Spatially resolved studies of lensed galaxies

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Outline

• Introduction
  ✫ Lensing magnification and source reconstruction
  ✫ Reconstruction techniques
• Applications:
  ✫ Morphology of lensed galaxies at high redshift
  ✫ Source reconstructions at longer wavelengths
• Conclusions

• Spatially resolved kinematics

• Resolved abundances and metallicity gradients

• Conclusions and Perspectives
Advantages of magnification

- Increase of the observed angular size: better spatial resolution in the intrinsic source.

- Increase of total flux: better sensitivity.

The gain in resolution is anisotropic: along the shear direction it varies between $\sqrt{\mu}$ and $\mu$. 

\[ \mu = \frac{1}{\text{det } A} = \frac{1}{(1 - \kappa)^2 - \gamma^2} \]
Strong lensing and magnification effect

- Maximal magnification effect in the vicinity of the critical lines
- $\mu$ drops more quickly away from the critical line for more massive lenses / largest Einstein radii
- Cluster lenses provide the largest image plane area with a large magnification
Strong lensing and magnification effect

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- Cluster lenses provide the largest image plane area with a large magnification
Model of distant galaxy with multiple components and 2 star-forming regions separated by 500 pc.

Only with the combination of lensing and high resolution imaging can we reach spatial resolutions \(< 1\text{kpc}\) in distant galaxies.
Historically: first source interpretation of a giant arc

CL2244

First spatially resolved source interpretation from the identification of bright clumps in a giant gravitational arc

Hammer et al. 1989

Hammer & Rigaut 1989
Strong Lensing models: constraints from multiple images
Strong Lensing models: constraints from multiple images
Strong Lensing models: constraints from multiple images
Multiple images and resolution

- Magnification differences between multiple images give different source-plane resolution

- Increase signal to noise by averaging the reconstructions of the 3 brightest images

Colley, Tyson & Turner 1996
Multiple images and caustic crossing

For sources crossing the caustic line, the multiple images probe different parts of the source.

$z = 2.07$ lensed source crossing the cluster caustics in Abell 1835

Image plane (Richard et al. 2010)
Multiple images and caustic crossing

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$z = 2.07$ lensed source crossing the cluster caustics in Abell 1835

Image plane (*Richard et al. 2010*)

Source plane reconstructions:
For a given source redshift, the mass model of the lens potential(s) provide the geometrical transformation between the source and image plane positions \((x_i, y_i) = F(x_s, y_s)\).

This transformation can be used for a direct reconstruction on a regular source plane grid, using the surface brightness conservation.
Direct reconstruction

+ Straightforward calculation
+ No assumption on the source morphology

- Correlated source plane pixels at the highest resolution pixel grid
- Point Spread Function remains in the source plane

This technique gives useful results when the PSF is small (Adaptive Optics, Hubble images, good seeing) and when the image to reconstruct is isolated.
Parametric source reconstructions

- Based on empirical galaxy morphology, small number of parameters
- The source is a linear combination of elliptical Gaussian or Sérsic profiles
- Similar idea as the Galfit fitting software (*Peng et al. 2010*), but including the lensing effect.

\[
\Sigma(r) = \Sigma_0 \exp \left\{ -b_n \left[ \left( \frac{r}{r_e} \right)^{1/n} \right] \right\}
\]
Non-Parametric reconstructions: Adaptive grid

Semi-linear inversion technique (Dye & Warren 2005)

- Advantage: PSF taken into account, full minimization of lens and source properties

- Unregularised source: adaptive grid depending on magnification factor

- Regularised source: better resolution using best-fit model

\[ S = F^{-1} D. \]

\[ F_{ik} = \sum_{j=1}^{J} f_{ij} f_{kj} / \sigma_j^2, \quad D_i = \sum_{j=1}^{J} f_{ij} d_j / \sigma_j^2. \]
Adaptive grid: application

Dye et al. 2008: results on the ‘Cosmic Eye’
Resolved morphology
Resolved morphology

Current galaxy formation models assume that disk galaxies form by gas accretion (quiescent star formation), and then transform into spheroidal stellar systems mostly by major mergers (intense starbursts).

Predictions from numerical simulations: isolated (non-interacting) massive star-forming galaxies show a thick disk extending up to \( \sim 10 \) kpc with large clumps of \( \sim 10^9 M_\odot \) each, and sizes \( < 1 \) kpc.

*Dekel et al. 2009*
Non-lensed examples: observations

Luminosity and colors of all compact regions (bulges, bulge-like regions and star-forming regions) of extended sources in UDF ($r_e > 0.3''$).

Typical clumps have masses of $10^8 \, M_\odot$ at $z > 0.5$.

So-called ‘Chain galaxies’ and 'clump clusters' which are spiral galaxies in formation.
Non-lensed examples: SINS
Non-lensed examples: observations

*Law et al. (2011)*: morphological measurements of LBGs with HST/WFC3.

- Typical sizes of massive galaxies at $z = 1.5 – 3.6$ range within $r_e \sim 0.7 – 3$ kpc

- The stellar mass-radius relation is observed at $z \sim 3$ with an evolution as $\sim (1 + z)^{-1}$
Non-lensed examples: size evolution

Mosleh et al. 2012

Extrapolation: $r_e < 1 \text{ kpc at } z > 3$ (high mass) or $z > 2$ (low mass)
Overzier et al. 2007: predictions using local LBG analogs.

At $z > 1.5$ only the brighter clumps are resolved ($0.15'' = 1$ kpc)

Gravitational lensing is the only way to resolve multiple star-forming clumps in distant galaxies.
Spectacular source reconstructions:
RCSGA032727-132609

- 38 arcsec long
- Less-magnified counter-image

- Identified in the RCS2 cluster survey (*Gilbank et al. 2011*)
- Spectroscopic redshift $z = 1.7$ (*Wuyts et al. 2010*)
- High resolution HST imaging (*Sharon et al. 2012*) in 6 filters from F390W to F160W
Spectacular source reconstructions: RCSGA032727-132609

- NIRSPEC long slit observations of the highest resolution part (Rigby et al. 2011)
- Hα measured only on a small region of the source
One of the first giant arc discovered, first spectroscopic measurement $z = 0.7$ (Soucail et al. 1988)

Original mass models based on ground-based data used a triple-image configuration.
Richard et al. 2010

Refurbished Hubble ACS imaging: F475W, F625W and F814W

Improved resolution and color information show spiral galaxy crossing 2 caustics (regions with 1, 3 and 5 multiple images), with a red bulge and multiple blue star forming regions.
Morphology at high redshift: star-forming regions

Pello et al. 1999

Reconstructed clumpy morphology: star-forming regions spaced by a few kpc.

Morphology at high redshift: resolved clumps at $z \sim 5$

Swinbank et al. 2009

- Famous Franx et al. 1997 $z = 4.92$ galaxy
- 2 separate lens models and reconstructions agree on a very clump structure
- The brightest clumps are well-detected in [$OII$] line
Comparison with $z=2-3$

- Keck/OSIRIS observations of $z \sim 2 - 3$ sources (Jones et al. 2010)

- Combination of lensing + AO-IFU: $\sim 300$ pc resolution: EELT science!
How do we select clumps / star-forming regions?

- Define a single isophote above a background (e.g. 3σ) and find all local maxima \( (\text{Jones et al. 2010}) \)

- daofind IRAF task \( (\text{Förster Schreiber et al. 2011}) \): assumption on the size of the clumps to find (good for unresolved clumps with PSF size)

- clumpfind algorithm \( (\text{Williams et al. 1994}) \): use of multiple isophotes at different thresholds. No assumption on the clump shape or profile
Size-SFR diagram
Size-SFR diagram
Possible explanations, tests

Luminosities in the HII regions are $\sim 50 \times$ larger than in local spirals, but diameters are consistent with the Jeans length for support by velocity dispersion.

On the size-SFR diagram, star-forming regions in lensed galaxies show star formation rate densities much higher than local spirals, comparable with the most vigorous local starbursts. This offset in $\Sigma_{\text{SFR}}$ cannot be explained by the different resolution or sensitivity of low and high-redshift observations.

Possible explanations:

1. There are two discrete star formation processes, one quiescent and the other activated in turbulent disks such as those generated in galaxy mergers or by cold flows

2. A continuous trend might exist with redshift, in which star formation always occurs in a range of sizes, but selection effects mean that only the most intense regions are visible at high-z.
Narrow-band H\(\alpha\) imaging program

- Test *modes* of star formation at \(z = 0 - 2\): continuous or bimodal?
- WFC3 narrow band filters correspond to H\(\alpha\) for \(z \sim 1.0\) and \(z \sim 1.5\)
- Selection of 7 extended arcs with visible star-forming regions for H\(\alpha\) (narrow-band excess) measurement
- Resolution: down to 50 pc and 0.02 M\(\odot\)/yr for a star-forming region
size-SFR at $z=1$ (Livermore et al. 2012)
HII region LF

- Size-luminosity diagram: $z = 1 - 1.5$ galaxies are closer to local relation
- High-$z$ clumps similar to bright SF regions at $z = 0$ but more compact
- LF of HII regions compatible with predictions by Hopkins et al. 2011
- Evolution in luminosity and surface brightness are connected, due to the higher gas fractions and surface densities at high $z$
High $z$ morphology at $z \sim 7$

Highest resolution achieved on $z > 6.5$ dropouts.

Clumpy morphology with clump sizes $\sim 500$-1 kpc.

Zheng et al. 2009: Predominance of dual nuclei in very high-redshift galaxies?
Fu et al. 2012: Herschel-ATLAS submm galaxy at $z = 3.256$

Discovered with Herschel (unresolved) at a bright source at 500 $\mu$m. Followed-up with Keck (adaptive optics), and at millimeter wavelength (SMA and JVLA)
Long wavelength observations and source reconstructions
Results

- **Keck Adaptive Optics**: quadruply imaged galaxy in the K band, emission from the stars

- **Submillimeter Array**: 880 µm continuum of dust emission, 2 images

- **Jansky Very Large Array**: CO (1-0) molecular gas, 2 images

Offsets and size differences measured in the reconstructed source between the 3 components.

The lensed source is warm (\(T_{\text{dust}}\) 40-65 K), hyperluminous (\(L_{\text{IR}} \sim 1.7 \times 10^{13} L_\odot\)), starburst (2000 M_\odot/yr), similar intrinsically to unlensed \(z > 2\) SMGs.
Very bright 870 $\mu$m source at $z = 2.3$ lensed by the cluster MACSJ2135 (Swinbank et al. 2010), $\mu = 30$

EVLA and PdBI high resolution observations show a clumpy morphology with 4 unresolved regions (folded along the critical curve) in dust continuum and molecular gas.

These regions (on scales of $L_J \sim 400$ pc, are $10 \times$ denser than in local galaxies: hint for a highly turbulent ISM (Swinbank et al. 2011).
Radio Interferometry source reconstructions

$Bussmann$ et al. 2012

$z = 4.243$ H-ATLAS submm source, 2 lensing galaxies.

Parametric source reconstruction in the visibility plane of the SMA data (0.6” resolution) to prevent correlated noise in the ’cleaned’ image. Especially important for large beams and limited coverage in the uv-plane.
Conclusions

Gravitational lensing is currently the only way to resolve physical scales of $100 - 500$ pc in distant ($z > 1$) galaxies.

This technique can be used in morphological studies to:

- Measure the profile, shape, and resolve the SED of intrinsic sources, down to very low masses ($10^7 - 9 \, M_\odot$)
- Measure the physical properties of compact regions within these galaxies: star-forming regions and the formation of bulges
- Measure the offsets in multiwavelength studies between the stellar, dust and cold gas components

High redshift star-forming galaxies show a very clumpy morphology, with star-forming regions being even more concentrated in the past than local galaxies: this is certainly due to the higher gas fractions leading to higher star formation surface brightnesses.

Drawback: currently only small samples of extended arcs at $z > 2$ to study morphological trends against, e.g. stellar mass or gas fraction.
Integral Field Spectroscopy

- At each wavelength you get an image
- At each position you get a spectrum
Different IFU concepts

- **Lenslets**
  - Focal Plane
  - Spectrograph Input
  - Spectrograph Output
  - Pupil Imagery

- **Lenslets + Fibres**
  - Fibres

- **Slicer**
  - Mirrors

Datacube

\[
\lambda \rightarrow \text{Datacube} \rightarrow x, y
\]
Resolved kinematics
Resolved kinematics: motivation

Study **galaxy assembling** at $z > 2$: test early stellar formation of massive galaxies observed at $z = 1 - 2$

**Internal properties** of early galaxies, such as their dynamical state, chemical properties and the distribution of their star-forming regions, provide key tests of galaxy formation models.

**Analysing the dynamics** of high redshift galaxies enables to distinguish chaotic or well-ordered velocity fields, depending on the maturity of the systems.

**Integral Field Spectrographs** with Adaptive Optics (SINFONI, OSIRIS, NIFS) are currently the best instruments for these studies.

Genzel et al.
Forster-Schreiber et al.

Law et al.
IFU+AO observing procedure for $z > 1$ galaxies

Target selection:

- Known spectroscopic redshift, avoid contaminating OH lines and near-infrared gaps
- Estimation (or measurement) of total emission line flux
- Size of the IFU adapted to source size for sky subtraction
- Presence of a Tip-Tilt star for optimal AO (ex: $R < 18$ within 30'' for SINFONI)

Data analysis: spectral line fitting: $\lambda_0(x, y)$ (velocity field) and $\sigma(x, y)$ (velocity dispersion field)
A few kinematical models

(based on Epinat et al. 2009)

Projection effect: inclination $i$ and position angle $\theta$.

Exponential model:

$$V(r) = \frac{r}{r_0} \sqrt{\pi G \Sigma_0 r_0 (I_0 K_0 - I_1 K_1)}$$

Isothermal model:

$$V(r) = \sqrt{4\pi G \rho_0 r_c^2} \left[ \frac{r_c}{r} \ln \left( \frac{r}{r_c} + \sqrt{1 + \frac{r^2}{r_c^2}} \right) - \frac{1}{\sqrt{1 + \frac{r^2}{r_c^2}}} \right]$$

Plateau model:

$$V(r) = V_t \frac{r}{r_t}, \text{ for } r < r_t,$$

$$V(r) = V_t, \text{ for } r \geq r_t.$$}

'Arctan' model:

$$V(r) = V_t \frac{2}{\pi} \arctan \frac{2r}{r_t}$$
Epinat et al. 2010

Smearing effects due to the Point Spread Function (PSF), the Line Spread Function (LSF) and the discrete pixels.

- Seeing increasing from 0.125 to 0.5
- Null local velocity dispersion
- Decrease of the observed velocity gradient
- Central peak appearing in apparent velocity dispersion
Observational results: $z \sim 1.2$

50 galaxies of the MASSIV sample (Contini et al. 2012)
Observational results: $z \sim 2$

Forster-Schreiber et al. 2009

rotation-dominated

dispersion-dominated

merger

1'' (8 kpc)
Observational results

• $z \sim 1.3$ MASSIV (Epinat et al., 2012): 50% of the galaxies show rotation, 35% are dispersion dominated. Ionized gas turbulence $\sigma \sim 60$ km/s.

• SINS (Forster-Schreiber et al., 2009): $\sim 60\%$ of the galaxies show rotation, 25-30% are dispersion dominated. Non-rotating objects support cold gas accretion.

A consensus is not reached on the interpretation of the kinematics.

One clear evidence: high redshift galaxies have higher velocity dispersion on average:

- $\sigma \sim 60$ km/s for MASSIV at $z \sim 1.2$
- $\sigma \sim 60 - 90$ km/s for SINS at $z \sim 2.2$ and LSD/AMAZE at $z \sim 3.3$
- Lower $z$ galaxies have $\sigma \sim 20 - 40$ km/s.

However, at $z > 2$, current samples contain only very massive and high-SFR galaxies: how about more typical high $z$ galaxies?
Where gravitational lensing kicks in....

- For a given source redshift, lensing does not depend on $\lambda$
- Plane-by-plane source reconstruction of the IFU datacube $F(x, y, \lambda)$
- But: PSF and LSF effects

$$
\sigma_{\text{measured}}^2 = [\sigma_{\text{intrinsic}} (1 + z)]^2 + \sigma_{\text{LSF}}^2 + \sigma_{\text{smearing}}^2
$$
Reconstruction of a lensed datacube: include velocity fields in the Bayesian optimisation, assuming all regions of the lensed galaxy share 1 velocity field.

2 steps optimisation:

1. optimise location, shape and total line flux of each clump from the collapsed cube and/or high-resolution image (HST) including PSF

2. optimise velocity field parameters ($\lambda_c$, $x_c$, $y_c$, $i$ or $e$, $\theta$, $r_t$, $v_t$, $\sigma_0$) including LSF+PSF and pixelisation from the full cube and its variance
Early IFU lensed studies

Sample of $z \sim 1$ lensed galaxies: evolution of the Tully-Fisher relation.

Swinbank et al. 2006
• Found in MACS2135 HST snapshot, z=3.07 (Keck) Smail et al. 2007
• Lyman-Break Galaxy, brighter than CB58, strong emission lines in rest-frame optical
• Further follow-up: HST (PI: Richard), CO (Coppin et al. 2007), lens model (Dye et al 2008), Spitzer/IRAC-MIPS-IRS (Siana et al. 2009)
• Simultaneous discovery of other lensed LBGs in SDSS: the 8 o’clock arc, the ”cosmic horseshoe”, the clone, etc...
Cosmic Eye interpretation

- Strong $[O II]$, H$\beta$, $[O III]$ detected, with biconic velocity field and FWHM peak at the centre, suggesting rotation

- $v_c=54\pm7$ km/s, $M_{dyn}=5\times10^9\ M_\odot$ (<1.8 kpc)

- Nature: rather than a major merger, 2 clumps formed by fragmentation. Random velocities are significant
Resolved kinematics: a small sample

Jones et al. 2010: OSIRIS+AO observations of 6 lensed galaxies
Resolved kinematics: extracted velocity field

Extraction of velocity field and velocity dispersion profiles along the kinematical gradient. 5 / 6 galaxies are isolated and the velocity fields are well-fitted by a rotation curve, 1 galaxy shows signs of a merger.

(almost) impossible to distinguish the resolved kinematics here without lensing!
RCS0224 high z kinematics
Swinbank et al. 2007

- $z=4.88$, magnification $\times 16$ ($\sim 3$ magnitudes), spreads over 15 arcsecs

- Kinematics from VIMOS ($\text{Ly}\alpha$, SiII) and SINFONI ($[\text{OII}]$)

- No adaptive optics. Seeing VIMOS: 0.8”. Seeing SINFONI: 0.6”
RCS0224 interpretation

- Lyα more extended and shifted in velocity by +200 ± 40 km s\(^{-1}\) from the ionized gas ([OII] emission)

- UV absorption lines offsetted by -400 ± 100 km s\(^{-1}\)

- Suggests the presence of superwinds linked with star formation
MS1358 high z kinematics


- Famous $z = 4.92$ arc from Franx et al. (1997)
- L* LBG, amplified by $\mu \sim 25$, SFR$\sim40$ $M_\odot$/yr
- NIFS-IFU: [OII] line emission + long slit optical spectroscopy.
- Kinematics results show a similar result to RCS0224
Eyelash: resolving a bright submm galaxy

- Found with APEX/LABOCA when following-up the “cosmic eye”
- Not detected with HST, brightest far-infrared / submm galaxy (800 mJy at 300\(\mu\)m)
- \(z = 2.3\) confirmed with CO, now 11 CO transitions covered and some resolved (Danielson et al. 2010)
Detailed observations with PdBI (CO 6-5) and EVLA (CO 1-0) at 100 pc resolution.
Velocity field and 'Butterfly diagram'

- Detailed observations with PdBI (CO 6-5) and EVLA (CO 1-0) at 100 pc resolution
- 'Butterfly' shaped position-velocity diagram showing symmetry
- Observed CO structures coincide with continuum-detected clumps from SMA
Resolved abundances
Resolved abundances and metallicity gradients


Variation of radial abundance gradients (metallicity gradients) with time is sensitive to galaxy formation history.
Metallicity gradients at high redshift

Measurements are challenging!

- Obtaining sufficient spatial resolution is difficult
- Must rely on strongline metallicity estimates
- HII regions blended with AGN and shock emission

Typical nebular line ratios diagnostics for abundances:

\[
\frac{[OIII]}{[OII]}, \frac{[NII]}{H\alpha}, \text{R23} ([OII], [OIII], H\beta)
\]
AGN contamination

AGN activity can mimic a strong metallicity gradient.

But we can identify AGN from the BPT diagram (Wright et al. 2010)
Shocks contamination

Shocks dominate at large radii and can mimic a metallicity gradient
Metallicity gradients at $z \sim 1.2$

Queyrel et al. 2011

Metallicity gradients in the MASSIV survey ($z \sim 1.2$): dominated by flat or increasing radial gradients.
Gradients at $z = 3$

LSD and AMAZE samples: 'evolution' of mass-metallicity at high $z$

Maiolino et al. (2009), Mannucci et al. (2009)

Cresci et al. (2010) measured positive metallicity gradients in large massive $z \sim 3$ galaxies using $\text{H} \beta$ and $\text{[OIII]}$
First lensed metallicity gradient measurement

OSIRIS + AO observations of the ‘clone’ arc (Lin et al. 2009) at $z = 2$. 

Jones et al. 2010b
Clone results

Gradient of decreasing metallicity seen from $\frac{[\text{N}II]}{H\alpha}$ and $\frac{[\text{OIII}]}{H\alpha}$

Supports a scenario of inside-out galaxy formation.
A grand-design spiral at $z = 1.5$

Yuan et al. 2011

- Lensed face-on spiral galaxy at $z = 1.5$ (Smith et al. 2009)
- Magnification $\sim 22 - 25$, relatively isotropic
- Keck/OSIRIS measurements of H$\alpha$ and [NII] line emission
A grand-design spiral at $z = 1.5$

Yuan et al. 2011

- Observations of H$\alpha$ and [NII] in MACS1149 $z = 1.5$
- Measurement of a gradient of decreasing metallicity from the center, less steep than the 'clone'
- Results in apparent contradiction with Cresci et al. 2010, but lower mass / SFR and more robust emission lines
Jones et al. 2012
4 lensed galaxies, observed with Keck/OSIRIS + AO
$z = 2.0 - 2.4$
0.5 - 4 hours in H\textalpha, [NII], [OIII], H\beta
- 3 galaxies isolated and rotating; 1 merger
- High velocity dispersion:
  \[ \frac{V}{\sigma} = 0.8-1.4 \]
- Gravitationally unstable.
  Toomre parameter \( Q \simeq 0.6 \)
Each point is an individual OSIRIS pixel. All regions are consistent with photoionization by massive stars. No strong shocks or AGN detected.
Interpretation

The graph shows the metallicity gradient (dex/kpc) against central metallicity (12+log(O/H)) for interacting and isolated galaxies. The data points are labeled as follows:

- **Rupke et al.**
- **Vila-Costas & Edmunds**
- **Rich et al.**
- **Considere et al.**

For interacting galaxies:
- **MACS J1149 z=1.5**
- **MASSIV z=1.2**
- **z=2.2 arcs (this work)**

The graph illustrates different types of gradients:

- **Steep gradient**
- **Flat gradient**
- **Inverted gradient**

The data points are color-coded to indicate the different studies and are accompanied by error bars to represent the uncertainty in the measurements.
Interpretation

- Need to compare appropriate galaxies at different redshifts.

- Determine host halo mass, and compare the same halos at different cosmic times. (Statistical description of gradient evolution)

- Halo mass estimated from stellar mass: $M^*/M_{\text{halo}}$ relation (e.g. Moster et al)

- Halo growth known from merger trees in Millennium simulations
Evolution of average metallicity gradients is consistent with expected radial growth: $R \propto (1 + z)^{-1.27}$ (van Dokkum et al. 2010)
A2667 triply-imaged arc

Yuan et al. 2012

- $z = 1.03$ giant arc in the lensing cluster Abell 2667

- Reconstructed morphology show clumpy morphology with color differences

- Face-on clumpy disk or merger?
A2667 triply-imaged arc: presence of shocks

- $[\text{NII}] / H\alpha$ measured in different parts of the source
- Enhanced $[\text{NII}] / H\alpha$ in the outskirts (B)
- Compatible with a shock model. Galactic winds?
Conclusions

- Integral-field studies of distant galaxies are now providing key diagnostics of dynamical states of galaxies, such as $v/\sigma$, distribution of star-formation, role of mergers.

- Coupling with gravitational lensing, source-plane studies can reach $\sim 100$ pc resolution and resolve the kinematics and abundance gradients in less massive galaxies.

- Coupling nebular lines with UV ISM lines (and Ly$\alpha$) also allows spatially resolved studies of feedback in young galaxies: measuring the energetics of the winds.

- A high fraction of isolated galaxies at $z = 2$ have steep and negative metal gradients.

- Gradients decrease by a factor $2.6^{\pm}0.9$ between $z = 2.2$ and $z = 0$ Consistent with radial size growth.
1x1 arcmin$^2$ IFU 4600-9600 Å: well adapted to cluster cores!
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A grand-design spiral at $z = 1.5$

A grand-design spiral at $z = 1.5$

More gradients

BPT diagram

Interpretation

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