

Question: What is PRISM?

PRISM is a space mission concept submitted to ESA in answer to the call for science themes for the second and third Large class missions of the Cosmic Vision programme. If selected, PRISM will revolutionize our knowledge in several areas of astrophysics and cosmology.

For instance, PRISM will bring us a complete census of matter, hot gas, and dust in the entire observable universe; it will, in particular, detect all galaxy clusters more massive than 5×10^{13} solar masses. It will also detect, via their imprint on CMB polarization, the elusive primordial gravitational waves generated by a wide range of inflation models. It will shed light on cosmic and galactic star formation, detect energy exchanges between radiation and matter throughout cosmic times, and much more!

Question: Why should this mission be selected by ESA as one of its next L-class missions?

SCIENCE: The science program of the PRISM mission is exceptional. The planned observations will achieve transformational science in not *one*, but *several* areas of astrophysics and cosmology.

SIMPLICITY. The PRISM mission concept has no complex critical element that puts the mission at a risk. The mission is expensive and hence fits only in an L-class budget, but is not technologically risky.

FLEXIBILITY. The mission can be ready for either 2028 or 2034. The performance of its various subsystems can be adjusted for the best compromise between cost and science within the timeline of their development.

TIMELINESS. With Herschel and Planck, Europe has trained a generation of young scientists that are now ready to prepare the next millimetre-wave to far-infrared space mission. Recent technological advances make it possible to launch PRISM for breakthrough science as early as 2028.

LEGACY. PRISM will not only bring long-awaited answers to crucial scientific questions. It will also deliver an unmatched set of observations of the entire sky that will be used in all branches of astronomy for decades to come.

Question: What is the biggest technological challenge for the PRISM mission?

There is none that would put the mission at risk.

The performance goals are ambitious. They translate into the requirement of actively cooling a large telescope in space. There is, however, flexibility on the size and temperature for the best compromise between science, feasibility, and cost.

Question: Some CMB observers are confident that the CMB polarisation B-modes can be detected from the ground before PRISM is launched. Could PRISM be scooped of

one of its main science objectives?

Short answer:

The *lensing B-mode* spectrum will be measured on small scales from the ground, but getting large, high quality maps of the lensing potential requires a space mission with a large telescope. As far as *primary B-modes* are concerned, the sensitivity of PRISM is about two orders of magnitude better than what can optimistically be achieved by sub-orbital experiments, and at least one order of magnitude better than what can be done with a small-scale CMB space mission. PRISM is optimally designed for both lensing and primary B-mode polarization, and if selected will have the final word on both of those science themes whatever happens.

Detailed answer:

Ground-based observations can reach high raw sensitivity by deploying very large focal planes of tens of thousands of detectors on a number of ground-based telescopes. It is a near sure bet that lensing B-modes will be directly detected on small scales with this type of observations, and that the lensing B-modes power spectrum will be measured. However, making clean maps of the lensing potential (and hence of matter distribution) from the ground will be hard.

Detecting primary B-modes will probably be even harder, and measuring them accurately is not feasible from the ground. A possible scenario, under the optimistic assumption that $r > 0.01$ so that the first B-modes acoustic peak is above the lensing contamination (an assumption by no means guaranteed), is that there will be a claimed detection from the ground at degree angular scales, that will require a confirmation from space. Ground-based experiments face formidable obstacles for a precise measurement of CMB polarisation on larger scales: systematic effects, and foreground emission. These intrinsic limitations cannot be overcome solely with the increased sensitivity achievable by deploying very large numbers of detectors from the ground. Clean observing conditions are required, that can only be obtained from space. For example, the important polarized foreground from interstellar dust cannot be observed with the required accuracy through the earth atmosphere. Moreover, ground spillover will always limit the performance of ground-based experiments at large angular scales, where the primordial B-modes signal lies. It should be noted that *all CMB temperature maps ever made from the ground or balloons have large-scale modes filtered out*. The situation is not likely to be any better for B-mode polarization, for which the target sensitivity to reach solely $r=10^{-2}$ is *three orders of magnitude down in amplitude* (six orders of magnitude in power)!

These intrinsic limitations are well known to CMB observers. This is clear from the number of proposed CMB B-modes missions in the past few years (SAMPAN in France, B-Pol and CORe at ESA, EPIC/CMBPOL, PIXIE in the US, LiteBIRD in Japan), which suggests considering statements about ground-based primary B-mode science with caution. People working from the ground are hedging their bets—for good reasons.

Competition from satellites (for instance the proposed PIXIE satellite in the US, and LiteBIRD in Japan) is a more plausible scenario (although none of these proposed missions is approved yet). Such small-scale CMB B-modes missions could reach $r > 10^{-3}$ on the basis of planned sensitivity. However, foreground emission is likely to degrade

the effective performance, because of lack of angular resolution (and hence of clean pixels on the sky) for PIXIE, and because of lack of frequency channels for LiteBIRD. Upscaling these missions to improve their performance is possible, but would increase their cost to a level significantly above what is currently planned. Implementing in addition a scheme for characterization of instrumental responses equivalent to that of PRISM, required to reach the best possible final sensitivity, would likely turn them into large-scale missions.

PRISM will be sensitive to $r > 10^{-4}$, two orders of magnitude better than what is considered as an optimistic objective from the ground, and more than one order of magnitude better than what can be achieved with a small-scale CMB space mission. Whatever happens, PRISM will have the final word on CMB B-mode science.

Question: Why are full-sky observations interesting for dusty galaxies and cosmic star formation?

Short answer:

High redshift dusty galaxies emit primarily in the 100-500 micron range. Atmospheric emission, opacity and noise severely limit ground-based observations. Overcoming the astrophysical confusion limit from source-blending requires a telescope significantly larger than the size allowed by the fairing of current launchers, and hence either complex deployable mirrors, or space interferometry, both complex and costly. Full-sky observations however make it possible to detect thousands of rare, strongly lensed galaxies at high redshift, and hence overcome the confusion limit by a significant factor thanks to the corresponding magnification. In addition, the observation of the full sky in many frequency bands opens the way to statistical methods to separate the CIB into independent contributions from different redshift shells, and hence trace the history of star formation throughout cosmic time.

Detailed answer:

The full sky maps of PRISM are the most effective way to probe the evolution of cosmic IR luminosity short of a costly FIR mission with a very large telescope or interferometer in space. We anticipate that the fundamental confusion limit will be partially overcome with PRISM by at least two means: the observation of strongly lensed, normal galaxies at high redshift, which will give access to the star formation associated with the large population of standard objects; the decomposition of the unresolved CIB into contributions coming from different redshift shells.

The 5σ confusion limits for a 3m telescope such as Herschel have been measured to range from 29 to 34 mJy/beam at wavelengths from 250 to of 500 μm (Nguyen et al., 2010, A&A, 518, L5). As shown by Negrello et al. (2010, Science, 330, 800) about 40-50% of 500 μm sources brighter than 100 mJy/beam (i.e. brighter than ≈ 3 times the 5 sigma confusion limit) are strongly lensed galaxies (the other extragalactic sources being easily distinguishable nearby galaxies plus a few radio sources).

As illustrated in Fig. 1 the magnification distribution has a substantial tail at $\mu > 10$. Sources with $\mu > 3$ probe intrinsic flux densities below the 5σ confusion limit. The foreground galaxies acting as lenses are generally massive ellipticals at $z < 1.5$ detectable

by Euclid or dedicated follow-up. The magnification of the lensed sources can be derived by sub-mm interferometry. Using the corresponding amplification probability we can determine the space density of unlensed sources, overcoming by a substantial factor the confusion limits.

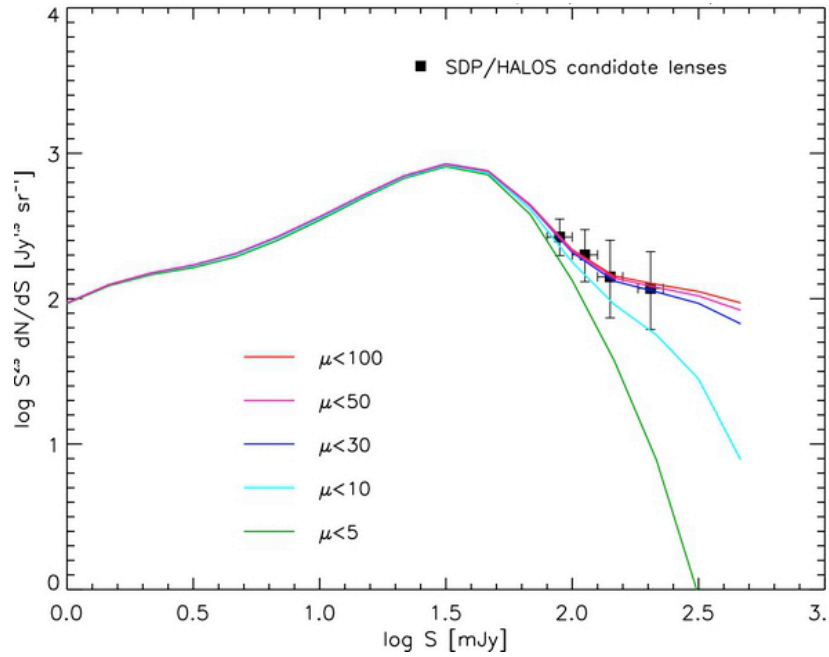


Fig 1. Euclidean normalized counts of lensed galaxies at 350 Ω_m . The filled squares are the estimated counts of strongly lensed galaxies in the Herschel-ATLAS Science Demonstration Phase (SDP) field. The lines show model predictions for different cuts in maximum amplification: $\mu_{max} = 5, 10, 30, 50,$ and 100 . Figure from Lapi et al., 2012, *ApJ*, 755, 46.

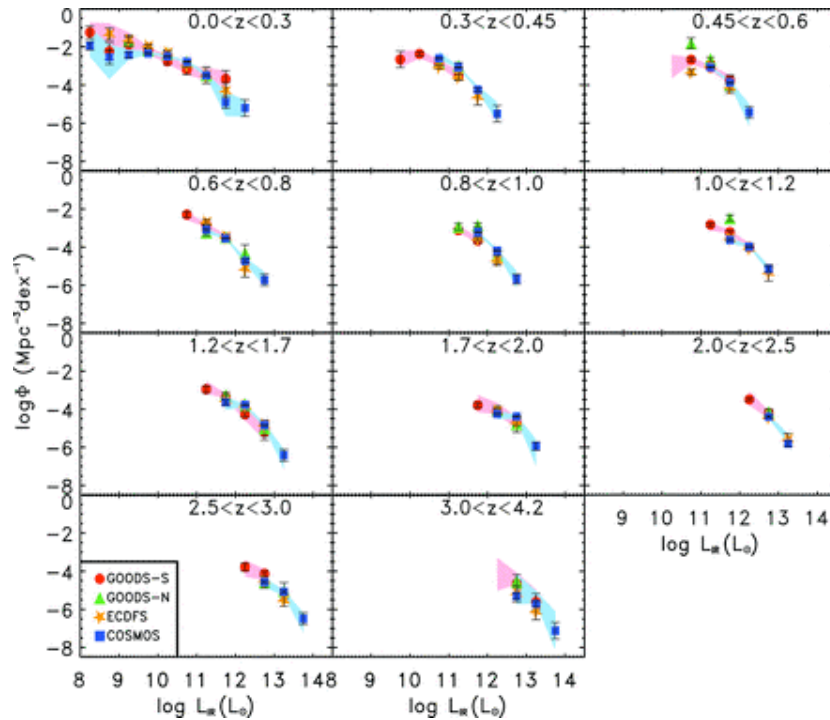


Fig 2. Total IR Luminosity Function estimated from the 160- Ω_m samples in the four

Herschel PACS Evolutionary Probe (PEP) survey fields. The pink and sky-blue shaded areas represent the range of values derived with 20 iterations by allowing a change in photo-z in the GOODS-S and COSMOS fields, respectively. See the bottom left panel for the meaning of the symbols. These are the deepest determinations of the total IR luminosity functions obtained from Herschel surveys. Figure from Gruppioni et al., 2013, MNRAS, 432, 23.

As illustrated in Fig. 2 at high redshifts even the deepest Herschel surveys were able to probe only the high luminosity tail of the galaxy luminosity functions, above the “knee” corresponding to the most effective star formers. Hints from lower redshifts and models converge in indicating that it would be enough to go a factor of a few deeper to have a direct look into these galaxies. Gravitational lensing allows us to get there with a 3m telescope. Of course, thanks to the gravitational amplification the exposure times for follow up observations can be a factor μ^2 shorter than for the corresponding un-lensed sources and the effective angular resolution increases by a factor $\mu^{1/2}$.

Another interesting route to overcoming the confusion limit is to use the many PRISM frequency bands to decompose the CIB into contributions from various redshift shells (a point also hinted at in the PRISM poster). This decomposition can be done using principal component analysis or independent component analysis methods. Such methods are effective if the statistics of the data can be computed accurately, which requires as large a data set as possible (to avoid random correlations between emission from different redshifts in the computed statistics) and hence the largest possible sky coverage and angular resolution. It is also needed to have at least as many frequency channels as there are independent redshift source planes with different average emission law across frequencies.

Additional constraints may be obtained by stacking of FIR maps towards primordial galaxy clusters at $z > 2$, a crucial epoch in poorly-understood build-up of stellar mass in dense environments.

Question: Is it better to observe galaxy clusters in the sub-mm or in X-rays?

The answer depends on the objective; for cosmology, PRISM is incomparably better and it opens the way to fundamentally new science that cannot be achieved with X-rays.

For cosmology, we need the large-scale view of structure, and out to high redshift. This requires efficient surveying of vast volumes to sufficient depth, for which the SZ (sub-mm) effect at PRISM's sensitivity is unmatched. PRISM will detect at least ten times more clusters than the X-ray survey planned with eRosita, and will reach out to $z > 3$, while eRosita is primarily limited to $z < 1.5$.

Cosmic velocity flows cannot be measured by any means other than kinetic SZ effect (sub-mm) over such large volumes. Moreover, the sub-mm observations give PRISM the essential capability of measuring cluster masses through gravitational lensing of the CMB out to the highest redshifts.

For studying the details of astrophysical processes at work in individual systems, it is interesting to follow-up the clusters detected by PRISM using high resolution multi-frequency observations with ground-based facilities such as ALMA, SKA, CCAT, and in X-rays. Clusters detected by Planck have been followed-up in this way using data from

SDSS and targeted observations with XMM and Chandra.

Question: What is the big science theme for which PRISM observations will lead to progress that is transformational rather than incremental?

The following science themes targeted by PRISM constitute, in our view, breakthrough science:

- A survey of the Hubble volume. No other existing or planned project can map out the distribution of mass (from CMB lensing), hot gas (from thermal SZ effect), and dust (from CIB emission) over the entire Hubble volume. No other planned survey can map large-scale velocity flows out to high redshift. PRISM will carry out on the scale of the entire observable Universe a complete census comparable to that of the Gaia space mission in our own Galaxy.

- Understanding the role of the magnetic field in Galactic star formation: This big missing piece in our understanding of galactic star formation can only be obtained through observations of dust polarisation at high resolution in the far infrared. PRISM will perform the necessary measurement over the complete sky with a sensitivity only limited by photon noise from sky emission, at an angular resolution ranging from few to few tens of arc-seconds.

- Primordial CMB B-modes: The detection and characterization of primordial gravity waves from inflation would radically impact our understanding of the physics at play in the very early Universe. Even if a preliminary detection is obtained earlier with ground-based experiments or a small satellite mission, PRISM will transform this tentative detection into a precise measurement of the primordial B-mode spectrum. Such a measurement probes physics near the GUT scale and places constraints on the unification with gravity of the fundamental forces. No other experiment can probe such high-energy scales to provide missing experimental clues.

- CMB spectral distortions: The PRISM spectrometer, more than a thousand times more sensitive than the COBE FIRAS instrument, will provide an exquisite measurement of the frequency dependence of all components of sky emission. Of particular interest, spectral distortions of the CMB blackbody probe energy injection up to $z = \text{few} \times 10^6$, well before the CMB anisotropy photosphere at $z \approx 1100$. Furthermore, there are a number of known almost guaranteed signals (γ distortion from re-ionization, distortion from Silk damping, H and He recombination lines). In addition, the discovery potential for surprises of great significance for the standard cosmological model is immense.

- The history of star formation: The PRISM full-sky survey in the FIR will give unprecedented constraints on the complete history of star formation out to the highest redshifts through (i) the analysis of rare extremely lensed objects, (ii)- separation of CIB maps into contributions from various redshifts.

Question: Is it possible to achieve the same science goals with a combination of ground-based and balloon-borne observations, or with one or possibly two small or medium-scale space missions, before 2028 or 2034?

No, this is impossible. The science goals of PRISM cannot be fully achieved by any means short of a large space mission similar to the one we propose.

1- A complete census of mass, hot gas and dust in our Hubble volume requires three types of observations:

- lensing of a clean, very distant background (for mass), CMB being the best candidate, as lensing of optical galaxies cannot reach a mass survey beyond $z > 1$ because of lack of background objects;
- sensitive thermal SZ observations in the 100-400 GHz frequency range (for gas), X-ray observations being inadequate at redshifts > 1.5 ;
- CIB observations in the FIR (possible only from space with a cold telescope).

This can be achieved only with a sensitive and clean survey in many frequency bands in the frequency range of PRISM.

2- Understanding the role of the magnetic field in galactic star formation requires observing the galactic magnetic field and its interaction with galactic dust. This cannot be done by any other means than polarized observations from space at sub-millimetre frequencies as planned with PRISM.

3- Observing the CMB does *not* require a space mission. However, observing CMB B-modes on large scales requires a clean, well-calibrated, well-characterised instrument in space. The PRISM polarised imager will benefit from a unique calibration scheme, with absolute calibration from the spectrophotometer, cross-channel calibration, and accurate characterization of instrumental response with the ancillary spacecraft. An M-class mission can do a large part of the CMB science, but cannot match the level of control of instrumental effects that is achievable with PRISM. An S-class mission can control neither systematic effects nor foreground contamination to the same level of accuracy. Ground-based observations will be severely limited by the atmosphere, ground pickup, and an unstable environment, and can only be competitive on small scale. This has been the case for intensity, and the situation can only worsen for polarization, for which foreground contamination and the impact of instrumental errors uncertainties are more severe by orders of magnitude.

4- The measurement of CMB spectral distortion and the zero level of sky emission can only be achieved with an absolute spectrophotometer in space. While it is possible to design a small-scale mission such as PIXIE to measure the absolute power spectrum, foreground contamination in large beams (such as the PIXIE 2.6° top-hat beams) is likely to limit the sensitivity of the observations. PRISM is unique in providing a way to correct for part of the foreground contamination with the joint exploitation of the spectrophotometer and imager data, with both instruments observing through the same zodiacal light emission foreground.

5- The history of star formation across cosmic time is best investigated by observing the far-infrared emission of dusty galaxies at all redshifts. This requires space observations, which however suffer from confusion because of insufficient angular resolution for a telescope with a monolithic primary fitting in the fairing of current and next-generation launchers. Short of a large deployable telescope or interferometer in space costly and technologically challenging, the PRISM all-sky survey is the best option to overcome

cosmic confusion, by observing thousands to ten of thousands of rare strongly lensed distant sources, which give access to the emission from the largest population of standard objects responsible of most of the star formation. In addition, PRISM will provide the best possible data set to cleanly separate the CIB emission from galactic dust and zodiacal light, and to attempt the decomposition of the CIB into independent maps from distinct redshift shells.