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LRP WHITE PAPER ON DARK MATTER, DARK ENERGY, AND PARTICLE ASTROPHYSICS

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ABSTRACT

Dark matter, dark energy, and particle astrophysics represent the dynamic and changing boundary between astronomy and unknown physics. In recent years astrophysics and cosmology have forced the push further into the unknown in order to account for observations. Here, we briefly discuss the shape of this exciting frontier and what might come next. Because of their nature, future breakthroughs in experimental dark matter astrophysics and other areas of particle astrophysics will require coordinated international efforts and Canadians are an integral part of these efforts. In the field of dark energy astrophysics a unique opportunity now exists for a world-class breakthrough by Canadian astronomers.

Subject headings: Dark Matter, Dark Energy, Particle Astrophysics

1. THE UNKNOWN FRONTIER

Astronomy and astrophysics have a rich tradition of pushing beyond the envelope of known fundamental physics. This is certainly true today. While the standard model of particle physics and general relativity (GR) are arguably the best-tested and most successful scientific theories in history, astronomical observations now suggest the former and perhaps even the later are fundamentally incomplete. New particles, and perhaps new or revised laws of physics are required by recent astronomical observations. In this *white paper* we take a snapshot of the present state of the “unknown physics" frontier of astronomy, and discuss prospects for progress at the boundary of fundamental physics and observational astrophysics while focusing on the topics of dark matter, dark energy, and particle astrophysics.

2. DARK MATTER

Abundance — While evidence for dark matter has long been known via its gravitational effects (1), its fundamental nature has remained elusive (see, for e.g., 2, for a pedagogical review of dark matter astrophysics). While there are other lines of evidence, observations of the fluctuations in the cosmic microwave background (CMB) now provide the cleanest evidence that dark matter is not a standard model particle (dark matter is non-baryonic). CMB observations are sensitive to both $\Omega_b h^2$ = (the density of baryonic matter) and $\Omega_d h^2$ = (the density of cold non-baryonic dark matter). Only with a baryon density near $\Omega_b h^2 \simeq 0.026$ and a collisionless dark-matter density near $\Omega_d h^2 \simeq 0.1123$ can the shape of the power spectrum measured by WMAP be fit (3).

The abundance of dark matter is already significant information. In canonical weakly interacting massive particle (WIMP) models this abundance requires the cross-section associated with the annhilation of dark-matter particles to be the same characteristic size as in the *electroweak* interactions.

Astrophysical Distribution — In the astrophysical and cosmological context the most important property of dark matter is its gravitational influence. It provides the scaffolding for the rest of the Universe to form around. The standard cold dark matter paradigm remains highly successful and can account for the observed distribution of galaxies in the Universe (the tension over the number of Milky Way satellites has lessened markedly). N-body simulations have shown that dark matter collects into a nearly-universal halo shape over a wide range of halo masses from dwarf galaxy to cluster scales (4). For large astrophysical structures, to the extent that dark-matter acts like cold gravitationally interacting particles the astrophysics of dark matter is by now well-established (at least in the limit that baryonic physics is unimportant). For smaller substructures there may be interesting imprints of dark-matter particle physics on the astrophysical distribution. This may arise because the dark-matter particle was once kinetically coupled to the primordial plasma (e.g., 5; 6), or perhaps because the dark matter is somewhat warm and free-streamed through the Universe prior to becoming non-relativistic (e.g., 7; 8). In either case the small-scale matter power spectrum of dark matter is suppressed, which leads to a minimal mass scale for the first protohalos that form in the Universe (e.g., 6). Interestingly, the unknown particle nature of dark matter might imprint itself gravitationally on the visible Universe even if it otherwise does not interact with standard model particles (8). Constraints on the free-streaming length (and mass of the dark matter particle) also are also imposed by measurements of the matter power spectrum via the Lyman-α forest (see, e.g., 9; 10).

We note that the large-scale distribution of dark matter, dark-matter substructure, and the shape of dark-matter halos can be directly probed by gravitational lensing because it is a purely gravitational effect that probes the *total* matter distribution (please see the white paper on *Gravitational Lensing* for further information).

Direct Detection — If WIMP dark matter makes up the halo of the Milky Way, then we expect these particles to have a lo-

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cal spatial density of about $n_\chi \sim 4(m_\chi/100\,\mathrm{GeV})\,\mathrm{m}^{-3}$. If they interact strongly enough with ordinary matter we should be able to detect Galactic WIMPs in a low-background underground detector. If they are detectable, then **Canada's SNOLAB** is a premier place to make that detection because it is the deepest (hence lowest background) laboratory in the world for direct dark matter searches (11). Canadian scientists are both developing their own experiments, as well as attracting leading foreign-led experiments to come to SNOLAB (such as SuperCDMS and COUPP). **SNOLAB scientists are located throughout Canada**.

Needless to say, the direct detection of dark matter would be a discovery of fundamental importance in both physics and astrophysics. If a detection is made future experiments could conceivably measure the local phase space density of dark matter (12), constraining the substructure distribution of the Milky Way and enabling a new kind of dark-matter-particle astronomy. Furthermore, by inferring the properties of dark matter particles the (perhaps subtle) astrophysical impact of dark matter in all environments in the Universe could be better understood.

Indirect Detection — It dark-matter particles annihilate or decay into standard model particles it may be possible to detect this by looking for these standard model particles. They energy injected by these particles may leave signatures in the CMB or in the cosmic gamma ray background (13; 14), or result in secondary observational signatures like synchrotron radiation. As we discuss below in the context of particle astrophysics, the products of a dark matter annihilation cascade (for instance, gamma rays or neutrinos) might be detected in high energy gamma ray or neutrino detectors. Interestingly, the intensity and angular distribution of the observed particles could reveal the dark-matter substructure distribution of the Milky Way (15; 16).

3. DARK ENERGY

Discovery — It has been suggested for almost two decades that a cosmological-constant dominated Universe (the simplest form of dark energy) was the best fit to cosmological data (17; 18; 19). After the accelerated expansion of the Universe was directly measured via the dimming of high redshift supernovae dark energy has become an integral component of the standard cosmology (20; 21). Almost a decade ago CMB (22), large scale structure (LSS) (23), and Hubble constant (24) measurements implied independently from supernovae that nearly 70% of the energy budget of the Universe must be in the form of dark energy. Further LSS measurements from SDSS (25) and larger supernovae catalogues (26; 27) have put dark energy on ever firmer ground. A correlation between CMB and LSS due to the Integrated Sachs-Wolfe effect is expected in a dark-energy dominated Universe (28), and has been reported at the 4.5σ level (29). Current limits indicate dark energy may constitute as much as 74% of the energy budget of the Universe in the standard cosmological model (e.g., 3).

Theory — Dark energy is arguably the most puzzling open question in physical science today. A vast phenomenology of dark energy models has emerged (which we will not comprehensively cover here), ranging from a minimal cosmological constant, to scalar field models, to models that modify gravity itself.

The simplest form of dark energy, a cosmological constant, is predicted in the standard model of particle physics, but with a value that is a factor of $\sim 10^{60}$ times larger than the observed dark energy density (and that is the optimistic case). The resolution of this *cosmological constant problem* (30) has the potential to revolutionize our understanding of physics. Paths to resolution may include the string-theory landscape, (e.g., 31), extra-dimensional models that decouple gravity from the quantum vacuum (e.g., 32; 33; 34), or alternatives to general relativity that are blind to vacuum energy (35). It is notable that, especially with respect to modified-gravity explanations of dark energy, **much of the work has been done in Canada**.

Matter density dilutes with cosmic expansion while a cosmological-constant does not. The fact that the observed dark energy density of the Universe is close to the current matter density presents a *coincidence problem*. Approaches to explain this coincidence include, for instance, relating dark energy density to the matter-radiation transition (36), neutrino mass (37), the formation of astrophysical black holes (38), or a cyclic Universe model (39).

In any model beyond a cosmological constant differences are predicted that can potentially be tested by future cosmological surveys. Theoretically, it is important to quantify these signatures in order to design and optimize future dark energy probes. Along these lines, progress has been made in understanding the potential of future observations to distinguish between different classes of models (40), and frameworks for testing GR using the growth of LSS have been developed (41; 42; 43; 44).

The bottom line is that dark energy is an unknown, and any explanation of this phenomena will require a new understanding of physics. Canada has strong efforts in dark energy theory throughout the country. Also, there is a **very fruitful relationship between theorists and observers studying dark energy**. Many Canadians are particularly well-placed because they work at this interface and should be strongly supported as this field develops observationally.

Observations — Dark energy science is data starved. The only way to learn about the nature of dark energy (or discover new surprises) is with new observations.

While the precise values and errors of the dark energy parameters depend on the assumed model, and the choice of phenomenological parametrization, all current data (CMB, SDSS, SNIa) are consistent with acceleration being due to a cosmological constant. If one *assumes* a cosmological constant ($w = -1$) and a flat Universe ($\Omega_k = 0$) then the dark energy density is measured to be $\Omega_\Lambda = 0.722 \pm 0.015$ from WMAP7 data combined with current SNIa and BAO data (3). If one allows for a constant $w \neq 1$ the constraints become $\Omega_\Lambda = 0.718 \pm 0.015$ and $w = -0.980 \pm 0.053$. Allowing for non-zero Ω_k impedes the ability of the CMB alone to constrain w, but still gives tight limits on w if the CMB is combined with other cosmological data (3).[10]

The quality of current data is insufficient to go beyond a constant w description. Stage IV dark energy experiments, as classified by the Dark Energy Task Force (DETF) (45), will offer the ability to test for varying $w(z)$. Many approaches to modeling and constraining $w(z)$ have been discussed, including: fitting models (46; 47; 48; 49) one of which is a simple few-parameter approximation developed by Canadian researchers which accurately paves the space of trajecto-

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[10] In addition to the galaxy power spectrum, we note that weak lensing shear and magnification fields have been observed by COSMOS and CFHTLS, adding to the arsenal of large scale structure probes of dark energy (see the LRP white paper on *Gravitational Lensing* for further details).

ries from quintessence/phantom-energy models (50); principal component analysis (PCA), (51; 52; 53), and direct differentiation of distance data (54). Each approach has potential advantages. In the PCA method, adopted by the JDEM Figure of Merit Science Working Group (55), $w(z)$ is binned in redshift or scale-factor, and the value in each bin used as a parameter of the model. The best measured principal components can be used to reconstruct $w(z)$. The PCA method was also recently utilized to study possible modifications of gravity as alternatives to dark energy (40).

While they provided the first concrete evidence for dark energy, Type Ia supernovae might have already reached their level of systematic uncertainty (27). Observations of large scale structure at large redshifts, however, promises to provide complementary constraints on the phenomenology of dark energy and/or modified gravity. The rate of growth of clustering of galaxies, weak lensing surveys, and redshift space distortions provide measures of different components of gravitational perturbations, which can distinguish dark energy from many modified gravity models (e.g., 56). Dark energy astronomy is an active field, and additional multinational-level surveys are being built and planned, such as DES (57) and LSST (58), which will be in a qualitatively better position to constrain alternative models.

Perhaps the most promising probe of the expansion rate of the Universe are baryon acoustic oscillations (BAO). In the early Universe the baryons and photons were coupled together by Thomson scattering into a single photon-baryon fluid. Until the time of recombination $\eta_{\rm dec}$, when baryons and photons decoupled, this fluid supported acoustic waves with sound-speed $c_s \simeq c/\sqrt{3}$. These cosmic sound waves imprint a characteristic length scale $l_{\rm BAO} \simeq c_s \eta_{\rm dec}$ on the baryons in the Universe (the corresponding effect in the photons results in the CMB acoustic oscillations), which is now embedded in the distribution of large scale structure. This effect has already been detected in current low-redshift surveys of large scale structure (59; 60).

The utility of BAO in terms of dark-energy science is that $l_{\rm BAO}$ provides a *standard ruler* which can be used to infer the distance out to sources of known redshift and determine the expansion history of the Universe (61).

To achieve a precision probe, large volumes of the Universe must be mapped. One promising way to do this is by observing fluctuations in the intensity of cosmic 21-cm radiation due to overdensities or underdensities of galaxies. This technique is ideally suited to mapping BAO because, since 21-cm radiation is a line, the source redshift is trivial to determine. It has been shown in (62) that 21-cm intensity mapping experiments can probe enormous volumes of the Universe at a comparatively low cost, and compare extremely favorably to future generations of dark energy experiments (see also the white paper on *21-cm Cosmology* for further information).

Figure 1 shows the approximate comoving volumes probed by various ongoing or proposed redshift surveys, with approximate completion dates. The power to constrain $l_{\rm BAO}$ is approximately proportional to volume, with some improvement at higher z due to less non-linear degradation of the BAO feature. The key short-term experiment is BOSS (63), which is composed of a 10000 sq. deg. galaxy redshift survey out to $z < 0.7$, and an 8000 sq. deg. survey of the Lyman-α forest absorption at $z > 2$ in quasar spectra, which provides a map of 3D structure on the BAO scale.[11] BOSS has started observing and will finish in 2014. On longer time scales, there are several expensive possibilities for BAO/LSS experiments with volumes of order 100 Gpc$^3h^{-3}$ including proposed satellites like Euclid (64) or JDEM (65).[12] A 21-cm intensity mapping experiment, like the **Canadian Hydrogen Intensity Mapping Experiment (CHIME)** initiative, can potentially cover a similar redshift range and sky area for a fraction of the cost of the satellites, and much more quickly.[13]

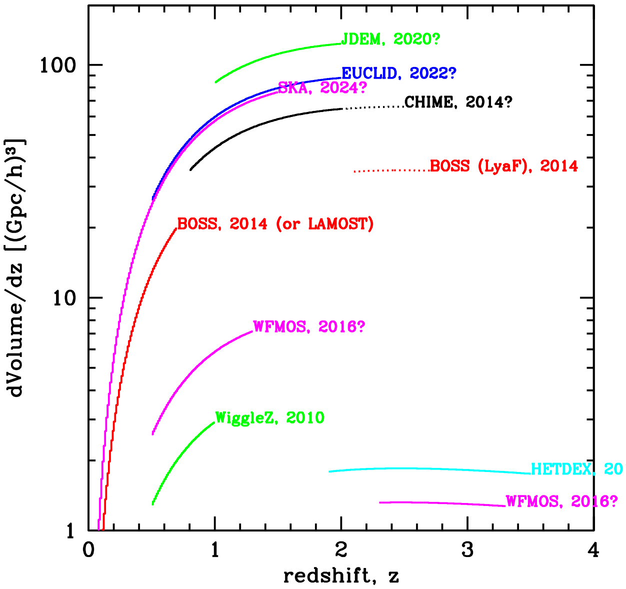

FIG. 1.— Comoving volume probed as a function of redshift by various ongoing or proposed BAO-oriented redshift surveys, along with approximate/potential completion dates.

Figure 2 shows projected constraints on the dark energy parameters w_0 and w' defined by $w(z) = w_0 + w'(1-a)$, for a few combinations of experiments. All include the CMB satellite Planck and DETF Stage II experiments (the completed and ongoing weak lensing, supernova, and cluster experiments). We see that CHIME could represent a remarkable acceleration of the rate of progress in measuring dark energy properties, perhaps achieving results comparable to proposed satellite missions (and would be straightforwardly extendable to a Southern hemisphere version and/or larger version to resolve higher z structure).

4. PARTICLE ASTROPHYSICS

Particle astrophysics covers the boundary between particle physics and astronomy on several fronts. It includes the study of subatomic particles of astrophysical origin (such as solar neutrinos, astrophysical neutrinos, or the search for particle dark matter). It also includes the study of particle physics properties that may impact upon astrophysics or cosmology (in for instance, by modifying the properties of stars, or changing the evolution of the early Universe). It further covers the study of astronomical sources using techniques adapted from the realm of particle physics experiment (such as atmospheric Cherenkov telescopes). Canada is involved in each of these fronts.

[11] This measurement by BOSS will fall significantly short of the sample variance limit due to sparse sampling

[12] We assume here that JDEM would cover 30000 sq. deg. at $1 < z < 2$ with number density $0.001\,h^3{\rm Mpc}^{-3}$ and bias $b = 2$.

[13] Note that, for a 100m telescope CHIME-class telescope, measurements at $z > 2$ would fall short of the sample variance limit due to limited resolution.

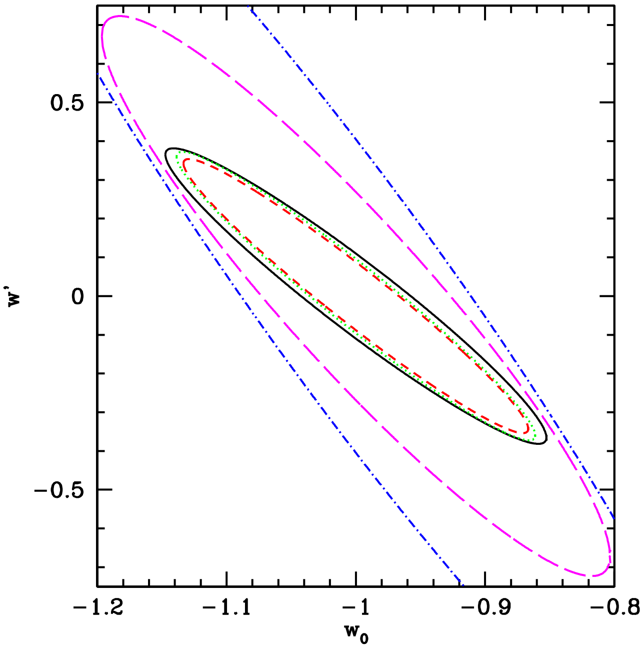

FIG. 2.— Projected $2-\sigma$ constraints on the dark energy parameters w_0 and w'. The blue (dot-dashed) lines show constraints from Planck and DETF Stage II experiments; magenta (long-dashed): Planck+StageII and BOSS and HETDEX galaxy redshift survey BAO constraints; green/red (dotted/short-dashed): Planck+StageII and EUCLID/JDEM satellite BAO constraints; black (solid): Planck+StageII and CHIME 21-cm intensity mapping BAO constraints.

Very High Energy Gamma-Ray Astronomy —

Very-high-energy (VHE) gamma-ray astronomy covers the energy range from 50 GeV to 50 TeV. Observations carried out with ground-based telescopes detect Cherenkov light produced in atmospheric air showers triggered by astrophysical gamma rays. These gamma rays typically arise from shock-accelerated electrons (which inverse-Compton scatter low energy photons to high energy) or protons (that produce π^0 mesons that subsequently decay to photons). The shocks are sometimes identified with Galactic sources like supernova remnants, or with extra-galactic sources like active galactic nuclei (AGNs).

Alternatively, as discussed above in the dark-matter section, in popular WIMP models dark matter particles may annihilate at the Galactic centre or in the substructure of dwarf spheroidal galaxies and yield energetic gamma rays that can appear in atmospheric Cherenov telescope bands (66). Complementary searches for WIMP annihilation are underway using data from the Fermi telescope. These astrophysical observations complement the particle physics effort at facilities like the Large Hadron Collider (LHC) because they can reach beyond the energies the LHC is able to explore and also provide the direct astrophysical connection that is lacking in purely accelerator-based discoveries (where the dark-matter is probably not the most easily produced particle). Very-high-energy gamma-ray astronomy can also be used to test violations of Lorentz invariance and the degree to which the speed of light is energy-dependent (which may occur in some theories of quantum gravity). By observing flares from distant AGNs interesting limits can be set on such models (67).

Starting in 2003, three major VHE gamma ray detectors have come on line worldwide: **VERITAS** (68), MAGIC (69), and HESS (70). They cover between them the entire sky with flux sensitivites of a few percent of the Crab with 20 hours of observation (a typical exposure in this field). The group at **McGill** is a key member of the VERITAS collaboration (currently the most sensitive of the three new VHE detectors) and in recent years, Canadians have been integral in the construction, commissioning and running of VERITAS.

The recently launched Fermi telescope, which operates in survey mode, is (besides its own very interesting science program) already identifying new sources for the source-targeted VHE detectors to observe. A particularly interesting recent VHE discovery was that M82, which is a starburst galaxy, is shining in VHE gamma rays (71). This provides evidence in favour of the idea that supernova remnants are the source of charged cosmic rays, and is an example of the interesting astrophysics that is possible when you open a new window onto the Universe they way VHE is now doing.

Neutrino Astronomy — In the past decade Canada has developed into a world leader in low energy neutrino astronomy with the incredible success of the **SNO** experiment located near Sudbury, Ontario. SNO provided a conclusive solution to the decades old solar neutrino problem, helping to confirm our basic understanding of the Sun, and has significantly enhanced our knowledge of basic neutrino properties (72).

High energy neutrino astronomy uses very large scale neutrino detectors to search for neutrinos from the most violent astrophysical sources: including supernovae, gamma ray bursts (GRBs) and AGNs. The elusive nature of the neutrino, due to its tiny interaction cross-section, makes it an ideal astrophysical messenger particle; traverssing large cosmological distances without deflection or absorption. Thus, unlike photons or charged particles, neutrinos can emerge from deep inside their source and travel with minimal interference to their point of detection. The challenge with this observational avenue is that the same property that makes the neutrino ideal also makes it very difficult to detect. However, when detections are made, neutrino astrophysicists will have a unique new window into the high-energy astrophysics and physics responsible for these violent sources.

There are solid theoretical expectations for the neutrino flux from various astrophysical phenomena. The observed cosmic ray flux at high energies places an upper bound on the high-energy neutrino flux produced in sources via p-p, p-n and p-γ collisions (which produce neutrinos via pion production). The protons that produce neutrinos are the very same high energy protons must also contribute to the cosmic ray flux, and so the observed cosmic ray flux bounds the neutrino emission rate (73). Current predictions suggest a km^3 detector may expect to detect $\sim$1 neutrino event per year from optically thin AGNs and GRBs. It is only recently, since about 2005, that neutrino detector technology has made it possible to consider volumes as large as 1 km^3. The **IceCube** neutrino observatory, for which the **University of Alberta** is a member institute, will be an $\sim$1km^3 detector located in the very pure deep ice at the South Pole. As of January 2010, IceCube construction is 93% complete and has 3 seasons of high quality data-taking with a partial observatory. IceCube currently leads the world in astrophysical neutrino searches from point (74) and GRB (75) sources and has a sensitivity nearing the Waxman-Bahcall upper-bound. Within Canada the University of Alberta group plays a significant role in searching for neutrinos at the lowest energy threshold for the current GRB astrophysical models (76). A northern hemisphere counterpart of IceCube, called Km3Net, is currently in the final design stages and is planned to be deployed in the Mediterranean Sea.

As mentioned in the dark-matter section, neutrino telescopes like IceCube can also search for indirect evidence of dark matter. Dark matter particles may accumulate in the gravitational wells of massive objects, like the Sun and the Galactic Centre, and in some models are predicted to annihilate and produce neutrinos. Dark-mater particle capture in the Sun (primarily made of light nuclei) allows one to probe theories where the coupling is primarily spin-dependent (77). Results from the partial IceCube dataset currently provide the most stringent limits on searches for spin-dependent dark matter in the Sun (78). The **Canadian IceCube** group provides leading expertise in the taking data with DeepCore (79), the low energy extension to IceCube, that enhances the sensitivity to astrophysical dark matter searches.

5. CANADIAN OPPORTUNITIES

World-leading experimental efforts are being planned or are already underway in Canada to further our understanding of dark matter, in particular the cutting edge direct detection efforts at **SNOLAB**, which has the opportunity to make the first detection of dark matter and usher in the era of dark-matter astronomy. Indirect astrophysical signatures of dark matter are being pursued by a worldwide community of scientists (including Canadians) working with new data from the Fermi gamma-ray space telescope and ground-based telescopes like the VERITAS array.

The next big step in VHE gamma-ray astronomy will be the construction of larger more sensitive instruments than **VERITAS**, MAGIC, or HESS. They will have an expanded energy range, wider field-of-view and sensitivity to fainter sources. Worldwide efforts include the Cherenkov Telescope Array (CTA) project in Europe and the Advanced Gamma-ray Imaging System (AGIS) in the US. These new facilities are expected to cost several hundred million dollars and will be built and run by large multinational teams (which will undoubtedly include important Canadian involvement).

The next breakthrough in neutrino astronomy will require a coordinated worldwide effort and new facilities like **IceCube** and Km3Net which are currently being completed or in final design stages. Canadian neutrino astronomers are plugged into these developments and are poised to reap the rewards of these significant efforts over the next decade (a share in the first discoveries from a brand new window on the Universe!).

The next breakthrough in our understanding of the expansion rate of the Universe, and dark energy, will very likely come from observations of BAO during the next decade. While an observational breakthrough in dark-matter astrophysics and particle astrophysics necessarily involves large international efforts, the same can not be said of dark energy astronomy. Future international efforts are being pursued, like the proposed JDEM space mission (65), that Canadians should be poised to contribute to. However, world-leading dark energy science could conceivably be explored at the scale of a purely Canadian astronomical effort.

In order to precisely probe the nature of dark energy with BAO a significant fraction of the volume of the Universe must be surveyed, and an efficient way to do this is to detect hydrogen in the radio. A 21-cm intensity mapping experiment, like the **Canadian Hydrogen Intensity Mapping Experiment (CHIME)** initiative, could be used to observe the expansion rate of the Universe and provide constraints on dark energy comparable to planned future generation experiments that use different observational techniques (see, for instance, Fig. 2). There is a unique opportunity for Canadian astronomers and cosmologists, by leveraging existing Canadian strengths like the DRAO and the strong Canadian cosmological community, to tackle the dark energy question during the start of the next decade — one step ahead of the world.

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