COPILOT: C+ Observations of the ISM with PILOT

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Summary: We present the COPILOT (C+ Observations of the ISM with PILOT) concept, a proposed balloon-borne experiment to measure the integrated intensity of 158µm C+ emission line in Galactic star-forming regions, the diffuse ISM of the Milky Way and in Local Group Galaxies. The COPILOT proposal is to modify the existing PILOT instrument to enable wide-field mapping of the C+ integrated emission with sufficient sensitivity to accurately characterise the faint end of the C+ intensity distribution. Here we present the science goals, planned observing strategy and expected performance of the COPILOT instrument concept. By observing wide fields in the local Milky Way, COPILOT will enable a statistically robust estimate of the relative contributions of the atomic gas, the ionised gas and the dense neutral medium to the C+ emission via a correlation analysis with other tracers of ISM phases. This result will be a key reference value for velocity-resolved studies in more complex regions such as the Galactic plane and star-forming regions, and for unresolved observations of the C+ emission in other galaxies. Compared to recent and upcoming heterodyne instruments to observe C+ emission, the low-cost CoPILOT mission occupies a unique niche in terms of sensitivity, resolution and wide-field coverage, enabling important studies of the ISM phase balance, the prevalence of dark gas, star formation and feedback in galaxies.

Key Science: The Dark Gas

We still lack a robust inventory of how mass is distributed between different phases of the ISM in galaxies. The 21 cm HI line and low-J transitions of CO have traditionally been used as tracers of the atomic and molecular gas, but these tracers provide only a partial view. Transitions between the dominant species of hydrogen and carbon in the ISM do not track each other perfectly: CO is more sensitive to photo-dissociation than molecular hydrogen, and is only emitted from the well-shielded interiors of fully-formed molecular clouds (see Figure 1). A significant reservoir of molecular hydrogen likely exists at column densities where carbon is still mostly in ionised or atomic form. This phase is often referred to as "dark gas", since its spatial distribution and mass cannot readily be estimated using HI or CO observations, but it is expected to emit strongly via the C+ line at 158µm.

COPILOT Instrument modifications

COPILOT will use most of the hardware of the PILOT instrument (see accompanying PILOT First Results poster). The layout of the cold optics in PILOT is illustrated in Figure 2. Our current plan is to replace the HWP of PILOT with a Fabry-Perot optimized for the detection of the C+ line at the center of the focal plane, and measuring the dust continuum emission with pixels in the outer regions of the focal plane. In this option, thePILOT polarizer is removed and only a single focal plane is used. This solution is currently being developed and tested at SRON. The rest of the COPILOT instrument will remain similar to PILOT and will take advantage of developments in cryogenics, pointing reconstruction, calibration, telemetry, observation scheduling, and flight qualification for PILOT.

Expected sensitivity

We have computed the expected sensitivity to extended sources S using:

$$\frac{S_{pix}}{\mathrm{MJy/sr}} = \frac{10^{20}}{\sqrt{2}} \times \frac{\mathrm{SNR}}{\mathrm{Tr}} \frac{\mathrm{NEP_{tot}}}{\mathrm{W}/\sqrt{\mathrm{Hz}}} \left(\frac{\mathrm{M}}{\square/\mathrm{hr}}\right)^{-1} \left(2 \times 60^2 \times \frac{S_{array}}{\square}\right)^{-1/2} \left(\frac{S\Omega_{pix}}{\mathrm{m^2 sr}}\right)^{-1} \left(\frac{\Delta_\nu}{\mathrm{Hz}}\right)^{-1} f_{reso}^{-1},$$

where SNR is the signal-to-noise ratio, T_r is the optics transmission, NEP_{tot} is the detector noise equivalent power, M is the mapping speed, S_{array} is the field-of-view surface, $S^*\Omega_{pix}$ is the solid angle of a pixel, $\Delta\nu$ is the bandwidth and f_{reso} accounts for the sensitivity increase at resolution lower than the array pixel resolution. The sensitivity for option 1 corresponding to SNR=3 is shown in Figure 3 as a function of resolution and mapping speed, assuming an NEP=4.6x10^{-16} W/√Hz, as observed during PILOT flight 2, the same fraction of operational pixels (72%) and a spectral bandwidth corresponding to Δv=2000 km/s, sufficient to encompass C+ emission for the MW and nearby galaxies. The sensitivity for option 2 remains to be evaluated carefully. Despite the lower number of detectors used, it could be higher than shown here due to the higher mutual rejection of the C+ and dust continuum contributions.

The sensitivity and mapping speed of COPILOT will be equivalent to that of FIRAS but with an angular resolution of 2', 200 times better than FIRAS and well matched to the ancillary data (HI, dust, Hα) needed for analysis. It will allow us to map the spatial distribution of diffuse C+ emission 100 times faster than the next C+ heterodyne mission (GUSTO), which will restrict its observations towards the inner MW plane.

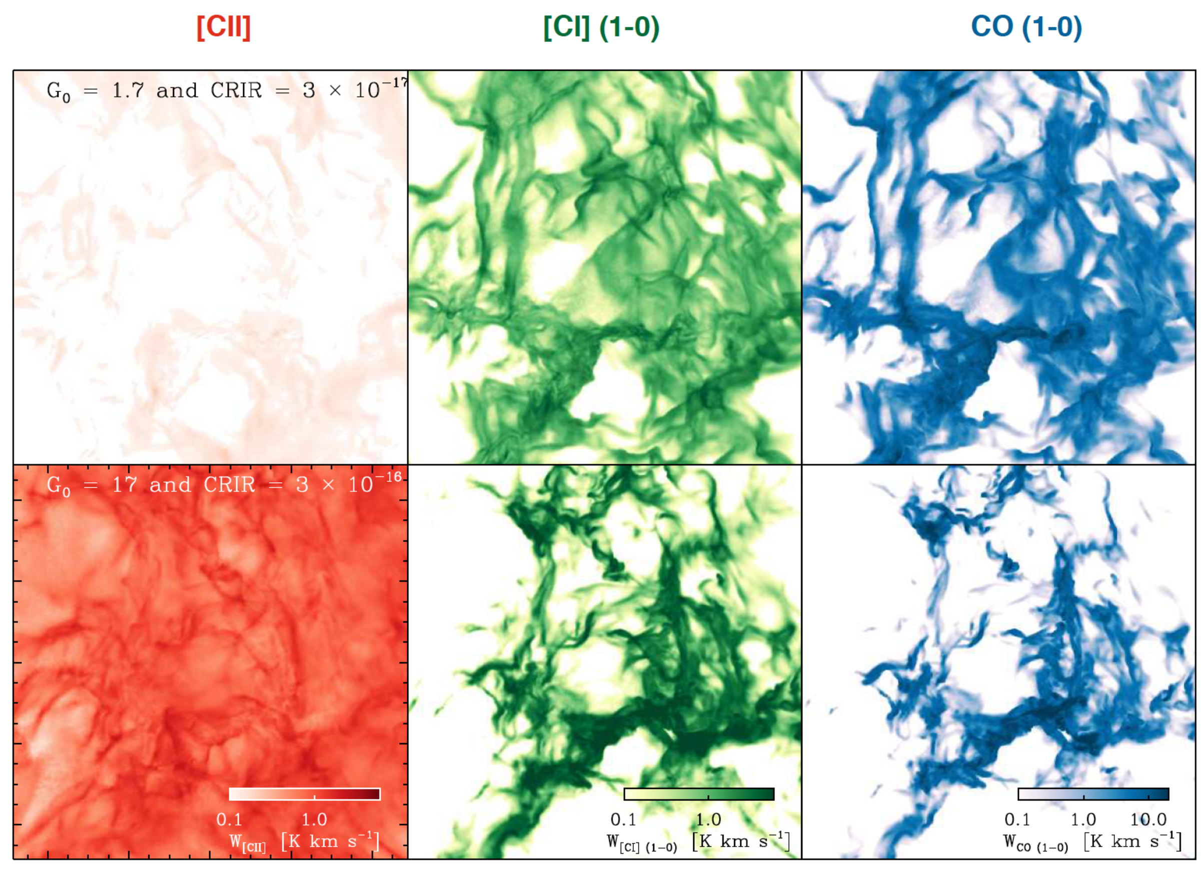
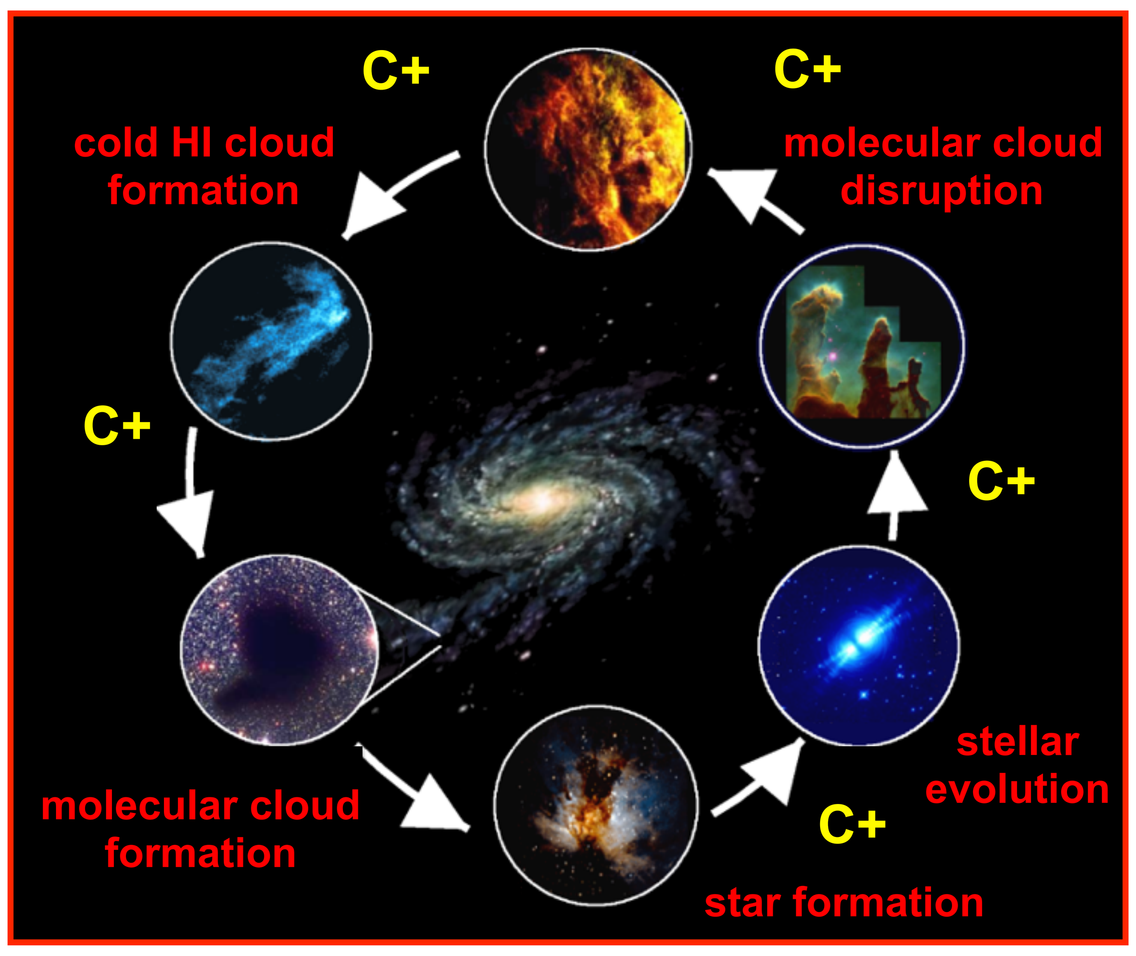


Figure 1: (Above) Predicted integrated intensity of 158µm C+ (left), CI (1-0) (middle), and 12CO(1-0) (right) for a 3D chemo-dynamical numerical simulation of a 10^{5}M$_\odot$ cloud exposed to a low (top) and high (bottom) UV radiation field and cosmic ray flux (Clark & Glover, in prep). There is a intermediate regime between the diffuse and dense ISM, where molecular hydrogen and C+ is abundant, but CO is photodissociated. The contribution of this phase to the total mass budget depends on local ISM conditions. (Below) Cartoon representing the cycling of matter between the ISM and stars in galaxies. C+ emission is expected to be present in many transitional phases, including a moderately dense neutral phase that is not traced by HI or CO. Cartoon adapted from Kulesa et al (2013).



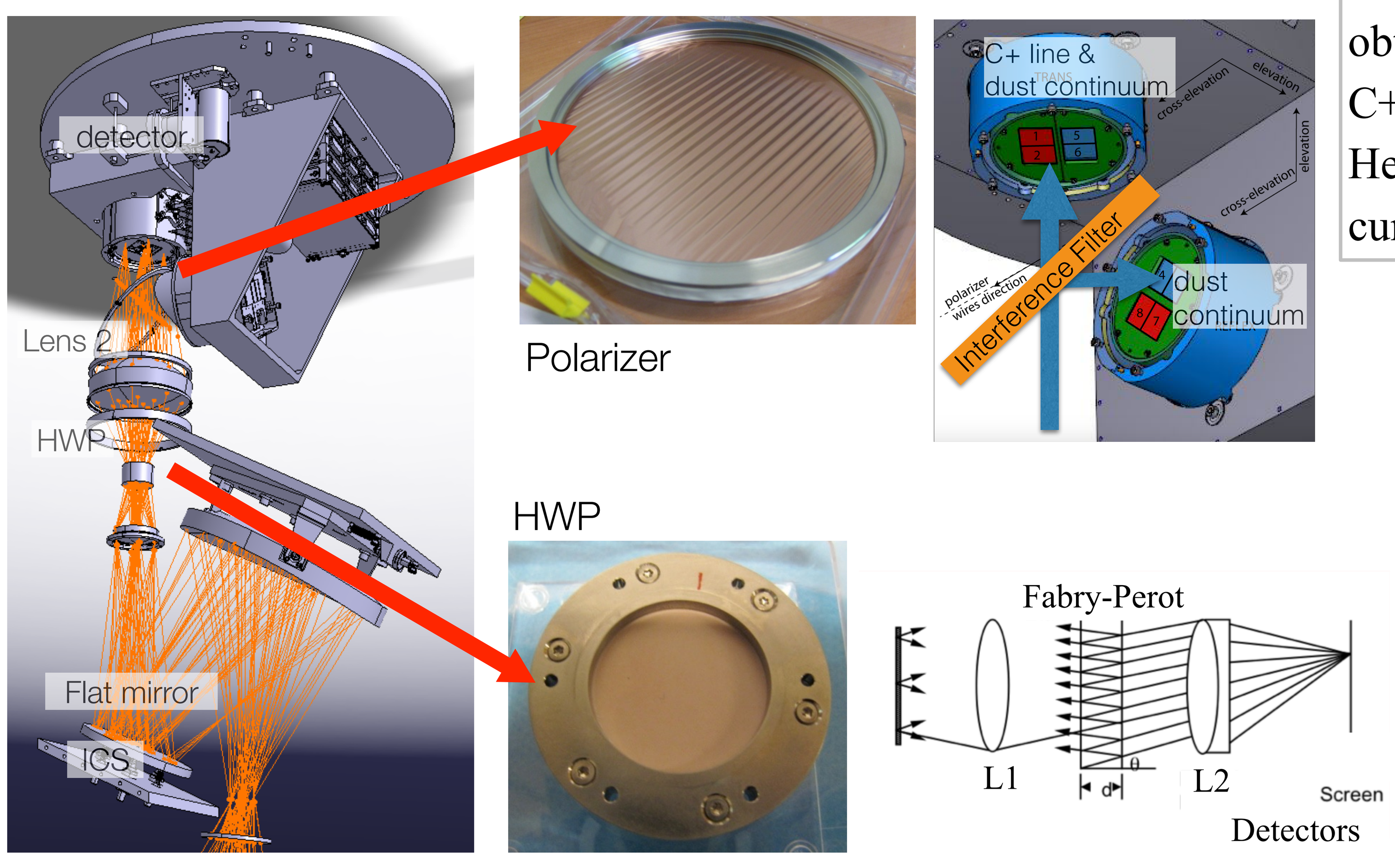


Figure 2: Illustration of the two options for transforming the PILOT optics for COPILOT observations. Option 1 is to replace the 45° inclined polarizer by an interference filter transmitting the C+ line and reflecting the surrounding continuum. In that option, the PILOT HWP is removed. Option 2 is to replace the PILOT HWP by a Fabry-Perot interferometer with fixed separation d, with transmission centered on the C+ line at the center of the focal plane and on the surrounding dust continuum at the edges of the focal plane. In that option, the PILOT polarizer and the REFLEX detector arrays are removed.

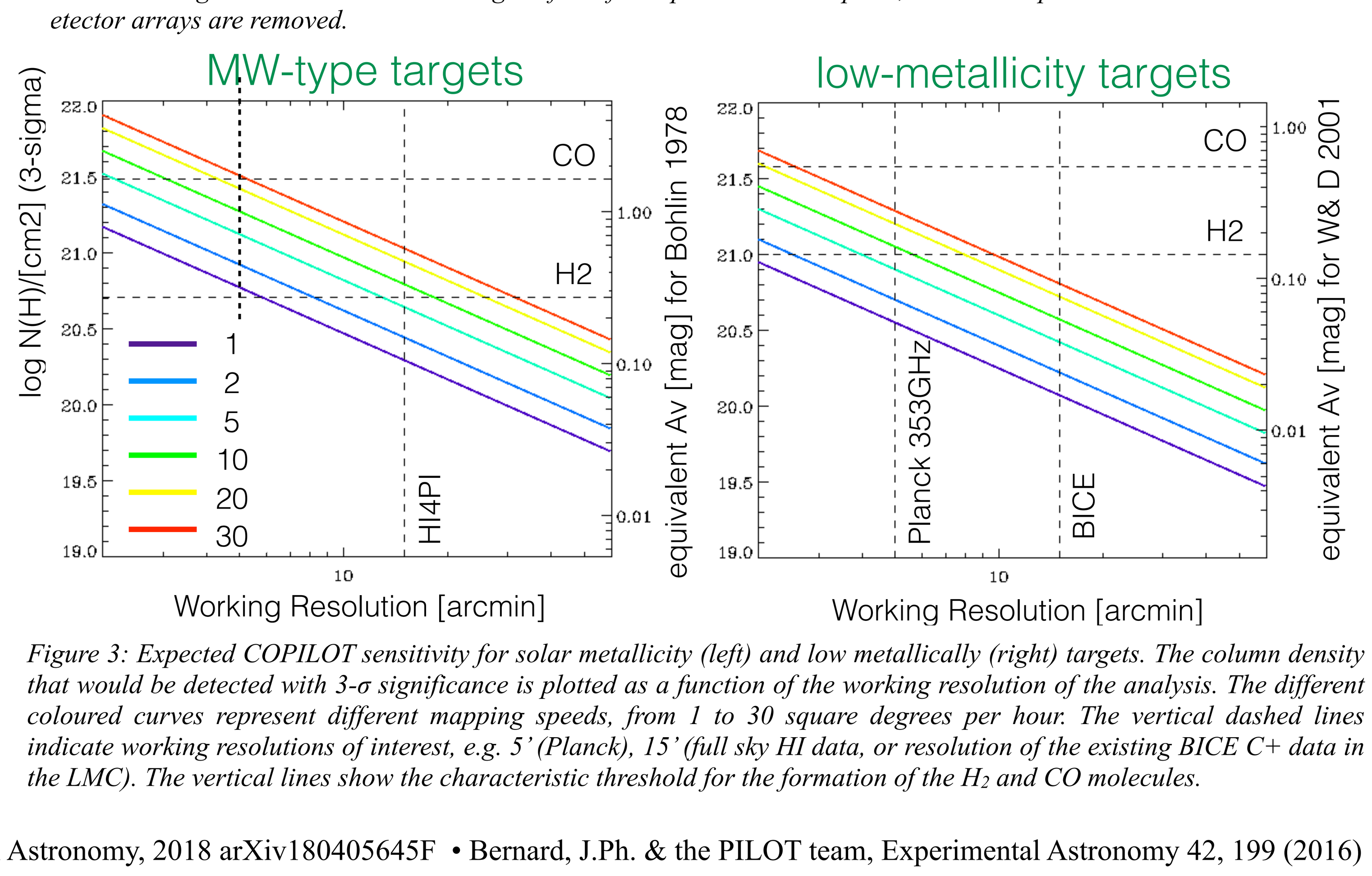


Figure 3: Expected COPILOT sensitivity for solar metallicity (left) and low metallically (right) targets. The column density that would be detected with 3-σ significance is plotted as a function of the working resolution of the analysis. The different coloured curves represent different mapping speeds, from 1 to 30 square degrees per hour. The vertical dashed lines indicate working resolutions of interest, e.g. 5' (Planck), 15' (full sky HI data, or resolution of the existing BICE C+ data in the LMC). The vertical lines show the characteristic threshold for the formation of the H_2 and CO molecules.

COPILOT Observing Strategy

The conditions under which the C+ 158um transition can be collisionally excited are encountered in both diffuse to moderately dense neutral gas and from ionised gas, in proportions that vary with galactic environment. To use C+ as a quantitative probe of ISM properties, these contributions must be disentangled. Two complementary observational approaches are possible.

Option 1: observations that are resolved in both the spatial and spectral domains, pinpointing the C+ emission originating from different ISM components. Separation is via correlation with spatial and spectral templates. This strategy is currently pursued by several heterodyne missions. It yields detailed C+ measurements that are sparsely distributed and biased towards bright, actively star-forming regions due to sensitivity limitations.

Option 2: sensitive, spectrally unresolved maps that can detect C+ emission over wide fields and under the full range of ISM conditions under which C+ emission is excited, but which cannot probe complex regions such as the Galactic Plane. Separation is via correlation with spatial templates. This is the COPILOT strategy.

COPILOT Observing Targets

COPILOT will map several hundred square degrees at high latitudes in the Milky Way and obtain spatially complete C+ maps of Local Group galaxies. This strategy will yield a statistically robust estimate of the relative contributions of the atomic gas, the ionized gas and the dense neutral medium to the C+ emission under different ISM conditions.

COPILOT is the only currently proposed instrument to obtain such wide-field, moderate resolution maps of C+ emission. Large FoVs were not possible with Herschel instruments, and they are not possible with current or upcoming heterodyne missions.

BOOST with SPICA-POL detectors

Ultimately, we plan to equip COPILOT with new bolometer detectors developed for the SPICA-POL instrument. These will be optimized for the very low background characteristics of SPICA and COPILOT, and have superior performance to the existing PILOT detectors. Their mechanical and electrical interface will be similar to the current detectors, simplifying integration in the cryostat.

Currently, PILOT's sensitivity is limited by detector noise and is a strong function of the focal plane temperature (FPT). Lowering the FPT from 321mK (flight 1) to 307mK (flight 2) increased the sensitivity by 15% (=30% faster mapping).

For PILOT, the photon noise contribution is 1.7x10^{-16} W/√Hz. The expected photon noise for COPILOT is much lower due to the narrow bandpasses: 3.2x10^{17} W/√Hz. Using the SPICA-POL detectors would therefore enhance COPILOT's sensitivity by a factor of ~10, allowing ~100x faster mapping than shown in Figure 3.

The SPICA detectors will require lower FPTs than PILOT. We have recently obtained IRAP funding (the BOOST proposal) to modify the PILOT cryostat for operation at ~200mK.

References: Mangilli, A. and the PILOT team, submitted to Experimental Astronomy, 2018 arXiv180405645F • Bernard, J.Ph. & the PILOT team, Experimental Astronomy 42, 199 (2016) • Misawa, R & the PILOT team, Experimental Astronomy 43, 211 (2017)