Mention the CR positron fraction:
Cholis, Hooper, PRD 2013 (1304.1840), Bergstrom, Bringmann, Cholis, Hooper, Weniger, PRL 2013 (1306.3983)

Discuss the Galactic center gamma-ray excess:
(Convince you the excess is REAL and relatively well understood) Linden & Hooper (1110.0006), Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, 1402.6703, Calore, Cholis, Weniger JCAP 2015 (1409.0042), Calore, Cholis, McCabe, Weniger PRD 2015 (1411.4647).
evidence for CDM (Cold Dark Matter)

- galactic rotation curves

- velocity dispersion of galaxies in clusters
• CMB data and SN Ia data

• Observed distribution of galaxies:
• strong lensing measurements of background objects (usually galaxies)
• collisions of galaxy clusters (e.g. bullet cluster)

• success of BBN (DM is non-baryonic)

• growth of structure (cold DM)
WIMP DM

Assuming thermal equilibrium:

For: \( T \ll M_\chi \quad N_{eq} \propto e^{-M_\chi/T} \)

\[ \Omega h^2 \approx 0.1 \times \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle} \approx 0.1 \times \frac{\alpha^2/(100 \text{GeV})^2}{\langle \sigma v \rangle} \]
Indirect detection: Dark matter annihilation into gamma-rays, cosmic rays, neutrinos.

Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:

Dark matter production at colliders

Thermal DM signals

LHC, CMS, ATLAS, ALICE

AMS, Fermi, Planck, HESS, PAMELA, LUX, CDMS
With CR spectral measurements we can understand the properties of the ISM, and probe sources of high energy CRs. Antimatter CRs indirectly also probe DM. Combine with gamma-ray and radio observations. Look for a DM signal.
A great new Era for CRs: The AMS-02 experiment

Lunched on May 2011, will collect data for 20 yrs. Will measure all CR nuclei species up to Ni.

positron fraction, positrons, electrons spectra, antiproton/proton B/C, Be10/Be9
Annihilating Dark Matter Interpretation Models

Physical models that work with various data; leptons/ antiprotons/ gamma-rays (Models with Sommerfeld enhancement)

Arkani-Hamed et al. PRD 2009

 phi mixing with the SM higgs

OR mix with EM

I. Cholis et al. JCAP 2009

Finkbeiner et al. JCAP 2011

IC, Dan Hooper, PRD 2013
Fig. 41. Constraints on the self-annihilation cross-section at recombination, $\langle \sigma v \rangle_\gamma$, times the efficiency parameter, $f_{\text{eff}}$ (Eq. 81). The blue area shows the parameter space excluded by the Planck TT,TE,EE+lowP data at 95% CL. The yellow line indicates the constraint using WMAP9 data. The dashed green line delineates the region ultimately accessible by a cosmic variance limited experiment with angular resolution comparable to that of Planck. The horizontal red band includes the values of the thermal-relic cross-section multiplied by the appropriate $f_{\text{eff}}$ for different DM annihilation channels. The dark grey circles show the best-fit DM models for the PAMELA/AMS-02/Fermi cosmic-ray excesses, as calculated in Cholis & Hooper (2013) (caption of their figure 6). The light grey stars show the best-fit DM models for the Fermi Galactic centre gamma-ray excess, as calculated by Calore et al. (2014) (their tables I, II, and III), with the light grey area indicating the astrophysical uncertainties on the best-fit cross-sections.
The absence of spectral features in the AMS positron fraction gives limits on light leptophilic DM that are \(10-100\) times stronger than current limits from CMB, or from dSph (similarly for the GC).
Known sources for the observed gamma-rays are:
i) **Galactic Diffuse**: decay of \( \text{pi}^0 \)s (and other mesons) from pp (NN) collisions (CR nuclei inelastic collisions with ISM gas), \textit{bremsstrahlung radiation} off CR e, \textit{Inverse Compton scattering} (ICS): up-scattering of CMB and IR, optical photons from CR e

ii) from **point sources** (galactic or extra galactic) (3033 detected in the first 4 years)

iii) **Extragalactic Isotropic**

iv) ”**extended sources**” (Fermi Bubbles, Geminga, Vela ...)

iv) **misidentified CRs** (isotropic due to diffusion of CRs in the Galaxy)
BUT ALSO the UNKNOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe:

\[
\frac{d\Phi_\gamma}{dE} = \int \int \frac{\langle \sigma v \rangle}{4\pi} \frac{dN_\gamma}{dE}_{DM} \frac{\rho_{DM}^2(l, \Omega)}{2m_\chi^2} dld\Omega
\]
Continuum emission, tree level, relatively hard spectrum, but featureless.

Final state radiation

Virtual Internal Bremss.

Two body annihilation to photons. Almost monochromatic Line, but suppressed at O(a^2).

Hardening of spectrum without a clear cut-off

Hardening of spectrum WITH a cut-off

Comes from radiative corrections to processes with charged particles. Suppressed by O(a), but with a much harder spectrum; FSR has an additional suppression factor of (mf/Mchi)^2
On the gamma-ray backgrounds ALONG THE LINE OF SIGHT towards the inner galaxy

- Spectrally the galactic diffuse gamma-ray components can be modeled (WITH significant variations though). In addition we can model their morphology on the galactic sky, WHICH varies with energy AND depends the physical assumptions (fast/slow diffusion, strong convection, energy losses)

- Extended sources can also be modeled (morphologically and spectrally) and subtracted (yet with some uncertainties related to the mechanism producing their signal)

Calore, Cholis, Weniger, 2014
We live inside the Milky Way; thus we see A LOT of emission from distances closer to us than the GC:

THUS WE NEED TO ACCOUNT FOR THESE UNCERTAINTIES.

• Extragalactic point sources can either be resolved or unresolved extragalactic sources (AGNs, Star forming or starburst galaxies etc). But are isotropic and thus can not contribute significantly to an excess in the inner galaxy. Misidentified GeV scale CRs are also isotropic due to diffusion.

• Galactic point sources that can give strong gamma-ray signals in the GeV range include SNRs in the inner part of the Galaxy and pulsars (please ask me later).

IMPORTANT CAVEAT!!! Calore, Cholis, Weniger, 2014
On the DM distribution in the inner galaxy

From hydrodynamical simulations there are suggestions from different groups in favor of contraction in the Milky-Way like halos with an inner slope gamma from 1.0 up to 1.5. Yet there still are groups suggesting flattening of the halo profile if baryonic feedback processes are efficient. Assuming NFW-like profile with some uncertainty in the inner slope is the way to treat any search for a signal of DM from the inner galaxy.

Gnedin et al. 1108.5736

Gottglober et al. 1005.2687


Looking for excesses in the inner galaxy

Smoothed Raw gamma-ray map

Hooper&Linden 1110.0006

POINT SOURCES
(2yr catalogue)

Model for Galactic Diffuse Emission

Excess Diffuse Emission

Similar results to earlier Hooper & Goodenough papers in 0910.2998 and 1010.2752 and later from: Abazajian & Kaplinghat (1207.6047), Gordon & Macias (1306.5725)
Repeating the exercise in different energies (updated analysis, using a new class of photon cuts allowing for better angular resolution)

- A clear excess emission in the galactic center emerges
- 90% of the total emission in the inner few degrees is removed
- Residuals not related to the galactic center (GC) are up to ~5% as bright as the GC residual
- Excess emission cuts-off at ~10 GeV (is in some dis-agreement with later findings)

Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, 1402.6703
Going to High Latitudes

For a DM signal you want to look outside the galactic disk but still just above the galactic center (also dSph galaxies can be an alternative target)

Advantages of going outside the inner few degrees:

i) if a DM signal: you have a prediction on how the spectrum should look (same shape) and how its normalization should be (contracted NFW)

ii) Different region on the galactic sky suffer from different uncertainties in the background models: In the inner part of the Galaxy point source subtraction is an important uncertainty, the gas density is also an important uncertainty and also the radiation field is an other. At higher latitudes: Fermi Bubbles, possibly unknown gas (unaccounted for in spectral line observations). Also propagation assumptions on the CRs may differ significantly between different regions of the Galaxy (due to strong winds outflows or magnetic fields causing anisotropic and preferential diffusion).
Excess emission towards the GC that extends up to possibly ~100 GeV and certainly above 10 GeV. It extends with a lower limit of 10 degrees away from the Galactic Center at 95% CL.

See also, Hooper & Slatyer 2013, Huang, Urbano, Xue 2013
Accounting for the galactic diffuse emission uncertainties

- Properties of the diffusion zone within which cosmic rays (CR) diffuse before escaping to the intergalactic medium

- How fast do CRs diffuse? Are there convective winds and how strong?

- How important are the effects of CR diffusive re-acceleration (diffusion in momentum space)

- Distribution of cosmic rays sources (does it follow SNRs?, pulsars? OB stars?)

- Spectral properties of CRs. Are they the same everywhere?

- How well do we understand the gas distribution along the line of sight and towards the inner Galaxy?

- How well do we understand the galactic magnetic field that affects the energy losses of CR electrons

- How well do we understand the interstellar radiation field properties? (these are the target photons that get up-scattered into gamma-rays from CR electrons).
We used models from the existing literature and created our own (60 models shown in our paper).

It turns out that it actually does not affect dramatically the DM annihilation-like GC excess spectrum:

Calore, Cholis, Weniger, 2014
An alternative way, look along the galactic disk: We basically repeat the same procedure but now change the window that we fit by moving it along the galactic disk; cross-checking every time with our 60 diffuse emission models.
One can then calculate a covariance matrix which allows to properly quantify the correlated systematic errors (associated to lack of better understanding of the galactic diffuse emission) which are bigger than the statistical (associated to number of gamma-ray events):

Residuals of the transported GCE template. No evident bias is seen. Green points show all 22 regions tested.

Decomposition of the covariance matrix in terms of principal comp. Only the first 3 are important. Only the 1st is above the statistical errors. The observed variations can be traced back to uncertainties in the pi0 and ICS slopes and amplitudes.
One can repeat the same exercise to smaller regions:
A different way of seeing the level of agreement between individual results

The flux associated to the excess emission at 2 GeV vs galactic latitude:

Calore, Cholis, McCabe, Weniger, 2014

The excess signals from different analyses, agree within a factor of less than 2 in terms of total emission (that is wether it is DM or MSPs or CR outbursts).
If this is a DM annihilation signal:
The range of possibilities (phenomenologically) becomes much larger. Because of the correlated errors.

BEFORE

The mass range preferred is actually higher. Even though still light DM models can work.

AFTER:

Gordon & Macias (1306.5725)  
Calore, Cholis, McCabe, Weniger, 2014

(see also P. Agrawal, B. Battel, P. Fox, R. Harnik, 1411.2592)
A specific example on MSSM

Figure 6: Mixed MSSM neutralino. We display the 1,2,3σ best-fit GCE regions for the WW final state in the $M_2 - M_1$ plane for CCW (green) and Fermi spectrum (b) (orange). We also overlay constraints from LEP chargino searches (brown) and LUX (gray). In the (red) region denoted $\Omega_{DM}$, the thermal relic abundance for the DM is within 3σ of the observed value. For convenience, we also show the mass of the DM and the annihilation cross section to WW as blue and yellow contours in units of GeV and $10^{-26} \text{cm}^2/\text{s}$ respectively. In the left plot we have fixed $\mu = 700 \text{GeV}$, $\tan \beta = 3$, while in the right plot we have fixed $\mu = -250 \text{GeV}$, $\tan \beta = 1.5$. 

P. Agrawal, B. Battel, P. Fox, R. Harnik
1411.2592
The amplitude of the signal is in general agreement with constraints from other indirect probes: Dwarf spheroidal galaxies, other DM galactic substructures antiprotons, gamma-rays from other regions of the galactic sky.

Strong limits from dwarf spheroidal galaxies (see results at 1503.02641)

Antiprotons can still give stronger limits for b-quarks by a factor of ~2.

For DM models with high BRs to leptons the AMS-02 data actually provide the best limits instead.
CR positron fraction has been of great interest in the last years, also in terms of a possible signal of local DM annihilations. Planck data place some strong constraints.

At low masses the lack of features in the positron fraction sets the tightest limits on DM annihilation rates.

The GeV gamma-ray excess is robust to background model systematics, very well correlated to the galactic center. The emission is observed both at the inner degrees and at higher-latitudes.

The DM case has been explored and seems compelling. We need to start looking in other indirect detection probes: antiproton CRs other gamma-ray targets.

Dwarf spheroidals is the next one. Further advances in extragalactic gamma-ray astronomy but also at other wavelengths will strengthen the indirect DM searches in the future as well. Also some direct detection signal?

The MSPs explanation has problems in terms of both the spectrum and the normalization of the needed “signal”.

Outburst of CRs… Especially CR electrons can produce an ICS signal that is ~spherical in nature, and be connected in their origin to the Fermi Bubbles
Thank you!
Important Questions regarding the Robustness of the DM-like signal

- How well have we probed the relevant uncertainties? Are the different methods used to probe the excess signal in the inner few degrees and at higher latitudes DIFFERENT/ORTHOGONAL ENOUGH?

- How well do we understand the diffusion/propagation of CRs in the inner part?

- Can we build up a new distribution of sources in the inner 1-2 kpc that have the right properties but are not close by to us? How would we see them?

- How about dSphs? (I will come back to this in a bit)

- How about galaxy clusters? (not optimistic yet due to large contamination from both background and foreground emission)

- How about the extragalactic diffuse emission? (see later discussion)
One can also study the ICS signal from DM annihilations (including astrophysical uncertainties):

Understanding the morphology of the signal in various windows can be crucial; FOR ANY model that wants to explain the GC excess via CR electrons(positrons) whether of DM origin or Not.
Some excitement the last few weeks…days

From Reticulum II (DES J 0355.6-5403) a new dwarf spheroidal galaxy

A. Geringer-Sameth et al.
arXiv:1503.02320

The Ret. II excess is still ~20 photons

From un-associated gamma-ray sources

B. Bertoni,
D. Hooper,
T. Linden
arXiv:1504.02087

D. Hooper & T. Linden
arXiv:1503.06209
Fermi Large Area Telescope

The Fermi LAT is a pair conversion detector on board the Fermi Gamma-Ray Space Telescope.

Characteristics:
- Energy range: 20 MeV to above 300 GeV
- Field of view (FOV): 2.4 sr
- Energy resolution: <10% (above 10 GeV)
- Angular resolution: < 0.15° (above 10 GeV)
- Launched: 2008

Main components:
- Anti-coincidence shield (plastic scintillator) with photomultiplier tubes
- Tracker (silicon strip detectors) with conversion foils (tungsten)
- Electromagnetic Calorimeter (CsI)