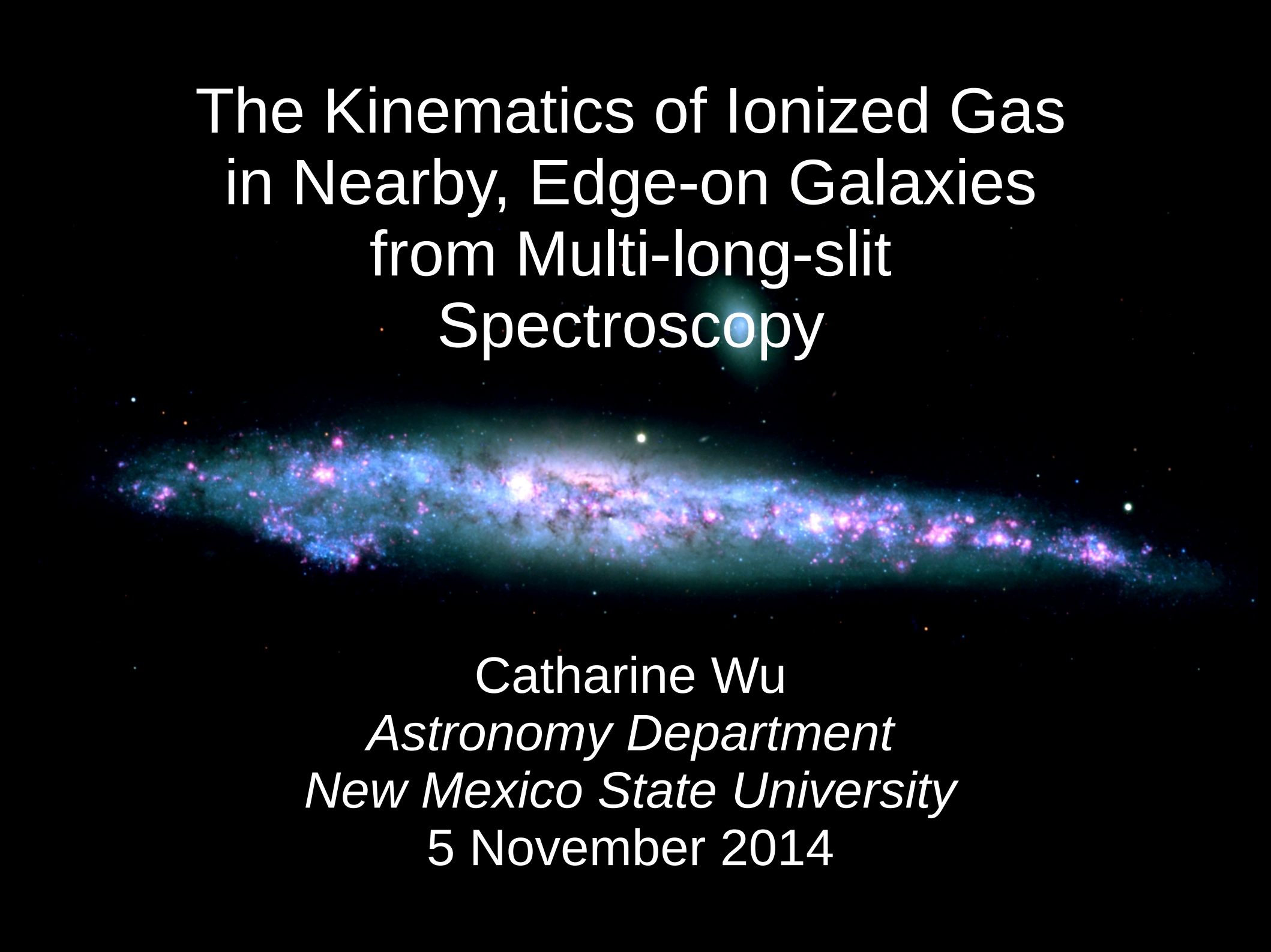
The Kinematics of Ionized Gas in Nearby, Edge-on Galaxies from Multi-long-slit Spectroscopy



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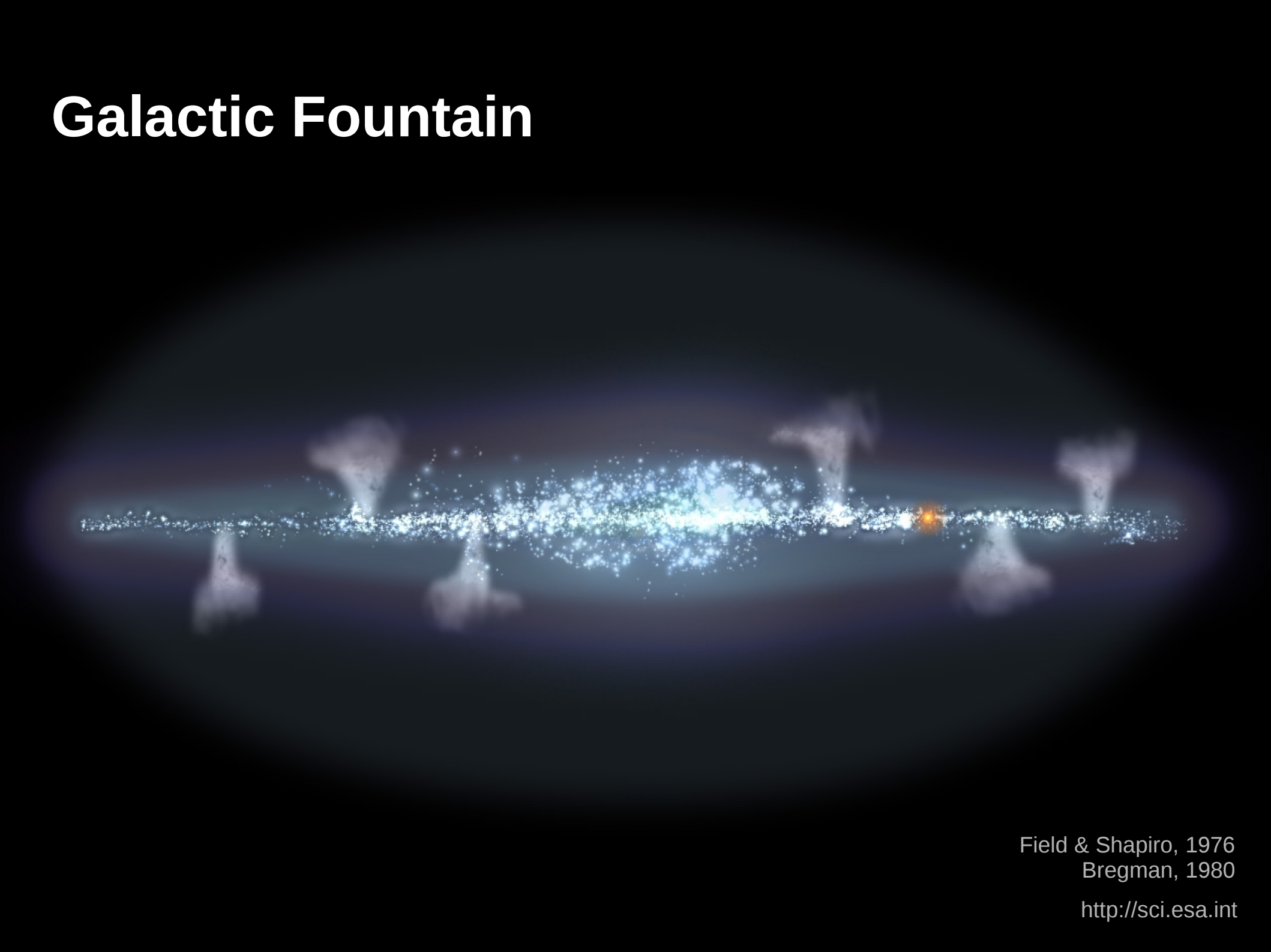
Outline:

- Extra-planar (EP) gas
- Lagging gas
- Sample galaxies
- Multi-long-slit spectroscopy
- Multi-long-slit modeling
- Individual targets and results
- Sample conclusions

Extra-planar (EP) gas

- Star-forming disk ↔ thick disk/CGM/IGM
- Multi-phase: X-ray, radio continuum, dust, HI, HII
- Milky Way: Reynolds Layer
- HII: Varied morphology
  Correlated with star formation

Galactic Fountain

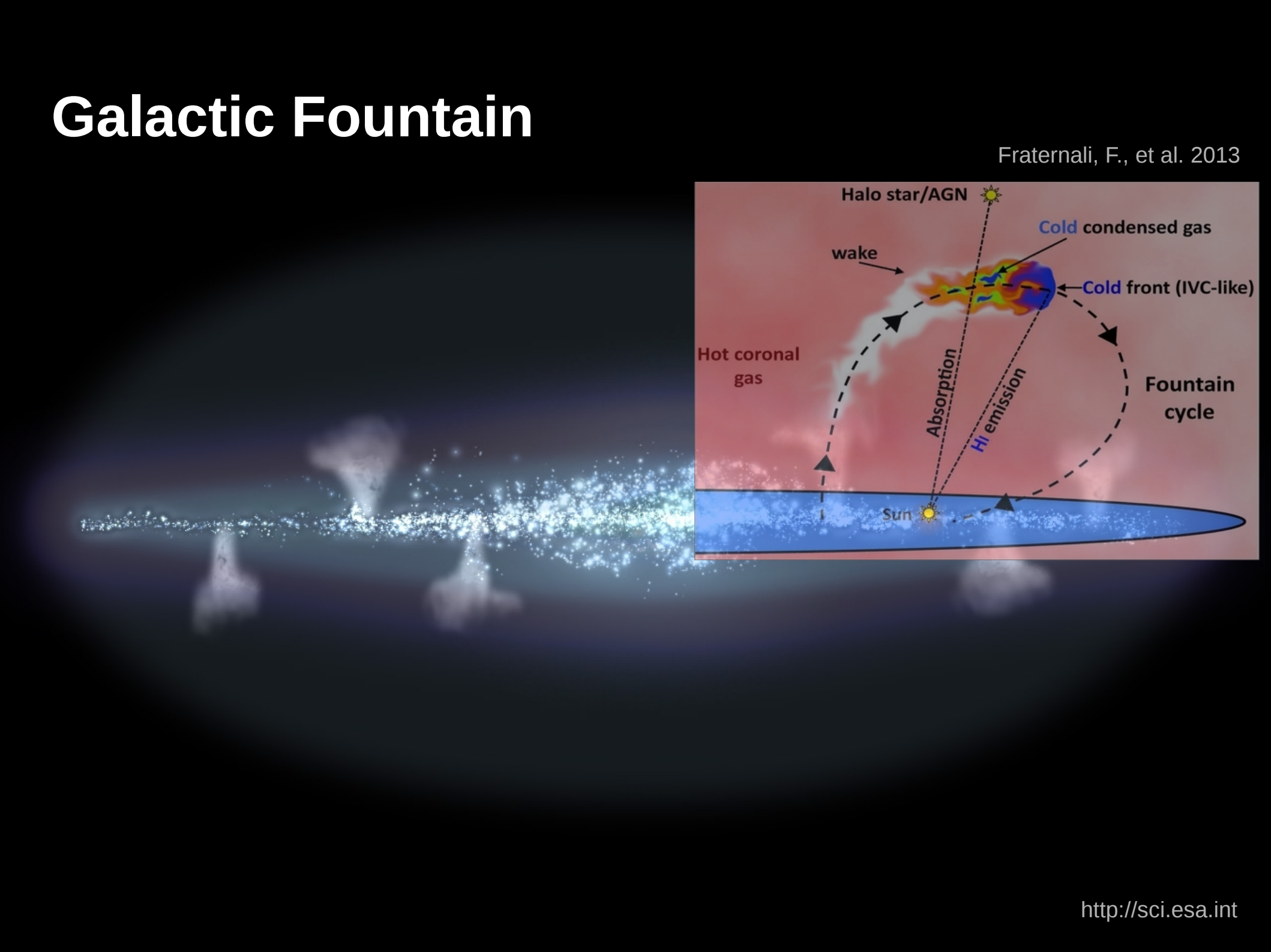


Field & Shapiro, 1976
Bregman, 1980

http://sci.esa.int

Galactic Fountain

Fraternali, F., et al. 2013



http://sci.esa.int

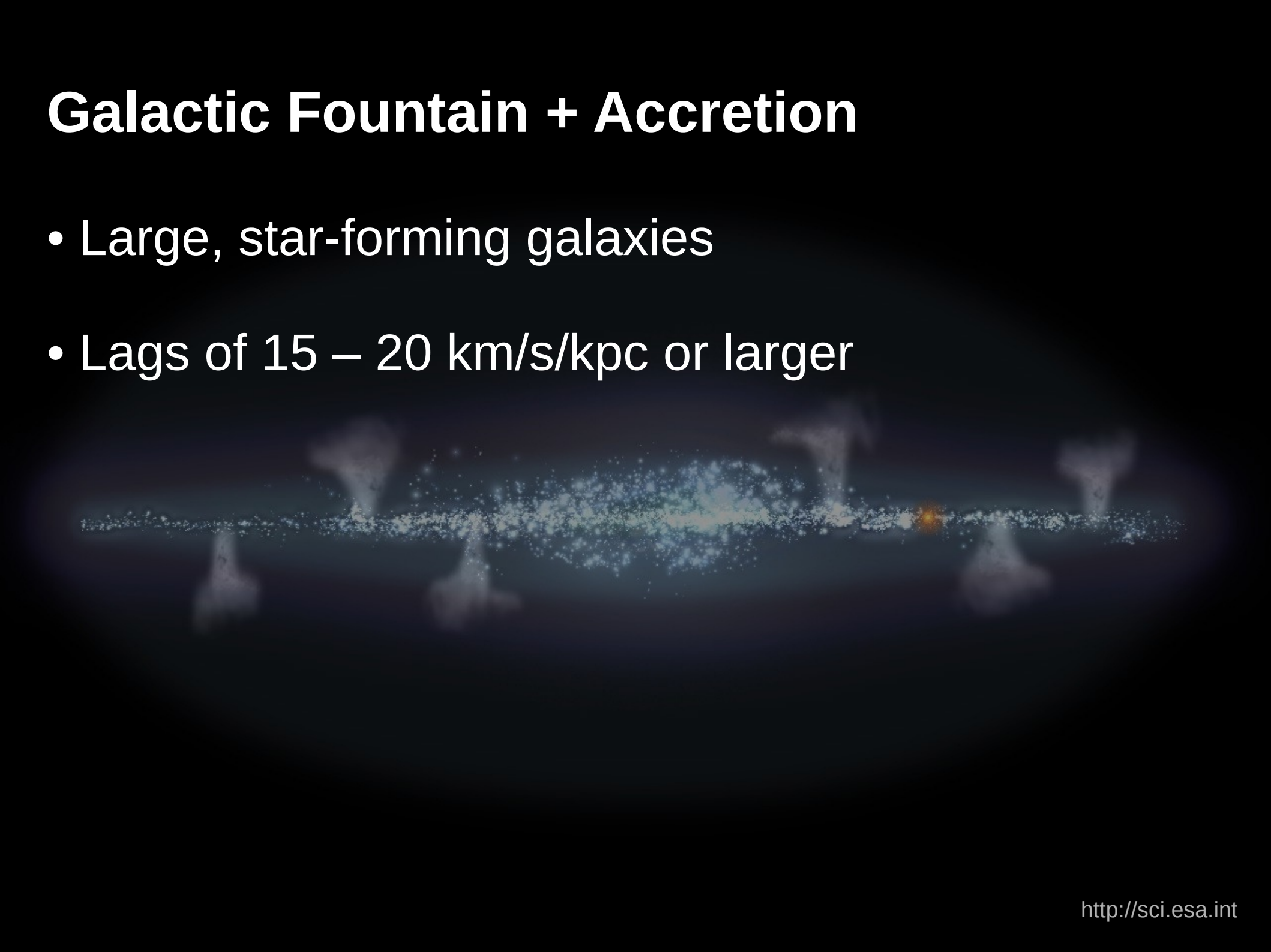
Galactic Fountain → Lagging Halo

- Fountain accepted as origin of EP gas
- Ballistic models – fountain flows only
  Collins et al. (2002); Fraternali & Binney (2006, 2008)
  Result: Lag is too small
- Hydrodynamic simulations – cloud-halo interactions
  Marinacci et al. (2011); Kaufmann et al. (2006)
  Result: Lag is just right

→ Accretion … in large, MW-type galaxies

Galactic Fountain + Accretion

- Large, star-forming galaxies
- Lags of 15 – 20 km/s/kpc or larger



Galactic Fountain + Accretion

- Large, star-forming galaxies
- Lags of 15 – 20 km/s/kpc or larger
- This study:
  - large, quiescent galaxies?
  - small, starbursting galaxies?
  - small, quiescent galaxies?

Galactic Fountain + Accretion

- Large, star-forming galaxies
- Lags of 15 – 20 km/s/kpc or larger
- This study:
  - large, quiescent galaxies?
  - small, starbursting galaxies?
  - small, quiescent galaxies?
  - How common are lags?
  - What are typical magnitudes of lags?
  - Does lag correlate with mass or SFR?

Sample Selection

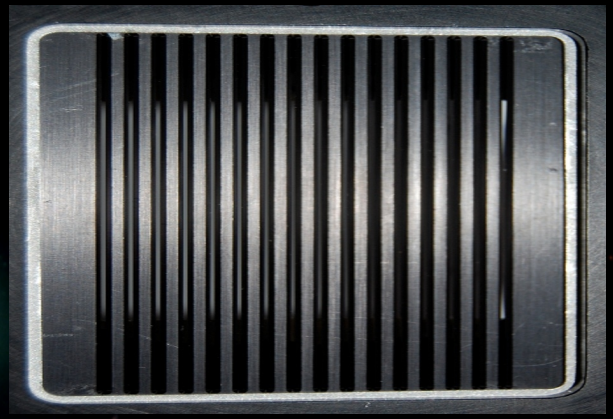
2MASS Large Galaxy Atlas:

- close to edge-on
- northern hemisphere
- $R_{K20} > 2.2'$
- $v_{hel} < 1600$ km/s

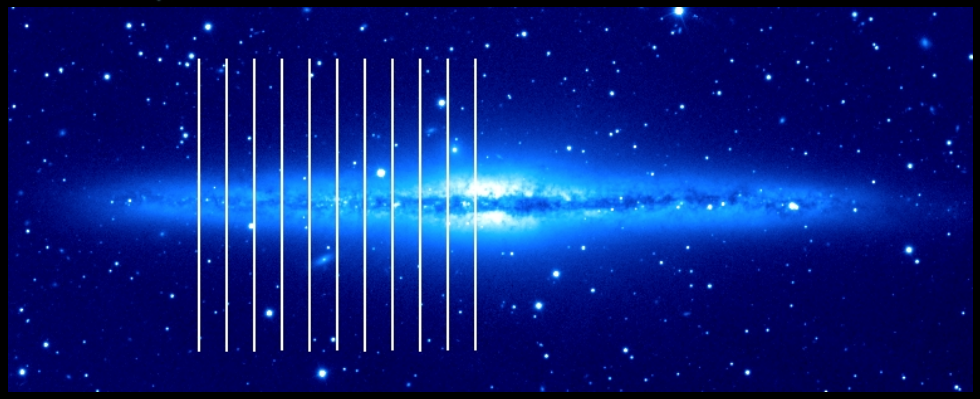
	inc (^{o})	v_{rot} (km/s)	L_{FIR}/D_{25}^2 (10^{40} erg/s/kpc^2)	Exp. time (hrs)
NGC 891	90	212.1	2.2	12.9
NGC 3044	85	153.1	3.3	6.4
NGC 3079	88	208.4	**8.9**	2.25
NGC 3628	87	211.7	2.0	6.0
NGC 4013	84	181.7	2.7	6.4
NGC 4517	87.4	139.8	0.5	4.3
NGC 4565	87.5	**244.9**	0.5	5.0
NGC 4631	85	138.4	1.8	0.8, 6.8, 3.0
NGC 4672	87	110.0	> 0.2	7.5
NGC 5229	90	**55.8**	> 0.1	5.0
NGC 5907	87	226.7	0.8	5.5
UGC 4278	90	78.9	0.2	7.2
UGC 7321	90	94.5	**0.03**	2.5

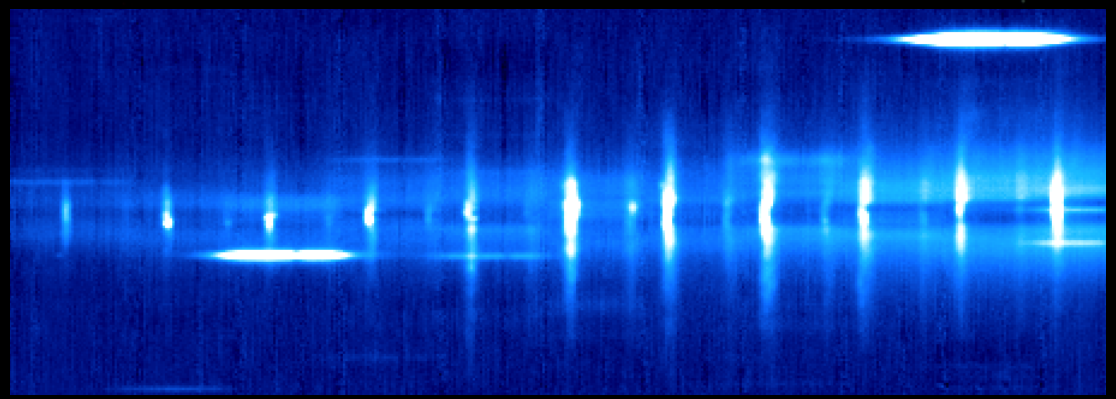
Size SFR

Multi-long-slit Spectroscopic Observing

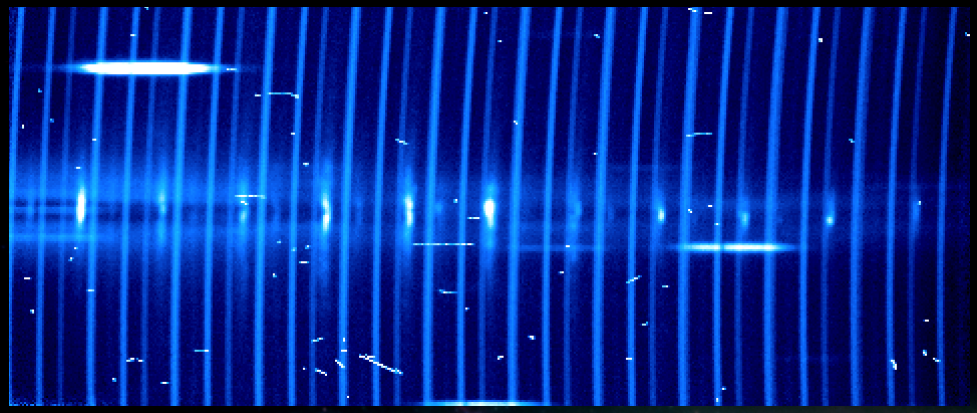


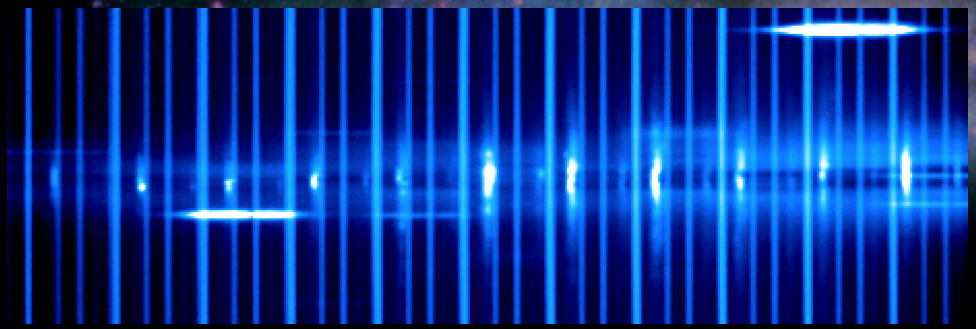
- 11 1.5'' slits, spaced 22.5''
- narrowband filter (25A)
- 3.75' x 4' FOV
- 0.58 A/pix → 65 km/s resolution
- DIS, ARC 3.5m telescope at APO

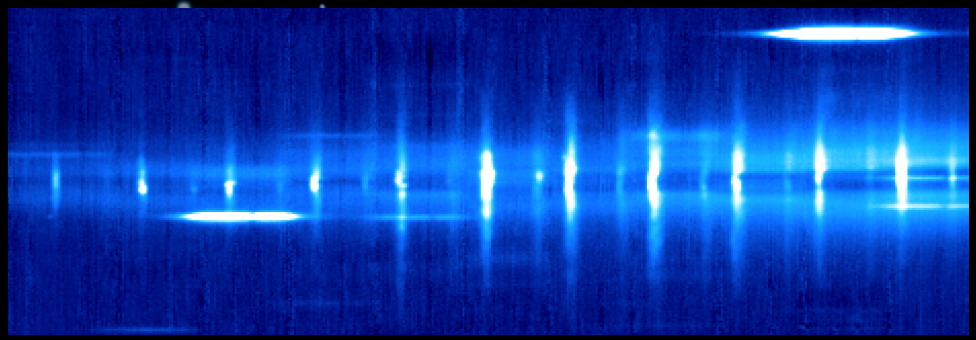


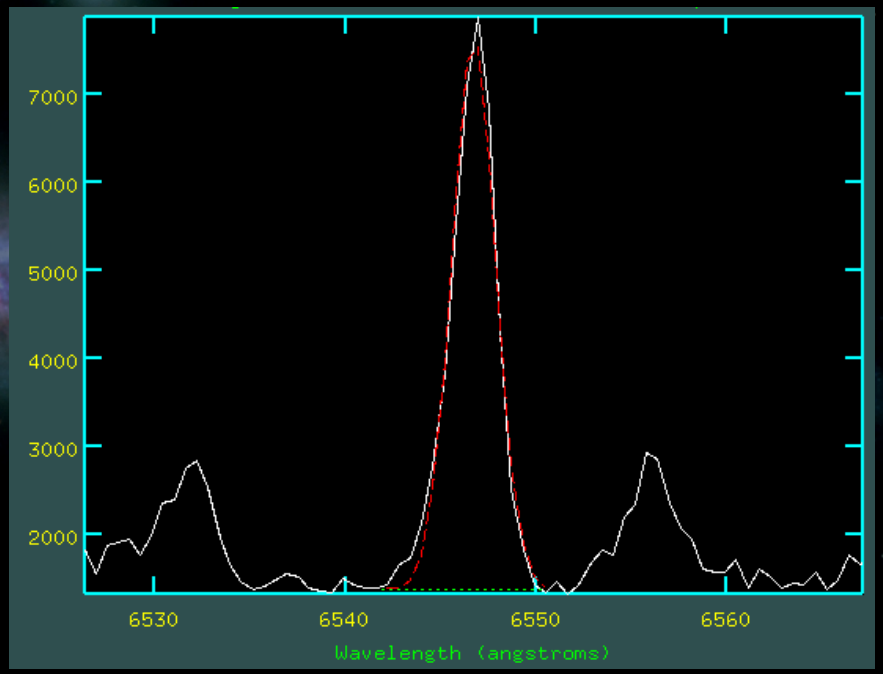


Multi-long-slit Spectroscopic Observing



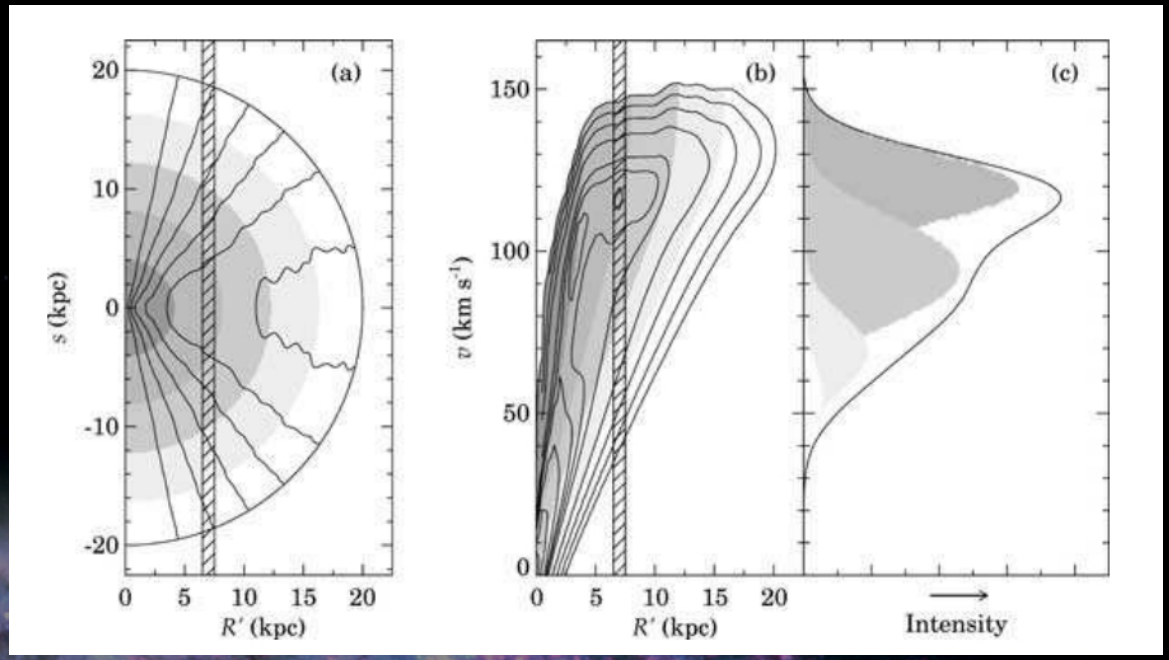


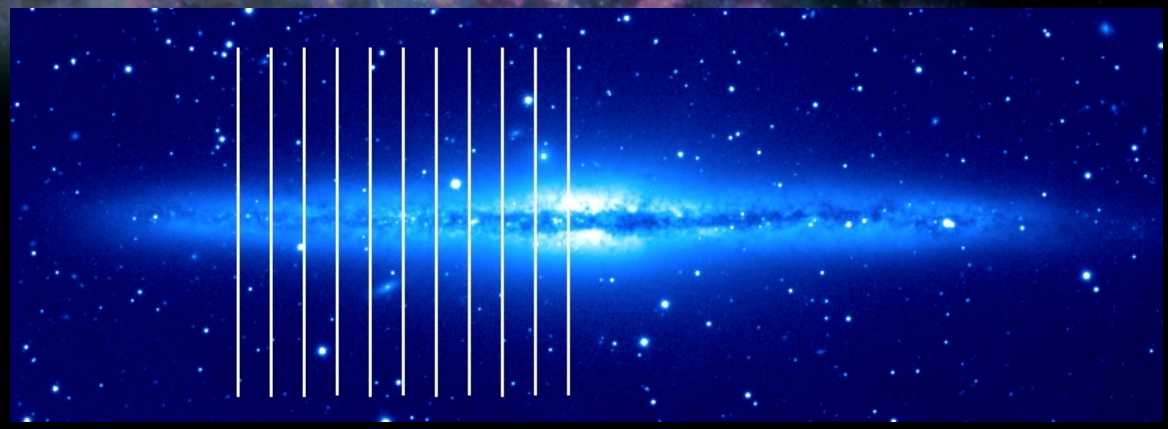




Multi-long-slit Modeling

Kregel & van der Kruit, 2014





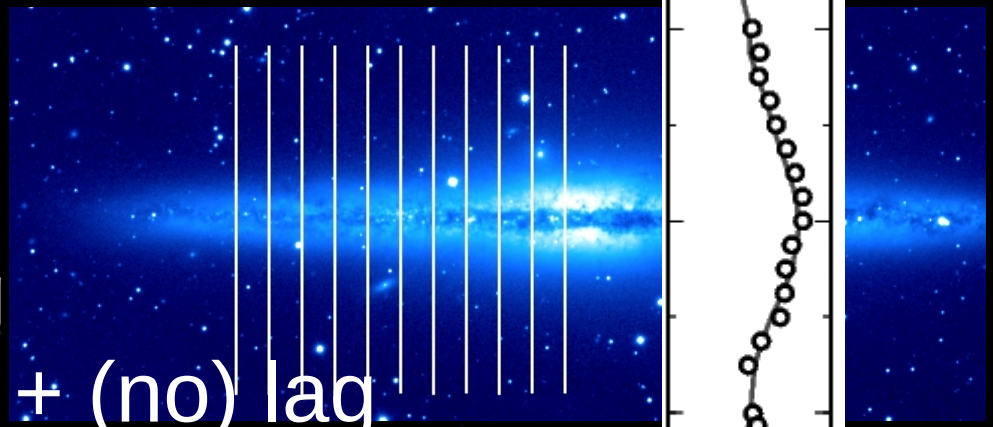
- scale height
  scale length
  (relative intensity)
- circular rotation
  lagging value
  (velocity)
- inclination

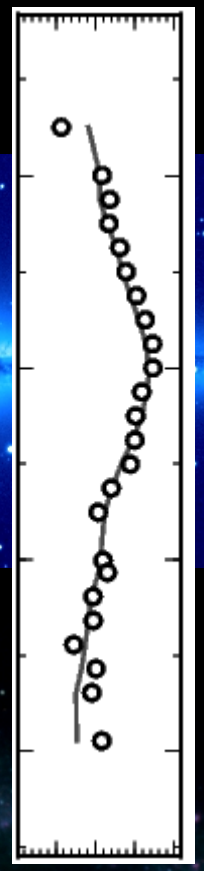
→ model profile

- Telescope Optics
- Instrument dispersion

Multi-long-slit Modeling

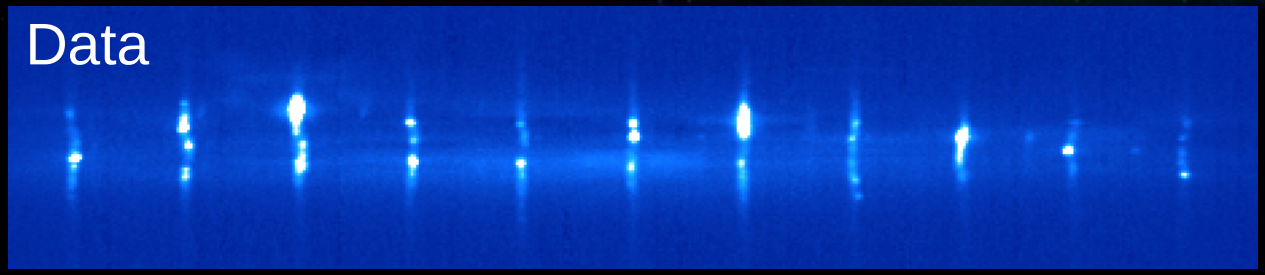
- “inclination effects”
  thick or thin, 90^{o} + lag
  thin disk, 86^{o} + (no) lag
  medium thickness, 88^{o} + (no) lag

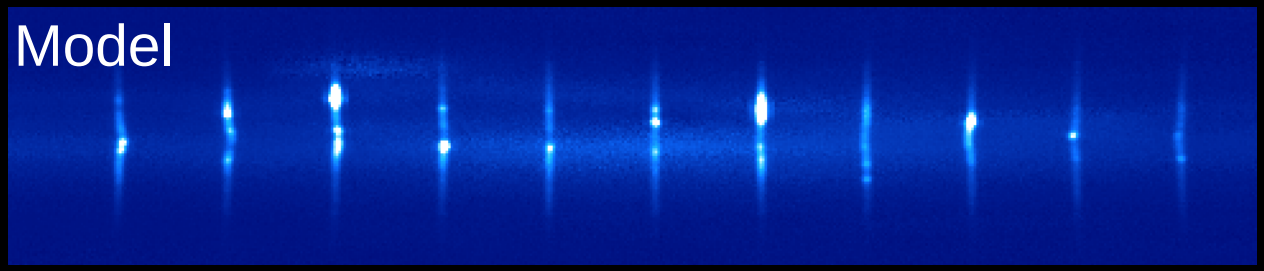




Velocity
(km/s)

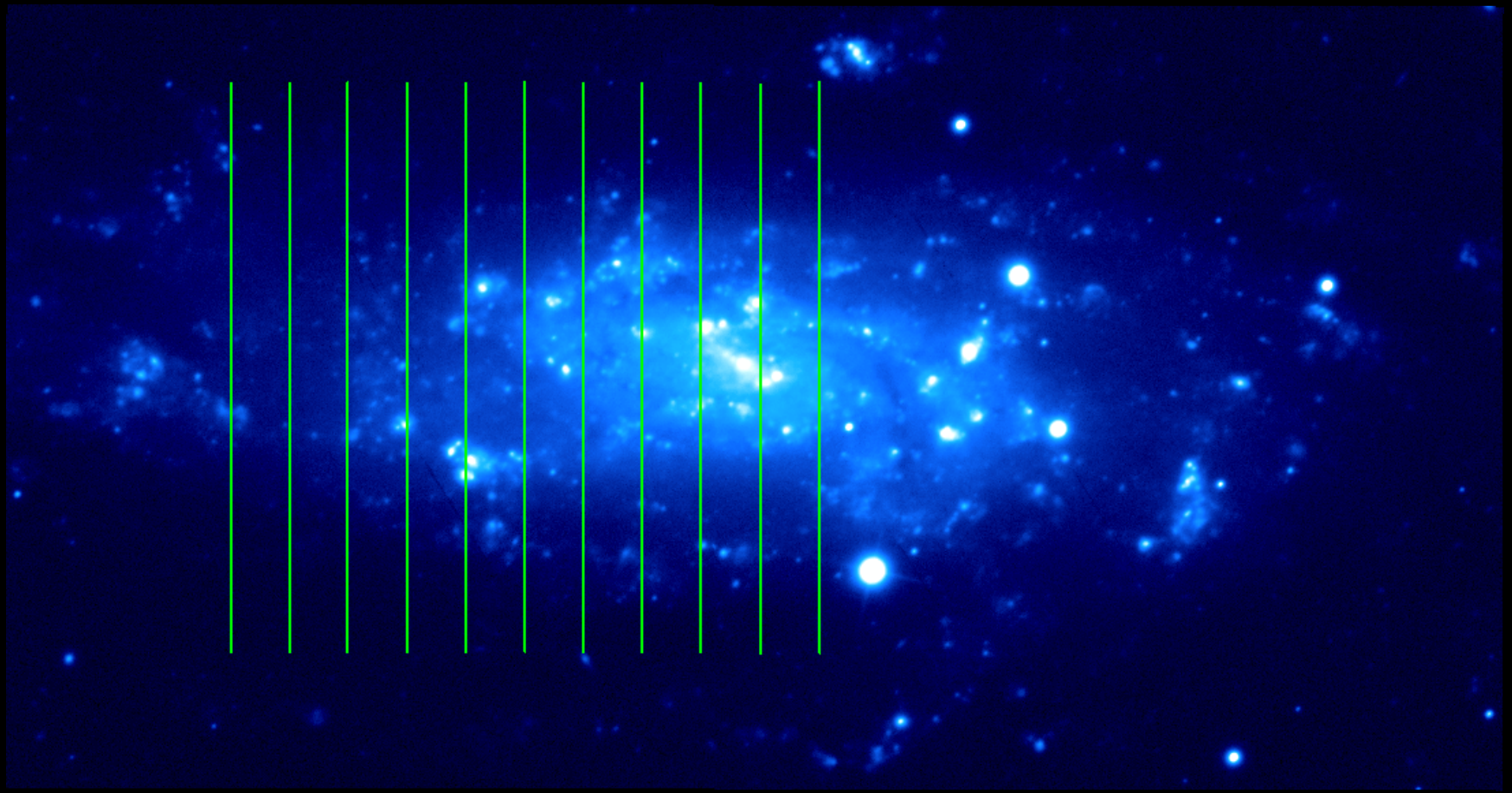
- 1-2 components
  S/N scaling





Multi-long-slit Test Galaxies

- NGC 4559
- test observational setup, calibration



Multi-long-slit Test Galaxies

- NGC 4559
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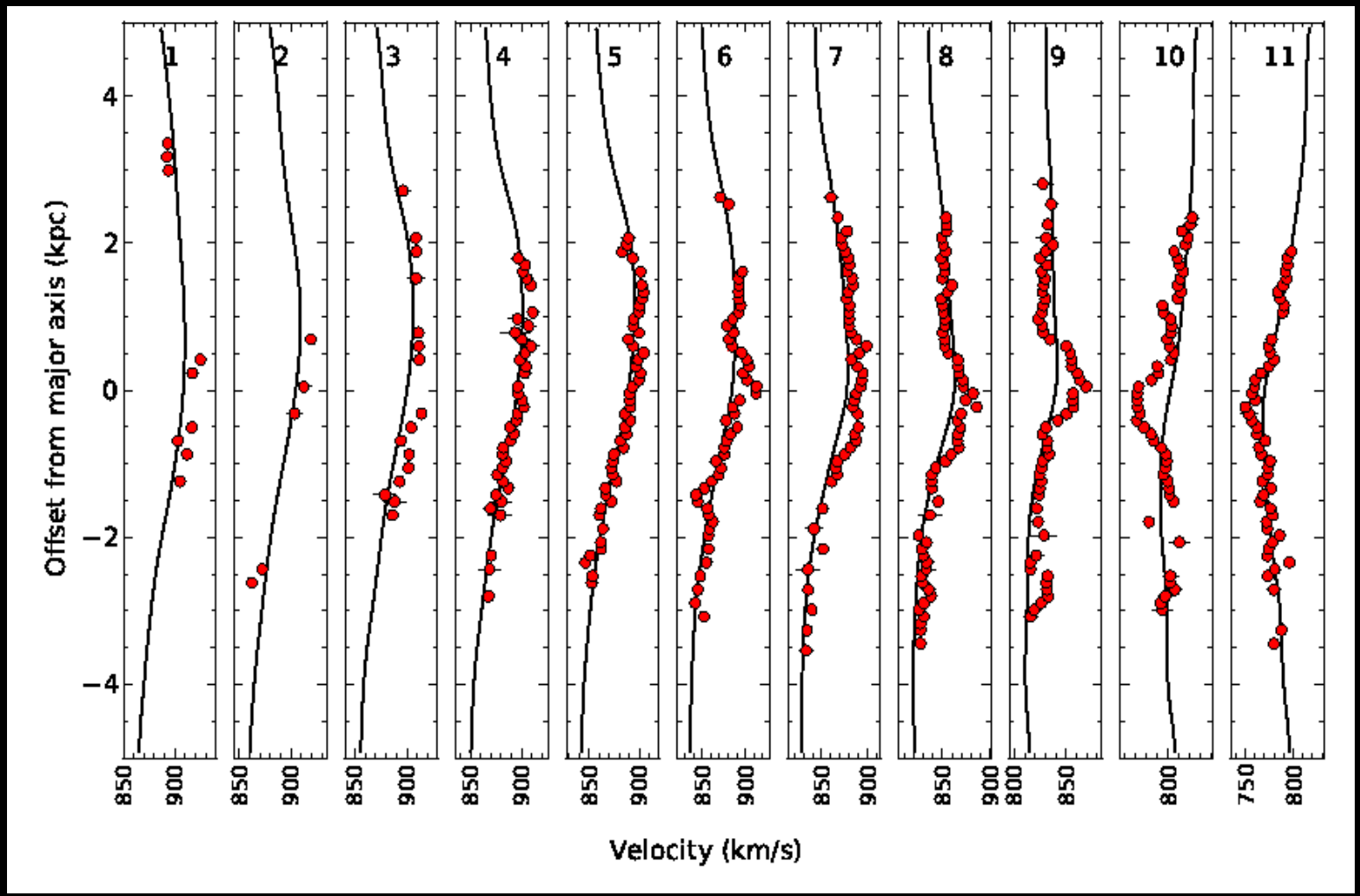


NGC 891

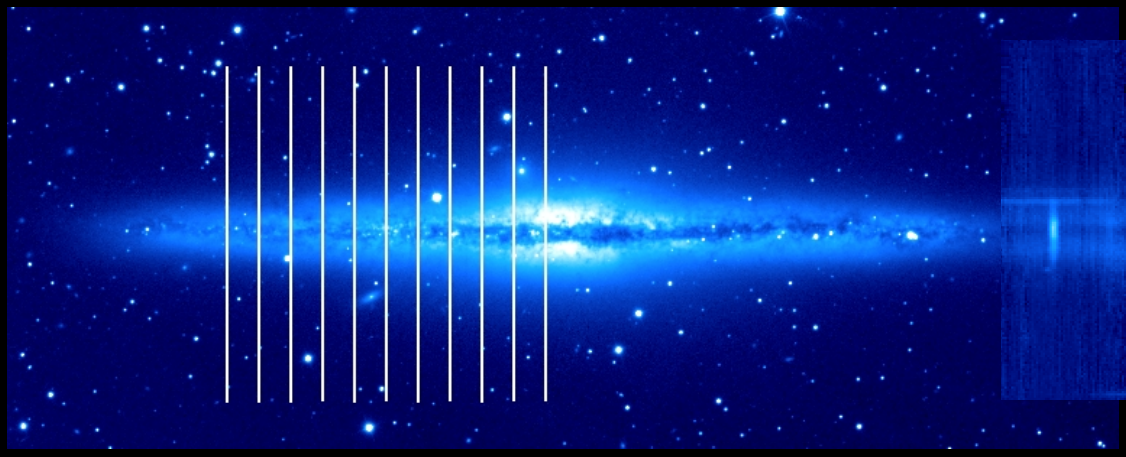
- High SFR (2.2); v_{rot} 212 km/s
- Thick, extended EP gas (HI, HII)
- Previous studies:

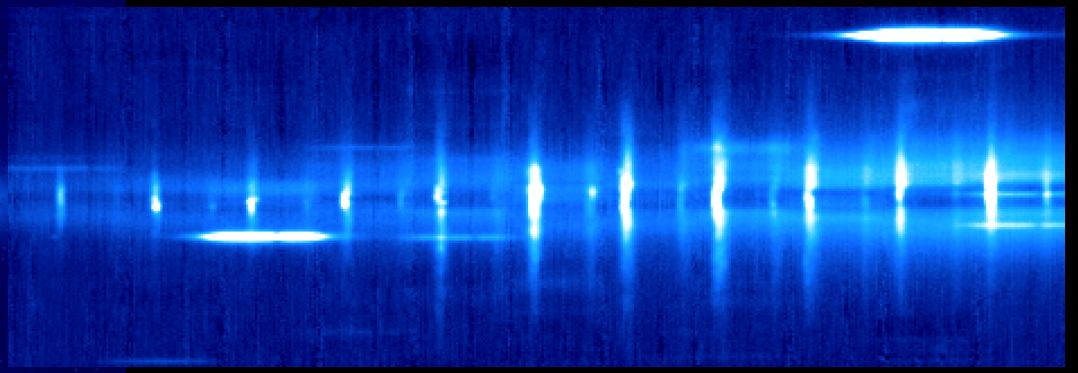
  Ha lag: 15-18, 18.8 km/s/kpc

  Heald et al. (2006b), Kamphuis et al. (2007)

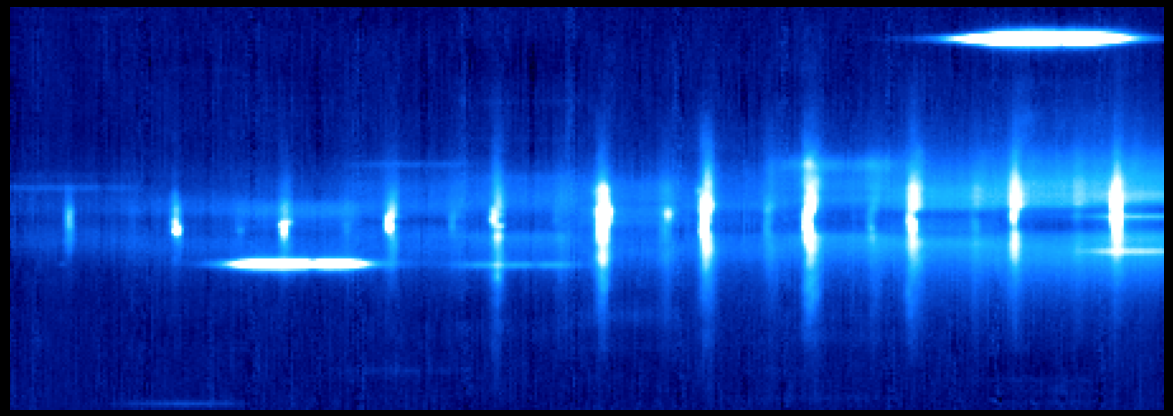
  HI lag: 20, 15, 15 km/s/kpc

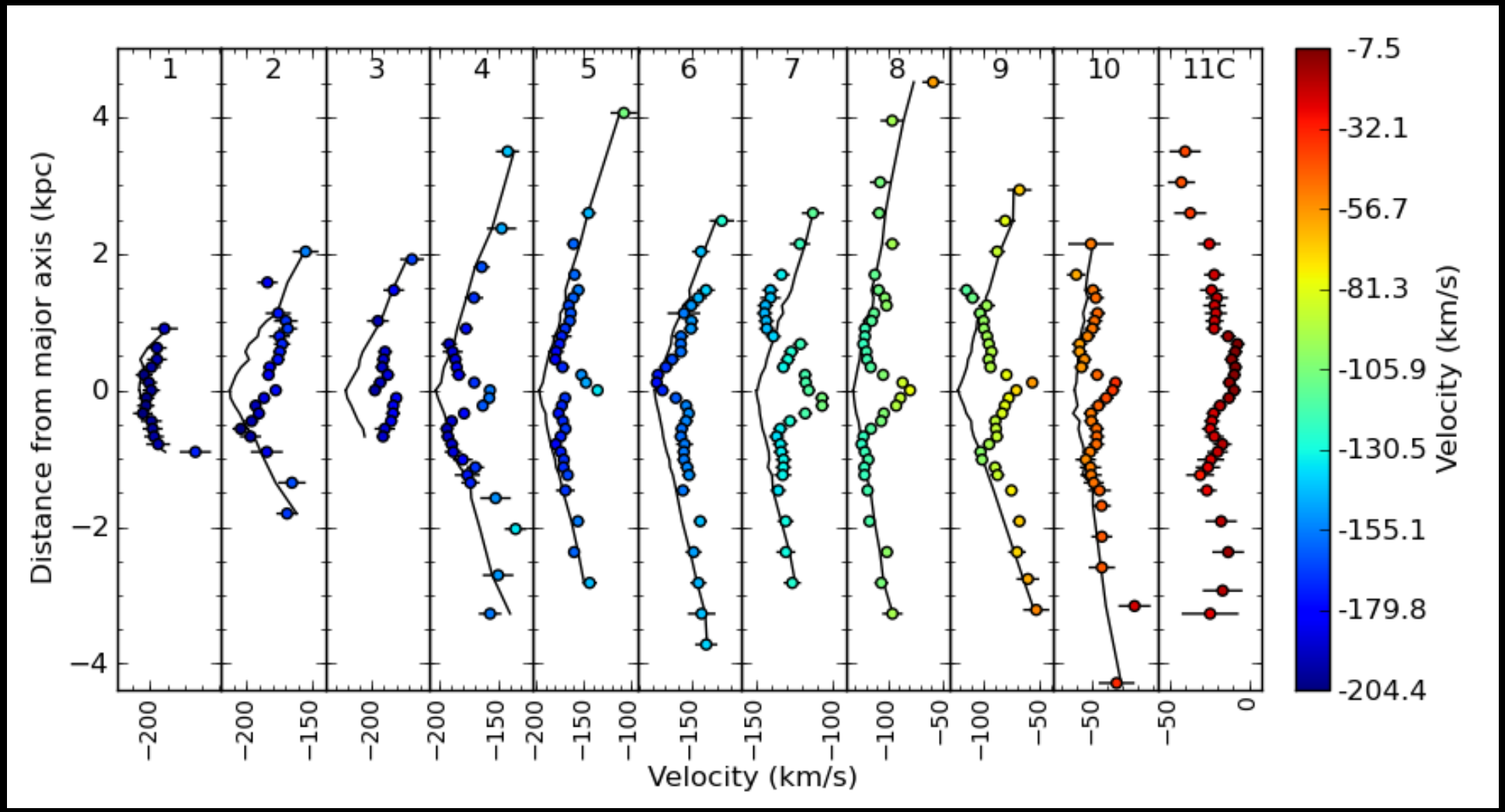
  Swaters et al. (1997), Oosterloo et al. (2007), Fraternali et al. (2005)





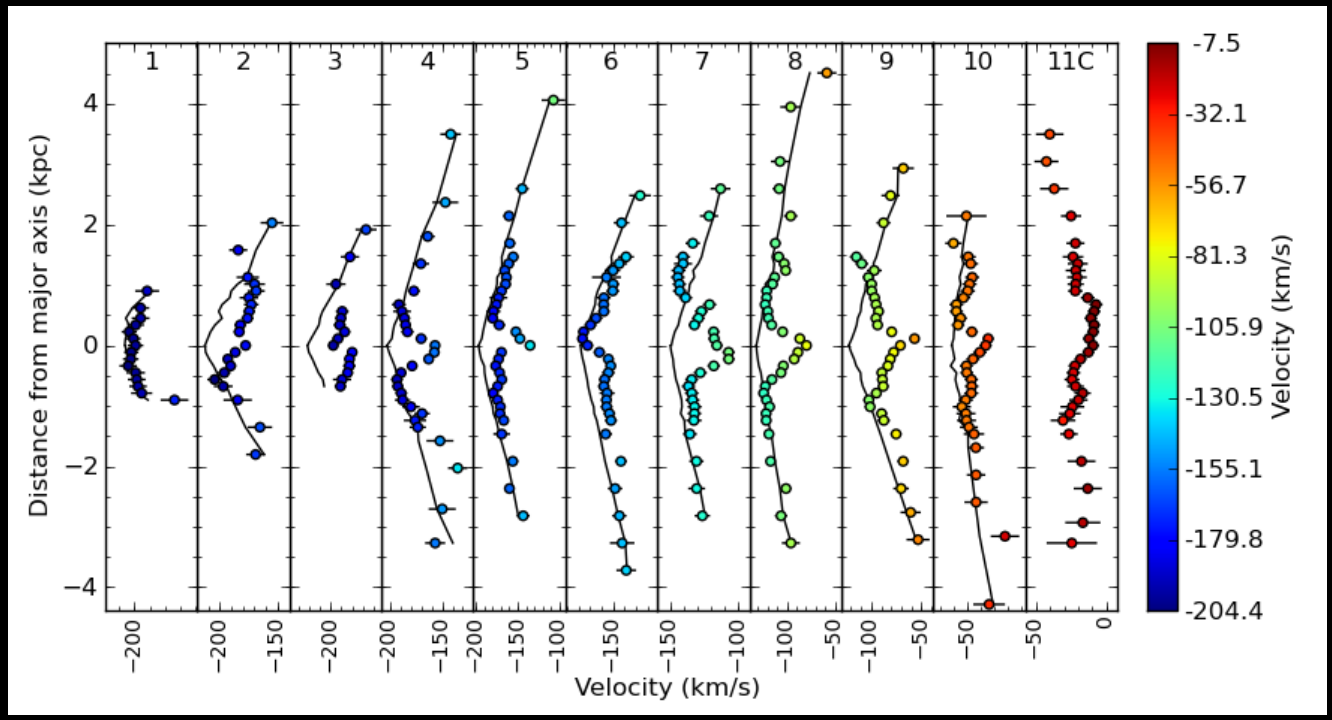
NGC 891

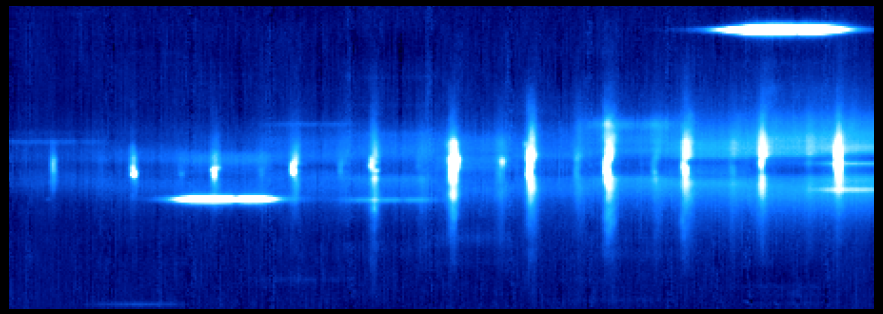


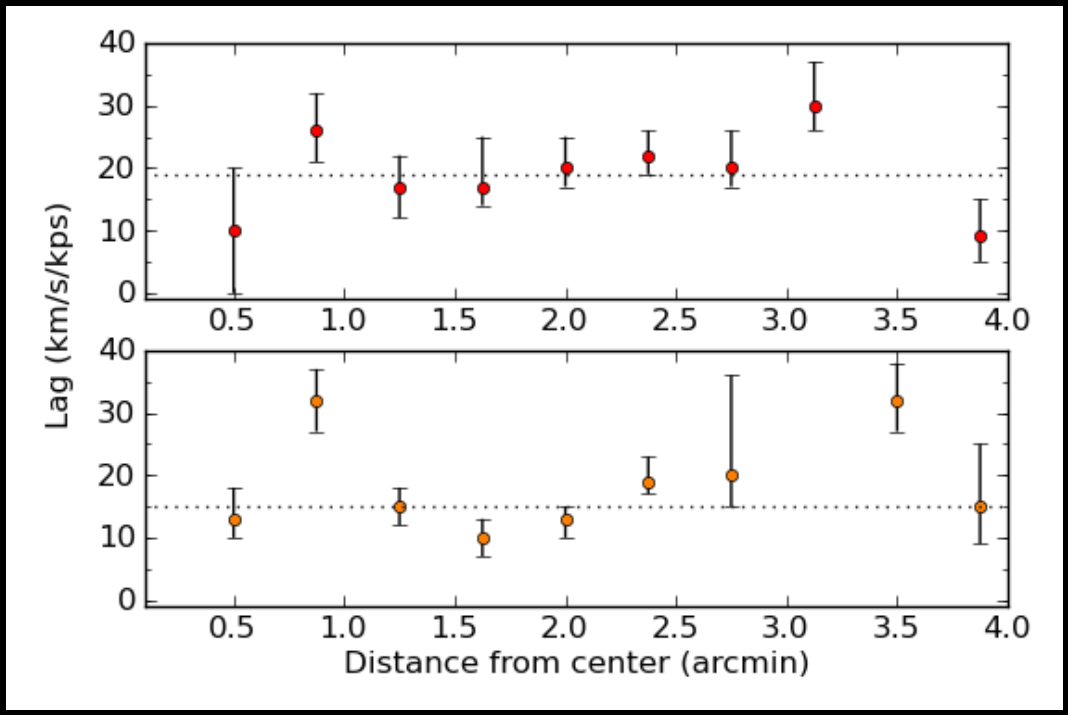

1
2
3
4
5
6
7
8
9
10
11C
Distance from major axis (kpc)
Velocity (km/s)
Velocity (km/s)
-7.5
-32.1
-56.7
-81.3
-105.9
-130.5
-155.1
-179.8
-204.4

NGC 891

Data and model profiles →



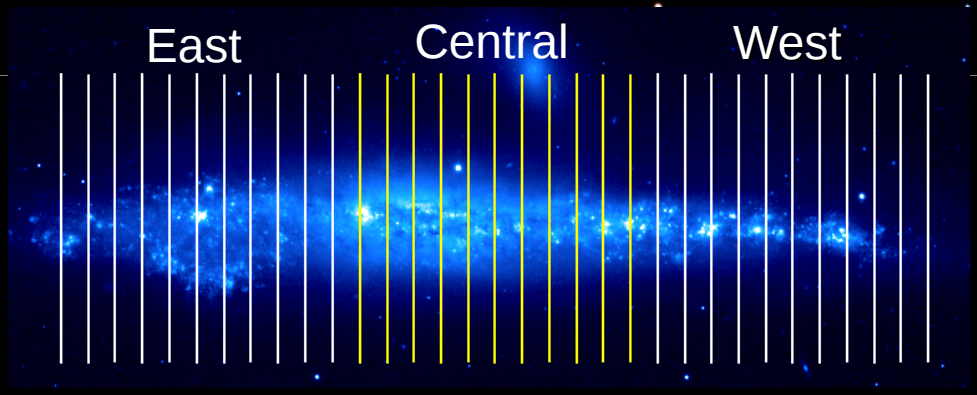


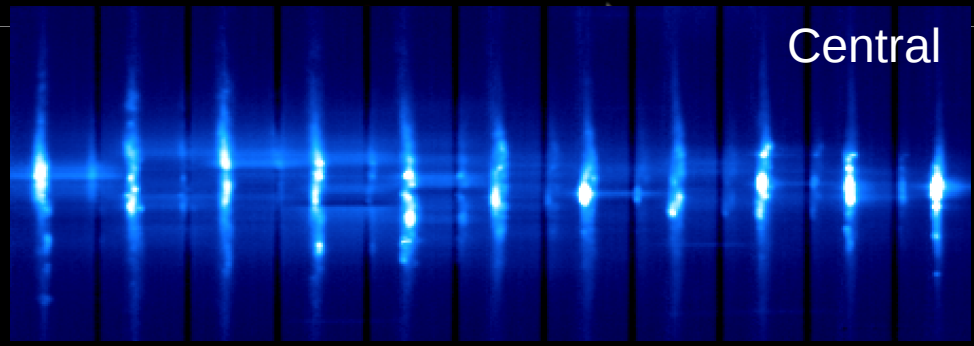


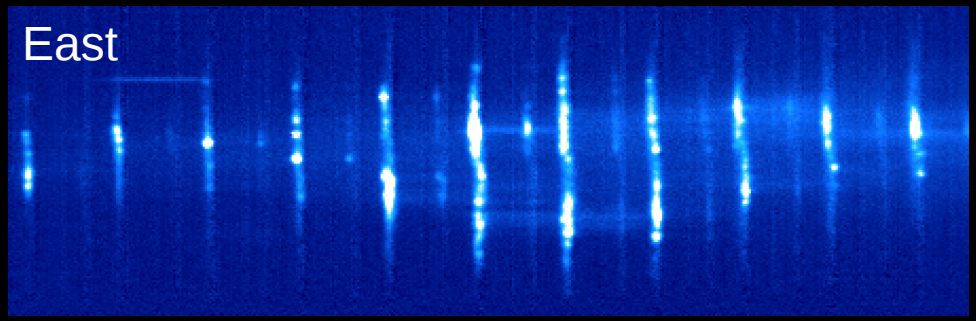
Lag: 15 - 20 km/s/kpc

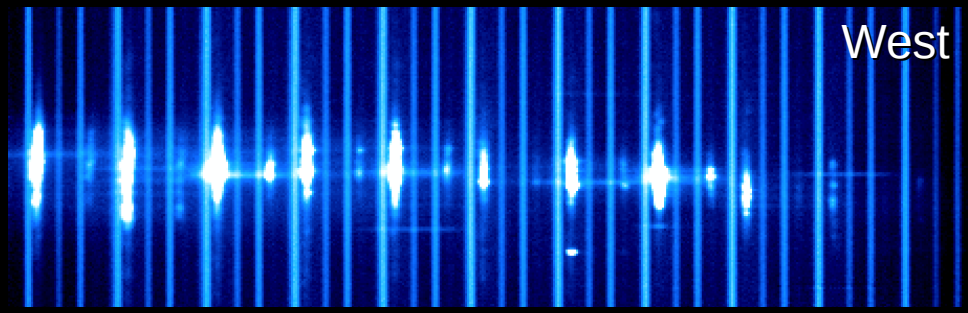
NGC 4631

- High SFR (1.8)
- v_{rot} 138 km/s
- Extensive EP gas
- Interacting







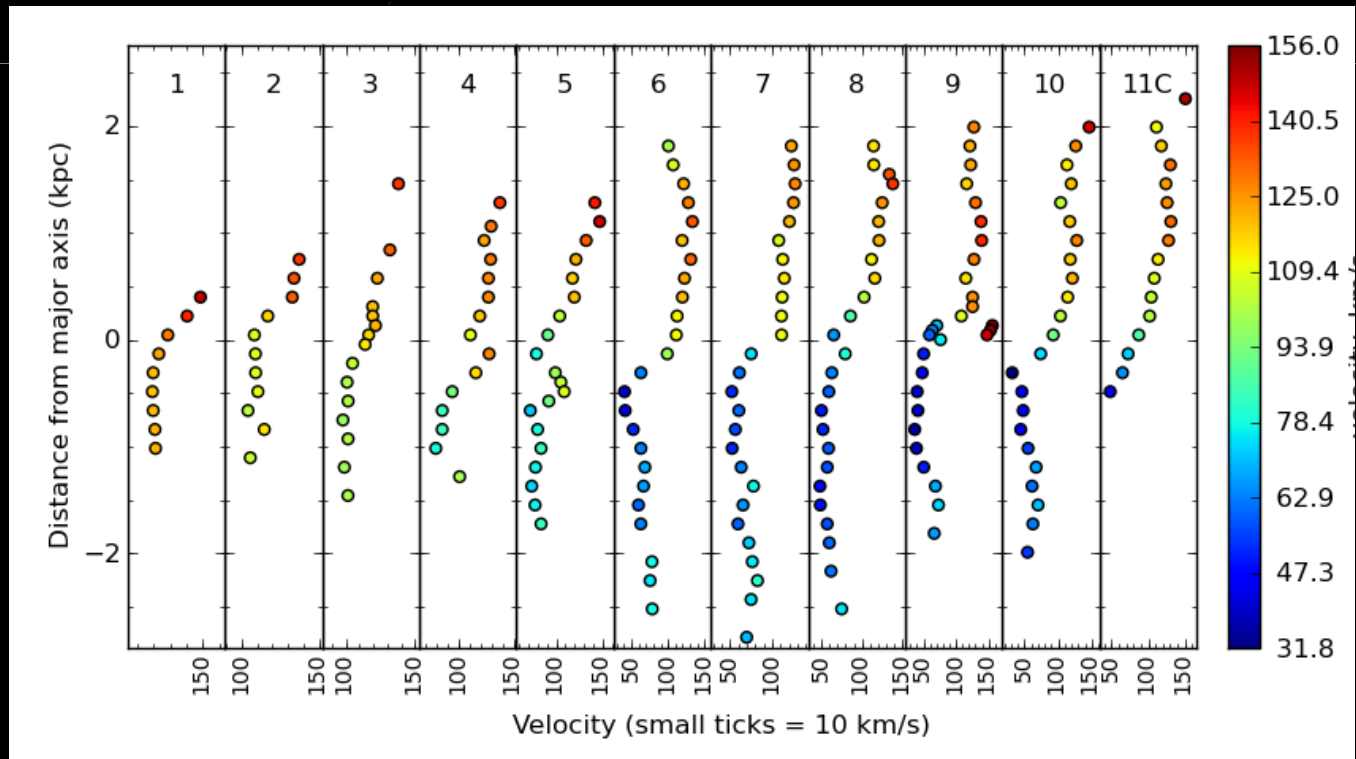


NGC 4631

East

Previous HI, CO studies:
Outflow feature?

Warped spiral arm



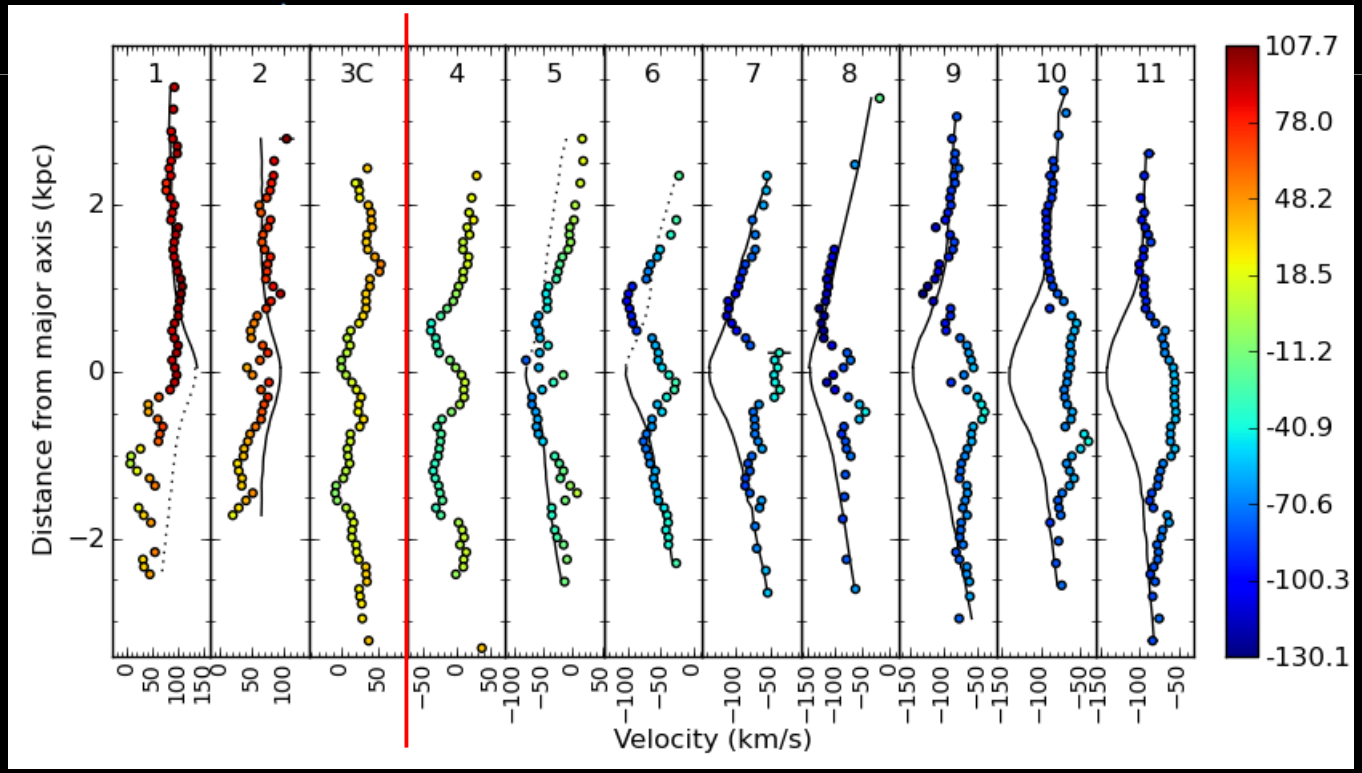
NGC 4631
Central

Accelerating halo?

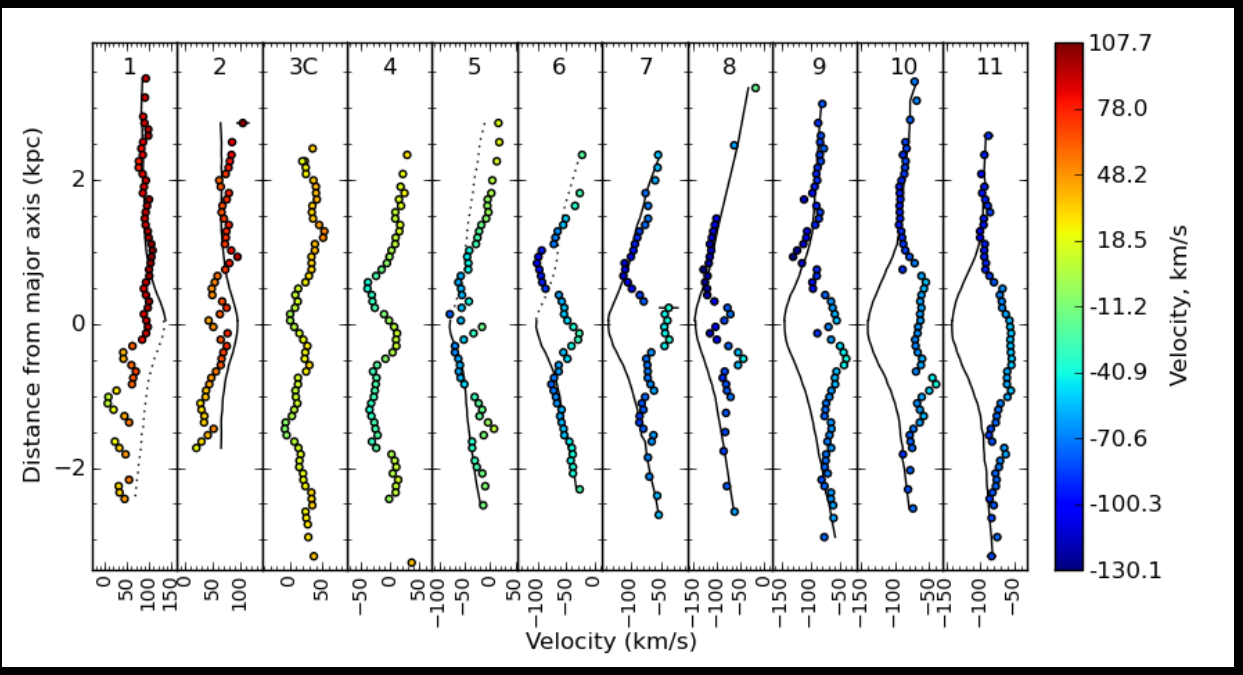
Counter-rotating gas?

Extreme lag?

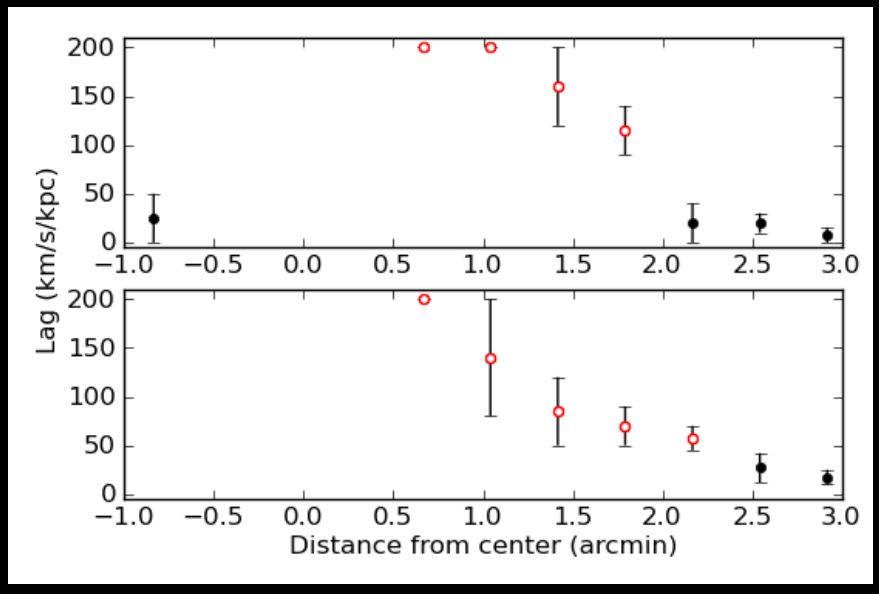
v_{rot} ~ 140 km/s



NGC 4631
Central

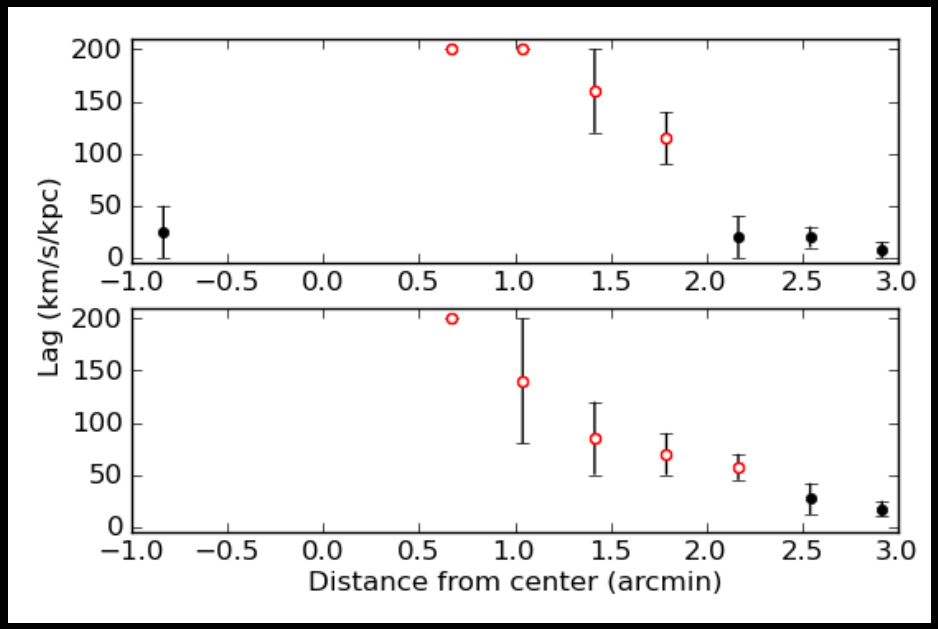


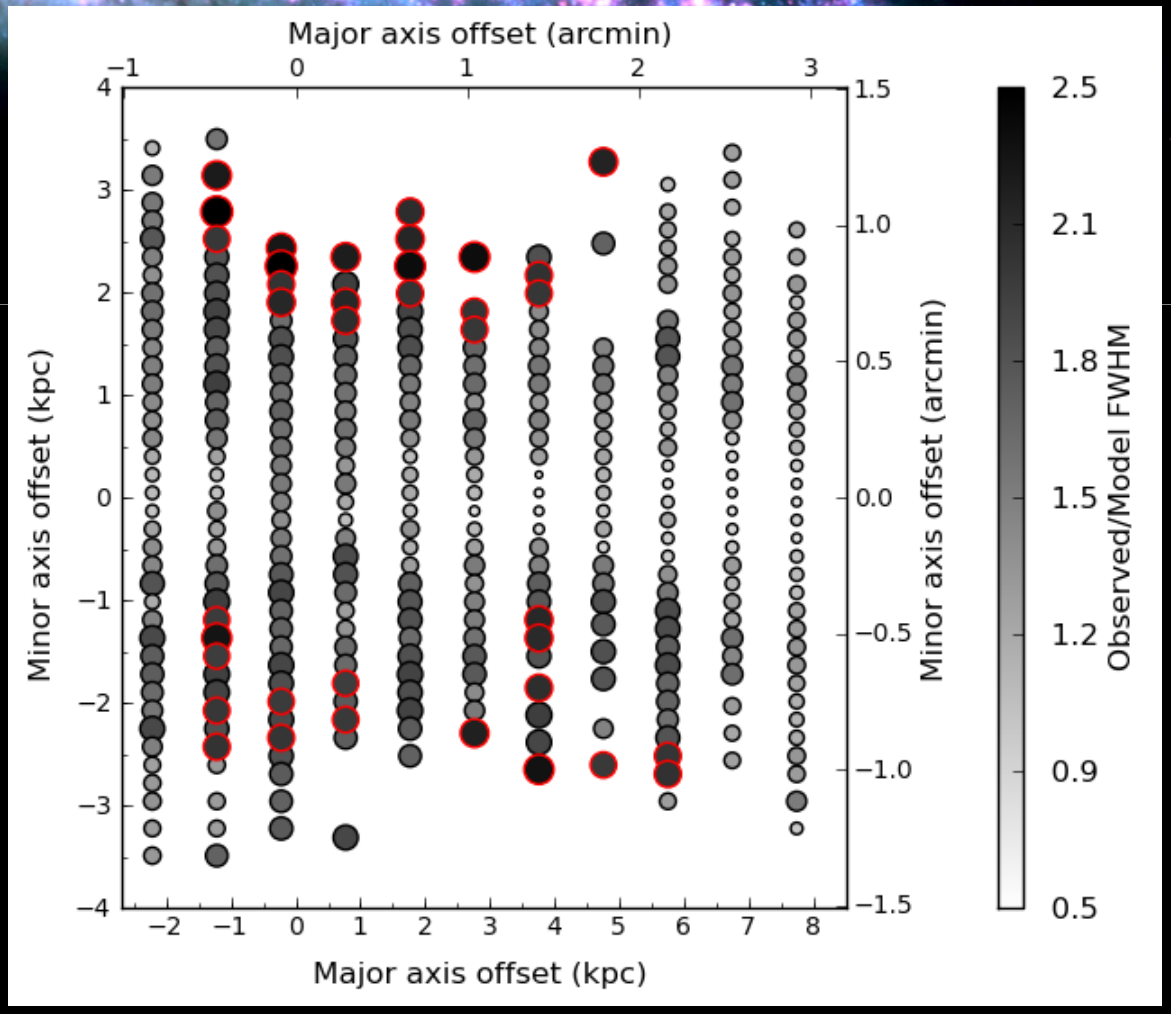
Extreme lag;
outflow event?

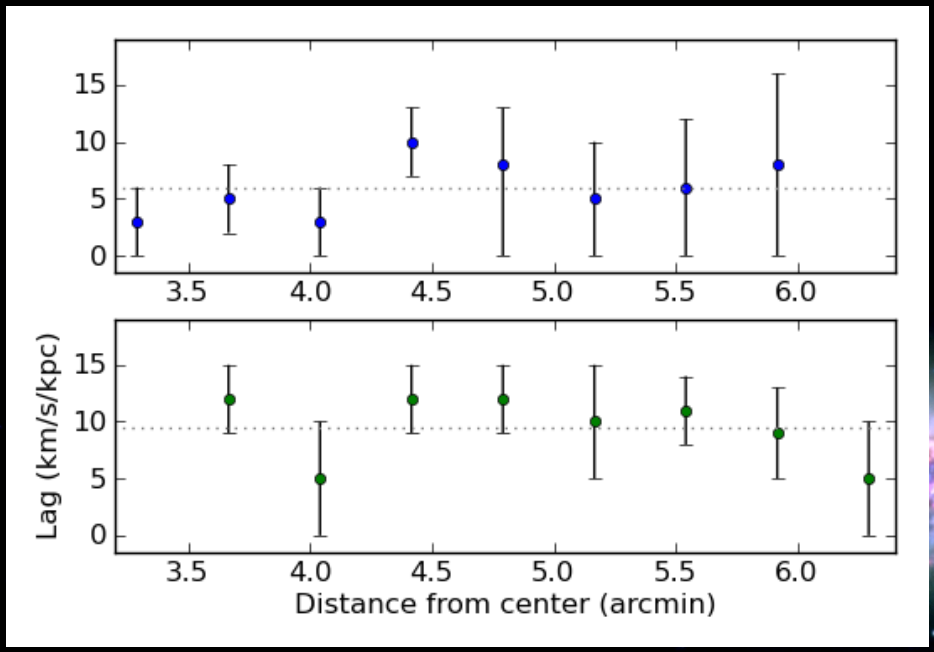


NGC 4631
Central

Outflow event?

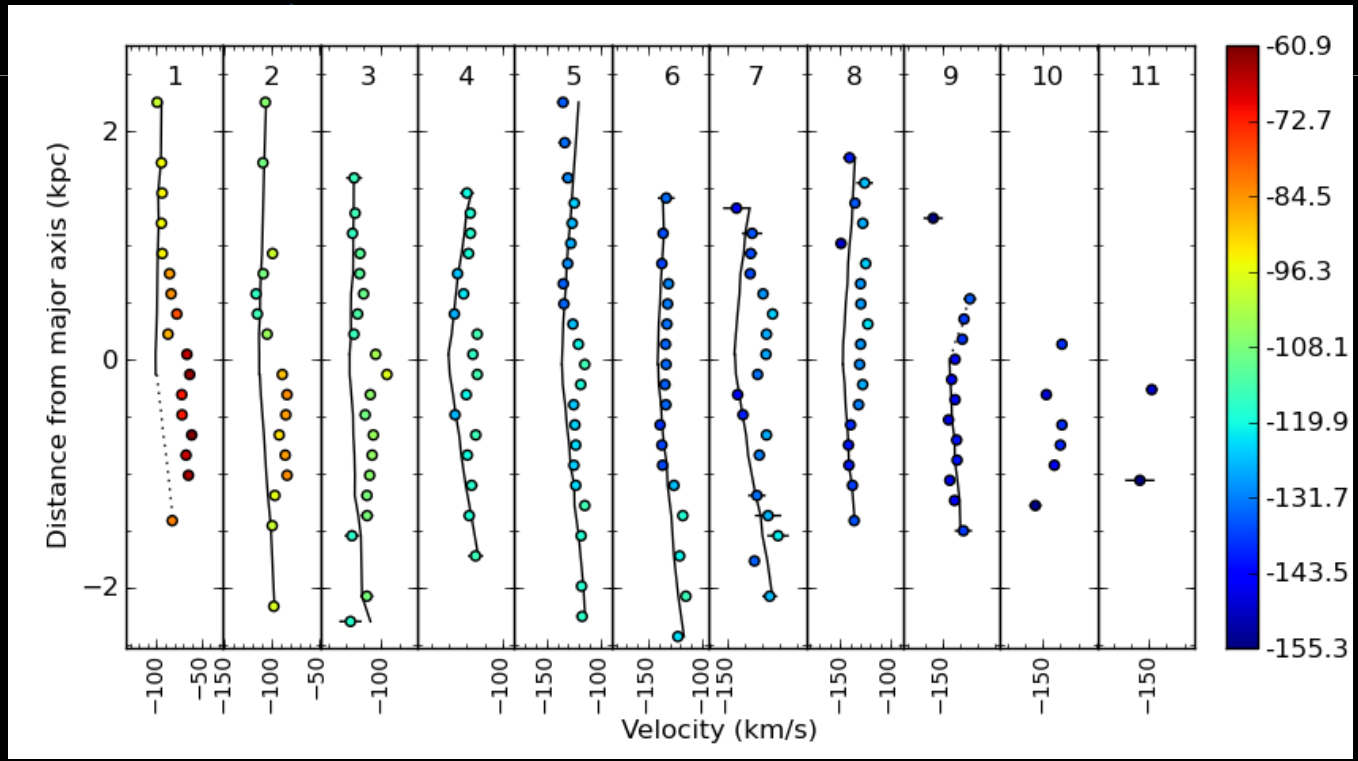




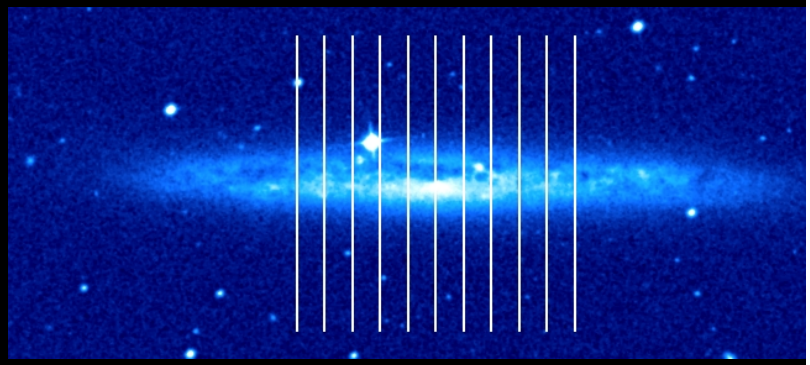


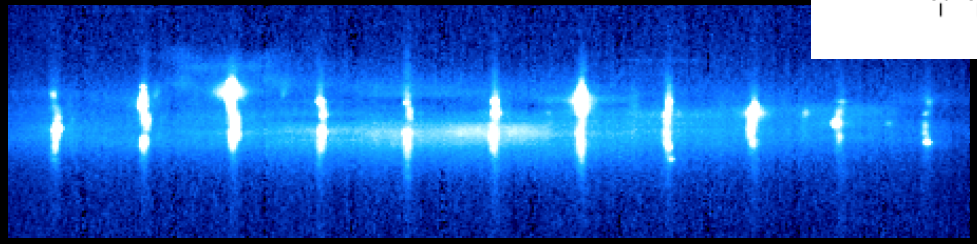
NGC 4631
West

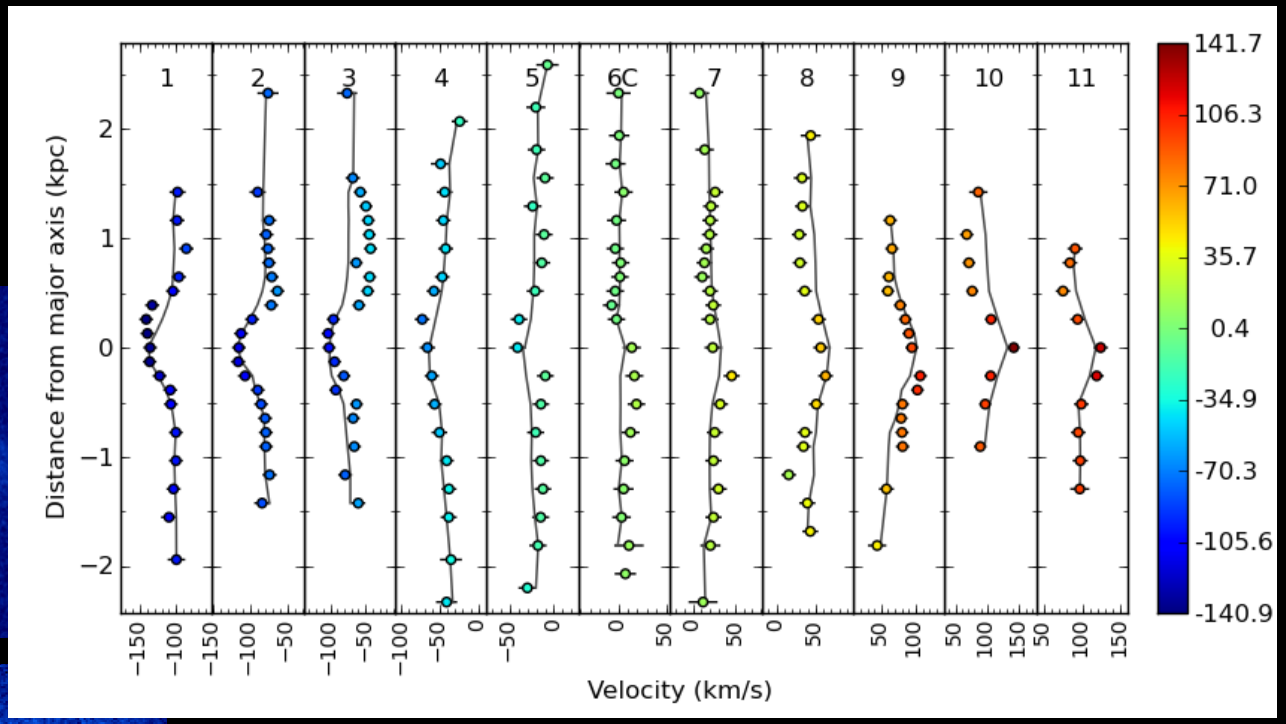
Lag 6 – 9 km/s/kpc

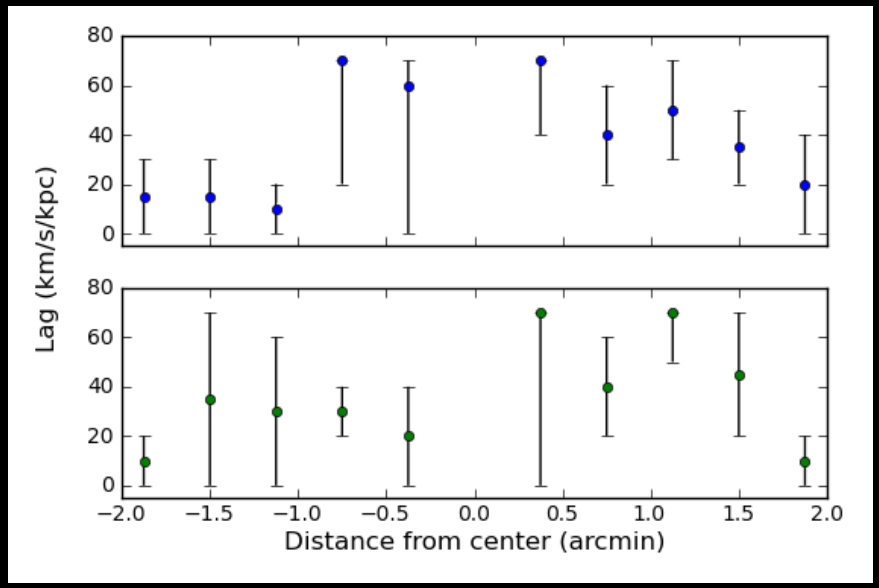


NGC 4517







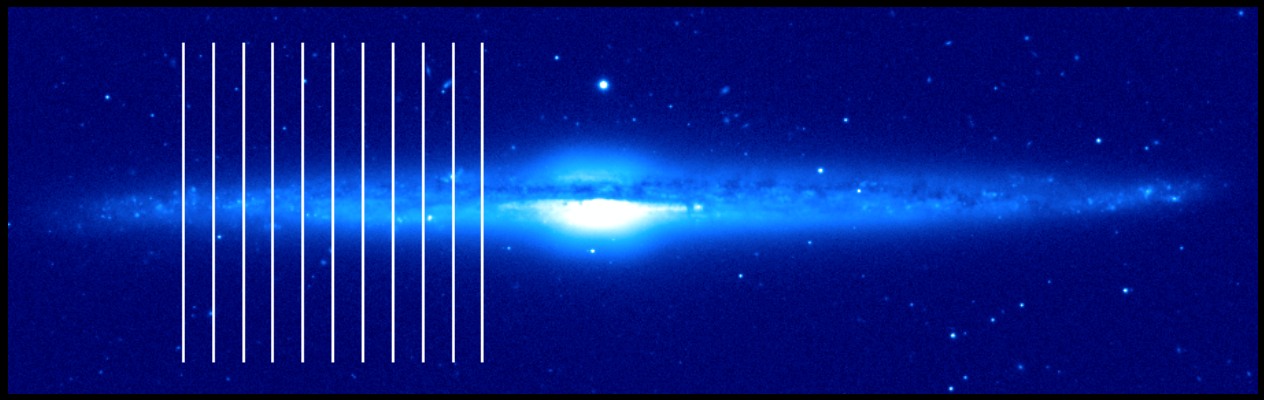


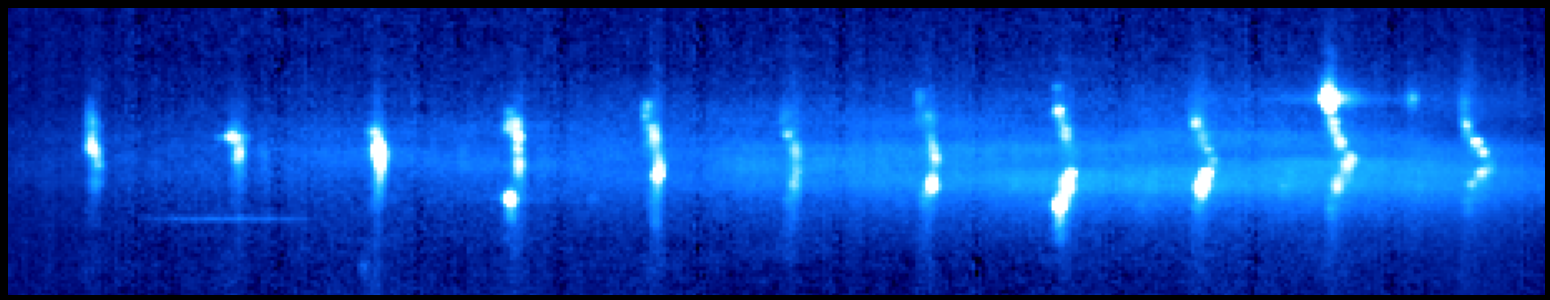
- Low SFR (0.5)
- v_{rot} 140 km/s
- EP studies?

- Inc 87.4^{o}
- Thin disk (150 pc)
- Thick disk (1 kpc)
  Radially varying lag

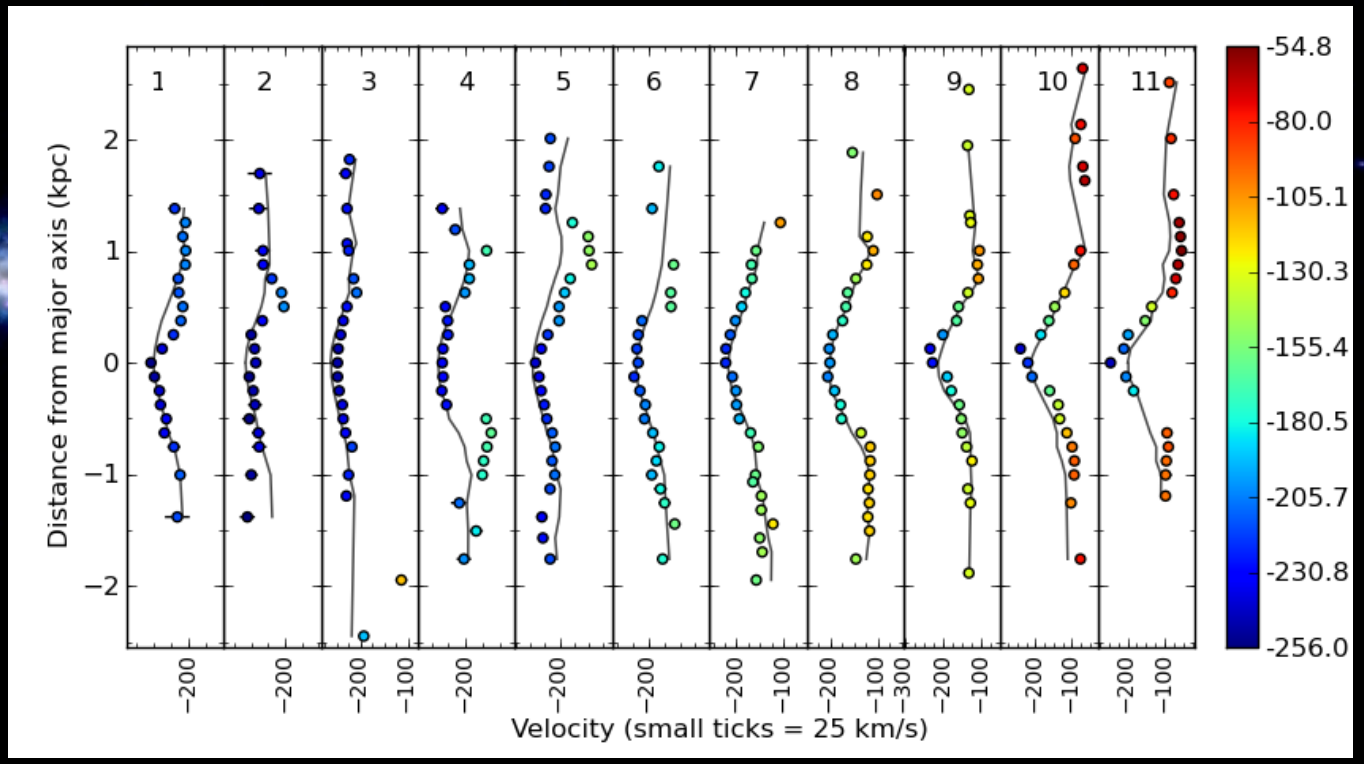
NGC 4565

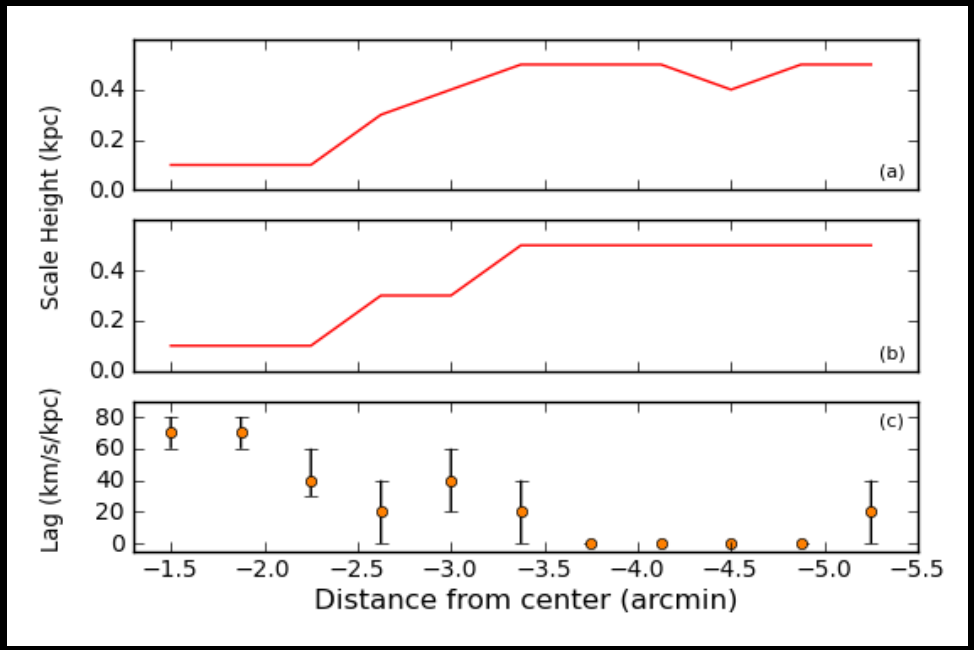
- Low SFR (0.5)
  (but soft X-ray halo)
- No extended HI or HII
- HI shows a lag
- v_{rot} 245 km/s





NGC 4565

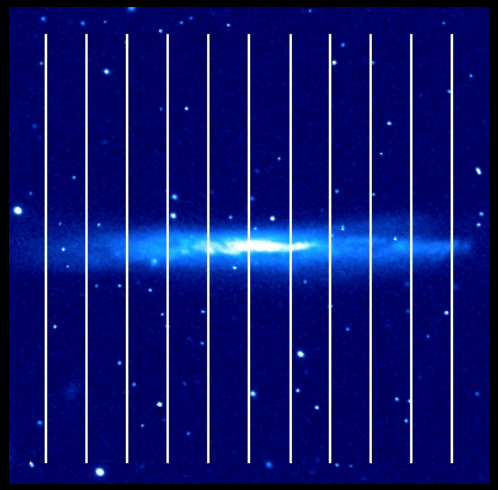




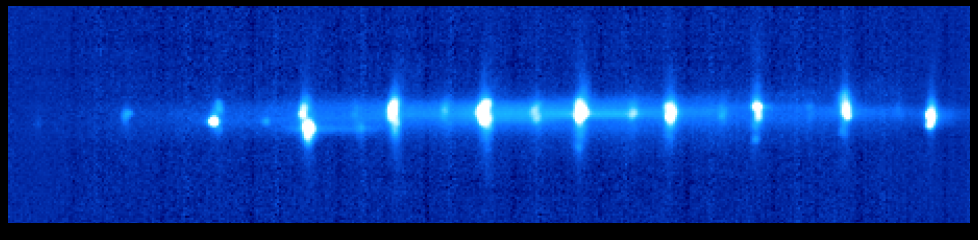
2-component model:

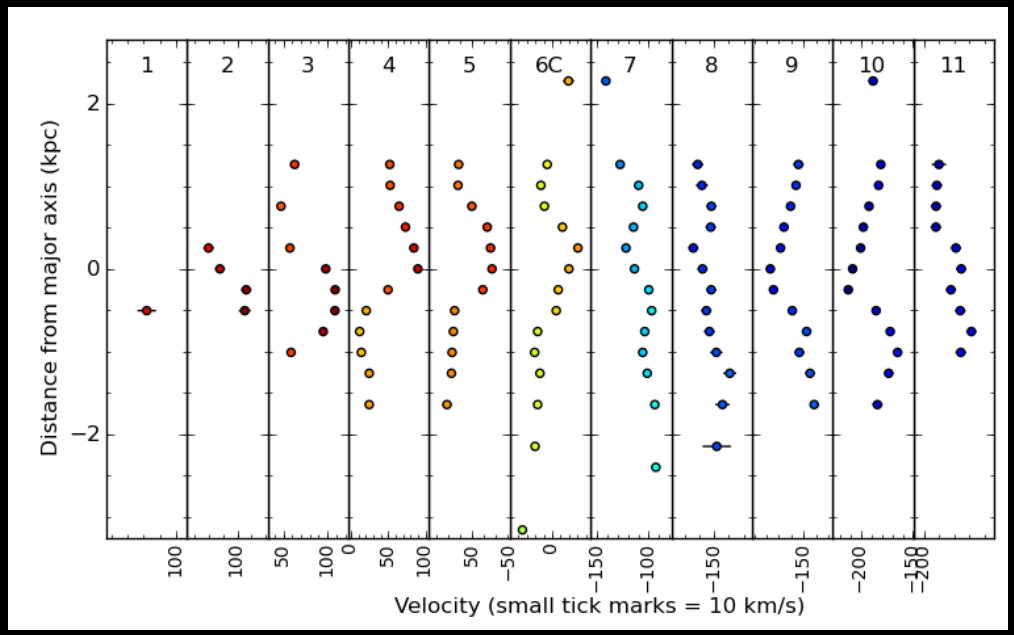
- Thin – flare
- Thick
  radially decreasing lag
- Both match HI models

NGC 3044

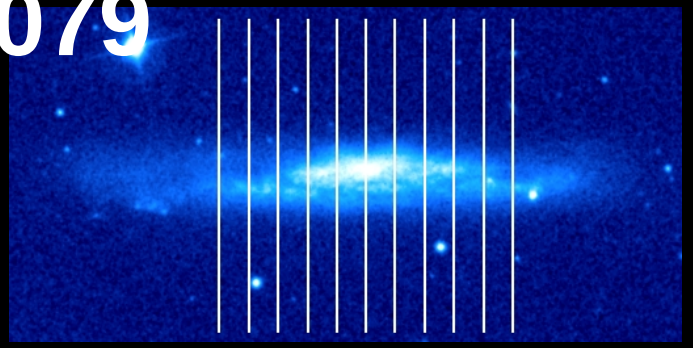


- Lag?
- 85º
- High SFR (3.3)
- Not interacting

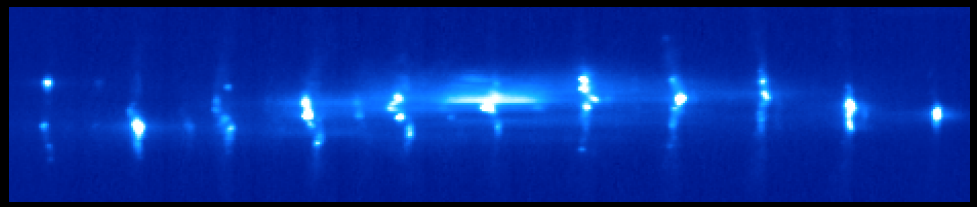


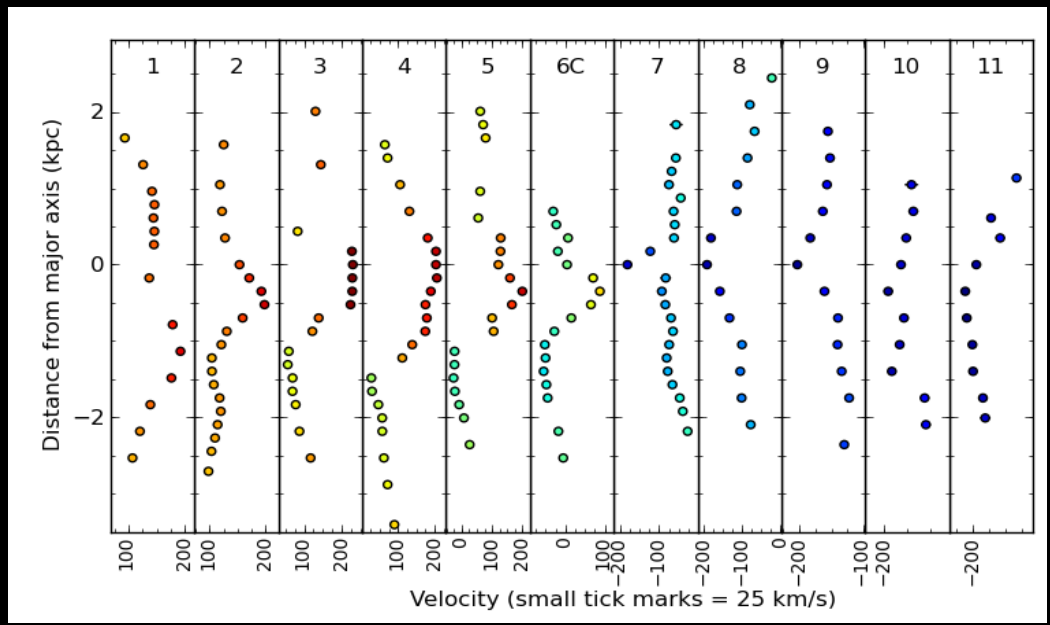


NGC 3079



- Lag?
- 88º
- Highly SFR (8.9)
- LINER/Seyfert
- May be interacting





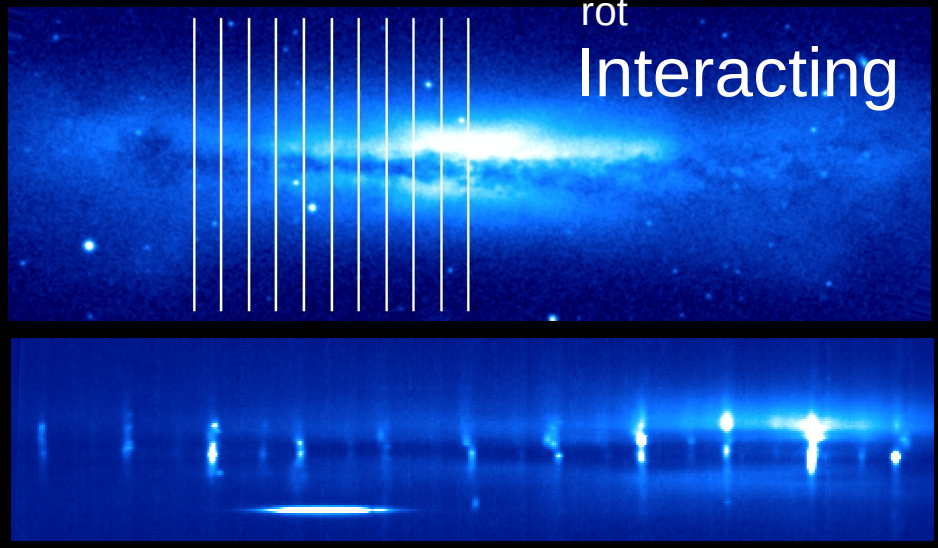
Non-lagging EP Gas

NGC 3628

High SFR (2.0)

v_{rot} 212 km/s

Interacting

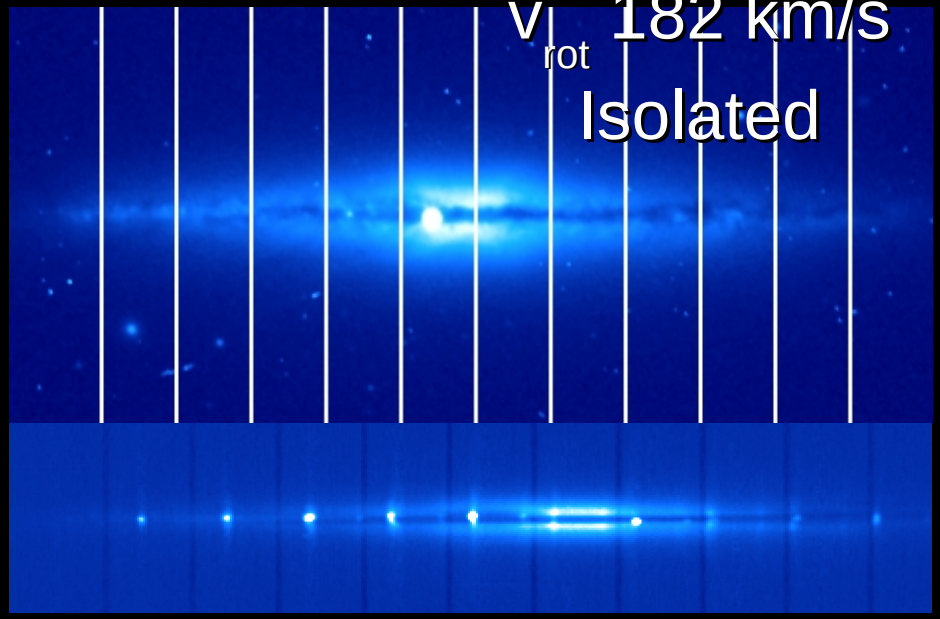


NGC 4013

High SFR (2.7)

v_{rot} 182 km/s

Isolated



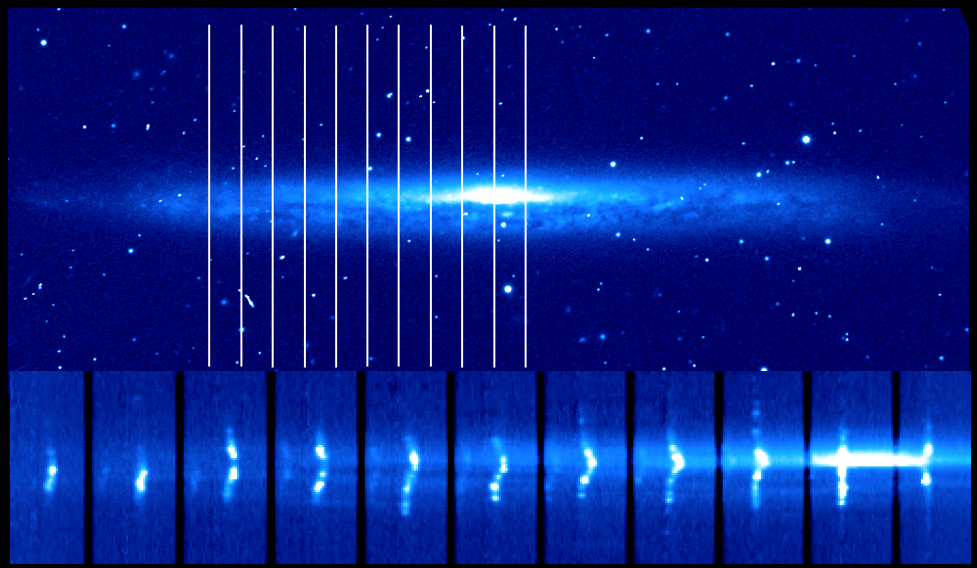
NGC 5907

Low SFR (0.8)

v_{rot} 227 km/s

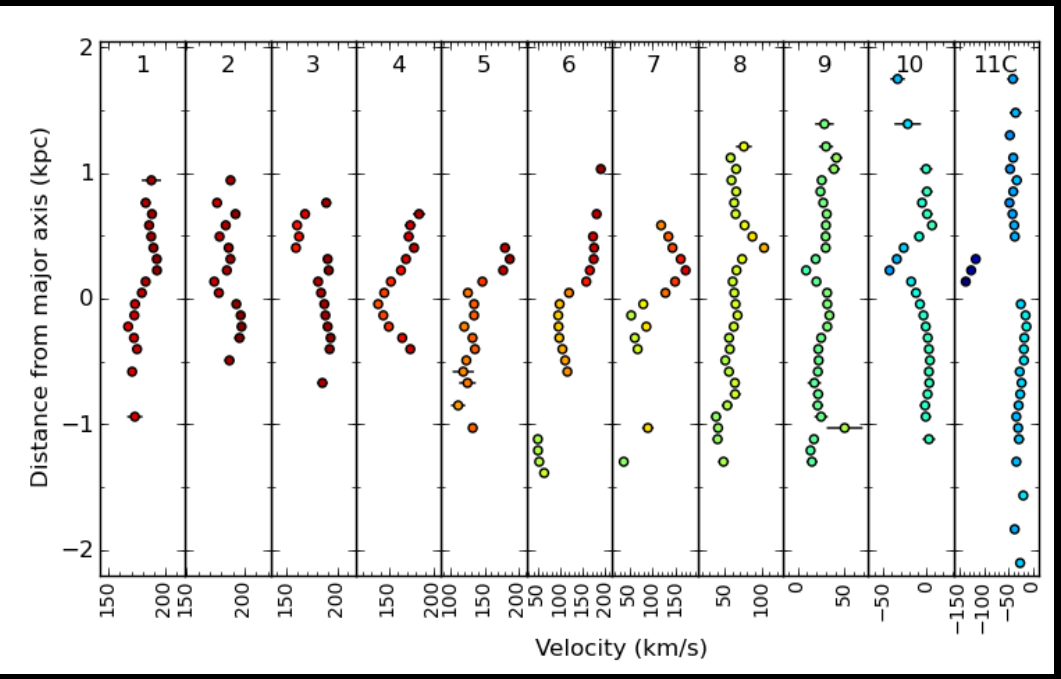
Isolated

Extended stellar streams

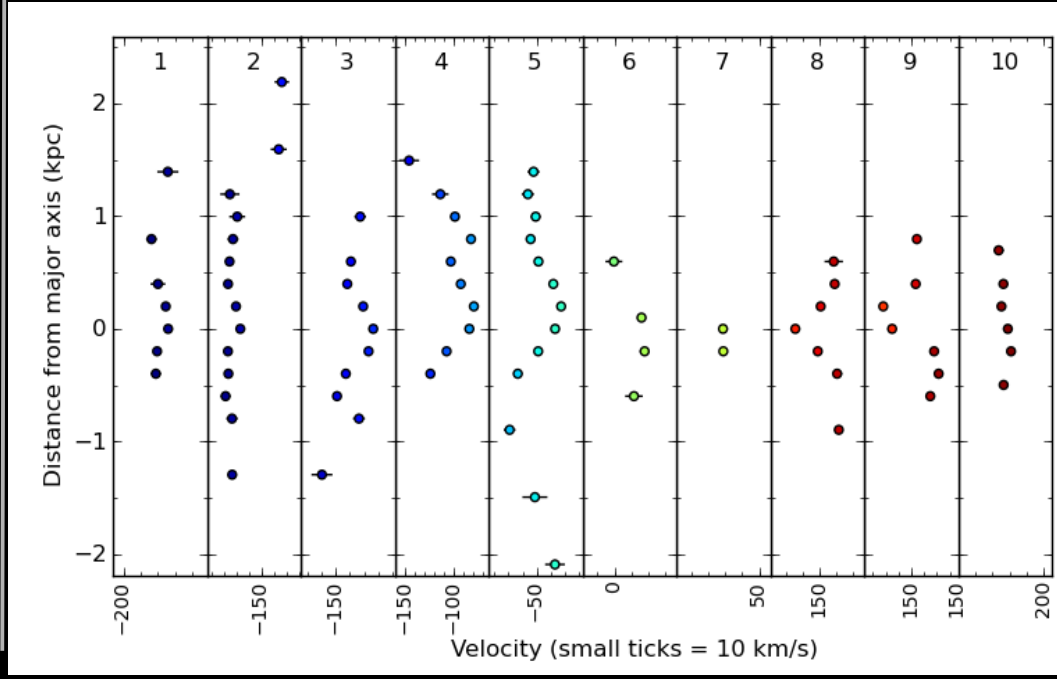


Non-lagging EP Gas

NGC 3628

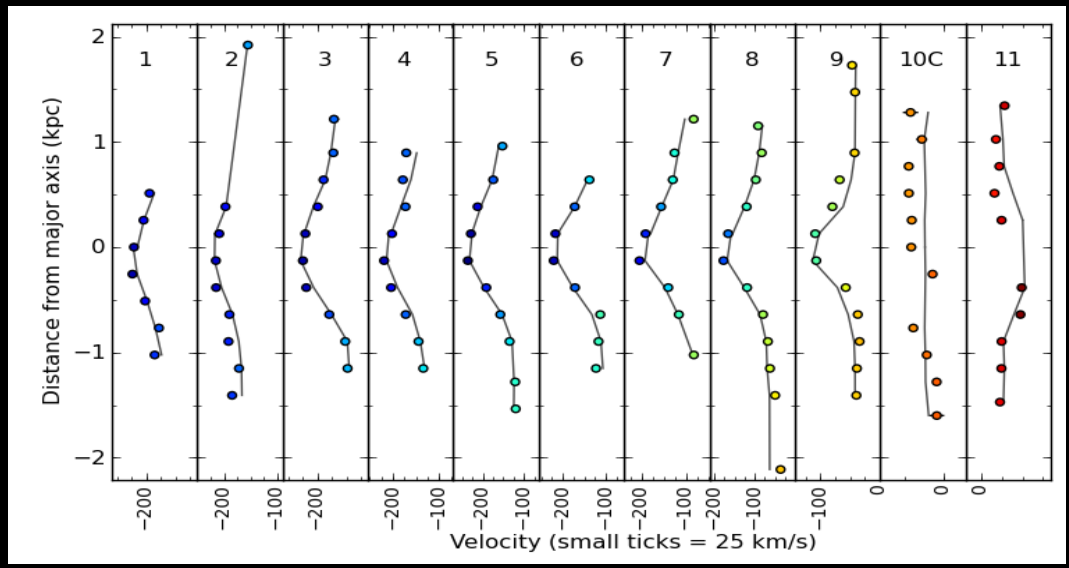


NGC 4013



NGC 5907

Models:
Thin disk, 87º

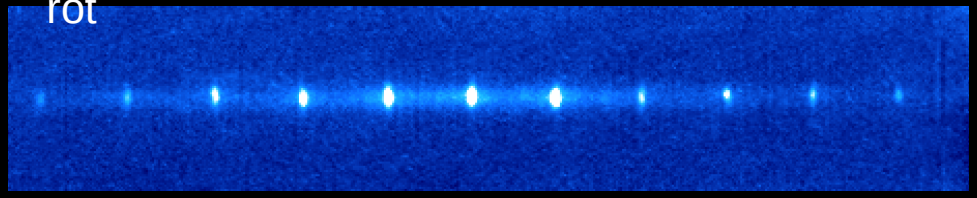


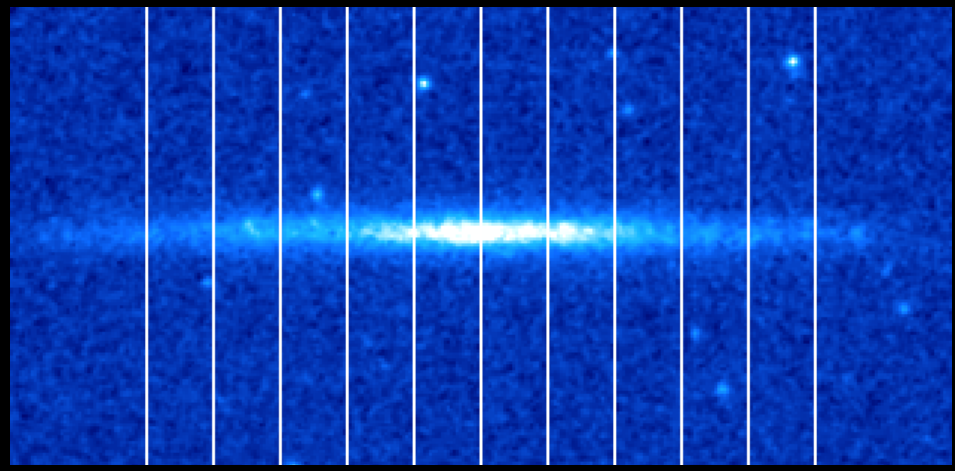
No EP Gas

UGC 7321

SFR (0.03) • Thick HI disk

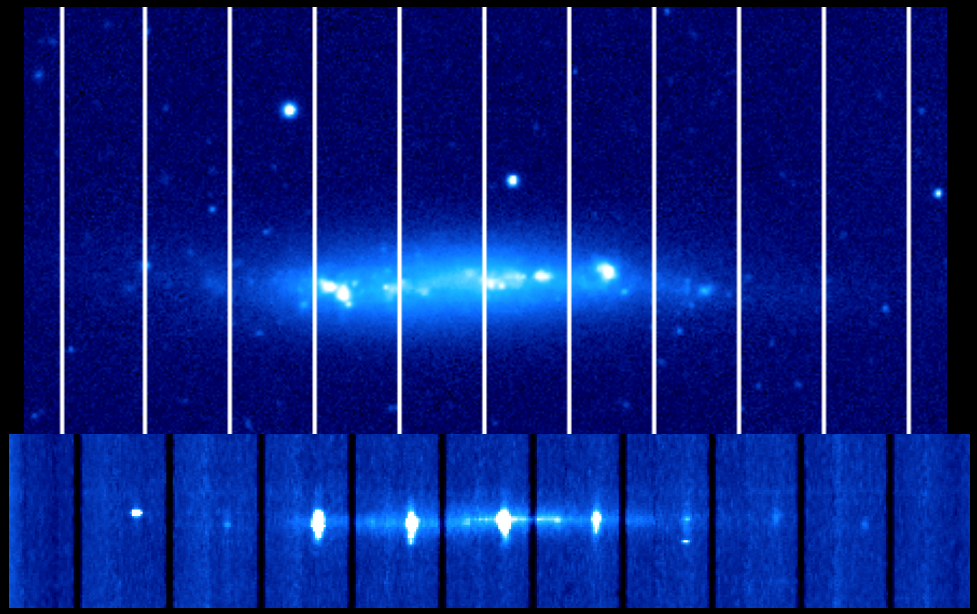
v_{rot} 95 km/s • Isolated





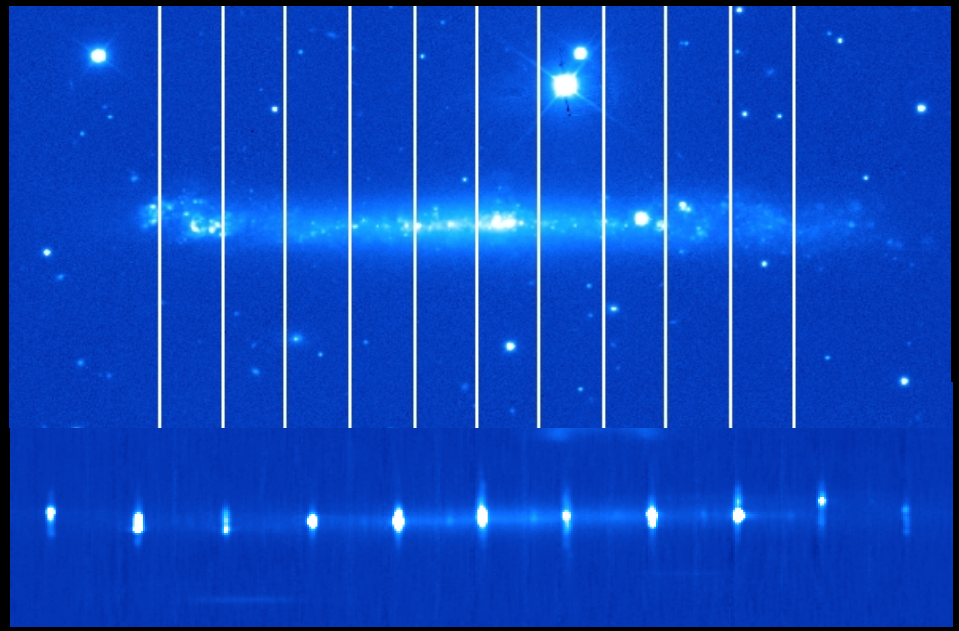
NGC 5229

SFR (>0.1) • v_{rot} 56 km/s



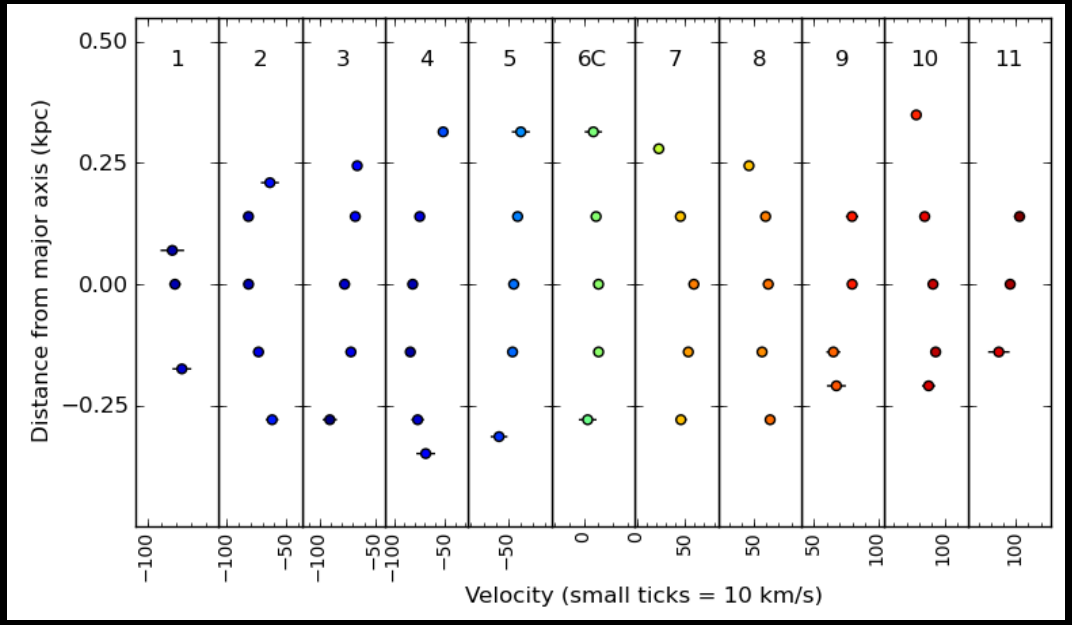
UGC 4278

SFR (0.2) • v_{rot} 79 km/s

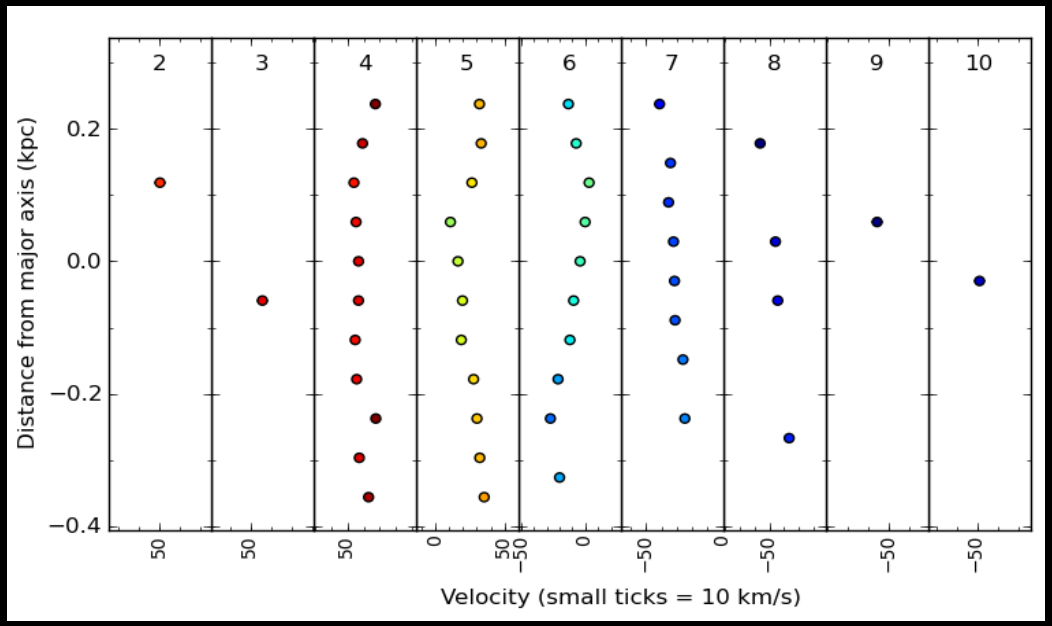


No EP Gas

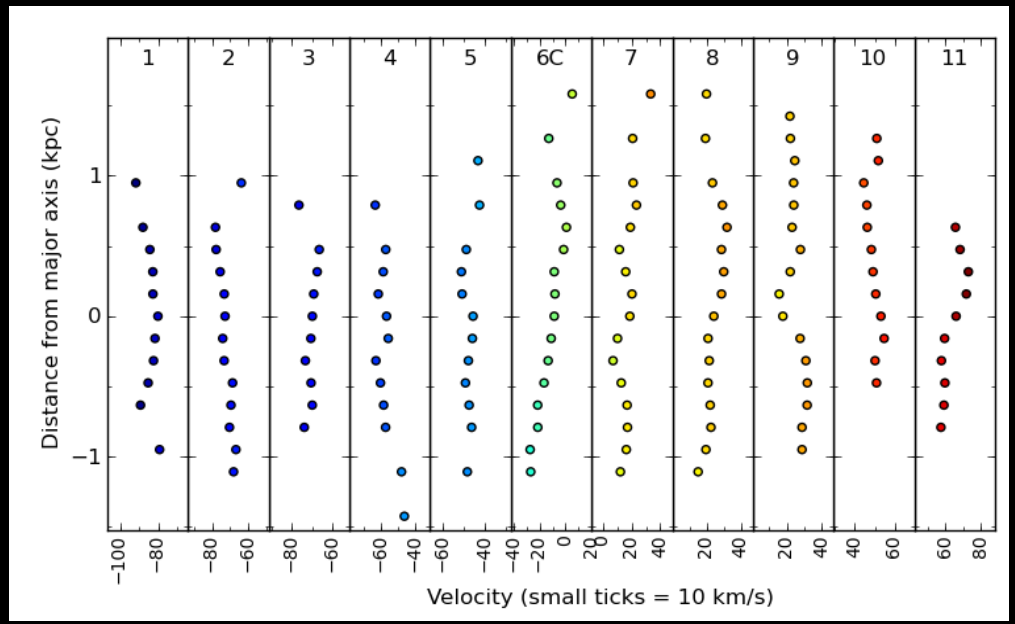
UGC 7321



NGC 5229



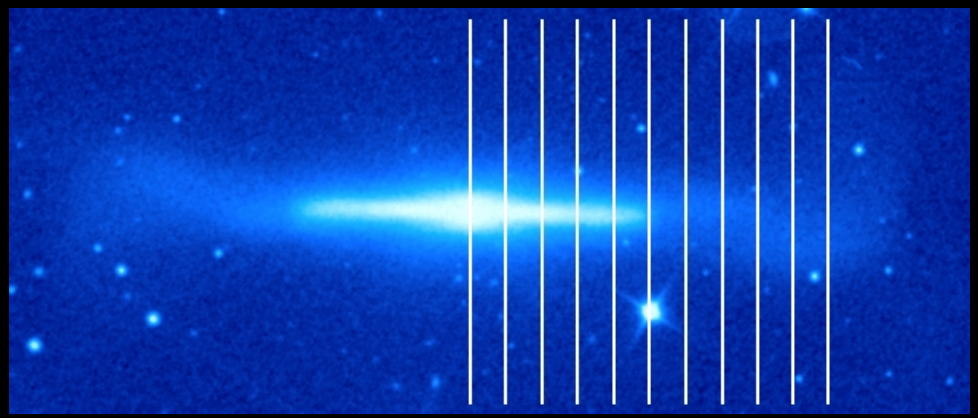
UGC 4278

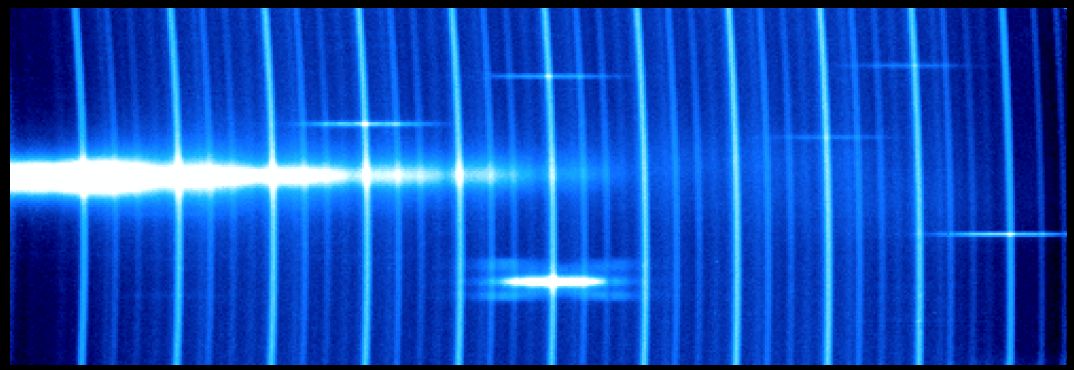


NGC 5229

UGC 4278

NGC 4762





Sample Conclusions

EP gas:

- 4 galaxies with a lag (891, 4517, 4565, 4631)
- 2 'maybe' galaxies (3044, 3079)
- 3 with no lag (3628, 4013, 5907)

No EP gas:

- 3 with no EP gas (4278, 5229, 7321)
- 1 non-detection (4762)

Sample Conclusions

- NGC 891, 4517, 4565:
  lags 15-20+ km/s/kpc
  galactic fountain + accretion

- NGC 4631:
  warped spiral arm (east)
  extreme lag/outflow (central)
  small lag (west) – galactic fountain alone

Sample Conclusions

	v_{rot} (km/s)	L_{FIR}/D_{25}^2 (10^{40} erg/s/kpc^2)	Hα extent (kpc)	Lag (km/s/kpc)	Interacting?
NGC 3079	208.4	8.9	3.50	?	Maybe
NGC 3044	153.1	3.3	3.00	?	N
NGC 4013	181.7	2.7	2.00	0	N
NGC 891	212.1	2.2	4.25	15-20	N
NGC 3628	211.7	2.0	2.00	0	Y
NGC 4631	138.4	1.8	3.50	outflow; 6-9	Y
NGC 5907	226.7	0.8	2.00	0	N
NGC 4565	244.9	0.5	2.50	70 → 0	N
NGC 4517	139.8	0.5	2.50	20-60	N
UGC 4278	78.9	0.2	1.50	-	N
NGC 5229	55.8	> 0.2	0.35	-	N
UGC 7321	94.5	0.03	0.35	-	N

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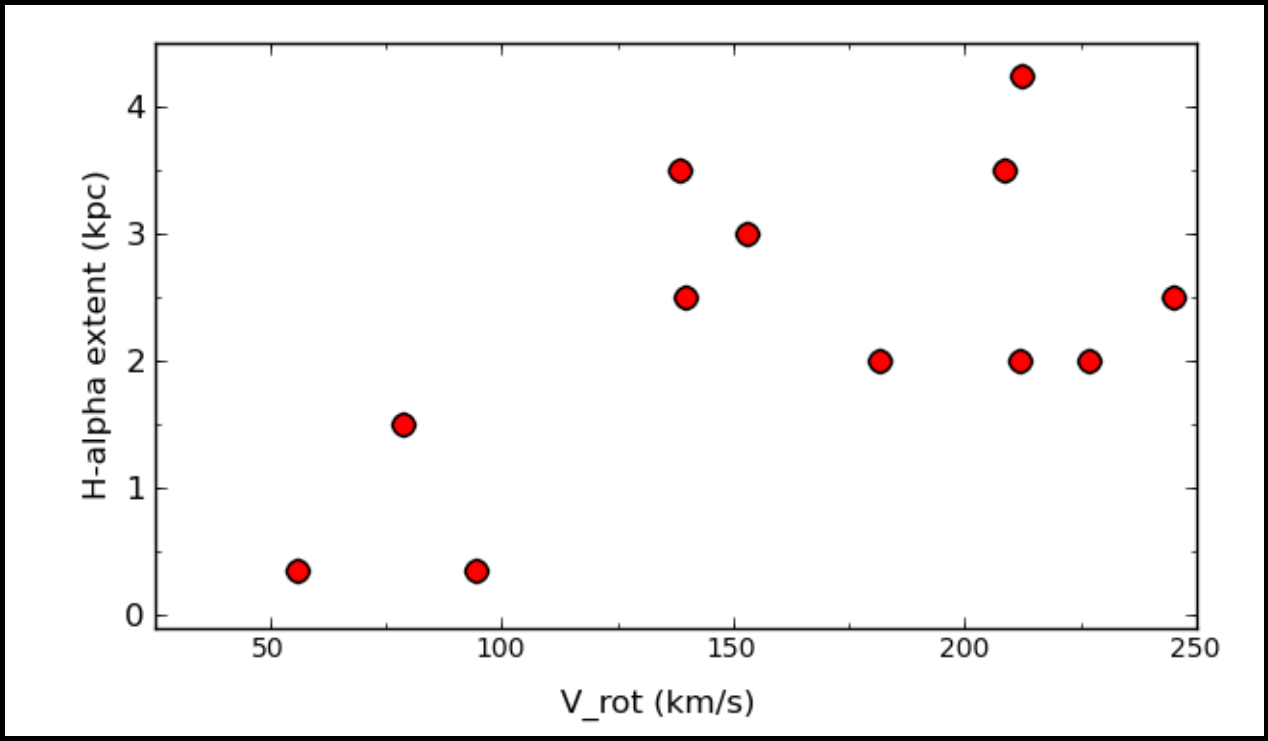
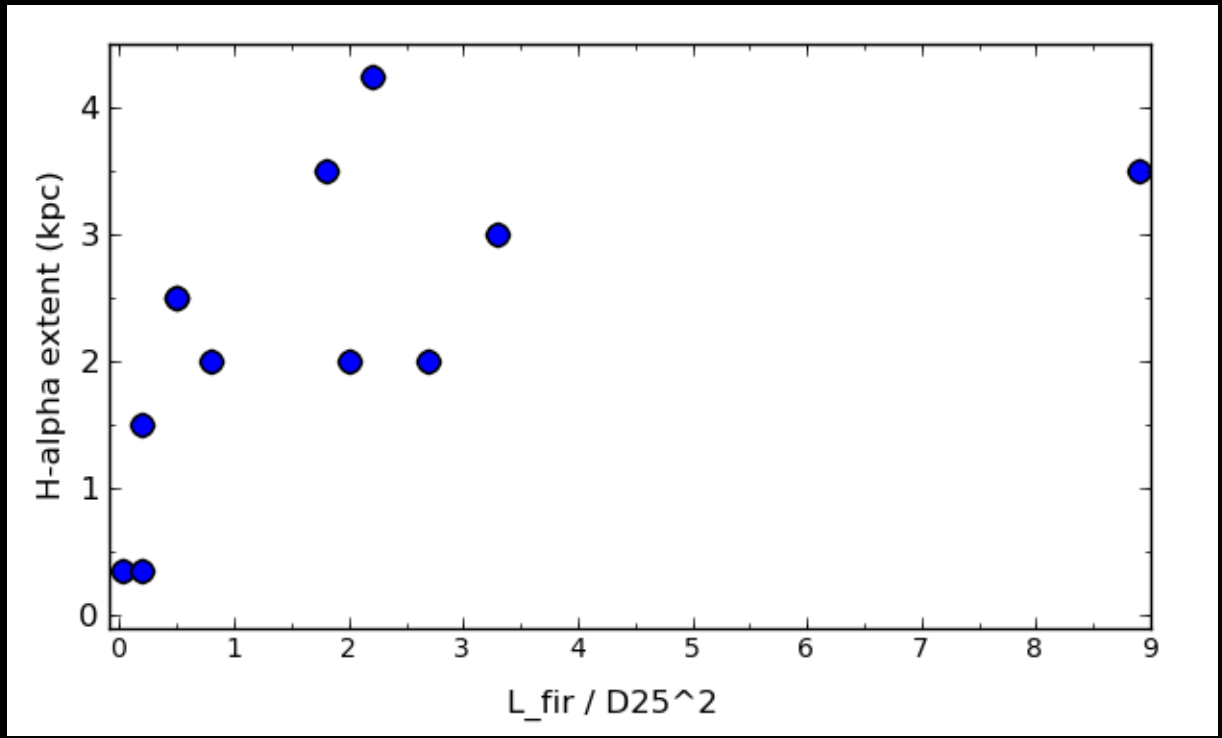


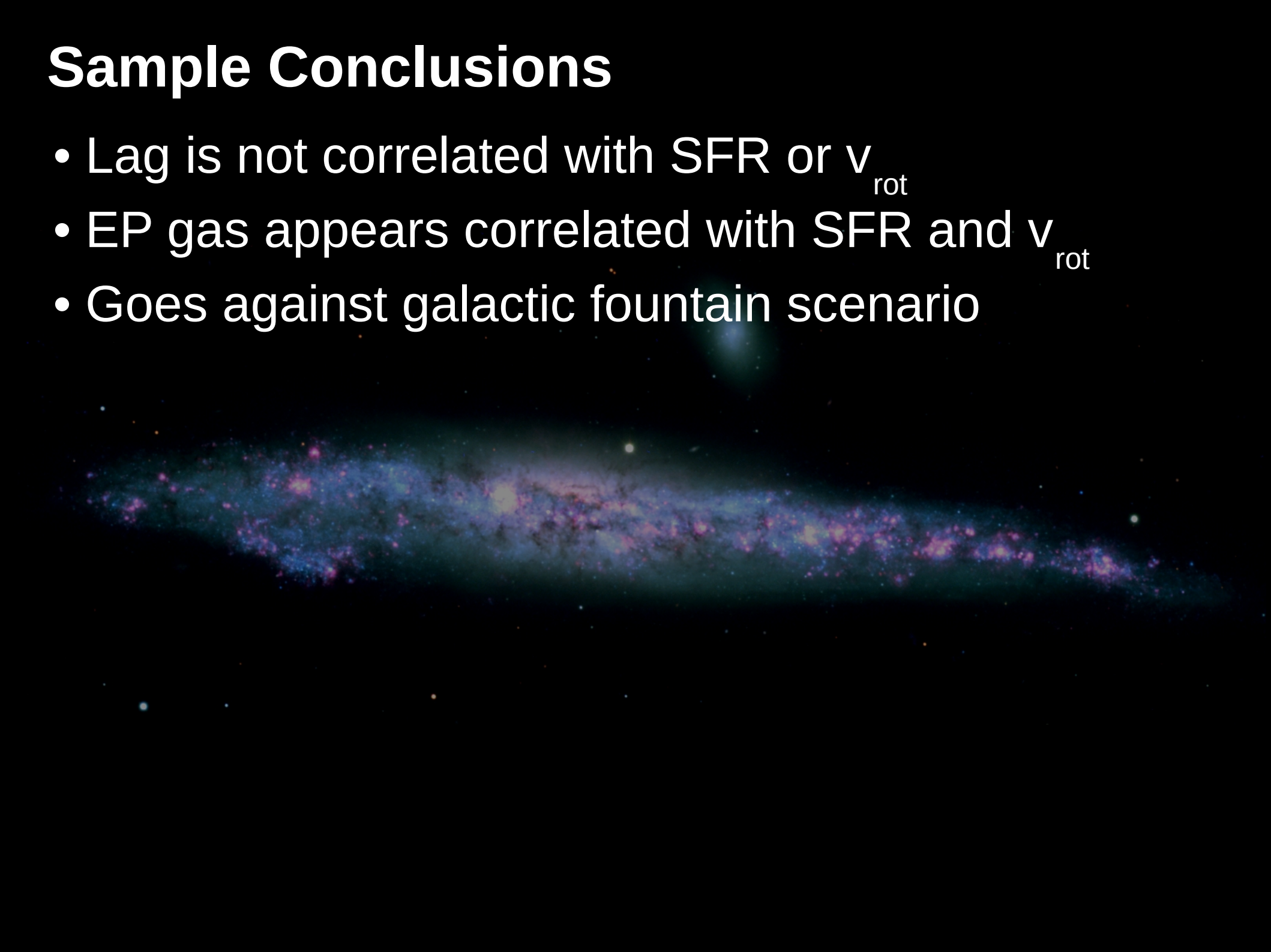
Hα extent vs. Rotation speed

Hα extent vs. SFR



Sample Conclusions

- Lag is not correlated with SFR or v_{rot}
- EP gas appears correlated with SFR and v_{rot}
- Goes against galactic fountain scenario



Sample Conclusions

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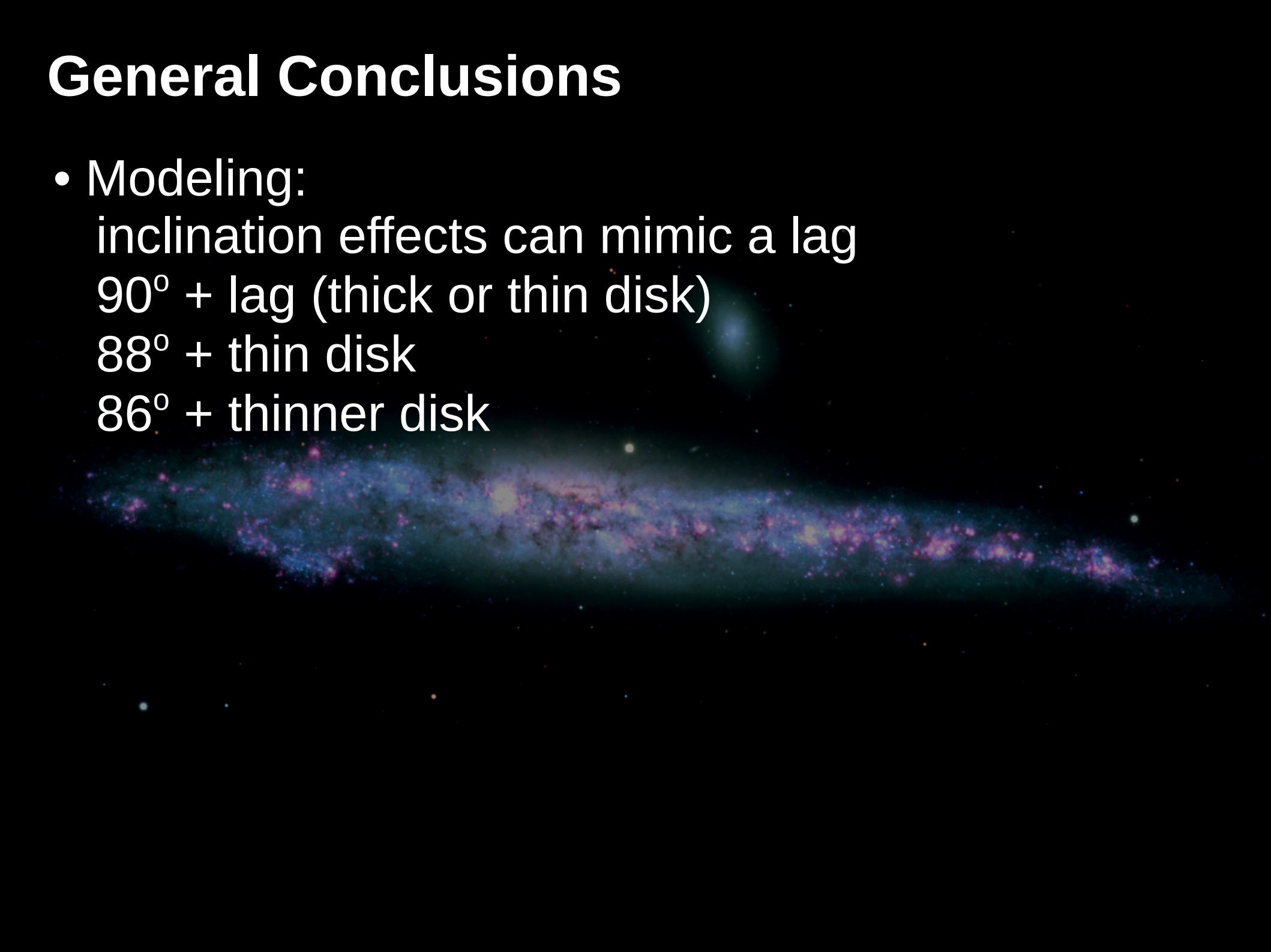
- Goes against galactic fountain scenario

- Mass distribution models + galactic fountain
  Jalocha et al. (2010)
  - large spheroidal mass component → small lags
  - disk-dominated potential → large lags

- EP gas, no lag:
  - Is 2 kpc not high enough to see a lag?
  - Bulge-dominated?
  - Kinematics of EP gas, constrain mass distribution

General Conclusions

- Modeling:
  inclination effects can mimic a lag
  90^{o} + lag (thick or thin disk)
  88^{o} + thin disk
  86^{o} + thinner disk



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- Observations:
  multi-slit setup for kinematics of extended objects
  edge-on/inclined galaxies
  nebula
  detection instead of kinematics

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- Observations:
  multi-slit setup for kinematics of extended objects
  edge-on/inclined galaxies
  nebula
  detection instead of kinematics

- A good acronym?

Acronyms...

- HALOGAS – Hydrogen Accretion in LOcal GalaxieS
  PI: G. Heald
- CHANGES – Complete H-Alpha imaging of Nearby Group EnvironmentS
  PI: C. Haines
- THINGS – The HI Nearby Galaxy Survey
  PI: F. Walter
- LITTLE THINGS – Local Irregulars That Trace Luminosity Extremes THINGS
  D. Hunter
- GHASP – Gassendi H-Alpha survey of SPirals
  B. Epinat

Acronyms...

- MUlti-SLit IMaging Study – MUSLIMS
- APO MUlti-Slit Imaging of Nearby Galaxies – AMUSING
- MUlti-Slit Hα Imaging – MUSHI
- MUlti-Slit Technique Applied to Studies of Hα Emission – MUSTASHE

Summary

- Developed observing method and data reduction pipeline for multi-slit spectroscopic setup
- Developed software to model galaxies specifically for the multi-slit setup
- Observed sample of galaxies to look for lagging gas
- Detected a lag in 4 of 13 galaxies; 3 have no lag; 3 have no EP gas
- Found possible correlation between Hα and SFR

Conclusions

	v_{rot} (km/s)	L_{FIR}/D_{25}^{2} (10^{40} erg/s/kpc^2)	Hα extent (kpc)	Lag (km/s/kpc)
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ionized gas – source of ionization is OB stars; could be H gas everywhere...and we have flashlights that only show us that gas at certain points (ionized)