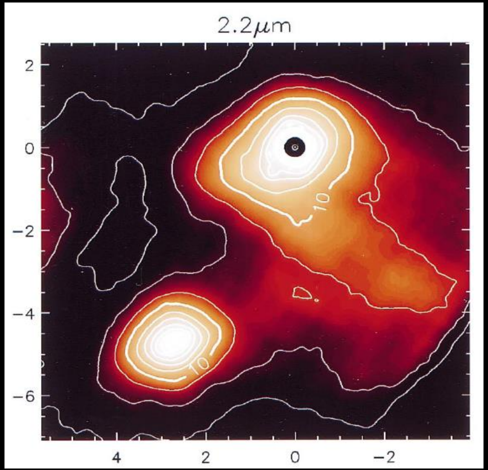




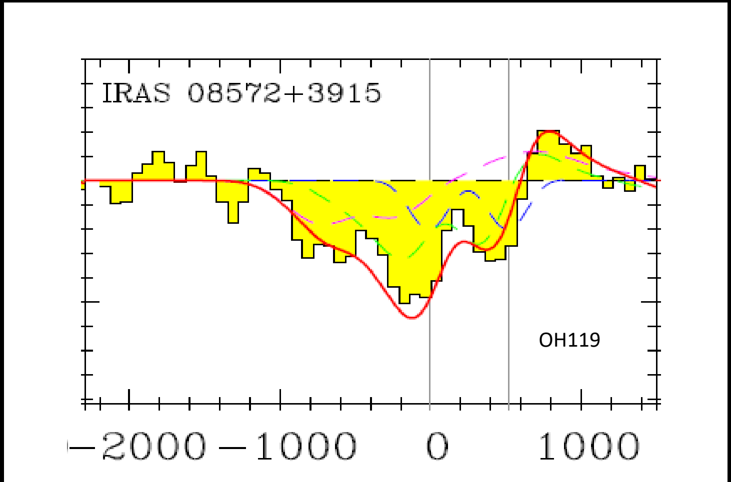


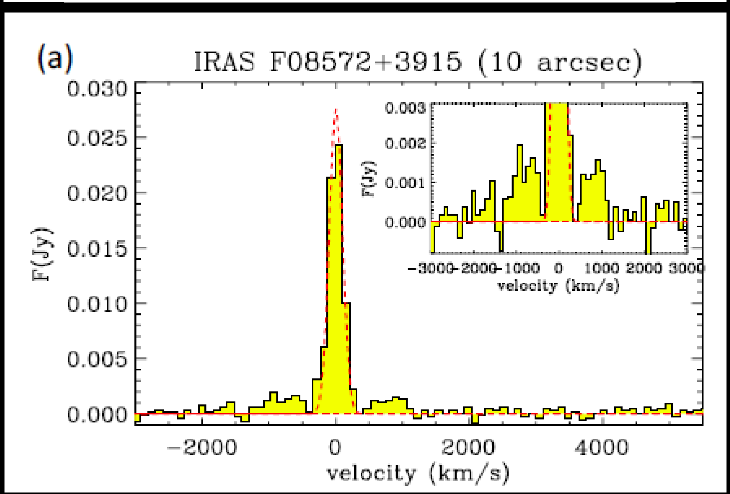
Feruglio+ 2010

IRAS F08572+3915

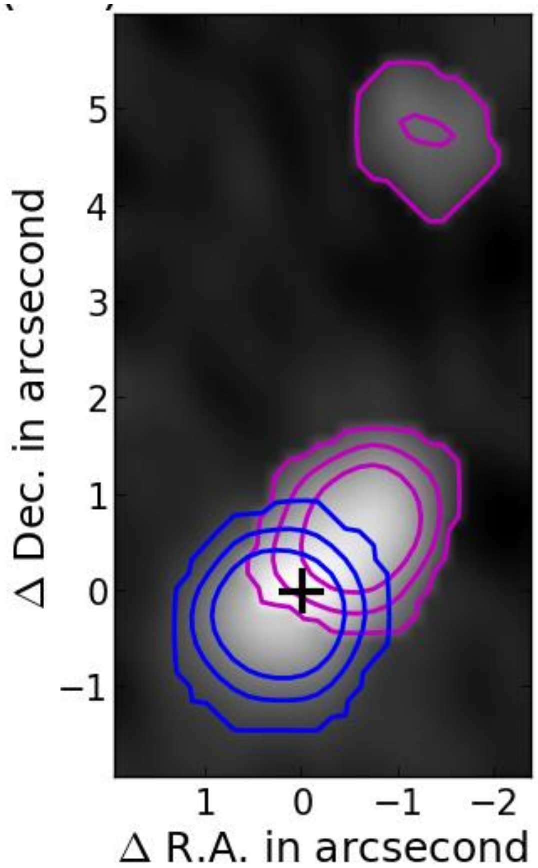


H-band image (Scoville et al. 2000).





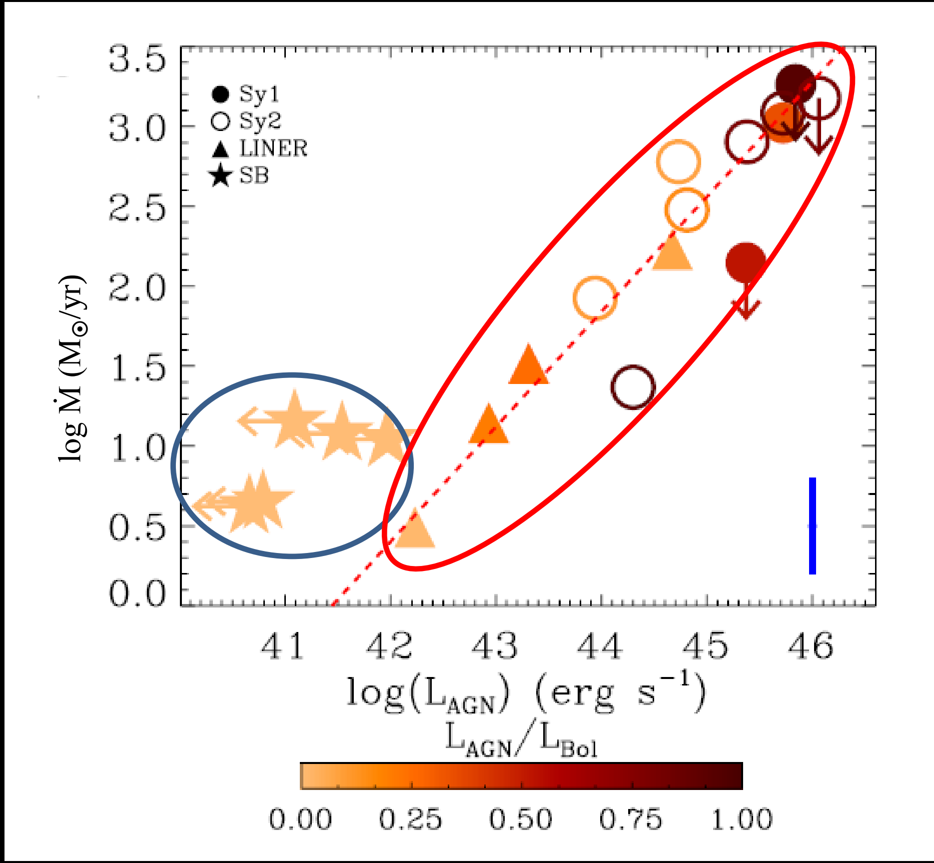
Cicone+ 2014, Janssen + 2016 b (PhD Thesis), Herrera-Camus+ in prep.



Main outflow: biconical outflow with a large opening angle, inclined w.r.t. line-of-sight.
→v_{max} close to the maximum observed velocity in the outflow: 1200 km s^{-1}.

The second redshifted outflow matches the description of an individual cloud 6 kpc away (→ AGN flickering).

Janssen + 2016 b (PhD Thesis), Herrera-Camus+ in prep.



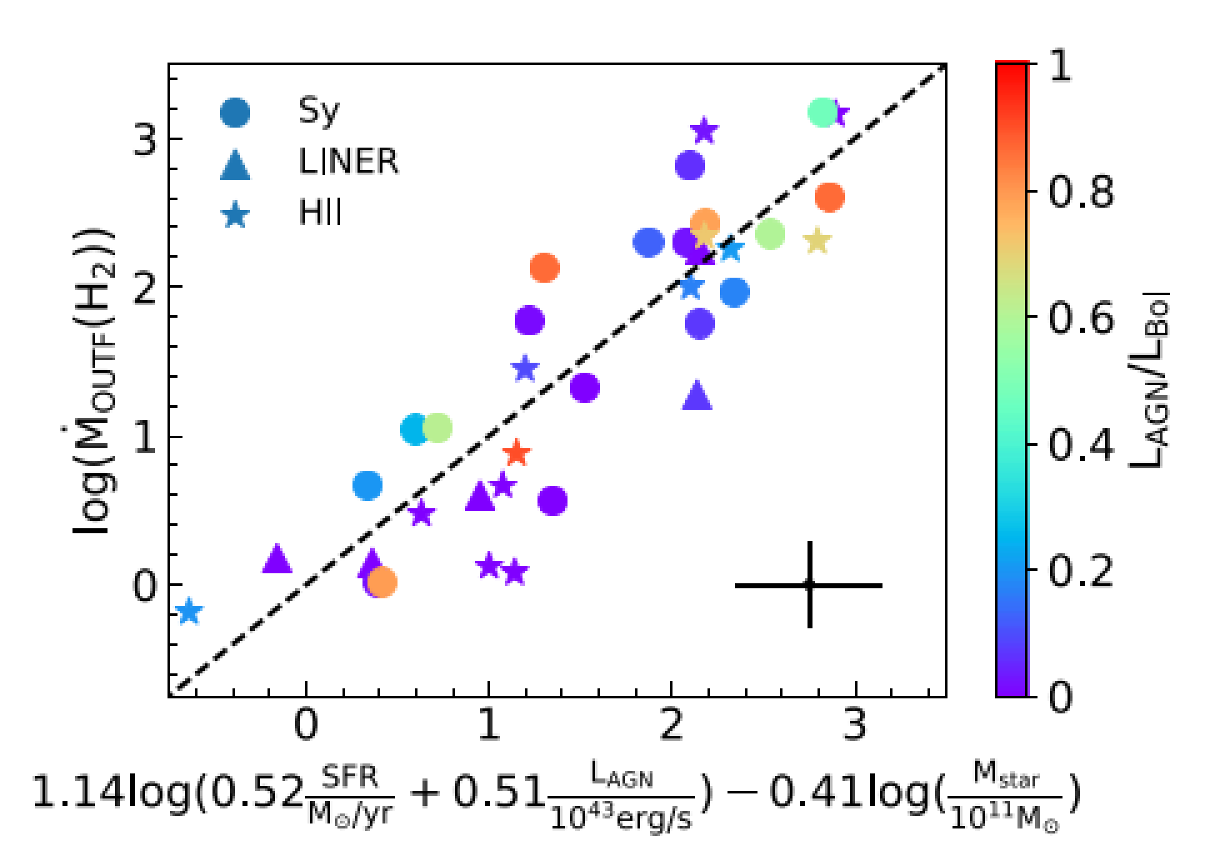
Cicone, Maiolino, Sturm + 2014

Today

CO outflows in local galaxies:
~50 objects (NOEMA/ALMA)

(cp. Fluetsch+ 2019, Lutz+ in prep.)

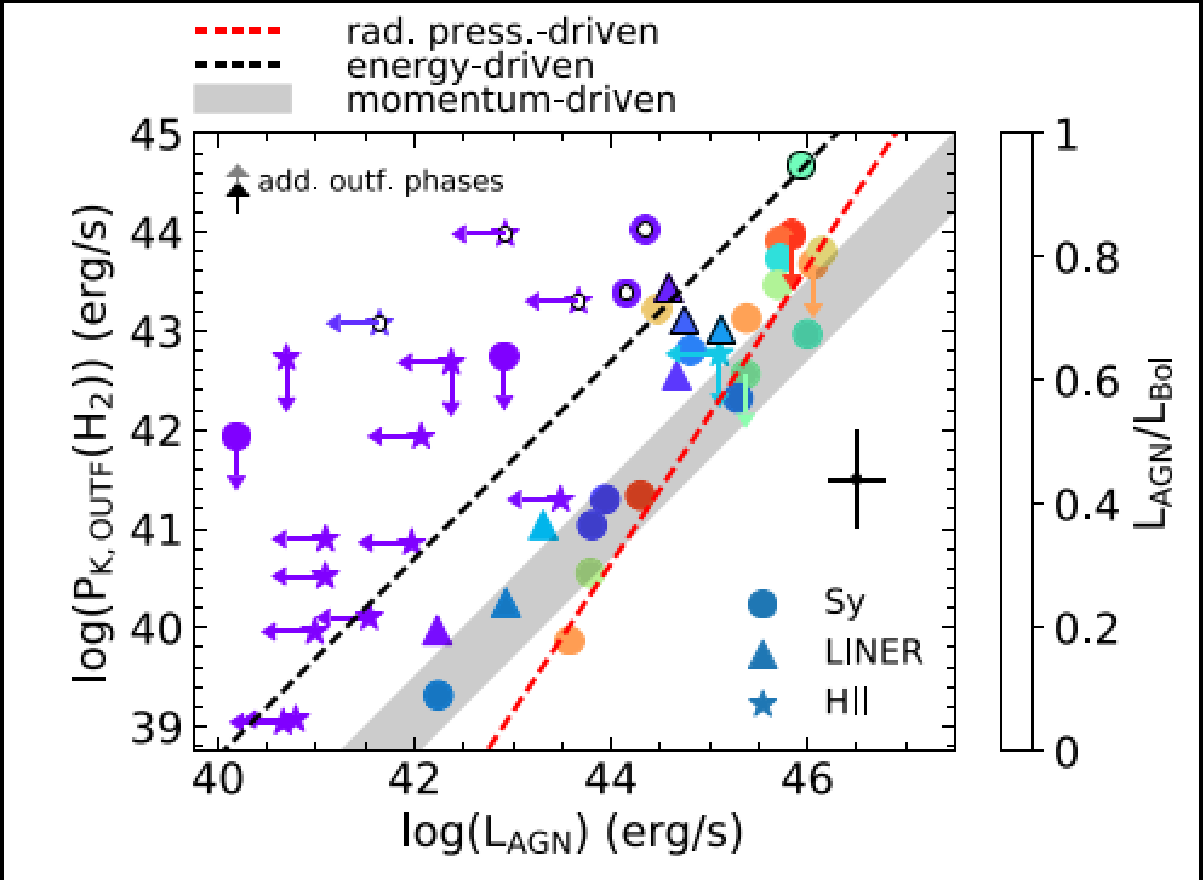
Molecular outflow rate as a function of SFR, stellar mass, and AGN luninosity



~50 objects

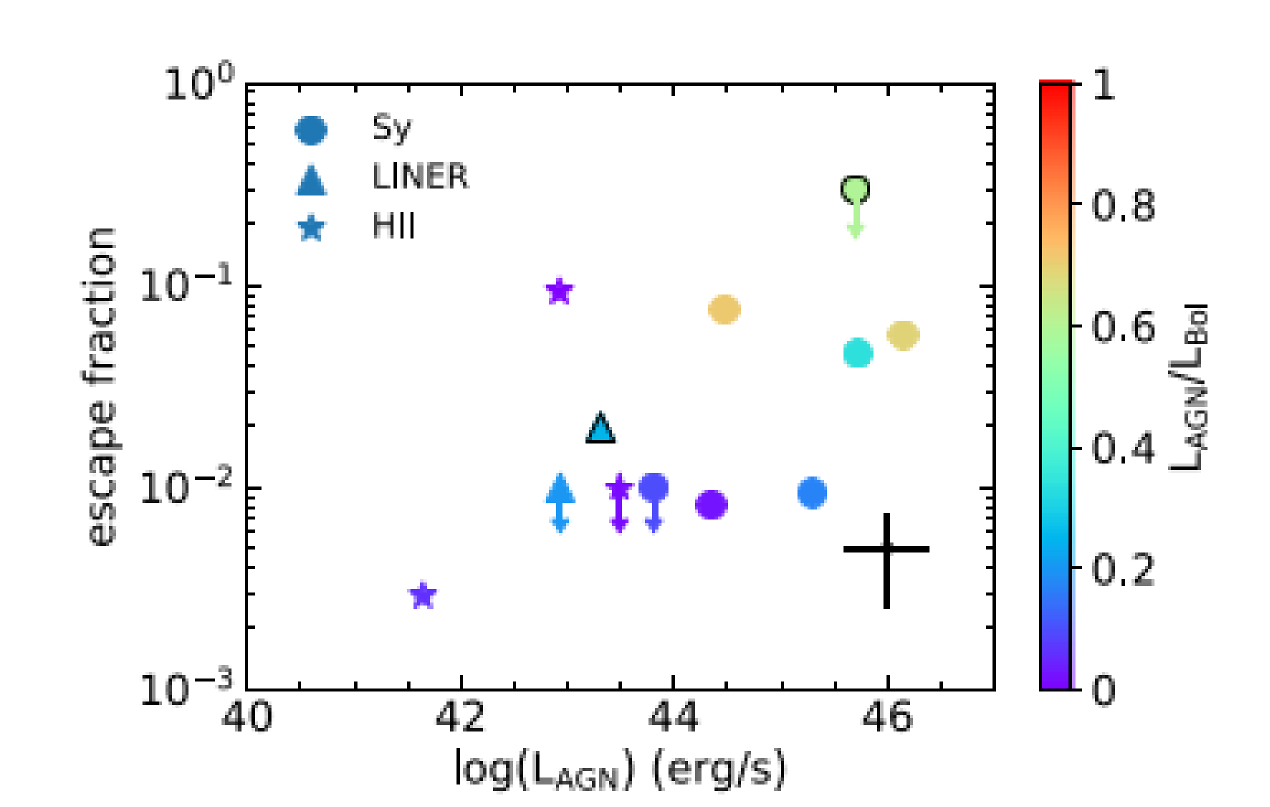
Fluetsch+ 2019

Kinetic power of the outflow as a function of the AGN luminosity



Fluetsch+ 2019
Ishibashi+ 2018

Fraction of the molecular outflow that escapes the galaxy as a function of AGN luminosity



Assuming ballistic motion

Fluetsch+ 2019

The synergy and complementarity of OH and CO studies

In the local Universe, CO complements Herschel studies, providing the necessary spatial resolution to resolve the outflows using low-J rotational transitions of the CO molecule and other dense gas tracers (HCN, HCO+)

The OH observations provide cross-calibration and guidelines where to search for outflows, e.g. ULIRGs, sources with high far-infrared surface brightness ($\Sigma_{FIR} > 10^{11.75}$ $L_{\odot}$ $kpc^{-2\wedge}$, see Lutz+ in prep.)

→ Better characterization of spatial extension / outflow geometry, gas excitation, the total molecular gas mass involved in the outflows and the mass outflow rates.

Challenges & comparison of CO - OH

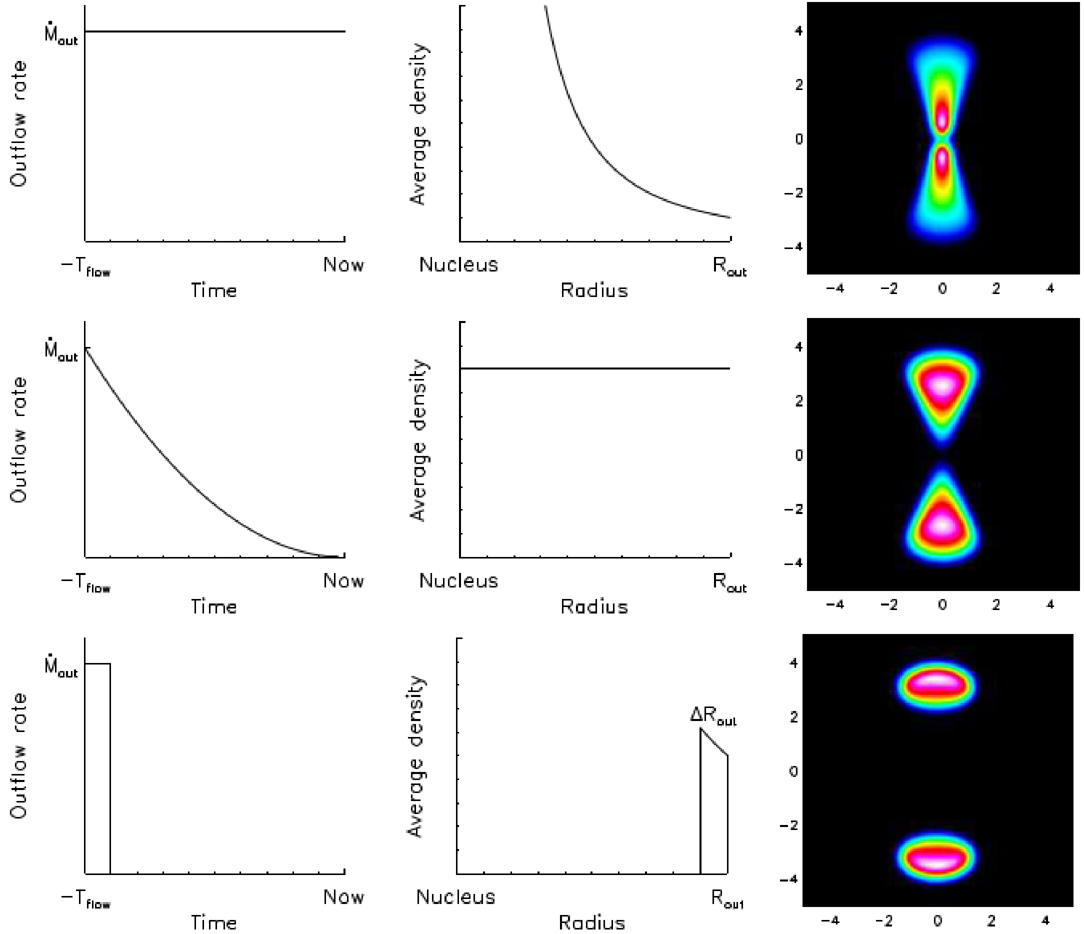
OH:

- wavelength needs space observatories (or high z)
- geometry,
- abundance (but see Stone+ 2018)

CO:

- separate outflow emission from host emission
- geometry
- conversion factor (CO-to-H2)   (but see Cicone+ 2018)

Challenges & comparison of CO - OH



$$\dot{M}_{\rm out} = v_{\rm out}\frac{M_{\rm out}}{R_{\rm out}}$$

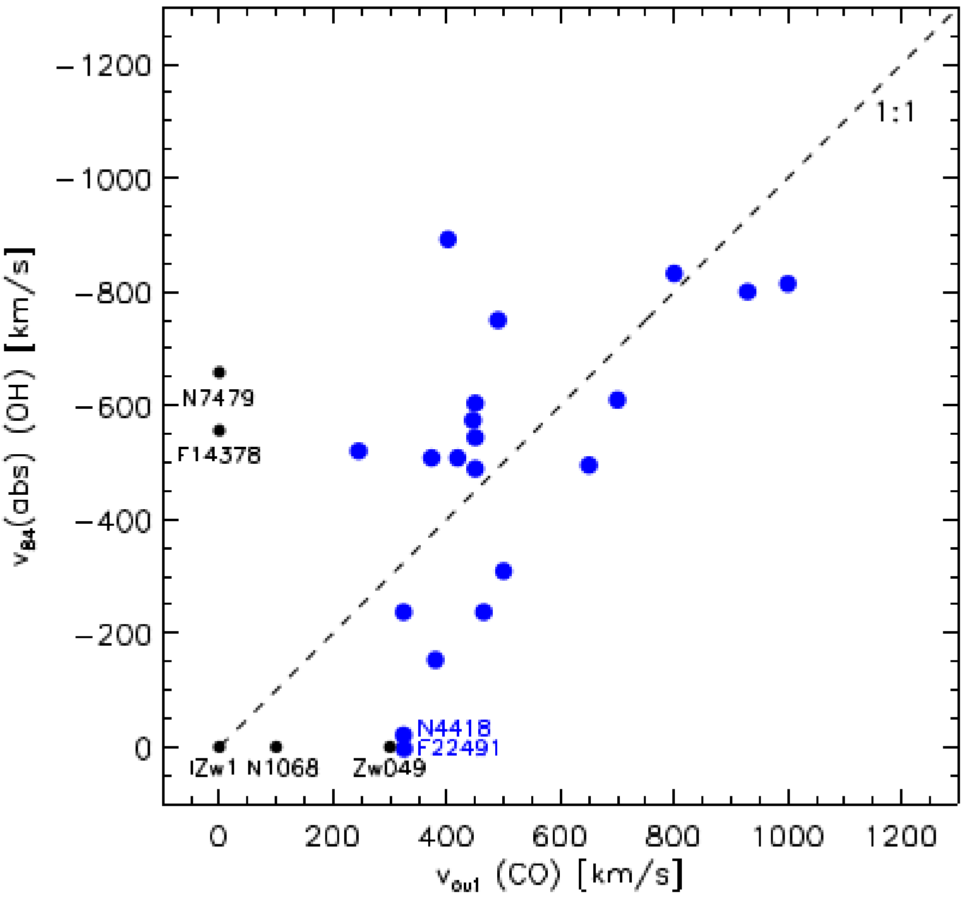
$$\dot{M}_{\rm out} = 3v_{\rm out}\frac{M_{\rm out}}{R_{\rm out}}$$

$$\dot{M}_{\rm out} = v_{\rm out}\frac{M_{\rm out}}{\Delta R_{\rm out}}$$

Lutz+, in prep.

See also Cicone+ 2014, Janssen 2016, Veilleux+ 2017

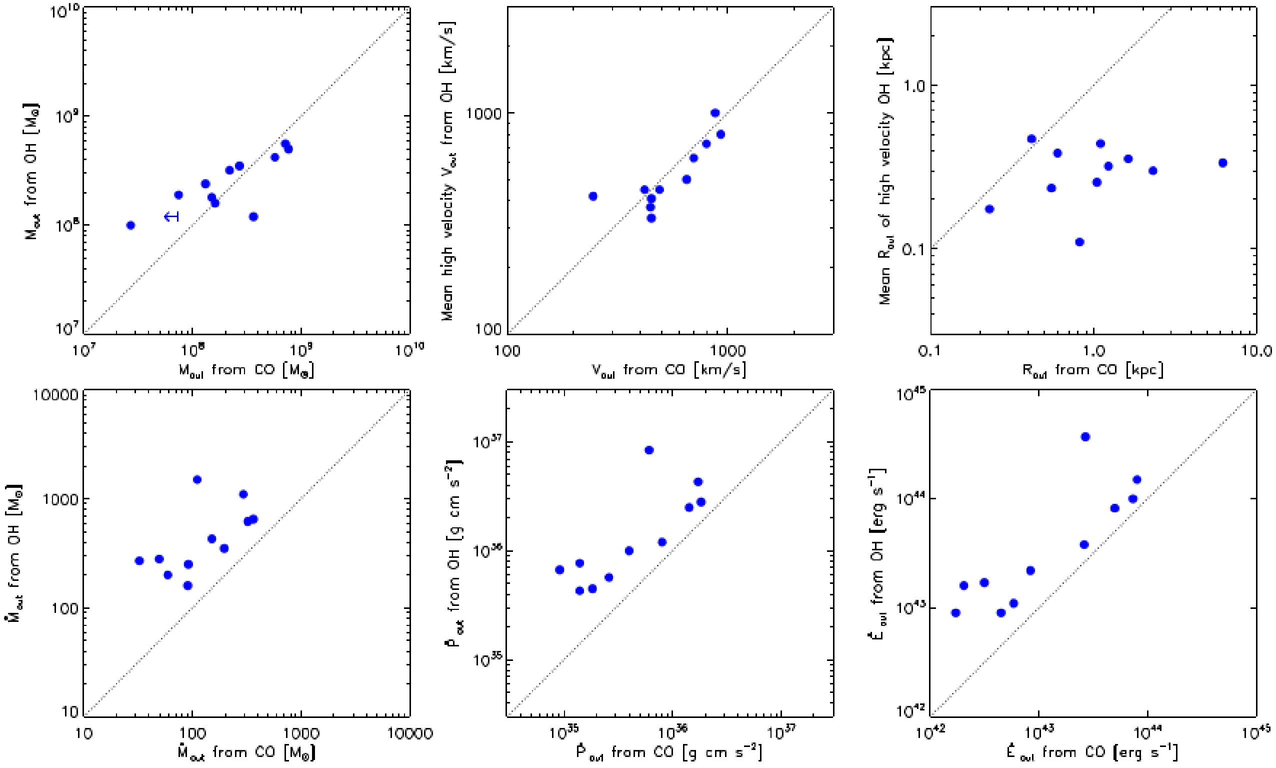
Challenges & comparison of CO - OH



- >80% of objects with OH outflow also show CO outflow (and vice versa)
- good agreement of outflow velocities

Lutz+, in prep., Gonzalez-Alfonso+ 2017

Challenges & comparison of CO - OH

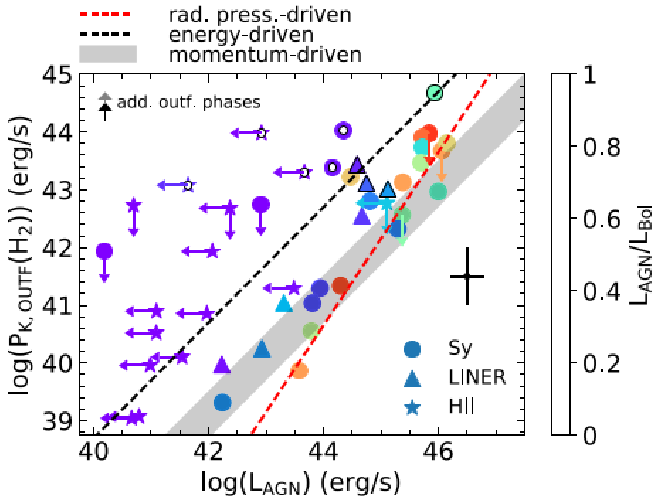


Succesful cross-validation of OH P-Cygni and CO interferometric methods (independent/different assumptions and uncertainties, like geometry, abundance/conversion factor, identification of outflows…)

Lutz+, in prep., Gonzalez-Alfonso+ 2017

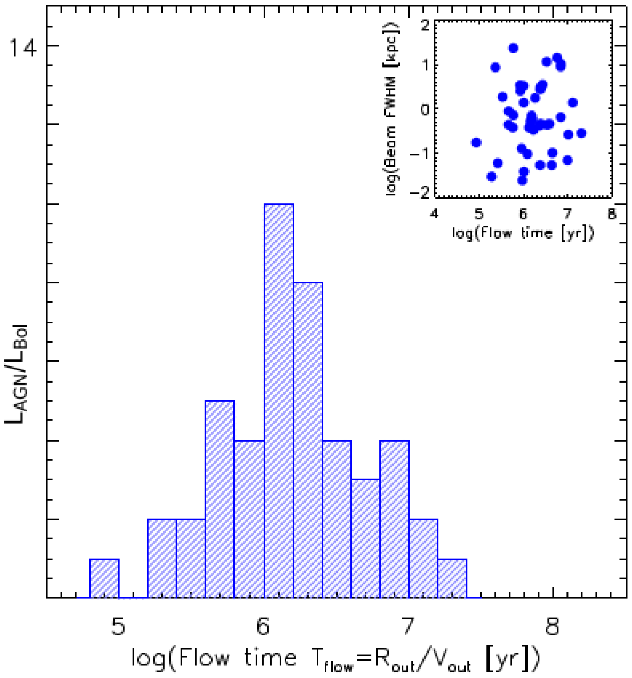
AGN „flickering“ – another complication

Some outflow energetics need stronger AGN in the past



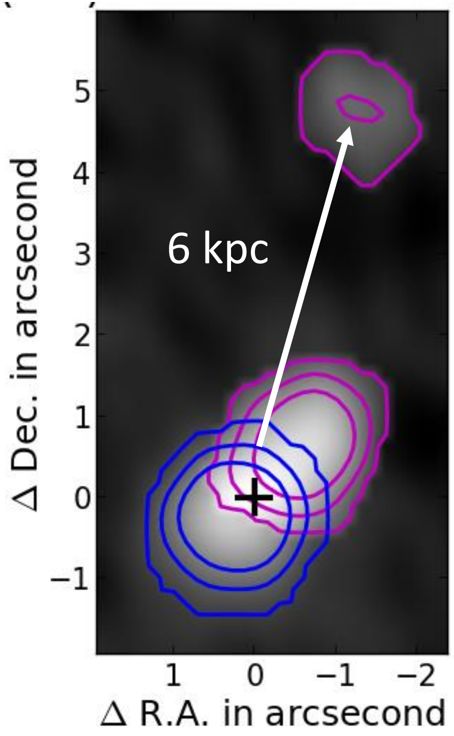
Fluetsch+ 2019

Low median flow time



Lutz+, in prep.

Spatially resolved blobs



Janssen + 2016 b (PhD Thesis), Herrera-Camus+ in prep.

Multi-phase studies

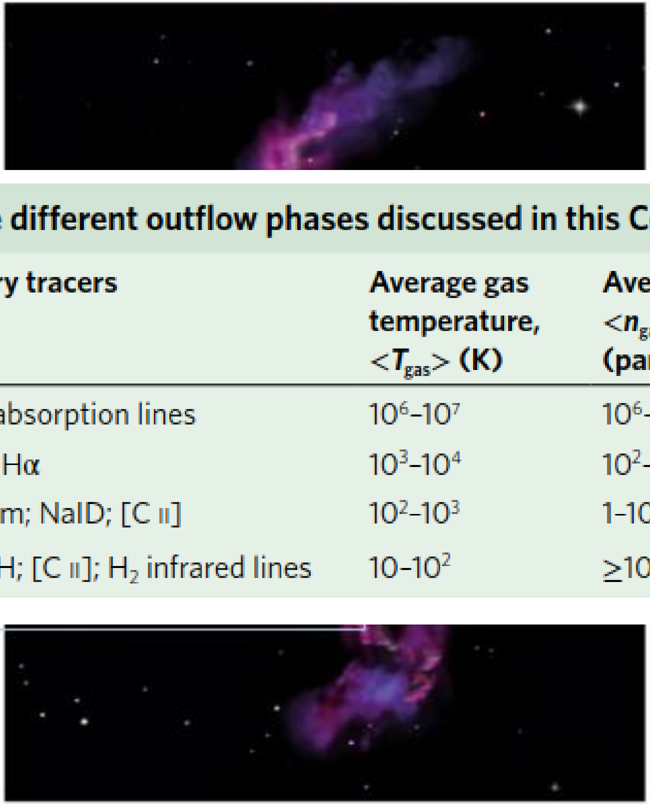
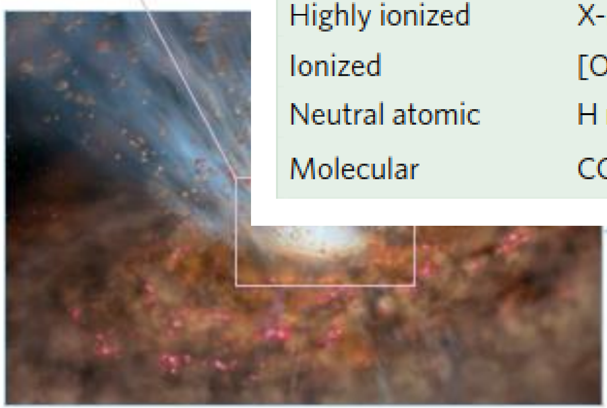


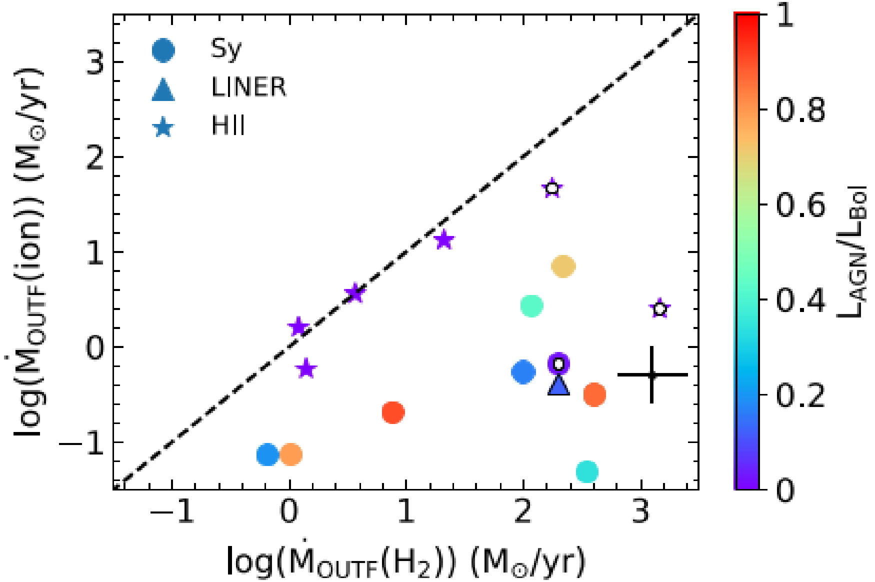
Table 1 | Properties of the different outflow phases discussed in this Comment

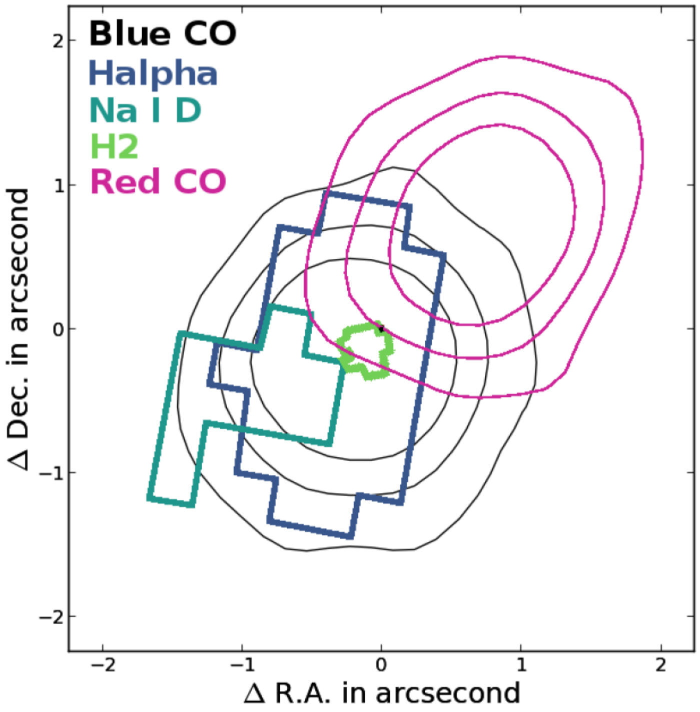
Outflow gas phase	Primary tracers	Average gas temperature, $\langle T_{gas} \rangle$ (K)	Average gas density, $\langle n_{gas} \rangle$ (particles per cm^3)
Highly ionized	X-ray absorption lines	10^6–10^7	10^6–10^8
Ionized	[O III]; Hα	10^3–10^4	10^2–10^4
Neutral atomic	H I 21cm; NaID; [C II]	10^2–10^3	1–10^2
Molecular	CO; OH; [C II]; H_2 infrared lines	10–10^2	$\geq 10^3$



Cicone+ 20018a, see also Tombesi+2015

Multi-phase studies





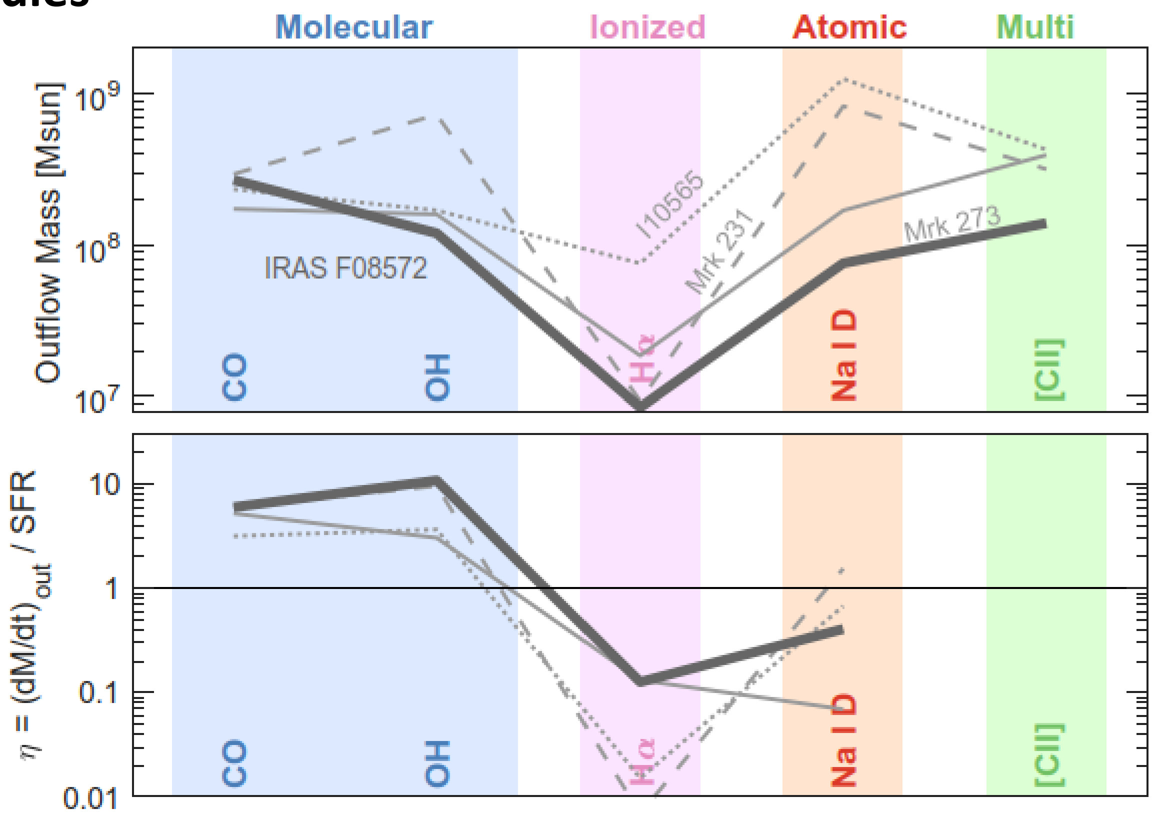
Fluetsch+ 2019

See also Cicone+ 2018a

Janssen+2016, + 2019

H2: Rupke&Veilleux 2013a OSIRIS / Keck
Hα and Na I D: Rupke & Veilleux 2013b GMOS/Gemini

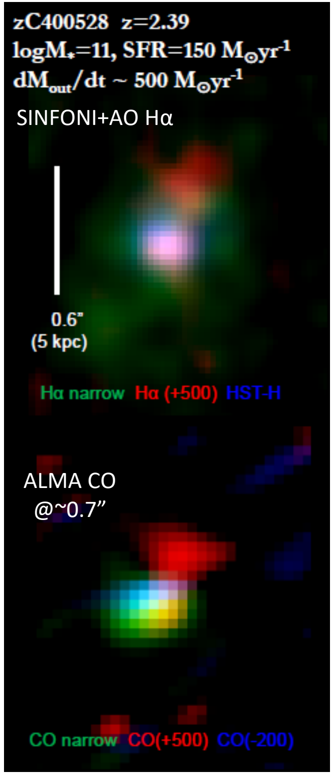
Multi-phase studies

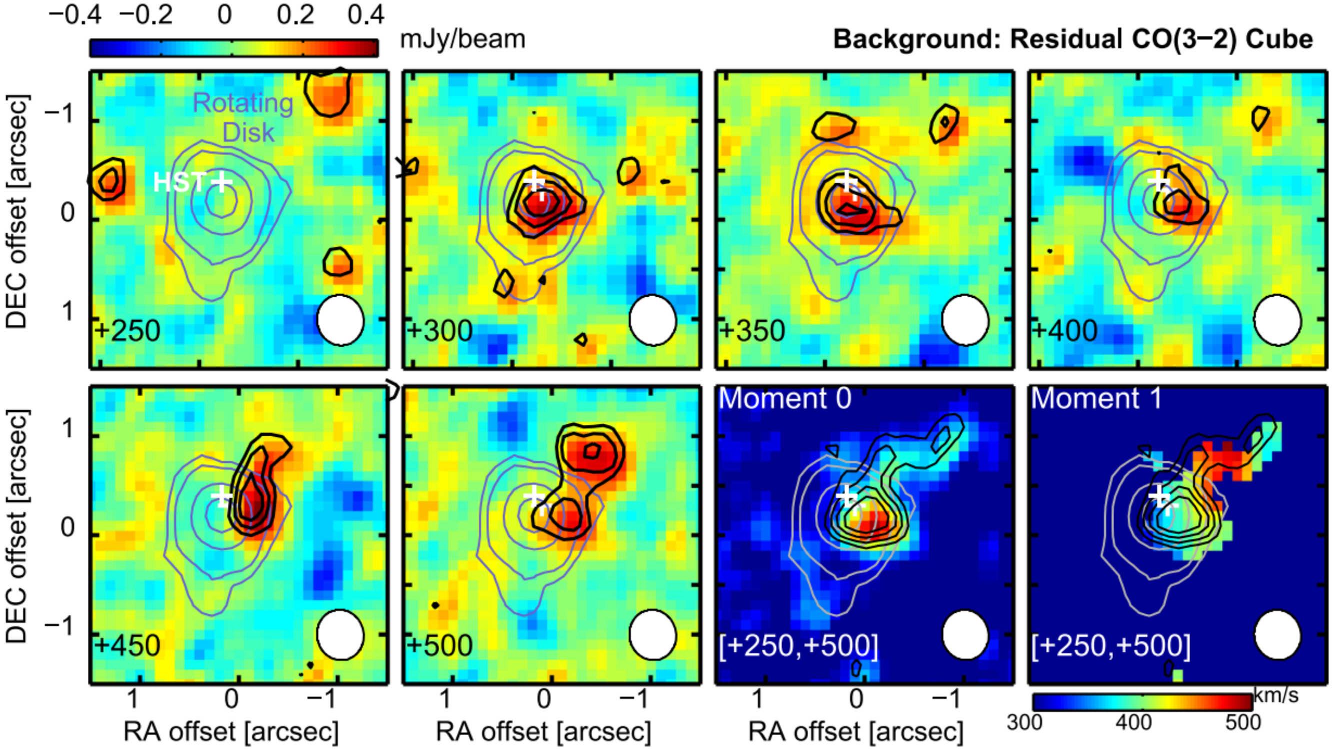


Herrera-Camus+ in prep.

CO at high redshifts

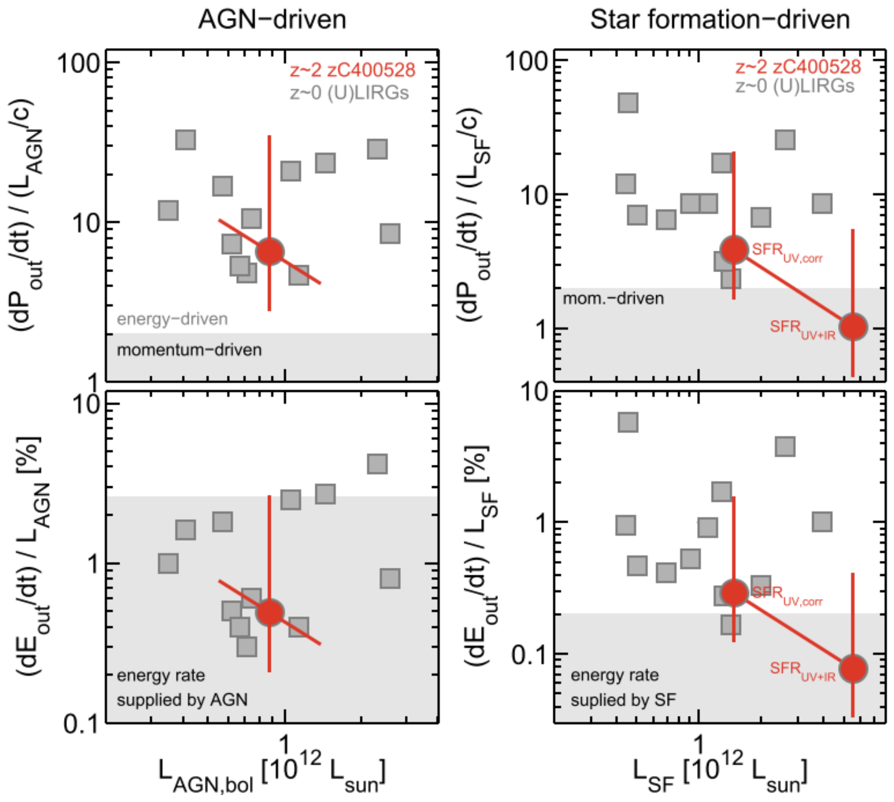
CO(3-2) in zC400528: an AGN-driven Outflow in a Typical Massive Galaxy at z≈2





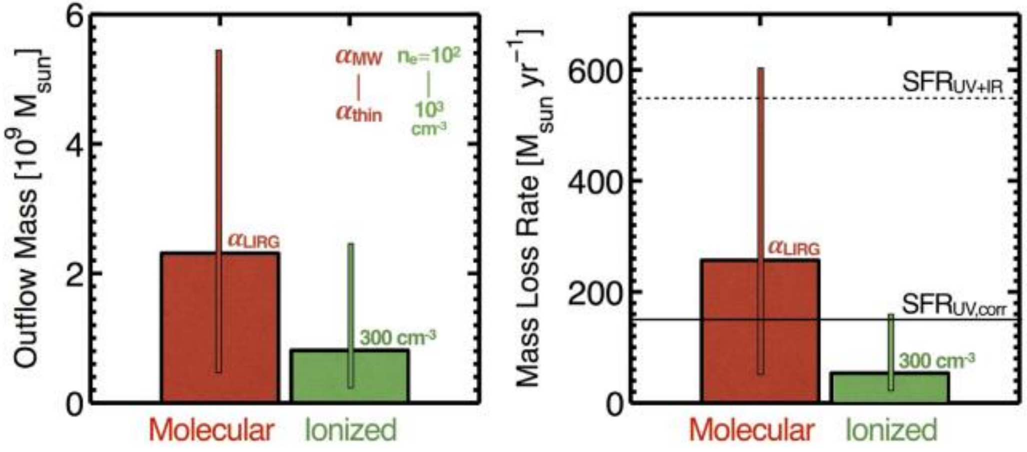
Herrera-Camus+ 2019

CO(3-2) in zC400528: an AGN-driven Outflow in a Typical Massive Galaxy at z≈2



Herrera-Camus+ 2019

CO(3-2) in zC400528: an AGN-driven Outflow in a Typical Massive Galaxy at z≈2



Herrera-Camus+ 2019

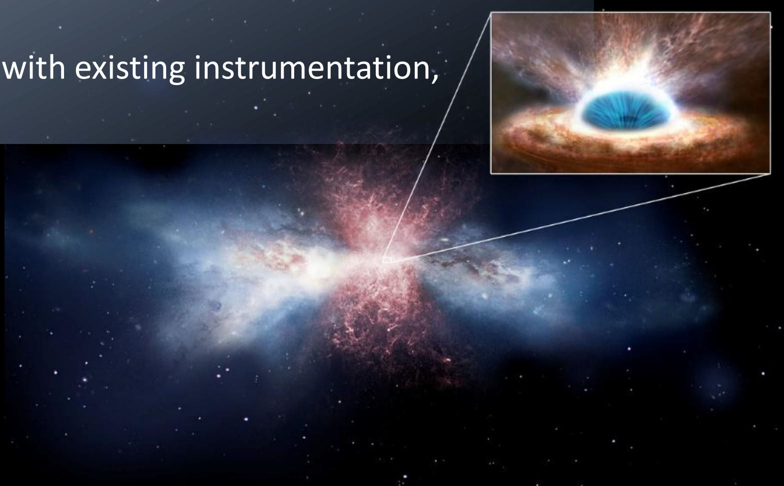
OH as an outflow diagnostic

Advantages:

- P-Cygni or blueshifted absorption unambigously indicate outflows
- Blueshifted absorption can be traced to low velocities, probing low-velocity outflows that may be missed from pure emission lines due to confusionwith the line core
- Main outflow parameters can be quantified

Disadvantages:

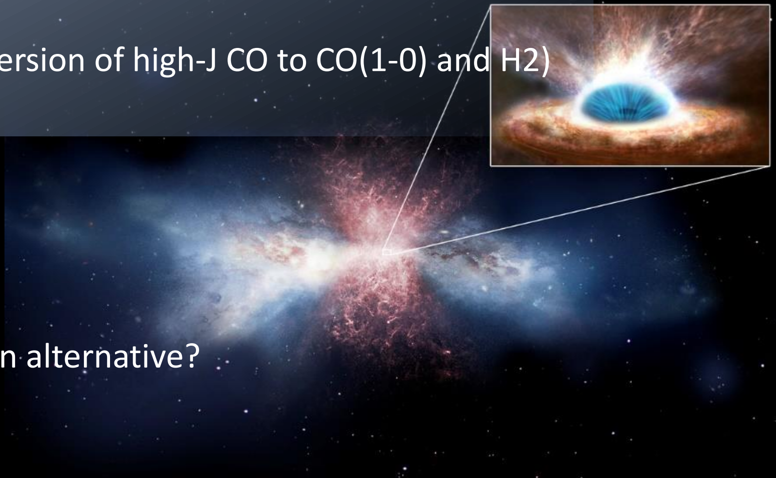
- Historically: low spatial resolution
- Currently: For low z not observable with existing instrumentation, and difficult at high z



CO as an outflow diagnostic

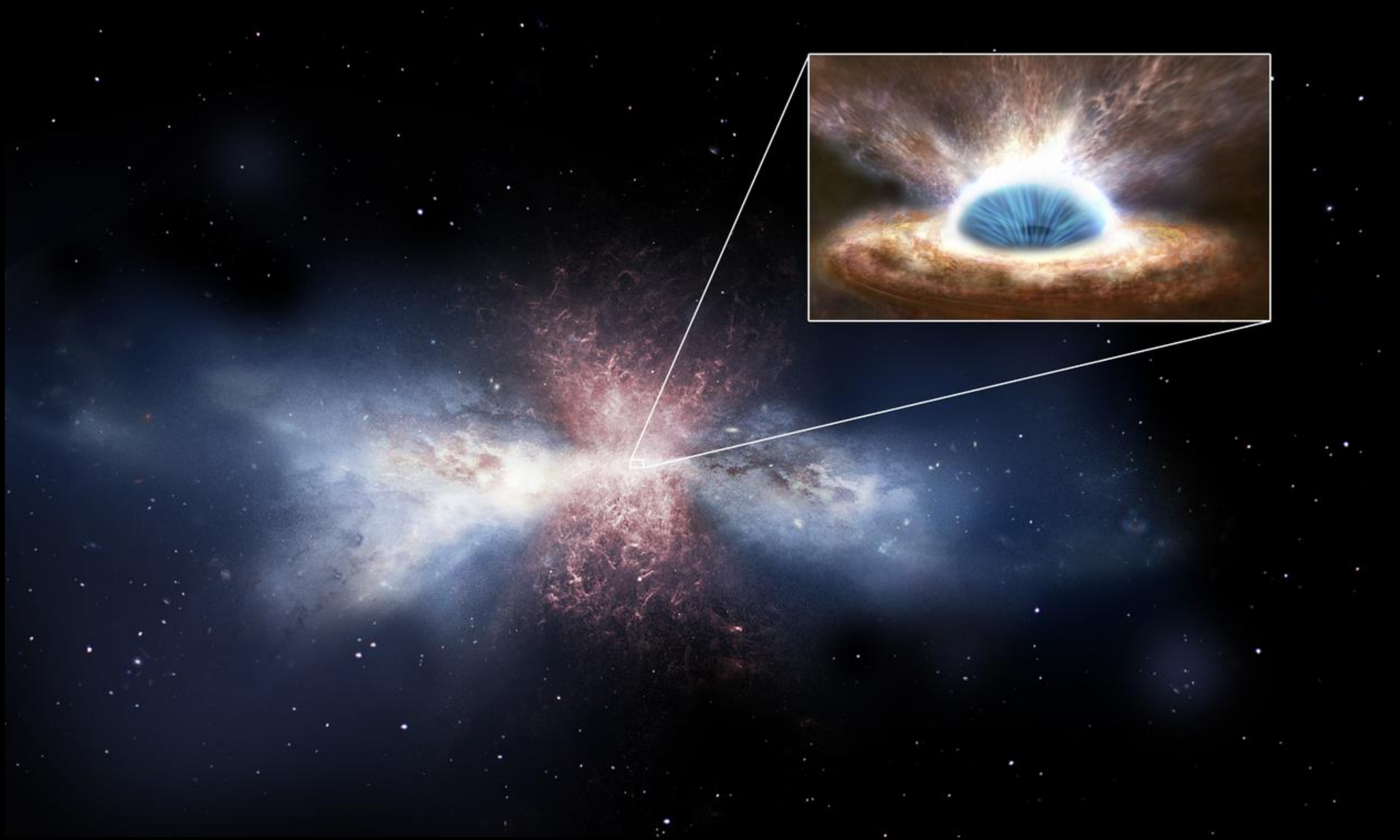
Advantages:
- Strong emission
- High spatial resolution
- Currently one of the main topics for ALMA and NOEMA

Disadvantages:
- emission ambiguous (outflow, inflow, turbulence, …)
- not sensitive to low velocity outflow (invisible under host galaxy profile) unless spatially resolved in imaging
- Not straight forward at high z (conversion of high-J CO to CO(1-0) and H2)
- Conversion factor

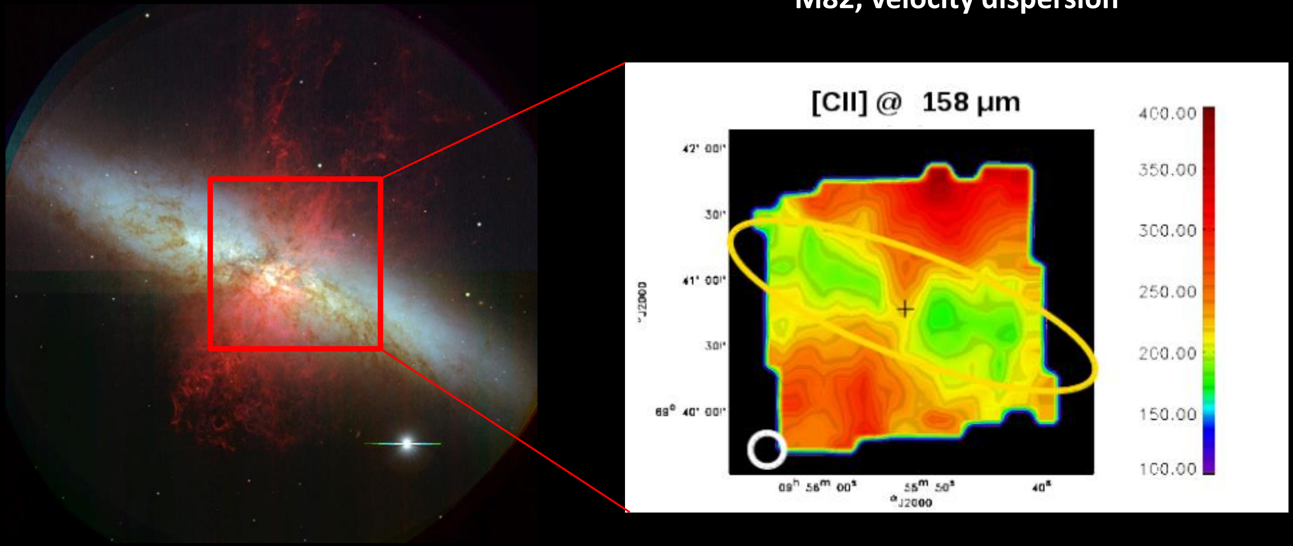


OH difficult at high z, too → is there an alternative?

III) [CII]

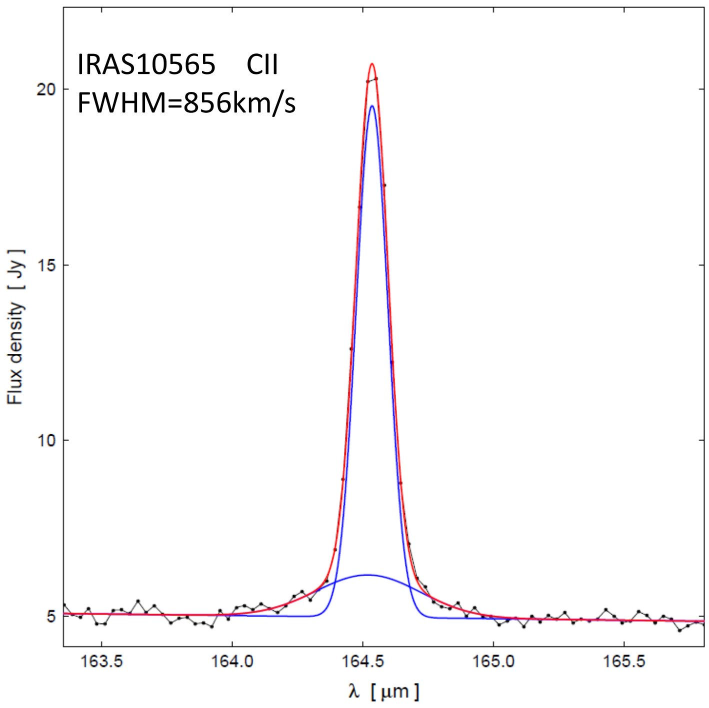


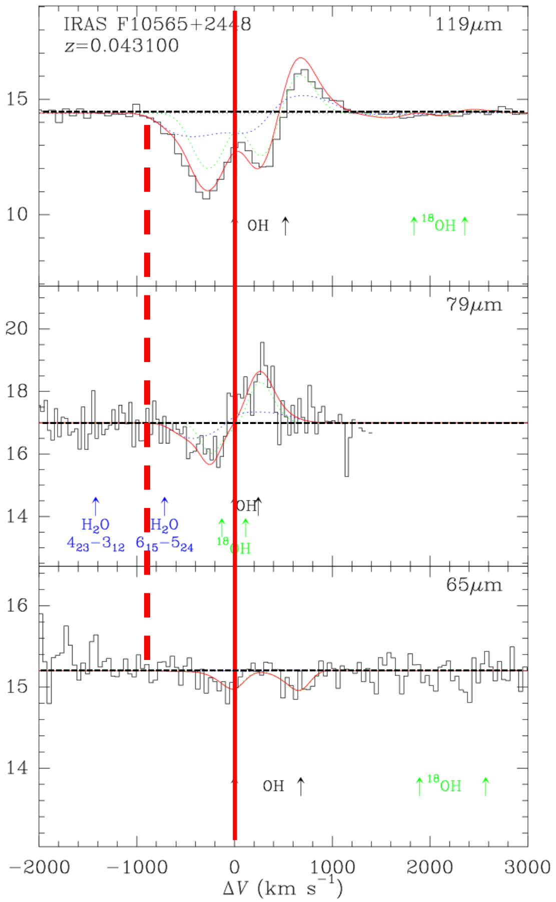
M82, velocity dispersion



Contursi + 2013

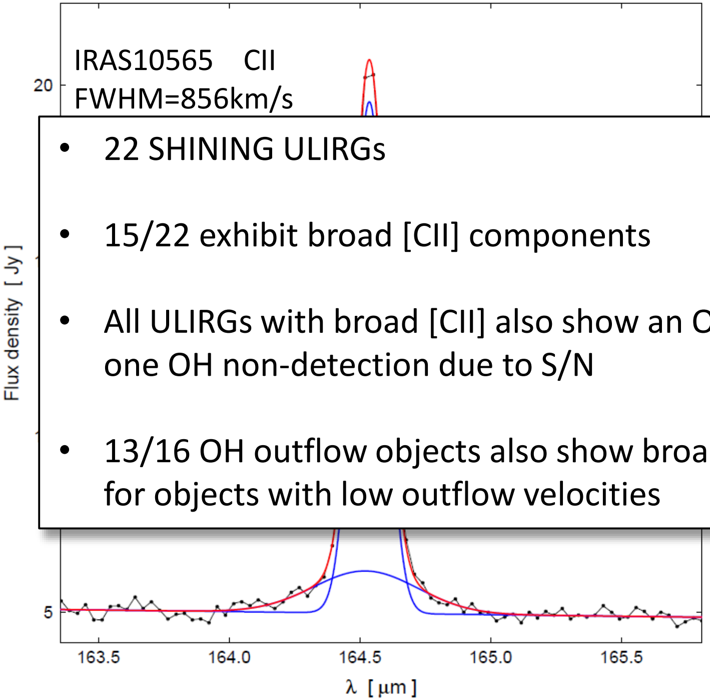
CII as tracer of (molecular) outflows

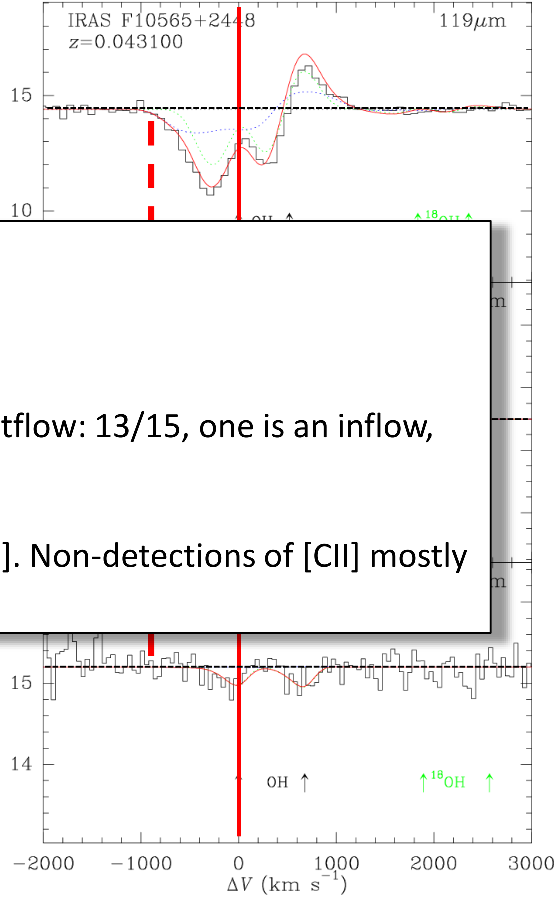




Janssen+ 2016

CII as tracer of (molecular) outflows

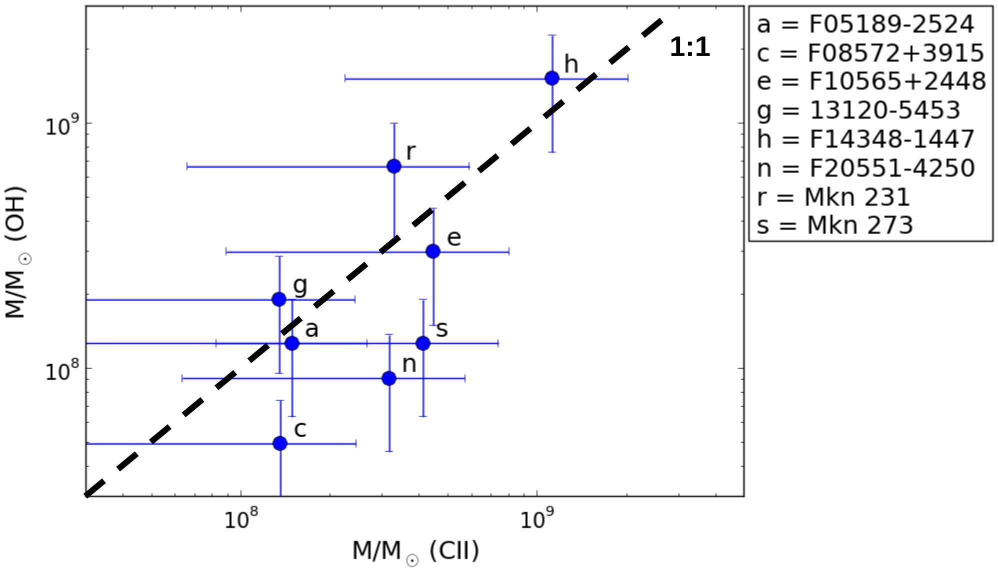




- 22 SHINING ULIRGs
- 15/22 exhibit broad [CII] components
- All ULIRGs with broad [CII] also show an OH outflow: 13/15, one is an inflow, one OH non-detection due to S/N
- 13/16 OH outflow objects also show broad [CII]. Non-detections of [CII] mostly for objects with low outflow velocities

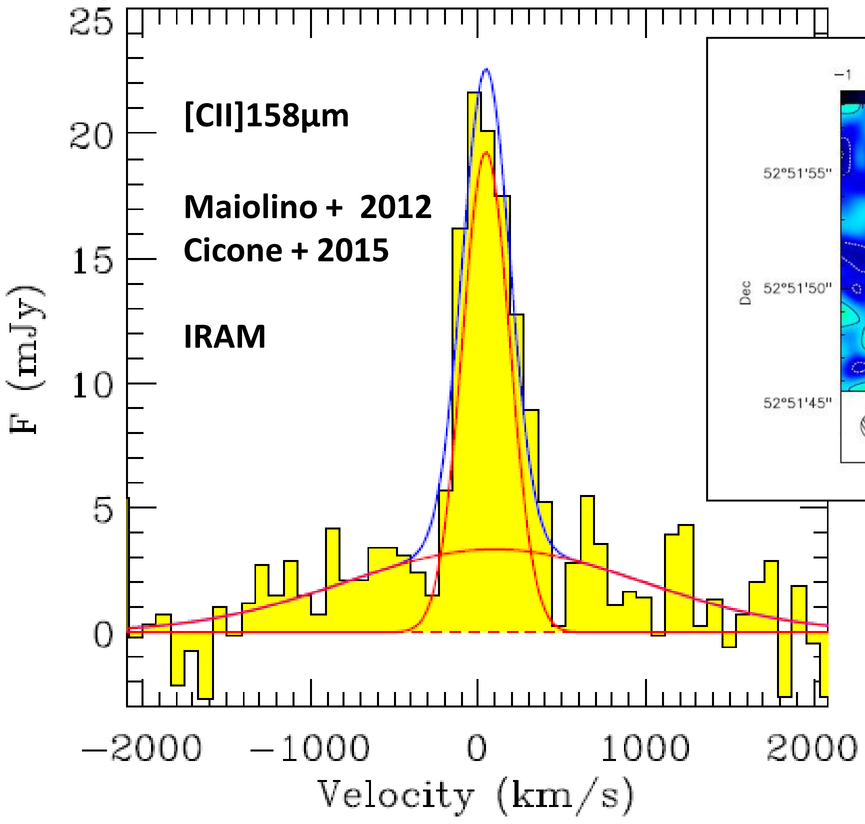
Janssen+ 2016

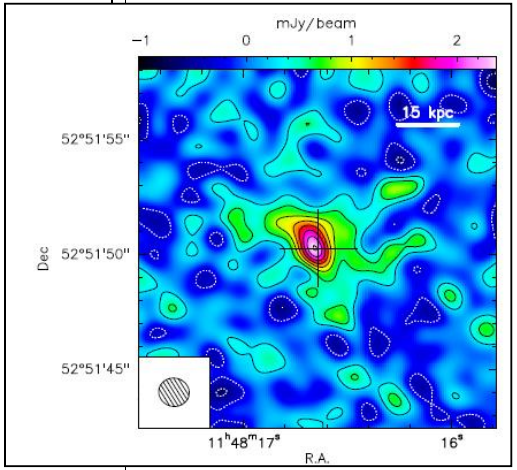
Outflow masses – OH vs. [CII]



Janssen+ 2016.

SDSS J1148+5152, z=6.4189



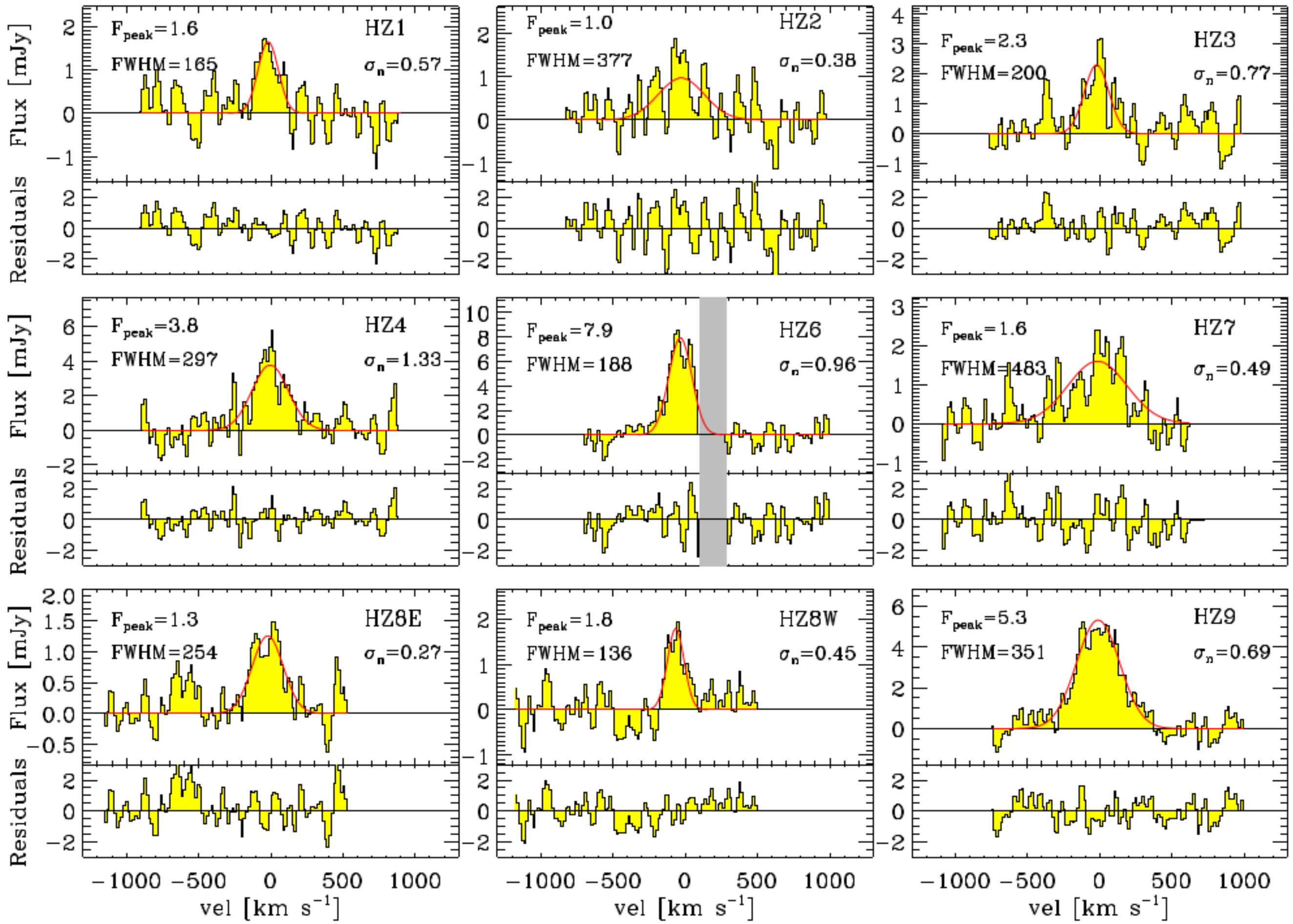


dM/dt > 3500 Msun/yr

Capak+2015, Gallerani+2016, Pallottini+ 2016,

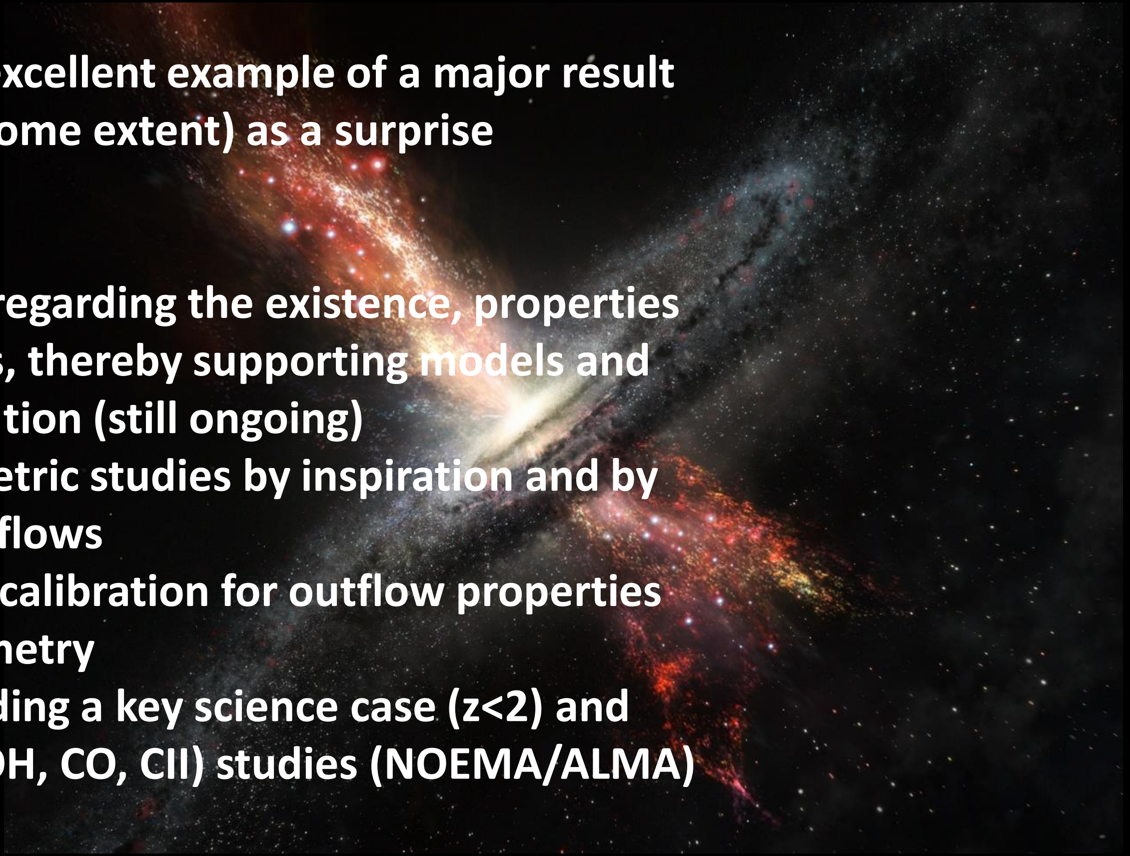
See also Riechers+2014 (z=5.3 SMG)

ALMA suggests outflows in z ~ 5.5 galaxies



Gallerani+ 2018

Conclusion



Herschel OH outflow studies are an excellent example of a major result from a space mission that came (to some extent) as a surprise

They

- provided significant new insights regarding the existence, properties and physics of molecular outflows, thereby supporting models and our understanding of galaxy evolution (still ongoing)
- kick-started (sub-)mm interferometric studies by inspiration and by instructions where to look for outflows
- provided independent validation/calibration for outflow properties derived from (sub-)mm interferometry
- paved the way for SPICA by providing a key science case (z<2) and for future ground-based (high-z, OH, CO, CII) studies (NOEMA/ALMA)